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Application of CAD-Neutronics Coupling to Geometrically Complex Fusion Systems

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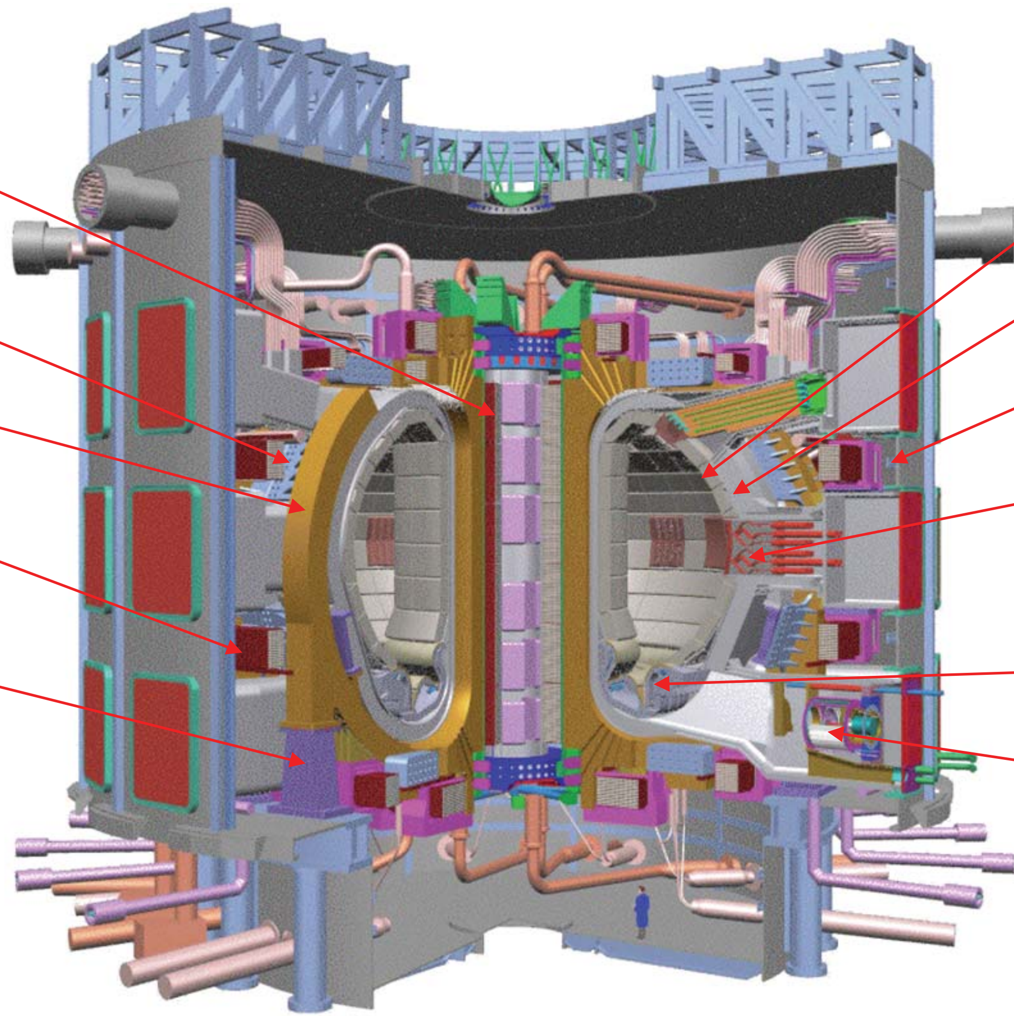
Outline

- Motivations
- DAGMC approach
- Implementation
- Acceleration Techniques
- Applications
  - ITER
  - ARIES-CS
  - HAPL

Fusion Reactors are Complex with Many Components



Central Solenoid
Nb_3Sn, 6 modules

Outer Intercoil Structure

Toroidal Field Coil
Nb_3Sn, 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

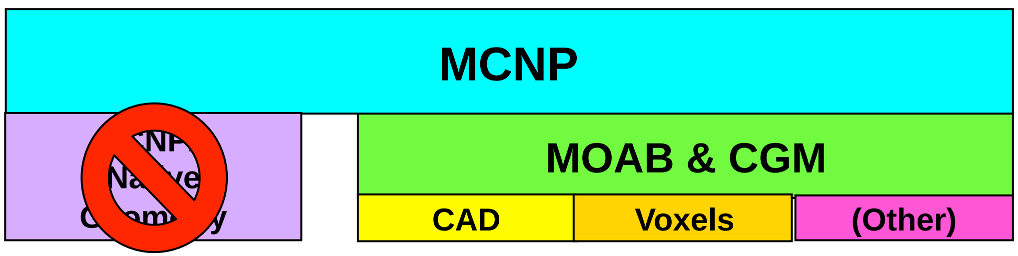
- Tritium production in breeding blankets to ensure tritium self-sufficiency
- Nuclear heating (energy deposition) for thermal analysis and cooling requirement
- Radiation damage in structural material and other sensitive components for lifetime assessment
- Provide adequate shielding for components (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

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

- 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

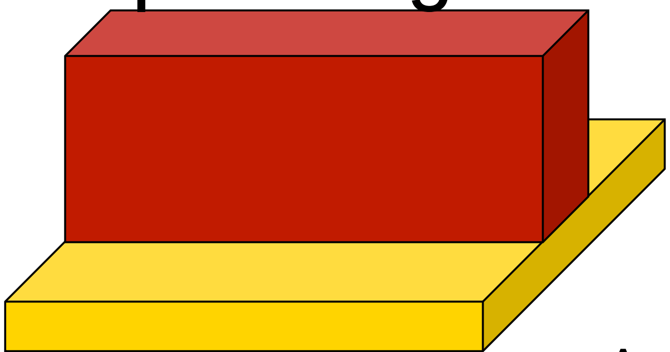
- Read Model and Initialize Search Tree
- Perform Random Walks
- Report Tally Results

Accelerations

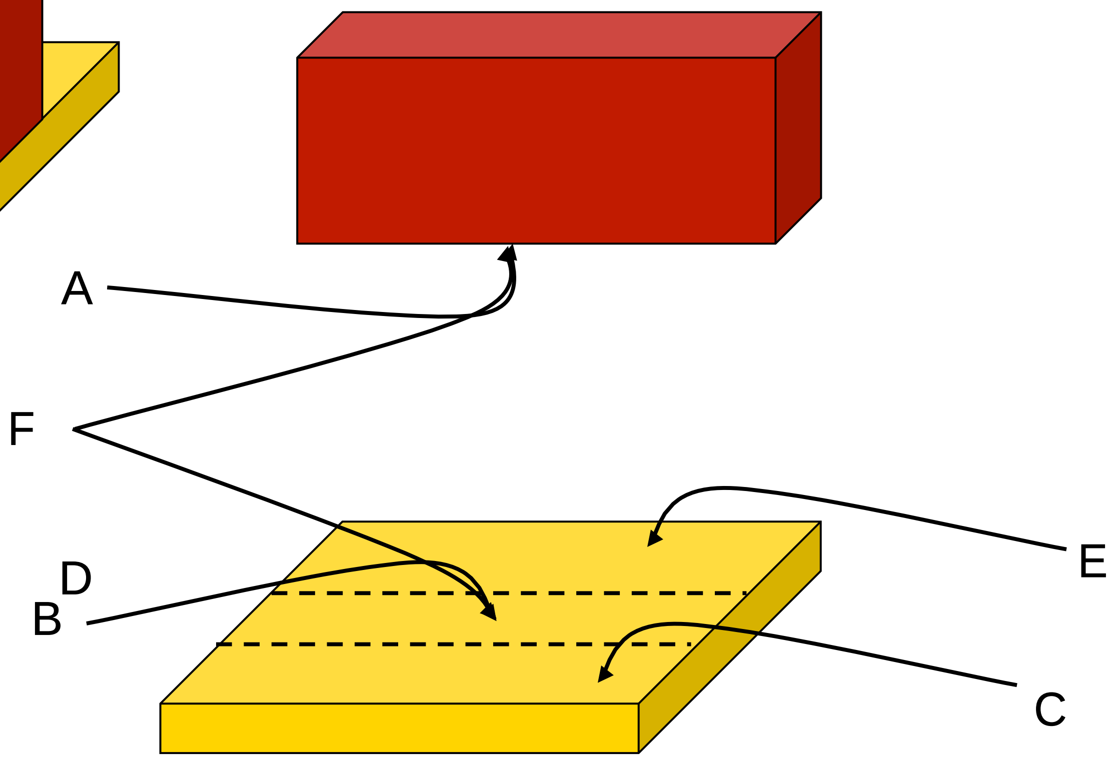
- Imprint & merge
  - Reduce complexity of determining neighboring regions in space
- Faceting
  - Reduce ray-tracing to always be on (planar) facets
- Oriented Bounding Box Tree
  - Accelerate search of millions of surfaces
  - Reduce number of surface tests

Accelerating the Neighboring Cell Determination

- Imprinting



- Merging



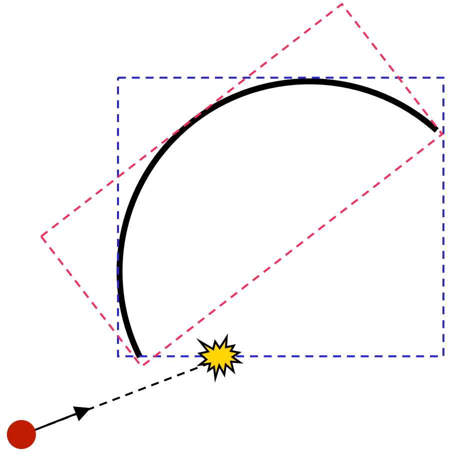
- Each surface in max. 2 cells

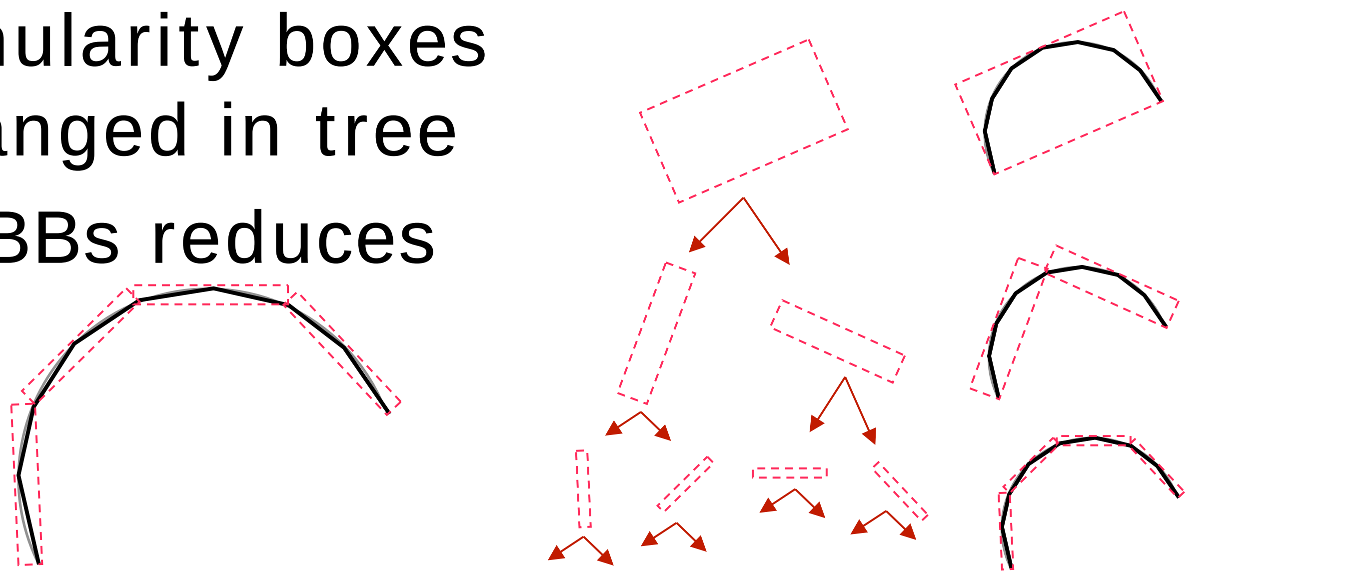
Avoiding the Explicit Calculation of the "Complement"

- 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

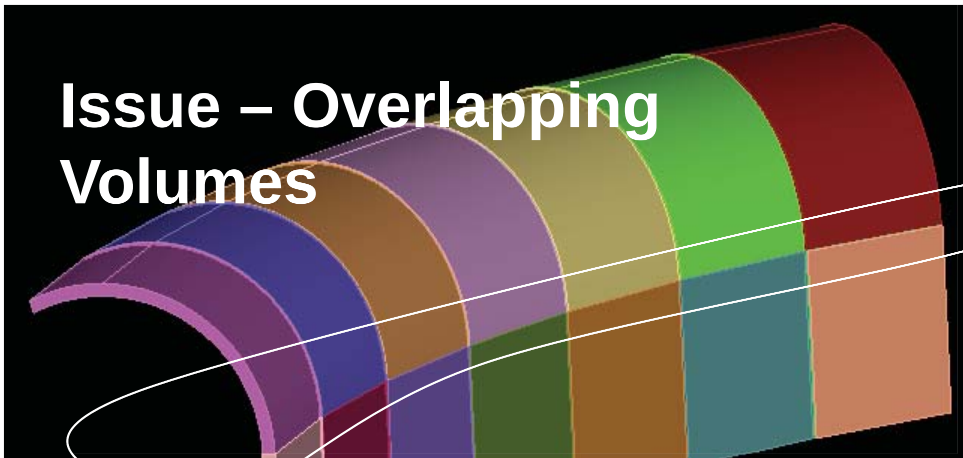
Oriented Bounding Box on Facets as Nodes in a Tree

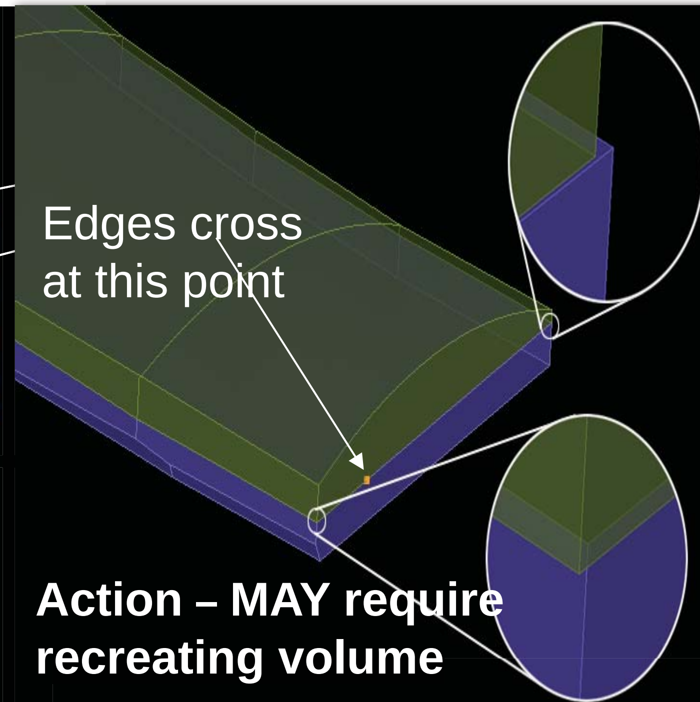
- Axis-aligned bounding box often larger than necessary
- *Oriented* bounding box makes smaller boxes
- OBB on facets allows finer-granularity boxes to be arranged in tree
- Tree of OBBs reduces # tests





CAD Issues Requiring "Repair"





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

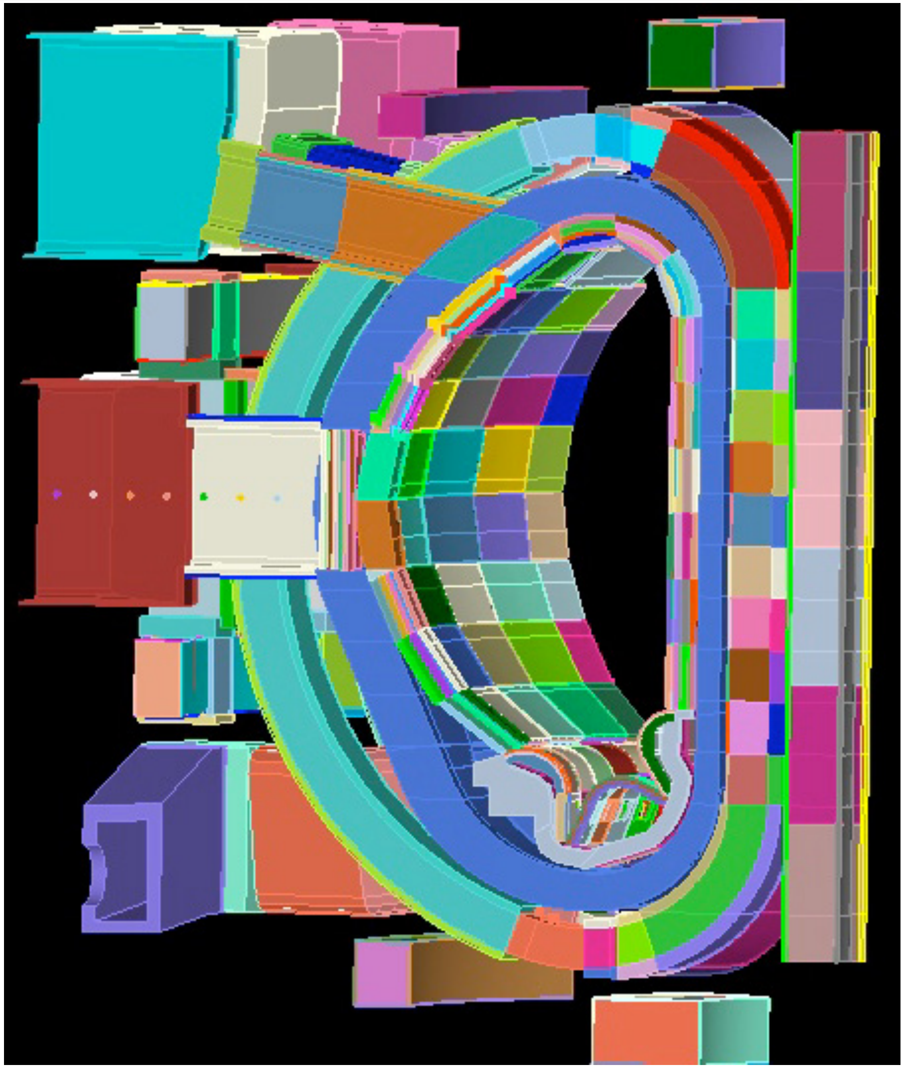
    Note: MCNP and MCNPX have different mesh tally implementations
  - Cell flagging – functional
  - Surface flagging – functional
  - Multipliers – functional
  - Segmenting – long term ??
  - Tally locations read from geom – functional

Applications

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

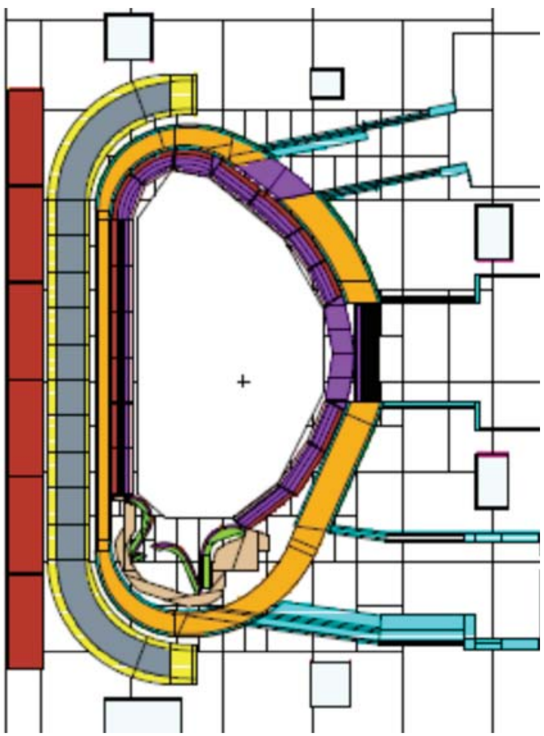
ITER Benchmark

- Comparing 4 results
  - Neutron wall loading
  - Divertor fluxes and heating
  - Magnet heating
  - Midplane port shielding/streaming
- Participants
  - UW, FZK, ASIPP, JAEA, UCLA

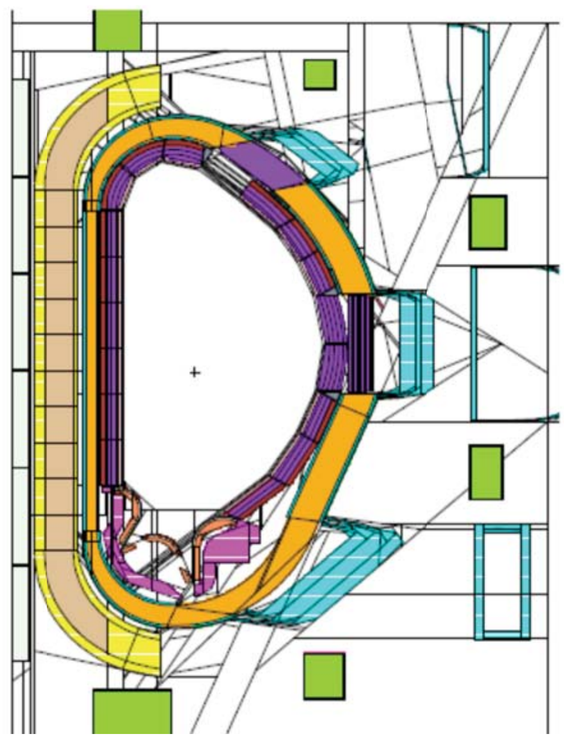


Performance Compared Translation Tools

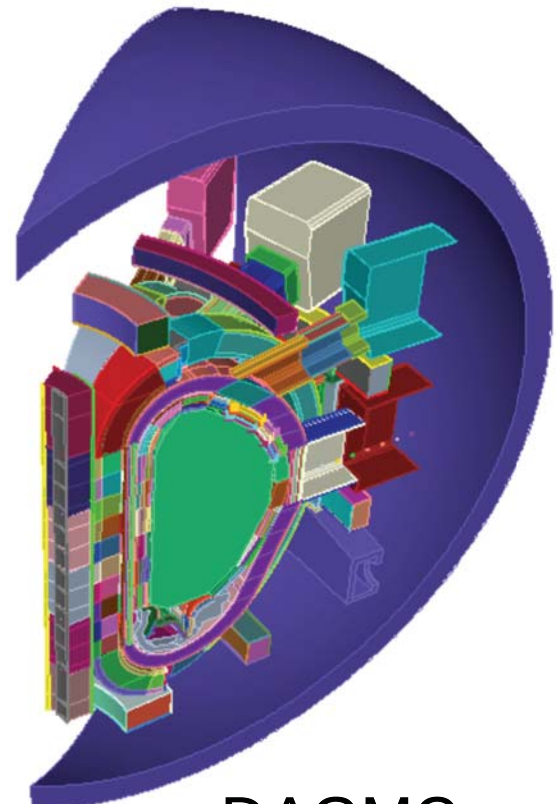
ITER Benchmark Model: >800 cells, ~10,000 surfaces



MCAM Translation



McCad Translation



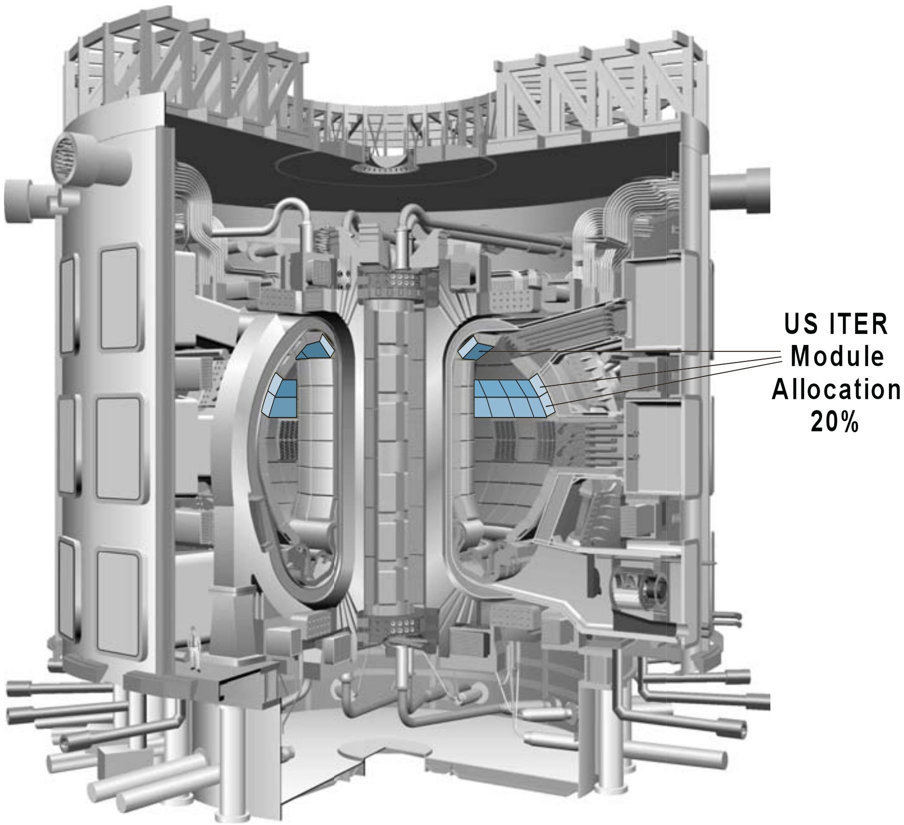
DAGMC Solid Model

Overall Performance Less than 3x Slower than Native Geometry

- Performance of translation approaches vary by 60%

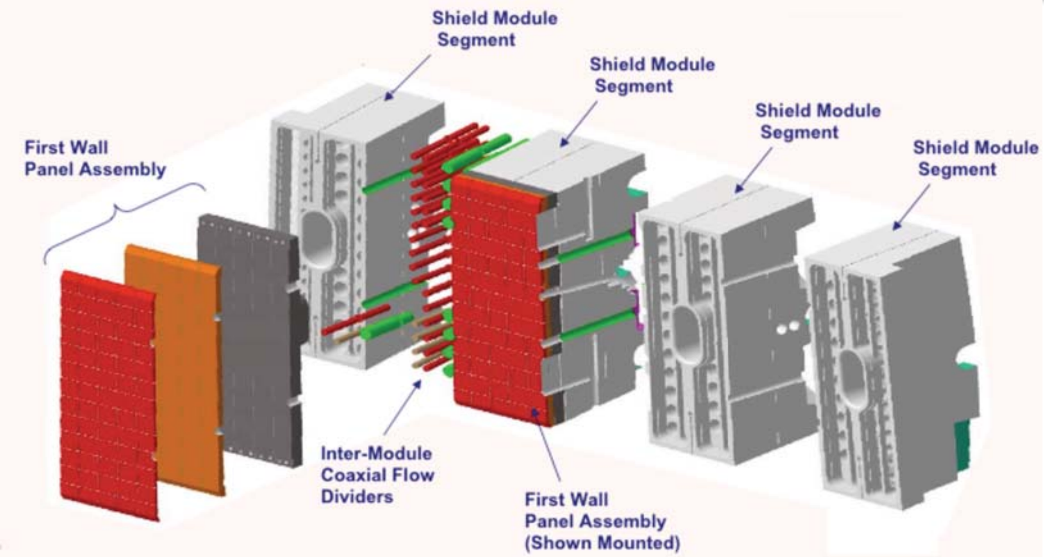
Model	Number of Volumes	Number of Surfaces	**Relative CPU-Time**
MCAM translation	4148	3192	**1**
McCad translation	6031	3800	**1.63**
DAGMC	802	9834	**2.46**

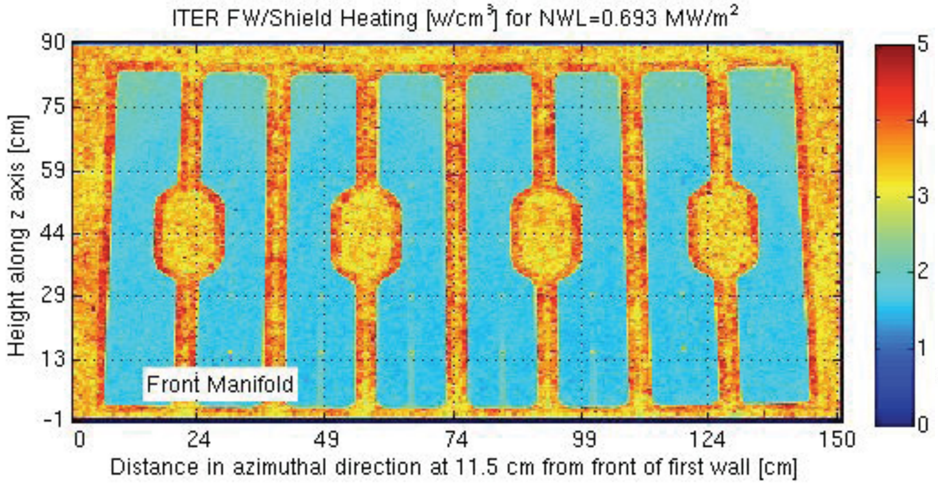
ITER First Wall & Shield

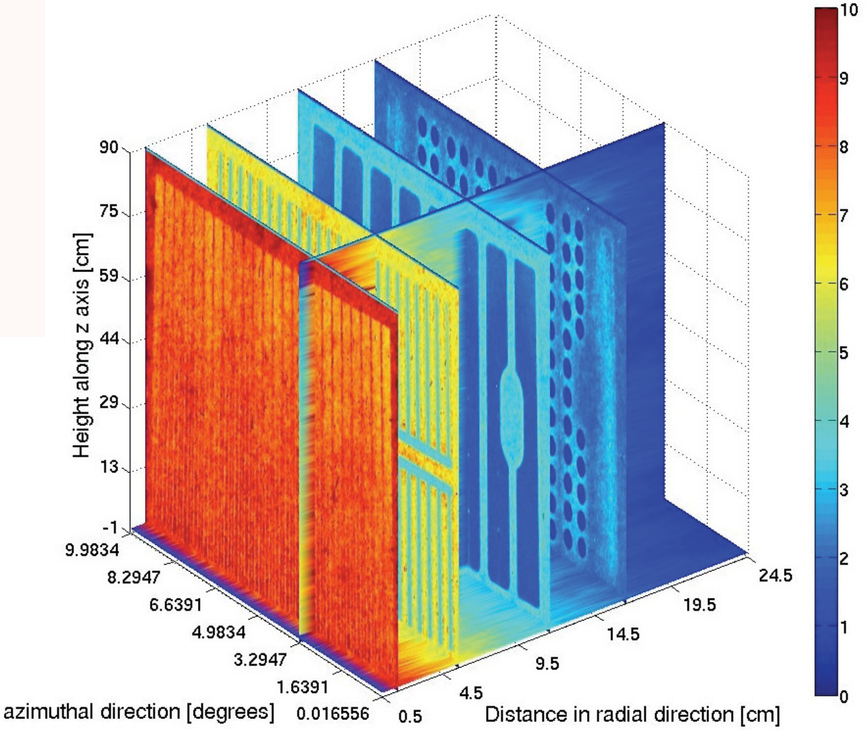


- Design includes performing detailed structural, CFD and EM analyses
- Detailed high-resolution mapping of nuclear parameters (nuclear heating, radiation damage) in the module is an essential input to design

Analysis for an Initial Mod 13 Design

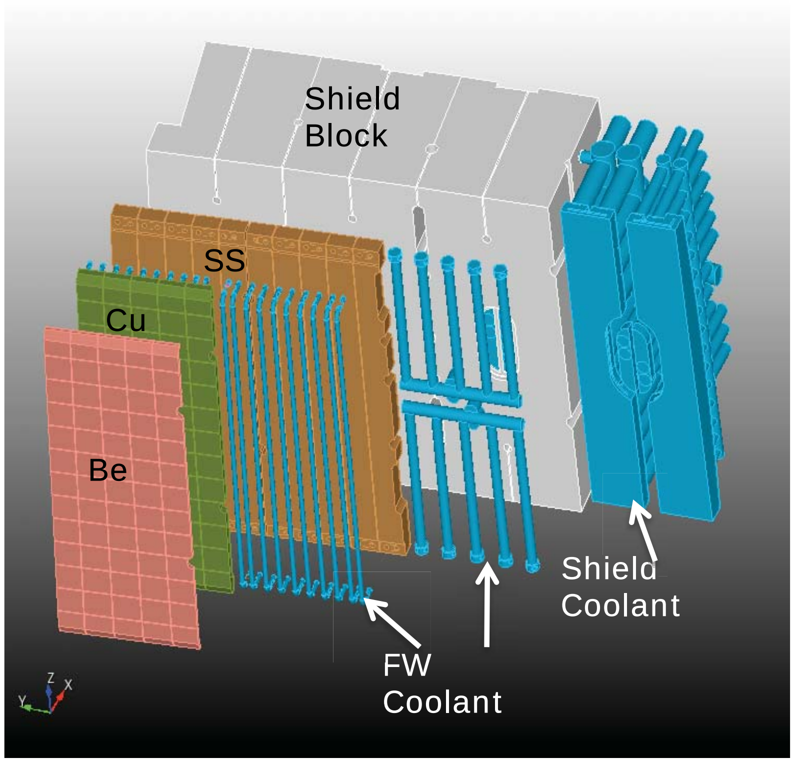


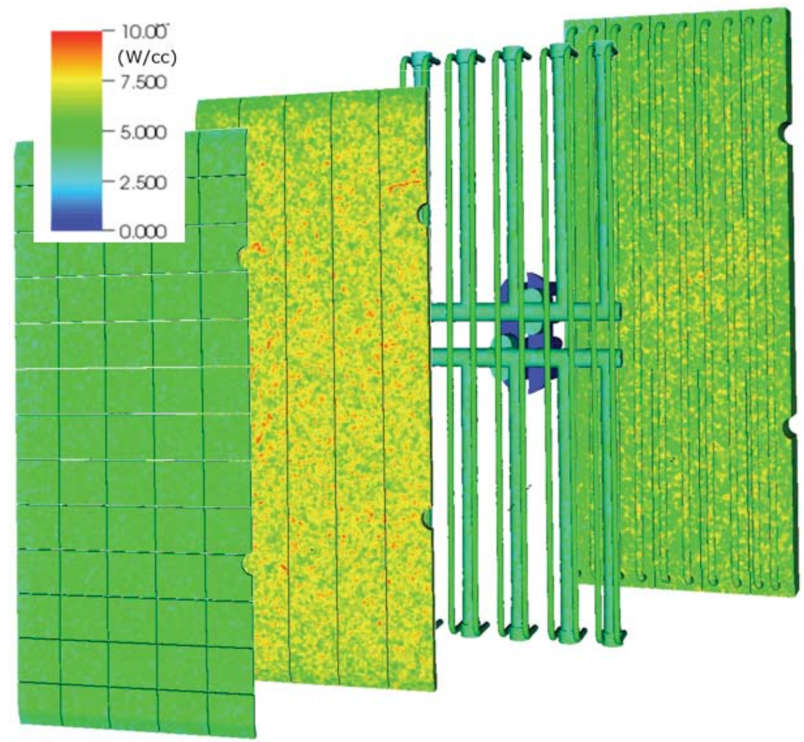




Used Surface Source for Analysis of Recent ITER FWS Module Design

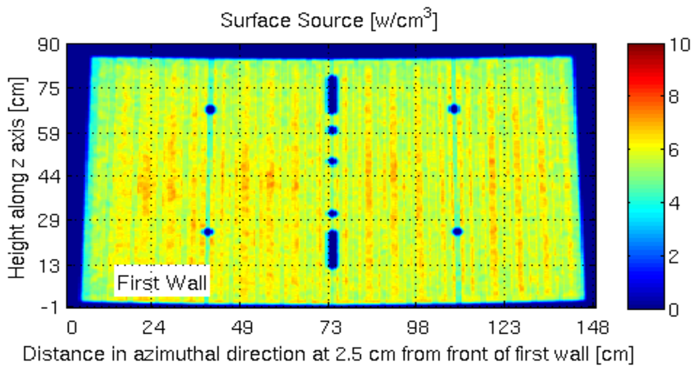
Surface source determined from calculations for the full ITER model to used at FW front surface to accurately account for the 3-D source representation



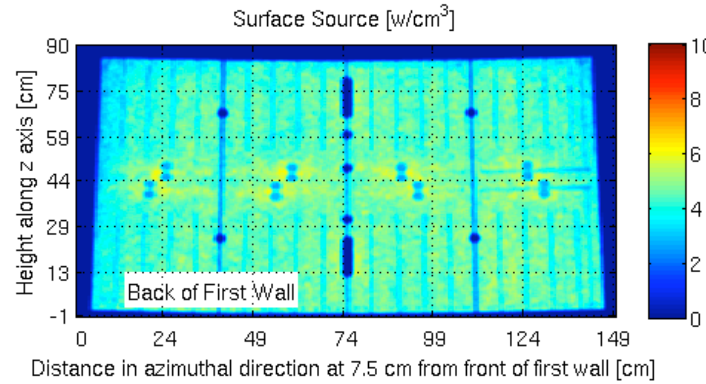


Nuclear heating calculated in FW layers

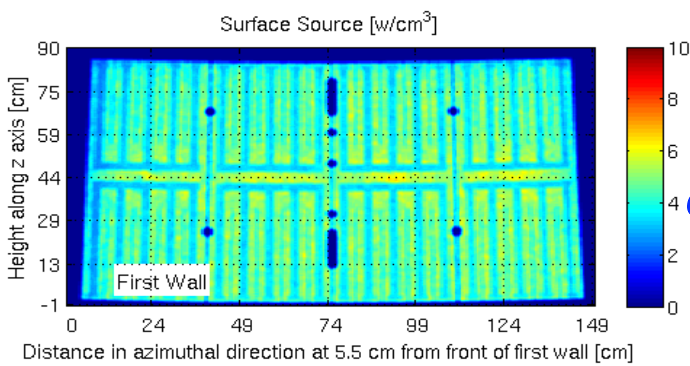
Cu Layer



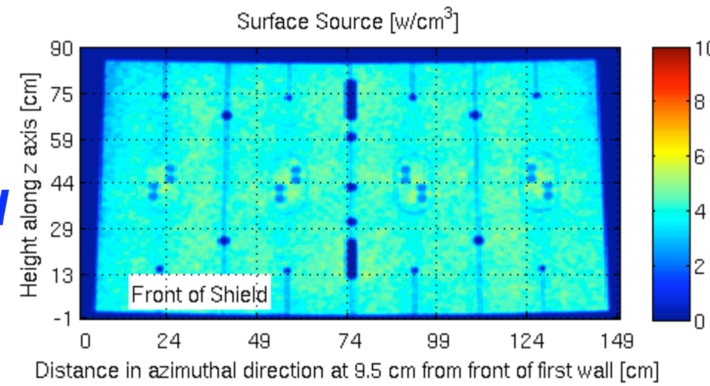
Back Surface of FW



SS Layer



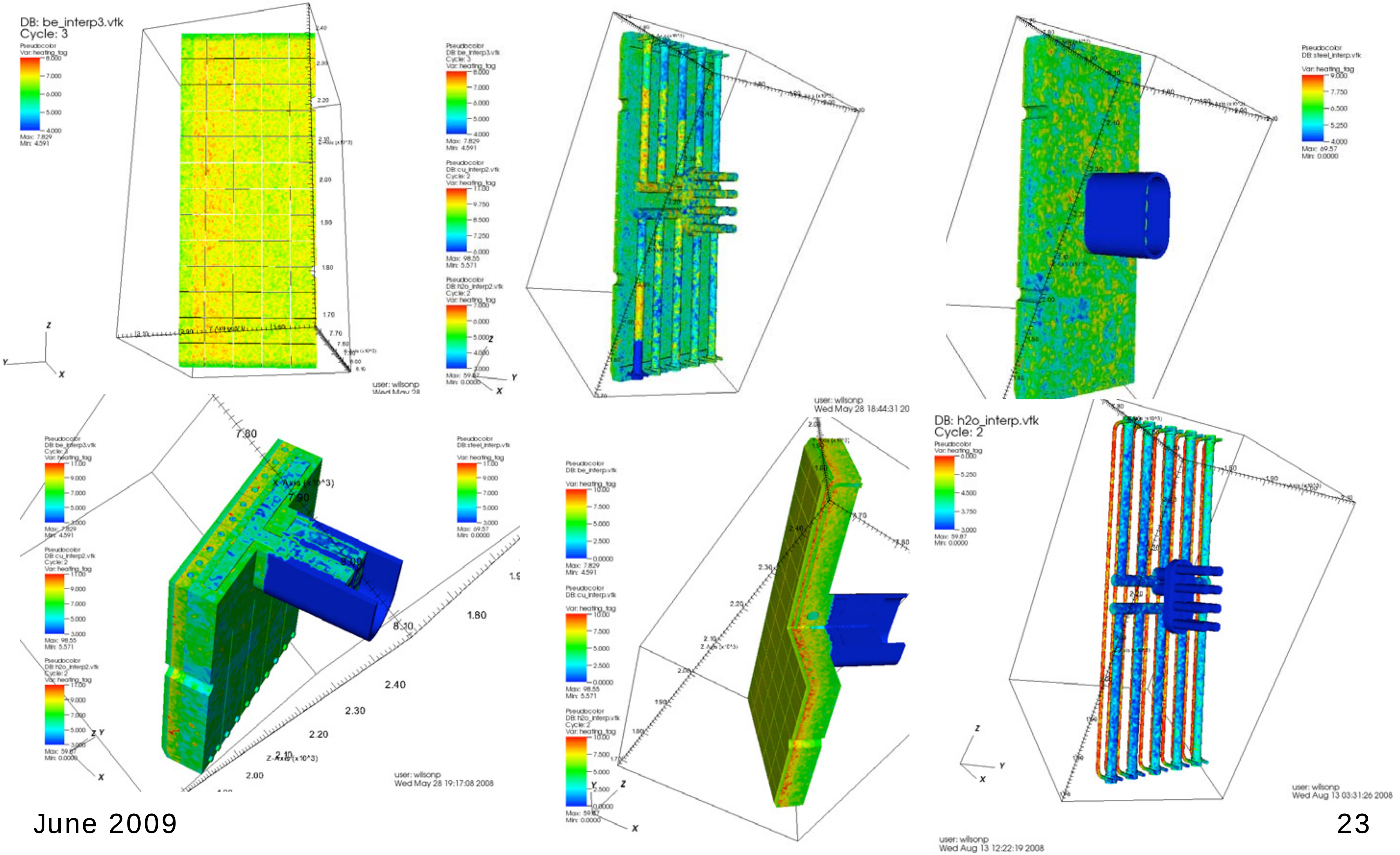
Front Surface of Shield



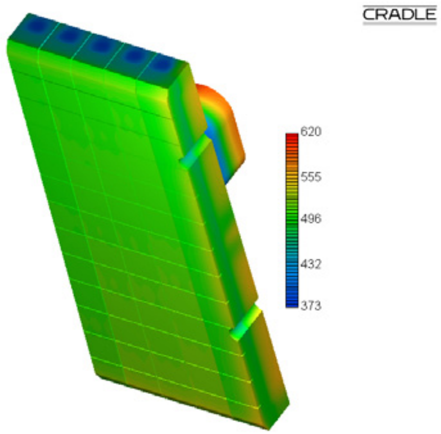
Mesh Interpolation for Multi-Physics Analysis

- 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

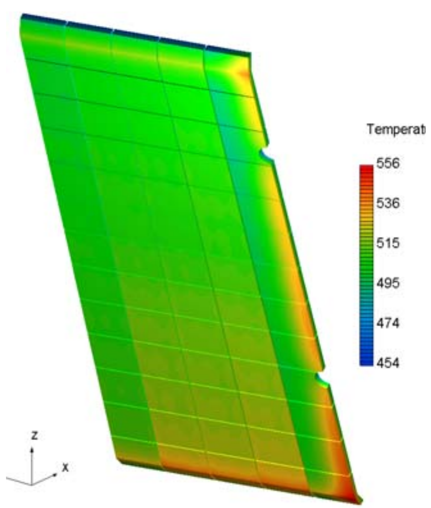
Nuclear Heating
Module 13 CFD Mesh



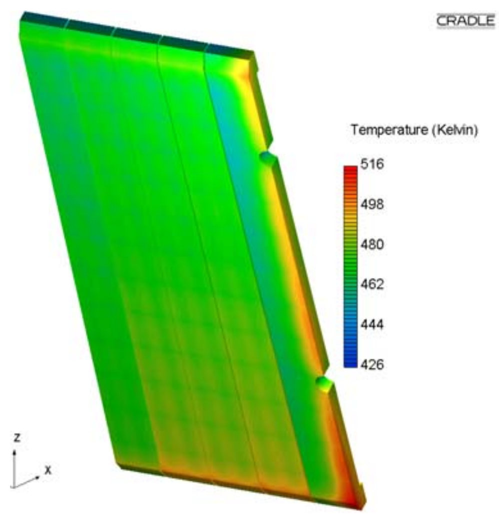
Interpolated mesh tallies used in CFD calculations (SC/Tetra code)



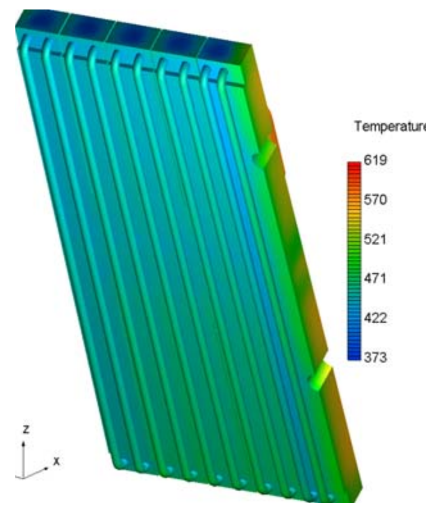
Temperature distribution in FW of Mod. 13 determined by Ying and Narula (UCLA) using the translated nuclear heating mesh tallies and the thermo-fluid CFD code SC/Tetra with ~11.5 million elements



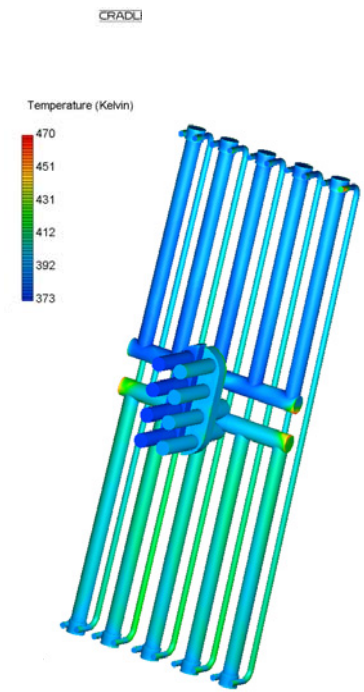
Be



Cu

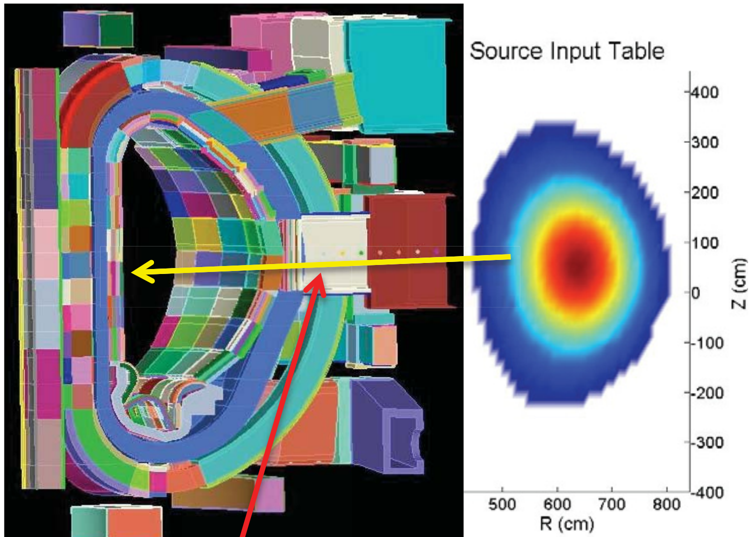


SS

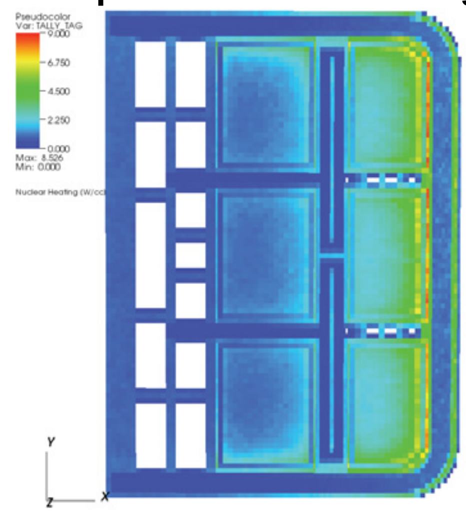


Water

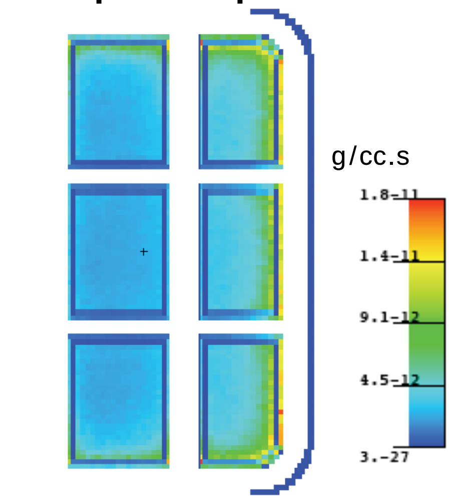
Detailed 3-D Neutronics for DCLL TBM

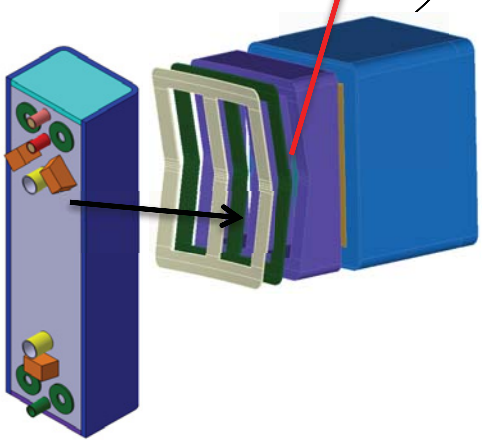


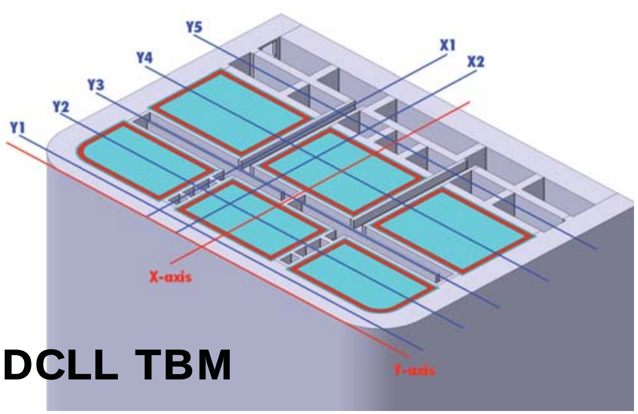
Mid-plane nuclear heating



Mid-plane T production

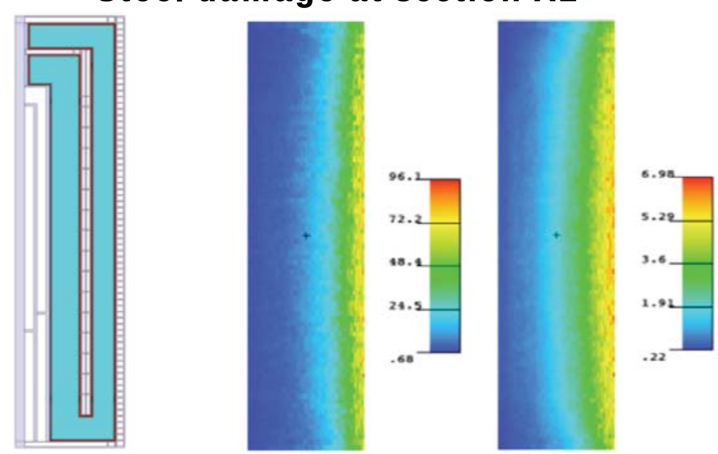






DCLL TBM

Steel damage at section X2



Cross section He appm/FPY dpa/FPY

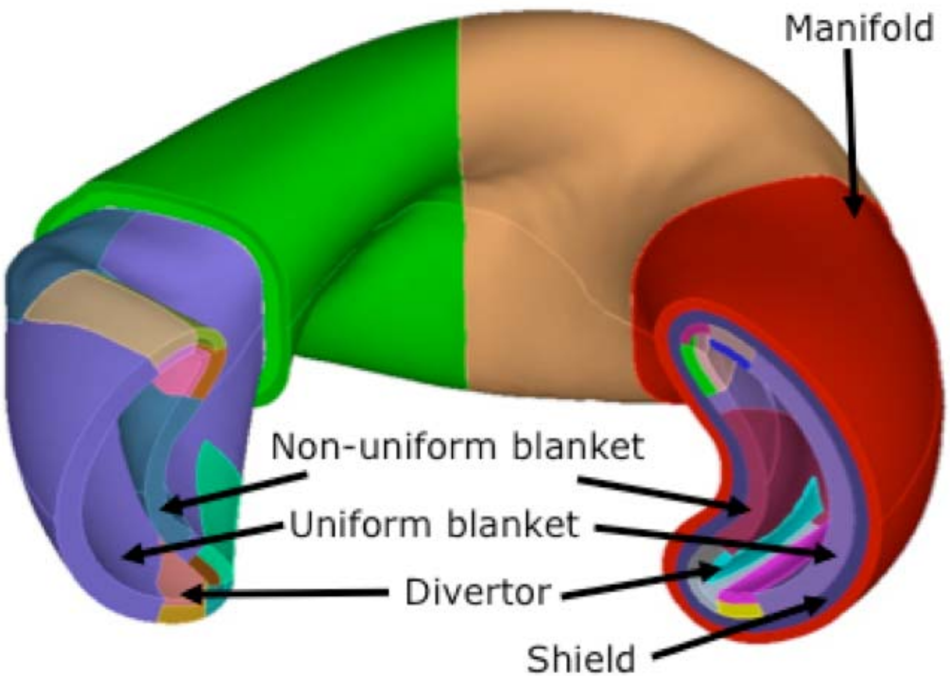
Overall TBM Nuclear Parameters

Material	Total Nuclear Heating (MW)
Ferritic Steel	0.121
Lead Lithium	0.218
SiC FCI	0.028
Be PFC	0.007
Total	*0.374*

- Tritium generation rate in the PbLi is 4.19×10^{-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 1.04×10^{-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

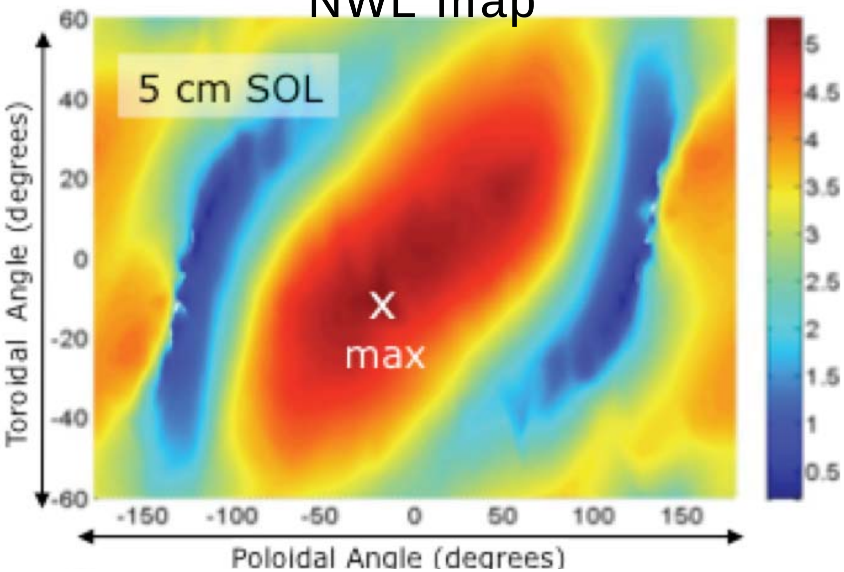


- Geometry complex
- FW shape and plasma profile vary toroidally within each field period
- Cannot be modeled by standard MCNP

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

Blanket Region	^{6}Li Enrichment 30%	60%	90%
Uniform	0.73	0.85	0.91
Nonuniform	0.15	0.21	0.24
Behind divertor	0.022	0.028	0.029
Total[a]	0.91 (±0.18%)	1.08 (±0.19%)	1.18 (±0.15%)

[a]The 1σ statistical error is indicated for each case.

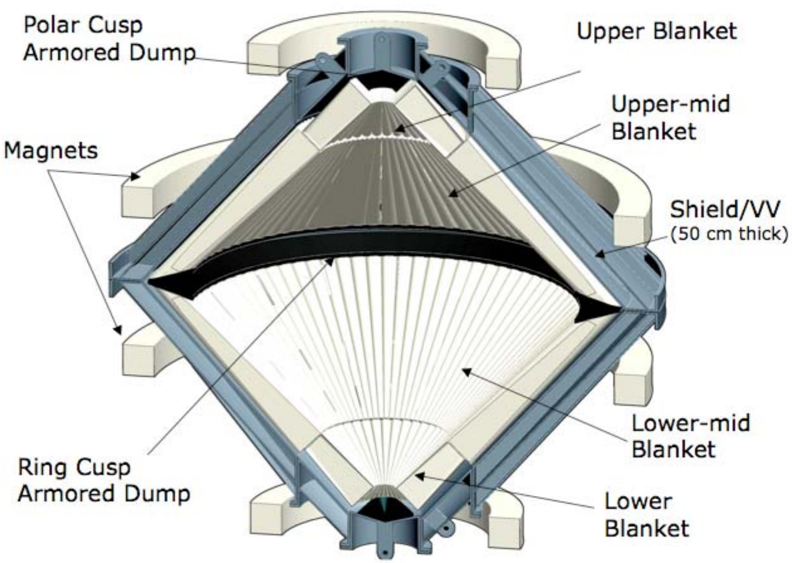
Summary of Energy Multiplication Results for LiPb/He/FS System

Component/ Region	^{6}Li Enrichment 30%	60%	90%
Blanket	0.99	1.01	1.03
Uniform	0.74	0.75	0.77
Nonuniform	0.24	0.25	0.25
Behind divertor	0.013	0.013	0.013
Shield	0.065	0.052	0.043
Main shield	0.045	0.034	0.026
Behind divertor	0.020	0.018	0.017
Manifold	0.0014	0.0014	0.0012
Divertor plates	0.10	0.091	0.086
ECH duct	5.7×10^{-5}	5.4×10^{-5}	4.8×10^{-5}
Total[a]	1.16 (±0.13%)	1.16 (±0.14%)	1.16 (±0.12%)

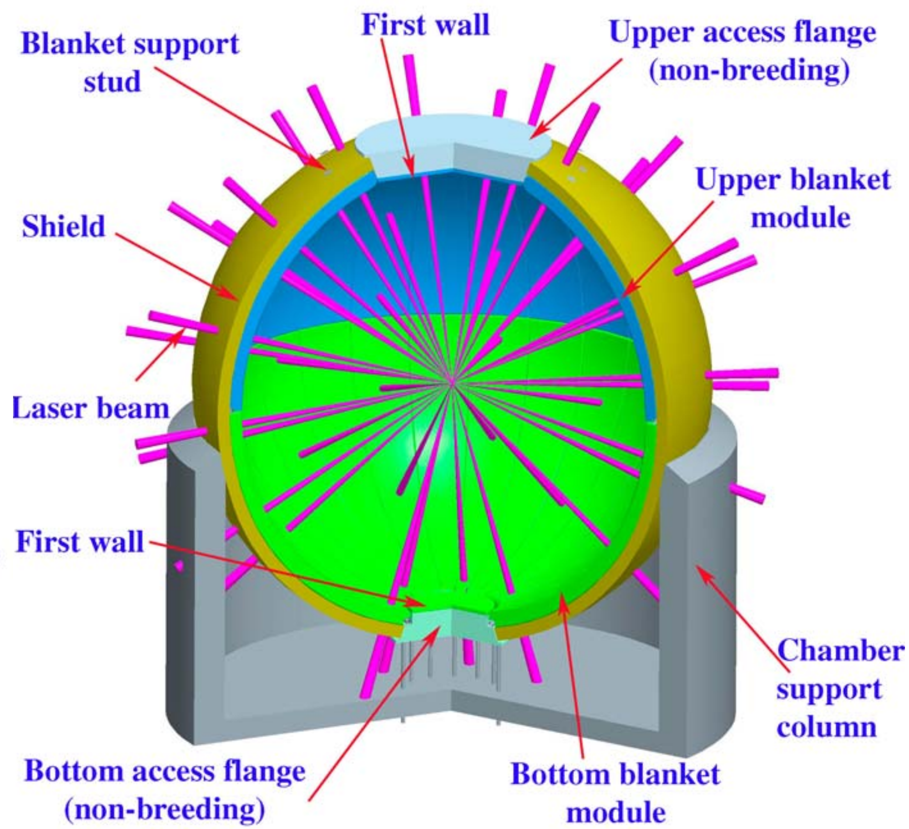
[a]The 1σ statistical error is shown for the total M_n in each case.

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

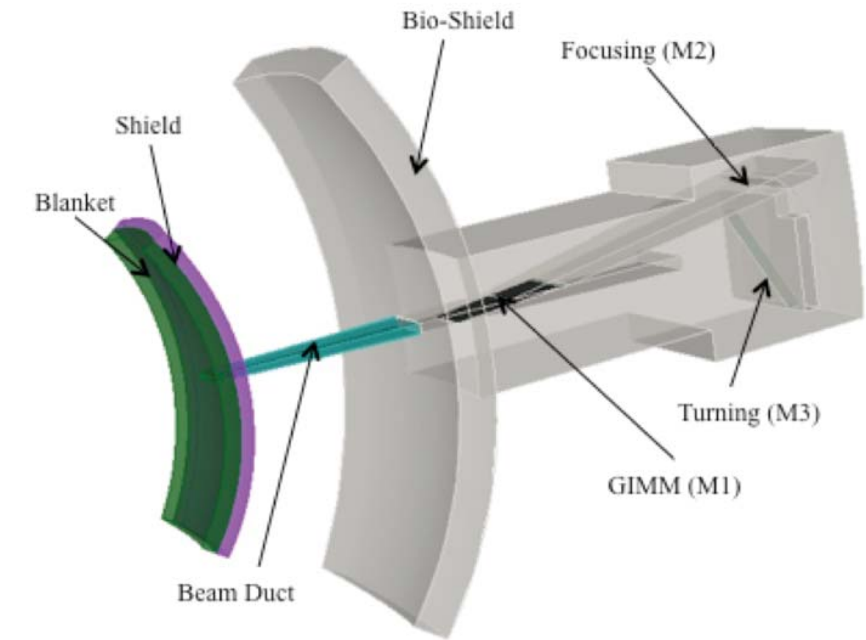


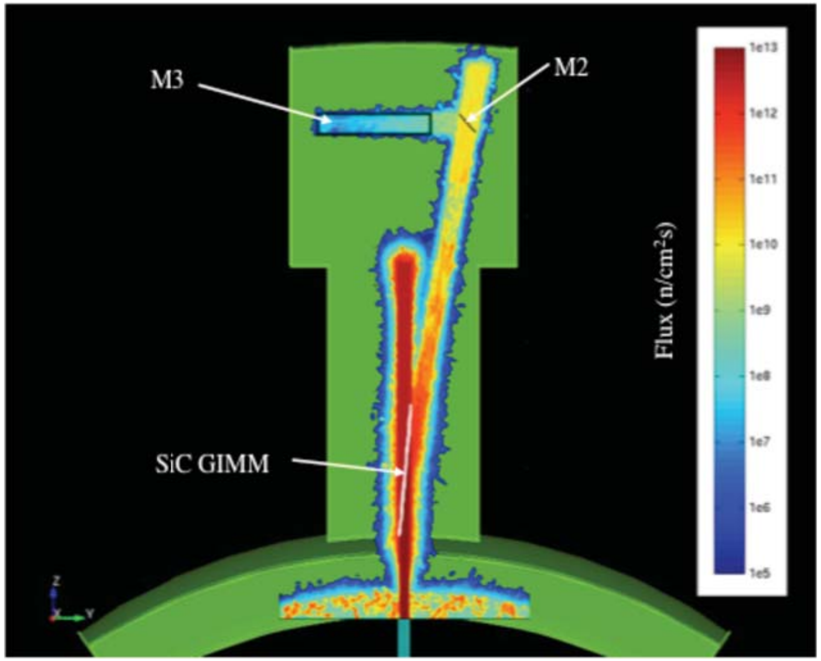
Design with Magnetic Intervention



Large Chamber Design

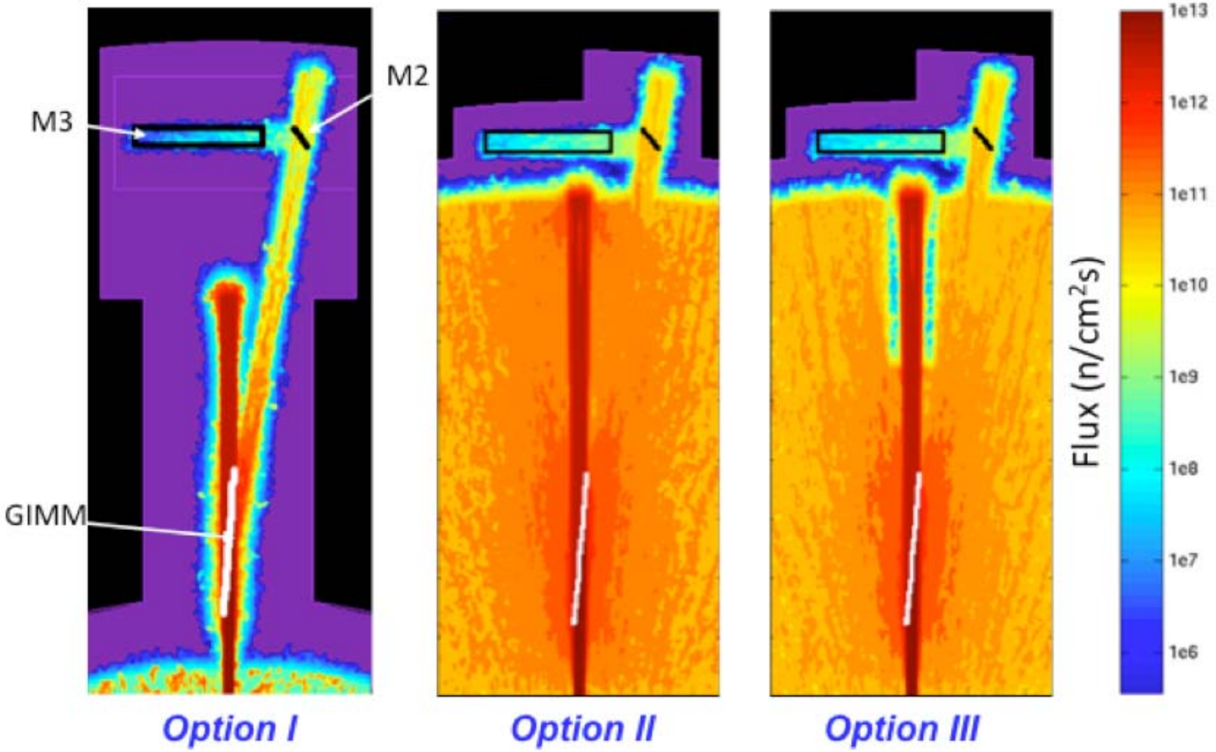
HAPL Final Laser Optics





- 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

Effect of Shielding Configuration



- 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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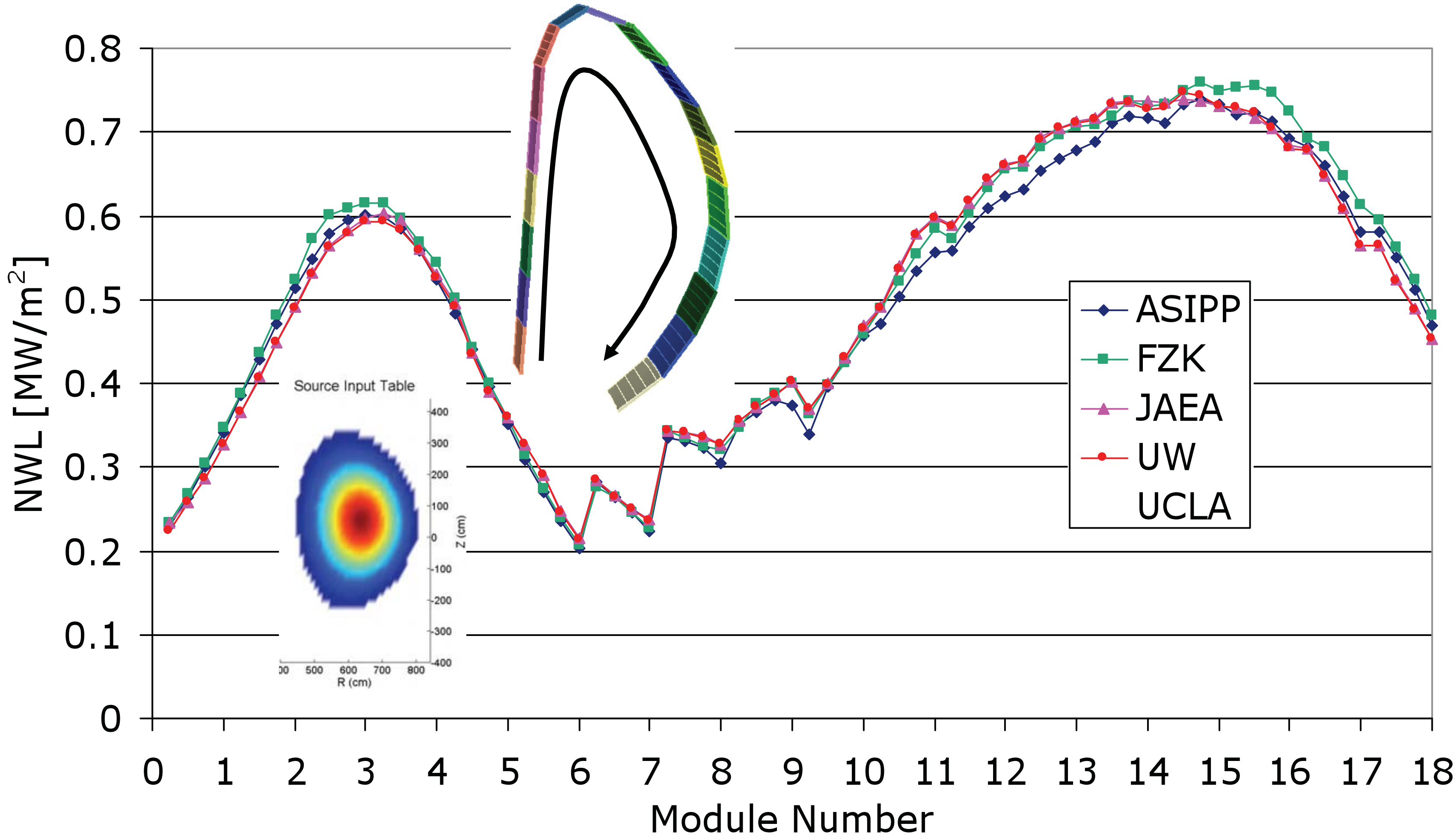
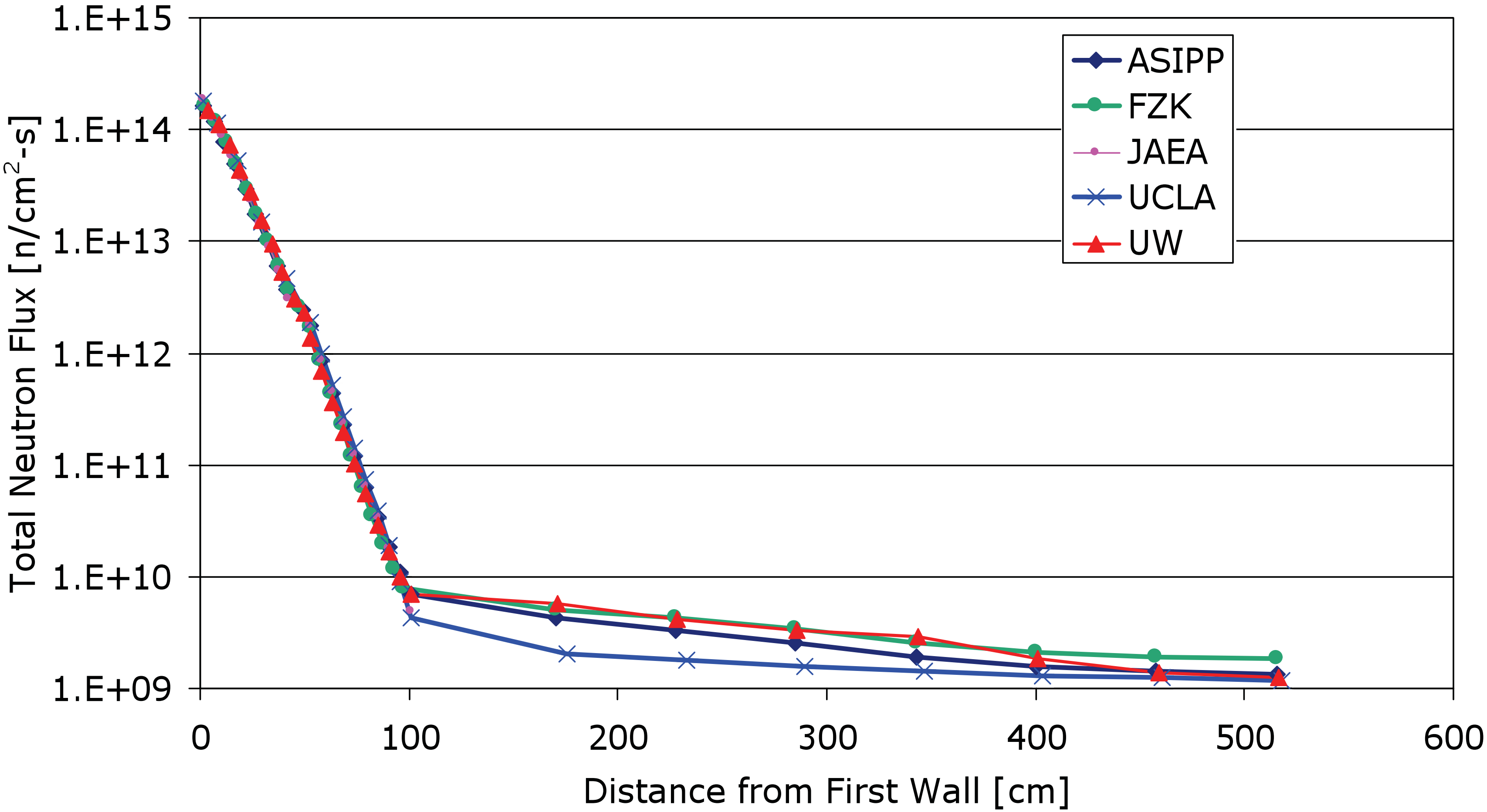
Neutron Wall Loading



Equatorial Port Results



Geometry Preparation

- 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

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”