https://doi.org/10.1051/epjconf/202124718006

APPLICATION OF SUPERMC3.2 TO PRELIMINARY NEUTRONICS ANALYSIS FOR EUROPEAN HCPB DEMO

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ABSTRACT

In the D-T fueled tokamak, the neutrons not only carry the approximately 80% energy released in the per fusion reaction, but also are the source of radioactivity in the fusion system. Therefore, high-fidelity neutronics simulation is required to support such reactor design and safety analysis. In the present work, taking European HCPB DEMO (Helium Cooled Pebble Bed demonstration fusion plant) developed by KIT (Karlsruhe Institute of Technology) as an example, the preliminary neutronics analysis covering the assessments of NWL (neutron wall loading), TBR (tritium breeding ratio), nuclear power generation, radiation loads on PFCs (plasma-facing components) and TFCs (toroidal field coils) has been carried out by using SuperMC in the case of both unbiased and biased simulations. The preliminary results indicate that the blanket scheme could satisfy the design requirements in terms of TBR and shielding of inboard blankets. Specially, a speed-up by ~164 times in the calculation for thick shielding region (TFC region) is achieved by using global weight windows generated via GWWG in SuperMC. In addition, compared to MCNP, SuperMC shows advantages in accurate and efficient modeling of complex system, efficient calculation and 3D interactive visualization.

KEYWORDS: SuperMC, HCPB DEMO, Neutronics, TBR, GWWG

1. INTRODUCTION

In the D-T fueled tokamak, the neutrons not only carry the approximately 80% energy released in the per fusion reaction, but also are the source of radioactivity [1][2]. Additionally, due to no practical external available tritium to fusion system beyond ITER, the future D-T fueled fusion reactors must breed the tritium by themselves via the reactions between neutron and lithium [3][4]. Thus, the high-fidelity neutronics simulation, especially in the prediction of tritium breeding capability, plays the key role in designing and licensing of such reactors [5]. Due to its good adaptability to handle complex geometry and utilization of continuous energy cross section of nuclear data, the Monte Carlo (MC) method is usually preferred to perform the neutronics simulations for the fusion reactors [4]. Super Multi-functional Calculation Program for Nuclear Design and Safety Evaluation (SuperMC) is a general, multi-functional, intelligent, accurate and precise software system for design and safety evaluation of nuclear systems [6-10].

In Europe, with the support of Power Plant Physics and Technology (PPPT) program [11-14], a series of conceptual designs of European demonstration fusion plant (DEMO) considering 4 different blankets schemes: Helium Cooled Pebble Bed (HCPB) [15][16], Helium Cooled Lithium Lead (HCLL) [17] and Water Cooled Lithium Lead (WCLL) [18], and Dual Coolant Lithium Lead (DCLL) [19] are still developing. In the present work, taking European HCPB DEMO developed by KIT in 2015 as an example, the preliminary neutronics analysis has been carried out by using SuperMC and compared their results with MCNP's ones, to demonstrate both SuperMC's correctness and its advanced capacities to fusion neutronics applications. In the following sections, the methodology of this work including geometry modeling and detailed source description are discussed in the Sec. 2, respectively. The analysis and comparisons of preliminary results are present in Sec.3.

2. Methodology

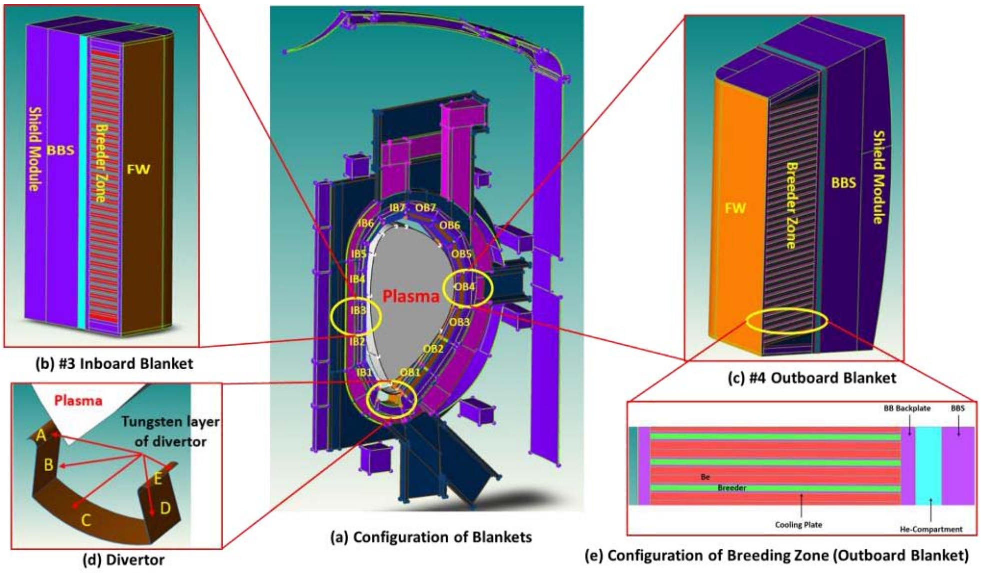
In this section, the methods of creating the neutronics model and plasma neutron source of European HCPB DEMO for SuperMC are presented in detail. Considering that the results calculated by SuperMC would be compared with ones from MCNP5 v.1.60 [20], the geometry model, source description, physical model, variance reduction technology (such as weight windows), cell importance, source particle history and data library must be kept the same in both simulations to ensure that the results obtained by the two codes are comparable.

2.1. Geometry modeling

Taking the full advantage of hierarchical modeling based on the philosophy of void-free modeling in SupeMC, an accurate European HCPB DEMO neutronics model for SuperMC was created on the basis of original MCNP input text. The void cells in MCNP input text, except the cells with important functions such as plasma cells acting as source, were commented firstly. And then the CAD models were generated by importing commented MCNP file into SuperMC for generating SuperMC calculation file. In this process, unlike that all the solids must be mandatorily explicitly described in certain MC codes such as MCNP, a larger box (i.e. World Volume) was automatically built to entirely comprise these CAD components, resulting in that the rest space unfilled by CAD model in the World Volume (such as the void gaps between blanket modules and plasma neutron source) could be implicitly automatically created in SuperMC. In this case, it just takes ~2 minutes to generate SuperMC calculation model for European HCPB DEMO on a PC with 3.10 GHz of Intel(R) Core(TM) i5-2400 CPU.). With the advanced geometry modeling capability in SuperMC, the designers and/or analysts can focus their attention on designing and/or simplifying reactor components themselves, ignoring the void cells which must be explicitly built in MCNP, thus significantly reducing the cost of creating the tokamak fusion reactor model. The detail structures of HCPB blankets and the configuration of breed units are presented in Figure 1.

2.2. Source modeling

In this work, a special source subroutine to sample the energy and position of source neutrons from a toroidal fusion plasma cell is implemented in SuperMC via the user-defined source module "PlugSource" based on the corresponding one in MCNP [22]. Before performing DEMO neutronics simulation, the consistency of plasma neutron source in SuperMC was checked with MCNP in terms of both spatial distribution and flux spectrum. A void plasma source with the same geometry and physical parameters as the one in DEMO is used for validating the source, as shown in Figure 2. Figure 3 presents the maps of neutron flux and error.



(b) #3 Inboard Blanket

(c) #4 Outboard Blanket

(d) Divertor

(a) Configuration of Blankets

(e) Configuration of Breeding Zone (Outboard Blanket)

Figure 1. Neutronic Model of European HCPB DEMO in SuperMC

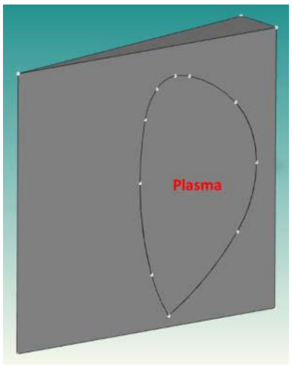
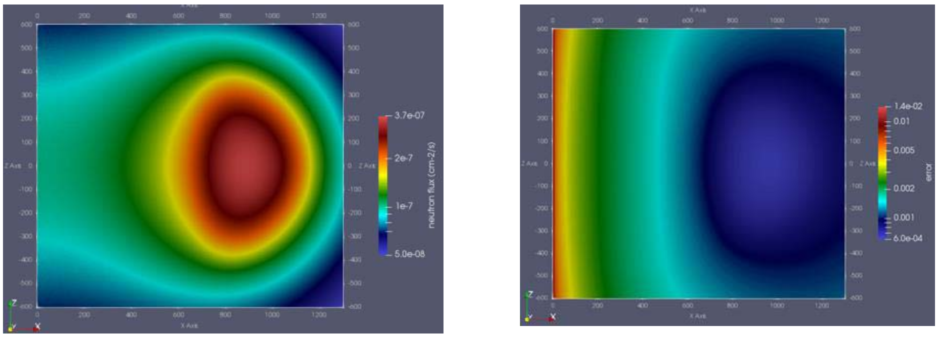


Figure 2. Neutronics model for validating European DEMO source



(a) Flux Map

(b) Error Map

Figure 3. Map of neutron flux and error calculated by SuperMC for void model

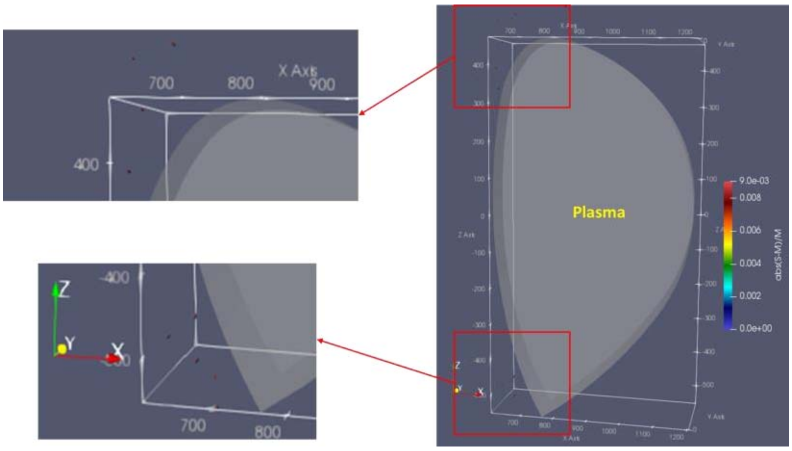


Figure 4. Map of neutron flux deviation |SuperMC-MCNP|/MCNP greater than 0.75%

In terms of spatial distribution, the deviation for neutron flux within the plasma zone didn't exceed 0.75%, as displayed in Figure 4 (there is no mesh voxel in plasma zone). Table I lists the spectra of neutron flux within plasma cell obtained by both codes. The average energy of source neutrons emitted from plasma is found to be 14.1 MeV. Spectra deviation for neutrons ranging from 12.21~15.68 MeV (whose fraction is close to 100%) is less than 0.226%. Although the deviation is 4.75% for neutrons with energies higher than 15.68 MeV, their fraction (~9.5×10^{-6} %) could be ignored, and their statistical error (1σ) are slightly large compared to those in other energy groups. Based on the results above, the plasma neutrons used in SuperMC can be considered as consistent with that in MCNP.

Table I. Spectra of neutron flux at plasma source cell

E/MeV	SuperMC		(S-M)/M*
	result (cm^{-2}/s)	stat. error	
<12.21	0.00000 E+00	0.0000	0.000%
12.21 ~12.84	9.77587E-05	0.0045	0.226%
12.84 ~ 13.50	2.92219E-01	0.0001	0.011%
13.50 ~ 13.84	2.45110E+00	0.0000	-0.004%
13.84 ~ 14.19	6.26633E+00	0.0000	0.000%
14.19 ~ 14.55	4.55457E+00	0.0000	0.002%
14.55 ~ 14.92	9.09510E-01	0.0001	0.008%
14.92 ~ 15.68	4.70277E-02	0.0002	0.004%
15.68 ~ 20.00	1.44450E-06	0.0377	4.751%
total	1.45209E+01	0.0000	0.001%

* S stands for SuperMC and M for MCNP

3. RESULTS AND DISCUSSIONS

In this section, the preliminary nuclear performance including neutron wall loading (NWL), tritium breeding ratio (TBR), radiation loads on TFC for European HCPB DEMO [12-13]with fusion power of 2119 MW was calculated with SuperMC and are compared with corresponding MCNP results. The JEFF3.2 data library was used in MC calculations.

3.1. Neutron Wall Loading

The neutron wall loading (NWL), which is one of key parameters reflecting plasma characteristics, was first evaluated using current tally. The comparable results between the two codes for the NWL further validates the plasma neutron source used in SuperMC. Figure 5 depicts the NWL poloidal distributions in inboard (IB) and outboard (OB). The maxima NWLs were found to be ~1.37 MW/m^2 at OB3-OB4 and ~1.14 MW/m^2 at IB3. And the average poloidal NWL is ~1.03 MW/m^2. In addition, as shown in Figure 5, a good agreement on NWL distribution between two codes was observed.

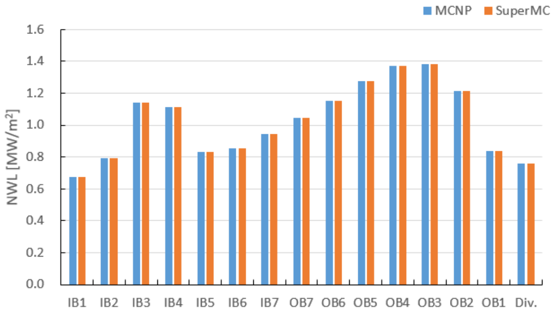


Figure 5. Profile of NWL on first walls

https://doi.org/10.1051/epjconf/202124718006

3.2. Tritium Breeding Ratio

The global TBR for the entire European HCPB DEMO and its breakdown in each blanket have been calculated based on the detailed 3D neutronics model mentioned above. In simulations, the statistical errors (1σ) of these reactions rates were less than 0.0009. The global TBR evaluated by SuperMC is 1.19318 (which is close to 1.19323 of MCNP), satisfying the DEMO design requirement for tritium self-sufficiency (net TBR >= 1.10). Figure 6 presents the TBR breakdown in each blanket. The maximums of TBR are located at equatorial blankets, IB3 and IB4 (~0.04), and OB4 (~0.16) in inboard and outboard side, respectively. With the larger volume, the TBRs in outboard blankets (which are always greater than these in inboard blankets) account for as high as ~76% of the global TBR. And a good consistency on TBR poloidal distribution between two codes was observed.

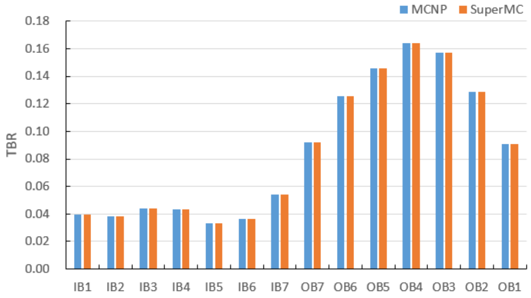


Figure 6. Distribution of TBR in blankets

3.3. Nuclear Heating

The nuclear heating generated by neutrons and photons in different reactor components are as listed in Table II. The energy multiplication factor (M_E) obtained by SuperMC is of 1.34 (=2266.81 MW / 2119 MW / 0.8); only deviating from that of MCNP by ~0.01%. From the results presented in Table II, it can be adduced that about 93.2% of total power comes from the nuclear heating generated in blankets. The remaining is mainly contributed by the divertor (~4.4%) and VV (~2.3%). And regarding poloidal distribution of nuclear heating within blanket, the maximum nuclear powers of inboard and outboard blankets are ~96 MW located at IB3 and ~280 MW located at OB4 (equatorial outboard blanket). In addition, a very good agreement between two simulations in which the statistical MC errors (1σ) are less than 0.002 is also found, as shown in Figure 7.

Table II. The breakdown of Nuclear Heating in reactor components

Components	Nuclear Heating calculated by SuperMC (MW)
Blankets	2111.92
Divertor	100.04
VV (Vacuum Vessel)	53.81
Ports	1.01
Manifolds in Port	0.02
Total	2266.81

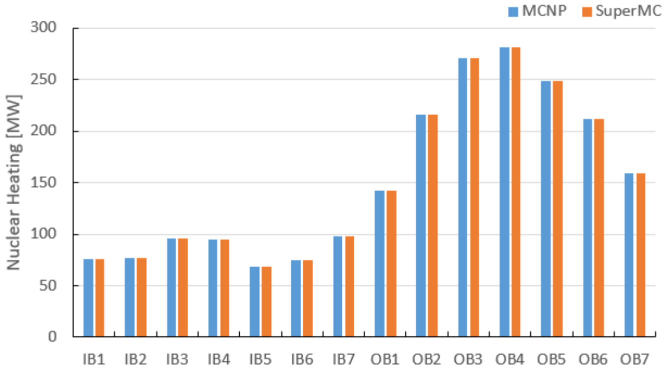


Figure 7. Profile of nuclear heating in blankets

3.4. Radiation Loads on TFC

The assessment of radiation loads (such as nuclear heating, fast neutron flux, DPA) on the superconducting coils is a very crucial task at design and analysis stage. It is also an established fact that, in the European DEMO, the shielding between inboard blankets and TFC is the weakest, so the main attention on radiation loads on coils is focused on inboard TFC. The nuclear heating density, fast neutron flux and displacement damage to copper on the slice of TFC closest to inboard blankets were estimated by the two codes. To calculate radiation loads distributions on TFC, the TFC cell (marked by yellow pane in Figure 8 left) was sliced into smaller 72 cells with thickness of ~5.0 cm and tallied accordingly as shown in Figure 8.

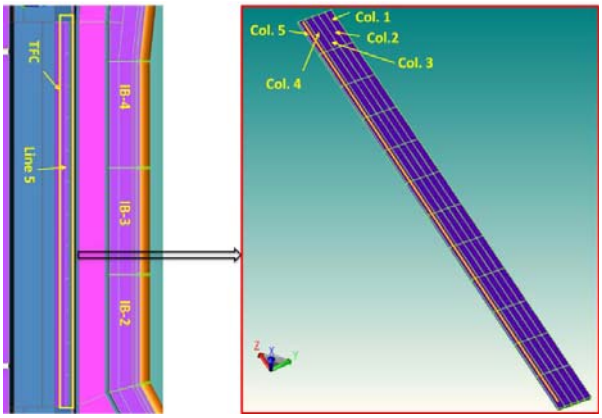


Figure 8. Tally cells for radiation loads on TFC

In calculating radiation loads on TFC, a global weight window generated by SuperMC using GWWG method were applied in both SuperMC and MCNP to obtain results with reasonably low statistical error around TFC region (thick shielding region). With the same source particles (5×10^{9}), the FOM obtained in analog is 2.51990×10^{-5} with maximum statistical error reaching ~100% and 111427.0 min·CPUs, while the one is 4.13135×10^{-3} with statistical error below 5% and 653548.8 min·CPUs in the case of GWWG. The simulation with global weight window generated via GWWG was speeded up by ~164 times compared to analog simulation in term of FOM [25].

In all cases, the statistical errors (1σ) for each cell tallies were around 1%~3%. The maximum of these radiation loads on TFC, which are found to be located at the mid-plane of plasma, were ~22 W/m^{3} for nuclear heating density, ~6.2×10^8 cm^{-2}/s for fast neutron flux and ~9.8×10^{-6} dpa/fpy for radiation damage to Cu; each of the result not exceeding the corresponding limits for TFC in the European DEMO (50 W/m^3, 10^9 cm^{-2}/s and 5×10^{-5} dpa, respectively). Besides, the results showed good agreements between the codes with average deviations of 1.7% for nuclear heating, of 2.2% for fast neutrons flux, and 2.7% for displacement damage to copper in the TFC.

4. CONCLUSIONS

SuperMC is a valid and unique 3D neutronics simulation tool with accurate modeling, efficient calculation and 3D visualization for design and safety analysis of complex advanced nuclear energy systems such as ITER, the European DEMO and other fusion reactors. The neutronics analysis for European HCPB DEMO was carried out using SuperMC, and the results were also compared with MCNP's ones. The preliminary results not only demonstrated that the blanket scheme could satisfy the design requirements from the viewpoint of neutronics, but also that SuperMC is consistent with MCNP in neutron flux/current, nuclear response (such as TBR, DPA, etc.) and nuclear heating using both unbiased and biased simulations techniques. Compared to MCNP, SuperMC has advantages in accurate modeling of complex system, efficient calculation and 3D interactive visualization: (i) void-free modeling can be performed in a few minutes for advanced nuclear systems with complex geometry such as tokamak; (ii) the proposed GWWG method efficiently reduces statistical error for deep penetration problems (for example, in term of FOM, it achieved speed-up by ~164 times for case of European HCPB DEMO); (iii) 3D interactive and intuitive geometry checking for complex model.

ACKNOWLEDGMENTS

The MCNP and SuperMC calculations leading to the results of this work were performed on the ForHLR II computer cluster at KIT funded by the Ministry of Science, Research and the Arts Baden-Württemberg and DFG ("Deutsche Forschungsgemeinschaft"). This work was supported by the National Magnetic Confinement Fusion Science Program of China (2015GB116000). And, the author would like to show their gratitude to other FDS Team members and the neutronics group in INR, KIT for supports to this research.

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