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Research paper

Verification of SuperMC with ITER C-Lite neutronic model

Shu Zhang[a,b], Shengpeng Yu[b], Peng He[b,*]

[a] School of Nuclear Science and Technology, University of Science and Technology of China, Hefei, Anhui, 230027, China
[b] Key Laboratory of Neutronics and Radiation Safety, Institute of Nuclear Energy Safety Technology, Chinese Academy of Sciences, Hefei, Anhui, 230031, China

HIGHLIGHTS

- Verification of the SuperMC Monte Carlo transport code with ITER C-Lite model.
- The modeling of the ITER C-Lite model using the latest SuperMC/MCAM.
- All the calculated quantities are consistent with MCNP well.
- Efficient variance reduction methods are adopted to accelerate the calculation.

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ABSTRACT

In pursit of accurate and high fidelity simulation, the reference model of ITER is becoming more and more detailed and complicated. Due to the complexity in geometry and the thick shielding of the reference model, the accurate modeling and precise simulaion of fusion neutronics are very challenging. Facing these difficulties, SuperMC, the Monte Carlo simulation software system developed by the FDS Team, has optimized its CAD interface for the automatic converting of more complicated models and increased its calculation efficiency with advanced variance reduction methods To demonstrate its capabilites of automatic modeling, neutron/photon coupled simulation and visual analysis for the ITER facility, numerical benchmarks using the ITER C-Lite neutronic model were performed. The nuclear heating in divertor and inboard toroidal field (TF) coils and a global neutron flux map were evaluated. All the calculated nuclear heating is compared with the results of the MCNP code and good consistencies between the two codes is shown. Using the global variance reduction methods in SuperMC, the average speed-up is 292 times for the calculation of inboard TF coils nuclear heating, and 91 times for the calculation of global flux map, compared with the analog run. These tests have shown that SuperMC is suitable for the design and analysis of ITER facility.

1. Introduction

Nuclear analysis is an essential part of the design and assessment of the ITER project, but at the same time such analysis is usually very difficult due to the ITER machine's complicated geometry, immense spatial size and thick shielding. Both the accurate modeling of the machine and precise simulation of the model is very challenging.

The ITER organization has released a series of reference models to allow consistent neutronics analyses to be carried out, which include the calculation of neutron and photon flux, nuclear heating, material damage, gas production and shutdown dose rate, etc. A reference model is a 40° sector of the facility with detailed geometry, material and plasma source definitions. The first of these is the Brand model [1]. In pursuit of more accurate simulation, the ITER organization has then released the "lite" series reference model. The first "lite" model, the A-Lite model was released in 2008, consisting of 4816 cells defined using over 3050 surfaces [2]. Then the B-Lite model was released in 2010, consisting more than 10,000 cells and 12,300 surfaces [3]. The C-Lite model [4] is the latest "lite" series model, and the version (ver_131031) studied in this work consists more than 15000 hierarchically organized solids and 29000 surface definitions.

The SuperMC code is a CAD-based Monte Carlo program for integrated simulation of nuclear systems [5]. The CAD geometry translation code, MCAM [6,7], has been integrated into SuperMC as its CAD interface and is now renamed as SuperMC/MCAM. This interface code has been extensively used in ITER neutronics group for modelling, with which a series of ITER reference

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[*] Corresponding author.
E-mail address: peng.he@fds.org.cn (P. He).

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neutronic models have been constructed. The SuperMC code is currently under development by FDS Team in China, which has long devoted into the study of fusion neutronics and design [8–12] and nuclear materials [13–15], etc. As a general-purpose Monte Carlo program, SuperMC is designed for high-fidelity simulation of nuclear-system problems such as reactor physics, radiation physics, medical physics, and nuclear detection, taking the radiation transport as its core and including the depletion, radiation source term/dose/biohazard, material activation and transmutation, etc. It is also designed to be coupled with deterministic transport methods [16]. The latest SuperMC (version 2.3) can accomplish the transport calculation of neutron/photon and it is integrated with the functions of automatic modeling, visualization and cloud computing. It has been applied to the design of fusion plants and test blankets [17,18], and the design of fusion driven hybrid systems [19–21].

SuperMC has been verified and validated by more than 2000 benchmark models and experiments, such as the International handbook of evaluated Criticality Safety Benchmark Experiments (ICSBEP), the Shielding Integral Benchmark Archive Database (SINBAD), and the comprehensive applications on various types of reactors. The previous verification on ITER is performed on the Benchmark model. To further enhance the verification and validation of its ability on automatic modeling and variance reduction ability for neutron-photon coupled calculations in complex ITER models, the analysis of C-Lite model are performed and compared with MCNP [22] in this work.

2. ITER C-Lite model

The C-Lite model was developed to address several problems found in the B-Lite model [4]. The problems mainly include nested universes in structure, overcomplicated or oversimplified representations of some components, misleading material definitions. Many components of B-Lite model are out-of-date including blanket, port-plugs and structures between the port plugs and the port walls, divertor, VV inter-wall shield, PFC support, control coils, etc. As a result, the C-Lite model contains no nested blocks, adopts reasonable complicated representations of the machine components, and updates the out-of-date components and material definitions.

The C-Lite model was built using many person-years and released by ITER organization in CAD format and MCNP input format. First the original detailed CATIA model was simplified by removing excessive details, such as clashes, splines, tori, etc. As MCNP cannot describe high-order surfaces in its native language, such surfaces on material boundaries and void cells were converted to 2nd-order surfaces. After this, the CAD models can be translated into MCNP representations by SuperMC/MCAM. Since the C-Lite model has a large spatial size while its components are specifically described to millimeters, there are more than 15,000 solids in this model. Even with automatic CAD interface codes, it was very challenging to convert such a complicated model in a single step. ITER has adopted the divide and conquer method, in which they divided the whole model into several regions, simplified and converted solids in each region separately, and then constructed the whole C-Lite model using universe and fill combinations.

3. Simulation method

3.1. Modeling

Currently, two primary methods, the CAD/MC interface method and the direct ray tracing method on CAD, have been kept developing to address the conversion problem. As a mature representative CAD/MC interface, SuperMC has been improved on the capability of handling large amount of solids as well as solids with complex boundaries. It can now convert the ITER C-Lite CAD model into CSG model for Monte Carlo codes in a single conversion. The DAG-MC code represented direct ray tracing method on CAD model has the main drawbacks of relatively lower calculation efficiency and loss of accuracy due to triangulated mesh approximation of high-order surfaces [23]. Therefore, SuperMC is currently the main code that's capable of automatically creating CSG format ITER C-Lite model and performing cross-validation with MCNP.

To obtain an input file for SuperMC from the released MCNP input file, first, with the help of the new 64-bit version of SuperMC (being able to handle millions of solids), the original MCNP file was inverted into a CAD model in a single step. Then this complicated CAD model was automatically translated region by region into SuperMC format. Concerning the void description, since SuperMC has adopted the Binary Space Partition to accelerate the locating of particles [24], it is not necessary to define all the transport space. As a result, vacuum regions other than the functional regions, such as the plasma region, were left un-converted to the SuperMC model. Without void definitions, the geometry navigation in the spaces between solids is largely simplified and thus more efficient, the probability of particle loses is also reduced. The full modeling procedure is shown as Fig. 1.

The plasma source defined by the ITER organization is described into SuperMC source format with the help of the source modeling module of the SuperMC. The source has 500 MW fusion power and the nuclear heating calculated in this work is normalized to this value. All the simulations performed in this work were supported by the Fusion Evaluated Nuclear Data Library FENDL2.1 [25].

3.2. Variance reduction

Due to the thick layers of shielding of the C-Lite model, the neutron flux attenuation across the whole model is more than 10 orders of magnitude. As a result, detailed calculation on C-Lite model is usually very challenging, which requires an effective variance method.

To address the above problem, SuperMC has developed a mesh weight window based global variance reduction (GVR) method, which is named as global weight window generator (GWWG). The parameters of the weight window are set to inversely proportional to the importance of phase space cells. The importance of each weight window cell is calculated as the expected contribution to the particle density uniformity generated by a unit weight particle after entering a certain cell. This method studies the contribution to a uniform particle distribution at a very fine level. On the other hand, since the weight window method solves the deep penetrating problem via splitting more in high attenuating zones, the simulation time per particle is usually prolonged. So the GVR method of SuperMC also tries to reach a balance between a deeper penetrating and a higher source particle sample rate. The effectiveness of this method is demonstrated in Section 4.3.

Starting from an effective global weight window, it is again possible to generate a relatively locally optimized weight window, using a MCNP like weight window generator (WWG) [22].

The quality of the weight window generated by the WWG can be significantly improved with an effective global weight window. Since the global weight window can distribute particles uniformly across the whole model, it not only ensures that tallies everywhere are scored but also avoids under-sampling of certain path. The global weight window also makes it possible to obtain responses in multiple tallies with an acceptable precision by a relatively short run, which is promising when applied to the linear combination WWG proposed by Solomon et al. [26]. This method is effective for accelerating the calculation of multiple responses at the same time. In section 4, the linear combination WWG is used in combination

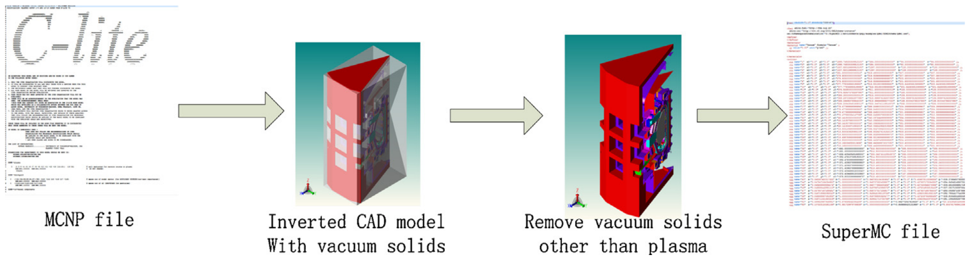

Fig. 1. Generating SuperMC calculation model.

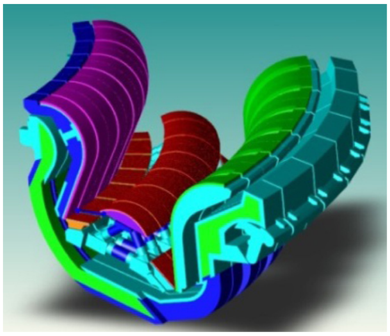

Fig. 2. The divertor cassette in the C-Lite model.

with the GWWG to speed up the calculation of nuclear heating in toroidal field coils.

4. Analysis

The toroidal field (TF) coils heating and the shut-down dose rates are two critical parts of the current ITER nuclear analysis [27]. Therefore, the main physical quantities calculated in the work are nuclear heating within the inboard TF coil and the diverter, and a whole model flux map. These calculated quantities are compared with the results of MCNP and the relative deviation is defined as:

$$\Delta \mathrm{X} = \frac{\mathrm{X}^{\mathrm{SuperMC}}}{\mathrm{X}^{\mathrm{MCNP}}} - 1,$$

where X is the quantity to be compared. The relative combined statistical error σ is defined in a similar way as the work of Jaboulay [28]:

$$\sigma = \left(\sigma^2_{\mathrm{SuperMC}} + \sigma^2_{\mathrm{MCNP}}\right)^{1/2}.$$

4.1. Neutron flux and nuclear heating in divertor cassettes

Neutron flux and nuclear heating in the divertor cassette are calculated to test the capability of modeling complex geometry and neutron responses in those objects. The divertor is divided into 5 groups for tally scoring. These five groups, listed as G1 to G5, are the outer vertical target, outer vertical carbon fiber composite (CFC), inner vertical CFC, inner vertical target and cassette body. Each group is further divided into 7 segments. Fig. 2 shows the C-Lite divertor model displayed in SuperMC. The test results are listed in Table 1. The relative errors are listed in italic. The relative deviations of SuperMC and MCNP in flux range from −0.72% to 0.03%. The relative deviations in nuclear heating vary from −0.66% to 0.26%. All the results are within 1% variation. Thus the results of the two codes are in good consistence.

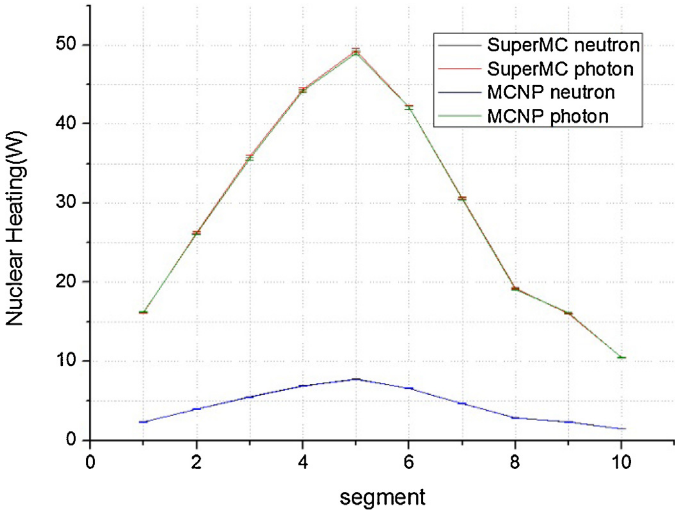

Fig. 3. Nuclear heat comparison in TF coils between SuperMC and MCNP with error bar in 1σ..

4.2. Nuclear heating in the inboard TF coils

The TF coils are protected by the thick shielding provided by the blanket and vacuum vessel against overheating induced losses of superconductivity. As a result, the calculation of detailed TF coil heating is very challenging. In this work, the nuclear heating in the inboard TF coil winding packs is calculated. The inboard To obtain acceptable statistical uncertainties for all the tallies considered, first a global weight window is generated, which used about 7.9 CPU-days. Then a 3.9 CPU-days linear combination WWG run is performed to generate the weight window for the TF coils calculation. The mesh of the weight window is 100 × 100 × 200 in x, y, z direction, respectively.

The calculation of the nuclear heating used 7.26 CPU-days. The calculated neutron and photon nuclear heating within the inboard TF coils are listed in Table 2. The relative errors are listed in italic. Fig. 3 has shown the comparison of the calculated nuclear heat between SuperMC and MCNP. All the relative deviations between the results of the two codes are within±2σ. The max relative uncertainty of all the neutron/photon coupled tallies given by SuperMC is 0.6% and the average relative uncertainty is 0.53%. The average relative uncertainty given by a 6.6 CPU-days analog run is 9.5%, so the average speed-up in figure of merit is about 292 times. The total nuclear heat given by SuperMC and MCNP is 334.9 W and 333.8 W, respectively. The relative deviation of the total nuclear heating is 0.33%. So in this case SuperMC and MCNP also show a good agreement.

Table 1
Divertor flux and nuclear heating distribution of C-Lite calculated by SuperMC and MCNP.

	Flux (cm^{-2})				Δ Flux	Nuclear Heating (W)				ΔHeating
	SuperMC		MCNP			SuperMC		MCNP		
G1	3.200E+00	*0.08%*	3.199E+00	*0.05%*	0.03%	1.795E+06	*0.09%*	1.797E+06	*0.05%*	−0.09%
G2	5.329E-01	*0.17%*	5.334E-01	*0.09%*	−0.08%	3.128E+05	*0.19%*	3.120E+05	*0.10%*	0.26%
G3	2.081E+00	*0.10%*	2.082E+00	*0.05%*	−0.07%	1.200E+06	*0.11%*	1.200E+06	*0.06%*	0.00%
G4	4.985E-01	*0.17%*	5.021E-01	*0.09%*	−0.72%	2.690E+05	*0.20%*	2.707E+05	*0.10%*	−0.66%
G5	1.920E+00	*0.11%*	1.921E+00	*0.06%*	−0.06%	8.710E+05	*0.13%*	8.703E+05	*0.07%*	0.09%

Table 2
Neutron and photon nuclear heating (W) in inboard TF coils.

	Neutron nuclear heating				ΔHeating	±σ	Photo Nuclear Heating				ΔHeating	±σ
	SuperMC		MCNP				SuperMC		MCNP			
Seg1	2.340	*0.62%*	2.347	*0.62%*	−0.30%	0.88%	16.197	*0.54%*	16.227	*0.54%*	−0.19%	0.76%
Seg2	3.962	*0.58%*	3.952	*0.57%*	0.25%	0.81%	26.265	*0.51%*	26.161	*0.50%*	0.40%	0.71%
Seg3	5.550	*0.55%*	5.497	*0.55%*	0.97%	0.78%	35.935	*0.49%*	35.640	*0.49%*	0.83%	0.69%
Seg4	6.886	*0.51%*	6.861	*0.50%*	0.37%	0.71%	44.400	*0.46%*	44.208	*0.45%*	0.43%	0.64%
Seg5	7.758	*0.62%*	7.722	*0.61%*	0.47%	0.87%	49.302	*0.55%*	48.981	*0.54%*	0.66%	0.77%
Seg6	6.556	*0.60%*	6.574	*0.59%*	−0.27%	0.84%	42.117	*0.53%*	42.095	*0.53%*	0.05%	0.75%
Seg7	4.665	*0.50%*	4.662	*0.51%*	0.06%	0.71%	30.627	*0.46%*	30.509	*0.46%*	0.38%	0.65%
Seg8	2.857	*0.64%*	2.841	*0.65%*	0.56%	0.91%	19.234	*0.56%*	19.105	*0.57%*	0.67%	0.80%
Seg9	2.334	*0.55%*	2.349	*0.55%*	−0.65%	0.78%	16.027	*0.49%*	16.147	*0.49%*	−0.74%	0.69%
Seg10	1.461	*0.67%*	1.459	*0.66%*	0.16%	0.94%	10.482	*0.59%*	10.461	*0.59%*	0.20%	0.83%

Table 3
Summary of test results of the global flux map calculation.

	Analog	Global Variance Reduction
Run time(min)	14250	14250
Average error (%)	67.9	3.13
Percentage not scoring (%)	19.9	0
FOM_G	1.23e-4	1.12e-2
Speedup	1	91.06

4.3. *Whole model flux map*

Obtaining a detailed flux map everywhere throughout the model is a key step in the shutdown dose rate analysis for the ITER reference model. Due to the complexity and immense size of the model, such kind of simulation with analog Monte Carlo will cost a prohibitive run time. An efficient global variance reduction technique needs to be employed to make the simulation computational practicable.

In this work the global weight window generator of SuperMC is used to accelerate the global flux map calculation. A cylindrical mesh of 100 × 200 × 20 in r, z, and theta directions is used both for the weight window and the flux tallies. The generation of the weight window and the flux calculation both used about 9.9 CPU-days.

The calculation results are listed in (Table 3). For the variance reduction case, all mesh cells are successfully scored. Relative statistical errors of 94.9% of the mesh cells are smaller than 10%, and the average relative error is 3.13%. The global figure of merit (FOM_G) is defined in the same way as the work of Andrew Davis [29]:

$$FOM_G = \frac{1}{t\sum_{n=1}^{N}\sigma_n^2/N}$$

where t is the total run time, σ_n is the statistical error of the nth mesh cell, and N is the total number of mesh cells. A speedup of 91 times in FOM_G is observed. Fig. 4 shows the comparison of the neutron flux and relative error map of the variance case and the analog case. The pictures are generated by the visual analysis module of SuperMC.

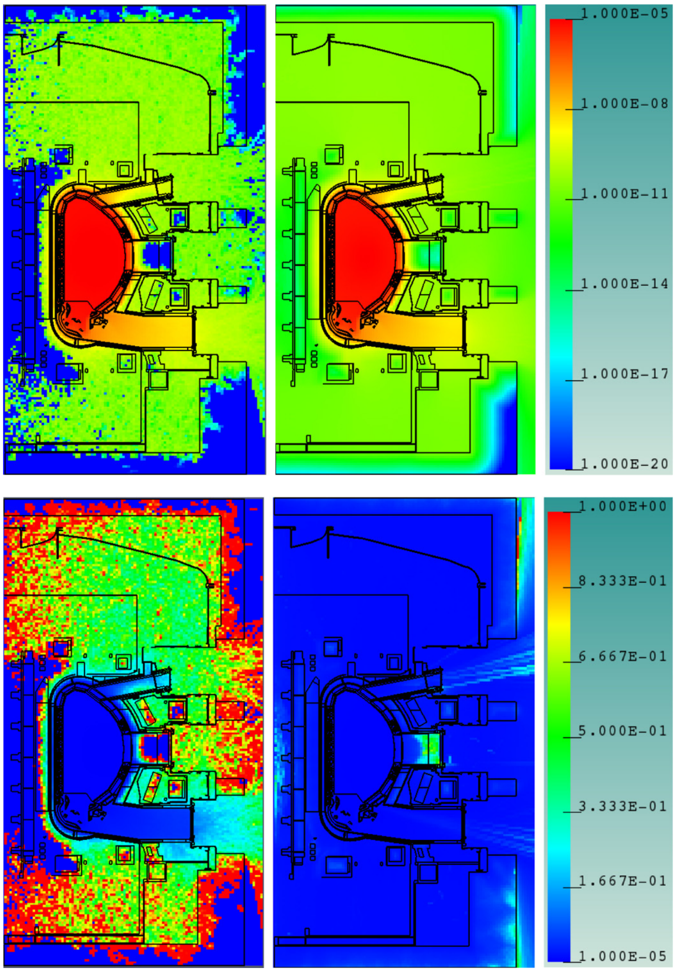

Fig. 4. Neutron flux (top) and relative error (bottom) maps of C-Lite model obtained using analogue (left) and GWWG (right) particle tracking method.

5. Conclusion

The C-Lite model is currently the latest and most complicated neutronic model of the ITER machine. Its complexity in geometry and thick shielding has posed great challenges to both the modeling and simulation of this model. In this work, a SuperMC C-Lite calculation model was built by directly inverting from the MCNP input file released by ITER IO in a single step. Several numerical benchmarks were then carried out with this model. Compared with the MCNP code, good consistencies have been observed for all the calculated quantities. By using the variance reduction methods developed in SuperMC, for the calculation of the nuclear heating in inboard TF coils, the speedup compared with the analog run is 292 times. In the calculation of the global flux map, the speedup in global FOM is 91 times compared with the analog run. All of these results have verified the advanced automatic modeling and efficient neutron/photon simulation capabilities of SuperMC. This demonstrated that SuperMC is an accurate and efficient tool for the design and analysis of ITER facility.

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