THE MINI LABYRINTH – A SIMPLE BENCHMARK FOR RADIATION PROTECTION AND SHIELDING ANALYSIS

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ABSTRACT

Since World War II there has been a significant development of methods and approaches used in the calculation of radiation shielding. This development was directly supported by the needs of industry (military technology, nuclear power plants, food processing, medical applications, accelerators, etc.). Over time, modelling and simulation of relevant effects shifted from an analytical modelling to methods based on the so-called primary principles and their stochastic nature. Even nowadays it is necessary to know the accuracy of available computation codes, used nuclear data and it is desirable to evaluate the influence of the user on the final calculated parameter. One of the most effective ways of gaining user experience and minimizing user effects on the results of calculation is international collaboration comprising the designing and constructing of relevant benchmark experiments, following simulation with tools available at the workplace (engineering tools vs. high-fidelity methods), comparison of work group results and subsequent identification of the source of observed deviations from the experiment. The proposed paper comprises a definition of the simple neutron and gamma shielding benchmark, inspired by the ALARM-CF-AIR-LAB-001 ICSBEP experiment. The experimental setup consists of the PuBe neutron source, several NEUTRONSTOP C5 shielding blocks (polyethylene with 5 % boron), H_2O filled PLA tank, plastic source holder and the active and passive detectors. The measured quantities are compared to values calculated by MONACO (as a part of SCALE 6.2.4 system) and MCNP 6 stochastic codes. The influence of different cross section libraries and propagation of cross section uncertainties is studied through the shielding analysis. The achieved results are included and finally, some discussions on further needed development are also included.

Description of the Mini Labyrinth

The Mini Labyrinth experiment is a simple neutron and gamma shielding experiment developed at STU, inspired by the ALARM-CF-AIR-LAB-001 ICSBEP benchmark experiment. The purpose of this experiment is to validate the computer codes of involved partners against real experimental data. Several experimental setups were created. In this document the V02 version of the experiment with 2 PuBe neutron sources is described. This experimental setup consists of the following pars:

- Desk made of HDF material on which the experimental apparatus is placed
- Labyrinth, made from NEUTRONSTOP C5 shielding blocks
- Graphite prism with cavity for neutron source
- 3D printed PLA tank with H_2O moderator
- Plastic adjustable neutron source holder
- PuBe Neutron source with emission rate 1.0E7 n/s
- RadEye SPRD-GN personal radiation detector

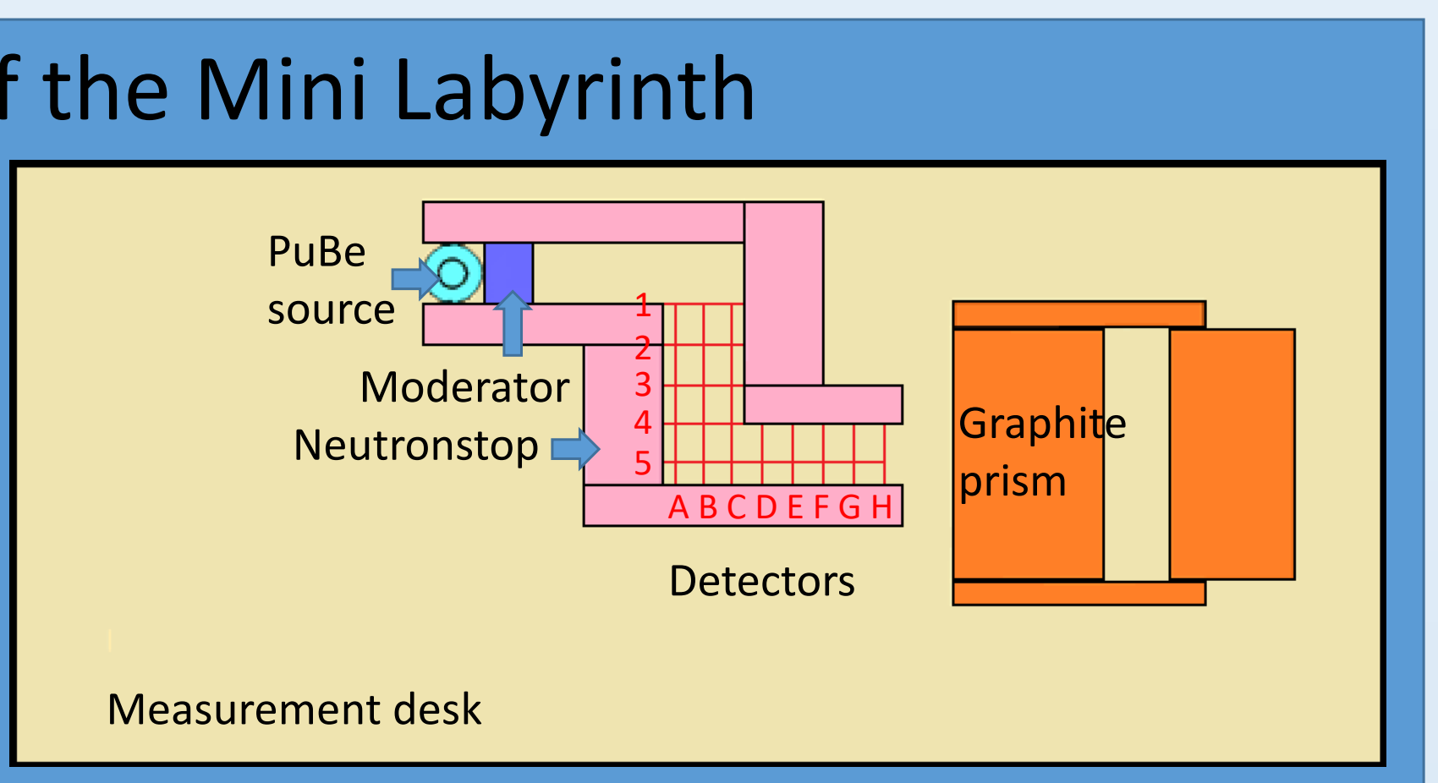

Fig.1 Measurement setup

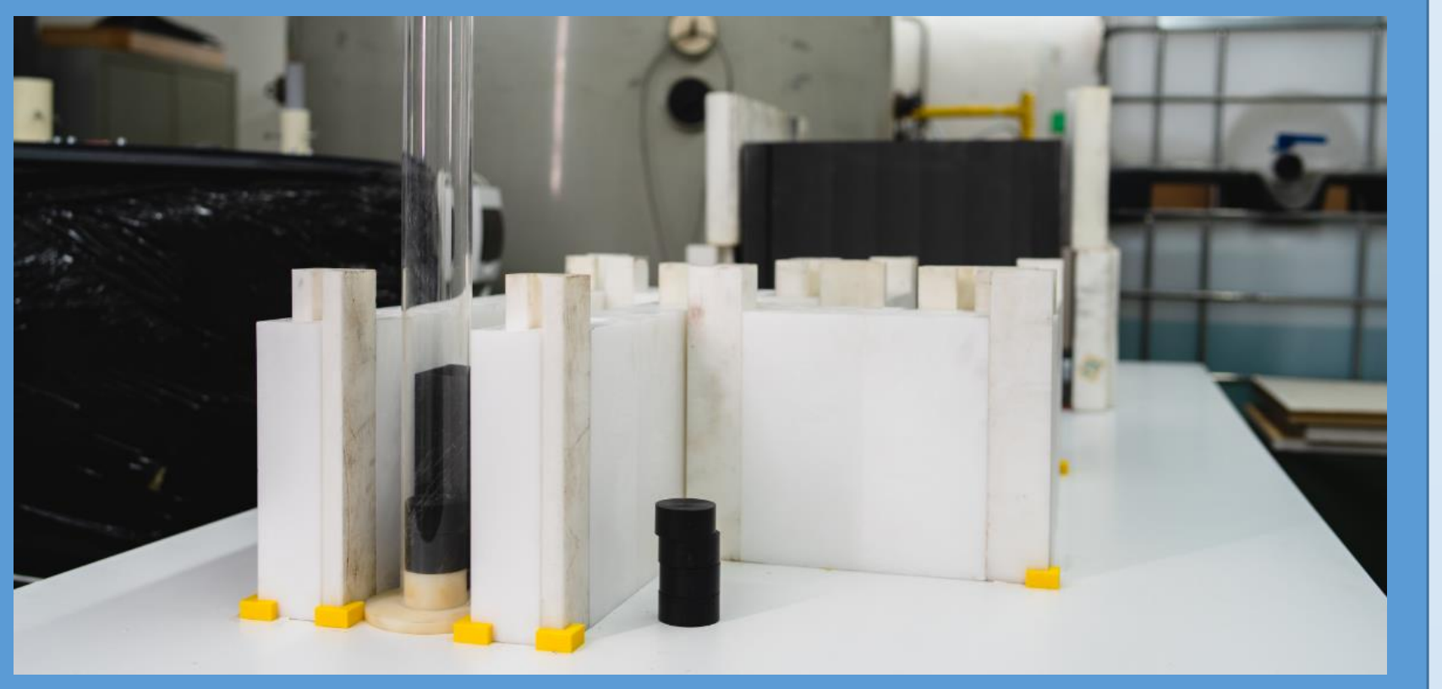

Fig.2 Photo of the workplace

The Labyrinth itself is made from 6x12x25 cm C-shape NEUTRONSTOP C5 shielding blocks and is placed on a special desk, equipped with additional shielding material and gear. The neutron source is loaded in the plastic adjustable source holder. The 3D printed tank with H_2O moderator is placed next to the neutron source, in order to moderate the neutrons entering the Labyrinth. The Experimental setup also includes the graphite prism, which, in case of a different measurement, can be used to produce thermal neutrons.

Simulation methodology

The simulation part of this analysis was performed using two stochastic Monte Carlo calculation code, MCNP6 and MONACO, which is part of the SCALE6.2 package. In case of both codes the detailed 3D model of the Mini Labyrinth was created, as shown in Fig. 1. The PuBe neutron source was modeled as a metallic cylinder with the strength of 1.0 e7 n/s. The emission spectra of the source are shown in Fig. 7 and Fig.8,

- That the gamma emission spectra consists of only primary gammas from the (α,n) reaction
- The angular distribution of the source was not taken into account.
- The calculations were performed as fixed source problems with the total number of 1e10 histories.
- In MCNP continuous energy cross-section libraries were used based on ENDF/B-VII.1 evaluated data
- In MONACO the calculations were carried in forward mode, without using variance reduction techniques, and with standard 27n19g ampx multi-group cross-section library, based on ENDF/B-VII.0 evaluated data.
- To estimate the gamma and neutron count rates, F5 type tallies were used both as meshtallies and as point detectors

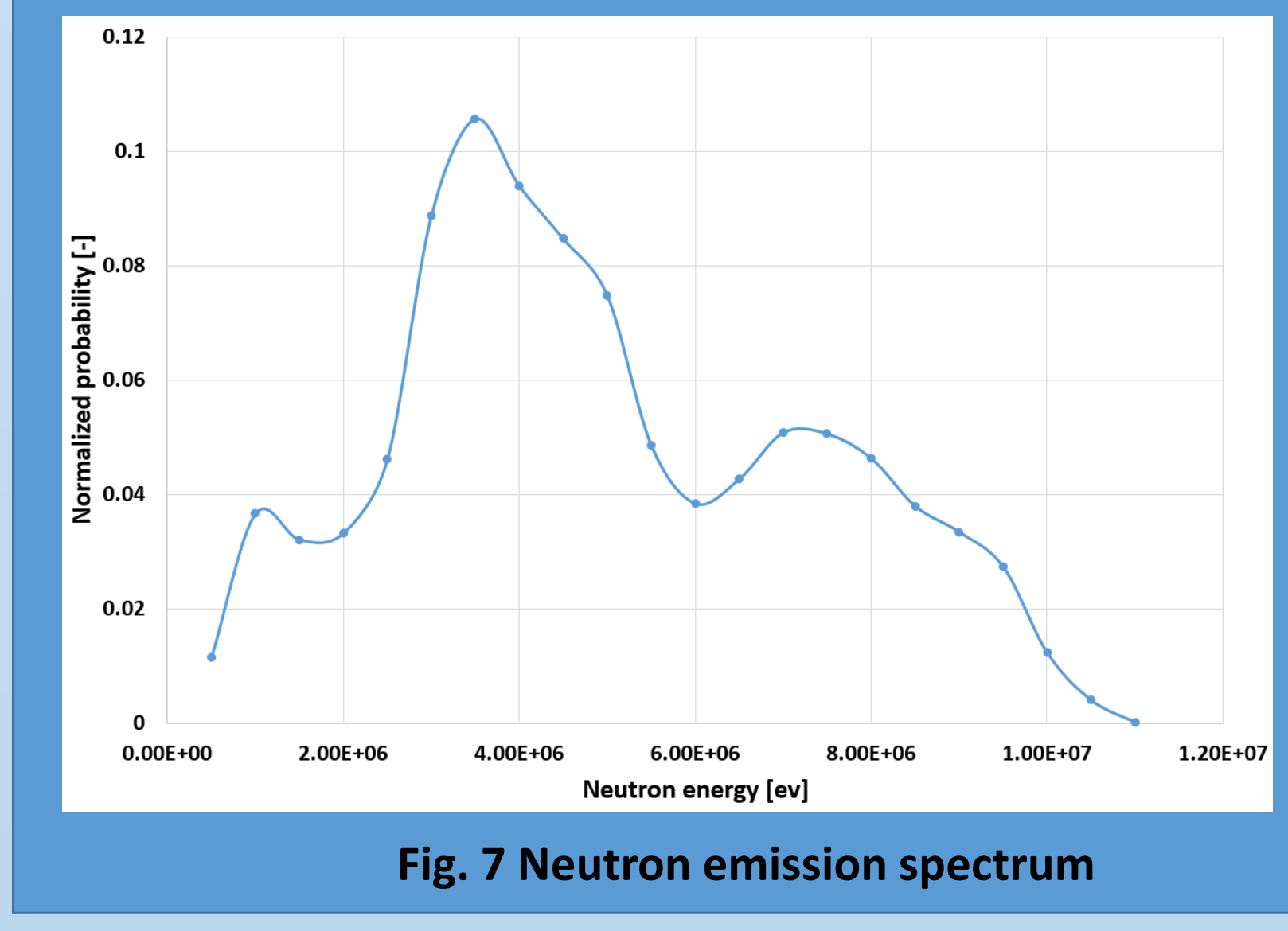

Fig. 7 Neutron emission spectrum

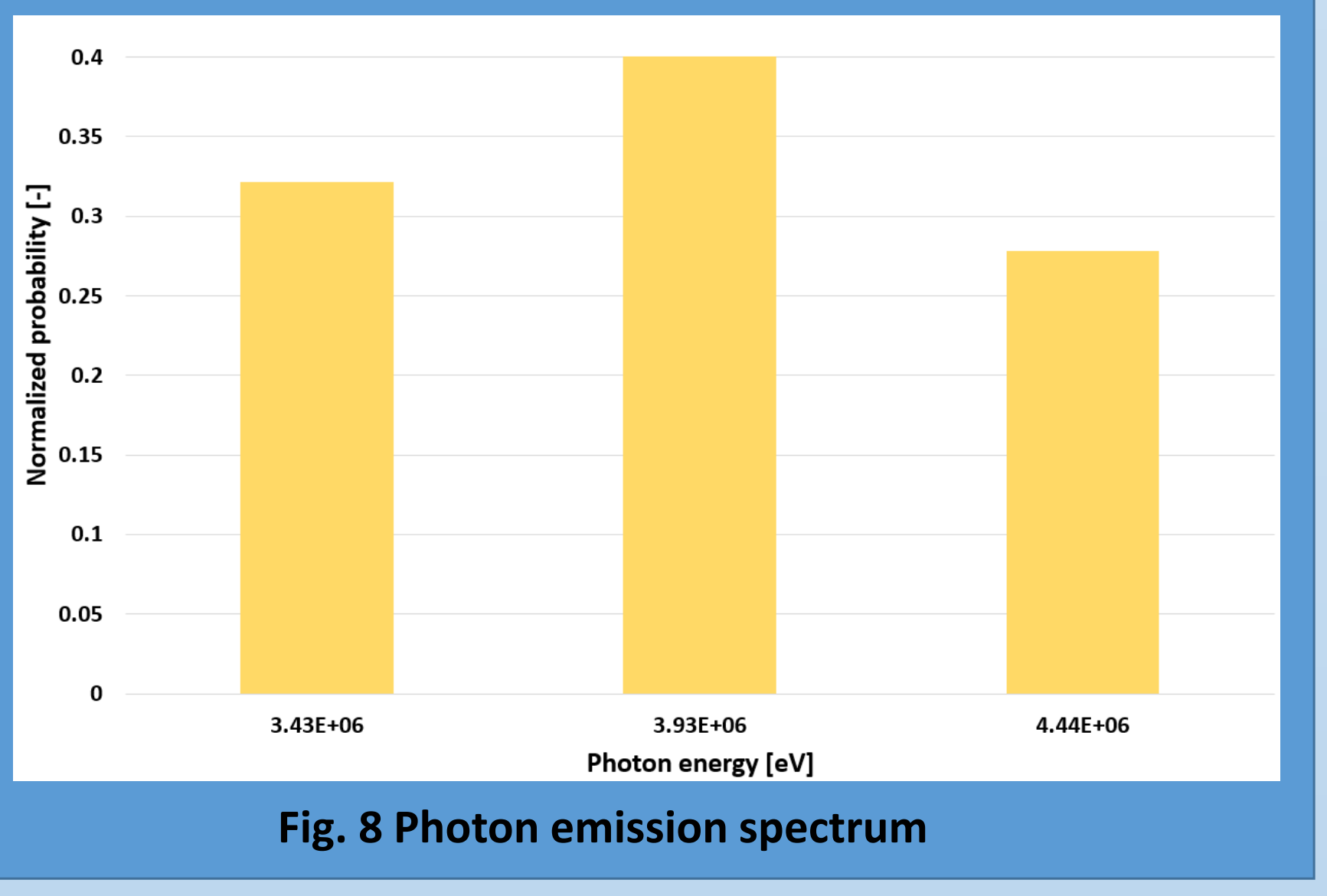

Fig. 8 Photon emission spectrum

Comparison with the original Labyrinth

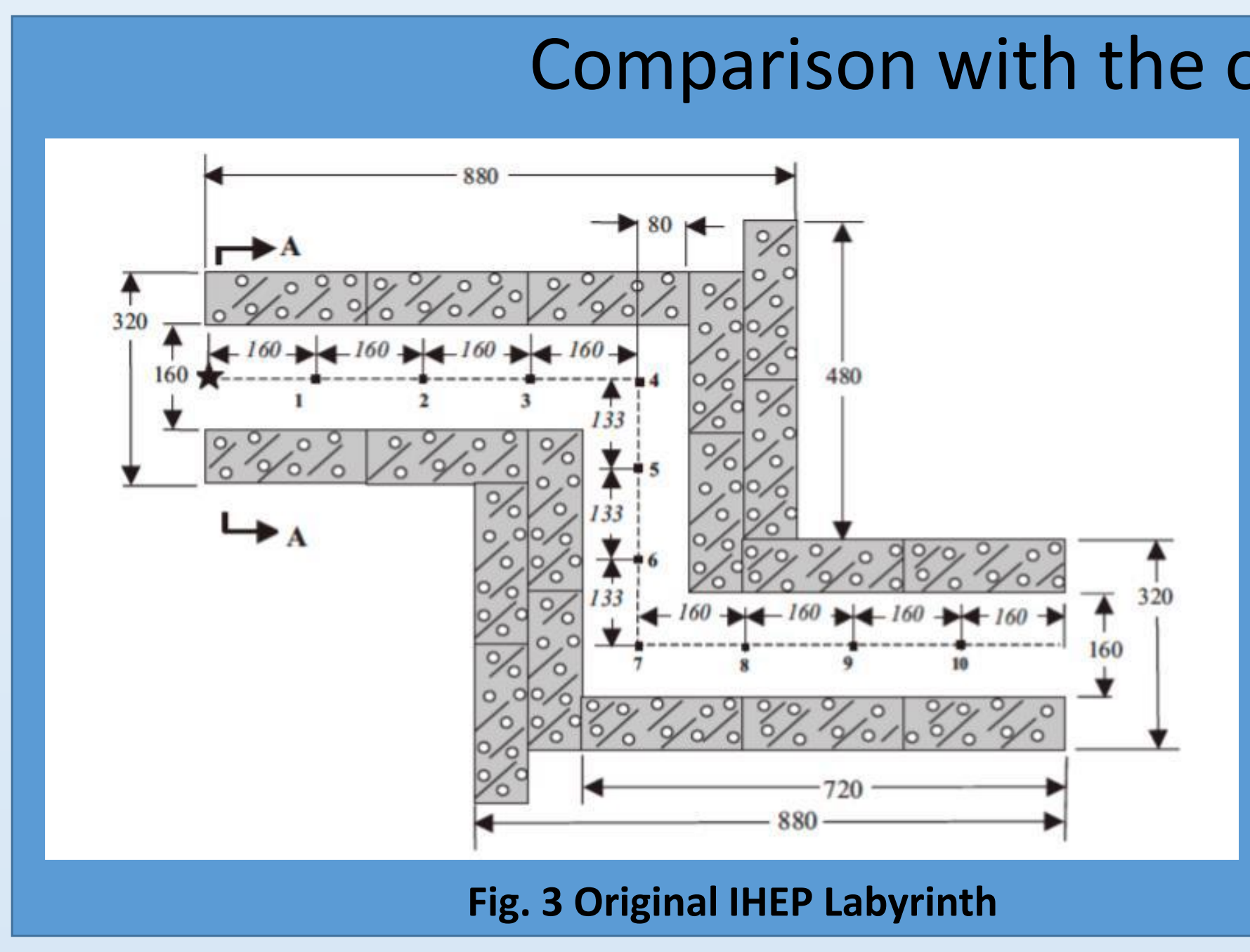

Fig. 3 Original IHEP Labyrinth

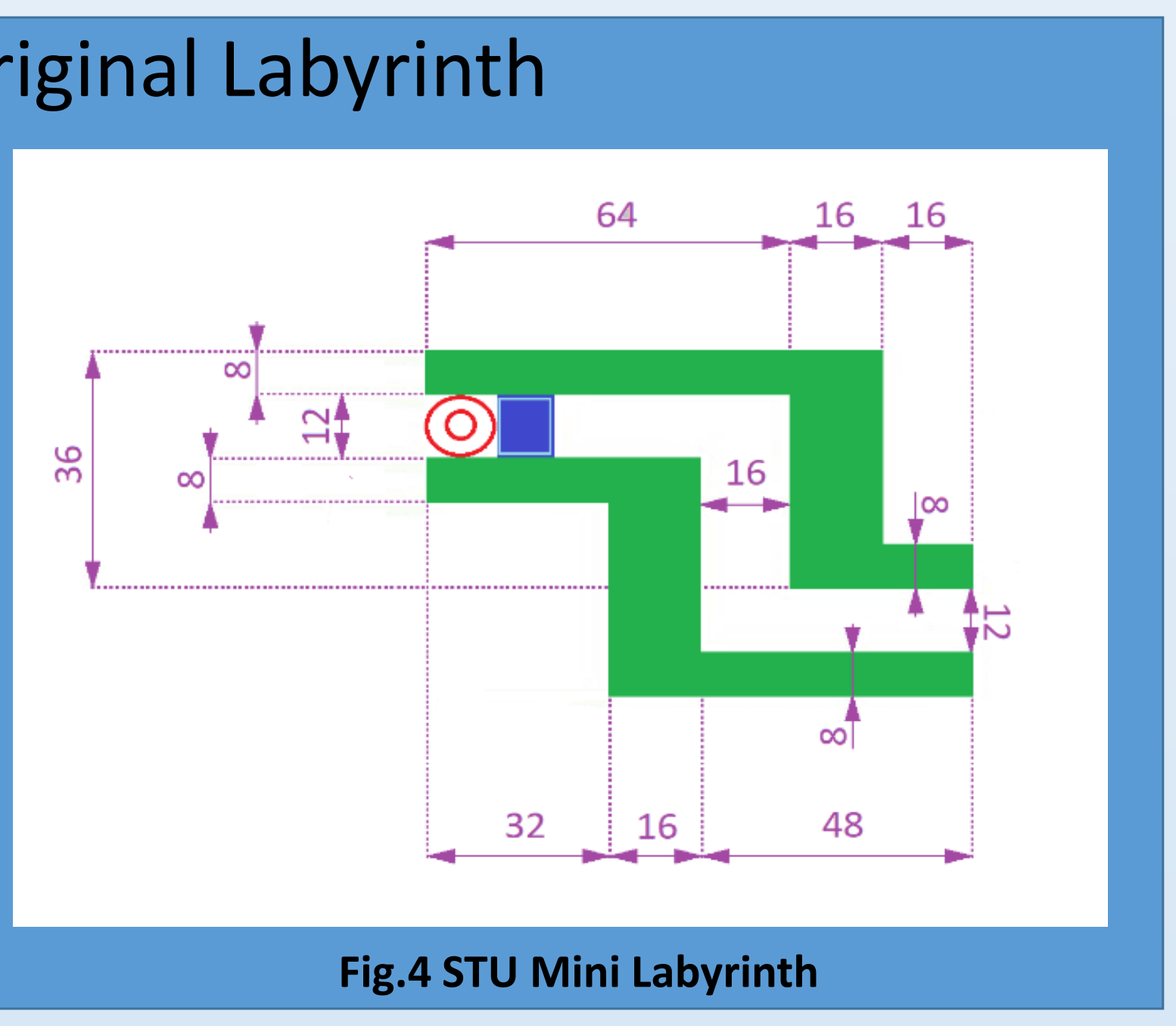

Fig.4 STU Mini Labyrinth

Measurement methodology

The measurements were carried out at the Mini Labyrinth experimental facility shown in Fig. 1. The measurement process consisted of the loading of the PuBe Neutron source in the plastic holder placed behind the plastic tank filled with 2.4 liters of demineralized light water and measurement of neutron and gamma dose rates in 17 positions. The measurement positions were chosen on 2D chessboard like grid shown in Fig. 1. The grid consists of 5 positions in the vertical direction (1-5) and 8 positions in the horizontal direction (A-H), while the first measurement position is referred to as A1 and the last one as H5. However, due to size limitations, the fifth vertical position was omitted, therefor only A1 – H4 positions were used.

In each measurement position the Thermo Scientific RadEyE SPRD-GN digital dose meter was used. RadEye (see Fig. 6) is CLYC (Cesium Lithium Ytrium Chloride) scintillation detector calibrated to measure neutron and gamma count rate in units of CPS or CPM and ambient dose equivalent H*(10) of gamma radiation in units of µSv/h. The neutron measurement range of this detector is 0 – 10 000 CPS and the gamma measurement range is from 10 nSv/h to 250 µSv/h. It operates in two modes, “ratemeter” and “scaler”.

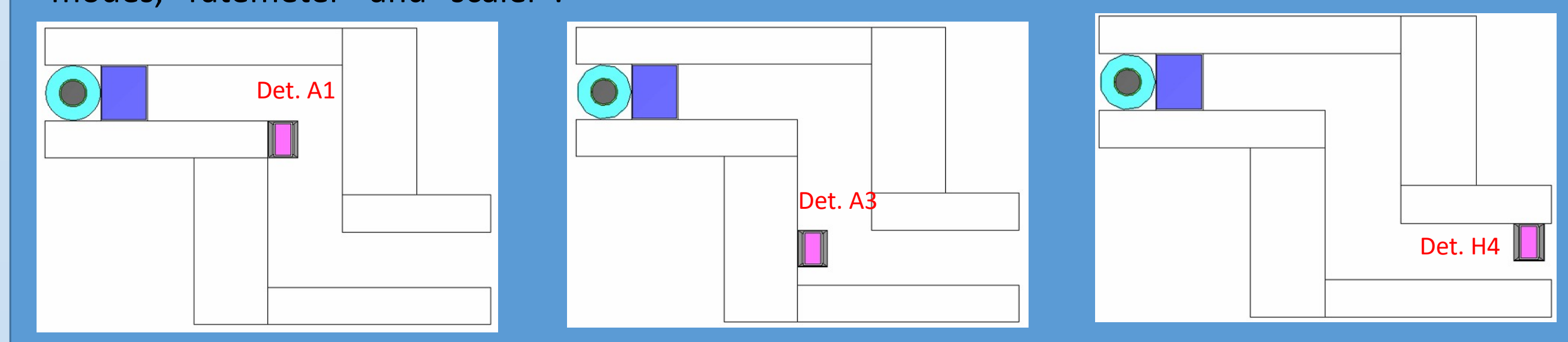

Fig. 5 Representation of the A1, A3 and H4 measurement positions

Fig. 6 RadEyE SPRD-GN

At each position, the detector was placed in upright position on the measurement table using an adjustable plastic holder ensuring that the crystal of the detector and the neutron source are in the same vertical position. 3 x 20 min measurement was performed, the ambient dose equivalent was obtained from the display and the neutron and gamma count rates were extracted from the RadEye Memory file. The final result per each position was the average from the 3 values.

Calculation cases

In order to compare the available experimental data, consisting of neutron and gamma count rates and ambient dose equivalents of gamma radiation in 17 specific positions, with simulations and the codes with each other, the following cases were defined:

- Code-to-code comparison
  - Neutron and gamma meshtailes
    - MCNP Vs. SCALE6
    - Energy integrated values
  - Neutron and gamma point detectors
    - MCNP Vs. SCALE6
    - Energy integrated values
- Measurement Vs. simulation
  - Ambient dose equivalent of gamma radiation
    - RadEye Vs. SCALE
    - Energy integrated values
- SAMPLER sequence
  - XS sampling done
  - A1 position assumed
  - 2x28 samples
  - 2 XS libraries
    - V70-27n19g
    - v7.1-200n47g

$$\Delta_{Exp} = \frac{R_{SCALE} - R_{EXP}}{R_{Exp}} . 100\%$$

Summary of Results

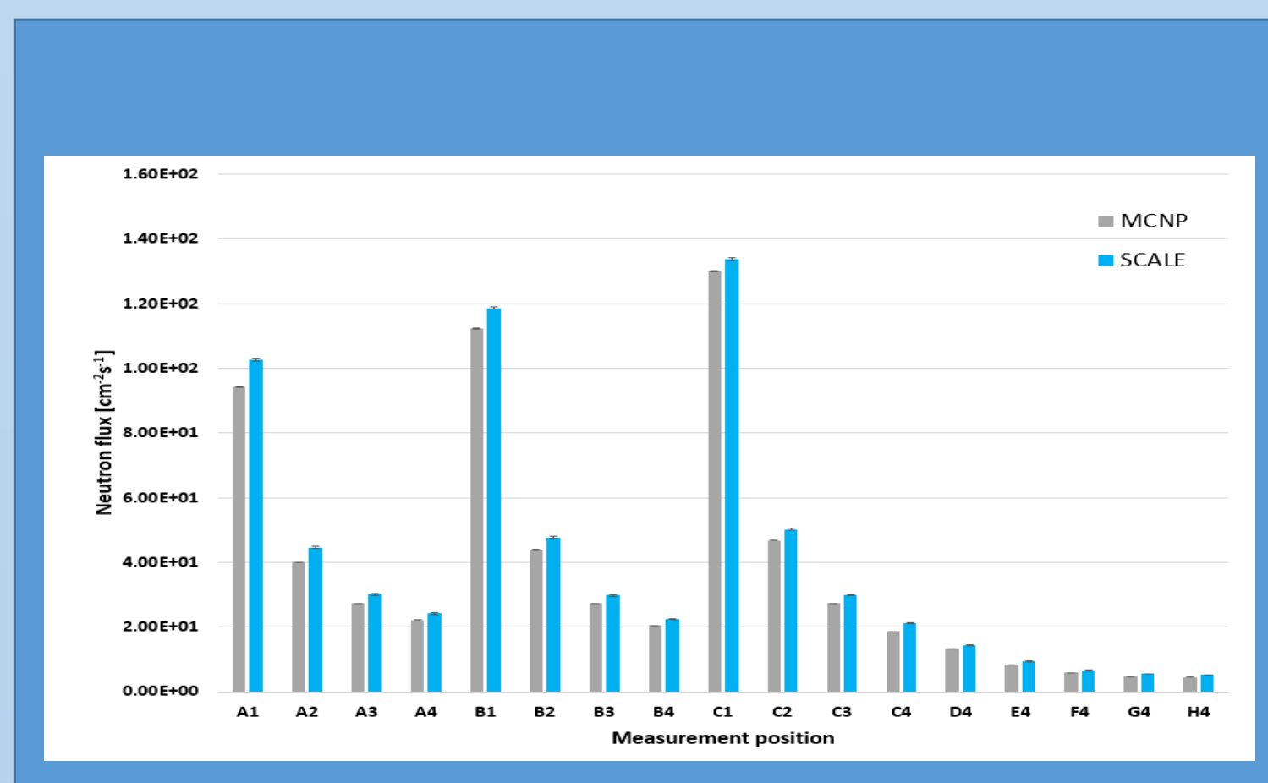

Fig. 9 Comparison of neutron fluxes – MCNP Vs. SCALE

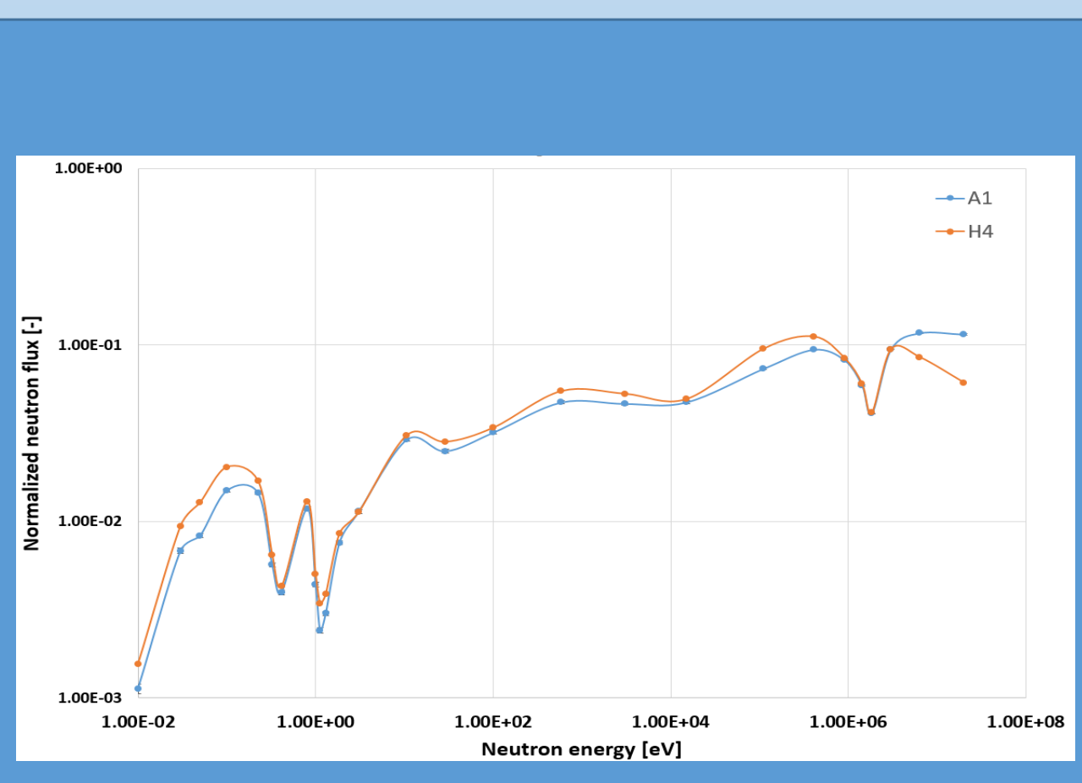

Fig. 11 Neutron spectra in A1 and H4 positions

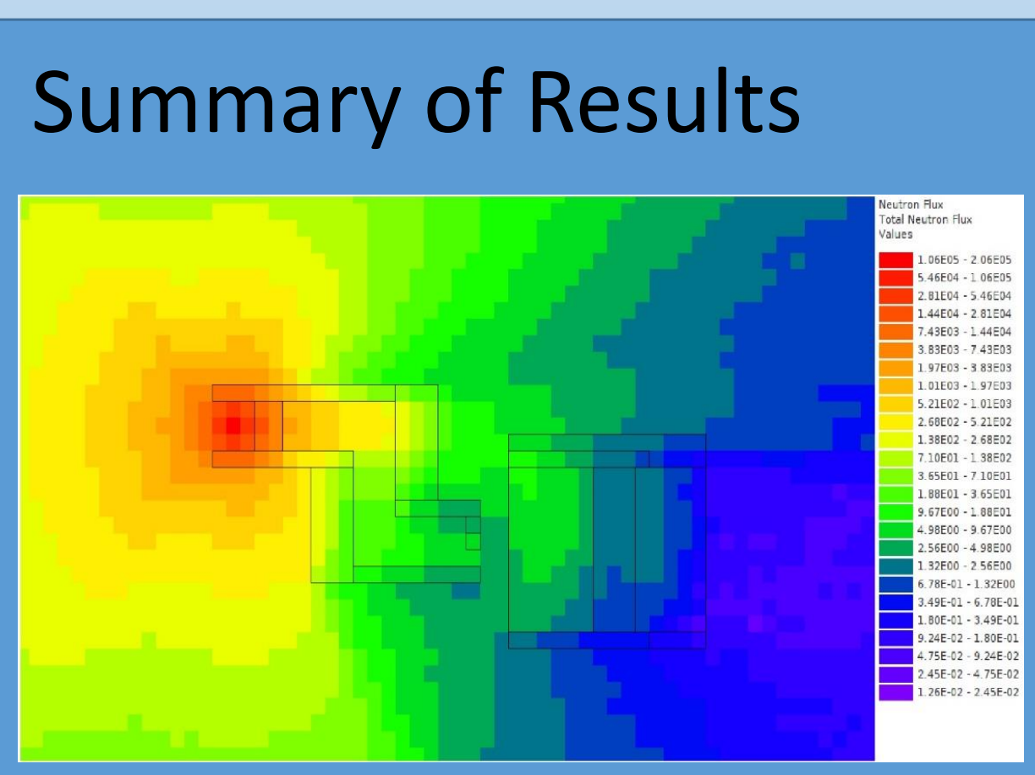

Fig. 13 Neutron meshtalie - SCALE

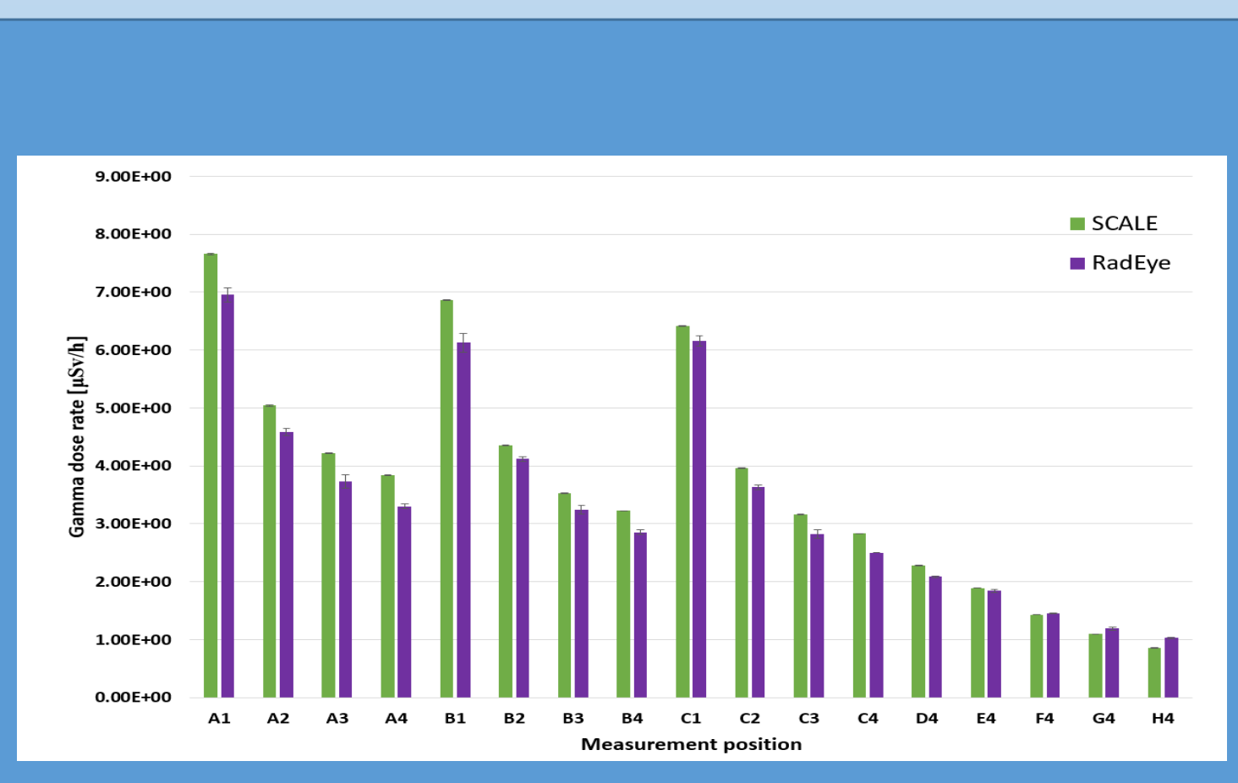

Fig. 15 Comparison of gamma fluxes – MCNP Vs. SCALE

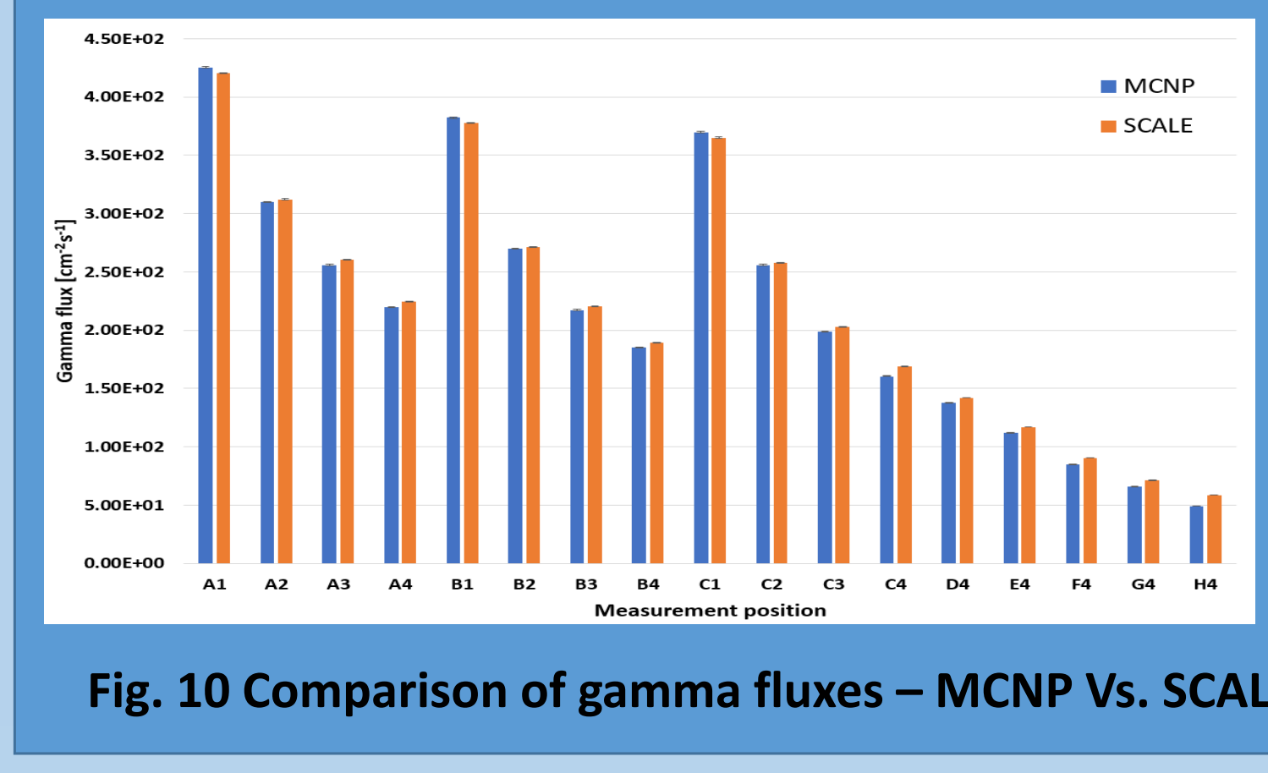

Fig. 10 Comparison of gamma fluxes – MCNP Vs. SCALE

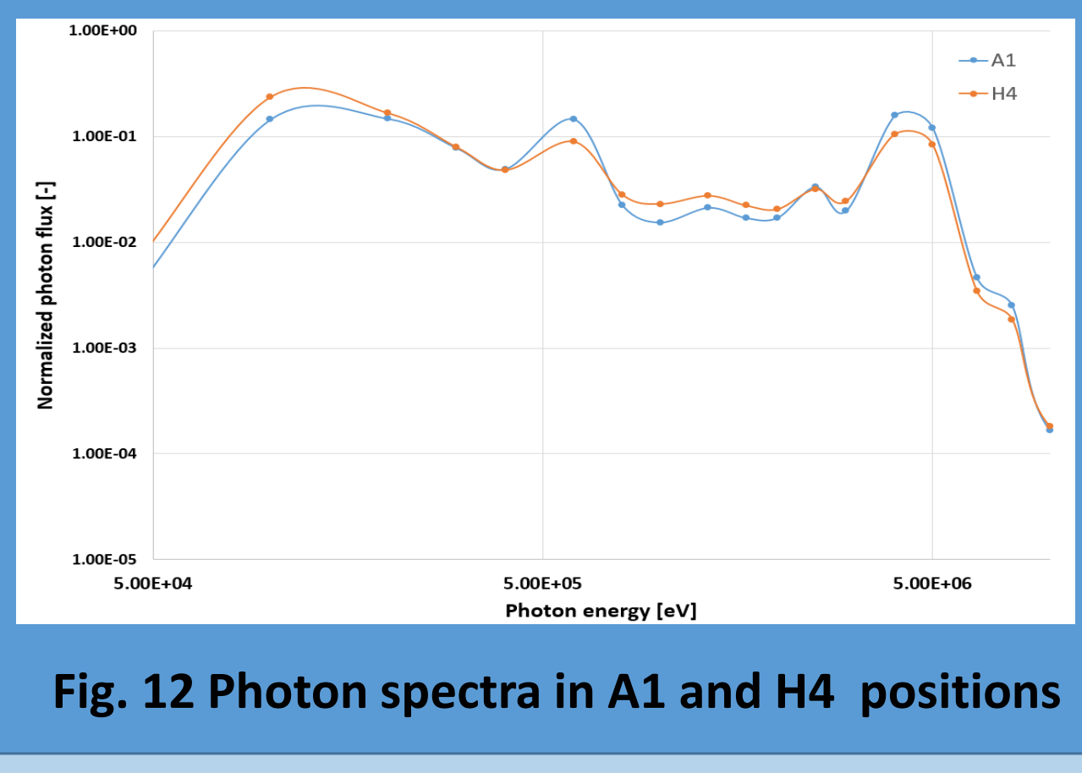

Fig. 12 Photon spectra in A1 and H4 positions

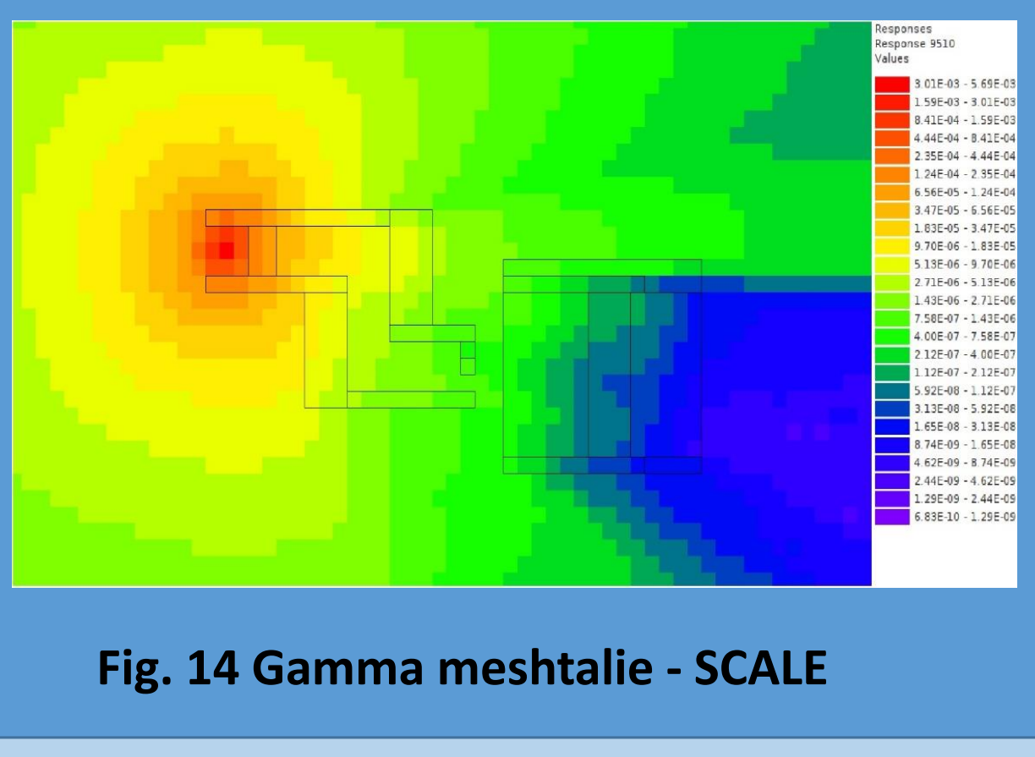

Fig. 14 Gamma meshtalie - SCALE

The SAMPLER results are not convincing. All samples utilizing the same source XS library produced exactly the same integral results. Moreover the group-wise data are also in perfect match. Due to the presence of thermalized neutrons in the neutron spectrum at detector positions, it is not likely that the XS induced uncertainty (or in the case of statistic sampling deviation of final results) is absolute zero. This specific aspect need to be further investigated and studied to clarify the nature of a such behavior.

Tab.1 Δ_{Exp} in each position

Position	Relative deviation
A1	10.15 ± 1.85 %
A2	9.90 ± 1.49 %
A3	12.92 ± 3.53 %
A4	16.29 ± 1.51 %
B1	12.01 ± 2.92 %
B2	5.70 ± 1.17 %
B3	8.85 ± 2.34 %
B4	13.00 ± 1.60 %
C1	4.21 ± 1.58 %
C2	9.30 ± 1.14 %
C3	11.79 ± 2.90 %
C4	13.12 ± 0.27 %
D4	9.35 ± 0.90 %
E4	2.65 ± 1.61 %
F4	-1.68 ± 0.36 %
G4	-8.03 ± 1.93 %
H4	-16.55 ± 1.18 %

Conclusions

This study presented the first results achieved at the Mini Labyrinth experimental workplace. The measurement performed at this workplace was aiming on the measurement of neutron and gamma count rate as well as ambient dose equivalent of gamma radiation inside the labyrinth and on the verification of experimental results by MCNP the SCALE6 MONACO code. For the measurements the Thermo Scientific RadEye SPRD-GN personal detector was used in 17 specific measurement positions. The results presented can be divided to the ones serving for code to code validations of MONACO against MCNP and to the ones serving to estimate the precision of simulation against measurement. In case of MCNP the continuous energy approach was used and in MONACO the multi-group cross-section libraries were used. The comparison of the energy integrated neutron and gamma fluxes showed a very good agreement between the calculation tools. In terms of the total neutron flux, MONACO slightly overestimated the result, but the average relative error from MCNP was 10,04 % and the maximal relative error was 17.92%. The largest errors were achieved in case of positions G4, H4, were the neutron flux values were very low. In case of gammas, the average error was only 3.23 % and the maximal error was 19,27 %, which was, again, achieved in measurement position H4. If we compared the gamma fluxes only for position A1 - C3, the relative error was only 1.11%. The mesthalies show good neutron attenuation properties of the Labyrinth, but also show relatively large error of gamma results in the bottom left corner of the model. These errors could be minimized by utilizing better calculation statistics. The errors between codes may be caused by the multi-group approach. or by the limitation of MCNP to use combine neutron-gamma source in a single calculation. The comparison of neutron and gamma spectra in the A1 and H4 measurement position showed a significant spectrum softening due to moderation of neutrons on H_2O, but also on the NEUTRONSTOP material, which consist of boron and polyethylene. In the future, also different H2O / Polyethylene ratios will be investigated to see the influence of NEUTRONSTOP on spectral softening. The comparison of simulated and calculated ambient dose equivalent of gamma radiation showed a relative error of 6,65% and a maximal error of ± 16 %. This agreement is acceptable, but we still see a space for further improvement. To minimize the relative error between the calculations and measurements, the source definition should be reviewed and to minimize the statistical uncertainty of measured values, the measurements should be repeated with better statistics. The results from the SAMPLER supersequence are unconvincing. Currently communication with code developers was established to reveal the nature of the zero cross section induced uncertainty to the investigated responses. The findings of this paper will be used to create the V3 configuration of the Mini Labyrinth, which will use a different neutron source, more precise measurement technique and multi detector setup.

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