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Neutronics for DEMO Fusion Power Plant: Serpent2 Modelling of 14.1 MeV Neutrons in Reactor Mock-Up Components

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ABSTRACT

This contribution presents the current status of the work carried out on benchmarking and validating Serpent2 for fusion energy applications. The benchmarking is done against MCNP5, while the validation is carried out for two fusion-specific experiments: the water-cooled lithium-lead (WCLL) mock-up for tritium breeding (EUROfusion tasks PMI-7.5-T002 and BB-S-05.02-T003), and the upcoming tungsten-based neutron shielding experiment (EUROfusion task FP9_WP_BB_Task 002). Both experiments are carried out at ENEA, Frascati, using the FNG (Fusion Neutron Generator) facility there. In the WCLL experiments, the neutron flux spectra and the reaction rates (RR) were calculated in the Nb foils of 7 detectors along the neutron injection direction. In the w shielding mock-up experiment, the neutron spectra and RR were calculated in the preliminary measurement positions. The benchmark between the codes resulted in a difference below 10% for both experiments. In the WCLL, where experimental data is already available, the C/E ratio was calculated for several RR, showing values between 0.88-0.99 for the statistically most favourable case.

1 INTRODUCTION

Since the conception of the peaceful use of fusion energy in the 1950's, the undeniable emphasis has been on understanding the behaviour of the plasma fuel in fusion-relevant conditions. More recently, also material questions have been gaining space when the fusion research facilities around the world have achieved very high-performing plasmas and the durability of the vessel walls has become a very relevant question to answer.

Research on fusion neutronics, on the other hand, has not been very visible. This is understandable considering the fact that fusion research is carried out using mock-fuel, pure deuterium, when the number of neutrons remains very low. This has to change now that the first fusion reactor, ITER[1], is being assembled in Cadarache, France. In its full operation, it will be running on 50:50 DT mixture, producing 500 MW of fusion power – and corresponding number of 14.1 MeV neutrons.

These fusion neutrons, with energies of almost ten times higher than in fission reactors, call for urgent attention. Not only does one have to worry about radiation protection and material lifetimes but, unlike in fission reactors, the future of fusion energy actually relies on neutrons: they are expected to produce more fuel by transforming lithium in the wall blanket into tritium, making the reactor self-sufficient with tritium. Without this tritium breeding taking place at high enough efficiency, it is hard to imagine a commercial fusion reactor.

For these reasons, in the pre-conceptual phase of the European DEMO reactor[2], serious attention is put on the issues related to neutrons.

In this contribution, the DEMO-related neutronics work carried out within the FinnFusion consortium to advance the understanding of fusion neutrons in reactor-relevant materials is presented. The focus is on modelling neutronics in two experiments: tritium breeding in LiPb blocks, and radiation shielding with tungsten-based shielding blocks. The desired outcome, in addition to increased physics understanding, is to validate the Serpent2[3] code against not only the experimental measurements but, in more detail, to the corresponding results from the MCNP5[4] code that has for long served as the golden standard in fission neutronics.

In Section 2, we introduce these two codes, making clear their parallels and differences. In

Section 3, the two experiments are briefly described. Finally, in Section 4, the results obtained thusfar are presented, and future work outlined.

2 SIMULATION TOOLS

The basic operating principles of both MCNP and Serpent are similar for neutron transport calculations: Both rely on the same ENDF reaction laws to model the neutron interactions and cross sections can be read directly from the same ACE format data libraries. Regarding the geometry implementation, both codes base their standard model on the constructive solid geometry (CSG) capability.

Although the neutron physics model is so similar that discrepancies between the codes are only expected within statistical error, the geometry options beyond CSG differ. While MCNP has recently introduced the possibility to combine CSG with unstructured meshes, Serpent can directly take in the geometry from CAD drawings. This feature becomes essential when simulating such complicated geometries like Wendelstein 7-X stellarator[4].

3 FUSION NEUTRON EXPERIMENTS

The most unambiguous benchmarking of the two codes should be done on a very simplified geometry so that the difference in how the two codes take it in does not complicate the comparison. Therefore, neutron irradiation experiments carried out with simple mock-up blocks and using a controlled neutron source are ideal for this purpose. Such experiments are provided at ENEA, Frascati, using the Fusion Neutron Source (FNG) there. Here, two experiments are modelled:

3.1 WCLL TRITIUM BREEDING EXPERIMENTS

In order for fusion energy to enter commercialisation phase, the self-sufficiency of the tritium fuel via breeding inside the reactor has to be demonstrated. This is foreseen to happen when ITER enters its nuclear phase. ITER is equipped with six Test Blanket Modules (TBM) to test tritium breeding. The time scale of such major experiment is, however, very long and, therefore, there is an urgent need to study the efficiency of tritium breeding in laboratory conditions. Of particular interest is the Tritium Breeding Ratio (TBR), telling how effective the fusion neutrons are in the foreseen blanket materials containing lithium. This was studied in the WCLL tritium breeding experiments, where a mock-up block with material composition corresponding to LiPb breeding blanket was used, see Fig. 1(a). The effect of cooling water was imitated by Perspex. The neutron flux and several reaction rates (RR) were measured by Nb foils at seven different distances along the original neutron beam direction as illustrated in Fig. 1(b).

These experiments were carried out in 2021 and modelled with both MCNP5[5] and Serpent2. The comparisons between the code results as well as to the experimental data are given in the next section.

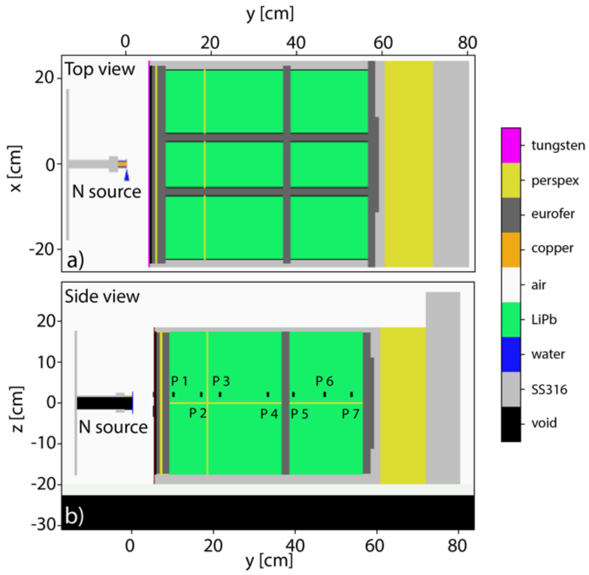

Figure 1: The WCLL tritium breeding experiment. (a) The geometry and composition of the mock-up. (b) Distribution of the Nb foil detectors.

3.2 TUNGSTEN SHIELDING EXPERIMENTS

As part of the EUROfusion FP9_WP_BB_Task 002 (Nuclear Experiments), a benchmark experiment concerning tungsten-based shielding system has been launched. The purpose of the experiment is to assess the shielding capability of the proposed system, as well as to predict the induced radioactivity that can jeopardize the integrity of the material. To optimize the geometry and material composition of the shielding block mock-up that consists, in addition to tungsten, of SS-316 and Perspex, a pre-analysis was performed using MCNP5, resulting in the experimental configuration illustrated in Fig. 2.

The assembly of the optimised experimental set up is taking place at FNG during the summer. To measure the neutron fluxes and reaction rates, both activation foils inside the mock-up and external spectrometers are used. The experiments are expected to take place by the end of the year, while the corresponding simulations with MCNP5 and Serpent2 are carried out as soon as the final setup, including the locations of the various detectors, are available.

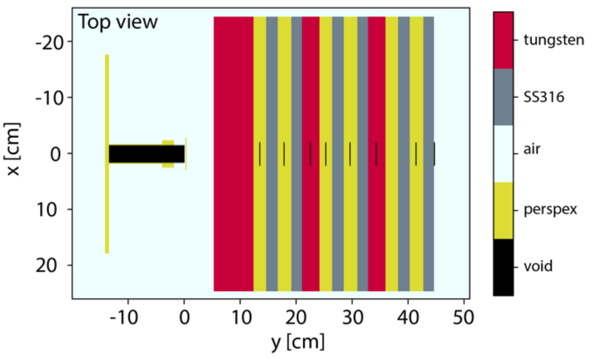

Figure 2: The experimental setup of the tungsten-based shielding block for European DEMO showing both the geometry and the composition of the mock-up. The detector locations along the midplane are indicated in black.

4 RESULTS AND CONCLUSIONS

In the breeding blanket study, Serpent simulation model was implemented according to the final WCLL mock-up geometry and material composition, together with the anisotropic, continuous-energy model for the FNG neutron source. For the nuclear reactions, the JEFF-v3.3 and the IRDFF-v2 cross-section libraries were used. The results of interest were the neutron transport and several reaction rates, which were used to benchmark Serpent against MCNP and, in the end, compared with experimental data.

The neutron flux and RRs were calculated in the Nb foils of the seven detectors shown in Fig. 1(b) and compared with MCNP. The differential neutron flux spectra from Serpent and MCNP are in excellent agreement, as shown in Fig. 3(a) for the detector location P2. Figure 3(b) compares the spectrum from Fig. 3(a) (red solid line) to the measured reaction rates obtained using the unfold procedure[6] (black dashed line). A good matching of the simulated spectrum with the unfold spectrum in the range $E=10^{-4}$-10^{2} MeV is evident. However, a detailed comparison of the total flux spectrum from MCNP and Serpent shows differences of about 10%, which is still considered unacceptable.

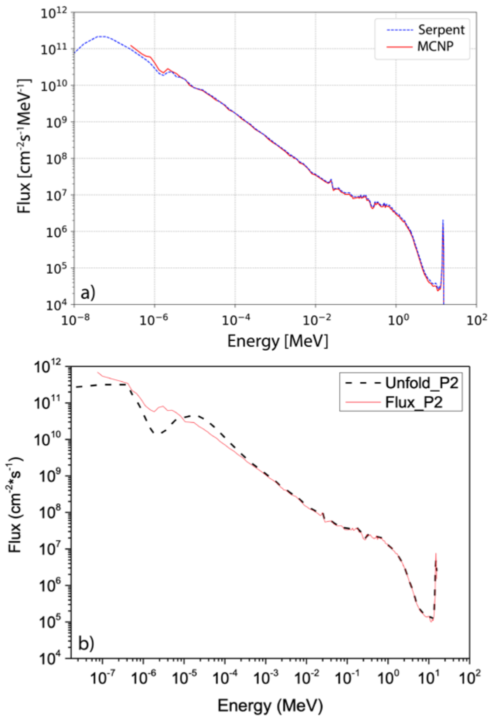

Figure 3: The differential neutron spectrum. (a) The spectra calculated by MCNP and Serpent. (b) Comparison of the simulated spectrum against the experimental one[6].

Also the reaction rates Nb(n,2n), In(n,n'), Al(n,α) and Ni(n,p) were compared with the experimental results at the different detector locations in the mock-up. The best agreement with the measured data was found for the In(n,n') reaction, with a C/E ratio between 0.88-0.99 and a maximum relative statistical error of 0.96%. Looking at the different cross sections as a function of the incident energy for all the reactions according to JEFF-3.3 data library, it was found that, among the four reactions under consideration, In(n,n') has the highest cross section and lower energy threshold, which increases the statistics significantly.

There are at least two possible error sources responsible for the observed discrepancies. First, the cross-section libraries, which often is the most challenging side of neutronic modelling. In the MCNP model, libraries JEFF (version 3.3) and IRDFF (versions 1.05 and 2.0) were used. In our Serpent calculations, the same version of JEFF was used, but only the version 2.0 of IRDFF was installed, which affected the dosimetric data of the detectors. We plan to repeat the RR calculations once the IRDFF-1.05 is installed. Another possible source of discrepancy is the low statistics achieved in some of the activation foils (e.g. gold foils are only 25µm thick). In future work, we will use the variance reduction method to improve the statistics in the thinner foils.

For the tungsten shielding mock-up, the neutron fluxes were calculated along with some RRs relevant for: neutron multiplication (Au(n,2n), Ni(n,2n)), gamma production (Au(n,γ), W(n,γ)) and potential material damage due to gas bubbles filled with hydrogen and helium (Al(n,α), Ni(n,p). The differential flux spectra at different distances from the source together with the corresponding RRs are presented in Fig. 4. The neutron flux was compared with that from MCNP, showing differences within 10%. These results will be validated by the end of the year when the experimental data become available.

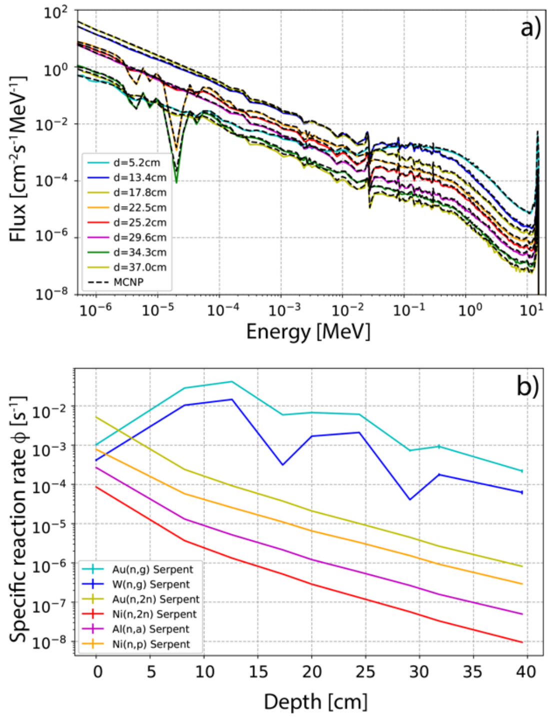

Figure 4: Serpent simulation results for the W-shielding block. (a) The differential neutron spectrum at different detector locations with MCNP results given in dashed black lines. (b) RRs as a function of the distance to the neutron source (b).

In conclusion, the benchmark between Serpent2 and MCNP5 shows a difference within 10% for both experiments. Among the future steps to reduce this discrepancy are the use of variance reduction methods and employing the Puhti supercomputer at CSC to carry out larger simulations with better statistics.

Also, experimental data from the WCLL experiment was used to validate the Serpent calculations, showing a C/E ratio of 0.88-0.99 for the In(n,n') RR.

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