ITER Neutronics Modeling Using Hybrid Monte Carlo/S_N and CAD-based Monte Carlo Methods

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INTRODUCTION

The neutronics modeling and simulation (M&S) of ITER is needed for the prediction and confirmation of expected nuclear parameters that represent an essential part of the reactor design process. The immense size and complex geometry of ITER require the development of special modeling techniques which can accurately and efficiently perform the neutronics M&S with minimal human input.

The hybrid Monte Carlo (MC)/deterministic methods CADIS [1] and FW-CADIS [2] have proved to provide a factor of >1000 increase in the MC figures-of-merit (FOM) for problems with scales both similar to and larger than ITER. These methods use approximate deterministic calculation(s), generally discrete ordinates (S_N), to create the biasing parameters needed for efficient MC. They were found ideal for the M&S of problems which are otherwise too challenging by either of the two approaches individually [3,4].

Due to the complexity of the geometry of fusion energy systems, the fusion-neutronics community developed many tools to combine the MC code MCNP [5] and computer aided design (CAD) software. This preserves geometry complexity, reduces human interference, and speeds up design iterations [6].

The goal of this work is to demonstrate the applicability of coupling the hybrid methods CADIS and FW-CADIS with CAD-based MC. The analysis calculated three quantities needed for ITER licensing and operation: the nuclear heating in the inboard (I/B) region of the toroidal field coils (TFC), the prompt operational dose outside the biological shield, and the total neutron and photon flux distributions.

ITER uses 18 superconducting toroidal field coils which operate at cryogenic temperatures. The allowable amount of nuclear heating deposited in these coils is constrained by the ability of the cooling system to remove that heat. One of the engineering limits of the ITER design is the nuclear heating in the I/B-TFC which accounts for >80% of the total TFC heating. The thick shielding provided by the blanket and the vacuum vessel makes the calculation of the total heating in these coils a challenging problem for MC methods, and hence reliable variance reduction techniques are necessary to achieve acceptable statistical precision within reasonable running time [7].

Estimates of the dose rates outside the biological shield are necessary for occupational safety and for the design of the reactor building. Calculating the prompt dose rate outside the bioshield during plant operation has been viewed as a challenging problem due to the massive amounts of shielding between the source and the exterior [7].

The nuclear analysis in ITER has always depended on analyzing each component separately using combinations of 1-D, 2-D and 3-D analysis [7]. The main reasons for these approaches are the complexity of the geometry and the difficulty of obtaining good MC statistics throughout the whole machine. To demonstrate the effectiveness of the FW-CADIS method, it was used to calculate the total neutron and photon fluxes on a mesh tally over the entire ITER plant and the results were compared to analog MC.

DESCRIPTION OF THE ACTUAL WORK

The ITER benchmark model [6] was used in this analysis. The ADVANTG code [8] was used to develop weight-window map for the MC simulations with the University of Wisconsin-Madison code DAG-MCNP [9]. ADVANTG drives the 3-D S_N code Denovo [10] to generate an approximate transport solution from which the MC biasing parameters are computed. ADVANTG uses the geometry sections in a native MCNP input file to create the Denovo input files necessary for the S_N calculation. The Karlsruhe Research Center (FZK) provided the MCNP input file. This input file was produced from the original CAD geometry of ITER by the McCAD translator developed by FZK [11]. The weight-window map created by ADVANTG was used in running DAG-MCNP. Direct accelerated geometry MCNP (DAG-MCNP) is a MC code that replaces the core geometry routines such as the ray-surface intersection functionality of MCNP with CAD routines defined in an external software library. It was successfully used in the neutronics modeling of several fusion applications such as ITER, HAPL, and ARIES [12].

The IAEA fusion evaluated nuclear data library (FENDL-2.1) was used in this analysis [13]. Two multi-group FENDL-2.1 libraries were created in ANISN format: a coarse 46 neutron/21 gamma groups library was used for the S_N portion of the hybrid MC/S_N calculations and a fine 175 neutron/42 gamma groups library was used

for the Denovo S_N calculation of the dose rate outside the bioshield.

I/B TFC nuclear heating

The I/B TFC leg has a height of 8 m, a radial thickness of 70 cm, and a toroidal extent of 80 cm. Since good MC statistics are required for both neutrons and photons in all the I/B-TFC segments, it is considered a semi-global problem for which FW-CADIS can be used to simultaneously optimize multiple MC responses (tallies) or the response throughout a large volume in one calculation. The response to be optimized was specified to be the total neutrons and photons heating everywhere in a rectangular parallel pipe enclosing all the I/B-TFC segments. In a FW-CADIS sequence, ADVANTG runs a forward S_N calculation to calculate the specified responses and uses the spatially-dependent inverse of these responses to weight the adjoint source strength for an adjoint S_N calculation. The adjoint fluxes are then used to calculate the biased source and the weight-window parameters for the MC calculation. Through some preliminary analyses, it was found that neither the source biasing nor the accurate representation of the ITER source in the S_N calculations was important since the source particles are born in vacuum with a very narrow Gaussian energy distribution centered on 14.1 MeV. An approximate source was used for the S_N calculations and the actual ITER source was used for the MC calculation.

Prompt dose rate during operation

The dose rate was calculated 1690 cm from the ITER center in the radial direction and 800 cm in the axial direction, representing a point outside the bioshield and below the cryostat of ITER. The CADIS method was used for optimizing the MC particle population to achieve good MC statistics at this point. CADIS uses one adjoint calculation to build the biased source and the weight-windows. The adjoint source was defined as a point source with a spectrum equal to the flux-to-dose-rate conversion factors in a 46 neutron/21 gamma group structure. The source biasing parameters were not used and the actual ITER source was used in the MC calculation. For comparison purposes, the dose rate was also calculated using a very high resolution mesh with Denovo. Denovo uses the KBA algorithm [14] to solve the S_N form of the transport equation on a 3-D orthogonal mesh in parallel. It has demonstrated excellent scaling capabilities when running massive problems with very high resolution on thousands of cores [10].

Total flux

The total neutron flux was calculated throughout the ITER plant to demonstrate the effectiveness of FW-CADIS in simultaneously optimizing the MC statistics everywhere in the plant. The adjoint source was defined to include the whole ITER geometry and the total neutron and gamma fluxes were used as the responses to be optimized.

RESULTS

The ITER MCNP model Alite03 [15], for which the CAD model does not exist, was used in this analysis. An approximated uniform volumetric source of 14.1 Mev neutrons was used instead of the Alite03 neutron source which is defined in a 40×40 R-Z cylindrical mesh.

The dose rate calculation showed the difficulty of obtaining reliable results outside the bioshield using analog MCNP even with a point detector tally. It also showed that the use of CADIS in ADVANTG increased the MC FOM by a factor >400 when compared to analog MCNP for which the point detector tally results are unreliable. ADVANTG was used to create a 280 million cell Denovo input file from the Alite03 MCNP model and an approximated source. The calculation, which was performed on 14,400 cores on the ORNL supercomputer, Jaguar using a 46 neutron/21 gamma FENDL-2.1 library, took a total of 610 computer days. The results showed only a factor of 2 difference between ADVANTG and Denovo results despite the 13 orders of magnitude of total neutron flux attenuation between the plasma source and the point. Table 1 shows the analog, CADIS/ADVANTG, and Denovo results of the prompt dose rate at the mentioned point.

Table 1: Preliminary dose rate calculation

	Dose rate (mrem/hr)	*Uncertainty*	*Time (days)*	*FOM*
Analog	0.04	67.90%	9.4	0.0002
CADIS	0.34	2.90%	9.7	0.084
Denovo	0.18	61.53 minutes on 14,400 cores = 610 processors days		

The preliminary calculations of the total neutron and gamma fluxes showed the effectiveness of FW-CADIS in decreasing the uncertainties throughout the ITER machine. Figures 1 and 2 show the cumulative distribution functions of the MC uncertainties for the analog and FW-CADIS calculations with equal running times. The parallel version of MCNP was with both of the analog and FW-CADIS cases and the calculations were limited to only 10 processors days for each case. This only represent <1% of typical MCNP running times for ITER relevant problems when good statistical accuracy is required and the Alite03 model is used [15]. Figure 1 shows that, for the total neutron flux, more than 35% of the mesh tally voxels have less than 10% uncertainty with

FW-CADIS, as compared with only 4.4% of the voxels in the analog case. The total gamma flux in Fig. 2 shows similar differences in the fraction of voxels with low uncertainties between the FW-CAIDS and the analog cases. Longer running time is required to achieve acceptable uncertainties for both cases.

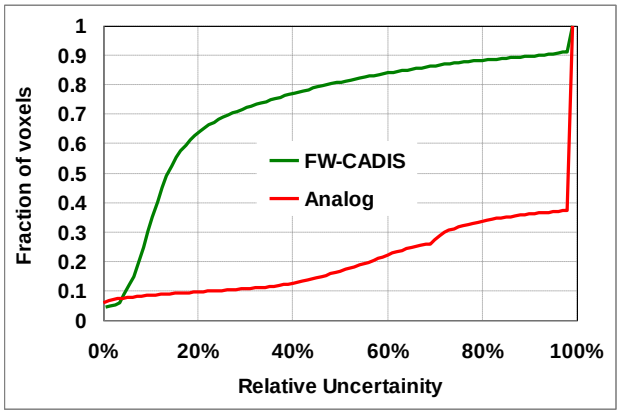

Figure 1: Cumulative distribution function of uncertainties in the total neutron fluxes throughout ITER

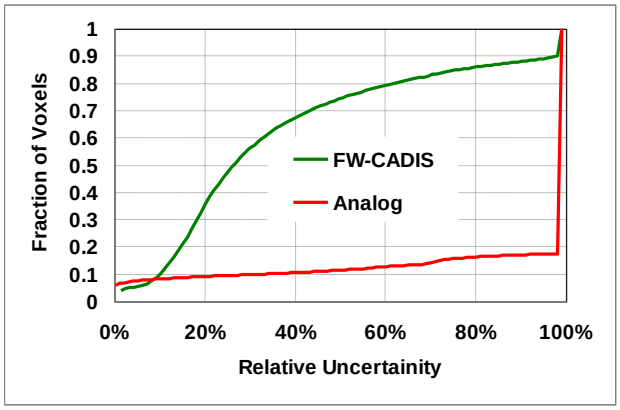

Figure 2: Cumulative distribution function of uncertainties in the total photon fluxes throughout ITER

More detailed results will be presented on all three parts of this study namely, the nuclear heating in the I/B TFC, prompt dose rate outside bioshield, and total flux distributions.

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