Advances in neutronics tools with accurate simulation of complex fusion systems

Mohamed Sawan
P. Wilson, T. Tautges (ANL), L. El-Guebaly, T. Bohm, D. Henderson, E. Marriot, B. Kiedrowski, A. Ibrahim, B. Smith, R. Slaybaugh

FNS/TBM Meeting, UCLA
9/19/07
Nuclear Analysis is Essential Part of Fusion Reactor Design

- Tritium production in breeding blankets to ensure tritium self-sufficiency
- Nuclear heating (energy deposition) for thermal analysis and cooling requirement
- Radiation damage in structural material and other sensitive components for lifetime assessment
- Provide adequate shielding for components (e.g., magnets) and personnel access
- Activation analysis for safety assessment and radwaste management
• Fusion systems are geometrically complex with significant heterogeneity
• Models are routinely generated as part of a CAD drafting/design process
• Recent advances in radiation transport simulation tools enable an increased fidelity and accuracy in modeling fusion complex geometries by coupling to these 3-D CAD-based geometries
• Tools:
  – Stochastic (Monte Carlo)
  – Deterministic
Stochastic Methods

• Have been used for modeling complex geometries in fusion systems. MCNP is the most commonly used tool.
• Accurate energy representation using continuous energy treatment.
• Substantial computational effort is required to sufficiently reduce the statistical uncertainty associated with results behind thick shields. Parallel by nature allowing using several parallel processors. Along with utilizing advanced variance reduction techniques and current high speed computers, accurate results can now be obtained in reasonable time.

• Provided results at a few specific locations.

Recent versions of MCNP utilize mesh tallies to generate detailed results over a (fine) mesh covering the geometry.
The geometric representation in MCNP is based upon Boolean combinations of 2nd- or lower-order surfaces (except for elliptical torus).

For complex geometries, converting a geometric description into the description language used by MCNP is a tedious, labor-intensive and error-prone process.

Two separate approaches are being explored to alleviate these difficulties:

**Automated translation**
- Translates CAD-based geometry into the input language of MCNP
- Requires a first step to simplify the solid model to eliminate high-order surfaces
- McCad (FZK), MCAM (ASIPP), GEOMIT (JAEA)

**Direct geometry utilization**
- Changes MCNP software to perform the ray-tracing directly in CAD model
- Can handle any complex surface without need for simplification
- New techniques have been used to accelerate this direct approach to reasonable speeds (x2)
- DAG-MCNPX (UW)
Deterministic Methods

- Due to limitations in representing features of complex geometries, deterministic methods have traditionally been limited to 1- or 2-D approximations

  *The ability to solve the discrete-ordinates formulation of the radiation transport equations on a tetrahedral, unstructured finite-element mesh has resulted in a dramatic increase in the complexity of models that can be analyzed with deterministic methods*

  - ATTILA (commercial code developed by Transpire and applied to fusion systems by UKAEA, UCLA, PPPL) [See Youssef presentation]

- Provide answers across the entire domain, and without statistical uncertainties

- For many large fusion systems, the geometry requires many mesh-elements, the angular approximation requires many angles, and the energy approximation requires many groups, leading to a solution that requires long computer runtimes and large available memory

  *Require limiting order of angular representation and number of energy groups. Coarse meshing with low order angular representation could lead to negative fluxes*
Common Issues for CAD-Based Neutronics Tools

- CAD models usually include design details (small bolt holes, rounded corners) that add substantial complexity but do not affect the important neutronics quantities. This requires making decisions regarding which features to remove and how to remove them.

- Solid models generally do not define the space between bodies, often referred to as the “void” or “complement” space. This space has to be defined by subtracting all the solid bodies from an encompassing volume and could introduce flaws and inconsistencies in the geometry.

- Experience to date shows that many CAD-based geometries have small flaws or inconsistencies that can inhibit their use in neutronics analysis. “Repairing” these flaws currently requires human intervention, but methods to produce “cleaner” geometries will be preferred in the future.
Human effort shifts from traditional 3-D neutronics model creation to CAD/Solid Model repair

- Overlapping Volumes (i.e.: clashes)
- Mating surfaces not contacting
- Slight "Misalignment"
Examples of Typical CAD Issues and Typical Repairs

**Issue – Overlapping Volumes**
- Action - Volume trimmed to contact only

**Issue – No Contact**
- Action – Edit geometry to establish proper contact

**Action – MAY require recreating volume**
- Edges cross at this point
ITER Benchmark

- Used for validation of CAD-based neutronics tools
- 40 degree machine sector
- ~800 cells
- ~10000 surfaces
- 17 material specifications
- Model is substantially simplified, based only on 2\textsuperscript{nd}-order surfaces and including partial or full homogenization of some components
ITER Benchmark

• Comparing 4 results
  – Neutron wall loading
  – Divertor fluxes and heating
  – Magnet heating
  – Midplane port shielding/streaming

• Participants
  – UW, FZK, ASIPP, JAEA, UCLA

• Despite small variations in results, the tools are considered sufficiently mature for further use in nuclear analysis of ITER machine and its components
Advances in Neutronics Tools with Accurate Simulation of Complex Fusion Systems

Neutron Wall Loading: results
TF Coils : results
Mid-plane Port: results

![Graph showing total neutron flux vs distance from first wall for different simulations: ASIPP, FZK, JAEA, UCLA, UW. The x-axis represents distance from the first wall in cm, ranging from 0 to 600, and the y-axis represents total neutron flux in n/cm², ranging from $1.0 \times 10^9$ to $1.0 \times 10^{15}$. Each simulation is represented by a different marker and line color.](image)
Monte Carlo Tools
McCAD
FZK (Germany)

- Translator approach
- Applied to perform nuclear analysis of Electron Cyclotron Resonance Heating (ECRH) system installed in an upper port of ITER

U. Fischer, et al
Monte Carlo Tools
MCAM
ASIPP (China)

- Bi-directional translator
  - Large geometry manipulation feature set
- Applied to perform nuclear analysis for the ITER port limiter

Y. Wu, et al
Monte Carlo Tools
TopAct
Ratheeon/LLNL

- Translator approach
- Production experience
  - NIF “Clamshell”
  - NIF target bay

J. Latkowski, et al
• Direct use of solid model geometry in MCNPX
• Interface MCNPX *directly* to CAD & other geometry data

Ray-tracing acceleration techniques used allowing for tracking speeds that are within a factor of 2-3 of the native MCNP

• Production experience
  – ARIES-CS
  – HAPL
  – ITER FWS
Motivations

• Reduce impacts of manual conversion of 3-D model data
  – Reduce preparation time and allow faster design iterations
  – Avoid need for geometrical simplifications to 2nd order polynomials
  – Eliminate possible human errors in modeling

• Extend richness of geometric representation by preserving geometrical details
Application to ARIES-CS
Compact Stellarator

- Geometry complex
- FW shape and plasma profile vary toroidally within each field period
- Cannot be modeled by standard MCNP

Examined effect of helical geometry and non-uniform blanket and divertor on NWL distribution and total TBR and nuclear heating
NWL Maps (colormaps in MW/m²)

- 5 cm SOL
- 30 cm SOL
- uniform src
- Radiative heating

Toroidal Angle (degrees)
Poloidal Angle (degrees)
Neutron Flux in Laser Beam Duct

SiC GIMM

M3

M2

Flux (n/cm²s)

10^13

10^12

10^11

10^10

10^9

10^8

10^7

10^6

10^5
ITER FWS Module Elements
Module 13 detail

Model generated by designers at SNL using standard tools (CATIA/CUBIT)

9/19/07
Advances in Neutronics Tools with Accurate Simulation of Complex Fusion Systems

3-D Modeling
Module 13 1-D/3-D hybrid analysis

IB Shield

Plasma

SS/water homogenized complement

Mod. 13
Nuclear Heating at a distance of 11.5 cm from front of FW
SS He Production at a distance of 11.5 cm from front of FW
3-D Visualization of Nuclear Heating in FWS Module 13
Important effects observed from high-fidelity 3-D results

- 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 because of gamma generation in the water itself and softer neutron spectrum in SS resulting in more gamma generation.
- He production in the steel immediately adjacent to the water is larger than the average He production in the steel due to softer neutron spectrum resulting in increased He production primarily in the B-10 in SS316LN-IG (has 10 wppm B) and Ni.
In 1D/3D hybrid model, angular distribution of source neutrons incident on FW is more tangential than in actual case resulting in more interactions at front surface with overestimated nuclear heating (up to ~50% at front surface of FW)

**Improved 1D/3D Hybrid Analysis**

Use a surface source at FW front surface that is determined from the ITER model (with approximate FWS) with exact source distribution

**Full 3-D Analysis**

CAD model for Mod. 13 is being inserted in a simplified full ITER model with accurate source profile in plasma
Conclusions

- CAD-based neutronics tools are developed to produce results with high-fidelity and high-resolution on complex fusion geometries.

- This eliminates human error, improves accuracy and cuts down turnaround time to accommodate design changes and iterations.

- While these new capabilities are currently under development and subjected to a quality assurance process for use on ITER, they are already providing important results as part of the design of ITER and other systems.

- Engineers and designers are already beginning to expect high-fidelity nuclear analyses on complex systems as part of the design process and taking advantage of the new insights that this offers.
Questions?

sawan@engr.wisc.edu

9/19/07