

Innovative Three-Dimensional Neutronics Analyses Directly Coupled with CAD Models of Geometrically Complex Fusion Systems

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Fusion systems are, in general, geometrically complex requiring detailed three-dimensional (3-D) nuclear analysis. This analysis is required to address tritium self-sufficiency, nuclear heating, radiation damage, shielding, and radiation streaming issues. To facilitate that, we developed an innovative computational tool (MCNP-CGM) for nuclear analysis that performs the neutronics calculations directly in the CAD model. This allows performing the calculations in a model that preserves the geometrical details without any simplification, eliminates possible human error in modeling the geometry for MCNP, and allows faster design iterations. In addition to improving the workflow for simulating complex 3-D geometries, it allows a richer representation of the geometry compared to the standard 2nd order polynomial representation. The MCNP-CGM approach uses the Common Geometry Module (CGM) software library to provide the ray-surface intersection capability directly on the surfaces of the CAD-based solid model. In cases where a solid model is used directly, the native MCNP ray-surface intersection algorithms are bypassed in favor of the CGM algorithms. Ray-tracing acceleration techniques were used allowing for Monte Carlo tracking speeds that are within a factor of 2-4 of the native Monte Carlo. Most features of the standard MCNP are now supported in the MCNP-CGM software. The integration of the direct geometry capability with the MCNP software was improved, largely by providing a more robust mechanism for changing the standard input file from its original format. This resulted in the ability to allocate materials with densities and define tallies in the solid model geometry file itself, reducing the burden on the user to manually determine the link between cell numbers and materials and tallies.

In order to validate the use of CAD-based neutronics tools for ITER analysis, a benchmark problem was developed based on a simplified 40° sector of the ITER machine. While the model includes all ITER components, detailed structures in each component are suppressed and homogenized material definitions are used. Even with these simplifications, the model includes 779 distinct volumes representing all the components in a 40° sector. These benchmark problems have been performed successfully with the MCNP-CGM tool. The model used in the calculations

is shown in Fig. 1. The calculations included determining the poloidal variation of the neutron wall loading, flux and nuclear heating in the divertor components, nuclear heating in the toroidal field coils, and radiation streaming in the mid-plane port.

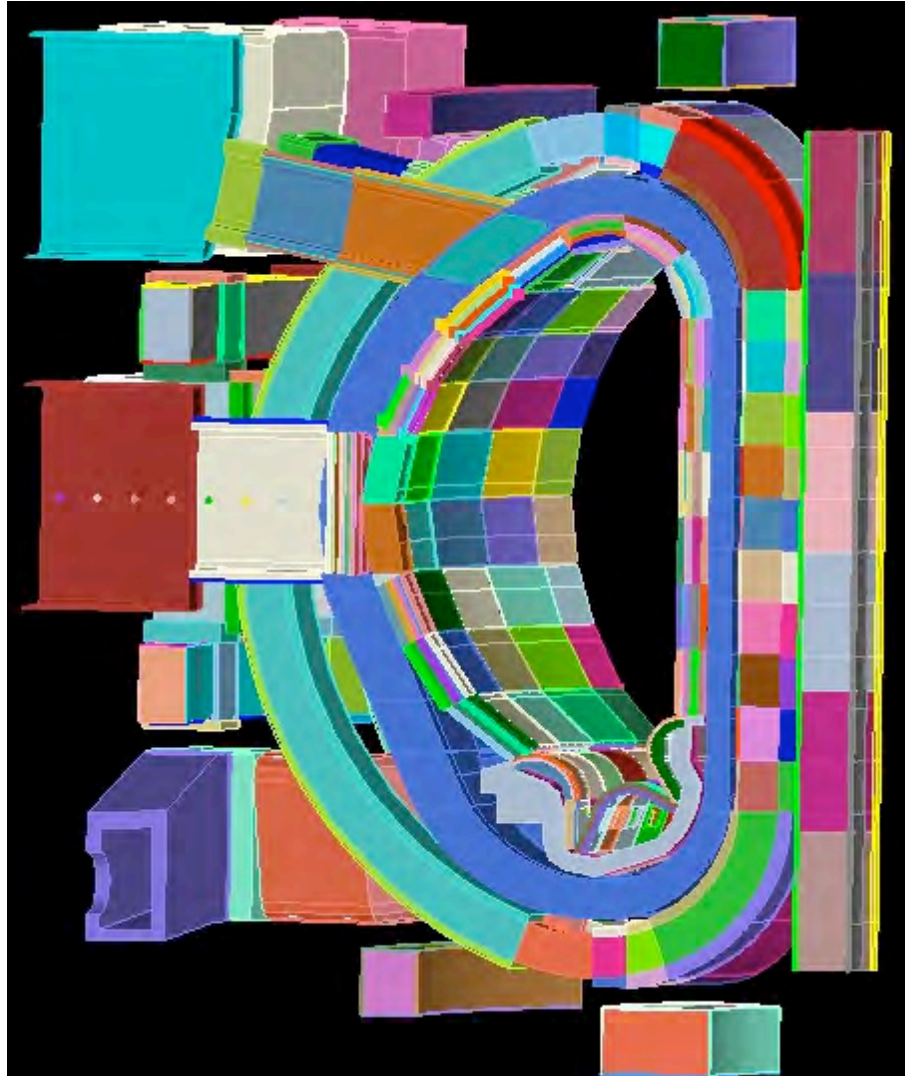


Fig. 1. ITER benchmark used for MCNP-CGM validation.

The tool has been applied to perform 3-D nuclear analysis for several fusion designs including the ARIES Compact Stellarator (ARIES-CS), the High Average Power Laser (HAPL) inertial fusion power plant, and ITER first wall/shield (FWS) modules. The ARIES-CS stellarator has a first wall shape and a plasma profile that vary toroidally within each field period compared to the uniform toroidal shape in tokamaks. Such variation cannot be modeled analytically in the standard MCNP code. A model of the full ARIES-CS system was developed based on a 1/6 toroidal solid model. The solid model was generated with blanket, shield,

manifold, and divertors as shown in Fig. 2. The impact of the complex helical geometry and the non-uniform blanket and divertor on the overall tritium breeding ratio and total nuclear heating was determined. In addition, we calculated the neutron wall loading variation in both the poloidal and toroidal directions.

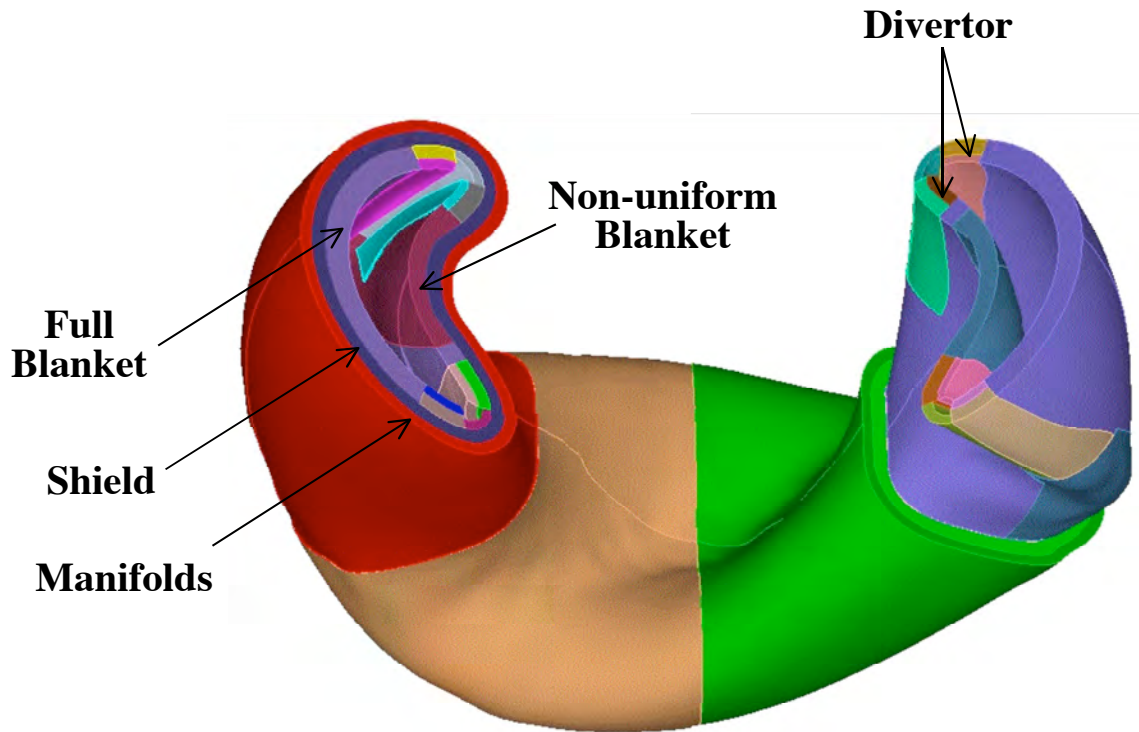


Fig. 2. Three-dimensional neutronics model of ARIES-CS.

In the HAPL program, power plant designs are assessed with 350 MJ yield targets driven by 40 KrF laser beams. The final optics system that focuses the laser onto the target includes a grazing incidence metallic mirror (GIMM) located at 24 m from the target with 85° angle of incidence. The GIMM is in direct line-of-sight of the target and has a 50 microns thick aluminum coating. Although the dielectric turning and focusing mirrors are not in the direct line-of-sight of the neutron source, radiation scattering and streaming through the laser beam ports requires an assessment of the nuclear environment at the final optics to predict their lifetime. We performed 3-D neutronics calculations to determine the nuclear environment at the final optics using the MCNP-CGM code. As shown in Fig. 3, the fast neutron flux decreases by about two orders of magnitude as one moves from the GIMM to the focusing mirror (M2) with an additional two

orders of magnitude attenuation at the turning mirror (M3) accompanied with significant spectrum softening.

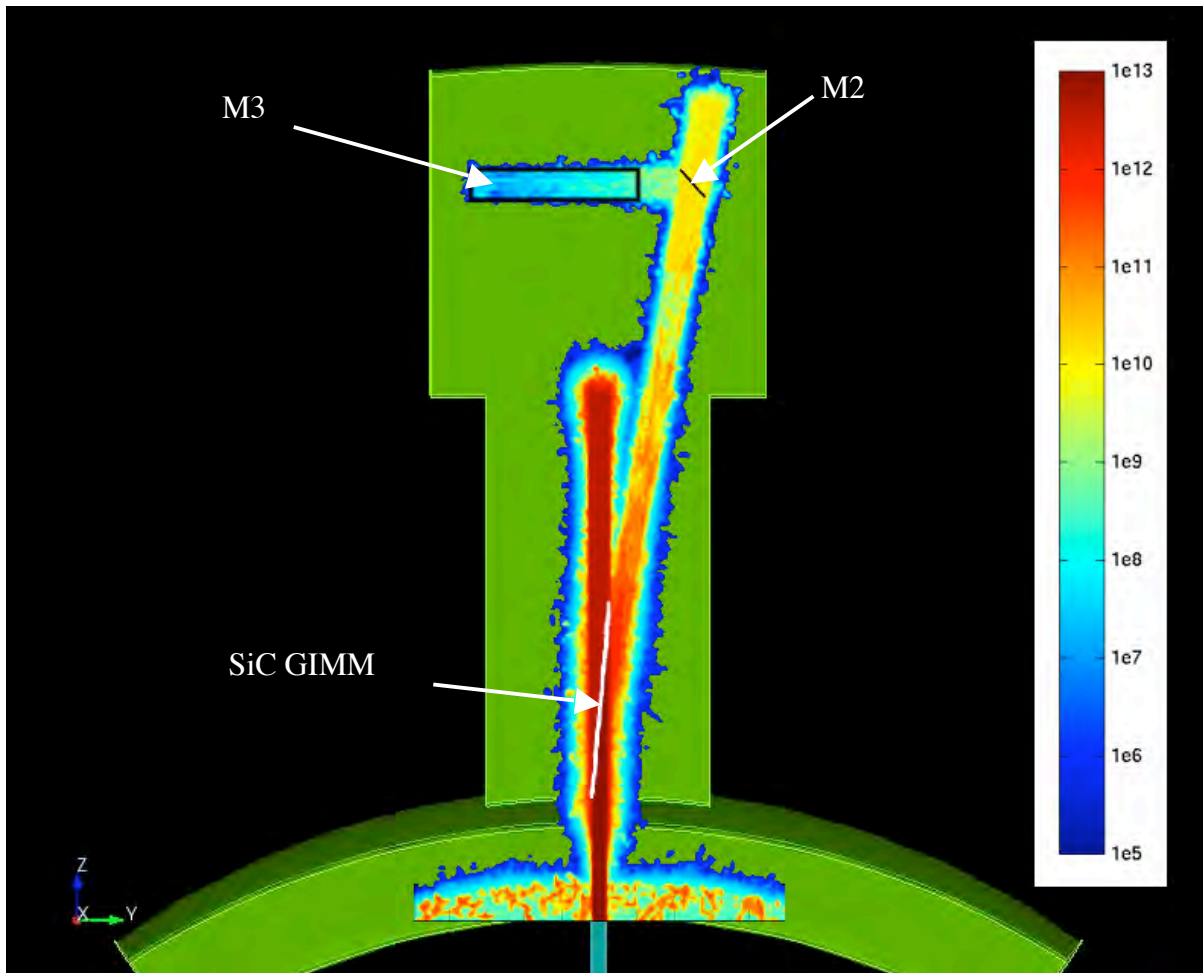


Fig. 3. Fast neutron flux distribution at final optics of HAPL.

Detailed CAD models of the ITER FWS modules were analyzed to produce high-resolution maps of nuclear heating, radiation damage and helium production. Nuclear heating, radiation damage, and helium production profiles are shown in Fig. 4 in the reservoir section of ITER FWS module 13 toward the front of the shield block. These high fidelity, high-resolution results revealed important heterogeneity effects on nuclear parameters. Significant variations in heating and He production occur at each radial location as a result of heterogeneity while much less variation is observed in dpa. While nuclear heating is higher in steel than in water regions, the steel nearest the water sees the highest nuclear heating. In addition, He production in the steel immediately adjacent to the water is larger than the average He production in the steel.

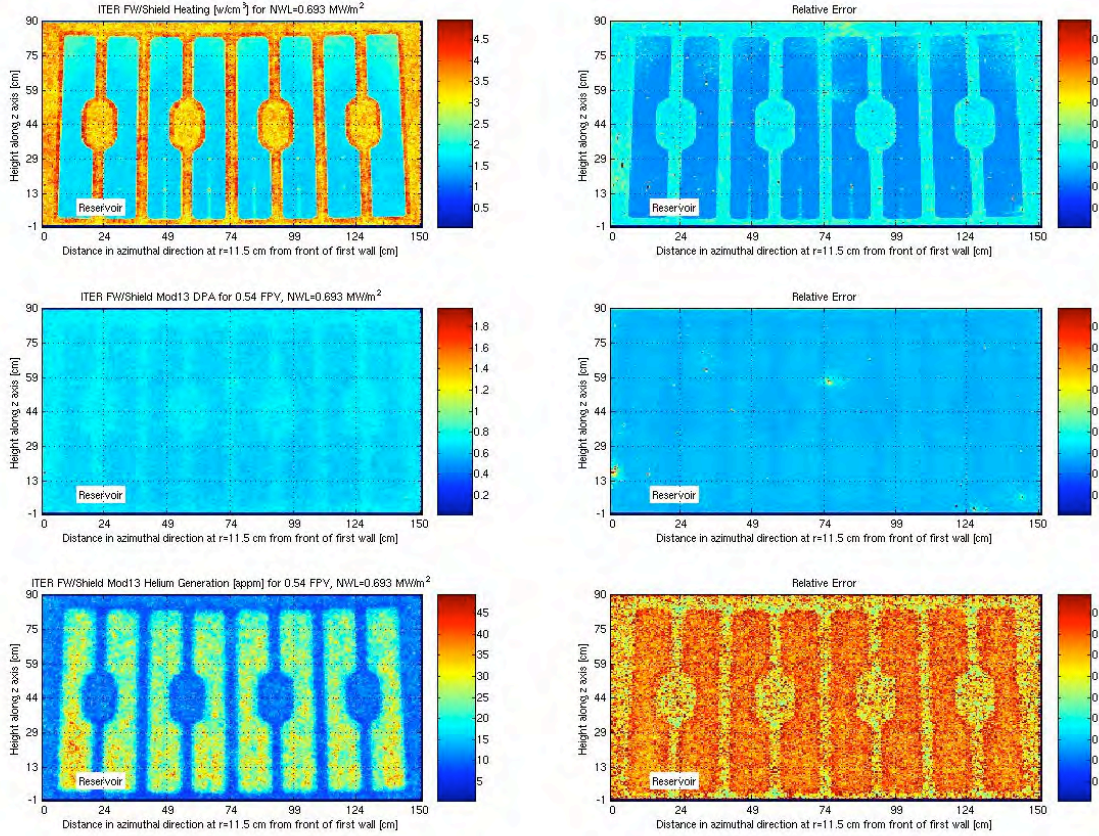


Fig. 4. Nuclear heating, radiation damage, and He production profiles in reservoir section of ITER FWS module 13.

We conclude that the MCNP-CGM code that performs the 3-D Monte Carlo neutronics calculations directly in the detailed CAD geometrical model allows efficient nuclear analysis of geometrically complex components of fusion systems. This eliminates human error, improves accuracy and cuts down turnaround time to accommodate design changes and iterations. The combination of exact geometry modeling and 3-D mesh tallies in the MCNP-CGM calculation results in high fidelity, high-resolution results that will significantly improve the design process.