CONFERENCE PRE-PRINT

RADIATION SHIELDING ANALYSIS OF IFMIF-DONES TEST CELL AND ADJACENT ROOMS

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Abstract

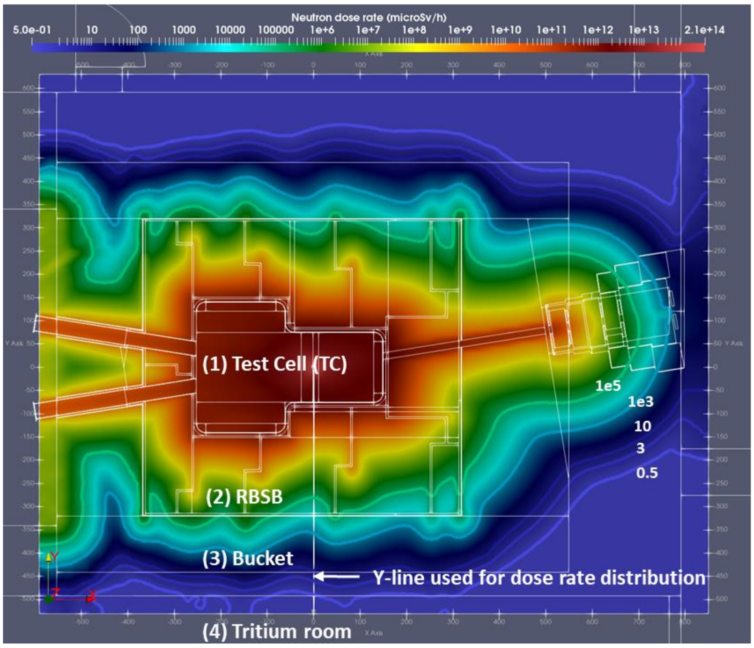
The neutronics calculations of the IFMIF-DONES Test Cell (TC) have been performed during one accelerator operation with deuteron ions (d) beam current of 125 mA impinging on the liquid Li target. The deuteron beam is accelerated up to 40 MeV delivering 5 MW power to the liquid Li jet. Neutronics analyses of the heating in the TC materials revealed the 5 MW heat power of the d-beam delivered by the IFMIF-DONES is released by 97% just in liquid lithium. The integral deuteron heat is 4860 kW released in the Li liquid target which is effectively removed by Li jet flow to the Quench Tank and Li loop. The rest power (~140 kW) is transferred by neutrons and photons outside the Li target, depositing energy to the surrounding components of Test Cell (TC) and further to the IFMIF-DONES building. The most energy is released in TC. The results of the paper indicated that inside TC the integral heating is 141.2 kW, distributed among Target Assembly (17.3 kW), HFTM (16.9 kW), and other seven Test Cell components (107 kW). For the forthcoming IFMIF-DONES users, neutron spectra characteristics have been analyzed in Complementary Experiments Room (CER) at the exit of the open Neutron Beam (NB) shutter. It is shown that fast neutron flux dominates in the neutron spectrum. With an open NB shutter, the fast neutrons could be used directly in irradiation tests on electronics, devices, and materials. For the users of thermal and epithermal fluxes, spectrum tailoring is required by the installation of the neutron energy filters Open NBT&S results in Red (forbidden) radiation zone with the Dose Rate (DR) above 1e5 microSv/h inside CER, by closing the shutter, the DR drops below 1e3 microSv/h, making CER the Yellow (limited regulated) radiation zone.

1. INTRODUCTION

Materials qualification is mandatory for the development of thermonuclear fusion facilities. Particular importance presents materials being irradiated with high energy neutrons of D-T plasma of the EU DEMO fusion power plant. For testing neutron-irradiated materials with DEMO-relevant parameters such as neutron damages, helium production, fluxes, fluences, nuclear heating, and temperatures, the International Fusion Materials Irradiation Facility – Demo Oriented NEutron Source, abbreviated as IFMIF-DONES is developing in the EU [1]. DONES will be suitable for testing the DEMO structural (Eurofer-97) and functional materials (beryllium and lithium compositions). The TC is like the heart of the whole body of DONES [2], producing neutrons and photons in the d-Li nuclear reactions for materials irradiation inside the TC modules, and supplying collimated neutrons to the adjacent DONES rooms for conducting a variety of neutron experiments by the DONES users [3]. To guarantee the DONES systems' functional reliability and personnel nuclear safety, conducting rigorous neutronics analyses is requested. Computational neutronics analyses have been performed for the DONES TC using the state-of-the-art CAD-based neutronics modeling, Monte Carlo methodology with variance reduction technique, software codes, interfaces, and the EUROfusion Marconi-Fusion High-Performance Computer. The results allow us to design sufficient shielding of the DONES systems, with an arrangement of the irradiated components for the most effective use of generated neutrons and managing the personnel access in the TC-adjacent rooms.

2. METHODOLOGICAL APPROACH

Due to the geometry complexity of the fusion facilities and the benefits of using the continuous energy representation of nuclear data, the Monte Carlo (MC) method is the most suitable computational method for particle radiation transport in fusion devices. The accuracy of the MC method is limited only by statistics and data uncertainties. The neutronic specificity of IFMIF-DONES is the precise modeling of the physical phenomena when the deuteron beam with a current of 125 mA, accelerated up to 40 MeV, strikes the liquid Li jet and slows down due to electrostatic energy losses and nuclear reactions with the lithium atoms delivering 5 MW of power. On the d-Li stripping nuclear reaction Li(d,nx), the total energy integrated neutron flux of $5{\cdot}10^{14}$ n/cm^2/s is produced with a peak energy of 14.1 MeV. In addition to neutrons, primary and secondary high-energy photons (gammas) are generated by Li(d,xγ) and (n,xγ) nuclear reactions. All these nuclear reactions have been incorporated in the McDeLicious-17 code [4], representing the MCNP6 code [5] modification. The McDeLicious source module explicitly defines the d-Li source of IFMIF-DONES by setting the emission parameters of neutrons and photons, whose transport is then calculated by the MCNP standard procedures. The applied neutronics methodology follows the integrated 3D CAD-based neutronics modeling approaches based on different levels of coupling interfaces with CAD modeling, activation, and thermohydraulic codes as summarized in [6]. The geometric description of DONES systems was converted by the McCad [7] and SuperMC [8] codes from the CAD format to the MCNP model. The accuracy of the MC calculations was improved by the On-The-Fly Global Variance Reduction (OTF-GVR) developed at KIT [9]. Using McDeLicious with OTF-GVR, the dose rate map shown in Fig. 1 (left) has been calculated behind the 6-m thick concrete shielding wall in the IFMIF-DONES model. The corresponding profile of 15 orders of magnitude dose attenuation along the Y-line distribution is shown in Fig. 1 (right).



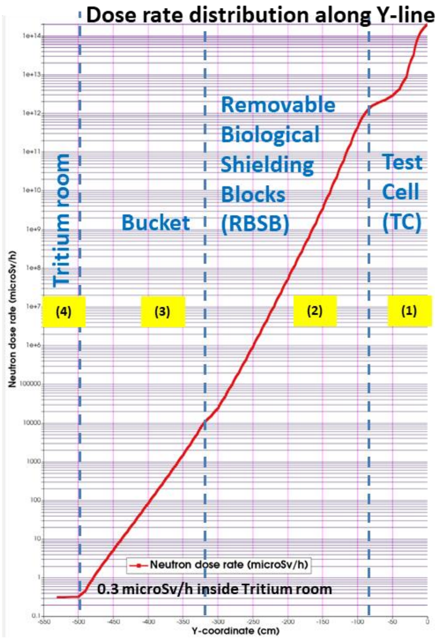


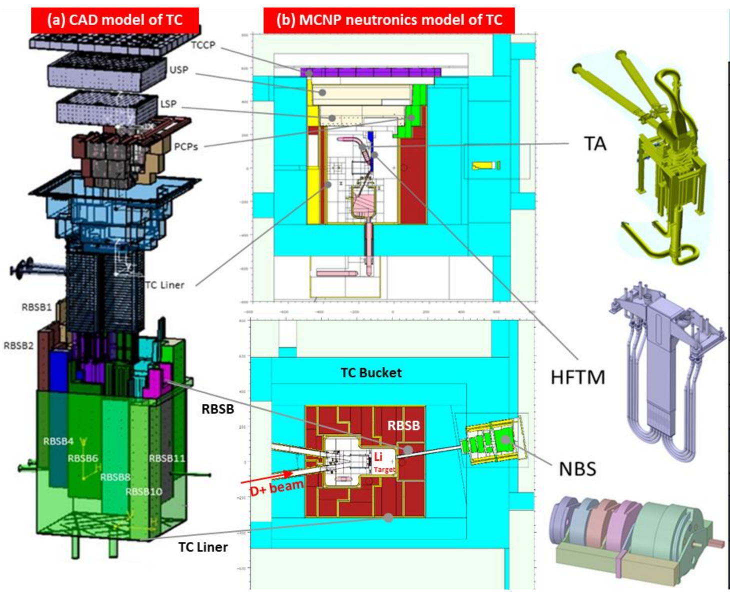
*FIG. 1. (**left**) TC map of biological dose rate (microSv/h) caused by neutrons; (**right**) profile of neutron dose rate (microSv/h) attenuation along the Y-line distribution from TC to Tritium room depicted in the left TC map picture.*

The methodology application to IFMIF-DONES is based on the fundamental code and nuclear data development originated from work [10], where evaluations of the nuclear and atomic reactions with neutrons production with energies up to 55 MeV have been performed, and a Monte Carlo (MC) neutron source model for the Li(*d,xn*) reaction was developed by using the MCNP transport code. Further developments are related to the conversion of geometric data generated by CAD systems into a representation appropriate for the MC transport codes [10] and the realization of activation and shutdown dose rate characterization of the neutron-irradiated materials of fusion facilities [11 - 13].

3. NEUTRONICS ANALYSES OF THE TEST CELL HEATING

The neutronics analyses of the IFMIF-DONES Test Cell (TC) have been performed during one accelerator operation with a deuteron ion (D+) beam current of I=125 mA impinging on the liquid Li target. The deuteron beam is accelerated up to 40 MeV delivering 5 MW power to the liquid Li jet. The CAD model of the IFMIF-DONES TC is shown in Fig. 2(a), and the MCNP model converted from CAD is plotted in Fig. 2(b). The McDeLicious calculations results of the integral heating calculations with neutron photon heat depositions are presented in tabulated format in Fig. 2(c). It follows from the results of Fig. 2(c) that, unlike extremely high heat released in the Li jet target locally by deuteron ions (D+), neutrons and photons transfer much lower energy and significantly longer distances from the Li target. Neutrons and photons deposit heat of 107 kW to the surrounding Li-target TC seven components. Additionally, according to [10] the heat in the Target Assembly (TA) structural parts is 17.3 kW, and the nuclear heating of the High Flux Test Module (HFTM) is 16.9 kW. Summing up all the integral heat transported by neutrons and photons to the TC components presented in Fig. 2(c), equaled 141.2 kW, plus the heat of 4858.8 kW released by deuterons in the Li target, the whole released heat output approximates very well the input power of 5 MW delivered by the D+ beam in DONES. The heating power balance between the delivered and released heating power by three particles (D+, neutrons, and photons) is summarized in Fig. 2(c). As the design of the TC components is developing [2], the presented heating balance is approximate, and the results are updating along with the TC design changes.

The Li jet with a velocity of 15 m/s effectively cools the target structure by removing the deuterons-released heat in lithium to the large lithium volume inside the TC Quench Tank. Unlike locally released deuteron heat of 4.8 MW at the beam footprint area of 5 x 20 cm^2 of the Li jet target, generated neutrons and photons transfer much lower energy and significantly longer distances from the Li target. Neutron and photon heating distributed at the TC distances range are presented in Figure 1. Neutrons and photons deposit heat of 107 kW to the surrounding Li-target TC seven components, where heating calculations have been updated in this work. Additionally, according to paper [13] the total heating from all the DONES Target Assembly (TA) structural parts including all tubes and the Quench Tank vessel is 17.3 kW, and the nuclear heating of the High Flux Test Module (HFTM) is 16.9 kW. Summing up all the integral heat transported by neutrons and photons to the TC components presented in Figure 1, equaled 141.2 kW, plus the heat of 4.8 MW released by deuterons in the Li target, the whole heat sum of 4.9412 MW approximates the power of 5 MW delivered by the D+ beam in DONES. In that power balance, the resting power of 58.8 kW is attributed to the endothermic reactions and heating dissipated by neutrons and photons to the circulated liquid Li and other distant components of TC (such as Test Cell Cover Plate - TCCP) and other parts of DONES main building. The heating power balance between the delivered and released heating power by three particles (D+, neutrons, and photons) is summarized in Table 1. As the design of the TC components is developing [2], the presented heating balance is approximate, and the results are updating along with the TC design changes.



(c) Power balance for the D+ beam energy released in the Test Cell (TC) components

Type of heat power	Heat, kW
Input heat power of D+ beam delivered by the IFMIF-DONES one accelerator beam current of I=125 mA	5000
D+ heat released in Li Target	**4858.8**
Neutron + Photon heat released in the TC components (numbered and displayed in the next slide):	
1) TC liner	**15.2**
2) Removable Biological Shielding Blocks (RBSB)	**77.3**
3) TC Bucket liner	**0.2**
4) TC Bucket	**1.6**
5) Piping and Cabling Plugs (PCP)	**2.6**
6) Lower Shielding Plug (LSP)	**9.9**
7) Upper Shielding Plug (USP)	**0.01**
The sum of 7 TC components:	**107**
Target Assembly (TA) structural parts	**17.3**
High Flux Test Module (HFTM)	**16.9**
Integral neutron and photon heat in all considered TC components	**~141.2**
Output: total integral heat released by D+, neutrons, and photons:	**4858.8+141.2 = 5000**

*FIG. 2. (**a**) CAD model exploded view of IFMIF-DONES Test Cell (TC); (**b**) TC neutronics model developed by conversion from CAD to MCNP; (**c**) calculation results of heat power released in the TC components.*

Recently, thermal-hydraulic and structural Computational Fluid Dynamics (CFD) simulations of TA have been performed in [14] using an updated two-dimensional matrix methodological approach of setting the deuteron beam profile called “IFMIF/EVEDA beam profile” as the source for transport of four particles: neutrons, photons, deuterons, and protons with the MCNP6.2 code calculations. The CFD simulations have been performed using commercial CFD code Simcenter Star-CCM+. The deuteron radiation source has been defined as a two-dimensional horizontal-vertical matrix processed from the deuteron. Deuterons lose their energy in Li by interactions with Li electron clouds and nuclei – all the processes have been taken into account in the energy deposition calculations with the MCNP6.2 code TMESH card. Deuteron beam stops in the lithium jet delivering a total power of 5 MW on a volume of 20×5×2.5 cm^3, with a d-Li footprint area of 20×5 cm^2, with the maximum heat deposition at the Bragg peak located at 1.86 cm deep in lithium. This peak is an absolute maximum of heat and neutron source in DONES. Considering that the liquid lithium jet thickness is 2.5 cm, a very short distance of 0.64 cm separates the extreme heat peak in the lithium jet from the steel material of the target back plate and HFTM behind it, as shown in Fig. 1. To calculate the lithium jet temperature, the D+ heat density distribution has been set up as a volumetric heat source inside the 2.5 cm Li jet for thermal-hydraulic analyses with the StarCCM+ code, as illustrated in Fig. 2. It was designed to have such a short distance from the peak to HFTM to irradiate its specimen structural materials with the highest neutron fluxes and the hardest energy spectrum. That imposed severe requirements on controlling the liquid Li thickness and waves on the Li surface utilizing the lithium jet diagnostics installed inside the DONES Target Interface Room (TIR) adjacent to TC. The DONES extreme heating loads have been investigated in work [15], with neutronics and thermal-hydraulic analyses of a more concentrated deuteron beam, which leaves a halved-size footprint of 10x5 cm^2 at the Li target. A more focused deuteron beam with a 10x5 cm^2 Li footprint caused a factor of 2 increase in heat deposition in Li, with a peak of 211 kW/cc vs. 110 kW/cc in the case of a 20x5 cm^2 footprint. Taking into account that the initial temperature of Li entering the target is 300 °C, for a 20x5 cm^2 footprint the lithium temperature increases to 428.8 °C by 128.8 °C, while for 10x5 cm^2 it rises to 552.2 °C by 252.2 °C. That means a more concentrated beam of 10x5 cm^2 resulted in a similar ratio of temperature heating up as the heat deposition, delta temperature increased due to the halved beam by the same factor of two. An extremely high heat load of 110 kW/cc or 211 kW/cc on a speedy Li-jet flowing at 15 m/s does not have time to heat the TA surrounding components. Results obtained from the thermal analysis [10] have shown that the maximum temperature within the TA structure does not exceed the maximum EUROFER allowable temperature of 550 °C. The maximum temperature of 389 °C is predicted to reach within the vacuum chamber and target structure. To perform the TA thermal analysis [10], the nuclear heating densities (W/cc) have been set as heat sources in the mesh superimposed over the TA and surrounded components such as HFTM and Quench Tank. The mesh-tally nuclear heating densities have been calculated for the following four separate 100% materials: EUROFER, steel, lithium, and thermal isolation. Such separation of the materials for nuclear heating calculation was necessary to prevent material mixing in the elements of the mesh. The mesh grid itself is converted from the rectangular mesh grid of MCNP to the tetrahedral mesh grid of STAR-CCM+. Therefore, the STAR-CCM+ code converts MCNP data from rectangular to tetrahedral mesh and approximates the data points from the mesh nodes of MCNP to STAR-CCM+.

4. NEUTRON STREAMING THROUGH NEUTRON BEAM TUBE AND SHUTTER

The collimated neutrons from the Test Cell (TC) will be supplied to Complementary Experiments Room (CER) for the IFMIF-DONES users to conduct variety neutronics experiments. This work includes the results of the neutronics modelling and analyses of the neutron tube and the Neutron Beam Tube and Shutter (NBT&S) with the two design configurations of the NB shutter: (1) Open NB shutter; (2) Closed NB shutter. The neutron and photon radiation transport has been performed by the McDeLicious-17 code package – MCNP modification, which simulates the deuteron-lithium (d-Li) nuclear reactions. The OTF variance reduction method [9] has been applied. The neutron cross-sections library FENDL-3.1d has been used. MCNP geometry was converted with the SuperMC code. The neutronics results were normalized to a 125 mA deuteron beam of 40 MeV deuterons impinging the lithium target. Neutrons born in TC were collimated by the neutron tube and NB shutter to enter CER by passing through the 6.9-m thickness of the bucket and TC wall, both made of ordinary concrete. The MCNP model is presented in Fig. 3. The results are provided in Figs. 4 – 6.

At the exit of NBT&S to CER, the total neutron flux equals 2.15e+10 n/cm2/s, and 88% of that value (1.90e+10 n/cm2/s) is attributed to a fast flux with energy above 0.5 MeV. To make it thermal, moderator blocks made of Polyethylene (PE) are set along the beam line inside the CER.

Correspondence to the radiation zoning of the rooms around TC has been checked out. For the open NB shutter design, the neutron Dose Rate (DR) exceeds 1e5 microSv/h in CER – it is a Red (forbidden) radiation zone., as shown in Fig. [5]. By closing the NB shutter, DR in CER drops down to 1e3 microSv/h shown in Fig. 6, allowing set CER to the Yellow (limited regulated) radiation zone: (10<DR<1e3) microSv/h.

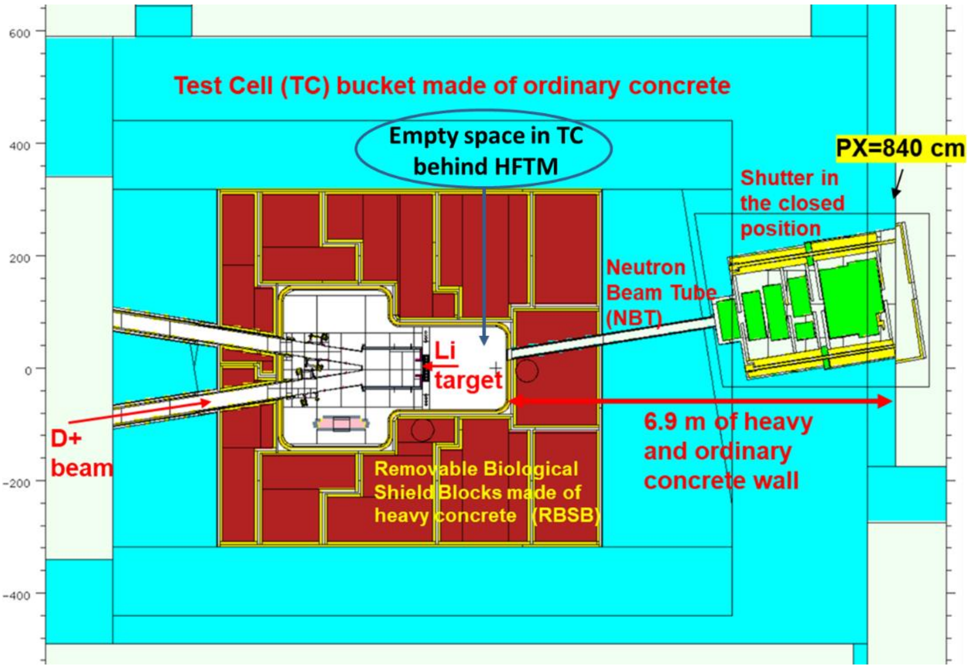


FIG. 3. MCNP model of the updated NBT&S design with increased by 50 cm bucket wall thickness (RBSB+ bucket =6.9 m) separated by surface PX=840 cm entrance to the Complementary Experiments Room (CER).

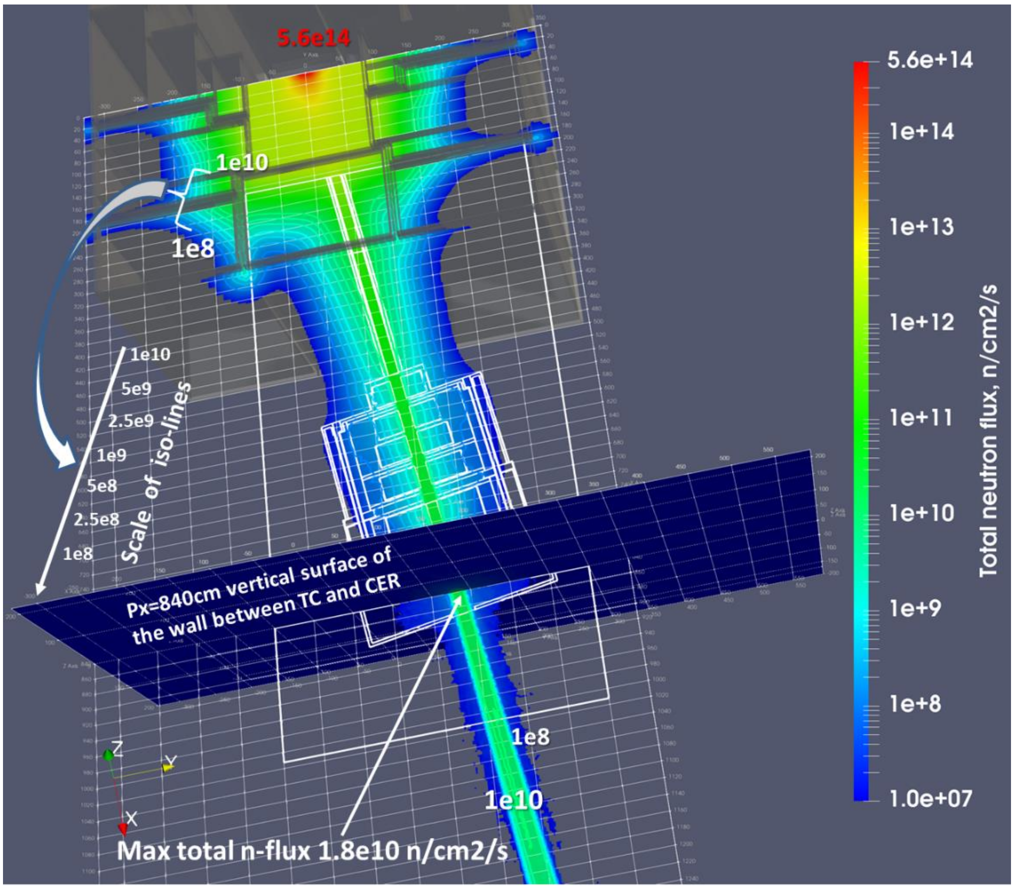


FIG. 4. Total neutron flux map for the open NB shutter position, with attenuation from 5.6e14 n/cm^2/s at the Li target to 1.8e10 n/cm^2/s at the entrance to CER.

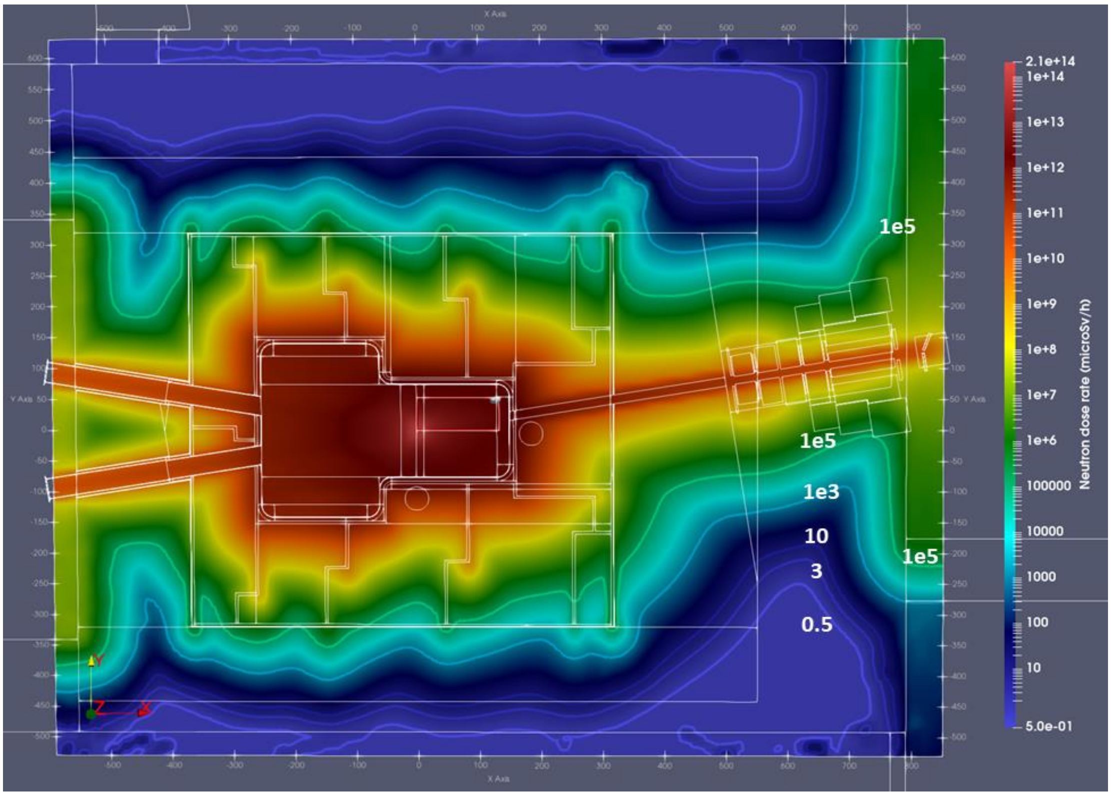


FIG. 5. Neutron dose rate maps for NB shutter open position.

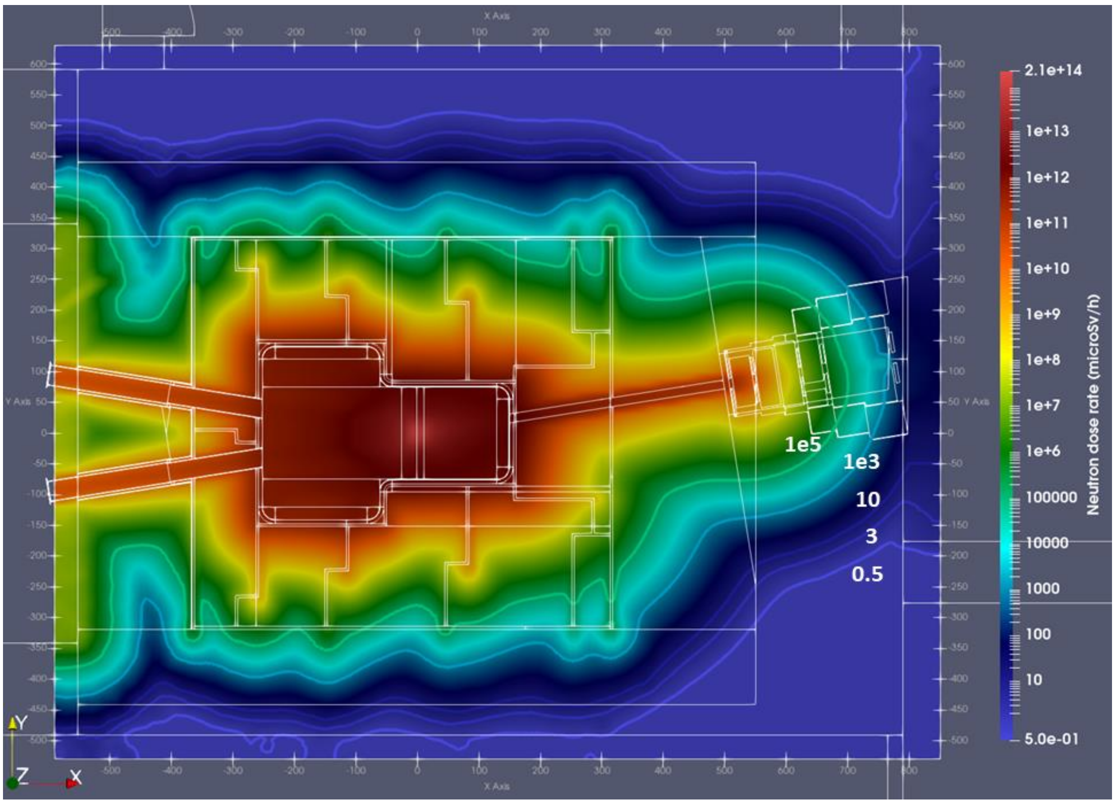


FIG. 6. Neutron dose rate maps for NB shutter closed position.

5. CONCLUSIONS

The IFMIF-DONES facility represents the unique neutron source to irradiate fusion-relevant structural and functional materials with neutrons of high energy and fluences, comparable with the radiation loads to be reached at the EU DEMO fusion reactor. The applied Monte Carlo CAD-based integrated neutronics methodology (CAD-to-MCNP models conversion, McDeLicious-17 transport code with OTF-GVR variance reduction) reproduces the d-Li neutron & photon source at the Li target, allowing to perform effective deep-penetration radiation transport calculations in heterogeneous IFMIF-DONES geometry with a strong radiation attenuation across ~6 m concrete shield. The biological dose rate from neutrons can attenuate by 15 orders of magnitude: from $2 \cdot 10^{14}$ microSv/h in TC to 0.3 microSv/h inside the Tritium room shown in Fig. 1. The neutron plus photon energy deposition is attenuated by 11 orders of magnitude: the heat of 110 kW/cc at the Bragg peak in the d-Li footprint is attenuated to ~ 1 microW/cc in steel inside the Target Interface Room (TIR). The integral heating calculations in IFMIF-DONES TC components reveal that d-energy deposition in liquid Li at a thin Bragg peak with a d-beam footprint area contributes 97% of total heating in all the TC components presented in Fig. 2. The 5 MW heat power of the d-beam delivered by the IFMIF-DONES is released by 97% just in liquid lithium. Such high heat necessitates maintaining a 15 m/s velocity of the Li-jet for effective cooling of the Li-target structure by removing the deuterons-released heat to the big volume inside the TC Quench Tank. For the forthcoming IFMIF-DONES users, neutron spectra characteristics have been analyzed in Complementary Experiments Room (CER) at the exit of the open Neutron Beam (NB) shutter. High total neutron flux ($1.8 \cdot 10^{10}$ n/cm^2/s) can be achieved in CER, with the majority of fast neutrons (~88%), part of epithermal ($1.8 \cdot 10^9$ n/cm^2/s), and the lesser flux of thermal neutrons ($7 \cdot 10^8$ n/cm^2/s). With an open NB shutter, the fast neutrons could be used directly in irradiation tests on electronics, devices, and materials. For the users of thermal and epithermal fluxes, spectrum tailoring is required by the installation of the neutron energy filters inside the channels of the shutter and neutron energy moderators (e.g. Polyethylene).

ACKNOWLEDGEMENTS

This work has been carried out within the framework of the EUROfusion Consortium, funded by the European Union via the Euratom Research and Training Programme (Grant Agreement No 101052200 — EUROfusion). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Commission. Neither the European Union nor the European Commission can be held responsible for them.

This scientific paper has been published as part of the international project co-financed by the Polish Ministry of Science and Higher Education within the programme called 'PMW' for 2024.

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