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

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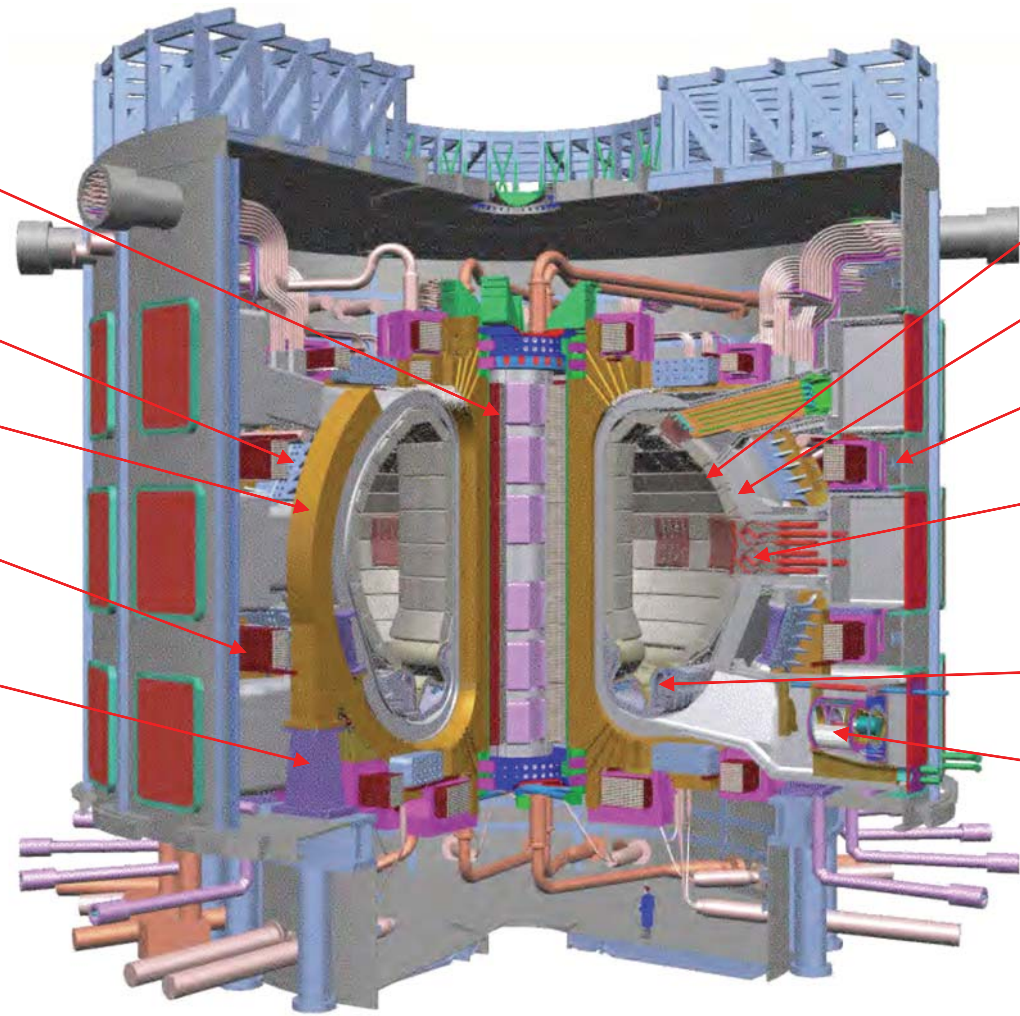
Fusion Reactors are Complex with Many Components



Central Solenoid
Nb_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

DAGMC Concept

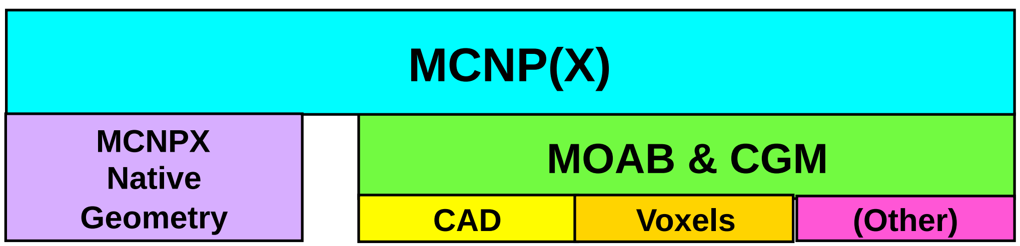
Motivation

- 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)

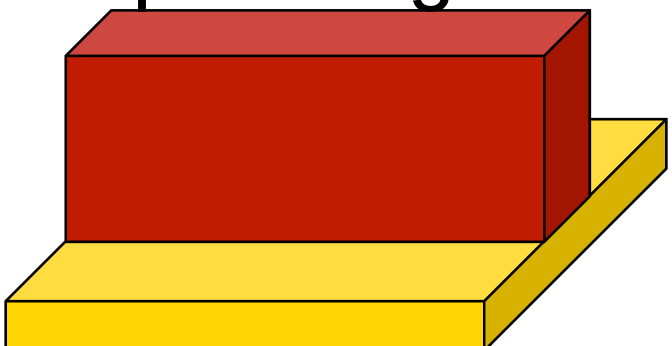
- Production experience
  - ARIES-CS
  - ITER Benchmark
  - ITER FWS
  - HAPL

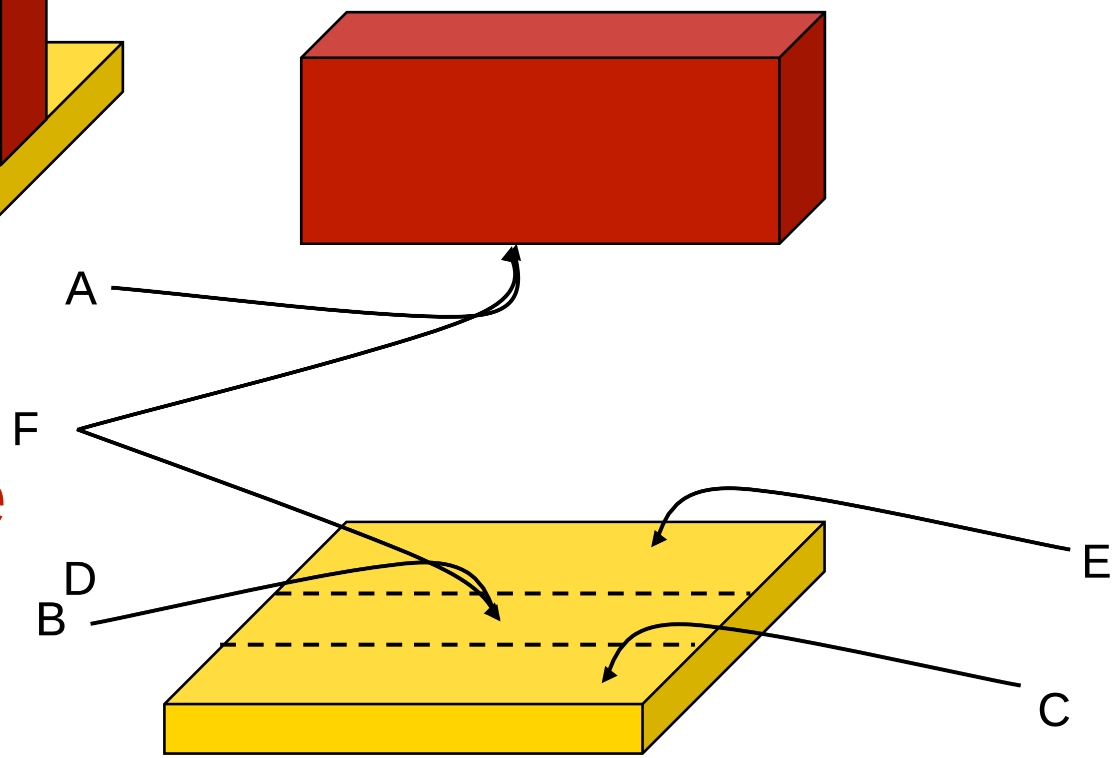
Overcoming Inefficiency

- 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

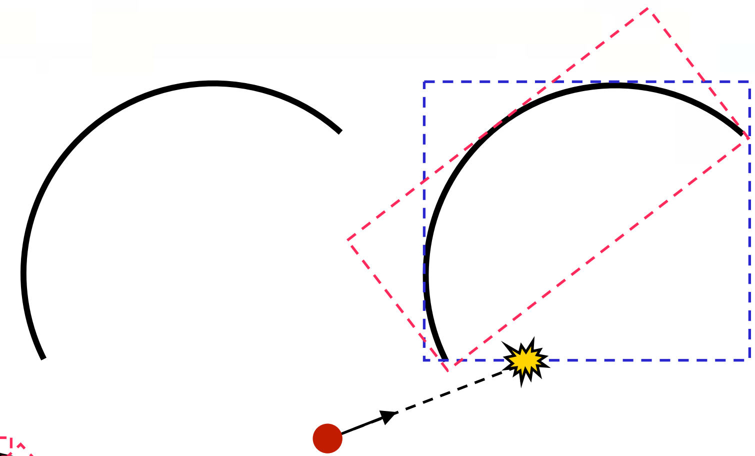




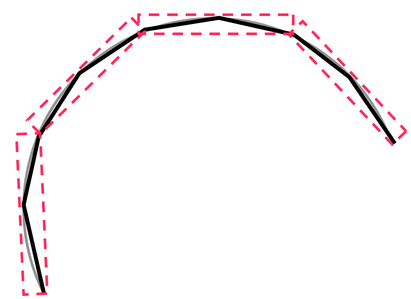
- Merging
- Each surface in max. 2 cells

Hierarchical Oriented Bounding Box

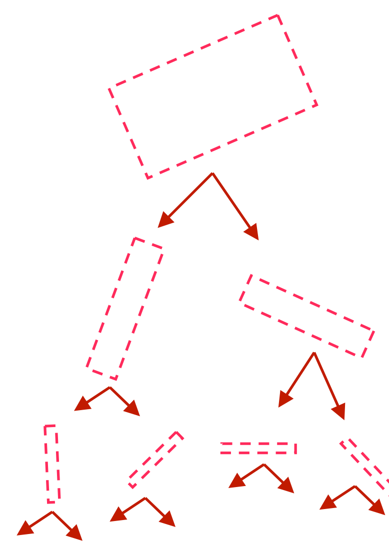
- Axis-aligned bounding box often larger than necessary



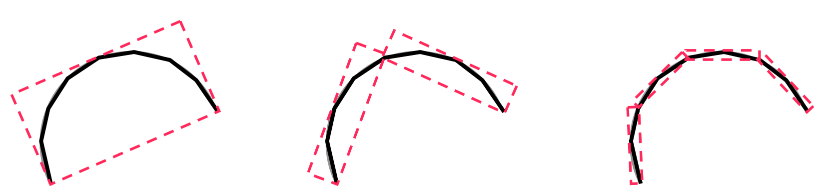
- *Oriented* bounding box makes smaller boxes



- OBB on facets allows finer-granularity boxes



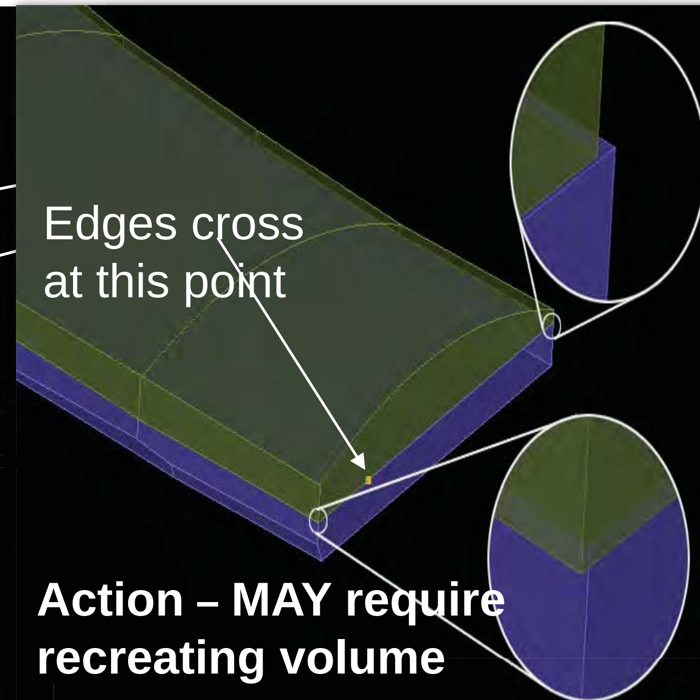
- Tree of OBBs reduces # tests



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”



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

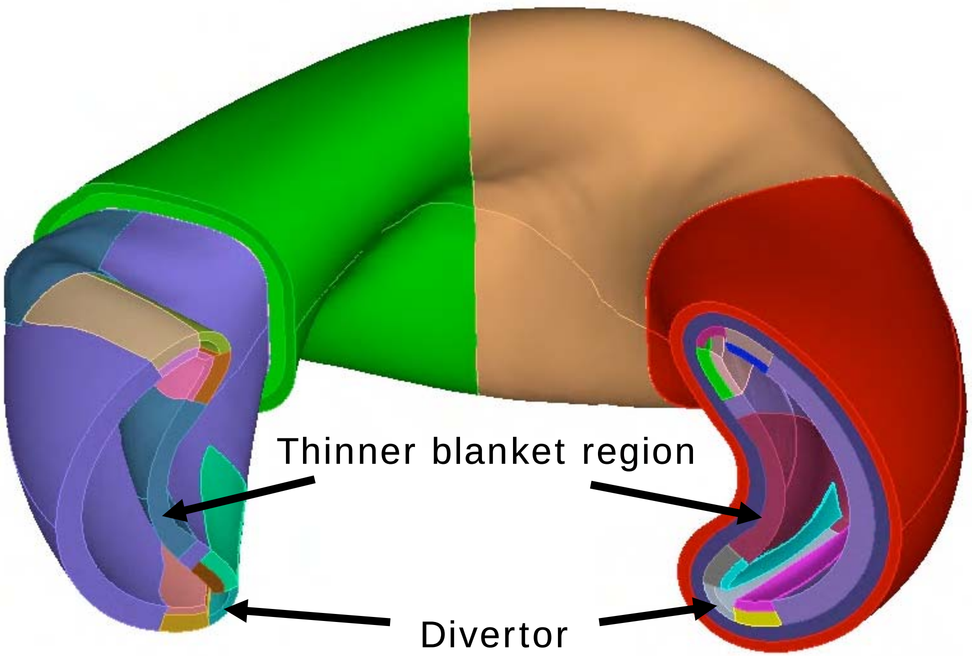
- **Tallies**
  - Surface current (type 1) – functional
  - Cosine bins – functional (directional ambiguity)
  - Surface flux (type 2) – functional
  - Cell flux (type 4,6,7) – functional
  - Pulse height (type 8) – testing
  - Point detector (type 5) – functional
  - Mesh tallies – functional in MCNPX

    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

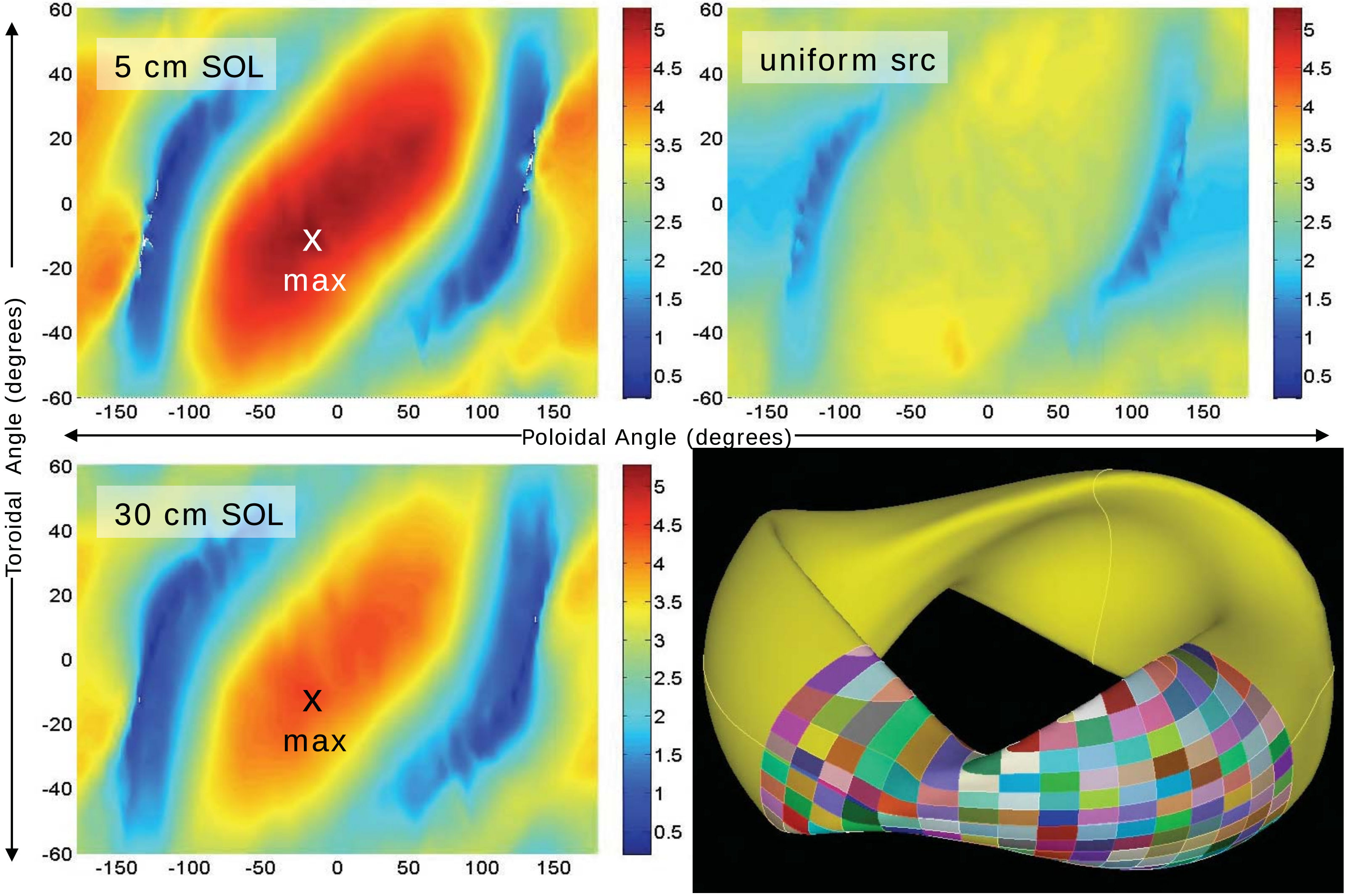
Application to ARIES-CS Compact Stellarator



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

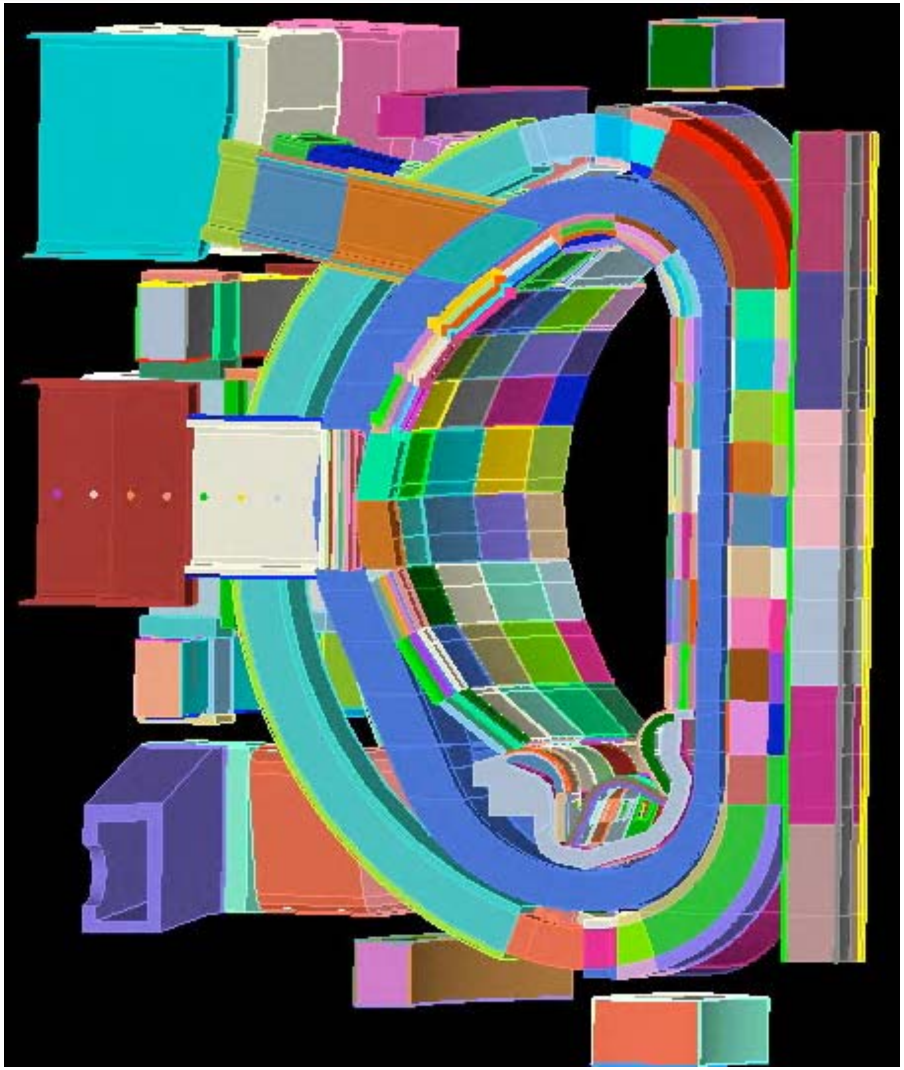
Examined effect of helical geometry and non-uniform blanket and divertor on NWL distribution and total TBR and nuclear heating

NWL Maps (colormaps in MW/m^2)

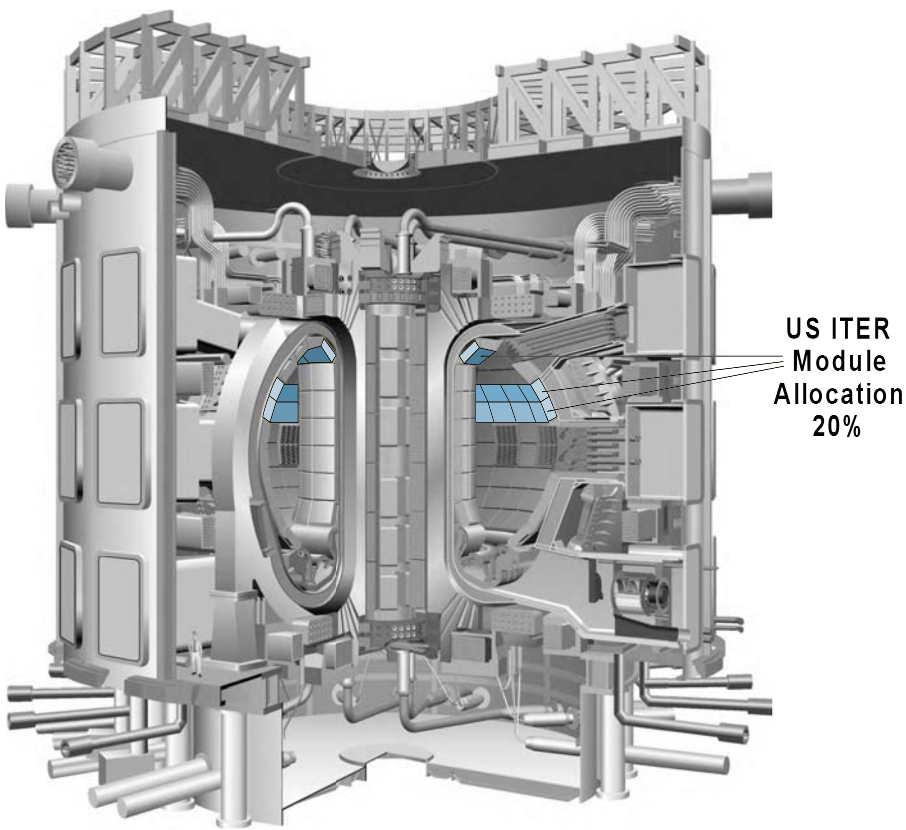


ITER Benchmark

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

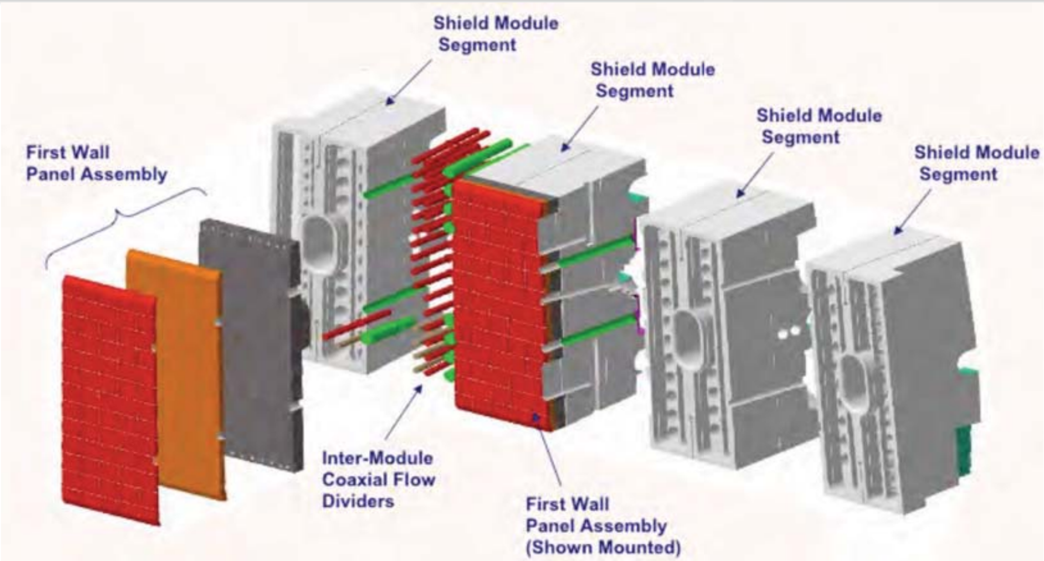


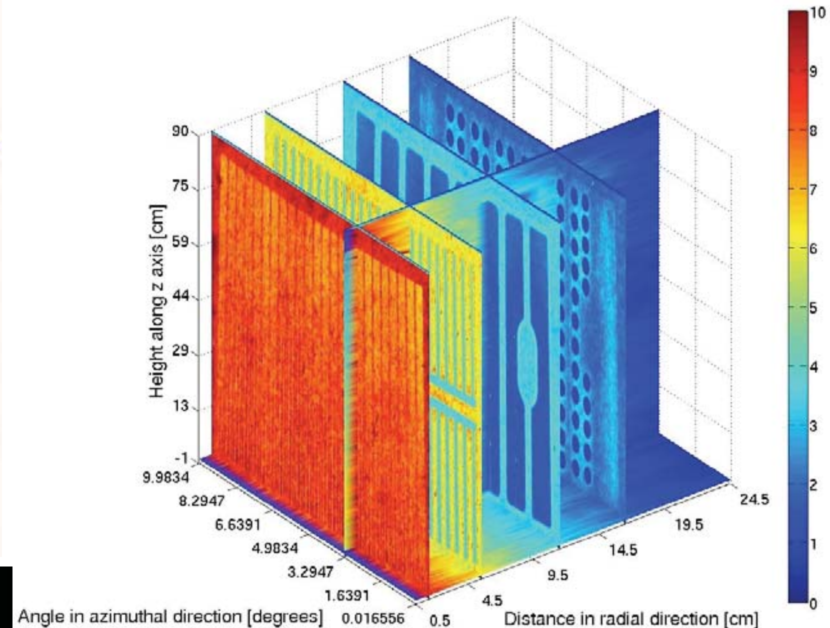
ITER First Wall & Shield

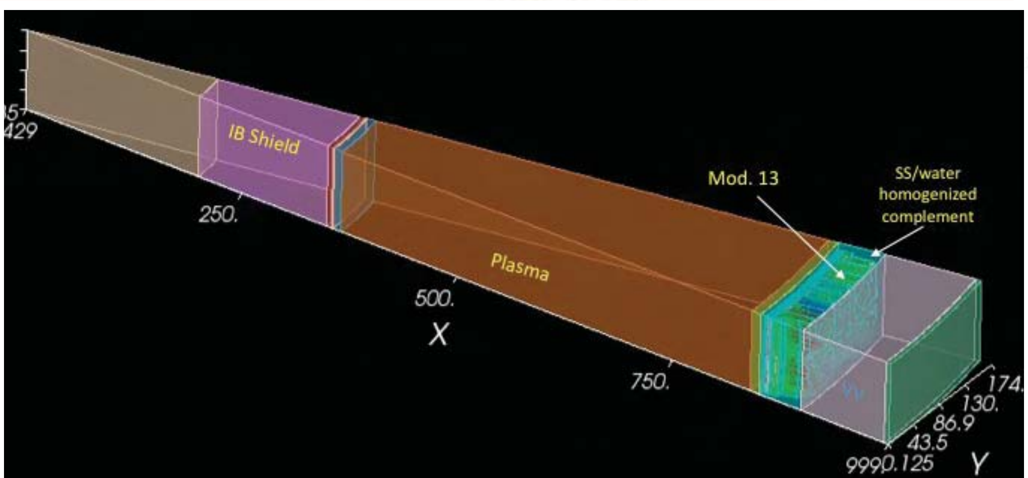


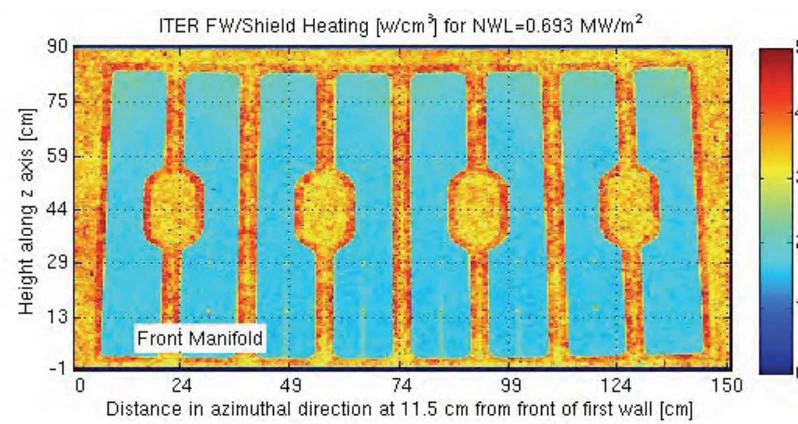
- FWS modules 7, 12, and 13 are allocated to the US
- Design includes assessment of stresses and performing detailed CFD and EM analyses
- Detailed distribution of nuclear parameters in the module is an essential input to design
- Accurate high-resolution nuclear heating results that can easily interface with finite element engineering analysis codes are required

Analysis Used a Hybrid 1-D/3-D Model and an Initial Mod 13 Design



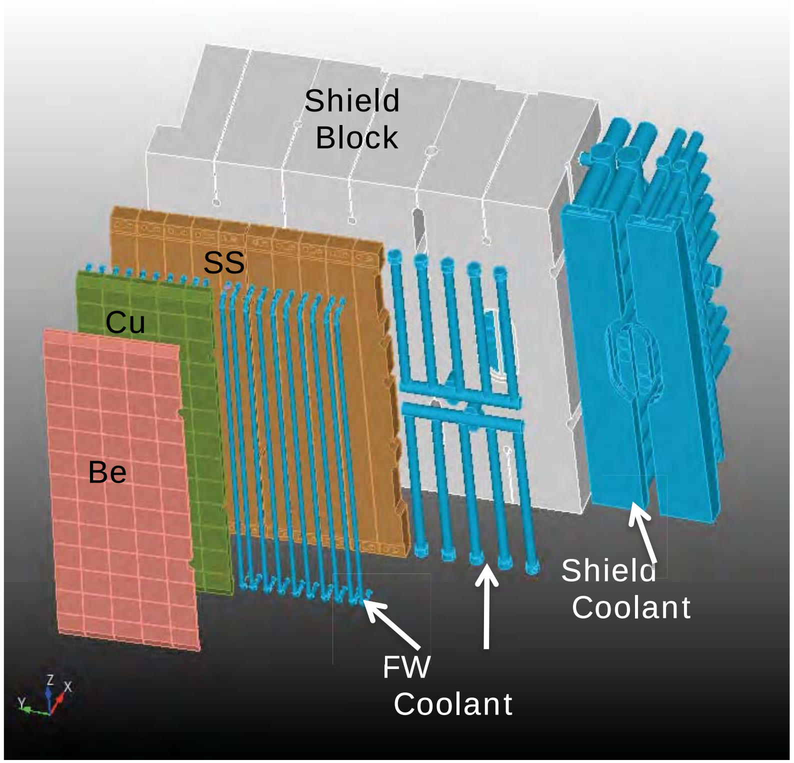


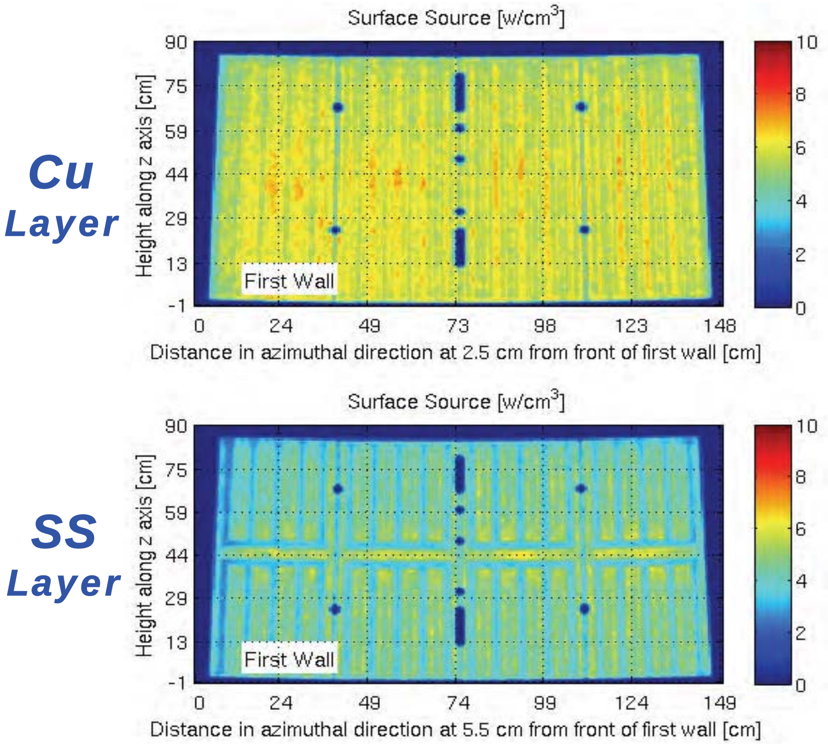




Used Surface Source for Analysis of Recent ITER FWS Module Design

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

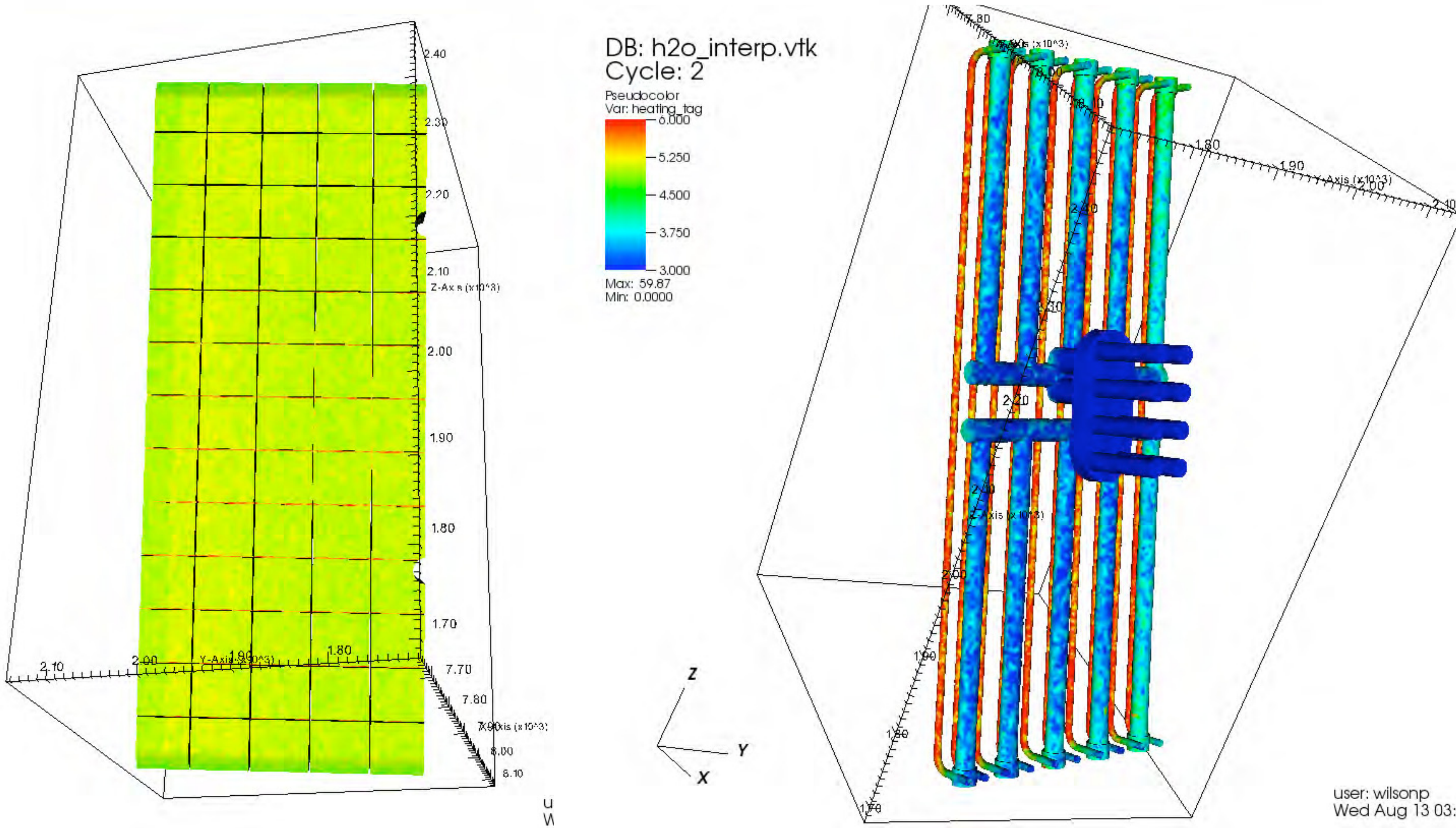




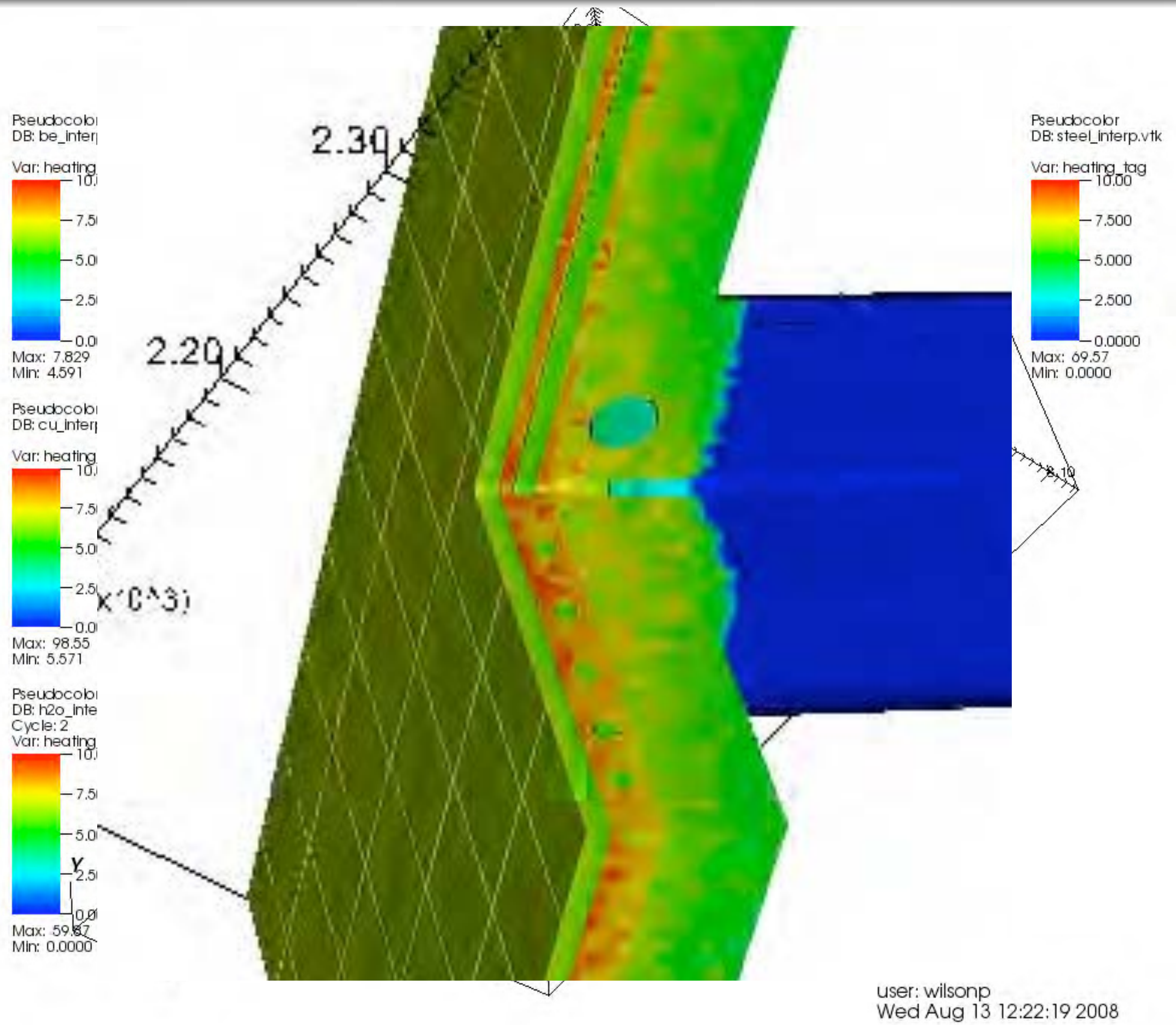
Mesh Interpolation for Multi-Physics Analysis

- 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

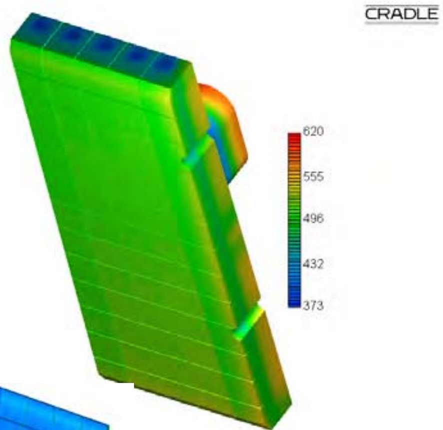
Nuclear Heating
Module 13 CFD Mesh



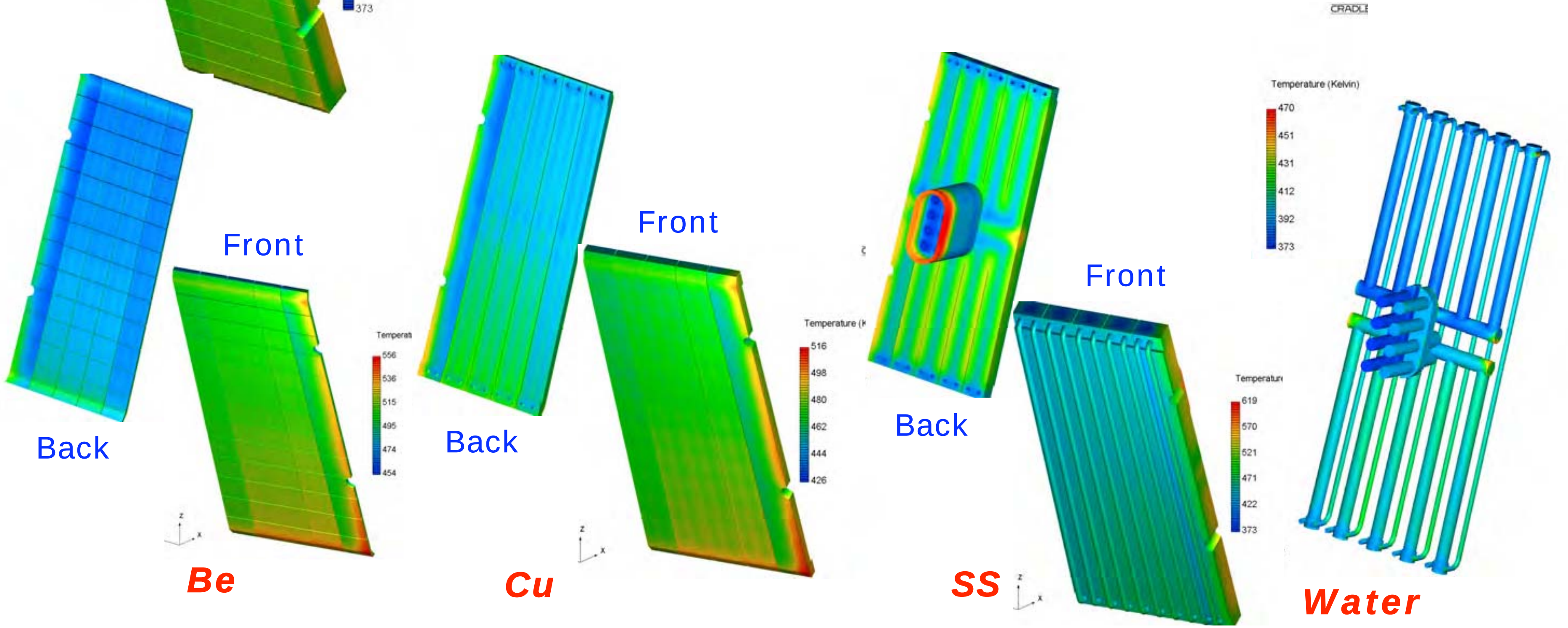
Nuclear Heating
Module 13 CFD Mesh



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

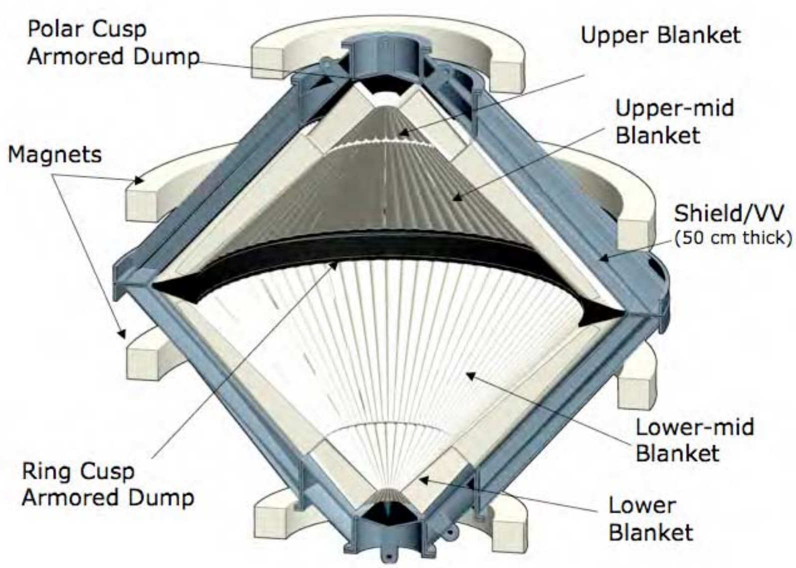


Temperature distribution in FW of Mod. 13 determined by Ying and Narula (UCLA) using the translated nuclear heating mesh tallies and the thermo-fluid CFD code SC/Tetra with ~11.5 million elements

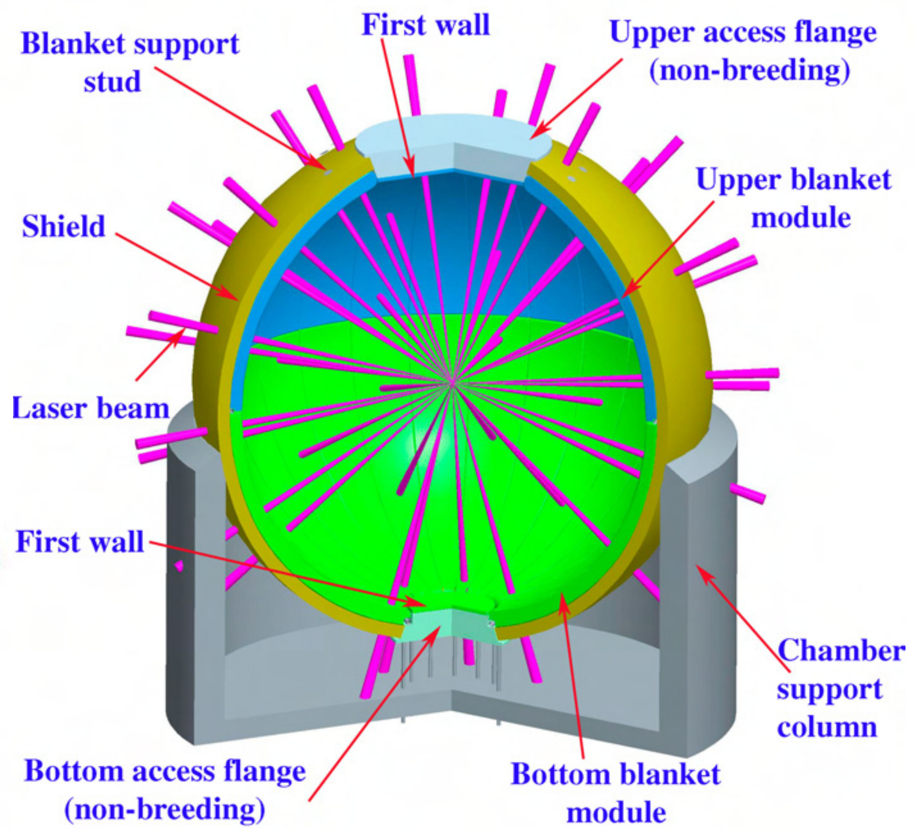


High Average Power Laser (HAPL) Conceptual Design

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

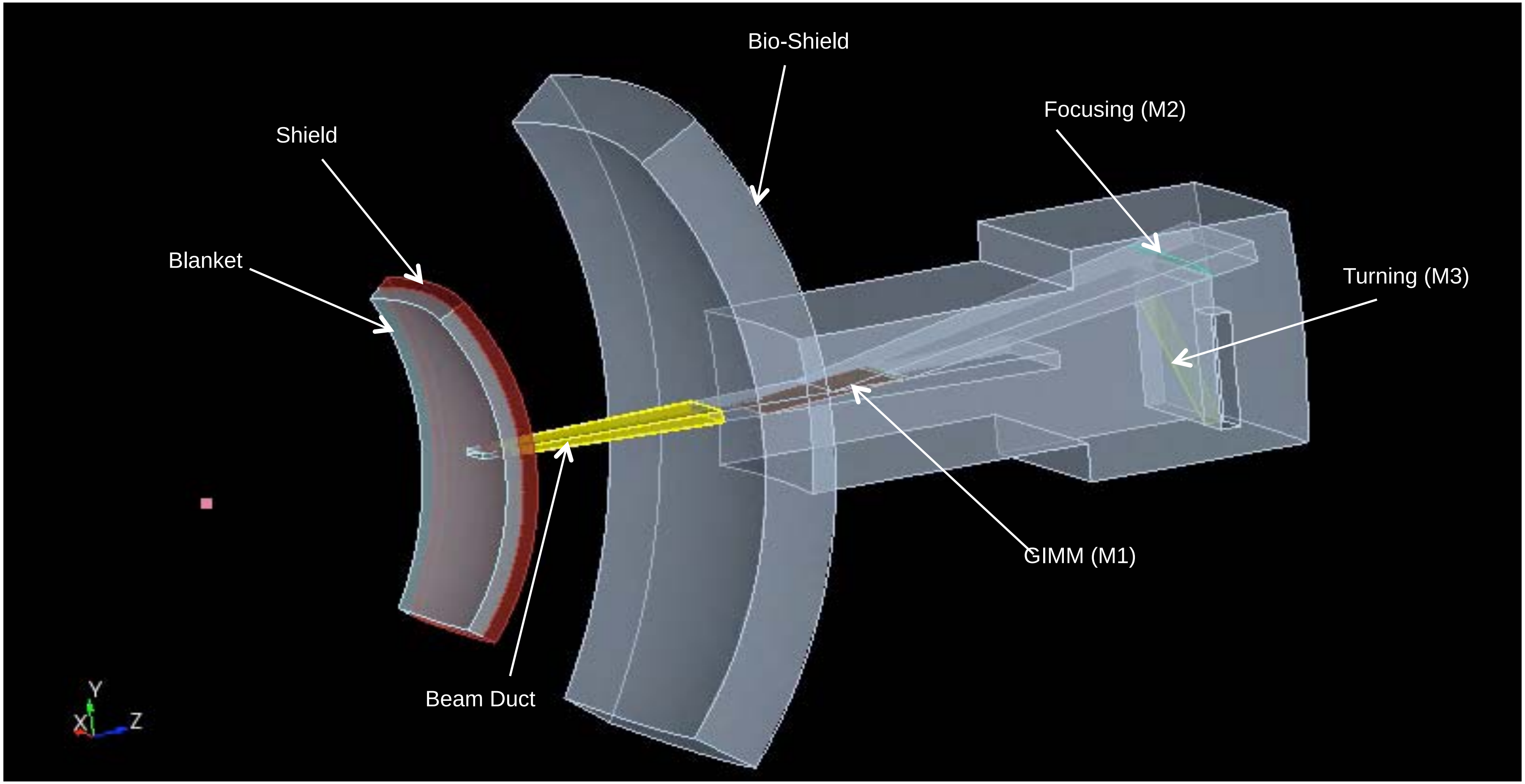


Design with Magnetic Intervention

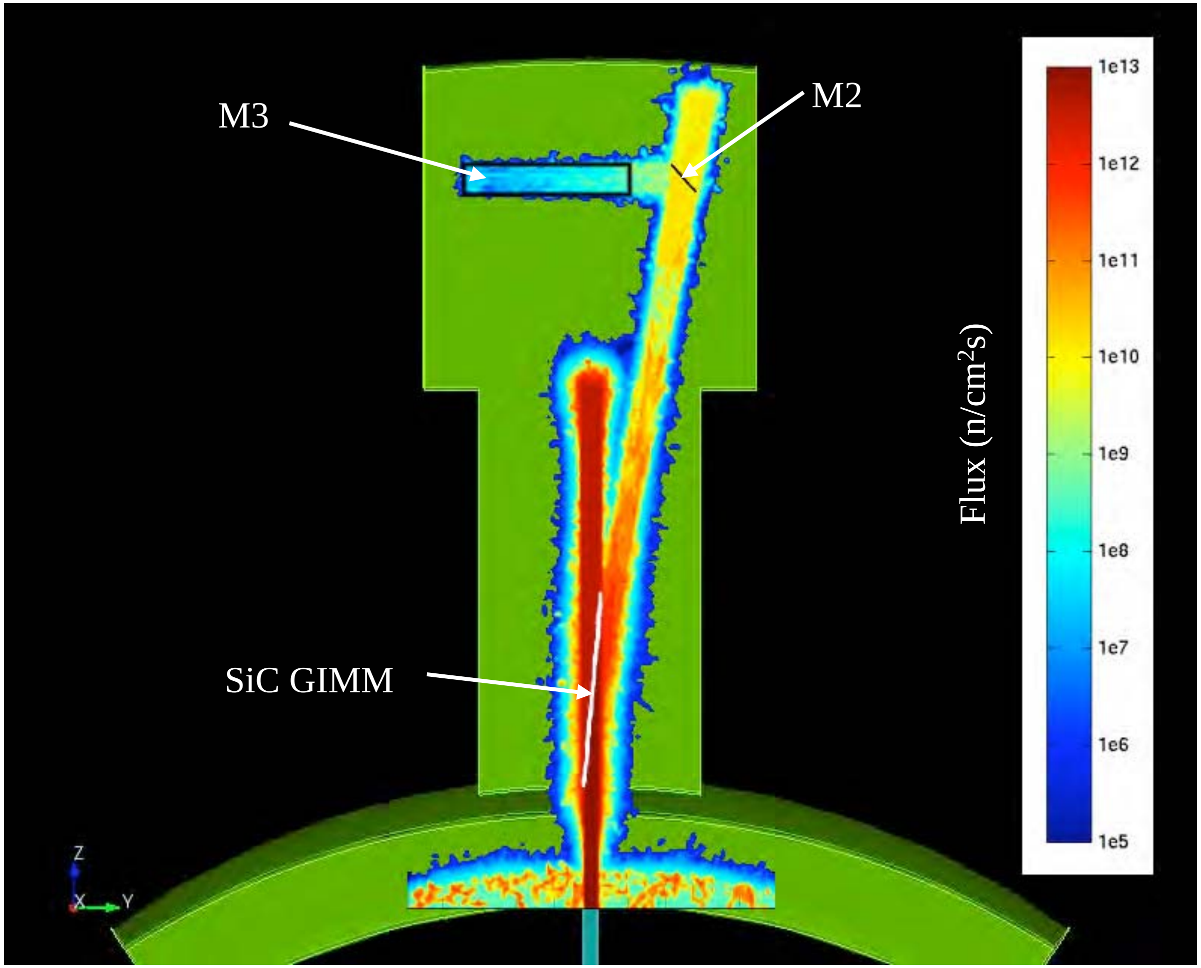


Large Chamber Design

HAPL Final Laser Optics



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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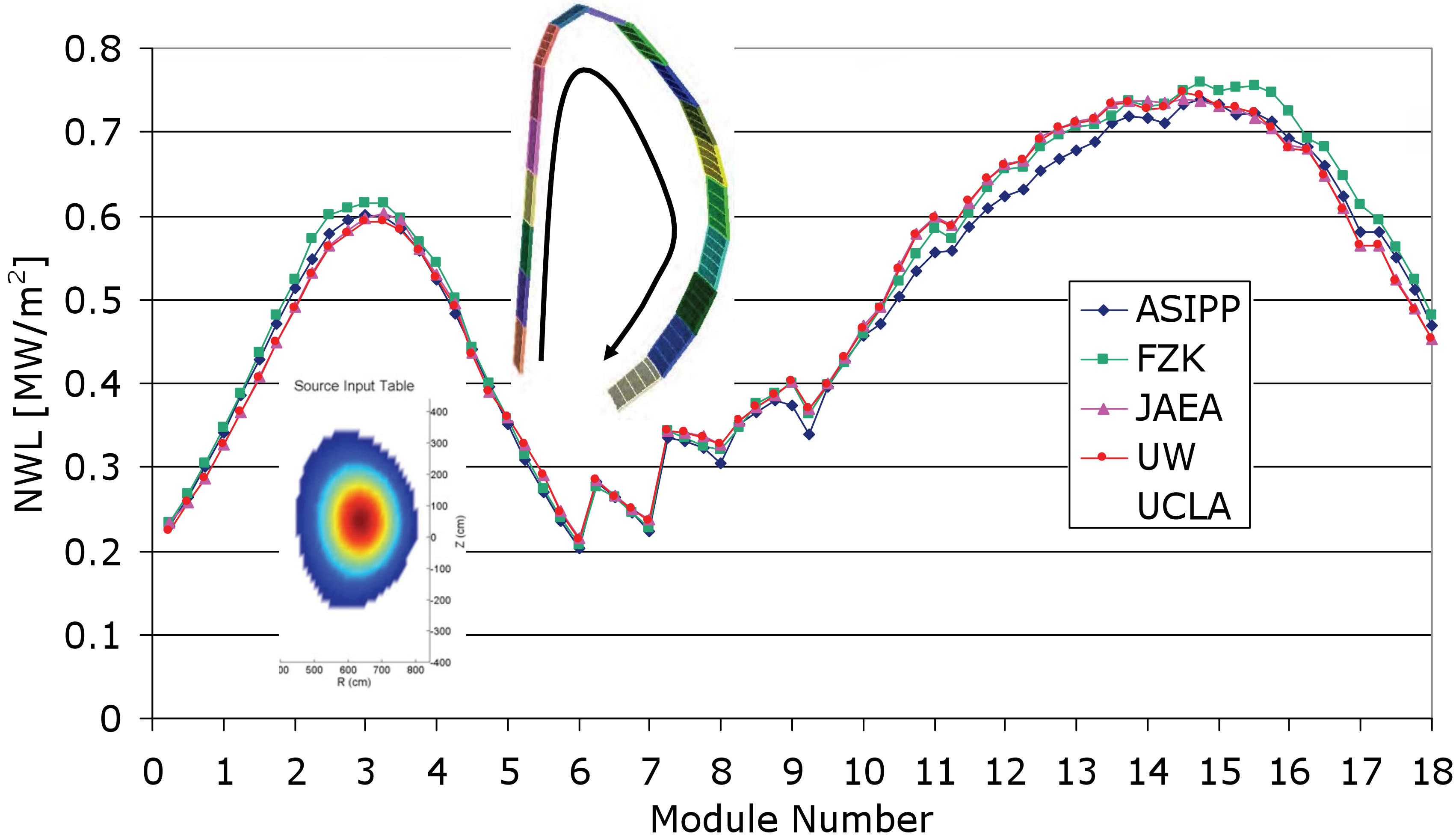
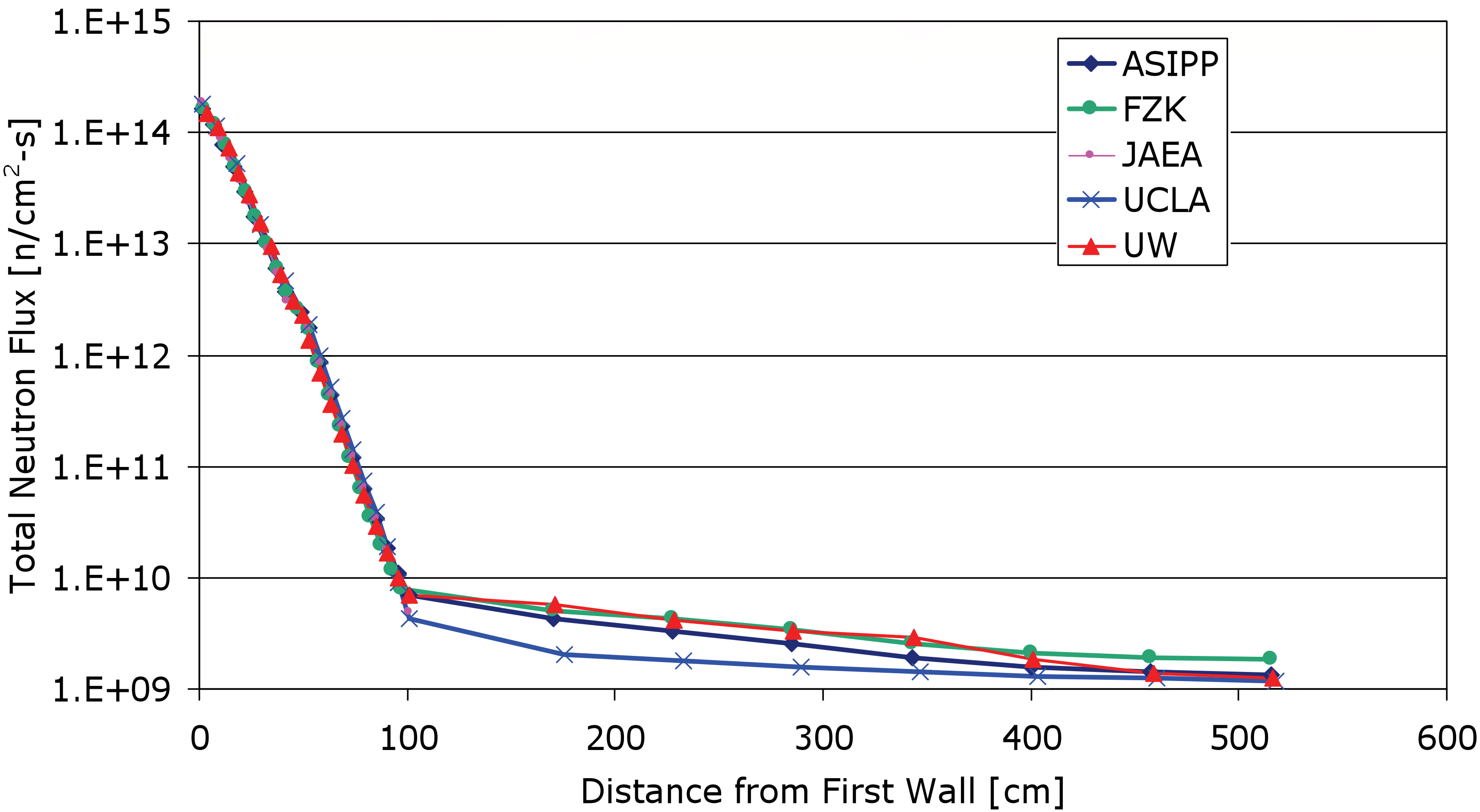
Neutron Wall Loading



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

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

Geometry Manipulation

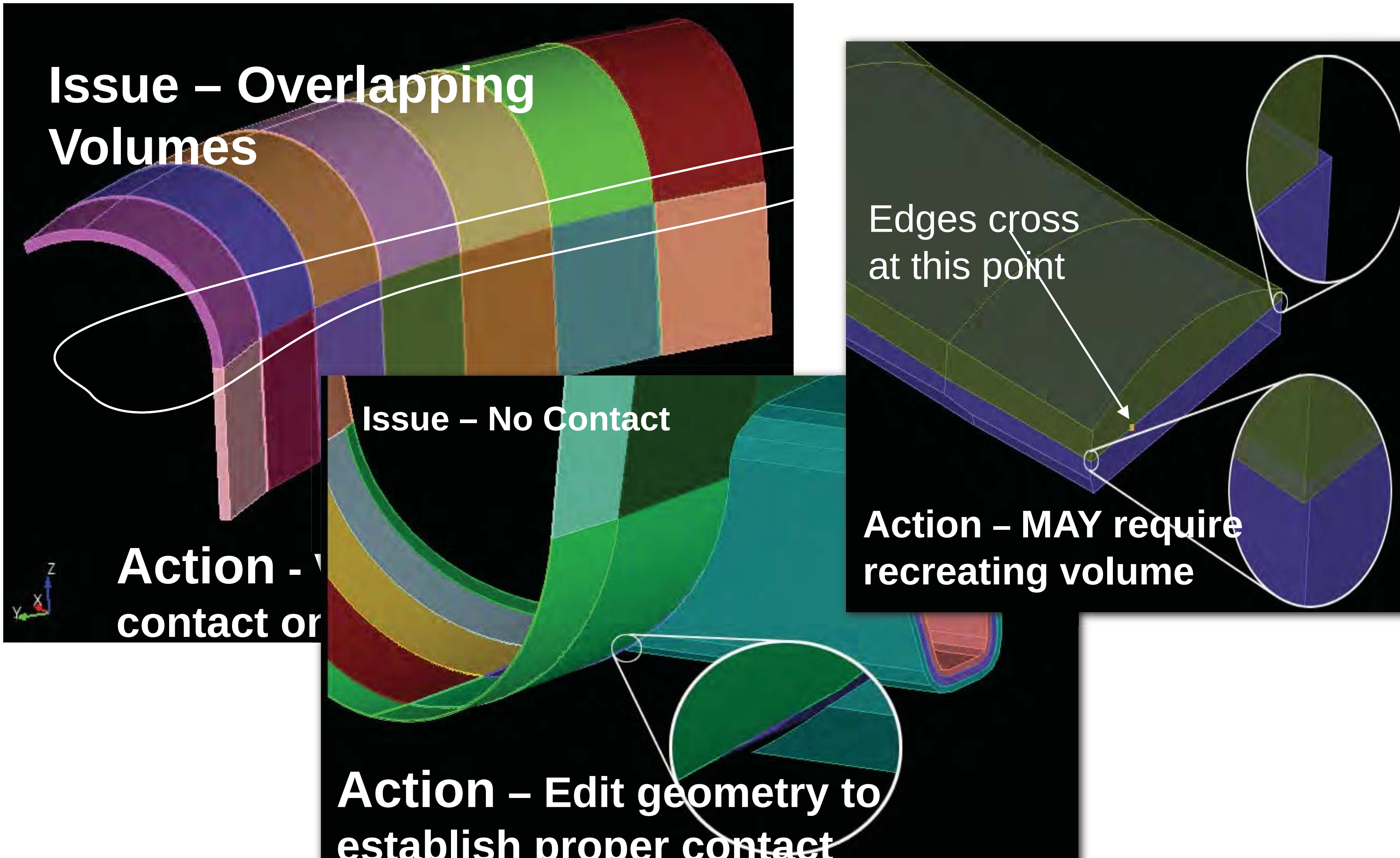
- Import into CUBIT
  - (Create complement in CUBIT)
- Imprint surfaces
- Merge surfaces
- Define MCNP info:
  - Material, density
  - Importance
  - Tally types/numbers
  - Reflecting surfaces
- Export in ACIS (.sat) format

CAD Issues Requiring "Repair"

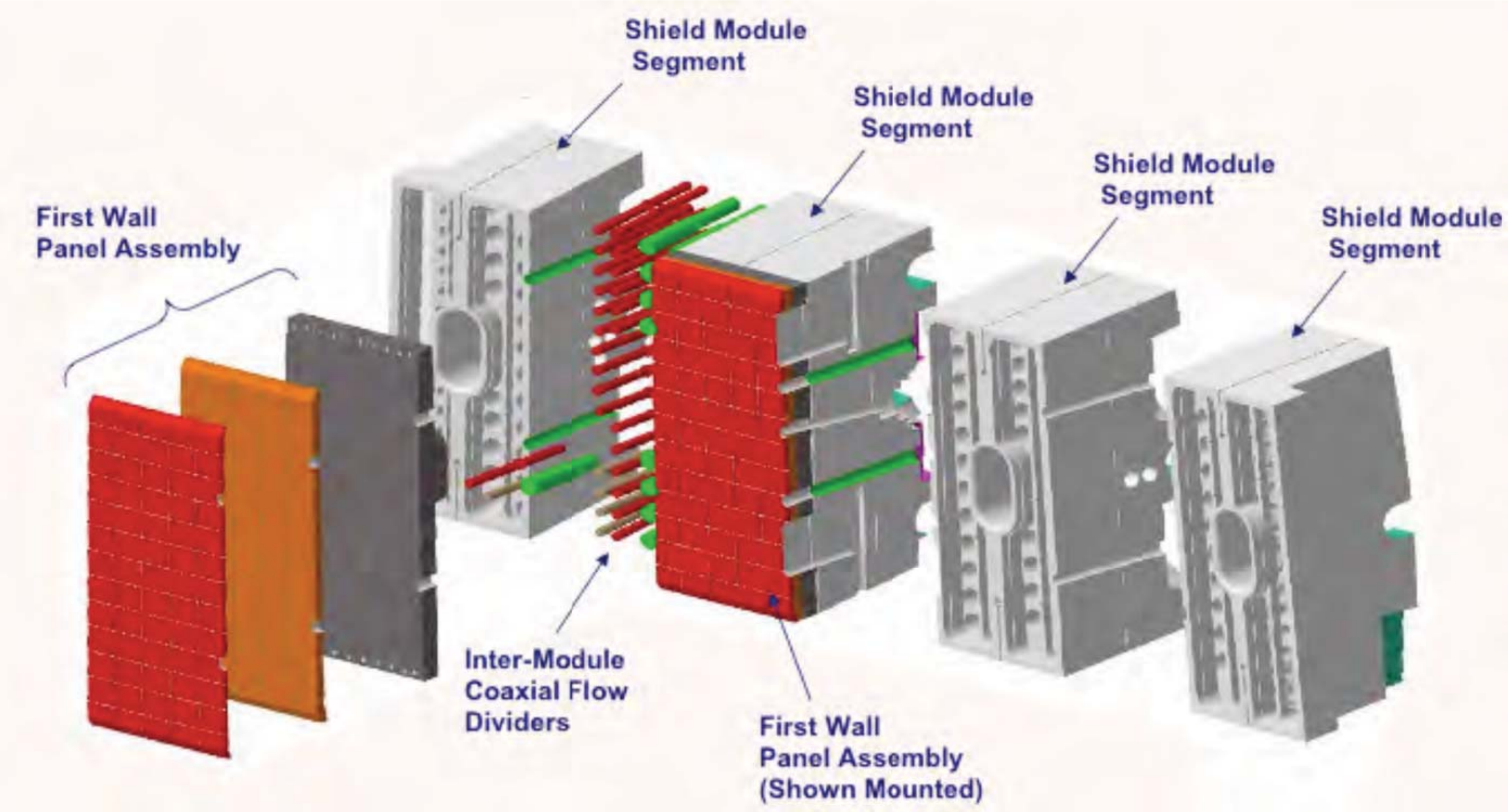
Human effort shifts from traditional MCNP model creation to CAD/Solid Model repair

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

Examples of Typical CAD Issues and Typical Repairs



ITER FWS Module Elements



Hybrid 1-D/3-D Analysis Parameters

- 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)