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CHALLENGES AND ACHIEVEMENTS IN IFMIF-DONES NEUTRONICS ACTIVITIES

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Abstract

The neutronics activities conducted for the IFMIF-DONES facility address the unique challenges of a first-of-a-kind facility, in which deuteron-induced neutron production and complex system integration are presented. High-fidelity CAD-based geometries have been developed for the accelerator, test cell, and lithium loop, enabling detailed dose assessments, shielding optimization, and safety analyses. Recent progress includes: global neutronics modelling, radiation source term assessments, and radiation dose map computations. In addition, dedicated workflows have been established for water and lithium activation, which consist of radioisotope products, mass transfer, and decay γ transport and radiation dose assessments. Radiation protection during beam-on and beam-off, including maintenance planning, component transport, and worker exposure, has been tackled with advanced tools, while skyshine and public dose assessments have been assessed based on tailored nuclear data and source modelling supported by an advanced variance reduction approach. A strong methodological foundation has been laid, thus allowing DONES neutronics to meet the requirements of design, licensing, and operation.

1. INTRODUCTION

IFMIF-DONES (International Fusion Material Irradiation Facility - DEmo Oriented Neutron Source) [1] is a one-of-a-kind material irradiation and testing facility providing irradiation data for the qualification of structural material for the construction of DEMO fusion powerplant. It is based on a 125 mA, 40 MeV deuteron accelerator providing a deuteron beam in continuous wave mode, and generates fusion-like neutrons through Li(d,xn) reactions. In the framework of EUROfusion work package Early Neutron Source, the design, analysis, prototyping and validation activities have being conducted by the contribution of in total 16 more research institutions, and now in the phase of design responsibility transfer in which the design and construction activities is being carried out by the DONES Joint Project team, located in Granada, Spain, taking over the responsibility for the activities.

Neutrons which are provided from the facility, are on one hand an essential tool for materials testing, and on the other hand, hazardous source terms or radiation protection point of view. The stripping reactions Li(d, xn) will generate intense neutrons with energies up to 55 MeV and peak fluxes of 10^{15} n/cm2/s[1], and will be used for continuous material irradiation that will interact with the material samples located in the test modules immediately behind the lithium target. The neutron spectrum from the target has a broad peak around 14 MeV, which resembles the fusion reactor irradiation environment, with similar primary knock-on atom (PKA) spectra and gas production being observed in the fusion reactor first wall. However, the neutrons and gammas produced from the accelerator and the target impose strong nuclear heat power on the vicinity structures that need active cooling with water and helium gas. The estimations of sources, and radiation protection of prompt neutrons and gammas, as well as the decay gammas from the activated structures, lithium, water, and air, are another main challenge to be addressed in DONES nuclear analyses.

This work aims to discuss and summarize the important source terms that are produced from the nuclear systems inside the facility, the underlying challenges, and the achievements in tackling these challenges which are discussed in [2]. It is important that studies through those systems, evaluate the facility irradiation performance, mitigating the radiation issues during beam-on and beam-off, and thus enable the assessment of radiation safety and provide key data for the licensing.

2. SOURCE TERMS OF THE IFMIF-DONES FACILITY

IFMIF-DONES facility consists of several major systems – Accelerator systems (AS), Test systems (TS), Lithium systems (LS), Site, Building and Plant Systems (BPS), and Central Instrumentation and Control system (CICS), as shown in FIG. 1 , and several plant-level transversal areas such as Remote Handling, Logistics and Maintenance, Neutronics, Safety, RAMI, etc. We focus here on the major systems and analyse the source terms that have a strong impact on the facility irradiation performance and radiation safety.

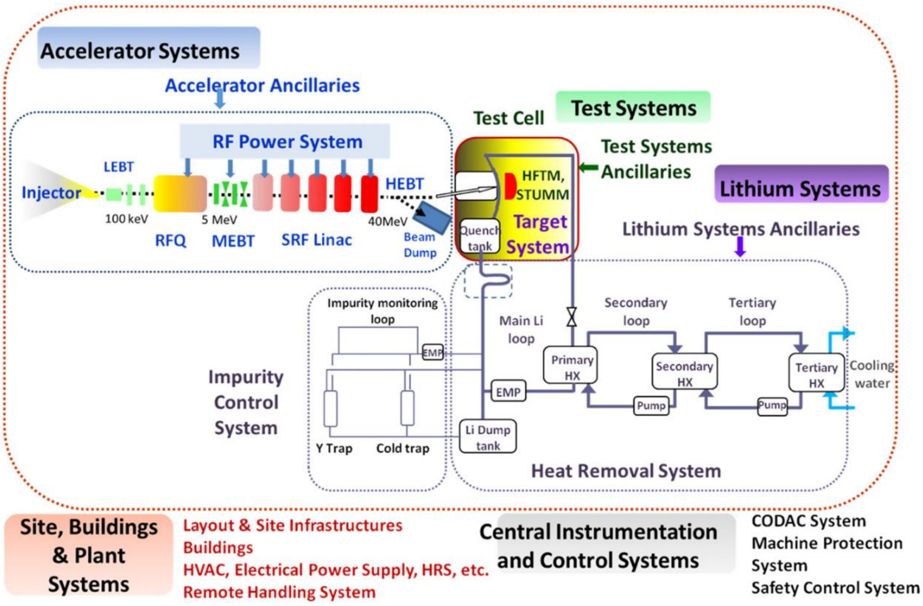

FIG. 1. IFMIF-DONES Schematic Plant Configuration [1]

The DONES accelerator systems (AS) [3] deliver a 125 mA, 40 MeV deuteron beam using a 175 MHz continuous-wave (CW) linear accelerator. The injector provides an ion source at 100 keV energy, coupled with a low-energy transport (LEBT) line. The Phase 1 commissioning will consist of the Injector system with a lower power beam dump (LPBD). During this phase, the Injector system will deliver a beam of up to 140 mA of 100 keV deuterons to the LPBD, in a 100% duty cycle (DC). The important source term is that the 100 keV deuterons can induce nuclear interactions with the deuterium previously implanted in the stopping material. This interaction will generate a 2.5 MeV neutron source due to the D-D fusion reaction.

The beam is then further bunched and accelerated by the radio frequency quadrupole (RFQ) up to 5 MeV, transported through the Medium Energy Beam Transport (MEBT) line. In the RFQ, beam losses as a function of beam energy have been taken, which are overall above 1 W/m, particularly in the RFQ upstream. The CuCrZr scrapers used for collimating the beam receive a 0.6 kW beam deposition at 5 MeV in two MEBT copper scrapers. Deuteron energy reaches the threshold energy, and interacts with the beam pipe, scraper, and produces secondary neutrons and gammas. Phase 2 commissioning of the RFQ, MEBT, and high-power beam dump (HPBD) is planned to operate the machine with a 20% duty cycle (DC) at a beam energy of 5 MeV for a maximum integrated beam time of two months; thus, a significant amount of neutrons will be produced from the HPBD in this phase.

The beam was accelerated by the Superconducting Radio Frequency (SRF) linear accelerator to the final energy of 40 MeV. In the High Energy Beam Transport (HEBT) line, the beam during the commissioning phase 3 will be dumped to the HPBD, and during normal operation, it will be shaped to a quasi-rectangular beam footprint by magnets and scrapers, and transported to the Li target. For the SRF and HEBT, 1 W/m beam loss assumptions were taken for the deuteron source contribution. The HEBT scrapers receive 2.4 kW beam deposition in the first HEBT scrapers at 40 MeV, and 3.2 kW in the second scraper. Phase 3 commissioning on the superconducting radio frequency (SRF) operates the accelerator at 1% DC at 40 MeV, with a secondary line guiding the beam to the HPBD, depositing a total of 50 kW beam power. The secondary neutrons produced mainly from the d-Cu interaction are much more energetic due to the 40 MeV beam.

The beam reaches the target systems and test systems and produces intensive neutron fields for the irradiation in the area of the test cell, and deposits a total of 5 MW of power. The test cell (TC), which houses the key components of the Target Assembly (TA) and the High Flux Test Module (HFTM), consists of massive shielding structures. The d-Li reaction produces neutrons through Li(d, n) stripping reactions, with a total yield of ~6.8×10^{16} n/s estimated from McDeLicious [4] with FZK-2005 data [5], and a broad peak around 14 MeV emitted at the forward angle. Neutrons with energy around 1 MeV were observed, which are produced isotropically from the evaporation process. The neutron flux is in the range of 1-5×10^{14} n/cm2/s and a photon flux of 5×10^{13} - 2×10^{14} p/cm2/s in the centre our columns of the HFTM capsules, where the material samples are loaded.

The energetic deuterons and neutrons will result in strong material activation. Major source terms for the Lithium System (LS) are the d-Li induced Be-7 and Tritium production [6]. Be-7 (half-life 53.2 d) is a gamma emitter produced from Li-6(d,n)Be-7 and Li-7(d,2n)Be-7. It emits 477 keV gammas with a 10.4% intensity. The production rate of 0.75 g/fpy (9.7×10^{15} Bq/fpy) has been estimated in [58]. It reaches an equilibrium inventory of 0.15 g (2.0×10^{15} Bq) after 1 fpy of DONES operation. Another important source term is Tritium (H-3), which is estimated to be 3.78 g/fpy (1.35×10^{15} Bq/fpy) in production rate. Also, for the activated erosion and corrosion products (ACPs), they are estimated from a coupled activation and mass transfer simulation on the primary loop, and the obtained value is that the dominant isotopes are Mn-54, Co-56, Co-58, and Co-60, which contribute to an important part of the energetic gammas from the Li.

Other radiation sources are the activated structures from the accelerator system and test systems, where the deuterons and neutrons contribute to the material activation near the beam and inside the test area. In the AS, the MEBT and HEBT scraper made of CuCrZr alloy, the copper cone of the HPBD, the beam facing materials, target and test modules inside the test cell, and the inner structures inside the test cell, such as steel liner, concrete, piping etc, are highly activated materials of concern. Regarding the cooling water used for cooling the accelerator, especially the HEBT scraper and the HBPD cooling water, is activated by secondary neutrons. Water activation results in a radioisotope dominated by N-16 (7.1 s) from the O-16(n, p)N-16 reaction, as well as O-15 (122 s) from the O-16(n,2n)O-15 reaction at the threshold energy of 16 MeV. Similarly, the gas inside the beamline, the atmospheric gas in the AS room, i.e., air in the AS vault and Argon in the Target Interface Room (TIR), and also the rest air inside the gaps of TC shielding blocks, are activated by the neutrons. The activation results in a short cooling time the radionuclide Ar-41(1.8h), which is an energetic gamma emitter, and in long half-life radionuclides as Ar-37 (35 d), H-3 (12.3 y), and C-14 (5700 y), which can accumulate along time if no active circulation ocurrs.

3. CHALLENGES AND ACHIEVEMENTS OF DONES NEUTRONICS

All these source terms are important to be fully studied, confirmed, and protected against, and to mitigate the impact on the radiation safety during beam operation and facility maintenance. They impose several challenges on IFMIF-DONES neutronics: the complexity of simulation geometry, estimation of the source and modeling of the source; simulation of the charge particle induced secondary neutron and gamma emissions, activations, and heat removal; comprehensive radiation dose maps based on accelerated shielding analysis, correctly model and simulate the distributed source, e.g. from the water activation in complex piping, gamma source from lithium in several lithium system. Also, several important topics such as radioactive waste transport, dose to the public via skyshine, etc. are being tackled with the help of advanced simulation methodologies.

3.1. Integrated geometry modelling

Since IFMIF-DONES is a highly complex nuclear facility, neutronics simulations require both localized analyses (e.g., shielding improvements) with dedicated and integrated models covering the entire system to compute global dose maps and account for all source contributions. For a long period, the accelerator system was represented with oversimplified geometries and conservative beam loss assumptions, leading to large uncertainties.

To support design optimization and safety assessments, the accelerator models have been fully rebuilt since 2020, starting from the injector, RFQ, and MEBT, to provide detailed input for commissioning studies. Engineering CAD models were simplified for neutronics use, while material definitions were aligned with design documents to ensure consistency. The SRF Linac was also remodelled, adopting the GEOUNED [7] approach to directly convert CAD into MCNP [8] geometry. With recent progress on the HEBT beam line, including collimators, isolation valves, and the high-power beam dump, a complete high-fidelity accelerator model is now established.

The test cell geometry was developed using a modular approach, with the target assembly, test modules, and shielding blocks organized in nested structures. This enables updates of individual components without rebuilding the entire geometry and ensures clear boundaries with building and accelerator systems. Based on this, a global model (FIG. 2) integrating accelerator system, test system, and lithium systems with the main building has been created—the first DONES neutronics model suitable for plant-level studies such as skyshine, waste management, maintenance dose assessments, and public exposure analyses.

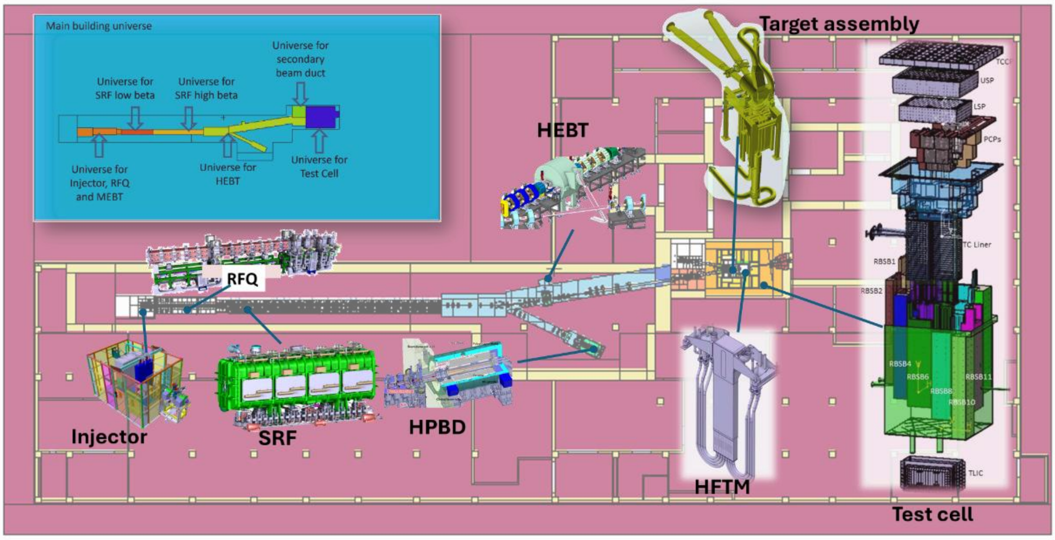

FIG. 2. DONES global model with the modular structure for integrating components from several systems.

3.2. Comprehensive source modelling for accelerator systems

As discussed in Chapter 2, DONES radiation sources are both complex—requiring simulations of deuterons, neutrons, and gammas—and extensive, as all aspects such as beam-on flux, heating, activation, shutdown dose, and waste management must be considered. Traditionally, a multi-step approach was used: first modelling deuteron transport and neutron production, then neutron transport, with deuteron- and neutron-induced activations calculated separately and summed for shutdown dose. Back-streaming neutrons from the test cell further adds complexities for the analyses, making full beam-on/off dose maps difficult to be produced, especially for the accelerator system.

Recent tool developments have significantly streamlined this process. The srcUNED-Ac [9] MCNP subroutine now provides neutron source modelling from deuteron interactions for key accelerator materials, providing double-differential neutron productions across the entire accelerator, with relatively simple input parameters (e.g., position, energy, power, beam losses, materials). For activation studies, the D1SUNED [10] code has been upgraded to the MCUNED-Plus[11], which implements a direct one-step (D1S) method of shutdown dose calculations that accounts for >99% of relevant pathways induced by both deuteron and neutron activation. This avoids the multi-step calculation of flux, activation, and decay gamma transport that is required by the more demanding Rigorous-2-step (R2S) method, while maintaining good accuracy. Additional tools such as MCR2S [12] and N1S [13], coupled with FISPACT [14], are also being validated for DONES, showing comparable accuracy and efficiency. Typical dose maps for the accelerator system are shown in FIG. 3, in which the source of beam deposition, beam losses, test cell back-streaming, and material activations are fully simulated upon the high-fidelity geometries.

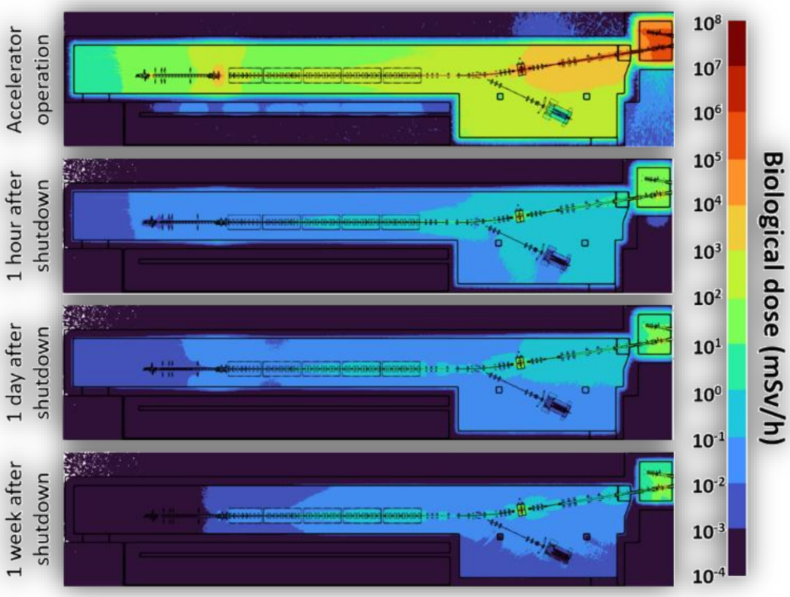

FIG. 3. The beam-on and beam-off radiation dose in the accelerator area.

3.3. Dose maps and shielding analysis

Dose map calculations, based on geometry modelling and source modelling, are require data for design optimization, including maintenance, diagnostic lifetime assessment, and radiation protection. The main challenges firstly those challenges from geometry and source modelling: frequent updates to reflect design changes, accurate treatment of source hotspot and streaming, and secondly the need for advanced variance reduction to achieve high-quality results for massive shielding with penetrations. In general, shielding calculations relied on manual flux and weight-window iterations (e.g., MAGIC method [15]), which were laborious since each source often required separate transport runs. Or tools such as ADVANTG [16], which offers effective variance reduction using weight window mesh (WWM) that are optimal for local statistics improvement and relatively simple source descriptions, however, their application to test cell simulations remains limited, mainly due to the anisotropic source distribution for generating high-quality maps of both neutrons and gammas.

To address this, an On-the-fly global variance reduction (OTF-GVR) method [17] was developed, where WWM are generated automatically after flux calculation iteration, and the upper and lower weight window bounds dynamically to mitigate particle over-splitting. Implemented in MCNP, this approach largely accelerated test cell shielding studies, reducing neutron dose errors to within 20% at distances of 4–6 m, while resolving streaming issues through ducts and tubes. The neutron dose maps shown in FIG. 4, which contributed over 90% of the total doses, and the secondary gamma doses, were successfully produced with this method.

For accelerator interfacing, back-streaming neutrons from the target were identified as the dominant source in the Target Interface Room (TIR) and accelerator vault, due to beam duct collimation. To simplify simulations, a surface source was generated at the TIR boundary, capturing test cell neutron contributions without recalculating the test cell source each time. This method has proven effective and is now routinely used.

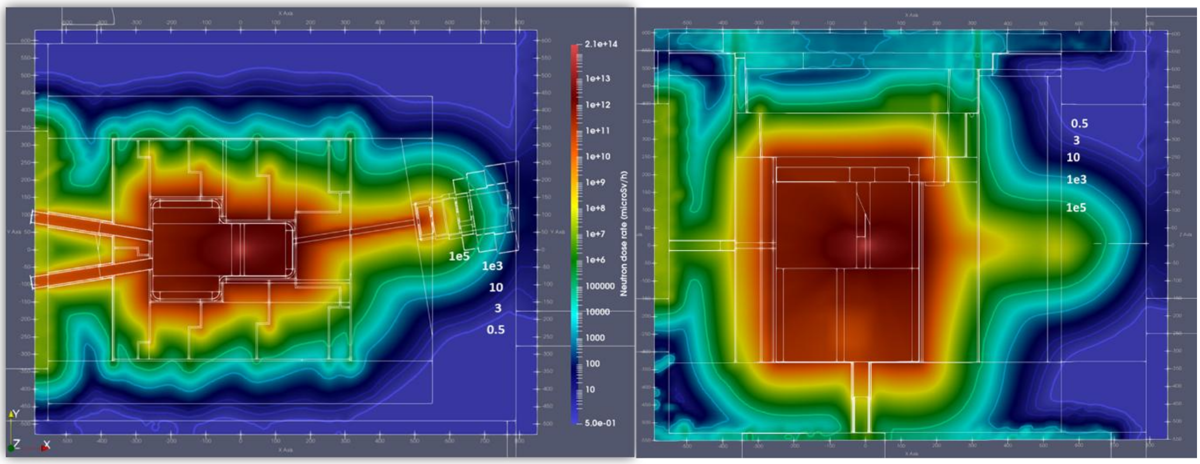

FIG. 4. The beam-on neutron dose rate (μSv/h) over the test cell shielding, horizontal cut-view on the left and vertical cut-view on the right.

3.4. Radiation source from water activation and Li activations

Water is used as a coolant for both the accelerator and test cell shielding. As is known from ITER experiences, water activation is a significant radiation source, since activated water loops can transport radioisotopes into areas housing non-nuclear systems. In DONES, the piping layout is especially complex due to steel liners and removable shielding blocks, while water activation occurs in highly non-uniform radiation fields with strong flux gradients. Different from fusion systems, DONES neutrons extend up to 55 MeV (vs. 14 MeV fusion neutrons). Above 16 MeV, reactions such as O-16(n,2n)O-15 become relevant, which produce O-15 (122 s) that emits 0.5 MeV gamma rays. Thus, cooling loop design strongly affects source term production: long residence times in shielding reduce N-16 but enhance O-15 activities. In addition, branching networks of piping further make the simulation challenging.

Fusion tools such as Actiflow [18] have been successfully applied to DONES. The code reconstructs piping flow paths from CAD, maps the paths to neutron fluxes and thus isotope productions, accounts for branching/recombination, and thus allows separate treatment of liners and individual RBSB before combining results. Studies have been made for the test cell water cooling system (TC-WCS) in FIG. 5, with a scaling analysis showing that a larger flow rate results in higher activities and doses. For activation corrosion products (ACP), which is a typical source term in reactor water coolant, a constant corrosion rate is assumed since corrosion is minor at <60 °C, and isotopes from ACP are concluded not to be dominant contributors to outlet water activity.

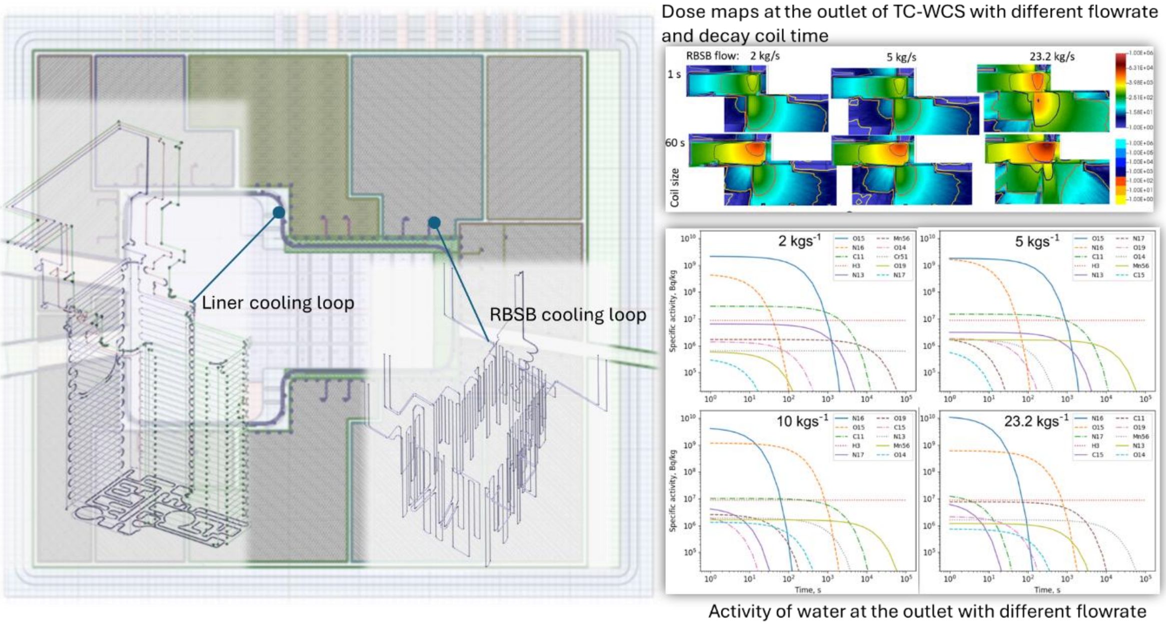

FIG. 5. The TC-WCS on the left, and the scaling analysis of water activity at the outlet under different flowrates and coil decay times.

Lithium activation, on the other hand, is different as deuterons dominate activation through interactions with Li. This produces isotopes such as Be-7 (γ source) and H-3 (β source). Corrosion and erosion products are activated, dissolved, and deposited within the primary lithium loop and the impurity control system (ICS), depending on deuteron and neutron radiation fields, Li-contacted materials (EUROFER or Stainless steel), temperature, and ICS conditions. Be-7 and ACP source analysis was performed by the following approach: first, nuclear analysis of production rates at loop segments inside the TC; then mass transfer modelling with Modelica using solubility data to predict concentrations and deposition; and finally, source-to-geometry mapping with the CAD2CDGS code [19], modelling the decay γ emission in the lithium volume and the radiation doses to the surrounding area. This workflow streamlines the comprehensive lithium loop dose, e.g. shows in the *FIG. 6* ,which includes assessments with the relevant source.

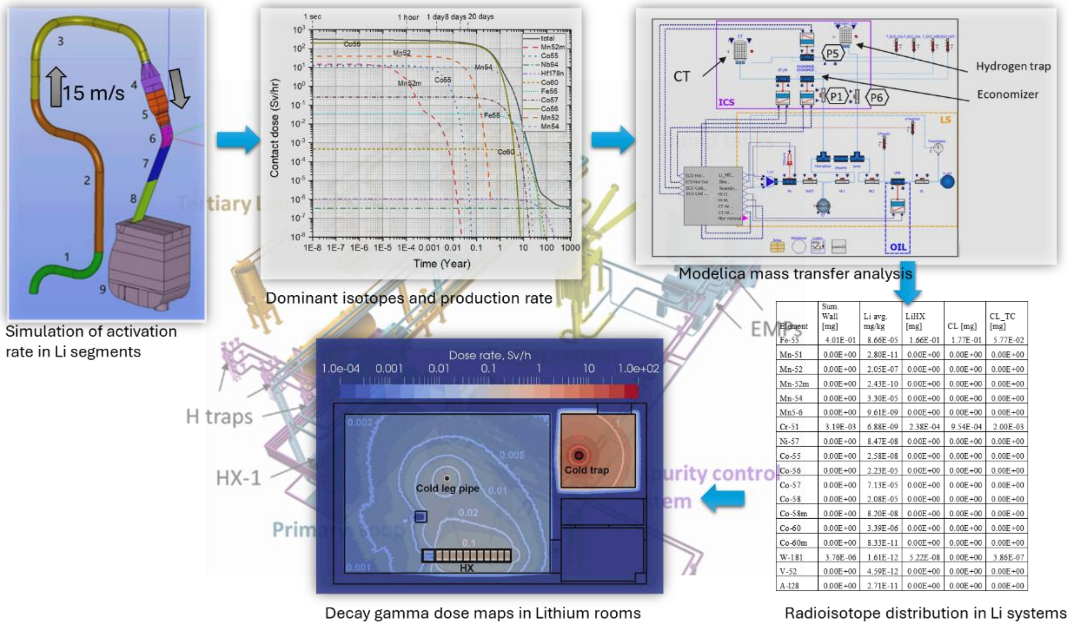

FIG. 6. The workflow of simulating the Li and ACP activation in the Li room.

3.5. Radioactive waste transport, maintenance

For facility operation, maintenance and replacement of highly activated components must be planned in advance to keep worker exposure as low as reasonably achievable. Two critical scenarios are considered: (1) transport of activated components, where radiation sources move along defined routes, and (2) hands-on maintenance scenarios, simulated through virtual roaming with a mannequin to estimate effective dose. Similar approaches, developed for ITER, are now applied to DONES.

The D1SUNED / MCUNED-Plus code has been adopted for cumulative dose assessment during HEBT scraper transport, from the accelerator vault via the shipping bay to the rad-waste cell. Radiation is calculated with time discretization, generating γ surface sources along the planned route and schedule, then accumulating doses step by step to obtain full transport dose maps.

In addition, some maintenance tasks, such as disconnecting/connecting beam pipes on the HEBT scraper and short inspections, still require human intervention despite the fact that remote handling is provided. Planning these operations requires detailed knowledge of radiation distribution and mitigation of radiation exposure via distance, time, and shielding. The virtual reality (VR) tool IVR-UNED [20] supports this by simulating route plans and dwelling times, estimating both effective and organ doses by a virtual mannequin. Interactive controls allow adjusting movement paths to record and optimize maintenance strategies.

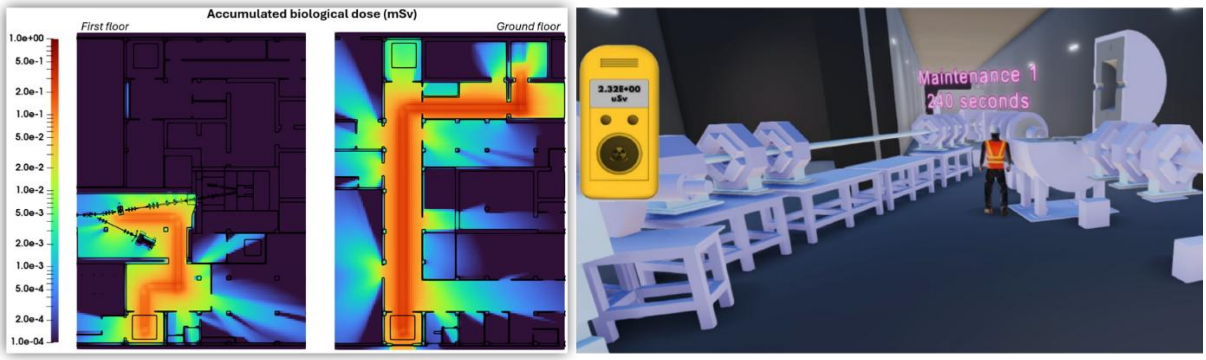

FIG. 7. Simulation of transport of activated components on the accumulated dose maps (left) and virtual hands-on maintenance simulation with the VR tool.

3.6. Dose to the public via skyshine and direct exposure.

Skyshine and direct radiation to the public are key aspects of radiological safety assessments, required to demonstrate compliance with the 1 mSv/year public dose limit. The DONES facility, located in the Escúzar industrial park near Granada, Spain, produces intense neutron fluxes from the test area with multiple penetrations that result in radiation streaming, thus raising local radiation levels. Shielding assessment is critical both for on-site personnel and to prevent excess dose beyond the facility boundary.

To address this, analyses were performed with the McDelicious code with weight-window meshes generated by ADVANTG. A tailored multi-group nuclear data library up to 60 MeV was prepared from FENDL-3.2b[21] evaluations for use in ADVANTG. Source particle distributions (volumetric, angular, energy) were obtained with MCNP SDEF format using particle track recording from McDeLicious, then reconstructed as fixed sources for ADVANTG WWM generation. Contribution-on-field calculations were applied to identify the most relevant regions of phase space for ambient dose equivalent at ground level. The results are shown in FIG. 8. This confirmed the need to extend the model vertically to 200 m to fully capture the skyshine effect.

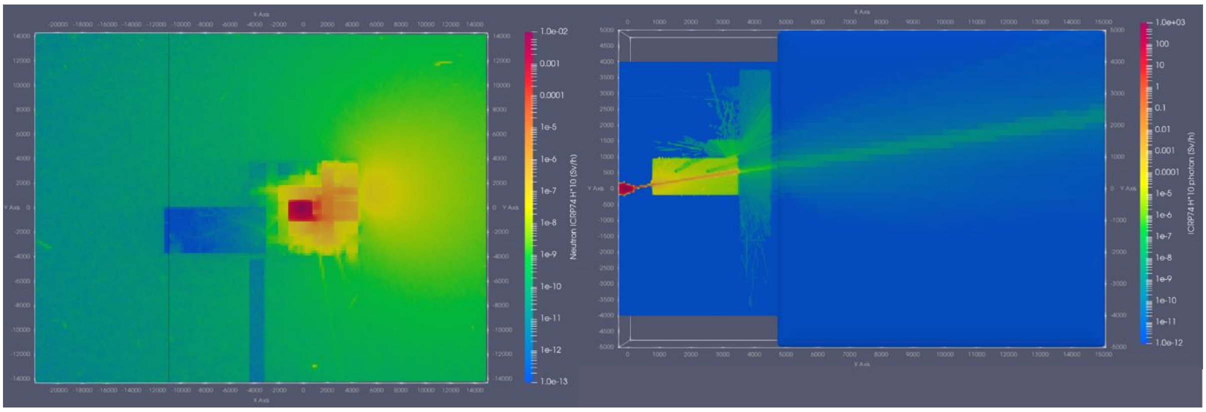

FIG. 8. Neutron doses at the ground level (left) and photon doses at the beam level (right) computed from the sky-shine and direct radiation up to the site boundary.

4. SUMMARY AND DISCUSSION

The work provides a comprehensive understanding of the complex radiation source terms from the accelerator, lithium target, test systems, and ancillary plant systems of the IFMIF-DONES facility. The analyses present the dominant contributors to radiation fields, including deuteron-induced neutron and gamma production in the accelerator and target, activation of lithium and Be-7/H-3 productions, activation of water, air, and structural materials, etc. These sources not only determine irradiation performance for material testing but also represent key challenges for radiation protection, maintenance planning, and waste management.

Significant progress has been achieved in recent years in tackling these challenges. High-fidelity, integrated geometry models now allow the consistent simulation of entire plant domains, enabling realistic dose mapping and shielding optimization. The development of advanced source routines such as srcUNED-Ac and improved activation codes such as MCUNED-Plus has streamlined the simulations of coupled deuteron and neutron activation, reducing the need for multi-step calculations and maintaining accuracy. Similarly, new variance reduction methods, particularly OTF-GVR, have substantially improved the efficiency and reliability of dose map generation in complex geometries of the test cell and accelerator vault.

The modelling of coolant and lithium activation, including mass transfer effects and solubility, has further improved source modelling. Moreover, the implementation of transport and maintenance dose analysis tools provides practical input to radiation protection strategies, helping to optimize component handling and hands-on maintenance. Finally, assessments of skyshine and direct exposure to the public assess the compliance with regulatory limits using the advanced modelling tools.

Significant challenges remain, as IFMIF-DONES is a first-of-a-kind facility with features that differ from conventional fission and fusion facilities. A key issue is deuteron data: since deuterons are the main source, neutron production in various materials across a wide energy range still carries relatively large uncertainties. Current analyses rely heavily on model-based evaluations such as TENDL[22], with limited experimental support. Furthermore, dedicated validation and benchmarking of the tools developed for the nuclear analyses are still lacking, except a few experimental benchmarks designed for nuclear data validation. Integral validation in large accelerator devices, such as the Linear IFMIF Prototype Accelerator (LIPAc), shows that simulation uncertainties remain high due to poor knowledge of beam-loss source terms and the underlying nuclear data gaps. Additionally, less-explored issues—such as concrete activation or studies of new irradiation modules—may also introduce unexpected radiation protection challenges. Nevertheless, a strong foundation has been established in DONES neutronics over the past years, and emerging challenges will continue to be addressed through design, commissioning, licensing, and the operation phase.

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