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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.

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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

* 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

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