Direct Coupling of 3-D Neutronics with CAD Models Applied to Fusion Systems

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Fusion Reactors are Complex with Many Components

Central Solenoid
- Nb$_3$Sn, 6 modules

Outer Intercoil Structure

Toroidal Field Coil
- Nb$_3$Sn, 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
DAGMC Concept

Motivation

- 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
- Direct geometry use provides richer surface representation
- Avoids need for geometrical simplifications to 2nd order polynomials
- Facilitates coupling to other analysis types through common geometry
Developed Innovative Computational Tool
DAGMC (Direct Accelerated Geometry Monte Carlo)

- Use Mesh Oriented dAtaBase (MOAB) and Common Geometry Module (CGM) to interface MC code *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(X)

- Production experience
  - ARIES-CS
  - ITER Benchmark
  - ITER FWS
  - HAPL
DAGMC Concept
Overcoming Inefficiency

- Previous efforts have been found slow (20-50x penalty)
- DAGMC relies on a growing number of accelerations
  - Imprinting and merging
    - Non-manifold geometry simplifies tracking between cells
  - Faceting
    - Simplify ray-surface interaction tests
  - Oriented bounding box trees
    - Reduce complex ray-surface interaction tests
Non-manifold Geometry

- Imprinting

- Merging
- Each surface in max. 2 cells
Hierarchical Oriented Bounding Box

- Axis-aligned bounding box often larger than necessary

- *Oriented* bounding box makes smaller boxes

- OBB on facets allows finer-granularity boxes

- Tree of OBBs reduces # tests
DAG-MCNPX Workflow

- 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
  - Implicit complement option automatically determines complement in DAGMC
- Export in format available to CUBIT/CGM
- Imprint surfaces
- Merge surfaces
- Define MCNP info:
  - Material, density
  - Importance
  - Tally types/numbers
  - Reflecting surfaces
- Export in ACIS (.sat) format
CAD Issues Requiring “Repair”

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

Issue – No Contact
Edges cross at this point
Action – MAY require recreating volume

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

- **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

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

Toroidal Angle (degrees) vs. Poloidal Angle (degrees)
ITER Benchmark

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

• Participants
  – UW, FZK, ASIPP, JAEA, UCLA
- FWS modules 7, 12, and 13 are allocated to the US
- Design includes assessment of stresses and performing detailed CFD and EM analyses
- Detailed distribution of nuclear parameters in the module is an essential input to design
- Accurate high-resolution nuclear heating results that can easily interface with finite element engineering analysis codes are required
Analysis Used a Hybrid 1-D/3-D Model and an Initial Mod 13 Design
Surface source used at FW front surface that is determined from calculations for the full ITER model to accurately account for the 3-D source representation.
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
Nuclear Heating
Module 13 CFD Mesh
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
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
HAPL Final Laser Optics

- Bio-Shield
- Focusing (M2)
- Turning (M3)
- GIMM (M1)
- Beam Duct
- Shield
- Blanket
Neutron Flux in Laser Beam Duct
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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Equatorial Port Results

Total Neutron Flux [n/cm$^2$-s]

Distance from First Wall [cm]

- ASIPP
- FZK
- JAEA
- UCLA
- UW
DAGMCNPX Workflow

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  - Require finite bounding cell with importance=0
- Dealing with “complement”
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    - Boolean operation in CAD tool to define complement volume
    - Implicit complement option automatically determines complement in DAGMC
- Export in format available to CUBIT/CGM
Implicit Complement

• Defining void space is common source of difficulty
• CUBIT performs imprinting & merging
  – All surfaces have only two volumes/cells
  – Often fails with explicit complement
  – Defines implicit complement = all surfaces with only one cell
• New OBB tree collects all surfaces of each volume into single tree
  – Efficient search of implicit complement
• 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”
Examples of Typical CAD Issues and Typical Repairs

Issue – Overlapping Volumes

Action – Edit geometry to establish proper contact

Issue – No Contact

Action – May require recreating volume

Edges cross at this point
ITER FWS Module Elements

- Shield Module Segment
- First Wall Panel Assembly
- Inter-Module Coaxial Flow Dividers
- First Wall Panel Assembly (Shown Mounted)
• 17M source particles
• 111 cpu-days (1.4/1.7 GHz Athlon)
• Mesh-based weight windows
• Results tallied on 0.5 cm x 0.5 cm x 1 cm mesh:
  – Nuclear heating (W/cm$^3$ in local material)
  – Radiation damage (dpa in stainless steel)
  – He production (appm in stainless steel)