Application of CAD-Neutronics Coupling to Geometrically Complex Fusion Systems

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Outline

• Motivations
• DAGMC approach
• Implementation
• Acceleration Techniques
• Applications
  - ITER
  - ARIES-CS
  - HAPL
Fusion Reactors are Complex with Many Components

Central Solenoid
Nb₃Sn, 6 modules

Outer Intercoil Structure

Toroidal Field Coil
Nb₃Sn, 18, wedged

Poloidal Field Coil
Nb-Ti, 6

Machine Gravity Supports
(recently remodelled)

Blanket Module
421 modules

Vacuum Vessel
9 sectors

Cryostat
24 m high x 28 m dia.

Port Plug (IC Heating)
6 heating
3 test blankets
2 limiters/RH
rem. diagnostics

Divertor
54 cassettes

Torus Cryopump
8, rearranged
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
Motivations

• Engineering designs dominated by computer-aided design processes
• Generating input files manually can be a tedious and error-prone process
• Automation (including translation) provides:
  – Reduced human effort
  – Increased quality assurance
  – Faster design iteration
• Direct geometry use (DAGMC) provides additional advantages
  – Richer surface representation that allows higher-order surface descriptions in analysis
  – Provide common domain for coupling to other engineering analyses
• Use Mesh Oriented dAtaBase (MOAB) and Common Geometry Module (CGM) to interface MC code \textit{directly} to CAD (\& other) geometry data

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

• Production experience
  – ITER Benchmark
  – ITER FWS
  – ITER TBM
  – ARIES-CS
  – HAPL
Workflow Includes a Variety of New Tools and Skills

Generate CAD Geometry

- Standard CAD software tools are used to define the solid model

Annotate CAD Geometry

- Allocate materials and densities
- Define boundary conditions
- Define tally locations
- Imprint & Merge

Prepare Input File

- Skip cell and surface definitions
- Provide data cards
  - Material definitions
  - Tally modifiers
  - Source definition
  - etc...

DAG-MCNP

- Read Model and Initialize Search Tree

Perform Random Walks

Report Tally Results
Accelerations

• Imprint & merge
  – Reduce complexity of determining neighboring regions in space

• Faceting
  – Reduce ray-tracing to always be on (planar) facets

• Oriented Bounding Box Tree
  – Accelerate search of millions of surfaces
  – Reduce number of surface tests
Accelerating the Neighboring Cell Determination

- Imprinting
- Merging
- Each surface in max. 2 cells
Avoiding the Explicit Calculation of the “Complement”

- CAD-based solid models do not typically represent non-solid regions
  - e.g. voids, coolants
- Explicit calculation
  - Boolean operations in CAD (or CUBIT)
  - Often computationally expensive
- Implicit determination
  - Volume bounded by surfaces with only 1 cell following imprint & merge
Oriented Bounding Box on Facets as Nodes in a Tree

- Axis-aligned bounding box often larger than necessary
- *Oriented* bounding box makes smaller boxes
- OBB on facets allows finer-granularity boxes to be arranged in tree
- Tree of OBBs reduces # tests
CAD Issues Requiring “Repair”

Issue – Overlapping Volumes
Action – Edit geometry to establish proper contact

Issue – No Contact
Action – MAY require recreating volume

Edges cross at this point

Human effort shifts from traditional MCNP model creation to CAD/Solid Model repair
DAG-MCNP Functionality Status
(compared to standard MCNP)

**Geometry**
- Cell volume/Surface areas – functional
- Boundary conditions
  - Specular reflection – functional
  - White reflection – functional
  - Periodic – long term
- Lattice/universe – long term
- Material/Densities read from geom – functional

**Source**
- Fixed source – functional
- Fission source – functional
- Surface source write/read – functional

**Variance Reduction**
- Cell importance – functional
- Exponential transform – functional
- Forced collision – functional
- Weight windows (cell-based) – functional
- Weight windows (mesh-based) – functional
- Detector tallies - functional

**Tallies**
- Surface current (type 1) – functional
- Cosine bins – functional (directional ambiguity)
- Surface flux (type 2) – functional
- Cell flux (type 4,6,7) – functional
- Pulse height (type 8) – testing
- Point detector (type 5) – functional
- Mesh tallies – functional in MCNPX

Note: MCNP and MCNPX have different mesh tally implementations
- Cell flagging – functional
- Surface flagging – functional
- Multipliers – functional
- Segmenting – long term ??
- Tally locations read from geom – functional
Applications

- ITER Benchmark
- ITER FW/Shield Modules
- ITER DCLL TBM
- ARIES Compact Stellarator
- HAPL Laser Fusion Design
ITER Benchmark

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

- Participants
  - UW, FZK, ASIPP, JAEA, UCLA
ITER Benchmark Model: >800 cells, ~10,000 surfaces
Overall Performance Less than 3x Slower than Native Geometry

- Performance of translation approaches vary by 60%

<table>
<thead>
<tr>
<th>Model</th>
<th>Number of Volumes</th>
<th>Number of Surfaces</th>
<th>Relative CPU-Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCAM translation</td>
<td>4148</td>
<td>3192</td>
<td>1</td>
</tr>
<tr>
<td>McCad translation</td>
<td>6031</td>
<td>3800</td>
<td>1.63</td>
</tr>
<tr>
<td>DAGMC</td>
<td>802</td>
<td>9834</td>
<td>2.46</td>
</tr>
</tbody>
</table>
ITER First Wall & Shield

- Design includes performing detailed structural, CFD and EM analyses
- Detailed high-resolution mapping of nuclear parameters (nuclear heating, radiation damage) in the module is an essential input to design

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Analysis for an Initial Mod 13 Design

ITER FW/Shield Heating [W/cm²] for NWL=0.693 MW/m²

Front Manifold

Distance in azimuthal direction at 11.5 cm from front of first wall [cm]

Height along z axis [cm]

Distance in radial direction [cm]

azimuthal direction [degrees]

0 10 20 30 40 50 60 70 80 90

1 2 3 4 5 6 7 8 9 10

0 1 2 3 4 5 6 7 8 9
Surface source determined from calculations for the full ITER model to used at FW front surface to accurately account for the 3-D source representation.
Nuclear heating calculated in FW layers

Cu Layer

Surface Source [w/cm²]

SS Layer

Surface Source [w/cm²]

Back Surface of FW

Front Surface of Shield

Front of Shield
Mesh Interpolation for Multi-Physics Analysis

- High-fidelity mesh tallies in MCNP
  - Large orthogonal regular grids (e.g. 26M voxels)
- Interpolate to CFD & heat transfer analysis mesh
  - Large unstructured tet-mesh (e.g. 15M elements)
- Based on MOAB scalable open-source infrastructure
  - KD-tree for MCNP mesh elements
  - Centroid or vertex interpolation on piecewise uniform mesh
  - Store
    - Volumetric heating on vertices, and/or
    - Integral heating on elements

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Interpolated mesh tallies used in CFD calculations (SC/Tetra code)

Temperature distribution in FW of Mod. 13 determined by Ying and Narula (UCLA) using the translated nuclear heating mesh tallies and the thermo-fluid CFD code SC/Tetra with ~11.5 million elements.

Be, Cu, SS, Water
Detailed 3-D Neutronics for DCLL TBM

Source Input Table

Mid-plane nuclear heating

Mid-plane T production

Steel damage at section X2

Mid-plane T production

DCLL TBM

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### Overall TBM Nuclear Parameters

<table>
<thead>
<tr>
<th>Material</th>
<th>Total Nuclear Heating (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferritic Steel</td>
<td>0.121</td>
</tr>
<tr>
<td>Lead Lithium</td>
<td>0.218</td>
</tr>
<tr>
<td>SiC FCI</td>
<td>0.028</td>
</tr>
<tr>
<td>Be PFC</td>
<td>0.007</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>0.374</strong></td>
</tr>
</tbody>
</table>

- Tritium generation rate in the PbLi is $4.19 \times 10^{-7}$ g/s during a 500 MW D-T pulse.
- For the planned 3000 pulses per year annual tritium production in TBM is 0.53 g/year.
- Tritium production in the Be PFC is $1.04 \times 10^{-3}$ g/year.

Detailed 3-D analysis of TBM with the surrounding massive water cooled frame and representation of exact source and other in-vessel components yields total tritium production and nuclear heating in TBM that are ~40% lower than the 1-D estimate.
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
ARIES-CS Overall Nuclear Parameters

NWL map

Summary of Energy Multiplication Results for LiPb/He/FS System

<table>
<thead>
<tr>
<th>Component/Area</th>
<th>6^Li Enrichment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30%</td>
</tr>
<tr>
<td>Blanket</td>
<td>0.99</td>
</tr>
<tr>
<td>Uniform</td>
<td>0.74</td>
</tr>
<tr>
<td>Nonuniform</td>
<td>0.24</td>
</tr>
<tr>
<td>Behind divertor</td>
<td>0.013</td>
</tr>
<tr>
<td>Shield</td>
<td>0.065</td>
</tr>
<tr>
<td>Main shield</td>
<td>0.045</td>
</tr>
<tr>
<td>Behind divertor</td>
<td>0.020</td>
</tr>
<tr>
<td>Manifold</td>
<td>0.0014</td>
</tr>
<tr>
<td>Divertor plates</td>
<td>0.10</td>
</tr>
<tr>
<td>ECH duct</td>
<td>5.7 x 10^-5</td>
</tr>
<tr>
<td>Total</td>
<td>1.16</td>
</tr>
<tr>
<td></td>
<td>(±0.13%)</td>
</tr>
</tbody>
</table>

aThe 1σ statistical error is shown for the total M_n in each case.

Summary of 3-D TBR Results for LiPb/He/FS System

<table>
<thead>
<tr>
<th>Blanket Region</th>
<th>6^Li Enrichment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30%</td>
</tr>
<tr>
<td>Uniform</td>
<td>0.73</td>
</tr>
<tr>
<td>Nonuniform</td>
<td>0.15</td>
</tr>
<tr>
<td>Behind divertor</td>
<td>0.022</td>
</tr>
<tr>
<td>Total</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>(±0.18%)</td>
</tr>
</tbody>
</table>

The 1σ statistical error is indicated for each case.
High Average Power Laser (HAPL) Conceptual Design

- Direct drive targets
- Dry wall chamber
- 40 KrF laser beams
- 367.1 MJ target yield
- 5 Hz Rep Rate

Design with Magnetic Intervention

Large Chamber Design
Fast neutron flux at dielectric optics depends on material choice for the GIMM and total GIMM areal density

- AlBeMet GIMM results in highest flux level (factor of ~1.6 higher than with lightweight SiC GIMM)
- Significant drop in nuclear environment occurs as one moves from the GIMM to dielectric focusing and turning mirrors
Quick assessment of configuration options was facilitated by use of DAG-MCNP.
Initial configuration yields least radiation environment at dielectric mirrors and was selected for baseline HAPL design.
Conclusions

• Fusion systems are geometrically complex with many components requiring detailed 3-D nuclear analysis

• DAG-MCNP was developed to perform the 3-D Monte Carlo neutronics calculations directly in the detailed CAD geometrical model

• This eliminates human error, improves accuracy, cuts down turnaround time to accommodate design changes and iterations, and allows efficient coupling to other engineering analyses

• The tool has been successfully validated using an ITER benchmark and applied to perform nuclear analysis for several fusion designs resulting in high-fidelity, high-resolution results that significantly improve the design process
Questions?

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Neutron Wall Loading

![Graph showing Neutron Wall Loading with various lines representing different data sets: ASIPP, FZK, JAEA, UW, and UCLA. The graph plots NWL (MW/m²) against Module Number. The inset shows a source input table with radial and axial dimensions.](image)
Equatorial Port Results

![Graph showing neutron flux vs. distance from first wall]

- ASIPP
- FZK
- JAEA
- UCLA
- UW

Total Neutron Flux [n/cm²-s]

Distance from First Wall [cm]
• Build solid model in CAD or similar tools
• Define “graveyard”
  – Solid models are finite in extent
  – Require finite bounding cell with importance=0
• Dealing with “complement”
  – Most solid models do not define space that surrounds objects
    • Boolean operation in CAD tool to define complement volume
    • Implicit complement option automatically determines complement in DAGMC
• Export in format available to CUBIT/CGM
DAGMC Workflow
Geometry Manipulation

• Import into CUBIT
  – (Create complement in CUBIT)
• Imprint surfaces
• Merge surfaces
• Define MCNP info:
  – Material, density
  – Importance
  – Tally types/numbers
  – Reflecting surfaces
• Export in ACIS (.sat) format
CAD Issues Requiring “Repair”

Human effort shifts from traditional MCNP model creation to CAD/Solid Model repair

- Overlapping Volumes (i.e.: clashes)
- Mating surfaces not contacting
- Slight “Misalignment”