Prague, Czech Republic
June 21-25, 2021

Contribution ID: **75** Type: **Oral presentation**

#04-75 3D thermal and radiation-matter interaction simulations of a SiC solid-state detector for neutron flux measurements in JSI TRIGA Mark II research reactor

Wednesday, June 23, 2021 2:40 PM (20 minutes)

In the nuclear reactor, it is crucial to measure key parameters such as neutron and photon fluxes or nuclear heating rate for a better understanding of the behavior of nuclear fuels or materials subjected to nuclear radiation. The coupling of different on-line measurement sensors is at the heart of these scientific objectives. The LIMMEX laboratory (Laboratory of Instrumentation and Measurement Methods in EXtreme media, a joint laboratory between Aix-Marseille University and the CEA) has been carrying out experimental and numerical works (innovation, design, characterization, calibration and optimization for laboratory and nuclear conditions) for accurate on-line measurements by means of differential calorimeters and semi-conductor detectors for many years. A new project, called SiC-CALO, aims to develop a multi-sensor device by coupling a Silicon Carbide (SiC) –solid-state based detector and a calorimeter for measuring simultaneously neutron fluxes and nuclear heating rates. Indeed, one objective is to know accurately the contribution of each radiation on nuclear heating rate thanks to the coupling of these two kinds of sensor and their combined interpretation. The finality of this project is to use this device in the core of the Jules Horowitz Reactor (JHR, under construction at the CEA Cadarache research center). The JHR core characteristics are, for a nominal power of 100 MWth, a high fast neutron flux (5.5×10^{14} n·cm^{-2}·s^{-1} for an energy > 1 MeV) leading to a high nuclear heating rate (up to 20 W·g^{-1} in Aluminum). To be able to endure all of these harsh conditions, a SiC-based detector has been studied within the framework of a previous joint European project, called I_SMART (Innovative Sensor for Material Ageing and Radiation Testing). SiC material was chosen, among other wide band-gap semiconductors, thanks to its several advantages like its fast response (a few ns), its stability under radiations thanks to its wide bandgap energy, its low leakage current and its low thermal resistance and temperature gradient. The I_SMART project was intended to develop an innovative system made of SiC for radiation detection at very high temperature (> 500 °C) and under high integral neutron flux (about 10^{14} n.cm^{-2}.s^{-1}). The main result of this project was the development of SiC p+n junction diodes with implanted 10-B thermal neutron converter layer to measure thermal and fast neutrons fluxes. With regard to the short-term outlooks, the SiC-based detector performances can be improved through the using of a 6-Li converter for a better neutron/gamma discrimination, by decreasing the metal contact thickness or by coupling the detector with a suited current amplifier and a treatment process of pulses. The middle-term outlook is to adapt the SiC-diodes for fast neutrons measurements inside tokamaks (high temperature about 400 °C - 500 °C and extreme magnetic fields about 4 T). The last outlook is to extend the measurement range to values higher than those which was measured previously during the I_SMART project, i.e. 9.4×10^{8} n·cm^{-2}·s^{-1}. Consequently, in 2021, an irradiation campaign at the Jožef Stefan Institute TRIGA Mark II research reactor in Slovenia is scheduled to measure higher neutron fluxes inside an in-core dry air triangular irradiation channel with a SiC detector and a commercial pCVD (polycrystalline Chemical Vapor Deposition) diamond detector (CIVIDEC Instrumentation). Main feature of this channel is its size, as it measures almost 6 cm in diameter. Because of the harsh conditions within this channel: a maximum integral neutron flux of about 1.2×10^{13} n·cm^{-2}·s^{-1}, a nuclear heating rate lower than 0.1 W·g^{-1} and a low heat transfer coefficient due to air natural convection, it is essential to predict the most precisely the behavior of the SiC detector for this environment.

Consequently, this paper will focus on 3D numerical studies dedicated to the definition of the most optimized device for the measurement campaign.

In a first part, a state of the art of the SiC detectors will be realized.

In a second part, 3D simulations dedicated to the interactions between nuclear radiations and matter will be

performed by means of MCNP calculation code (Monte-Carlo N-Particle transport code). The goal of these simulations is to estimate the flux attenuation and the nuclear heating rate in each part of the studied system for different axial positions by considering input source spectra, which represent the irradiation conditions of the triangular dry-air channel of the JSI TRIGA Mark II reactor core. The studied system will contain all of the components of the detector such as the housing, the duralumin support, the SiC diode putted on its alumina support, the connectors, the screws and the instrumentation cables.
In the last part, 3D thermal simulation results will be presented. A 3D thermal model built and solved with COMSOL Multiphysics finite element code will be detailed for the same system as that used for MCNP code. The thermal model will take into account heat sources estimated by MCNP simulations, conductive, convective and radiative heat transfers inside the system and natural convection boundary conditions by applying specific heat transfer coefficient values determined thanks to a correlation formula depending on the heat sources. The aim of these thermal simulations is to determine the temperature field inside the system and in particular in the SiC diode. A parametrical study will be given and discussed in order to define the optimized detector design.

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Session Classification: 04 Research Reactors and Particle Accelerators

Track Classification: 04 Research Reactors and Particle Accelerators