

A High Fidelity Model of the IFMIF-DONES Accelerator for Nuclear Analysis

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Abstract

IFMIF-DONES will produce neutrons by irradiating liquid lithium with a 125 mA beam of 40 MeV deuterons. These deuterons will be accelerated by a linear accelerator, which is housed in the accelerator vault within the IFMIF-DONES main building. Neutronics modelling is crucial to determine radiation safety and component lifetimes, with accurate geometric models being the cornerstone of the analysis. However, the computationally demanding nature of Monte Carlo methods requires components outside the areas of interest to be simplified to reduce the burden. Therefore, a high-fidelity model of the accelerator has been produced in CAD and converted to CSG in the MCNP format using the conversion tools GEOUNED and TopMC. It consists of over 22,000 bodies, with materials assigned, and is organized into a hierarchical universe structure. This allows parts to be easily interchanged with less detailed versions – or even modified versions – without having to recreate the entire accelerator model. This model is compatible with the neutronics workflows produced for IFMIF-DONES analysis including source definitions and shutdown dose rate routines. To demonstrate the model, a beam-on neutronics analysis of the HEBT section of the accelerator has been conducted and the magnet heating results calculated in MCNP. It was found that the magnet dose rates varied from 0.0085 Gy/hr to 2.19 Gy/hr with the magnets closest to the test cell absorbing the greatest dose.

Keywords: MCNP, Radiation Transport, IFMIF-DONES, Modeling, Linear Accelerator

1. Introduction

For the successful delivery of commercial fusion energy, materials present within reactors are required to endure high neutron fluences. The International Fusion Materials Irradiation Facility – DEMO Oriented Neutron Source (IFMIF-DONES) aims to validate the performance of structural materials by irradiating samples with a high-flux, fusion-like neutron source. These neutrons will be produced via lithium stripping reactions from a 125 mA, 40 MeV deuteron beam impinging on a liquid lithium target [1].

Deuterons are charged particles and thus have a short range in air but may undergo nuclear reactions with structural materials, either by escaping the beam confinement or as a result of beam stoppage (such as at collimators or beam dumps). These reactions present a radiation risk as they lead to material activation and production of secondary radiation such as photons and neutrons, which are significantly more penetrating due to their lack of electric charge. These neutral particles will induce nuclear heating within the accelerator and can cause material activation, which poses a radiation hazard after shutdown.

Radiation transport is modeled through the use of computational tools, such as the Monte Carlo N-Particle (MCNP) transport code[2], which are heavily dependent on both the geometry

and material make-up of the device. As a result, it is important that the modeled structure accurately represents the actual device.

Section 2 describes the workflows involved in producing the model, including source term creation as well as the analysis workflows. Section 3 discusses the IFMIF-DONES model itself, and Section 4 briefly presents some results acquired using the new model.

2. Workflows

2.1. Model Creation & Conversion

During the design phase of IFMIF-DONES development, Computer Aided Design (CAD) models are produced by design engineers. These provide a basis for neutronics model development, however they typically include highly detailed features such as screws and etchings, which increase the complexity of the model without greatly affecting the overall radiation transport properties.

In addition, spline surfaces can also be present, which cannot be represented in the Constructive Solid Geometry (CSG) format used in many neutronics codes including MCNP, a promi-

ment radiation transport code used by the fusion neutronics community.

Therefore, the engineering models have to be ‘de-featured’ by removing complex details, to decrease computational burden, and converting splines to analytical surfaces. Along with simplification, the model must also have materials clearly assigned to it. MCNP assigns materials to cells by prepending the material ID – defined in the input as a mixture of isotopes – and density to the cell definition. To avoid manually assigning materials to each cell, the CAD is modified to separate the bodies by materials via either appending the material number to the body name or by assigning specific colors to them corresponding to a material, depending on the tool used in the conversion.

Once the model is created in CAD, it is converted to CSG by CAD-to-CSG converters, such as GEOUNED [3] and TopMC [4]. Each cell is converted and the material assignments are carried over from the CAD definition to the cell definition in MCNP.

2.2. Source Creation

The radiation source is a critical component of nuclear modelling, requiring careful thought and accurate implementation to ensure no source terms are missed. In the case of IFMIF-DONES, deuterons are the primary particle although neutrons produced in deuteron reactions will also undergo nuclear interactions, and so their production must be modelled as a source.

MCUNED [5] is a tool developed by UNED that allows MCNP6 to use nuclear data libraries to simulate charged particle interactions and is therefore especially useful to model deuteron interactions with matter. However, simulations of charged particle transport are computationally expensive even with MCUNED’s variance reduction implemented to increase the efficiency of secondary particle generation. This inefficiency makes simulations of extended radiation sources such as in IFMIF-DONES challenging. Furthermore, since the deuterons are being accelerated, they have a continuous energy distribution which would require a large number of simulations to model. To overcome this, a module called srcUNED-Ac [6] samples the secondary radiation spectra at two different energy points and exponentially interpolates between them to simulate the effects of deuteron acceleration.

Combining these methods allows for flexible source creation necessary to conduct analysis on individual sections of the accelerator.

2.3. Analysis

Nuclear analysis on IFMIF-DONES can be split up into two categories: beam-on and beam-off. Beam-on simulations are when the accelerator is running and requires transport of deuterons, neutrons and prompt photons to determine on-line dose rates and accumulated dose in components and areas of the building during operations. These are calculated using MCNP with tallies placed over the areas in question to determine important outputs such as component lifetimes and shielding effectiveness.

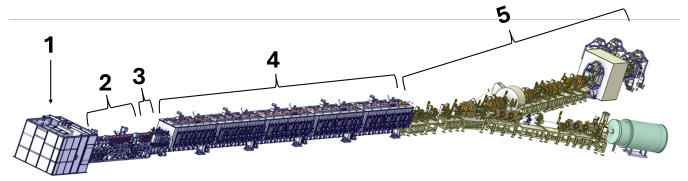


Figure 1: CAD of the neutronics model of the IFMIF-DONES accelerator. Numbers correspond to the following sections of the accelerator; 1: Injector & LEBT, 2: RFQ, 3: MEBT, 4: SRF, 5: HEBT

Beam-off simulations are used to determine the residual radioactivity after the beam is turned off. This requires an initial beam-on simulation to calculate the level of activation, followed by a secondary one to transport the decay photons. Often, these are conducted with the Rigorous-2-Step (R2S) method [7] in which the beam-on simulation is followed by a series of inventory calculations and lastly, another simulation to transport the decay photons after each time step of interest. However, the Novel-1-Step (N1S)[8] and Direct-1-Step (D1S)[9] methods are able to complete the beam-off calculations in a single step by transporting the decay photons in the same transport simulation as the deuterons & neutrons, by utilizing adapted nuclear data libraries.

It has been found that the beam-off dose rates calculated by the R2S, N1S and D1S methods are in good agreement with each other [10].

3. IFMIF-DONES Models & Sources

3.1. IFMIF-DONES Accelerator Model

The accelerator consists of five main sections, shown in Figure 1: the Injector & Low Energy Beam Transport (LEBT), Radio Frequency Quadrupole accelerator (RFQ), Medium Energy Beam Transport (MEBT), Superconducting Radio Frequency modules (SRF) and High Energy Beam Transport (HEBT). These sections have been combined into a model which consists of over 22,000 bodies with the input file containing over 450,000 lines. The large size of the model can make model revisions and geometry conversion computationally challenging, so it has been split up into six separate universes, corresponding to each individual section in Figure 1 (aside from the SRF, which is split into 2 universes).

The advantage of splitting the model up is that each universe acts as a self-contained piece of the geometry, meaning that each section can be individually converted, checked and revised without having to take into account the entire model. Moreover, multiple models of the same section can be easily interchanged, depending on the requirements of the simulation. For instance, the beam shutters are open during beam operations and closed when the beam is off. By placing the shutters in their own universe and having two models (closed and open), they can be swapped out by changing the FILL card in the universe cell definition as opposed to reconverting the entire model. Thus, by ordering components into universes, it significantly simplifies making small edits and maintains high geometric fidelity.

Section	CAD Volume (cm ³)	CSG Volume (cm ³)	Percentage Difference
Injector & LEBT	2.83346E+06	2.83202E+06	0.05%
RFQ	2.45380E+06	2.44519E+06	0.35%
MEBT	4.74105E+05	4.73758E+05	0.07%
SRF: Low Beta	4.80706E+06	4.80794E+06	0.02%
SRF: High Beta	7.56689E+06	7.56989E+06	0.04%
HEBT (Shutters Closed)	2.82468E+07	2.82542E+07	0.03%

Table 1: Table comparing the volumes of the accelerator sections in CAD and CSG. CAD volumes are calculated with SpaceClaim and CSG calculated with an SVC calculation in MCNP.

The MCNP model conversion has been validated by comparing the volumes of each section to the corresponding volumes in CAD. The volumes were calculated in MCNP using the Stochastic Volume Calculation (SVC) method whilst ANSYS SpaceClaim's built-in volume calculator was used to determine the CAD body volumes. As shown in Table 3.1, the volumes are all within 0.5% of each other.

In addition to geometry, the material composition is also an important part of the model as it determines cross-sections for nuclear interactions and, in the case of off-load calculations, may also be used in the calculations of activation inventory (R2S) or decay photon production (D1S/N1S). This creates two challenges: identifying the material that constitutes the body and determining its elemental composition, including impurities. The make-up of a component can be found by consulting design description documents and speaking to engineers involved in the design of the accelerator. Once the material is known, it is assigned a color in the CAD model and a material number added to the body name. While the model is detailed, many simplifications are still made, for example the HEBT magnets are made from coils of copper, insulated by epoxy G10 and cooled with water. Modeling each coil individually would drastically increase the complexity of the model so it was decided to homogenize the magnets and remove the distinction between individual coil windings. To maintain accuracy, the materials were mixed by volumetric ratio to preserve mass and overall composition.

The isotopic material composition is found by checking the manufacturer's documentation (if known) and consulting standard material compendia, such as the Compendium of Material Composition Data for Radiation Transport Modeling[11]. Material impurities are typically given as a range, however, to remain conservative, the maximum values are used in the compositions.

3.2. Integration with the Main Building Model

The main building housing the accelerator needs to sufficiently contain the radiation emitted by the accelerator to keep

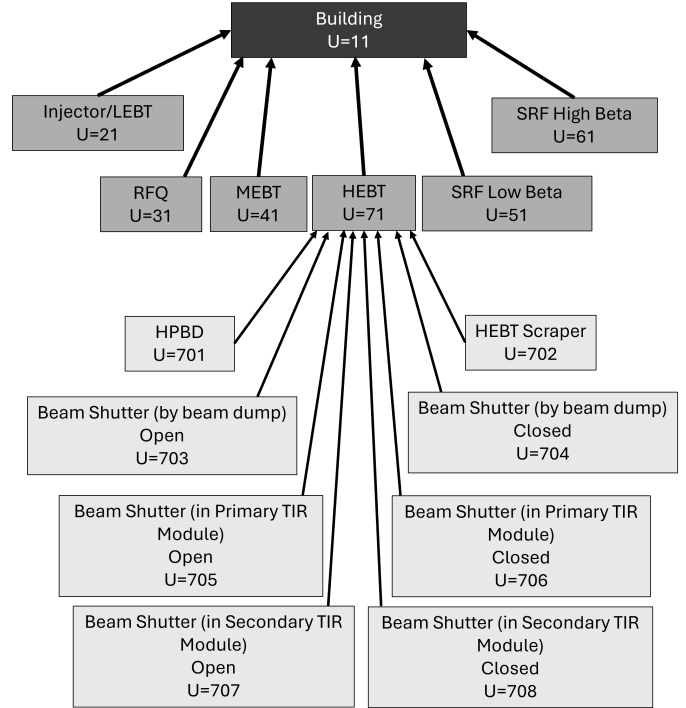


Figure 2: Universe structure of the current IFMIF-DONES neutronics model. By setting the FILL card to 10 (instead of 11) the building will be omitted from the model.

public dose rates below 250 μ Sv per year and worker dose rates below 2 mSv per year [12]. Therefore, it is necessary to include the building in the model to allow for neutronics analysis to extend beyond the accelerator and determine shielding needs to minimize exposure. To accomplish this, the universe structure of the accelerator was extended to include the building as the top level universe and the accelerator its sub-universe. The universe structure, along with the numbering convention, is shown in Figure 2. The Figure presents the current structure, in which only the HEBT has been subdivided into smaller universes of specific components. The logic of the numbering system is that a number beginning with 1 is the universe housing the accelerator (10 for empty space and 11 for building with the option to use 12, 13, etc., for other building models) and any two digit numbers not starting with 1 are the major accelerator components. The subcomponents, then, start with the original number of the major component followed by any two digit number. For simplicity, the current model counts up from 01.

The advantage of this system is that it establishes a clear hierarchy and allows for further universes to be added to the list. For instance, supporting equipment in the accelerator vault can be added as universe 81 and components within the RFQ can be subdivided into universes numbered 301-399.

The building model fidelity is low in order to minimize model complexity while accounting for particle reflection and bulk shielding. As a result, it contains the main concrete structure and only the doors that lead to the accelerator and neighboring rooms are included. The seismic supports, fittings and façade have been removed to reduce the number of cells and surfaces.



Figure 3: CAD model of the building housing the accelerator. Labeled is the accelerator vault and the Target Interface Room (TIR). A slice has been taken in the Y-plane

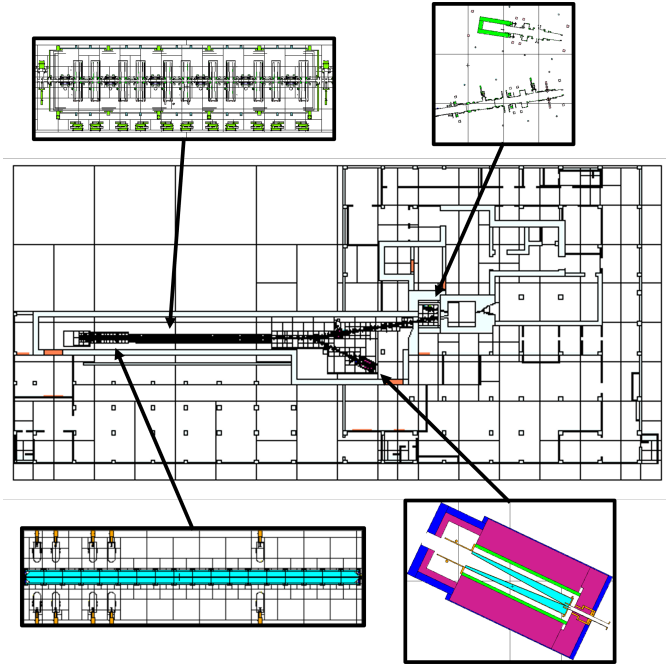


Figure 4: Z=0 slice of the main building plus accelerator model in the MCNP plotter. Clockwise from top left: SRF Cryomodule, TIR components, Beam Dump and RFQ. Note, the void cells are included.

The CAD model of the building containing the accelerator can be seen in Figure 3 and the MCNP plotter image in Figure 4.

3.3. Source Terms

The DONES accelerator contains a number of different radiation sources which contribute to the radiation field in the accelerator vault. One of the most important sources is the beamline source, which is caused by deuteron interactions with the beam pipe materials. Beam losses have been estimated at 1 W/m throughout the beamline, although realistic higher beam losses have been used in the RFQ based on loss rates found at IFMIF-EVEDA (Engineering Validation and Engineering Design Activities), a prototype DONES accelerator. This source has been robustly tested in the model and takes into account the material changes that occur along the beamline. One approach is to have a separate source term for each different material that is encountered per major component, whereas alternatively the material can be homogenized and a single source term used for the beam pipe. In either case, there is generally good agree-

ment between the neutron and photon flux maps regardless of the method used.

A specific reaction occurring around the beamline is deuterium fusion, which leads to the so-called d-D source. Deuterons can become embedded within the material and form deuterium atoms which will begin to build up. New deuterons entering the beam pipe can interact with the deuterium nuclei and undergo $D(d,n)^3\text{He}$ reactions, releasing 2.5 MeV neutrons. The neutron production rate has been measured to be 9.7×10^9 n/C of beam lost [13]. This source is implemented as a line source up to the end of the RFQ, but typically does not extend beyond the LEPT as it is only dominant at energies below the threshold for nuclear interactions with beam-facing materials.

The scraper and collimator sources are strong and localized compared to the beamline source. Since the beam naturally spreads, beam scrapers have been placed in the MEBT and HEBT along with a collimator just before the test cell. These are made of CuCrZr and consist of four movable blades to cover the transverse and longitudinal directions. Together they cause beam losses of 600 W, 2.2 kW, and 3.2 kW for the MEBT scrapers, HEBT scrapers and HEBT collimators, respectively[14]. These sources are included as srcUNED terms, with MCUNED used to simulate deuteron interactions at a single energy.

The final source is the test cell source. This source has the greatest total intensity as it represents all neutrons and photons produced by 40 MeV deuterons on the target and the resulting interactions with the materials in the test cell. The d-Li reactions have been simulated with McDeLicious[15], and a source term produced for the accelerator through the use of an MCNP SSR surface source term, provided by KIT. The source term includes prompt neutron and photon radiation as well as delayed photons for shutdown dose rate calculations. The inner surface of the wall to the test cell in the Target Interface Room (TIR) is used as the starting point of the radiation.

The neutron flux maps of the beamline source, test cell source and scraper sources on the HEBT can be seen in Figure 5.

4. Magnet Heating Analysis

Many neutronics studies have been conducted on individual sections of the accelerator [16], which have typically used detailed models of the parts under study. However, this global model brings together all the detailed segments and allows for an exploration of radiation effects from all sources on individual components. For instance, the radiation dose to magnets in the HEBT is of interest to DONES, as these must be able to withstand the radiation damage during full power operation (125 mA).

There are 31 magnets in the HEBT (labeled in Figure 6) of four different types: dipole, quadrupole, octupole, and dodecapole. All the magnets are made from the same magnet material discussed in Section 3.1, however, since the water is being continuously pumped through the solenoids, only the absorbed dose on the copper and epoxy is of consequence to magnet lifetime. A material multiplier, including a density modification,

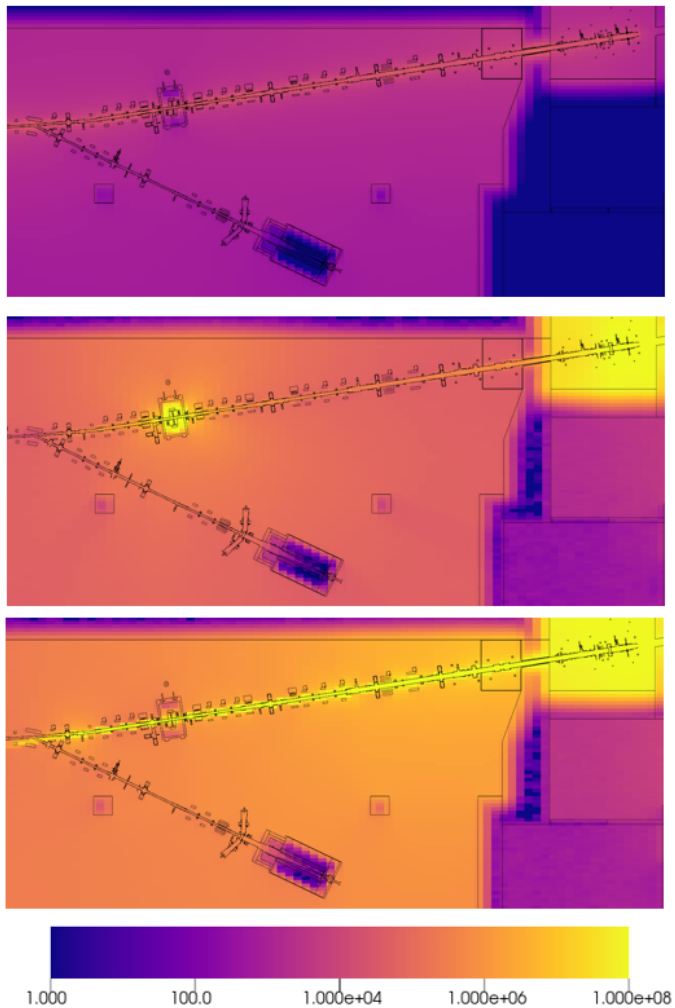


Figure 5: Neutron fluence maps of the HEBT geometry at Z=0 in the XY plane with scale (in n/cm^2) underneath. From top to bottom: beamline source, HEBT scraper & collimator source, test cell source.

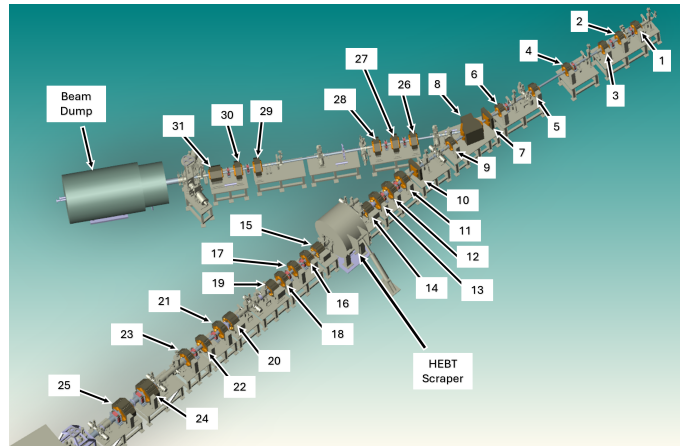


Figure 6: Labeled diagram of the locations of the HEBT magnets and their arbitrarily assigned numbers. Also included are the location of the beam dump and HEBT scraper. Screenshot taken in TopMC.

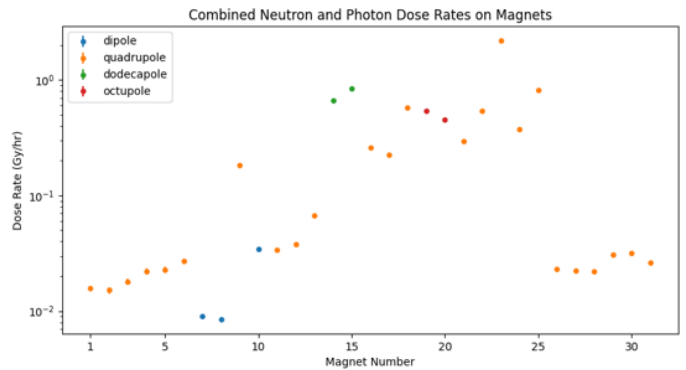


Figure 7: Graph of combined neutron and photon energy deposition in copper and epoxy (Gy/hr) parts of the magnet coils.

was applied to an MCNP F4 tally to consider only interactions with the copper and epoxy resin. This approach ensures that water moderation is accounted for but that its heating is excluded from the results.

The results of the analysis are shown in Figure 7, where it can be seen that the total dose rates vary from 0.0085 Gy/hr to 2.19 Gy/hr. The shape of the graph shows that the majority of the dose is absorbed by the magnets closest to the scraper & TIR, which is supported by the flux map in Figure 5. The low dose rate observed in magnets 26-31 is due to their position on the beam dump transport line (BDTL), separated from both the TIR and the beamline source (see Figure 6). There is a local peak in dose rate at magnet 9. Upon closer inspection, the greatest contributors to the dose rate are the solenoids on the right-hand side of the magnet yoke, when facing the TIR. Since the test cell and scraper are the dominant sources and the beam pipe is a streaming path (see Figure 5), magnet 9 – specifically the right-hand solenoids – is exposed to it from both sources due to its position on the bend with a line of sight to the scraper and TIR. The dipole magnets are well shielded by their yokes as they produce a noticeable dip in the absorbed dose (blue dots in Figure 7) despite their proximity to the scraper. On top of their efficient shielding, one other potential explanation for this could

be due to their geometry, which is that they consist of only two solenoids. The quadrupoles – and especially the dodecapoles – on the other hand, have 4 and 10 coils, respectively, surrounding the beamline. As a result, the higher-order magnets will experience a greater dose rate from the beam pipe, as a greater surface area is directly exposed to the beamline radiation. This is supported by a modest decrease in the octupole dose rate, which should be greater given their positioning in a relatively low dose region.

5. Conclusion

A high-fidelity neutronics model of the IFMIF-DONES accelerator has been created in CAD and converted to MCNP format with GEOUNED and TopMC. The model consists of over 22,000 bodies, each with materials assigned, and is divided into six top-level universes corresponding to the main accelerator sections. Additional sub-universes — introduced to represent key HEBT components in more detail — bring the total number of universes to 15. This model allows for radiation transport calculations to be conducted in MCNP and for neutronics studies on specific components.

A study on magnet absorbed dose rates was conducted and all radiation sources accurately accounted for, due to the global nature of the model. As a result of this, these results provide the most accurate estimates for the heating experienced by the magnets and can be used to inform engineers on the lifetime and frequency of maintenance required for each individual magnet. In addition, the magnet designs can be modified and quickly simulated by adding a universe around the magnets and interchanging different designs to optimise dose rates.

Due to the modular structure of the model, and consistency with the corresponding CAD, small sections can be modified and inserted into the model without having to entirely reconvert it, significantly speeding up analysis time. Furthermore, there are two configurations of beam shutters – closed and open – which allows for both beam-on and beam-off calculations to be conducted by changing the appropriate FILL cards.

This model provides a basis for future DONES neutronics analysis, with the ability to adjust fidelity of accelerator and main building sections in order to optimize calculations. There is scope for further sub-division of the model and integration of new models as they become available, such as a high-fidelity model of the building and supporting components. This facilitates comprehensive neutronics analyses on all parts of the IFMIF-DONES main building in support of licensing.

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