9th ANIMMA VALENCIA SPAIN

9-13 JUNE 2025

BOOK OF ABSTRACTS

The 9th International Conference on Advancements in Nuclear Instrumentation Measurement Methods and their Applications

cea

IFIC Institut de Física Corpuscular

CSIC Consejo Superior de Investigaciones Científicas

Vniversitat de València

Excelencia Severo Ochoa

amU Aix Marseille Université

Filière Instrumentation Faculté des Sciences

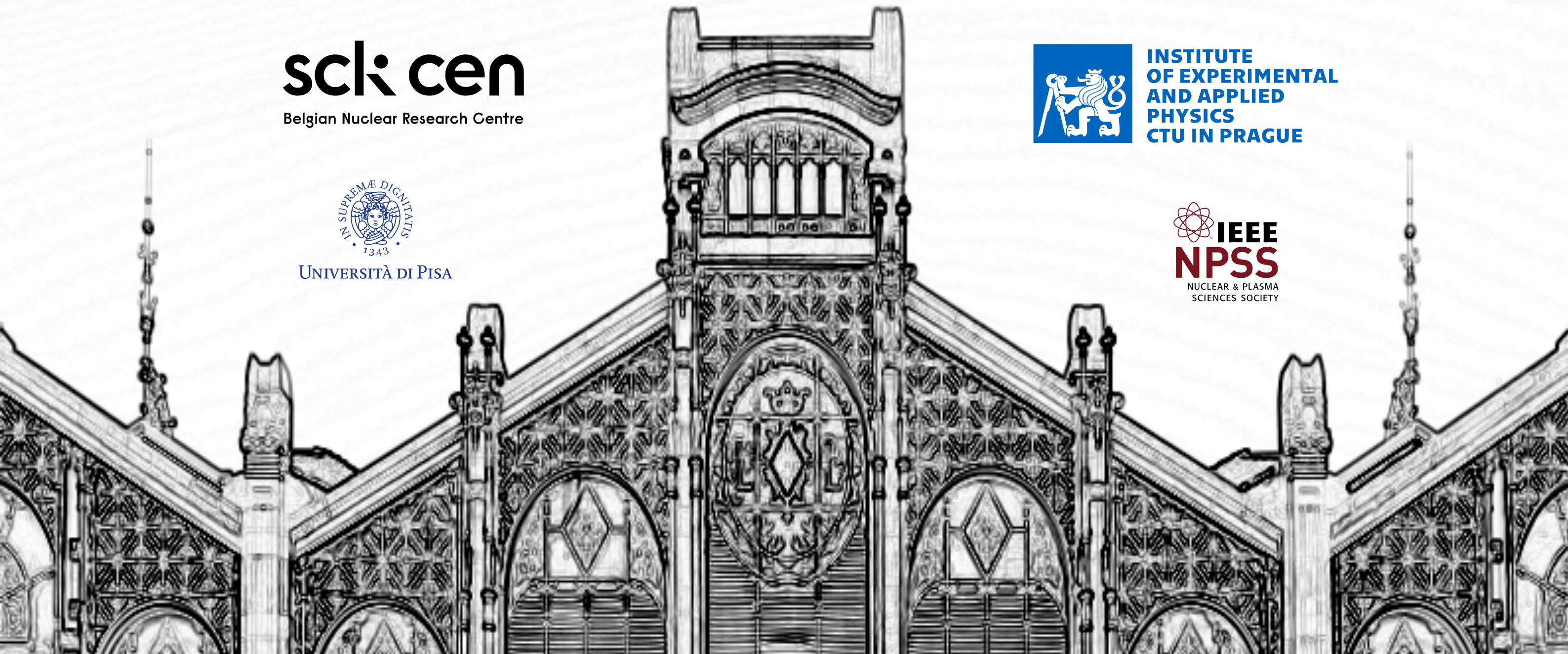
Jožef Stefan Institute Ljubljana, Slovenia

sck cen Belgian Nuclear Research Centre

Institute of Experimental and Applied Physics CTU in Prague

Università di Pisa

IEEE NPSS Nuclear & Plasma Sciences Society



Book of Abstracts of the ANIMMA 2025 conference.

Contents

#06 - Nuclear Safeguards, Homeland Security and CBRN / 2

#6-2 Combined peak searching and machine learning algorithm for identification of radionuclides

Author: Aliaksei Hutouski[1]

[1] *Polimaster Europe UAB*

Corresponding Author: hutouski@polimaster.com

Identification of radionuclides is an essential problem especially for border security and field measurements. Today there are two widely used types of methods for identification. They are: classical methods that process separate peaks (so called "peak-by-peak"methods) and newer methods that include different types of machine learning or spectrum convolution ("fit-at-once"methods). Each type has its own pros and cons. Traditional "peak-by-peak"methods consist of two steps: peak searching/filtering and some kind of decision-making sub-algorithm.

In our work we present the method that is a combination of machine learning and peak searching. We perform peak searching as usual, but without peak filtering step and then we use machine learning algorithm as a decision-making tool. Using peak searching as a first step give us more accurate data then the whole unprocessed spectrum and more predictable and controlled behavior of machine learning algorithm. Main advantages of our method are: absence of necessity to train machine learning algorithm on real spectra, we need only library data, and we don't need to create complicated "if-else"-based decision-making system.

The flowchart of our algorithm is following: searching peaks on the spectrum using spectrum convolution with second derivative of Gauss function; comparison of peaks found with library and creating the peak-presence matrix (at the first variant of our algorithm we use only information about presence of peaks); predicting of the result using the pretrained machine learning k-nearest neighbors-model.

We have tested our algorithm on more than 400 different gamma spectra including special nuclear materials natural occurring, industrial and medical radionuclides. As a result, we have all correct identifications except 6 false-positive results on Potassium-40. For the future work we are going to do the next steps: add more information in the peak matrix (such as peak amplitudes, deltas between library energy and energy measured and so on); collect more spectra for testing; enhance our algorithm with possibility to simultaneously identify more than one radionuclide.

#10 - Current Trends in Development of Radiation Detectors / 6

#10-6 ScintiPulses: A python package to simulate signal from scintillation detector

Author: Romain Coulon[1]

[1] *The International Bureau of Weights and Measures*

Corresponding Author: romain.coulon@bipm.org

Scintillation detectors are essential in fields such as nuclear physics, medical imaging, and radiation detection. Simulating their signals is key to develop advanced signal processing algorithms. This paper introduces a Python package, scintiPulses, which simulates signals from scintillation detector with a quantum illumination function, and comprehensive set of parameters and noise models.
In its theory of scintillation published 1964, J.B. Birks introduced the concept of illumination function to describe the pulse shape induced by an ionising particle interacting with a scintillation detector. This sum of exponentially decaying functions is parametrised with decay periods of the prompt and delayed fluorescence of the scintillator. While this model fits well with energetic pulse, it departs from the reality in the low energy domain where the quantum nature of the energy quanta (scintillation photons) deforms the pulse with a shot noise which could lead to a pulse train far from the original model.
A quantum illumination function is proposed in scintiPulses to simulate this shot noised pulses. It consists of sampling the number of energy quanta is a Poisson distribution parametrized with the deposited energy and the scintillation light yield to draw an illumination function corresponding to the average number of charges as a function of the time (inhomogeneous Poisson process).
These scintillation pulses, with arrival times taking values in the exponential distribution parametrised with the inverse of the input count rate, are concatenated to form a full stochastic train of pulses.
The thermionic noise (dark noise) is added with the Dirac-shaped pules of single charge those inter-arrival times taking values in an exponential distribution (homogenous Poisson process).
The resulting signal (scintillation pulses + dark noise) converted to a voltage given a transimpedance capacitance and is then smoothed with a gaussian kernel with standard deviation equal to the spread time of the photodetector.
The gaussian white noise (thermal noise) is added followed by an anti-aliasing Butterworth low-pass filter parametrized with the bandwidth of acquisition system. The model also considers the quantization noise from digital electronic with their voltage dynamic range to account for pulse saturation.
The resultant output signal is the combination of the scintillation signal, shot noise, dark noise, thermal noise and quantization noise. Additionally, the scintiPulses program offers the possibility to return the signal from the RC filter of a preamplifier and the CR filter of a fast amplifier.
As a case example, the program has been coupled with the TDCRPy Python code, a tool to simulate the scintillation physics, to simulate scintillation signals from realistic quenched deposited energies.
scintiPulses simulates realistic signal from scintillator and is therefore a key tool to develop advance signal processing especially useful to train machine-learning algorithms. An example a of signal filtering using Recurrent Neutral Network RNN and tagged dataset from scintiPulses is described to illustrate how the tool can be used to develop efficient signal processing. The scintiPulses package is made available to any Python developers on https://pypi.org/project/scintiPulses and open for collaborative development on https://github.com/RomainCoulon/ scintiPulses.

#01 - Fundamental Physics / 7

#1-7 SO(10) Model with Peccei-Quinn Symmetry and Impact of Family Symmetry on Neutrino Oscillations

Author: Marouane Benameur[1]

Co-authors: Rachid Ahl Laamara [2]; El Hassan Saidi [2]

[1] *University Mohammed 5 Facuty of science Rabat*

[2] *LPHE-MS, Science Faculty, Mohammed V University in Rabat, Morocco*

Corresponding Author: marwan1benameur@gmail.com

In this work, the grand unified theory (GUT) of SO(10) is analyzed in the context of Peccei-Quinn ($\mathrm{U}(1)_{\mathrm{PQ}}$) symmetry and family symmetries. The SO(10) framework is chosen because it's a good candidate that can offer a possible solution for reconciling the Standard Model (SM) interactions with many problems that are currently facing particle physics, including dark matter, baryon asymmetry, and neutrino masses .

One of the notable characteristics of SO(10) is that the seesaw mechanism provides a natural explanation for the small neutrino masses. Right-handed neutrinos are part of the model by nature; they contribute to the production of light neutrino masses through the seesaw mechanism, which explains why neutrinos are substantially lighter than other fermions in the Standard Model. Furthermore, by considering the added axions as possible dark matter candidates, the Peccei-Quinn symmetry offers a very convincing solution to the strong CP problem. These axions are produced by breaking Peccei-Quinn symmetry and can be used as cold dark matter in cosmological models.

The integration of family symmetries into the SO(10) GUT model is a significant component of this work. These symmetries present new point of view to address the leptonic interactions and especially neutrino interactions, primarily by the introduction of new criteria that influences mixing angles and neutrino mass hierarchies. They can change the neutrino oscillation patterns, which is useful in understanding difficult phenomena like neutrinoless double beta decay. These changes can largely assist in solving some of the open experimental issues in the field of neutrino research today.

A key part of the work is addressing the unification of gauge coupling constants in the SO(10) GUT framework. The breaking of our model's gauge group is made possible by using multiple Higgs representations in one step, directly to the SM symmetry which is a good indicator that a Grand Unified Theory (GUT) is viable. A proton lifetime lower than 4.5×10^{34} years is predicted, and this is within the sensitivity range of soon to come experiments such as Hyper-Kamiokande. One of the main predictions of GUTs, the detection of proton decay, that could offer strong evidence of the unification at very high energy scales.

This model examines the influence of family symmetries on neutrino oscillations, as well as some potential implications for mixing angles and mass parameters. These symmetries can account for discrepancies in oscillation data observed in experiments like Super-Kamiokande and KamLAND. Data from accelerator, reactor, solar, and atmospheric neutrino experiments can help verify how sterile neutrinos fit into the model. Even a simple numerical analysis shows some irregularities in the usual oscillation patterns, suggesting the possibility of new physics beyond the Standard Model.

By combining family symmetries with Peccei-Quinn ($\mathrm{U}(1)_{\mathrm{PQ}}$) symmetry, the model creates a solid framework for explaining both neutrino oscillations and dark matter. Connecting these theoretical ideas with experimental results opens up new ways to explore the fundamental nature of particles and forces in the universe.

#08 - Severe Accident Monitoring / 8

#8-8 SAIGA: a highly innovative instrumented in-pile experiment dedicated to measuring the events occurring during an Unprotected Loss Of FLow-type severe accident in a Sodium Fast Reactor

Author: François Charollais[1]

Co-authors: Grégoire De Izarra [2]; Gwendal Blevin [3]; Frédéric Michel [3]; Emmanuelle DUFOUR [2]; Laurent Trotignon [4]; Pierre Gubernatis [4]; Yves Lejeail [1]; Andrea Quaini [5]; Laurent Maurin [6]; Thomas Blanchet [6]; Erlan Batyrbekov [7]; Alexandr Vurim [7]; Alexandr Pakhnits [7]; Viktor Baklanov [7]

[1] *CEA, DES, IRESNE, DTN, Cadarache, F-13108 St Paul Lez Durance, France*

[2] *CEA, DES, IRESNE, DER, Cadarache, F-13108 St Paul Lez Durance, France*

[3] *CEA, DES, IRESNE, DTN, Cadarache, F-13108 St Paul Lez Durance, France*

[4] *CEA, DES, IRESNE, DTN, Cadarache, F-13108 St Paul Lez Durance, France*

[5] *CEA, DES, IRESNE, DER, Cadarache, F-13108 St Paul Lez Durance, France*

[6] *Université Paris-Saclay, CEA, LIST, F-91120 Palaiseau, France*

[7] *NNC-RK, Kurchatov, Kazakhstan*

Corresponding Author: francois.charollais@cea.fr

In case of a severe accident in a Sodium Fast Reactor (SFR), several successive physical phenomena, such as temperature rise, sodium boiling, in-vessel pressure increase, relocation of UO2 molten core and neutron fluxes evolution, are coupled. These phenomena can lead to power excursions. In order to inhibit potential power excursions in SFR core in the case of a hypothetical severe accident, in-core mitigation devices have been designed. One of these devices is the discharge tube, whose aim is to relocate core molten materials towards a core-catcher placed in the bottom part of the reactor vessel, and thus prevent prompt criticality. Among the three main possible severe accident scenarios, CEA decided to focus on the Unprotected Loss Of Flow (ULOF). Even if large number of experiments have already been conducted in CABRI reactor through SCARABEE tests program, several gaps in experimental knowledge were identified.
In that context, CEA and NNC-RK are jointly preparing an in-pile test under the SAIGA (Severe Accident In-pile experiments for Gen-IV reactors and the Astrid prototype) program. The goal is to study the degradation of the SFR fuel sub-assemblies during the ULOF phase in the case of multi-sector test. Two fuel sub-assemblies composed of 16 fuel pins with different enrichments allow getting two different powers, while one sector filled with sodium (without fuel) corresponds to a corium discharge tube. The test device currently under construction will be hosted within the Impulse Graphite Reactor (IGR) operated by NNC-RK in Kazakhstan, and is scheduled for experimental testing by the end of 2025. A sodium loop will be connected to the in-pile device to bring sodium flow inside the in-pile test device. The main objectives of this SAIGA experiment are:
- to improve our understanding of mitigation strategy in case of degradation of the SFR fuel during the ULOF phase;
- to enrich the experimental database needed to validate the mechanistic scientific computational tool named SIMMER-V within the SEASON platform dedicated to the simulation of SFR core degradation during severe accidents.
From the experimental point of view, the SAIGA test will be carried out in two phases: a first phase which aims to reach a nominal steady state of SFR, followed by a second one corresponding to the ULOF event. While the liquid sodium is circulating at 400°C within the test section, the IGR will quickly reach its nominal power in order to bring the test section into a thermal equilibrium representative of SFR nominal thermal hydraulics conditions. This first phase during which steady state is reached is estimated to last about 10 seconds. While maintaining reactor power, the sodium flow rate will be progressively reduced, leading rather quickly to sodium boiling (estimated to occur less than 10 seconds after starting the progressive shutdown of sodium pumps). The degradation of the fuel, before the breakthrough of walls between fuel sub-assemblies and discharge tube, is estimated to occur between 5 and 10 seconds later.
In order to record the various physico-chemical events occurring at a rather high frequency and collect precious experimental data, special attention is being paid to the instrumentation of the SAIGA test section. Despite very strong constraints in terms of pressure, temperature, tightness and available space, the SAIGA test section will include a large number of different types of sensors, which

will be detailed in this article. Some of these, such as the Optical Fiber Bragg Grating sensors helically wounded around the fuel pins in place of the spacer wire, are highly innovative and exposed to high levels of radiations never experienced before. The introduction of each type of sensor is also justified in terms of events predicted by the SIMMER-V code.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 9

#6-9 An Italian software infrastructure for the safe use and tracking of HASS and their use and management

Authors: Erica Fanchini[1]; Francesco Teodori[2]; Lorenzo Isolan[2]; Marco Sumini[2]

Co-authors: Francesco Rogo [3]; Giacomo Mangiagalli [3]

[1] *CAEN s.p.a.*

[2] *UNIBO*

[3] *CAEN*

Corresponding Author: e.fanchini@caen.it

In recent years, the management of radioactive materials, especially High Activity Sealed Sources (HASS), has come under increased scrutiny due to heightened concerns regarding radiation safety and regulatory compliance. These sources, which have a wide array of applications in industry, medicine, and research, require strict control mechanisms to ensure their safe use and handling. To address these needs and comply with the new Italian regulation DGLS 101/2020, CAEN, in collaboration with the University of Bologna, has developed a robust software infrastructure that integrates seamlessly with the Italian national ISIN STRIMS portal for the management and tracking of radioactive materials with a handheld gamma spectroscopy system, the RadHand to associate the source information to the Hass database. This solution provides an all-encompassing framework for ensuring both safety and compliance in the management of HASS while improving operational efficiency. The regulation mandates rigorous protocols for the management of radioactive sources, including real-time reporting to the national authorities via the STRIMS portal. This platform is designed to ensure full transparency and traceability of radioactive materials within Italy. A central feature of the software is its integration with the STRIMS portal. This integration significantly reduces the administrative burden on organizations by automating the process of submitting information to national authorities, ensuring that all required data is accurately reported in real time. In addition to compliance with STRIMS, the system includes not only the registration of radioactive materials, but also the control of their movements, and detailed logging of their use using the RadHand system and RFID tags associated to sources, containers and users. A key innovation is the use of RFID technology for identifying both operators and the radioactive sources they are working with. Each source is equipped with an RFID tag that allows for its unique identification, while operators are also equipped with RFID badges that identify them within the system. This dual-identification mechanism ensures that only authorized and qualified personnel are allowed to handle radioactive materials. Another critical feature of the software is its ability to track not only the radioactive sources but also the activities and locations in which these sources are being used thanks to the RadHand that, in parallel to provide physical information allows the user to work safely providing dose rate and spectroscopic information. In addition to real-time tracking and safety features, the software infrastructure also stores all collected data in a secure, centralized database. This database not only facilitates the generation of the required outputs for STRIMS but also serves as a repository for historical data on the use of radioactive sources. Organizations can use this database for internal audits, performance reviews, and future planning. The availability of historical data also aids in identifying trends in the use of radioactive materials, allowing organizations to improve their operational procedures over time.
In conclusion, the infrastructure developed by CAEN and the University of Bologna represents a significant advancement in the management of High Activity Sealed Sources. By integrating real-time tracking, automated regulatory reporting, comprehensive safety features, and a complete database, this solution offers a robust framework for the safe and efficient handling of radioactive materials. The system not only improves worker safety and operational efficiency but also simplifies the compliance process, making it easier for organizations to meet the stringent requirements of DGLS 101/2020. As the use of radioactive materials continues to grow in various industries, solutions like this will play a critical role in ensuring both safety and regulatory compliance.

#07 - Decommissioning, Dismantling and Remote Handling / 10

#7-10 Nuclear Waste Characterization with Novel Spectroscopic Scintillator Systems for Free-release measurements in D&D Activities

Authors: Cristiana Del Bene[None]; Erica Fanchini[1]; Lucas Gevaert[2]; Paola Garosi[3]

Co-authors: Giacomo Mangiagalli [4]; Massimo Morichi [4]

[1] *CAEN s.p.a.*

[2] *Aix-Marseille Université*

[3] *CAEN S.p.A.*

[4] *CAEN SpA*

Corresponding Author: e.fanchini@caen.it

Nuclear waste management requires testing and analyses of the radioactive content and assessing the quality of the final waste forms and packages to characterize the waste and check for potential radiological hazards. The radioactive substances can be contained into a variety of materials, like concrete, steel, wood, etc. Quality of the measurements as well as time and adaptability to specific different geometries will be an asset especially during nuclear decommissioning activities where maximization of material recycling together with minimization of waste volume is a key cost driver. Scintillators allow to execute in many cases most of the required characterization measurements thanks to the very high efficiency they are offering and that are scalable in size, to allow also even very large forms/packages up to BigBags and ISO container or large metal plate of conveyor belt for soil sorting.
The work presents a detailed characterization with a 220 l mock-up nuclear waste drum composed of four different layers of materials with different thickness and density. The MDAs (Minimum Detectable Activities) have been calculated in all the configurations using a Cs-137 radioactive source and different types of organic scintillating crystals, like NaI(Tl), BGO, CeBr3 of different sizes and comparison with HPGe. In addition, other measurement conditions were tested, including the depth of the source in the matrices, the distance between the detectors and the drum, and the rotation angle, to be able to obtain a comprehensive study of the MDA in different configurations of the setup.
The study intends to offer an analysis for the selection of the detectors most suited for efficient gamma spectroscopy in nuclear waste applications and the characterization of the waste packages. This work can make a significant contribution in the determination of the specific setup (detector and geometry configuration) for the best waste characterization where MDAs below the national regulation limits for free release are required.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 11

#6-11 Novel nuclear measurements and systems for facilitating the implementation of Safeguards and Safeguards-by-design in new SMR, AMR and Microreactor

Author: Massimo Morichi[1]

[1] *CAEN SpA*

Corresponding Author: m.morichi@caen.it

Over the last five years starting in 2019, several nuclear measurement systems have been conceived and realized for specific nuclear safeguards applications, as well as for nuclear security, implementing some innovative technologies and methods for attended and unattended nuclear measurements.

Some of those technologies imply the integration of combined gamma and neutron detection systems both for counting and spectroscopic applications that allow the SNM (Special Nuclear Material) verification and quantification through specific simultaneous measurements (gamma and neutron) from standard to high count rate due to high flux irradiation.

IAEA has implemented some of these technologies in key international safeguards inspections worldwide like a Fast Neutron Collar Monitor for fresh fuel verification of U235 mass (used during inspections for material declaration verification) or for unattended measuring systems with a novel shift register installed in an anti-tampering sealed housing in unattended mode (remote inspection and continuous monitoring) together with a novel Unattended Multichannel Analyzer for spectroscopy analysis of SNM like canisters.

Such developments, realized with integrated mid resolution scintillators (FWHM : <3,5%) together with organic scintillator such as Stilbene detectors or Liquid sealed scintillators like EJ-309 with great pulse shape discrimination managed by a fast DAQ and with high level of system integration, are offering in the near term the possibility to enhance further their implementation, reducing the form factor in order to facilitate their implementation in many critical parts of the Nuclear Fuel Operations as well as of the Next generation of Nuclear Reactors. This will facilitate embedding these novel technical solutions in the next generation of nuclear installations, assuring the implementation of the Safeguards by Design requested by IAEA for all future/novel nuclear installations.

This work presents the most recent designs/systems and provides some clear examples of on-going applications on the Fuel Cycle-Fuel Fabrication as well as for the new SMR/AMR and microreactors.

Detailed technology testing and validation in different configuration if provided together with some case-studies and operational implications.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 13

#6-13 Assessment of radiological dispersal devices in densely populated areas: simulation and emergency response planning

Authors: Yassine El Khadiri[1]; Ouadie Kabach[1]; El Mahjoub Chakir[1]; Mohamed Gouighri[1]

[1] *Materials Physics and Subatomics Laboratory, Physics Department, University Ibn Tofail, Kenitra, Moroc*

Corresponding Author: yassine.elkhadiri@uit.ac.ma

The increasing threat of terrorism involving Radiological Dispersal Devices (RDDs) necessitates comprehensive evaluation and preparedness strategies, especially in densely populated public areas. This study aims to assess the potential consequences of an RDD detonation, focusing on the effective doses received by individuals and the ground deposition of radioactive materials in a hypothetical urban environment. Utilizing the HotSpot code, simulations were performed to model the dispersion patterns of cesium-137 (Cs-137) and americium-241 (Am-241) under varying meteorological conditions, mirroring the complexities of real-world scenarios as outlined in recent literature. The motivation behind this research stems from the ongoing concerns regarding public safety in major urban centers. The objectives of this study include (1) developing realistic hypothetical scenarios involving an RDD explosion in a crowded area, (2) simulating the dispersion of radioactive materials to predict the health impacts on the population, and (3) providing actionable insights for emergency response planning. The analysis will focus on key parameters such as effective dose calculations and the extent of ground contamination, aiming to enhance preparedness protocols for first responders and public health officials.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 14

#5-14 Improvements of gamma radiotracer measurements and modelization on the Colentec loop in Cadarache for the quantified analysis of the clogging phenomena in Steam Generators

Author: Laurent Loubet[1]

[1] *CEA Cadarache*

Corresponding Author: laurent.loubet@cea.fr

The Tube Support Plate blockage, also named clogging, is a complex phenomenon that can occur in the steam generator of Pressurized Water Reactors. This deposit of iron oxides, that can reduce the coolant flux and constraint the primary tubes, could have significant consequences on heat exchanges and the integrity of the primary tubes. Since 2014, the representative dedicated equipment, named COLENTEC loop at Cadarache had already provide a large number of results on the physico-chemical properties of the deposit formed in specifics thermohydraulic and chemical stable conditions. A major improvement was the switch to an active configuration in 2017 allowing the injection of a gamma radiotracer 59Fe inside the circuit. Using dedicated gamma measurement stations specifically designed by our laboratory, coupled with post-processing numerical modelling, we became able to determine on-line and then to quantify the influence on clogging of the following parameters such as the chemistry, the temperature, the pressure without waiting for the opening and the dismounting of the test section. The knowledge acquired over four active campaigns now gives us an overall view of the test section and the experimental configurations required for a pertinent analysis of the phenomena. This experience feedback is also now sufficient to enable us to make our modeling more reliable, with a view to advanced quantitative analysis.
Based on previous results and limitations, this paper first presents the specific experimental equipment recently set up on the loop on a dedicated location, in order to obtain measurements that are more representative of the phenomena involved.
The experience gained from previous campaigns has also given us a better understanding of the loop's peculiarities. As a result, the previous partial models previously developed individually for each campaign have been reviewed and optimized. The new model presented here now takes into account the entire test section. The code's architecture, its modularity, its iterative conception now makes it simple and efficient to take into account any changes in detector, geometry, emission source, etc.
The document presented here, on the improvements made to both measurement and modeling, now makes it possible to envisage more relevant acquisitions and even more precise quantifications. It therefore improves the understanding of clogging and could lead to better management of the maintenance of steam generators in power plants.

#04 - Research Reactors and Particle Accelerators / 15

#4-15 Interest of optimizing the response of a high-temperature ultrasonic transducer by integrating a porous aluminum backing element for detection of structures immersed in liquid sodium.

Authors: Gregory Chabanol[1]; Didier Laux[1]; Eric Rosenkrantz[1]; Aubin Paveyranne[2]; Florian Baudry[1]; Jean-Yves Ferrandis[1]

[1] *IES, Univ Montpellier / CNRS*

[2] *IES, Univ Montpellier / CNRS & CEA/DES/IRESNE/DTN/STCP/LETH*

Corresponding Author: jean-yves.ferrandis@umontpellier.fr

With the emergence of major applications in harsh environments, the scientific and industrial community expresses a real need for developing a range of instrumentation dedicated to monitor, control, and check resistance to ageing and damage of a large panel of structure. In nuclear domain, there are needs in the frame of instrumentation of Material Testing Reactors (MTR) and of the new generation of nuclear reactors and power plants but also in the field of nuclear reactors cooled by optically opaque liquid heavy metals such as sodium, lead and lead-bismuth for visualization or telemetry. Ultrasonic transducers are particularly well adapted to address this issue. Up to date, only a few prototypes of ultrasonic transducers exist.

A conventional ultrasonic transducer is generally constituted of several layers: an active element (piezoelectric disc), a backing element, one or more quarter-wave matching layers, all acoustically coupled. The backing element is of first importance as it controls the sensitivity and broadens bandwidth via its acoustic impedance, increasing the temporal resolution of the reflected echoes. It is therefore important to find new backing materials suitable for manufacturing high-temperature ultrasonic probes.

Thanks to the use of a specific backing material produced by uniaxial pressing of an aluminum powder containing a small amount of wax followed by sintering, we designed an ultrasonic prototype transducer dedicated to continuous high temperature experiments. The first experiments were tested with a 1-centimeter-thick steel sample. The probe is a homemade Cerium-modified NBT based 10 MHz. This sensor, with a thickness of 5 mm, tested from room temperature up to 350℃, turned out to be entirely consistent with what one might expect for echographic time-resolved measurements. We also managed to determine temperature-dependent velocity propagation equations consistent with the literature.

Because the small sensor thickness, it can be used in a variety of experiments in difficult environments where space is limited or when the medium is opaque : measurement in sodium reactors was envisaged. The response of the sensor with and without backing was modelled for the visualization of metal structures immersed in liquid sodium. The modification of the sensor bandwidth and therefore the length of the echoes allows better temporal separation of the objects.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 16

#6-16 Advancements in Illicit Material Detection Using Active Photon Interrogation and Photoneutron Spectrometry: Proof of Concept and Application to Homeland Security

Author: Clément Besnard-Vauterin[1]

Co-authors: Benjamin Rapp [2]; Valentin Blideanu [2]

[1] *French Atomic Energy Commission*

[2] *Université Paris-Saclay, CEA-List, Laboratoire National Henri Becquerel (LNE-LNHB) F91120, Palaiseau, France*

Corresponding Author: besnard.clement@gmail.com

The growing threat posed by the trafficking of illicit materials, including explosives, narcotics, and chemical weapons, requires the development of robust, non-intrusive detection techniques capable of providing fast and accurate on-site assessments. In this context, active photon interrogation methods have shown potential interest but have remained underexplored in applications not related to actinide detection [1]. Over the past two years, we achieved significant progress in the development of a novel approach using active photon interrogation combined with photoneutron spectrometry to address this challenge. This paper presents a comprehensive update on the research, demonstrating its successful transition from early-stage simulations and fundamental measurements to the proof of concept and its validation through realistic detection scenarios with direct relevance to homeland security.

Traditional non-intrusive inspection techniques, often based on neutron-induced reactions [2], rely heavily on gamma-ray spectrometry, which presents significant limitations due to high levels of background noise and the complexity of interpreting spectra in real-time. In contrast, active photon interrogation offers a promising alternative, particularly when applied to the detection of conventional explosives, narcotics, and other illicit materials containing light elements such as nitrogen, oxygen, and carbon. These elements can undergo photo-nuclear reactions when exposed to high-energy photons, producing photoneutrons whose energy spectra can be analyzed allowing the identification of the material's composition.

Two years ago, preliminary work on this method was presented at the 2023 ANIMMA conference [3], where Monte-Carlo simulations using FLUKA, GEANT4, MCNP and PHITS codes were used to explore the feasibility of the application based on photo-nuclear reactions for the detection of illicit materials. These initial studies demonstrated significant differences in the modeling of light elements' nuclear levels across the simulation codes and highlighted the need for improved experimental validation and data-driven methods for interpreting photoneutron spectra. Since this initial contribution, substantial progress has been made in the experimental and analytical development of the proposed method, allowing the transition from theoretical simulations to practical applications, leveraging both the photon source based on our Varian TrueBeam medical accelerator and deep learning algorithms, in order to detect illicit materials in very realistic, and consequently challenging scenarios.

A series of experiments were conducted using a Varian TrueBeam medical accelerator, specially adapted to fulfil our needs, to generate photon beams with energies up to 22 MeV. The resulting beams were directed on various target materials, inducing photo-nuclear reactions at the origin of measurable photoneutron spectra. To ensure accurate results, we employed a carefully designed detection set-up. EJ309 and BC-501-A liquid organic scintillators were calibrated and successfully used to measure the fast photoneutron spectra in the very challenging mixed short-pulsed fields with intense photon flashes generated during the irradiations. Multiple types of unfolding techniques were used to accurately reconstruct the photoneutron energy distributions [4].

The proof of concept is presently successfully provided through a series of detection experiments involving realistic scenarios for homeland security applications. One of the key breakthroughs was the detection of melamine, an explosive simulant material with high nitrogen content, hidden in various complex and realistic environments. The first case was a suitcase filled with clothing interrogated using our active photon method. Despite the presence of a high quantity of non-threatening

materials (10 kg of clothes), we successfully identified the presence of melamine, as indicated by the characteristic photoneutron signatures from the reactions on nitrogen. The second case was a more complex scenario where melamine was concealed inside a large wooden freight box containing copper cables and electronic equipment weighting more than 10 kg. Even with the highly attenuating copper and high photoneutron contribution from metallic parts, our method was able to detect also in this case the presence of melamine, showcasing the robustness of the approach for real-world applications.

The experimental results achieved validate the potential of the active photon interrogation combined with photoneutron spectrometry in detecting illicit materials in complex environments and therefore extending the use of active photon interrogation to the detection of threats other than actinides. Future work will focus on expanding the range of detectable materials, refining the machine learning models for enhanced accuracy, and conducting additional field trials to further validate the system's performance in operational environments. This research lays the groundwork for a new generation of non-intrusive inspection techniques capable of addressing the evolving threats posed by illicit material trafficking.

[1] M. Gmar et al., "Detection of nuclear material by photon activation inside cargo containers", Proceedings of SPIE Defense and Security Symposium, Orlando, Florida, 17 –21 April (2006).
[2] Y. Zhao, T. Cui, Y. Yang, "The design of a photoneutron source for the narcotic drugs detection in a large-truck", Proceedings of 2017 IEEE Nuclear Science Symposium and Medical Imaging Conference (NSS/MIC 2017), Atlanta, Georgia, 21-28 October (2017).
[3] C. Besnard-Vauterin, V. Blideanu, B. Rapp, "Development of a new method for the detection of illicit materials based on the active interrogation method and photoneutron spectrometry", in Proc. of 8th Int. Conf. Advancements in Nuclear Instrumentation Measurement Methods and their Applications (ANIMMA), Lucca, Italy, June 12–16, 2023.
[4] C. Besnard-Vauterin, B. Rapp, V. Blideanu, "Neutron detection in mixed short-pulsed fields with intense photon flashes for LINAC-based active interrogation applications", Nuc. Inst. Meth. in Phys. A, 1064, 169403, (2024).

#07 - Decommissioning, Dismantling and Remote Handling / 17

#7-17 Ultrasonic detection of radiolysis bubbles generated in bitumen for dose between 6 and 100 kGy.

Authors: Didier Laux[1]; Hanaa Houjeij[2]; Céline Montsanglant-Louvet[2]; Georges Matta[3]; Sylvain Poirier[2]; François Millet[4]; Jean-Yves Ferrandis[1]

[1] *IES, Univ Montpellier / CNRS*

[2] *IRSN-PSN-RES/SCA/LECEV*

[3] *IES, Univ Montpellier / CNRS & IRSN-PSN-RES/SCA/LECEV & IRSN-PSE-ENV/SPDR/USDR*

[4] *IRSN-PSE-ENV/SPDR/USDR*

Corresponding Author: jean-yves.ferrandis@umontpellier.fr

Low and medium activity nuclear sludges generated during the reprocessing of nuclear spent fuel have been stored since the 1960's in bitumen. Indeed, bitumen presents many advantages regarding criteria for a long-term storage: high agglomerating power, high chemical inertness, non-permeability, low solubility in water, high confining power…In practice, coprecipitation salts are added to nuclear sludges (BaSO4, NaNO3…) to avoid any solubilization of liquid wastes in bitumen matrix. Even if it seems that on a chemical point of view, the bitumen packages are stable, radiolysis due to self-irradiation occurs and leads to the formation of gas bubbles (essentially hydrogen) which can significantly elevate the fire and explosion risk when released. Consequently, the role of these bubbles has to be precisely determined. More precisely, the aim of this work is to better understand the mechanisms of formation and evacuation of radiolysis gases when the temperature increases. Obviously, direct optical observation of bubbles is not possible because of bitumen opacity.

Some bitumen samples had been made in order to study these bubbles. Only X-ray tomography can be used on these small samples, previously irradiated to form H2 bubbles with various radii and volume fractions. This type of studies has been widely investigated in previous studies. Even if X-Ray tomography is the most actual accurate tool, it is not possible to perform measurements online during irradiation. Furthermore, no study at high temperature (namely 100-150°C) to evaluate bubble rising in the event of fire is available. To address this issue and refine existing results in term of bubbles properties versus irradiation dose or temperature, and to improve understanding of bitumen package thermal behaviour, we have proposed to use ultrasonic waves.

In this context, we will investigate the influence of bubbles on ultrasonic wave velocities in a first step, in order to detect bubbles in an elementary representative volume. In this framework, the ARISE project, supported by the National French Research Center (CNRS) and the Institute of Radioprotection and Nuclear Safety (IRSN), began in 2023 to explore the feasibility of ultrasonic methods to detect the appearance of radiolysis bubbles under gamma irradiation and track them in real-time during temperature increases.

In the present communication we present very first results concerning bitumen irradiated in IRMA French irradiator, from IRSN BOREE experimental platform, with total integrated doses of 6, 50 and 100 kGy. Regarding our previous work on non-irradiated bitumen, investigations were conducted with 500 kHz transducers in transmission mode. Ultrasonic velocity measured is very sensitive to bubbles (their presence and morphology was proved with X-Ray comparative tests) and a decrease of

around 350 m.s-1 was observed between non-irradiated bitumen and irradiated bitumen at 100 kGy. These first results, which clearly demonstrate the potentialities of ultrasound for radiolysis bubble cloud evaluation, will be presented and discussed. First interesting elements concerning the minimum dose leading to H2 bubbles appearance and nucleation will be given.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 19

#5-19 Radiation-Induced Attenuation and Drift in Fiber-Optic Sensors at Extreme Neutron Fluence

Author: Christian Petrie[1]

Co-authors: Bryan Conry [1]; Matthew Kurley [1]; Eddie Lopez Honorato [1]; Daniel Sweeney [1]

[1] *Oak Ridge National Laboratory*

Corresponding Author: petriecm@ornl.gov

The use of fiber-optic sensors in extreme fission- and fusion-based reactor applications requires that the sensors provide strong, reliable signals during prolonged exposure to a high neutron flux. The primary limitations for fiber-optic sensors in high-radiation environments are radiation-induced attenuation (RIA) of the transmitted light signal and radiation-induced drift that cannot otherwise be separated from the variable of interest (e.g., temperature or strain). Despite many decades of research, gaps remain in the current understanding of both RIA and drift. These gaps include the separate effects of fiber composition, coatings, dose, dose rate, and temperature, as well as the effects of different types of inscribed fiber Bragg gratings (FBGs). Data are particularly lacking at high neutron fluences corresponding to dose levels on the order of displacements per atom (dpa).

This work evaluated the response of a wide range of fiber-optic sensors during irradiation testing in Oak Ridge National Laboratory's High Flux Isotope Reactor to a fast neutron fluence as high as 3×10^{21} n/cm^2, which corresponds to approximately 4.2−4.5 dpa. The goal was to separate the effects of fiber attenuation vs. attenuation of the FBGs by including fibers with and without inscribed FBGs and to evaluate trends with respect to fiber dopants, coatings, and FBG types. Singlemode fibers were tested with various core and cladding dopants (Ge, F, or pure SiO2), fiber coatings (acrylate and polyimide), and inscribed FBGs (Types I and II). All FBGs were inscribed with approximately similar reflectivity and the same center wavelength (~1,550 nm) but could still be isolated using an optical frequency domain-based interrogation method. Specifically, an Optical Backscatter Reflectometer Model 4600 from Luna Innovations was used to sweep across a range of approximately 42 nm and record the backscattered light intensities originating from the FBGs and/or Rayleigh backscatter from density fluctuations within the fiber. Fourier analysis was performed to isolate reflections at specific locations along each fiber. These reflections were transformed back into the spectral domain to determine wavelength shifts (drift) and changes in the reflectivity originating from FBGs or other mechanisms (e.g., Rayleigh backscatter).

Similar to results from previous studies, the results from this study showed superior FBG stability in fibers with a pure SiO_2 or F-doped SiO_2 core compared with fibers with a Ge-doped core (telecommunications fibers). Additionally, Type II FBGs showed significantly higher stability compared with Type I FBGs. Interestingly, the Type II FBGs inscribed in fibers with F doping in both the core and the cladding showed significantly higher stability than those inscribed in a pure silica core fiber with F-doped SiO_2 cladding, indicating that F-doped core fibers can improve RIA, FBG stability, or both under these conditions. By contrast, a Ge-doped core fiber exhibited increased RIA relative to the pure silica core fibers with F-doped SiO_2 cladding. All fibers (with and without FBGs) exhibited prohibitively large signal drift that was found to be unrelated to radiation effects in SiO_2 (i.e., compaction). Subsequent out-of-pile thermal testing was performed to elucidate the evolution of the fiber coatings in different environments (oxygen, inert) and temperatures. Raman spectroscopy performed on the fiber coatings that were heated under certain conditions provided convincing evidence that both coating materials decompose into glassy carbon, which is known to be particularly susceptible to radiation-induced dimensional changes. These results have important implications for the future development of fibers and FBGs for various high-dose nuclear applications. The most important findings are (1) the combination of F-doped core fibers and Type II FBGs offers the most promising performance at high neutron fluences and (2) polyimide and acrylate coatings should be avoided for intrinsic fiber-optic sensors because they decompose into a glassy carbon that compacts significantly when irradiated, causing prohibitively large drift.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 20

#6-20 A Compact Solution for Detecting and Identifying Radioactive Gases Through Coincidence Quenching

Author: Benoit Sabot[1]

Co-authors: Christophe Dujardin [2]; Fréderic Chaput [3]; Fréderic Lerouge [4]; Matias Rodrigues [1]; Sylvie Pierre [1]; Yannis Cheref [2]

[1] *Université Paris Saclay, CEA, LIST, Laboratoire National Henri Becquerel (LNE-LNHB), 91192 Palaiseau, France*

[2] *Université Claude Bernard Lyon 1, CNRS, ILM UMR 5306, Villeurbanne, France*

[3] *Laboratoire de Chimie, Ecole Normale Supérieure de Lyon, Université Claude Bernard Lyon 1, CNRS, UMR 5182, Lyon, France*

[4] *3Laboratoire de Chimie, Ecole Normale Supérieure de Lyon, Université Claude Bernard Lyon 1, CNRS, UMR 5182, Lyon, France*

Corresponding Author: benoit.sabot@cea.fr

The measurement of pure β-emitting radioactive gases, such as tritium (^3H) and krypton-85 (^{85}Kr), is critically important for nuclear safety authorities, particularly for environmental and safety assessments of nuclear facilities. The demand for these measurements is expected to increase with the global expansion of nuclear energy production and the growing need for radioactive waste management. Due to the limited penetration depth of β particles in air, direct detection of gaseous β emitters requires their interaction with radiosensitive materials. Traditionally, these gases are detected through gas-gas mixtures in ionization chambers or gas-liquid mixtures in liquid scintillation systems. However, these methods are often destructive, especially in primary measurement techniques such as triple-differential proportional counters. Moreover, they are typically used to measure high concentrations—on the order of hundreds of $Bq\cdot cm^{-3}$—which are much higher by about 6 orders of magnitude than the concentrations found in the environment, often around hundreds of $Bq\cdot m^{-3}$. This leaves a gap in accurate and non-destructive methods for detecting lower concentrations in everyday environmental scenarios.

In this study, we introduce a novel concept and set of methods designed for non-destructive, direct measurement of radioactive gases at concentrations as low as $kBq\cdot m^{-3}$, with measurement times as short as 100 seconds. This new approach is based on a gas-solid mixture using highly porous inorganic aerogels as scintillators, that act as the detection medium. These aerogels are specifically designed to emit light when they interact with ionizing radiation from radioactive gases. The light emitted by the aerogels is detected by a system incorporating double or triple photomultiplier tubes (PMTs), providing efficient real-time measurement of β-emitting gases at low concentrations.

The device we developed is compact and designed to be integrated into routine monitoring systems at nuclear facilities or environmental sites. The measurement method relies on a simple yet effective coincidence quenching technique, which we developed within the scope of this study. This technique allows for the accurate detection of low-energy β particles by improving signal clarity through coincidence counting between multiple PMTs. Additionally, this method supports the measurement of gas mixtures (even pure beta emitters), which is a significant advance over traditional techniques that often struggle with complex mixtures of multiple radioactive isotopes. We will present the unmixing method developed to separate the signals from different gases, allowing individual radionuclide identification in mixed samples.

Experimental results from tests performed in a unique radioactive gas mixture chamber will be presented, showcasing the device's performance in detecting both ^3H and ^{85}Kr gases. These tests include a full characterization of the system's linearity and detection efficiency for each gas, both individually and when combined in mixtures. The system was found to provide accurate measurements over a wide range of concentrations, demonstrating its robustness and flexibility in various applications. The ability to efficiently and non-destructively measure low concentrations of β-emitting gases in real-time represents a significant step forward for nuclear safety monitoring and environmental protection.

In terms of future applications, this technology has the potential to be scaled and adapted to a wide range of radioactive gases beyond ^3H and ^{85}Kr. Its use in conjunction with portable or stationary

monitoring systems could provide valuable insights into atmospheric or industrial contamination, ensuring safer working conditions and improving compliance with safety regulations.

The authors acknowledge support from the European Community through grant n° 899293, HORIZON 2020 –SPARTE and the support of Laboratoire National de Métrologie et d'Essais (LNE) in the framework of SCINTIPLUS project.

#03 - Fusion Diagnostics and Technology / 21

#3-21 Characterization of the KATANA water activation loop in the JSI TRIGA reactor by reactor pulse operation using neutron detectors

Author: Julijan Peric[1]

Co-authors: Domen Kotnik [2]; Domen Govekar [1]; Luka Snoj [1]; Vladimir Radulović [2]

[1] *Jozef Stefan Institute*

[2] *Jožef Stefan Institute*

Corresponding Author: julijan.peric@ijs.si

KATANA is a water activation facility located in the Jožef Stefan Institute TRIGA Mark II reactor in Ljubljana, Slovenia. Since its commissioning at the end of 2023, it has completed three experimental campaigns that have contributed to a better understanding of the water activation processes and their modeling, which are important in the context of research in nuclear fusion, in particular for the future operation of the ITER machine. The facility is designed to provide a flexible benchmark-quality environment for the validation of computational tools for the activation of water and corrosion products. It will also support shielding experiments, in particular for ITER-relevant materials, and serve as a stable source of high-energy gamma rays and neutrons. The computational tools developed for ITER cooling loop characterization consist of two primary methods: computational fluid dynamics (CFD) in conjunction with neutronic simulations. These methods are crucial for the accurate modeling of distributed radioactive sources, such as the cooling water in future fusion plants. CFD focuses on detailed modeling of the thermal-hydraulics, while neutronic simulations are used to predict the behavior of neutrons and their interactions. By integrating these two approaches, a more accurate and comprehensive understanding of water activation under different operating conditions can be achieved. Usually, these calculation tools are validated by dose rate measurements at different positions around the radiation source to ensure the accuracy and reliability of the simulations. This approach is holistic, as the measurements combine neutron and flux information, which cannot be separated from each other. In the present study, a novel method was developed to characterize the water activation loop using neutron detectors during operation of the JSI TRIGA reactor in pulse mode. Pulse operation allows the irradiation of a finite amount of water in the inner end of the KATANA water activation loop in a short length of time, typically below 1 s. As the irradiated water circulates through the loop, it emits neutrons along the way; by measurements using neutron detectors around the loop it is possible to track the flow of the volume of activated water and infer information on the flow dynamics in the system. This approach provides valuable information on the KATANA device characteristics and enables increasing the accuracy of experimental data and improving predictive models for future fusion reactors.

#02 - Space Sciences and Technology / 22

#2-22 Ions and electron discrimination by Pulse Shape Discrimination technique : Application to solar energetic particles fluxes measurement around Mars (M-MATISSE-SP@M instrument)

Author: Vincent Thomas[1]

Co-authors: Benjamin Jeanty-Ruard [2]; Benoît Tezenas-du-Montcel [2]; Nicolas Andre [1]; Pierre Devoto [1]; Quentin Nénon [1]

[1] *IRAP/CNRS*

[2] *Artenum*

Corresponding Author: vthomas@irap.omp.eu

The M-MATISSE (for Mars - Magnetosphere ATmosphere Ionosphere and Space-weather SciencE) is an ESA Medium class (M7) candidate currently in Phase A study by the Europen Space Agency (ESA). The mission concept consists of two satellites observing Mars simultaneously from two different spatial positions. In particular, M-MATISSE will shed light on how the solar wind influences Mars' atmosphere, ionosphere and magnetosphere. The mission aims to study the impact of these interactions on the lower atmosphere and surface of Mars, a key aspect in understanding the habitability of the Red Planet, as well as the evolution of its atmosphere and climate. The SP@M (for Solar Particles @ Mars) instrument will measure Solar Energetic Particles (SEPs, mostly alpha particles, proton and electron) throughout the Martian magnetosphere and atmosphere. While most of today's on-board instruments discriminate particles using coincidence processing between 2 or more silicon detectors (SST) arranged as a telescope, where cross-contamination between detectors always occurs, SP@M proposes to use a single 1.5 mm thick silicon detector and to discriminate particle types using digital processing based on charge carrier collection time; proportional to particle penetration length inside the detector medium. This Pulse Shape Discrimination (PSD) concept, which has already proved successful in other fields as neutron/gamma ray discrimination, could drastically reduce data post-processing complexity, minimize the size of on-board electronics, and reduce the costs of future on-board instruments dedicated to solar particle measurement. After importing the CAD model of the SP@M system into Geant4, we irradiated (Monte-Carlo simulation) the silicon detector with proton, alpha and electron fluxes in the [30 keV - 10 MeV] energy range, representative of real solar particles fluxes around Mars. As output, the locations where electron-hole pairs for each incident particle are created are saved. Then, using the Garfield++ framework developed by the European Organization for Nuclear Research (CERN), we applied different electric fields to study the impact on charge drift velocity to the electrodes and necessary collection time. Finally, by integrating and convolving this number of collected charges with the transfer function of our charge sensitive preamplifier, we were able to estimate the pulse Rise Time. Even for low energetic particles (around 100 keV or lower), Rise Time measurement enables us to discriminate without ambiguity the type of simulated incident particles: 140 ns Rise Time duration for electron @ 100 keV vs 310 ns Rise Time duration for protons @ 100 keV. The next step of the project is to experimentally test our Geant4 model with 1.5 mm thick silicon detectors prototypes, using alpha and conversion electrons calibration sources under vacuum. If the experiment fits the Geant4-based simulations, this innovative concept will be a major breakthrough in solar particles measurement technique and viability.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 24

#6-24 Comparative analysis of automatic identification of radionuclide in gamma-ray spectrometry: machine learning versus statistical approaches

Author: Dinh Triem Phan[1]

Co-authors: Cheick Thiam [1]; Christophe BoBin [1]; Jérôme Bobin [1]

[1] *CEA*

Corresponding Author: dinh-triem.phan@cea.fr

Gamma-spectrometry is a widely used technique for identifying and quantifying gamma-emitting radionuclides in many nuclear applications such as rapid identification to prevent illegal trafficking of nuclear materials, decommissioning of nuclear facilities or in situ environmental analysis following a radiological or nuclear accident. For many years, there has been a growing trend to address the problem of automatic identification of gamma-emitting radionuclides by implementing Machine Learning (ML) approaches such as the multilayer perceptron or the convolutional neural network (CNN). This method is an end-to-end ML that uses a large training data set of different radionuclide mixtures. It is used as a black box, so the physical property such as Poisson noise or the linear nature of the mixture model is not explicitly taken into account. Besides this approach, the statistical method based on full-spectrum analysis with Poisson likelihood gives solid results. This method decomposes the observed spectrum into individual characteristic energy spectra depending on the decay scheme of each radionuclide (called spectral signatures) and employs the Maximum likelihood estimator (MLE) and statistical tests to identify radionuclides, quantify and calculate the uncertainty of the estimated counting. This study compares the identification performances of the ML and MLE approaches in three scenarios: firstly, spectral signatures are assumed to be known, corresponding to well-defined measurement conditions; secondly, spectral signatures are deformed due to physical phenomena such as Compton scattering and attenuation; and thirdly, spectral signatures are shifted due to factors like temperature changes. A large dataset of 200000 simulated spectra was generated for each case, varying the number of radionuclides present in the source, statistical levels, and mixing weights. A dictionary of spectral signatures of nine radionuclides (^{57}Co, ^{60}Co, ^{99m}Tc, ^{123}I, ^{131}I, ^{133}Ba, ^{137}Cs, ^{152}Eu and ^{241}Am) and an experimental natural background is investigated in this work. The spectral signatures were simulated using the Monte Carlo code Geant4 for a 3"$\times$3" NaI(Tl) detector. Regarding the ML approach, recent studies have shown that, among all the ML methods available in the gamma-ray spectrometry literature, CNN gives the best results and is therefore used in this work. In the current literature, radionuclide identification can be treated as a multi-label or binary classification problem in ML. This work integrates these two ML approaches by fine-tuning the various hyperparameters of the CNN, such as the number of layers, the learning rate, the number of filters, etc. Concerning the statistical approach, for the case of spectral deformation, a hybrid approach combining ML to model spectral signatures with variability and MLE, as well as statistical hypothesis testing, is applied. Numerical results show that the statistical approach outperforms the ML approaches for three tested scenarios in terms of accuracy and also has the ability to control the false alarm rate close to the predefined value, which is not possible for ML methods. However, the performance of this approach can be significantly reduced when spectral signatures are not modeled correctly. Thus, the full-spectrum statistical approach is most effective where spectral signatures are assumed to be known, corresponding to well-defined measurement conditions, or where spectral variability can be modeled. In other cases, where measurement conditions are not well-defined or difficult to model, end-to-end ML is a suitable alternative.

#09 - Environmental and Medical Sciences / 25

#9-25 First attempts at scalable readout electronics to efficiently exploit Cherenkov radiation in PET instrumentation

Author: Andrea Gonzalez-Montoro[1]

Co-authors: Antonio J. Gonzalez [1]; David Sanchez [1]; Francis Loignon-Houle [1]; Julio Barbera [2]; Riccardo Latella [3]

[1] *Institute for Instrumentation in Molecular Imaging (i3M), CSIC-UPV*

[2] *Oncovision S.A.*

[3] *Institute for Instrumentation in Molecular Imaging (i3M), CSIC-UPV; Metacrystal S.A.*

Corresponding Author: andrea.gm@i3m.upv.es

Positron Emission Tomography (PET) is established as the molecular imaging modality of choice for the study and diagnosis of different medical conditions such as cancer or neurodegenerative diseases. Current instrumentation research focuses on increasing the sensitivity of PET systems to provide faster imaging or/and a reduction of the dose administered to the patient. With this objective, it has been proposed to construct large axial coverage PET systems and/or boosting the signal-to-noise ratio (SNR) of the reconstructed PET images by including precise time-of-flight (TOF) information of the detected annihilation photons. Yet, implementing large coverage scanners presents, in addition to a huge investment (high cost), major mechanical challenges since they require large volumes of materials (big clinical facilities), a lot of electronical components and the ability to process massive amounts of data. Besides, enabling accurate TOF capabilities requires the development of fast and low-noise electronics in a scalable format.

Finding a compromise between the two-above mentioned solution will be the ideal scenario, and way to accomplish this is building large axial coverage PET systems using Bismuth Germanate Oxide (BGO) scintillators since they present high density, high photo-fraction, short attenuation length for 511 keV photons and a manufacturing price that can be a factor 2-3 times cheaper than the conventional lutetium-based scintillators. Moreover, the BGO's emission spectra has two main components, namely: i) scintillation light, which itself contains two components, the faster one having a decay time of 45 ns (8% of the scintillation emission) and a slower one having a decay time of 365 ns (92% of the scintillation emission), and ii) Cherenkov light, which represents ~0.2% of the scintillation emission, but has an ultrafast emission time in the range of picoseconds. These promptly-emitted photons (Cherenkov light, ~17 above BGO's absorption band) can be exploited to boost TOF performance since this type of light is generated much faster than the scintillator's main luminescence yield and thus can be used to derive faster timestamps for the photon arrival time to the detector.

However, detecting these Cherenkov photons is challenging and requires the implementation of specific readout electronics able to discriminate the events based on their dynamics (ultra-fast or fast), at a reasonable cost. The discrepancy regarding the dynamic characteristics of the events arises from the varying number of detected Cherenkov photons that affects the temporal behavior of the signals. Exploiting this low yield for timing measurements requires the implementation of novel detector electronics able to discriminate between these two emissions. Such electronic readout has to mitigate the influence of electronic noise on achievable timing performance, which is especially difficult and, to date, there are no scalable BGO-TOF detectors.

In this contribution we show our first steps towards designing and implementing a scalable readout solution for large coverage BGO-PET systems. Our custom-readout circuitry is based on a balun transformer to split the photodetector signals combined with a two-channel method for event discrimination. The discrimination is based on the estimation of the rising time of the signals which will be done by feeding the split signals into two ASIC channels with different threshold levels. We have already designed and fabricated the electronic board which provides identical split energy (x2) and timing (x2) signals. The output signals were fed the PETsys TOFPET2 ASIC for digitization.

For evaluation we used 3x3x5 mm3 BGO pixels with all lateral and entrance faces polished and covered with Enhanced Specular Reflector (ESR), to promote light collection. The exit face of the pixel was also polished but coupled to an FBK-HD-MT 3x3 mm2 Silicon Photomultiplier (SiPM) by means of optical grease which was also connected to the splitting boards. We assembled two of these detector elements and placed them inside a light tightened environment with the temperature stabilized to 23°C. A 22Na source was placed in between the two BGO pixels and coincidence data was acquired. To determine optimal measurement conditions different SiPM values of Vbias = [42.0-44.5] V in steps of 0.5V and different PETsys thresholds (thE, th1-low, th1-high, th2) were tested. Note that thE and th2 were the same for both split signals while th1 was different (th1-low, th1-high) to allow for the rise time estimation.

Despite very preliminary, these results served us to understand the BGO signal behavior and compatibility with the TOFPET2 ASIC. So far, we have results for the energy channels which already reported < 850 ps CTR. We are currently calibrating the timing path signals, which will enable us to apply software-based corrections based on signal dynamics to improve CTR. Note that, we have validated this hypothesis by testing the boards with a high-frequency oscilloscope, the CTR results improve from 390 ps (energy signals) to 240 ps when using the timing signals. We target for ~350 ps CTR using our readout solution + ASIC, and after applying corrections based on the signal dynamics.

#04 - Research Reactors and Particle Accelerators / 27

#4-27 EU OFFERR Project IRRADCOEFH Gamma Tolerance Test of Thermal COEFH Innovative Sensor

Authors: Olivier Braillard[1]; Stephane GAILLOT[2]

Co-authors: Jan Prehradny [3]; Martin Marecek [3]; Michal Cihlar [3]

[1] *CEA*

[2] *CEA-DES-IRESNE France*

[3] *CVR Rez*

Corresponding Authors: olivier.braillard@improveheat.com, stephane.gaillot@cea.fr

In the context of experiments aimed at characterizing the thermal exchanges between fluids, the determination of the h thermal exchange coefficient at the wall is requested.
In this context, an innovative COEFH thermal sensor has been developed and optimized to precisely measure this coefficient. The robustness of its measurement is obtained by performing various tests of the COEFH sensor's resistance to severe environmental conditions (pressure, temperature, irradiation,…). In this case, the tests presented in this paper aim to verify the gamma dose tolerance resistance of the sensor (at room temperature, without pressure).
The framework of this action is the European OFFERR program underway over the period [2022-2026] and which aims to carry out R&D actions in the facilities identified in the OFFERR network (https://snetp.eu/offerr/). The present action is called IRRADCOEFH.
This action was carried out in 2024 April-May through a collaboration between the CEA-DES-IRESNE (France) and the CVR located in the Czech Republic.
Tests performed with CVR's gamma irradiator allowed the electrical characteristics of the COEFH sensor to be continuously tested up to a gamma dose of 50 kGy. These tests were carried out over a period of 3.5 days. The first results obtained show a good behaviour of the sensor in the face of gamma irradiation without any observed degradation of its characteristics.
These tests made it possible to validate the use of the sensor under gamma radiative environment.
After a general description of the OFFERR project, the paper describes the irradiation tests performed with the COEFH sensor at the CVR and provides the first results obtained.

#10 - Current Trends in Development of Radiation Detectors / 28

#10-28 Neutron instrumentation of the LFR-30: case of the ex-vessel flux monitoring system

Authors: Kévin Irazoqui[1]; Quentin POUILLE[2]

Co-authors: Aurélien Bernard [2]; Axel Rizzo [1]; Florestan Ogheard [2]; Quentin Gestes [1]

[1] *Photonis*

[2] *newcleo*

Corresponding Authors: k.irazoqui@exosens.com, quentin.pouille@newcleo.com

The development of next-generation nuclear reactors, particularly those using lead as a coolant, has opened up new possibilities in reactor design, safety, and efficiency. One of the most critical aspects of ensuring the safe and effective operation of these reactors is the development of advanced neutron instrumentation systems. Traditional neutron monitoring technologies face significant challenges in the harsh environments presented by lead-cooled fast reactors (LFRs), which operate at high temperatures and involve complex neutron flux profiles due to the lack of moderation compared to traditional reactors such as Light Water Reactors (LWRs). Thus, neutron instrumentation tailored specifically for these reactors is, therefore, essential to enhance both performance monitoring and safety protocols.

Within this framework, a collaboration between newcleo and Photonis started in mid-2022, to define the most suitable solution to address the challenges of both in-vessel and ex-vessel neutron flux monitoring of the LFR-30 prototype, currently being designed by newcleo. This paper deals with ex-vessel instrumentation for intermediate and power monitoring, while future studies will tackle the in-vessel instrumentation.

After briefly presenting the main features of the LFR-30 reactor, the neutron instrumentation strategy is introduced, and illustrates how the neutron flux is measured during the different operating phases. From there, a focus is made on the requirements to be fulfilled by neutron detectors located outside of the core vessel: these requirements encompass temperature, humidity, neutron spectrum, gamma exposure, mechanical integration, electrical signals to be delivered, etc. Based on these specifications, the solutions designed for intermediate and power monitoring are both presented.

The following steps will include prototyping phases of the above-mentioned detection systems to ensure manufacturability, and then incremental testing of the neutron detection system, from elementary separate-effect experiments (irradiation with a calibrated neutron / gamma source at room temperature, electrical tests at room temperature; thermal tests; etc.) to full-scale experiments (irradiation performed on nuclear facilities with environmental conditions representative of expected operating conditions on the LFR-30).

#04 - Research Reactors and Particle Accelerators / 29

#4-29 Results of South East Flux Trap Dosimetry Measurements for the Advanced Test Reactor Critical Facility in support of Advanced Sensors and Instrumentation Development

Author: Michael Reichenberger[1]

Co-authors: Dani Ottaway [1]; Kelly McCary [1]; Kevin Tsai [1]; Teancum Quist [1]; Tommy Holschuh [1]

[1] *Idaho National Laboratory*

Corresponding Author: kelly.mccary@inl.gov

Reactor dosimetry measurements are commonly used to validate simulation and modeling in nuclear reactor experiments. Numerous standard dosimeter materials exist which are commonly utilized for their sensitivities to different energy ranges of neutrons. At the Advanced Test Reactor, cobalt alloy and pure nickel wires are installed every cycle to monitor thermal- and fast-neutron fluence rates. However, there is growing interest in exploring less commonly used materials which are either more sensitive to different parts of the neutron energy spectrum or which can incorporate multiple activation paths in a single material. Epithermal and fast-neutron energies beyond the typical 1-MeV threshold are of particular interest. Two Advanced Test Reactor Critical Facility Flux Runs took place during 2024; each flux run included supplemental dosimetry packages in the South-East Flux Trap. The focus of the dosimetry package for flux run 23-4 was to test two novel dosimetry methods that can provide simultaneous thermal and threshold (fast) sensitivity in a single dosimeter wire. A selection of 3% gold in copper alloyed wires was available that provided sensitivity to fast and thermal neutrons through 5 different reactions. Likewise, iron offers multiple interaction pathways with sensitivity to both thermal and fast neutrons. The main question to be answered by these irradiations was if sufficient radioactivation would take place in the Advanced Test Reactor Critical Facility South-East Flux Trap during a nominal 20-minute irradiation at typical power levels (near 600Wth) to allow the observation of the threshold reactions with smaller activation cross-sections than the thermal reactions, without being saturated by interfering interactions and Compton continuum during the High-Purity Germanium measurements. The results from comparing the measurement results to anticipated activity levels provide confidence in our ability to activate both traditional and novel dosimetry materials in Advanced Test Reactor Critical Facility, however not all the measured values matched with the predicted activities. This leaves further room for investigation both on the experimental and computational approaches for future irradiation experiments.

#10 - Current Trends in Development of Radiation Detectors / 30

#10-30 MCNP-based study and validation of scattered neutrons for neutron metrology

Author: Quentin Ducasse[1]

Co-author: Marcel Tallier [1]

[1] *Institut de radioprotection et de sûreté nucléaire*

Corresponding Author: quentin.ducasse@irsn.fr

The CEZANE facility at the Micro-Irradiation, Neutron Metrology, and Dosimetry Laboratory (LMDN) is equipped with an irradiator using various neutron sources such as ^{241}Am-Be, ^{252}Cf, and (^{252}Cf+D_2O)/Cd. In the context of its accreditation activities, service provision, and R&D, the laboratory performs calibrations of ambient dose rate meters and individual dosimeters in accordance with ISO 8529 standards. One of the main challenges of these calibrations is the assessment and subtraction of neutrons scattered by the environment, a phenomenon that significantly influences detector response.
Standardized experimental methods, such as the shadow cone technique, are limited in certain specific detector or distance configurations. To address these limitations, a detailed model of the CEZANE installation was developed using the MCNP simulation code, allowing for precise evaluation of the influence of scattered neutrons at any calibration position.
The results for ambient dose equivalent rate showed good agreement between experimental data and simulations for a reference rate meter, with discrepancies of 4.7% for the ^{252}Cf source and 2.0% for the Am-Be source at a standard distance of 150 cm. The contribution of scattered neutrons to the ambient dose equivalent rate was also precisely quantified using the shadow cone method, with discrepancies of 2.3% and 0.9% for the ^{252}Cf and Am-Be sources, respectively.
A preliminary analysis of scattered neutron trajectories was conducted using MCNP's Particle Track Output (PTRAC) tool. Specifically, the origin of the last collision of neutrons before detection at the calibration point revealed that most scattering phenomena originate from elements near the source and the measurement bench, rather than from building structures like walls or concrete flooring.
These observations have enhanced the understanding of scattered neutron contributions, offering promising insights for further simulations. Additionally, this work will be extended to study scattered neutrons involving the (^{252}Cf+D_2O)/Cd source to meet calibration requirements for individual dosimeters placed on a phantom at distances from the source where the shadow cone method cannot experimentally measure the contribution.
Overall, this work opens up new perspectives for improved measurement control on the CEZANE installation and for other neutron metrology devices, thus enhancing the reliability of calibrations in complex environments that require a fine understanding of the influence of scattered neutrons.

#07 - Decommissioning, Dismantling and Remote Handling / 31

#7-31 Automated Maximum a Posteriori Localization of a Radioactive Source using an UAS

Author: Claudia Bender[1]

Co-authors: Alexander Charlish [1]; Christoph Vollweiter [1]; Sebastian Kühn [1]

[1] *Fraunhofer FKIE*

Corresponding Author: claudia.bender@fkie.fraunhofer.de

The objective of this work is to develop techniques that allow for a rapid and accurate localization of radioactive sources in a large area using a highly automated unmanned aerial system. It is proposed that searching for sources using paths generated by probabilistic methods can leading to significant reductions in the time taken to localize a source. Additionally, it is also proposed that a new localization method that exploits a priori knowledge on the source activity can improve localization accuracy, which also leads to a faster localization. The proposed methods are tested in trials comprising a Cs-137 emitter that must be detected and localized using a DJI M600 equipped with a radionuclide sensor and a processing unit. During the trials, first, a fixed exploration path was followed. After hitting a radiation threshold, the source was localized using paths generated by a non-probabilistic and a probabilistic method. It was found that the probabilistic method was able to localize the emitter in less than 5 minutes in a 400 x 400 m area, with a localization time depending on the position of the source relative to the starting point of the unmanned aerial vehicle. To compare the performance of the new localization method with previous works, multiple state-of-the-art algorithms are implemented and evaluated on the real measurement data with respect to real-time capability, runtime complexity and localization accuracy. It was found that the novel estimator equals or surpassed the localization accuracy achieved by previous works in all tested scenarios. These results indicate that unmanned aerial vehicles that utilize these proposed techniques to enable online path planning, instead of relying on the conventional approach of predefined search patterns. In contrast to predefined search patterns, significant improvements in the time to localization and the localization accuracy can be achieved with these methods in comparison to the state of the art.

#04 - Research Reactors and Particle Accelerators / 32

#4-32 Preliminary Study on Joint Imaging Detection Technology of Wide Energy Zone n/ gamma ray Based on Research Reactor

Author: Sheng Wang[1]

Co-authors: Hang Li [1]; Chao Cao [1]; Yang Wu [1]; Heyong Huo [1]; Yong Sun [1]; Wei Yin [1]; Bin Liu [1]; Xin Yang [1]; Rundong Li [1]; Bin Tang [1]

[1] *Institute of Nuclear Physics and Chemistry, CAEP*

Corresponding Author: mritn5851@gmail.com

X/γ/neutron radiography is the most important radiography technology at present, of which X-ray imaging with different energy and different imaging forms is the most developed and widely applied. At the same time, however, due to differences in the principles of neutron imaging and matter interaction, neutron imaging can complement X/gamma imaging in specific areas, such as detection of hydrogen-containing substances in heavy metals (e.g. water, oil, plastics, resins, biological tissues, etc.) and detection of highly radioactive samples. In view of the complementarity of neutron imaging and X/γ imaging technology in nondestructive testing, in recent years a number of research institutions have started to build joint neutron X/ gamma imaging detection platforms and developed related experimental methods, image processing techniques and quantitative analysis techniques. The difference is that some of the joint images are mainly X-rays, while others are mainly neutron rays, with different combinations of neutron and X/ gamma-ray energy. The development of neutron-X/ gamma composite imaging has broad application prospect. According to different types of detection objects, the characteristics of different rays are fully used to improve the information acquisition ability of detection objects, and the recognition ability of elements is formed through joint detection.

A thermal neutron imaging facility is built in Mianyang Research Reactor, China. The maximum thermal neutron flux intensity at the imaging position is about 1e8 cm-2s-1, which can achieve a spatial resolution of up to 50 μ m. Based on this device, fission neutrons (energy > 0.1 MeV) have been obtained by a combined filter on the basis of the original thermal neutron beamline. When the collimation ratio is approximately 172, the flux of the fission neutrons is close to 3e5 cm-2s-1. The fission neutron imaging system has a maximum field of view of 400 mm x 400 mm and experimental spatial resolution is better than 0.5 mm. Imaging detection of three kinds of rays can be achieved by using thermal neutrons, fission neutrons and gamma rays in the beamline. At present, the device has completed three kinds of ray imaging and preliminary tomography experiments. For samples consisting of copper and polytetrafluoroethylene, it has the ability to detect internal flaws, as cracks with a minimum width of 0.1 mm and as holes with a minimum diameter of 1mm. In the future, gamma-ray imaging detection ability will be optimized, the reconstructed images from three rays will be fused, and the element identification capabilities of joint imaging detection technology will be validated through standard sample experiments.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 34

#5-34 CeBr3 gamma-ray logging probe qualification for uranium mining applications

Authors: Bertrand Pérot[1]; Thomas Marchais[1]

Co-authors: Bruno Legros [2]; Dragomir Savov [3]; Hervé Toubon [3]; Matthew Schubert [2]; Michaël Pernette [2]; Patrick Van Eyll [2]; Romain Mieszkalski [3]; Sebastien Hocquet [3]; Youcef Bensedik [3]

[1] *CEA, DES, IRESNE, Nuclear Measurement Laboratory, F-13108 Saint-Paul-Lez-Durance, France*

[2] *Advanced Logic Technology*

[3] *Orano Mining*

Corresponding Author: thomas.marchais@cea.fr

The development and optimization of gamma-ray spectrometry tools is crucial for ORANO Mining and uranium geophysical exploration. This study presents a comprehensive characterisation of the ALT QL40-SGR-2G spectrometric probe, equipped with a cerium bromide (CeBr3) detector. This characterization was carried out at the Nuclear Measurement Laboratory of IRESNE, at CEA Cadarache, France. We report different measurements of its energy calibration and resolution, detection efficiency, crystal length, angular response, count losses due to dead time or gamma self-absorption, and spatial sensitivity with depth profile measurements at different radii inside a calibration sand silo. We also report the validation of the CeBr3 probe numerical model through a comparison between experimental data and MCNP simulations, showing a very small discrepancy (2.4 % in average) across the whole energy spectrum for a series of standard gamma sources measured at 15 cm. The investigations on the crystal length with a finely collimated 137Cs source confirm the manufacturer specifications, while the angular characterization shows variations lower than 4 %. The use of the two-source method allowed a dead time estimation, which remains lower than 5 % up to 5000 ppm of uranium. Finally, the spatial response of the probe, measured with a 137Cs source moved in the instrumentation channels of the sand silo, also shows a good agreement with the MCNP profiles at different radii, validating the ability of the MCNP model to reproduce gamma logging profiles in a realistic environment. Future tests will be performed in real boreholes of uranium ISR (in situ recovery) mines, in Kazakhstan, in view to correct for the radioactive imbalance in roll fronts thanks to innovative spectroscopic approaches, and thus to better estimate the uranium grade.

#02 - Space Sciences and Technology / 35

#2-35 ANAQIN-X: A prototype low noise ASIC for the readout of highly dense semiconductor X-ray detectors

Author: Hani Boulfani[1]

Co-authors: Aline Meuris [2]; David Baudin [3]; Olivier Gevin [3]; Olivier Limousin [4]

[1] *The French Alternative Energies and Atomic Energy Commission (CEA)*

[2] *DAP AIM, IRFU, CEA Saclay*

[3] *DEDIP, IRFU, CEA, Paris Saclay University*

[4] *DAP AIM, IRFU, CEA Saclay,*

Corresponding Author: boulfanihani@gmail.com

IDeF-X (Imaging Detector Front-end in X-rays) is an integrated circuit family devoted to Read semiconductor detectors for space science application. Most of those circuits are based on one-dimensional analog channel (Strips). A new branch of 2-dimensional (pixels) IDeF-X has been designed to be able to reach ultra-low noise levels (D2R1 & D2R2). For this new branch, we have designed two previous pixelated integrated circuits with promising results. However, a high-level of noise has been spotted and yet to be explained. This article presents ANAQIN-X (Advanced Noise-optimized ASIC for Quantifying and Imaging in X-rays) the latest 2-Dimentionnal integrated circuit designed to investigate the origin of that noise. ANAQIN-X is dedicated to test different architectures of Charge Sensitive Amplifiers, the first stage of the spectroscopic signal processing analog circuit. The chip is designed to read out low leakage current (~ 20 pA), low capacitance (< 1 pF), X-rays photon counting (CdTe/CdZnTe/Si) detectors in order to perform high-resolution (500 eV FWHM at 60 keV) hard X-ray (1-220 keV) spectroscopy. Its main bloc is a mini matrix of pixels of 250 µm x 250 µm designed in X-FAB's 0.18-µm CMOS technology. Each channel consume 250 µW in nominal mode. It consists of a tunable gain Charge Sensitive Amplifier followed by a Pole-Zero Cancelation circuit operating as a CR-RC filter with a tunable peaking time (from 144 ns up to 3,6 µs) , and a peak detector. The different CSA architectures integrated on this chip are based on continuous reset nMOS and pMOS architectures with various W/L ratio of the input transistor. The chip include also, AC-coupled first stages with a tunable input capacitance (from 100 fF to 30 pF). A novel AC-coupling architecture has been developed, which involves integrating the coupling capacitor inside the feedback loop of the amplifier. This configuration allows a reduction in the thermal noise generated by the reset transistor and the usage of small value capacitance. An overall noise reduction of 10% at 10 pA of leakage current, and coupling capacitance of 1 pF is enough to get 98 % of gain according to the mathematical model. Simulation results have shown that with 300 fF detector connected to the input, the best performing pixel should be able to reach an Equivalent Noise Charge (ENC) of 18 el.rms. The circuit has been designed, is currently in production, and will be tested by January 2025. Space borne application requires a radiation hardness test to the Total Ionizing Dose (TID). An irradiation of the frontend electronics is planned using a 60Co gamma ray source by March 2025. The pixel showing the best noise performances will be selected and used in a "full-scale" (32x32 or 48x48 matrix) readout integrated circuit intended for an integration in MC2 (Mini CdTe on-Chip), a 4 sides connectable, compact, and fully digital counting X-rays photons imaging spectroscopy module designed for future space borne science applications.

#04 - Research Reactors and Particle Accelerators / 36

#4-36 NEREA: a Python package for expedite Neutron Energy-integrated Reactor Experiment Analysis

Author: Federico Grimaldi[1]

Co-authors: Federico Di Croce [1]; Antonin Krása [2]

[1] *Belgian Nuclear Research Centre, Université libre de Bruxelles*

[2] *Belgian Nuclear Research Centre*

Corresponding Author: federico.grimaldi@sckcen.be

The VENUS-F zero power reactor was first operated in 2011 at SCK CEN in the framework of the MYRRHA project. Over time, many experimental campaigns were carried out at VENUS-F in support of several - mostly heavy metal cooled - fast reactor designs.
Knowledge about the processing procedures of such experiments is retained by expert users knowing how to interact with the many codes developed in the years for this purpose.
The NEREA (Neutron Energy-integrated Reactor Experiment Analysis) open source Python package is now available to enable expedite reactor experiment analysis.
The object oriented design of NEREA grants three main advantages:
- easy user interaction with each class independently from others;
- modularity enabling fast new feature implementation;
- possibility of automated A-to-Z processing with minimal effort.

To date, NEREA enables processing of reaction rate traverses, reaction rate ratios as spectral indices and control rod worth measurements.
The code is structured in four major components. A first set of classes is designed to gather and pre-process the experimental data (reaction rates, fission fragment spectra and fission chamber effective masses). The pre-processed raw experimental data are fed to classes enabling reaction rate traverse, spectral index and control rod worth processing. Parallel to that, classes are defined to read model results from Serpent 2 Monte Carlo code outputs. Finally, an independent suite is designed to compare the processed experimental results to the calculated ones. The uncertainty is propagated through the whole processing chain, with automatic calculation of variance fractions. Moreover, all uncertainty components can be computed enabling for explicit uncertainty management.
Git version control is used in the development of NEREA. Unit tests with a 95% coverage ensure code stability during its development. NEREA is currently hosted on GitHub (https://github.com/GrimFe/NEREA) and on test Pypi (https://test.pypi.org/project/nerea/).
As compared to the codes previously used at SCK CEN, NEREA stands as faster processing tool that enables for automatized processing in a Python environment. This results in a reduced user mistake and ensures consistent processing methodologies among different experiments.
NEREA features preferential interfaces with the data acquisition systems used by SCK CEN at VENUS-F, yet the modularity inherent to its object oriented design enables easy implementation of new features. Future plans foresee implementation of modules for the processing of solid state detector and activation foil measurements in NEREA.

#09 - Environmental and Medical Sciences / 37

#9-37 Traceability in terms of average glandular dose to primary national references of CEA-List LNE LNHB for numerical mammography

Authors: Jean-Marc BORDY[1]; Johann PLAGNARD[1]; Jérémie LEFEVRE[1]; Meriem Djaroum[1]

Co-authors: Claire VAN NGOC TY [2]; Isabelle Fitton [2]

[1] *CEA-List, Université Paris Saclay*

[2] *AP-HP, Hôpital Européen Georges Pompidou, Paris, France*

Corresponding Author: meriem.djaroum@cea.fr

Introduction: A significant advancement in mammography examinations is tomosynthesis, which allows for the three-dimensional reconstruction of breast images and improves detection sensitivity. However, it also leads to an increase in the absorbed dose to the breast. The accuracy of the estimation of the average glandular dose is crucial to ensure the optimal functioning of mammography equipment and the safety of patients. Following the Dance and Boone model, the Average Glandular Dose is derived from air kerma measurement multiplied by conversion factors obtained through Monte Carlo simulations. This Average Glandular Dose is used for the optimization of examinations but only imperfectly represents the absorbed dose to the breast. We propose to present the methodology for measuring and modeling X-ray spectra, resulting in the production of clinical mammography beams on the X-Rays generators of the French national metrology Laboratory, the National Laboratory Henri Becquerel. Materials and Methods: Our methodological approach is based first on the measurement of spectra emitted by the Hologic Selenia Dimensions® digital mammographer (Hologic Inc., Bedford, MA, USA; Software version: V1.11.0.8) at the Hôpital Européen Georges Pompidou, using a Cadmium/Tellure spectrometer. The following anode/filtration pairs were studied: tungsten/rhodium, tungsten/silver, and tungsten/aluminium, with tube voltages ranging from 22 kVp to 49 kVp. These measurements were complemented by Half-Value Layer measurements, used as an indicator of beam quality, using a PTW 23342 ionization chamber. The measured spectra were compared to those obtained in the National Laboratory Henri Becquerel generator beams for the same anode/filtration pairs and high volatge. The Half Value Layers were then measured with the primary reference free air chamber. The variation of the calibration coefficients in terms of air kerma for a PTW 2334 ionization chamber was measured in National Laboratory Henri Becquerel beams reproducing those of Hôpital Européen Georges Pompidou. The air kerma at Hôpital Européen Georges Pompidou was measured with a PTW23344 chamber placed 60 mm from the edge of the potter, with the compression paddle in place, for the different radiation qualities studied and for each pair of polymethyl methacrylate and polyethylene equivalent phantoms used for quality control of the mammographer. Results: The comparison of spectra measured at Hôpital Européen Georges Pompidou and National Laboratory Henri Becquerel shows excellent agreement. The measurements and calculations of the Half-Value Layer highlight minor discrepancies between Hôpital Européen Georges Pompidou and National Laboratory Henri Becquerel. These discrepancies are accounted for by the monotonic variation of the calibration coefficient of a PTW 23344 ionization chamber. Perspectives: The calibration beams available at National Laboratory Henri Becquerel will allow for the testing of the principle and later the prototype of an instrumented breast phantom planned for the continuation of this study.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 38

#5-38 Benchmark between MCNP and PHITS for passive and active neutron measurement simulations

Authors: Coralie Coisser[None]; Cyrille Eleon[1]; Mehdi Ben Mosbah[2]

[1] *CEA/DES/IRESNE/DTN/SMTA/LMN*

[2] *CEA, DES, IRESNE, Nuclear Measurement Laboratory*

Corresponding Author: mehdi.benmosbah@cea.fr

The accurate assessment of fissile mass within radioactive waste drums is crucial for effective radioactive waste management, nuclear safety, and criticality prevention. Passive and active neutron measurements are indispensable tools for quantifying residual actinides of interest, such as plutonium and uranium, in both waste management and spent fuel reprocessing contexts. For several years, the Nuclear Measurement Laboratory (NML) at CEA Cadarache (France) has conducted preliminary studies, feasibility demonstrations, measurement station designs, and performance evaluations using the Monte Carlo code MCNP. Recently, the NML successfully employed the PHITS Monte Carlo code to simulate large-gap solid detectors for neutron spectroscopy and neutron activation analysis of rare metals. To assess PHITS' performance for neutron measurements, this study presents a comparative analysis with MCNP, the established reference code.

The specific case study involves a modular neutron measurement station designed within the European MICADO project. This station aims to characterize the mass of plutonium and uranium in 40- to 400-liter drums using coincidence and Die-Away Differential Technique (DDT) measurements with 84 Helium-3 proportional counters. This work compares MCNP and PHITS for relevant physical quantities associated with passive (detection efficiency, real coincidences counting and calculation of calibration coefficient CC40 for Pu-240 equivalent mass) and active (fission rate, active calibration coefficient for Pu-239) neutron measurements. Additionally, the computational efficiency of both codes is also evaluated.

The results demonstrate excellent agreement between MCNP and PHITS, with the majority of deviations not exceeding 10%. This high level of concordance instills confidence in the broader application of PHITS for neutron measurement simulations. While PHITS exhibited longer computation times in certain cases, the PHITS development team through a dedicated patch has addressed this issue.

#01 - Fundamental Physics / 40

#1-40 Upgrade of the Belle II Vertex Detector with depleted monolithic CMOS active pixel sensors

Authors: Justine Serrano[1]; Alice Gabrielli[2]

[1] *Aix Marseille Univ, CNRS/IN2P3, CPPM, Marseille, France*

[2] *INFN Pisa, Italy*

Corresponding Author: alice.gabrielli@pi.infn.it

The Belle II experiment currently records data at the SuperKEKB e+e- collider, which holds the world luminosity record of 4.7x10^34 cm-2 s-1 and plans to push up to 6x10^35 cm-2 s-1. In such luminosity range for e+e- collisions, the inner detection layers should both cope with a hit rate dominated by beam-induced parasitic particles and provide minute tracking precision. A research and development program has been established to develop a new pixelated vertex detector (VTX), based on the most recent CMOS pixel detection technologies. The VTX strategy entails higher space-time granularity, lighter overall structure and services compared to the current operating vertex detector based on two different technologies. The expected gains include more robustness against the machine background as well as higher vertexing and tracking performance.
The VTX design matches the current vertex detector radial acceptance, from 14 mm up to 140 mm. It includes 5 to 6 layers equipped with the same depleted monolithic active pixel sensors, OBELIX. Specifications target to sustain a maximal average hit rate of 120 MHz/cm2 with triggered read-out within an overall material budget lower than 3 % of X0. The two innermost layers are made of 4-sensor long modules cut out from processed wafers and submitted to post-processing operations in order to connect them at one end. Air cooling is currently under study for those two layers. The three to four outer layers use a light mechanical structure supporting a liquid-cooled plate in contact with the sensors connected to a flex printed cable.
The OBELIX sensor is designed in the Tower Jazz 180 nm technology, which pixel matrix is derived from the TJ-Monopix2 sensor originally developed for the ATLAS experiment. Featuring a 33 µm pitch and a time over threshold digitization over 7 bits, OBELIX time-stamps hits with a 50 ns binning. The digital trigger logic matches the required 30 kHz average Belle II trigger rate with 10 µs trigger delay.
Two switchable additional features are intended for the outer layers coping with hit rates below 10 MHz/cm2. One corresponds to time stamping hits outside the matrix with 3 ns precision. The other provides continuous hit-information with 30 ns binning but with degraded position-precision for track-triggering. Recent simulations, showing that the degraded spatial granularity can still lead to useful track reconstruction efficiency at the first trigger level, will be discussed. The radiation environment requires a tolerance to 5x10^14 1 MeV n_eq/cm2 and 1 MGy. In addition, the minimal material budget limits the cooling power and hence necessarily means warm operation of the sensor. This is a considerable challenge taking into account its estimated power dissipation around 200 mW/cm2 at the maximal average hit rate of the inner layer.
We will review all project aspects: the latest characterization of the TJ-Monopix2 forerunner sensor in beam after irradiation, design of OBELIX sensor, optimization of the geometry and cooling.

#11 - Education, Training and Outreach / 41

#11-41 From real-size to model: the life of CROCUS in the student's mind

Author: Vincent Lamirand[1]

[1] *Ecole Polytechnique Fédérale de Lausanne*

Corresponding Author: vincent.lamirand@epfl.ch

EPFL operates the CROCUS reactor for both teaching and research purposes. While research is inherently valuable and motivated across various topics, the educational mission of the laboratory and the team is equally central. Educational activities span all levels, from providing base access and concepts to numerous visitors, to advanced education at the Bachelor's, Master's, and doctoral levels, as well as training for professionals.

CROCUS is a uranium-fueled, light-water moderated, zero power reactor with a maximum power of 100 W. It is as simple as an operational nuclear reactor can be. This apparent simplicity is a major asset: visible and accessible fuel rods, vessel and hydraulic systems, neutron detectors and power monitors, etc. This accessibility aligns with the pedagogical concept of *affordance*: as an object, CROCUS serves as a highly effective tool for supporting understanding. In a *trialogical learning approach*, it provides the necessary materiality that bridges the explanations of the teacher with the students'active learning process. Students can walk around the vessel, touch it, lean over it to see the inside and the fuel positioning, and even, to an extent, "touch"the fuel. There is virtually no distance, as well as no risk, with a negligible dose rate nearby. However, CROCUS still includes many specificities –physical, instrumental, and mechanical –and can be considered a complex system from an educational point of view. Once basic concepts and systems are understood, it requires a deeper effort to comprehend the machine and the underlying physics at an appropriate level. To achieve this, a variety of tools are employed, all centered on *active learning* principles to facilitate accessibility.

The first and most obvious tool is a Monte Carlo model. When performing computations, students (typically at the Master's level) deepen their understanding of the reactor, its design, and its behavior. Although a valuable complement to time spent on CROCUS, computations lack the tangible quality needed to fully grasp its dynamic, inner workings: it provides a static description and non-functional representation. A more in-depth operational understanding involves a different type of experience: all PhD students whose research includes an experimental component in CROCUS complete the reactor operator license. As a consequence, not only do they gain detailed knowledge of the machine and its working, but they also develop an operational understanding. They come to know CROCUS better than anyone for their specific experimental applications, having operated it for and by themselves. However, this learning path is time-intensive.

To address intermediate educational level, and as a complement during hands-on learning courses, another set of tools has been developed, consisting of tangible models. The first one is a detailed 3D-printed model, made with virtually no approximation. Based on the CAD model of CROCUS, which itself is based on original blueprints, this 1/5th replica is highly detailed and visually attractive. However, it is delicate and requires careful handling. Its fragility and limited movability (as well as cost) mean that it is not well-suited for manipulation but rather serves as a demonstration tool. Furthermore, certain "hidden"features of CROCUS, such as the startup source, or water intake and expansions vases, remain as difficult to visualize as in the actual reactor. While it captures the reactor's appearance, this model's affordance is limited by the same restrictions as the actual reactor, without having the same impressive appearance.

For this reason, a second model was constructed from Lego bricks. This Lego model accurately includes all key features with minimal approximations: the appearance and relative scales of each system are preserved. Its size and structure are appropriate for manipulation and exploration: the core can be "unloaded"similarly to the real one, and it can be disassembled without being damaged. It includes movable parts, such as the spillway and absorber rods, and the vessel can be opened to reveal the internals. This is especially helpful for visualizing difficult-to-see elements, such as the startup source and expansion vases openings, which are typically challenging for students to understand.

In this contribution, we present the educational objectives that we aim to cover, the challenges of communicating a system functioning, and the benefits of using CROCUS and its models. Additionally, we discuss results from evaluating the impact of the new Lego model in classroom teaching.

#07 - Decommissioning, Dismantling and Remote Handling / 42

#7-42 Commissioning and calibration of the MICADO passive and active neutron measurement system for the characterization of radioactive waste drums

Author: Quentin Ducasse[1]

Co-authors: Bertrand Pérot ; Cyrille Eleon [2]; Erica Fanchini [3]; Frédéric MOUTET [4]; Giada Gandolfo [5]; Joël LORIDON [4]; Luigi Lepore [5]

[1] *Institut de radioprotection et de sûreté nucléaire*

[2] *CEA/DES/IRESNE/DTN/SMTA/LMN*

[3] *CAEN s.p.a.*

[4] *CEA, DES, IRESNE, DTN, SMTA, Nuclear Measurement Laboratory*

[5] *ENEA*

Corresponding Author: cyrille.eleon@cea.fr

The accumulation of radioactive waste from legacy nuclear facilities presents a critical challenge for long-term environmental safety, as precise quantification of nuclear material within these waste drums is necessary to inform safe storage and disposal strategies. In this context, a passive and active neutron measurement system was developed within the MICADO H2020 project to estimate the nuclear material mass inside legacy waste drums with low and intermediate levels of radioactivity. The MICADO neutron system was installed in the CEA Danaides casemate at the Nuclear Measurement Laboratory, where measurements have been conducted. Calibration tests in passive neutron coincidence counting were performed using a Cf-252 neutron source, yielding a total neutron efficiency of 3.8%. Measurements in 12 different positions were conducted to account for source localization effects. Mock-up drums filled alternately with materials representative of real drums, such as stainless steel, wood, polyethylene, and PVC, were measured in neutron coincidence counting and in a transmission measurement to evaluate the impact of matrix effects on the neutron signal. Experimental and simulated transmitted signals showed good agreement, within 10%.
The measurement of real coincidences and the calculation of calibration coefficients using Monte Carlo simulations allowed for an estimation of nuclear material mass inside mock-up drums, with results agreeing within approximately 0–20% of the actual mass of the nuclear material. This validated both the simulation model and the experimental findings. In active neutron total counting, a neutron generator was used to induce fission in a Pu-239 neutron target located at the drum's center. The total neutron background measured in the prompt neutron time window showed agreement with simulations to within 10%. The estimated Pu-239 mass was within approximately 15–40% of the actual mass across most matrices, though larger discrepancies were observed with PVC, attributed mainly to uncertainties in matrix modeling. Finally, a matrix correction model was developed using an artificial neural network, achieving accurate calibration predictions for four test drums in both passive and active modes. This model was scaled up for 200 L drums and employed in the final demonstration at ENEA Casaccia (Italy) to improve nuclear material mass estimates.

#07 - Decommissioning, Dismantling and Remote Handling / 44

#7-44 UGV-related radiologic sensors developments for gamma and neutron spectroscopy and alpha/beta contamination scan in D&D applications

Authors: Alberto Lucchesi[1]; Bruno Angelucci[1]; Cristiana Del Bene[None]; Daniele Ninci[1]; Erica Fanchini[2]; Ferdinando Giordano[2]; Francesco Pepe[1]; Francesco Rogo[1]; Massimo Morichi[3]; Matteo Corbo[3]; Paola Garosi[4]

[1] *CAEN*

[2] *CAEN s.p.a.*

[3] *CAEN SpA*

[4] *CAEN S.p.A.*

Corresponding Author: e.fanchini@caen.it

The dismantling and decommissioning (D&D) of nuclear facilities have become an increasingly significant global endeavour, driven by the number of infrastructures, aging, and technology evolution and awareness in the field. Dimensions of the infrastructures, harsh radiological environment, safety requirements, reliable process, and not least costs, are some of the technical aspects affecting D&D activities. At the same the improvements in the automation sector, the industry 4.0 is becoming part of our lives driving all the operation that are critical.
The dismantling of these facilities necessitates these advanced techniques to meet international safety standards, minimize radiation exposure, ensure operational efficiency and reduce costs and operational. In response to these challenges CAEN is involved in two EU-funded projects, CLEANDEM (H2020 -GA945335) and XS-ABILITY (Horizon GA101166392) to develop and upgrade radiologic sensors for inspections and monitoring of the environment. This work represents the results obtained for the sensors developed within CLEANDEM, focusing on the Gamon-UGV drone and a large area contaminameter and their expected evolution in XS-Ability.
The Gamon-UGV drone is a gamma and neutron detection system with spectroscopic capabilities, based on the NaIL scintillator. A description of the realization and characterization performed within the CLEANDEM project will be described tests as well the ones performed at the AINT laboratory and the integration in the DigitalTwin platform. The prototype obtained good results within CLEANDEM, but it highlights also aspects that have to be re-evaluated. One concern the possibility to work with more compact electronics to better meets UGV requirements within XS-Ability.
The second system that will be described is a large surface contamination monitor system for alpha and beta contamination measurements. It can work in continuous mode to scan extensive surfaces, an extremely useful capability during the dismantling phase to verify absence of remaining of superficial contamination. The system was embedded in the TECNALIA UGV used in CLEANDEM and was tested at the ENEA laboratory and results will be reported based on standard protocols of the category. It will also be described the new development for the XS-Ability project. A robotic platform will also be used to scan large surfaces at higher heights, enhancing the ability to detect radiation over extended areas.
The successful outcomes of CLEANDEM demonstrate that unmanned systems not only reduce worker exposure to radiation but also enhance the overall efficiency of D&D processes. These systems can be further adapted for broader applications, including radiologic safety, security, and crisis management, where remote and autonomous interventions are critical for minimizing risk.
We will also prepare a description of the XS-Ability prj and its primary objective to develop and deploy a swarm of autonomous Unmanned Ground Vehicles (UGVs) and Unmanned Aerial Vehicles (UAVs) equipped with advanced radiation detection technologies. The robotic systems developed in XS-ABILITY will be designed to address several key challenges in nuclear D&D, including accessing hard-to-reach areas.
In conclusion, CLEANDEM and XS-ABILITY represent a significant step forward in the application of autonomous robotics in the nuclear D&D sector. The technologies developed under these projects will enhance safety, improve operational efficiency, and reduce the financial and logistical burden of D&D processes.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 45

#6-45 3D-Printed Modular Radiation Sources for Testing Radiation Detectors and Advancing Radioisotopes Identification Algorithms

Author: Ghaouti Bentoumi[1]

Co-authors: Anil Prasad [1]; Hassan Tanvir [1]; Liqian Li [1]; Nikolaos Kotsios [1]; Oluwadara Afolabi [1]

[1] *Canadian Nuclear Laboratories*

Corresponding Author: liqian.li@cnl.ca

The international radiological and nuclear (RN) community recognizes Improvised Nuclear Devices (INDs) as a significant security threat. Therefore, efficient, and reliable detection solutions at points of entry, our first line of defense, are critical for maintaining secure yet open borders. Screening of containerized cargo for INDs, and RN materials in general, is primarily done using drive-through radiation portal monitors (RPMs). RPMs scan containers and trigger an alarm if the analysis of gross counts and ratios in specific energy windows exceed a set threshold. Globally, advanced computing algorithms, including machine learning and artificial intelligence, are being developed and enhanced to improve the consistency and accuracy of RN materials identification and reduce the burden of unnecessary inspections for containers with naturally-occurring radioactive material. However, these data analytics algorithms require augmentation with true positive sample scan data covering the full threat space, including data representing INDs of various intensities and shielding materials. The scarcity of, and strict access to, large quantities of special nuclear materials (SNM) in various geometries and isotopic compositions have led to RPMs and other portable detectors being deployed without testing their performances against INDs, resulting in a high number of false alarms which require a significant amount of time to manually resolve.

Self-shielding in bulk SNMs, such as those occurring in INDs, limits the detection of gamma/X-rays originating more than a few millimeters below a sample's surface, leaving mostly high- energy gamma rays and surface low-energy gamma/X-rays detectable in search scenarios. Thus, a thin layer of nuclear material deposited on a metallic or plastic shell could be designed to precisely match the gamma-ray emissions, in terms of energy spectrum and rate, as a bulk-quantity of nuclear material. Hence, versatile, well-characterized, optimized, and traceable radiation sources could be fabricated for the envisioned applications by controlling the geometry, thickness of the deposited layer, overall dimensions, and isotopic composition.

Canadian Nuclear Laboratories (CNL) is exploring the applicability of additive manufacturing technologies for making modular radiation sources using natural uranium (NU). The 3D-printed thin layers of NU within plastic shells have been demonstrated at CNL. Using less than a hundred grams of NU, careful balancing of the shape and size has permitted for accurate replication of the gamma spectrum and emission rate of a bulk NU sample with a mass of a few kilograms. This presentation highlights the Geant4 simulations for designing and optimizing the radiation source's shape and size while minimizing the NU mass, the fabrication techniques, and the first experimental comparisons between the 3D-printed source and a bulk mass of NU. Based on that, it is believed that these modular radiation sources will enable the creation of true positive datasets that mimic those expected from a real IND, and therefore the development of an algorithm to help assess the significance of the alarms. Work is still underway to fabricate thin and modular highly enriched uranium (HEU) and U-233 radiation sources to match the gamma/X-ray emissions of a bulk mass of 25kg HEU and U-233 respectively.

#01 - Fundamental Physics / 46

#1-46 Harnessing Digital Twins and Simulation for Advancing Neutron Experimentation

Author: Paolo Mutti[1]

Co-authors: Cristina Cocho [1]; Shervin Nourbakhsh [1]; Yannick Le Goc [1]

[1] *Institut Laue-Langevin*

Corresponding Author: mutti@ill.fr

Data from virtual experiments are becoming a valuable asset for research infrastructures: to develop and optimise current and future instruments, to train in the usage of the instrument control system, to study quantifying and reducing instrumental effects on acquired data. Furthermore large sets of simulated data are also a necessary ingredient for the development of surrogate models (supervised learning) for faster and more accurate simulation, data reduction and analysis. So far, the production and usage of data from virtual experiments have been mostly reserved to simulation experts. In this work, we present how at ILL data from virtual experiments are made available to the general users. The presented framework wraps in a digital twin of the facility instruments, the knowledge of its physical description, the simulation software and the high performing computing setup. The twin presented in this paper has been developed at the ILL in the framework of the PANOSC European project in close collaboration with other research facilities (ESS and EuXFel) for some of its essential components. An overview of the core simulation software (McStas), its Python API (McStasScript), the public instrument description repository and the instrument control system (NOMAD) are given. The choices on the communication patterns, based on ZMQ, and interaction between the different components are also detailed. A flavour of advanced features like collision prediction will also be provided.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 47

#6-47 Laboratory tests of SNM identifier with respect to ANSI standard reference: technology, test scenarios, and measurements results

Authors: Cristiana Del Bene[1]; Giacomo Mangiagalli[1]; Massimo Morichi[1]; Paola Garosi[1]

[1] *CAEN S.p.A.*

Corresponding Author: m.morichi@caen.it

The SNIPER-GN, a special nuclear material (SNM) portable identifier developed by CAEN S.p.A., was tested at ENEA's Nuclear Material Characterization and Radioactive Waste Management Laboratory. This advanced neutron-gamma detection system underwent thorough evaluation with a variety of neutron and gamma sources. The primary goal was to assess the system's performance, particularly its neutron and gamma identification capabilities, in alignment with ANSI standards. The tests included static and dynamic measurements, conducted under challenging conditions, also with moderating and shielding materials interposed between the radioactive sources and the detector. Two plutonium oxide neutron sources with varying neutron emission rates and compositions, along with several gamma sources such as Cs-137, Am-241, and Co-60, were used in the tests. These sources were placed at different distances from the detector to simulate real-world scenarios. The system successfully identified SNM sources even with low neutron count rates and sometimes also in the presence of a masking gamma field. Key results demonstrated the system's ability to maintain accuracy in neutron identification even with a neutron count rate oscillating around 1 CPS (neutron background approximately 0-0.1 CPS) and successfully distinguish between shielded and unshielded configurations. This was possible thanks to the exceptional performance of the unique identification algorithm, which is capable of detecting neutron-emitting nuclides through neutron detection (U.S. Patent No. 11835477). Additionally, the system's performance in angular response tests showed a high degree of sensitivity, with the lowest relative gamma efficiency at 70% in correspondence with the back of the detector. The dynamic tests validated the system's capability to detect radioactive sources in motion, a critical requirement for homeland security applications. Overall, the SNIPER-GN surpassed the performance criteria established by ANSI standards, demonstrating its exceptional reliability for real-time neutron and gamma identification. Notably, the system's capability to detect 5.5 grams of plutonium from a distance of 1 meter in under 1-minute highlights its effectiveness, solidifying its value as a critical tool for accurate and timely SNM detection.

#04 - Research Reactors and Particle Accelerators / 48

#4-48 Validation of an acoustic sensor for characterizing fission gas releases under harsh conditions up to 350°C and 120 bar, for integration in experimental loops at the Jules Horowitz reactor.

Authors: Florian Baudry[1]; Gaetan Galeron[2]; Eric Rosenkrantz[1]; Philippe Combette[1]; Paul Vincent Bonzom[2]; Christophe Destouches[3]; Florence Martin[4]; Dominique You[5]; Romain Abadie[5]; Jean-Yves Ferrandis[1]

[1] *IES, Univ Montpellier / CNRS*

[2] *CEA/DES/IRESNE/DTN/STCP/LISM*

[3] *CEA/DES/IRESNE/DER/SPESI*

[4] *CEA/DES/IRESNE/DER/SPESI/LDCI*

[5] *Université Paris-Saclay, CEA, Service de Physico-Chimie*

Corresponding Author: gaetan.galeron@cea.fr

For several years, the IES laboratory has been working in collaboration with the CEA on the development of acoustic instrumentation in the nuclear field. Within the framework of this collaboration, the IES acoustic team is developing a miniaturized gas composition sensor for in situ measurements of gas composition in material testing reactor. The first experimental evidence of an acoustic measurement to perform a gas composition measurement date back to 2010 with the REMORA 3 experiment, which measured the release of fission gas from fissionable fuel. This experiment was carried out in the OSIRIS reactor located at CEA Saclay center in France. The installation allowed the devices to be tested under irradiation at 150°C, which corresponded to the maximum operating Curie temperature allowed by PZT element. But the new sensors presented in this paper will be able to operate up to 350 degrees. This performance is possible by the utilization of a modified Bismuth Titanate piezoelectric (NBT). NBT family has been confirmed for the piezoelectric ceramic which is deposited by serigraphy on alumina. Glass-ceramic such as MACOR® is used for the fabrication of the acoustic cavity and the reflector. These choices were motivated by the low thermal expansion of these materials taken individually, their resistance to the radiative fluxes and their maximum operating temperature well higher than 300°C. Particular attention has been paid to the complete assembly of the sensor, including gluing of the various components and electrical connections.
In the present communication, we focus on the experiment carried out in a pressure vessel located at the CEA Saclay center in January 2024. This facility allowed to test the acoustic sensors up to 350°C and 120 bar with different types of gas mixtures (from pure He to mixture with 20% of Xenon). Two types of measurements were performed: electrical impedance and acoustic signals were monitored by an appropriate instrumentation. Two sensors were simultaneity tested. The results made it possible to estimate the ageing and the evolution of the performance of the sensors during a few days. The first results showed some slight alteration of the acoustic performance of the sensor after a total of 79 hours of experimentation but measurements are still possible. At 350°C and a pressure higher than 70 bar in gas mixture, the sensor emitted acoustic waves and showed the possibility of performing a reliable in situ gas composition measurement.
These experiments allowed us to validate the concept and design of this high temperature device before final validation tests under irradiation in 2025.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 49

#5-49 Effect of turbulence on ultrasound propagation for vibration measurements of PWR assemblies in the HERMES P loop of the POSEIDON platform.

Authors: Aubin Paveyranne[1]; Florian Baudry[2]; Philippe Latil[3]; Eric Rosenkrantz[2]; Guillaume Ricciardi[3]; Jean-Yves Ferrandis[2]

[1] *IES, Univ Montpellier / CNRS & CEA/DES/IRESNE/DTN/STCP/LETH*

[2] *IES, Univ Montpellier / CNRS*

[3] *CEA/DES/IRESNE/DTN/STCP/LETH*

Corresponding Author: aubin.paveyranne@cea.fr

In the frame of the partnership between Électricité de France (EDF), Commissariat à l'énergie atomique et aux énergies alternatives (CEA) and FRAMATOME, ultrasonic acoustic instrumentation is developed to measure mixing grid vibrations on assemblies in the HERMES P loop on the POSEIDON platform at CEA Cadarache. This facility is a full-scale model of a Pressurised Water Reactor assembly, reproducing the temperature, pressure and flow conditions of a reactor without the irradiation aspect. This project is being carried out by the Institut d'Electronique et des Systèmes (IES) and the Laboratoire d'Essais et d'Etudes Hydromécanique (LETH) at CEA Cadarache. The loop will be instrumented with ultrasonic devices that will measure the vibrations of the assembly's mixing grids due to an earthquake, or due to flow turbulence ('fretting'). The advantage of using ultrasonic instrumentation is that the vibrations can be characterised remotely, without modifying the structure of the assembly and without disturbing the flow.
In this abstract, we focus on the influence of the propagation environment and in particular on ultrasound propagation in turbulent flow. The literature shows that flow influences the propagation of ultrasound. For example, in laminar flow, ultrasound is accelerated or slowed depending on the direction of flow. For a turbulent flow, the presence of vortices disturbs the ultrasound, for example with known vortices such as those of Kelvin Helmotz or for a Von Karman alley.
A series of tests was carried out to quantify the disturbance to the ultrasonic measurement at different flow rates, i.e. for uncharacterised turbulence. The tests were performed at near-ambient temperatures, in a mock-up that reproduce a flow similar to the HERMES P loop. We studied reproducibility and repeatability of the measurements. The transmission tests showed an increase in the dispersion of the measurement as a function of the turbulence, although this dispersion can be corrected by averaging the measurements. The reflection tests showed a slight influence of turbulence on ultrasound propagation. This phenomenon can be explained by considering the flow as frozen and assuming that the phenomena accelerating the ultrasound on the way out slow it down on the way back.
With high frequency sensors (5 to 10 MHz), these first results allow us to measure displacement smaller than 50 micrometres (which correspond to earthquake assembly vibrations) in laboratory configuration. Effect of temperature is under investigation before performing measurements in Hermes P loop conditions.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 50

#5-50 Experimental and numerical examination of different springs dimensions for non-destructive measurement of the internal pressure and composition of PWR fuel rods

Authors: Diba Ayache[1]; Stanislas Gillet[2]; Liana Ramiandrisoa[3]; Christopher Reece[2]; Jean-Yves Ferrandis[1]

[1] *IES, Univ Montpellier / CNRS*

[2] *EDF/DCN/PEL/DER*

[3] *EDF/R&D/PRISME*

Corresponding Author: diba.ayache@umontpellier.fr

During the irradiation process, fission gases, such as helium, xenon and krypton, are released and the pressure inside the fuel rods increases. The internal pressure as well as the composition of the fission gases present within the plenum of the fuel rod are of major interest to nuclear power plant operators as they can be accurate indicators of the fuel behavior and reflect the overall fuel performances in operation, during shipping and in long term storage. These parameters can be used, notably, for the definition of fuel burn up limits. The Acoustic team of the Institute of Electronics and Systems (Montpellier University & CNRS), in collaboration with EDF, are working on the implementation of a non-destructive acoustic method to perform measurements on fuel rod assemblies stored in spent fuel pools. Performing non-destructive measurements directly on-site would prevent heavy, sensitive and costly operations and would enable larger measurement campaigns to enrich statistical databases.
The principle of the measurement is to determine the speed and attenuation of the acoustic waves propagating in the gas at the plenum level of the rod. This measurement is performed using a piezoelectric transducer pressed onto the rod to generate an acoustic wave. Then, the reflections of the sound wave are received by the transducer and analysed : the composition is linked to the time of flight of the acoustic signal and the pressure can be retrieved by a calibration process analysing the amplitude of the reflected signal. In 2012, the feasibility of the measurement has been proved on tests performed on irradiated fuel rods. During the past 10 years, important improvements have been carried out on the sensor design and the data processing method in order to target lower pressure and composition ranges. The actual generation of sensors enable measurements covering a wider range of the fuel cycle from 30 bars to 70 bars and down to 0.0% of xenon, i.e. pure helium. The challenge of the measurement lies in the different parameters, which can evolve during the fuel cycle, and need to be taken into account.
The spring used to maintain mechanically the fuel pellets inside the rod constitutes one of the most important parameter to consider. The spring is located at the plenum level and can affect the propagation of the acoustic waves and more precisely, decrease their intensity. It implies that, the thicker the spring, the smaller is the measured amplitude. Nevertheless, this effect cannot be simply investigated during the calibration process as for different assemblies and manufacturers, the springs are geometrically different. Therefore, in our model, this element is studied as part of the losses that are recalculated for a given dimension. The different improvement that led to the validation of the system in laboratory conditions will be presented as well as the consideration, by the numerical model, of the different type of springs.

#07 - Decommissioning, Dismantling and Remote Handling / 51

#7-51 Nuclear Waste Characterisation using Bayesian approaches

Authors: Achment Chalil[1]; Rodolphe Antoni[None]; Pierre-Guy ALLINEI[2]; Mehdi Ben Mosbah[3]; Cyrille Eleon[4]

[1] *CEA, DES, IRESNE, Nuclear Measurement Laboratory, Cadarache F-13108 Saint-Paul-lez-Durance, France*

[2] *CEA Cadarache*

[3] *CEA, DES, IRESNE, Nuclear Measurement Laboratory*

[4] *CEA/DES/IRESNE/DTN/SMTA/LMN*

Corresponding Author: achment.chalil@outlook.com

The relance of the nuclear industrial sector in France is an ambitious plan expected to meet the energy needs of the general public in the 21st century. Along with the construction of new nuclear power plants, significant steps are being taken in the fields of the nuclear fuel cycle and nuclear waste management. In order to comply with the criticality limits, nuclear waste is stored in special drums and different types of nuclear measurements are employed in order to determine the amount of the nuclear matter (U, Pu) contained inside them. These measurements are an indispensable part for various fields of the nuclear industry and active research is ongoing on new methods for improving their precision, especially on the statistical analysis of the data and the modeling of the measurement techniques. In this work, we present an experimental design for the measurement of waste drums using the SYMETRIC 3He detector array located at CEA Cadarache. Simulated data have been produced for different parametrisations of waste drums in order to establish a model that has the potential of sufficiently predicting the calibration coefficient CP9, which is directly related to the amount of fissile matter inside the drum. This coefficient serves as constant of proportionality between the measured prompt signal and the equivalent mass of 239Pu contained in the drum. Up until now, the models trained by the simulated data of the experimental design were exported by multiple linear regression. In an attempt reduce the statistical uncertainties, Bayesian non-parametric methods, such as the Gaussian process, have been tested in the present work. Such methods offer a direct measure of the model uncertainty and are ideal for relatively small datasets. The results are compared with other methods, such as multiple linear regression and Kernel ridge regression. The present work can serve as a starting point for the application of more advanced machine-learning algorithms in view of a better model description along with a potential reduction of the uncertainties.

#04 - Research Reactors and Particle Accelerators / 52

#4-52 Experimental investigation of the VENUS-F core model underestimation of the fast neutron spectrum component

Author: Federico Grimaldi[1]

Co-authors: Enrica Belfiore [2]; Federico Di Croce [3]; Antonin Krása [4]; Jan Wagemans [5]; Guido Vittiglio [4]; Pierre-Etienne Labeau [6]; Patrick Blaise [7]; Mehdi Ben Mosbah [2]; Rodolphe Antoni [2]

[1] *Belgian Nuclear Research Centre SCK CEN, Université libre de Bruxelles*

[2] *CEA Cadarache, DES/IRESNE/DTN/LMN, 13108 Saint-Paul les Durance, France*

[3] *SCK CEN and Université libre de Bruxelles*

[4] *Belgian Nuclear Research Centre*

[5] *SCK CEN*

[6] *Université libre de Bruxelles*

[7] *Framatome, DTIPD, Rue Professeur Jean Bernard 2, Lyon, France*

Corresponding Author: federico.grimaldi98@gmail.com

At the VENUS-F zero power reactor, miniature fission chambers have been used to measure fission rate ratios in order to get insights on the neutron flux energy distribution. Monte Carlo models of VENUS-F have been validated against those experimental results.
Customarily, non-threshold (e.g.: of ^{235}U and ^{239}Pu) and threshold fission rates (e.g.: of ^{237}Np, ^{240}Pu and ^{238}U) are considered to retrieve information on the whole and fast energy spectrum, respectively.
Recently, the CoRREx (Complement to the Reaction Rate Experiments) campaign has been carried out to characterize the latest core configuration loaded at VENUS-F.
Fission chambers with various deposits (^{235}U, ^{239}Pu), ^{237}Np, ^{240}Pu and ^{238}U) were irradiated and discrepancies were found in the modeled fission spectral index of ^{238}U-to-^{235}U. Such a discrepancy was attributed to underestimation of the fast neutron flux spectrum in the Monte Carlo model of the experiment.

Parallel to CoRREx, to measure the fast neutron flux spectrum, the VALUE (VENUS-F Automated Learning Unfolding Experiment) campaign is planned.
With the progress of machine learning techniques, new neutron flux spectrum unfolding methodologies have been investigated. Those offer now a chance to take the problem of the neutron flux spectrum measurement from a different angle.
Among the several possible detector-unfolding methodology combinations, the ones relying on solid state detectors are investigated with great interest because of their large operation domain, allowing for diverse reactor applications.
VALUE foresees irradiation of solid state detectors (SiC and diamond) and fission chambers in the VENUS-F CoRREx configuration.

In this contribution, we present the first results of VALUE: namely, deposited energy in the solid state detectors and spectral indices measured with different fission chambers than in CoRREx (e.g., $^{nat.}$U, ^{232}Th).
For the first time at VENUS-F, a calculation-to-experiment comparison of the energy deposited in solid state detectors will be presented.
Moreover, the new measurements of threshold spectral indices outlined above would allow the investigation of the calculation-to-experiment observed in CoRREx.
Finally, the spectral index measurements presented are a fundamental first step in the validation for the neutron flux spectrum unfolding methodology developed at CEA.

#11 - Education, Training and Outreach / 53

#11-53 EducTUM - An interactive platform for education and training as well as the maintenance of competence in the non-destructive analysis of radioactive materials from decommissioning and dismantling

Author: Thomas Bücherl[1]

Co-authors: Christoph Lierse von Gostomski [1]; Thomas Narr [1]

[1] *TU Munich*

Corresponding Author: thomas.buecherl@tum.de

The decommissioning of nuclear facilities poses major challenges for the declaration of the resulting waste. This will be further exacerbated by changes to existing regulations and the introduction of new ones, also with regard to existing (old) waste. As dismantling will continue for decades to come, this requires the long-term maintenance of the relevant specific specialist skills.
This can only be achieved through continuous further and advanced training of the people already involved, while at the same time training the next generation of technical and scientific experts. The general information of the population must not be neglected either.
The EducTUM project, funded by the Federal Ministry of Education and Research (BMBF 15S9443), aims to provide basic and advanced training, maintain skills and impart general information in the fields of radioactive waste characterization and product control. It is aimed at a wide range of people, from those with a general interest in the subject to users and technical experts. The way in which knowledge is imparted therefore depends on the level of knowledge of the individual groups of people.
The starting point for this is the website https:\\educTUM.de. In the first phase of its development, which is currently underway, the focus is on non-destructive metrological investigations of radioactive waste packages and, in particular, on measurement methods that use gamma and X-rays. Other subject areas are to be included in the course of further development.
The subject area of segmented gamma scanning is currently being worked on. The information provided is divided into four user groups according to their qualification: beginners, intermediate, users and experts. For the former two, this is done by means of a logically structured "journey"through the subject area, whereby the individual subject areas are described in a generally understandable way and previous mathematical knowledge is largely dispensed with. The information is conveyed in the form of texts, pictures, animations and short films. The learning process is supported by accompanying questions. Users are taught the necessary basics, which only require simple mathematical knowledge. E.g. for segmented gamma-scanning, this includes a description of the various measurement modes and their areas of application, the basic procedures for carrying out segmented gamma-scan measurements and the evaluation of the data and its complete and traceable documentation. All topics are underpinned with practical examples. Finally, in segmented gamma-scanning, the expert section deals with the mathematical background of various evaluation methods, the application of ISO standards (e.g. DIN EN ISO 19017 or 11929) to the various measurement methods with practical examples. Furthermore, various calculation tools are made available online, which allow in-depth investigations into the individual topics. Examples include the evaluation of segmented gamma-scan measurements on the basis of uncertainty considerations in accordance with DIN EN ISO 11929, the effect of changes in individual parameters on calculated variables, and the performance of what-if analyses. This knowledge can, for example, support the development of new or optimized measurement systems or the development of new evaluation and/or measurement methods.
What all these measures have in common is that they aim to impart and preserve existing knowledge.
In addition, EducTUM offers the opportunity to use professional programs online to deepen the content taught. This enables a direct link to practice. One example of this is the gamma spectrometry program LVis, which enables online measurements with different detectors on real samples. The samples are located at a measuring station at Radiochemistry Munich RCM of the Technical University of Munich and are regularly exchanged.
The eductum.de website is currently only available in German. A translation into other languages is planned. However, preliminary use in other languages is already possible using the automatic translation functions integrated in modern web browsers.
The aim of the website is to build up and provide the most comprehensive knowledge and application base possible in the respective subject areas. For this reason, the development team is also very

interested in input from external persons and groups in order to integrate their know-how and/or take their interests and questions into account in the further development of the website.
The EducTUM project and its specific features, which set it apart from a "normal"Wikipedia webpage, will be presented.

#08 - Severe Accident Monitoring / 54

#8-54 Correlation between the release of fission products and the fragmentation of irradiated nuclear fuel subjected to temperature transients

Author: Yves Pontillon[1]

Co-author: Kelian Ronne [1]

[1] *CEA*

Corresponding Author: kelian.ronne@cea.fr

The prevention of nuclear accidents is partly sized by a precise assessment of the quantity of radionuclides potentially emitted from nuclear fuel and transported into the environment for a given accidental sequence. LAMIR (a French acronym for Laboratory for the Analysis of the Migration of Radioelements) has specialized for many years in the development of experimental devices deployed in high activity cells. Generally speaking, these types of set up provide access to the kinetics and release rates of fission products from irradiated nuclear ceramics submitted to given temperature transients representative of accident conditions (typically Reactivity Initiated Accident (RIA), Loss Of Coolant Accident (LOCA) or Severe Accident (SA)).
MERARG in operation in the LECA-STAR Nuclear Installation of CEA-Cadarache's centre is a perfect illustration of this point. The corresponding experimental assembly consists of three main parts: the annealing treatment furnace itself located in a high activity cell, the gamma spectrometry detector and finally the gloves box including the gas micro-chromatography and the gas recovery apparatus. The fuel pellet to be characterized (generally with its cladding) is placed in a metal crucible. It is positioned at the centre of the induction coil of the furnace supplied by a high-frequency power generator. It therefore also acts as a susceptor with respect to the HF heating. The sealed enclosure of the furnace consists of a quartz tube inside which the crucible is located. During a typical experiment, this whole assembly is swept by circulation of a so-called "sweeping" gas (argon or dry air) at a low flow rate (approximately 60 cm3/min).
In addition to the fission product release measurement capabilities, MERARG has recently been equipped with a system for imaging and recording the evolution of the sample morphology correlated with a measurement of the surface temperature by thermal radiation spectrometry as a function of the thermal sequence applied. It is thus possible to monitor online and in real time the fragmentation of the fuel, which occurs during a thermal transient, and to link these observations to the release of fission gases and/or fission products (also measured online) and the temperature of the sample.
After recalling the main characteristics and performances, in terms of possible temperature transients, of the MERARG device, the development, the so-called "cold qualification (i.e. outside the active laboratory) phase"and, finally, the active commissioning of the new imaging and surface temperature measurement system will be described in detail. The first results obtained on high burnup UO2 fuel will then be presented in order to highlight the unique capabilities to date of the experimental set up, thus making it possible to better understand the mechanisms involve in the release of fission products. Future experimental developments planned to allow the application of thermal sequences representative of a severe accident (i.e. up to fuel fusion) in an oxidizing atmosphere will be the subject of the last part of this presentation.

#07 - Decommissioning, Dismantling and Remote Handling / 55

#7-55 Preliminary study: spectroscopic characterization of high dose rate small drums with newly developed ultracompact HPGe detector to optimize waste streams

Author: Jonathan Wiseur[1]

Co-authors: Damian Ralet [2]; Julien Masseron [2]; Tony Dieudonné [1]; Vincent Geller [1]

[1] *Institute for Radioelements*

[2] *Mirion Technologies*

Corresponding Author: jonathan.wiseur@ire.eu

IRE (Institute of radioelement in Fleurus - Belgium) produces radioisotopes for medical use. To produce them, irradiated uranium targets are dissolved through chemical processes.
These processes generate various kind of high activity waste. These wastes are conditioned in small drums (10L) placed in interim storage in order to decrease the dose rate. When the dose rate is low enough, the waste can be conditioned into 220L drums for final characterization before sending them to the Belgian national authority for waste (ONDRAF-NIRAS). Up to date the strategy is based on dose rate measurement at the arrival of each waste and a second measurement is foreseen after few months. The isotopic vector is quite variable in each waste and so the dose rate could decrease rapidly or not. The dose rate can vary from few millisievert to few sievert per hour.
The purpose of this work is to improve this process with studying the possibility to characterize the isotopic content of each waste drum through gamma spectroscopy using newly developed detection technologies in order to optimize the decreasing time and so the waste stream.
Several constraints have to be considered. Indeed, the measurement location is already defined and cannot be moved. The drum to characterize is placed in a small shielded bunker. A small removable aperture is available to look inside this bunker. The measurement system has to be placed in a restricted environment (in terms of available space) with a high radiological environment (drum waste storage room with an ambient dose rate between 5 and 30 µSv/h). The measurement time of each drum is fixed to 600s. The number of isotopes to identify and quantify is limited to 13 elements. The dose rate of the drum can vary from few mSv/h to hundred Sv/h in extreme cases.
A screening of available detectors technology on the markets has be done (classical HPGe, MicroGe™, CZT and NaI detectors). A series of preliminary tests are carried out to determine which detector is the best candidate to reach the initial aim. The identification and quantification capabilities are tested. Resolution of peak in function of dead time are also analyzed. Some typical drums are selected and measured with the different systems. The results of the preliminary tests conduct to further investigate the use of a MicroGe system.
The newly developed MicroGe detector is commercialized by Mirion. This system is relatively compact and suitable for high gamma-ray flux environments and adapted to high count rate. Two different size of crystal are available (10 x 10 mm crystal and 20 x 20 mm for increased efficiency). Tests conducted during this study are done with a crystal of 10 x 10 mm with an energy resolution around 1.7 keV at 661 keV. This detector is very compact and have a cooling down time under half an hour. The relative efficiency is around 0.04% at 1332.5 keV. Efficiency curve can be obtained by simulation. A MicroGe version optimized for higher fluxes has a saturation for 137Cs source at a dose rate up of 8 mSv/h, to be compared with 1 mSv/h for the standard version; while maintaining very good spectroscopic performance.
One of the main topics of this study is to establish the theorical measurable activity knowing the geometrical constraints of the measurement and the saturation dose rate of the detector. For this, some Monte Carlo calculations are done considering some hypothesis. Calculating the dose rate at contact of the detector for some isotopic vector and fixed activity in the drum then the dose rate around the drum is calculated. Comparisons are done with input data concerning dose rates. These results fixed a range for operation.
Additional studies are required, however, as some waste cannot be measured, given their excessive dose rate. The high variability of the dose rate is also a challenge that needs to be addressed, for instance by implementing an automated adaptive collimation/shielding process based on a dose rate or dead time measurement of the MicroGe detector.
The MCNP model also needs to be validated by experimental measurements of a reference drum.
Finally, before the implementation of a fully automated characterization system using MicroGe, tests of the entire process under real conditions must be carried out.

#09 - Environmental and Medical Sciences / 56

#9-56 Future Trends in Nuclear Medical Imaging

Author: Paul Lecoq[1]

[1] *CERN*

Corresponding Author: paul.lecoq@cern.ch

Nuclear Medical Imaging is at the forefront of molecular imaging diagnostic, theragnostic and treatment follow-up techniques for a number of diseases (cancer, neurodegenerative impairment, cardiovascular disorders, etc⋯), particularly in the rapidly growing context of personalised medicine.

Although Positron Emission Tomography (PET) already provides the best molecular sensitivity and quantitative accuracy among all the other medical imaging modalities, there is a strong motivation for pushing even further the sensitivity, to allow reducing the radiation exposure to the patients and personnel, reducing the scan time, opening the way to follow-up on slow dynamic processes with long half-life isotopes (particularly important in the context of immunotherapy), as well as addressing new medical challenges, such as tracking a small number of cells.

Two routes are extensively explored to reach this ambitious objective. The first one is based on increasing the geometrical acceptance of the PET scanner by extending its axial field of view. This is the Total Body PET approach, initiated by the group at UC Davis and already producing impressive results.

The second route exploits the potential of time-of-flight (TOF) performance to improve the signal-to-noise ratio (SNR) of the reconstructed image and to increase the PET effective sensitivity. The accuracy of TOF is bound to the whole detector chain, namely scintillator, photosensor and readout electronics. One possible approach to overcome the timing resolution limits of standard scintillators commonly used in PET scanners, such as BGO, LSO, LYSO, LGSO, etc , is based on the metascintillator concept, a deep-tech approach, benefiting from recent important progresses in a number of disruptive technologies, to combine and optimize several functionalities in the same scintillator heterostructure. Capitalising of progress in nanotechnologies and in particular nanophotonics, high speed highly integrated electronics, artificial intelligence and more generally information technologies, metascintillators are a new class of multifunctional multi-intelligent scintillators combining the high stopping power and photo-fraction of well know scintillators, such as BGO, LSO, and the ultrafast scintillation of quantum confined excitons in nanocrystals. But the very fruitful cross-fertilisation between physics and medicine opens also the way to the development of cost-effective and portable imaging approaches, allowing a better deployment of nuclear imaging modalities in low- and medium-income countries (LMICs). As presented in this talk, this ambitious goal is supported by the IAEA (International Atomic Energy Agency) and is in line with an initiative being prepared by the WHO (World Health Organization) and the 3d out of 17 NATO sustainable goals for 2030: Good Heath and Well Being for everyone.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 57

#6-57 Measurement of Neutron Active Interrogation Contraband Signatures Using Organic Scintillators

Author: Colton Graham[1]

Co-authors: Junwoo Bae [1]; Shaun Clarke [1]; Sara Pozzi [1]; Igor Jovanovic [1]

[1] *University of Michigan*

Corresponding Author: coltwgra@umich.edu

Concealed contraband (e.g., explosives, illicit drugs, and special nuclear material) can be detected by neutron active interrogation. For detecting explosives and narcotics, prompt gamma rays from fast neutron inelastic scattering on carbon, nitrogen, and oxygen and delayed gamma rays from thermal neutron capture on hydrogen, nitrogen, and chlorine are the primary signatures. Pulsed accelerator-driven neutron generators are commonly used for activation since the pulse structure allows for the measurement to be divided into a prompt time region, during the neutron pulse when fast neutrons dominate the neutron flux, and a delayed time region between neutron pulses, during which the neutron flux consists of thermalized neutrons. The use of pulsed time gating improves the signal-to-background ratio for signatures based on their timing and the neutron interaction type that produced them. Despite their potential, active interrogation systems are yet to be widely deployed at security checkpoints because the systems require prohibitively long measurement times, can deliver a substantial radiation dose to operators, and are not yet cost-effective. While inorganic scintillators and semiconductor detectors are commonly used for detection of these contraband gamma-ray signatures, organic scintillators offer several advantages. Their fast response times make them pileup resistant, enabling higher neutron fluxes during irradiation. Additionally, organic scintillators are cost-effective and scalable to large volumes to create efficient detection systems. This work explores the use of spectral reconstruction to enhance gamma-ray spectroscopy capabilities of organic scintillators and demonstrates the detection of contraband signatures using fast neutron active interrogation and organic scintillators. Spectral reconstruction is implemented using maximum likelihood estimation maximization, an iterative algorithm that determines the incident gamma-ray spectrum with the highest probability of resulting in the measured light output spectrum, given Poisson counting statistics and a known detector response. The detector response matrix is simulated in the Geant4 framework, using energy deposition convolved with measured energy resolution parameters. The energy resolution parameters are measured by fitting simulation data to measured gamma-ray check source data using a genetic algorithm. The spectral reconstruction algorithm was tested on several gamma-ray check sources and shown to be in good agreement with the known gamma-ray spectrum. Fast neutron active interrogation measurements were conducted using Thermo Scientific P211 DT and MP320 DD pulsed generators and graphite, sugar, salt, and melamine contraband simulants to measure hydrogen, carbon, nitrogen, oxygen, and chlorine contraband signatures. Activation gamma rays were measured using hydrogenous and deuterated liquid organic scintillators. The detection system makes use of a reconfigurable water-based collimation system to reduce the production of activation gamma rays in the environment, which constitute active background, and to shield the detectors from fast and thermal internal neutron activation. We successfully reconstructed the major hydrogen, carbon, nitrogen, oxygen, and chlorine gamma-ray signatures from active background subtracted light output spectra. We additionally show discrimination of contraband simulants and benign activation targets based on the measurement of the ratio of the intensity of carbon and oxygen signatures in reconstructed spectra. We show that time gating on the prompt time region shows an increased signal-to-background ratio for neutron inelastic scattering gamma rays, and gating on the delayed time region improves the signal-to-background ratio for neutron capture gamma rays, evincing the value of pulsed neutron generators. We demonstrated the advantage of short neutron pulses by measuring the signal intensity and signal-to-background ratio for neutron capture gamma ray signatures for various pulse lengths, which were set by adjusting the duty factor of the DD generator. Future work will include the extension of these techniques to measurement of contraband gamma-ray signatures with Cherenkov detectors, which may provide greater pileup resistance but which pose additional unique challenges due to their relatively low light output.

#10 - Current Trends in Development of Radiation Detectors / 58

#10-58 Characterization of a High Efficiency Multi-Element Neutron Dosemeter Based on Thick Gas Electron Multiplier

Authors: Haoshuai Wang[1]; Soo Hyun Byun[1]

[1] *McMaster University*

Corresponding Author: wangh167@mcmaster.ca

We present characterization of a high efficiency multi-element neutron dosemeter, which is built upon the THick Gas Electron Multiplier (THGEM) technology. The multi-element design enables high neutron detection efficiency and is therefore ideal for building tissue-equivalent proportional counters (TEPC) for taking microdosimetric measurements in weak neutron fields. Unlike traditional TEPCs, the THGEM is better suited for constructing multi-element TEPCs, as its lack of an anode wire structure greatly simplifies fabrication and assembly. Following the development of our first version THGEM multi-element detector, consisting of twenty-one gaseous sensitive volumes, we recently developed a second version with ninety-five sensitive volumes. Comprehensive experiments to characterize its signal and dosimetric performance are currently underway using the ^{238}PuBe and ^{7}Li(p,n) neutron sources at the McMaster accelerator laboratory. The experimental results of the new detector in terms of neutron dose response and detection efficiency will be presented alongside Monte Carlo simulation results and experimental results from the first version detector.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 59

#6-59 Cyber security of instrumentation and radiation monitoring systems based on programmable digital devices such as FPGAs in New Nuclear Power Plant

Author: Seunghoon Park[1]

Co-author: Kihaeng Nam [2]

[1] *Korea Institute of Nuclear nonproliferation and Control*

[2] *Korea Institute of Nuclear Nonproliferation and Control*

Corresponding Author: shpark@kinac.re.kr

New nuclear power plants such as Small Modular Reactors (SMR) are making efforts to replace conventional analogue instrumentation and control devices, electronic cards, and etc. or to introduce the latest programmable digital devices (PDD) such as Field Programmable Gate Arrays (FPGAs) for securing diversity and device stability. In Korean nuclear power plants, the systems based on FPGAs are used in non-safety systems of some nuclear power plants. The FPGAs are tried to substitute analogue signal processing devices of ex-core and in-core neutron measurement systems of a nuclear reactor. Also, environment radiation monitoring systems (ERMS) and measurement equipment with digital devices were already used to nuclear power plants. However, there is no history of using it in full-fledged safety systems such as other SMR cases, so it needs to be reviewed in terms of cyber security

The U.S. NRC revised "RG1.152, Rev.3, Criteria for Use of Computers in Safety Systems of Nuclear Power Plants"which focuses on computer use in nuclear power plants with the revision, digital assets limited to computers were expanded to PDD clearly in order to include non-computer type digital assets including FPGAs in safety regulations in "RG1.152, Rev.4, Criteria for Programmable Digital Devices in Safety-Related Systems of Nuclear Power Plants". Regulatory guide for safety in Republic of Korea, FPGAs used in safety systems are applied by IEC 62566 standard that reflects hardware characteristics in verification and validation (V&V) of regulatory guidance. Existing cybersecurity requirements with respect to establishing cybersecurity program of a nuclear power plant, such as U.S. NRC "RG5.71, Rev.1, Cybersecurity programs for Nuclear Power Plants"and Korean "KINAC/RS-015, Rev.2 Security for Computer and Information System of Nuclear Facilities", can be applied to all types of digital assets. However, attack surfaces and security characteristics of FPGAs may vary depending on the detailed design characteristics. It is necessary to study the characteristics of the digital asset, including the latest cyberattack cases and public vulnerabilities. Current cybersecurity regulatory requirements include software development security requirements, but additional research is required on security requirements at the hardware development, manufacturing, and supply stages. In particular, in a development environment based on hardware characteristics using HDL (Hardware Description Language) compared to existing software. There has been no specific consideration of cybersecurity for SDOE (Secured Development and Operation Environment) safety regulatory requirements. Separate research was deemed necessary without consideration malicious and intentional attacks for safety requirements. Therefore, considering the detailed characteristics of PDD, it is possible to cover the development and operation stages. This may include developing regulatory requirements and applying classification schemes such as "NEI 13-10, Rev.6, Cyber security control assessment"and security measures accordingly. Research on the regulatory position on differentiation is needed, and this should be clearly identified before the device introduction stage in new nuclear power plants.

#04 - Research Reactors and Particle Accelerators / 60

#4-60 SiC neutron detectors for subcritical system monitoring and education applications

Author: Vladimir Radulović[1]

Co-authors: Danilo Bisiach [2]; Takahiro Makino [3]

[1] *Jožef Stefan Institute*

[2] *Instrumentation Technologies doo*

[3] *National Institutes for Quantum and Radiological Science and Technology*

Corresponding Author: vladimir.radulovic@ijs.si

Silicon carbide (SiC) semiconductor radiation detectors are being researched in the field of radiation detection as a promising technology offering superior performance characteristics that address many limitations of traditional detector materials, thanks to inherent advantages of SiC. These are, for radiation detection in particular, its wide bandgap, high thermal conductivity and exceptional radiation hardness, which make SiC highly suitable for use in harsh environments.
This paper presents research into the application of SiC detectors for measurements of the neutron flux in a nuclear reactor in subcritical conditions, relevant for neutron measurements / monitoring of subcritical and zero power reactors or spent fuel facilities. This application is made possible by the implementation of wide area SiC Schottky Barrier Diodes (SBDs) enabling high detection efficiency. Two wide area SiC SBDs were fabricated at the National Institute for Quantum Science and Technology in Japan. 6LiF converter layers were realized by dispersing 6LiF powder in ethanol and subsequent deposition on the front contact of the SiC SBDs. Measurements were performed in the Jožef Stefan Institute TRIGA research reactor in Slovenia in subcritical conditions, at neutron flux levels in the source range, with the objectives to monitor the neutron population during a controlled approach to criticality and to measure the axial neutron flux distribution in steady-state subcritical conditions. Measurements were carried out using the Libera MONACO 3 fission chamber data acquisition system, developed at the French Atomic and Alternative Energies Commission (CEA), and commercialized by the Instrumentation Technologies company in Slovenia. The results obtained demonstrate excellent performance of SiC detectors for measurements in subcritical conditions.
The application of SiC detectors for neutron measurements is also particularly suitable as an experimental activity in nuclear education, due to the fact that the experimental setup can be made visually more interesting compared to e.g. sealed gaseous detectors. The use of standalone neutron converters makes it possible to observe and visualize the response of a SiC detector to charged particles from a radioactive source, or charged particles due to neutron interactions, as well as attenuation in the air gap between the source/converter and the detector, or self-absorption effects in the converter layer. Experiments with SiC detectors can therefore enable demonstrations of a range of phenomena relevant for neutron / charged particle detection, facilitating understanding and knowledge retention, and have already been implemented at the JSI in the framework of hands-on education activities organized by the European Nuclear Experimental Educational Platform (ENEEP).

#10 - Current Trends in Development of Radiation Detectors / 61

#10-61 Real-time gamma-neutron discrimination with a trainable polynomial kernel

Authors: Jan Král[1]; Jiří Čulen[1]; Matyáš Hlavinka[1]; Václav Přenosil[1]; Zdenek Matej[2]

[1] *Masaryk University*

[2] *Masaryk university*

Corresponding Author: 514422@mail.muni.cz

This paper presents an implementation of a fully pipelined polynomial Support Vector Machine (SVM) decision function in a Field Programmable Gate Array (FPGA), featuring external training and modifiable vectors. Specifically tuned for pulse shape Gamma-Neutron discrimination within the established NGA-01 Neutron Gamma Analyzer, the method would aid in the differentiation of low-energy pulses. Discrimination is achieved by analyzing the voltage pulse output from an external photomultiplier that gathers light from a scintillation crystal. Here, the primary point of interest is on the tail end of the pulse. The method was shown to have very good separation results in an offline setting. The aim of the paper is thus to create an embedded solution for a real-time application. The SVM is trained on data classified using the conventional tail integral ratio method and is then transformed to avoid division, which better separates the low-energy end. This however, separates the classes non-linearly, so we cannot choose a simple discrimination constant and have to find a separating hyperplane. The computed support vectors can be loaded into the decision function without requiring re-synthesis, allowing for on-the-fly adjustments. This is essential if a different scintillation material is used or if the device is recalibrated, as a single embedded pre-calculated solution would have to be re-synthetized in this scenario. The output of the solution is classification, while the amplitude and total energy can be passed on from the measurement needed for the input. The current design employs 18-bit fixed-point arithmetic and a cubic kernel, chosen to match the FPGA's available DSP multipliers, which have a maximum multiplier width of 18x25 bits. This approach yields a numerical deviation of about 3–5% from a 32-bit floating-point implementation in C due to cumulative error. However, since classification depends on the signum function, this deviation does not impact the results except for values very close to the hyperplane, although this requires further validation. Given that the spectrometer has a 12-bit measurement accuracy, this error can either be disregarded or addressed during training. The primary development goal was to ensure real-time implementation with high-speed performance. Vectors, coefficients, and output values are stored in a register array, allowing full parallel access and significantly reducing the time required for summing the calculated values. A straightforward implementation would require 6 DSP slices per cubic kernel calculation, which is space-intensive on the FPGA. Although theoretically feasible and capable of calculating a different result per clock cycle, it would be inefficient. Given the spectrometer's high measurement frequency, the decision function is conversely needed only after an entire pulse has been collected. This allows for a state machine that uses a single DSP block per kernel for multiple calculations or a sequential call of kernel calculations, freeing up FPGA resources. Furthermore, no additional multiplication is necessary, as summing operations are implemented via lookup tables. This implies that the maximum number of dynamic vectors depends on the available DSP slices, while the remaining module is structured to handle varying numbers efficiently, with summation scaling logarithmically with the total vector count. As a proof of concept, the design is synthesizable and implementable with current testbenches used to compare the results with the aforementioned C implementation. The registers are currently filled directly in the testbench. Further research requires greater emphasis on the processed data and the offline learning of the decision function.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 62

#6-62 Development of the Uranium Verification System for Nuclear Material Management in Korea

Authors: Hee Seo[1]; Jihyun Ahn[1]

Co-authors: Jinho Ryu [2]; Seungho Ahn [2]; Seungmin Lee [2]

[1] *Jeonbuk National University*

[2] *Korea Institute of Nuclear Nonproliferation and control*

Corresponding Author: ahnjh@jbnu.ac.kr

The international community has consistently prioritized the peaceful application of nuclear energy, establishing a framework of safeguard agreements with the International Atomic Energy Agency to monitor and verify nuclear materials globally. A cornerstone of these efforts is uranium verification, a critical process designed to ensure that nuclear materials are not diverted for non-peaceful purposes. Among various verification techniques, Non-Destructive Analysis has become widely adopted due to its efficiency and capability for on-site material analysis without causing damage. Gamma spectrometry, a prominent Non-Destructive Analysis method, is particularly effective in assessing uranium enrichment levels, facilitating timely evaluations across different settings. However, despite these advantages, the accuracy of Non-Destructive Analysis in uranium verification can vary due to factors such as detector performance, environmental conditions, and sample characteristics, all of which impact the outcome. This variability highlights the necessity of a uranium enrichment analysis system that accounts for such influencing factors, thereby improving verification accuracy and reliability. In response to these challenges, this study focuses on developing a uranium verification system optimized for domestic applications, adhering to the uranium verification methodologies established by the IAEA. The primary aim is to enhance the precision and reliability of uranium verification in Korean, thereby contributing to a more secure and transparent nuclear material management framework. To achieve this, the study carefully examines the International Atomic Energy Agency's uranium verification techniques, paying particular attention to the unique environmental conditions associated with verification targets in Korea, such as uranium pellets, fuel rods, and UF6 cylinders. Based on these insights, the research proposes a customized uranium verification approach tailored to meet the specific requirements of the national environment. Future research will focus on developing this proposed system into a practical verification tool, evaluating its effectiveness through comprehensive field trials, and refining its design for optimal performance. By pursuing these objectives, this research seeks to establish a verification system that not only reinforces national nuclear safety but also strengthens international trust and cooperation, reaffirming the commitment to the peaceful use of nuclear energy.

#10 - Current Trends in Development of Radiation Detectors / 64

#10-64 Fast neutron detector based on vertically aligned carbon nanotubes

Author: Jean Nippert[1]

Co-authors: David Tisseur [1]; Mathieu Pinault [2]; Ugo Forestier-Colleoni [2]

[1] *CEA, DES, IRESNE, DER, Cadarache*

[2] *Université Paris-Saclay, CEA, CNRS, NIMBE*

Corresponding Author: jean.nippert@gmail.com

The unique physical properties of carbon nanotubes have spurred numerous applications across various fields. In this study, we investigate their electrical properties to develop a detector for fast neutron flux measurement. Previous research has demonstrated their potential in dosimetry for thermal neutrons and gamma radiation using random networks of carbon nanotubes.

For the measurement of fast neutron flux, we utilize vertically aligned multi-walled carbon nanotubes and monitor the changes in their electrical resistivity under neutron irradiation using a four-probe technique. The vacancies generated in the nanotube structures due to irradiation directly affect their electrical properties, allowing us to deduce the neutron flux from variations in resistivity.

Future fusion reactors, such as ITER, are expected to generate intense neutron fluxes in high-temperature environments. These fluxes are challenging for traditional detectors, which tend to degrade quickly under such conditions. Carbon nanotube carpets, with their low density, reduce the number of interactions caused by neutron irradiation, thereby extending the device's operational lifetime. Additionally, the thermal properties of carbon nanotubes make them well-suited for high-temperature environments like fusion reactors. Furthermore, the low production cost of these detectors presents a compelling case for their development.

In this work, we present the development of our prototype, starting with a description of the material and dimensions of the nanotubes. We also detail the results of simulations performed using Geant4, which provide valuable insights into reaction rates and the spatial distribution of defects within the device. These simulations allow us to make informed predictions about the detector's behavior under irradiation. While the precise evolution of the device's electrical resistance cannot be fully simulated, it can be approximated by treating each nanotube as a parallel resistor. Defects in the nanotube structure increase its electrical resistance, enabling us to estimate the device's electrical resistance change during irradiation.

The next phase involves building a prototype, where we will outline the construction process and present the first test results of these initial prototypes.

#09 - Environmental and Medical Sciences / 65

#9-65 Discerning Y-90 ingrowth from Sr-90 for in-situ groundwater monitoring with the ABACUS logging probe

Author: Soraia Elísio[1]

Co-authors: Chris Gunn [2]; Emma Coghill [2]; James Graham [3]; Jeremy Andrew [2]; John MacGregor [2]; Malcolm Joyce [4]; Tom Calverley [5]

[1] *Lancaster university*

[2] *Nuclear Restoration Services*

[3] *National Nuclear Laboratory*

[4] *Lancaster University*

[5] *Sellafield*

Corresponding Authors: m.joyce@lancaster.ac.uk, s.elisio@lancaster.ac.uk

Measurements showing the potential to discern the ingrowth of yttrium-90 (Y-90) from its parent strontium-90 (Sr-90) in aqueous media, based on direct β- particle detection will be described. These have been made using an unshielded cerium bromide (CeBr3) detector in a dedicated depth monitoring probe, hereafter referred to as 'ABACUS', in media stripped of yttrium. Whilst similar radiologically, Y-90 and Sr-90 contrast significantly in terms of their aqueous solubilities and tendencies to migrate as elemental species. Consequently, they may not always be in secular equilibrium due to their relative proportions in solution changing with time especially given groundwater flow or disturbances acting to resuspend or wash out yttrium precipitates. A temporal count profile has been obtained of aqueous samples stripped of yttrium indicating the in-growth of Y-90 in this initially, Sr-only-containing groundwater sample. A plateau was reached in 21 days consistent with secular equilibrium having been achieved (~ 8 half-lives of Y-90) based on a combined scintillation response indicating not only characteristic features in the X-/γ-ray response but also the potential for the direct detection of Y-90 β- particles in CeBr3 evidenced by spectra consistent with the anticipated Y-90 β- particle response. ABACUS is a groundwater X-/γ-ray prototype logging instrument designed for in-situ assessment of radioactivity in underground, water-logged environments, particularly in boreholes and sumps. It comprises a commercially available, 10 × 9.5 mm CeBr3 scintillation crystal attached to a small, full-featured MCA Topaz-SiPM module, contained in a Ø 7 cm & 28 cm long cylindrical aluminium case. ABACUS can be deployed to meet most on-site requirements and is controlled/read via an Ethernet-based logging cable, including a motorised winch to aid deployments particularly in boreholes up to 100 m depth affording accurate depth measurements and also in laboratory settings concerning off-line sample measurement. A first study (presented at ANIMMA 2023) focused on the mathematical algorithm used to analyse the X-/γ-ray photon spectra from ABACUS, which afforded dual-mode detection and discrimination of Cs-137 alongside the β-emitting radionuclides as Sr-90/Y-90 based on comparison of X- and γ-ray photon spectra, Sr-90/Y-90 being important as relatively high-yield, long-lived anthropogenic fission product derivatives from the nuclear fuel cycle. The assessment of Cs-137 and Sr-90 in surrounding soil formations close to a borehole and the location of the probe is achieved by detecting both γ rays and bremsstrahlung X-ray photons, respectively, the latter arising from the interactions of β- particles emitted by Sr-90 and subsequently Y-90 in the steel of the blind-tubes or aluminium of the probe case etc. A computer-implemented algorithm is used to detect and discriminate a primary (distinguished usually in terms of having easily-identified discrete γ-ray lines) source of radiation over the more continuous background, with a semi-empirical fitting procedure. To analyse the depth of individual nuclides, count profiles are processed using a development of the Moffat point-spread-function (PSF) model verified by a series of tests using Cs-137 sealed point sources and applying the combined algorithm demonstrating the effectiveness to identify changes in one-dimensional vertical source distributions from a baseline anomaly response curve, over successive log runs on a laboratory testbed. Here, the focus is on the implementation of a qualitative approach to discern the relative contribution of Cs-137 and Sr-90/Y-90 in solution with an unshielded ABACUS probe, based on comparison of X- and γ-ray photon spectra via the bremsstrahlung yield from Sr-90/Y-90 and the Cs-137 γ-ray full-energy peak response, using spectral shape analysis to derive two count-independent parameters to indicate the extent of X- and γ-ray mixing. This not only enables spectral shapes linked to different source distributions and isotopes but also, given the very high-energy, β- particle stimulus from Y-90, the isolation of characteristic responses consistent with continuous β- particle spectra and their semi-characteristic end-point energies, especially where detectors are fabricated to enhance this response, i.e., to incorporate a thin window. Direct assessment of Sr-90 and Y-90 is known to be particularly challenging

due to the short range of their β- emissions in matter, relative to X-rays and γ rays, and their lack of characteristic γ rays in contrast to Cs-137. However, this is not impossible given the high energies of said β- particles, as this research will illustrate.

#07 - Decommissioning, Dismantling and Remote Handling / 67

#7-67 Enhancing history management of Low and Intermediate Level Radioactive Waste: Systems and Future Direction

Author: Jun Lee[1]

Co-authors: Dong-Ju Lee [1]; Yun-Geon Jung [1]; Jin-Woo Lee [2]; Hee-Chul Eun [3]

[1] *KAERI(Korea Atomic Energy Research Institute)*

[2] *KAERI (Korea Atomic Energy Research Institute)*

[3] *Korea Atomic Energy Research Institute*

Corresponding Author: junlee2@kaeri.re.kr

KAERI(Korea Atomic Energy Research Institute) includes diverse R&D environments, such as a research reactor, a nuclear fuel cycle facility, and a radioisotope production facility. These facilities generate low and intermediate level radioactive waste during operational and decommissioning phases. To ensure effective radioactive waste management, we oversee storage and processing facilities that support robust history management across the radioactive waste lifecycle. A centralized database in the intranet enables to manage from waste generation to disposal, allowing for comprehensive oversight. Additionally, KAERI has implemented a full-cycle history management system for waste drums, developed in compliance with the Republic of Korea's the radioactive Waste Acceptance Criteria (WAC) and the radioactive Waste Certification Program (WCP).
However, the database system has several limitations, such as processing large volumes of text data and the need for supplementary information. To overcome these issues, the system has been designed to provide data analysis and visualization. This study proposes a framework for radioactive waste management system and linked analysis system, detailing specific procedures at each step with the application of traditional radiation detectors. The preceding steps in the radioactive waste management process are to receive waste history from the waste generators. These include an application for a specified container, pre-inspection, and management request. Next, the succeeding steps consist of repackaging, treatment, characterization, and evaluating the suitability of disposal, for a process to manage radioactive wastes transparently. A unique identification (ID) number is assigned to each package, linking it to the centralized database that manages all radioactive waste activities throughout its life-cycle. The major nuclides and contamination routes are evaluated during pre-inspection to verify the classification as radioactive waste.
During transportation between facilities, the surface dose rate and contamination level are measured and used as variables to make the handling plan(e.g., loading position) within the radioactive waste storage facility. The system is enhanced to manage dynamic information, including the profiles of radioactive waste stream throughout the treatment and repackaging processes. In conclusion, we focus on the necessity and direction of an integrated system for safely and efficiently managing radioactive waste, focusing on the linkage between the operational system that manages the full-cycle history database and the data analysis system.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 68

#6-68 OMNISCINTI™: From quintuple discrimination scintillator to prototype detection head.

Authors: Guillaume Bertrand[1]; Pauline Vergnory[None]; Matthieu Hamel[2]; Camille Frangville[1]; Victor Buridon[1]; Dominique Tromson[1]

[1] *CEA/DRT/LIST/DIN/LCIM*

[2] *CEA*

Corresponding Author: guillaume.bertrand@cea.fr

When facing unknown sources of radiation, first responders are often confronted to the problem of choosing an apparatus to evaluate the nature of the contamination. Multiple detection solutions exist but all are specialized or assume some kind of knowledge of the targeted radiation nature. From the past three years, we developed the Omniscinti™ technology to answer this challenge.
Omniscinti™ is a layered organic scintillator able to discriminate the five main types of radiation: alpha, beta, gamma, fast neutron and thermal neutron. Each layer is designed to enable simultaneous detection and separation of the five emitters'contributions using the Pulse Shape Discrimination (PSD) method. The Omniscinti™ technology is a combination of several developments from our team expertise,
- 6Li doping in plastic scintillator for thermal neutron detection
- High concentration of fluorophore for fast neutron / gamma discrimination
- Phoswich geometry for alpha and beta difference in penetration
- Tunable decay time of plastic scintillator for better phoswich PSD

Previous presentation reported optimizations and performances of each layer in ideal benchtop situation. We present here our latest advances in integration and design towards a fully functional detection head.

We discuss the influence and optimization of alpha and beta detection of our system with different aluminized Mylar© layers to ensure optical isolation. After optimization a fully functional detection head is fabricated keeping in mind the final application constraints. Its performances in quintuple discrimination are tested indoor and the results show comparable alpha's and beta's efficiency to commercial detectors. Gamma and neutron energy calibration is underway and will be discussed. We will also present our strategy to implement this detection head in a fully functional prototype with dedicated electronics, HMI and power supply.

This crucial final design step is also the opportunity to probe the larger community about this technology outside of the envisioned first responder application.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 69

#6-69 HV effect on neutron coincidence counting

Authors: Monika Risse[1]; Olaf Schumann[1]; Sebastian Chmel[1]; Theo Köble[1]; Thorsten Teuteberg[1]

[1] *Fraunhofer INT*

Corresponding Author: monika.risse@int.fraunhofer.de

Neutron detection is important in the field of Nuclear Safeguards, Homeland Security, and CBRN (Chemical, Biological, Radiological, and Nuclear) defense. In these areas, precise as well as efficient detection and analysis of neutron emissions are necessary for identifying nuclear material or monitoring radioactive sources. On the one hand, neutrons are very difficult to shield and, taking into account the very low intrinsic background for neutrons, even weak sources can be detected. On the other hand, neutrons only interact weekly with the detector material and in most cases, they need to be moderated, making the detection a veritable challenge. Therefore, specialized materials and technologies, such as neutron-sensitive gases, are employed to facilitate detection.
Normally, a count rate measurement is sufficient to determine that a neutron source is present, but other techniques must be used for more specific identification. In neutron coincidence counting, the temporal correlation of neutrons is considered to distinguish between the prompt emission of a bunch of neutrons, which often indicates the presence of nuclear material, and a random emission of neutrons from industrial sources like Am/Be. This approach therefore is particularly valuable in nuclear security or safeguards, as it enhances the detection capabilities for spontaneous fission and nuclear chain reactions. Neutron Multiplicity Counting goes further by analyzing the frequency of single, double, triple, or higher-order coincidences, which provides even more detailed information concerning the fissile material.
Although many alternative materials have been developed in recent years due to Helium-3 (He 3) shortages, He-3 detectors still remain the standard. The He-3 isotope is highly effective for neutron capture due to its high cross-section for neutron capture, which allows these detectors to operate with high efficiency and even at low neutron flux levels. A configuration of multiple He-3 detectors within a detection array can improve overall detection efficiency, and allows for more accurate coincidence analysis. This technique has found widespread application in nuclear monitoring and control, particularly in identifying and quantifying fissile materials, assessing radioactive sources, and ensuring compliance with international regulatory standards.
Measurements of a commercial neutron multiplicity counter using a set of 30 He-3 tubes were performed. Depending on the applied high voltage (HV), the count rate, Feynman variance (Y2F), and Rossi-α values are examined. With increasing HV, the measured count rate rises, making a higher HV desirable for an increased efficiency of the detector. However, this increase also affects the Feynman variance and Rossi-α value in such a way that above a given HV value the measurement no longer qualifies for accurate analysis. In this case, the instrument can only be used for count rate measurements, and successful multiplicity measurements are no longer possible.
To distinguish nuclear, and in particular fissile, material from industrial neutron sources, the detector must be accurately calibrated and appropriately set to ensure reliable and valid results. This will be demonstrated in the presentation.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 70

#5-70 Discrimination of plutonium and curium in passive neutron multiplicity counting with PVT plastic scintillators

Author: Vincent Bottau[1]

Co-authors: Bertrand PEROT [1]; Cyrille ELEON [1]; Filip D'ALMEIDA [1]

[1] *CEA*

Corresponding Author: vincent.bottau@cea.fr

In the framework of plutonium characterization in radioactive waste drums by passive neutron multiplicity counting, the Nuclear Measurement Laboratory of CEA Cadarache is studying plastic scintillators as a cost-effective alternative to 3He gas proportional counters. Plastic scintillators offer a three order of magnitude faster time response than 3He detectors, large and easy-to-shape detection volumes, and a similar neutron detection efficiency at a much lower cost when using basic PVT scintillators without PSD capabilities, like EJ-200 or BC-408 commercial models. However, their high sensitivity to gamma rays makes it difficult to use plastic scintillators in neutron-gamma mixed fields. Previous studies conducted at the Nuclear Measurement Laboratory of CEA DES IRESNE, at Cadarache, France, have shown that it is possible to measure plutonium spontaneous fission neutrons despite the presence of parasitic (α,n) neutron emitters and gamma-ray sources, using data processing techniques based on the historical shift register method combined with time-of-flight analysis.This work present a new patent-pending data processing, based on several time-of-flight windows combined with multiplicities analysis, to further allow for plutonium quantification even in the presence of perturbing spontaneous fissions from 244Cm. The performances are studied through the development of a full factorial design using MCNP-PoliMi simulations of a measurement system for 118 liters waste drums, composed of sixteen 10×10×100 cm3 EJ-200 plastic scintillators. The drum is homogenously filled with an organic matrix of density 0.3 g. cm-3 contaminated with plutonium and curium quantities equivalent to a 240Pu effective mass between 0 and 500 g. The matrix is also uniformly contaminated by 60Co with an activity between 0 and 2 MBq. In order to account for the multiplication effects associated with high plutonium masses concentrated in clusters, an additional experimental design was developed with spherical PuO2 samples of density 3 g.cm-3. They are located in the center of the organic matrix and cover a 240Pu effective mass from 0 to 650 g, while the curium background still ranges from 0 to 500 g of 240Pueff. Data processing algorithms are used to reconstruct the detectors response from the MCNPX-PoLiMi collision files, including real and accidental coincidences, a low-energy threshold of 50 keVee (electron-equivalent), and a time resolution of 3 ns (FWHM) to each detection channel. The measured quantities of interest, to highlight the contrast between Cm and Pu are for instance, the singles, doubles and triples of traditional multiplicity counting, but here recorded in specific time windows to take advantage of the slight difference in the time-of-flight (ToF) of Pu and Cm spontaneous fission neutrons. Simulations indicate that this time difference can be exploited for Pu/Cm differentiation in Rossi-Alpha and two-dimensional time histograms, based on the relative detection times of the particles involved in double and triple coincidences respectively. All these input data (explanatory variables) are fed into a multilinear regression algorithm, or a machine learning artificial neural network, to obtain predictive models of the 240Pu effective mass. Monte Carlo methods are finally used to account for the impact of explanatory variables uncertainties on the accuracy and robustness of the models. In addition, test configurations are simulated, different from the training set but included in the limits of the factorial design, to assess the predictive capabilities of the numerical models. The best model obtained for the prediction of plutonium mass involves five explanatory variables: Singles (S), doubles counted between 10 and 20 ns (D10-20) after the first detected particle (which is often a fission gamma ray) and between 10 and 60 ns (D10-60), triples between 10 and 20 ns (T10-20) and between 10 and 60 ns (T10-60). This approach allows a prediction of the plutonium mass on the full range of the experimental design, i.e. from 0 to 650 g of 240Pueff, whatever the quantity of Cm between 0 and 500 g of 240Pueff. This is a promising result in view of future experimental validation tests planed with the setup, and this new approach would increase the state-of-the-art limit of Cm/Pu mass ratio by one decade to allow Pu assay.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 71

#6-71 NaTIF a Radiation Portal Monitor: multiparametric analysis towards performances optimization, source anisotropy and threats tracking.

Author: Victor Buridon[1]

Co-authors: Aly Elayeb [2]; Clément Lynde [3]; Francesca Belloni [2]; Frederick Carrel [2]; Guillaume Amoyal [2]; Gwenole Corre [2]; Roberto De Stefano ; Simon Foucambert

[1] *CEA-LIST*

[2] *CEA-List*

[3] *DES/ISAS*

Corresponding Author: victor.buridon@cea.fr

The NaTIF (NaIL-based Threats radIation emitters Finder) project is developing a patented next generation Radiation Portal Monitor (RPM) at CEA List Institute. This technology highlights a RPM that can be deployed, on the ground or mounted on vehicles, in highly frequented civilian areas and at national borders. The main goals are to ensure the monitoring and protection of these areas against radiological and nuclear threats, while providing, in addition, the capability to respond to such threats.

The technology uses inorganic scintillators [NaI:Tl(6Li)], denoted hereafter as NaILTM. NaILTM are price attractive, compared to He-3 based detectors, and relevant for the identification of both radiological and nuclear signatures. Regarding gamma spectrometry, the energy resolution of the Cs-137 gamma ray at 661.7 keV is estimated at 6-8% that is very close to classic NaI(Tl) detectors. Besides, NaILTM are doped with Li-6 that enables efficient thermal neutron detection in the most widely used gamma-ray scintillator, while still preserving the favorable scintillation characteristics of standard NaI(Tl). Each neutron and gamma contribution can be separated by using Pulse Shape Discrimination (PSD) method. In case of NaILTM, the discrimination power is important and given by a Figure of Merit (FoM), around the thermal bump, estimated at 3.8 in the scope of the current work.

The RPM consists in the combination of two NaILTM detectors with three surrounding EJ-200 plastic scintillators. Each inorganic and organic scintillator has an active scintillation volume of 1000 cm3. EJ-200 detectors serve the dual function of fast neutron detectors and moderators, thereby enhancing the RPM's overall sensitivity.

Our study focuses on optimizing the technical and the operational performance of the global RPM through a multi-parametric analysis. This was carried out by tuning parameters of the NaILTM detectors, specifically the high voltage, triggering threshold, and Constant Fraction Discrimination (CFD) settings. The goal was to minimize the energy resolution, maximize gamma/neutron discrimination capability, and improve the detection of low-energy gamma rays emitted by radiological threats, such as Am-241. Moreover, additional studies were conducted by changing orientation of the sources to highlight their anisotropy. Other studies involving the tracking of threats through the relative response of both NaILTM were also performed. The reported results were obtained in a laboratory environment using Cs-137, Cf-252 and Am-241 as radiological simulants.

#07 - Decommissioning, Dismantling and Remote Handling / 72

#7-72 Miniaturized single-head active dosimeter : application to extremities dosimetry

Author: Victor Buridon[1]

Co-authors: Dominique Tromson [1]; Johann Plagnard [1]

[1] *CEA-List*

Corresponding Author: victor.buridon@cea.fr

Worker radiation protection is essential in many fields, from nuclear to medical. In particular, tasks such as decommissioning operations or interventional radiosurgery require accurate measurement of the dose received at the extremities. This measurement is efficiently performed using passive dosimeters, but the informations are delayed in time. As a result, incidents or dose exceedances are not monitored effectively.

In the frame of UDD@Orano, CEA-List Institute develop an active miniaturised dosimeter aiming to measure the equivalent dose to the extremities for risk prevention and radioprotection. This single head detector is based on plastic scintillator coupled to SiPM, connected to a miniaturized electronic and data acquisition system. The dimensions are carefully chosen to make the final head mounted on a ring and worn on the finger, the resulting scintillator is 3x3x3.5 mm3 and the SiPM is a single pixel 3x3mm2, microFC 30035 SMT from from SensL®. The X and gamma rays interaction in the scintillator produces visible photons which will be converted into electrics signals in SiPM. The goal of our work is to rely information received by the detection head to the effective dose the worker is exposed.

We present a new procedure in two major steps, the calibration and the validation of the method that enables the determination of the dose received to the extremities. We compare our results to the ED3 commercial active dosimeter in same measurement condition using reference beams from Laboratoire National Henri Becquerel (LNHB). We demonstrate the applicability of our dosimeter and associated method in this measurement configuration.

#09 - Environmental and Medical Sciences / 73

#9-73 Performance Evaluation of the Seafood Radioactivity Inspection System

Author: Jimin Shin[1]

Co-authors: Dowon LEE [1]; Hee SEO [1]; Soo Mee KIM [2]

[1] *Jeonbuk National University*

[2] *Korea Institute of Ocean Science & Technology*

Corresponding Author: shinjm@jbnu.ac.kr

In the wake of the Fukushima nuclear accident, global concerns have been raised about the potential contamination of seafood imported from Japan. In particular, the recent release of treated water into the ocean has caused public concern in neighbouring countries. In the Republic of Korea, various organisations carry out inspections of seafood to ensure the safety of the food supply and to guarantee that it does not contain radioactive substances. Most inspection techniques are based on precision analysis, which offers a high level of reliability. This approach requires significant time for pre-processing and measurement, making it unsuitable for rapid decision-making. To overcome these limitations, we have developed Rapid Seafood Radioactivity Inspection Systems (RS-RIS) using polyvinyl toluene (PVT) plastic scintillators and sodium iodide (NaI(Tl)) scintillators, respectively. These instruments are designed to verify whether the regulatory criteria for radioactive materials in seafood (i.e., 100 Bq/kg for 134Cs+137Cs and 131I) are satisfied while maintaining the original form of the food. In this study, a series of test items, conditions, and procedures were selected to evaluate the performance of the developed RS-RIS, and to verify the achievement of the established objectives for each test. The test items were designed to evaluate (1) the accuracy of the activity concentration (Bq/kg) calculated by the RS-RIS, (2) the accuracy of the determination of the presence of radionuclides in seafood, (3) the minimum detectable amount of each radionuclide present in seafood, and (4) the accuracy of the mass measurement of the built-in balance for weighing the samples required to calculate the activity concentration. The precision of the activity concentration was assessed by confirming that the calculated activity concentration (A_exp), determined after uniform distribution of 100 Bq/kg of liquid unsealed source in oysters and measurement for 1 minute, satisfied the 95% confidence interval (i.e., A_exp-1.96σ≤100 Bq/kg≤A_exp+1.96σ). The accuracy of determining the presence of radionuclides was evaluated using false-positive and false-negative rates. The false-positive rate is the probability of incorrectly identifying a sample as containing a nuclide above the threshold (i.e., 100 Bq/kg) when in fact it does not contain any nuclide. The false-negative rate is the probability of incorrectly identifying a sample as not containing a nuclide above the threshold when it does contain one. The performance targets for false-positive and false-negative rates were set at 0.1% and 1 in 60, respectively. The accuracy of the balance was evaluated by calculating the difference between the indicated value and the actual mass of standard weights of 10, 20, and 30 kg. Through various test items (i.e., radioactivity measurement accuracy, nuclide presence accuracy, radioactive substance detection performance, and balance accuracy), it is expected to verify the performance of the RS-RIS as seafood radiation detectors. This study was supported by the Korea Institute of Marine Science & Technology Promotion (KIMST) funded by the Ministry of Oceans and Fisheries, Korea (20210671). It was partly supported by a research grant from Korea Institute of Ocean Science and Technology (PEA0202).

#09 - Environmental and Medical Sciences / 74

#9-74 The ENEA TRIGA RC-1 facility inside the SECURE project: production of medical isotopes by neutron activation

Authors: Lucrezia Spagnuolo[1]; Luigi Lepore[1]

Co-authors: Angela Pagano [2]; Francesca Limosani [1]; Letizia Cozzella [1]; Tiziana Guarcini [1]; Simone Placidi [1]; Luca Falconi [2]; Valentina Fabrizio [2]; Davide Formenton [2]; Andrea Roberti [2]; Marco Capogni [3]

[1] *ENEA, NUC-IRAD-CRGR, Nuclear Material Characterization Laboratory and Nuclear Waste Management*

[2] *ENEA, NUC-IRAD-RNR, Research Nuclear Reactor Laboratory*

[3] *ENEA, NUC-INMRI, National Institute of Ionizing Radiation Metrology*

Corresponding Author: lucrezia.spagnuolo@enea.it

The TRIGA RC-1 is a research reactor with a thermal power output of 1 MW, located at the ENEA Casaccia Research Centre in Rome (RM). This facility is extensively utilized for neutron activation analyses and various neutron-related experiments and applications, owing to its capability to produce a broad range of thermal spectral neutron fluence rates.

Neutron Activation Analysis (NAA) can be employed for radionuclide production, such as generating a new radioactive source for technical applications or supplying medical isotopes. In this process, a non-radioactive material is exposed to neutrons, resulting in the generation of radioactive nuclei.

In this context, the ENEA TRIGA RC-1 is involved in the EU-funded SECURE Project (HORIZON-EURATOM-2021-NRT-01 call, Strengthening the European Chain of sUpply for next generation medical RadionuclidEs, October 2022-September 2025), which aims to explore the feasibility of local radionuclide production for medical applications in Europe, including traditional and innovative ways. Specifically, the ENEA team is investigating the potential to produce terbium-161 (^{161}Tb), an isotope that shows promise for targeted radionuclide therapy and may offer advantages over lutetium-177 (^{177}Lu), which is currently used in cancer treatment. ^{161}Tb production exploits the reaction channel ^{160}Gd(n,γ)^{161}Gd(β^{-})^{161}Tb, involving the neutron activation of a gadolinium (Gd) target that is highly enriched in gadolinium-160 (~98%). After the appropriate chemical processes, both ^{161}Tb (the raw radionuclide precursor for radiopharmaceuticals used in cancer therapy) and ^{160}Gd oxide (which can be reused for future irradiation cycles) are extracted and purified.

To assess the production capabilities of the TRIGA RC-1, simulations were conducted using the MCNP and FISPACT-II codes alongside experimental irradiation trials for validation of simulated data. These irradiation trials took place at the reactor's Central Thimble, which is the location with the highest available neutron fluence rate (~5E+13 cm^{-2} s^{-1}) and inside the rotatory rack where the neutron fluence rate is about 3E+12 cm^{-2} s^{-1} (named "Lazy Susan"). The initial calculations, based on 1 g of Gd_2O_3 (with 98.2% enrichment in ^{160}Gd), were performed using FISPACT-II, sometimes combined with MCNP to determine appropriate neutron self-shielding correction factors. The operational constraints of the reactor management allow for sample irradiation for 6 hours a day, 5 days a week. According to the hypothesis of a 12-day irradiation (72 hours of irradiation actually), the expected final yield for ^{161}Tb is ~7 GBq (activity concentration of ~8 MBq$_{Tb-161}$/g$_{Gd-160}$).
The experimental trials conducted at the Lazy Susan involved the irradiation of 190 mg and 1.34 mg of Gd_2O_3 with a natural isotopic abundance at the reactor thermal power of 10 kW and 1000 kW, respectively, for 2 hours each. These trials showed an activity concentration at the end of irradiation (EOI) of approximately 310 kBq$_{Tb-161}$/g$_{Gd-160}$ for the 190 mg sample and approximately 69 MBq$_{Tb-161}$/g$_{Gd-160}$ for 1.34 mg sample.
The experimental trial conducted at the Central Thimble involved the irradiation of 8.7 mg of 98.2% ^{160}Gd-enriched Gd_2O_3 at the reactor thermal power of 1000 kW, for 12-day irradiation (~77 hours of irradiation actually). This trial showed an activity concentration at the end of irradiation (EOI) of approximately 15 GBq$_{Tb-161}$/g$_{Gd-160}$. It should be noted that this trial is not directly comparable to the simulation data before due to the actual timing of the irradiation/shutdown of the reactor. The effective comparison will be done by performing the realized irradiation cycle in FISPACT simulation and comparing homogeneous data. The analysis of data is still ongoing. The final output will be the maximum activity concentration, i.e. GBq of ^{161}Tb per gram of ^{160}Gd, that the ENEA TRIGA RC-1 reactor can produce.
After the reactor irradiation, the irradiated sample needs to be extracted and treated with chemical

dissolution and separation to recover both ^{161}Tb and ^{160}Gd oxide. The effective separation and purification of those streams is crucial: i) to achieve a usable batch of precursor ^{161}Tb to be sent to radiopharmaceutical preparation, ii) to recover ^{160}Gd oxide raw material to new irradiation batches, as to keep the economic feasibility of the production cycle.
The paper herein describes the work carried out in the SECURE Project and major results achieved, giving experimental evidence that, even with a lower efficiency and underutilization of the 98.2% ^{160}Gd-enriched Gd_2O_3, also research reactors and low-magnitude neutron-flux facilities may contribute to the radiopharmaceutical production supply panorama.

#04 - Research Reactors and Particle Accelerators / 75

#4-75 From Prototype to Production: Industrialization and Application of the Libera MONACO 3 Neutron Flux Monitoring System

Authors: Aleš Bardorfer[1]; Danilo Bisiach[1]; Grégoire de Izarra[2]; Jure Trnovec[1]; Loic Barbot[3]; Manuel Cargnelutti[4]; Marko Vučković[1]; Matjaž Škabar[1]; Peter Paglovec[1]; Sebastjan Zorzut[1]

[1] *Instrumentation Technologies doo*

[2] *Commissariat à l'Energie Atomique*

[3] *CEA/IRESNE/DER/SPESI/LDCI*

[4] *Instrumentation Technologies d.o.o.*

Corresponding Author: danilo.bisiach@i-tech.si

From 2020 to 2023, CEA Cadarache and Instrumentation Technologies collaborated on the industrialization of the Libera MONACO 3 (Multichannel Online Neutron Acquisition in Campbell mOde) neutron flux measurement system for research reactors. This instrument provides four independent input channels, enabling data processing across a broad operational range, and can be used with Fission Chamber (FC) detectors. The signal from the FC detector is initially processed by the frontend, which includes: a transimpedance preamplifier unit that converts current pulses from the detector into voltage pulses; a high voltage unit that can polarize the detector with either positive or negative voltage up to ±900 V; and a current meter unit capable to measure up to ±1 mA. The signal is digitized by ADCs and further processed within the FPGA, where additional functionalities such as Pulse Height Analysis and signal statistics are computed. A graphical user interface on a local PC provides real-time system monitoring and control. Neutron flux monitoring can be performed in pulse, Campbell, and current modes in parallel, covering the full reactor dynamic range.

The outcome of the collaboration between CEA Cadarache and Instrumentation Technologies were two prototypes. During the tests and validation of the two prototypes, several hardware, software, and GUI improvements were identified. For this reason, and industrialization phase started in June 2023 to get to an industrial design that can be produced in series. A first series of instruments was produced in 2024, with the first five instruments delivered to CEA Cadarache. An additional instrument was produced as an internal unit, dedicated to conducting measurements at various research reactors, foreseen at IJS in Slovenia and SCK-CEN in Belgium.

Some preliminary tests with the industrial version of the instrument were performed at the TRIGA reactor at IJS and confirmed the system's ability to measure neutron flux across the full operating range in counting mode. Some additional tests were also performed using CVD diamond and SiC detectors, broadening the applicability of the instrument to fusion reactors.
In this paper, an overview of the industrialized system is provided, including the improvements introduced before the series production. Additionally, the measurement results from the above-mentioned campaigns are presented.

#02 - Space Sciences and Technology / 76

#2-76 Miniature radiation spectrometer HardPix

Author: Robert Filgas[1]

[1] *IEAP, CTU in Prague*

Corresponding Author: robert.filgas@utef.cvut.cz

HardPix is a miniature radiation monitor based on the Timepix3 sensor and developed for space application by the Institute of Experimental and Applied Physics, Czech Technical University in Prague (IEAP CTU). Its low volume (<0.1 U), mass (<150 g), power consumption (~2 W) and cost make it ideal even for small cubesats and networks of space weather monitoring nanosatellites. Thanks to the built-in onboard processing it can provide particle identification, energy spectra, flux and dose rates using minimum data transfer rates allowing for continuous operation. It is building upon the space heritage of SATRAM, IEAP CTU's radiation monitor onboard ESA Proba-V satellite celebrating 11+ years of ongoing operation in space since 2013, as well as upon REM units onboard ISS. The first HardPix was launched onboard D-Orbit ION satellite in June 2023, two more units will be part of ESA's European Radiation Sensors Array (ERSA) onboard Lunar Gateway, with several more missions already in preparation including mission to ISS and LEO which should launch in the first half of 2025. Also presented will be the potential use of HardPix as a neutron spectrometer for mapping of water deposits in lunar subsurface onboard lunar rovers.

#09 - Environmental and Medical Sciences / 77

#9-77 Impact of Ultra-High Dose Rate on Water Radiolysis till Homogeneous Chemistry: A Monte Carlo Simulation Study

Authors: Mustapha Chaoui[1]; Yahya Tayalati[2]; Othamne Bouhali[3]

[1] *Faculty of Sciences, University Mohamed V in Rabat*

[2] *University Mohamed V in Rabat (MA)*

[3] *Texas A&M University at Qatar*

Corresponding Author: mustapha-chaoui@um5r.ac.ma

Introduction: Ultra-high-dose rate FLASH radiation therapy (UHDR) is an innovative modality that delivers higher dose rates (40 Gy/s) in a pulsed beam structure. At the core of this exciting approach lies the ability to reduce major normal tissue complications without compromising tumor control efficacy, referred to as the "FLASH effect." However, the underlying mechanisms governing the biological FLASH effect remain elusive. Numerous studies have shown that UHDR can reduce the production of hydrogen peroxide (H_2O_2) in irradiated water under physiological O_2 conditions. The main objective of this study is to track the yields of water radiolysis under UHDR compared to Conventionel dose rates , with particular focus on H_2O_2, over a long time scale (1 hour post-processing).

Materials and Methods: This investigation uses the TOPAS-nBio Monte Carlo track structure and the Gillespy package to analyze steady-state chemical yields under varying dose rates and dissolved oxygen levels. TOPAS-nBio delivers the required dose with a microsecond pulsed beam to achieve UHDR up to 500 Gy/s. Species are tracked until the system reaches stability (escape yield), after which the yields are fed into Gillespy for the homogeneous stage simulation over 1 hour. A water phantom with a volume of 27 μm^3 was used, and proton beams (100 MeV) were compared to electrons (1 MeV).

Results: A significant reduction in H_2O_2 yields was observed at ultra-high dose rates compared to lower dose rates for both proton and electron beams. These findings highlight the importance of considering homogeneous chemistry, where reactions occurring on a 10-second timescale influence H_2O_2 generation, in understanding the FLASH effect. This study contributes to ongoing efforts to elucidate the complex mechanisms behind the FLASH effect, potentially leading to improved cancer treatments and patient outcomes.

Conclusion: The study emphasizes the significance of homogeneous chemistry, particularly in reactions related to O2 removal and H2O2 generation, occurring within a late timeframe (10 s) and being influenced by dose rates. In addition, our findings support experimental observations.

#09 - Environmental and Medical Sciences / 78

#9-78 Positron Emission Tomography imaging using polarization-correlated annihilation quanta measured by single-layer Compton polarimeters

Author: Ana Marija Kožuljević[1]

Co-authors: Darko Grošev [2]; Luka Pavelić [3]; Mihael Makek [4]; Siddharth Parashari [4]; Tomislav Bokulić [4]; Zdenka Kuncic [5]

[1] *Department of Physics Faculty of Science, Department of Physics*

[2] *University Hospital Centre Zagreb, Department of Nuclear Medicine and Radiation Protection*

[3] *Institute for medical research and occupational health, Division of Radiation Protection*

[4] *University of Zagreb Faculty of Science, Department of Physics*

[5] *The University of Sydney, School of Physics*

Corresponding Author: amk@phy.hr

Positron emission tomography is an important medical diagnostic tool that exploits the process of positron annihilation with an electron in a patient's tissue, resulting in two gamma-ray photons with 511 keV energy and opposite momenta. The two annihilation photons are also entangled in their polarizations, specifically, their polarizations are mutually orthogonal, a property not yet utilized by conventional PET devices. This property could potentially be used as an energy-independent handle for background noise rejection that lacks this correlation, thus enhancing the image quality. We developed a novel type of PET scanner demonstrator, capable of measuring the correlations in the polarization of the entangled annihilation quanta, offering for the first time the opportunity to test the possibility of image quality and sensitivity improvement with respect to standard devices that are based on photoelectric detection. The scanner consists of four detector modules mounted on an annular construction capable of precise rotation around the annihilation source at different diameters. The detector modules are single-layer Compton polarimeters, consisting of 16x16 square matrices, assembled of four 8x8 matrices of scintillating crystals, either GAGG:Ce or LYSO:Ce, read out by silicon photomultipliers on one side, using the TOFPET2 ASIC read-out system for data acquisition. The crystals are 20 mm long, and detector modules mounted opposite one another have identical matrix pitches of 3.2 mm and 2.2 mm, respectively. This setup allows the emulation of 16 trans-axial PET rings, with the possibility of determining and reconstructing the polarization correlations of the annihilation quanta by measuring their azimuthal Compton scattering angles. The scanner was tested at University Hospital Centre Zagreb with sources with clinically relevant activities: Ge-68 line sources (1.6 mm active diameter, ~45.5 MBq) and small animal NEMA phantom (NU 4-2008, initial activity of Ga-68 ~400 MBq). After data acquisition and analysis, the obtained list-mode data is fed to OMEGA image reconstruction software. The images are reconstructed using the Ordered Subsets Expectation Maximization (OSEM) algorithm and analyzed in MATLAB. We will report on the scanner's properties and present the reconstructed images of Ge-68 line sources and NEMA phantom filled with Ga-68. The results demonstrate it is possible to image sources using only entangled gamma photon pairs which undergo Compton scattering in the detectors. The spatial resolution, evaluated by imaging the Ge-line sources was ~4 mm for the photoelectric events and ~8.5 mm for the polarization-correlated events, respectively. The signal-to-random-background ratio achieved using polarization-correlated events shows an improvement of up to 40% compared to only photoelectric events. We will discuss the potential of further imaging signal-to-background improvements through measurements of the correlated quanta at different activities.

#04 - Research Reactors and Particle Accelerators / 79

#4-79 COLIBRI Phase 2 –Experimental study of fuel rods vibration in 3D using the SAFFRON core mapping array in CROCUS

Authors: Vincent Lamirand[1]; Thomas Ligonnet[2]; Andreas Pautz[1]; Oskari Pakari[3]

[1] *Ecole Polytechnique Fédérale de Lausanne*

[2] *LRS (EPFL)*

[3] *EPFL*

Corresponding Author: vincent.lamirand@epfl.ch

Since 2018, EPFL has been conducting an experimental program called COLIBRI, focusing on fuel rod displacement within the CROCUS reactor. This program allowed contributing to the European project CORTEX on noise analysis. Through three dedicated experimental campaigns COLIBRI has provided relevant validation data on fuel rod vibrations, which are a known source of power noise in pressurized water reactors (PWR), particularly in Siemens Konvoi and pre-Konvoi types. In some instances, these vibrations can lead to power fluctuations that require operational power reductions, and possibly increase in the risk of fuel deterioration.

In the framework of CORTEX and a doctoral thesis at EPFL, a novel type of miniature neutron detector, named MiMi, was developed. This scintillation-based detector enables real-time measurement of the thermal neutron flux via the lithium-6 reaction, with an active volume below 1 mm3 and a total volume in the millimeter range, using optical fibers for light collection. After the initial developments using analog acquisition electronics, the SiPM (silicon photomultiplier) signals were digitized via FPGA (field-programmable gate array) boards, allowing scalable neutron event counting.

For COLIBRI phase 2, this technology was expanded to create an array of up to 160 MiMi detectors, allowing for 3D mapping of the neutron flux within the CROCUS core. Named SAFFRON, this system is positioned interpin (between the rods), and is complemented with reference fission chambers located outside the core for these experiments. Together, these detectors enable detailed mapping of the modulation noise induced by fuel rod oscillations inside the core –an improvement over previous campaigns that were primarily limited to ex-core data and a smaller subset of in-core measurements. In addition, the use of the same reference setup enables easy comparison between datasets. Notably, the array intrinsic synchronization between MiMi detectors allows a better study of the impact on the phase. The phase is directly related to the non-point kinetics component of the noise, providing enhanced understanding of reactor kinetics.

In this contribution, we will present the experimental setup, the experiments carried out, and first key results compared to previous campaigns. This new dataset represents a major step forward in the modeling and mitigation of neutron noise in nuclear reactors, paving the way for future applications in monitoring and managing fuel vibrations in operational settings.

#09 - Environmental and Medical Sciences / 81

#9-81 Microdosimetry of kidney cells exposed to Am-243 and X-ray irradiation

Author: Pia Kahle[1]

Co-authors: Anja Seifert [1]; Anne Heller [1]; Christian Senwitz [1]; Steffen Taut [1]; Thomas Kormoll [1]

[1] *Technische Universität Dresden*

Corresponding Author: pia.kahle@tu-dresden.de

In vitro experiments with rat kidney cells (NRK-52E) exposed to $^{243}\mathrm{Am}$ in cell culture medium show a decreasing cell viability with increasing americium concentration. Both the chemical cytotoxicity of americium and the dose caused by ionizing radiation have to be considered as possible causes. To determine the dose rate, the influence of α-, β- and γ- radiation was examined intra- and extracellularly in a detailed microdosimetric model. In the in vitro experiments, the dose rate is essentially caused by extracellular α-radiation. At the americium concentrations used, dose rates up to the Gy/h range were achieved. Noteworthy the geometry of the cells is a crucial parameter. In addition, reference samples of untreated kidney cells were exposed to analog doses in an X-ray field. The cell viability curves depending on the dose show good agreement for both approaches.

#07 - Decommissioning, Dismantling and Remote Handling / 82

#7-82 The integration of a neutron induced activation module in the Monte Carlo calculation code RayXpert® as part of the Simβ-AD project

Author: Ines Duarte[1]

Co-authors: Abir HASSANI [2]; Cédric DOSSAT [1]; Frédéric STICHELBAULT [3]; Jean-Michel HORODYNSKI [4]; Nathalie CHATRY [1]; Nicolas Arbor [5]; Steven ROBIN-CHABANNE [1]; Stéphane HIGUERET [6]; The-Duc LE [6]

[1] *TRAD Tests & radiations, Labège, France*

[2] *iRSD, CNRS, Paris*

[3] *Ion Beam Applications, Louvain-la-Neuve, Belgique*

[4] *iRSD CNRS Paris*

[5] *IPHC (University of Strasbourg - CNRS)*

[6] *IPHC, UMR7178, 67037, Strasbourg, France*

Corresponding Author: nicolas.arbor@iphc.cnrs.fr

One of the key challenges in cyclotron infrastructures is the accurate determination of nuclear isotopes inventory, both for radiation protection studies and decommissioning. Indeed, radioactive waste management during the operation and dismantling of cyclotron facilities is a highly demanding process. Until now, radionuclides inventories can be carried out using several software, such as the combination of a Monte Carlo calculation code and an activation software, coupled with other resource-intensive procedures, including administrative, financial processes or radiological characterization.

The Simβ-AD consortium aims to develop and prove the feasibility of a methodology for assessing the activation of cyclotrons, and in particular pure β-emitters, difficult to detect. As part of the project, TRAD Tests & Radiations has developed a neutron-induced activation module in the 3D Monte Carlo calculation code RayXpert® that will be used to compare real-time measurements. The latter is a software designed for a wide range of applications in the nuclear, medical and industrial sectors. It is especially used in radiation protection in order to optimize shielding designs for facilities using ionizing sources.

In this presentation, the Simβ-AD project, driven by iRSD and IPHC instances of CNRS, IBA and TRAD, will be first introduced in order to understand all the resources deployed to optimize radioactive waste management. Then, the steps involved in integrating the neutron-induced activation module into RayXpert® will be discussed. This section will include a presentation of the software and highlights one of its main features, its CAD interface, which helps a great deal for modelling complex cyclotron facilities.

Finally, a comparison between several Monte Carlo calculation codes and experimental results of proton and neutron fluences will be presented. Based on these results, radionuclide inventories calculated with RayXpert® and others calculation codes coupled with an activation software will be compared as part of the validation of the development of the neutron induced activation module.

#02 - Space Sciences and Technology / 83

#2-83 Overview of the LUMINA experiment: a fiber optic dosimeter inside the Columbus module of the International Space Station

Authors: Sylvain Girard[1]; Martin Roche[2]; Nicolas Balcon[3]; Florence Clément[3]; Pierrick Cheiney[4]; Diego Di Francesca[5]; Jean-Christophe Malapert[3]; Nourdine Kerboub[3]; Lourdes Oro Marot[6]; Adriana Morana[2]; Daniel Ricci[5]; Enrico Chesta[5]; Rémi Canton[3]; Gilles Mélin[4]; Thierry Robin[4]; Gustavo de la Fuente[7]; Emmanuel Marin[2]; Julien Mekki[3]

[1] *Université Jean Monnet, Saint-Etienne, France*

[2] *Université Jean Monnet*

[3] *CNES*

[4] *Exail*

[5] *CERN*

[6] *Telespazio*

[7] *ESA*

Corresponding Author: sylvain.girard@univ-st-etienne.fr

Today, fiber optic dosimetry is booming technology. This class of detector exploits the effects of radiations, either radiation-induced attenuation (RIA) or radioluminescence (RIL), in silica-based optical fibers to monitor radiation levels. LUMINA is an active point dosimeter, exploiting RIA measurement in a phosphosilicate optical fiber to monitor the dose. This is possible because it was shown that RIA in this type of optical fiber, at certain wavelengths, are directly proportional to the dose deposited in the optical fiber by any type of particle (proton, neutron, photons…), and not dependent on dose rate or temperature (at least over the range between 0℃ and 80℃). This is particularly the case around 1550 nm, corresponding to the third telecommunications window and around 630 nm in the visible domain. Depending, on the wavelength, the fiber radiation sensitivity differs, from about 4 dB km-1 Gy-1 at 1535 nm to about 130 dB km-1 Gy-1 at 638 nm. The range of dose that can be measured by a dosimeter is then fixed at low doses by the minimal amount of loss that the detector can measure precisely and at high doses by the dynamic range of the detector. For this reason, LUMINA has two separate measurement channels, with their own performances, operating at these two wavelengths, and measuring optical losses in a 7 km (1535 nm) and a 2km -(638 nm) coils of single mode phosphosilicate optical fibers. The LUMINA dosimeter was installed in August 2021 by ESA astronaut Thomas Pesquet as part of his ALPHA mission. Since then, LUMINA has provided regularly in-flight data demonstrating its ability to measure the low dose increment within the Columbus module as the international space station passes through the South Atlantic Anomaly, an area where Earth's inner Van Allen radiation belt comes closest to Earth's surface. Thanks to the fairly intense solar activity of the past year, the obtained results also demonstrated LUMINA's ability to detect some of the most recent solar storms. During the conference, the preparation of the LUMINA mission and the main acquired results will be presented as well as the different limitations that have been observed during the mission. The advantages and limitations of fiber-optic dosimeters for future space missions will then be discussed.

#10 - Current Trends in Development of Radiation Detectors / 84

#10-84 Intelligent Dosimeter Plug for Endoscopic Sleeve in Critical Equipment Applications for Nuclear Industry

Authors: Sylvain Girard[1]; Luca Weninger[2]; Stéphane Lemière[3]; Sébastien Franco[3]; Yannick Heleine[3]; Lionel Tondut[3]; Pascal Rouet[4]; Olivier Haas[4]; Lorenzo Sostero[5]; Fiammetta Fricano[2]; Adriana Morana[2]; Matteo Ferrari[2]; Mathieu Bergont[6]; Jean-Reynald Macé[3]

[1] *Université Jean Monnet, Saint-Etienne, France*

[2] *Université Jean Monnet*

[3] *ORANO*

[4] *ObdO*

[5] *Università degli Studi di Brescia*

[6] *Exail*

Corresponding Author: sylvain.girard@univ-st-etienne.fr

This paper presents a research project carried out as part of the BPI France udd@ORANO project to instrument the plug of a diagnostic sleeve with a fiber-optic dosimeter. These endoscope sleeves are used to insert tools for monitoring the ageing of the bowl of a decanter centrifuge used in ORANO's La Hague plant. The objectives of this study are the following: 1) to monitor the concerned industrial process via continuous dose rate monitoring (γ-rays) within the facility. This will help optimize the cyclic cleaning phases; 2) to protect operators via knowledge of the residual dose rate before removing the plug from the sleeve. Both objectives can be achieved by measuring the dose rate in real time, which ranges between a maximum of 100 Gy/h during operation phases and a minimum of 1 Gy/h during shutdown. This was made possible by the use of two active fiber optic dosimeters based on the radioluminescence of silica-based probes, integrated into a functionalized or "intelligent"plug and then connected to an optimized acquisition chain. For the selected radioluminescent fibers, X-ray testing demonstrated that the measured radioluminescence is directly proportional to the dose rate to which the two radiation-sensitive silica-based optical fibers are exposed. We will first present the architecture chosen for the intelligent plug, as well as the acquisition chain developed by the consortium, from the fiber optic cable to the radiation detector. The sensor was first evaluated using the X-ray machines of Laboratoire Hubert Curien, then calibrated at a γ-rays (Cs-137) facility at ORANO La Hague, and finally deployed on-site under operational conditions. The results of this calibration campaign will be analyzed, based on complementary Geant4 Monte Carlo simulations of the complete plug geometry and of the specific radiation environment. The on-site results from the intelligent plug will then be presented to demonstrate the strong capability of the developed sensor to monitor the dose rates associated to the various stages of the industrial process and to help the plant control. Finally, prospects for use of this type of instrumentation within nuclear facilities will be discussed.

#04 - Research Reactors and Particle Accelerators / 85

#4-85 Reactor test of beryllium as self-powered neutron detector emitter for fast neutron flux measurement

Author: Elsa Dupin[1]

Co-authors: Loic Barbot [1]; Stéphane Normand [2]; Jean-Marc Fontbonne [3]; Nicolas Thiollay [1]; Christophe Destouches [4]

[1] *CEA/IRESNE/DER/SPESI/LDCI*

[2] *CEA/DAM*

[3] *Laboratoire de Physique Corpusculaire*

[4] *CEA/DES/IRESNE/DER*

Corresponding Author: loic.barbot@cea.fr

Neutron flux in nuclear reactors causes damages to material components. Fast neutrons, above 1 MeV, can modify mechanical and structural properties of materials. These damages are expressed as displacements per atom (dpa). Some experiments carried out in research reactors study the behaviour and ageing of materials irradiated by high neutron fluxes. In these experiments, it is therefore essential to monitor fast neutron flux to which tested materials are exposed. The selective on-line measurement of fast neutron flux in a water-pool type reactor environment remains an in-core measurement challenge. The aim of this work is to experimentally validate the use self-powered neutron detector technology to monitor fast neutron flux in a water-cooled reactor.

A self-powered neutron detector (SPND) is a coaxial detector that operates without high voltage supply. It is composed of three components: an emitter, an insulator and a sheath. Operating only for high fluxes, SPND is ideally adapted to on-line monitoring of irradiation experiments. Material choice and, in particular, emitter choice favour interactions with specific particles of interest. In our case, SPND material design must maximize fast neutron contribution. After a systematic review of the periodic element table, beryllium appears to be the most suitable emitter material for measurements sensitive and selective to fast neutrons. Due to its threshold cross section to fast neutrons and its low interaction probability with gamma rays, beryllium seems the appropriate candidate as emitter material for reactor environment use. Few beryllium SPND prototypes are designed and manufactured. This presentation first details the final prototype design, composed of beryllium emitter, MgO insulator and Inconel600®sheath.

In June 2024, beryllium SPND prototypes have been tested in the Slovenian TRIGA Mark II reactor (Jožef Stefan Institute). Tests first qualified the irradiation locations with different measurements techniques such as dosimetry, standard SPND measurements and axial profiles with fission chambers and ionization chamber. It also validates the irradiation conditions (thermal neutrons, fast neutrons, and gamma rays) in support of dedicated TRIPOLI4® calculations for each experimental location.

Then, the study goes on performance analysis of the beryllium SPND prototypes in a real reactor environment. The analysis yields encouraging outcomes, particularly following a comparison with SPND numerical modelling. These results permit an evaluation of beryllium benefits as an emitter. It also concludes with a potential improved design simplifying SPND fast neutron measurement.

These specific reactor tests in well-characterized irradiation conditions enforce fast neutron SPNDs as a new option for on-line monitoring of technological irradiations.

#04 - Research Reactors and Particle Accelerators / 86

#4-86 Measurement and estimation of secondary neutrons in so-called 'monoenergetic'fields. Routine measurement implementation on AMANDE facility by the time-of-flight method

Authors: Diane Quevauvillers[1]; Christelle Reynard-Carette[2]; Michaël Petit[3]

[1] *IRSN/PSE-SANTE/SDOS/LMDN*

[2] *Aix-Marseille University*

[3] *IRSN*

Corresponding Author: michael.petit@asnr.fr

The production of so-called 'monoenergetic'neutrons is standardized by ISO 8529 and can be achieved using ion accelerators such as the one at AMANDE facility from the Laboratory for micro-irradiation, neutron metrology and dosimetry (i.e. the LMDN from IRSN/Cadarache/France). The ions, typically proton or deuteron, are accelerated to speeds of up to a few MeV and are sent to a target containing abundantly a "well-chosen"nucleus of low atomic number (typically 2H, 3H or 7Li). The main energy at a given angle is then linked to the kinematics of the YZ(x,n)AB reaction allowing the neutron to be "ejected" from the compound nucleus (YZ+x). However, one or more 'parasitic' neutron production reactions are possible, particularly with deuteron beams. In this case, one or more additional groups of neutrons are present at different energies, for example from undesired presence of a different nucleus as the main one. These contributions can have several origins, sometime very surprising. For example, despite the care taken in target production, there have already been cases of nuclei migrating into the target support or the presence of unwanted nuclei such as 12C or 16O. Consequently, the complete absence of secondary production concerns only a small part of the available neutron fields. So, in order to establish the fluence energy distribution, it is necessary to be able to determine the fluence of each group and therefore to have the widest possible measurement range. One way of obtaining this quantity is to have a high-performance neutron spectrometer, which is however difficult to do in practice and required a long procedure. A more effective and easy way of identifying and evaluating neutron energy groups is to discriminate them by their time of flight. This technique, which can be done if the time of neutron production is known, is usually implemented using scintillators. Scintillators have three decisive advantages: high efficiency, very fast reaction time (~1ns) and the ability to detect and discriminate between photons and neutrons. Historical scintillator limitation is an energy threshold of around 1 MeV neutron. As a result, some of the contributions below this threshold may be poorly identified or not identified at all. Since 2018, the LMDN has been working on extending the lower time-of-flight limits down to 100 keV or better and within the same time, modernizing the measurement procedure. This work is being carried out under the behalf of the French National Metrological Institute (NMI, the "LNE"), which has designated the LMDN as a reference laboratory for the determination of neutron fluence and associated dosimetric quantities. Work carried out since 2018 has demonstrated that the new stilbene crystals have detection capabilities below 100 keV, enabling the detection threshold to be lowered by around a decade. Four scintillators (2 stilbenes and two EJ309) coupled to digital acquisition have been characterized by the LMDN in both neutrons and photons. The two aims of the project are: first to extend the time-of-flight references on AMANDE over the 100 keV - 1 MeV decade for wide and complex neutrons fields, and second to modernize the acquisition and analysis tools. These scintillators will determine the fluence energy distributions on AMANDE, using the time-of-flight technique if necessary. The energy range covered in a single measurement has been considerably increased and is now 100 keV to 22 MeV. The new functionalities provided by the developed system will give a much better assessment of these parasitic reactions, which are unfortunately still too often not considered or not well considered. The system is operational, as demonstrated by the time-of-flight measurement experiments carried out in September 2023 at Neutrons For Sciences Facility (NFS) and in November 2023 at the German NMI (PTB, Brunswick Germany). The entire system will be installed at the AMANDE facility early 2025. In this article, we will present the time-of-flight experiments carry out at NFS and PTB facility with a comparison between measure at some ISO 8529 reference energy. After this result, implementation on AMANDE will be presented with a particular attention to the 100 keV - 1 MeV energy range, since there are few, if any, equivalent measurements. After this, we will present the various secondary contributions observed and the process used to demonstrate their origin. Even the lack of contribution below 1 MeV could be an interesting result. A general assessment of the fluences of the secondary reactions observed and compared with the main reactions will be presented and we will finish by listing the potential reactions in relation to the beam configurations. The irradiation certificates delivered by the LMDN could provide new information for users. The

improvement of these references will be an important contribution to scientific research and will allow better characterization of neutron detectors.

#07 - Decommissioning, Dismantling and Remote Handling / 87

#7-87 Characterizing Neutron Emission Sources in Irradiated CANDU Reactor Components: Mechanisms, Measurements, and Implications

Author: Andrei Hanu[1]

Co-author: Jovica Atanackovic [2]

[1] *Bruce Power*

[2] *Ontario Power Generation*

Corresponding Author: hanua@mcmaster.ca

This study presents a detailed characterization of neutron emissions from irradiated components within Canada Deuterium Uranium (CANDU) reactors, specifically investigating the mechanisms underlying neutron production in pressure and calandria tubes after operational periods of up to 30 years. Given the unique neutron flux profile and heavy water moderation in CANDU reactors, these components undergo substantial exposure to thermal neutrons, leading to the formation of spontaneously neutron-emitting isotopes.

In this study, we conducted over 30 neutron spectroscopy measurements on nine shielded containers holding irradiated reactor components, with approximately half containing pressure tubes and the remainder calandria tubes. Neutron fields were analyzed outside each container to examine spectral characteristics and gain insights into potential production mechanisms within. Measurements were performed using a Rotating Spectrometer (ROSPEC) and Nested Neutron Spectrometer (NNS), with results validated through Geant4 and MCNP Monte Carlo simulations to ensure correlation with expected neutron emission profiles for various neutron-emitting mechanisms.

Our findings indicated that spontaneous fission from Cf-252, produced via neutron activation of trace uranium impurities in the structural materials, was a primary contributor to neutron emissions. Gamma spectroscopy of individual and bulk container samples detected high-energy gamma rays in the 6-9 MeV range, consistent with ongoing fission and supporting our hypothesis regarding Cf-252. Additionally, simulations and experimental data provided compatible estimates for neutron emission rates, correlating closely with components' exposure history and positioning within the reactor core, as components nearer the core center experienced higher neutron flux and thus higher activation rates. Furthermore, we performed a longitudinal study on one container to measure the half-life of the mechanism, which aligned with the 2.647-year half-life of Cf-252.

This work documents one of the first direct identifications of Cf-252 in irradiated CANDU reactor materials, enhancing our understanding of neutron emission sources during refurbishment activities. These findings hold significant implications for dosimetry, radiation protection protocols, and waste management for long-term storage, emphasizing the need to account for neutron emissions in radiation field assessments. This research provides a foundation for refining safety protocols in CANDU reactors, highlighting considerations for future component management and disposal strategies.

#10 - Current Trends in Development of Radiation Detectors / 88

#10-88 Applications of 4H Silicon Carbide Radiation Detectors in Fission and Fusion Reactor Environments

Author: Frank Ruddy[1]

Co-authors: Abdallah Lyoussi [2]; Christophe Destouches [3]; Laurent Ottaviani [4]; Michael Houry [5]; Christelle Reynard-Carette [6]; Quentin Potiron ; Olivier Llido

[1] *Ruddy Consulting*

[2] *CEA Cadarache*

[3] *CEA/DES/IRESNE/DER/SPESI*

[4] *AMU*

[5] *CEA*

[6] *Aix-Marseille University*

Corresponding Author: frankhruddy@gmail.com

Semiconductor radiation detectors based on the 4H polytype of Silicon Carbide (4H-SiC) have many advantages for high-temperature, high-radiation and mixed-radiation applications. The wide band gap of 4H-SiC (3.27 eV) allows measurements at temperatures up to 700 ℃ and probably much higher. Conventional lower band-width semiconductors such as silicon or germanium are limited by thermally generated noise to measurements at lower temperatures and can require external cooling. 4H-SiC has a high thermal conductivity, high breakdown voltage, and high electron saturation velocity. Furthermore, 4H-SiC detectors have also been demonstrated to have outstanding radiation hardness.

These properties make 4H-SiC Schottky barrier and p-n diode detectors compatible with radiation monitoring applications in both fission and and fusion reactors. For fission reactors, measurements of the neutron fluence rate and energy spectrum characteristics are required and monitoring environments with temperatures up to and exceeding 700 ℃ can be encountered. For fusion reactors, extremely high-temperature monitoring environments will also be encountered. In both cases, the detector service lifetime in the extreme radiation environment is a prime consideration. 4H-SiC Schottky barrier detectors have been demonstrated to be operational after 137Cs gamma ray doses up to 22.7 MGy and fast-neutron (E> 1 MeV) fluences up to 1.7 x 1017 cm-2.

4H-SiC detectors have been demonstrated to provide linear count-rate responses as a function of fluence-rate for thermal, epithermal and fast fission neutrons. In addition, linear fluence-rate responses have been demonstrated for deuterium-deuterium (D-D) and deuterium-tritium (D-T) fusion neutrons. In the latter case, the 14-MeV neutron energy exceeds the thresholds for 12C(n,α)9Be and 28Si(n,α)25Mg reactions and allows peaks to be observed from neutron reactions with the SiC detector. The energy widths of these reaction peaks can be used to deduce information on the plasma temperature as well as neutron yield for fusion devices. 4H-SiC detectors with lithium neutron convertor foils can be used to monitor 6Li(n,α)3H reaction rates directly to measure tritium breeding rates in fusion reactors.

In this paper we will review relevant developments in 4H-SiC radiation detectors and discuss their potential and planned applications in fission and fusion reactors.

#09 - Environmental and Medical Sciences / 89

#9-89 A high-volume environmental radioactivity monitoring station integrating prompt and high-sensitivity γ-measuring systems

Author: Massimo Altavilla[1]

Co-authors: Giorgio Angeli [2]; Monica Gattinoni [2]

[1] *ISIN - ISpettorato Nazionale per la Sicurezza Nucleare e la Radioprotezione*

[2] *TNE - Technology Nuclear Electronics*

Corresponding Authors: massimo.altavilla@isinucleare.it, monica.gattinoni@tnenuclear.com

The automatic network of environmental radioactivity, REMRAD, managed by the National Inspectorate for Nuclear Safety and Radiation Protection (ISIN), consists of highly sensitive radiological monitoring stations through automatic sampling and spectrometric analysis systems of atmospheric particulate matter, deposited on a large filter splitted into 15 separate circular areas where the same particulate matter is collected; the monitoring stations are able to detect in "almost real time"the minimal radiometric anomalies present in the air. The extremely high detection sensitivity of the REMRAD stations is guaranteed both by the high sampling rate, up to 500 m3/h, and by the measurement configuration adopted. The stations are equipped with both an "early alarm" system, based on a LaBr3(Ce) spectrometric detection system placed in an orthogonal position with respect to the sampled filter, patented by ISIN, and which guarantees measurement sensitivity below 10 mBq/m3 on Cs-137, and a BeGe "Broad Energy Germanium" detector type, which operates in delayed mode on the same filter, guaranteeing sensitivity below 10 μBq/m3, always with reference to the Cs-137 radionuclide. The technological advancement of these monitoring stations mainly lies in the "early alarm" which allows the quantitative definition of any radioactive contamination in the air thanks to the use of the proprietary patent which allows the calculation of the absolute detection efficiency using the Monte Carlo calculation code, which is used for modelling the LaBr3(Ce) scintillation based radiation detector and a structure containing the absolute glass fibre filter. The absolute efficiency curve is functional with respect to the LaBr3(Ce) scintillation based radiation detector, component of the high volume airborne particulate sampling system, as it permits the "quantification"of the radionuclides in terms of radiological activity deposited in the 15 circular areas of the glass fibre filter, and the subsequent determination of the airborne radioactive concentration. The absolute efficiency curve is calculated with respect to the particulate deposited in the 15 circular areas of the filter system. Each of the 15 circular areas of the glass fibre filter contributes with its own specific probability of particulate deposition to the computation of the absolute efficiency curve.
A customized management software integrates this powerful algorithm and allows multiple authorized recipients to receive prompt SMS and email in case of alarm or malfunctions.
Indeed, these stations can function without operator intervention for up to a month thanks to a software that manages all the hardware devices automatically performing the spectra acquisitions, quantitative analysis and saving measurements in a proper database. The energy calibration of the "On line" detector is constantly checked and updated while Quality Assurance is automatically performed every filter change on the Germanium detector by measuring a source installed on the robot.
A Control Center Software allows authorized users to manage remotely a network of up to 36 stations. Main features are: Area surveillance via webcam, system parameters and thresholds setup, real-time display of the measurements status in progress, display of the latest measurement data including weather parameters, query the historical measurements archive with visualization of trend graphs.

#10 - Current Trends in Development of Radiation Detectors / 90

#10-90 Charged & Neutral Particle Tissue Equivalent Proportional Counter - A Microdosemeter with Particle Type Identification

Author: Soo Hyun Byun[1]

Co-authors: Andrei Hanu [2]; Eric Johnston [1]

[1] *McMaster University*

[2] *Bruce Power*

Corresponding Author: soohyun@mcmaster.ca

We present development of the Charged & Neutral Particle Tissue Equivalent Proportional Counter (CNP-TEPC) instrument that is aimed at measuring charged particle and neutron dose rates in real time in the low Earth orbit (LEO). The CNP-TEPC consists of a central TEPC and a plastic scintillator guard detector, which enables both an accurate radiation dose measurement and a particle identification, since the tissue-equivalent composition of the central detector simulates radiation interactions with soft tissues while the types of the detected particles can be identified via a coincidence between the central and the guard detector events. The central TEPC simulates 2 μm thick soft tissue, allowing precise measurement of the lineal energy distribution of incident radiation within the range of 0.1 to 1,000 keV/μm. The guard detector is built into a hemisphere using an 8 mm thick plastic scintillator. The signals from each detector are processed by the data acquisition module, which measures the arrival time and pulse height of each detection event. The module employs an analog-to-digital converter and a Field-Programmable Gate Array for the TEPC, an ASIC chip for an array of silicon photomultipliers which are optically coupled to the scintillator. The 1st generation of the CNP-TEPC instrument was developed as the payload for the NEUtron DOSimetry & Exploration (NEUDOSE) CubeSat, which was deployed into the LEO in 2023. Following this, the 2nd generation is currently under development with a major upgrade in digital pulse processing. Comprehensive performance measurements are carried out to characterize its response to fast neutrons using the 238PuBe and 7Li(p,n) neutron sources at the McMaster accelerator laboratory. The new instrument will be deployed on an external platform of the International Space Station in 2027 for a mission lasting up to 16 weeks.

#02 - Space Sciences and Technology / 91

#2-91 Optimization of Radioluminescent Fiber Dosimetry for Space Missions

Author: Selyan Acid[1]

Co-authors: Adriana Morana [2]; Aziz Boukenter [3]; Bruno Capoen [4]; Fiammetta Fricano [3]; Hicham El Hamzaoui [4]; Jeremy Guillermin [5]; Julien Mekki [6]; Marine Aubry [5]; Maxime Darnon [7]; Mohamed Bouazaoui [4]; Nourdine Kerboub [6]; Sylvain Girard [8]; Youcef Ouerdane [3]

[1] *French Space Agency (CNES)*

[2] *Laboratoire Hubert Curien*

[3] *Université Jean Monnet*

[4] *Université de Lille*

[5] *TRAD*

[6] *CNES*

[7] *CNRS*

[8] *Université Jean Monnet, Saint-Etienne, France*

Corresponding Author: selyan.acid@univ-st-etienne.fr

Abstract - Optical fiber-based dosimeters are valuable tools for space missions, enabling the measurement of the dose received by humans or equipment in a spacecraft or onboard satellites. These devices could serve to detect the premises of solar eruptions allowing to protect more efficiently through mitigation techniques both electronic systems and humans. In space, especially for human radioprotection, the monitoring of dose rate (or particle flux) is a key functionality for those applications. Accurate dosimeters with low dispersion in their radiation sensitivities are essential for ensuring reliability and safety. A very efficient technique based on specialty silica-based optical fibers consists in measuring the radioluminescence generated by radiation in the fiber. This generated photons intensity, propagated along the fiber to a detector, is directly proportional (through the radiation sensitivity coefficient) to the particle flux or dose rate. By integrating the dose rate over a period, one can calculate the dose received by the fiber during that period.
We investigated here the dosimetric properties of two differently doped multimode silica-based radioluminescent optical fibers under 40 keV mean energy fluence X-rays. One fiber under test has its core doped with copper , while the other has a cerium/copper-co-doped core fiber. The dose rates studied ranged from 5×10^(-3) Gy(SiO_2)/s to 1.5Gy(SiO_2)/s and for each of the tested sample, we did a series of tests by varying the dose rate to measure the radiation sensitivity coefficient expressed in number of photons received per second and for a dose rate of 1 Gy/s. It should be noted that in previous studies, we showed that the copper-doped fiber is also able to monitor the dose rate deposited by ▯▯rays or protons. The results obtained here under X-rays can therefore be extrapolated to other environments, even mixed ones.
We performed in this work a systematic study of the parameters affecting the value of this radiation sensitivity coefficient: the influence of a pre-irradiation of the radioluminescent fiber, the influence of the sensor probes-manufacturing process and the influence of the cerium doping of the copper glass. For this purpose, we repeated the calibration of 112 different probes that have been characterized through 112 irradiation runs.
The effect of pre-irradiation was studied by considering four different pre-irradiations conditions on 4 sets of 14 probes for both the copper and copper/cerium-doped optical fibers. The pre-irradiations conditions were pristine (no pre-irradiation), 250kGy, 1MGy and 2MGy(SiO2). The influence of probe manufacturing was demonstrated by investigating the variation coefficient of radioluminescent signals across the same set of probes. The results are extremely promising with a measured mean variation coefficient of their sensitivities of 13 % for the copper-doped probes and 17% for copper/cerium-co-doped ones. This demonstrates the high potential for fiber-based dosimetry using copper-doped optical fibers.
Furthermore, the variation coefficient for copper-doped fibers varied from 20% in the pristine condition to 9% after 2 MGy of pre-irradiation. In contrast, for copper/cerium-co-doped fibers, the variation coefficient increased from 12% in the pristine condition to 27% following 2 MGy of pre-irradiation. These results highlight the importance of pre-irradiation for the stability of the radioluminescence, suggesting that pre irradiated copper doped fiber may offer more consistent and accurate performance for dosimetric applications after pre-irradiation.

To further investigate the effect of copper/cerium co-doping on the RIL and explain the larger variation observed between the probes, a spectral analysis will be conducted by replacing the photomultiplier tube by a spectrometer for the detection. All other parameters will remain as in the previous analysis. This approach will allow us to better understand the origin of the largest observed dispersion for this fiber compared to the copper one and clarify the respective role of cerium and copper ions in the sensor response.
Previous studies highlight the presence of two distinct peaks in the RIL spectrum of copper/cerium co-doped fiber: one at 460 nm associated with cerium ions activation and another at 540 nm link to copper ions activation. We expect that one of the contributions will dominate the RIL process of the co-doped fiber, potentially leading to the observed dispersion for high dose.
From an applicative point of view, the copper-doped fiber demonstrates very promising performances with low dispersion in its radioluminescent signal. We will therefore discuss the potential performances of these fibers for dosimetry in the low dose rate space environments.

#04 - Research Reactors and Particle Accelerators / 92

#4-92 Irradiation Rig Design and Preliminary Dosimetry Experiment for CORANI Phase 1 at HANARO Reactor

Authors: Junesic Park[1]; Christophe Destouches[2]

Co-authors: Seong Woo Yang [1]; Byung-Gun Park [1]; Jong Woo Kim [1]; Sung Jae Park [1]; Kishore B. Dasari [3]; Loïc Barbot [2]; Christophe Domergue [2]; Hervé Philibert [2]

[1] *Korea Atomic Energy Research Institute*

[2] *CEA, IRESNE, Cadarache, DER*

[3] *Gyeongsang National University*

Corresponding Author: jp@kaeri.re.kr

The Korea Atomic Energy Research Institute (KAERI) and France's Commissariat à l'énergie atomique et aux énergies alternatives (CEA) have initiated the CORANI (KAERI/CEA cOllaboration for Research reactor Application of Neutron dosimetry and Instrumentations) project, a collaboration aimed at testing CEA's instrumentation sensors within KAERI's research reactor, HANARO (High-Flux Advanced Neutron Application Reactor). This collaboration highlights the importance of international partnerships in advancing nuclear sensor technology and enhancing real-time monitoring in irradiation environments. This project is designed in two phases: Phase 1 focuses on neutron field characterization within irradiation holes using CEA's self-powered neutron detector (SPND) and fission chamber (FC), including their acquisition systems (Libera Current Meter for SPNDs and Libera MONACO 3 system for FCs), while Phase 2 will involve testing sensors for gamma and temperature measurement. Currently, the project is in Phase 1, with irradiation tests scheduled to begin at HANARO in the first half of 2025. The HANARO reactor, an open-pool type reactor with a maximum thermal power of 30 MW, contains seven vertical holes in the core that provide neutron fluxes up to 4.39×10^{14} and 1.54×10^{14} neutrons/cm²/sec for thermal ($E < 0.625$ eV) and fast ($E > 1.0$ MeV) neutrons, respectively, along with 17 vertical holes in the reflector region with fluxes up to 1.95×10^{14} and 2.20×10^{12} neutrons/cm²/sec. The Phase 1 experimental setup includes two irradiation rigs designed to accommodate the specific conditions of HANARO's operating environment. The first rig, intended for dosimetry experiments using activation foils, allows measurements at 3–5 axial points in the center of the vertical hole. An activation foil container was designed to accommodate an approximately 1.5-mm-thick B4C filter. The second rig, designed for online sensor testing, accommodates six FC and three SPND sensors arranged axially and enables simultaneous dosimetry. This presentation focused on the design and fabrication of the irradiation rigs, along with preliminary dosimetry results in preparation for Phase 1. The preliminary experiment was a dosimetry test for the HANARO irradiation hole using the dosimeters and mobile HPGe spectroscopy acquisition system from CEA's MADERE (Measurement Applied to DosimEtry in REactors) facility. This first irradiation campaign was realized in an almost fully thermalized neutron spectrum (98%) leading to specific analysis of the X and gamma-spectrometry to unfold some unusual contributions from isotopes produced by high-level thermal reactions. The analysis results were compared with those measured using the HPGe measurement system at the HANARO facility. This experiment has demonstrated the performance of the new CEA mobile spectrometry acquisition device; it allows precise X and Gamma emitter measurements with the identical HPGe diode.

#07 - Decommissioning, Dismantling and Remote Handling / 93

#7-93 The development of Smart Radioactive Waste Management System using new ICT technology

Author: Jin-Woo Lee[1]

Co-authors: Hee-Chul Eun [1]; Jun Lee [1]; Sung-Bok Lee [2]; Hoseog Dho [2]; Dahye Jyon [2]

[1] *KAERI (Korea Atomic Energy Research Institute)*

[2] *KORAD (Korea Radioactive Waste Agency)*

Corresponding Author: jinwoo@kaeri.re.kr

The Radioactive Waste Information Management System (RAWINGS) for the safe management of low- and intermediate-level radioactive waste has been operated in Korea Atomic Energy Research Institute (KAERI) since 2021. From the operation of RAWINGS, KAERI can effectively manage the inventory and history of waste generated at research sites. The system generates information based on data manually input by radiation workers at waste-related sites. This system has the risk of entering incorrect information or missing information during the radioactive waste treatment process.

Recently, the Korea Nuclear Safety and Security Commission (NSSC) and the Korea Radioactive Waste Agency (KORAD) have been conducting pre-inspection before transportation of radioactive waste to final disposal site based on waste acceptance criteria (WAC). So, the smart open digital system using new ICT technology for the safety management of radioactive waste is needed to solve the problems of the current system and meet the acceptance criteria of the final disposal. Augmented reality (AR) technology is used to allow inspectors to check the contents of small packages of radioactive waste without opening drums after packing. Internet of Things (IoT) sensor has been developed to monitor the status of drums in radioactive waste storage facility. The basic data of the radioactive waste used in the AR is processed with RAWINGS including the small packaged waste and repackaged drums. In addition, real-time monitoring of the radioactive waste drums located in the radioactive waste storage facility where they will be stored until their final disposal, was accomplished by sending IoT sensor attached to the drums. IoT sensor signals attached to the drums are being transmitted to digital twin (DT) system.

From this project, it is possible to inspect the radioactive waste contained in the drum from the remote inspection of a digital twin, rather than from the on-site inspection of radioactive waste storage facility. This technology will be useful in verifying the compliance of radioactive waste drums with the acceptance criteria required by KORAD.

#04 - Research Reactors and Particle Accelerators / 94

#4-94 AlphaBeast: a CMOS-based neutron counter for radiation protection

Author: Nicolas Arbor[1]

Co-authors: Djokhar Betelgueriev [1]; Lucia Victoria Garcia Garcia [1]; Stéphane HIGUERET [2]; The-Duc LE [2]; Abir HASSANI [3]; Jean-Michel HORODYNSKI [4]; Nathalie CHATRY [5]; Cédric DOSSAT [5]; Ines Duarte [5]; Frédéric STICHELBAULT [6]

[1] *IPHC UMR7178*

[2] *IPHC, UMR7178, 67037, Strasbourg, France*

[3] *iRSD, CNRS, Paris*

[4] *iRSD CNRS Paris*

[5] *TRAD Tests & radiations, Labège, France*

[6] *Ion Beam Applications, Louvain-la-Neuve, Belgique*

Corresponding Author: lucia-victoria.garcia-garcia@iphc.cnrs.fr

Neutrons are a major source of secondary radiations in particle accelerators, posing significant challenges in radiation protection for research, medical, and industrial facilities. Key concerns include radiation dose exposure (impacting workers and patients) and neutron activation, which affects accelerator components and surrounding materials. Regardless of application, minimizing these risks and improving operational efficiency depends on enhanced characterization of neutron fields during accelerator use. However, achieving regular spatio-temporal monitoring of neutron production remains challenging, as current reference methods—such as activation foils, Bonner spheres, and solid nuclear track detectors—are costly in both economic and human terms, limiting the quantity and quality of available neutron data essential for a better risk management.

To address these limitations, the IPHC-DeSIs team is developing an innovative CMOS-based counter for real-time neutron monitoring. The *AlphaBeast* CMOS sensor, leveraging XFAB 0.35 µm technology, is a fully integrated device with high photon transparency and optimized for low power consumption. Neutrons are detected from their conversion into protons (fast neutrons, PE converter) and alpha particles (thermal neutrons, 10B converter). Internal thresholds are used to separate the two populations, providing real-time insights into thermal and fast neutron fluxes. Accurate measurements in complex radiation environments requires a comprehensive assessment of the CMOS sensor's response to various particles, including photons, electrons, protons, and alpha particles. To this end, we present a thorough experimental characterization of the *AlphaBeast* sensor, performed across multiple test beam facilities. Complementary Geant4/GATE Monte Carlo simulations further define the sensor's efficiency and refine the precision of selection criteria for thermal (alpha) and fast (proton) neutron separation. Additionally, we examine various background sources—such as direct neutron interactions within the silicon substrate—and apply necessary correction factors to enhance data accuracy. *AlphaBeast*'s measurements of fast and thermal neutrons have been validated across diverse facilities, including research cyclotrons, medical (LINAC) and industrial (rhodotrons) accelerators, with results benchmarked against Monte Carlo calculations and CR-39 reference detectors.

The *AlphaBeast* sensor is a foundational component of an upcoming real-time neutron mapping system dedicated to improving radiation safety in particle accelerators and associated applications. This system envisions a network of connected, autonomous CMOS sensors strategically positioned throughout irradiation facilities, enabling continuous, real-time monitoring of neutron production. It will be instrumental in the on-going Simβ-AD project (BPI-ANDRA), a methodology initiative focused on calculating cyclotron activation to support safe dismantling procedures. By enabling on-line monitoring of secondary neutron production, *AlphaBeast* sensors offer critical, experimentally verified data to reinforce the reliability of neutron activation models during accelerator operations. This breakthrough promises a significant advancement in radiation safety protocols, offering an affordable, scalable, and highly accurate real-time neutron monitoring solution adaptable across various high-radiation applications.

#10 - Current Trends in Development of Radiation Detectors / 95

#10-95 A Neural Network Approach for On-line Reconstruction of Bremsstrahlung Spectra Produced by Electron Accelerators

Author: Lucas Tasinato[1]

Co-authors: Abdallah Lyoussi [2]; David Tisseur [3]; Florent Kuntz [1]; Nicolas Arbor [4]

[1] *Aerial*

[2] *CEA Cadarache*

[3] *CEA*

[4] *IPHC*

Corresponding Author: l.tasinato@aerial-crt.com

The characterization of Bremsstrahlung spectra generated by electron accelerators is becoming increasingly crucial, particularly in radiation processing applications such as sterilization of medical devices or food irradiation. The growing transition from isotopic to electric irradiators presents new challenges related to the control of beam properties. In this context, the technologies and resources centre Aerial is looking to develop a tool and methodology in order to characterize, on-line, the properties of the Bremsstrahlung spectra produced in the installation feerix®. This step is very important for their irradiation operations to ensure precise dose deposition in the sample and to prevent activation processes by exceeding the photonuclear reaction threshold of the photons generated in the installation. However, conventional direct and indirect methods are limited in meeting the constraints of on-line measurement of Bremsstrahlung spectra produced by electron accelerators. In previous work we carried out on this topic, we presented a method based on the measurement of a dose distribution and the use of inverse methods to reconstruct the Bremsstrahlung spectra from the dose distribution. For this purpose, we introduced a simple and compact experimental setup that enables on-line measurement of the dose distribution. This setup consists of a scintillator irradiated at its edge and a sCMOS camera positioned above the scintillator to capture the resulting scintillation photons. From the 2D distribution representing the number of photons collected by the camera, we are then able to retrieve an equivalent of the dose distribution in the scintillator along the beam axes. In this initial approach, we then used conventional regularization methods (Tikhonov) to reconstruct the Bremsstrahlung spectra from the dose distribution. In this study, we propose a new theoretical approach using Neural Networks to address the ill-posed inverse problem, using the same experimental setup. This approach is motivated by the limitations of previously discussed regularization methods, where the regularization parameter is highly sensitive to the shape of the incident spectra and to the noise level in the measured dose distribution. To accurately reconstruct the Bremsstrahlung spectra, the regularization parameter would need to be optimized for each reconstruction, which is incompatible with on-line reconstruction. Furthermore, regularization methods are limited in their ability to estimate the maximum energy of the reconstructed spectra, a critical parameter for Aerial. In this context, our new approach appears to be more efficient and better suited for on-line reconstruction, provided that our training dataset is representative of the problem. Thus, we focus here on an analytical approach for generating realistic training and validation datasets, consisting of Bremsstrahlung spectra and their corresponding dose distributions in the scintillator. The architecture of the proposed neural network is also presented, along with a multi-parameter study focused on optimizing the experimental setup. Specifically, we evaluate the method's performance with different scintillators, leading to varied dose distribution profiles, and with varying pixel sizes in the measured dose distribution. The neural network approach will be compared to regularization methods, and recommendations will be made for developing an experimental setup that maximizes reconstruction efficiency according to this new method.

#04 - Research Reactors and Particle Accelerators / 96

#4-96 Design and development of a high-temperature irradiation facility in the JSI TRIGA reactor

Author: Klemen Ambrožič[1]

Co-authors: Romain Chevrier [2]; Vladimir Radulović [3]; Loïc Barbot [2]; Christophe Destouches [4]; Grégoire De Izarra [2]

[1] *Jožef Stefan Institute*

[2] *CEA, DES, IRESNE, DER, SPESI, LDCI, Cadarache*

[3] *Jožef Stefan institute*

[4] *CEA, DES, IRESNE, DER, Cadarache*

Corresponding Author: klemen.ambrozic@ijs.si

A high number of new fission and fusion reactor designs are set to operate at high temperatures, on the account of increasing the overall electrical energy production efficiency, rely on passive heat dissipation for cooling after shutdown, or use other types of coolant than water such as liquid metal or molten salt. The behavior of these materials and the associated instrumentation must therefore be rigorously tested in a representative, high temperature radiation environment.

Within the framework of the JSI-CEA bilateral agreement, a project was undertaken to design and implement a highly insulated tube-type furnace with a maximum operating temperature of 900℃. The facility should be designed to integrate seamlessly with the existing irradiation infrastructure of the JSI TRIGA reactor. It must operate at an external temperature below 100℃ and exhibit low levels of residual radioactivity following irradiation. Additionally, the facility should be positioned within a representative neutron and gamma radiation field. Due to these stringent limitations, the aim was to identify an appropriate insulating material. We have decided on using nanoporous silica material which has a low thermal conductivity of between 0.020-0.045 Wm-1K-1, depending on the temperature. The thermal analysis using the COMSOL software confirmed that using this material, an irradiation facility with a central hot zone diameter of 5 cm and uniformly heated length of 60 cm would reach the temperature of 900 ℃ with just 300 W of injected power, while still fitting inside a horizontal irradiation facility with diameter of 15 cm and maintaining the outside temperature some 20 K above ambient. Although these results consider perfectly closed thick furnace cap and a bulk insulation material, not layers of materials with potential gaps, the margins are satisfactory to proceed with the design. Apart from the nanoporous silica material, pieces of rigid, machinable calcium silicate insulation material were also selected to perform the function of structural holders. Samples of both materials were procured and tested for neutron activation potential, which was negligible. We also tested whether sheets of these materials could be cut using a laser cutter, which was remarkably effective. Hence, we ordered sheets of both insulating materials, that would fit the laser cutter bed and have the appropriate thicknesses for the best cutting performance.

The second part was procuring a suitable heating element, that can withstand the desired temperatures, while being made of materials that do not readily become radioactive under neutron irradiation. Commercial silicon carbide heaters were selected, due to their excellent performance, high purity silicon carbide and aluminized contacts. A small sample heater was obtained, to perform a test irradiation and assess neutron activation. The activity of the sample was of the same level as the background level a few hours after the test irradiation.

While silicon carbide is a particularly good material in terms of neutron activation, it is very brittle, and the first silicon carbide heater for the irradiation facility broke during shipping, which delayed our testing for a month.

Nevertheless, we have obtained all the insulating materials, cut them to size using the laser cutter, and inserted them into a custom-built aluminum enclosure. The heating element was also inserted, with the rigid calcium silicate insulation holding it in place. Type k thermocouples were put on the outside of the aluminum enclosure, to monitor the outside temperatures, and another one inserted into the hot zone, using the Zircalloy-4 rod as a guide-tube. The heater in the initial test was powered using a variable AC supply, although a high-power DC power supply is envisioned

for the final experiment, to remove unwanted AC interference. Inner zone temperature of above 700 ℃ was reached in 45-50 min with the injected power at approximately 700-800 W was reached during the initial testing, while the wall remained cold to the touch. The maximum temperature on the outside of the enclosure reached the maximum temperature of about 50 ℃ an hour after the shutdown.

In terms of device manufacturing, we are currently waiting for the shipment of the power supply and some more testing, with the final design finished by the end of 2024. Efforts on temperature monitoring and heater control are also underway, with the aim of making a programmable application, with a simple user interface, where the user would be able to program the desired temperature profile.

#01 - Fundamental Physics / 98

#1-98 The Compact Processing Module for the Upgrade of the ATLAS Tile Calorimeter Towards the High-Luminosity LHC

Author: Fernando Carrió Argos[1]

Co-authors: Antonio Cervello Duato [2]; L. Fiorini [2]; D. Hernandez [3]; A. Ruiz [2]; A. Valero [2]

[1] *Instituto de Física Corpuscular (CSIC-UV)*

[2] *Institu de Fisica Corpuscular - CSIC/UV*

[3] *Department of Physics, University of Hong Kong, Hong Kong*

Corresponding Author: fernando.carrio@cern.ch

The Tile Calorimeter (TileCal) is the central hadronic calorimeter of the ATLAS experiment at the Large Hadron Collider (LHC) at CERN. In 2026, the LHC will undergo a series of upgrades leading to the High-Luminosity LHC (HL-LHC), which will provide an instantaneous luminosity 5 to 7 times larger than the nominal LHC design value. The ATLAS Tile Calorimeter Phase-II Upgrade (2026-2030) will completely replace the readout electronics with a new clock distribution and readout architecture with a fully digital trigger system to process more complex physics events while maintaining the trigger selection performance.

In the upgraded readout architecture, the on-detector readout electronics will transmit detector data to the Compact Processing Modules in the counting rooms for every bunch crossing (~25 ns). This new architecture will increase the data bandwidth required to read out the detector from the present 165 Gbps up to 40 Tbps. The Compact Processing Modules will transmit calibrated energy and time per cell to the first level of the ATLAS trigger system through the Trigger and DAQ interface system (TDAQi), as well as Level-0 selected data to the Front-End LInk eXchange (FELIX) system. In addition, the Compact Processing Modules will be responsible for distributing the LHC clock towards the on-detector electronics for the sampling of the PMT signals. A total of 128 CPMs, hosted in 32 ATCA carriers, will be required to read out the entire calorimeter during the HL-LHC data taking.

The communication with on-detector electronics is implemented using the GigaBit Transceiver (GBT) protocol with fixed and deterministic latency. Up to 32 uplinks running at 9.6 Gbps are required to read out detector and to monitor data from two TileCal modules, while the 16 downlinks at 4.8 Gbps are used to configure the on-detector electronics and distribute the bunch-crossing accelerator clock.

The energy per channel is reconstructed and calibrated in real-time for every bunch-crossing (~25 ns), and then transmitted to the TDAQi for the computation of complex trigger objects. In parallel, raw channel data and its associated reconstructed energy are stored in pipeline memories with a depth of 10 µs. Upon receiving a Level-0 trigger acceptance signal, the selected data is transmitted to the FELIX system through Full-Mode links at 9.6 Gbps. The CPM tracks and corrects with subnanosecond resolution phase drifts of the distributed clock to the on-detector electronics.

The CPM has been designed as a single Advanced Mezzanine Card (AMC) form factor equipped with six Samtec FireFly modules and a Xilinx Kintex UltraScale KU115 FPGA handling the readout, processing and configuration functionalities. A dedicated jitter cleaner is also included in the CPM to achieve synchronous communication between the on-detector electronics and subsequent levels of the ATLAS DAQ system. Each CPM can operate up to two TileCal modules via the Samtec FireFly modules and it provides seven high-speed interconnections through the ATCA carrier for the communication with the TDAQi. Two SFP modules located in the front panel enable the communication with the FELIX system for the transmission of triggered events. The complexity of the PCB design of the CPM and ATCA carrier required numerous signal and power integrity simulations. These simulations, performed using ANSYS electromagnetics, minimized impedance mismatch along the high-speed interconnections, and guided the selection of dielectric materials for controlling the signal attenuation.

This contribution describes in detail the design of hardware, firmware and software components of the Compact Processing Modules for the ATLAS Tile Calorimeter at the HL-LHC. Results from integration tests and test beam campaigns are presented, as well as the commissioning of the CPM for the readout of the Tile Phase-II Upgrade Demonstrator module in the ATLAS experiment.

#04 - Research Reactors and Particle Accelerators / 99

#4-99 Investigation of AISI 316L oxide film formation under PWR PW conditions using Electrochemical Noise (EN)

Author: Emmanouil Ramoutsakis[1]

Co-authors: Christian BATAILLON [2]; Edmond BLANCHARD [2]; Céline CABET [3]; Catherine GUERRE [2]

[1] *Université Paris-Saclay, CEA, Service de recherche en Corrosion et Comportement des Matériaux, 91191, Gif-sur-Yvette, France*

[2] *Université Paris-Saclay, CEA, Service de recherche en Corrosion et Comportement des Matériaux*

[3] *Université Paris-Saclay, CEA, Service de Recherche en Matériaux et procédés Avancés*

Corresponding Author: emmanouil.ramoutsakis@cea.fr

Oxide film formation is a critical factor in the corrosion resistance of steel components in Nuclear Power Plants (NPPs), providing a protective barrier against aggressive environments. The stability and integrity of this oxide layer are key to maintaining the durability of steels over time. Electrochemical Noise (EN) has emerged as a promising in-situ monitoring tool for investigating oxide film behavior under operational conditions. It has the ability to capture the naturally occurring (stochastic) fluctuations in current/potential that reflect oxidation dynamics, without the need for external perturbation, as required in techniques like Electrochemical Impedance Spectroscopy (EIS). In stainless steels exposed to Pressurized Water Reactor (PWR) primary water (PW) conditions, the oxide layer typically develops a duplex morphology: an outer layer made of micrometric, individual magnetite crystallites, and a thin inner layer composed of a mixed Fe-Ni-Cr spinel oxide. According to the Available Space Model [*L. Martinelli et al., Corrosion Science 100, 253 (2015)*], the outer layer is developed through the time-continuous (noiseless) cationic release from the base metal, generating metal vacancies. These vacancies can cluster into nano-voids [*B. Eyre, Journal of Physics F: Metal Physics 3.2, 422 (1973)*] and allow O^{2-} anions to diffuse inward and drive the time-discrete growth of the inner oxide layer, resulting in anodic current transients (current noise). The primary objective of this study was to check the occurrence of such current transients and to analyze them in the frequency domain. Achieving this objective provides a foundation for using EN as a tool to monitor and better understand oxide layer dynamics in real-time. The experimental configuration consisted in a 3-electrode setup with two identical 316L AISI samples acting as the Working Electrode (WE) and pseudo-Reference Electrode (pseudo-RE), while a 304 AISI tube of much larger surface served as Counter Electrode (CE). All electrodes were positioned within a static stainless steel autoclave under simulated PW conditions at 320°C and connected via electrically insulated terminals to a BioLogic SP-200 potentiostat. A series of anodic potentiostatic polarizations of the WE (100 to 400mV above the reference) is conducted to promote oxide film formation. Once the stationary anodic current was reached, recording of the current was performed. Using the BioLogic SP-200, the lowest available cutoff low-pass filter is 5 Hz. Respecting the Nyquist-Shannon theorem, the sampling frequency for the current signal was established at 10 Hz (0.1 s). The current recordings consist of 10 individual samples, each purposely lasting 2^{17} s (i.e., 2^{18} data points per sample), to accommodate the upcoming *Fast Fourier Transformation (FFT)* calculations over a frequency domain ranging from 5Hz down to mHz scale. The EN data analysis was performed in the frequency domain via the Welch' s algorithm. The original signal is divided to a number of segments (*N*) of length (*L*), overlapping by (*D*) points (i.e., avoiding any loss of information at the intervals'edges). Each of these overlapping segments was detrended to remove the signal's DC component & then windowed with selected window functions (e.g., Hann, Hamming) removing amplitude inconsistencies at the extremities of time records [*S. Ritter et al., Materials and Corrosion 63.4, 297 (2012)*]. The resulting *Power Spectral Density (PSD)* spectra describe the signal's power density per frequency "*bin*" in (A^2/Hz). Slight increase of stationary current values was observed between experiments, indicating that the rate of metal vacancy generation weakly increases with overpotential. The spectral representations of current noise primarily exhibited flicker-type noise, characterized by a single high-frequency roll-off slope of non-integer exponents. However, large amplitude transients followed by an exponential-like decay introduced lobes & oscillations in the corresponding PSD spectra. The occurrence rate of these strong anodic events increases with the anodic overpotential, suggesting that the annihilation of large vacancy clusters is enhanced. In summary, passivation actually develops an EN signature which still needs to be fully analysed. The results obtained confirm the feasibility of developing an in-situ measurement technique to investigate the oxidation behavior of 316L AISI under PW conditions, initially in the absence of neutron flux.

#01 - Fundamental Physics / 100

#1-100 Upgrade of ATLAS Tile Calorimeter for the High-Luminosity LHC

Authors: Antonio Cervello Duato[1]; Jana Faltova[2]

Co-author: on behalf of the ATLAS Tile Calorimeter group

[1] *Institu de Fisica Corpuscular - CSIC/UV*

[2] *Charles University*

Corresponding Author: antonio.cervello@ific.uv.es

The Tile Calorimeter (TileCal) is a sampling hadronic calorimeter covering the central region of the ATLAS experiment with steel as the absorber and plastic scintillators as the active medium. Scintillators are read out by wavelength shifting fibers coupled to photomultiplier tubes (PMTs), positioned at the outermost part of the modules. TileCal is crucial for detecting hadronic particles, discriminating muons, electrons and photons, and measuring hadronic particle energy and transverse missing momentum.
The upcoming High-Luminosity phase of the LHC, starting in 2030, will increase the nominal instantaneous luminosity by a factor of five, alongside an upgraded ATLAS Trigger and Data AcQuisition architecture. This upgrade necessitates a complete redesign of the readout electronics and power systems of TileCal. Additionally, 10% of the most exposed PMTs will be replaced with a new model. The on- and off-detector TileCal electronics will be replaced during the Long Shutdown from 2026 to 2030 to handle a 40 MHz input rate, a 1 MHz trigger output rate, and harsher radiation and pile-up conditions. The upgrade involves digitizing signals from each TileCal cell and directly transmitting them to off-detector electronics at every bunch crossing. Once received off-detector, signals are reconstructed, stored, and forwarded to the first trigger level system at a 40 MHz rate. This upgrade improves calorimeter signal precision for the trigger system, enabling the development of more effective trigger algorithms.
The modular front-end electronics incorporate radiation-tolerant Commercial Off-The-Shelf components and a redundant design to mitigate single points of failure. The timing, control, and communication interface with off-detector electronics utilizes modern Field Programmable Gate Arrays (FPGAs) and high-speed fiber optic links operating at up to 9.6 Gb/s.
The TileCal upgrade program has involved extensive research and development, including test beam studies and the construction of a Demonstrator module. The Tile Demonstrator was integrated into ATLAS in July 2019 for testing in real detector conditions, while ensuring fully compatibility with the current ATLAS Trigger and Data AcQuisition system. This presentation will outline recent progress in the development of the on- and off-detector systems, expected performance characteristics, and results from test-beam campaigns featuring the latest electronics prototypes will be presented.

#10 - Current Trends in Development of Radiation Detectors / 101

#10-101 Organic Eutectics : an unexpected solution for solvent free liquid scintillators

Author: Pauline Vergnory[1]

Co-authors: Guillaume Bertrand [2]; Victor Buridon [3]

[1] *CEA*

[2] *CEA/DRT/LIST/DM2I/LCAE*

[3] *CEA-LIST*

Corresponding Authors: guillaume.bertrand@cea.fr, victor.buridon@cea.fr

Liquid scintillation is a well-established technique for the detection and measurement of radiation, particularly effective for low-energy beta radiation and low-intensity alpha emitters. This method relies on converting the energy of ionizing particles, into light that are subsequently detected by photodetectors. Various applications use liquid scintillators, including medical diagnostics, nuclear research, security and industrial fields. Liquid scintillators consist of an organic solvent combined with primary and secondary fluorophores to maximize energy-to-light conversion efficiency according to the photodetectors. The ideal liquid scintillator must exhibit chemical stability, a high flash point, low volatility, and low toxicity. However, commonly used solvents like toluene, xylene, and more recently, di-isopropylnaphthalene and phenylxylylethane, do not fully meet these criteria. As a result, these scintillators must be sealed or cannot be used in high volume, for safety concerns and environmental challenges.
Research is currently focused on developing safer formulations, including alternative solvents, aqueous mixtures, and environmentally friendly scintillators but until now, the results presented in literature show inferior scintillation properties. Despite these limitations, liquid scintillators have certain advantages over plastic scintillators, such as good radiation hardness, low impurity levels, and greater scalability.
Our work focuses on an innovative new class of solvent-free liquid scintillators, based on an organic eutectic mixture. These eutectics contain several solid organic compounds with individual relatively high melting points (between 68°C and 76°C), lowered at 4°C when mixed solution. The organic molecules used in our work are well known for their scintillation properties; however, their combination has led to the unexpectedly results of a new liquid scintillator. Our solvent-free liquid scintillators exhibit huge benefits, including a high flash point, non-volatility, and non-flammability. This new class of liquid scintillators still at the very first stage of development and we are continuously exploring different formulation and molecules of interest. To highlight this fact, we present here four different mixtures of eutectics liquid scintillators and their full radio physical characterization. Among them our best candidates achieves Light yields of 9.700 ph/MeV. We also performed fast neutron/gamma discrimination with remarkable FoM values of 2.4 comparable to commercial standard BC501A (FoM 2.8).
This discovery and its results represent a new and previously unknown class of solvent-free liquid scintillator with great potential. These scintillators enable effective neutron-gamma discrimination in small volumes and contain no flammable or volatile solvents, making them safer for both production and use.

Acknowledgments:
This project has received funding from the French NRBC-E research program.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 102

#6-102 Study of the industrial feasibility of Neutron Resonance Transmission Analysis (NRTA) for spent nuclear fuel reprocessing exploitation

Author: Melissa Azzoune[1]

Co-authors: Ludovic Mathieu [2]; Ngoc Duy Trinhb [3]; Mourad Aïche [2]; Sylvain Pelletier [4]; Fabrice Piquemal [2]; Lionel Tondut [3]; Laurence Villatte [4]

[1] *CNRS, LP2I Bordeaux*

[2] *LP2i UMR5797, Université de Bordeaux, CNRS*

[3] *Orano Recyclage, Établissement de la Hague, 50444 La Hague, France*

[4] *Orano Recyclage, 125 Avenue de Paris, 92320 Châtillon, France*

Corresponding Author: azzoune@lp2ib.in2p3.fr

For nuclear fuel cycle reprocessing, accurate determination of the isotopic composition of nuclear materials, including Uranium, Plutonium, and minor actinides, is crucial for optimizing the spent fuel reprocessing process and ensuring nuclear safety. Current physico-chemical analysis methods face limitations concerning time-consumption, complex chemical operations, and/or lack of precise isotopic composition determination. Neutron Resonance Transmission Analysis (NRTA) is emerging as a promising novel solution, thanks to its isotopic specificity over a wide range of isotopes mentioned above. However, its use remains confined to research laboratories, due to the need for large-scale facilities to generate high neutron flux with good temporal resolution, such as the GELINA accelerator at JRC-Geel. Our work aims thus to assess the industrial feasibility of NRTA by developing a compact system optimized for industrial use, including a tabletop accelerator, a short flight path, and the ability to measure some realistic object used in La Hague facility.

In this work, we will present the objective of this research project with a description of the NRTA technique and its challenges for industrialization. We will present some results of Monte Carlo simulations and our quantification method developed to analyze the neutron resonance transmission through certain samples. Experimental validation of the simulations and data analysis methodology will also be discussed.

#04 - Research Reactors and Particle Accelerators / 103

#4-103 In-core Gamma and Neutron Irradiation of Glass Samples used in the Design of Optical Sensors for Pressurized Water Research Reactors

Author: Marion Agoyan[1]

Co-authors: Ayoub Ladaci [2]; Aziz Boukenter [3]; Christophe Destouches [4]; Florence Martin [5]; Guy Cheymol [6]; Sylvain Girard [7]

[1] *Laboratoire Hubert Curien*

[2] *CEA Saclay*

[3] *Université Jean Monnet*

[4] *CEA/DES/IRESNE/DER/SPESI*

[5] *CEA/DES/IRESNE/DER/SPESI/LDCI*

[6] *CEA*

[7] *Université Jean Monnet, Saint-Etienne, France*

Corresponding Author: marion.agoyan@univ-st-etienne.fr

In the context of climate change, the goal of achieving carbon neutrality by 2050 represents a major challenge. In France, although renewable energies provide a much greater proportion of electricity than they did a few years ago, their intermittent contribution demands more variability to the nuclear industry. As a result, increasing stresses in the structure and components of nuclear reactor cores requires greater attention and study of fuel rod behavior. As part of this approach, a current project involves developing instrumentation for in-core testing devices at the Jules Horowitz research reactor; in particular an optical sensor to measure fuel rod's swelling in an in-core test device. This optical sensor called « confocal chromatic sensor » aims to perform non-contact and precise measurements. A fundamental step in the design of such a sensor is to qualify the behavior of the candidate optical glasses for its design under the severe conditions expected for the test devices of the future research reactor. Candidate glasses for the confocal chromatic sensor have to be radiation-resistant and chromatic glasses. It is well known that when exposed to radiations, optical glasses are affected by different phenomena such as radiation induced attenuation, radiation induced emission, radiation induced refractive index change and compaction. To test the candidate optical glasses, an irradiation campaign at the Belgian Reactor 2 occurred in December 2023. Online measurements were performed to measure optical path variations of a few selected bulk glasses. The optical path corresponds to the product of the glass refractive index by its physical length. Glass samples for online measurements were housed in measurement modules of 9-milimeters in diameter, which collected a signal formed by the interference of reflections from both sides of a parallel-sided glass sample. The measurement modules were located in a temperature-controlled portion (400 mm) of a 5-meter-long needle that has been immersed into the reactor core. During the entire irradiation process, the temperature measured close to the samples was recorded every minute, along with the gamma dose. The neutron fluence reached at the end of the run was of about 1.5× 〖10〗 ^19 n_fast (>1MeV)/cm^2. Interference spectra were collected for samples of Suprasil 1 (silica) and Sapphire at the wavelength of 1220 nm, allowing us to measure the optical path variations of these two glasses at the operating wavelength of the chromatic sensor under such extreme conditions. Performing such an interferometric measurement in a reactor core remains difficult, and because of these difficulties, we were unable to fully test other chromatic glasses due to a loss of signal either during the needle installation or during the irradiation. For sapphire and silica samples, we were able to measure an increase in the optical path values as the power of the reactor increased. This increase quickly stabilized, followed by a decrease, until about the initial value for sapphire and twice as low for silica sample (indicating probable compaction). Optical path variations differ between the two glasses in terms of absolute values but also in terms of fluence dependences. The relative optical path variations obtained have been corrected for thermal effects, assuming independence of the contribution of variations due to temperature and those due to nuclear radiation. Online measurements ensure that the variations measured are not underestimated due to the annealing phenomenon. To our knowledge, this is the first time that such online measurements have been carried out on glass samples in the reactor core. Post-mortem measurements will also be carried out on samples that were in the container in one of the needles during the irradiation campaign. In particular, this will enable us to collect information on samples that were not tested during the irradiation, as the chromatic glass SF6G05 from SCHOTT manufacturer for instance. These additional tests will also give information about the compaction of these various glass samples and help in decorrelating variations of

refractive index and of length. By combining the results obtained during this irradiation campaign with simulations with optical design tools, we will propose an initial design for a chromatic sensor able to operate in highly radiative environment.

Keywords: optical glasses, interferometry, high neutrons and gamma irradiation, research reactor, online measurements, radiation induced refractive index change, compaction

#09 - Environmental and Medical Sciences / 104

#9-104 Use of New Pixel Detector Technology for Radiotherapy Treatment Monitoring

Author: Eliska Soharová[1]

Co-authors: Jan Jakůbek [1]; Jaroslav Solc [2]; Laurent Kelleter [3]; Maria Martisikova [3]; Richard Kaderabek [4]; Tereza Kracmerova [5]

[1] *ADVACAM s.r.o.*

[2] *Czech metrology institute, Prague, Czech Republic*

[3] *German Cancer Research Centre DKFZ, Department of Medical Physics in Radiation Oncology, Heidelberg, Germany.*

[4] *Radalytica a.s., Olomouc, Czech Republic*

[5] *Motol University Hospital, Prague, Czech Republic*

Corresponding Author: eliska.trojanova@advacam.cz

The application of pixel detector technology in medical imaging and radiotherapy monitoring has significantly advanced the precision and efficiency of cancer treatment. Recent innovations, particularly the integration of Timepix3-based pixel detectors, have enhanced treatment monitoring for therapies such as FLASH, carbon ion radiotherapy, and thyroid cancer treatment. These detectors enable high-resolution, real-time tracking of particle interactions, providing critical insights into dose delivery, tumor localization, and treatment adjustments.

In radiotherapy, precise beam targeting is essential for minimizing damage to healthy tissue while effectively treating the tumor. Pixel detectors, such as those used in the novel particle tracking system for carbon ion therapy, track charged nuclear fragments produced by carbon ion interactions with patient tissue. The system, composed of 28 synchronized Timepix3 pixel detectors arranged in seven units, provides nanosecond timing precision and enables the reconstruction of particle trajectories. This technology allows for the accurate localization of fragment origins and can detect positional shifts as small as 1.5 mm, ensuring precise treatment delivery across therapy fractions. Testing with clinical phantoms has confirmed the system's capability to monitor changes in patient morphology and positioning, improving treatment alignment during therapy.

In the domain of thyroid cancer, ThyroPIX utilizes Timepix3 technology in a mobile Compton camera to provide enhanced imaging of the thyroid gland during treatment monitoring. ThyroPIX offers superior spatial resolution and sensitivity compared to traditional imaging methods, enabling the detection of residual cancer cells after surgical removal of the thyroid. By measuring the position, energy, and timing of gamma photons, the system can localize the source of radiation with high precision, providing valuable information to guide treatment decisions. The absence of bulky collimators, along with its lightweight design, makes the ThyroPIX system portable and suitable for both planar and tomographic imaging, facilitating quick, accessible examinations in any part of the hospital.

These advancements in pixel detector technology are transforming radiotherapy and cancer treatment monitoring by providing real-time feedback, improving accuracy, and enabling personalized treatment. The integration of Timepix3 detectors into various therapeutic modalities highlights their promising role in enhancing the efficacy and safety of cancer treatments across different clinical settings.

#08 - Severe Accident Monitoring / 105

#8-105 Infrared multispectral pyrometry for rod cladding temperature monitoring in loss of coolant conditions in test reactors

Authors: Austin Flemming[1]; Ayoub Ladaci[2]; Quentin Grando[3]

Co-authors: Gil Boioli [3]; Guy Cheymol [4]

[1] *Idaho National Laboratory*

[2] *CEA Saclay*

[3] *Authority for Nuclear Safety and Radiation Protection (ASNR)*

[4] *CEA*

Corresponding Author: quentin.grando@asnr.fr

In the study of Loss of Coolant Accidents (LOCAs), monitoring the cladding temperature in areas affected by swelling is one of the most critical parameters. The extreme conditions experienced by the rod, such as the presence of steam and high temperatures leading to a decrease in the mechanical properties of the cladding, make accurate temperature measurement challenging through conventional methods. Such techniques often introduce experimental artifacts, limiting reliability. Therefore, pyrometry, a non-contact temperature measurement technique, holds significant promise for these applications, as it minimizes the intrusiveness of measurements. However, implementing pyrometry under LOCA conditions remains difficult.

Among available pyrometry methods, multi-wavelength pyrometry (a hybrid approach combining infrared (IR) monochromatic and multispectral techniques) shows the greatest suitability for these experimental conditions. Three research entities, CEA, INL, and IRSN, each with unique applications for temperature measurement, have converged on using multi-wavelength pyrometry for in-pile temperature monitoring. The CEA focuses on monitoring experiments within the Jules Horowitz Reactor (RJH), INL applies this technique within the Transient Reactor Test Facility (TREAT), and IRSN deploys it for various in-pile and out-of-pile experiments. While each organization's system is based on the same principle, they vary in collection optical head, spectral range and data processing methods (4 wavelengths for CEA and full spectrum for INL and IRSN).

This study evaluates the performance of these three systems under identical conditions, including same optical heads, using the MAKI facility, an experimental setup capable of simulating LOCA thermal and hydraulic conditions. MAKI can recreate environments ranging from ambient temperatures up to 900 ℃, targeting cladding temperatures up to 1000 ℃, with light steam flow pressurized to 65 bars. The test section flow channel simulates surrounding rods, with the heater rod being ballooned for this series of tests.

The three pyrometry systems were subjected to the same experimental conditions, with light collected by three similar separate sapphire light guides positioned close to the cladding in the channel. The test conditions included:

- Heating the cladding alone from 600 to 900 ℃,
- Heating both the cladding and the test channel from 600 to 1000 ℃,
- Repeating the previous condition with steam added up to 10 bars.

This work presents the comparative measurements obtained from each system under these test conditions.

#04 - Research Reactors and Particle Accelerators / 106

#4-106 Mixed Neutron and Gamma radiation effects on Optical Fibers performed at CERN's n_TOF NEAR irradiation station

Author: Jérémy Perrot[1]

Co-authors: Adriana Morana [1]; Ana-Paula Bernardes [2]; Aziz Boukenter [3]; Daniel Ricci [2]; Emmanuel Marin [3]; Johan Bertrand [4]; Marco Calvani [2]; Matteo Cecchetto [2]; Matteo Ferrari [3]; Mickael Denis Crouvizier [2]; Ruben Garcia Alia [2]; Sylvain Girard [5]; Ygor Aguiar [2]; Youcef Ouerdane [3]

[1] *Laboratoire Hubert Curien*

[2] *CERN*

[3] *Université Jean Monnet*

[4] *ANDRA*

[5] *Université Jean Monnet, Saint-Etienne, France*

Corresponding Author: jeremy.perrot@univ-st-etienne.fr

Optical fibers provide significant benefits for use in radiation-rich environments. They are immune to electromagnetic interference, support signal multiplexing, and provide high bandwidth for substantial data transfer. Their distributed sensing capabilities can replace complex networks of individual sensors with a single optical fiber, reducing both weight and volume and making them ideal for low-intrusiveness instrumentation in radiation zones. Additionally, optical fibers with appropriate coatings can withstand extreme temperatures (ranging from a few K up to 1000 K), making them suitable for environments where both radiation and thermal constraints apply. These advantages make optical fibers invaluable across numerous applications such as the nuclear and space industries, high energy physics facility monitoring, and radioactive waste storage monitoring. The ability of optical fibers to support reliable measurements in harsh environments, relies not only on the intrinsic radiation tolerance of the fiber glass (enabling proper signal transmission) but also on the tolerance of their coatings to high temperature and radiation doses. Coatings, used as protective layers, are often polymer-based materials made of acrylate or polyimide, depending on the specific application. While traditional acrylate coating degrades above a temperature of 80 ℃, polyimide coatings can withstand higher temperatures up to 300 ℃. However, polyimide is known to be sensitive to ambient humidity inducing radial strain on the sensing fiber. New types of acrylate coatings have been developed to enhance their temperature tolerance up to 150 ℃ (high-temperature acrylate). Other coatings such as aluminum or carbon (or a combination of both) have been proposed for their mechanical properties to prevent H2-gas diffusion into the fiber core, which could alter the fiber's optical response and compromise its function as a sensor, plus their high temperature tolerance (up to 400 ℃). Radiation tolerance constraints continuously evolve, becoming harsher and more complex, as progress is made in the development of devices operating under extreme conditions and as radiation fields grow increasingly challenging. Accordingly, experimental studies are continuously needed to characterize the optical fiber response to different irradiation conditions for various and new applications. So far, optical fiber coatings have not been extensively tested under intense mixed neutron and gamma fields, despite the relevance of these characterizations for many applications. In this context, the mixed neutron and gamma radiation fields available at the NEAR irradiation test station of the n_TOF facility at CERN offer a unique opportunity to assess radiation effects in material and to compare the response to different fields (such as more conventional 60Co gamma sources and X-rays) already assessed in previous works. In particular, it is of interest to deliver a mixed neutron and gamma dose in the MGy range to the selected material. This study reports the mechanical and functional structural response of polyimide, three types of acrylate coatings, and a carbon layer, irradiated in mixed neutron (with a fluence ranging from 3.14× 〖10〗 ^17 n/cm2 to 1.10× 〖10〗 ^17 n/cm2) and gamma radiation fields at NEAR. Optical fiber samples have been passively irradiated at NEAR during a period of one operational year of the facility. Similar samples have also been irradiated up to 250 kGy and 1 MGy gamma-cumulated dose at the 60Co-irradiation IRMA facility from IRSN (CEA France). Post-mortem experiments have been performed to assess and quantify radiation-induced degradations on silica-based polyimide-, acrylate- and carbon-coated optical fibers. Cut-back measurements have been performed to measure the radiation induced attenuation spectra in the near infrared range, in combination with Optical Time Domain Reflectometry-based loss measurements at 1310 nm, 1550 nm and 1625 nm. Macroscopic coating physical degradation will be reported: optical microscopy images for both irradiated and pristine samples show large physical degradations of the tested high-temperature acrylate. High-temperature acrylate showed melted sections from the irradiation exposure whereas other acrylate formulations presented no specific degradation other than a coloration darkening. Polyimide coatings showed no measurable degradation. Optical Frequency Domain Reflectometry trace measurements have been performed on both irradiated and pristine samples, showing a significant radiation-induced increase in the Rayleigh gain, suggesting a measurable Radiation-Induced Refractive Index Change caused by the compaction of the fused silica under high neutron fluences, as already reported after reactor neutron field exposures. This result will be confirmed and quantified by Refractive Index Profile measurements on both pristine and irradiated samples. A comparison between samples irradiated at NEAR and at IRMA, currently ongoing, will deepen the understanding of the neutron contribution to the refractive index change compared to a gamma MGy dose. In addition, we already reported that the carbon coating layer can get slightly damaged by gamma irradiation up to 1 MGy. Through hydrogen-loading experiments, the integrity of the physical barrier blocking H2-diffusion will be quantified for pristine, gamma and NEAR irradiated samples. Hydrogen diffusion-induced temperature monitoring error for samples irradiated at 1 MGy of gamma dose and hydrogenated at 80 ℃ under a 100 bar H2-atmosphere has previously been quantified at +0.2 ℃. We expect higher degradation for carbon-coated samples irradiated in mixed neutron and gamma field. This study opens to further scientific studies to better understand those phenomena and, possibly, to develop a structured approach in the selection of optimal fibre coatings. We believe that these results will allow meaningful advancements to be made in the selection of optimal optical fiber coatings for emerging fiber-based technologies that are pivotal in present and future harsh environments, where intense mixed radiation fields are present, such as the nuclear and space industries and particle accelerators facilities.

#01 - Fundamental Physics / 107

#1-107 Charge signal formation in the TPC Vertical Drift design of DUNE

Author: Joshua Pinchault[1]

[1] *LPSC/LAPP*

Corresponding Author: pinchault@lpsc.in2p3.fr

Giant Liquid Argon Time-Projection Chambers will be used for the far detectors of the next generation of neutrino oscillation experiment: Deep Underground Neutrino Experiment (DUNE). This work focuses on design of the Vertical Drift module (VD), where the chamber consists of two drift volumes separated by a central cathode allowing a nominal electric field of 500 V/cm in each of them. The electrons produced by the ionisation of argon atoms by charged particles passing through the chamber will drift to two independent anode planes located at the top and at the bottom of the detector. A distinct feature of this TPC design is the use of a new type of anode made by a stack of perforated print circuit boards with etched channel strips. This new anode enables the detection of the ionization electrons through two inductions views and a charge collection view. Extensive R&D has been carried out at CERN in the past years to optimize the VD anode design. In this presentation, I will present the numerical simulations of the signal formation on all induction views of the anodes based on the Shockley-Ramo's theorem and the physics of charge carriers'motion on liquid argon. Comparisons with cosmic data taken at CERN with prototypes will be presented. A good understanding of the collected signal shape and strength is essential to achieve the track reconstruction efficiency and calorimetric measurement resolution needed by the DUNE experiment to study neutrino oscillations.

#10 - Current Trends in Development of Radiation Detectors / 108

#10-108 'Pile-up' and 'dead time' corrections for digital acquisition using a Monte Carlo method

Authors: Michaël PETIT[1]; Menad Hara[2]; Steven Hertay[2]; Diane Quevauvillers[3]; Christelle Reynard-Carette[4]

[1] *IRSN*

[2] *IRSN/LMDN Cadarache*

[3] *IRSN/PSE-SANTE/SDOS/LMDN*

[4] *Aix-Marseille University*

Corresponding Author: michael.petit@asnr.fr

At present, there is no 'ideal'detector. In consequence, the electrical signals induced by 'events'in a detector can sometimes be 'falsely'recorded or may not be recorded at all. For scintillators, for example, acquiring an event by integrating the electrical charge requires a minimum integration and recording time. During this integration time, one or more other events may occur and are then summed and recorded as a single event. This type of recording is commonly called 'pile-up'. Moreover, the recording of events and the return time to standby configuration requires a minimum duration which is commonly called 'dead time'. Correcting these events has always posed some difficulty. For 'old analogue acquisitions' for example, it was common to limit the count rate in order to reduce the fraction of 'pile-up'events to negligible quantity and thus to not have to apply any correction. Other methods can obviously be used, such as the pulser method to correct for 'dead time' and 'pile-up', but their implementation is generally complex and cumbersome and has not been used in many applications. The development of digital acquisition since the 2000 years has changed practice. For example, digitizing all the signals leads to identifying the 'pile-up'events in post-processing and so apply corrections. However, this method suffers from two strong flaw: firstly, it requires large amounts of computer data, which need many hard disk storages and even more serious, can limit the acceptable count rate according on the acquisition specifications. Secondly, when the time separating the two signals is too close or one signal is too small, it may be impossible to identify the 'pile-up'. Furthermore, estimating the dead time can also be a difficulty when the acquisition time of an event varies. However, the development of digital acquisitions offers another correction possibility, with or without recording the waveform, based on a Monte Carlo method using probabilities. Indeed, by using the events timing, it is possible for stable measurement configuration to deduce the 'true'count rate from the statistical distribution of events. This can offer a first correction possibility. However, the count rate can also be used to carry out a Monte Carlo random sampling of event arrival times and thus simulate a measurement statistically equivalent for the time sampling to the true one. In the same way, the study of real individual events can be used to create a set of statistical data that can be used with a Monte Carlo random sampling. The aim is then to randomly assign recording parameters to each simulated event that are consistent with the measurement. In this way, it is possible to completely simulate the measurement and so deduce the 'pile-up'and dead time corrections by studying these simulated events. The method generally requires an iterative algorithm, since the initial statistical data is not perfect. At the end of the analysis, these corrections can be compared with the parameters of the true measurement using some physical observables. For using digital acquisitions in neutron metrology, the Laboratory for micro-irradiation, neutron metrology and dosimetry (i.e. the LMDN from IRSN/Cadarache/France) has developed such a model based on Monte Carlo simulation. The model uses a random selection of the arrival time and the PSD parameters of each event. Some information must be known in advance (as for the signal shape) or deduced from the very experiment (as the temporal description and the PSD matrix). This model does not require routine digitization of the waveform. The model was successfully tested on a white neutron spectrum, during a time-of-flight measurement carried out on NFS (GANIL/France) with a stilbene scintillator coupled to digital acquisition. The model was used to estimate corrections of 10% for dead time and pile-up. Comparison of the measurements with the simulation enabled us to estimate this correction uncertainty at around 0.2%, i.e. less than the other measurement uncertainties. Since waveforms are not required, the amount of data to be recorded is divided by a factor of 100 in our case, which considerably increases the admissible measurement statistics while reducing the experiment time. The method requires a few obvious to be possible/effective, such as having statistics sufficiently representative of the data. It can be adapted to most detectors and measurements. In this presentation, the model implemented for NFS measurements with the scintillator and digital acquisition will be presented in detail. The optimization methodology and comparisons used to validate the effectiveness of the method will also be presented.

#04 - Research Reactors and Particle Accelerators / 109

#4-109 HONEY: High-Resolution Reactor Kinetics experiments in the CROCUS reactor

Author: Cecilia Montecchio[1]

Co-authors: Thomas Ligonnet [2]; Davide Mancusi [3]; Wilfried Monange [4]; Oskari Pakari [1]; Andrea Zoia [3]; Vincent Lamirand [5]

[1] *EPFL*

[2] *LRS (EPFL)*

[3] *CEA*

[4] *IRSN*

[5] *Ecole Polytechnique Fédérale de Lausanne*

Corresponding Author: cecilia.montecchio@epfl.ch

The first HONEY (High-resolution Online Neutronics Experiments for dYnamics) experiment took place in the CROCUS research reactor of EPFL (Switzerland) in April 2024. With this campaign, designed to enhance our knowledge of the physical parameters governing the reactor kinetics, we aim to achieve a high spatial resolution analysis of the reactor's time response to both reactivity insertions and withdrawals, obtained through adjustments in the absorber rod positions and water level.

The campaign targets comprehensive experimental measurements of the global kinetic responses to reactivity perturbations, relying primarily on two reference fission chambers located outside the core that serve as reactor power monitors. More importantly, it exploits high-resolution detection to enable the analysis of local spatial effects, through the SAFFRON detection system, previously developed within the H2020 CORTEX framework and during a doctoral thesis at EPFL. SAFFRON consists of an array of 160 miniature scintillation-based detectors, known as MiMi, which can measure the thermal neutron flux via the lithium-6 reaction. Placed at various inter-pin positions and on three main heights, these detectors provide exceptional spatial and temporal resolution, allowing for a precise mapping of the reactor core and recording of localized time-dependent phenomena that would otherwise remain undetected.

The experimental results of the first HONEY campaign are used to validate the reactor kinetic simulation capabilities of TRIPOLI-4, a high-fidelity Monte Carlo particle-transport code developed at CEA (France). HONEY enables unique insights for a significantly robust code validation: while exploiting global results in the context of code validation is essential to improve the predictive power of simulation tools, the true breakthrough of this work lies in its focus on localized effects. The approach proposed not only addresses the challenge of obtaining precise local data using the SAFFRON detection system, but also paves the way towards a detailed analysis of how effectively computational models can reproduce the local phenomena.

In this contribution, we present the experimental setup, methodologies and key results, with strong emphasis on comparing experimental and computational outcomes. Particular attention is given to the miniature detectors positioned near the perturbations (i.e., the lifted or inserted absorbers rod), with the objective of characterizing their magnitude and determining their propagation distance. This includes identifying the point at which localized effects vanish and the detector response relaxes to the global behavior, with the complementary goal of assessing whether the TRIPOLI-4 code can accurately replicate these experimentally observed effects.

#10 - Current Trends in Development of Radiation Detectors / 110

#10-110 Ultra-short/Ultra-high X-ray pulse spectrometry based upon FDS/OSL spectrometer and Bayesian unfolding algorithms: spectrometer design and online X-ray source qualifications

Author: Sylvain Magne[1]

Co-author: Johann PIEKAR [2]

[1] *CEA LIST*

[2] *CEA List*

Corresponding Author: sylvain.magne@cea.fr

X-ray spectrometry is routinely performed with fast scintillators associated with Pulse Height Analyzers (PHAs). A PHA discretizes the signal amplitude (proportional to the energy of the incoming photon) and counts the number of pulses incoming in each register, thus generating a pulse-height energy spectrum. In practice, the combination of scintillator and electronics imposes a dead time between successive pulses (period during which no counting is possible). Although 100-MHz count rates are achieved with the fastest electronics and scintillators (rise & fall times of several tens of nanoseconds), significant pile-up occurs under ultra-high-count rate situations, thus hindering routine PHA spectrometry.
X-ray spectrometry already proves difficult with conventional Linear Accelerators (LINACs) delivering peak dose rates of about 10 kGy/s (mean dose rate ~ 10 mGy/s). It is an even more challenging task with dedicated LINACs delivering ultra-high dose rates of about 1 MGy/s (mean dose rates of some Gy/s), e.g. for Flash Therapy, fast X-ray imaging, etc.
Conversely, ultra-short pulses are encountered with femtosecond (fs) laser-based X-ray sources. An intense laser power (~ TW (1012 W)) is achieved by focusing the light from a fs titanium-sapphire (Ti-Sa) laser in a gas, leading to plasma generation and wakefield electron acceleration (Laser Plasma Acceleration –LPA). The electron bunch is eventually projected onto a metal target (most often tungsten) to generate Bremsstrahlung. PHAs are not appropriate because the dead time of counting electronics is at least three orders of magnitude larger than the time width of the X-ray pulse, similar to the laser pulse duration (several 10 fs, i.e. 10-14 s).
In the context of the European MULTISCAN 3D Project, CEA List designed and qualified an online X-ray FDS (Filter-Detector Stack) spectrometer for assessing the spectral behavior of X-ray beams generated by fs-LPA processes. The spectrometer consists in a cradle hosting 16 OSL/FO (Optically Stimulated Luminescence/Fiber Optics) sapphire detectors alternating with metal filters of increasing density. Light elements (stainless steel, molybdenum) are placed at the front part and are used to cut the low energy part of the spectrum. Heavier ones (tantalum, tungsten) are placed at the rear part and provide medium- and high-energy discrimination. After irradiation, laser light remotely stimulates each OSL/FO probe and the OSL light is transported back to the readout unit by the same optical fiber. Laser stimulation also leads to OSL erasure so that the spectrometer may be irradiated again (no disassembly is required). The 16 OSL/FO probes provide an experimental dose vector from which we reconstruct the X-ray spectrum with the help of Bayesian unfolding algorithms (Maximum Likelihood Expectation Maximization –ML-EM, Maximum a posteriori –MAP-EM). Such algorithms involve an inversion matrix whose coefficients are determined by Monte-Carlo modeling (MCNP6, PHITS) to account for both probe/filter attenuation and internal/external build-up. We provide a complete description of the basics and performance of ML-EM and MAP-EM algorithms in another paper of the same conference. The X-ray FDS/OSL spectrometer has been qualified in the range of 10 MeV with radionuclides sources (192Ir, 60Co and 137Cs) and a Varian LINAC (6 MV, 9 MV). The reconstructed spectra compared favorably to expected ones. Final tests are planned with a fs Ti-Sa laser (SHERIL installation) in order to fully characterize the fs-LPA process for X-ray generation.

This work is performed in the framework of the MULTISCAN 3D Project (101020100), granted by the European Commission (H2020-SU-SEC-2020). We thank Johann Plagnard, Marion Catheline and Victor Hernandez-Elvira (CEA List/LNHB) for giving us access to 60Co/137Cs multisource equipment and the 192Ir source projector, respectively, Jean-Marc Bordy (CEA List/LNHB) for the MCNP6 modeling of the 60Co/137Cs multisource, Adrien Sari (CEA List) for operating the LINAC, Olena Kolonenko and Cédric Thaury (LOA/ENSTA, Ecole Polytechnique, Palaiseau, France) for giving us access to the SHERIL laser installation.

#10 - Current Trends in Development of Radiation Detectors / 111

#10-111 Ultra-short/Ultra-high X-ray pulse spectrometry based upon FDS/OSL spectrometer and Bayesian unfolding algorithms: assessment of ML-EM and MAP-EM algorithms for spectrum reconstruction

Author: Johann Piekar[1]

Co-author: Sylvain Magne [2]

[1] *CEA List*

[2] *CEA LIST*

Corresponding Author: sylvain.magne@cea.fr

The spectrometry of X-ray pulses is hindered whenever ultra-high dose rate or ultra-short pulses are involved because of electronics dead time and pile-up phenomena occurring in PHAs (Pulse Height Analyzers). Ultra-High dose rates (i.e. 1 MGy/s) are produced by dedicated Linear Accelerators (LINACs) for Flash Therapy or fast X-ray imaging purposes, for instance. Ultra-Short X-ray pulses are encountered with femtosecond (fs) laser-based X-ray sources. An intense laser power (~TW (10^{12} W)) is achieved by focusing the light from a fs titanium-sapphire (Ti-Sa) laser in a gas, leading to plasma generation and wakefield electron acceleration (Laser Plasma Acceleration –LPA). The electron bunch is eventually projected onto a metal target (most often tungsten) to generate Bremsstrahlung.
In the context of the European MULTISCAN 3D Project, CEA List designed and qualified an online X-ray spectrometer for assessing the spectral behavior of X-ray beams generated by fs-LPA processes. The Filter-Detector Stack (FDS) spectrometer consists in alternating metal filters (stainless steel, molybdenum, tantalum and tungsten) with passive OSL/FO (Optically Stimulated Luminescence/Fiber Optics) sapphire detectors. We describe its complete design in another paper of the same conference. The X-ray spectrometer hosts 16 OSL/FO detector probes providing an experimental dose vector from which we reconstruct the X-ray spectrum with the help of Bayesian unfolding algorithms: Maximum Likelihood Expectation Maximization (ML-EM), Maximum A Posteriori Expectation Maximization (MAP-EM). Such algorithms involve an inversion matrix (16x25) whose coefficients are determined by Monte Carlo modeling (MCNP6, PHITS) to account for both probe/filter attenuation and build-up within the spectrometer body (including 5-cm-thick lateral lead shield and a 10-cm-thick lead collimator). Those algorithms are well suited to ill-posed inversion problems like spectrum reconstruction, as they allow the incorporation of a priori information and constraints. For continuous spectra such as Bremsstrahlung, a guess spectrum (associated with the assumption of spectral smoothness) facilitates the convergence process. Compared to other inversion techniques, these algorithms offer the advantage of both noise and uncertainties management, leading to more stable and accurate solutions.
The resulting energy spectrum is divided in 25 energy bands. In the low-energy part of the spectrum (up to 1.5 MeV), the energy bin is 100 keV, whereas it is 500 keV in the range [1.5 MeV- 3 MeV] and 1 MeV up to 10 MeV. We applied variance reduction techniques, including the Weight-Window (WW) generation method provided in PHITS, to improve statistical convergence and simulation efficiency.
The X-ray FDS spectrometer has been qualified up to 10 MeV using radionuclide sources (^{192}Ir, ^{60}Co, and ^{137}Cs) and a Varian LINAC (6 MV, 9 MV). The reconstructed spectrum of the iridium source was consistent with simulations, with a mean energy deviation within an acceptable range. However, for cobalt and cesium, additional environmental factors were considered in the simulations, as these sources are housed in a steel casing with an aperture, which affects the spectra received by the spectrometer. Final tests are planned with a fs Ti-Sa laser (SHERIL installation) to fully characterize the LPA process for US X-ray generation.
This work is performed in the framework of the MULTISCAN 3D Project (101020100), granted by the European Commission (H2020-SU-SEC-2020). We thank Frédérick Carrel (CEA List) for his help in the implementation of the ML-EM algorithm and Adrien Sari (CEA List) for assistance with Monte Carlo modeling and for operating the LINAC.

#04 - Research Reactors and Particle Accelerators / 112

#4-112 Assessment of Thin Plastic Scintillation Detectors to Improve Fission-Product Beta-Particle Measurements for the Advanced Test Reactor Critical Facility Power Distribution Measurements

Author: Kelly McCary[1]

Co-author: Michael Reichenberger [1]

[1] *Idaho National Laboratory*

Corresponding Author: kelly.mccary@inl.gov

The Fission Wire Measurement System is a custom measurement system designed in the 1960s to measure the beta-particle activity of irradiated uranium-aluminum fission wires. This measurement is conducted to determine the fission rate profile of the Advanced Reactor Test Critical facility. The Advanced Test Reactor Critical facility is an open-pool, low-power test reactor used to qualify experiment configurations and verify core models prior to full-power experiment irradiations in the Advanced Test Reactor. Power distribution measurements in ATR-C use uranium-aluminum wires that are distributed throughout the core to validate simulation and modeling results. These measurements require from 340 to 1500 wires to be irradiated and measured within a 12-hour window. The system consists of 4 measurement channels and one reference channel, each with a 2-pi proportional gas flow detector and the measurement channels each have an automated sample changer. The gas flow detectors are of a custom design for this detector system that use methane gas with a large anode wire compared to modern proportional counters. These detectors, which are nearly 60 years old are irreplaceable. The measurements from these gas detectors are affected by the gas flow rate, atmospheric and line pressure, and are very sensitive to the applied high voltage. Recent improvements have been made to the control and data acquisition system, but the detectors have remained the same. The nature of the measurement of the fission product decay activity is such that the energy spectrum of the signal is changing with time. Thin, 250-um thick, plastic scintillators were commercially obtained as a potential replacement for the gas flow detectors. The original calibration of the uranium-aluminum fission wires was conducted in 1965 using a series of irradiations of gold foils and the wires in a well-characterized thermal neutron field. These measurements provided a time-dependent fission rate conversion factor from the gold foil data to calibrate the fission wires based on the response from the 2-pi proportional gas detectors. Transitioning to the new detectors requires qualification and testing. The sensitivity of the scintillators to changes in the energy spectrum of the fission wires and translation of the calibration factor have been completed. These measurements indicated that the sensitivity of the scintillators over time changes at a different rate than the sensitivity of the gas flow detectors. However, the inverse activity of measurements of both detector types is linear with time. Initial results indicate that the scintillator detectors will be a sufficient replacement for the gas detectors with minor adjustments to the fission rate conversion factor. Replacement of the detectors will improve the fission wire measurements and provide a more stable and reliable measurement system.

#01 - Fundamental Physics / 113

#1-113 Simulation of Signal Reconstruction Algorithms in the ATLAS Tile Calorimeter PreProcessor for the HL-LHC

Author: Sonakshi Ahuja[1]

Co-authors: Antonio Cervello Duato [2]; Fernando Carrió Argos [3]; F. Curcio [4]; L. Fiorini [2]; A. Gómez [2]; D. Hernandez [5]; F. Hervás [6]; A. Ruiz [2]; A. Valero [2]

[1] *IFIC- CSIC*

[2] *Institu de Fisica Corpuscular - CSIC/UV*

[3] *School of Physics, University of the Witwatersrand, Johannesburg; South Africa*

[4] *INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy*

[5] *Department of Physics, University of Hong Kong, Hong Kong*

[6] *CERN, Geneva; Switzerland*

Corresponding Author: sonakshi.ahuja@cern.ch

The Tile Calorimeter is a central sampling hadronic calorimeter of the ATLAS experiment at LHC. The calorimeter is build of alternating layers of stainless steel and plastic scintillating tiles oriented perpendicular to the beam axis. The calorimeter plays a crucial role in the reconstruction of jets and hadronically decaying tau leptons, as well as of the missing transverse energy. Moreover, it provides input signals to the Level 1 calorimeter trigger.
A new phase of the LHC, High-Luminosity LHC (HL-LHC), is expected to start its operation in 2030. The HL-LHC accelerator is designed to deliver five times the LHC nominal instantaneous luminosity. The demanding conditions in the detector during the HL-LHC operation, are driving significant upgrades to the ATLAS detector to enhance data processing and maintain its discovery potential. A crucial part of this upgrade is the replacement of the readout electronics for the ATLAS Tile Calorimeter.
The new Tile PreProcessor (TilePPr) system will serve as the interface between the calorimeter's on-detector electronics and the central Trigger, Detector Control, and Data Acquisition systems of ATLAS. Developed using the Advanced Telecommunications Computing Architecture (ATCA), the TilePPr module features high speed optical links and advanced data processing capabilities to ensure efficient handling of the increased data rates and harsher radiation environments characteristic of HL-LHC. One of the primary and most challenging functions of the TilePPr is to perform real time signal reconstruction, delivering calibrated data for each bunch crossing in a fixed and low latency path. Given the limited FPGA resources, reconstruction algorithms must be optimized for fixed-point arithmetic, reduced latency, and precise energy calculation for each bunch crossing, despite significant pile-up challenges.
To meet these demands, a dedicated framework has been developed to facilitate the design and assessment of various reconstruction algorithms within the TilePPr's FPGA architecture. This framework allows for in-depth evaluation using both simulated and real detector data to ensure the algorithms perform within the strict pile-up environment and timing constraints of the trigger system. This contribution will focus on the design, implementation and performance studies of various reconstruction algorithms within the TilePPr for the HL-LHC requirements.

#04 - Research Reactors and Particle Accelerators / 114

#4-114 Understanding the origins of the Signal-to-Noise Ratio of CABRI hodoscope

Author: Vincent Chevalier[1]

Co-author: Jacques Di Salvo [1]

[1] *IRSN*

Corresponding Author: vincent.chevalier@irsn.fr

The CABRI experimental pulse reactor is devoted to the study of Reactivity Initiated Accidents (RIA), for the purpose of the CABRI International Program (CIP), managed by the French Radioprotection and Nuclear Safety Institute (IRSN). CABRI's hodoscope equipment detects the fast neutrons emitted during a power pulse by a tested rod, positioned inside a dedicated test loop reproducing either sodium reactor or Pressurized Water Reactor (PWR) conditions. Among other experimental acquisitions, its first role is to monitor the fuel displacements inside the test rod during the pulse. Complementary, Hodoscope measurements are used to estimate the axial power profile on the test rod, and the so-called coupling factor, involved in the determination of the deposited energy on the test rod during the pulse. To reach these results, one of the most important parameters measured by the hodoscope detectors is the Signal-to-Noise Ratio (SNR), characterizing the fraction of neutrons directly coming from the test rod ("signal") over neutrons coming from the core ("noise").

In this article, the method used to calculate the SNR using a 2D model of CABRI, with the MCNP6.2 Monte Carlo code, will be detailed. The model consists of a full description of the CABRI core, as well as the hodoscope equipment. It is interesting to note that the SNR indicator is quite independent of the Z-axis, so as a 2D description is well suited to estimate this parameter.

This model has been applied to a calibration experiment of the hodoscope equipment, with a fresh UO2 rod used as a test rod. This calibration step involves acquisition performed during a steady-state 10 MW power plateau; no power pulse being required for this goal. The measured signals have been reproduced by the calculation, in order to estimate the SNR. The calculation allows to explain the shape of the experimental curves, thanks to a precise localization of the origin of the noise in the CABRI core.

Finally, calculated and measured signals show a quite good agreement. However, a discrepancy can be observed for the noise measured by a set of detectors, which is not described by the simulation, and which will require further investigations.

#04 - Research Reactors and Particle Accelerators / 115

#4-115 Characterization of optical components dedicated to optical fission chamber in nuclear environment

Authors: Christian Jammes[1]; Grégoire de Izarra[2]; Marc Pouradier Duteil[1]; Vladimir Radulović[3]

[1] *CEA*

[2] *Commissariat à l'Energie Atomique*

[3] *Jožef Stefan Institute*

Corresponding Authors: gregoire.deizarra@cea.fr, vladimir.radulovic@ijs.si

The French Alternative Energies and Atomic Energy Commission (CEA) is developing innovative neutron detectors to support Generation IV reactors. For this purpose, the CEA is working on optical fission chambers, a technology based on noble gas scintillation. An optical fission chamber is a non-polarised fission chamber that uses de-excitation photons emitted by the gas filling the chamber, which is excited by a fission fragment. The signal is transmitted from the core via an optical fibre to a single-photon avalanche photodiode, which provides a count rate proportional to the number of photons detected.
One of the main challenges of this technology is related to signal transport in a nuclear environment. Indeed, irradiated fibers suffer from a phenomenon known as radiation-induced attenuation, which restricts the use of optical fission chambers, as the measured optical signal is no longer proportional to reactor power. Moreover, radiation-induced emission, particularly the Cherenkov effect in fibers, is also a limitation for optical fission chambers, as it is superimposed on the neutron radiation from the gas and introduces optical noise into the measurement due to gamma interactions.
For this reason, an experimental campaign was conducted on JSI's TRIGA reactor in June 2024 to characterize the radiation-induced properties (emission and attenuation) of various optical material irradiated in a mixed neutron/gamma field, in order to determine which optical elements are most suitable. These experiments demonstrated that the OH content in the core of an optical fiber strongly affects the fiber's radiation-induced attenuation and highlighted preferential spectral ranges that may be useful for optical fission chambers. Phenomena related to the reactor environment, such as neutron activation of silica, were also observed. Lastly, measurements taken on sapphire glass, known for its resistance to radiation and high temperatures, showed that its use in reactors would be unwise due to its radiation-induced emission, which is much more intense than that of silica.

#09 - Environmental and Medical Sciences / 116

#9-116 Response of RPL Passive Dosimeters in 6 and 7 MeV γ Field Around the KATANA Water Activation Facility

Author: Domen Govekar[1]

Co-authors: Domen Kotnik [1]; Julijan Peric [1]; Vladimir Radulović [1]

[1] *Jožef Stefan Institute, Ljubljana*

Corresponding Author: domen.govekar@ijs.si

Water activation is a critical consideration in fusion reactors, where the interaction of neutrons with cooling water leads to the production of radioactive isotopes, including $^{16}_{7}N$, which emits high-energy γ rays. The activated cooling water contributes to intense radiation fields around fusion reactor cooling loop that require careful monitoring to ensure the safety of personnel and the integrity of surrounding facilities. Accurate dose measurements are essential in these environments to assess radiation levels, optimize shielding strategies and minimize exposure during operation and maintenance. Reliable dosimetry instrumentation is critical for assessing radiation doses in the vicinity of activated water systems, which is essential for both routine monitoring and the development of safety protocols in fusion reactors.

In this study, the response of radio-photoluminescence dosimeters (RPL) and radiation-responsive field-effect transistor dosimeters (RADFET) to high-energy γ radiation, in particular 6 and 7 MeV photons emitted during the decay of $^{16}_{7}N$, is investigated in the vicinity of the KATANA water activation facility, JSI. The main objective is to evaluate the dosimetric performance, sensitivity and reliability of RPL and RADFET dosimeters under controlled high-energy γ radiation, simulating the complex radiation fields typical in nuclear facilities. The study includes both experimental and simulation methods, using the Monte Carlo N-Particle (MCNP) code to model energy deposition and particle transport, providing a solid basis for interpretation and validation of the dosimeter response.

Some dosimeters are shielded with lead to assess the attenuation and evaluate the response of the shielded dosimeters to high-energy γ radiation. The performance of lead shielding is analyzed by comparing the readings of shielded and unshielded dosimeters, providing practical insights into radiation protection and shielding concepts. The MCNP simulations allow a analysis of particle transport in the γ radiation field, which enables accurate prediction of dose distribution and provides a complementary tool for the interpretation of experimental results, improving radiation monitoring and safety protocols in nuclear and radiological applications.

#04 - Research Reactors and Particle Accelerators / 117

#4-117 Photon flux characterization of a 15 MeV electron linear accelerator in the CINPHONIE irradiation facility

Author: Benoit Geslot[1]

Co-authors: Alix Sardet [2]; Bertrand Pérot ; Cédric Carasco [1]; Daniel Eck [1]; Emmanuel Payan [1]; Frédéric Moutet [1]; Malo Lebreton [1]; Nicolas Estre [1]

[1] *CEA, DES, IRESNE, DTN, SMTA, Nuclear Measurement Laboratory, Cadarache, F-13108 St Paul Lez Durance, France*

[2] *CEA DES IRESNE*

Corresponding Author: benoit.geslot@gmail.com

Electron linear accelerators (LINACs) are versatile and powerful X-ray sources, which can be used in medical radiotherapy as well as in various industrial applications including non-destructive testing, imaging and security inspection. LINACs accelerate electrons by passing them through a series of oscillating electric fields within a vacuum tube. These high-energy electrons are then directed toward a metallic target, producing X-rays (bremsstrahlung radiation) when they decelerate upon impact.
In the field of non-destructive radioactive waste characterization, high-energy photon imaging (radiography, tomography) is used on large cemented radiological waste containers, with a volume of the order of 1 m3, to check their integrity and assess their content [1][2]. However, for such packages, passive gamma-ray spectroscopy, passive neutron counting and even active neutron interrogation fail in measuring nuclear materials, like plutonium and uranium. Therefore, high-energy photon interrogation techniques is being studied to detect and quantify nuclear materials through the detection of induced-photofission particles.
For the past years, CEA has been developing high-energy imaging [3] and photon interrogation techniques [4] in CINPHONIE irradiation bunker (CHICADE facility, CEA IRESNE, Cadarache, France). CINPHONIE was recently upgraded with a new K15 VARIAN accelerator, reaching a maximum dose rate of 130 Gy/min at 1 m from the target. The stability of the dose rate, as well as the reproducibility was greatly improved compared to the previous setup with a legacy SATURNE LINAC [4]. New features are also available: two operation modes (9 MeV or 15 MeV), online dose rate monitoring and beam shaping thanks to high-density collimation blocks.
For advanced techniques (high-energy photon and photoneutron activations, photofission, bi-energy imaging), it is paramount to simulate precisely the irradiation field. For that purpose, a numerical model of the LINAC internals was built (with MCNP 6.3). It aims at simulating photon and neutron fields in view to calculate dose rates and reaction rates in irradiation samples, waste packages, but also in the whole casemate (background).
A thorough characterization campaign carried out to validate and calibrate this MCNP model against various experiments will be reported, including dose rate measurements in a water tank and delayed gamma-ray spectroscopy of thin gold and nickel foils activated in the X-ray beam. These experimental results will be used to fine-tune the electron source energy distribution, in view to model as reliably as possible the X-ray energy spectrum. Its high-energy part is indeed particularly crucial for photofission studies, and modeling properly the whole spectrum shape at 9 MeV and 15 MeV is of utmost importance for bi-energy studies. We will also check consistency of the simulated spectrum intensity with the experimental LINAC current.

[1] B. Pérot, et al., "The characterization of radioactive waste: a critical review of techniques implemented or under development at CEA, France, "EPJ Nuclear Sciences & Technologies, 4, 3 (2018). doi.org/10.1051/epjn/2017033
[2] M. Kistler, et al., "Simulated performances of very high energy detectors for nondestructive computed tomography characterization of large objects."IEEE Transactions on Nuclear Science, 65(9):2527–2532, 2018.
[3] N. Estre, et al., "High-Energy X-Ray Imaging Applied to Nondestructive Characterization of Large Nuclear Waste Drums,"IEEE Transactions on Nuclear Science, 62(6), 3104–3109, (2015). doi.org/10.1109/TNS.2015.2498190
[4] M. Delarue, et al., "New measurements of cumulative photofission yields of 239Pu, 235U and 238U with a 17.5 MeV Bremsstrahlung photon beam and progress toward actinide differentiation,"Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, 1040, 167259, (2022). doi.org/10.1016/J.NIMA.2022.167259

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 118

#5-118 Improvement of the high-temperature performance of multi-element ultrasonic transducers

Author: Hauriann Moisson[1]

Co-authors: Gaëtan Galeron [1]; Paul-Vincent Bonzom [1]; Samuel Margueron [2]

[1] *CEA*

[2] *FEMTO-ST*

Corresponding Author: hauriann.moisson@cea.fr

As one of the world's pioneers in nuclear energy, France has long relied on nuclear power to meet its growing energy needs. In response to the aging of the reactors, fourth-generation sodium-cooled reactor projects have been initiated, requiring advanced instrumentation such as high-temperature ultrasonic transducers developed by the CEA to monitor submerged structures. The High-Temperature Ultrasonic Transducer, developed by the CEA for sodium-cooled fast reactors, is a piezoelectric sensor designed to withstand extreme conditions. In addition to the challenges related to high temperatures and irradiation in sodium-cooled fast reactors, these transducers must support various applications, including event detection, telemetry, and visualization in liquid sodium. The CEA is currently developing several models tailored to these specific applications and more.

One of these models is the High-Temperature Multi-Element Ultrasonic Transducer. A doctoral thesis is currently underway in partnership between the FEMTO-ST Institute and the CEA, focused on the development of this transducer. Multi-element transducers are considered the most suitable tools for continuous inspection or periodic inspections of reactors during shutdowns. These transducers offer greater sensitivity compared to single-element piezoelectric transducers. Unlike single-element transducers, multi-element transducers can generate images without the need to scan the target, resulting in time savings and a reduced equipment footprint. Furthermore, they enhance spatial resolution, providing more precise obstacle localization through parallel control of the individual piezoelectric elements. The High-Temperature Multi-Element Ultrasonic Transducer consists of a stack of a matrix of piezoelectric elements and metals.

This transducer must meet various technical and environmental constraints. For instance, the spatial resolution directly affects the size of the piezoelectric elements; to achieve a resolution of 0.5mm, the element size must be smaller than 0.25mm. However, manufacturing elements of this size currently seems difficult, with a target element size of 2.5mm being more feasible. Additionally, for continuous monitoring, the transducer must operate at the nominal temperature of liquid sodium, around 550℃. Since it is located inside the reactor, the transducer must also withstand corrosion from sodium and irradiation caused by nuclear fission reactions.

To meet these constraints, lithium niobate was selected as the piezoelectric material. This material has a high melting of approximately 1250℃, enabling it to resist the nominal temperature of liquid sodium. Additionally, lithium niobate exhibits a good coupling coefficient (0.15 to 0.49), depending on the crystal orientation. The Y36° cut of lithium niobate is preferred for its sensitivity to vibrations and high coupling coefficient of 0.49. However, the Z-cut of lithium niobate can be used due to its thermal expansion coefficient, which offers better mechanical stability, despite its lower coupling coefficient of 0.17. Furthermore, ultrasonic transducers made from lithium niobate crystals maintain their integrity and performance even at high temperatures. Regarding metals, 304L and 316L stainless steels were selected for their melting points of approximately 1400℃, which allow them to tolerate the nominal temperature of liquid sodium in the reactor. Due to their low carbon content, 304L and 316L stainless steels provide good corrosion resistance.

The objective of this study is to develop a fabrication method for the piezoelectric element matrix as well as an assembly method between this matrix and the metallic components. Cleanroom fabrication techniques are employed to ensure the best possible performance of the transducer. The first phase of the study involves material characterization, specifically analyzing surface conditions and thermomechanical stresses applied to lithium niobate and stainless steel. The second phase focuses on developing an assembly method using cleanroom manufacturing processes. Finally, the last phase will involve high-temperature tests, acoustic tests, and resistance evaluations. Ultimately, this research aims to contribute significantly to the advancement of monitoring technologies in the nuclear industry, enhancing safety and operational efficiency.

#04 - Research Reactors and Particle Accelerators / 119

#4-119 Modern Measurements of Fission Reactor Power Spectral Density

Authors: Gilles Caulier[1]; Romain Boffy[2]

Co-author: Jean-Paul Goossens [2]

[1] *CEA CADARACHE CABRI*

[2] *CEA Cadarache CABRI*

Corresponding Author: romain.boffy@cea.fr

The power spectrum measurements are key elements to estimate the power spectral density of a fission reactor used in production. At CABRI institute, a research reactor used to simulate a sudden and instantaneous increase in power, known as a power transient, SPESI team developed a dating portable instrumentation named X-MODE to perform this kind of data acquisitions and analysis. The materials have been shared all over the world at different places where nuclear fission reactors require power profiling.

The **CABRI** experimental reactor, located at the Cadarache nuclear research center, southern France, has been successfully operated during the last 30 years, enlightening the knowledge of FBR and LWR fuel behavior during Reactivity Insertion Accident (RIA) and Loss Of Coolant Accident (LOCA). Since 2003 a whole facility renewal program have been commissioned for the need of the CABRI International Program (CIP), focused on the control of major gaseous neutron absorber He3, in the core geometry.

The CABRI team worked to modernize the X-MODE instrumentations due to electronic components, computer, and software obsolescence. The new **SCHMITT** system dedicated to replace X-MODE is based on CAEN R7771 neutron pulse train recorder to digitalize data from the sensors. In parallel, the software in charge of data acquisitions, calculations, and post processing have been fully re-written, including plenty of new features, as advanced inline computations, segmented storage, and graphs.

The paper describes the complete development of the SCHMITT instrumentation, which has been modernized by integrating modern materials. The software part has been re-implemented in an object-oriented approach and based on Qt framework for enhanced code portability. The usage of open-source components have been generalized, such as Linux operating system, the standard shared libraries dedicated for computing purposes as Boost, FFTw3, and Eigen3, the high performance time series database InfluxDB, and the Grafana analytics visualization tools. All these modern standard software technologies will allow porting and integrate other instrumentations used at CABRI in the future.

The new SCHMITT instrumentation has been successfully completed and is ready for a future qualification and usages. Current developments aim at including support for advanced nuclear data post-processing.

#09 - Environmental and Medical Sciences / 120

#9-120 Dosimetry with a phoswich detector

Author: Nicolás Ávila[1]

Co-authors: Anja Seifert [1]; Dirk Döhler [1]; Thomas Kormoll [1]

[1] *TU Dresden*

Corresponding Author: nicolas_alejandro.avila_perez@mailbox.tu-dresden.de

The determination of operational dosimetric quantities such as ambient dose equivalent $H^*(10)$ and directional dose equivalent $H'(0.07, 0°)$ in photon radiation fields is of great importance in radiation protection monitoring. This assessment typically involves configurations of several detectors, each of them calibrated and intended for the measurement of one single quantity, which leads to complex and expensive setups with multi-channel readouts. In the present work, a phoswich detector is designed to simplify the simultaneous measurement of $H^*(10)$ and $H'(0.07, 0°)$. In a phoswich detector two or more scintillation materials are optically coupled to a common light sensor. The difference between the time constants, and therefore between the different pulse shapes, allows to measure the energy deposition in each material. The feasibility of using this additional information for the calculation of a second operational quantity with a single detector in a photon radiation field is the main subject of this project. Furthermore, the functionality of this solution under pulsed and low energetic radiation fields will also be investigated. The detector in this study consists of an organic scintillator cast in a cylindrical shape and embedding a Gadolinium-Aluminium-Gallium-Garnet (GAGG) crystal in the form of a rectangular prism. The compound pulses from this detector are read by a single photomultiplier tube and processed digitally. Preliminary measurements have been carried out with an 18 mm diameter $\times$ 20 mm height existing prototype. Pulse shape discrimination results in excellent separation of the light signals from each material. The analysis shows that materials with comparable light yields work best together. The organic scintillator is produced and cast in-house. This enables adjustments to its properties to suit particular needs such as tissue equivalence or appropriate light yield. Simulations using Geant4 toolkit are used to study different detector geometries before manufacturing and experimental tests. These indicate that the ratio of energy deposition in the different materials varies over two orders of magnitude from 10 keV to 100 keV incident photon energy. This provides a highly sensitive measure to calculate the two operational quantities, whose ratio is also very dynamic in this energy range. Measurement results of the dosimetric quantities with an actual detector will be presented during the conference. It will be discussed under which circumstances such a detector can meet the requirements of the national metrology institute of Germany, Physikalisch-Technische Bundesanstalt Braunschweig (PTB).

#10 - Current Trends in Development of Radiation Detectors / 121

#10-121 A neutron-sensitive detector based on 3D-printed scintillators and a fast optical camera.

Author: Adam Barr[1]

Co-authors: Cinzia Da Via [2]; John Allison [1]; Michael Taylor [1]; Mosst Tasnim Binte Shawkat [1]; Stephen Watts [1]

[1] *University of Manchester*

[2] *The University of Manchester, UK*

Corresponding Author: adam.barr@manchester.ac.uk

In this presentation, we will outline the development of a neutron-sensitive scintillator produced through 3D-printing and its integration into a detector using a high-speed optical camera. The scintillator was produced using the Fused-Deposition Modelling (FDM) method of 3D-printing, whereby a thin plastic filament is heated and extruded to create layers of an object. Two methods for creating scintillating filaments are explored. The first used an organic scintillator based on polystyrene. The polystyrene was doped with PTP and POPOP to give visible scintillation, biphenyl to give appropriate mechanical properties for FDM printing and 6LiF for neutron sensitivity. The quantities of these additives were tested, with the greatest light emission found at 2% PTP, 0.05% POPOP and 0.1% 6Li by weight. The second method to be explored will use perovskite crystals in an inert plastic binder; in this case, the transparent plastic PETG, commonly used in 3D-printing. Crystals of (PEA)2PbBr4:Li and CsPbBr3 are to be synthesized and combined with the PETG to produce a filament, along with 6Li to enhance neutron sensitivity. Each of these filament types was used to 3D-print scintillators, the design of which was optimized using MCMC simulations with Geant4. These were used to test the response of the material to neutron emission in a variety of configurations, allowing for the selection of designs with the highest light yield. The Geant4 simulations were also used to calibrate the detector, determining the expected neutron spectrum. The final 3D-printed scintillators were imaged with a TimePix3-based camera, offering high spatial (16 µm) and temporal (1.56 ns) resolution. This was combined with an image intensifier, offering single-photon capability. This setup enabled the development of a neutron-discrimination algorithm that leverages the capabilities of the TimePix3 camera's capabilities. Finally, the detector was tested by exposing the scintillators to electrons, gamma-rays and thermal neutrons, with the results being compared to Geant4 simulations, allowing for a determination of the most effective filament. This work supports the construction of a cheap, easily customisable radiation detector that can be tailored to suit any required application, offering significant promise for flexible, cost-effective radiation sensing.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 122

#6-122 Single-plane readout Compton camera - laboratory performance evaluation

Author: Om Prakash Dash[1]

Co-authors: Damir Bosnar [1]; Mihael Makek [1]; Tomislav Bokulić [1]

[1] *University of Zagreb Faculty of Science, Department of Physics*

Corresponding Author: ompd@phy.hr

In the evolving landscape of radiation imaging for applications in astrophysics, medical imaging, and homeland security, the Compton gamma camera has proven to be a highly advantageous and versatile tool for imaging and localizing gamma radiation sources. Compton cameras take advantage of Compton scattering kinematics to reconstruct the direction of the incoming gamma rays and hence to localize the source. The scintillator-based Compton gamma cameras, read out by silicon photomultipliers, offer a compromise between angular resolution, efficiency and compactness, which are crucial to build lightweight and portable devices. Most scintillator-based Compton gamma cameras comprise at least two separate readout planes, necessary to accurately determine the locations of the scattering and of the absorption of an incoming gamma ray. We developed a novel single-plane Compton gamma camera, based on segmented scintillators read out only on a single side by silicon photomultipliers. The detector features an 8x8 matrix, where each element consists of two 3x3x3 mm^3 GAGG:Ce scintillator crystals optically coupled on both sides of a 3x3x20 mm^3 plexiglass light guide, forming two separate but optically coupled layers of crystals. The front layer functions as the scatterer and the back layer as the absorber, while both are read-out by a single SiPM array placed on the back of the matrix. This novel configuration reduces the number of read-out channels by half compared to dual-plane readout, maintaining compactness and portability. We performed in-depth laboratory characterization of our novel Compton gamma camera, by measuring its energy resolution and angular resolution across a range of gamma energies, including 511 keV and 662 keV, and by imaging radioactive sources at different positions within the field-of-view. In addition to measurements, we performed GEANT4 simulations to help us identify the noise sources, attributed to specific light interactions, aiding in refining the dataset for improved image reconstruction fidelity. The camera's energy resolution measured at 662 keV, is 8.9 ± 1.9% for the front layer and 10.8 ± 1.6% for the back layer. In the preliminary imaging tests with Cs-137 or Na-22 source placed 100 mm in front of the module, we clearly reconstructed the source image, with angular resolution measure of 14.0° (FWHM) for 662 keV and 14.2° (FWHM) for 511 keV gammas, respectively. We will also compare reconstructed images obtained using Simple Back Projection and Maximum Likelihood Expectation Maximization algorithms, demonstrating sensitivity for imaging off-axis sources within the field of view. This study underscores the capability of the novel Single-plane readout Compton camera to image gamma sources, with promising applications as a compact device in environmental gamma-ray detection and homeland security monitoring.

#07 - Decommissioning, Dismantling and Remote Handling / 123

#7-123 Determination of Absolute Activities and Neutron Fluence Rates Using a Coincidence Method

Author: Shokhrukh Mirzo Bakhodirov[None]

Co-authors: Anja Seifert [1]; Dirk Döhler [2]; Pia Kahle [1]; Thomas Kormoll [1]

[1] *Technische Universität Dresden*

[2] *TU Dresden*

Corresponding Author: shokhrukh_mirzo.bakhodirov@mailbox.tu-dresden.de

This work focuses on determining the fluence rate of a moderated (α, n) neutron source, a key parameter required for assessing the activation levels in metal and concrete samples. Activation studies are an important tool for nuclear decommissioning. By activating material samples in controlled conditions in a known neutron fluence rate, the expected activity in decommissioning can be estimated. The fluence rate is determined by an absolute measurement of the accumulated activity of neutron-activated reference samples with a well known composition and a cross section using a $\beta\gamma$ coincidence setup. Accumulated activity determination requires both single β - and γ - detection, as well as coincidence data. A main advantage of this technique is that the resulting measurement is mostly independent of individual detector efficiencies. The current setup uses three detector combinations, consisting of three γ (High Purity Germanium (HPGe), 2×2 inch cylindrical cerium bromide ($CeBr_3$), and 3×3 inch cylindrical sodium iodide (NaI) scintillators) and two β detectors (a sample-enclosing and a 1 mm thick cylindrical plastic scintillators), paired with a multichannel data acquisition system, separately recording hits in the β - and γ - channels including their timestamps. Coincidences are extracted in the offline analysis from the stored data. Having non- and coincident data in one dataset reduces the impact of certain corrections, e.g. dead time. Additionally, Monte Carlo techniques were implemented to assess γ - interactions in the β - detector and to account for finite energy resolution in γ - detectors. Samples, including aluminum (^{27}Al), gold (^{197}Au), silver (^{107}Ag and ^{109}Ag), Vanadium (^{51}V) and sodium chloride (NaCl) were activated. Calculated thermal fluence rates from different samples agree within uncertainties, with an average fluence rate of $(2.11 \pm 0.09) \times 10^5$ cm^{-2} s^{-1} (uncertainty is given with a coverage factor of 2, that is the true value is within 95 % probability within this interval). Reaction products from (n, p) and (n, 2n) reactions induced by fast neutrons are also detected. Their fraction is, however, too low to be exploited quantitatively.

#09 - Environmental and Medical Sciences / 124

#9-124 MACACO III+ characterization and tests with I-131

Authors: Luis Barrientos[1]; Karol Brzezinski[1]; José V. Casaña[1]; Fernando Hueso-González[2]; Javier Pérez-Curbelo[1]; Ana Ros García[3]; Rita Viegas[1]; Gabriela Llosá[4]

[1] *IFIC (CSIC-UV)*

[2] *IFIC (CSIC - UV)*

[3] *IFIC (UV-CSIC)*

[4] *Instituto de Física Corpuscular (IFIC- CSIC/U. Valencia)*

Corresponding Author: gabriela.llosa@ific.uv.es

The IRIS group of IFIC has developed a Compton camera for medical applications made of LaBr3 crystals coupled to SiPM arrays. The prototype MACACO III consists of three detector planes, each one composed of a LaBr3 monolithic crystal coupled to a 64-channel SiPM array. The readout is carried out with the ASIC VATA64HDR16 operated with the AliVATA readout board. Besides the tests conducted with this system for protontherapy treatment monitoring, it has been tested also for radionuclide therapy with very promising results. Test were carried out in La Fe Hospital (Valencia, Spain) filling 3D printed Derenzo-like phantoms with 18F-FDG and I-131. Rods of 6, 5 and 4 mm diameter were visible in the images. Tests were also carried out with patients undergoing treatment with 131I-NaI. Metastatic lesions imaged with MACACO III could be correlated with the images obtained by the gamma camera Bright View XCT from Philips. The system was also employed for imaging Ac-255. Alpha emitters are promising in radionuclide treatmens due to the high LET and short range of alpha particles, sparing healthy tissue. However, the activities are much lower than those employed with beta emitters and they usually emit high energy photons, thus making imaging with gamma cameras very challenging. The system was able to image the 6 mm diameter rods of the phantom filled with Ac-225, in collaboration with the hospital Léon Bérard of Lyon, but with a long acquisition time. The measurements with MACACO III evinced the need of enhancing the system efficiency. Thus, a new system has been assembled, MACACO III+ with four detectors in the second detection plane, with a total amount of 256 channels. The system has been characterized in the laboratory to equalize the response of the data acquired in the four different possible combination of detectors, with photons interacting in the detector that composes the first plane and in any of the four detectors of the second plane. The image reconstruction software has been modified accordingly. The system was able to image arrays of Na-22 souces separated 8, 6 and 4 mm. The prototype MACACO III+ has also been tested in La Fe hospital with a 3D printed thyroid-shaped phantom filled with I-131. Tests were done filling the phantom uniformly and also with hot spots in a warm background in a 10:1 activity ratio. In addition, at CICbiomaGUNE, tests with a mouse phantom and living mice have been carried out. The resulting images have been compared with those obtained with a gamma-cube SPECT system from Molecubes. In the mouse phantom, four organs were filled: brain, heart, kidneys and bladder. Two living mice were tested, showing uptake in the thyroid and bladder. Data were taken for 120 minutes with the SPECT system and for 30 minutes with MACACO III+, yielding similar images. The system efficiency is being further enhanced by assembling another detector plane composed of four individual detectors. Detector characterization as well as simulations to estimate the response of a system composed of two four-detector planes (MACACO IV) are ongoing. The data analysis is also being improved through the use of neural networks for event selection.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 125

#6-125 Fast Neutron Multiplicity Counting for High Mass Plutonium Assay

Author: Xiaobo Liu[1]

Co-author: Jiansheng Li [1]

[1] *Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics*

Corresponding Author: 13881190590@163.com

The fast neutron multiplicity counting apparatus was consisted of 26 pieces of liquid scintillator detectors in two rings layout, multi-board 500M 14bit digitizers based on PXIe platform, and mechanical mounting structure. Each detector's light output was calibration with Cs-137 source. The apparatus efficiency for fast neutron detection calibrated with Cf-252 source was about 0.17, and the cavity was 35 cm in radius and 70 cm in height for holding the standard container. The fast neutron multiplicity counting experiment was performed with a serial of different high mass plutonium metals ranging from 0.5 kg to 4 kg and the mass assay results were constant with the sample nominal value. This research progress is showing a promising application for nuclear material assay and verification.

#04 - Research Reactors and Particle Accelerators / 126

#4-126 3D flux measurements of pile-oscillation: initial results of the BLOOM program in CROCUS using the SAFFRON detector array

Author: Thomas Ligonnet[1]

Co-authors: Andreas Pautz [2]; Daniel Clément [3]; Nicolas Weiss [3]; Oskari Pakari [3]; Vincent Lamirand [2]; alexis Dupont Bembinoff [3]

[1] *LRS (EPFL)*

[2] *Ecole Polytechnique Fédérale de Lausanne*

[3] *EPFL*

Corresponding Author: thomas.ligonnet@epfl.ch

The BLOOM experimental program is an ongoing pile-oscillation program taking place in the CROCUS reactor at EPFL since summer 2024. Pile-oscillations are a type of semi-integral experiment in which a sample is periodically inserted in and extracted from a reactor, inducing a reactivity change. Modern programs, such as BLOOM or the CEA MAESTRO program, go beyond measuring and analysing the changes in reactivity or, more generally, in the global perturbation of the reactor state. Instead, they place additional emphasis on assessing the local effect of the sample on the neutron flux, thereby providing supplementary and complementary information on the sample' s impact. BLOOM is the first pile-oscillation program performed in CROCUS. It was designed as a follow-up to the PETALE program focused on stainless steel nuclear data, using samples directly cut from the spare reflectors of PETALE. Unlike PETALE, which concentrated "only"on the main components of stainless steel –iron, nickel, and chromium –, BLOOM aims at to explore a broader range of samples relevant to the evaluation and validation of stainless steel-related nuclear data. This includes common minor alloy elements and different steel alloys such as molybdenum, titanium, silicium, zinc, stainless steel 316, and inconel-800, but also more exotic alloy element elements such as yttrium, tungsten, and tantalum, totalling 25 different materials and 40 samples. The oscillations are carried out in open-loop, meaning without compensation of the changes in criticality caused by the samples, with the previously qualified POLLEN linear oscillator. The experimental channel used for oscillation has been designed to fit inside one of CROCUS'control rod guide tubes, thus requiring no modifications to the core geometry and enabling easy and rapid sample insertion or removal as it is air filled. In the current setup, it accommodates samples up to 1 cm in diameter. From a neutron flux measurement perspective, BLOOM takes advantage of EPFL's previous developments in miniature neutron detectors. During the oscillations, a comprehensive 3D monitoring of the neutron population is achieved thanks to the SAFFRON detectors array, which comprises 149 fixed detectors distributed throughout the core of CROCUS, along with 11 mobile ones. With a total count rate of 200'000 counts per second per watt, SAFFRON enables both measuring the entire core response to the perturbation and verifying the point kinetics hypothesis. In addition, due to the small size of the detectors, some of the mobile ones are used to instrument the oscillation channel itself: 9 additional miniature detectors are arranged in a ring around the sample at its mid-height irradiation position, thereby capturing the local flux perturbation with exceptional proximity –at only 2 mm from the perturbations. This unprecedent proximity in pile oscillation experiment is coupled to an exceptional sensitivity to the sample, as their small size (sub mm) compared to the sample (i.e., form factor) also maximizes the observed flux variation. These factors result in a high precision estimation of the local flux perturbations, which will be advantageous for the subsequent validation and assimilation efforts. In this contribution, we present the experimental setup, the conducted experiments, the initial experimental results, and a preliminary comparison to their Monte Carlo simulations.

#01 - Fundamental Physics / 127

#1-127 Results of the LEGEND-200 experiment in the search for 0νββ

Author: Carmen Romo Luque[1]

[1] *Los Álamos National Laboratory*

Corresponding Author: carmenromoluque@gmail.com

The LEGEND experiment is looking for the extremely rare neutrinoless double beta decay of ^{76}Ge using isotopically-enriched high-purity germanium (HPGe) detectors. The detection of this process would imply that the neutrino is a Majorana particle and the total lepton number would not be conserved, which could be related to the cosmological asymmetry between matter and antimatter through leptogenesis. The LEGEND technology consists of a core of germanium detectors arranged in vertical strings within a surrounding volume containing 64 m^3 of liquid argon. Scintillation light produced by interactions in the liquid is detected by SiPMs, which are coupled to wavelength-shifting fibers arranged in two barrels. The cryostat is housed within an ultra-pure water tank equipped with PMTs that serve as a shield against external neutrons and gamma radiation and as a Cherenkov detector for muon rejection. This way the experiement is designed to maximize the background rejection. LEGEND is being developed in phases. The first phase, LEGEND-200, has been collecting physics data at Gran Sasso National Laboratory in Italy for more than a year with 140 kg of HPGe detectors. Additional germanium detectors are being installed, and increased exposure is anticipated in the coming months. The collaboration has been focused on analyzing the initial LEGEND-200 data, evaluating sensitivity, and characterizing residual backgrounds. The ultimate goal is the construction of LEGEND-1000, which will operate with 1 ton of germanium detectors and is planned to run for 10 years. In this talk, a detailed overview of the LEGEND-200 experiment and its analysis will be presented. The current observed background levels in the region of interest, the performance of the experiment in terms of background rejection and signal acceptance will be covered. Lastly, an update on the status of the future LEGEND-1000 phase will be provided. This work is supported by the U.S. DOE and the NSF, the LANL, ORNL and LBNL LDRD programs; the European ERC and Horizon programs; the German DFG, BMBF, and MPG; the Italian INFN; the Polish NCN and MNiSW; the Czech MEYS; the Slovak RDA; the Swiss SNF; the UK STFC; the Canadian NSERC and CFI; the LNGS and SURF facilities.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 128

#6-128 Active Fast Neutron Multiplicity Counting with DT Neutron Generator

Author: Xiaobo Liu[1]

Co-author: Jiansheng Li [1]

[1] *Institute of Nuclear Physics and Chemistry, China Academy of Engineering Physics*

Corresponding Author: 13881190590@163.com

The active fast neutron multiplicity counting apparatus was consisted of 26 pieces of liquid scintillator detectors in two rings layout, multi-board 500M14bit digitizers based on PXIe platform, the DT neutron generator which was located on the bottom of detector ring, the shielding cone with a hole for neutron injecting to the sample assay area and mechanical mounting structure. The DT neutron generator was the type of alpha-associated and each neutron injecting into the assay area can be tagged. The alpha signal was used as gating signal when doing active fast neutron multiplicity counting. A preliminary experiment was performed with 10kg HEU metal in standard container for technical verification of this alpha-gating active fast neutron multiplicity counting technology. The experimental results demonstrated this method works well and dramatically reduced the random or non-correlated neutron signal noise when the alpha signal gating was enabled.

#10 - Current Trends in Development of Radiation Detectors / 129

#10-129 Unfolding method based on Artificial Neural Network. Application to a neutron activation detector dedicated to criticity and comparison with Bayesian method and simulation results

Author: Thibaut Vinchon[1]

Co-authors: Francois Trompier [1]; Jeremy Bez [1]; Quentin Ducasse [1]; Rodayna Hmede [1]; Wilfried Monange [1]

[1] *IRSN*

Corresponding Author: quentin.ducasse@irsn.fr

The Laboratory for micro-irradiation, neutron metrology and dosimetry (LMDN) at IRSN is responsible for characterizing various neutrons fields that necessitate the utilization of advanced unfolding techniques. Usually, the LMDN and the laboratory of ionizing Radiation dosimetry (LDRI) use well known unfolding methods among Bayesian inference and GRAVEL algorithm. However, those methods require an initial and arbitrary guess of the spectrum solution, which may significantly impact the unfolding result. To address this bottleneck, we propose with the Neutronic Laboratory (LN) at IRSN, an innovative method for neutron spectrum reconstruction using machine learning techniques trained on a large dataset of spectra built by using a dynamic genetic algorithm and the response function of the studied detector. This genetic algorithm has been developed during the project in order to build a balanced dataset in term of variety. A new convolutional neural network architecture is then employed and is specially adapted for unfolding neutron spectra. This methodology is applied to a neutron activation spectrometer comprising of foils of different materials (the SNAC) with a response function recomputed by the MCNP code using the IRDFF library. This choice was motivated by recent results measured in the AMANDE facility that were in better agreement with this library. For a set of criticity experiments performed at the Silene reactor in Valduc, the different neutron spectra are inferred from the reaction rates measured by the activation of the foils composing the SNAC. These experimental neutron spectra are compared with those resulting from a Bayesian approach or from Monte Carlo simulations of the Silene platform as well as from other reference measurements performed on this platform in the same conditions in terms of screening of the reactor, position of the SNAC and mode of the criticity accident.
The transposability of this approach to other neutron activation detectors needing unfolding is then discussed. We will present at ANIMMA 2025 the methodology, the preliminary results obtained for activation detector measurements performed on the Silene installation in different configuration. A large discussion about generalization of that method will then be presented.

#07 - Decommissioning, Dismantling and Remote Handling / 130

#7-130 Detection of Uranium Contamination by Innovative Non-Destructive Measurements

Author: Francisco Salvador[1]

Co-authors: Thomas Marchais [1]; Bertrand Pérot [1]; Frédéric Morales [1]; Pierre-Guy Allinei [1]; Julien Venara [2]; Marie Cuozzo [2]; Olivier Gueton [3]; Frédéric Mayet [4]

[1] *CEA, DES, IRESNE, DTN, SMTA, Nuclear Measurements Laboratory, 13108 Saint-Paul-lez-Durance, France*

[2] *CEA, DES, ISEC, DPME, SEIP, LNPA, Univ. Montpellier, Marcoule, F-30207 Bagnols-sur-Cèze Cedex, France*

[3] *CEA, DES, IRESNE, Nuclear Technology Department, 13108 Saint-Paul-lez-Durance, France*

[4] *Laboratory of Subatomic Physics and Cosmology, CNRS/IN2P3, Grenoble Alpes University, 38026 Grenoble, France*

Corresponding Author: francisco.salvadorbarba@cea.fr

Dismantling constitutes the final stage in the life cycle of a nuclear facility, and after the removal of components, the decontamination of civil engineering structures (floors and walls) is an important step in view of its final decommissioning. This decontamination process is costly and time-consuming, therefore employing fast, precise, and reliable measurement methods is crucial to identify and characterize the contaminated areas. Cleaning is then restricted to these zones to limit intervention time and expenses, as well as the volume of produced waste and the associated storage costs. After decontamination, very sensitive measurements are also needed to check that the contamination has fallen below the objective residual activity level. In this context, CEA is developing innovative nuclear measurement methods for detecting uranium contaminations. These methods allow for a rapid scanning of UDG uranium enrichment facilities, in Pierrelatte, France, which include several hundred thousand square meters of civil engineering surfaces. However, natural radiations of uranium and thorium radioactive chains, as well as 40K present in concrete floors and walls, constitute a significant background. This makes it challenging to detect residual contamination when aiming for objectives below 1 Bq/cm². To address these challenges, CEA IRESNE in Cadarache and ISEC in Marcoule, develop combined alpha, beta, and gamma measurements. A 1st-level fast detection of the contamination is carried out with alpha and beta ZnS(Ag) and plastic PVT scintillators, respectively, with a 900 cm2 detection area each and measurement times of less than 3 min. This primary detection is then completed by a 2nd-level low-resolution gamma spectrometry measurement using a cluster of 3×3 NaI(Tl) scintillators, each measuring 4”×4”×2”. With a total detection surface similar to alpha and beta scintillators and a longer measurement time, around 15 min, this step confirms the activity level with a smaller uncertainty and provides an estimate of its 235U enrichment. Finally, 3rd-level high-resolution X- and gamma-ray spectrometry with electrically cooled CdTe and HPGe detectors, as well as autoradiography measurements, are also performed on an occasional basis. These measurements require much longer counting times (several hours) and are conducted on smaller detection surfaces. They allow to accurately corroborate the activity of selected contaminated areas estimated by the 1st and 2nd level measurements, and verify the 235U enrichment level estimated with the NaI(Tl) detector. Additionally, they assist in estimating the migration depth of the contamination in concrete and its surface distribution, which is not uniform. All this information helps reduce the uncertainty of the alpha, beta and low-resolution gamma measurements.

#09 - Environmental and Medical Sciences / 131

#9-131 Performance evaluation and comparative analysis of new NM-2023 neutron monitors within the global cosmic ray monitoring network

Author: Michael Aspinall[1]

Co-authors: Carla Andreani [2]; Carlo Cazzaniga [3]; Christopher Frost [3]; Cory Binnersley [4]; Dakalo Mashao [1]; Giovanni Romanelli [2]; James Wild [1]; Lee Packer [5]; Malcolm Joyce [1]; Roberto Senesi [2]; Stephen Croft [1]; Steve Bradnam [5]; Tilly Alton [1]; Tony Turner [5]; Triestino Minniti [2]

[1] *Lancaster University*

[2] *University of Rome Tor Vergata*

[3] *STFC Rutherford Appleton Laboratory*

[4] *Mirion Technologies (Canberra UK) Ltd.*

[5] *United Kingdom Atomic Energy Authority (UKAEA)*

Corresponding Author: m.d.aspinall@lancaster.ac.uk

This paper presents an analysis of initial operational data from three newly developed ground-level neutron monitors, the NM-2023, and compares them with established monitors reporting to the Neutron Monitor Database (NMDB). The NM-2023s are deployed at the Camborne Met Office Observatory in Cornwall, United Kingdom, Lancaster University, United Kingdom, and the University of Rome Tor Vergata, Italy. Neutron monitors operate in a globally distributed network that deduces the primary cosmic ray flux in the upper atmosphere based on variations in cosmic ray and solar energetic particles at the Earth's surface. While most neutron monitors follow the 1964 NM-64 design by Carmichael, the NM-64 is large, costly, and reliant on toxic boron trifluoride gas-filled proportional counter tubes. The NM-64s are configured in 3, 6, 9 or 18 tube configurations. After evaluating various detector options, based on operational experience, experiments and simulations, a new design was conceived which exploits the established supply chain serving nuclear safeguards and security. The new NM-2023 monitors offer similar count rate performance to a 6-NM-64 but features a compact, cost-effective design with a 64% smaller footprint, 80% smaller volume, and 55% less mass. Optimised for helium-3 gas-filled counters and increasing the counter packing density, eliminating the air-void and the lead rings seen in the NM-64 design, resulted in an easier and cheaper design to fabricate. The NM-2023 design was optimised using experimentally validated Monte Carlo simulations. Data from the 4-NM-2023 at Camborne shows similar count rates to a 6-NM-64 at a similar altitude and latitude. The 1-NM-2023 monitors at Lancaster and Rome exhibit proportional performance to one-quarter of a 4-NM-2023. Several months of NM-2023 data are consistent with the NM-64 monitors considered by this study and confirms the NM-2023's promise for more complete time series analysis in future work.

#08 - Severe Accident Monitoring / 132

#8-132 Next-Generation Hydrogen Mitigation Technology for Nuclear Safety

Author: Kévin Touchet[1]

Co-authors: Ayoub Ladaci [1]; Firmin BOURGES [1]; Guy Cheymol [1]

[1] *CEA*

Corresponding Author: kevin.touchet@cea.fr

A Loss of Coolant Accident (LOCA) in a nuclear reactor, where coolant levels drop significantly, can lead to core overheating and hydrogen generation through chemical reactions between the hot zirconium cladding and water. However, LOCA is not the only scenario where hydrogen production becomes a concern. Severe overheating, core melt scenarios, and even the radiolysis of water by intense radiation can also lead to hydrogen buildup within the reactor containment. Rising hydrogen concentrations present a significant explosion risk, as evidenced by historical accidents such as Three Mile Island and Fukushima-Daiichi.

To mitigate these risks, modern reactors are equipped with hydrogen management systems like Passive Autocatalytic Recombiners (PARs) and hydrogen igniters. However, during a reactor accident, hydrogen production can increase rapidly, pushing these devices to their operational limits. Additionally, high temperatures and elevated steam levels can contaminate and reduce their effectiveness. This limitation is particularly concerning in reactor accidents, where hydrogen accumulation can potentially compromise reactor containment.

In this work, we present a highly efficient approach developed at the CEA to improve current hydrogen management systems. This passive technology uses autocatalytic amplification to significantly accelerate the hydrogen recombination process. Advanced materials are also employed to enhance the active surface area, greatly increasing reaction rates and enabling efficient recombination even at low concentrations of hydrogen and oxygen. These materials can withstand high radiation levels and temperatures up to 500 ℃, providing a more robust solution for managing hydrogen-related risks in severe reactor accident scenarios.

#10 - Current Trends in Development of Radiation Detectors / 133

#10-133 MATRIX: GaN diode arrays for proton monitoring and imaging

Author: Nico Brosda[1]

Co-authors: Andreas Wieck [1]; Jean-Yves Duboz [2]; Matilde Siviero [2]; Maxime Hugues [2]; Stéphane Higueret [3]; Thê-Duc Lê [3]

[1] *Lehrstuhl für angewandte Festkörperphysik, Ruhr-Universität Bochum, D-44780 Bochum, Germany*

[2] *Université Côte d'Azur, CNRS, CRHEA, 06560, Valbonne, France*

[3] *Université de Strasbourg, CNRS, IPHC UMR 7178, F-67000 Strasbourg, France*

Corresponding Author: nico.brosda@rub.de

The MATRIX project is pioneering advancements in proton therapy for cancer treatment by developing novel, highly durable detectors that enhance real-time control of irradiation doses, aiming to make treatments faster, more accurate, and reliable. Proton irradiation is one of the most precise cancer therapies available, enabling high-dose tumor targeting while sparing nearby healthy tissue. Currently, high-energy protons (ranging from 65 to 230 MeV) can be detected using various devices, including ionization chambers, scintillators and semiconductor-based detectors. Among these, silicon semiconductor detectors offer high spatial resolution and sensitivity but suffer from rapid degradation under prolonged exposure to high-energy particles, making them unsuitable for long-term monitoring.

To overcome these limitations, the MATRIX team is advancing a breakthrough approach with gallium nitride (GaN) semiconductors, which exhibit approximately ten times greater radiation resistance than traditional silicon. GaN is a robust material widely used in LED technology, making it readily available and cost-effective. This advancement allows for the creation of detector arrays with enhanced longevity and stability. The GaN detector is paired with silicon-based electronics for data acquisition and processing; placed strategically outside the irradiation field to avoid degradation, thus maximizing system durability and performance.

The MATRIX project is producing GaN-based devices with unprecedented capabilities in proton detection, including linear diode arrays of 128 elements and two-dimensional imaging arrays up to 11x11, covering an area of 1 cm^2 with up to 500 µm spatial resolution. This level of resolution and durability surpasses that of any existing detector systems in proton therapy. Thanks to the microelectronics processes, a much higher resolution can be obtained if needed.

To validate the MATRIX-GaN system, a comprehensive experimental characterization of the GaN diode detectors has been undertaken, including extensive testing in research cyclotrons (such as Cyrcé in Strasbourg) and clinical settings (like the CAL Proton Therapy Center in Nice). These experimental results are cross-referenced with Monte Carlo simulations and benchmarked against established Gafchromic detectors. Further simulations using Geant4/GATE tools are being conducted to assess the array's response efficiency relative to various beam characteristics. The MATRIX system has also undergone rigorous live monitoring, imaging, and long-term irradiation tests to ensure sustained performance and reliability.

The MATRIX GaN sensor represents a transformative leap in proton therapy, serving as the core component of a real-time proton monitoring system. Beyond providing precise control over beam parameters and enhancing dose delivery accuracy, it has the potential to significantly improve imaging resolution, aiding in the development of more effective, individualized treatment plans. This advancement not only marks a technical milestone but also reinforces MATRIX's commitment to pioneering safer, more effective cancer therapies.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 134

#6-134 Augmented X-rays: New Functionalities for High energy X-rays Cargo Scanner

Author: Serge Maitrejean[1]

Co-authors: Abdellatif El-Jaafari [2]; Khanh-Hung Tran [1]; Najib Gadi [3]; Thi-Xiu Le [1]

[1] *Smiths Detection France*

[2] *Smiths detection France*

[3] *Smiyhs Detection France*

Corresponding Author: thi-xiu.le@smithsdetection.com

Customs organizations are using since the last 90's high energies X-rays scanners as a routine inspection technic for detecting smuggling or tax fraud in trucks at terrestrial borders or in containers at ports. This technic is actually 2D radioscopy in a range of energy from 3 to 9 MeV of X-rays. The X-rays source is most of the time a linear accelerator while detection is insured by a pixellated column made of thick scintillators coupled with photodiodes. In some case, an average material discrimination information of effective atomic number is obtained by using a dual pulse (3.5 MeV/6 MeV) accelerator and a dual transmission measurement at the two energies.
This technology didn't change a lot and no other imaging functionalities than the 2D image and the discrimination information were carried out since the beginning. Through two H2020 EU projects, C-BORD (GA 653323 –H2020 BES 2014-2015) and ENTRANCE (GA 883424 –H2020 SU SEC 2019), in collaboration with more than fifteen EU partners, including six EU customs organizations, we have developed four totally new imaging functionalities which have been validated by the end-users partners during field tests. These functionalities, under the generic name Augmented X-rays, are based on the use of multi-column detectors (Matrix detector) and are in-depth information, boom movement compensation, wall removal and de-overlapping of material discrimination.
In-depth information is using the slight stereoscopic effect which occurs when scanning at low speed with a matrix detector: each column is providing with an image corresponding to a slightly different angle than the other. Usual stereoscopic methods are insufficient but with energy minimisation technics, we have demonstrated the possibility of extracting a basic depth information. This information allows to determine whether objects in cargo are located on the source side, in the middle of the cargo or on the detectors side. This was completely impossible before with single column of detectors. From end-users point of view, this functionality revealed to be instrumental for a better understanding of the content as well as for speeding up manual checking when the content of a cargo is suspicious.
Boom movement compensation is a method which allows to suppress waves artefact of mobile cargo X-rays scanner. Boom movement artefact occurs when the scan is done with a scanner moving along a steady cargo: oscillations of the boom containing the detectors during the scan are spawning waves on the image. Based on the redundancy of the information given by the different columns and using optical flows algorithmic technics, it has been demonstrated that the amplitude of the boom movement can be estimated for each pixel in the image and therefore can be corrected. In the corrected image, straight edges of objects appear as straight line and not anymore as oscillations, making it more readable for the operators.
Wall removal and de-overlap of material discrimination are two major improvements of material discrimination. As material discrimination, it is based on the used of two spectra of X-rays (typically 6/3.5 MeV, 7/4 MeV or 9/6 MeV). The method relies on the linearisation of the link between transmission measurements and thickness of the materials crossed by X-Rays thanks to a specific calibration process. As it can be done in dual energy medical radioscopy for bone or soft tissues, this new linear representation can provide with an image in which a chosen material is removed. When this material is iron, it removes from the image the wall of the containers and gives a direct view of the organic content, making easier the detection of drugs or explosives smuggling. De-overlapping of material discrimination is based on another property of the linear property and on advanced segmentation process. It allows to subtract, for each object in a cargo, all the other objects which are superimposed to it. It is then possible to get an estimation of the atomic number for each objects instead of an average value on the whole thickness crossed by X-rays.
As it has been demonstrated in the C-BORD and ENTRANCE projects, Augmented X-rays functionalities open a new way for customs organisations in their use of high energy X-rays cargo scanner by making their operation quicker and more efficient. It is newly deployed on the new generation of cargo scanners.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 135

#5-135 Nondestructive volumetric examination of irradiated tristructural isotropic (TRISO) fuels using X-ray computed tomography

Author: William Chuirazzi[1]

Co-authors: John Stempien [1]; Joshua Kane [1]; Rahul Reddy Kancharla [1]; Swapnil Morankar [1]

[1] *Idaho National Laboratory*

Corresponding Author: william.chuirazzi@inl.gov

One promising next-generation fuel form for advanced nuclear reactors is TRISO (tristructural isotropic) fuel, which consists of sub-millimeter-diameter uranium-bearing fuel kernels encapsulated in multiple layers of carbon and ceramic materials. Thousands of these micro-spheres are then dispersed in a carbon or ceramic matrix. The U.S. Department of Energy's (DOE) Advanced Gas Reactor (AGR) program focuses on developing and demonstrating the viability of high-temperature gas-cooled reactors (HTGRs) using TRISO fuel. As part of the assessment of TRISO fuels, post irradiation examination (PIE), is performed to provide information on changes in microstructure, mechanical properties, and potential degradation. X-ray computed tomography is a nondestructive technique that collects a series of two-dimensional radiographs as a function of sample rotation, and mathematically reconstructs them into a three-dimensional dataset that provides volumetric information on the sample's internal features. At Idaho National Laboratory, XCT is performed using a ZEISS Xradia 620 VERSA X-ray Microscope to examine irradiated TRISO particles and AGR compacts with the objective of observing evolution of kernel and layer morphologies, particle sphericity and location in the matrix, and degradation pathways to further inform fuel performance. This 620 VERSA consists of two detection modes, the first employs a solid-state flat panel detector to provide a large field-of-view with relatively coarse spatial resolution (~100 μm/voxel- ~5 μm/voxel), while the second utilizes a series of X-ray scintillators coupled to an optical microscope and a charge-coupled device (CCD) camera to provide a smaller field-of-view but increased spatial resolution (down to ~300 nm/voxel). Quantitative data, including particle layer thicknesses, fission-induced porosity size distribution in the fuel kernels, radiation-induced swelling of the fuel kernels, and kernel sphericity, have all been obtained nondestructively with XCT measurements. Details about custom sample shielding and preparation needed to adequately protect both personnel and electronic laboratory equipment when imaging highly radioactive fuel specimens (the most radioactive to date being 1.2 Sv/hr from ɣ-rays on contact), including radioactive fuels'impact on the imaging detectors, are also featured. Lastly, this discussion concludes with an outlook on future work and how XCT can be used to inform traditional destructive analysis as well as provide inputs and validation for modeling and simulation efforts, ultimately aiding in the reduction of the timeline for commercial implementation of new nuclear concepts.

#04 - Research Reactors and Particle Accelerators / 136

#4-136 Characterization of low output portable neutron generators operated at FNSPE CTU in Prague

Author: Tomas Bily[1]

Co-authors: Ondrej Huml [1]; Ondrej Novak [1]; Pavel Suk [1]; Filip Fejt [1]; Jan Frybort [1]; Zhao-Ming Pan [1]; Jan Rataj [1]

[1] *Czech Technical University in Prague*

Corresponding Author: tomas.bily@fjfi.cvut.cz

Low output portable DD and DT neutron generators are used at Faculty of Nuclear Sciences and Physical Engineering of the Czech Technical University in Prague for variety of research and educational applications. The paper summarizes the acquired experience related to characterisation of these devices (i.e. of the P385 type DD neutron generator and of the MP320 type DT neutron generator both produced by Thermo Fisher Scientific; the former capable of producing up to ca. 7E6 neutrons/s, the latter one up to 1E8 n/s).The neutron generator emission have been determined via activation foil technique for DT tube comparing multiple foil materials; for DD neutron generators, the choice of appropriate foil material is limited due to lower energy of emitted neutrons, thus making the use of 115In(n,n')115m reaction the most promising candidate, although it is typically used for higher neutron output devices. The paper demonstrates its limit when used with the low neutron output device. Also, manganese bath technique, well-know to characterize radionuclide neutron sources, has been applied to determine the total neutron output of DD neutron generator. Further, the pulsed mode operation has been analysed over wide range of frequencies utilizing in-house developed set-up based on RedPitaya Stem-lab. The verification of the set-up for the purpose is provided as well as the discussion of using epithermal (cadmium covered thermal neutron gas-filled detector) and fast neutron detector (of diamond type) for the purpose. Finally, the discussion is provided on measurement of neutron output dependence on operational parameters, as well as on self-activation of the devices and characteristic X-ray produced during their operation.

#04 - Research Reactors and Particle Accelerators / 137

#4-137 Subcritical Neutron and Gamma Noise Measurements at the Seven Percent Critical Experiment (7uPCX)

Author: Cole Kostelac[1]

Co-authors: George McKenzie [1]; Jesson Hutchinson [1]; Nicholas Whitman [1]; Robert Weldon [1]

[1] *Los Alamos National Laboratory*

Corresponding Author: kostelac@lanl.gov

As part of a collaborative international effort organized by Lawrence Livermore National Laboratory (LLNL), with key participants from L'Institut de radioprotection et de sûreté nucléaire (IRSN), Los Alamos National Laboratory (LANL), and Sandia National Laboratories (SNL), a series of high-multiplication subcritical neutron and gamma noise measurements were planned and executed. The primary aim of this research was to advance detector technology, assess the validity of gamma noise for subcriticality measurements, and nuclear criticality safety, focusing on collecting list-mode or time-series data from various reactor configurations with multiplication values ranging from 10 to 310. This comprehensive dataset enabled a detailed comparative analysis of multiple detector systems and the results of both neutron and gamma noise measurements.

Sandia National Laboratories' Seven Percent Critical Experiment (7uPCX) was chosen as the optimal facility for these measurements, due to its well-established benchmarks, capabilities, and suitability for this type of research. This zero-power reactor is a light water moderated and reflected array of 6.9% enriched uranium dioxide fuel rods that was designed to investigate the physics of light water nuclear reactor systems at varying fuel-to-moderator ratios

In this study, we specifically explore the use of in-core gamma noise measurements in combination with ex-core neutron noise measurements to assess the subcriticality of the reactor system as well as other kinetic parameters. Four small-volume EJ-309 liquid scintillators were placed within the reactor core, while four portable neutron multiplicity counters, developed by LANL and referred to as MC-15s, were positioned outside the reactor tank. These MC-15 counters consist of 15 He-3 tubes embedded in polyethylene and are equipped with on-board list-mode data acquisition and analysis capabilities, which allowed for detailed real-time data processing.

The results of this experiment show excellent agreement between the two detector systems, despite their differing positions—one in the core and one outside the reactor tank—and the fact that the two systems were measuring different types of particles. This outcome further validates the usage of prompt gammas to infer reactivity, and the reliability of the detection methods employed. Furthermore, the findings show the potential of combining neutron and gamma noise analysis as a powerful tool for subcriticality assessment in nuclear systems.

#10 - Current Trends in Development of Radiation Detectors / 139

#10-139 Fast Simulation of Gamma Ray Logs for Uranium Exploration in Roll-Front Deposits

Author: Arthur Pellet-Rostaing[1]

Co-authors: Bertrand Pérot [2]; Thomas Marchais [1]; Nadia Pérot [3]; Hervé Toubon [4]; Youcef Bensedik [4]; Sebastien Hocquet [4]; Christophe Pouet [5]; Mitra Fouladirad [6]

[1] *CEA/DES/IRESNE/DTN/SMTA/LMN*

[2] *CEA DES IRESNE*

[3] *CEA/DES/IRESNE/DER/SESI/LEMS*

[4] *Orano Mining*

[5] *Aix Marseille Université, CNRS, Centrale Méditerranée, I2M*

[6] *Aix Marseille Université, CNRS, Centrale Méditerranée, M2P2*

Corresponding Author: arthur.pellet-rostaing@cea.fr

Orano Mining is evaluating the potential of the CeBr3 spectrometric gamma ray logging probe developed by Advanced Logic Technology (ALT) for estimating uranium concentration in roll-front deposits, where decay chain disequilibrium disrupts its relationship with gamma total count rate. The Nuclear Measurement Laboratory of CEA IRESNE, in Cadarache, France, is working on automatic prediction algorithms capable of fully exploiting the shape of the recorded gamma spectra. However, the current number of logged wells is insufficient to properly train and evaluate such algorithms. This calls for the creation of a database of simulated gamma logs, using the Monte Carlo N-Particle (MCNP) transport code. Until now, we have carried out analog simulations of single CeBr3 spectroscopic logging probe measurements, with a detector response provided by MCNP pulse-height (F8) tally. However, several requirements makes building the database with this approach impractical. First, each individual simulation is time-consuming since a good statistics is needed in every energy bin. Secondly, actual borehole measurements are conducted every 10 centimeters over several meters, making the number of probe vertical locations to simulate considerable. Thirdly, we need to model a wide range of stratified geological profiles to maximize the diversity of the training samples. Given this explosive computational cost, designing a more efficient yet sufficiently accurate simulation procedure is crucial. We propose a two-step method, where the flux reaching the probe surface and the detector response to this flux are simulated separately. The bulk of simulation time reduction is achieved in the first step. Two options are available to perform fast probe surface flux estimation. The first hinges on the point-detector (F5) tally, which provides a semi-deterministic estimate of the flux at a point. The variance reduction brought by this tally accelerates the completion of each individual simulation. Furthermore, its pointwise nature allows leveraging the fact that we model measurements taken at close successive vertical locations. Several point detector tallies can effortlessly be arranged along the vertical path of the probe, thereby providing flux estimation at multiple locations simultaneously. Modeling the probe surface as a point might be too much of a simplification however, raising concern about potentially significant bias in the point-detector tally. This motivates the investigation of a variant of the first step based on the surface flux (F2) tally. Although using this tally does not address the first driver of high simulation time (achieving good statistics), it still allows taking advantage of the spatial contiguity of probe locations during logging. Since probe surfaces overlap along its vertical trajectory, it is redundant to estimate the flux on each of them independently. By stacking 10-centimeter high cylindrical surface flux tallies all along this path and later merging their output appropriately, it is possible to get the probe surface flux at multiple locations in one shot. We assess the accuracy of the two variants of our two-step method by comparing the resulting spectra with reference spectra yielded by the original analog approach. The comparison is performed on an initial dataset of simulated single-point measurements in homogenous wells, with varying geological and drilling parameters to ensure the validity of the comparison across a broad range of situations. We use the results of the comparison to develop a post-simulation correction method that models bias as a function of energy, for each variant of the two-step approach. Finally, we evaluate the corrected two-step approach on an actual gamma ray log acquired in a uranium in-situ recovery (ISR) mine.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 140

#5-140 Reactor power monitoring for advanced reactors

Author: Pattrick Calderoni[1]

Co-authors: Ahmad Al Rashdan [2]; Anthony Birri [3]; Anthony Crawford [2]; Callie Goetz [3]; Dianne Ezell [3]; Haoyu Wang [4]; Kevin Tsai [2]; Richard Vilim [4]; Roberto Ponciroli [4]

[1] *INL*

[2] *Idaho National Laboratory*

[3] *Oak Ridge National Laboratory*

[4] *Argonne National Laboratory*

Corresponding Author: pattrick.calderoni@inl.gov

The renewed interest in nuclear power as clean energy source is fueled by the development of a new generation of advanced reactor concepts focused on compact and modular designs. These small modular reactors (20 to 300 MWe) and microreactors (1 to 20 MWe) are designed to enable flexibility and scalability for deployment, which increases their marketability while maintaining the promise of enhanced safety common to larger advanced reactor concepts. Additionally, depending on the application, extended operations with minimal maintenance, a higher level of autonomy and transportability are desired. These requirements present new challenges to the design of instrumentation and control systems, particularly so for the essential function of reactor power monitoring and control.

The US Department of Energy, Advanced Sensor and Instrumentation program addresses many of these new challenges by performing research activities for the development of instrumentation and monitoring processes that support advanced reactors operation. Performance improvement with respect to commercial technology used in the current fleet also include extended temperature range and the need for discrimination of neutron energy, which are shared with other advanced reactor concepts. However, size constraint, autonomous operation and remote deployment must also be taken into consideration for compact and modular designs. This work reports on outcomes of research activities on the development of in-core, high temperature neutron flux sensors, their spectral calibration with metrology processes based on dosimetry and their integration with commercial ex-core detectors as part of power reconstruction methods for reactor control. Results are collected from demonstration experiments in several Universities research reactors (the Ohio State University Research Reactor, the Texas A&M Testing, Research, Isotopes, General Atomics Reactor and Purdue University Reactor One) and the Microreactor Automatic Control System at the Idaho National Laboratory.

The following topics will be discussed in detail:

• Assessment of the performance of self-powered neutron detectors at temperatures up to 850 C and development of related neutron energy spectrum unfolding methods.

• Development of physics-based models for self-powered neutron detectors and the assessment of their impact on reactor power synthesis.

• Development of a data-driven approach for reconstructing core power distribution using ex-core sensors.

• Demonstrate spectral calibration and power reconstruction methods using the non-nuclear prototype of the MARVEL microreactor.

#04 - Research Reactors and Particle Accelerators / 142

#4-142 Measurement of the Thermal Neutron Fluence Rate in the Instrument Thimble 11 Position in the Advanced Test Reactor Critical

Author: Dani Ottaway[1]

Co-authors: Kelly McCary [1]; Michael Reichenberger [1]

[1] *Idaho National Laboratory*

Corresponding Author: kelly.mccary@inl.gov

The Advanced Test Reactor is a highly versatile, pressurized, light water cooled, beryllium moderated test reactor with a nominal power capacity of 250 Megawatts (thermal). Its unique core design utilizes a serpentine clover leaf of 40 fuel elements to create 9 different flux traps. The Advanced Test Reactor Critical is a full-scale replica of the Advanced Test Reactor core but in a pool in lieu of a pressure vessel and usually operates at a power level near 600 Watts. The Advanced Test Reactor Critical is primarily utilized for physics, instrument, and experiment testing prior to being irradiated in the Advanced Test Reactor. Test impacts on core power distribution in the Advanced Test Reactor Critical are utilized to indicate how an experiment will perform during the full irradiation in the Advanced Test Reactor. The cores were designed with space to accommodate 12, dry, in-pile tubes located outside the main reactor tank that are used as instrument thimbles. Eight instrument thimble tubes have been installed in the Advanced Test Reactor Critical, 6 of which hold instrumentation that is essential to operation. Two instrument thimbles are held in reserve if one of main thimbles is compromised. Instrument Thimbles 6 and 11 are often unused and could be made available to researchers and programs during irradiations. Measurements of the neutron fluence rate in Instrument Thimble 11 in the Advanced Test Reactor Critical will be used to assess the position for nuclear instrumentation development, research, and testing. Gold and indium foils, and pure cobalt, nickel, silver and gold wires have been irradiated and measured. These combined experiments established the processes needed to execute experiments in the instrument thimbles, as well as aided in refining the material selections for further dosimetry packages. Fast neutron fluence rates were below the minimum detectable level. The high thermal-neutron ratio in the instrument thimble makes it a good environment to test thermal neutron instrumentation with minimal interference from epithermal and fast neutron interactions. Thermal neutron fluence rates have been calculated using standard methods outlined by the American Society for Testing and Materials International using the measured specific activity of dosimeters after irradiation. Thermal neutron fluence rates between 1.00 x 106 n·cm-2·s-1 and 1.00 x 107 n·cm-2·s-1 have been observed depending on axial dosimeter placement relative to core elevation. It can be difficult, costly and time consuming to get experiments placed into the Advanced Test Reactor. The Advanced Test Reactor Critical can provide a simplified, faster and more affordable way to test new instrumentation, assess design and material performance during irradiation and facilitate further research and development efforts in the nuclear industry.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 143

#5-143 Rising Edge Pulse Shape Discrimination in Ultrathin YAG:Ce Scintillators

Author: Valentin Fondement[1]

Co-authors: Igor Jovanovic [1]; Junwoo Bae ; Leandro Frigerio [1]

[1] *University of Michigan*

Corresponding Author: vfondeme@umich.edu

Detecting and discriminating heavy charged particles from background radiation at high temperatures is of interest for nuclear applications, including basic research in fusion and fission energy, reactor monitoring, fuel reprocessing, and isotope production. We investigated the detection and discrimination between alpha and beta particles compatible with liquid environments, significantly above room temperature (>90°C). Yttrium aluminum garnet doped with cerium (YAG:Ce) is a scintillator that has the advantages of being non-hygroscopic and chemically inert. YAG:Ce has a relatively high light output, about 20 000 photons per MeV of deposited electron energy. Its emission spectrum peaks at 525 nm, which matches the transmission spectrum of the electrolyte solution where it is intended to operate in our application. By using an ultrathin (30 µm) crystal, sensitivity to gamma rays and X-rays can be minimized, such that charged particles can be detected with high specificity. In the experiment, we used a CAEN DT5730S digitizer to record detailed waveforms from YAG:Ce exposed to various radiation sources. Pulse shape discrimination (PSD) capabilities of YAG:Ce are well-documented using the traditional metric relying on the falling edge of the scintillation time profile. While processing the calibration data acquired with alpha sources (241Am and 210Po) and beta sources (90Sr and 204Tl), we observed significant differences in the rising edge of scintillation pulses. This dependence of rise time on the charged particle stopping power could lead to improvements in particle identification. Additionally, preliminary measurements suggest a sensitivity of the time profile of scintillation emission to the energy deposited by beta particles. A mechanism for this may be the significant difference in average stopping power for beta particles of different energy in thin crystals, but more detailed measurements are needed to investigate this effect. Future measurements should also be sensitive to the known dependence of the scintillation spectrum of Ce:YAG on the charged particle stopping power.
Depending on the particle identification performance obtained from the combination of the rising and falling edges of the scintillation time profile, it may be possible to implement YAG:Ce as a "monolithic phoswich"detector. Other potential applications of such a detector include decommissioning of nuclear power plants and gas enrichment plants, online monitoring of the uranium content extracted from the ground, and space exploration.

This research was performed with support from ARPA-E under cooperative agreement DE-AR0001734.

#07 - Decommissioning, Dismantling and Remote Handling / 145

#7-145 Bayesian Optimization for real-time γ-localization measurements with robotic platforms

Author: Ioannis Tsitsimpelis[1]

Co-authors: Andrew West [2]; Kartikey Mathur [1]; Anže Jazbec [3]; Luka Snoj [3]; Shengshu Liu [2]; Andrew Kennedy [1]; Francis R. Livens [4]; Barry Lennox [2]; C. Taylor [1]; Malcolm J. Joyce [1]

[1] *School of Engineering, Lancaster University, United Kingdom*

[2] *School of Electrical and Electronic Engineering, University of Manchester, United Kingdom*

[3] *Reactor Physics Department, Jožef Stefan Institute, Slovenia*

[4] *Research Centre for Radwaste Disposal, Williamson Research Centre and Dalton Nuclear Institute, University of Manchester, United Kingdom*

Corresponding Author: i.tsitsimpelis3@lancaster.ac.uk

An adaptive measurement approach driven by Bayesian Optimization is described for applications where remote radiation measurements made with robots are constrained by stringent upper thresholds on the mass and power payload of the necessary instrumentation, as well by the time window within which measurements must be made, ultimately affecting their quality and maximum area coverage. The radiation detection hardware comprises a miniature cylindrical cerium bromide (CeBr3) detector, encased in an aluminium body with a photomultiplier tube (PMT) and a High Voltage (HV) module; and a RedPitaya Field Programmable Gate Array (FPGA, STEMlab 125-14) board configured as a Multi-channel Analyzer (MCA). The detector is coupled to a lightweight porous collimator, and mounted to a gimbal to enable energy-resolved angular scans in azimuth and incline. The apparatus is controlled via the Robot Operating System 2 (ROS2) middleware. Gaussian Process regression and a variety of kernel functions are employed to model the underlying radiation distribution of the measurement space, with the selection of subsequent measurement points driven by the model's uncertainty estimates. The algorithm initializes by requesting measurements at the boundaries of the measurement space and a user-specified number of measurement locations within the boundaries (using stratified random sampling). Subsequent measurement locations are requested dynamically based on the Expected Improvement acquisition function with an exploration bonus term, while the measurement stopping conditions are based on the model's stability and the predicted uncertainties. This method allows reconstructing complex response curves while minimizing the number of required measurements. Its benchmark performance is compared against both non-time and time constrained, yet high spatial granularity laboratory datasets, under different geometric scenarios and radiation fields (serving as look-up tables of simulated measurements in the algorithm). Furthermore, its in-situ deployment performance at the TRIGA research reactor facility of the Jožef Stefan Institute is evaluated and utilised to fine-tune the method's capability in real-world environments (through the addition of bespoke and composite kernels). This approach constitutes a systematic and efficient strategy for radiation data acquisition that maximizes information gain in resource constrained robotic missions, and can be used both as a stand-alone characterisation activity and embedded to robotic navigation algorithms.

#09 - Environmental and Medical Sciences / 146

#9-146 Prompt-gamma impact localization in pure Cherenkov crystals for proton range verification

Authors: Leonor Rebolo[1]; Ryan Heller[2]; Michael Backfish[3]; Pedro Correia[4]; Ana Luisa Silva[4]; Eric Prebys[5]; Sara St. James[6]; Joshua Cates[2]; Gerard Arino Estrada[7]

[1] *University of Aveiro / University of California Davis*

[2] *Lawrence Berkeley National Laboratory*

[3] *Crocker Nuclear Laboratory*

[4] *University of Aveiro*

[5] *University of California Davis / Crocker Nuclear Laboratory*

[6] *Huntsman Cancer Institute - University of Utah*

[7] *IFAE-BIST / UC Davis*

Corresponding Author: garino@ucdavis.edu

Motivation: We present a gamma detector concept for high-energy prompt-gammas based exclusively on Cherenkov light for use in proton range verification (PRV) in proton and heavy ion therapy. The radiation backgrounds in these environments are very harsh, with a high abundance of 511 keV photons due to positron activation, fast neutrons, and pulsed sequences that lead to high emission rates of the prompt-gammas themselves. We propose to use exclusively the Cherenkov light emitted in a pure Cherenkov emitter, PbF_2 in this case. The motivation is three-fold: First, the detected Cherenkov intensity by 511 keV gammas in PbF_2 is less than 5 photons, therefore the detector is practically insensitive to this source of background by just placing the threshold above this level. Second, Cherenkov emission happens within picoseconds, therefore the main contribution to dead time is on the photodetector and electronics, thus allowing for much higher count rates than any scintillation material. And third, the production costs of PbF_2 are low compared to other gamma-detector materials, thus allowing to produce a medium-size imager cost-effectively.

Methods: The detector consisted of a monolithic 25×25×10~mm^3 PbF_2 crystal coupled to a 8x8 SiPM array readout in a column/row fashion. We evaluated its performance in the laboratory with a ^{228}Th gamma source, which has an energy line at 2.6 MeV, and a slit of 1 mm width. The detector was mounted on a 2D translation stage, and we acquired 35 positions in 1 mm increments along one dimension. The range was intentionally set well outside the size of the detector (25 mm). Figure 1 shows the acquisition setup. Each event consisted of 16 waveforms: 8 rows and 8 columns recorded with a record length of 1 μs and a sampling rate of 1 Gs/s. The signals from the 8 columns were multiplexed, combined into a single one and used to trigger the events. Two algorithms were used to determine the impact point for each event: the center of gravity (CoG) and rise to the power (RTP). CoG is a linear combination among of the rows (or channels) with a weighted probability that is linearly proportional to the fraction of signal detected in that element. The RTP follows a similar principle but the probability for each element is obtained by elevating the fraction of the signal detected to the k exponent. Two k values were evaluated: k=2 and k=3.

Results: A histogram was obtained for each position and algorithm for one of the detector axes. Figure 2 shows three representative distributions for 8 mm, 18 mm and 28 mm using the CoG algorithm. For each of such histograms, a gaussian git was applied and the center of the gaussian and the full width at half maximum (FWHM) were recorded as figures of merit. Figure 3 shows the position scan for the CoG, RTP(k=2) and RTP (k=3). The active area of the detector was identified between positions 5 and 29, which matches the width of the crystal (25 mm). A linear fit was applied to this range and the FWHM/slope of the fit was taken as the figure of merit for the resolution. The average of the resolutions across this range was 7.4 mm, 5.6 mm, and 4.8 mm for the CoG, RTP(k=2) and RTP (k=3) algorithms, respectively.

Discussion and Future Work: In the first part of the evaluation of this detector concept, we conclude the Cherenkov light generated by prompt-gammas of up to 2.6 MeV can be used to extract position information of the impact point of the prompt-gamma within the crystal. Specifically, we tested the spatial resolution along one dimension. We found significant sources of background, such

as the plateaus outside the gaussian distributions in Figure 2. We are currently studying their nature and strategies to remove them.

The resolution values obtained are 2 to 3 times greater than one would desire for the PRV application. Dealing with such background might help reduce that value. Very preliminary data acquired at the proton cyclotron at Davis hinted resolutions below 3 mm. An improvement of resolution in the beam line compared to the benchtop setup could be explained by the greater energy of prompt gammas (up to 6.1 MeV vs up to 2.6 MeV), which leads to a greater Cherenkov light generation and thus significantly higher signal-to-noise ratio when detecting such prompt-gammas.

We continue to study the behavior of this detector concept using the same ^{228}Th gamma source under different setup configurations (SiPM bias, trigger strategy, detector segmentation) and event reconstruction strategies. Moreover, by the time of the meeting, we expect to present data equivalent to Figures 2 and 3 acquired at the cyclotron at Davis, with a proton anergy of 67.5 MeV and beam currents of several nA.

#04 - Research Reactors and Particle Accelerators / 147

#4-147 Phenomenological Analysis on 1,000℃ Material Irradiation Testing in HANARO using the Instrumented-Capsule(15M-03K)

Author: Jong Woo Kim[1]

Co-authors: June Sic Park [1]; Seong Woo Yang [1]; Kee Nam Choo [1]

[1] *Korea Atomic Energy Research Institute*

Corresponding Author: jw@kaeri.re.kr

The HANARO research reactor has conducted various irradiation tests to meet the demands from academia, industry, and research institutions for nuclear materials and fuel testing. Recently, as research on next-generation nuclear systems designed for high-temperature operations—such as Molten Salt Reactors (MSR), Sodium-cooled Fast Reactors (SFR), and Very High-Temperature Reactors (VHTR)—has advanced, the demand for irradiation testing of nuclear materials for these systems has also grown. This study covers the process, results, and main phenomena observed during an irradiation test in HANARO, reaching temperatures up to 1,000℃. For the HANARO irradiation test, the instrumentation-capsule (15M-03K) was designed and fabricated based on thermal and neutron transport calculations. The capsule contain tensile specimens and features a double thermal media structure (Ti/Fe). The fabricated capsule underwent a series of out-of-pile tests, including loading/unloading tests, hydraulic testing, and high-temperature integrity verification. The first irradiation test in HANARO was conducted in December 2018, during the 99th cycle of operation at 30 MW, where the maximum specimen temperature recorded was 791℃. Although an unexpected reactor shutdown led to the early termination of the test, the feasibility of high-temperature irradiation testing using HANARO was confirmed. The second irradiation test resumed in 2024, achieving two primary objectives. First, the test successfully achieved a maximum specimen temperature of 1,000℃ during the 108-1 cycle of operation at 27 MW, fulfilling the final goal for this phase of high-temperature irradiation test technology development. Second, the specimen temperature was stably maintained at 800℃, 850℃, and 900℃ during the 108-3 cycle (27 MW), 109-1 cycle (27 MW), and 109-2 cycle (25 MW), respectively, thereby providing valuable data on the stability of high-temperature irradiation test technology. During irradiation testing, two main phenomena were observed. First, after reaching the target temperature of 1,000℃, a subsequent temperature drop occurred, attributed to potential reactions between specimen impurities and the internal thermal media. Second, temperature variations were observed at different thermocouple positions in response to changes in the reactor control rod positions. This effect was analyzed through nuclear calculations to determine the impact of temperature variation at each thermocouple location.

#07 - Decommissioning, Dismantling and Remote Handling / 148

#7-148 Shield-free and lightweight alpha-beta radiation dust monitor for high-dose environments

Author: Youichi Tsubota[1]

Co-authors: Hugo Laffolley [1]; Tomoya Tsuji [1]; Fumiya Honda [1]; Naoki Sagawa [1]; Shinji Tokonami [2]; Masahiro Suzuki [1]

[1] *Japan Atomic Energy Agency*

[2] *Hirosaki University*

Corresponding Author: tsubota.yoichi@jaea.go.jp

The Fukushima Daiichi Nuclear Power Station (FDNPS) has experienced extensive contamination due to core meltdowns and subsequent hydrogen explosions. This has resulted in elevated levels of α and β surface contamination within the reactor buildings. The ambient radiation dose rate inside these buildings is also high, ranging from several tens to 100 mSv/h. Investigations of the primary containment vessel (PCV) and decontamination efforts within the reactor buildings are ongoing, requiring strict exposure controls. Numerous zones within the reactor buildings pose significant decontamination challenges, such as rubble on the floor and piping on the ceiling. Consequently, it is crucial to monitor and control radioactive dust that may be resuspended from the surface contamination in these areas. As the extraction of fuel debris from the PCV is just starting, considerations for mechanical cutting tools and laser cutting methods for future full-scale retrieval are underway. These processes must account for the generation of dust containing actinides and fission products, which may leak out from the PCV due to unknown openings or instability in negative pressure management. Additionally, since the air ventilation system is not functioning within the reactor buildings, radioactive dust will remain airborne for a long time, posing a risk of secondary contamination and potential leakage outside the building. Therefore, in situations where the dispersal and resuspension of radioactive dust are anticipated, it is necessary to contain dust in the vicinity of the source and to monitor it effectively to minimize secondary contamination risks. The optimal approach for monitoring radioactive dust involves placing measurement equipment in close proximity to the work area, enabling *in-situ* collection and radioactivity measurement. However, because high ambient radiation necessitates significant lead shielding to minimize spurious counting due to γ-rays, the devices typically weigh several tens of kilograms, complicating transportation and deployment. To address this challenge, we are developing a dust monitoring system that can be mounted on a robot, enabling quick deployment near dust sources in various work environments. Our solution incorporates a two-dimensional radiation imaging sensor (MiniPIX, ADVACAM s.r.o.) for radiation measurement, utilizing machine learning (ML) post-processing techniques to analyze radiation signals collected from dust collection filter paper. The sensor generates energy-proportional grayscale images where each event triggers a cluster of pixels through direct interaction or energy transfer between neighboring pixels. The ML software identifies higher energy transfers from α-ray interactions and then extracts shape parameters for each event. In this context, γ-rays produce small pixel clusters due to their quasi-linear paths through the semiconductor matrix, while β-rays follow a winding path through the detector due to Coulomb interaction, resulting in snake-like pixel clusters. By employing multiple feature values for image classification, we can effectively mitigate the impact of ambient radiation without the need for lead shielding. In the irradiation tests using a ^{137}Cs source, we successfully measured and distinguished α from β radiation sources that simulated filter paper, even in conditions of γ-ray irradiation at approximately 10 mSv/h. The integration of these sensors and radiation discrimination technologies with dust collection and control devices has resulted in a prototype measuring unit that weighs approximately 3 kg. This unit was installed on a four-legged walking robot and is intended for effective measurement in contaminated environments.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 149

#5-149 Evaluation of high temperature tolerance of BGaN detectors for in-core nuclear instrumentation systems for high temperature gas-cooled reactors

Author: Takayuki Nakano[1]

Co-authors: Kohei Hayashi [1]; Tatsuhiro Sakurai [1]; Yoku Inoue [1]; Toru Aoki [1]

[1] *Shizuoka University*

Corresponding Author: nakano.takayuki@shizuoka.ac.jp

The High Temperature Gas-cooled Reactors (HTGRs), which have been developed as a next-generation nuclear reactor, have an in-core temperature of about 900 oC. The ultra-high temperatures make it difficult to use conventional nuclear instrumentation systems, and novel neutron detectors with high temperature tolerance are expected to be realized. Neutron detection using BGaN semiconductor is a novel neutron detection system expected to allow the development of neutron-imaging sensors. BGaN is a mixed alloy semiconductor of BN and GaN and is a group-III nitride semiconductor, which is a kind of wide bandgap semiconductor. Wide-bandgap semiconductor detectors using SiC and diamond have been developed as radiation detectors for operation in high-temperature conditions. However, the high temperature tolerance of BGaN has not been evaluated, and the investigation of its radiation detection characteristics at high temperatures is require. In this report, the characteristics of the BGaN detector at high temperature conditions were evaluated as a verification of the in-core nuclear instrumentation system for HTGR.

The BGaN films were grown on an α-Al2O3 substrate using metal-organic vapor phase epitaxy (MOVPE). After growing pin BGaN structure, pin-type BGaN diodes were fabricated by using each device process. The electrical and radiation detection characteristics of the pin-type BGaN and GaN detectors were evaluated. For electrical characteristics, CV measurement, and IV measurement were performed from room temperature to 600 oC. 241Am α-particle source was used for radiation detection and measurement. The distance between the α-particle source and the detector was set for the incident energy to be 2.3 MeV. The α-particles energy spectra were measured from room temperature to 450 oC.

Group-III nitride semiconductor detectors were used to measure the energy spectrum of 241Am α-particles at each temperature. In case of a pin-BGaN diode detector, the α-particles spectrum was detected at 300 oC, but it was difficult to discriminate the detection signal from the noise signal at 350 oC. In case of a pin-GaN detector, the α-particles spectra were detected under 450 oC, which is the measurement limit for this experimental setup. Furthermore, X-ray diffraction crystallinity evaluation has confirmed that BGaN crystals are less crystalline than GaN crystals. These results indicated that crystal defects in BGaN are one cause of the device's performance temperature being reduced. It is indicated that the pin-GaN detector is operated at even higher temperatures.

The temperature dependence of the peak position for each detector was evaluated. In the case of a BGaN detector, the peak position was confirmed to be constant at over 100 oC. In the case of a GaN detector, a low channel shift at the peak position was confirmed over 100 oC. These results indicate that the depletion layer thickness, the sensitive layer, decreased with rising temperature. It was confirmed that reducing the thick sensitive layer has a more significant effect on high-temperature tolerance.

Furthermore, the temperature dependence of the leakage current of each detector was evaluated. The leakage current of the BGaN detector was confirmed to be larger than that of the GaN detector. The increase in leakage current is due to crystal defects. The significant degradation of breakdown voltage at high temperatures with large initial leakage currents suggests that crystal quality affects high-temperature tolerance.

In this study, the high-temperature tolerance of BGaN detectors was evaluated as an in-core nuclear instrumentation system for HTGR. The results of the initial study indicate that a BGaN detector, which is a group-III nitride semiconductor, has the potential to detect neutrons at high temperatures. Further development of the BGaN detector is expected to lead to nuclear instrumentation technology that can be used for HTGR.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 151

#5-151 Evaluation of Starlite Survey Meter Against Spectroscopy Measurements in CANDU Neutron Fields

Author: Jovica Atanackovic[1]

Co-authors: Andrei Hanu [2]; Anthony Waker [3]; Craige Boyd [3]

[1] *Ontario Power Generation*

[2] *Bruce Power*

[3] *Ontario Tech University*

Corresponding Author: jovica.atanackovic@opg.com

Raylab Starlite neutron survey meter was evaluated in CANDU neutron fields, against Nested Neutron Spectrometer (NNS) and a current official CANDU neutron survey meter Canberra's NP-100, also known as Snoopy. The NNS is a cylindrical neutron spectrometer, based on Bonner sphere principles, while Starlite is a novice, multidetector, light neutron survey meter, designed and manufactured by Italian company Raylab. The purpose of the spectroscopy measurements was to assess neutron energy spectra in terms of energy dependent neutron fluence rates and to evaluate integrated operational dosimetric quantity, neutron ambient dose equivalent (H*(10)). Furthermore, quantities such as neutron fluence averaged mean energy and neutron ambient dose equivalent averaged mean energy were calculated for each measured spectrum, indicating the softness of CANDU neutron fields. Starlite neutron survey meter has unique polyhedral shape and contains 30 thermal neutron solid state detectors, arranged symmetrically along 3 orthogonal axes and surrounded by a diamond shape high density polyethylene (HDPE) moderator. The polyhedral shape of the HDPE moderator provides an isotropic response, while reducing the overall body weight. The Starlite meter is relatively light, weighing only 4 kg, which gives a great advantage when performing daily surveys inside nuclear power plants. The measurements took place at the Bruce Power CANDU plant, around primary heat transport pumps (PHT) and in front of the entrance door of the D2O moderator rooms. In total, 14 spectroscopy measurements at different positions were taken, using two NNS units, while ambient dose equivalent surveys of all those positions were conducted using Starlite and Snoopy meters. In addition, measurements were taken at the Bruce Power Am/Be calibration track room, exposing Starlite to a very energetic neutron fields from Am/Be source. The fluence averaged mean energies of CANDU fields were found to be between 70 and 200 keV, while the average energy of neutrons from Am/Be source is around 4.5 MeV. In all these fields, Starlite performed very well, when compared to NNS and Snoopy, having the ambient dose equivalent response close to 1. Both Starlite's superior performance and its good ergonomic properties qualify this instrument to be a new official neutron survey meter for CANDU power reactor fleet.

#04 - Research Reactors and Particle Accelerators / 153

#4-153 Development of a High-Resolution Neutron Detector for the SAM Instrument at ILL Using 6Li Scintillator Glass and SiPM Technology

Authors: Emilio Ruiz[1]; Paolo Mutti[2]

Co-author: Patrick Van Esch [1]

[1] *Institut Laue Langevin*

[2] *Institut Laue-Langevin*

Corresponding Authors: mutti@ill.fr, vanesch@ill.fr

Small Angle Neutron Scattering (SANS) is an essential analytical technique in material science, enabling the study of structural and dynamic properties at the nanoscale.

The SAM instrument at the Institut Laue-Langevin (ILL) in Grenoble, France, is a pinhole geometry instrument for SANS experiments, aiming at the determination of the structure of large-scale objects (1 –100 nm) in various systems of physical interest. These span the fields of biophysics, magnetism, material science, soft matter & superconductivity.

This paper presents the development of a neutron detector of 50 x 50 mm2 using a lithium-6 (6Li) scintillator glass (Epic Crystals) coupled with silicon photomultiplier (SiPM) arrays technology (ONSEMI), alongside with a high-performance readout system specifically designed for the readout of SiPM based on Weeroc's Radioroc 2 ASIC.

The detector configuration focus on the properties of the 6Li scintillator glass SG101 doped with Ce3+/Ce4+. The control of the ratio between 6Li and Ce is critical to achieving the correct light emission, optical decay, and optical transmission characteristics. The 6Li glass is chosen for its high sensitivity to thermal neutrons due to the interaction of 6Li with neutrons, producing ionization and in result, the emission of photons. The scintillation light is then collected by four silicon SiPMs ARRAYJ–30035–64P provided by ONSEMI, which are optimized for high photon detection efficiency, compactness, and fast response times.

The performance goal of the SAM's SiPM based neutron detector is achieving a spatial resolution of 1 mm and a timing resolution of 100 ns. The spatial resolution is enhanced by carefully optimizing the thickness and composition of the 6Li scintillator glass to maximize light output while minimizing light scattering, ensuring precise location tracking of neutron interactions. Each SiPM array offers reliable, high photon detection efficiency, low noise, and a pixel pitch of 3.36 mm. To achieve the targeted spatial resolution of 1 mm with the SiPM array pixel pitch, a centroid algorithm is applied to interpolate neutron event positions and improve spatial accuracy. This technique enables precise neutron localization, ensuring that SAM achieves the spatial resolution necessary for detailed structural studies.

The timing resolution is another critical requirement, with the detector design. This is facilitated by the integration of Weeroc's Radioroc 2 front–end ASIC, a dedicated application-specific integrated circuit developed for high-speed readout in photon-detection applications. Radioroc 2 is engineered for high-speed operation with low noise and a large dynamic range, supporting accurate and efficient processing of scintillation signals generated by each neutron interaction.

The detector will be placed in the direct neutron beam path after the sample, where a flux of approximately 10000 neutrons per second per cm^2 is expected. Given this exposure, radiation damage of the detector components, especially the sensitive SiPMs and ASIC, is of significant concern.

The electronics are positioned outside the direct beam path to minimize radiation damage, preserving long-term performance and reliability. In addition to the performance metrics, we discuss considerations regarding the thermal stability, radiation tolerance, and scalability of the detector components, which are essential for reliable, long-term operation of the SAM beamline.

The detector prototype has been tested under laboratory conditions to evaluate its spatial and timing resolution, efficiency, and neutron-gamma discrimination capabilities. Preliminary results demonstrate that the 6Li scintillator and SiPM-based configuration provides spatial precision down to 1

mm, achieving the critical resolution needed for detailed neutron scattering analysis on the SAM instrument. Timing resolution tests also show promising performance, approaching the 100 ns target, with further optimizations planned to reach this target under operational conditions at ILL.

#10 - Current Trends in Development of Radiation Detectors / 154

#10-154 Optimization of a Convolutional Neural Network-Based Pulse Shape Analysis Model for Gamma/Neutron Signal Discrimination

Author: Sunlee SHIN[1]

Co-authors: Hayoung SIM [1]; Hee SEO [1]

[1] *Jeonbuk National University*

Corresponding Author: sunlee@jbnu.ac.kr

Reliable discrimination between gamma-ray and neutron signals is essential for accurate neutron detection when using an organic scintillation detector. Pulse Shape Discrimination (PSD) techniques are methods of distinguishing between gamma ray and neutron pulse signals by analysing the variations in pulse formation and decay patterns associated with each type of radiation. The Charge Comparison Method (CCM) is widely used in PSD and classifies signals based on the total charge over a specified interval. However, CCM has limitations in low energy regions where accurate signal differentiation becomes difficult, reducing measurement reliability. To address this limitation, we propose a PSD approach that uses a Convolutional Neural Network (CNN)-based model to improve the discrimination of gamma-ray and neutron signals. The CNN model, selected for its ability to extract complex features through supervised learning, is implemented in a PSD process comprising five key steps: (1) data acquisition, (2) preprocessing, (3) model design, (4) training and validation, and (5) performance evaluation. This study uses gamma-ray and neutron data obtained with a pixelated EJ-276 detector exposed to Californium-252. Four pre-processing steps were applied to optimize CNN performance in the PSD: (1) signal magnitude normalization, (2) noise reduction using a moving average filter, (3) extraction of distinct gamma-ray and neutron signal intervals, and (4) labelling of gamma-ray and neutron signals as '1' and '0', respectively. Then, a CNN layer was designed and optimized for effective PSD. The layers of the CNN-based model used convolution, maximum pooling, dropout, flattening, and dense layers to effectively extract key features from the input signal. The optimized model showed high predictive performance, achieving 99.9% accuracy, 99.9% precision and 99.9% recall. In conclusion, this study has developed a CNN-based PSD model that effectively discriminates between gamma-ray and neutron signals in the low energy regions, overcoming the associated limitations of the charge comparison method. The optimized convolutional neural network model exhibits high accuracy and precision, indicating its potential to overcome the limitations of conventional techniques and improve the accuracy of neutron measurements by effectively classifying gamma-ray and neutron signals.

#07 - Decommissioning, Dismantling and Remote Handling / 155

#7-155 Development of Scaling Factor Method for Activated Metal Wastes of Medical Cyclotrons: Correlation Analysis of Key and DTM Nuclides

Author: Yeijin Bang[1]

Co-authors: Byeonghyeon Park [2]; Hee Seo [1]; Sangmin Lee [2]

[1] *Jeonbuk National University*

[2] *Korea Institute of Nuclear Safety*

Corresponding Author: yjbang@jbnu.ac.kr

Medical cyclotrons, which are used to produce radiopharmaceuticals such as 18F-FDG for cancer diagnosis, cause the activation of the medical cyclotron itself and surrounding structures through various nuclear reactions. In 2024, approximately 30% of the cyclotrons are effectively out of operation in the Republic of Korea. Therefore, there is a growing need for indirect assessment methods to reduce the costs and time involved in analyzing the activities of radionuclides when cyclotrons are decommissioned or dismantled. In the case of radioactive waste from nuclear power plants, the scaling factor method is used for waste management based on technical documents from international standards such as the International Organization for Standardization (ISO) and the International Atomic Energy Agency (IAEA). It is used to indirectly estimate the activities of difficult-to-measure (DTM) nuclides, such as alpha- and beta-emitting nuclides, based on the activities of key nuclides, such as gamma-emitting nuclides, by using correlation between nuclides. However, the applicability of the scaling factor methods to activated metal waste from medical cyclotrons has not been fully verified and implemented. In this study, activation scenarios were constructed on the basis of technical documents for nuclear power plants and CERN technical documents for high-energy accelerators in order to verify the applicability of the scaling factor method for medical cyclotrons. These activation scenarios take into account the operating conditions of medical cyclotrons in Korea. The Monte Carlo simulation code, PHITS-DCHAIN, was used to evaluate the activation of materials. PHITS is a particle transport code and DCHAIN is a radiation analysis code, using default libraries for cross-section data. Based on the results for various activation scenarios, SPSS software was used to conduct scatter plots and Pearson correlation analyses to determine the relationship between key nuclides and DTM nuclides. The target foil, known as Havar foil, used to maintain a vacuum in the target system, was chosen for evaluation. The target foil is located close to the target material and thus activated by both primary protons and secondary neutrons, and the H218O liquid target was considered, as it is the most commonly used target material. The activation scenarios included variations in beam energy, material composition, irradiation time, and decay time. These variables were integrated into discrete scenarios. The target foil's irradiation conditions, which is proton beam energy and current, were fixed at 16.5 MeV and 50 μA, respectively, matching the specifications of the GE PETtrace 880. Material composition was determined based on XRF analysis and literature review: cobalt (40–44.2%), chromium (18.8–22.2%), iron (18–19%), nickel (11.6–13%), manganese (1.3–2%), molybdenum (1.4–2%), tungsten (0.9–3%), carbon (0–2%), and beryllium (0–0.3%). The irradiation and decay times were chosen to 2–30 months and 1–6 years, respectively. These parameters were chosen to reflect the replacement cycle of target foils and typical domestic operation intervals for medical cyclotrons. In the absence of complete historical data on cyclotron operation, decay time was uniformly assumed across the irradiation duration to conservatively approximate the actual operational history with irradiation patterns. Ultimately, 40 variable combinations were randomly selected to produce 40 activation scenarios. Simulation results identified a range of nuclides, including 3H, 14C, 54Mn, 55Fe, 58Co, 60Co, 59Ni, and 63Ni, which exceeded clearance levels. 54Mn, 56Co, 58Co, and 60Co are considered as key nuclides, while 55Fe and 63Ni are considered as DTM nuclides. Scatter plots and Pearson correlation analyses indicated a generally linear relationship between most key and DTM nuclides, except for 56Co, which emerged as an outlier. The correlation coefficients for 54Mn, 58Co, and 60Co were above 0.80 with DTM nuclides, suggesting that these nuclides are reliable for estimating the activities of DTM nuclides. However, 56Co showed weak and statistically insignificant correlations, with correlation coefficients of -0.09 and -0.07, respectively. The low correlation of 56Co with DTM nuclides was attributed to differences in production mechanisms and its shorter half-life, making it unsuitable as a key nuclide. Nuclear reactions of the type (p, n) or (n, p) are responsible for the production of 58Co and 60Co from natural occurring isotopes of iron or manganese. Unlike other nuclides, 56Co production involves intermediate nickel isotopes. Future work will include verifying the nuclide correlations observed in this study through the analysis of actual irradiated samples from decommissioned cyclotrons. Through regression analysis, specific

scaling factors for the target foil will be derived, further refining the indirect estimation method. This verification step will help assess the reliability and accuracy of the scaling factor method for medical cyclotrons, supporting sustainable and cost-effective decommissioning practices.

#11 - Education, Training and Outreach / 156

#11-156 A strong link between education and research thanks to experiments conducted on calorimetric sensors under irradiation conditions in nuclear research reactors.

Authors: Christelle Reynard-Carette[1]; Adrien Volte[1]; Michel Carette[1]; Abdallah Lyoussi[2]; Rafal Prokopowicz[3]; Vladimir Radulović[4]; Luka Snoj[5]; Gordon Kohse[6]

[1] *Aix-Marseille University*

[2] *CEA Cadarache*

[3] *NCBJ*

[4] *Jožef Stefan Institute*

[5] *Jozef Stefan Institute*

[6] *MIT Nuclear Reactor Laboratory*

Corresponding Author: christelle.carette@univ-amu.fr

With the revival of the nuclear sector, recruitment needs for the next ten years are very high in France (over 10,000 employees per year). Several initiatives at different academic levels are conducted to promote the nuclear field, its various applications and its shortage occupations, to attract students, graduates and attracted already-employed professionals to this field, and to provide them strong skills by means of training leading to a diploma or continuing job education or professional development.

In this context, the Filière Instrumentation (Instrumentation unit) of the Physics Department of the Sciences Faculty at Aix-Marseille University (AMU) has expanded its actions over the past 6 years in nuclear instrumentation, measurement and metrology.
Its increased involvement is achieved in partnership with various key players (in France such as CEA, INSTN, EDF, "Campus des Métiers et des Qualifications d'Excellence –Industrie du Futur Sud –Région PACA"and "Université des Métiers du Nucléaire", CAPGEMINI···and abroad such as the Nuclear Reactor Laboratory of the MIT, Jožef Sfefan Institute, ENEEP, CNESTEN, SCK-CEN, ···) and with a strong link between education and research. This latter is realized within the framework of a joint laboratory (LIMMEX: Laboratory of Instrumentation and Measurement Methods under EXtreme conditions) created in 2009 by between AMU (IM2NP institute) and the CEA (IRESNE institute) in collaboration with the Jules Horowitz Reactor program.

Actions are carried out in particular at master level. For instance, the actions are:
- International mobility corresponding to intense short study-periods abroad on the thematic "Nuclear Instrumentation and measurement in research reactors"for work-study students (apprentices) in the first year of the Master Instrumentation, Measurement, Metrology (MOBIL-APP program, created in 2018),
- A second year of master dedicated to Instrumentation and Measurement Science for major Nuclear research facilities (IMSci-Nu master track, created in 2022 with ISFIN institute) with new courses and research projects linked to work performed on sensors designed, studied and qualified in the LIMMEX laboratory,
- A 1-week winter school on instrumentation and measurement for fission and fusion facilities (research reactors, tokamaks, SMRs/AMRs, NPPs) including lectures, a visit to the CEA, poster session (IMSci-Nu School, created in 2022),
- Different types of scholarships to attract new talents such as study grants, internship scholarships and mobility scholarships (founded by EDF, A*MIDEX foundation through the its TIGER project, ISFIN institute and the "Excellence Nucléaire Sud"project and more recently by "Université des Métiers du Nucléaire"),
- A new 28-hour course on the fundamentals of engineering for nuclear power plants in operation (Master 3I, funded by the OPPEN project, currently being set up).

The presentation will deal with the strong link between education and research.
The presentation will show how experimental work carried out during irradiation campaigns in nuclear research reactors is used to introduce students to the nuclear sector and train them in the field.

The presentation will start with examples of irradiation campaigns realized to characterize calorimetric sensor prototypes developed in the LIMMEX laboratory for the online measurement of the nuclear heating rate in in-core experimental channels of research reactors (MARIA, JSI TRIGA, MITR reactors). The research work is based on a comprehensive approach from out-of-flux laboratory conditions to nuclear irradiation conditions by coupling experimental studies, 1-D calculations and 3-D simulations.
Then the presentation will detail the different activities for students using these irradiation campaigns from their preparation to their realization and the associated comprehensive approach: specific lectures and seminars, student research project topics, escape games, hands-on activities on a new bench, on computers and on a new virtual reality room, study-cases in real-time during irradiation campaign, …
The presentation will conclude to the transformative effects on the pedagogical approach and the student interest.

#10 - Current Trends in Development of Radiation Detectors / 157

#10-157 Development and Performance Analysis of a Portable 4H-SiC-Based Spectrometer for Radiation Monitoring in Harsh Conditions

Author: Andrea Chierici[1]

Co-authors: Riccardo Ciolini [2]; Francesco d'Errico [1]; Gianpaolo Roina [2]

[1] *Università di Pisa*

[2] *University of Pisa*

Corresponding Author: gianpaolo.roina@phd.unipi.it

Silicon carbide or SiC is widely used in various semiconductor devices, including PIN diodes, MOSFETs, and MEMS, due to its wide bandgap, large critical electric field, high thermal conductivity, high electron saturation velocity, chemical inertness, and radiation resistance. Among SiC polymorphs, 4H-SiC, with a bandgap of 3.26 eV, is the most studied and preferred for power electronics, bipolar devices, and quantum sensing due to its high isotropic charge carrier mobility. Recently, 4H-SiC has gained considerable attention as a promising material for radiation detection in extreme environments characterized by high temperatures and high radiation fluences. Despite previous challenges related to charge carrier trapping and recombination, as well as compensation effects from electrically active deep-level defects, advances in high-quality epitaxial 4H-SiC production have led to exceptional detection properties for alpha particles and neutrons. Additionally, promising results have been reported for the detection of low-energy gamma and X-rays. Notably, 4H-SiC detectors have demonstrated remarkable radiation hardness, maintaining functionality even after exposure to neutron fluences up to 1×10^{16} n_eq/cm^2. This resilience is attributed to the material's wide bandgap and high displacement energy, which mitigate radiation-induced defects. Furthermore, 4H-SiC devices exhibit low leakage currents and stable performance at elevated temperatures, making them suitable for applications in nuclear reactors and space missions.
This study presents the design of a versatile, cost-effective, and portable spectrometer for SiC radiation detectors intended for use in extreme environments. The spectrometer was initially characterized for alpha particle detection, leveraging the well-documented detection properties of SiC for such particles. Building on previous research demonstrating the effectiveness of 4H-SiC Schottky diodes with a thin ^{6}LiF converter for neutron detection via the ^{6}Li(n,α) reaction (with a Q-value of 4.78 MeV and a thermal cross-section of 940 barns), preliminary tests were also conducted for thermal neutron detection. These tests aim to evaluate the spectrometer's ability to distinguish neutron-induced reaction signals from gamma radiation background based on pulse height discrimination. The integration of 4H-SiC detectors into portable spectrometers offers a robust solution for radiation monitoring in harsh environments, combining durability, sensitivity, and operational stability.

#04 - Research Reactors and Particle Accelerators / 158

#4-158 Predicting neutron noise detector responses for zero-power Molten Salt Reactor experiments

Author: Oskari Pakari[1]

Co-authors: Julia Świątkowska [1]; Michel Saliba [1]

[1] *EPFL*

Corresponding Author: oskari.pakari@gmail.com

We use Monte Carlo simulations to predict the experimental conditions for neutron noise experiments in Molten Salt Reactors (MSRs). Several MSR designs are in the process of obtaining construction and operation licenses around the world. For example, the Danish company Copenhagen Atomics recently announced a cooperation with the Swiss Paul Scherrer Institute (PSI) to deploy their 100 MW 'onion core'MSR at PSI by 2026. As for conventional reactors, the initial testing of a newly constructed reactor often comprises zero-power tests and criticality experiments. In zero-power environments, neutron noise experiments can be part of the experimental portfolio to provide experimental data on integral kinetic parameters such as the prompt neutron decay constant α, reactivity ρ or the effective delayed neutron fraction β_{eff}. Neutron noise experiments exploit the statistical correlations in neutron detector signals via noise analysis methods, such as the Rossi-α method. By auto-correlating a detector signal in time, one can observe the exponential decay associated with the prompt chain decay, thereby enabling the determination of α via curve fitting. The results are then used for code validation, nuclear data feedback or safety monitoring purposes. For MSRs, the flowing fuel –and the therefore flowing precursors –leads to a unique dynamic behaviour that could be experimentally studied with neutron noise techniques. For example, β_{eff} depends on the fluid velocity: For higher velocities the precursors are swept out of the core and therefore might not contribute to the reactivity, and in many MSR designs β_{eff} therefore goes down with higher flow rate. The validation of this sort of behaviour has yet to be accomplished in experiments, and the prediction of what neutron noise experiments would measure in a zero-power testing environment has hitherto not been performed. In this work, we present simulations using several MSR models (the Molten Salt Reactor Experiment and a Molten Salt Fast Reactor) in OpenMC and Serpent 2 to predict the Rossi-α curves for different operational scenarios. We investigate the effect of flow rate, primary circuit length, and possible detector locations to achieve the desired measurement results with sufficient statistical certainty. Our approach is novel in its use of explicit Monte Carlo modelling for noise experiments in MSRs, as well as in providing early feedback on experimental design and instrumentation needs. Our results indicate that noise experiments in zero-power MSRs are feasible and that noise responses could reveal fuel velocity, recirculation time, and kinetic parameters. We discuss potential challenges in the experimental implementation and required measurement times.

#04 - Research Reactors and Particle Accelerators / 159

#4-159 Direct Observation of Xenon-135 Poisoning in a Zero-Power Reactor via Gamma Spectroscopy

Author: Oskari Pakari[1]

Co-authors: Andrew Lucas [2]; Flynn Darby [2]; Michel Saliba [1]; Sara Pozzi [2]; Vincent Lamirand [3]

[1] *EPFL*

[2] *University of Michigan*

[3] *Ecole Polytechnique Fédérale de Lausanne*

Corresponding Author: oskari.pakari@gmail.com

Xenon-135 (Xe-135) is a high yield fission product with high neutron capture cross section, a commonly encountered reactor reactivity poison. Direct observation of Xe in reactors typically relies on off-gas measurement techniques, which can be challenging or costly to implement and often require high-flux reactors. Gamma spectroscopy of irradiated U or Pu samples provides an alternative method for obtaining fission yields and population estimates. When predicting the Xe populations of a given reactor, we rely on calculations and models to estimate the instantaneous reactivity worth and post-shutdown dynamics of Iodine-135 (I-135) and Xe-135 decay that leads to the so-called 'Xenon pit'. In our work, to achieve a direct estimate of the total Xe-135 population in an operating reactor, we measured the gamma-ray emissions of Xe-135 and I-135 emanating from the CROCUS zero-power reactor using a high-purity germanium detector in an irradiation channel. CROCUS is a uranium fueled, light water moderated, zero-power reactor operated by the Laboratory of Reactor Physics and Systems Behavior at EPFL, Switzerland. Specifically, we placed an Ortec GEM-15180-P detector in the irradiation beam port of CROCUS at roughly 4.3 meters from the core center. We measured the gamma ray spectra using a CAEN DS5730 500 MS/s digitizer to obtain gamma-ray time stamps and pulse integrals for the start-up, at-power operation for 1 hour at 20 W, and subsequent shutdown of the reactor for 100 hours. We show the obtained gamma ray spectra for the different reactor states. At power, the spectrum is dominated by the gamma ray emission from fission and neutron capture in water and aluminum. Following shutdown, the spectrum transforms, displaying a dense set of characteristic line emissions. To observe Xe135, we used its 250 keV emission, whilst for I-135 we observed the 1260 keV emission. We binned the spectra in time for 60-minute intervals to accumulate sufficient counts under the photopeak of interest. The time dependent behavior of the I-135 count rates was then fitted with an exponential decay, while the Xe-135 population used a combined exponential decay with production from I-135 model. The Xe-135 population indeed shows the famous 'Xenon pit'shape, peaking in intensity at roughly 14 hours after shutdown.
We also simulated the experiment using Serpent 2 to obtain the detector efficiency in counts per emission in the fuel - taking into account the fission rate distribution from a k-static calculation. This allowed us to finally estimate the whole-core Xe-135 and I-135 populations for 100 hours after reactor shutdown. Our results are among the only direct measurements of Xe-135 in a nuclear reactor. Given the published IRPhE geometry of CROCUS, this dataset holds significant potential as a validation benchmark for reactor poison prediction models.

#04 - Research Reactors and Particle Accelerators / 160

#4-160 Test of fission chambers at high temperature in the OSU Research Reactor

Authors: Grégoire de Izarra[1]; Kevin Tsai[2]; Loic Barbot[3]

[1] *Commissariat à l'Energie Atomique*

[2] *Idaho National Laboratory*

[3] *CEA/IRESNE/DER/SPESI/LDCI*

Corresponding Author: gregoire.deizarra@cea.fr

Between the 1970s and the late 1980s, the CEA developed several fission chambers operating at high temperature to instrument French sodium-cooled fast reactors (SFR). These developments, carried out in collaboration with the Exosens Company, led to the marketing of ex-core detectors, referenced CFUC, as well as miniature detectors such as referenced CFUE. These developments were put on hold in the late 1990s before being resumed in the 2010s through the ASTRID project. For reactor core monitoring, ex-core fission chambers with 10 decades of neutron flux operational range have been proposed. However, miniature detectors were not targeted. With the renewed interest in SFRs and molten salt reactors thanks to the spread of advanced modular small reactor concepts, development of high-temperature miniature neutron detectors are required.
In this context, two types of miniature high-temperature fission chambers: CFUE43 detectors (dedicated to high temperatures with a diameter of 7 mm), and CF3 detectors (reference detectors for neutron flux monitoring in research reactors at the CEA LDCI lab) were identified for testing. Filling gases are respectively argon and a mixture of argon with 4% nitrogen at 5 bars.
As part of a collaboration between CEA and INL through the US Department of Energy, these two types of detectors have been tested under irradiation at high temperatures in the Ohio State University Research Reactor (OSURR) to check their behaviour at 900 K.
Two CFUE43 and one CF3 were installed in a furnace made of an SiC heating element and silica fibre insulating material. This furnace was settled at the bottom of a dry irradiation channel located in the vicinity of the reactor core. At maximum reactor power, 200 kW, the maximum neutron flux at the irradiation location was 1012 n/s/cm².
Thanks to the tests carried out in the OSURR, it is demonstrated that the CF3 fission chamber operating in pulse mode is a good option for the instrumentation of a high-temperature reactor. Optimisation is underway to be fully operational in such conditions. Mineral cables with magnesia are also being considered for improvement. Future experiments will test the Campbelling mode to determine the measurement range of this high temperature CF3. CFUE43 works well in current mode, but unfortunately the interpretation of the signal is more complicated than in pulse or Campbell mode because there is no gamma compensation.

#09 - Environmental and Medical Sciences / 161

#9-161 Gamma ray monitors for Multimod'Air, a mobile environmental monitoring platform

Author: Olivier Limousin[1]

Co-authors: Christian Colin [2]; Clément Fisher [3]; Martine Mayne [4]; Simon Foucambert [1]; Sébastrien Morilhat [5]; Thierry Hedde [5]

[1] *Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM, 91191 Gif-sur-Yvette, France*

[2] *CEA*

[3] *Université Paris-Saclay, CEA, List, F-91120, Palaiseau, France*

[4] *CEA/IRAMIS/NIMBE*

[5] *Nuclear Technology Department, CEA, DES, IRESNE, Cadarache, 13108 Saint Paul les Durance, France*

Corresponding Author: olimousin@cea.fr

Multimod'Air is a CEA internal project aiming at developing a demonstrator of a mobile platform for environmental measurement in any place of interest from cities, rural or industrial outdoor areas.

The platform comprises a dozen of detectors including gas sensors (NO2, O3, NH3, N3, CL2, Ox, H2S, SO2), fine particle sensors (PM1, PM2.5, PM10) for pollution monitoring, as well as a complete weather station (rain fall intensity, wind speed, atmospheric pressure, relative humidity, temperature, …) and gamma-ray monitors. The platform is engineered to receive any type of additional sensor which can be hot plugged and operated independently and autonomously while their data can be combined for analysis. All sensors are connected via RS485, Ethernet or Lora protocols to a central node computer. Detectors can be deployed up to 20 meters away from their central node offering flexibility to fit any local installation constraints.

The central node computer is equipped with a full custom board based on NXP i.MX8 Cortex A-53 processor units, that processes and combines the data in real time, involving conventional or AI algorithms. The raw data, the preprocessed data and the alerts are sent to a cloud server database accessed from anywhere by authorized users by means of a dedicated GUI application for online monitoring or for further offline finer data analysis, verifications, validations and AI model training aim at data corrections and predictions.

The paper is specifically devoted to the gamma ray detectors for radiation monitoring. Their architecture, real time and offline data analysis process and performance are presented. Two different gamma ray monitors have been developed in the project by a collaborative team involving CEA DRF/Irfu, DRT/List and DES/Iresne: One gamma ray monitor is based on a KROMEK GR1+ (1 cm3 CZT, coplanar grid single channel) coupled to a local ODROID XU4 microcomputer for data acquisition, management and communication. The other sensor is based on Caliste-O detectors (0.4 cm3 CdTe, 256 independent spectrometry channels) initially developed at CEA/Irfu with 3D PLUS for space science and used for gamma ray cameras. The latter is readout by a full custom data acquisition system involving a Zynq SoC, routed to an ODROID XU4 computer as well, for data preprocessing such as energy calibration and histogramming, and data management. While GR1+ detector sends an integrated spectrum every minute, Caliste-O both sends accumulated spectra over all channels every minute and photon event list on demand.
Both detectors are fully autonomous. They can be configured, operated and reset remotely. The different detector geometries are fit into specific 3D printed carriers attached to a common housing enabling a standard detector packaging definition.

Regarding the data analysis, the central node computer collects the gamma ray monitors raw data and runs real time algorithm for data reduction and analysis on the fly: 10-minutes, 1-hour and 1-day accumulated spectra are processed every minute, 10-minutes and hours respectively, to search for possible spectral anomalies with respect to a prerecorded gamma-ray background reference spectrum. In addition to a simple overall-count-rate monitoring, in case of an anomaly detection, the algorithm attempts an isotope identification and reports an alert. An anomaly detection confidence level is provided as well.

Both gamma ray monitors are complementary and may work together or independently. GR1+ is well suited for measurement from 60 to 2000 keV while Caliste-O shows high spectral response from 10 to 900 keV. Both detectors nicely cover the energy range where most of natural radioactivity lines are expected such as Uranium decay chain, Thorium decay chain and Potassium 40.

Currently the detectors are deployed outdoor on two monitoring stations for evaluation in real conditions in Paris (AIRPARIF station) and at CEA LSCE lab station in a suburban area. Thanks to this instrumentation, natural radioactivity is monitored in real time. Detector architecture and performance, as well as data analysis results will be presented, including Radon daily fluctuations measurements, natural radioactivity fluctuations with rain falls, atmospheric muons rate dependency with atmospheric pressure for instance.

#02 - Space Sciences and Technology / 162

#2-162 MC2-1K, a novel 250 µm CdTe based imaging spectrometer for space science

Author: Olivier Limousin[1]

Co-authors: Aline Meuris [1]; David Baudin [2]; Denis Chesnais [3]; François Visticot [1]; Hervé Bervas [2]; Hugo Allaire [4]; Marin Prieur [1]; Mitsunobu Onishi [5]; Olivier Gevin [2]; Samuel Couronné [1]; Shin'ichiro Takeda [4]; Thomas Chaminade [2]; Toshihiko Arai [5]

[1] *Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM, 91191 Gif-sur-Yvette, France*

[2] *CEA, IRFU, Université Paris-Saclay, F-91191 Gif-sur-Yvette, France*

[3] *3D PLUS SA*

[4] *Kavli Institute for the Physics and Mathematics of the Universe (Kavli IPMU, WPI), The University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Chiba 277-8583, Japan*

[5] *iMAGINE-X Inc.*

Corresponding Author: olimousin@cea.fr

Hard X-ray focusing optics technologies for solar physics space missions aiming at direct imaging of solar flares or hard X-ray space astronomy are challenging the development of time-resolved, high spectral and spatial resolution CdTe detectors.

CEA and 3D PLUS, in the frame of ALB3DO laboratory with support of CNES, the French space agency, have initiated the development of an entirely new detector, namely MC2. On the mid-term, the detector will be a scalable, 4-side buttable 3D module including a pixelated CdTe detector with 64x64 pixels, with 250µm pitch. The patterned pixel sensor is flip-chip on top of a mosaic of full custom readout ASIC named IDeF-X D2R2.

In the development path, a preliminary prototype MC2-1K has been constructed and operated successfully. The device consists of a quarter of the MC2 module, i.e. a 32x32 CdTe detector with 250 µm pitch flip chipped on top a unique IDeF-X D2R2 ASIC circuit. The detector is mounted onto a 2D printed circuit board and installed into a vacuum chamber associated to a dedicated readout bench for system studies and performance assessment. A fully energy calibrated spectrum involving most of the 1024 channels has been successfully recorded under illumination of a 241Am source. An energy resolution of 900 eV FWHM at 59.54 keV have been measured.

In this paper, the construction of the detector prototype will be described and first performance results will be demonstrated. Performance limitations will be discussed and future work towards an entire module which will be integrated in 3D will be described.

#10 - Current Trends in Development of Radiation Detectors / 163

#10-163 Reconstruction of Neutron Spectra Using Silicon Carbide Detectors in Monoenergetic Fields with Machine Learning approach

Author: Enrica Belfiore[1]

Co-authors: Mehdi Ben Mosbah [2]; Rodolphe Antoni ; Olivier Llido [3]; Abdallah Lyoussi [1]; Christophe Destouches [3]; Tomas Slavicek [4]; Andrea Šagátová [5]; Jean-Emmanuel Groetz [6]

[1] *CEA Cadarache*

[2] *CEA, DES, IRESNE, Nuclear Measurement Laboratory*

[3] *CEA, DES, IRESNE, DER, Cadarache F-13108, Saint-Paul-Lez-Durance, 13108, France*

[4] *Institute of Experimental and Applied Physics, Czech Technical University in Prague, Husova 240/5, 110 00 Prague, Czech Republic*

[5] *Institute of Nuclear and Physical Engineering, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology, SK- 841 04 Bratislava, Slovak Republic*

[6] *Laboratoire Chrono-Environnment, UMR CNRS 6249, Université de Franche-Comté, 16 route de Gray, 25030 Besancon cedex, France*

Corresponding Author: enrica.belfiore@cea.fr

Recent advancements in machine learning have shown significant
promise in nuclear applications, particularly in optimizing reactor operations, core design, and improving neutron spectroscopy techniques. This study introduces a novel approach that leverages machine learning algorithms to predict neutron spectra based on data obtained from solid-state detectors, with a specific focus on the performance of 4H-Silicon Carbide detectors under various monoenergetic neutron fields. These sensors are considered excellent candidates for fast neutron spectroscopy due to several key properties, such as wide bandgap, high radiation resistance, fast response times and thermal stability.
The experimental measurements were conducted at the Van de Graaff accelerator facility in Prague and at the TOTEM facility in Cadarache. In the first installation, the Silicon Carbide detector was exposed to multiple monoenergetic neutron beams generated via p+T, D+T, and D+D reactions. In the second infrastructure, the detector was subjected to a monoenergetic beam generated by GENIE16 D-T neutron generator. The sensor used in this study has dimensions of 2 mm × 3 mm × 60 μm. These experiments are the result of an international collaboration in the frame of the 'Timepix SiC detector'project under the DANUBE region strategy program. The measurements were post-processed to collect the deposited energy in the detector which is used as input for the machine learning algorithm in order to obtain the reconstruction of neutron spectra. The automated learning spectra prediction is performed considering a training database built with the simulated response of the detector subjected to different synthetic spectra, generated as a combination of different mathematical functions. For the test base, the simulations were performed considering the detector exposed to measured spectra taken from the IAEA Compendium database. Simulations were done using the PHITS code and the machine learning model adopted is Kernel Ridge. Preliminary findings demonstrate that the machine learing-based approach can successfully reconstruct monoenergetic neutron spectra with high accuracy, showcasing its potential for improving fast neutron spectroscopy with semiconductor sensors.
Ongoing research at the IRESNE Institute of CEA Cadarache, precisely in the Department of Nuclear Techniques and Department of Reactor Study, aims to further assess the application of this machine learning technique in complex mixed-field environments, such as reactor pits, to evaluate its feasibility and reliability in real-world nuclear facility conditions. This work underscores the potential of integrating machine learning in nuclear instrumentation and measurement, providing innovative tools for neutron field analysis.

#04 - Research Reactors and Particle Accelerators / 164

#4-164 Computational Evaluation of JSI TRIGA Fuel Burnup Effects on Neutron Activation Dosimetry

Author: Anže Pungerčič[1]

Co-authors: Luka Snoj [1]; Loic Barbot [2]; Christophe Domergue [3]; Hervé Philibert [3]; Vladimir Radulović [1]

[1] *Jozef Stefan Institute*

[2] *CEA/IRESNE/DER/SPESI/LDCI*

[3] *CEA/DES*

Corresponding Author: anze.pungercic@ijs.si

Knowing the neutron fields in irradiation facilities is crucial for experimental research work in nuclear science and technology. Monte Carlo particle transport techniques are becoming the reference in the context of nuclear reactor analysis and are extensively used for detailed computational characteritzation of irraditation facilities, including the determination of neutron energy spectrum. Experimentally, neutron activation dosimetry is one of the main techniques for neutron flux or fluence determination and for neutron spectrum characterization. Main utilized reactions are sensitive either to the thermal and resonance energy ranges (radiative capture reactions –(n,gamma) reactions) and the fast energy range (threshold reactions). In addition, due to development of new reactor technologies, there has been an increasing interest in nuclear reactions which are sensitive specifically to neutrons in the intermediate –epithermal –energy range. In recent years, several experimental campaigns utilizating neutron activation dosimetry have been conducted at the JSI TRIGA Mark II research reactor at the »Jožef Stefan« Institute. In this work the dosimetry reactions, mainly sensitive in the thermal (197Au(n,gamma)198Au, 59Co(n,gamma)60Co) and in the fast region (27Al(n,gamma)24Na) of the neutron spectrum, were analyzed and the effect of neutron spectrum changes was studied. The computational support of dosimetry experiments was performed with Monte Carlo neutron transport code MCNP, the basis of which is a detailed computational model. In the case of JSI TRIGA reactor, such computational model has been developed and upgraded since 2006. The most recent upgrade is the inclusion of nuclide inventory of burned nuclear fuel. Since the reconstruction of the JSI TRIGA in 1991, the same fuel elements has been in use, resulting in accumulation of average burnup of 18 MWd/kg(HM), which is relatively low for typical 19.9 % enriched esearch reactor, however as shown in the results not negligible. Consequently, an investigation of fuel burnup effects on reactor parameter calculations has been performed. The fuel burnup was determined with Serpent-2 Monte Carlo neutron transport and depletion code. From the standpoint of neutron activation dosimentry, the main effects of interest were in the neutron spectrum changes and the integral parameter keff changes due to fuel burnup. The former are important for calculation of reaction rate and the latter for normalization to obtain absolute values. The results indicate a 6 % increase in the thermal peak of the neutron sperctrum in main JSI TRIGA irradiation channels and keff overestimation of 4400 pcm, compared to steady-state calculations using fresh fuel. This paper presents the computational and part of experimental analysis on how the fuel burnup affects the reaction rates of neutron dosimentry reactions sensitive in the thermal and fast part of the spectrum. Fuel burnup effects are evaluated on absolute dosimetry calculations as well as ratios in which reaction rates on a known standard dosimetry reaction 197Au(n,gamma)198Au is used for normalization. The presented work is crucial for the final goal of benchmarking the JSI TRIGA neutron activation dosimetry measurements and for the characterisation of neutron spectra in irradiation facilities.

#04 - Research Reactors and Particle Accelerators / 165

#4-165 A step-by-step approach to validate a new thin-film deposited heating element integrated into a calorimeter from laboratory to irradiation conditions in the JSI TRIGA reactor

Author: Adrien Volte[1]

Co-authors: Vladimir Radulović [2]; Florian Baudry [3]; Alain Giani [3]; Jérémy Rebaud [4]; Michel Carette [4]; Abdallah Lyoussi [5]; Luka Snoj [2]; Jean-Yves Ferrandis [3]; Christelle Reynard-Carette [4]

[1] *Aix-Marseille University*

[2] *Reactor Physics Division, Jožef Stefan Institute, Ljubljana, Slovenia*

[3] *IES, University of Montpellier, CNRS, Montpellier, France*

[4] *Aix Marseille Univ, Université de Toulon, CNRS, IM2NP, Marseille, France*

[5] *CEA/DES/IRESNE/DER, Section of Experimental Physics, Safety Tests and Instrumentation, Cadarache, F-13108, Saint Paul-lez-Durance, France*

Corresponding Author: adrien.volte@univ-amu.fr

The intense mixed neutron and photon fluxes found in nuclear environments, such as research reactors, lead to energy deposition within the material. This energy deposition is called absorbed dose rate or nuclear heating rate in the case of extreme conditions. This latter quantity is a key parameter for the design and interpretation of the experiments, conducted using major facilities such as Material Testing Reactor (MTR), for safety and security reactor operation, optimization of fuel and radioactive waste as well as testing new concepts of reactor.
Due to the aging of the major research facilities, particularly the MTRs, the Jules Horowitz Reactor is currently under construction at the CEA Cadarache center in the south of France. It will produce extreme and harsh conditions: high fast neutron flux of 5.5x1014 n/(cm^2.s) (from 1 MeV) leading to a high accelerated aging (up to 16 dpa/year) and a high absorbed dose rate (up to 20 W/g in aluminum). These unequalled conditions in Europe, launched new collaborative research topics in 2009 between Aix-Marseille University and the CEA thanks to the joint laboratory LIMMEX - Laboratory for Instrumentation and Measurement in Extreme Environments) and its IN-CORE program (Instrumentation for Nuclear Radiations and Calorimetry online in REactor).
One of the objectives is to develop and design innovative sensors and measurement methods dedicated to the on-line nuclear heating rate quantification using non-adiabatic calorimeters. The associated challenge is to increase the measurement range (from very low to high nuclear heating rate values), while working on the miniaturization of the calorimeters, the optimization of the metrological performances (sensitivity, linearity, response time, etc.), the development of new calibration and measurement methods and the measurement of the associated thermal properties as a function of the temperature.
Consequently, a new research program within the framework of the LIMMEX laboratory, called MICRO-CALOR, began in 2020 to design and study miniaturized single-cell calorimeter integrating new thin-film heating element (patented by AMU and the CEA), under laboratory and real conditions.
This paper will present a step-by-step approach to study a new thin-film deposited heating element integrated in a CALORRE single-cell calorimeter. This approach is realized from the design of this thin-film heating element to its characterization under laboratory conditions and under irradiation conditions in the dry Triangular Irradiation Channel (TIC) of the JSI TRIGA reactor.
The first part of the paper will briefly present the CALORRE single-cell calorimeter.
The second part will focus on the new thin-film heating element. This part will describe its design and fabrication achieved using the serigraphy technique. Then, its chemical, dimensional, electrical, and thermal characterizations out-of-calorimeter will be presented. Finally, the metrological characteristics of the calorimeter integrating this new heating element will be detailed in the case of the calorimeter calibration by Joule effect under laboratory conditions (sensitivity, linearity, range, reproducibility, response time, and maximum temperature obtained).
The last part will present the irradiation inside the dry Triangular Irradiation Channel (TIC) of the JSI TRIGA reactor at the median plane of the fuel. Firstly, the JSI TRIGA reactor core conditions and the TIC channel as well as the nuclear-hardened CALORRE integrating the new heating element will be detailed. Secondly, the out-of-flux calibration curves obtained by using this heating element before and after irradiation will be presented to confirm the stability of the sensor. Finally, the qualification and the validation of the new heating element under real conditions and the nuclear heating rate measurement as a function of the reactor power (from 12.5 kW to 250 kW) thanks to

two measurement methods (one based on out-of-flux calibration curves and the other one using the heating element during the reactor operation) will be shown and discussed.

#03 - Fusion Diagnostics and Technology / 166

#3-166 Spectroscopic models for tokamak edge and divertor plasma diagnostics

Author: Joël Rosato[1]

Co-authors: Ibtissem Hannachi ; Mohammed Koubiti ; Roland Stamm ; Yannick Marandet

[1] *Université d'Aix-Marseille*

Corresponding Author: joel.rosato@univ-amu.fr

Passive spectroscopy is used as a non-intrusive tool for the diagnostic of tokamak edge plasmas [1]: an analysis of the shape and the intensity of atomic spectral lines yields spatially resolved values of the plasma parameters (N_e, T_e etc.), provided a suitable model is used. In this work, we report on models and codes that have been developed in our group for the spectroscopic diagnostic of magnetic fusion devices. First, the physical mechanisms underlying the broadening of a spectral line are discussed: they include atomic processes that occur at the place where the light is emitted (Doppler effect, Stark effect etc. [2]) as well as the instrumental broadening inherent to the spectrometer involved in the measurement [3]. Next, following recent works [4] and workshops [5,6], we address the accuracy of models through the setting up of error bars. Several codes that are available in our group will be cross-checked on dedicated benchmark cases, both obtained numerically (through simulations) and from experiments.

[1] B. C. Stratton et al., Special Issue on Plasma Diagnostics for Magnetic Fusion Research –Chapter 5: Passive Spectroscopic Diagnostics for Magnetically Confined Fusion Plasmas, Fusion Sci. Technol. 53, 431 (2008).
[2] H. Griem, Principles of Plasma Spectroscopy (Cambridge University Press, 1997).
[3] J. James, Spectrograph Design Fundamentals (Cambridge University Press, 2007).
[4] J. Rosato, Y. Marandet, and R. Stamm, Quantifying the statistical noise in computer simulations of Stark broadening, J. Quant. Spectrosc. Radiat. Transfer 249, 107002 (2020).
[5] J. Rosato, Report on the third SLSP code comparison workshop, High Energy Density Phys. 22, 60 (2017).
[6] A. Calisti, Review of the 7th Spectral Line Shapes in Plasmas code comparison workshop, Oral presentation at the 20th International Workshop on Radiative Properties of Hot Dense Matter, Paris, France, Nov 18-22, 2024.

#04 - Research Reactors and Particle Accelerators / 167

#4-167 Update status of the CABRI research reactor

Author: Jean Paul Goossens[1]

Co-authors: Adrien Gruel [1]; Benoit Petitprez ; Frederic Witters [2]; Pierre Jaecki [2]

[1] *CEA*

[2] *cea*

Corresponding Author: jean-paul.goossens@cea.fr

The CABRI experimental reactor, operated by CEA at the Cadarache research center, is a versatile facility, which can function at steady-state power (up to 25 MW), and allows the realization of energetic transients with a peak power up to 20 GW.
Our facility is involved in the realization of two important experimental programs. The first one concerns the safety studies of the PWR fuel and their cladding behaviour under Reactivity Initiated Accident (RIA) conditions in the frame of CABRI International Program (CIP), funded by IRSN (French Institute of Nuclear Safety and Radioprotection) under the auspices of the OECD/NEA. The CABRI International Program (CIP) tests submit irradiated UO2 or MOx fuels to RIA in Pressurized Water Reactor thermal-hydraulic conditions, namely 280°C and 155 bar. The main objective of this program is to improve understanding of the thermomechanical behavior of such fuel under RIA transient, not only during the Pellet Clad Mechanical Interaction phase, but also for the entire duration of the boiling crisis triggered by the deposited in the test rod during the transient. Three CIP experiments have been realized between 2022 and 2024.On the other hand, for the needs of irradiation of inert components, we have extended the experimental capabilities of CABRI by two new irradiation positions within the pool, easily accessible from above the core and without interference with transient tests. These locations are located outside the core and behind the graphite reflector, with a useful space of 800 x 200 x 200 mm3. They allow the irradiation of various inert materials, to study their behaviour under neutron and gamma fields. A first experimental program, as part of a CEA' s research program on inert materials has been carried out between 2022 and 2024, consisting in irradiations experiments on steady state and pulsed mode. At this stage, 14 irradiations have been carried out for this program.
This communication deals with the current abilities of the CABRI experimental reactor and highlights the specificities and the strengths of CABRI. We are also continuing additional feasibility studies to explore the options of extension of the experimental capacities of CABRI reactor for perspectives of realization beyond 2027.

#04 - Research Reactors and Particle Accelerators / 168

#4-168 Design of oscillation experiments at the VENUS-F zero power reactor

Author: Federico Di Croce[1]

Co-authors: Federico Grimaldi [2]; Antonin Krása [3]; Pierre-Etienne Labeau [4]; Guido Vittiglio [3]; Jan Wagemans [5]

[1] *SCK CEN and Université libre de Bruxelles*

[2] *Belgian Nuclear Research Centre, Université libre de Bruxelles*

[3] *Belgian Nuclear Research Centre*

[4] *Université libre de Bruxelles*

[5] *SCK CEN*

Corresponding Author: federico.di.croce@sckcen.be

One of the challenges for the deployment of advanced, heavy-metal-cooled reactor technologies is to improve nuclear data of key materials in the fast energy range. VENUS-F, the zero-power fast spectrum research reactor operated at SCK CEN, can play a major role in addressing this challenge. Sample reactivity worth experiments can be performed in VENUS-F to measure the reactor response to a sample material insertion in well-defined spectral conditions, testing the sample evaluated nuclear data. Oscillation techniques, in particular, are employed to increase the precision of such measurements when dealing with small reactivity effects of the order of 1 to 10 pcm.

This work analyses the requirements for the experimental setup to be used in VENUS-F oscillation experiments. Oscillation techniques can be classified based on the following features: the use reactivity compensation by automated pilot rod to maintain stable the reactor power in the closed loop configuration, as opposed to the open loop configuration without compensation and with reactor power fluctuation, the oscillation frequency and waveform and the detector location (local and global). The open loop configuration is preferred to the closed loop in VENUS-F. They have equivalent accuracy and the former is technologically easier to implement since no reactivity compensation mechanism is required. In open loop experiments, the global detectors (far from the oscillator location) provide the global system response. The sample reactivity worth is obtained by processing the global detectors' output with inverse point kinetics algorithms. The validity of point kinetics for the range of perturbations envisaged for the experiments is tested by assessing the consistency of the signal coming from different detectors during a preliminary experimental test. Pseudo-square oscillations are considered for experiments in VENUS-F. The development of a hybrid pile oscillator combining both the local and global signal perturbations is considered for the first time in a fast reactor. Synthetic oscillation simulations and the preliminary experimental tests are analyzed to investigate the optimal oscillation frequency as well as to select the best detector positions. With this process we seek uncertainty reduction of the measured response, estimated as the reactivity worth variations over the repeated oscillations.

Both design and interpretation of the experiment rely on the modeled reactor response. The integral response and its energy and reaction channel breakdown are simulated in the design phase using the Serpent Monte Carlo code. On the one hand, the experimental zone is selected to increase the sensitivity to specific reactions. On the other hand, the experimental channel is dimensioned based on the sample masses, which must cause a measurable reactivity effect. Oscillation experiments interpretation consists of the analysis of calculation-to-experiment discrepancies, which trace back to the nuclear data. This information is eventually used to improve the sample nuclear data for specific applications.

#09 - Environmental and Medical Sciences / 170

#9-170 Unveiling the easyPET/CT

Author: Regina Oliveira[1]

Co-authors: Ana Luísa Silva [1]; João Veloso [1]; Pedro Correia [1]; Pedro Encarnação [1]

[1] *University of Aveiro*

Corresponding Author: regina.oliveira@ua.pt

Multimodal imaging systems, such as micro-PET/CT scanners, are essential tools in preclinical research, enabling the acquisition of both anatomical and physiological information in a single imaging session. In these systems, CT-based attenuation maps can be applied to PET data as a correction factor, enhancing the molecular image quality and enable precise PET quantification.

The easyPET.3D is a compact benchtop micro-PET system, based on a patented technology by Aveiro University in Portugal. This scanner features two opposing detector arrays (16x2) designed to detect coincidence events. Its innovative scanning technique leverages two axes of rotation: one rotates the detectors 360º (axial rotation), while the other performs a fan motion for each position of the 360º, defining the full field-of-view.

This work explores a novel approach to integrating CT functionality into the easyPET.3D, without adding complexity and volume to the system, using the existing PET detectors to detect low energy (< 60 keV) photons, typically used for CT. An Americium-241 (241Am) radioactive source is used as the radiation source. It is positioned above and centered with one of the detector arrays (not used in CT acquisition mode), while the other array measures the incoming radiation from 241Am source.

Experimental tests were conducted on the scintillation detectors in the easyPET/CT system, which use a combination of LYSO:Ce (Lutetium Yttrium Orthosilicate Cerium doped) crystals and Hamamatsu SiPM (S13360-1350PE) sensors. The results showed that the detectors could detect the 241Am emissions, confirming that the system has a high dynamic range. These detectors successfully measured both the 241Am energy peaks (26.3 keV and 59.5 keV) and the peak from Sodium-22 (511 keV) with a single gain setting. The detection of the two emission energies of 241Am open the opportunity of dual-energy imaging, which could ease material differentiation in phantoms or, ultimately, tissue contrast in live animal studies.

The proposed CT system was simulated in GATE v9.0. A cylindrical phantom (3.2 cm of diameter and 4 cm of height) filled with air and containing copper wires of different diameters (1 mm, 0.5 mm, 0.25 mm, 0.125 mm, and 0.0625 mm) was used. Simulation results indicate that the proposed CT system can resolve objects as small as 0.125 mm, which aligns well with the intended goal of imaging small animals.

The simulation results were further validated by replicating the phantom in the experimental setup. The sinograms obtained experimentally showed detectable data for objects of 1 mm, 0.5 mm and 0.2 mm; however, using the inverse radon transform, only the 1 mm and 0.5 mm objects were visible in the reconstructed image. This could be probably overcome using another reconstruction methods, like iterative ones, or increasing the statistics of acquisition. On the other hand, achieving submillimeter resolution, with detection down to 0.2 mm, suggests that the easyPET/CT system holds significant potential for preclinical applications without additional dedicated CT detectors.

Given the unique detector configuration, the next step includes developing a custom iterative image reconstruction solution to optimize image quality. Following this, we will evaluate system performance and characterization to further refine the CT capabilities of this multimodal system.

#09 - Environmental and Medical Sciences / 171

#9-171 SmartX: Advancing Darkfield X-ray Imaging for Lung Disease Detection

Authors: Daniela Pfeiffer[1]; Edoardo Charbon[2]; Franz Pfeiffer[3]; José María Benlloch[4]; Laura Moliner[4]; Paul R. Lecoq[4]

[1] *Klinikum rechts der Isar, Technical University of Munich (TUM)*

[2] *Ecole Polytechnique Fédérale de Lausanne (EPFL)*

[3] *Technical University of Munich*

[4] *Instituto de Instrumentación para la Imagen Molecular (i3M)*

Corresponding Authors: benlloch@i3m.upv.es, paul.lecoq@cern.ch

Lung diseases represent a significant global health challenge, with conditions like chronic obstructive pulmonary disease ranking as the third leading cause of death worldwide, according to the World Health Organization. The disease causes inflammation and destruction of lung tissue, making early detection of this and similar conditions crucial for reducing mortality and enhancing patient outcomes. However, conventional diagnostic tools, such as chest X-rays and computed tomography scans, are limited in their ability to detect early stages, particularly in assessing subtle changes in the alveolar structure. Spirometry, though widely used, is dependent on patient cooperation, making it unreliable in some cases. Therefore, innovative imaging methods are urgently needed to address these diagnostic gaps. Darkfield X-ray imaging is a novel technology that offers significant potential for visualizing early stages of these disease by exploiting small-angle scattering of X-rays. Unlike conventional imaging, which measures X-ray attenuation, darkfield imaging detects scattering patterns generated by microstructures, such as the alveoli in lung tissue. This makes it particularly valuable for assessing chronic obstructive pulmonary disease, where early changes often occur at the microscopic level. Several techniques have been developed to implement darkfield imaging, including interferometric approaches, analyzer-based techniques, and free-space propagation methods. These techniques require either highly monochromatic X-ray beams or microfocus X-ray sources, which are not readily available in clinical settings. A promising alternative is grating-based phase-contrast imaging, which uses three gratings to generate interference patterns and is compatible with conventional X-ray tubes. This method, has shown potential for clinical use and a feasible approach for lung imaging, but still faces limitations. The main of these is the requirement for an analyzer grating that absorbs half of the X-ray dose, reducing efficiency and increasing radiation exposure for patients. Recent progresses in nuclear instrumentation, particularly in the domain of micro- and nano-structured scintillators and single photon detection techniques, are opening the way to a quantum leap in ultra-high resolution X-Ray detection systems, and particularly in the very promising domain of phase contrast and dark field X-ray imaging. In this context the SmartX project, in the framework of a European Research Council Synergy Grant, aims to overcome the main limitation by developing a new detector technology that eliminates the need for the 50% absorbing analyzer grating. By combining nanostructured scintillation materials with Single Photon Avalanche Diode sensor technology, SmartX will enable direct resolution of the interference pattern produced by the reference grating. The proposed detector will present spectral features, which can further enhance diagnostic capabilities. We expect this approach not only improves the detection of the darkfield signal but also reduces the radiation dose by 50% compared to current methods, making it safer for patients. This work presents the first detector concept that will be developed in the coming years.

#04 - Research Reactors and Particle Accelerators / 172

#4-172 Development of a Time-of-Flight Spectrometer for Characterizing a 30-MeV Cyclotron-based Quasi-monoenergetic Neutron Beam

Author: Tzu-Hsiang Lin[1]

Co-authors: How-Ming Lee [2]; Kuo-Yuan Chu [3]; Ting-Shien Duh [3]; Hui-Yu Tsai [1]; Ming-Wei Lin [1]

[1] *Institute of Nuclear Engineering and Science, National Tsing Hua University*

[2] *Department of Physics, National Atomic Research Institute*

[3] *Department of Isotopes, National Atomic Research Institute*

Corresponding Author: thlin@m109.nthu.edu.tw

We report the results of time-of-flight (TOF) measurements used to characterize the spectrum of a neutron beam generated by a proton cyclotron at the National Atomic Research Institute in Taiwan. The quasi-monoenergetic neutron beam is produced through the interaction of 30-MeV protons with a 1-mm-thick beryllium target via the $^9Be(p,n)^9B$ nuclear reaction. To effectively discriminate between neutron and gamma-ray signals emitted from the target, the time-of-flight spectrometer was constructed using two EJ-309 liquid organic scintillators. The first trigger detector, a 2-inch EJ-309 used to measure gamma rays and initiate the TOF measurement, was positioned 20 cm from the beam port at an angle of 45 degrees relative to the beam axis. Meanwhile, a 3-inch EJ-309 record detector was placed 294 cm away from the beam port to measure the output neutrons. The time differences between gamma rays and neutrons detected by the trigger and record detectors, respectively, were analyzed as "gamma-neutron coincidence events" to evaluate neutron flight times and determine the energies of neutrons based on the known flight distance. Since the 30-MeV cyclotron operates at a radio frequency of 73.13 MHz to produce proton bunches with a period of 13.67 ns, the TOF measurements were triggered by gamma-ray bursts that were synchronously emitted from the target with the proton bunches. Consequently, repetitive distributions for the gamma ray-gamma ray and gamma ray-neutron coincidences were obtained in the measured TOF results, limiting the analyzable time window to between 39.44 ns and 53.11 ns (39.44 + 13.67 ns), which corresponds to neutron energies ranging from 30 MeV to 16.19 MeV. In this manner, neutrons with energies below 16.19 MeV contributed to chance coincidences in the measurements, forming a DC background in the TOF spectrum. By eliminating these chance coincidences, the measured neutron spectrum exhibits a quasi-monoenergetic distribution peaked at 25 MeV, showing remarkable agreement with the spectrum simulated by the Monte Carlo model MCNP. Our TOF method has been highly successful in characterizing the spectrum of fast neutrons from a cyclotron-based neutron source. The results provide reliable spectral properties of neutrons and facilitate quality assurance of the neutron beam for downstream applications.

#11 - Education, Training and Outreach / 175

#11-175 Leadership and Culture for Safety and Security basis of Regulatory Capacity Building AMSSNuR experience and lessons learned

Author: Taib Marfak[1]

Co-authors: Réda Nour [1]; Saïd Mouline [1]

[1] *Moroccan Agency for Nuclear and Radiological Safety and Security (AMSSNuR)*

Corresponding Author: s.mouline@amssnur.org.ma

In Morocco, the nuclear and radiological applications are covering various socio-economic fields (health, industry, agriculture, security, scientific research, and higher education). The government adopted in 2014 the law 142-12 on nuclear and radiological safety and security and the creation of the regulatory body 'AMSSNuR'.
AMSSNuR has established an integrated strategic approach to develop and maintain the main capacity building pillars: human resources, necessary knowledge and competences, education and training programmes and international cooperation.
AMSSNuR adopted several tools developed by IAEA: self-assessment of knowledge management programme, SARCoN and systematic approach for training.
AMSSNuR conducted a national strategy for education and training in nuclear and radiological safety and security and identified more than 13,000 people to be trained or retrained. Under this strategy, AMSSNuR established training programmes, including KM and training trainers with the parties concerned and adapted the identified needs to legislative and regulatory requirements.
In its approach, AMSSNuR considered the regional cooperation needs by including training programmes within the framework of the GNSSN, FNRBA, AFRA, ANNuR, IAEA, the EU, and bilateral agreements.
In this this paper, AMSSNuR presents the programmes of leadership and culture for Safety and Security as a basis of Regulatory Capacity Building pillars and the experience and lessons learned.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 176

#6-176 Benchmarking TRIPOLI-4, MCNP6, PHITS and DIANE Monte Carlo codes against photofission experiments using a 9 MeV electron accelerator

Authors: Adrien Sari[1]; Alexis Jinaphanh[2]; Amine Nasri[3]; Andrea Zoia[4]; Cédric Jouanne[4]; Louis Garnaud[2]

[1] *CEA/List Saclay*

[2] *CEA/SERMA France*

[3] *CEA/DAM France*

[4] *CEA/SERMA*

Corresponding Author: louis.garnaud@cea.fr

Photofission reactions represent an important aspect of photonuclear physics, with significant implications for various applications, including the detection of Special Nuclear Materials (SNM) in cargo containers for homeland security, radioactive waste packages characterisation or production of radioisotopes. To obtain the precision required in these high-stakes applications, accurate simulations of industrial or experimental setups are vital. Monte Carlo simulations are widely used for this purpose, using state-of-the-art nuclear data libraries and nuclear reaction models. Benchmark comparisons specifically targeted at the Monte Carlo simulation of photonuclear reactions have revealed significant inconsistencies between simulations and experimental data, but also among the results of different codes. These discrepancies emphasize the need for further research to refine nuclear data, improve modeling techniques, and enhance the reliability of simulation results, thereby ensuring that applications of photofission reactions can be effectively and safely implemented in practice. In this context, the aim of this work is to benchmark several Monte Carlo codes, i.e., TRIPOLI-4, MCNP6, PHITS and DIANE against experimental measurements of delayed neutrons from photofission. The experiments were performed at the SAPHIR facility operated at CEA Paris Saclay, France. The setup is based on a linear electron accelerator, which generates high-energy gamma-rays through the Bremsstrahlung effect on a tungsten target. The accelerator, designed by Varex Imaging Corp., is a Linatron® M9A. In our experiments, a photon beam from 6 or 9 MeV electrons pulsed at 100 Hz is produced. Reference photofission samples (235U, 238U, 239Pu) are investigated. The detection part of the experiment is composed of ten 3He filled-gas proportional counters embedded in a block made of high-density polyethylene, which is surrounded by a cadmium layer, in order to thermalize and detect delayed neutrons from photofission, without contribution from spurious neutrons thermalized in the irradiation hall. The simulation is conducted in two key steps for comparison with experimental results. In the first step, the photofission rate within the sample is calculated using the electron source from the accelerator. In the second step, the simulation accounts for the delayed neutron source, tallying the reaction rate for the neutroninduced (n,p) reactions within the 3He gas. Subsequently, a time dependent correction factor is taken into account to address the six families of delayed neutrons associated with each sample. The findings of this study could help Monte Carlo practitioners and codes developers, as well as nuclear data evaluators, to improve the accuracy of the photofission reaction simulation.

#04 - Research Reactors and Particle Accelerators / 177

#4-177 Report on TESCA irradiation of optical sensors and tests of glasses

Author: Guy Cheymol[1]

Co-authors: Ayoub LADACI [1]; Christophe Destouches [2]; Florence Martin [2]; Marion AGOYAN [3]

[1] *Université Paris-Saclay, CEA, Service de Recherche en Matériaux et procédés Avancés*

[2] *CEA, IRESNE, Cadarache, DER/SPESI*

[3] *Univ. Lyon, UJM, CNRS, IOGS, laboratoire Hubert Curien, UMR 5516*

Corresponding Author: guy.cheymol@cea.fr

Thanks to their remote sensing capabilities and compact size, Fibre Optic (FO) sensors are exceptionally well-suited for in-pile experiments in Materials Testing Reactors (MTRs) where space is limited. Their lightweight design reduces gamma heating, minimizing thermal effects. These sensors can measure a large range of physical parameters—including strain, displacement, vibration, pressure, and temperature—using various optical measurement principles. Testing under irradiation and representative conditions is essential for qualifying sensor prototypes. The TESCA irradiation campaign, conducted from November 16 to December 17, 2023 (one reactor operating cycle) in the SCK.CEN BR2 reactor, enabled testing of optical sensors at different development stages under intense radiation: fast neutron fluence (E > 1 MeV) of 1 to 2 x 10^{19} neutrons/cm^2 and gamma doses of about 5 GGy. Our sensors and experiments were situated in the in-pile sections of three needles, constrained by a reduced diameter (9 mm) due to auxiliary electrical heating arrangements surrounding the dedicated volume, used to regulate temperature despite reactor power and gamma heating fluctuations. TESCA facilitated on-line testing of Fabry-Perot extensometers, and miniature, non-contact, high-temperature optical pyrometry sensors. We also conducted tests on glasses to collect data on physical parameters—such as dimensional changes, optical attenuation, and refractive index shifts under irradiation—critical for developing a chromatic confocal measurement sensor. These tests required the development of specialized sensors for glass measurements. We will present the effective irradiation and temperature conditions (ranging between 250℃ and 500℃). Because all sensors are temperature-sensitive, it was crucial to either maintain stable temperatures or accurately monitor them to assess the impact of radiation on sensor response stability at constant load or on glass parameters. Brief temperature jumps were also applied to vary the load and test sensor accuracy.
An overview of results from monitoring the various sensors and experiments throughout the irradiation cycle will be provided. Additionally, glass samples irradiated in one of the three needles were retrieved for post-irradiation measurements to complement the online data.

#10 - Current Trends in Development of Radiation Detectors / 178

#10-178 Neutron field spatial distribution from the DD neutron source determined by the KOSTKA experimental device

Authors: Vendula Filová[1]; Branislav Vrban[2]; Jakub Luley[3]; Štefan Čerba[1]; Otto Glavo[1]; Filip Revai[1]; Vladimír Nečas[1]

[1] *Slovak University of Technology, Faculty of Electrical Engineering and Information Technology*

[2] *Slovak University of Technology in Bratislava, Slovakia*

[3] *Slovak University of Technology in Bratislava*

Corresponding Authors: jakub.luley@stuba.sk, filip.revai@stuba.sk

The presented work introduces the results from the KOSTKA experimental device, designed for the measurement of the spatial distribution of the ionizing radiation. KOSTKA consists of a 3D-printed holder of cubic shape, designed to surround the source of the particles of interest with PADC detectors (with maximum of 25 detectors per one side). Structure of KOSTKA allows adding of material (such as aluminum) between the source of the particles and the detectors. PADC detectors represent a passive method of measuring ions and fast neutrons. The response to the incidence of the particle is the creation of a latent track, which is subsequently enlarged by chemical etching. The etched tracks are visible under the optical microscope and can be further analyzed. The TASTRAK detectors of dimensions of 25x25x1.5 cm3 were used in the experiment, together with the TASLImage system for etching, scanning and analysis. The result of the analysis is the information about the number of etched tracks registered per 1 cm2 of the surface of the detector. The response of the detectors to the fast neutron radiation is linear and the energy range is between 0.1 and 10 MeV. The demonstration experiment was performed at the tandem electrostatic accelerator of the Tandetron type, and KOSTKA was used to monitor the spatial distribution of neutrons originating in the Deuteron-Deuteron (DD) reaction. The experiment was divided into two parts, one with bare PADC detectors and one where aluminum layer was inserted to shield the protons. To process the data, the detectors were etched and analyzed using the TASLImage system. The numbers of registered tracks per unit of area were assigned to the corresponding coordinates relative to the reaction center. The data were analyzed using an in-house developed software KOSTKACode, written in Python programming language. The code is based on the Monte Carlo simulation, and its purpose is to convert the data from the cubic arrangement to the spherical arrangement, and thus provide information about the angular distribution of the measured quantity. The results of the presented work are the description of the fast neutron field around the DD reaction, based on the two described measurements. This approach might be used also to other neutron sources.

#10 - Current Trends in Development of Radiation Detectors / 179

#10-179 Optimization of a VCO-Based Pixelated Particle Detector for particle discrimination and tracking

Author: Karine Coulié[1]

Co-authors: Wenceslas Rahajandraibe [1]; Valentin Valero [2]; Laurent Ottaviani [3]

[1] *IM2NP - Aix-Marseille Université*

[2] *Aix Marseille Univ, Université de Toulon, CNRS, IM2NP, Marseille, France*

[3] *Institute of Materials Microelectronics Nanosciences, Aix-Marseille University*

Corresponding Author: valentin.valero@im2np.fr

This work deals with the study and optimization of a particle detection chain based on a CMOS-SOI voltage-controlled oscillator (VCO) circuit associated to a 3x5 matrix of detection. The matrix is a semiconductor radiation detector, also called solid-state detector. This detector is based on charge collection and amplification using a semiconductor volume such as a p-n junction. For a better detector sensitivity and tracking requirements, a pixel organization including several junctions is used. The solution was first optimized for the recognition and tracking of low energy particles but high energy particles can also be detected.

The detection chain presented in this work relies on an indirect particle detection through a voltage-controlled oscillator. Previous works have demonstrated the feasibility of identifying input signals from specific particles by analyzing the average output voltage of the VCO chain. This method offers significant advantages, in particular the comprehensive acquisition of input signal characteristics, including waveform, magnitude, and current duration, all with a high detection sensitivity.

The proposed detection system is composed of a detection matrix together with an innovative read-out circuit based on a high frequency voltage-controlled oscillator. The detection chain has been designed and implemented on 130nm CMOS SOI technology, then simulated at circuit level using "Spectre"simulator (SPICE-based) under Cadence Virtuoso © CAO tool. The VCO chain is composed of three parts: a CMOS based pixel detector, a shaping circuit based on a voltage controlled ring oscillator and a system for frequency and amplitude detection. This system allows the evaluation of the circuit sensitivity to radiation by measuring the oscillator responses. As the lastest solution reaches an operating frequency of 4.8GHz, the shape of the signal is directly reproduced at the output of the VCO (Fig. 1). This method avoids most of the design problems. Then, the information is extracted by correlating the initial oscillation signal of the system with the oscillating signal after the particle has passed the detector. The only requirement to allow particle recognition is then to link the output information (i.e. voltage variation of the oscillating signal) to the input information (current stimuli).

Several pixel configurations have been explored in previous works. In this study, we will focus on a 3x5 matrix (Fig. 2). The current source comes from the realistic simulation of the matrix using TCAD device simulation tools (Synopsis ©). The effect of the ion strike is simulated using the Heavy Ion module of Synopsis, considering an electron-hole pair column centered on the ion track axis. The Linear Energy Transfer is defined as the energy lost by the particle, by unit of length and varies along the track. In this paper, an actual variation of the LET was integrated in our simulations, based on the value given by SRIM tables. The VCO based chain presented here is optimized for the detection and identification of particle fluxes lower than 109 particles per detection area and per second. This chain could be particularly suitable for the detection of low energy particle but also for more energetic particles. Then we decided to analyze the VCO response for different energies. The low energy will be studied through the particles generated by the initial interaction of a thermal neutron with boron-10, i.e. one Li with an initial energy of 0.9 MeV and one Alpha with an initial energy of 1.5 MeV. The case of a more energetic particle will also be examined. This is a 50MeV Aluminum (Fig. 3) which could be produced by the interaction of fast protons with silicon.

After the particle generation inside the matrix of detection, the key point is how the output parameters of the VCOs chain can give information about the input current. This could be done through the analysis of various characteristics extracted from the average voltage variation (Fig. 1). After a first step of calibration, a curve of reference is obtained (Fig. 2). When the detection is good, the variation of the average output signal (ΔVmax) versus the maximum of the input current (Imax) fits

a linear evolution. Through the calibration curve, the output parameters can be linked to the input currents, which could allow the incoming particle identification. Then tracking ability including particle discrimination can be evaluated by comparing the Imax-ΔVmax evolution of the studied particles to the calibration curve.

It is presented there for two particles: an Alpha and an Aluminum particle. Other configurations will be presented in the final paper. Both particles have been injected sequentially in the VCO. The average voltage is presented in Fig. 4 for the highest currents of the pixels, corresponding to the two particles. The metrics Imax-ΔVmax corresponding to these currents and voltages have been reported in Fig. 2. All the currents are correctly reproduced excepted the N10 current of the aluminum. This current should be large enough to be correctly detected by the VCO but, it is too high and its maximum value meets the saturation value of the VCO. To avoid this problem, one interesting application for the VCO based detector could be a spectrometry analysis. Then the oscillator frequency could be calibrated to select particles with various characteristics. In that case, several VCO working at different frequencies could be used, giving the opportunity to characterize accurately a given environment. This possibility will be explored in the final paper.
In the final paper, another aspect of our work will be to investigate the feasibility of utilizing a greater number of pixels (i.e. of VCOs) in terms of power consumption. The aim is to adopt a comprehensive approach to improve the capabilities and robustness of our detection and tracking methodology.

#04 - Research Reactors and Particle Accelerators / 180

#4-180 Design and testing of a fiber-coupled fast neutron scintillation detector for low-power research reactors

Author: Alexis Dupont Bembinoff[1]

Co-authors: Oskari Pakari [1]; Daniel Clément [1]; Andreas Pautz [2]; Mathieu Hursin [1]; Vincent Lamirand [2]

[1] *EPFL*

[2] *Ecole Polytechnique Fédérale de Lausanne*

Corresponding Author: alexis.dupont-bembinoff@epfl.ch

Miniature in-core neutron detectors are of interest for a variety of experiments in research reactors, for instance for highly local flux measurements, multi-physics high-resolution measurements, or even in-core noise experiments. The typical challenge associated with in-core detectors is the limited space available within the core between fuel elements. To address the geometrical challenges, miniature scintillation detectors (in the range of mm^3 or below) provide cost-effective local detection means, as demonstrated recently at EPFL in the thermal energy range (MiMi detectors and SAFFRON array). As radiation in the core can perturb or damage commonly used light collection systems such PMTs, and especially SiPMs, one common solution is to fiber-couple the scintillator, thereby enabling out-of-core signal analysis, and further increasing space-saving within the core.

To detect fast neutrons, plastic scintillators capable of pulse shape discrimination can be employed. Thanks to the difference in pulse decay shape by electron-induced scintillation vs proton-recoil-induced scintillation, individual pulses can be classified and discriminated into gamma ray or neutron-induced pulses. The relatively compact dimensions of the detectors, while keeping reasonable sensitivity, might also lead to the reduction of gamma-induced signals, thereby enhancing the specificity of neutron signals. The general application case of such small fast neutron scintillators is to observe local fast flux changes in the reactor core, at reduced cost allowing for scalability, which is a hitherto relatively poorly explored domain of reactor measurements.

In this contribution, we present the design and first testing of a fiber-coupled plastic scintillator for fast neutron detection. We outline the design, electronics, and challenges encountered. Fast neutron scintillators, due to the inherently smaller interaction cross-section, could provide experimental results at powers up to 100kW, which is relevant for the instrumentation developments and experiments in the framework of the Horizon Europe project EVEREST dedicated to multi-physics validation. Our detector comprises a cube of EJ-276D plastic scintillator coupled to an optical fiber (Super ESKA with 2 mm core and 3 mm total diameter). Two plastic cube scintillators are tested: a 10x10x10 mm cube and a 5x5x5 mm cube. An aluminum holder is used to ensure the centering of the fiber on the scintillator. The fiber is then coupled to a Hamamatsu H3178-51 Photo-Multiplier Tube (PMT). To optically couple the surfaces we use the EJ 550 optical grease. For signal acquisition we use a 500MS/s CAEN DS 5730S digitizer using the DPP-PSD firmware.

The first tests were conducted with a PuBe neutron source in the water of the CARROUSEL facility at EPFL to demonstrate the feasibility of a pulse shape discrimination with the 10x10x10 mm and 5x5x5 mm cubes. To solve light losses and pile-up issues, we investigated the effect of fiber diameter and fiber length to determine practical limits. We also investigated different pulse shape discrimination parameters and post-processing strategies (e.g. pulse integration times) to recover the neutron-induced signals. Future developments include the testing of other organic scintillator materials, such as organic glass scintillator and stilbene, sub mm3 detector volumes, and wavelength shifting fibers. In-core tests are carried out in the EPFL reactor CROCUS to assess the detectors'performance. Further experiments at the Slovenian JSI TRIGA and the Hungarian BRR reactors are planned within EVEREST.

#04 - Research Reactors and Particle Accelerators / 181

#4-181 Design of a Liquid Neutron Filter Device at the JSI TRIGA Reactor for Fission Rate Measurements under Simulated High-Temperature Conditions

Author: Blaž Levpušček[1]

Co-authors: Vladimir Radulović [1]; Andrej Trkov [1]; Gilles Noguere [2]; Olivier Serot [2]; Christophe Destouches [2]

[1] *Jožef Stefan Institute*

[2] *CEA/DES/IRESNE/DER/SPESI*

Corresponding Author: blaz.levpuscek@ijs.si

Accurate nuclear cross-section measurements are fundamental to advancing nuclear science and technology. To enhance data quality, a novel device is under development with the objective of experimentally simulating high temperatures, enabling fission rate measurements for heavy actinides that significantly influence temperature feedback effects in nuclear reactors. This is achieved with a liquid neutron filter: a container filled with water and boric acid. By varying the concentration of boric acid dissolved in water, the device simulates a thermal spectrum shift due to the characteristic "1/v"absorption cross-section behavior of B-10. This research is being conducted as part of a bilateral project between the Jožef Stefan Institute in Slovenia and the French Atomic and Alternative Energies Commission, Cadarache Research Centre. The device design includes three measurement tubes extending into the liquid filter. One tube will be used for neutron activation analysis, while the other two will house fission chambers—one with a fissile deposit of U-235 serving as a reference and the other with fissile deposits of nuclides of interest. Calculations of the predicted measurement results were performed for U-238, Am-241, Np-237, and Pu-239, in addition to U-235. By monitoring the relative changes in the signals of each fission chamber as the boron concentration varies, changes in fission cross-sections as a function of the spectrum shift can be accurately assessed. Neutron activation analysis will be possible through the irradiation of samples in an aluminum holder equipped with either a cadmium or aluminum box filter. A selection of foils for the activation tube indicated that reactions on the In-115, Ag-109, and Au-197 isotopes are the most sensitive to the thermal spectrum shift. A preliminary device design has been developed through neutron transport simulations using the MCNP and ADVANTG codes. After evaluating all potential beam port locations in the TRIGA Mark II reactor at the Jožef Stefan Institute, the Radial Beam Port was determined to provide the most suitable neutron flux conditions for device installation. Due to the geometric similarity among the beam ports, the device can also be used for measurements in different reactor locations in the future. Two methods are considered for the measurement of boric acid concentration: volumetric measurement during solution preparation and dilution, and a relative measurement using an external neutron source and an additional neutron detector positioned near one of the inlet pipes leading into the liquid filter, with changes in boric acid concentration inferred from variations in the neutron detector signal.

#10 - Current Trends in Development of Radiation Detectors / 182

#10-182 Radiation effects on photosensors and electronics with impedance spectroscopy

Author: Pierluigi Casolaro[1]

Co-authors: Alberto Aloisio [1]; Antonio Vanzanella [2]; Claudio Principe [2]; Riccardo Vari [3]; Vincenzo Izzo [4]

[1] *Università degli Studi di Napoli Federico II and INFN Napoli*

[2] *INFN Sezione di Napoli (IT)*

[3] *INFN Sezione di Roma (IT)*

[4] *NFN Sezione di Napoli (IT)*

Corresponding Author: casolaro@na.infn.it

Understanding radiation effects on detectors and electronics is essential for the success of word-class experiments in fundamental physics at particle accelerators. This is of paramount importance in view of the High Luminosity Large Hadron Collider (HL-LHC) program, which aims at discovering new physics beyond Standard Model by increasing the LHC luminosity by up to a factor of 7.5. This scientific goal poses significant challenges for the reliability of detectors and electronics, as they must operate in high radiation environments. In this context, we are performing radiation qualification of key elements of the new readout system of Resistive Plate Chambers (RPC) of the ATLAS muon trigger for HL-LHC.

Conventional analysis of radiation effects on electronics is mainly based on I-V curves, signal integrity, and noise measurements. In addition, we deploy an approach based on impedance spectroscopy. Impedance spectroscopy is a non-invasive technique commonly used in electrochemistry with applications to the characterization of solar cells, fuel cells, batteries, biosensors, and corrosion studies. In impedance spectroscopy, a small sinusoidal perturbation is applied to the Device Under Test (DUT) over a broad frequency range (typically from a fraction of Hz up to a few MHz) superimposed to a constant bias level [1]. The impedance response is analyzed using Nyquist plots, which graphically represent the imaginary part of the impedance vs. its real part. Fitting Nyquist plots with equivalent circuit models provides insights into charge transfer mechanisms. We recently applied impedance spectroscopy to assess Total Ionizing Dose (TID) effects on different device sections of Low Voltage Differential Signaling (LVDS) receivers, including power rail, input and output networks [2]. This approach complements conventional analysis of radiation effects by revealing aspects that are difficult (or even impossible) to observe by traditional methods.

In the present work, we extend this analysis to LSF0102 level translators and Si photodiodes for which impedance spectroscopy is particularly effective in assessing radiation-induced degradation. Level translators of the LSF family rely on MOSFET switches, which conduct during the low input pulses and switch off during high pulses [3]. Translation between voltage levels is achieved through external pullup resistors. Si photodiodes, on the other hand, are solid-state devices based on pn or p-i-n junctions. TID irradiations, up to 15 kGy, are performed at the CERN CC60 facility equipped with a ~10 TBq 60Co gamma source, while displacement damage effects are evaluated with 18 MeV proton beams from the Beam Transfer Line (BTL) at the Bern medical cyclotron. We developed a specific test bench that allows the DUTs to be powered, exposed to the radiation and remotely controlled by a Raspberry Pi 3 Model B+. During the test of level translators, we monitor the DUT current consumption, variations in amplitude, rise/fall time, jitter, signal-to-noise ratio, and infer bit error rate from oscilloscope eye diagrams. During the test of Si photodiodes, we monitor their output current.

Characterization with impedance spectroscopy is performed before and after irradiation for all DUTs using a Solartron ModuLab XM ECS-Photoechem-MTS system. It includes a potentiostat/galvanostat for controlling DC levels (up to ±100 V and ±100 mA), a frequency response analyzer from 10 μHz to 1 MHz, a light source, a monochromator and a reference photodetector operating in the range 350 nm - 1100 nm. It enables impedance measurements both in dark and under controlled light exposure, as well as measurements of Intensity-Modulated Photocurrent Spectroscopy (IMPS) and Intensity-Modulated photoVoltage Spectroscopy (IMVS). In IMPS and IMVS, the light source intensity is modulated and the DUT response, either in current or voltage, is recorded as a function of modulation frequency.

Using this setup, key properties of a DUT can be studied including charge carrier transport, recombination, lifetime, accumulation, and interface mechanisms. By combining impedance spectroscopy with Mott-Schottky analysis and capacitance-frequency measurements, we can also determine the built-in voltage, doping density, depletion width, trap density distribution and surface uniformity. This characterization is relevant for LSF level translators, which are based on simple MOSFETs and resistors. TID damage on MOSFET, extensively addressed in the literature [4], leads to charge buildup in the SiO2 gate and at the Si-SiO2 interface, primarily causing shift of the threshold voltage. Proper modeling of level translators with impedance spectroscopy provides insights into radiation-induced changes in the charge carrier transport of the MOSFET, and the value of the pullup resistor, which is crucial for the proper functioning of these devices.

We recently applied impedance spectroscopy to study the impedance response of a narrow-base Si diode [5]. Here, the pn junction has been modeled with equivalent circuits that take into account depletion and diffusion processes, as well as interfacial effects, potential and capacitance distributions. We are extending this approach to model the impedance of Si photodiodes under both dark and illumination. This characterization is completed with Photon Detection Efficiency (PDE) measurements pre- and post-irradiation, which are relevant for Si photodiodes.

References
[1] A. C. Lazanas, , & M. I. Prodromidis (2023). ACS Measurement Science Au, 3(3), 162-193. doi: 10.1021/acsmeasuresciau.2c00070
[2] P. Casolaro, V. Izzo, M. D'Angelantonio, C. Principe, A. Vanzanella, and A. Aloisio, 2024 IEEE NSS-MIC-RTSD, Tampa, FL, USA, 2024, pp. 1-1, doi: 10.1109/NSS/MIC/RTSD57108.2024.10656982.
[3] Voltage-Level Translation With the LSF Family, Application Report SLVA675B, available: https://www.ti.com/lit/an/slva675b/slva675b.pdf
[4] J. R. Schwank et al. (2008). IEEE Transactions on Nuclear Science, 55(4), 1833-1853. doi: 10.1109/TNS.2008.2001040
[5] P. Casolaro, V. Izzo, M. D'Angelantonio, C. Principe, A. Vanzanella, and A. Aloisio, J. Appl. Phys. 136, 115702 (2024). doi: 10.1063/5.0230008

#04 - Research Reactors and Particle Accelerators / 183

#4-183 Acoustic Microscopy Sensor to Estimate the Water-Channel Thickness in a Research Reactor Spent Fuel Element

Author: Rhofrane Mrabti[1]

Co-authors: Emmanuel Le Clezio [1]; Thomas Delaunay [1]; Yoann Calzavara [2]; Gilles Despaux [1]; Diba Ayache [1]

[1] *University of Montpellier*

[2] *Institut Laue Langevin*

Corresponding Author: diba.ayache@umontpellier.fr

High Performance Research Reactors (HPRR) produce neutrons for material testing and scientific experiments in a wide range of fields. These neutrons are produced by fissions in the reactor's fuel elements. During an irradiation cycle, various micro-structural and physical-chemical transformations take place in the HPRR fuel element depending on its specific irradiation history.

The High-Flux Reactor (RHF) of the Institut Laue Langevin produces the most intensive thermal neutron flux in the world with a thermal power of 58.3 MW. In the framework of the global nonproliferation initiative, the ILL is deeply engaged in the conversion of the RHF from highly enriched uranium to low enriched uranium. This conversion is a challenging process, requiring strict adherence to safety standards and the preservation of similar performance levels in the new fuel elements.

In this context, the Institut Laue Langevin and the Institute of Electronics and Systems of the University of Montpellier have launched a collaboration known as the PERSEUS project. Its goal is to ensure that the RHF fuel under irradiation behaves consistently with its qualification. In order to achieve this, and as the swelling process is the most interesting phenomenon for the RHF, we estimate fuel plate behavior by measuring the water channel thickness after irradiation.

Several ultrasonic devices were therefore specifically engineered and manufactured to perform these measurements. In a previous work, we demonstrated that this type of devices is suitable for in-situ measurements. In the present presentation, we
propose a new design for the device, which now comprises of a 100-MHz-double-element-ultrasonic transducer whose performances were quantified using laboratory equipment to prepare for the in-situ measurements. A mechanical system was also developed to control the ultrasonic device underwater and record the device's position inside the water channel while testing the RHF fuel element. This experimental set-up will be presented along with the signal processing. We will then discuss the results of an in-situ measurement performed along 50 cm of a fuel element water channel.

#03 - Fusion Diagnostics and Technology / 184

#3-184 Characterization of Neutron Detectors for DD and DT Fusion Operation on ITER

Author: Andrei Kovalev[1]

Co-authors: Silvia di Sarra [1]; Giovanni Mariano [1]; Quentin Potiron [1]; Dmitry Gin [1]; Vitaly Krasilnikov [1]; Bruno Coriton [1]

[1] *ITER Organization*

Corresponding Author: andrei.kovalev@iter.org

The neutron diagnostics on ITER are essential for the measurement of the fusion power with high accuracy and temporal resolution. The neutron diagnostics will be equipped with a variety of detectors including fission chambers, diamond and germanium detectors and scintillators. These detectors are known for their accuracy and stability, making them suitable for high-radiation environments.
Fission chambers are used in the design of neutron flux monitors and neutron cameras thanks to their high sensitivity and compatibility with nuclear environments. Fission chambers on ITER will be coated with uranium-235 or high-purity uranium-238 for higher sensitivity to either DD (2.45 MeV) or DT (14.1 MeV) neutrons. Their resilience to high-radiation fields and broad dynamic range make fission chambers an essential tool for applications in fusion power control and neutron profile measurements on ITER. Diamond and germanium detectors are suitable for applications requiring high energy resolution. Germanium detector will be used in the ITER Neutron Activation System to quantify the fluence on ITER first wall. Diamond detectors will be used in the neutron cameras and high-resolution spectrometers to provide accurate measurements of the DT source neutron spectrum. Scintillators are highly-sensitive but they require shielding from the high magnetic field fluctuations present in tokamaks.
Specific characterization of the ITER neutron detectors will improve the measurement accuracy and reduce the impact of biases in the measurements. The characterization of neutron detectors will involve a comprehensive analysis of detectors energy resolution for different types of radiation and their sensitivity. Optimization of these parameters will allow the development of reliable systems for various applications, including radiation monitoring, plasma control and safety.

#07 - Decommissioning, Dismantling and Remote Handling / 185

#7-185 A spectroscopic gamma ray scanner/imager system for radioactive waste (re)conditioning

Authors: Chiara Rita Failla[1]; Fabio Longhitano[2]; Gaetano Elio Poma[3]; Gianfranco Vecchio[3]; Luigi Cosentino[3]; Paolo Finocchiaro[3]

[1] *INFN - Laboratori Nazionali del Sud*

[2] *INFN Sezione di Catania*

[3] *INFN Laboratori Nazionali del Sud*

Corresponding Authors: failla@lns.infn.it, finocchiaro@lns.infn.it

The Proximity Imaging System for Sort and Segregate Operations (PI3SO) is a gamma radiation proximity scanner table for radioactive waste that aims at speeding up the waste management (re)cycle while reducing direct human intervention. The system exploits proximity imaging to detect hot-spots, then in a second step it performs a medium resolution spectrum analysis for a coarse isotopic recognition preliminary to sorting and separate of radioactive waste. The gamma image, with a color scale indicating the measured counting rate, can be superimposed to the corresponding visible image produced by a hovering videocamera. Such a semi-quantitative data, along with the quantitative spectral data, can be stored for archival purposes.

The large amount of existing nuclear waste, as well as the predicted amount from future decommissioning processes, represent a significant task to the nuclear decommissioning program. Such an amount varies depending on when the dismantling operations are completed. Delaying it could increase the quantity of Very-Low-Level Waste (VLLW) that can be exempt from regulatory control while decreasing the amounts of Intermediate-Level Waste (ILW) and Low-Level Waste (LLW). Sorting and segregating radioactive waste, in particular ILW and LLW, are the first steps in the process of safely and economically rehabilitating nuclear facilities while respecting both people and the environment. These materials are usually bundled into specialized drums and stored in near-surface disposal sites. They include gamma emitters of various activities whose identification is crucial to manage radioactive waste properly and essential for safety and regulatory compliance.

To reduce costs and accelerate the implementation of decommissioning plans, innovative solutions are required that allow waste to be moved more quickly and efficiently, along with detailed records and traceability of all operations and decisions made during the nuclear waste management process. A crucial feature of potential novel solutions is the emphasis on operator safety, with a strong effort to reduce direct human engagement in waste management activities by maximizing the use of existing or emerging technology. In such tough nuclear-related circumstances, the PI3SO strategy promises to improve the safety and well-being of operators while reducing errors in waste investigations caused by human mistakes.

An easy-to-use automated system can considerably reduce the need of human operators near active materials by adhering to the "As Low As Reasonably Achievable" criterion (ALARA). Similar systems using a single germanium detector sliding over the material under investigation have recently been proposed. While they offer high energy resolution, they are slow, bulky, and expensive. However, speed is critical to accomplish results as soon as possible, because of the vast amount of the already existing and foreseen waste that must be (re)conditioned.

Our scanning system, conceived for sorting and segregation operations of ILW, LLW, and VLLW, is based on two linear arrays of 64 CsI(Tl) scintillators of 1x1x1 cm3 coupled with silicon photomultipliers (SiPMs). They are installed on a motorized bridge that slides horizontally over and below a thin and robust table covering an active area of 64cm x 108cm. Accurate information on the location and amount of radioactive elements can be obtained by producing a gamma image that displays gamma-emitting sources placed on the table. Furthermore, the identification of radioactive isotopes is made possible by the spectroscopic features of the CsI(Tl) scintillators which achieve an interesting 5% energy resolution at the 662 keV reference peak of 137Cs.

Many successful tests have been performed by using radioactive sources, proving that the minimum detectable activity (MDA) is of the order of a few hundred Bq. Quite recently a few parts of the old dismantled electrostatic deflector of the INFN-LNS superconducting cyclotron were examined. The produced images highlighted the presence of active hot-spots, and the immediately following spectroscopic investigation, compatibly with the energy resolution of the CsI(Tl) PI3SO detectors, showed the presence of peaks presumably related to 44Ti, 44Sc, 22Na, 60Co, 133Ba. A subsequent comprehensive examination with a germanium detector validated these hypotheses, demonstrating the effectiveness of the system.

In conclusion, PI3SO is suitable for the quick semi-automatic sorting and segregation of low- and

intermediate-level radioactive waste, required for the decommissioning of nuclear power plants and for the (re)conditioning and packaging of radwaste, possibly removing exempt waste thus releasing costly storage room.

#04 - Research Reactors and Particle Accelerators / 186

#4-186 Gamma and neutron dose rate measurements around the KATANA water activation loop at JSI TRIGA reactor

Author: Domen Kotnik[1]

Co-authors: Julijan Peric [2]; Domen Govekar ; Luka Snoj [3]; Igor Lengar [3]

[1] *Jožef Stefan Institute*

[2] *JSI Ljubljana*

[3] *Jozef Stefan Institute*

Corresponding Author: domen.kotnik@ijs.si

Water as a primary coolant will play an important role in the performance of fusion reactors, as it causes an ionising radiation field throughout the facility after its irradiation and activation and requires improved shielding for instrumentation and personnel. To support ITER, the KATANA irradiation facility, which utilises a closed-water activation loop, was successfully licenced, built and commissioned at the end of 2023 at the JSI TRIGA research reactor in Slovenia. The KATANA serves as a well-defined and stable high-energy (6 MeV - 7 MeV) gamma and $\sim$1 MeV neutron source. Such a high-energy irradiation facility will enable various experiments based on water activation. The ultimate goal of KATANA is to perform benchmark-quality experiments, e.g. validation of fluid activation codes, and to establish itself as a reference facility for the calibration of high-energy γ detectors, which will significantly support the operation of ITER and other future water-cooled fusion reactors.

During the commissioning phase, and with a focus on safety, γ and neutron dose rate measurements were conducted around the KATANA circuit (within the experimental area enclosed by concrete walls) and across the reactor hall to create a comprehensive dose rate map under various operational scenarios. These measurements were executed in three phases, focusing on different radiation sources: (a) background levels from the reactor without activated water, (b) during steady-state reactor operation with activated water, and (c) with activated water in pulse-mode operation. Dose rates, quantified as dose rate equivalents of H*(10)/time, were measured using a certified neutron probe (Berthold LB 6411) and two γ detectors: a pressurized ionization chamber (Fluke Victoreen 451P-DE-SI-RYR) and a scintillator probe (Automess 6150AD-b/H). The peak γ dose rate observed was up to 5 mSv/h at the close vicinity of the main observation part of the circuit (Snail head), with neutron contributions markedly lower, by more than three orders of magnitude. Due to these elevated dose rates, the experimental zone within the concrete walls has been designated as a red zone, subject to stringent access restrictions. Outside these walls, however, dose rates remained below the limit value of 10 μSv/h, indicating no need for additional shielding. Mapping of the dose field has provided crucial insights into the radiological safety of personnel and established guidelines for the optimal placement/arrangement of detectors within high γ and neutron fields for future experiments at the KATANA facility.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 187

#6-187 An Overview of the MULTISCAN 3D Project: An Advanced Inspection System Integrating Cutting-Edge Technologies to Improve Cargo Container Security Checks at European Borders

Authors: Christine Mer[1]; Guillaume Sannié[2]; Sylvain Magne[3]; Adrien Sari[4]

[1] *Université Paris-Saclay, CEA, List, F-91120 Palaiseau, France*

[2] *Université Paris-Saclay, CEA, List,*

[3] *CEA LIST*

[4] *CEA*

Corresponding Authors: sylvain.magne@cea.fr, adrien.sari@cea.fr

The European MULTISCAN 3D project addresses the urgent need for enhanced container inspection technologies for customs border checks, especially in high-throughput seaports such as Rotterdam and Antwerp. Current 2D X-ray systems : suffer from limitation when threat have not well defined shape . This is the case of drugs for example.. Customs agencies typically select containers for inspection based on risk analysis or surveillance information. Inspections generally involve scanning the entire cargo using large, high-energy systems, either in single or dual views, from a centralized fixed or mobile inspection facility. With projected increases in cargo volume, customs administrations require advanced solutions to maintain or improve border control efficiency without additional resources.

The MULTISCAN 3D project aims to achieve a significant technological breakthrough by developing a user-friendly, flexible, and relocatable all-in-one inspection system. This system will provide high-quality information via fast, high-energy 3D X-ray tomography, making it suitable as a first-line inspection tool (https://multiscan3d-h2020.eu/).

Leading European customs authorities have identified specific needs and requirements in a technologically-neutral way, which have been translated into detailed technical specifications. The core research focuses on three main areas: laser-plasma-based accelerators for X-ray sources, 3D reconstruction for multi-view configurations with advanced data processing, and detector and source monitoring systems.

A primary challenge is leveraging laser-plasma acceleration technology. Enhancing the average power of the laser system is essential for achieving the desired multisource X-ray production performance. The number of sources distributed around the container is also being optimized, along with the development of advanced algorithms for 3D reconstruction from multi-view X-ray data—essential for accurately interpreting complex cargo contents. Reliable and precise dosimetry and beam monitoring from multiple X-ray sources are crucial to the safe and effective operation of the inspection system. : complementary technics are also investigated including chemical and special nuclear material (SNM) identification to provide comprehensive inspection capabilities

At this stage, the various technological components have been developed and tested at the laboratory scale. Realistic environmental trials with containers provided by customs teams will be conducted toward the project's conclusion to assess system performance.

The MULTISCAN 3D project seeks to revolutionize customs border checks by creating an advanced inspection system that meets the evolving demands of global trade and security. This system promises to enhance the efficiency and effectiveness of container inspections, offering customs administrations a powerful tool for ensuring compliance and safety in international logistics. This work is carried out as part of the MULTISCAN 3D Project (101020100), funded by the European Commission (H2020-SU-SEC-2020).

#09 - Environmental and Medical Sciences / 188

#9-188 Development of an X-ray fluorescence spectro-imaging instrument, based on Timepix3 counting chip, adapted for electronic waste sorting.

Author: Aurore Vazzoler[1]

Co-authors: Adrien Stolidi [2]; Guillaume Amoyal

[1] *CEA*

[2] *CEA/DRT/LIST/DIN/SMCD/LIMTEC*

Corresponding Author: aurore.vazzoler@cea.fr

The increasing use of electronic devices in our daily lives makes the recycling of these devices a major challenge. Indeed, the production of such equipment requires the use of many metals, including rare earth elements, whose extraction raises numerous environmental, strategic, and economic issues. In nature, these mineral deposits are sparsely concentrated, making their extraction complex, costly, and polluting. Moreover, Europe has very few rare earth deposits, which makes it highly dependent on foreign powers for its supply. Thus, better utilization of urban mining would not only reduce the environmental impact of rare earth extraction, but also make better use of resources that are currently wasted, and decrease dependence on producing countries. Despite all these challenges, the recycling of WEEE (Waste Electrical and Electronic Equipment) is still underdeveloped today. Due to the low concentration of these elements in electronic devices, current sorting methods make their recovery difficult and economically unprofitable, hence the need to develop new innovative sorting methods. The CEA IRAMIS institute is currently developing different sorting strategies. One of these strategies involves optical sorting of electronic waste using artificial intelligence. This artificial intelligence has been trained on a database of electronic components in order to associate an elemental composition with a specific component shape. Thus, the combination of this artificial intelligence with a simple visible camera theoretically allows the sorting of different components. However, similar-shaped components may differ in their chemical composition, so optical information alone is insufficient for sorting. Therefore, a sorting strategy using X-ray transmission spectrometry is considered. This method involves irradiating electronic components with an X-ray source, while a detector placed on the other side of the samples measures the energy of the transmitted radiation. By measuring the intensity of the X-rays transmitted compared to the incident intensity, they can determine the nature of the elements present in the sample, as each element has a characteristic absorption spectrum. Unlike the previous method, this one has the advantage of directly providing information on the elemental composition of the samples; however, X-ray transmission is not usually used for this purpose, as other methods are better suited. The objective of this work is to design a new strategy for sorting WEEE that complements methods presented earlier. In this work, the chosen method for elemental discrimination relies on X-ray fluorescence spectro-imaging. When irradiated by an X-ray source, samples emit X-ray fluorescence radiation, with energy levels specific to the chemical elements they contain. Thus, by measuring theses radiations, we can determine the elemental composition of the sample. Analysing an energy signature, rather than an absorption profile, gives X-ray fluorescence spectrometry greater sensitivity compared to X-ray transmission spectrometry. On the other hand, imaging of the fluorescence radiation from the samples is made possible by using a pixelated detector equipped with a collimator designed for X-ray imaging. The combination of spectrometry and imaging, known as spectro-imaging technique, would significantly enhance the sorting process by enabling the localisation and identification of samples within in a given field-of-view. The developed system in place is as follows: an X-ray generator irradiates the sorting bench; while a Timepix3 based pixelated detector, comprising 256×256 pixels with a 55 µm pitch, hybridized with a 100 µm thick silicon semiconductor, faces the conveyor belt and is equipped with a coded-aperture collimator to detect the fluorescence radiation emitted by the samples. This experimental setup has shown promising performance during several trials, which include the analysis of pure element samples as well as samples more representative of the WEEE sorting application.

#10 - Current Trends in Development of Radiation Detectors / 189

#10-189 Visible-Near Infrared Light Attenuation Measurements of Radiophotoluminescence FD7 Dosimeters irradiated with X-rays and Electrons at High Doses

Author: Aditya Raj Mandal[1]

Co-authors: Matteo Ferrari [1]; Ygor Aguiar [2]; Adriana Morana [1]; Ruben Garcia Alia [2]; Emmanuel Marin [1]; Antonino Alessi [3]; Olivier Cavani [3]; Sylvain Girard [1]

[1] *Laboratoire Hubert Curien, Université Jean Monnet, Saint Etienne, France*

[2] *CERN*

[3] *CNRS Ecole Polytechnique, Institut Polytechnique de Paris 91120 Palaiseau, France*

Corresponding Author: aditya.raj@univ-st-etienne.fr

Protection of opto-electronics devices and components susceptible of radiation damage is of foremost importance in intense ionizing radiation environments like the ones produced by particle accelerators, radioisotopes production facilities nuclear infrastructures and waste. Monitoring such radiation levels using accurate dosimetry is accordingly necessary to prevent components'failure and maximize their lifetime. Few known dosimeters provide a reliable response dosimetry in kGy-MGy range, generally considered as high dose level. One of the emerging candidates are silver doped metaphosphate glasses commercially known as FD7 dosimeters. These are in the form of cylindrical rods (1.5mm×8mm) employed currently for medical and environmental radiation monitoring purposes. Radiation induces photoluminescent centers in this glass, that emit orange light as a result of their excitation with ultraviolet light. This phenomenon is referred to as Radiophotoluminescence (RPL), and it is the principle driving the dosimeter's response. The emitted light is proportional to absorbed dose (up to few hundreds of Gy) and it is exploited for dosimetry. Radiation induces additional point defects in dosimeters causing attenuation of the light transmitted through their volume (commonly termed as Radiation Induced Attenuation, RIA). The sensitivity range of the readout system can be increased by combining Radiophotoluminescence signal with transmitted light system. This system is in use at the European Organization for Nuclear Research (CERN) to passively measure doses absorbed in operation in several locations of interest of the accelerator complex. Limited knowledge on the behavior of FD7 glass material in different radiation fields, specifically at high doses, motivates us to further characterize their response. Reported experiments were conducted at the X-ray irradiation facilities of the Laboratoire Hubert Curien and at the SIRIUS irradiation (2.5 MeV electrons) facility of the Laboratoire des Solides Irradiés. For this purpose, a dedicated setup has been developed for online (during irradiation) and offline characterizations of the dosimeters in a free-space configuration. The setups allow to characterize the signal dependence on wavelength, dose, dose rate and previous thermal treatments, such as the ones performed for dosimeters regeneration. It also allows to measure the signal evolution after irradiation, the so-called recovery. Recent irradiation and testing campaigns targeted spectral Radiation Induced Attenuation measurements in the Near Infrared range at high doses ranging between 500 Gy and 100 MGy. Previous study focused on transmission in visible spectral range concluded that radiation induced attenuation starts saturating at doses ranging between 1 and 50 kGy due to glass darkening. On the other hand, light transmission in NIR range remains measureble up to several hundred kGy. For this reason, the present work focuses on Near Infrared analysis, with the goal of combining both visible and Near Infrared knowledge extend the detection range of FD7 dosimeters at high doses. Spectral analysis plays an important role in understanding the full potential of this dosimetry technique, as it could enhance sensitivity and accuracy at extreme dose levels. Recovery of radiation induced attenuation is recorded for at least 3 hours after irradiation conclusion, as it might impact passive radiation readout as well. The dependency of radiation induced attenuation and recovery on total absorbed dose, dose rate, wavelength and pre-irradiation thermal treatments will be discussed. Discussion with findings from prior works in visible spectrum will be presented. The results allow the current knowledge on optically active defects responsible for signal kinetics, overall not fully understood and debated in the community, to be integrated. This study reports data at doses higher than those typically investigated and describes a new type of spectral analysis in the Near Infrared range, which has not previously been explored for dosimetry purposes. These parametric investigations of the dosimeter response, so far largely unexplored at high doses, are crucial for deeper understanding of the response mechanisms exploited by the existing readout system to attribute the total absorbed dose. Successful radiation induced attenuation measurements encourage the possibility of using an adapted version of the current setup for time-resolved analysis of

the Radiophotoluminescence light as well. Future studies will include the dependency of radiation induced attenuation, recovery and Radiophotoluminescence signal on dose rate, temperature and different configurations of samples.

#10 - Current Trends in Development of Radiation Detectors / 190

#10-190 SolarBlind: UV-imaging of alpha radioactivity with Micromegas and Timepix

Author: Alice Guerra-Devigne[1]

Co-authors: David ATTIE [2]; Guillaume Amoyal [3]; Thomas PAPAEVANGELOU [2]; Philippe MAS [2]

[1] *Laboratoire Capteur et d'Instrumentation pour la Mesure (LCIM), CEA Saclay, France*

[2] *IRFU, CEA, Saclay, France*

[3] *LCIM, CEA-List, Saclay, France*

Corresponding Author: alice.guerra-devigne@cea.fr

Nuclear materials such as uranium and plutonium commonly used in industries or laboratories are major emitters of alpha particles (or α particles). Monitoring contamination of infrastructures and people in contact with them is a major radiation safety issue. Detectors currently in use for this purpose have to be close to the radiation sources. It increases the likelihood of contamination on workers handling the detectors.

The α particles as they travel a few centimeters through the ambient air ionize the nitrogen on their path. The nitrogen then de-excites, emitting UVB (280 nm - 315 nm) and UVC photons (100 nm - 280 nm) with a main UVB peak at 337.1 nm. At normal pressure, about twenty photons are emitted per one MeV of energy released. Detecting α particles through them indirectly by measuring the UVs is studied since those past years because photons have a significant longer path in air, allowing remote detection.

A key limitation is that UVB photons are part of the UV solar emission spectrum that reaches the ground, along with emissions from many commonly used light sources. This restricts detection capabilities to dark environment. In contrast, UVC photons could enable remote measurement of alpha contamination even in daylight or indoor lighting. In this context, the SolarBlind prototype, aimed at performing "alpha imaging", has been developed, with the ambition to perform measurements in daylight environment.

The alpha imaging part of SolarBlind is an important aspect of the detector. Characterizing alpha surface contamination on industrial infrastructures such as gloveboxes or storage spaces is a necessary aspect of dismantling planning and safe equipment use. Obtaining rapid images of the intensity and position of α emitters thanks to alpha imaging is an asset.

The SolarBlind prototype is the following step of the proof-of-concept developed in collaboration between CEA- List and CEA- Irfu in 2021. This proof of concept showed that α particles can be detected from a distance under indoor light by coupling a photocathode with a micropattern gaseous detector, Micromegas (MICRO MEsh GAseous Structure). An 11 MBq 241Am source was sucessfully detected through the UVC created by α particles. The 241Am source was located in front of the setup at distances varying from 10 cm to 40 cm. Duration of exposures were between 1 minute and 2 hours.

The current SolarBlind prototype is divided into three main parts. An UV grade lens with large aperture that focuses surrounding lights into a photocathode with a higher quantum efficiency in the UVC than in the UVB. When collected by the photocathode, UVs photons will be converted into photoelectrons that are amplified through the gas-filled box and the Micromegas inside. Finally, the photoelectrons interact within the sensitive area. The sensitive area is based on the Timepix technology, developed by the international collaboration Medipix led by CERN. It consists in a matrix of 256×256 pixels with a 55 µm pitch. Timepix is an ASIC whose specific function is photon counting. It's a time framed based detector. The readout electronic of the Timepix chip provides 2D frames. The position and intensity of the charges collected are observed on the frames. Coupled with knowledge of the setup, we can trace the direction in which the source is located.

SolarBlind prototype is currently undergoing robustification and each step of the manufacturing process is carefully characterized. Preliminary experiments are conclusive in terms of detection of UV particles from an UV spot, 30 cm apart from the lens. The setup faces lot of challenges in terms of measurement time and repeatability. A particular effort is also made regarding the coupling technics between the Micromegas and the Timepix chip, which is currently one of the major limitation. After improving the prototype, further experiments will be carried out with a 241Am source in laboratory.

#04 - Research Reactors and Particle Accelerators / 191

#4-191 TRIPOLI-4 model of the JSI TRIGA Mark II reactor applied to experimental fission chamber neutron profiles measurements

Author: Clément Fausser[1]

Co-authors: Loic Barbot [1]; Vladimir Radulović [2]; Anže Pungerčič [2]

[1] *CEA/IRESNE/DER/SPESI/LDCI*

[2] *Jožef Stefan Institute*

Corresponding Author: loic.barbot@cea.fr

This article focuses on the fission chamber axial profiles performed by the CEA LDCI lab within the JSI TRIGA Mark II reactor during a bilateral CEA/JSI experimental campaign. Discretized neutron flux distributions at reduced power are experimentally assessed in different locations inside the reactor core. Four different irradiation locations were specially identified for potential further innovative nuclear instrumentation developments and qualification: central channel (highest neutron flux), small measuring positions in-between full elements (unperturbed environment), large triangular channel and peripheral channel (called F8, within the thermal neutron bump at the outskirt of the core). Different irradiation environments were evaluated: in air solely for the triangular channel, in water for both central channel, measuring position n° 17 and F8 irradiation channel. For each of these locations, local fission rate measurements were performed using uranium-235 and uranium-238 miniature fission chambers, fabricated at the CEA Cadarache fission chamber workshop, forming neutron flux profiles using a JSI pneumatic driven system ensuring precise and reproducible fission chamber positioning. Detector acquisitions were achieved using the recently industrialized Libera MONACO 3 system dedicated to fission chamber measurements in any neutron flux range conditions. Those absolute measurements were extended to altitudes above and under reactor support grids to assess the ability of the TRIPOLI-4 modeling to calculate neutrons flux outside the reactor fuel region.
Providing those recent measurements, the calculation to experiment comparison results aim at improving neutron transport simulations, increasing the reliability of the characterization of the reactor's neutron calculation scheme and helping future characterization of the TRIPOLI-4 gamma calculation scheme under development.

Such specific calculation to experiment benchmarks contribute to the constant refining calculation methods and numerical tools for nuclear instrumentation developments in support of future reactor experimental campaigns, and also highlighting the importance of calibrated fission chambers in the development of innovative nuclear instrumentation and the understanding of reactor behavior.

#09 - Environmental and Medical Sciences / 192

#9-192 Real-Time Proton Therapy Monte Carlo Simulations in Highly Parallelised Systems

Authors: Declan Garvey[1]; Gabriela Llosá Llácer[1]; Fernando Hueso González[1]

[1] *Instituto de Física Corpuscular, University of Valencia*

Corresponding Author: declan.garvey@ific.uv.es

Proton therapy represents an advancement in modern brain cancer treatment, offering high precision in targeting tumours while sparing healthy brain tissue. A significant challenge still faced in proton therapy is uncertainty in the depth of proton penetration, which critically impacts successful treatment. The current leading candidate to tackle this problem is prompt gamma-ray monitoring, showing great promise in minimising collateral damage to healthy tissue. These techniques rely heavily on Monte Carlo simulations, which can take up to several hours to produce reliable results. However, treatment lasts approximately 2 minutes, and as such the simulations provide valuable insights only after treatment has been completed.

For a pencil-beam treatment plan of a typical tumour size, a simulation of ~1000 proton beams is required. If computation time of single proton beam could be reduced to an order of one tenth of a second, the entire simulation would be complete in under two minutes, matching the irradiation time of a patient in each treatment session. This reduction would allow real-time synchronisation of the simulations with beam delivery, enabling an alarm signal to be issued if a large deviation was observed between the experimental measurement and the simulation, before proceeding with the next beam treatment.

To achieve these simulation times, standard Monte Carlo simulation engines, even if parallelised in several CPU threads, have shown to be insufficient. Therefore, parallelisation of these algorithms in architectures with a higher degree of parallelism is the theoretical solution to the problem. A promising candidate for this purpose is SYCL (SYstem-wide Compute Language), a cross-platform and hardware-agnostic language that supports parallelisation on both GPUs and FPGAs. We are implementing pencil-beam dose calculation algorithms in this framework with promising results: computational speed has been increased by one order of magnitude. The future aim of this project is to gradually increase the complexity of these models to include nuclear reactions for prompt gamma-ray production, gamma-ray transport in the patient, and detection in an external scintillation detector used for monitoring, using established Monte Carlo simulation engines as a reference. The finalised algorithms will then be benchmarked against other hardware-specific methods such as cuda and OpenMP.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 193

#5-193 Detection of 2.223 MeV γ Rays for Water Identification in Spent Nuclear Fuel Assemblies

Author: Damilola Folley[1]

Co-authors: Brendan Green [1]; Kartikey Mathur [2]; Steve Croft [1]; Andrew Kennedy [1]; Robert Mills [3]; David I Hambley [3]; Malcolm Joyce [1]

[1] *Lancaster University*

[2] *School of Engineering, Lancaster University, United Kingdom*

[3] *National Nuclear Laboratory*

Corresponding Author: d.folley@lancaster.ac.uk

The detection of 2.223 MeV γ-ray emissions resulting from neutron capture on hydrogen, as a means to monitor water presence in spent nuclear fuel (SNF) assemblies is described. Water detection is crucial because water ingress into dry storage systems or other containment environments poses safety risks and potential criticality concerns. This study thus aims to explore the use of the characteristic 2.223 MeV γ rays for reliable detection of water within SNF assemblies, with a focus on understanding how neutron interactions, such as scattering and absorption, impact the γ-ray production and detection in different fuel configurations. This approach will provide a non-invasive and accurate approach for nuclear monitoring and maintaining nuclear safety. To achieve this objective, we employ a combination of experimental testing and computational modelling using Monte Carlo simulations. A GR5021 high-purity germanium (HPGe) detector has been used to measure γ-ray emissions from neutron capture events under controlled conditions. Several californium-252 (Cf-252) point neutron sources were used to provide a well-characterised neutron field representative of those in SNF environments. Various test configurations were created using high-density polyethylene (HDPE) blocks and 3D-printed metal foams such as SS316L stainless steel, zinc oxide, and tin oxide. The HDPE blocks serve as analogues to simulate the neutron moderation characteristics of water whilst the metal foams serve as analogues for fuel-containing materials. Water slabs of varying thicknesses between 2 mm and 40 mm were also introduced to allow for a controlled study of how neutron capture rates and γ counts varied with water content. Each of these materials was chosen to replicate the geometric and compositional characteristics of real fuel assemblies and to study neutron capture in the thermal and epithermal regions. Results consistently showed the detection of 2.223 MeV, with γ counts changing consistent with expectations as material thickness increased. In parallel with the experimental testing, MCNP simulations were performed to model neutron propagation and γ-ray production in identical configurations. Both thermal and epithermal neutron regions were examined to capture the full spectrum of neutron interactions. The simulation results showed strong agreement with experimental results and confirmed the accuracy of the computational approach. Both methods demonstrated that material composition and geometry significantly impact neutron behaviour and γ-ray emissions. Simulations of heterogeneous fuel assemblies, such as those in advanced gas-cooled reactors and prototype fast reactors were also performed. These simulations highlight the importance of considering specific assembly configurations, as material heterogeneity can cause localised variations in neutron flux and γ-ray production. The overall results suggest that the 2.223 MeV γ-ray is a reliable and sensitive indicator for detecting water in SNF assemblies, with significant implications for nuclear safety and fusion reactor environments.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 194

#6-194 Directional Detection and Fissile Material Identification: Results from tests campaign at STUK and SCK-CEN with the nFacet 3D detector

Author: Kaciel Béraud[1]

Co-authors: Antonin Vacheret [1]; Gregory Lehaut [1]; Kari Peräjärvi [2]; Sakari Ihantola [3]

[1] *Normandie Univ, ENSICAEN, UNICAEN, CNRS/IN2P3, LPC Caen*

[2] *Radiation and Nuclear Safety Authority*

[3] *NeutronGate Oy*

Corresponding Author: beraud@lpccaen.in2p3.fr

Robust and timely detection, localisation and identification of a radioactive source are critical to applications in security, verification treaty and decommissioning. These measurements are usually done with different instruments. Here, we present results from a detector system relevant to security, non-proliferation or decommissioning activities. Nfacet 3D is a segmented dual-scintillator detector sensitive to gamma-rays and neutrons. It's a directional detector system composed of 64 polyvinyl toluene (PVT) voxels arranged in a 4 × 4 × 4 lattice, each voxel is equipped with a 6LiF:ZnS(Ag) phosphor screen to capture neutrons. The two types of sensitive material enable a simultaneous detection of neutrons and gammas through Pulse Shape Discrimination (PSD) of the scintillation signals. The segmentation of the detector enables the reconstruction of the direction of the gamma-ray and neutron fields as well as count rates and energy deposited that depends on the energy of the incoming radiation, which in turns provide basic information for identifying and localising the source of radiation. We will present results on those measurements and the achieved directional resolution, bias and distance. The directionality and range of the system have been assessed at the STUK facility, Finland in September 2024. We characterised the response of the system for a range of angles and distances with various well-calibrated gammas and neutrons sources. During this measurement campaign, we were also able to test the capability of the system to sense the presence of a neutron source at large distance of tens of meters in an open field. We have also tested the ability of the system to localise the position of a source without prior knowledge of its true position using iterative placement of the detector. The detection range is at least 50 meters, making use of the skyshine effect to detect the source at greater distance than 30 meters. We achieve an angular resolution of 10 degrees at 50 meters with 1,500 neutron counts. The system is also capable to reconstruct the direction of origin of gamma-ray radiations within the detection range, then we assessed the angular resolution and the bias of the system with a Co-60 and a Cs-137 source at fixed distance. We achieve a resolution of less than a degree with 450,000 counts at 20 meters. The source identification capabilities of the system have been assessed during the BeCamp2 measurement campaign, a technical exercise in the context of Verification Treaty measurements, done at the SCK CEN laboratory, Belgium in September 2023. The objective where to determine the potential of different technology to identify undisclosed fissile nuclear material and shielding objects based on reference templates. Using key features of the fissile matter, we were able to distinguish between Uranium-based and Plutonium samples. The detection of U235 was done indirectly with high-energy gamma-rays spectra. The Plutonium was identified using both fast and thermal neutrons in combination with gamma-ray spectra.

#04 - Research Reactors and Particle Accelerators / 195

#4-195 Multi-Particle irradiation of CubeSat components using the ENEA Distributed Facility: Experimental Setup and Radiation Response Analysis

Author: Michele Croia[1]

Co-authors: Alessandro Ampollini [2]; Alfonso Santagata [1]; Andrea Colangeli [2]; Androniki Vezyri [3]; Barbara Bianchi [1]; Concetta Ronsivalle [2]; Emiliano Trinca [2]; Giulia Bazzano [2]; Guglielmo Pagano [2]; Luca Falconi [1]; Luigi Scaramuzzo [1]; Maria Denise Astorino [2]; Matteo Cesaroni [1]; Nicola Fonnesu [2]; Nunzio Burgio [1]; Paolo Nenzi [2]; Pierpaolo Ricci [1]; Stefano Loreti [2]

[1] *ENEA - Casaccia research center*

[2] *ENEA - Frascati research center*

[3] *Physics Department, University of Ioannina, 45110 Ioannina, Greece*

Corresponding Author: michele.croia@enea.it

The ENEA distributed irradiation facility offers a versatile environment for irradiating samples and conducting experiments with various particles, including neutrons, protons, and electrons. This facility comprises several advanced sub-facilities: the TAPIRO fast nuclear research reactor as a fission neutrons source, the TOP-IMPLART linear accelerator capable of producing proton beams up to 71 MeV, the neutron generator (FNG), which generates neutrons of 2.5 MeV and of 14 MeV, and the REX linear accelerator for electron beams up to 5 MeV. Together, these facilities support a broad range of irradiation experiments and are especially valuable for studies requiring exposure to multiple particle types on the same sample.

In a previous work we evaluated with the SPENVIS code the energetic spectra at 6000 km of altitude from the Earth's surface, obtaining such a quantity for trapped particles (TP) and Galactic Cosmic Rays (GCR). The primary purpose was to compare the mean energy of TP and GCR with our facilities' energy. We found that our distributed facility could be representative of the trapped electron (TP-e) and proton (TP-H), which are the dominant radiation terms, up to the inner Van Allen Belt. In the same work, taking as reference the irradiation condition of the ABCS mission and with the aid of some FLUKA simulations, we presented the design of a set of experiments to be carried out on our distributed facility.

The current work deals with the presentation and discussion of the first results of such irradiation experiments carried out with electrons (REX), neutrons (TAPIRO and FNG) and protons (TOP-IMPLART) using as target a dummy 1 unit CubeSat mounting a RadFET chip like the one used in the ABCS mission to compare the dose measured under irradiation in the distributed facility with the outcomes of our simulations tools.

From such experimental outcomes, supported by further simulations in which more refined modeling and numerical techniques will be implemented, we will be confident in enhancing our design tools to support the radiometric characterization of components and systems used, at least in near-Earth spatial missions.

#07 - Decommissioning, Dismantling and Remote Handling / 196

#7-196 NANOPIX3: a compact multimodal gamma spectro-imager for enhanced imaging

Author: Quentin Gendre[1]

Co-authors: David Fras [1]; Guillaume Amoyal ; Jean-Philippe Poli [1]; Kamel Benmahi [1]; Vincent Schoepff [1]; Yoann Moline [2]

[1] *CEA*

[2] *CEA/DRT/LIST/DM2I/SCI/LCAE*

Corresponding Author: quentin.gendre@cea.fr

Across nuclear sectors, localizing, visualizing and identifying radioactive objects is crucial for security and safety. With uses ranging from waste management and decommissioning to nuclear medicine and homeland security, finding so-called radioactive hotspots has been at stake for many decades. For over thirty years, CEA List has been working on compact and miniaturised gamma imaging systems based on semiconductor hybridised pixelated detectors from the Medipix collaboration, Timepix, and developed the Nanopix gamma camera prototype, today used in the field. This system uses a MURA rank 7 coded aperture and a sensitive area of about 2 cm² for 1 mm thick. However, despite its performance, the system lacks a spectroscopic information and has a narrow field of view (44°) that can interfere with real-life conditions. In a scene with multiple radioactive sources of various energy ranges and activities, some hotspots can easily be overshadowed by the intensity of others while some, located further than the field of view, will not be localised at all.
Recent developments using a newer Medipix technology, Timepix3, gave birth to a new prototype of the most compact and miniaturised coded-aperture spectro-imaging system in the world, Nanopix3. Nanopix3 is composed of a Timepix3 detector and a rotating coded-aperture managed by two micromotors. While the former technology only gave access to information about the position and the time of interaction or about the energy deposited in a synchronous way, the latest gives simultaneously access to all three values as a continuous flow of data. This difference in operation allows Nanopix3 to couple different modalities of imaging: coded aperture imaging and Compton imaging. Pairing both techniques brings the advantages of both into a single camera while minimising their respective drawbacks. Reconstructing hotspots images in coded-aperture modality can be tricky if the source is located on the edge of the fully coded field of view (FCFOV) of the camera. In this area, called the partially coded field of view (PCFOV), hotspots will be reconstructed as well as artefacts, or ghost sources, that appear mathematically during the reconstruction of the image. Late studies have shown that it is possible to extend the size of the reconstructed gamma image to include both the PCFOV and FCFOV, which eventually, provide to the camera a much wider field of view in coded aperture modality. Still, this method does not help distinguishing the real source from the so-called ghost one. The use of Compton imaging comes as a decision support by providing localisation information on a field of view of 2π sr. We tested Compton imaging in laboratory conditions and were able to reconstruct Ba-133, Na-22, Cs-137 and Co-60 radionuclides. In a complementary way, bringing spectroscopic information into the measurement, thanks to spectroimaging, helps to identify gamma-emitting radioisotopes by analysing their specific spectral signature. Timepix3's spectroscopic abilities make it possible to reconstruct energy peaks up to 1.5 MeV and laboratory tests showed an energy resolution of 5.6 keV (9.4 %) at 59.5 keV for Am-241, 27.24 keV (4.1 %) at 661.7 keV for Cs-137 and 47.4 keV (3.5 %) at 1.332 MeV for Co-60 using a 1 mm thick CdTe semiconductor hybridised Timepix3 chip. Reconstructing hotspots by taking into account the energy spectrum can reveal some hidden hotspots that were obscured by other sources, providing complementary information about the different elements in a scene. With up to four different radionuclides in a single measurement in laboratory conditions, it is possible to identify each hotspot independently. Nanopix3 will also be tested on the field in forthcoming measurements.
Overall, the development of Nanopix3 provides a solid foundation for the future of compact gamma imaging systems, offering enhanced and more complete analysis to end users by performing spectro-imaging in two different modalities, coded aperture imaging and Compton imaging, and responding to the ever-increasing need for safety and security in the nuclear industry.

#02 - Space Sciences and Technology / 197

#2-197 Overview of the GlowRIA radiation monitor: a miniaturized fiber optic dosimeter compatible with Cubesat missions

Author: Nourdine Kerboub[1]

Co-authors: Julien Mekki [1]; Nicolas Balcon [1]; Pierrick Cheiney [2]; Steven Fosset [2]; Sylvain Girard [3]

[1] *CNES*

[2] *EXAIL*

[3] *Université Jean Monnet, Saint-Etienne, France*

Corresponding Author: nourdine.kerboub@cnes.fr

Abstract - Optical fiber based dosimetry is a fast growing research topic, that in most of the cases exploits either Radiation Induced Attenuation (RIA) or Radiation Induced Luminescence (RIL) processes in silica or plastic based fibers. The RIA based optical fiber dosimetry was developed and greatly improved in the particle accelerator domain, and was later on extended to space applications during the ALPHA mission that launched the first optical fiber based dosimeter (the LUMINA experiment) to the International Space Station (ISS). This experiment is based on the use of two several kms long spools of fiber that have been specifically developed and selected for its dosimetric properties. More specifically, it is able to detect radiation without dependence to the dose rate, temperature, or type of particles which are important aspects for space applications. LUMINA was installed in August 2021 by ESA astronaut Thomas Pesquet and has shown great performances in orbit at monitoring the radiation levels inside ISS, detecting for instance each pass inside the most intense region of the 400 km orbit called the South Atlantic Anomaly. This experiment is well suited for the ISS missions associated with very low dose rates, low doses thanks to its very long spool of fiber. In order to target other missions in satellites and cubesats, characterized by higher radiation constraints, we decided to adapt the existing architecture of the experiment and create a miniaturized space version named GlowRIA. One important difference to mention is that the LUMINA experiment was developed to be used in ISS environment inside COLUMBUS module for which it was not mandatory to use radiation hardened electronics for the acquisition chain as the radiation levels is low (about 300 uGy/h) whereas in the case of GlowRIA, the targeted environment requires the use of radiation tolerant or hardened electronics. GlowRIA is using the same optical fiber as LUMINA with a shorter length of several hundreds of meters, that can be adjusted to the expected dose for the mission. New optoelectronics (laser and photodiodes) components have been selected to reduce their electrical consumption and form factor. Concerning the electronic readout, a radiation tolerant microcontroller has been implemented to replace the raspberry board that was used in the LUMINA experiment. With this architecture, the dosimeter could resist to both cumulated dose effects and single event effects.
This paper intends to present the architecture of the GlowRIA dosimeter, including the results of the characterization tests that were performed during its development to evaluate the performance of the equipment. More specifically, we tested the ability of the dosimeter to resist under harsh conditions in orbit such as vacuum, large temperature variations, electromagnetic perturbations and total ionizing dose. We also plan to present the different approaches we could use to adapt such dosimeter to different space missions and their related radiation environment.
Preference : Oral
Session : Space Sciences and Technology

#04 - Research Reactors and Particle Accelerators / 199

#4-199 Development of an Event Tracking Feature in OpenMC for Neutron Noise Analysis.

Author: Michel Saliba[1]

Co-authors: Andreas Pautz [2]; Oskari Pakari [3]

[1] *École Polytechnique Fédérale de Lausanne*

[2] *Ecole Polytechnique Fédérale de Lausanne*

[3] *EPFL*

Corresponding Author: michel.saliba@epfl.ch

We outline the development of explicit neutron noise simulations via Monte Carlo codes to determine integral kinetic parameters such as the prompt decay constant of fissile systems. Experimentally, measuring the prompt decay constant during steady-state reactor operation offers a non-invasive way to determine point kinetic parameters, which are important for predicting reactor behaviour during transients or can be used for code validation or nuclear data feedback. Simulating detector responses explicitly (i.e. tracking individual events as opposed to averaging scores) is necessary in certain scenarios, where e.g. the timing information of events is important –such as noise, time-of-flight or imaging experiments. Currently, this kind of capability is available in export controlled codes such as MCNPX PoliMi or MCNP 6.3. For this purpose, we present a new event tracking feature that we developed for OpenMC. OpenMC is a community-driven, open-source Monte Carlo radiation transport code. Tracking individual interactions in Monte Carlo transport can be memory-intensive, and thus the implementation consists of a suite of customizable filters—including reaction type, energy, cell, and material—in which it discriminates then saves single neutron interaction information. The user can also choose to save to a separate external file in two formats: OpenMC's native HDF5-based format or Monte Carlo particle lists (MCPL). With the main focus being on neutron noise simulation, we present how to use the new event tracking feature and how to determine integral kinetic parameters, such as the prompt decay constant, via the Rossi-alpha method. The Rossi-alpha method is a neutron noise analysis technique used to estimate the prompt neutron decay constant (α), which characterizes the time-dependent behaviour of neutron populations in a reactor. In this method, the time intervals between detected neutron events are measured and analysed statistically via auto-correlation. To achieve results to match with experiment we propose this simulation procedure: first, a k-static calculation is run, and the fission distribution is saved after convergence. This is followed by an external source simulation, where the source is defined as the saved distribution from the previous k-static simulation. In the external source simulation, filters from the event tracking feature are set to record individual fission events in the external file. After collecting a sufficient number of fission events, the Rossi-alpha method is applied to the data to calculate the prompt decay constant via curve fitting. We verified our OpenMC results with simulations conducted using Serpent 2, employing benchmark geometries like Godiva and Jezebel, as well as a model of the CROCUS zero-power research reactor. JEFF 3.3 was utilized as our library for nuclear data in both OpenMC and Serpent 2. We also provided a first validation case of the feature for critical and subcritical states of the CROCUS reactor from previous experimental campaigns. The calculated prompt decay constants in OpenMC showed agreement with the simulation in Serpent 2 as well as with the experimental data of CROCUS. Our results therefore confirm the reliability of the new feature in accurately simulating noise experiments. The feature is intended to be part of the official OpenMC release and paves the way to open source Monte Carlo simulations of reactor physics experiments.

#04 - Research Reactors and Particle Accelerators / 200

#4-200 Optimization of a new neutron imaging station at the CROCUS zero-power reactor

Author: Michel Saliba[1]

Co-authors: Andreas Pautz [2]; Eberhard Lehmann [3]; Oskari Pakari [4]; Vincent Lamirand [2]

[1] *École Polytechnique Fédérale de Lausanne*

[2] *Ecole Polytechnique Fédérale de Lausanne*

[3] *PSI*

[4] *EPFL*

Corresponding Author: michel.saliba@epfl.ch

We outline the development and optimization of a neutron imaging beamline at the CROCUS zero-power research reactor by the means of Monte Carlo simulations. Neutron imaging is a radiographic technique that uses neutrons, providing advantages due to its sensitivity to light elements, such as hydrogen. It has the potential to support neutron imaging, serving as a neutron source for this technique. Neutron imaging provides a non-destructive way to analyse internal structures and material compositions in which are found important for applications in material science, nuclear engineering, and cultural heritage studies. For example, new hydrogen-based materials (Yttrium hydrides moderators) are being explored for small modular reactors, and neutron imaging is useful for iterating and verifying these new materials. CROCUS has a unique geometrical properties that need to be taken into account in the design of a neutron imaging station. For instance, an already existing irradiation channel in the concrete shielding is conveniently located at mid-core height, non-tangential but direct, allowing for flexible detector placement in a range from 0.5 to 7 meters to the core centre. The irradiation channel has an aperture of 30 cm, thus taking the advantage of the collimated neutrons exiting the core and entering the channel, making them suitable for neutron imaging. A neutron imaging detector can be flexibly installed behind the channel. In order to estimate neutron fluxes and spectra in possible detector locations, we employed the Serpent 2 Monte Carlo code. Initial simulations revealed that the reactor's default configuration was unsuitable due to a very low neutron output in the irradiation channel behind the 30 cm water thick reflector of CROCUS. To address this, several design iterations were tested, including introducing an air channel (i.e. an empty tube submerged into the water) in the reactor reflector to increase neutron intensity. Our simulations show that an added air channel, namely, a plastic tube of diameter 10 cm and 25 cm length, would increase the neutron flux by 50 folds. Other parameters, like the air channel's diameter and length, were further optimized, e.g. by shortening the channel and allowing a water section between it and the fuel to further convert fast neutrons to thermal neutrons without significantly decreasing flux. The reactor configuration with optimized air channel was then chosen as the basic design for a proof-of-principle experiment.

Following the computational optimization, first neutron radiography measurements will be performed at CROCUS in Spring 2025. The imaging system is composed of a commercial neutron imager ("MIDI") which includes an ANDOR DW936N-#BV (Ikon-L) CCD camera cooled to −62℃, paired with a Zeiss Makro-Planar 2/100 ZF.2 T* lens, providing a 77 mm x 77 mm field of view (up to 150 mm * 150 mm possible, depending on the beam size). The system captures images at a resolution of 2048 x 2048 pixels with a pixel size of 0.038 mm, a focal length of 0.5 m, and a readout speed of 0.33 µs per pixel. We plan to further optimize these parameters to produce the highest possible resolution of neutron images. In this contribution, we present the design optimization and results of the first experiments and compare them to similar neutron imaging efforts such as the station in VR-1 reactor in Czech republic and AKR-2 in Germany. Further developments are planned to enable computed tomography, mixed fast and thermal imaging and gamma radiography. Once commissioned, we also plan to open the neutron imaging facility to other scientific and industrial users as a potential national platform for neutron imaging, in support of higher-end imaging facilities like the ones (NEUTRA, ICON, BOA) at the Swiss Spallation Neutron Source SINQ, PSI.

#09 - Environmental and Medical Sciences / 201

#9-201 The POSiCS handheld gamma-ray camera for radio-guided surgery

Authors: Alberto Gola[1]; Aramis Raiola[2]; Cyril Alispach[2]; Domenico della Volpe[3]; Fabio Acerbi[1]; Habib Zaidi[4]; Hossein Arabi[4]

[1] *Fondazione Bruno Kessler*

[2] *Université de Genève*

[3] *Universite de Geneva*

[4] *Hopitaux Universitaire de Genève*

Corresponding Author: domenico.dellavolpe@unige.ch

At the frontier between research and innovation, POSiCS is a project aiming to build a scalable and handheld gamma-camera for radio-guided surgery. The project is shared between three partners: the University of Geneva, the University Hospital of Geneva and the Fondazione Bruno Kessler. These consortium of institutions have been granted an European grant for innovation and have filled together a patent for this innovative technology and are starting to develop business activities for the European market.

Targeting the imaging of lymph nodes for biopsies in the context of breast cancer and cutaneous melanoma, the camera aims at reducing the invasiveness of the sentinel lymph node biopsy procedure by imaging above the skin while improving the surgery success probability. Patients undergoing sentinel lymph node biopsy are injected a pharmaceutical radio-tracer that binds to the cancerous cells. The radio-tracer used is technetium-99m and produces distinct 140.5 kilo electron-volt gamma-ray emission line via isomeric transition.

For such an application, we designed and produced a wireless handheld gamma camera, based on an innovative position-sensitive linearly graded silicon photo-multiplier technology. By using an array of 3x3 tiles of linearly graded silicon photo-multiplier, the position of a beam of light can be reconstructed with a sub-millimeter resolution over a large area of nine 10x10 mm2 chips for a total area of about 9 cm2 with only 8 readout channels. The 140.5 kilo electron-volt gamma-rays are converted to optical photons by a lutetium–yttrium oxyorthosilicate pixelated (30x30) 1.1 mm pitch and 2 mm thickness scintillator. A parallel-hole tungsten collimators is used to assign each pixel position a dedicated gamma-ray direction. Two types of collimators a high-resolution collimator and a high-sensitivity collimator can be interchanged depending on the imaging application. With only 8 channels and weighting less than 1 kilogram for 900 pixels, the power consumption and size of the camera is minimized thus making it a portable wireless device and operable on a battery.

Small non-linearity in energy and position reconstruction of the acquisition chain as well as the non-uniformity in the trigger response require a proper calibration of the camera. In order to correct the end-user image for these effects as well as rejecting background. The calibration of the camera that will be presented. In particular we will present the measurements and corrections of non-linearity as well as energy calibration based on a technetium-99m flood of the camera.

The images are cleaned from the Compton-scattered gamma-rays and from intrinsic radiation of the scintillator. The full reconstruction pipeline from the raw data to the graphical user interface will be presented. All computing and displaying can be performed on a standard laptop and the reconstruction pipeline is able to display without perceived latency the camera recordings even at high trigger rates of about 40 kHz.

From the final images, the position resolution and sensitivity of the device are assessed with phantoms and are compared to Monte-Carlo simulation. We evaluated the spatial resolution, across the camera surface, using an source placed behind a block partially covering the camera. The edge spread function of the block allowed us to measure a resolution of 5.5 mm with a source positioned 15 mm for the high-sensitivity collimator in agreements with our simulations. Additionally, we measured the photo-peak energy resolution of 18% at 140.5 kilo-electronvolts.

The results of an on-going clinical evaluation of the device with mice experiments will be shown. In this study, 10 mice were injected with malignant cells. After a couple of weeks, to let the cells grow,

each mouse is injected with a technetium-99m pharmaceutical radio-tracer. Shortly after the injection, the mice are imaged with an animal single-photon emission computed tomography scanner and compared to the images from the POSiCS camera.

#11 - Education, Training and Outreach / 202

#11-202 Testimonial of an Educational Immersion Experience in Fukushima Prefecture: A Technical and Sociological Approach

Author: Franck Falco[1]

[1] *Aix-Marseille University*

Corresponding Author: franck.falco@univ-amu.fr

The Health and Safety Department of Aix Marseille University trains future technicians specializing risk management. Among its programs is the Bachelor's degree in Radiation protection and Nuclear Safety which able to advise managers about the complex risks in nuclear workplaces as power plants, fuel cycle facilities, research centers or naval propulsion sites.
With the aim of providing new insights into major nuclear accidents and crisis management, Franck FALCO, organized an educational trip with some of his students to Fukushima area in Japan last November.
On March 11, 2011, time stood still on the northeast coast of Japan. An earthquake followed by a tsunami devastated part of the region, leading to a nuclear accident at the Fukushima Daiichi Nuclear Power Plant.
Since the disaster, people had to be relocated across several perimeters, and their return to the land is dependent on several factors, such as the level of soil contamination, the ambient dose rate, and also the willingness of families to come back to their roots being away for more than a decade.
Jointly organized with the Fukushima Dialogue association, this educational trip aims to help bachelor students discover the cumulative effects of the disaster and the nuclear accident on the current and future sociological situation faced by the population. Focused on numerous field visits like interim storage facility or ambient dose rate measurements in forest and various encounters, this immersion aims to demystify the current situation to a foreign audience.
This discussion will highlight the deep desire among the inhabitants of the province to look forward the future without erasing all traces of the past. On a sociological level, the presentation will focus on better understanding the complexity often faced by the scientific community when dealing with a population seeking answers about its present and future.

#04 - Research Reactors and Particle Accelerators / 203

#4-203 Development of the pile oscillation method for the determination of integral cross section data at the AKR-2 training and research reactor

Author: Alexander Knospe[1]

Co-authors: Antonio Hurtado [1]; Carsten Lange [1]; Juan José Gómez Rodriguez [1]; Marco Viebach [1]

[1] *TU Dresden*

Corresponding Author: alexander.knospe@tu-dresden.de

With the growing interest in Generation-IV reactor designs, such as the molten salt fast reactor, new materials are envisioned for use in reactor components, including fuel, structural materials, and coolants. Accurate knowledge of the nuclear properties of these materials is crucial not only for assessing the safety of these designs but also because many of these reactors will operate with neutron energy spectra that differ significantly from those of conventional light water reactors. For example, in chloride-based molten salt fast reactors, various fuel compositions are being considered, with varying uranium enrichment and even potential enrichment of chlorine-37. Once fabricated, these fuel compositions require testing in experimental facilities to validate the predictions of nuclear codes and to ensure the safe operation of the reactor design. To address this need, the NAUTILUS project was initiated at the Chair of Hydrogen and Nuclear Technology using the AKR-2 training and research reactor at TU Dresden. This project aims to develop experimental and simulation expertise to establish an experimental platform for validating nuclear codes and measuring nuclear data. Among the project's key objectives is the development of the pile oscillation method for measuring integral cross section data. This contribution presents advancements in developing this method at the AKR-2 training and research reactor. The experimental design of the pile oscillation device, driven by a linear motor axis, and the detector setup, comprising four pairs of He-3 proportional counters, are described. The drive mechanism, being fully customizable, is restricted in this contribution to a trapezoidal profile, oscillating the sample between the core center and a position 20 cm outside the core, which is well-suited for measuring absorption cross-sections. Signals from the detectors are acquired using a custom ZYNQ FPGA-based data acquisition system at AKR-2. This system registers individual neutron detection events, enabling statistical analysis and user-defined dwell times during post-processing. The signals are then transformed to the frequency domain and processed to obtain the cross-power spectral density between different detectors to reduce biases. To validate the feasibility of this method at AKR-2, experimental data obtained through pile oscillation measurements on foils of natural materials were compared with simulation data generated using the Monte Carlo transport code Serpent 2.2.1. The predicted self-shielding factors for an increasing number of stacked foils of natural indium and iridium show good agreement between simulation and experiment. Furthermore, results for samples of natural gold, indium, iridium, copper, zirconium, and carbon are presented. As expected, the method demonstrates good performance with strong absorbers, yielding results that agree well with simulations, with C/E-1 being below 6 %. For weakly absorbing materials, the method provides generally good results, with C/E-1 ranging between 40 % for copper and 1000 for carbon, where no good agreement was expected, due to the low absorption cross section. These results demonstrate that the developed experimental design, data acquisition, and processing methods for the pile oscillation experiment can be successfully employed at AKR-2. This provides a valuable tool for obtaining integral cross section data and validating numerical models of the AKR-2 reactor.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 204

#5-204 Different Approach Method for RCS Flow Rate Measurement to be Used in i-SMR

Author: Sanghoon Bae[1]

[1] *Korea Atomic Energy Research Institute*

Corresponding Author: shbae@kaeri.re.kr

The small modular reactor which of development is underway has 170 MW power. As supposed, this reactor is a type of integrated with core, pressurizer, steam generator, and reactor coolant pump, which are all enclosed by the containment vessel as pressure barrier. Despite lots of advantage of the small modular reactor like enhanced safety and less severe accident risk, the narrow space in the structure leaves many constraints of sensors and their assembly installing. Moreover, the environmnetal condition inside containment vessel gets much severer than ever including radiatioin condition. In particular,the area surrounding core is expected so high neutron flux that may impair the sensor function and accelerlate degradation by embrittlement.

The reactor coolant is forced to circulate by four channels of reactor coolant pumps which keeps running during normal operation including startup and shutdown. This parameter is so vital to run reactor operation by keeping cooling margin to the safety level and should also be continuously monitored as a safety variable that send a signal to the reacotr protection system and post accident monitoring system in order to ensure the safety of the plant.
The way to accurately measure the flow rate in the reactor coolant of the small modular reactor is firstly using ultrasonic flow meters, challenges such as turbulent flow conditions and thick wall-induced signal attenuation must be addressed. This study explores technical solutions to mitigate these issues, enhancing measurement accuracy under such constraints.Mitigating turbulence effects should be firstly considered and employing multi-path ultrasonic flow meters was designed so that it can reduce the impact of turbulence by averaging velocities across multiple paths, improving measurement accuracy in complex flow conditions. Additionally, optimizing piping configurations, such as lengthening straight pipe sections or installing flow conditioners, can help stabilize flow and minimize turbulence near the sensor.

The next issue is thick wall attenuation and using low-frequency ultrasonic signals, which are less prone to attenuation through thick walls, is effective for this applications. Furthermore, signal amplification and advanced filtering techniques can enhance signal quality, compensating for attenuation as the ultrasonic waves travel through thick-walled structures. Through these methods, ultrasonic flow meters can be effectively applied in SMR RCS systems, providing reliable flow measurements despite structural and operational challenges.

#10 - Current Trends in Development of Radiation Detectors / 205

#10-205 Assessment of Gamma-Ray Spectrum Transmission with Scintillator Shading Variations for Determining Minimal Transmission Diameter

Author: Tadeáš Zbožínek[1]

Co-authors: Břetislav Mikel [1]; Michal Jelínek [1]

[1] *Brno University of Technology, Czechia*

Corresponding Author: xzbozi03@vutbr.cz

Gamma ray spectroscopy represents a fundamental instrument for the characterisation of gamma radiation and the identification of its sources. The most common approach is the utilisation of scintillator detectors. In this method, the photodetectors are situated in direct contact with the scintillator and are frequently also subjected to gamma radiation. To enhance the stability and reliability of the monitoring process, an optical fibre could be positioned between the two, effectively conveying the signal from the irradiated area to photosensitive electronic components situated in a location that remains outside of the radiation field. Consequently, this eliminates the need for direct exposure of personnel to radiation, thus ensuring safety while facilitating long-term, high-activity, and high-energy monitoring. The measurement is linear in trend and variable with the utilisation of disparate scintillator materials and shapes. Nevertheless, the introduction of optical fibres between the scintillator and the photosensitive equipment presents certain challenges, most notably a reduction in the capacity to recognize gamma spectra. The observed signal degradation is primarily attributed to the diameter of the fibre and several phenomena, including modal and chromatic dispersion, which limit light transmission and ultimately yield a distorted signal. Although plastic fibres with larger diameters and correspondingly sized scintillators are capable of transmitting spectra over relatively short distances, their vulnerability to high-energy radiation significantly limits their applicability in the field of research. In order to address this issue, the optical fibre link was replaced with an adjustable iris, which permits precise regulation of the aperture diameter. This modification enables the simulation and assessment of the fibre's spectral transmission properties. By means of a systematic modification of the iris, the influence of aperture size, and consequently the impact of optical fibre diameter on signal transmission, is addressed. This process allows for the identification of the optimal diameter for the optical link and the determination of the threshold beyond which reliable spectral recognition becomes unattainable. The methodology provides valuable insights into the improvement of spectral clarity and represents the initial step toward effective spectral transmission through silica optical fibres from scintillators. This ensures the reliable identification of ionising radiation sources over longer distances, even in challenging environments characterised by high radiation activity.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 206

#6-206 Differential Die Away and Delayed Neutron Temporal Analysis to Determine Fissile Mass and Isotopes in Uranium Samples

Author: Caryanne Wilson[1]

Co-authors: Oskar Searfus [2]; Shaun Clarke [1]; Sara Pozzi [1]; Igor Jovanovic [1]

[1] *University of Michigan*

[2] *Sandia National Laboratories*

Corresponding Author: caryanne@umich.edu

Special nuclear material is often identified and quantified through gamma-ray spectroscopy or characteristic neutron signatures. However, the passive gamma signature of ^{235}U can be easily shielded, and its passive neutron signature is negligible. To address this challenge, we propose using a neutron generator to probe uranium and induce fission, from which the prompt and delayed neutrons can be used to quantify the isotopic content. In this work, a ^{4}He-based fast neutron detector was used to perform differential die away (DDA) analysis while the delayed neutron emission time profile was simultaneously measured with moderated ^{3}He detectors. High-pressure ^{4}He scintillators were chosen for this application due to their ability to record the fast neutron spectrum and their intrinsic insensitivity to gamma rays when a ~300 keV energy deposition threshold is applied. The detectors and neutron generators were housed in a custom well-like cubic structure that comprised inner layers of ordinary high-density polyethylene (HDPE) and an outer layer of borated high-density polyethylene (B-HDPE) to eliminate room-return neutrons. The intensity of the measured DDA signal is related to the fissile mass of the sample, such that this signal can be used to quantify fissile mass. The delayed neutron time profile provides information on the fissile material composition in the sample. When these two measurements are combined, both the fissile mass and isotopic composition of the sample can be determined. Experiments with uranium were conducted at the National Criticality Experiments Research Center at the Nevada National Security Site. Two MC-15s, consisting of 15 moderated ^{3}He tubes each, were used to measure delayed neutrons, and an Arktis S670 ^{4}He detector was used to measure prompt neutrons. Four uranium source configurations were measured: a 3.7 cm highly enriched uranium (HEU) sphere, the same 3.7 cm HEU sphere surrounded by 1.2 cm of depleted uranium (DU), a 3.8 cm DU sphere, and a 3.8 cm DU sphere surrounded by 1.3 cm of HEU. A Thermo-Fisher P211 D-T neutron generator emitting ~10 μs pulses with ~10^{6} neutrons per pulse at 100 Hz, served as the interrogating source. The detectors were surrounded with HPDE and B-HDPE in a box configuration with open space in the center. A large amount of polyethylene was used to provide a consistent and intense thermal neutron environment to drive the DDA signature. The source was placed in the center of the box, and the D-T generator was placed at the bottom of the box. The generator was operated in one-minute on, three-minutes off cycles. The DDA time profiles were measured between pulses, while the delayed neutron time profiles were observed in the three minutes following generator shutoff. Since ^{235}U and ^{238}U have different delayed neutron group yields, analysis of the measured delayed neutron time is used to reconstruct the isotope's relative abundance while the DDA signal is used to determine the fissile mass.

#02 - Space Sciences and Technology / 207

#2-207 Timepix3 Neutron Detector for the Search of Water on the Lunar Surface

Authors: Benedikt Bergmann[1]; David Netusil[2]; Hugo Natal da Luz[3]; Hugo Nathan Cintas[2]; Jindrich Jelinek[4]; Milan Malich[2]; Robert Filgas[5]; Stefan Gohl[2]; Tomas Slavicek[6]

[1] *Institute of Experimental and Applied Physics*

[2] *IEAP CTU Prague*

[3] *ÚTEF*

[4] *IEAP CTU Prague + DPNC, University of Geneva*

[5] *IEAP, CTU in Prague*

[6] *Institute of Experimental and Applied Physics, Czech Technical University in Prague, Husova 240/5, 110 00 Prague, Czech Republic*

Corresponding Author: jelinj40@cvut.cz

Although water presence in lunar polar regions has been confirmed by orbiters, it remains unclear how accessible these resources are for extraction and use. Sustainability of a potential astronaut base on the Moon would be enhanced if water from local environment could be used. An in-situ exploration by a rover capable of drilling is essential for a better understanding of water abundance in the top few meters of lunar soil and rocks. However, since drilling is time- and power-intensive, it would be advantageous to develop a method to identify the promising sites for drilling with presumed high concentration of water.

Interactions of cosmic rays in the top few meters of lunar soil generate secondary particles, including neutrons. Hydrogen in water molecules has a significant cross section for collisions with neutrons, thereby altering the spectrum of neutrons observed above lunar soil. A neutron detector based on Timepix3 with silicon sensor is proposed to detect these changes in neutron field and identify potential drilling sites. Timepix3 would employ HardPix readout which was developed for space applications and has already been used in space.

The detector incorporates LiF converters enriched in Li-6 isotope, known for its high cross-section with slow neutrons through the Li-6(n, H-3)He-4 reaction. The converter is positioned directly above the silicon sensor, allowing Timepix3 to detect the resulting tritium and helium nuclei. The particle identification capabilities of Timepix3 enable it to filter out background events effectively and to identify tritium and helium nuclei with high sensitivity. Part of the LiF region is covered by additional Cd metal sheet to block neutrons with energies smaller than ~0.5 eV. Another part of the sensor will be covered by polyethylene converter sensitive to fast neutron and part of the sensor area is without any converters and Cd shielding for background subtraction. By comparing particle counts in the LiF, LiF+Cd and polyethylene regions of the sensors, it will be possible to find lunar sites with altered neutron spectrum that might contain higher densities of water.

Multiple Timepix3 detectors will be used to increase the sensitive area and shorten the acquisition time. The design of the detector and the analysis method will be presented, as well as results from laboratory measurements in known neutron fields and simulation validations. We will show results of simulations predicting the time on lunar surface needed to distinguish varying levels of water in the soil and the power consumption as a function of number of detectors.

#04 - Research Reactors and Particle Accelerators / 208

#4-208 Evaluation of 4H-SiC based sensor performances for thermal neutron flux measurements in nuclear power reactor fission facilities

Authors: Abdallah Lyoussi[1]; Christelle Reynard-Carette[2]; Christophe Destouches[3]; Heiko Jasper[4]; Laurent Ottaviani[5]; Olivier Llido[6]; Patrick Weidenauer[7]

[1] *CEA Cadarache*

[2] *Aix-Marseille University*

[3] *CEA/DES/IRESNE/DER/SPESI*

[4] *Framatome*

[5] *AMU*

[6] *CEA, DES, IRESNE, DER, Cadarache F-13108, Saint-Paul-Lez-Durance, 13108, France*

[7] *Framatome GmbH*

Corresponding Author: olivier.llido@cea.fr

Silicon Carbide (SiC) based neutron sensors present very promising properties for neutron flux measurements: selectivity between neutron and gamma radiations, response linearity, radiation and temperature hardness, pixilation⋯In particular, p-n and SCHOTTKY diode designs are studied since more than 20 years for almost fission, fusion, medical, spatial and high-energy physics application cases.
In 2021, CEA, AMU (Aix-Marseille University), within the framework of their joint laboratory LIMMEX, and FRAMATOME started a study to explore 4H-SiC diodes as possible ex-core thermal neutron detectors by using 10B converter for nuclear power plants. Following a first exploratory measurement campaign of Boron implanted 4H-SiC p-n diode sensors performed in 2021 in the Slovenian TRIGA reactor facility (Jožef Stefan Institute), new diodes have been manufactured with the aim of improving their thermal neutron sensitivity: larger surface (around 1 cm²) and a 1 µm thick layer of B4C coating.
These diodes have been irradiated in the same reactor in March 2023. A degradation of diode responses was observed as neutron fluence becomes significant. Investigations of the possible phenomena at the origin of the observed degradation of detector performances raise suspicions of defects induced linked to 10B(n, ⍰)7Li reaction product impacts which deposit their whole energy in the diode depleted area. A literature review confirmed this hypothesis. A model, based exclusively on carbon vacancies concentration, was proposed to simulate degradation of detector performances. It gives a good estimate of the typical fluence of reaction products that leads to a loss of counting rate (around 109 particles.cm-2).
In addition, a simulation analysis using SRIM software showed that detector sensitivity might be slightly improved by increasing B4C layer thickness up to 3.5 µm and also by using other converter materials, like 10B4C (100 % enriched in 10B) or 6LiF (100 % enriched in 6Li). However, it doesn't appear to be possible to extend the detector service life to a high neutron fluence without reducing its efficiency.
This study concludes with an analysis of the performances and limitations of this kind of sensor as sensor for thermal neutron flux measurement in reactor facilities.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 209

#5-209 Fast neutron imaging using D-D generator and plastic scintillator.

Authors: Branislav Vrban[1]; Filip Révai[2]; Jakub Luley[3]; Otto Glavo[4]; Vendula Filová[4]; Vladimír Nečas[4]; Štefan Čerba[4]

[1] *Slovak University of Technology in Bratislava, Slovakia*

[2] *Faculty of Electrical Engineering and Information Technology of STU in Bratislava*

[3] *Slovak University of Technology in Bratislava*

[4] *Slovak University of Technology, Faculty of Electrical Engineering and Information Technology*

Corresponding Author: filip.revai@stuba.sk

Neutron radiography is a powerful non-destructive testing method that employs neutron flux to visualize internal structures and defects in materials. Our research focuses on the use of imaging techniques in combination with a deuterium-deuterium (D-D) neutron generator. The primary technique is neutron defectoscopy utilizing fast neutrons. Main advantage of this method is that it allows us for the visualization of defects that are not visible with other imaging methods, such as X-ray imaging or eddy current imaging. The objective of this paper is to examine the potential of fast neutron defectoscopy utilizing a D-D neutron generator as a compact and efficient neutron source. This paper focuses on the design of the apparatus and the method of obtaining the initial images. Moreover, this paper demonstrates the capability of plastic scintillator detectors in detecting fast neutrons and producing high-resolution images. D-D neutron generators are capable of producing fast neutrons with energies of approximately 2.5 MeV, which are particularly effective in imaging materials with low atomic number and detecting features such as voids, cracks, and corrosion in complex geometries. Furthermore, the utilization of D-D neutron generators presents the additional benefit of a portable and on-demand neutron source, which is particularly advantageous for in-field and real-time inspections. In our laboratory the apparatus consists of the previously mentioned D-D generator, plastic scintillator and an astro camera, which we utilize for imaging. This paper presents the initial findings of our research, which consist of images of an industrial mockup that have been affected by set-up defects. It is possible that these defects may manifest during the operational lifetime of the industrial component. The results of this research will demonstrate the feasibility and potential of fast neutron defectoscopy with D-D neutron generators in industrial applications, particularly in the inspection of high-performance materials and large IV-Gen. reactor components. The results may contribute to the advancement of non-destructive testing techniques for a wide range of industries, particularly those related to nuclear energy, where precision and reliability are of significant importance.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 210

#5-210 Excore Measurement in the European pressurized water reactor (EPR)- An Overview

Author: Patrick Konrad[1]

[1] *Framatome*

Corresponding Author: patrick.konrad@framatome.com

The Excore measurement system is crucial for maintaining the performance and safety of the European Pressurized Water Reactor (EPR). As a Generation III+ nuclear reactor, the EPR incorporates state-of-the-art safety systems designed to enhance operational safety and reliability. The Excore system further strengthens this safety architecture by enabling continuous, real-time monitoring of core conditions. This precise data collection is crucial for the early detection of anomalies, supporting proactive measures to prevent incidents and ensuring rapid, effective mitigation, if necessary, thereby reinforcing the reactor's overall safety and operational integrity.
The Excore neutron detectors in the EPR reactor are located outside the reactor pressure vessel, within the biological shield. The neutron detectors are mounted in movable container chains suspended on steel ropes and are lowered through guide tubes to their measurement positions around the reactor vessel in the vessel pit. Their placement around the core allows them to monitor the fast neutrons emitted from the reactor core. By measuring the neutron flux, these detectors provide data for monitoring reactor power, guiding adjustments to control systems, and ensuring safe and efficient operation of the reactor. Excore detectors are utilized for different operational ranges: Boron-lined proportional counters are used for low-power source range measurements, compensated boron-lined ionization chambers for intermediate range measurements and post-accident monitoring, and uncompensated boron-lined ionization chambers for full reactor power measurements. This talk aims to provide a comprehensive overview of the Excore measurement system in the EPR. The presentation will cover the essential components of the Excore system, including detectors, transmission lines, and detector assemblies. It will illustrate how each element contributes to the monitoring of neutron flux, as well as the measurement of global power and azimuthal imbalance within the reactor core. By exploring the functionality of these components, attendees will gain valuable insights into the critical role of the Excore system in ensuring safe reactor operations. Ultimately, our objective is to inform and inspire collaborative efforts for the future.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 211

#5-211 Digital Excore Channel based on TXS Platform –An Overview

Author: Patrick Konrad[1]

[1] *Framatome*

Corresponding Author: patrick.konrad@framatome.com

In the past years, a standard channel solution for the Excore Neutron Flux Instrumentation System has been developed by Framatome. The Framatome Excore standard channels are a highly integrated solution which comprises the analog and digital processing part. One advantage of the automated solution is the use of the Teleperm XS (TXS) Service Unit for calibration and testing with a proven service software (graphical user interface, masks and scripts) which leads to significant time savings for the operator during regular maintenance by ensuring the highest nuclear safety standards at the same time. This standard solution has been successfully integrated into several nuclear power plants, demonstrating its effectiveness and reliability in enhancing operational efficiency and safety.
On the other hand, Framatome has made significant progress in developing the new TXS Compact platform. TXS Compact is an automation system based on FPGA technology that can be used with different modules from the TXS portfolio (signal conditioning, TXS cabinet, TXS power supply subrack, etc.) to implement safety I&C systems able to fulfill requirements of safety related I&C systems in nuclear power plants.
TXS Compact offers a wide range of function block types that can be easily combined to implement most of functional requirement and safety functions. Safety I&C solutions on TXS Compact contain no CPU and no software but is entirely operated on configurable hardware logics in the FPGA and memory cells. TXS Compact enables the development of class 1 safety I&C systems according to IEC standards (IEC 61513, IEC 62566, IEC 60987; etc.) and to the system needs and functional requirements.
A proof-of-concept performed by Framatome in 2023 integrated the synergistic potential of both technologies, exploiting the modular design of the Excore TXS modules alongside the TXS compact technology.
The primary goal of this poster is to provide a comprehensive overview of Framatome digital Excore system based on TXS platform. Additionally, this poster will offer valuable insights into future developments, highlighting the importance of maintaining high safety standards while enhancing reliability and efficiency across all types of nuclear reactors. Ultimately, our objective is to inform and inspire collaborative efforts for the future.

#10 - Current Trends in Development of Radiation Detectors / 212

#10-212 A Novel Measurement Setup for the Data Acquisition and Evaluation for Hydrogen-Filled Proportional Detectors and Stilbene Scintillation Detectors

Author: Vincent Melzer[1]

Co-authors: Sascha Weichel [1]; Robert Reisdorf [1]; Marco Viebach [1]; Carsten Lange [1]; Antonio Hurtado [1]

[1] *TU Dresden*

Corresponding Author: vincent.melzer@tu-dresden.de

The NAUTILUS project aims at determining nuclear data for chlorine to contribute to the research on chloride-based molten salt fast reactors. Therefore, experimental methods based on the principles of neutron activation analysis, neutron transmission and pile oscillation are utilized in the neutron field of the AKR-2 training reactor (Chair of Hydrogen and Nuclear Energy, Dresden University of Technology, Germany). However, a quantitative evaluation of the experimental data is only possible if its underlying field is precisely characterized. Thus, a further goal of the NAUTILUS project is the determination of the spectral neutron flux for different energy ranges of the AKR-2's neutron spectrum.

Regarding the evaluation of the fast neutron spectrum, neutron detection via elastically scattered recoil protons can be exploited. Different kinds of detectors exist for this purpose. However, they are suitable for measuring neutrons of different energy ranges. Hydrogen-filled proportional detectors can be utilized for measuring neutrons with energies between about 50 keV and 1.2 MeV. Stilbene scintillation detectors can be used for measuring neutrons with energies higher than approximately 1 MeV. Both detector types hold pulse shape discrimination capabilities allowing separation between neutron- and photon-induced detector events. Histograms of deposited energies by neutrons can be unfolded if the detectors response matrices are known. By this, the spectral neutron flux for fast neutrons can be determined.

This contribution presents a novel setup for measuring neutron energy deposition in the fast energy region. It is suitable for pulses generated from hydrogen-filled proportional detectors and stilbene scintillation detectors alike. In the setup, the detector's analog signals are digitized via an analog-to-digital converter. The latter is coupled to a field-programmable gate array which digitally realizes pulse shaping, baseline restoration and threshold triggering via custom-made logic modules. Additional custom software is used for configuring the setup and controlling the data acquisition and evaluation process.

Experimental results yielded by utilizing the setup for measurements with hydrogen-filled proportional detectors and stilbene scintillation detectors will be shown. Characterization methods and pulse shape discrimination capabilities of the detectors will be discussed by means of evaluated measurement data. Analog data from particle transport simulations with the Monte Carlo code Geant4 will be examined for comparison. Further steps in the scope of the NAUTILUS project to determine the spectral neutron flux of the AKR-2's fast neutron spectrum will be illustrated.

#04 - Research Reactors and Particle Accelerators / 213

#4-213 Characterization of thermal and epithermal contributions in a neutron field using Neutron Activation Analysis, the NFM detector, and MCNP simulations

Author: Enya Mobio[1]

Co-authors: Daniel Santos [2]; Nadine Sauzet [2]; Olivier Guillaudin [2]; Amokrane Allaoua [3]

[1] *IRSN LMDN*

[2] *LPSC*

[3] *LMDN IRSN*

Corresponding Author: enyamobio@gmail.com

The Laboratoire National de Métrologie et d'Essais (LNE) coordinates French metrology and represents it internationally across various domains. To fulfill this mission, LNE collaborates with several associated laboratories, including the Laboratoire de micro irradiation, de Métrologie et de Dosimétrie des Neutrons (LMDN) from IRSN/Cadarache/France, which is responsible for the national reference standards in neutron dosimetry. As part of its activities, the LMDN has an experimental facility for generating reference neutron fields, comprising irradiators that produce neutron fields from 241Am-Be and 252Cf sources. This facility also includes a plateform named CARAT, which includes an accelerator, the SAME T400. In combination with various moderators, this accelerator can generate realistic neutron fields representative of those encountered at nuclear industry workstations, as well as fields with a strong thermal component (En < 0.025 eV). Additionally, a second facility, AMANDE, is an accelerator producing reference monoenergetic neutrons fields with energies ranging from 2 keV to 20 MeV.

To expand the range of reference neutron fields available and meet emerging needs, such as Accelerator-Based Boron Neutron Capture Therapy (AB-BNCT) development, the LMDN is developing an epithermal neutron field with energies from 0.5 eV to 10 keV. The 7Li (p, n)7Be reaction was chosen for this purpose due to its threshold reaction at 1.880 MeV, which allows neutrons to be emitted at energies close to 10 keV. A moderator was designed to decelerate these neutrons to epithermal energies when threshold-level proton energies initiate the reaction at the AMANDE facility.

Since the neutron energies generated are close to the epithermal range, a few centimeters of high-density polyethylene suffice to moderate these neutrons to epithermal levels. After modeling and constructing this moderator, an experimental campaign was conducted in January 2024 to characterize the generated neutron field and to establish a characterization method for epithermal fields. Two detection systems were selected: the gold foil activation method and a new Neutron Field Monitor (NFM) detector. The activation method, which uses two 197Au foils, one covered with natural cadmium, enables the measurement of both thermal and epithermal fluxes. The NFM detector, based on neutron capture by 10B, was developed by the LPSC in Grenoble, France. Using these two systems enabled the determination of the thermal and epithermal fluxes of the neutron field in complementary ways. Experimental and simulated results were compared using Monte Carlo simulations on MCNP6.

The LMDN aims to establish a high-flux epithermal neutron field capable of delivering a dose of 1 mSv within six hours of irradiation. A new accelerator, expected to arrive at the LMDN facility in 2025, will generate neutrons through a deuteron-on-deuterium reaction. With neutron energies reaching 3 MeV, a larger multi-material moderator will be necessary. While the larger dimensions of the moderator will reduce particle flux due to the thermalization of fast neutrons, this will be compensated for by a high beam intensity of 6 mA, in contrast to the AMANDE accelerator's 5 μA.

#04 - Research Reactors and Particle Accelerators / 214

#4-214 The basis for a feasibility study for a high-power cyclotron to be used as a multi-purpose irradiation facility

Author: Michele Croia[1]

Co-authors: Alfonso Santagata [1]; Antonino Pietropaolo [2]; Giuseppe Ragonesi [1]; Luca Falconi [1]; Nunzio Burgio [1]

[1] *ENEA - Casaccia research center*

[2] *ENEA - Frascati research center*

Corresponding Authors: giuseppe.ragonesi@enea.it, michele.croia@enea.it

Industrial cyclotrons to accelerate protons have proven their robustness and technological maturity in preparing various kinds of radioisotopes for nuclear medicine, once bonded with suitable biomolecules, and used both as diagnostic and therapeutic against cancer and cardiocirculatory diseases. On the radiopharmaceutical market are present cyclotrons of various sizes, ranging from 9 to 70 MeV in energy and current up to 750-800 μA (there are also offers for current up to 1500 μA). There are also cyclotrons designed for Hadrontherapy whose energy can reach 280 –300 MeV, but for their particular mission, they have a current of the order of the nA.

Our final goal is the production of a feasibility study for the creation of a multi-purpose, cyclotron-based irradiation facility for various activities related to radiation damage for Aerospace, fission and fusion technologies, Molecular and crystal structure (Pharmaceuticals, Geophysics), design of quality tests for industry, RadioBiology. Such a facility should be classified as a regional testing facility in which new ideas, proof of concept and training will be carried out at a relatively low cost were posed on trial and, once passed a robust experimental campaign, transferred to the European Central facilities to be further investigated and exploited.

This work aims to identify, via FLUKA, PHITS and beam dynamics simulation codes, the main parameter for such a multi-purpose facility, defining the kind of particle to be accelerated starting from protons, deuterons and alpha, the respective proper range of currents, the targets'material necessary to obtain further particles as secondary emission field (neutrons, photons, and possibly low-intensity emission of pions and muons), and the main issues related to radioprotection and post-irradiation handling.

Based on the outcomes of the present work, an interlocution with the cyclotron manufacturer will be initiated to identify (or design) the cyclotron that fits our purpose. Contemporary, a discussion with the possible stakeholders will also be initiated.

#04 - Research Reactors and Particle Accelerators / 215

#4-215 Application of Unfolding Methods on Thermal Neutron Data Measured with a Single-Chopper Time-of-Flight Setup

Author: Vincent Melzer[1]

Co-authors: Alexander Knospe [1]; Louis Stein [1]; Marco Viebach [1]; Carsten Lange [1]; Antonio Hurtado [1]

[1] *TU Dresden*

Corresponding Author: vincent.melzer@tu-dresden.de

To support the research on chloride-based molten salt fast reactors, the NAUTILUS project focuses on measuring nuclear data of chlorine. Experimental approaches to reach this goal utilize neutron activation analysis, neutron transmission and pile oscillation methods within the neutron field of the AKR-2 training reactor (Chair of Hydrogen and Nuclear Energy, Dresden University of Technology, Germany). However, performing an accurate quantitative analysis of the experimental results depends on a detailed characterization of the underlying neutron field. Thus, another key objective of the NAUTILUS project is to determine the spectral neutron flux across various energy ranges for the AKR-2.

The neutron flux in the thermal energy range can be experimentally determined by Time-of-Flight measurements with neutron choppers. The latter are disk-like instruments that are placed in the neutron beam and rotated at desired frequencies. Through a plating of their turning blades with a material with a high capture cross section for thermal neutrons –cadmium or gadolinium are suitable for this purpose –different velocities can be filtered from the neutron beam. The combined use of multiple neutron choppers allows further filtering for narrower velocity regions. This especially can be utilized for determining the spectral neutron flux of individual thermal energies.

However, the described method is only practical if a sufficiently high thermal neutron flux is available at the given source. Otherwise, one must account for long measurement times to assure counting statistics with small relative measurement uncertainties. Neutron facilities that fall under this category are zero power reactors like the AKR-2.

Within the scope of the NAUTILUS project, a method is being developed for the experimental determination of the spectral thermal neutron flux with a single-chopper Time-of-Flight setup. It uses the moments of opening a disk-type neutron chopper spinning at a set frequency as start times. The events inside a helium-3 counter are utilized as stop times. With knowledge of the flight distance, flight times are determined and sorted into a histogram. Then, the unfolding method is applied using the flight time responses of different neutron velocities. The latter have their origin in the energy-dependent neutron capture cross-section of helium-3 and the finite opening width of the neutron chopper. Finally, the unfolding method yields the initial flight times from which the spectral neutron flux can be calculated.

Currently, different unfolding methods have been tested on data measured with a single-chopper Time-of-Flight setup. This was done to further validate this approach and to draw comparisons between the different unfolding techniques. Theoretically determined neutron flight times seemed to be reproduced by some of the unfolding algorithms. However, further investigations are planned to fully validate this method.

In general, this contribution will present experimental data obtained with a single-chopper Time-of-Flight setup. The results after applying the different unfolding algorithms to the data will be discussed. Analog data yielded with the neutron ray-trace simulation package McStas will be used for comparison. Further validation approaches for the presented method will be covered.

#10 - Current Trends in Development of Radiation Detectors / 216

#10-216 SPID-X Gamma ray imaging spectrometer performance evaluation in real conditions for the decontamination and clean-up of a LECA STAR hot cell

Authors: Kelian RONNE[1]; Rémy LE BRETON[2]

Co-authors: Abel VANEL [3]; Bruno BIARD [1]; Christian COLIN [1]; Geoffrey DANIEL [4]; Olivier LIMOUSIN [3]

[1] *CEA, DES, IRESNE, DEC, Cadarache F-13108 Saint-Paul-Lez-Durance, France*

[2] *Université Paris-Saclay, CEA, IRFU, Gif-sur-Yvette, 91191, France*

[3] *Université Paris-Saclay, Université Paris Cité, CEA, CNRS, AIM, 91191 Gif-sur-Yvette, France*

[4] *Université Paris-Saclay, CEA, Service de Génie Logiciel pour la Simulation, 91191, Gif-sur-Yvette, France*

Corresponding Authors: kelian.ronne@cea.fr, remy.le-breton@cea.fr

The LECA-STAR hot cell laboratory (Laboratory for Active Fuel Studies and the Treatment, Decontamination, and Reconditioning Station) is a facility dedicated to R&D activities on irradiated nuclear fuel, located at the CEA-Cadarache center. Seventeen shielded cells and a microanalysis laboratory allow the handling of fuel elements, from rod size to sub-micronic scale. Four of these cells are operated by the Laboratory for Radioelement Migration Analysis (LAMIR) to conduct tests on irradiated fuels, known as annealing tests, representative of incidental or accidental scenarios. These experiments monitor physical phenomena (temperature, pressure, gamma spectrometry ⋯) in experimental loops specifically designed to reach experimental conditions as close as possible to such desired conditions.
One of the LECA STAR cells has the unique feature of a transparent polycarbonate panel with glove ports, allowing human interactions in glove-box configuration when radiological conditions permit. In cases of unfavorable radiological conditions, this panel can be reinforced with biological shielded doors, and then, handling within the cell is carried out solely using telemanipulator arms. This hot cell has hosted three distinct experimental programs since 2010 (VERDON, VINON-LOCA, ESTER). Due to their nature, these different programs have contributed to some radiological contamination of the cell.
To reduce the contamination level of the hot cell and facilitate human interventions in glove-box mode, or even allow direct human interventions, decontamination campaigns were conducted. These clean-up phases start with dose mapping using a dose rate meter and/or smear tests, performed remotely with telemanipulators. This is followed by further decontamination phases using smears, also performed with telemanipulators. Once the contamination level is low enough, personnel wearing specific protective gear can be deployed for deeper decontamination, first through the glove box panel, then inside the cell. New mappings and delayed smear measurements are carried out throughout these phases to confirm their progress.
In an effort to improve and enhance the efficiency of this process, aiming also at lowering the dose for the operators (ALARA principle), the LAMIR, in collaboration with ALB3DO laboratory (DRF/IRFU –3D PLUS), has undertaken the implementation of a prototype of the Spid-X gamma camera, developed by ALB3DO, to perform comprehensive mapping of hot cell.
Spid-X is a portable gamma integral-field spectrometer weighing less than 4 kg. Built on the Caliste technology, Spid-X utilizes finely pixelated CdTe semiconductor detectors paired with low-noise ASICs from the IDeF-X family. Originally developed for space astronomy and high-energy solar observation in the hard X-ray and gamma-ray domains, the Caliste technology has already proven successful operations with STIX spectrometer on-board of the Solar Orbiter satellite.
Spid-X is designed to automatically identify and locate radioisotopes in real-time, compute the dosimetry at the device level, and quantify proportions when multiple radioisotopes are present in an environment. With the help of a Convolutional Neural Network trained on synthetic data, Spid-X requires only a few dozen of photons to detect one or more radioactive sources within a scene. Within Spid-X's energy range from 2 keV to 2 MeV, and depending on their type and extension, weak sources of the order of few nSv/h can be identified and localised in few minutes through either coded mask aperture imaging or Compton imaging. Compton imaging is still under development together with ongoing optimizations, including the integration of artificial intelligence algorithms, which are showing promising results, reducing localization time and improving accuracy.
In the end of 2022 and beginning of 2023, Spid-X was brought to several nuclear test facilities in order to test its performances in such conditions, and to identify potential improvements. Results from theses campaigns were presented at ANIMMA 2023. Spectroscopy, imaging and dosimetry performances were validated in unknown, yet simple environments: background levels were ten times

higher than in our laboratory, but the number of sources was low, between 1 and 3, and only point sources were studied. Imagining accuracy was confirmed to be near 1 degrees for coded mask aperture imaging, and around 10 degrees for Compton imaging. Our dosimetry model was successfully compared to calibrated commercial instruments.
The hot cell gamma characterization during clean-up operation involved installing the device behind the polycarbonate panel to acquire visual images and gamma spectra maps of the cell's interior. The objective was to obtain a map of the distribution and dispersion of contamination points within the cell to guide, accelerate, and improve the decontamination phases. In this complex environment the positions and the number of sources were not known, and with a high probability of presence of extended sources.
In this contribution, a brief overview of the Spid-X system is given, and results from the acquisition campaign at LECA-STAR are discussed as well as the benefit of the use of Artificial Intelligence algorithms.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 217

#6-217 Estimation of the time of exposure from the differential fading of luminescent detectors

Author: Gianpaolo Roina[1]

Co-authors: Debora Siqueira Nascimento [2]; Francesco d'Errico [1]; Riccardo Ciolini [1]

[1] *School of Engineering, University of Pisa*

[2] *National Institute of Geophysics and Volcanology*

Corresponding Author: gianpaolo.roina@phd.unipi.it

Containment and surveillance (C/S) and monitoring are important measures to complement nuclear material accountancy and control (NMAC) in pursuing IAEA's Nuclear Safeguards objective of timely detecting the diversion of significant quantities of nuclear material to proscribed purposes. They address the need for maintaining the continuity of knowledge of a safeguarded area or item over the period between two successive inspections, when an inspector is not physically present on site. However, devices for such unattended and remote monitoring are often made of complex electronic components and circuits which make them potentially vulnerable to tampering and snooping. In this work, we assessed the feasibility of a passive, tamper-indicating device able to record and, most importantly, timestamp an undeclared removal of radioactive material that could possibly occur from a storage area.
The study utilized GR-200A (LiF:Mg,Cu,P), which is available as discs of 4.5 mm in diameter and 0.8 mm thick. Its increased sensitivity with respect to the widespread TLD-100 (LiF:Mg,Ti) allows the measurement of much lower doses that can be important in the foreseen application. A typical glow curve of LiF:Mg,Cu,P comprises six peaks in the temperature range from 90 ℃ to 350 ℃. In particular, the study focused on peaks II and III, which fade with time after exposure, and on the time-stable peak IV, used as reference for comparison. Their different half-lives of approximately one day and 3-4 months, respectively, provide information on the short- and medium-term after irradiation.
A solid water crystal holder disc, fastened at the center of a purposely designed Plexiglas apparatus, hosted the crystals to be irradiated, fixing to 38 mm their distance from a 2.22 MBq Ra-226 radioactive source laid on top of the apparatus. A 2-mm solid water layer was added as build-up thickness. Irradiated discs were readout using a Harshaw TLD Reader with a linear Time Temperature Profile from 40 ℃ to 240 ℃ in 200 seconds. An annealing phase followed the data acquisition, keeping the thermoluminescent element at 240 ℃ for 10 s. The residual signal was measured to be 1-2 % of the corresponding readout value. Glow curve deconvolution was finally performed by means of the GlowFit v1.3 software, which is based on a first-order kinetics model and allows to determine the trap depth and temperature and intensity of the maximum associated to each peak of the glow curve.
The first phase of the experiment aimed at characterizing the response of each crystal composing the initial set, in order to identify as large a group as possible of extremely homogenous crystals having the same response to the given dose value, with a maximum deviation of 5 %. They underwent two irradiation-readout cycles at different doses (~1 mGy in 4 h and ~4 mGy in 15 h) so as to further exclude those showing an apparent dose dependency in their response. The mass of each crystal was also accurately measured, and the total and peak-specific generated charges were referred to the unit mass of phosphor. By using techniques of combinatorial analysis, the crystals were compared with each other based on the fraction, of the total collected charge, under each of the three peaks of interest. In parallel, Chauvenet's criterion was continuously evaluated to identify and automatically remove any possible outlier.
Once the selection process was concluded, the identified suitable crystals were irradiated once again and read out according to a suitable schedule. The variation in time of the II-to-IV and the III-to-IV peak area ratios generated the fading curves needed for the intended application. A non-linear least-squares fitting method was used to fit experimental data points (ratios) from each crystal series with a one-term exponential decay model of the form y=ae^bx (b<0). The strict homogeneity requirements imposed during the initial crystal selection process resulted into a remarkable consistency in the fading curves associated with the several crystal series. Consequently, the maximum uncertainty affecting estimations of the time elapsed since irradiation in preliminary trials (minimum temporal resolution of the system) was found to be of ± 1 day and ± 1 week over, respectively, the first week and the first two months.
For what concerns the sensitivity of the system, we used a method reported in the literature to estimate the Minimum Detectable Dose (MDD) of the dosimeter, i.e. the minimum dose to be absorbed by the crystal to generate a charge that can be distinguished from the background noise. Such a

method sets it equal to three times the standard deviation of the zero-dose reading of the dosimeter, resulting in our case in an MDD of a few µGy.
To deepen the study, a supplementary research focus attempted to statistically describe the internal structure of the crystals employed in the work. The purpose was to determine the depth of the localized energy levels responsible for the thermoluminescent properties. For each glow peak, we constructed a histogram showing the observed distribution of the corresponding values of the trap depth calculated by the GlowFit software for the several crystals. Afterward, by knowing the time elapsed between the end of the irradiation and their readouts, we could separate the contributions to each histogram coming from sets of crystals characterized by a similar fading time. This approach revealed an apparent evolution of the distribution of the electrons trapped in each localized level. The phenomenon is evident for peaks II and III, while it only suggests a possible fine structure of the energy level corresponding to the dosimetric peak IV.
The limited data available precluded further investigation of different hypotheses that we formulated. However, further investigation is underway to validate the findings, as an adequate characterization of the phenomenon will introduce an additional approach to determine the time elapsed since the irradiation event. It will complement peak area ratio calculations and possibly reduce the uncertainty of the results.
In addition, it is important to highlight that the material choice plays a crucial role in determining the system's suitability for exposure timestamping since the half-life of the corresponding glow peaks correlates directly with the expected inspection frequency.

#04 - Research Reactors and Particle Accelerators / 218

#4-218 Distributed Fiber Optic Dosimetry using a multi-wavelength Optical Time Domain Reflectometer

Author: Adriana Morana[1]

Co-authors: Aziz Boukenter [2]; Cosimo Campanella [3]; Emmanuel Marin [2]; Sylvain Girard [4]; Youcef Ouerdane [2]

[1] *Laboratoire Hubert Curien*

[2] *Université Jean Monnet*

[3] *Université Jean Monnet Saint-Etienne*

[4] *Université Jean Monnet, Saint-Etienne, France*

Corresponding Author: adriana.morana@univ-st-etienne.fr

Fiber Optic Dosimeters (FOD), in particular silica-based ones, are catching on in harsh environments, characterized by ionizing radiations, such as nuclear reactors, space, high energy physics, medical field…Such dosimeters employ mainly two phenomena induced by radiations in the optical fiber (OF) material: the radiation-induced attenuation (RIA) and the radiation-induced emission (RIE), which is constituted by the Cherenkov emission and/or the radioluminescence. The RIA consists in an increase of the OF attenuation due to the absorption bands associated with the radiation-generated centers. Consequently, the RIA-based dosimeters deduce the deposited dose into the optical fiber, by measuring the radiation-induced losses. Therefore, these sensors exploit radiation-sensitive fibers, among which phosphosilicate fibers have, to date, the best dosimetry properties, above all in the NIR range. These P-doped fibers, indeed, present a very stable center, known as P1, that is induced by radiations and whose absorption band, peaked around 1550 nm, is responsible for the RIA in the NIR range. Consequently, the 1550 nm RIA linearly increases with the dose up to ~500 Gy, with almost no dose rate and temperature dependence. The RIA-based dosimeters can be both point or distributed sensors, depending on its architecture. In the case of a point sensor, the losses induced on the whole fiber length are measured; generally, this is a double-ended sensor able to detect very low radiation levels, as LUMINA, a FOD installed in August 2021 inside the International Space Station (ISS). Distributed fiber dosimeters, instead, can be obtained by coupling the sensitive fiber with single-ended reflectometry techniques, as Optical Time Domain Reflectometer (OTDR) or Optical Frequency Domain Reflectometer (OFDR), which allow to measure locally the RIA with different spatial resolution. Several distributed FODs based on OTDRs working at 1550 nm are today installed at CERN.

The RIA-based dosimeter exploiting the P-doped fiber at 1550 nm is characterized by a radiation sensitivity of 4 dB km-1 Gy-1. This high sensitivity is generally considered an advantage of such dosimeter but sometimes it reduces its sensing length, because of the limited optical budget of the instrumentation, that is about 10 dB. To overcome this difficulty, we propose to replace a classical single wavelength OTDR with a multi wavelength one. We had the opportunity to test an OTDR whose laser source can be tuned between 1270 and 1610 nm with a step of 20 nm, for a total of 18 investigated wavelengths. It is worth noticing that the investigated range is still affected by the presence of the same defects, the P1, in the P-doped fiber. As an example, the radiation sensitivity of the P-doped fiber reduced by about 40 % when working at 1270 nm, compared to the value obtained at 1550 nm. This increases by a factor almost two the sensing length of the distributed dosimeter, because, when the losses induced at 1550 nm will be too high to investigate all the fiber length (at the farthest positions along the fiber from the input end the signal reached the noise level) the dose measurement will be still accessible by working at shorter wavelengths. This multi-wavelength approach extends the sensing length of the dosimeter.

At the ANIMMA conference, we will present the dose-rate and temperature dependences of the radiation-sensitivity of the P-doped fiber in this wide spectral range. Moreover, in the search for other sensitive fibers, suitable for dosimetry applications, other samples with different composition, as the Al-doped core ones, were tested and will be reported.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 220

#5-220 Recommissioning, calibration and numerical simulation of a passive neutron counter

Authors: Guillaume ROUSSEAU[1]; Loic VOISIN[1]

Co-author: Sébastien COLAS [1]

[1] *CEA Valduc*

Corresponding Author: loic.voisin@cea.fr

CEA Valduc center produces nuclear waste that must be characterized before being discarded. The characterization is mainly done by gamma spectrometry. However, in the case of waste containing high-density metallic items, passive neutron measurements are necessary. To meet this need, and constrained by the difficulty of obtaining supplies of helium-3 tubes, the waste characterization unit had to reactivate an old "JCC-71" measuring station [MIRION-CANBERRA] that had been out of service for about ten years. The JCC-71 is a passive neutron system consisting of four rectangular counting blocks, each made of high-density polyethylene to allow thermalization of the fission neutrons. Each block contains six Helium-3 detectors connected to an fast AMPTEK amplifier. The four amplifiers are connected in series to a neutron coincidence analyzer JSR-15 [MIRION-CANBERRA], a computer and an analysis software. The first step in recommissioning the station was to determine its operating parameters: detector high voltage plateaus, preamplifier discrimination threshold, predelay value, mean neutron lifetime in the cell, coincidence window duration and station detection efficiency. These parameters are necessary to be able to perform experimental calibration. Unfortunately, a problem in characterizing nuclear waste is that there is no representative standard for each object. Therefore, it is necessary to use a computational code (in this case Monte Carlo N-Particle code "MCNP") to model the measuring station in order to numerically estimate the detection efficiency. Consequently, in a second step, the results obtained with the MCNP code were compared with experimental calibration coefficients obtained with several standard sources. This experiment also provided an opportunity to test the OpenMC Monte Carlo computational code, a community-developed Monte Carlo neutron and photon transport simulation code characterized by its Python programming interface. In this paper, the calibration method is presented. The results and uncertainties obtained experimentally are compared with MCNP and OPEN-MC results and discussed.

#10 - Current Trends in Development of Radiation Detectors / 221

#10-221 Study of fs-void Bragg Gratings in radiation sensitive fibers for radiation measurement purposes

Author: Benjamin Sapaly[1]

Co-authors: Thomas Blanchet [1]; Sylvain Magne [1]; Adriana Morana [2]; Emmanuel Marin [2]; Christophe Destouches [3]; Sylvain Girard [4]; Guillaume Laffont [1]

[1] *Université Paris-Saclay, CEA, List, F-91120 Palaiseau, France*

[2] *Hubert Curien Laboratory, UJM Saint-Etienne, CNRS, IOGS, F-42000 Saint-Etienne, France*

[3] *CEA, DEN, DER, Instrumentation, Sensors and Dosimetry Laboratory, Cadarache, F-13108 Saint-Paul-lez-Durance, France*

[4] *Hubert Curien Laboratory, UJM Saint-Etienne, CNRS, IOGS, F-42000 Saint-Etienne, France / Institut Universitaire de France (IUF), Ministère de l'Enseignement Supérieur et de la Recherche, Paris, France*

Corresponding Author: benjamin.sapaly@cea.fr

Fiber Bragg Gratings (FBGs) offer significant advantages for monitoring harsh environments, particularly within nuclear facilities. Their compact size, immunity to electromagnetic interference and their large variety of radiation responses, enable accurate, real-time monitoring of temperature, strain and/or radiation levels, providing reliable data with high detection sensitivity. These characteristics make FBGs appealing for ensuring safety and operational control in radiative environments.
This study focuses on the development of type-III FBGs inscribed in highly radiation sensitive fibers using femtosecond laser technology. This process creates periodic voids within the fiber core, which leads to an optical cut-band filter in transmission and an optical pass-band filter in reflection. The peak reflectivity is located at the Bragg wavelength. Changes in void periodicity or effective refractive index both result in a shift of the Bragg wavelength. By exposing these FBGs to X-rays while monitoring temperature, we leverage the Radiation-Induced Bragg Wavelength Shift (RI-BWS) for accurate radiation dose measurements.
The study further compares the Bragg wavelength shift due to X-rays in extreme radiation sensitive fibers (Phosphorus (P)-doped, Aluminum (Al)-doped and Phosphorus/Cerium (P/Ce) co-doped) in comparison with a conventional telecom-grade optical fiber (e.g. SMF-28, 5 wt% Germanium-doped) used as reference. Type-III FBGs inscribed in fibers with different dopants (P, Al, P/Ce, Ge) were studied under irradiation at room temperature. The different fibers were tested in an X-ray irradiation chamber at dose rates of 1 Gy(SiO2)/s and 10 Gy/s up to doses exceeding 50 kGy. Due to their high sensitivity to radiation, only 5 cm of uncoated radiation sensitive fibers were irradiated, the samples were spliced to conventional fibers.
Our results show that RI-BWS follows an exponential trend for the first 50 kGy of irradiation dose. The levels of those shift are of around 25 pm, 41 pm, 65 pm and 12 pm –which correspond to equivalent errors of 2.2℃, 3.6℃, 5.8℃ and 1.1℃ for FBGs inscribed in P-doped fibers, P/Ce co-doped, Al-doped fibers and Ge-doped fibers respectively. P and P/Ce-co-doped fibers then exhibit a linear grow of RI-BWS while the RI-BWS of Al and Ge-doped fibers both reach a plateau. This behavior aligns with Radiation-Induced Attenuation (RIA) behavior in the same fibers. Additionally, the Phosphorus-doped fibers demonstrated strong potential as a dosimeter, since for doses higher than 50 kGy, the Bragg wavelength shifts almost linearly with dose (0.06 pm/kGy and 0.18 pm/kGy for FBGs in respectively P and P/Ce fibers). The grating response in such fiber was studied in terms of detection limit, resolution, and saturation by exposing the fiber to an integrated dose exceeding 2 MGy.
The lowest detection limit was about 1 pm set by the measurement systems (Luna Hyperion, Si-255) and the uncertainties are due to the Bragg peak detection.
We also investigated the grating behavior in Phosphorus-doped and Germanium-doped fibers, under combined high temperature (at 280℃) and X-ray irradiation (10 Gy(SiO2/s –100 kGy). Under these conditions of radiation and temperature, it turns out that Bragg grating response is independent of fiber composition, with a RI-BWS near zero (± 10 pm or less than a degree Celsius and ± 20 pm errors or 1.8℃ respectively for P-doped and Ge-doped fiber Bragg gratings). These uncertainties are due to the temperature variations of the heating plate.
Further research studies are set to explore the use of those fibers and dopants combined with Type-III FBGs as sensors in challenging high temperature and radiation environments as well as combined neutron and gamma radiation. The low detection limits are to be studied by testing the response with dose rates lowered by several decades for use in dismantling for example.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 222

#5-222 Hot Combo: A measurement device for B10 in samples with T»100°C

Author: Andreas Guettler[1]

[1] *Framatome GmbH*

Corresponding Author: andreas.guettler@framatome.com

In pressurized water reactors (PWRs), including VVER-type reactors, slow changes in reactivity are controlled using boric acid dissolved in the coolant of the primary circuit. Dissolved boric acid is also one of the solutions used by the nuclear industry to prevent any criticality events in spent fuel pools.
Framatome's Continuous Measurement of Boron Concentration (COMBO) allows the early detection of disturbances on an almost real-time basis. The measuring principle is based on the absorption of neutrons by the isotope B-10, which depends on the boron content of the coolant. Neutrons from an Am-Be source diffuse through the coolant and a portion of these neutrons is absorbed by the B10 content. The remaining neutron radiation is then detected by suitably positioned counter tubes. For signal acquisition and processing TELEPERM XS –Framatome's instrumentation and control platform for safety-related applications –is used.
Today it is still standard to use Polyethylen (PE) as a moderator in the Boronmeter devices which limits the temperature range due to the softening temperature of PE to 0 - 100℃.
Post-Fukushima requirements for VVERs include the new request to enable a boron concentration measurement of the primary coolant during station black out and / or a seismic event at higher temperatures. Also calculation algorithms in current nuclear power plant design can be replaced with an online measurement, directly at the location of interest on the circuit, where the temperature range is not limited to 0-100℃, giving the relevant value online to the processing systems.
In this talk Framatome's safety related qualified Hot COMBO is presented, a measurement device using Graphite as moderator and covering the total temperature range of NPP coolants, while still keeping the strong performance requirements (accuracy, response time, seismic events etc.) for this kind of safety related applications.

#01 - Fundamental Physics / 224

#1-224 Development of a possible secondary standard to determine the neutron emission rates from 252Cf and 241Am-Be calibration sources

Author: Michaël Petit[1]

Co-authors: A. Stabilini [2]; Christelle Reynard-Carette [3]; Diane Quevauvillers [4]; F. A. Geser [2]; M. Kasprzak [2]; N. J. Roberts [5]; Steven Hertay [6]; Thibaut Vinchon [7]

[1] *Nuclear Safety and Radiation Protection Authority*

[2] *Paul Scherrer Institute, Department of Radiation Safety and Security, Switzerland*

[3] *Aix-Marseille University*

[4] *IRSN/PSE-SANTE/SDOS/LMDN*

[5] *National Physical Laboratory (NPL), Teddington, UK*

[6] *IRSN/LMDN Cadarache*

[7] *IRSN*

Corresponding Author: michael.petit@asnr.fr

The Laboratory for micro-irradiation, neutron metrology and dosimetry (i.e. the LMDN from IRSN/Cadarache/France, close to Marseille) has two radioactive reference sources (241Am-Be and 252Cf) whose neutron emission rates have been determined using the Manganese bath method at LNE-LNHB (CEA/Saclay/France, close to Paris). These sources are the French metrological reference for neutron fluence and associated dosimetric quantity. The radioactive decay of these sources is assumed to be equal to the decay of the main actinide contribution (respectively the 241Am and 252Cf). However, the 252Cf source (t ½ = 2.645 years) contains Californium isotopes with generally 10%-15% of 250Cf (t ½ = 13.08 years) which has a significant spontaneous fission branch (0.077% compared with 3.092% for 252Cf). The contribution of 250Cf to the total neutron emission rate, negligible close to the production time, is no longer so after a few years. Therefore, according to the initial 252Cf/250Cf isotopic ratio, the age of the source and the time between manufacture and measurement by the Manganese bath method, it is necessary to apply a correction. This correction is increasingly important and difficult to follow as the source ages, especially as the contribution of the descendant of 252Cf (the 248Cm) ends up no longer being negligible. For this reason, ISO 8529 recommends recalibrating the 252Cf source every five years. Similarly, the ISO8529-1:2021 standard recommends recalibrating 241Am-Be (and 241Am-B) sources every five years. For the LMDN, recalibrating its sources would mean moving them over 1600 km. This requirement is cumbersome in practice, costly and means that the device is unavailable for several weeks. The LMDN is therefore working, with the help of the Paul Scherrer Institute (PSI Switzerland) and the National Physical Laboratory (NPL United Kingdom), on a dedicated device and an associated methodology that will make it possible to monitor, in situ and in relative, the evolution of the sources and thus determine the correction factor. This would make it possible to apply a correction and maintain metrological traceability. The primary objective of the study is to be able to determine experimentally the number of 250Cf and 252Cf nuclei in the source and thus avoid having to repeat several measurements over time. A method has been proposed and developed to meet this need. It is based on the use of 4 scintillators placed approximately at 1 meter from the source and at 90° one to the other. They will detect in coincidence mode neutrons and photons emitted. The scintillators will: identify the incident particle (neutron or photon), allow the energy deposited to be determined by calibration, and determine the reaction time in scintillator with an accuracy of better than 1 ns. Differences are known in the fission process between 252Cf and 250Cf, particularly the number of neutrons per fission, their directional probability and energies. Statistical variations in coincidence are therefore expected, according to the 252Cf or 250Cf spontaneous fission and the relative position of the detectors (at 90° or 180°). These differences can be predicted and estimated from a simulation of the fission process, which helps to determine experimental signatures of the spontaneous fission of 250Cf and 252Cf. Eventually, and once clearly identified, any equivalent set-up could be calibrated on already known 252Cf sources. Several experiments were carried out on seven 252Cf sources of different ages, from 40 years to a few years old. These experiments were carried out at LMDN, at PSI and at NPL. In particular, the source used for the CCRI(III)-K9.Cf.2016 intercomparison, with is about the measure of the total neutrons emission with the manganese bath device was also measured at NPL. This work is being carried out under the behalf of the French National Metrological Institute (NMI, the "LNE"), which has designated the LMDN as the French reference laboratory for the determination

of neutron fluence and associated dosimetric quantities. The presentation will present: the 252Cf sources status, the measurement device as well as the first results of the inter-source comparison. The calculation scheme used to estimate the experimental differences will also be presented. Finally, the qualification of an operational system as a secondary standard will also be discussed.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 225

#5-225 Shortwave infrared hyperspectral imaging for analysis of simulated spent nuclear fuel

Author: R. David Dunphy[1]

Co-authors: Andrew J. Parker [2]; C. James Taylor [2]; Daniel Hutchinson [3]; David Eaves [3]; Jaime Zabalza [1]; Malcolm Joyce [4]; Manuel Bandala [2]; Neil Cockbain [5]; Patrick Chard [6]; Paul Murray [1]; Paul Stirzaker [3]; Xiandong Ma [2]

[1] *University of Strathclyde*

[2] *University of Lancaster*

[3] *Westinghouse Springfields Fuels Ltd.*

[4] *Lancaster University*

[5] *National Nuclear Laboratory*

[6] *Mirion Technologies*

Corresponding Author: m.bandala1@lancaster.ac.uk

This study will describe how hyperspectral imaging (HSI) can be used as a tool to detect and quantify fission products in uranium dioxide (UO_2) nuclear fuel pellets. The rapid, non-contact capabilities of HSI offer a promising approach for spent nuclear fuel analysis in high-risk hot cell environments. An HSI system is used to analyse sintered UO_2 pellets and SIMFuel pellets (UO_2 doped with non-active fission product surrogates). We hypothesise that fission products alter the spectral response of UO_2 pellets, making these changes detectable through HSI and providing valuable information for nuclear fuel characterisation. Pellets are produced using both traditional and spark plasma sintering methods. In addition to SIMFuel pellets, pellets doped exclusively with lanthanides, grey-phase oxides, or epsilon particles are prepared to isolate the source of observed spectral differences. Imaging is performed with two cameras, covering the visible to near-infrared (VNIR) range of 399 to 1001 nm and the short-wave infrared (SWIR) range of 949 to 2472 nm. Reflectance spectra are then compared, focusing on how different dopant compositions affect the spectral response. Spectra are analysed by normalising data with quadratic detrending, which reduces intraclass variance and highlights differences among pellet sub-groups. Results show that pure UO_2 pellets exhibit consistent spectral features in the SWIR range, with distinct absorbance bands at 1116 nm, 1630 nm, and 2257 nm, and prominent peaks at 1862 nm and 1994 nm, while VNIR spectra contain no distinctive features. In contrast, SIMFuel pellets display a much flatter spectral response, significantly suppressing key absorbance features. Analysis of pellets doped with specific substances indicates that lanthanide-doped pellets similarly exhibit this flatter spectral response, while grey-phase and epsilon-particle-doped pellets retain a spectral response closer to pure UO_2. These findings confirm that fission products impact the SWIR spectral characteristics of UO_2, with lanthanides exerting the most significant effect. We propose an index based on spectral values at 1870 nm and 2257 nm as an empirical metric to differentiate between pellet types, demonstrating that this index shows significant differentiation between pure and doped pellets, supported by statistical analysis. Traditional spectral similarity metrics, including spectral angle mapper (SAM) and spectral information divergence (SID), further indicate that doped pellets are most similar to each other but distinctly different from pure pellets. Additionally, the spatial data from hyperspectral imaging reveal regions of spectral variation, with lanthanide-doped samples exhibiting localised "hot spots"where spectral peaks are more pronounced. These findings suggest hyperspectral imaging as an effective, non-contact technique for nuclear fuel characterisation, particularly in post-irradiation examination. The rapid acquisition time of HSI, combined with its spatial and spectral insights, positions it as a valuable tool for screening hazardous materials in hot cell environments, potentially streamlining the analysis of spent nuclear fuels. Future research will explore the physicochemical mechanisms underlying the spectral changes introduced by fission products, especially lanthanides, with a focus on quantifying lanthanide content using complementary techniques such as Raman spectroscopy and scanning electron microscopy. Additionally, SWIR-HSI imaging of spent reactor fuel samples will be needed to confirm the general applicability of the identified methods. Overall, this study demonstrates the significant potential of hyperspectral imaging for non-invasive nuclear fuel characterisation, offering a method to identify and quantify fission products and ultimately supporting improved post-irradiation examination and spent fuel storage decision-making.

#10 - Current Trends in Development of Radiation Detectors / 227

#10-227 Enhancing Imaging Stability in Hybrid Semiconductor Detectors with CdTe sensors with Pulsed Bias Voltage Switching

Author: Katerina Sykorova[1]

Co-authors: Daniela Doubravova [1]; Martin Konecny [1]; Jan Jakůbek [2]; Roman Nebel [3]

[1] *Advacam*

[2] *ADVACAM s.r.o.*

[3] *Advacam, s.r.o.*

Corresponding Author: roman.nebel@advacam.cz

Hybrid semiconductor detectors using Timepix-family and Medipix-family chips, developed by the Medipix collaboration at CERN, offer direct radiation detection by converting radiation particles into electrical signals within the semiconductor sensor. This design provides excellent detection sensitivity and eliminates analog noise. The sensor chip is divided into 256x256 individual pixels, each with a 55 µm pitch, which gives the detectors high spatial resolution. The sensitivity of a sensor for imaging applications depends on its ability to absorb photon radiation across a wide energy spectrum, from X-rays in the keV range to highly penetrating gamma rays. For such a range, heavier materials like CdTe are advantageous due to their superior absorption capabilities, making them suitable for applications such as non-destructive material testing and dense material imaging. Despite unprecedented development in the quality of CdTe with pixelated electrodes, there are still challenges in practical use. A significant issue arises from crystal defects within the CdTe sensor, which lead to the buildup of spatial charge in the sensor. This spatial charge disrupts the internal electric field, degrading the spatial and spectral quality of the images produced. These defects often appear as vein-like artifacts in images, worsening over time. To improve image stability over time, pulsed bias voltage switching can be used. Ideally, this method resets the accumulated spatial charge to a "fixed state"before each image capture, ensuring any remaining artifacts are consistent across images taken in extended period of time. This temporal consistency makes it possible to remove now fixed image artifacts with standard flat-field correction. We investigate various pulsed bias voltage switching schemes and their effectiveness in achieving a stable "fixed state"of spatial charge. The temporal stability of this state is also tested. The optimized pulsed bias switching scheme is found to most effectively reduce spatial charge buildup and enhance the imaging stability of sensor detection performance over time.

#03 - Fusion Diagnostics and Technology / 228

#3-228 Activation of the inner irradiation Snail after long-term operation of the KATANA irradiation facility

Author: Ylenia Kogovšek Žiber[1]

Co-authors: Domen Kotnik [1]; Igor Lengar [1]; Julijan Peric [1]; Luka Snoj [1]

[1] *Jožef Stefan Institute*

Corresponding Author: ylenia.ziber@ijs.si

The KATANA irradiation facility was commissioned at the Jožef Stefan Institute in early 2024 with the aim of investigating water activation in fusion reactors such as the International Thermonuclear Experimental Reactor (ITER) and the Demonstration Power Plant (DEMO). It is a closed-water activation loop designed to perform benchmark experiments to validate the newly developed fluid activation computer codes using the TRIGA Mark II research reactor at the Jožef Stefan Institute (JSI TRIGA). The KATANA water circuit consists of a pipe loop that is partially inserted into one of the horizontal irradiation channels, namely the radial piercing port (RPP), of the JSI TRIGA reactor. The inner part of KATANA consists of three components: the inner irradiation part, namely "irradiation Snail", which it is in close proximity to the reactor core where most of the water activation process occurs, and the corresponding gamma & neutron shielding plugs behind it. Since the RPP also penetrates the concrete bioshield of the reactor and thus practically touches the reactor core, the inner part of the KATANA is exposed to the high neutron flux, resulting in the neutron activation of the material. To minimise neutron activation, aluminium was chosen as the main material for the inner Snail (and also for other tubes) instead of stainless steel, even though this led to greater difficulties in construction. The aim of this work is to assess the long-term neutron activation of the inner part of the KATANA facility, especially the inner irradiation Snail, which will be the most problematic part in terms of the highest activation achieved. At the end of 2025, the existing inner Snail is planned to be replaced by a new ITER-relevant irradiation head designed to address conditions that are more relevant to ITER. Prior to this, a comprehensive neutron activation analysis of the existing inner part of KATANA is required to support the licencing process. The aim is to determine the waiting time for safe maintenance of the inner part of KATANA after 2 years of irradiation (reactor TRIGA operation) in order to ensure to minimise radiation doses for personnel (dealing with the activated material) and reduce radiation damage to the equipment. The final goal of this research is to calculate the activation of the inner Snail and dose rate over time after irradiation to determine when the inner Snail can safely be exchanged. The obtained results are also viable for decommissioning assessment. The activation calculations are performed with an already developed KATANA model, specifically the inner Snail model, using the neutron transport code MCNP based on the Monte Carlo method, and the isotopic activation and transmutation code FISPACT-II. The results of this analysis will be of crucial importance and will provide essential guidelines for future activities. In addition, the obtained results will be crucial in the decommissioning phase, when the radioactive components will have to be removed and stored appropriately.

#04 - Research Reactors and Particle Accelerators / 230

#4-230 Characterization of the neutron field of a proton accelerator using Monte Carlo simulation and gamma spectrometry-SSNTD measurements

Author: Jonathan Collin[1]

Co-authors: Abdelmjid Nourreddine [2]; Guilhem Lacaze [3]; Jean-Michel Horodynski [4]; Nicolas Arbor [5]; Yves Schutz [6]

[1] *Institut pluridisciplinaire Hubert Curien, Strasbourg, France*

[2] *Institut pluridisciplinaire Hubert Curien*

[3] *Transmutex SA*

[4] *iRSD CNRS Paris*

[5] *CNRS - IPHC*

[6] *Institut pluridisciplinaire Hubert Curien, Strasbourg*

Corresponding Author: nicolas.arbor@iphc.cnrs.fr

Nuclear activation is the process of production of radionuclides by irradiation. This phenomenon concerns all operating or soon-to-be dismantled particle accelerators used in various fields, from medical applications with the production of radioisotopes or radiotherapy cancer treatments to industrial applications with the sterilization of materials and food preservation. For more than three decades, the possibility of using cyclotrons for nuclear power generation and nuclear waste disposal has also been discussed, based on the Accelerator-Driven System technology.
This work focuses on the lower energy range of such cyclotrons, in particular with the study of the radioactivity induced in various materials (Sc, Tb, Ta, W, Au) of known composition, irradiated by protons of 13.5, 16.5 MeV and 18 MeV energies in the cyclotron facilities CYRCé and Cycéron. We have performed Monte Carlo simulations based on GEANT4, FLUKA, and PHITS to estimate the neutron fields and their associated induced activities, associated with FISPACT-II, DCHAIN-PHITS and TMX_Bateman.
A comparative study with nuclear data and MC codes highlighting discrepancies for certain nuclear reactions has been analyzed with relevance. We confronted the simulation calculations results with experimental activation measurements performed by high-resolution gamma-ray spectrometry (HpGe, LABSOCS). For this comparison, a new decay database was produced and used based on latest results from NUBASE20 and ENSDF.
These results are strongly correlated to the neutron fields. These fields were characterized experimentally through their thermal and fast neutron components using Solid-State Nuclear Track Detectors (CR-39, Chiyoda Technol) to validate the MC simulations.

#04 - Research Reactors and Particle Accelerators / 231

#4-231 Nuclear heating rate measurement in the MIT research reactor using a new compact CALORRE differential calorimeter

Authors: Christelle Reynard-Carette[1]; Adrien Volte[1]; Gordon Kohse[2]; David CARPENTER[3]; Yakov Ostrovsky[4]; Michael AMES[4]; Sara Hauptman[5]; Abdallah Lyoussi[6]; Michel Carette[1]

[1] *Aix-Marseille University*

[2] *MIT Nuclear Reactor Laboratory*

[3] *NRL*

[4] *NRL, MIT*

[5] *Massachusetts Institute of Technology*

[6] *CEA Cadarache*

Corresponding Author: christelle.carette@univ-amu.fr

To design and propose innovative nuclear instrumentation, Aix-Marseille University and the CEA as part of the LIMMEX joint laboratory (Laboratory for Instrumentation and Measurement in Extreme Environments) created in 2009 are conducting several research programs addressing key values for research reactors and tokamaks, such as fast and thermal neutron fluxes, prompt and delayed photon fluxes and intense absorbed dose rates (nuclear heating rate). A comprehensive approach has been developed particularly regarding heat-flow calorimetric sensors by coupling experimental work with 1D calculations and 3D simulations (heat transfer, ray-matter interactions) from out-of-flux laboratory conditions to irradiation campaigns in nuclear environments. Two types of calorimeter integrating at least one heater have been patented by AMU and the CEA (one differential calorimeter in 2015 (CALORRE) and one single-cell calorimeter in 2020 (Mono-CALO)). After successful tests of a first prototype of the CALORRE differential calorimeter in the MARIA reactor in November 2015, different challenges associated to this sensor type were and are targeted such as the extension of the measurement range from very low values for TRIGA reactors to high values for MTRs such as the JHR reactor, the sensor miniaturization to design a micro-sensor in the future, and the characterization of different materials for fission and/or fusion purposes.
In this context, a research program, called CALOR-I (compact-CALORimeter Irradiations inside the MIT Research Reactor), funded by Aix-Marseille University foundation (A*Midex) and involving the Nuclear Reactor Laboratory of the MIT and the CEA, began in 2020 with four main objectives: (1) the design of a new CALORRE prototype, (2) the study of this prototype from laboratory to irradiation conditions, (3) the axial mapping of an in-core channel of the MIT Research Reactor (MITR) in terms of nuclear heating rate (never realized before by a calorimeter), and (4) the comparison of measurement methods and sensors. By taking the feedback from the MARIA campaign into account and carrying out thermal and neutron modeling, a new CALORRE calorimeter prototype of reduced size and similar height to that of the usual single-cell calorimeters was defined and manufactured. This paper will deal with the experimental study realized on this reduced-size CALORRE prototype under laboratory conditions and inside the in-core water loop of MITR in October 2024.
The first part of the paper will present the design of this CALORRE calorimeter and its main features (mass, geometry, size, materials, etc.) will be given. The second part will be dedicated to the experimental characterization of CALORRE under laboratory conditions by simulating the nuclear heating rate by Joule effect. The main metrological performances of the CALORRE prototype (sensitivity, linearity, range, reproducibility, response time and maximum temperature) will be detailed. The last part will present the results obtained during the MITR irradiation campaign. Firstly, the calorimeter vehicle placed into the water loop autoclave and its components will be shown. Then the experimental operating protocol by moving the calorimeter with the reactor in operation will be described. The influence of several experimental conditions on the calorimeter response will be presented (reactor power, axial position, temperature and velocity of the coolant fluid). The axial profile of the nuclear heating rate in the B3 channel for the fuel zone and beyond the fuel top will be shown for a reactor power of 5 MWth with different space resolutions depending on the axial position. The measured nuclear heating rate as a function of the reactor power at a specific position will be presented. A comparison of the nuclear heating rate obtained by moving or not the sensor will be realized to see the impact of the reduction of the sensor size. The nuclear heating rate measurement will be confirmed thanks to different measurement method applied (with or without the use of the 4-wire heaters of the calorimeter) at a specific axial position. The measurement of the delayed nuclear heating rate from the reactor shutdown will presented. Finally, the reliability and the robustness of

the calorimeter will be demonstrated by comparing the calibration curves obtained in the shutdown reactor before and after the irradiation campaign for different coolant fluid temperatures.

#04 - Research Reactors and Particle Accelerators / 232

#4-232 Sensitivity analysis of a current-mode micro ionisation chamber for IFMIF-DONES under pulsed beam conditions in LI-PAc Accelerator

Author: Pablo Araya Carmona[1]

Co-authors: Claudio Torregrosa Martín [1]; David Jiménez-Rey [2]; Florian Benedetti [3]; Juan Carlos Morales Vega [1]; Juan Manuel García [2]; Lucas Maindive [1]; María Esther Puertas Garcia [4]; Moisés Weber Suárez [1]; Saerom Kwon [5]; Santiago Becerril [1]; Takahiro Narita [5]; Álvaro Marchena Díaz [6]

[1] *IFMIF-DONES España*

[2] *CIEMAT*

[3] *F4E*

[4] *Universidad de Granada*

[5] *QST*

[6] *BTESA*

Corresponding Author: pablo.araya@ifmif-dones.es

The IFMIF-DONES facility will be an accelerator driven neutron source, delivering around 10E17 n/s with a spectrum tailing above 40 MeV for the irradiation of structural materials for fusion applications. This study focuses on the testing and evaluation of a current-mode micro ionisation chamber (uIC) with experiments conducted in the Linear IFMIF Prototype Accelerator (LIPAc) environment. This detector is developed for integration within STUMM (Start-Up Monitoring Module), the module to be used during the IFMIF-DONES commissioning to characterise and monitor the neutron and gamma field. The main objective is to evaluate the sensitivity of the current-mode micro ionisation chamber under pulsed radiation fields, reproducing the conditions expected during the commissioning and operation phases of IFMIF-DONES. Accurate monitoring and characterisation of pulsed radiation fields are essential to verify whether this detector maintains its sensitivity and reliability in such environment.
The LIPAc facility was selected as an ideal to perform this test due to its capability to generate radiation environments with a time-structure similar to those expected in IFMIF-DONES. For this reason, the experimental campaign focused on the current-mode micro ionisation chamber's response under pulsed conditions. Specific objectives included evaluating signal stability, measuring response accuracy, and optimizing data acquisition methods to reduce noise and improve overall data fidelity.
To perform the test campaign, the uIC was integrated into the High Energy Beam Transport (HEBT) line at LIPAc, positioned within lead shielding near the Beam Dump to ensure exposure to radiation fields while minimizing background and electromagnetic noise.
Results demonstrated that the micro ionisation chamber could operate effectively in a pulsed radiation regime, maintaining stable and accurate measurements even under challenging conditions. Data acquisition using Keysight instruments provided insights into their relative strengths, with the electrometer exhibiting superior sensitivity for low-current measurements. The success of the micro ionisation chamber operation and data consistency in the LIPAc environment validate its potential use within IFMIF-DONES with no need to use pulsed-mode micro ionisation chambers.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 235

#6-235 Development of a radiation detection system for the prevention of illicit trafficking of special nuclear materials and radiation sources

Author: Luís Marques[1]

Co-authors: Alberto Vale [2]; Francisca Moita [3]; Pedro Vaz [4]

[1] *Centro de Investigação da Academia da Força Aérea*

[2] *Instituto de Plasmas e Fusão Nuclear, Instituto Superior Técnico, Universidade de Lisboa*

[3] *Instituto Superior Técnico, Universidade de Lisboa*

[4] *Centro de Ciências e Tecnologias Nucleares - Instituto Superior Técnico*

Corresponding Author: lumarques@academiafa.edu.pt

The reinforcement of detection and control measures for Special Nuclear Materials (SNM) and other radioactive substances used in sectors such as medicine, industry, environment, energy, agriculture, space, and research are critical for global security and the safe, sustainable use of radiation sources. SNM, including plutonium and highly enriched uranium, pose significant risks if misused, potentially leading to improvised nuclear devices. Additionally, the illicit trafficking of radioactive materials raises concerns regarding their malicious use in radiological dispersion devices (e.g., "dirty bombs") and radiological exposure devices, with highly disruptive social, economic, and psychological consequences. Effective control of radiation sources throughout their lifecycle—"from cradle to grave"—requires stringent oversight, especially at borders, airports, and seaports. While radiation monitoring portals (RPM), are essential to detect and monitor gamma and in some cases neutron radiation, their high cost and limited applicability present challenges in preventing the trafficking of radioactive sources and materials.

This study details the development and optimization of a radiation detection system designed for security and defense applications, characterized by short source-to-detector distances and the presence of hidden sources. The developed system, employing EJ-200 and EJ-426HD scintillators coupled with Silicon Photomultipliers (SiPM), simultaneously detects gamma/beta radiation and neutrons. Tailored for use with Unmanned Aerial Vehicles (UAV), the system is compact, lightweight, and cost-effective, validated through Monte Carlo simulations, laboratory experiments, and field tests. Key results of the work performed are summarized below:
(i) Development of a compact portable neutron detection system: The system employs an EJ-426HD scintillator coupled with SiPM and high-density polyethylene (HDPE) neutron moderators to detect both thermal and fast neutrons. The addition of HDPE moderator plates around the detector enhanced detection efficiency while minimizing gamma radiation sensitivity—a critical factor in avoiding false positives;
(ii) Optimization and comparison of EJ-200 scintillator with a CsI(Tl) scintillator: Measurements with a 137Cs source at distances ranging from 1 to 5 meters demonstrated that the EJ-200 scintillator exhibited a gamma detection efficiency approximately three times higher than CsI(Tl);
(iii) Integration of the detection system into an UAV for maritime container inspections: The system was integrated into a UAV multi-rotor platform for inspecting 20-foot-long maritime shipping containers. During a field inspection, the system successfully detected and localized 137Cs sources (4 MBq) and neutron sources (1.45 GBq 241Am-Be) within the container, demonstrating its effectiveness in real-world conditions;
(iv) Informative path planning algorithms based on profit functions were developed, enabling the detection system to dynamically adjust the inspection path based on real-time information about the source's location. The algorithms used either source position estimates, obtained through Maximum Likelihood Estimation (MLE) or real-time count data to adjust the UAV path, optimizing the inspection process. The use of a set of parameters to indicate the source position estimation confidence (exit condition), allowed to reduce the inspection time while maintaining a high accuracy in the localization of 137Cs sources, within 0.6 m for an Up and Down (UD) profit function (performs a vertical scan to the container when a hot spot is detected) and within 0.4 m for "Step and UD"(STUD) profit function (performs a sinusoidal movement when a certain threshold is achieved). The STUD profit

function also minimized inspection time, reducing it to under 45 seconds. This capability represents a significant advancement over traditional manual and fixed inspection methods;

Other methods are described in literature to detect and localize radiation sources in urban areas, such as:
(i) Fixed Detector Networks, by using several stationary detectors spatially distributed (unpracticable for large areas such as a seaport);
(ii) Portable RPM (limited use due to lack of mobility); and
(iii) Mobile radiation detection systems composed by large and heavy radiation detection systems transported by cars or vans.

The developed detection system can be carried by small mobile platforms such as multi-rotors and provides a cost-effective alternative or complement to traditional RPM, fixed detector networks, and mobile radiation detection systems based on large radiation detection systems. It also provides an alternative to manual inspections, which are performed every time an alarm is triggered at a RPM, thus reducing significantly the secondary inspection times (which can take up to 20 minutes per container in ports) and avoiding the need for physically opening containers to inspect cargo.

Some system advantages and contributions of the portable detection system offers several advantages: it is lightweight, cost-effective, and integrates into UAVs or other mobile platforms (land, maritime, or hybrid). It efficiently detects gamma/beta radiation and neutrons, accurately locates gamma radiation sources, reduces the risk of false positives, and can detect SNM and other neutron sources like 252Cf and 241Am-Be. The main features of the developed radiation detection system encompass:
(i) The development of a portable radiation detection system with enhanced detection efficiency and modular neutron detection capabilities;
(ii) The Integration of SiPMs to reduce system size and weight, facilitating its use in mobile platforms with payload constraints;
(iii) The Creation of data processing algorithms for real-time operation, allowing the system to perform autonomously or with mobile platforms;
(iv) The introduction of informative path planning to optimize the detection process and reduce inspection time.

The impact of cargo material, such as plastic, aluminium and lead (radiation attenuation) in the source detection outside the container will also be addressed using the state-of-the-art Monte Carlo software program Monte Carlo N-Particle (MCNP).

Future work will enhance the detection system position accuracy measured at each instance by using more advanced GNSS receivers with inertial measurement unit (IMU) or real-time kinematic GNSS, testing multiple sources, and adapting the technology for other applications, such as nuclear forensics, nuclear facility inspections or post-radiological accident surface mapping.

In conclusion, the developed system represents a significant advancement in radiation detection technology, offering a practical and efficient solution for detecting and localizing illicit nuclear materials and radiation sources in a variety of security scenarios. The possible system's integration into an UAV platform and the use of informative path planning based on profit functions and real-time data provide an innovative approach to radiation monitoring.

#04 - Research Reactors and Particle Accelerators / 236

#4-236 Single crystal diamond detector of fast neutrons generated by D-T nuclear reaction

Author: Bohumir Zatko[1]

Co-authors: Andrea Sagatova [2]; Eva Kováčová [3]; Mehdi Ben Mosbah [4]; Abdallah Lyoussi [5]; Christophe Destouches [6]; Olivier Llido [7]; Joël LORIDON [8]

[1] *Intitute of Electrical Engineering, Slovak Academy of Sciences*

[2] *Slovak University of Technology in Bratislava*

[3] *Institute of Electrical Engineering, Slovak Academy of Sciences*

[4] *CEA, DES, IRESNE, Nuclear Measurement Laboratory*

[5] *CEA Cadarache*

[6] *CEA/DES/IRESNE/DER/SPESI*

[7] *CEA, DES, IRESNE, DER, Cadarache F-13108, Saint-Paul-Lez-Durance, 13108, France*

[8] *CEA, DES, IRESNE, DTN, SMTA, Nuclear Measurement Laboratory*

Corresponding Author: bohumir.zatko@savba.sk

Detectors based on wide bandgap semiconductors and high radiation hardness are very promising for detection of fast neutrons. Single crystal diamond is a very attractive semiconductor material. It has a bandgap energy of 5.48 eV at room temperature, which gives it an extremely high resistivity. The electron and hole mobilities are 2200 cm2/Vs and 1800 cm2/Vs, respectively. Diamond detector is able to operate at increased temperature up to several hundred degrees Celsius and is suitable for operation in harsh environments. In our work we used 500 m thick electronic grade single crystal diamond substrate for fabrication of detector. On top side we prepared a square contact of 3.5×3.5 mm2 using Ti/Pt metallization. On the opposite site a full area Ti/Au back contact was deposited. The diamond detector structures were characterized by current-voltage measurements up to 1000 V. Detector demonstrated a flowing current below picoamperes in whole range of measurement. Following, the detector was connected to the spectrometric chain and used for alpha particle spectrometry. As a source of -particle the 238Pu239Pu244Cm triple radioisotope was used. Diamond detector shows the energy resolution in full width at half maximum of about 23 keV for 5.5 MeV -particles. Subsequently, detector was used for the detection of monoenergetic fast neutrons from the deuterium-tritium nuclear reaction where deuterons were targeted to the tritium. The energy of deuterons varied from 60 keV up 90 keV. Detection of fast neutrons in diamond detector is realized through elastic and inelastic scattering on carbon nuclei. The detected energy of fast neutrons was about 14.5 MeV. In measured spectra we observed the peaks corresponding to the nuclear reactions between fast neutrons and carbon nuclei of diamond material. The observed relative energy resolution of the peak resulting from the 12C(n,α)9Be reaction between fast neutrons and 12-C nuclei was about 4.0%. In detected spectra we noticed a bifurcation of the main detected peak which indicated that neutrons were generated not only by accelerated monoatomic deuterons but also accelerated molecular deuterons were impinging the tritium target.

#10 - Current Trends in Development of Radiation Detectors / 237

#10-237 Development of a neutron spectrometer prototype: DONEUT project

Author: Marc Labalme[1]

Co-authors: Jean-Lionel Trolet [2]; Sebastien Bozec [2]; Yohann Brelet [3]

[1] *ENSICAEN / LPC Caen*

[2] *EAMEA*

[3] *LPC Caen*

Corresponding Author: labalme@lpccaen.in2p3.fr

To accurately estimate neutron dose rates, accurate measurements of both the initial kinetic energy and the incident flux of neutrons are crucial. This presentation will discuss a project focused on developing a transportable neutron spectrometer/dose rate meter, using multiple detectors embedded within a moderator volume. This development has resulted in the creation of a novel multi-detector prototype as part of the DONEUT (DOsimetre NEUTrons) project initiated 4 years ago. This prototype has been optimized to measure neutron dose rates from 0 to 20 MeV.
The spectrometer employs a polyethylene moderator with thermal neutron detectors positioned at varying depths to reconstruct neutron energy spectra. A first prototype has been developed and tested. It is based on a 25 cm diameter polyethylene cylinder with 32 embedded detectors. These detectors use a combination of lithium fluoride and zinc sulfide (ZnS:LiF) scintillators, glued to a light guide and coupled with a wavelength-shifting fiber that channels scintillation to a SiPM matrix.
Recent efforts have focused on optimizing the spectrometer's design through simulation and tests. Simulations were performed to optimize the detector configuration and design. For this purpose, unfolding methods, MAXED and GRAVEL, were applied to different moderator volume designs and to a range of neutron energy spectra—using both moderated and unmoderated sources of Am/Be and 252Cf—simulated with the GEANT4 Monte-Carlo code. These simulations led to the development and testing of a "dome"design prototype which improved response uniformity across a wide range of vertical angles and reduced the prototype's weight. Additionally, a sixth detection depth was added to enhance the robustness of the deconvolution, particularly in the epithermal range, and the number of detectors was reduced from 32 to 24 while maintaining measurement accuracy. For both the original and the dome configurations, the dose equivalent rate (H*(10)) achieved an accuracy within 15%, even at lower dose rates around 2 µSv/h in a 10-minute measurement period.
In terms of data processing, a new Python-based implementation of the GRAVEL deconvolution algorithm has been developed based on [1]. This code replaced GRAVEL and MAXED codes and provides enhanced flexibility, efficiency, and speed for reconstructing the energy spectra of radioactive sources
This presentation will cover the simulation studies, the Python unfolding method and the corresponding results for both the spherical and "dome"designs. Results from the new prototype tests with moderated and non moderated Am/Be sources will also be presented and compared to the dose rate measured by the NNS [2].
[1] Tyler Doležal, « Unfolding the AmBe Neutron Spectra using GRAVEL and MLEM », Department of Engineering Physics, Air Force Institute of Technology (2021) https://github.com/tylerdolezal/Neutron-Unfolding
[2] Dubeau, J et al.. "A neutron spectrometer using nested moderators", Radiation Protection Dosimetry, 150 (2), 217 (2012)

#09 - Environmental and Medical Sciences / 238

#9-238 Range monitoring in proton and carbon therapy with the TIARA detector

Author: Maxime Pinson[1]

Co-authors: Adélie André [1]; Alicia Garnier [2]; Christian Morel [2]; Christophe Hoarau [1]; Daniel Maneval [3]; Jean-François Muraz [1]; Joel Herault [3]; Johan-Petter Hofverberg [3]; Laurent Gallin-Martel [1]; Marco Pullia [4]; Marie-Laure Gallin-Martel [1]; Matheiu Dupont [2]; Pavel Kavrigin [1]; Sara Marcatili [1]; Yannick Boursier [2]

[1] *LPSC*

[2] *CPPM*

[3] *CAL*

[4] *CNAO*

Corresponding Author: maxime.pinson@lpsc.in2p3.fr

Hadron therapy offers a significant advantage over conventional gamma-ray radiotherapy: its specific dose deposition profile with a maximum, called Bragg peak, at the end of the hadron range allows for more precise tumour targeting while sparing the healthy tissues. However, uncertainties in the prediction of the range in the patient leads to the use of relatively large safety margins, thus hindering the potential of this kind of therapy. In this context, we have developed a range monitoring detector, the Time-of-Flight Imaging ARrAy (TIARA), dedicated to Prompt Gamma Imaging. Prompt Gammas (PG) are secondary radiation resulting from the nuclear interactions occurring in the patient. TIARA exploits the existing correlations between the proton + PG Time-Of-Flight (TOF) distribution and the distribution of PG emission vertices, which reflects dose deposition along the proton path.

The current TIARA prototype consists of 8 Cherenkov detectors placed around the patient, which are readout in time coincidence with a fast beam monitor placed upstream. The beam monitor is composed of a plastic scintillator read-out by four strips of SiPMs placed on the sides, used to tag in time the incident particle with a time resolution of 120 ps FWHM with 63 MeV protons. The Cherenkov detectors are composed of $2 \times 1.5 \times 1.5$ cm^3 PbF_2 crystals, coupled to a 2×2 SiPM array to determine the PG time of arrival. These detectors have the advantage of being insensitive to neutrons, which represent the main source of background for this application. The system coincidence time resolution is of the order of 250 ps FWHM, allowing to precisely measure the proton + PG TOF.

The prototype has been tested extensively at cyclotron, synchro-cyclotron and synchrotron facilities, with proton and carbon ions. The system has proven its adaptability to the peculiar time structures of these accelerators. The different approaches proposed for the determination of the hadron-gamma coincidences and the different performances obtained will be described, by discussing the main experimental campaigns.

The prototype was tested at the Centre Antoine Lacassagne (CAL) in Nice, France using the S2C2 proton synchro-cyclotron. An anthropomorphic head phantom was irradiated with 148 MeV protons at the level of one of the sinuses. In a first experiment, the sinus was left empty, while in a second irradiation it was filled with ultrasound gel, mimicking an anatomical change in the patient. These two irradiations provided noticeably different proton + PG TOF distributions, providing information on the proton range shift and on the density of irradiated tissues. In general, proton range accuracies of the order of 2 mm or less (at 2 σ) have been obtained at the level of a single irradiation spot of approximately 10^7 protons.

More recently, the adaptability of the TIARA prototype to 12C beams delivered by the CNAO synchrotron in Pavia, Italy was studied. The use of 12C beams poses several challenges. Carbon ions may go through fragmentation, generating lighter and faster secondary particles which, in turn, may create PGs beyond the Bragg peak, making the proton + PG TOF distribution less sharp and the projectile range more difficult to measure. Moreover, energetic secondary particles produced by the patient/target may also be directly detected by the TIARA modules, especially those placed downstream, thus leading to background contamination and a degradation of the measurement SNR.

Despite these challenges, CTRs of around 250 ps FWHM, close to the one obtained with synchrocyclotron protons, was obtained in a comparable low intensity configuration.

A large PMMA target was employed to estimate the sensitivity of the system by slightly varying the beam incident energy. For energy variations corresponding to millimetric range shifts, TIARA provided small (~ 10 ps), but measurable time differences. The analysis of these data is currently on-going and will provide a quantitative measurement of the system range measurement accuracy with carbon ions.

#10 - Current Trends in Development of Radiation Detectors / 239

#10-239 Utilization of periodic nanostructures to improve detection efficiency and time/energy resolution of inorganic scintillators

Author: Stuti Surani[1]

Co-authors: Douglas Wolfe [1]; Federico Scurti [1]; Marek Flaska [1]; Roman Samulyak [1]

[1] *Penn State University*

Corresponding Author: mflaska@psu.edu

Inorganic scintillators are commonly used in various gamma spectroscopy applications due to their excellent energy resolution, reliable performance, relatively low cost, and high detection efficiency. Nevertheless, many inorganic scintillators have high refractive indices and experience significant light losses at the collection surface caused by total internal reflection (TIR). This project uses optimized periodic nanostructures, also known as photonic crystals (PHCs), to recover some of the light initially lost due to TIR. The PHC layer creates an optical pathway through constructive interference between the scintillator and the photosensor for the originally trapped light photons. Enhancing the light extraction from an inorganic scintillator also improves its energy resolution, time resolution, and overall detection efficiency. This work has many applications, particularly in nuclear security and nonproliferation, where enhanced energy resolution is crucial. It also holds significant potential for medical applications requiring an improved time resolution. During this project, we first simulated an optimized PHC geometry to maximize the light output using codes Geant4 and OptiFDTD. The optimization simulations for a 10 x 10 x 3 mm^3 LYSO scintillator coupled with 2D block structure Si_3N_4 PHC show an improvement in light output of more than 60% for a single light pass. Following the simulations, manufacturing efforts were made to reproduce the proposed PHC geometry and then characterize the scintillators with and without the PHC deposition. The manufacturing process for the block structure PHC geometry involves electron beam lithography followed by reactive ion etching. The required electron beam lithography resolution depends on the spacing between the PHC. For the initial tests, an unoptimized PHC geometry was selected to troubleshoot and optimize the manufacturing process for our scintillator substrate (LYSO). The LYSO samples deposited with PHC were then characterized through radiation measurements with a Cs-137 source. The radiation measurements showed an improvement in pulse size and total counts, which suggests an improvement in the scintillator's light output. The results also showed an improvement in the energy resolution of the scintillator, which for a specific LYSO sample improves from 12.5% for a bare sample to 11.9% for a PHC deposited sample. Air coupling between LYSO and a PMT was used for simplicity. The work so far demonstrates the potential of PHC structures for improving the overall light output and energy resolution of a LYSO scintillator. The reported results are for a LYSO sample with approximately 80% PHC coverage and unoptimized PHC geometry. Future work will include further improving the PHC manufacturing quality and manufacturing fully optimized nanostructures with greater surface coverage. Future work will also include simulations for lanthanum bromide and sodium iodide scintillators; due to their high refractive indices their light output and energy resolution should be improved more substantially than for LYSO. Finally, other PHC manufacturing methods will be explored, such as spin coating to produce PHC nanospheres.

#04 - Research Reactors and Particle Accelerators / 240

#4-240 SiC Timepix3 Detectors: Characterizing Wide Energy Ranges of Various Particle Types Produced in Medical Accelerators

Authors: Cristina Oancea[1]; Carlos Granja[2]; Andreas Resch[3]; Giulio Magrin[3]; Jan Jakubek[4]; Loïc Grevillot[3]; Sandra Barna[5]; Andrea Sagatova[6]

[1] *ADVACAM*

[2] *ADVACAM, U Pergamenky 12, 17000 Prague 7, Czech Republic*

[3] *MedAustron Ion Therapy Centre, Marie-Curie-Strasse 5, 2700 Wiener Neustadt, Austria*

[4] *Advacam, Research and Development Department, Prague, Czech Republic*

[5] *Medical University of Vienna, Waehringer Guertel 18-20, 1090 Vienna, Austria*

[6] *Institute of Nuclear and Physical Engineering, Slovak University of Technology in Bratislava, Ilkovičova 3, 841 04, Bratislava, Slovak Republic*

Corresponding Author: cristina.oancea@advacam.cz

Silicon carbide (SiC) detectors have become essential in advancing dosimetry for high-energy and high-dose rate radiotherapy. Achieving accurate dose tracking under high-dose-rate and high-energy conditions requires dosimeters that can withstand challenging environments and provide reliable measurements. Conventional silicon detectors, although sensitive, often experience degradation under such conditions due to radiation damage and thermal and dose-rate dependencies, affecting their long-term accuracy and stability. In contrast, SiC detectors demonstrate resilience under radiation, minimal leakage current, and thermal stability due to their wide bandgap, high radiation hardness, and low sensitivity to environmental fluctuations. The Timepix3 with SiC sensors is a high-resolution radiation detection camera capable of real-time beam monitoring and particle tracking. SiC-based detectors are a strong candidate for precise, stable measurements in complex radiation environments, thus supporting the reliable dose delivery essential for modern radiotherapy applications. This study aims to characterize radiation fields in terms of beam structure, particle tracking, and flux using a novel SiC pixelated detector. Moreover, this work provides methodologies for measuring radiation quality in both primary and mixed radiation fields of various beams including protons, carbon ions, electrons and other particles.
The detector is built with an active 65 µm-thick SiC sensor, bump-bonded to a Timepix3 ASIC chip. This combination functions as a pixelated radiation-sensitive volume, enabling spatially resolved measurements and detailed particle tracking. The detector operates under a reverse bias of +200 V and supports per-pixel energy calibration, enabling the measurement of individual particle interactions within its pixel matrix.
Each pixel measures 55 × 55 µm, allowing for high-resolution tracking of particle paths and energy deposition. The full field-of-view (2π) and advanced per-pixel electronics facilitate the detection of various radiation types, including protons, carbon ions, electrons and even fast neutrons. The detector's compact build and ease of integration with data processing systems make it well-suited for real-time dosimetry and radiation imaging, supporting precise tracking and dose distribution measurements.
An experiment was carried out at MedAustron. It is a medical facility for proton and carbon ion therapy, where high-energy particle beams are used for both treatment and research purposes. The experimental setup at MedAustron allows for precise control over beam parameters, with protons accelerated to energies between 62 and 250 MeV and carbon ions up to 402 MeV/u. The facility supports high particle fluxes, reaching up to 109 particles/cm^2/s in clinical mode. A reduced current mode is also available for proton beams, yielding approximately 105 particles/cm^2/s for detailed measurements without excessive particle overlap.
In these experiments, the Minipix Timepix3 SiC detector was placed above the beam isocenter, where single-energy pencil beams were directed at the detector to capture particle interactions. This setup enabled the collection of high-quality data with minimal background interference, allowing the evaluation of the detector's response under clinical particle flux conditions for both proton and carbon ion beams.
The Minipix Timepix3 SiC detector was used to provide single particle tracking of carbon and proton beams. The results demonstrate the potential of the Minipix Timepix3 SiC as a new detector sensor material for quality assurance and beam characterization in various accelerators.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 247

#6-247 Inter-laboratory comparison within the RESORAD Italian network on the natural occurring radioactive materials (NORMs)

Authors: Aldo Fazio[1]; Andrea Petrucci[1]; Giuseppe Menna[2]; Marco Capogni[1]; Mauro Capone[1]; Pierino De Felice[1]; Pierluigi Carconi[1]; Sonia Fontani[2]; Valeria Innocenzi[2]; Michele Croia[1]

[1] *ENEA Casaccia Research Center, Rome, Italy*

[2] *ISIN - Ispettorato nazionale per la sicurezza nucleare e la radioprotezione*

Corresponding Author: michele.croia@enea.it

Environmental radioactivity monitoring is of fundamental importance not only in routine situations but also in the event of accidental occurrences, such as the Fukushima incident in 2011, and extraordinary situations, such as those currently experienced in war-torn countries with nuclear facilities. In Italy, the National Network for Environmental Radioactivity Surveillance –RESORAD is operational, and it is technically coordinated by the National Inspectorate for Nuclear Safety and Radiation Protection (ISIN). The network is constituted by the laboratories of 21 Regional and Autonomous Provinces Agencies for Environmental Protection (ARPA/APPA) and 3 Experimental zooprophylactic Institutes. The quality of the data provided by the laboratories within this network and the efficiency of the measurement systems are highly important requirements for fulfilling the various tasks that ISIN is entrusted within the country, in terms of radiation protection and nuclear safety. ISIN promotes, under RESORAD technical coordination, national programs for the reliability of the measurements from its laboratories. At the same time, the National Institute of Ionizing Radiation Metrology (INMRI) of ENEA has the legal duty to develop standards and disseminate units of measurement in the field of radioactivity through inter-laboratory comparisons (ILCs), calibration campaigns, and performance evaluation tests. In the two-year period 2020-2022, an agreement has been signed between ISIN and ENEA, which allowed the realization of an ILC for the RESORAD laboratories, called NORM-2021, focusing on the measurements of naturally occurring radioactive materials (NORMs). Specifically, the ILC was focused on determining NORMs present in natural sand of volcanic origin. To create the solid reference material (MRS) for the ILC, samples of sand were collected from seven distinct volcanic lake sites in the Lazio region; different samples, each with a volume of 1 L, were collected and measured through gamma spectrometry at INMRI, limiting the analyses to the gamma emissions of K-40 and the radioactive series of uranium and thorium. Among the sampled sands, the one from the site with the highest concentration of NORMs, particularly from the thorium series, was chosen. The MRS was then produced using sand from the selected lake site, sampled near the shoreline, where the grain size is more uniform. To test the measurement capabilities of the participating laboratories, the organizers of the ILC decided to introduce an artificial imbalance in the uranium radioactive series by adding a known quantity (approximately 400 Bq/kg) of Ra-226 to the sampled sand at the INMRI laboratories, thus increasing the natural activity concentration of this radionuclide by a factor of 3. A series of samples was then produced from the MRS, with each sample sent to each participant after ensuring sample homogeneity. The participants were then provided with instructions for performing measurements with their high-resolution gamma spectrometers and a sheet to record the results of their analyses. In addition to identifying the radionuclides present in the sand matrix and quantifying the activity concentration (by measurement), each participant was also asked to determine the minimum detectable activity concentration (M.D.A.) under the measuring conditions used and for some radionuclides not necessarily present in the sample matrix received. The analysis of the results provided by each participant was carried out in terms of indicators commonly used in performance evaluations and inter-laboratory comparisons [ISO, 2010; ISO, 2016], including: the percentage deviation R between the measured value, M, provided by the participant and the reference value, Mrv, provided by INMRI; the normalized error or compatibility index En defined in terms of extended uncertainty (coverage factor k=2), U, associated to M, the extended uncertainty Urv associated to Mrv and the uncertainty component, Ucp, in common to both the participant and the reference value provided by INRMI, whose value should be between ±1 for acceptable results.

The final data analysis highlighted false positives (radionuclides incorrectly detected and not present in the MRS) from some laboratories and false negatives (radionuclides present but incorrectly not reported) from others. Given the low level of radioactivity, all participating laboratories performed measurements at a distance of the sample with the detector of less than 5 cm, which required the use of corrections for summing effect both during the calibration of the spectrometers used by the participants and during the measurement phase. The results obtained showed an En value between

±1 for 87% of the participants. In order to provide explanations for possible sources of error in the measurements performed, INMRI invited the laboratories for bilateral discussions as the final phase of the inter-laboratory comparison.

#10 - Current Trends in Development of Radiation Detectors / 248

#10-248 Experimental analysis of Schottky-barrier SiC-detector-response to fast neutrons: comparison with Si and diamond detectors

Author: Andrea Sagatova[1]

Co-authors: Abdallah Lyoussi [2]; Benedikt Bergmann [3]; Bohumir Zatko [4]; Christophe Destouches [5]; Eva Kováčová [6]; Mehdi Ben Mosbah [7]; Nikola Kurucova [8]; Olivier Llido [9]; Radu Emanuel Mihai [10]; Stanislav Pospisil [11]; Tomas Slavicek [10]; Vladimír Nečas [12]

[1] *(Institute of Nuclear and Physical Engineering, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology, Ilkovicova 3, SK- 841 04 Bratislava, Slovak Republic*

[2] *CEA Cadarache*

[3] *Institute of Experimental and Applied Physics*

[4] *Intitute of Electrical Engineering, Slovak Academy of Sciences*

[5] *CEA/DES/IRESNE/DER/SPESI*

[6] *Institute of Electrical Engineering, Slovak Academy of Sciences*

[7] *CEA, DES, IRESNE, Nuclear Measurement Laboratory*

[8] *Institute of Nuclear and Physical Engineering, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava*

[9] *CEA, DES, IRESNE, DER, Cadarache F-13108, Saint-Paul-Lez-Durance, 13108, France*

[10] *Institute of Experimental and Applied Physics, Czech Technical University in Prague, Husova 240/5, 110 00 Prague, Czech Republic*

[11] *IEAP CTU in Prague*

[12] *Slovak University of Technology, Faculty of Electrical Engineering and Information Technology*

Corresponding Author: andrea.sagatova@stuba.sk

The 4H-polytype of SiC still remains a promising semiconductor material for detector preparation. Its wide band-gap (3.23 eV @ room temperature) predestines it for operation not only at room temperature but also at rather high temperatures up to several hundred degrees Celsius. High breakdown voltage (4 MV/cm) leads to high drift velocity of radiation-generated charge carriers and so to fast detector response. The 4H-SiC stands out in a high atomic displacement energy (20-35 eV) among semiconductor materials, which makes it very promising in terms of resistance against radiation damage. However, the defects in semiconductor structure cause noise signal and their concentration should not exceed 1e14 cm-3 to ensure reasonable signal to noise ratio during radiation detection. In the case of SiC, this condition is at the edge of recent production technology limits. We have prepared single pad Schottky type detectors based on 4H-SiC material of sufficient quality prepared as 80 μm thick epitaxial layer on base material substrate. The Schottky electrode of 3 mm diameter was created as an Au/Ni double layer evaporated on the top side (epitaxial layer) of the wafer and the full area ohmic contact of Ti/Pt/Au was deposited on its back side. Measured current-voltage characteristic of prepared structures have shown that the reverse current flowing through the structures is in the range of pA which enables to achieve very good pulse-height spectrometry. The exceptional thermal and radiation resistance of SiC as a semiconductor material implies its application as a detector in today's nuclear reactors, fusion or fission ones, or in other radiation and thermally harsh technologies. The SiC detectors have shown suitability as detectors of fast neutrons. The atoms of the material react as targets for neutron conversion and the products of neutron absorption and scattering are created directly in the detector volume. We have tested the fabricated 4H-SiC detectors with two neutron sources, the Van de Graaff accelerator of CTU in Prague, producing neutrons through T(p,n), D(d,n) and T(d,n) nuclear reactions and the DANAIDES T(d,n) generator at CEA in Cadarache, in the frame of the 'Timepix SiC detector' international project under the DANUBE2022 region strategy programme. The given reactions at multiple projectile energies were chosen to obtain the numerous responses of the detectors to fast neutrons in the entire range of energies from 0.3 to 17 MeV, to evaluate detector suitability for neutron classification in neutron fields. The response of SiC detector was analysed and compared with the responses of commercially available reference Si diode and with a single crystal diamond detector fabricated at SAS in Bratislava. All these three detectors were placed in the same relative position with respect to neutron source and have been exposed to the neutrons of the same energies during measurement. The pulse-height spectra measured by silicon detector and diamond detector separately, have confirmed the interpretation of the

structure of the pulse-height spectra measured by the SiC detector, merging the interaction of neutrons on both types of SiC nuclei together: on silicon in reference silicon detector and on carbon in diamond detector. Besides, the two target nuclei as a part of SiC detector volume increase the amount of the reactions to be used for fast neutron spectrometry enabling to achieve more precise results.

The authors would like to acknowledge the support by the Slovak Research and Development Agency under the Contract no. DS-FR-22-0012.

#04 - Research Reactors and Particle Accelerators / 249

#4-249 Techniques for Accurate Energy Calibration in Reactor Neutrino Detectors

Author: Ilham El Atmani[1]

[1] *Hassan II University of Casablanca, Fsac and CEA Paris Saclay*

Corresponding Author: ilham.elatmani-etu@etu.univh2c.ma

Recent years have seen significant advancements in neutrino physics, particularly in the study of reactor neutrinos, which have played a key role in resolving the long-standing reactor neutrino anomaly. Accurate calibration of detectors in reactor neutrino experiments is essential for measuring reactor antineutrino interactions and understanding neutrino oscillations, key phenomena in particle physics. This paper focuses on the calibration techniques used to establish a reliable energy scale for detecting neutrinos through inverse beta decay (IBD), a crucial process for reactor monitoring and neutrino physics. Several calibration methods are employed, including the use of scintillators, radioactive sources (both gamma and neutron emitters), cosmic muon detection, neutron capture events (such as those from AmBe sources), and LED light injection to calibrate the photomultiplier tubes (PMTs) and monitor the linearity of the electronics. These techniques play a critical role in ensuring an accurate energy scale, which is fundamental for precise neutrino measurements. Scintillators and radioactive sources are used to inject known signals into the detector, enabling direct calibration of the energy scale and control detector response stability. Cosmic muon detection helps to understand the spatial response and efficiency of the detector, while neutron capture events provide additional insight into the detector's nuclear response. Additionally, advanced simulations using Geant4, FIFRELIN, and Monte Carlo methods help to correct for energy nonlinearity, model complex gamma cascades, and improve neutron capture efficiency, further reducing uncertainties in energy reconstruction. These methods significantly enhance energy resolution and reduce systematic errors, resulting in more accurate reactor neutrino measurements. The combined application of these techniques improves data accuracy for reactor antineutrino spectra analysis and enables better interpretation of neutrino energy distributions, offering deeper insights into reactor operations and the properties of neutrinos. These advancements not only enhance the sensitivity of ongoing and future neutrino experiments but also contribute to the optimization of reactor monitoring and neutrino oscillation studies. Ultimately, improved calibration methods are crucial for advancing research in both particle physics and nuclear science.

#10 - Current Trends in Development of Radiation Detectors / 250

#10-250 Comparison of 4H-SiC Radiation Detectors based on PN junctions and Schottky contacts

Author: Nikola Kurucova[1]

Co-authors: Andrea Sagatova [1]; Bohumir Zatko [2]; Damien Barakel [3]; Laurent Ottaviani [3]; Olivier Palais [3]

[1] *Institute of Nuclear and Physical Engineering, Faculty of Electrical Engineering and Information Technology, Slovak University of Technology in Bratislava*

[2] *Institute of Electrical Engineering, Slovak Academy of Sciences*

[3] *Institute of Materials Microelectronics Nanosciences, Aix-Marseille University*

Corresponding Author: nikola.kurucova@stuba.sk

Silicon carbide (SiC) is a promising semiconductor material for the fabrication of radiation detectors, largely due to its advantageous characteristics, including high chemical and temperature stability, as well as radiation hardness. Silicon carbide (SiC) is capable of crystallising in several different modifications, including 3C, 4H and 6H polytypes. The most favourable for the fabrication of radiation detectors is 4H-SiC polytype. The detectors based on 4H-SiC are capable of functioning not only at room temperature but also at elevated temperatures, due to the wide bandgap, high mobility of charge carriers, and high saturation velocity. Furthermore, the material is commercially available, which represents a significant benefit. A major advantage of SiC-based radiation detectors is also their ability to directly register neutrons, as they contain light carbon atoms compared to silicon-based detectors.
Two types of 4H-SiC semiconductor detectors for ionizing radiation can be distinguished on the basis of their way to block the thermally and by defects generated current flowing through the structure. One group is based on PN junctions, while the other is based on Schottky contacts. The objective of this study is to compare these two types of 4H-SiC radiation detectors. Additionally, the study will examine the impact of varying thicknesses of the n-layer or epitaxial layer of 4H-SiC material on the quality of the fabricated detectors in terms of electrical characteristics measurements.
Two sets of 4H-SiC detectors were prepared. The first set of detectors is based on PN junction and was prepared from 350 µm substrate with three different n-layer thicknesses of 20, 60 and 100 µm and contact diameter of 1.5 mm. The set of detectors with Schottky contacts was also made from 350 µm 4H-SiC substrate and four different epitaxial layer thicknesses of 25, 50, 80 and 100 µm with a Schottky contact diameter of 2 mm. The results indicate that the Schottky type detectors exhibit a predisposition for better detection and spectrometric properties, particularly in regard to the reverse current, which represents the background noise to the signal from the registered radiation, as well as the breakdown voltage, which limits the operating voltage. The reverse current density for 4H-SiC detectors with Schottky contacts is approximately 10e-11 A/mm^2, while results in the range of 10e-9 to 10e-8 A/mm^2 have been obtained for PN junction detector samples. The thickness of the epitaxial layer also affects the electrical properties of the detectors, with superior results being obtained when the epitaxial layer is thinner.

The authors acknowledge funding from the Slovak Research and Development Agency (Research Projects APVV-22-0382 and APVV-18-0243).

#06 - Nuclear Safeguards, Homeland Security and CBRN / 251

#6-251 Neutron/gamma discrimination with proportional counter using artificial intelligence

Author: Aya Kanj[1]

Co-author: Richard Babut [1]

[1] *Authority for Nuclear Safety and Radiation Protection (ASNR)*

Corresponding Author: aya.kanj@asnr.fr

The Micro-irradiation, Neutron Metrology and Dosimetry Laboratory (i.e. the LMDN) from IRSN Cadarache in France, is responsible for the national references in the field of neutron dosimetry. For this purpose, the LMDN produces reference neutron fields and has spectrometers to characterize them. Among these instruments is ROSPEC (ROtating SPECtrometer), a multidetector system comprising six spherical proportional counters designed for neutron detection and spectrometry across a wide energy range. Four of the counters, called SP2-1, SP2-4, SP2-10 and SP6, are designed to cover neutron energy ranges between 50 keV and 5 MeV. The fifth counter is a 3He-filled detector designed to detect thermal neutrons (E < 25 meV), while the final counter, 3He+10B, has a boron-coated inner surface for detecting neutrons between 1 eV and 10 keV. The proportional counters are sensitive to both neutrons and gamma rays. Neutrons are detected through elastic scattering with hydrogen atoms, which produces recoiling protons that ionize the gas and generating a signal. Gamma rays interact with the cathode of the detectors, producing electrons that also ionize the gas.

The main objective of this work is to improve the ROSPEC working by extending the energy range below 50 keV. To achieve this, it is necessary to discriminate between neutrons and gamma rays. This study concerns the SP2-1 counter which covers the energy range from 50 to 250 keV. A numerical acquisition is used by coupling the preamplifier of the SP2-1 counter with a digitizer. The digitizer records the set of detected signals. To detect low-energy signals (< 50 keV), we need to lower the detection threshold, which will consequently increase background signals.

Therefore, the first step is to eliminate noise from the data. One solution is to use an AI-based method called Convolutional Neural Network (CNN). To be efficient, the algorithm must be trained with simulated signals (sigmoïde functions for neutrons and photons, and mixture of different operations on normal distribution for background signals). The CNN method applied to the measured data has proven to be effective, as it provides reliable probability estimates. These estimates are essential for setting a discrimination threshold (X) to classify gamma and neutron signals separately from noise. Specifically, a signal classified as a neutron or gamma with a probability ≥ X% is accepted as such, while signals below this threshold are considered noise. The disadvantage of this method is the high demand for computing resources for neural network training. As well as the risk of overfitting should be considered.

After noise reduction, the second step is to determine the amplitudes and rise times of the remaining signals. The rise time gives an information about the particle type and the amplitude an information about the particle energy. A smoothing method based on the algorithm of SavitzkyGolay was used. Once this analysis has been carried out for all the pulses, a plot of rise time versus amplitude can be obtained. Two distinct groups theoretically appear: neutrons, which exhibit high amplitudes and short rise times (τ), and gamma rays, with low amplitudes and long rise time τ.

The final stage involves neutron/gamma discrimination. One way is to use a machine learning method called clustering. Several algorithms exist as DBSCAN, OPTICS or KMEANS. The challenge is to apply the right algorithm by choosing the right input parameters.

The first two steps in signal processing, noise reduction and determining amplitude and rise time, produce consistent results. The final step which is neutron/gamma discrimination using clustering method is in progress. If successful noise filtering and clustering are achieved, only neutron pulses should remain, enabling the creation of a 1D histogram that represents the neutron distribution by channel, which can then be compared to MCNP (Monte-Carlo N-Particles) simulation results for validation.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 252

#5-252 Advancing Uranium Hexafluoride Conversion: Machine Intelligence in the Integrated Dry Route Process

Authors: Andrew Parker[1]; C. James Taylor[2]; Daniel Hutchinson[3]; David Eaves[3]; Jaime Zabalza[4]; Malcolm Joyce[1]; Manuel Bandala[1]; Neil Cockbain[5]; Patrick Chard[6]; Paul Murray[4]; Paul Stirzaker[3]; R. David Dunphy[4]; Xiandong Ma[7]

[1] *Lancaster University*

[2] *School of Engineering, Lancaster University, United Kingdom*

[3] *Westinghouse Springfields Fuels Ltd.*

[4] *University of Strathclyde*

[5] *National Nuclear Laboratory*

[6] *Mirion Technologies*

[7] *University of Lancaster*

Corresponding Author: m.bandala1@lancaster.ac.uk

This research presents an enhancement to the Integrated Dry Route (IDR) process for uranium conversion in nuclear fuel fabrication, aiming to create a more adaptive system capable of dynamically responding to fluctuations in key variables. The approach involves applying advanced data conditioning and feature extraction methods to process historical industrial datasets, ensuring effective extraction of critical information for accurate analysis. Central to this modification is the development of Bidirectional Long Short-Term Memory (Bi-LSTM) sequence classification networks, specifically designed, trained, and rigorously tested to predict the quality of uranium dioxide (UO_2) output, with a focus on controlling fluorine content—a crucial factor in nuclear fuel applications. Fluorine content in uranium (F-in-U) is critical because it directly depends on the IDR process. Although other parameters may be influenced by subsequent processes, such as blending before palletisation, the F-in-U level remains essential despite fluorine's limited role in the fission reaction. High fluorine levels or other impurities can indirectly impact reactor performance by altering the fuel's thermal conductivity and expansion properties, potentially disrupting heat transfer within fuel rods and reducing reactor efficiency. Additionally, fluorine can react with reactor materials, causing corrosion or degradation of fuel cladding, which affects reactor integrity. While fluorine itself is not a strong neutron absorber, impurities like uranium fluorides can influence neutron moderation and absorption, altering reactor behaviour. High fluorine levels or other impurities can compromise the fuel's mechanical and chemical stability, leading to fuel degradation, increased retention of fission products, or reduced fuel assembly lifespan. From the available data, a set of features from the IDR process was selected, and additional features were generated using the kiln operator's datasheet and tacit knowledge gathered through conversations with the kiln's operators. Several training experiments using the Bi-LSTM were conducted: (1) using features from primary magnitudes (flow rate, temperature, and pressure) of the chemical elements involved (UO_2, H_2O, and H_2); (2) using the features described in (1) plus a set of variables (mostly temperatures and pressures) from other kiln sections; (3) using the features in (1) and (2) plus additional sequences created from operators' tacit knowledge and documented experiments; and (4) using only the features derived from tacit knowledge and previous experiments. The Bi-LSTM network demonstrated the highest level of effectiveness in test case (3), accurately predicting UO_2 quality outcomes (98% for rejected batches and 97% for acceptable batches), underscoring its potential as a foundational element in developing digital twins for the IDR process. Digital twins—virtual models that replicate real-world processes—would enable the IDR system to simulate and predict process variations in real time, facilitating immediate adjustments to kiln conditions. As the Bi-LSTM models are further refined, this technology could support a fully adaptive IDR process, allowing instantaneous responses to process conditions, optimizing efficiency and consistency in uranium conversion, and ensuring stringent quality control in nuclear fuel manufacturing.

#08 - Severe Accident Monitoring / 256

#8-256 Understanding and Optimizing Nuclear Thermocouples through Materials Science

Authors: Brian Jaques[1]; Richard Skifton[2]; Scott Riley[1]

[1] *Boise State University*

[2] *Idaho National Laboratory*

Corresponding Author: brianjaques@boisestate.edu

Stable, accurate, and precise temperature measurements are critical for efficient reactor operation, reactor lifetime extensions, and for the advancement or reliable modeling and simulation routines. In addition, traditionally implemented thermocouples experience decalibration and drift when they are exposed to the high temperatures and neutron fluence, common to the next generation nuclear reactor designs. Accordingly, the INL has recently developed high temperature irradiation resistant thermocouples (HTIR-TCs) composed of phosphorus doped niobium and lanthana doped molybdenum thermoelements, an alumina insulation, and a niobium sheath. In order to stabilize the signal generated from the dissimilar metal junction during extended operation and use, the thermocouples must undergo a preliminary heat treatment above its maximum service temperature. In this presentation, we have used a materials science approach to understand drift mechanisms in HTIR-TCs as well as traditionally used thermocouples. Interaction regions of each component of the thermocouples are individually investigated at each stage of the fabrication process and after extreme environment exposures. Accordingly, prior to reactor deployment, the primary factors altering thermocouple performance are defects from cold working, as well as chemical diffusion and grain restructuring due to preliminary heat treatments. Post reactor deployment, thermocouple drift is primarily attributed to advanced chemical diffusion, secondary phase formation, and transmutation of thermoelement materials. In this study, we demonstrate an understanding of drift mechanisms and present an empirical model to predict drift due to transmutation and thermal phenomena.

#09 - Environmental and Medical Sciences / 257

#9-257 Toward quantitative bremsstrahlung medical imaging by custom gamma camera device

Authors: Evaristo Cisbani[1]; Giulia Limiti[2]; Marco Capogni[3]; Maurizio Pilade[4]; Paolo Musico[5]; Silvio Murri[6]; Valerio Cosmi[7]

Co-authors: Alessandro Spurio [1]; Fabio Santavenere [8]; Fausto Giuliani [8]; Maurizio Lucentini [8]; Michele Croia [3]

[1] *National Centre of Innovative Technology in Public Health, Istituto Superiore di Sanità (ISS)*

[2] *STMicroelectronics*

[3] *ENEA*

[4] *Sapienza University of Rome*

[5] *INFN Sezione di Genova*

[6] *Azienda Ospedaliera-Universitaria Sant'Andrea, Roma*

[7] *Technische Universiteit Delft*

[8] *National Centre of Innovative Technology in Public Health, Istituto Superiore di Sanità (ISS),*

Corresponding Author: michele.croia@enea.it

Radiometabolic therapy is a class of clinical treatments that involves administering radiopharmaceuticals to kill and prevent further development of cancer cells by targeting them at the molecular level. The specificity of this treatment and the possibility of a personalized approach make radiometabolic therapy one of the most promising therapeutic protocol in clinical precision medicine. On the other hand, the effectiveness of the radiometabolic approach depends on maximizing radiation damage to the tumour region while minimizing its potential toxicity on healthy organs and tissues. For that purposes it is important, among other aspects, to be able to quantitatively evaluate the spatio-temporal distribution of the radioactive substance in the patient in order to optimize and personalize the methodology and dosage of radiopharmaceutical. This process involves defining a patient-specific treatment plan, as accomplished in external radiation therapy and brachytherapy. Equally relevant is the determination of the biodistribution of the therapeutic agent during treatment: this would make it possible to evaluate, in post-treatment verification phase, the actual administered dose. This information can be obtained non-invasively, possibly in combination with blood tests or other clinical analyses, by imaging the radiation emitted by the therapeutic radioactive substance, which is capable of escaping from the patient's body. Quantitative analysis of these images permits the estimation of distribution of the radiopharmaceutical isotope activities in each region of interest. The time dependent activity can then be related to relevant radiobiological quantities, in primis absorbed dose.
Performing quantitative imaging in radiometabolic therapy is generally challenging due to different factors, including the peculiarities of involved radionuclides. Moreover, defining and quantifying the volumes of interest are also critical: images in nuclear medicine are functional-based, so the volumes identified from these images do not necessarily correspond to anatomical volumes, which are instead reconstructed in Computed Tomography (CT) or Magnetic Resonance Imaging (MRI). In this context, the bremsstrahlung radiation imaging technique may play an important role for radiopharmaceuticals with (almost) pure $\beta-$ (and $\beta+$) emitters, such as yttrium-90 (90Y), used in radiometabolic therapy. While electrons perform their therapeutic task by releasing most of their energy to cells close to the point of radionuclide decay, the bremsstrahlung gamma radiation emitted from the same electrons can escape from the patient and be detected. However, this indirect radiation makes imaging quite complex, especially when administered radiopharmaceutical distribution shall be quantified. In fact, despite initial attempts at quantitative bremsstrahlung imaging dating back to 1980s and improvements on image reconstruction are progressing, clinical exploitation is still at the research level and not yet routinely adopted. Therefore, the main aim of the proposed work has been the setup of an experimental apparatus and methodology to investigate quantitative bremsstrahlung imaging aspects, in order to highlight critical issues and pitfalls, and identify, whenever possible, directions to overcome, mitigate or likely take advantage of some of them. It is worth point out that optimal quantitative imaging reconstruction techniques could be different from those

developed for diagnostic. Respect to most of the previous works in this field, we are considering relatively simplified, but as much as possible controlled experimental conditions: well-known emitter activities (90Y), custom gamma camera including readout electronics and reconstruction algorithms; we also minimized attenuation and scattering effects by adopting a simple, small phantom. This approach should help to better disentangle physics and reconstruction effects that contribute to the bremsstrahlung quantitative imaging, allowing for a more straight analysis of potential sources of image degradation and identifying potential improvements. The data acquired on real measurements have been complemented by Monte Carlo simulations and corresponding data analysis, which are then used to produce quantitative assessment but also better evaluate the overall imaging process.
The experimental apparatus and conditions are characterized by the following main components:

• Radionuclide: weighted solution of yttrium-90 Dichloride (90YCl2)
• Portable ENEA-INMRI Triple-to-Double-Coincidence Ratio (TDCR) counter for direct activity measurement on site of the radioactive solution
• Phantoms: two simple PMMA cylinders (40 and 60 mm diameter, 13.9 and 19.7 mm height) with 3 cylindrical cavities each used for the 90Y solution, in the bottom part and a PMMA lid on top.
• Detector consists of a compact, custom gamma camera based on two detection heads with complementary collimators and sizes. The small head includes a pin hole tungsten collimator with 1.2 mm hole diameter, 2 mm thickness, an NaI(Tl) pixellated scintillator with 2 mm pitch, 50 × 50 mm2 active area and 5 mm thickness, optically coupled to a single Hamamatsu H8500 Photomultiplier. The other larger detection head is equipped by a 20 mm thick, 150 × 200 mm2 active area defined by a parallel hexagonal holes lead collimator with 2.1 mm pitch and 0.3 mm septa, a pixellated NaI(Tl) scintillator 1.5 mm pitch, 6 mm thickness coupled to a 3×4 matrix of H8500.
• Monte Carlo simulator is based on Geant4 toolkit.
In the presentation we will details:
• Fine tuning of Monte Carlo simulation parameters
• Definition and analysis of figures of merit on the simulated data for the choice of the reconstruction conditions
• Improved anodic equalization procedures and centroid reconstruction from the experimental data
• First attempt of quantitative determination by simulation-measurement comparisons
• Comparison of the quantitative imaging results with the reference activity provided by TDCR counter.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 258

#6-258 Experimental verification of nuclear fuel analogues for the detection of water

Author: Brendan Green[1]

Co-authors: Andrew Kennedy [1]; Damilola Folley [1]; Kartikey Mathur [1]; Malcolm Joyce [1]; Robert Mills [2]

[1] *Lancaster University*

[2] *National Nuclear Laboratory*

Corresponding Author: d.folley@lancaster.ac.uk

The presence of water in a spent nuclear fuel (SNF) analogue has been determined by measuring the prompt 2.223 MeV γ-ray produced by neutron capture in hydrogen (or deuterium production). These measurements have been made using a 1"diameter Stilbene scintillator, an EJ-309 liquid scintillator (both from Scionix) and a GR5021 reverse electrode germanium detector (REGe) from Mirion. The detectors from Scionix have been used for initial proof of concept measurements before the REGe detector was set up. The basis of this work focuses on the UK's large inventory of spent advanced gas cooled reactor (AGR) fuel, the majority of which is currently in wet storage. Water ingress into spent fuel assemblies due to fuel cladding failures presents a risk of instability for long term dry storage. Water present and the subsequent radiolysis may lead to, and latterly accelerate, corrosion of the cladding, resulting in an additional radiological hazard. There is also a limited risk of conditions suitable for criticality arising within the storage vessel. Early, non-destructive detection of water to take proactive, preventative action is necessary for appropriate measures to be taken. Prompt gamma activation analysis (PGAA) is a promising method for the measurement of water in SNF due to the highly penetrative nature of ~2 MeV ⍰-rays. PGAA also presents an opportunity to detect water in larger fuel masses which may have been wetted. These include fuel containing materials such as those at Chernobyl and Fukushima where the (n, γ) reaction may be induced by the intrinsic radioactivity of these materials containing large quantities of fission products. Simulations have been performed using the simulation toolkit Geant4 and compared to other work which utilised MCNP6 for validation of the Geant4 physics in use. Geant4 simulations comprised two main focus areas: detection of water in a AGR fuel storage element and selection of a suitable analogue for spent nuclear fuel. For the former modelling work, an AGR fuel assembly was constructed in Geant4. Different configurations of flooding the annular space within the fuel elements, space between the fuel pins and both empty volumes were simulated. In these simulations, limits of detection were similar to that observed in the previously mentioned MCNP6 model. For experimental work, a fuel assembly composed of SNF is not feasible for use in the laboratory. Subsequently, an analogue for SNF is required to build mock fuel assemblies. Calculations informed the selection of potential fuel analogues which were then defined within Geant4 and exposed to a simulated 252Cf source. The neutron attenuation was measured and materials comparable to SNF for AGR pellet dimensions were zinc oxide, molybdenum oxide, tin oxide, and 316L stainless steel. In this work, experimental validation of the results obtained in the previously discussed simulations has been carried out. Targets composed of zinc oxide and 316L stainless steel were placed in front of a neutron source and the neutron attenuation was measured for comparison to the simulations. These targets were produced by pressing powders of each material resulting in rectangular solid masses with a thickness of 14.5 mm, equivalent to an AGR fuel pellet. Results using the Stilbene and EJ-309 detectors for targets with thickness equivalent to the diameter of AGR fuel pellets were agreeable with the results observed in the simulations. For measurement of the 2.223 MeV γ-ray, stearic acid was added as a water analogue due to it possessing a hydrogen density similar to water. Stearic acid was added to the metal powders at 5% and 10% concentrations by volume and pressed to form targets with the same dimensions as the "water"-free targets. Using the GR5021 REGe, a clear variation in the 2.223 MeV peak intensity was observed between the 5% and 10% volume concentrations of water in the metal analogues. A similar intensity of 2.223 MeV γ-rays from SNF containing water is seen in the simulations when only neutrons from spontaneous fission are considered. This suggests the materials identified as analogues for SNF from calculations and simulations are suitable for this application.

This work has shown the viability of PGAA by means of the 2.223 MeV γ-ray emitted from deuterium production for the detection of water in a spent nuclear fuel analogue. Further work is to be done into the spatial resolution of the germanium detector as well as the optimisation of fuel analogues to more closely represent the behaviour of SNF. Spatial resolution will be determined using activated copper foils spread around the lab space so as to represent a distributed source. Understanding the spatial resolution of the detector will inform work concerning the localisation of water pockets.

Optimisation of the spent fuel analogue will be carried out using Geant4 now the model has been experimentally validated.

#04 - Research Reactors and Particle Accelerators / 259

#4-259 In-core Real-time Mechanical Testing of Structural Materials Project Instrumentation

Authors: James Jewell[1]; Malwina Wilding[1]; Pattrick Calderoni[1]

[1] *Idaho National Laboratory*

Corresponding Author: malwina.wilding@inl.gov

Idaho National Laboratory (INL), in collaboration with the Electric Power Research Institute (EPRI), Nuclear Regulatory Commission (NRC), French Atomic and Alternative Energies Commission (CEA), Joint Research Centre (JRC), Nuclear Research and Consultancy Group (NRG), and Research Center Rez (CVR), is the operating agent of a joint experimental program (JEEP) project that operates within the Nuclear Energy Agency's (NEA) Framework for Irradiation Experiments (FIDES II) program. The first objective of the INCREASE project is to design a shared capsule that can house a variety of in-core real-time mechanical testing instrumentation for enabling smart irradiation experiments for most material test reactors (MTRs). The second objective is to collect in-core real-time stress relaxation data pertaining to high priority stainless steel (SS) materials under light water reactor conditions. The shared capsule design produced under this project will, for phase one, be demonstrated in the Massachusetts Institute of Technology Nuclear Research Reactor (MITR), and for phase two in the Petten High Flux Reactor (HFR). Currently, irradiation-induced stress relaxation is assessed both pre- and post-irradiation, thanks to complex and costly pre- and post irradiation examination efforts. A shared conceptual design was produced between INCREASE core group members and Institute for Energy Technology (IFE) based on the MITR and HFR position constraints, along with their pressure, neutron fluence and temperature distributions. The MITR irradiation test will have four fully instrumented (LVDT bellows pre-loaded configuration) SS specimens, four passively instrumented pre-loaded (pre-loaded and static configuration) SS specimens, and four or more passively instrumented non-loaded SS specimens (total number of passive specimens based on the final available space in the capsule). The target temperature for the MITR irradiation is 340℃ +/-20℃ and a minimum neutron damage of 2 dpa, with a preference of achieving 4-5 dpa or until stress relaxation saturation is achieved. The initial stresses for both, four fully instrumented SS specimens and four passively instrumented pre-loaded SS specimens, are about 80% of the nominal yield strength of each material at target temperature. Only the fully instrumented SS specimens will produce in-core real-time stress relaxation, temperature, and neutron fluence data that will be analysed as received during the MITR irradiation. The passively instrumented pre-loaded and non-loaded SS specimens will have to be analysed during PIE. In core stress relaxation measurement data will be collected using a new hybrid type-3.5 LVDTs supplied by IFE, where they will build and supply six of these LVDTs: four for the irradiation test and two for out of core verification testing in a flowing autoclave. Prior to the irradiation, INL will use its in house LVDT calibration system, located at the Measurement Science Laboratory (MSL), to characterize, optimize, and do final sensor validation of each LVDT prior to irradiation. INL also figured out a way to read temperatures using the IFE's LVDT in addition to displacement values without any physical change to the sensor—something critical for obtaining accurate LVDT calibration data and replacing the need for use of additional thermocouples (i.e. additional sensor feedthroughs). The temperature of each fully instrumented specimen will be monitored via two type K thermocouples for axial distribution within each capsule. Additionally, all the specimens (instrumented, passive pre-loaded, and unloaded) will have passive silicon carbide temperature monitors that can measure averaged peak irradiation temperatures during PIE. Additionally, HFR uses gas gaps between experiment capsule and reactor position to control and implement target temperatures, which create larger temperature gradients and uncertainties within length and axial positions than in the MITR. This will require implementation of fiber optics within the shared capsule design to validate thermal models for better temperature estimation. Lastly, the capsule will be placed in the top half of the MITR core length to accommodate long-term irradiation needs, creating neutron fluence (neutron damage rates) gradients between the top and bottom of each capsule. This requires the use of active (self-powered neutron detectors) and passive (neutron dosimeters and retrospective dosimetry) instrumentation to measure more precisely neutron fluence at various locations within each capsule. As a conclusion, this shared capsule design within INCREASE project can be easily and cost effectively leveraged to meet future in-core mechanical testing needs for various MTRs and different types of materials; furthermore, implement and verify advanced instrumentation techniques for better understanding of the measurements collected during irradiation.

#04 - Research Reactors and Particle Accelerators / 260

#4-260 Simultaneous Analysis of Noise Detectors and Spectroscopy of a Low-power Experiment (SANDcaStLE)

Author: Flynn Darby[1]

Co-authors: Andrew Lucas [1]; Cole Kostelac [2]; Michel Saliba [3]; Vincent Lamirand [4]; Shaun Clarke [1]; Andreas Pautz [4]; Sara Pozzi [1]; Oskari Pakari [5]

[1] *University of Michigan*

[2] *Los Alamos National Laboratory*

[3] *École Polytechnique Fédérale de Lausanne*

[4] *Ecole Polytechnique Fédérale de Lausanne*

[5] *EPFL*

Corresponding Author: fdarby@umich.edu

Measurements of reactors inform nuclear data through validation benchmarks and serve to monitor reactor behavior during critical, startup, and shutdown phases. Reactor measurements contribute to the accuracy of reactor modeling, support safe operational practices, and provide insights for design and operating teams, as well as regulatory bodies. The CROCUS zero-power research reactor provides an excellent platform for these experiments. CROCUS is a light water, low enriched uranium (1% Uranium-235) facility that provides a flexible environment for detector measurements in a thermal reactor setting, with a maximum power of 100 W and neutron flux of 2.5 x 10^9 n/cm^2-s. With options for detector deployment at various reactor positions—such as control rod locations, watertight tubing, and outside the vessel, along with cable ports to the control room—this reactor supports extensive analysis of fission kinetics and gamma-ray fields. We conducted a measurement campaign named the Simultaneous Analysis of Noise Detectors and Spectroscopy of a Low-power Experiment (SANDcaStLE) to (1) use various detection systems to derive kinetic parameter estimates from fission chain "noise", and (2) to evaluate the gamma-ray energy spectrum both at power and post-shutdown. We deployed neutron detectors across multiple positions, including four CFUL-01 fission chambers around the core perimeter and the SAFFRON array, consisting of 160 compact ZnS:^{6}Li(Ag) scintillators distributed across three main axial planes (15, 50, and 85 cm). The distribution of the SAFFRON array provides high spatial resolution, while the detectors and fiber optic readout enable precise temporal tracking, making SAFFRON well-suited for detailed mapping of core kinetics and reactivity changes, especially near control rod regions. Gamma-ray detectors were similarly positioned to assess both kinetic parameters and the gamma-ray energy spectrum. A $CeBr_3$ detector in a control rod position measured in-core, while two BGO detectors and one HPGe detector outside the reactor offered additional data ex-core. Initial analysis of both gamma and neutron systems has provided estimates of the prompt neutron decay constant at critical (155-160 s^{-1}), aligning with benchmark values. Ongoing analysis will extend to estimating the effective delayed neutron fraction using both fission chambers and, for the first time, the SAFFRON. Our kinetic analysis will include comparisons across neutron and gamma-ray detectors to evaluate convergence times, investigating the efficiency and spatial advantages of distributed systems for kinetic estimates. Additionally, the HPGe detector resolved the post-shutdown gamma-ray energy spectrum, capturing isotope behavior for over 56 gamma-ray emitting fission products. Quantification of isotopes post-shutdown will offer insights for modeling isotope decay and simulating resultant reactivity changes, validating our understanding of the fission product populations in low-power thermal systems.

#04 - Research Reactors and Particle Accelerators / 261

#4-261 Characterization of the fast neutron source facility at STU

Authors: Jakub Luley[1]; Branislav Vrban[2]; Štefan Čerba[3]; Filip Révai[None]; Vendula Filová[3]; Otto Glavo[3]; Vladimír Nečas[3]

[1] *Slovak University of Technology in Bratislava*

[2] *Slovak University of Technology in Bratislava, Slovakia*

[3] *Slovak University of Technology, Faculty of Electrical Engineering and Information Technology*

Corresponding Author: jakub.luley@stuba.sk

This study presents a new facility developed at Slovak University of Technology in Bratislava. The laboratory aims to production of the fast neutrons for research and educational activities. The main component is the Deuterium- Deuterium neutron generator with the emission rate about 1E8 neutron/sec. to 4π placed in the room with dimensions approximately 11×11×7.5 m3. Internal construction of neutron generator employs titanium-coated copper target, which makes neutrons emission anisotropy unique for each new device and thus extensive measurement characterization of the source is required. Accelerated deuterium is trapped in the titanium lattice and when the saturated level is reached, the neutrons are emitted in the relevant amount. Intensive SCALE MONACO Monte Carlo simulations were carried out to evaluate primary characteristics and ambient dose rates within laboratory and adjacent area. Unfortunately, the real neutron source anisotropy was unknown and therefore theoretical anisotropy defined based on the point-source calculation was used. The paper characterizes the neutron source from the point of view of spatial and energy distribution of the neutrons around the generator head. However, the laboratory benefits from relatively large volume, the room effect can play a relevant role in the neutron spatial distribution and then must be properly characterized. The comprehensive characterizations is need not only for future experimental activities, but also for ambient dose rate evaluation and operation licensing issues. The facility aims to support precise fast neutron radiography of large industrial components deployed within Gen-IV reactor concepts. Neutron radiography presents a promising alternative for industrial applications especially where large penetrations are required and light nuclides are presented. The laboratory is also equipped by the X-ray lamp and flat panel to cover large area of non-destructive testing techniques and defects identification.

#10 - Current Trends in Development of Radiation Detectors / 262

#10-262 SiC-based detectors for fast neutron measurements in a multi-energy field

Author: Quentin Potiron[1]

Co-authors: Abdallah Lyoussi [2]; Christelle Reynard-Carette [3]; Christophe Destouches [4]; Michael Houry [5]; Olivier Llido [6]

[1] *Aix Marseille University*

[2] *CEA Cadarache*

[3] *Aix-Marseille University*

[4] *CEA/DES/IRESNE/DER/SPESI*

[5] *CEA*

[6] *CEA, DES, IRESNE, DER, Cadarache F-13108, Saint-Paul-Lez-Durance, 13108, France*

Corresponding Author: quentin.potiron@iter.org

Wide-bandgap semiconductor-based fast neutron detectors, such as silicon carbide (SiC), show promise in meeting the implementation and performance requirements for fusion and fission environments. These requirements include radiation hardness, as well as thermal and mechanical stability. Therefore, controlling the detector's performance based on neutron energy and sensor characteristics is essential for neutron detection and monitoring in mixed radiation environments with high levels of fast and thermal neutron fluxes and gamma emissions at large energy scales.

The diodes under study, made with 4H-SiC polytype, feature a 60µm "p-n"junction that collects electron/hole pairs generated in the space charge region by the interaction of neutron reaction products and gammas in mixed radiation fields. The recorded electric signal can then indicate the energy of the registered reaction products, providing information on the energy of the fast incident neutrons. The use of the sensor in a mono-energetic field has shown in previous work encouraging results for a first estimation of the absolute value of the fast neutron flux. However, qualifying the sensor's response over a wide energy range in a multi-energetic field is complex.

In this work, a solution is proposed using response functions for neutron spectrum unfolding. Due to the limitations of the simulation tool, which relies on nuclear data with large uncertainties for the studied reactions, experimental data were necessary for deconvolution methods using a response matrix. The calibration of these response functions was performed using Time of Flight (ToF) measurements at the Neutron For Science facility of GANIL, which allowed the construction of a response matrix with enough energy channels to meet the requirements of iterative deconvolution methods necessary for neutron spectrum deconvolution.

The presented results are promising across the entire energy range of the neutron spectrum, demonstrating the sensor's ability to estimate neutron flux in a high-energy neutron field with deviations of around 10% over most of the energy spectrum. The experimental campaign has thus demonstrated the sensor's capability to measure neutron flux in a continuous neutron field using an experimental response matrix constructed with Time of Flight (ToF) measurements.

#10 - Current Trends in Development of Radiation Detectors / 263

#10-263 The FPGA-controlled biasing of the photomultiplier tube based on the Cockcroft-Walton voltage multiplier

Author: Jiří Čulen[1]

Co-authors: Aleš Jančář [2]; Jan Král [1]; Zdeněk Matěj [1]

[1] *Masaryk University*

[2] *VF, a.s.*

Corresponding Author: jiri.culen@mail.muni.cz

A common approach to photomultiplier tube biasing is to use a high-voltage power supply and a passive or active voltage divider to create the necessary electrical potentials to power the amplification process in the photomultiplier tube. The lowest current flows from the photocathode to the first dynode. The highest current flows from the last dynode to the anode. If a standard voltage divider is used, the current to the dynode must flow through the entire divider chain between that dynode and the photocathode potential. Due to this principle, the highest current flows from photocathode potential. This mechanism causes high power losses and can create a well-known strong dependence of the photomultiplier gain on the measured signal. The Cockcroft-Walton voltage multiplier can solve this problem when the voltage multiplier chain starts on the anode side. In this case, the direction of increasing currents is the same in the voltage multiplier as in the photomultiplier tube. This topology is especially suitable for a negative high-voltage topology with an anode potential close to the ground. We studied the existing topologies of the Cockcroft-Walton voltage multiplier and possible ways to excite this voltage multiplier. We used simulations of different circuit topologies. We focused on voltage stability, minimizing the number of discrete components, and minimizing the used printed circuit board area. We created an experimental setup based on FPGA signal processing to control and verify the proposed topology. Our experimental setup, based on FPGA signal processing, allowed us to maintain and verify the proposed topology. This setup included a photomultiplier socket with voltage multiplier, inverting switched power converter for excitation for voltage multiplier, A/D and D/A converters for control loops and state monitoring functions, the amplifier of the output anode signal, and auxiliary power supplies. This socket is connected to the FPGA development board. We tested and compared the proposed solution with classic passive and active voltage dividers. Our target applications for using photomultiplier tubes are gamma spectroscopy and mixed neutron/gamma measurement based on pulse-shaped discrimination. The stability of gain for the whole system at various count rates is essential. We use CeBr3 crystal in different strengths of Cs-137 gamma ray. A digital multichannel analyzer measured the output signal, and the position of the 661 keV peak was checked. The results show that the proposed solution can achieve similar or better stability than the active divider and a classic high-voltage source.

#11 - Education, Training and Outreach / 264

#11-264 Precision in Pixels: An Innovative Tool for Particle Analysis in Medicine, Space, and Nuclear Fields.

Author: Lukas Marek[None]

Co-authors: Carlos Granja [1]; Cristina Oancea [2]; Jan Jakůbek [3]; Roman Nebel [4]

[1] *ADVACAM, U Pergamenky 12, 17000 Prague 7, Czech Republic*

[2] *ADVACAM*

[3] *ADVACAM s.r.o.*

[4] *Advacam, s.r.o.*

Corresponding Author: roman.nebel@advacam.cz

Single-photon counting detectors with direct conversion to electrical signals enable highly accurate, noise-free, real-time particle detection, which is essential for high-precision applications such as dosimetry and beam diagnostics. The Timepix family of hybrid semiconductor pixelated detectors, known for their wide energy range detection capability and high-resolution positional accuracy, is well-suited for applications that require precise radiation measurement and monitoring. Their small size and low power consumption make them highly suitable for mobile and remote applications, including space radiation monitoring and particle physics research. Timepix3 detectors have found use in applications as diverse as medical radiotherapy, space radiation monitoring on satellites, radiation safety in nuclear power plants, and particle physics in accelerator environments.

This talk will present the design and implementation of a versatile, user-friendly data analysis tool called TraX Engine, which supports fast, reliable data analysis for Timepix-family detectors across multiple platforms, including a graphical user interface as a desktop application, a Python API, command-line tool, and a web-based interface. With cross-platform availability, it is accessible for both research and practical applications, with a focus on educational use through its online web portal.

The modular processing workflow addresses the unique demands of Timepix-family detector data across three primary levels:

1) Pre-processing –In this phase, adjacent pixels activated by a single particle are clustered, then calibration and corrections are applied. Clusterization extracts essential particle parameters, including energy, time-of-arrival, and spatial size. Cluster formation criteria vary by mode, with frame-based clustering relying on spatial proximity, and data-driven mode using both spatial and temporal criteria.

2) Processing –Machine learning-based algorithms in the presented analytical tool enhance particle classification and radiation field recognition even further. Particle identification techniques classify particle clusters by estimating particle type, energy, and morphological properties. Neural networks developed specifically for Timepix and Timepix3 detectors with various sensors classify particles into categories such as protons, photons, electrons, and ions. A hierarchical classification model provides further detail, distinguishing particle types and energies, such as low- to high-energy protons and helium ions.

3) Post-processing –Advanced data analysis methods, including directional and coincidence analysis, support complex assessments of radiation fields. Coincidence analysis identifies correlated particle events within defined time windows, essential in multi-detector setups or high-energy particle beam experiments where simultaneous particle detection provides critical insights. Directional analysis calculates particle trajectories by determining azimuth and elevation angles, a key factor in proton therapy and space radiation studies. Spatial mapping generates detailed visualizations of parameters like energy deposition and particle flux, aiding applications in beam profiling, field visualization, and material analysis.

The advanced analytical and processing capabilities makes TraxEngine a versatile tool across several fields, including:

Nuclear Power Plants –Accurate radiation monitoring in nuclear facilities is critical, where the Trax-Engine supports real-time tracking of radiation fields and particle flux, ensuring reliable operation of dosimeters and radiation safety protocols.

Space and Aircraft Radiation Monitoring –Compact and energy-efficient, the MiniPIX Space radiation monitor continuously measures space radiation with minimal power usage. Equipped with the data-analysis software, it tracks dose rates, flux, and provides alerts for solar events, contributing to astronaut safety and spacecraft system protection.

Medical Applications –In proton therapy, this tool enables precise measurements of beam characteristics, including flux, energy deposition, and spatial distribution, ensuring accurate targeting of cancerous tissues. In imaging applications, such as gamma detection with Compton cameras, it aids in reconstructing photon origin, supporting internal radiation imaging critical to cancer treatment.

Particle Physics and Accelerator Environments –At particle accelerators, Timepix-family detectors are valuable for beam diagnostics, tracking particle interactions, and monitoring time structures in high-energy beams. Their comppactness and low power requirements make them ideal for placement near active beams and in hard-to-reach areas within accelerator facilities, where traditional detectors may be impractical. TraX Engine enables particle flux analysis, time structure monitoring, and temporal characterization, crucial for high-precision measurements in accelerator physics.

Educational and Practical Utility –The web-based portal facilitates remote data analysis and visualization, making it a useful tool in educational settings. Users can upload and process data from real-world scenarios, such as space radiation or medical imaging, providing hands-on experience in radiation field analysis.

The presented data analysis tool offers a comprehensive, user-friendly solution for real-time analysis of complex radiation fields from Timepix-family detectors. Through advanced pre-processing, machine learning-based particle classification, and post-processing techniques, it has great potential in precise radiation field analysis in nuclear power, space exploration, particle physics, medical applications and others. The system's compatibility across graphical user interface, Python API, command-line, and web platforms ensures broad accessibility for research, operational, and educational purposes. To illustrate its effectiveness, data from ongoing projects such as space radiation monitoring and medical beam diagnostics will be presented, highlighting its application in environments with diverse and complex radiation fields.

#09 - Environmental and Medical Sciences / 265

#9-265 Towards Clinical Integration of a SPECT Detection Module for BNCT Dose Monitoring

Authors: Filippo Ghisio[1]; Tommaso Ferri[1]; Anita Caracciolo[1]; Stefano Agosteo[1]; Saverio Altieri[2]; Carlo Fiorini[1]; Marco Carminati[1]; Luca Grisoni[1]; Giuseppe Iaselli[3]; Yasuaki Ichikawa[4]; Davide Mazzucconi[1]; Nicoletta Protti[2]; Letizia Santini[5]; Kazuki Tsuchida[6]; Giacomo Borghi[1]

[1] *Politecnico di Milano & INFN*

[2] *University of Pavia & INFN*

[3] *Politecnico di Bari*

[4] *Okayama University*

[5] *Politecnico di Milano*

[6] *Japan Atomic Energy Agency*

Corresponding Author: filippo.ghisio@polimi.it

Boron Neutron Capture Therapy (BNCT) is a cancer treatment technique that combines the power of radiation therapy with targeted therapy. In this technique, patients are administered a targeted pharmaceutical containing 10B that selectively accumulates in tumor tissues and are then irradiated with a beam e [epi-]thermal neutrons. These neutrons interact with 10B through a large-cross-section neutron-capture reaction [n (10B, 7Li) α] whose products are high linear-energy-transfer particles that release their energy locally killing tumor cells. Differently from other radiotherapy techniques, the beam does not need to be focused and the patient can be irradiated by a wide neutron field in order to treat diffused (metastatic) tumors. Despite being known since decades, BNCT is gaining new momentum thanks to the advancements in the development of clinical neutron production facilities based on compact accelerators.
During BNCT treatments, the 478-keV gamma photons emitted in 94% of the reactions by 7Li could be used to localize and estimate in real-time the delivered dose using SPECT technique. The main challenges come from the low 478-keV gamma signal, the strong secondary gamma-ray background field (including the 511-keV annihilation peak), the required system spatial resolution (<10 mm), and the constraints given by the integration with the neutron irradiation facility.
During the past years, we have developed a dedicated detection module for BNCT-SPECT application based on a wide scintillator detector and a channel-edge pinhole collimator. When combined with artificial neural network for planar image reconstructing, it provides a geometrical resolution of 8.2 mm. The detector is built using a square LaBr3(Ce+Sr) scintillator (5cm side, 2cm thick) coupled to an array (8 by 8) of SiPM (NUV-HD by FBK) readout but a custom-designed ASIC, allowing energy discrimination at ASIC level to reject background events and avoid count rate saturation. This crystal offers a suitable field of view and achieves a high efficiency (better than 60% at 478keV) and a good energy resolution (better than 3% FWHM at 662 keV).
Two measurement campaigns were recently carried out to test the performance of the BNCT-SPECT module during neutron irradiations, both of which were prepared and designed performing extensive Monte Carlo (MC) simulations. The results of these campaigns will be presented at the conference. The first one was carried out at the Prompt Gamma Neutron Activation Analysis (PGNNA) facility of TRIGA Mark II reactor of the applied Nuclear Energy Laboratory (LENA) in Pavia (Italy). During this campaign a tomographic acquisition of two vials containing an aqueous solution of 10B (~7000 ppm) at a distance of about 1 cm was acquired. The acquisition was performed with the SPECT detection module measuring four different projections of the sources at four different angles with respect to the beam direction and was repeated for two reactor powers (70 kW and 250 kW). In both cases, the results of the measurements significantly matched with the predictions obtained with the MC simulations and the two sources could be visualized and resolved in the reconstructed tomographic images (using 10 iterations of the MLEM algorithm in the STIR reconstruction software).
The second measurement campaign has been performed at the newly constructed BNCT facility of Nagoya University (Japan), which is a more relevant validation environment being an actual clinical facility. Here the major challenge is the abundant presence in the walls of the treatment room of borated polyethylene used to shield thermal neutrons, which create a large background at 478keV demanding additional shielding from the surrounding gamma rays. Data are being acquired and results will be presented at the conference.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 266

#6-266 Evaluating the performance of a photofission prompt neutron detection system based on threshold activation scintillation coupled with a 9 MeV electron accelerator

Author: Luna Sobczak[1]

Co-authors: Adrien Sari [2]; Frédérick Carrel [3]

[1] *CEA Paris-Saclay*

[2] *CEA/List Saclay*

[3] *CEA LIST*

Corresponding Author: luna.sobczak@cea.fr

Photofission prompt neutron detection methods are of great interest for research and development in the field of nuclear instrumentation and measurement, whether for nuclear waste package characterization, border control and homeland security, but also fundamental nuclear physics. The photofission reaction is generally induced by a linear electron accelerator (LINAC), converting electrons into Bremsstrahlung photons, by slowing them on heavy atomic nuclei target, as tungsten or tantalum for instance. Yet, when those high-energy photons (> 6 MeV) interact with actinides, i.e., U-235, U-238, Pu isotopes, etc., photofission reactions may occur and emit prompt and delayed neutrons and delayed gammas. Prompt neutrons are emitted instantaneously while the measurement system and electronics, commonly He-3 proportional counters, are saturated by the intense photon flash delivered by the LINAC. Thence, applications regarding photofission particles emission mostly concern delayed neutrons and delayed gammas whereas 99% of the emitted neutrons are prompt. In addition, their detection after Active Photon Interrogation (API) is relevant for actinide quantification when matrix effects can complicate the measurement by thermalizing delayed neutrons, attenuating and self-absorbing gamma signatures. In this work, we evaluate the performance of a photofission prompt neutron detection system coupled with a 9 MeV LINAC, with the aim of investigating the use of a third photofission signature, in addition to delayed neutrons and delayed gamma rays. This, to reduce uncertainties in the detection of shielded actinides or contained in large hydrogenated volumes, as well as to quantify and differentiate them. In a first step, we performed Monte Carlo simulations to assess the parameters of a setup designed for the photofission prompt neutron detection, based on an indirect method. It consists in delaying the detection of prompt neutrons, by activating a radionuclide and then measuring the decay of the reaction product. The detection of the 6.131 MeV gamma radiation emitted by N-16, resulting from (n, α) reactions with F-19, has been deployed since the earliest advancements in neutron detection for nuclear reactors. Developments with pentafluorostyrene plastic scintillator and CaF2 threshold activation detectors have led to more recent progress in this area. Based on this approach, we can avoid the photon flash of the LINAC and a strong background noise of photoneutrons, created in the conversion target. In a second step, we conducted experimental tests with a 9 MeV electron accelerator, Linatron® M9A designed by Varex Imaging Corp., at the SAPHIR platform (CEA Paris-Saclay, France). The photofission experiment is simulated using PHITS and MCNP6 Monte Carlo codes and the respective nuclear data libraries: ENDF/B-VIII.0 and JENDL-5. First, we evaluate the photoneutron background produced in the tungsten of the accelerator. Considering the (γ, n), (γ, 2n) and (γ, Xn) cross-sections and reaction threshold, the photoneutron production happens to be 90 times higher for a LINAC operated at 15 MeV compared to 9 MeV. Then, the calculation of the photofission reaction rate in uranium leads to the conclusion that the signal-to-noise ratio is optimal for an accelerator operated at 9 MeV, i.e., for a photoneutron production about 40 times higher than the prompt neutron yield. Second, we machined polytetrafluoroethylene layers to be disposed against a bismuth germanate scintillator and we irradiated a depleted UMo sample. Finally, by designing and optimizing a photofission prompt neutron detection system, and investigating the use of a third photofission signature, we are enhancing the API technique for border control of cargo containers and particularly in cases where terrorists would use shielding around hidden Special Nuclear Materiel (SNM). This work should help to push back the frontiers of the API developments and contribute to the advancement of the associated research community.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 272

#6-272 The photofission reaction against the illicit transport of nuclear material in cargo containers: A review on recent achievements and future challenges in active photon interrogation

Author: Adrien Sari[1]

[1] *CEA-List*

Corresponding Author: adrien.sari@cea.fr

The photofission reaction, which forms the basis of the Active Photon Interrogation (API) nuclear measurement technique, is of great interest from fundamental to applied physics, in particular as part of security checks on cargo containers to detect Special Nuclear Material (SNM) at border controls, as uranium and plutonium isotopes could be potentially involved in terrorist attacks. To prevent illicit trafficking of SNM in Europe, inspection of cargo containers is required at borders and X-ray scanning techniques are widely used by customs to control visually containers. If the images show a suspicious area, a second line technology based on the photofission reaction could be used to detect SNM in a non-destructive manner. This paper reviews recent developments in photofission through a saga built around three successive projects of the European Union's Horizon 2020 research and innovation programme, and identifies future challenges to be addressed in API. In the frame of the C-BORD project (2015–2018), the largest seaport in Europe (*Maasvlakte*, in the suburbs of Rotterdam, Netherlands), was chosen to test the first stationary photofission measurement system dedicated to SNM detection in cargo containers in Europe, where 9 MeV electron accelerators are used day-to-day in industrial operations by Dutch customs for X-ray scanning. Experimental tests have been carried out on depleted uranium samples and mock-ups of cargo containers. Setting up a temporary API system on an industrial facility initially designed for X-ray scanning was a challenge, which has been successfully met. In the frame of the ENTRANCE project (2020–2023), the capability of SNM detection in cargo containers at the European borders was tested with a mobile system including a more compact 7 MeV X-ray scanner, thereby challenging the 5–6 MeV energy threshold of the photofission reaction on actinides (²³⁵U, ²³⁸U, ²³⁹Pu, etc.). We go through the field tests conducted at the *Škrljevo* container terminal at the port of Rijeka, Croatia, using the 7 MeV mobile X-ray scanner operated in photofission mode, samples of depleted uranium and a mock-up of cargo container. The performance as well as the limitations of such a system are examined. More recently, in the frame of the MULTISCAN 3D project (2022–2025), a major breakthrough in the field of API has been achieved. The feasibility of implementing the photofission reaction on depleted uranium using an Inverse Compton Scattering (ICS) source based on a femtosecond laser was demonstrated experimentally. This world first, at the frontier of three physics –laser, plasma, nuclear –paves the way for groundbreaking technologies in nuclear security and border control, which steers future researches and developments in the field of API towards a technological revolution in the fight against illicit trafficking of SNM by photofission.

Acknowledgements
Should be gratefully acknowledged, the active involvement and support from:
- Smiths Detection, France, National Centre for Nuclear Research (NCBJ), Poland, Symetrica, UK, and Dutch Customs Administration (DCA), Netherlands;
- *Ruđer Bošković Institute* (RBI), the Ministry of Interior, the Ministry of Finance –Customs Administration, and the Port of Rijeka (*Luka Rijeka d.d.*), Croatia;
- *Ludwig-Maximilians-Universität München* –Centre for Advanced Laser Applications (LMU-CALA), Germany, and the University of Padova, Italy.

Funding
The C-BORD, ENTRANCE and MULTISCAN 3D projects have respectively received fundings from the European Union's Horizon 2020 research and innovation programme under grant agreement nos. 653323, 883424 and 101020100. Disclaimer: this text reflects only the author's views and the Commission is not liable for any use that may be made of the information contained therein.

#04 - Research Reactors and Particle Accelerators / 273

#4-273 Do Not Throw Away Old HPGe!

Author: Maciej Ziemba[1]

Co-authors: Antoni Zawadka [1]; Dariusz Furmańczyk [1]

[1] *Narodowe Centrum Badań Jądrowych*

Corresponding Author: maciej.ziemba@ncbj.gov.pl

Building an Automated Setup for Measuring and Reporting linear Neutron Flux Density distribution Using Activation Wires.

As advancements in nuclear instrumentation continue, the High Purity Germanium detectors, a mainstay in gamma spectroscopy, remains an invaluable tool. This poster presents the development and implementation of an automated system utilising an older High Purity Germanium detector and readily available materials for measurements of neutron flux density. Leveraging activation wires, automation and data processing methods, we devised a time-effective solution for linear distribution of neutron flux density inside MARIA research reactor.
Our approach incorporates automation for sample measurement - data acquisition, and reporting. After irradiating activation wires in the reactor, they are transported to the measuring setup. Hardware part consists of 2.6m lead housing with 10mm gap –collimator, linear drive, and High-Purity Germanium. Software is a combination of Windows scripts, REXX script and Python. Software integration enables automated gamma spectrum acquisition and neutron flux calculations, with results promptly stored and accessible in a digital format. This setup maximises the utility of existing High Purity Germanium detectors, reduces manual intervention, and provides reliable, standardised results.
We have measured samples of moderate and high dose rates. Using this setup allowed us to minimise radiation hazards, as well as measure several activation wires at once. One need to a priori select activation wires (mass and concentration) and calculate activities in order to get reliable results.
The project demonstrates that legacy High Purity Germanium detectors, with tailored automation and software support, remain highly effective for neutron flux density measurements. Our work underscore the potential to modernise nuclear measurement facilities without discarding established instrumentation, presenting a compelling case for integrating older detectors in contemporary nuclear systems. This innovation fosters both cost efficiency and sustainability in nuclear measurement technologies, with implications for reactor measurements, radiation protection.

#11 - Education, Training and Outreach / 274

#11-274 Fukushima-Hamadohri Environmental Radiation School

Author: Masaharu Nomachi[1]

[1] *OSAKA University*

Corresponding Author: nomachi@rcnp.osaka-u.ac.jp

The nuclear disaster in 2011 urged the public to reconsider disaster prevention and energy issues. Osaka University has been working to measure environmental radioactivity in Fukushima Hamadori. Through this work, we have communicated with local people and learned a great deal. We found that the measurements in Hamadori are educational not only from a radiation science perspective but also from a social science perspective. Therefore, we started a school program for students.

The aim of the school is not simply to learn how to measure radioactivity. It is to understand the situation in Fukushima-Hamadohri based on hands-on experience with radiation measurements. Knowledges of physics are necessary to understand radioactivity, and knowledges of chemistry and geophysics are required to understand how radioactive substances exist and circulate in the environment. Understandings of biology and medicine are essential to grasp how these substances affect the human body. However, natural science perspectives are not enough to fully understand how human society responds to environmental radiation.

At the Fukushima Environmental Radiation School, experts from various fields gather. However, the school places great importance on students seeing with their own eyes, feeling, and measuring things for themselves. The aim of the school is for students to develop the ability to synthesize information obtained in Fukushima-Hamadohri, understand issues through discussions among students, and search for solutions.

The school began in 2016 with 10 students. Since then, the number of students has increased each year, and we continued to hold in-person classes even during the pandemic. In 2024, 215 students participated. We also emphasize diversity in students' areas of study. By not setting restrictions on fields, grade levels, nationalities, etc., students from various backgrounds have been able to share their ideas and perspectives.

We will present our activities.

#11 - Education, Training and Outreach / 275

#11-275 Progress is Always People-Powered: Rising to the Challenge of Building Poland's Nuclear Workforce

Authors: Gaweł Madejowski[1]; Aleksandra Madejowska[2]

[1] *National Centre for Nuclear Research*

[2] *SWPS University*

Corresponding Author: madejowski.g@gmail.com

Poland's commitment to establish a nuclear energy program highlights both challenges and opportunities in human capacity building for this emerging sector. The nascent stage of Poland's nuclear workforce development offers unique insights, underscoring the need not only for specialized training and education programs but also for a robust organizational culture that prioritizes safety, inclusivity, and continuous skill advancement to address the growing expectations for responsible practices amid security and social imperatives. A significant challenge in building Poland's nuclear workforce is the limited availability of nuclear-specific higher education programs combined with a scarcity of widely recognized internships and scholarships, which limits prospective talent acquisition. Nonetheless, Poland's comparatively high share of women in engineering within the OECD framework offers an opportunity for closing the gender gap and cultivate a more diverse nuclear workforce. Additionally, Polish nuclear experts demonstrate a proactive approach to fostering international collaboration, actively seeking partnerships with counterparts abroad through grassroots efforts. This approach has translated into establishing institutional-level collaborations, despite the absence of a centrally-driven national policy in this area. The National Centre for Nuclear Research (NCBJ) has emerged as a key player in this endeavor, actively addressing these needs through initiatives that combine practical education with advanced technical training. The MARIA research reactor at NCBJ, with its adaptable core, flexible setup, and open architecture, provides a unique environment for hands-on learning, enabling tailored experiments and measurements that address diverse training needs across technical disciplines. This presentation provides a critical perspective on Poland's approach to building a skilled and resilient nuclear workforce by addressing training needs, fostering a safety-oriented and inclusive culture, and emphasizing practical education and international collaboration in alignment with industry demands. It also presents novel frames of reference for addressing human capacity building in nuclear field from the behavioral science vantage point by applying Organizational Behavior Management (OBM) framework to promote consistent performance and cultivate a proactive safety culture that aligns with the industry's rigorous demand. In light of Poland's growing commitment to social responsibility, climate action, and safety standards, this contribution presents the country's path toward a sustainable and forward-thinking nuclear workforce.

#04 - Research Reactors and Particle Accelerators / 276

#4-276 News of the European Spallation Neutron Source, ESS, Radioactive Waste Management

Author: Holger Tietze-Jaensch[1]

Co-authors: Nikola Markovic [1]; Per Lidar [2]; Per Roos [1]

[1] *European Spallation Source ESS*

[2] *Studsvik Waste Management Technology AB*

Corresponding Author: holger.tietze-jaensch@ess.eu

The European Spallation Source ESS is under construction and located at Lund, Sweden. ESS is funded and supported by currently 13 European Countries from in- and outside the EU.
ESS has a 700m long linear accelerator for a 14Hz / 62mA pulsed proton beam heading on a spinning wheel solid state elementary Tungsten target which is directly He-gas cooled in a closed circuit. ESS is designed for 5 MW average beam power on target, albeit ESS shall run at a 2MW power level after a 3 years ramp-up period and subsequent 10 years long period of gathering experience.
As a long-pulse (3ms) neutron source ESS utilizes an unprecedented versatility of neutron wavelength tuning and pulse frame multiplexing from its specific multi-wavelength and wide-angle moderator design that serve the total of 42 individually time-tuned beamlines for neutron scattering instruments all dedicated to specific and supplementary tasks if condensed matter research in physics, chemistry, life-science, soft matter and material research, spanning from cosmology and fundamental particle physics to pharmacological and engineering development, from fundamental and applied magnetic properties research and even exploring into geoscience and archeology.
As an accelerator based subcritical facility, ESS will not produce long-lived fissile or actinoid radioactive waste. Almost all radioactive waste is fairly short-lived and most of it can be free-classified after some manageable period of time. ESS comprises state-of-the art radioactive waste characterization and conditioning methods, following the Swedish national regulations and good practice.
As a novel example, the gentle and fairly low-temperature thermolysis of spent ion exchange resins shall be employed for the safe and gentle disintegration of these resins, collected in 200L standard steel drums. This method has been recently invented by Studsvik Nuclear AB, and a test facility at Studsvik site is under commissioning. This inDRUM © technique is also suitable for the controlled disintegration of oily/organic liquids and for contaminated plastic materials. The residual ash can be compacted reducing the low-level disposable volumes to ca. 20% while the volatile off-gases are scrubbed and quenched in a commonplace off-gas treatment before sea-based and air-borne discharge.
Another cutting-edge option for ESS will be the advanced tritiated water treatment AWD offered by Laker Ltd from Oakville, ON, Canada. The same company is installing such an HTO clean-up facility at ITER. ESS has an option for such an installation, if needed. Major advantages are the very flexible and versatile controlled detritiation of tritiated radioactive water residues. HTO vs. H2O separation factors on the applied throughput vs. the pushed volumes of radwater, i.e. the operational capacity of the facility. The technical dimensioning of the AWD device can be tuned to the individual needs and budget.
With this lecture I shall present an overview of the ESS research facility, its unique technical features and scientific prospects and shall emphasize some topics of of radiation monitoring and radioactive waste characterization and management.

#05 - Nuclear Power Reactors and Nuclear Fuel Cycle / 277

#5-277 Reactor Core Instrumentation - From the principle design to installation and operation in nuclear power plants

Author: Heiko Jasper[1]

Co-author: Patrick Weidenauer [2]

[1] *Framatome*

[2] *Framatome GmbH*

Corresponding Author: heiko.jasper@framatome.com

Nuclear Power reactors of all generations and types require for their safe and efficient operation a set of instrumentation systems to monitor reactor conditions and allow for countermeasures in case the measured parameters exceed certain thresholds. The lifecycle of the instrumentation systems encompasses several steps from design and development of a prototype to operation in a commercial application, and even decommissioning. While some of these steps are generic and also used by other industries worldwide, the special needs for application in harsh environment with high demands on safety aspects require specific activities. The development of a reactor instrumentation tailored to the plant needs starts with gathering of needs coming from several stakeholders. Such needs comprise not only technical aspects but also demands on the capability of the solution to be industrialized and have to follow local and international nuclear standards. After the needs are analyzed and translated into a set of requirements, the design and later the manufacturing of the instrumentation is performed. Before the designed solution can be deployed, it needs to be qualified for its intended use. Qualification is a process specific to nuclear application, which requires analysis and specific testing of the equipment under representative conditions, but also stipulates demands on the manufacturing follow-up and impacts the industrial scheme. The qualification needs to be approved by local authorities and accompanied by independent bodies. Once the equipment is finally qualified and can be put into operation, operational support is needed which includes a supply chain management maintaining qualification for the equipment. Changes of equipment –in design, but also in manufacturing or supply chain –need to be assessed and analyzed regarding their impact on the obtained qualification. No unqualified equipment is allowed to be used for commercial nuclear power reactors. At the end of life, also special demands on decommissioning need to be considered, e.g. when the equipment is activated or contaminated.
The presentation will provide an overview of the development of a nuclear instrumentation system from design to operation and even decommissioning, including all relevant steps which are necessary to derive a series product which can be used in commercial nuclear power reactors from a prototype. It focusses on the special needs for nuclear application, such as qualification and supply chain maintenance. The presentation will use EPR incore instrumentation as example to outline the necessary steps.

#09 - Environmental and Medical Sciences / 278

#9-278 Hybrid Compton-PET imaging for ion-range monitoring in hadron therapy

Author: Javier Balibrea Correa[1]

Co-authors: Begoña Fernández-Martínez [2]; Carlos Guerrero [3]; César Domingo-Pardo [1]; Ion Ladarescu [1]; Jorge Lerendegui Marco [4]; Jose Manuel Quesada [3]; Maria del Carmen Jiménez-Ramos [2]; Teresa Rodríguez-González [3]; Victor Babiano [5]

[1] *Instituto de Física Corpuscular IFIC-CSIC*

[2] *CNA*

[3] *Universidad de Sevilla*

[4] *Instituto de Física Corpuscular (CSIC-UV)*

[5] *Instituto de Física Corpuscular IFIC*

Corresponding Author: javier.balibrea@ific.uv.es

Hadron therapy offers significant advantages over conventional radiotherapy, primarily due to the maximization of the applied dose during treatment at the Bragg peak. However, additional benefits could be realized if a quasi-real-time monitoring system for ion-range verification were available. Such a system would help reduce safety margins and enhance the therapy's potential benefits by addressing various sources of systematic uncertainty.

Two of the most promising methodologies for in-room, real-time monitoring are positron emission tomography and prompt-gamma imaging. The PGI technique is particularly well-suited for real-time monitoring because of the prompt nature of the emitted radiation. In contrast, PET imaging offers tomographic and functional information, making it valuable for studying physiological processes and tumor response.

In 2016, Parodi discussed the concept of a PGI-PET hybrid imaging system as an alternative to address some of the limitations inherent to each technique. As suggested by Lang in 2014, this concept could be realized by adapting systems based on multiple Compton cameras. Hybrid PGI-PET systems are anticipated to open new avenues for in-vivo real-time range monitoring. This expectation arises from the complementary strengths of the two techniques: prompt-gamma emission is more suitable for real-time monitoring, while PET imaging provides tomographic and functional information valuable for studying physiological processes and tumor response.

For the first time in hadron therapy, we have implemented a hybrid imaging system that combines both PGI and PET within the same setup, thereby harnessing the advantages of both approaches. This is achieved using an array of Compton cameras in a twofold front-to-front configuration operating in synchronous mode.

In this contribution, I will present a summary of a proof-of-concept experiment conducted under pre-clinical conditions at the HIT-Heidelberg facility with proton, alpha, and carbon ion beams, and the the preliminary results of the 2024 campaigns with only protons at two different facilities such as WPE (Germany) and IBA-Reading (UK).

#02 - Space Sciences and Technology / 279

#2-279 Si-microstrip LGAD detectors for cosmic-ray space-borne instruments

Authors: Matteo Duranti[1]; Valerio Vagelli[2]

Co-authors: Alberto Oliva [3]; Barbara Negri [2]; Elisabetta Cavazzuti [2]; Jiayu Hu [4]; Marco Miliucci [2]; Maria Movileanu [4]; Matteo Mergè [2]; Mattia Barbanera [4]; Valerio Formato [5]

[1] *INFN Perugia (IT)*

[2] *Italian Space Agency (IT)*

[3] *INFN Sezione di Bologna (BO)*

[4] *INFN Sezione di Perugia (IT)*

[5] *INFN Roma Tor Vergata (IT)*

Corresponding Author: valerio.vagelli@asi.it

Silicon microstrip (Si-μstrip) sensors are employed in most of current space detector tracking systems for charged cosmic-rays, such as the DAMPE satellite detector or the AMS-02 detector onboard the ISS. As they allow for large-area coverage with contained electronic channels and power consumptions, they are ideal sensors for high-energy physics applications in space-borne instrumentation, and are planned to be instrumented in envisioned follow-up cosmic-ray space-borne missions such as the AMS-100 or the ALADInO next-generation magnetic spectrometers.

The efficiency of such systems is however already currently impacted by "backsplash" particles generated from downstream calorimeters, which can degrade tracking efficiency by tens of percent, especially at energies approaching 1 TeV.

One potential solution to overcome this limitation and enable new measurement approaches in next-generation instruments is the development of 5D tracking systems, which provide charge, time, and three-dimensional coordinate measurements for each layer of the tracker. This approach integrates the 3D-spatial coordinate and charge |Z| measurements with layer-resolved timing information, to: i) enable improved track finding; ii) provide a redundant and independent time-of-flight system to standard scintillator based detectors; iii) remove spurious tracker hits; iv) contribute independent particle ID information to transition radiation detectors (TRDs) or calorimeters. A key benchmark for timing resolution in next-generation space detectors is a timing accuracy below 100 ps, while a finer resolution of less than 50 ps could allow to achieve additional break-through objectives such as precise isotope separation that could allow groundbreaking sensitivities in understanding cosmic-ray physics and searches for heavy nuclear antimatter in cosmic-rays.

Such performances are already well within the capabilities of pixel LGAD systems developed for accelerator physics application. However, this level of performance in space applications requires significant reduction in readout noise and further advances in front-end electronics and consumption to comply with the stringent requirements of space operations.

LGAD-based tracking systems are primarily being developed for high-energy and high-intensity collider detectors, where timing resolution below 30 ps and spatial resolution on the order of 10 micrometers are required. These developments position LGAD as an optimal candidate for 5D tracking devices in large-scale detectors. In space, radiation hardness requirements are largely less demanding than those for high-intensity collider experiments. However, the integration of LGAD microstrips, currently available in O(cm^2) area, to O(m^2) area detectors necessitates careful consideration on capacitance noise and power consumption.

To address these challenges, in the context of the Pentadimensional Tracking Space Detector project (PTSD) we are investigating and developing an innovative concept of LGAD Si-microstrip instrument based on a detector capacitance mitigation design. The integration of LGAD and standard Si-μstrip sensors in a serial readout architecture will allow for a combination of two-dimensional coordinates and timing measurements, while minimizing the detector capacitance. A breadboard laboratory model will validate the requirements and space qualification of LGAD Si-microstrips. In this contribution, the status of R&D activities which are currently progressing will be presented.

In addition, a conceptual flight-demonstrator is being designed to be housed in a 3U CubeSat platform. This demonstrator will serve as a proof-of-concept for 5D tracking in space and will open new diagnostic opportunities for cosmic-ray and gamma-ray detection. The successful development of LGAD Si-microstrip based 5D tracking will enable sensitivities to perform ambitious objectives otherwise hardly achievable in the next generation of space-borne cosmic-ray instruments, paving the way for future discoveries in particle astrophysics.

#09 - Environmental and Medical Sciences / 280

#9-280 Experimental proof-of-concept and first field tests of the dual gamma-neutron imager GN-Vision

Authors: Jorge Lerendegui Marco[1]; Gastón Cisterna[1]; Andrea Sanchis Moltó[1]

Co-authors: James Hallam [1]; César Domingo-Pardo [2]; Victor Babiano [3]; Javier Balibrea Correa [2]; David Calvo [1]; Gabriel de la Fuente [1]; Bernardo Gameiro [1]; Ion Ladarescu [1]; Pablo Torres-Sánchez [1]

[1] *Instituto de Física Corpuscular (CSIC-UV)*

[2] *Instituto de Física Corpuscular IFIC-CSIC*

[3] *Instituto de Física Corpuscular IFIC*

Corresponding Author: andrea.sanchis@ific.uv.es

Compton imaging represents a promising technique for Prompt Gamma (PG) imaging for range verification in hadron therapy (HT) treatments. As for neutron monitoring, a drawback of most of the available systems is that only integral off-field neutron-fluence values are registered but no information is obtained from its spatial origin. Dual neutron and gamma imaging is also of prime interest for nuclear safety and security applications. In this context, we have designed and patented a innovative dual neutron and γ-ray imaging tool, so-called GN-Vision, that aims at addressing the most relevant challenges for the aforementioned applications. The system consists of a compact and handheld-portable device capable of measuring and simultaneously imaging γ-rays and slow –thermal to 100 eV –neutrons.

The GN-Vision device follows the design of the previous i-TED detector, an array of Compton cameras based on large monolithic position sensitive $LaCl_3$(Ce) crystals that were initially designed for neutron-capture experiments at CERN. Moreover, the applicability of i-TED to range verification in ion beam therapy and imaging-based dosimetry in BNCT has been explored with promising results. In addition to i-TED, GN-Vision exploits a neutron-gamma discriminating detector together with a passive collimator to achieve neutron imaging, while keeping the Compton imaging of γ-rays.

Following the conceptual demonstration of the simultaneous neutron and gamma-ray imaging in a first Monte Carlo study, we have been working at IFIC in the technical implementation of the earliest prototype. In this contribution we will first review the development and characterization of a position-sensitive CLYC detector that acts as the neutron imaging layer and γ-ray Compton scatterer of GN-Vision. The successful development of the position-sensitive neutron-gamma discrimination capability has laid the foundations for the first proof-of-concept experiment of the neutron imaging capability, that will be reviewed in this talk.

By the time of the conference, we expect to have carried out important advances towards the experimental integration of the neutron and gamma imaging capabilities and the full experimental validation of GN-Vision. Together with these recent progresses, we will also show preliminary results of the first field test of GN-Vision for nuclear safety and medical applications.

As an outlook, the contribution will present simulation studies that aim at evaluating and optimizing the performance of the utter GN-Vision device, and will outline the plans for upcoming pilot experiments for its validation in relevant scenarios.

#09 - Environmental and Medical Sciences / 282

#9-282 Ultra-thin scintillator as dose monitor for pulsed proton beams at FLASH rates

Authors: Alicia Reija[1]; Michael Seimetz[2]

Co-authors: Aarón Alejo [3]; Carmen Torres Muñoz [4]; Demetrio Saucedo [4]; Jessica Juan [2]; José Benlliure [5]; M. Carmen Jiménez-Ramos [6]

[1] *Instituto de Instrumentación para Imagen Molecular (i3M) and Instituto Galego de Física de Altas Enerxías (IGFAE)*

[2] *Instituto de Instrumentación para Imagen Molecular (i3M)*

[3] *Instituto Galego de Física de Altas Enerxías (IGFAE)*

[4] *Centro Nacional de Aceleradores (CNA, US-Junta de Andalucía-CSIC)*

[5] *Instituto de Física Corpuscular (IFIC)*

[6] *Centro Nacional de Aceleradores (CNA, US-Junta de Andalucía-CSIC) and Departamento de Física Aplicada II, Universidad de Sevilla*

Corresponding Author: mseimetz@i3m.upv.es

In particle therapy of cancer, patients are typically submitted to a total radiation dose of a few tens of Gy fractionated in several daily sessions of some minutes of treatment time. During recent years evidence has been provided for reduced therapeutic side effects when the same total dose is applied in less than a second. This so-called FLASH effect is the subject of clinical and pre-clinical research. In order to understand the underlying, physical and biological mechanisms and to identify ideal therapy conditions a wide parameter space in terms of total dose, mean dose rate, and peak dose rate is to be explored. This is experimentally challenging; many clinical accelerators are not capable of reaching the necessary, high beam currents. As a consequence, dedicated beamlines for the irradiation of biological samples have been built at accelerator facilities for fundamental or applied research. In addition, standard instruments for dose measurement, such as ionization chambers, suffer from saturation effects at high dose rates.

A beam monitor for the measurement of the proton flux in pencil beams has recently been developed at Institute for Instrumentation in Molecular Imaging (i3M, Valencia). Its active volume consists of an ultra-thin plastic scintillator making it capable for transmission operation with protons of a few MeV which are especially interesting for in-vitro irradiation studies with cell cultures and other, preclinical models. Part of the scintillation light is guided to a photomultiplier tube which anode pulses are registered on a fast oscilloscope. Tests at the 3 MV tandem accelerator of Centro Nacional de Aceleradores (CNA, Sevilla) have shown a linear relation between beam current and signal levels for pulsed proton beams of 4 MeV over a wide range of intensities. The total dose, up to about 60 Gy within a spot of 3 mm diameter, is calculated from the known particle fluence considering water as reference medium. Independent, absolute dose measurements have been provided with radiochromic film sheets of type EBT3-Unlaminated placed behind the scintillator. Experiments were carried out with mean dose rates below and above 40 Gy/s, the value currently considered as onset of the FLASH regime. Various configurations in terms of pulse duration and pulse rate have been tested. We present the detector layout and the calibration and test results from CNA.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 283

#6-283 A computer-vision aided Compton-imaging system for radioactive waste characterization and decommissioning of nuclear power plants

Author: Víctor Babiano Suárez[1]

Co-authors: César Domingo-Pardo [2]; Ion Ladarescu [3]; Javier Balibrea Correa [2]; Jorge Lerendegui Marco [3]; José Luis Leganés Nieto [4]

[1] *Universitat de València*

[2] *Instituto de Física Corpuscular IFIC-CSIC*

[3] *Instituto de Física Corpuscular (CSIC-UV)*

[4] *ENRESA*

Corresponding Author: vbabiano@ific.uv.es

Electricity production primarily based on uranium fission is considered a viable alternative to reduce greenhouse gas emissions. However, the generation and subsequent storage of radioactive waste remain significant challenges associated with this technology. Given the cost, duration and limited space for radioactive waste storage, effective management is essential to minimize the amount of material classified, which necessitates dedicated storage centers. In this work, we address this challenge by evaluating the applicability and performance of a high-efficiency, cost-effective and portable Compton camera for detecting and visualizing low- and medium-level radioactive waste generated during both the decommissioning and regular operation of nuclear power plants. Results will be presented to demonstrate the good performance of Compton imaging for this type of application, both in terms of efficiency or measuring time and image resolution. A technical readiness level of TRL7 has been thus achieved with this system prototype, as demonstrated with dedicated field measurements carried out at the radioactive-waste storage plant of El Cabril (Spain) utilizing drums with residues from decommissioned power plants and different amounts of radioactivity contents. The system's performance has been enhanced by means of computer-vision techniques in combination with advanced Compton-image reconstruction algorithms based on Maximum-Likelihood Expectation Maximization. The feasibility of 3D tomographic reconstruction from a series of relatively short measurements around the objects of interest will be also shown. Finally, next steps and upgrades of this system will be summarized.

#09 - Environmental and Medical Sciences / 284

#9-284 Progress report of a long axial FOV PET (IMAS) with TOF and DOI capabilities

Authors: Antonio J. Gonzalez[1]; David Sanchez[2]; Santiago Jimenez-Serrano[2]; Alvaro Anreus[2]; Marta Freire[2]; Andrea Gonzalez-Montoro[3]; Irene Torres[4]; Alfonso Rios[5]; José María Benlloch[6]

[1] *Institute for Instrumentation in Molecular Imaging, i3M-CSIC*

[2] *Institute for Instrumentation in Molecular Imaging (i3M), CSIC-UPV*

[3] *Instituto de Instrumentación para Imagen Molecular (I3M), Centro Mixto CSIC-UPV*

[4] *La Fe*

[5] *Full Body Insight*

[6] *Instituto de Instrumentación para la Imagen Molecular (i3M)*

Corresponding Author: agonzalez@i3m.upv.es

Total-Body Positron Emission Tomography (TB-PET) technology and designs have become very popular in the recent years. These systems are very attractive because of their high sensitivity resulting from their extended axial Field of View (FOV) and potential Time of Flight (TOF) capabilities, allowing for the simultaneous study of the kinetics of multiple organs. Most of TB-PET designs and implementations are based on LYSO crystal pixels without Depth of Interaction (DOI) capabilities.

In this work we present a TB-PET system, named IMAS, based on semi-monolithic crystals to simultaneously enable TOF and DOI capabilities. Our design makes use of a reduction of signals without compromising performance. The system geometry is based on 5 rings of 10 cm in the axial direction each, and gaps of about 5 cm, resulting in a total axial length of 71.4 cm. The system has been constructed and installed (June 2023) at the largest hospital in Valencia named La Fe. Very preliminary experimental tests already predict an almost homogeneous spatial resolution below 4 mm in the whole FOV (as far as at 30 cm off-radial), outperforming any other scanner with a long axial FOV. The system sensitivity is 7.6% with a source at the Center of the FOV (CFOV). The detectors reached a TOF of about 350 ps FWHM. We aim to report a full characterization of the scanner during the conference, including images with first patients taken at the largest hospital in our region (La Fe).

In more detail, we present real data obtained for the IMAS system and report on the extensive work performed on its geometry, detector performance, and image quality, with very preliminary reconstructed images already available. The scintillation slab configuration effectively balances 3D photon impact positioning (x, y, DOI) and timing resolutions due to its monolithic-like and pixel-like structures, respectively. This configuration achieved a Coincidence Time Resolution (CTR) of around 300 ps at the detector level, combined with a spatial FWHM of 3 mm in the monolithic direction. Additional tests yielded a DOI resolution of 4 mm. We arranged 4×4 mini-modules in the super-modules (SM) configuration. Each SM returns 256 channels and is temperature-controlled by water cooling. Each ring comprises 24 SM, totaling 5 rings. The system's energy is calibrated per slab to correct differences in light collection between SiPMs and slab position. Moreover, an energy filter implemented by PETsys filters data based on channels fired and total energy before sending it to the PC, doubling the IMAS dynamic range, with room for improvement by optimizing those parameters.

Preliminary tests with real data have been carried out including DOI information, but still lacking TOF. The spatial resolution remains almost constant and below 3.5 mm FWHM at 20 cm off-radial position when DOI is included. The deterioration for the case without DOI at 30 cm would be almost 6 mm. For comparison purposes, the measured values of other large axial FOV scanners are significantly worse.

The sensitivity profile was determined for the whole scanner, using a bar filled with FDG reporting 4.4%. This increases to 7.6% if using a source at the CFOV. Other tests with phantoms have been also carried out. We tested the Jaszczak phantom with a cold Derenzo-like region. A uniformity of the image in the range of 75% was achieved, together with Contrast to Noise Ratio (CNR) coefficients as good as 60%. Moreover, the cold phantom allowed us to distinguish well the 6.4 mm rods.

#09 - Environmental and Medical Sciences / 285

#9-285 Compton imaging for dosimetry and real time monitoring in boron neutron capture therapy

Author: Pablo Torres-Sánchez[1]

Co-authors: Bernardo Gameiro [1]; Carmen Ruiz-Ruiz [2]; Caterina Michelagnoli [3]; Cristina Méndez-Malagón [2]; César Domingo-Pardo [4]; Ignacio Porras [2]; Ion Ladarescu [4]; Javier Balibrea Correa [4]; Jean-Marie Daugas [3]; Jorge Lerendegui Marco [1]; Maribel Porras-Quesada [2]; María José Ruiz-Magaña [2]; María Pedrosa-Rivera [2]; Patricia Álvarez-Rodriguez [2]; Ulli Koester [3]; Victor Babiano [5]

[1] *Instituto de Física Corpuscular (CSIC-UV)*

[2] *U. Granada*

[3] *Institut Laue-Langevin*

[4] *Instituto de Física Corpuscular IFIC-CSIC*

[5] *Instituto de Física Corpuscular IFIC*

Corresponding Author: pablo.torres@ific.uv.es

Boron Neutron Capture Therapy (BNCT) is an experimental form of radiotherapy that uses boron, injected to the patient attached to a target molecule that accumulates selectively in cancerous cells. This therapy exploits the large neutron capture cross-section of boron to deliver a targeted dose from neutron irradiation. One of the primary challenges in current BNCT is the accurate determination of the dose delivered to the patient. The state-of-the-art methods are very limited and rely on several assumptions and extrapolations from boron concentration in blood before and after the irradiation. Since neutron captures in boron produce 478 keV gamma rays in 94% of reactions, this radiation could be potentially used for real-time dose monitoring using various imaging techniques. To date, SPECT and Compton imaging have been explored; however, the main challenges remain in achieving the spatial resolution required, true online capabilities and dealing with the harsh radiation backgrounds induced by the neutron beam during treatment. The i-TED Compton Camera array, originally designed for nuclear physics measurements with neutron beams, is an excellent candidate for overcoming this challenge in BNCT. Its unique -large efficiency- design with one scatter-detector and four absorber detectors, as well as its low neutron sensitivity make i-TED especially well suited for this gamma-ray energy and this application. Profiting from this, some adaptations of the original i-TED imager are being carried out to optimize its performance for the BNCT dosimetry application. In this context, an evaluation of the detectors has been performed to optimize them for 478 keV gamma rays. Moreover, given the need for imaging of large areas (e.g. the human head or torso) we are integrating 3D image reconstruction with list mode Maximum Likelihood Expectation Maximization algorithms into our imaging suite. A series of experimental campaigns are carried out in order to test and validate the i-TED capabilities and performance towards BNCT, including a first campaign at the Institut Laue Langevin for proof-of-concept of sensitivity and imaging of 478 keV gamma rays from neutron irradiated cell lines; and a second campaign aiming at reproducing realistic conditions in terms of background and boron concentrations comparable to actual BNCT treatments. A summary of our most recent developments and experiments will be presented.

#08 - Severe Accident Monitoring / 286

#8-286 Experimental study of boron nitride thermowell geometry effect on temperature measurements at high temperature of liquid metal oxide corium.

Author: Arthur Denoix[1]

Co-authors: Solène Tissot [1]; Jules DELACROIX [1]; Viviane BOUYER [1]

[1] *CEA Cadarache*

Corresponding Author: arthur.denoix@cea.fr

The Severe accident experimental lab of CEA IRESNE in Cadarache (LEAG) is a laboratory whose main mission is to increase the knowledge of corium behavior and thermophysical properties and performs experiments on its PLINIUS platform. "Corium"refers to melted core materials and by extension, to other melted materials gradually included all along the severe accident in the nuclear power plant. In this objective, LEAG realizes experiments at high temperature (1500℃-3000℃) with prototypical corium, composed of depleted uranium dioxide and other oxides from the basement but also metals from the vessel. At these very high temperatures, we use type C thermocouple that are able to measure up to 2300℃. However, we need to use a sheath to protect it from the corium melt otherwise it will be rapidly damaged or melt. For corium mostly composed of oxides, tungsten thermowell is a good way to protect the thermocouple. However, when there is a significant fraction of metal in the corium, it is not possible to use tungsten because of a low melting point eutectic between metal and tungsten. That is why LEAG has selected a new material for thermowell: boron nitride, chosen for its compatibility with metal at high temperatures. In this paper, we will present the study of the impact of the geometries of the boron nitride thermowell, including thickness and immersion length, on measurement accuracy. In the first series of experiments, a type K thermocouple was covered with a boron nitride thermowell and placed inside a tube furnace. It was heated up to 500℃ and we varied the length (25 mm and 50 mm) and the thickness (2 mm, 3.5 mm and 5 mm) of the thermowell. In the second series of experiments, the parameters were the same, except that we used a bared type C thermocouple and carried out some experiments with a tin load in the crucible. The third series of experiments was carried out with type K thermocouple in the VITI advanced facility of the PLINIUS platform with three configurations: without crucibles, with no load in the crucibles and with tin load in the same crucibles. The fourth series of experiments was also carried out with the crucible in the VITI advanced facility but with type C thermocouple allowing to study new metal: copper with melting point at 1085℃. The study underscores the necessity of considering thermowell geometries in the measurement of temperature. The finding on the VITI experiment highlights that the immersion length has a greater impact than the thickness.

#07 - Decommissioning, Dismantling and Remote Handling / 288

#7-288 Accurate Simulation of Neutron Fields using Tramo

Authors: Alexander Ponomarev[1]; Alexander Rommelmann[1]; Astrid Barkleit[1]; Benjamin Keßler[2]; Jörg Konheiser[1]; Kerstin Spornhauer[None]; Marcus Seidl[3]; Martina Lamesa Colado[4]; Maud Emilie Zilbermann[1]; Patricio Adriano Barbisan[3]; Pia Kahle[4]; Shokhrukh Mirzo Bakhodirov[None]; Silvio Baier[1]; Sophie Schichtholz[4]; Thomas Kormoll[4]

[1] *HZDR*

[2] *TU Dresden, HZDR*

[3] *Preussenelektra*

[4] *TU Dresden*

Corresponding Author: benjamin.kessler2@tu-dresden.de

Efficient nuclear dismantling requires a separation of activated materials from nonradioactive materials. To determine which regions of a nuclear reactor are activated, the spectral fluence of neutrons has to be known. It can be measured using activation probes while the reactor is still operational, but after it has been shut down, the neutron fluence has to be simulated using a Monte Carlo simulation. Simulations need to be verified in known setups to produce accurate results. The irradiation facility at the TU Dresden can be used for this purpose. The irradiation facility is composed of multiple alpha-N sources and a large moderating volume. It allows for the irradiation of samples in a neutron field. The alpha-N sources produce fast neutrons with an energy of up to 12 MeV. The moderating volume consists of approximately 50 cm of PET, where the outer layer also contains boron for shielding. Activation samples of materials can be placed inside the irradiation facility close to the alpha-N sources. There the sample is activated by fast neutrons coming directly from the source as well as intermediary and thermalized neutrons scattered from the moderating volume. In addition to neutrons, the alpha-N sources also produce photons of various energies. For the simulation, the Monte-Carlo code Tramo developed at HZDR is used. Tramo is designed to simulate the spectral fluence of neutrons in nuclear reactors. Tramo simulates the transport of both neutrons and photons in a defined geometry. In order to use Tramo for the simulation of the irradiation facility, parts of the code have to be adapted. Tramo will be used to simulate the spectral fluence of neutrons at the irradiation facility. By utilizing measurements done at the facility, the accuracy of the simulation can be verified. Additional simulations using Geant4, Serpent and MCNP of the same facility will be done for comparison.

#09 - Environmental and Medical Sciences / 292

#9-292 The Radiological Emergency Program in the Valencia Region

Author: Jose Diaz[1]

Co-authors: Mireia Simeó Vinaixa [2]; Nadia YAHLALI [3]; T. Cámara [1]; V. Delgado [1]

[1] *Instituto de Física Corpuscular (IFIC), Centro Mixto, Universitat de València-CSIC*

[2] *Instituto de Física Corpuscular (IFIC). Centro Mixto Universitat de València (UV) - CSIC*

[3] *Instituto de Física Corpuscular (IFIC), CSIC-University of Valencia, Spain*

Corresponding Author: mireia.simeo@ific.uv.es

The global use of radioactive isotopes across diverse sectors—such as industry, research, energy production, medicine, and healthcare—has led to the widespread distribution of these materials in society. This proliferation has raised significant concerns among governments and organizations about the potential for accidental radioactive releases into the environment, which could lead to radiological emergencies. To address these risks, it is essential to establish robust safeguards and monitoring systems that can prevent such incidents and protect the public in case of a radiological event.

In response to these concerns, the Laboratory of Environmental Radioactivity at the University of Valencia (LARAM) has collaborated with the Valencian Agency for Safety and Emergency Response (AVSRE) to develop an environmental monitoring plan specifically focused on radiological emergencies. The potential sources of these emergencies have been carefully analyzed and categorized.

To support the objectives of this comprehensive monitoring plan, a portable measurement and analysis system was designed and constructed in the LARAM laboratory. The system includes two gamma detectors—NaI and HPGe—mounted on a mobile platform with an integrated stabilization system. Both detectors were calibrated and characterized for key performance factors, including efficiency, energy resolution, and dead time. This setup allows for rapid gamma radiation measurements in the field during a radiological emergency. In-situ measurements are less sensitive to variations in local soil conditions, enabling swift surveys of large areas to identify radioactive isotopes and hotspots. Meanwhile, laboratory measurements provide detailed analysis for detecting smaller radiation peaks.

In addition, it is crucial to perform background radiation measurements near radioactive facilities before any incident occurs. These pre-accident measurements help to characterize the environment and assess how the area might recover following a radiological event.

Using this system, a radiological survey was conducted across key radiological facilities in the Valencian Autonomous Community, yielding valuable reference data for assessing how these areas might recover in the event of an emergency. Simulations of various emergency scenarios were also carried out, predicting potential radioactive contamination under different meteorological conditions. These dosimetric simulations were performed at the Laboratory of Environmental Radioactivity at the University of Valencia using JRODOS software, the Java version of the RODOS (Real-time Online Decision Support) system for off-site emergency management in the aftermath of radiological and nuclear accidents.

Based on this research, a comprehensive radiological emergency protocol was developed, emphasizing the importance of rapid in-situ measurements using the emergency detection system created at LARAM. This protocol, along with the reference data and background radiation map of key radiological facilities in the Valencia region, was tested successfully during emergency drills organized by local authorities. Additionally, JRODOS simulations help assess potential risks to the population in the critical initial hours following a radiological incident.

In conclusion, the efforts of LARAM, in collaboration with AVSRE, have produced valuable tools and protocols that enhance preparedness for radiological emergencies in the region.

#01 - Fundamental Physics / 293

#1-293 Time response of fast PTMs matching a cerium-doped lanthanum bromide crystal

Author: M. Caballero[1]

Co-authors: L.M. Fraile [2]; J.M. Udías [2]; S. Gaitán [2]; V. Martínez-Nouvilas [2]; V. Sánchez-Tembleque [2]

[1] *Grupo de Física Nuclear, EMFTEL & IPARCOS, Facultad de CC. Físicas, Universidad Complutense de Madrid*

[2] *Universidad Complutense de Madrid*

Corresponding Author: mirica01@ucm.es

Within the framework of the HISTARS (HIE-ISOLDE Timing Array for Reaction Studies) project at the ISOLDE facility at CERN, plans are underway to implement a gamma-ray array dedicated to fast-timing measurements of lifetimes of excited nuclear states populated in Coulomb excitation and transfer reactions.
Advanced scintillator materials such as cerium-doped lanthanum bromide and cerium bromide inorganic crystals are typically employed for gamma-ray fast-timing spectroscopy, due to their superior performance in both energy and time resolution. These crystals are generally coupled to photosensors, including photomultiplier tubes (PMTs) and silicon photomultipliers, matching their spectral response and high photon yield. The commercially-available PMT that provides the best time resolution to date for both CeBr3 and LaBr3(Ce) is model R9779 by Hamamatsu, but its production has been discontinued.
In this study, we have conducted a detailed characterization of four different head-on photomultiplier tubes with bialkali photocathodes, all manufactured by Hamamatsu, in combination with a cerium-doped lanthanum bromide scintillator crystal. The crystal, shaped as a truncated cone, has a height of 1.5 inches and base diameters of 1.5 inches and 1 inch. The photomultiplier tubes tested include a customized version of the already mentioned 2-inch, 8-stage bialkali photocathode model R9779, integrated into the H10570 assembly, which was used as a reference, since it has been proven to provide the best time response.
The other devices evaluated were three newer PMT models: a 1.5-inch, 8-stage R13408, and two 2-inch, 8-stage R13089 models housed in different assemblies (H13719-Y006 and H13719-Y007). For coincidence resolving time measurements, the reference detector was paired with each newer photomultiplier tube, positioned in a face-to-face configuration. Data acquisition was performed using a fast digitizer module, with a sampling rate of 5Gb/s and the collected signals were processed fully digitally with techniques including digital constant fraction discrimination and a first-order recursive filter. Processing parameters were optimized specifically for timing resolution using a genetic algorithm. Both anode and last-dynode signals were investigated.
The results of this investigation reveal the time responses of these photomultiplier tubes for photon energies from Na-22 and Co-60 sources. The reference detector delivered the best timing resolution, achieving 155 ps for sodium-22 and 110 ps for cobalt-60. Among the newer models, the R13089 with assembly H13719-Y007 exhibited excellent performance, achieving 120 ps for cobalt-60. Similarly, the anode signal of the R13408-Y006 demonstrated good results, with a timing resolution of 180 ps for Na-22. All tested PMTs showed minimal time-walk, good energy resolution, and, notably, the newest PMTs displayed excellent linearity across the tested conditions. A full account of the results will be provided.

#10 - Current Trends in Development of Radiation Detectors / 294

#10-294 Study of the time response of an undoped lanthanum chloride crystal

Author: M. Caballero[1]

Co-authors: V. Sánchez-Tembleque [2]; L.M. Fraile [2]; S. Gaitán [2]; V. Martínez-Nouvilas [2]; J.M. Udías [2]; E. Nácher [3]

[1] *Grupo de Física Nuclear, EMFTEL & IPARCOS, Facultad de CC. Físicas, Universidad Complutense de Madrid*

[2] *Universidad Complutense de Madrid*

[3] *IFIC-UV*

Corresponding Author: mirica01@ucm.es

Undoped lanthanum chloride scintillator crystals possess remarkable capabilities for pulse shape discrimination, leading to the ability to distinguish between different types of radiation based on the shapes of their emitted pulses. This property, together with a reasonable energy resolution, makes it a highly suitable candidate for diverse applications, such as spectroscopy, national security, safety systems, and space exploration.

Prior research has demonstrated that the pulses generated by this crystal exhibit a very short rise time, which is a key characteristic directly linked to an excellent time response. This may render the material particularly advantageous for applications requiring precise timing measurements. To investigate these properties further, we have conducted a comprehensive characterization of a detector equipped with an undoped lanthanum chloride scintillator crystal. The crystal has the shape of a truncated cone with a largest diameter of 22.5 millimeters, a shortest diameter of 16 millimeters, and a height of 16 millimeters. It is coupled to a fast Photonis XP2020/URQ photomultiplier tube, which is known for its rapid response characteristics.

We characterize the time response by means of coincidence resolving time measurements. To this aim we employed a reference detector composed of a cerium-doped lanthanum bromide scintillator, also with a truncated cone shape, with a height of 1.5 inches and base diameters of 1.5 inches and 1 inch, coupled to a well-known, previously characterized, Hamamatsu photomultiplier tube model R9779, integrated into a H10570 assembly. We measured the time response of the undoped lanthanum chloride detector at photon energies from sodium-22 and cobalt-60 sources. A fast 5 Gs/s digitizer module was utilized for data acquisition. Data processing was fully digital employing digital filters and pickup methods optimized using a genetic algorithm.

By fine-tuning the bias voltage of the photomultiplier tube and the digital parameters of the timing algorithm, we achieved full width at half maximum (FWHM) deconvoluted time resolutions of 250 picoseconds at Co-60 energies and 450 picoseconds for the 511-keV gamma-ray from Na-22. Additionally, the detector exhibited good energy resolution and linearity, together with sufficient efficiency, demonstrating its potential for use in applications that require a fast time response and spectroscopic capabilities in addition to pulse-shape discrimination.

#10 - Current Trends in Development of Radiation Detectors / 296

#10-296 TOF characterization of new MAPD-3NM-II SiPM

Author: Afonso X. Pinto[1]

Co-authors: F. Ahamadov [2]; Pedro Correia [3]; Michael Holik [4]; G. Ahmadov [5]; A. Sadigov [2]; Z. Sadygov [2]; Ondrej Pavlas ; Patrik Kučera [6]; Ondřej Urban [6]; Eric David Bosne [7]; Fadahat Mamedov [7]; João Veloso [3]; Ana Luísa Silva [3]

[1] *I3N - Physics Department, University of Aveiro, Aveiro, Portugal*

[2] *Ministry of Science and Education & Department of Nuclear Research of IDDA, Baku, Azerbaijan*

[3] *University of Aveiro*

[4] *CTU-IEAP; UWB-FEE*

[5] *Ministry of Science and Education & Department of Nuclear Research of IDDA, Baku, Azerbaijan; Joint Institute for Nuclear Research, Dubna, Russia*

[6] *University of West Bohemia*

[7] *IEAP CTU in Prague*

Corresponding Author: afonsoxp@ua.pt

The use of Time-of-Flight (TOF) information has become a standard in Positron Emission Tomography (PET). It allows a more precise determination of the radioisotope location, resulting in an improvement of the reconstructed images and better diagnosis of pathologies in patients. The high-performance photodetectors used in clinical scanners are one of the key components for TOF-PET, playing a key role in achieving the precise timing resolution required for accurate imaging. As a result, there is an increasing demand for photodetectors capable of reaching timing resolutions in the order of the few hundreds of picoseconds.

In this work we have investigated the timing capabilities of the new MAPD-3NM-II silicon photomultiplier (SiPM) for PET. These new SiPMs utilize advanced technology with buried pixel structures, enabling a pixel density of up to 40,000 pixels/mm², resulting in high photodetection efficiency and 100% fill factor. The MAPD-3NM-II photodiode used in this experiment has the following parameters: PDE-35% (450nm), gain~3*105, operation voltage-54-56.5 V, capacitance-150 pF, number of total pixels of 66500 pixels and a sensitive area - 3.7 x 3.7 mm2. Such a design allows for a much broader dynamic range. Although the MAPD-3NM-II photodiode area is 52% larger than its counterpart, its capacitance is 3.4 times smaller. Despite the MAPD-3NM-II photodiode's area being 52 % larger than that of its counterpart, its capacitance is 3.4 times smaller, making it particularly well-suited for timing measurements.

To evaluate their timing performance, a coincidence setup was tested using the SIPMs coupled to a PETSYS TOFPET2 evaluation kit for data readout, inside of a light tight box kept at a constant temperature of about 21 ºC. As scintillator was used LYSO(Ce) crystal with dimensions of 3 × 3 × 5 mm. All sides of the crystal were wrapped in Teflon, except for one side, which was attached to the photodiode using optical grease. An energy resolution of 6 % was achieved on the 511 keV photopeak of a Na-22 source. The best achievable coincidence timing resolution (CTR) was determined by measuring this parameter across a range of different biases and thresholds. Through this method a value of 304±3 ps was achieved at an overvoltage of +4.5 V. By correcting time walk effects correlated to different rise times in the used energy window it was possible to achieve a timing resolution of 301±5 ps. More studies will be done to: characterize the temperature coefficient of these SIPMs and its effect on the CTR, fully calibrate the system to correct possible non-linearities that may be affecting the energy resolution and to improve the time walk correction to achieve the best possible CTR, using the same setup configuration.

A similar setup with the S14160-3015PS SiPMs from Hamamatsu was used for comparison. These SiPMs were chosen because they have the same pixel pitch size of 15 µm as the MAPD-3NM-II. At the same overvoltage these were able to achieve a CTR of 308±10 ps and an energy resolution of 10 %.

This study presents an overview of the timing capabilities of a new technology of SiPMs. Results are promising and will be shown and discussed. Further development of these photodetectors

with a larger pitch size holds potential for achieving state-of-the-art CTR values in TOF applications.

#11 - Education, Training and Outreach / 297

#11-297 A miniaturized reading interface Timepix2 Lite developed for use in a new generation of the educational kit SEST2RA applicable for real time demonstration of microcosmos experiments

Author: Ondrej Pavlas[1]

Co-authors: Michael Holik [2]; Milan Malich [1]; Petr Smolyanskiy [1]; Vladimir Vicha [1]

[1] *IEAP CTU in Prague*

[2] *IEAP CTU Prague; UWB-FEE*

Corresponding Author: pavlaond@cvut.cz

Timepix2 Lite is a new highly miniaturized readout interface applicable for particle physics experiments. The main part of the readout device is the hybrid pixel radiation detector Timepix2, developed by the CERN Medipix Collaboration, a successful successor of the former Timepix pixel detector. Dimensions of the entire Timepix2 Lite device are 73.4 x 22 x 13.5 mm (i.e. size comparable to a regular USB memory stick). The read-out interface is composed of two functional parts, two boards stacked on each other, in order to keep dimension small and form the device flexible. The first board is a chipboard integrating Timepix2 detector, bias source (allowing variant assembly to support different sensor layer materials and thicknesses). The second is a mainboard containing a microcontroller, power converters and communication interface. The device is equipped with USB type C connectivity serving for data transfer as well as for its powering.

Timepix2 Lite device is fully supported by the acquisition control software TrackLab. The advanced software tool which is capable of online clustering and particle track classification, smart configurable event filtering, continuous data recording as well as real time visualization via various kinds of plots as histograms, dependency charts, integral pixel matrix images, etc.

The combination of Timepix2 Lite and TrackLab represents high potential in the field of education. Both these well made tools were successfully exploited in the creation of a new generation of educational kit SEST^{2}RA (School Educational Set with Timepix2 for Radiation Analysis). The kit highly benefits from the advanced data processing and real-time visualization features allowing to perform more impressive demonstrations of particle physics experiments and results become even more comprehensible for students. Moreover, Timepix2 detector (in comparison to its predecessor Timepix) provides extended functionalities. Timepix2 pixels can be programmed in various digital operation modes selecting a type of information recorded in pixel counters. It is possible to simultaneously record ToA value (corresponding to time of particle interaction) and also ToT value (corresponding to energy deposited by particle) with a precision up to 10ns. Further, the analog part of the pixel structure supports the adaptive gain avoiding pixel saturation when high energy is deposited in a sensor. Accessibility of these features opens a way in designing a new kind of progressive exercises practicable with the new generation SEST^{2}RA kit.

#10 - Current Trends in Development of Radiation Detectors / 301

#10-301 A particle discrimination algorithm for lanthanum halide scintillators

Author: Davide Rigamonti[1]

Co-authors: G. Guarino [2]; C. Cazzaniga [3]; S. Colombi [2]; A. Dal Molin [1]; N. Fonnesu [4]; G. Gorini [2]; F. Gugliotto [2]; G. Grosso [1]; G. Marcer [1]; A. Muraro [1]; M. Nocente [2]; E. Perelli Cippo [1]; M. Rebai [1]; L. G. Tedoldi [2]; M. Tardocchi [1]

[1] *CNR-ISTP*

[2] *University of Milano-Bicocca, Italy*

[3] *Rutherford-Appleton Laboratory, UK*

[4] *ENEA, Frascati, Italy*

Corresponding Author: davide.rigamonti@istp.cnr.it

In the last few decades, lanthanum halide scintillators ($LaBr_3$(Ce), $LaBr_3$(Ce+Sr), $LaCl_3$(Ce)) have been extensively used for gamma ray spectroscopy measurements. They offer excellent energy resolution (about 3-4% at 662keV) and fast scintillation time, allowing high counting rate measurements (>300 kHz). These scintillators find applications in various research fields such as nuclear physics, astrophysics, nuclear fusion and nuclear medicine. More recently, thanks to the exploitation of the n-^{35}Cl nuclear reaction channel, $LaCl_3$(Ce) crystals have been use as neutron spectrometer. This opened up the opportunity to explore pulse shape discrimination algorithms for enabling the neutron/gamma discrimination.
In this work, an innovative algorithm for particle discrimination applied to lanthanum halide scintillators will be presented. The effectiveness of the algorithm has been demonstrated first on the intrinsic radioactivity measurement of the crystals, which is characterized by gamma ray emissions from ^{138}La decay and alpha decays due to actinides contamination, and then with neutrons. The particle discrimination feature allows for a better description of the intrinsic activity of the crystal and improved background suppression when performing gamma ray spectroscopy measurements in low cross-section measurements or in a mixed gamma-neutron radiation field.

#04 - Research Reactors and Particle Accelerators / 302

#4-302 Development of a wireless transmitter for in-core monitoring of reactor irradiation experiments

Author: Alexander Fedorov[1]

Co-authors: T.J. Schröder [1]; A. S. Booij [1]; D. N. Verbruggen [1]; P. R. Hania [1]; E. de Visser –Týnová [1]

[1] *Nuclear Research and consultancy Group (NRG), The Netherlands*

Corresponding Author: fedorov@nrg.eu

A wireless in-core radio transmitter which is currently under development will be able to amplify a signal measured inside a reactor core and transmit the signal to a receiver located outside the core without using instrumentation cables. The transmitter uses vacuum tubes as active components as these are judged –unlike transistors based on semi-conductors –to be able to withstand in-core radiation field. The transmitter is self- powered by means of a thermo-electric generator (TEG) utilizing nuclear heating present in the core.

Within the preparation phase a selection of electronic components envisaged to be used in the transmitter is irradiated in steps in a gamma field of 20 kGy/h reaching an accumulated irradiation dose of 720 kGy. The irradiation took place in the spent fuel pool of the High Flux Reactor (HFR). The electronic parameters of the components were measured before and after every irradiation step. The tested components included three types of miniature low anode voltage vacuum tubes, variety of capacitors and resistors of different nominals, structure and composition, and a commercial bismuth telluride TEG unit.

In a separate dedicated irradiation experiment electronic characteristics of vacuum tubes and capacitors were measured on-line during irradiation. These types of experiments were focused on operation of the components in strong gamma field rather on the effect of permanent radiation damage.

In all irradiation experiments the pre-selected electronic components behaved reasonably well and did not show any significant degradation of properties.

Details on the irradiation conditions and results of the measurements are presented.

#06 - Nuclear Safeguards, Homeland Security and CBRN / 303

#6-303 Development of Portable Radiological Monitoring Systems for CRBN Emergencies

Authors: Luca Fabiano Ferrante Vero[1]; Giuliano Mini[1]; Gabriele Zorloni[1]; Giacomo Paolo Manessi[2]

[1] *Else Nuclear Srl, Milano, Italy*

[2] *ELSE NUCLEAR s.r.l.*

Corresponding Author: giacomo.manessi@elsenuclear.com

Radiological emergencies, such as those involving contamination of food supplies and inhalation of radioactive isotopes like I-131, pose a significant threat to both public health and environmental safety. The accurate detection and quantification of radiological contamination are critical for implementing effective countermeasures, minimizing exposure, and guiding emergency response efforts. The availability of reliable, field-deployable screening tools is essential for mitigating the consequences of accidental or deliberate radiological releases. To address these challenges, two advanced systems, FOOMON and THYMON, emphasizing a rigorous scientific approach to ensure accuracy and applicability in field scenarios, ensuring portability (< 25 kg), rapid deployment (< 5 minutes), and ease of installation and use, yet maintaining appropriate detection reliability and measurement accuracy.

This work focuses on the development and validation of these two systems, detailing the methodologies employed in their design, the role of Monte Carlo simulations in performance evaluation, and the experimental campaigns carried out to verify their accuracy under real-world operational conditions.

FOOMON, designed for the radiological screening of food samples, employs a 2"× 2"NaI(Tl) detector. The system is self-contained in a rugged, high-protection case to ensure reliability across diverse environmental conditions, including temperature variations and high humidity levels. This system enables quantitative analysis of radionuclides, specifically I-131, Cs-134, and Cs-137. Comprehensive Monte Carlo simulations were conducted to model detection efficiency across various food matrices, accounting for density and composition variations. These simulations revealed Minimum Detectable Concentrations (MDCs) as low as 30 Bq/kg for I-131 and 40-50 Bq/kg for Cs isotopes within a 10-minute measurement period. The accuracy of these predictions was confirmed through dedicated experimental campaigns.

THYMON, a system for thyroid monitoring, addresses the critical need to assess internal contamination from inhaled I-131. It integrates a collimated 1.5"× 1.5"NaI(Tl) detector with precise hardware to ensure optimal positioning and minimize measurement uncertainties. The system supports both handheld and hands-free operation, with an ergonomic design that ensures correct detector placement to reduce operator variability. Monte Carlo modelling was used to refine detection efficiency and positional alignment, achieving Minimum Detectable Activities (MDAs) below 100 Bq. This value corresponds to the threshold for no significant thyroid exposure in the most critical accident scenario considered by the TMT handbook. The system also limits dose estimation uncertainties to within ± 20%, which remains lower than the variability introduced by anatomical differences among individuals. A dedicated age-dependent numerical thyroid phantom was eventually developed to refine detection efficiency and then implement age-specific activityto-dose conversion coefficients for five defined age groups: 1, 5, 10, 15 years old (Adult Female), and Adult Male.

Monte Carlo simulations played a dual role in both projects, not only evaluating key detection quantities but also serving as a predictive tool to guide system design and optimization, both hardware and software. Dedicated validation campaigns were performed employing reference radioactive sources of different energies, intensities, and geometries. The experimental campaigns were designed to cover a broad range of operational conditions, assessing accuracy, precision, and reproducibility of the detection methods. The experimental campaigns demonstrated the appropriateness of the implemented Monte Carlo models, both qualitatively and quantitatively, with observed discrepancies always lower than 15% for energies ranging from about 30 keV up to
2.8 MeV, with both Marinelli and point-like sources, and in different measurement geometries. The agreement between simulated and measured data demonstrates the robustness of the implemented

models and supports the reliability of the proposed monitoring solutions. The systematic approach adopted in this study ensures that FOOMON and THYMON meet the highest scientific standards for radiological assessment while being applied to emergency CBRN scenarios.

These systems effectively bridge the gap between laboratory-grade instrumentation and field deployable solutions for first responders, offering reliable, portable tools for radiological monitoring in CBRN emergencies. Their integration of numerical modelling with experimental validation highlights the robustness of the simulation-guided design approach. The results obtained provide a solid foundation for further developments.

#10 - Current Trends in Development of Radiation Detectors / 304

#10-304 Novel spectral gamma ray logger device

Author: Jan Tous[1]

Co-authors: Karel Blažek [2]; Tomáš Brunclík [3]; Petr Mašek [3]; Tomáš Žitný [4]; Monika Kotyková [2]

[1] *CRYTUR, spo. s r.o.*

[2] *CRYTUR, spol. s r.o.*

[3] *Georadis, Brno, Czechia*

[4] *Diamo, Czechia*

Corresponding Author: tous@crytur.cz

The CORELA GRG-01 is a state-of-the-art spectral gamma logger designed for versatile use in both laboratory and field settings. It enables precise K-U-Th concentration pattern logging and gamma ray measurements. These measurements can be supplemental to chemical analysis or XRD. Equipped with a novel array of compact, high-sensitivity radiation detectors, the instrument offers enhanced accuracy while maintaining a lightweight and compact design.

In our study, the CORELA GRG-01 detection system was used to accurately determine the content of K, U and Th isotopes in boreholes from the Zlaté Hory area. This device allows, using scintillation detectors in massive shielding, effective analysis of even low isotope concentrations. The advantage of this system is its modular design, thanks to which the device can be easily relocated and measurements can be made directly at the exploration sites. The results on the cores of the investigated boreholes from the Zlaté Hory show a clear correlation between the type of rock and the content of K, U and Th isotopes. Measurements, carried out at five-centimeter intervals, revealed a significant increase in the concentrations of potassium, uranium and thorium at the interface between quartzites and metatuffs - up to double the values. In our paper, we will present detailed results of chemical analyses and their comparison with data obtained by measuring KUTh concentrations, which bring a new perspective on the petrographic classification of rocks in this area.

#10 - Current Trends in Development of Radiation Detectors / 305

#10-305 Thermal neutrons detectors using carbide heterostructures

Author: Gabriel Ferro[1]

Co-authors: L. Auvray [1]; D. Chaussende [2]; F. Mercier [2]; J.M. Bluet [3]; M. Lazar [4]; Laurent Ottaviani [5]; Abdallah Lyoussi [6]

[1] *Laboratoire des Multimateriaux et Interfaces, UCB Lyon*

[2] *Sciences et Ingénierie des Matériaux et Procédés, Univ. Grenoble Alpes*

[3] *Institut des Nanotechnologies de Lyon*

[4] *Lumière, nanomatériaux, nanotechnologies, Univ. Techn. Troyes*

[5] *Institute of Materials Microelectronics Nanosciences, Aix-Marseille University*

[6] *CEA, DES, IRESNE, Cadarache*

Corresponding Author: gabriel.ferro@univ-lyon1.fr

CADOR project (French ANR) aims at developing a new generation of neutrons detectors (NDs) based on the highly stable carbide heterostructure boron carbide (BxC)/silicon carbide (SiC). In such devices, the few µm thick BxC layer will serve as thermal neutrons converter for the 4H-SiC based semiconductor detector. The high amount of 10B close to SiC detector should enhance the detection efficiency, allowing considering on-line nuclear reactor monitoring. This should be favored by the high stability of these carbides which are expected to withstand high temperature operation, up to at least 500℃. Applications to low neutron flux measurements can be also considered for cleaning and dismantling operations, radioactive waste management and homeland security applications.

Three versions of BxC/SiC detector are targeted. In the simplest approach (Demo1), amorphous to polycrystalline films grown by PVD or CVD will be used as the neutron-converter layers on top of the 4H-SiC p-n junction. Thanks to the recent mastering (by LMI partner) of BxC epitaxial growth by CVD on 4H-SiC [1], a higher crystalline quality version of neutrons detector (Demo2) will be elaborated with an expected gain in terms of interface stability upon thermal stresses. A more innovating design to be investigated (Demo3) will take advantage of the intrinsic semiconducting properties of BxC material (which is known to be naturally p-type doped). It will involve a p-type epitaxial BxC film deposited on n- doped 4H-SiC in order to form the p-n junction.

CADOR multidisciplinary project goes from material elaboration to device fabrication and testing, completed by device simulation. Fabricating the three types of neutrons detectors requires important material developments and various characterizations for controlling the layers crystallinity, purity and intentional doping, as well as the different processing steps (dry etching, contacts⋯) for device fabrication. The fundamental electronic and optical properties of BxC material, which are largely unknown, are to be determined. Note that the chemical and mechanical stability of the BxC/SiC interface up to 500℃ is of main concern for the application.

At ANIMMA conference will be presented the advancement state of CADOR project, focusing on Demo1 device. This will include not only device simulation (for both optimization of the designs and performance prediction) but also BxC material development (thickness, roughness, strain, chemical composition, dry etching⋯).

#09 - Environmental and Medical Sciences / 307

#9-307 Design of a new 2D amorphous Silicon-based detector for Particle Therapy

Author: Khalil El Achi[1]

Co-authors: Eduardo Cortina Gil [1]; Alexis Warnier [2]; Victor De Beco [2]; Severine Rossomme [2]

[1] *Catholic University of Louvain, Belgium*

[2] *IBA Dosimetry, Louvain-la-Neuve Belgium*

Corresponding Author: khalil.elachi@uclouvain.be

Proton and Radiotherapy are leading particle therapy tactics used to combat chronic and malignant cancers [1]. Ultrahigh dose rate (UHDR) flash therapy, is a new treatment modality that is currently being studied by several groups. The treatment delivers high doses in a short period of time (40 Gy/s) and is highly effective against tumor cells while maintaining healthy cells. Moreover, particle therapy also has radiobiological advantages compared to conventional therapy [2]. UHDR dosimetry presents a crucial challenge to detectors when performing proper quality assurance (QA) measurements.

This work aims to develop a high-resolution 2D solid-state detector for accurate QA clinical routine in particle therapy. Amongst semiconductor materials, amorphous silicon (aSi) is characterized by durable radiation hardness [3], thus it is a notable candidate for material to build the active region of a solid-state detector.

To build a solid-state-based detector that can handle a wide range of doses and dose rates delivered by particle beams, the following solution is thus investigated. The active region will comprise a p-n junction that is composed of a lightly p-doped bulk aSi (Np ≈ 10^{15}cm^{-3}) and highly n-doped implants (Nn ≈ 10^{18}cm^{-3}), represented in Figure 1a. At this unbiased state, the detector can withstand large charges generated with flash measurement. At lower doses, a reverse bias voltage would be applied up to Vrb = 5V to fully deplete the detector and expand the active region to ≈ 2µm, to grant a decent signal-to-noise ratio (SNR). Monte Carlo simulation [4] will be used to compute the response of the active region, pertaining to the different beam modalities. In addition, COMSOL Multiphysics will be used to characterize and design the photodiode with the coupled thin-film transistor (TFT).

Early irradiation measurements using the IBA Razor diode performed at different proton beam intensities were done at UCLouvain cyclotron to validate simulation accuracy. The measured values using an IBA DoseX electrometer show pristine charge linearity and close correlation with the simulation estimation where the measurement falls in between the 2σ approximation with a 10% offset from the most probable value, shown in Figure 1b. Further tests will be performed in clinical settings using high-energy gamma rays and flash proton intensities for both aSi and cSi-based diodes to understand the different behaviors of both materials and their usability in patient QA.

#03 - Fusion Diagnostics and Technology / 342

#3-342 Comprehensive Calibration Strategy for ITER Neutron Diagnostics

Author: Quentin Potiron[1]

Co-authors: Andrei Kovalev [1]; Giovanni Mariano [1]; Silvia di Sarra [1]; Dmitry Gin [1]; Vitaly Krasilnikov [1]; Bruno Coriton [1]

[1] *ITER Organization*

Corresponding Author: quentin.potiron@iter.org

Neutron diagnostics play a crucial role in fusion reactors by providing key information for plasma and fusion control, machine protection and nuclear safety. In ITER, the neutron diagnostics will be exposed to a wide range of neutron energies, from thermal to fast neutrons, and cover a broad neutron flux range, from 10^6 to 10^{14} n.cm^{-2}s^{-1}. They are used to quantify fusion plasma parameters such as neutron emissivity, D-T ion fueling ratio, total neutron yield and fusion power.

Achieving high accuracy during operation necessitates in-situ calibration deploying inside the tokamak neutron generators with neutron energies of 2.45 MeV and 14.1 MeV as in DD and DT plasmas. The neutron generators are equipped with monitoring systems to record the neutron source emissions during the calibration campaign. As demonstrated at JET, precise characterization of the neutron generators and monitoring systems is essential prior to their use in ITER.

The finality of the in-vessel calibration is to determine accurately the detector calibration coefficients that link experimental counts to physical fusion plasma parameters. This involves considering the detector response, machine integration, and plasma neutron source profile. However, full in-situ calibration is challenging due to the size of the ITER tokamak, the limited yield of the neutron generator and the low sensitivity of systems designed for high-fusion power operation. Therefore, a comprehensive calibration strategy that incorporates high-detail neutronic simulations is necessary to minimize uncertainties and improve cross-calibration accuracy. This strategy includes sensitivity studies to address the effect of uncertainties in the geometrical factors of the tokamak environment and in the material nuclear properties.

This work outlines the calibration strategy for the ITER neutron diagnostics, detailing the characterization of individual detectors, the development of detailed neutronic models and the preparations for in-vessel calibration.

#10 - Current Trends in Development of Radiation Detectors / 343

#10-343 Resource-Efficient Hybrid TDC Architecture on FPGA for Scalable High-Precision Timing

Authors: Diego Real Mañez[1]; David Calvo[1]; M. Manzaneda[1]; A. Moreno[1]; I. Burriel[2]

[1] *Instituto de Física Corpuscular (CSIC-UV)*

[2] *Instituto de Física Corpuscular (CSIC-UV*

Corresponding Author: real@ific.uv.es

Time measurement poses a significant challenge in electronics due to its broad range of applications. While conventional architectures have already achieved picosecond-level precision, the current focus shifts toward minimizing resource usage and scaling up the number of measurement channels. This work introduces a novel architecture for implementing Time-to-Digital Converters (TDCs) tailored for resource-constrained environments. The proposed Field Programmable Gate Array (FPGA)-based TDC achieves a resolution of 415.84 ps and a single-shot precision of 0.45 Least Significant Bits (186 ps r.m.s), while maintaining minimal resource usage.

Built on a multi-shift phase counter, the architecture is enhanced through the use of tap delay elements via the FPGA's hardware input delay features, effectively doubling the TDC's resolution. Compared to existing low-resource TDCs, this design significantly reduces logic utilization, requiring only 102 Look-Up Tables and 213 registers. It also demonstrates favorable performance metrics, with a Differential Non-Linearity (DNL) of 0.2 LSB and an Integral Non-Linearity (INL) of 0.15 LSB.

The TDC has been successfully implemented on a Xilinx Artix-7 FPGA, offering an efficient solution for applications demanding high precision and low resource consumption. Additionally, some preliminary results from an implementation on a Xilinx Ultrascale FPGA will be presented, highlighting the scalability and adaptability of the proposed architecture across different FPGA families.