Innovative 3-D Neutronics Analyses Directly Coupled with CAD Models of Geometrically Complex Fusion Systems

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Fusion Reactors are Complex with Many Components
Central Solenoid
\( \text{Nb}_3\text{Sn}, 6 \text{ modules} \)

Outer Intercoil Structure

Toroidal Field Coil
\( \text{Nb}_3\text{Sn}, 18, \text{ wedged} \)

Poloidal Field Coil
\( \text{Nb-Ti}, 6 \)

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
ITER Status

- Agreement signed on November 21, 2006
- Seven parties with more than half of the world population
- Cost ~$7B
- ITER construction starts in 2007 at Cadarache, France
- First plasma in 2016 and 20 year operation
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
**Developed Innovative Computational Tool**

**MCNP-CGM**

- **Direct use of solid model geometry in MCNP**
  - Use Common Geometry Module (CGM) to interface MCNP *directly* to CAD & other geometry data

<table>
<thead>
<tr>
<th>MCNP</th>
<th>CGM</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCNP Native Geometry</td>
<td>CAD</td>
</tr>
<tr>
<td></td>
<td>Voxels</td>
</tr>
<tr>
<td></td>
<td>(Other)</td>
</tr>
</tbody>
</table>

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

- **Production experience**
  - ITER Benchmark
  - 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
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”
Examples of Typical CAD Issues and Typical Repairs

**Issue – Overlapping Volumes**

Action – Edit geometry to establish proper contact or trimming to contact only.

**Issue – No Contact**

Action – May require recreating volume.

Edges cross at this point.
ITER Benchmark

- 40 degree machine sector
- Used for validation of MCNP/CAD tool
- 802 cells
- 9834 surfaces
- 17 material specifications
ITER Benchmark

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

- Participants
  - UW, FZK, ASIPP, JAEA, UCLA
Neutron Wall Loading: results

![Graph showing neutron wall loading vs. poloidal distance]
TF Coils: results

**Nuclear Heating per Coil (W)**

<table>
<thead>
<tr>
<th>Distance from top of I/B TF coil [cm]</th>
<th>Neutron</th>
<th>Photon</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.39 ± 0.05</td>
<td>17.0 ± 0.6</td>
<td>18.4 ± 0.6</td>
</tr>
<tr>
<td>100</td>
<td>2.47 ± 0.06</td>
<td>29.4 ± 0.6</td>
<td>31.8 ± 0.7</td>
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<tr>
<td>200</td>
<td>3.82 ± 0.04</td>
<td>44.6 ± 0.4</td>
<td>48.4 ± 0.5</td>
</tr>
<tr>
<td>300</td>
<td>5.41 ± 0.05</td>
<td>60.4 ± 0.6</td>
<td>65.8 ± 0.6</td>
</tr>
<tr>
<td>400</td>
<td>6.03 ± 0.12</td>
<td>65.6 ± 0.9</td>
<td>71.6 ± 1.0</td>
</tr>
<tr>
<td>500</td>
<td>5.16 ± 0.08</td>
<td>57.0 ± 0.7</td>
<td>62.2 ± 0.8</td>
</tr>
<tr>
<td>600</td>
<td>3.38 ± 0.04</td>
<td>40.9 ± 0.5</td>
<td>44.3 ± 0.6</td>
</tr>
<tr>
<td>700</td>
<td>2.27 ± 0.04</td>
<td>29.9 ± 0.5</td>
<td>32.2 ± 0.6</td>
</tr>
<tr>
<td>800</td>
<td>3.66 ± 0.08</td>
<td>45.7 ± 1.3</td>
<td>49.4 ± 1.4</td>
</tr>
<tr>
<td>900</td>
<td>1.88 ± 0.05</td>
<td>24.0 ± 0.7</td>
<td>25.9 ± 0.7</td>
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<tr>
<td>Total</td>
<td>35.5 ± 0.2</td>
<td>415 ± 2.3</td>
<td>450 ± 2.5</td>
</tr>
</tbody>
</table>

8.1 kW in all TF I/B legs

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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/m$^2$)

5 cm SOL

30 cm SOL

uniform src

Radiative heating

X max

X max

Toroidal Angle (degrees)

Poloidal Angle (degrees)
TBR: 3-D Results Differ from 1-D

![Graph showing TBR and Energy Multiplication required vs. 6Li Enrichment]

- Required TBR range is marked.
- 1-D Estimate is indicated with an 'X'.

Nuclear Response vs. 6Li Enrichment graph.
HAPL Final Laser Optics
Neutron Flux in Laser Beam Duct

SiC GIMM

M3

M2

Flux (n/cm²s)
ITER First Wall/Shield
Module 13 Mockup

Model generated by designers using standard tools (CATIA/CUBIT)
Nuclear responses at reservoir (11.5 cm from front of FW)
FWS nuclear heating results
Conclusions

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

• An innovative calculation method was developed where the 3-D Monte Carlo neutronics calculations are performed directly in the detailed CAD geometrical model

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

• The tool has been successfully tested for 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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