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

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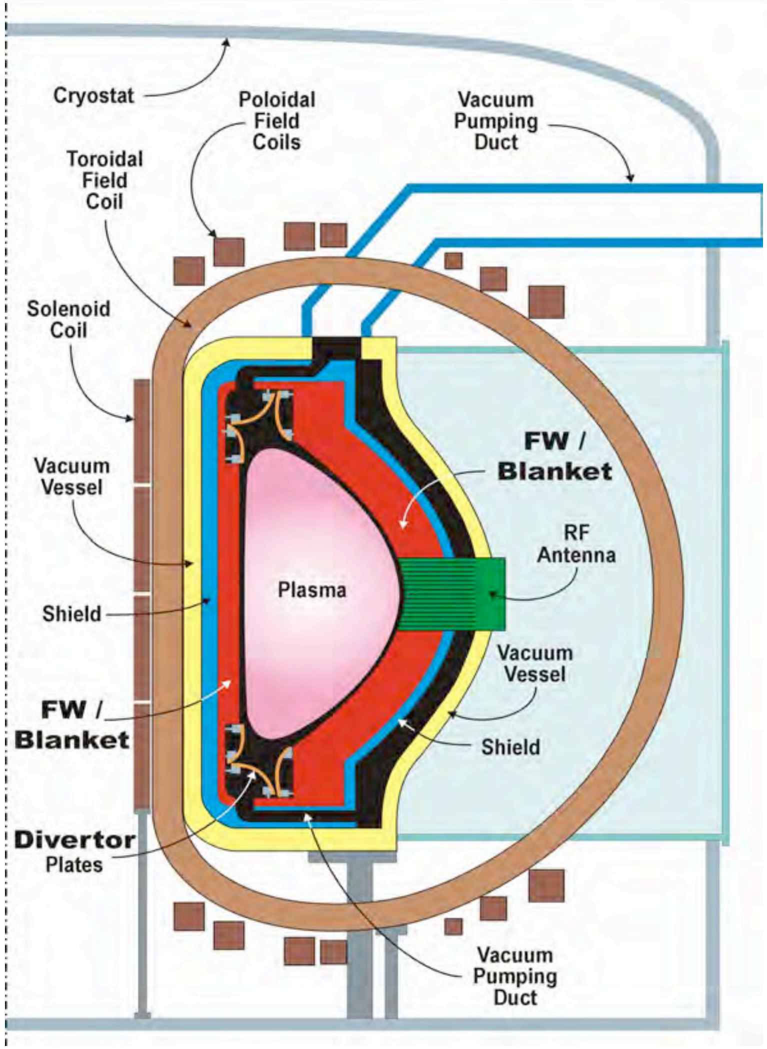
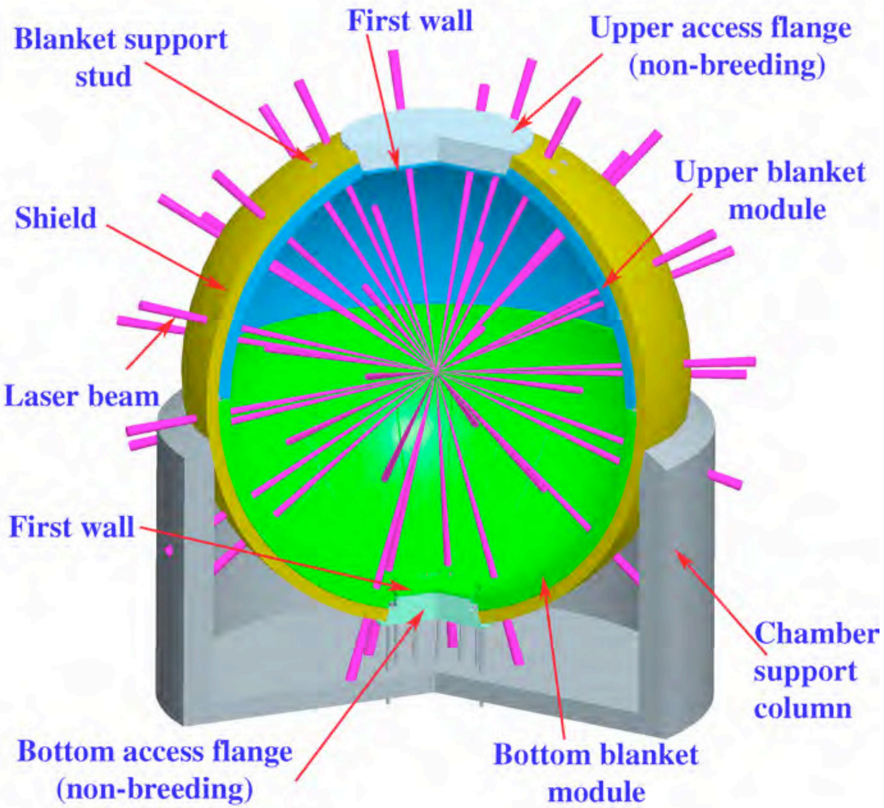
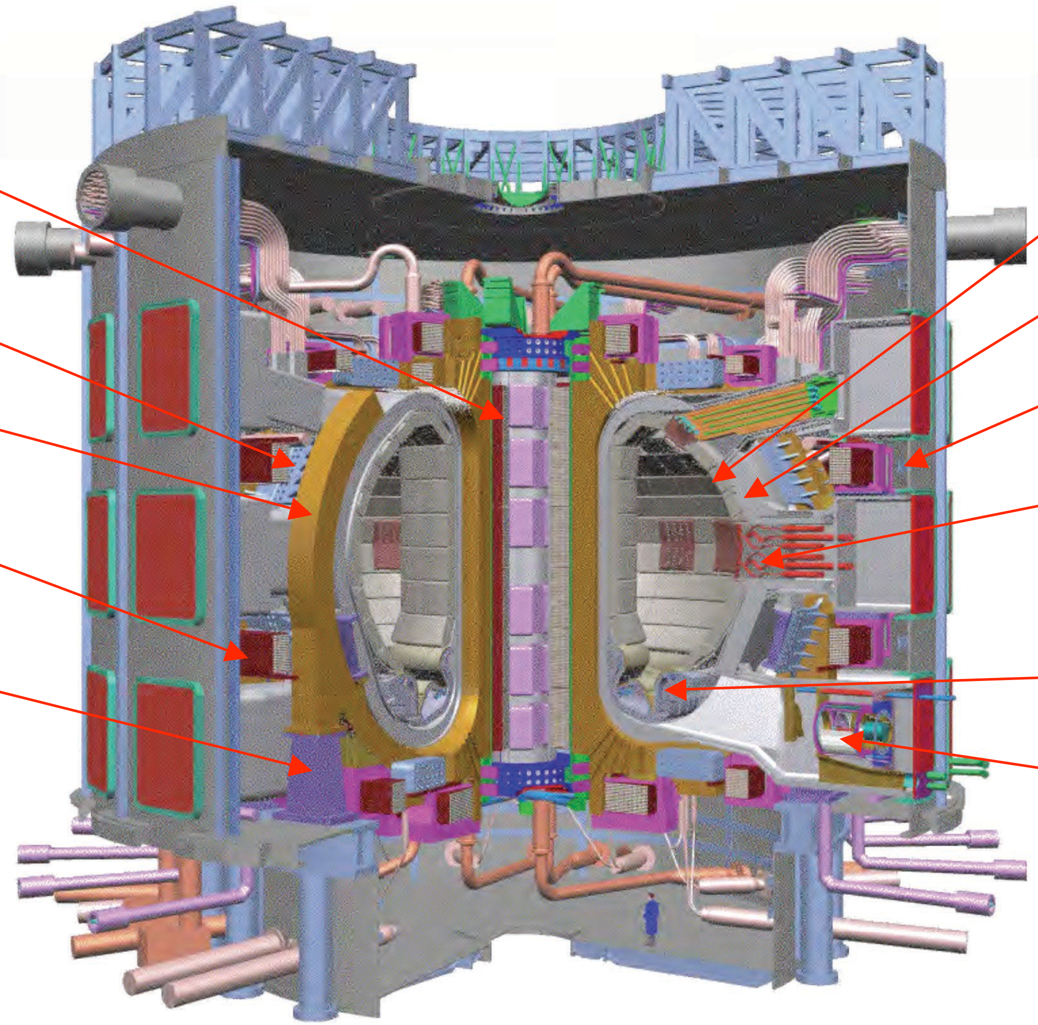
Fusion Reactors are Complex with Many Components





ITER

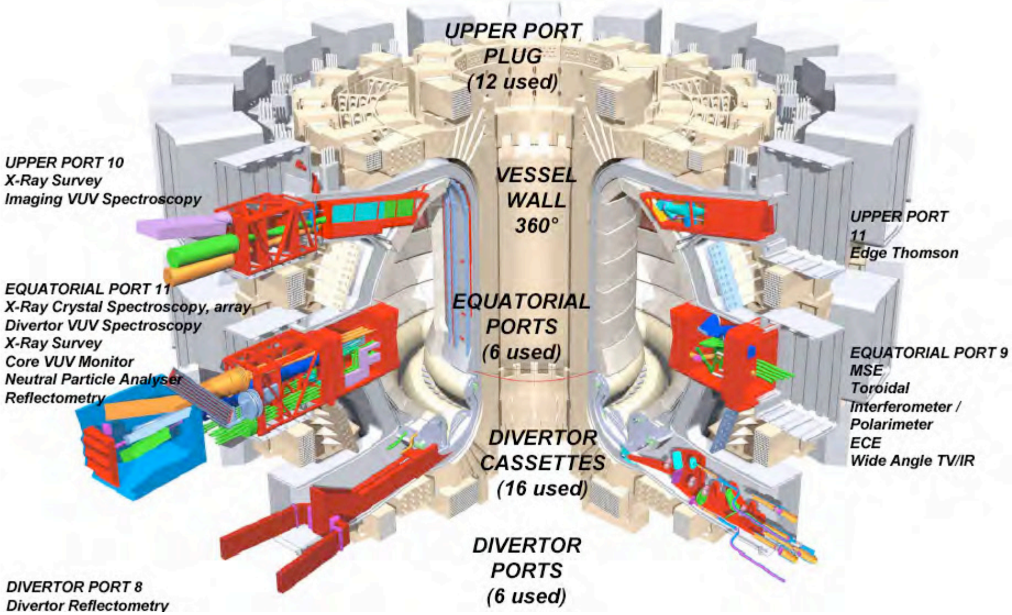
1st Integrated Fusion Test Reactor



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

ITER diagnostics landscape

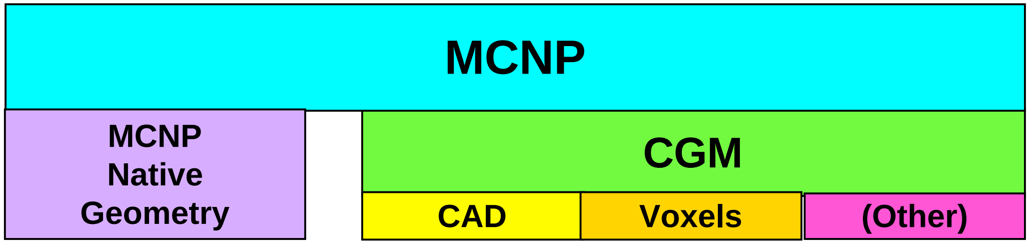


Nuclear Analysis is Essential Part of Fusion Reactor Design

- 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



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

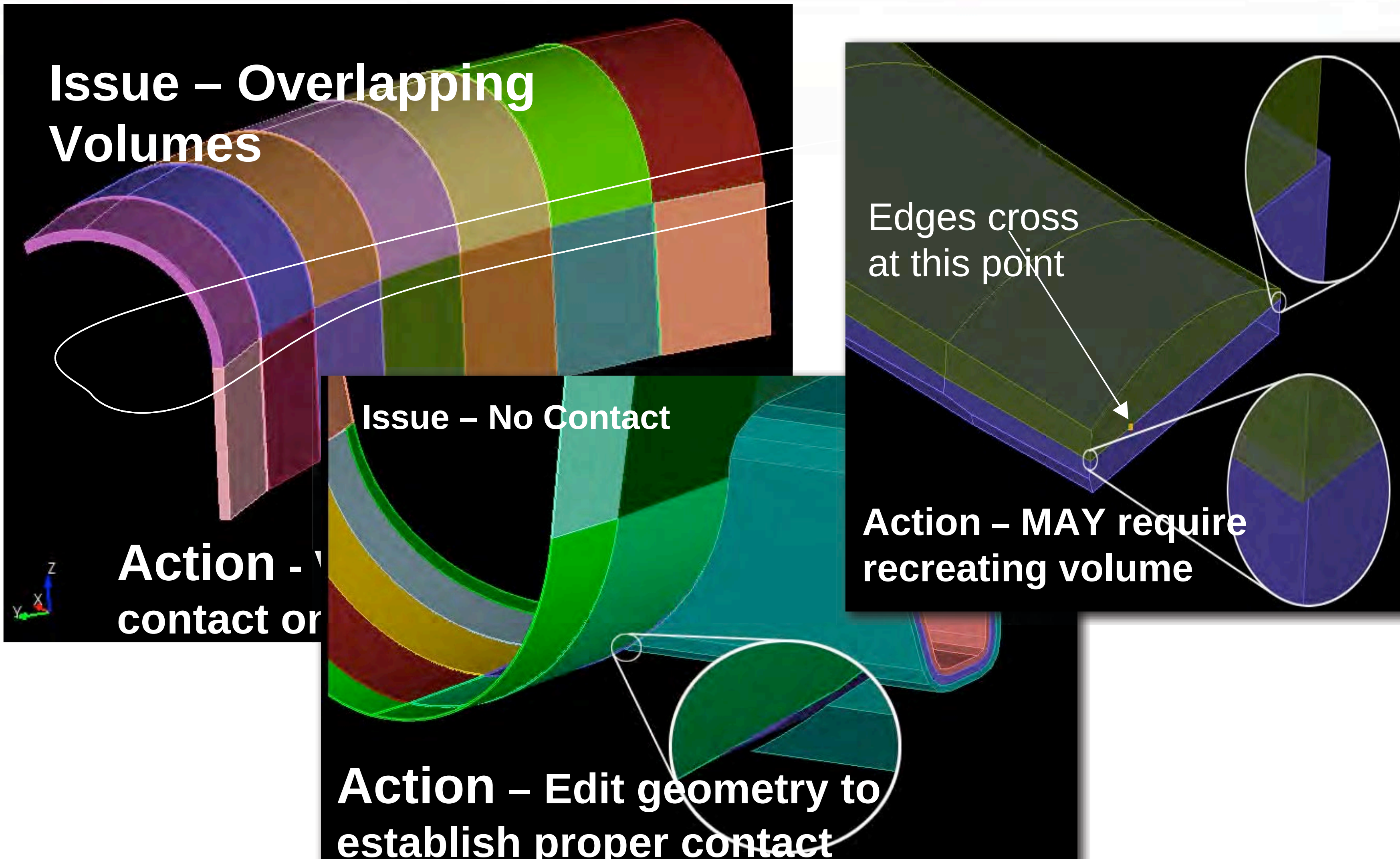
- Reduce impacts of manual conversion of 3-D model data
  - Reduce preparation time and allow faster design iterations
  - Avoid need for geometrical simplifications to 2nd order polynomials
  - Eliminate possible human errors in modeling
- Extend richness of geometric representation by preserving geometrical details

CAD Issues Requiring "Repair"

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

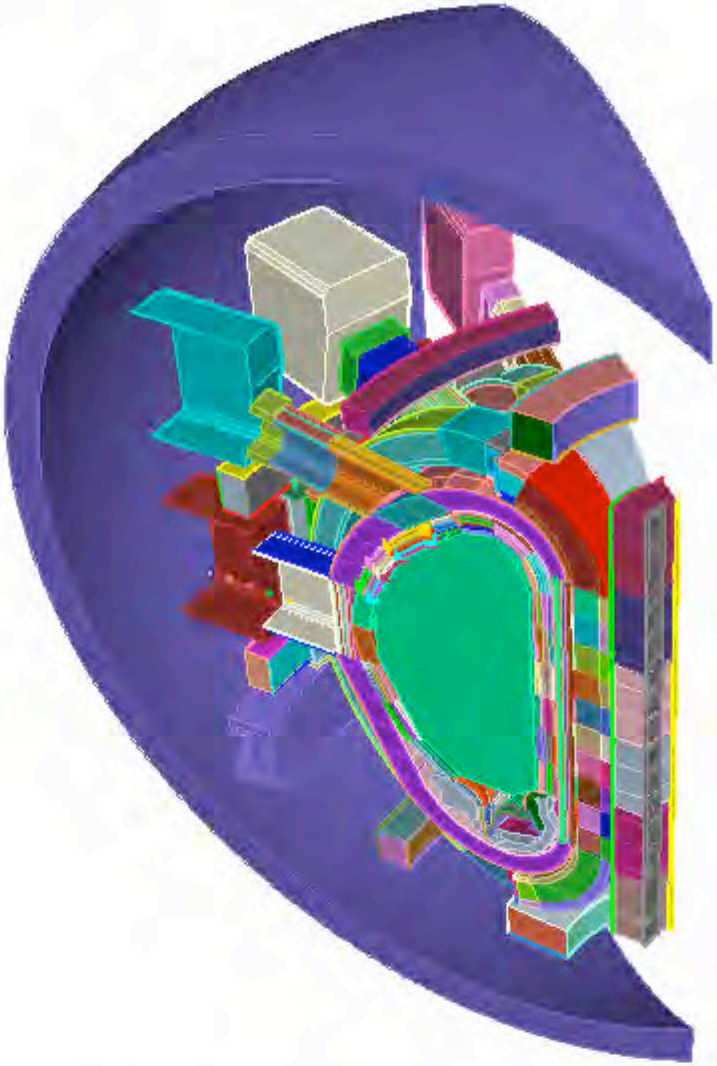
- Overlapping Volumes (i.e.: clashes)
- Mating surfaces not contacting
- Slight "Misalignment"

Examples of Typical CAD Issues and Typical Repairs



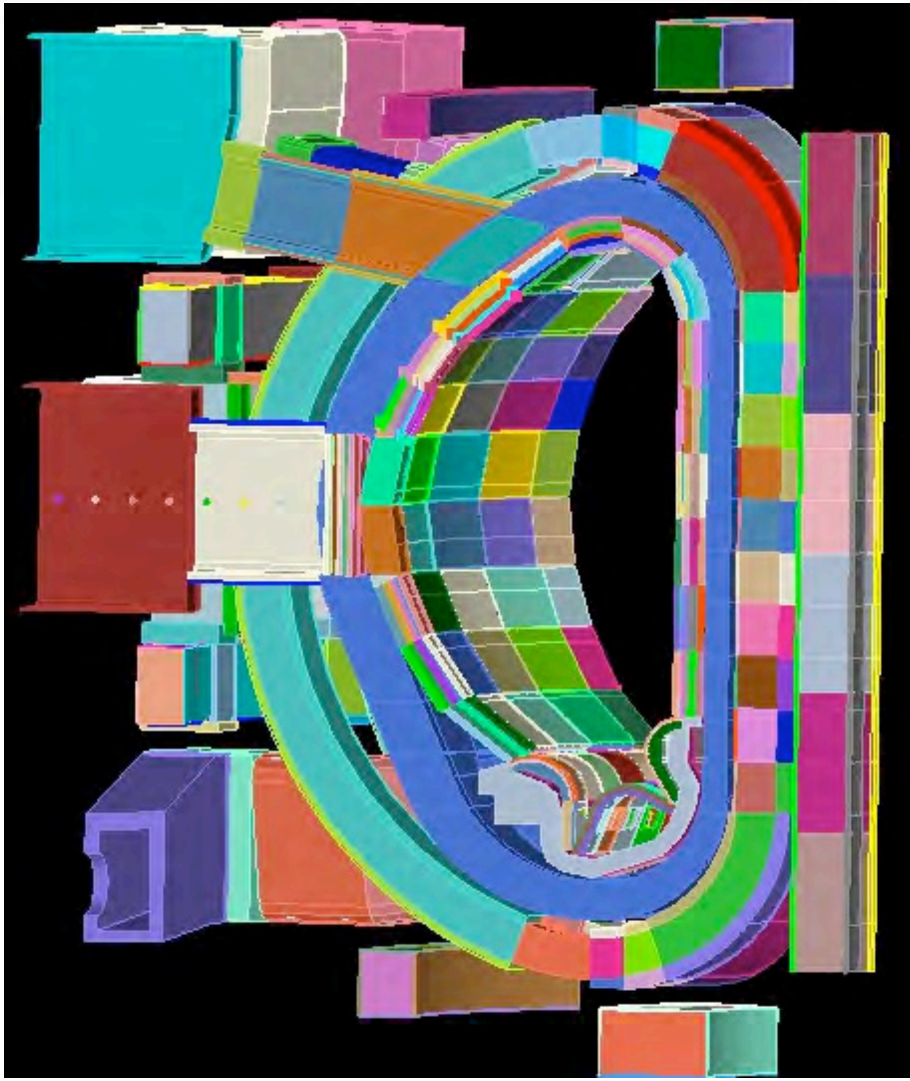
ITER Benchmark

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

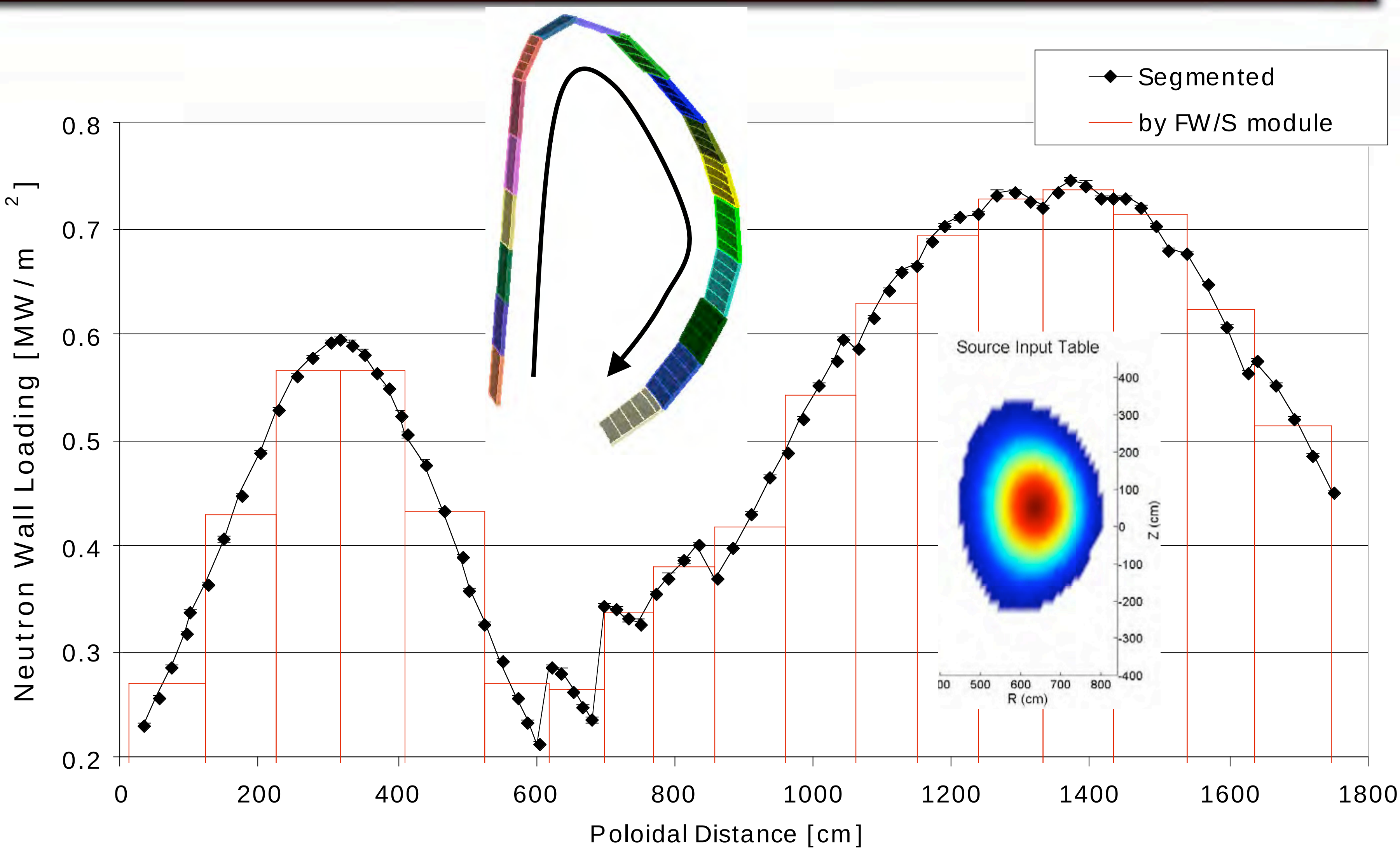


ITER Benchmark

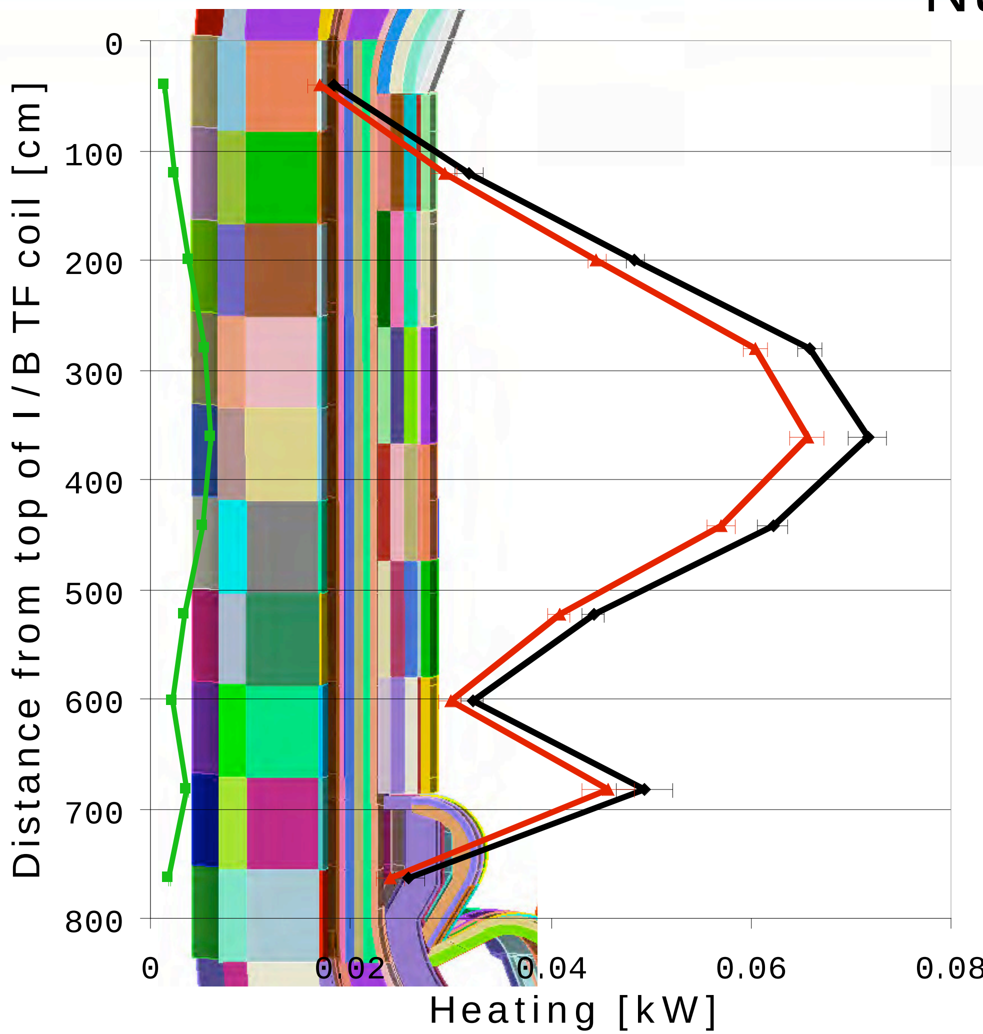
- Comparing 4 results
  - Neutron wall loading
  - Divertor fluxes and heating
  - Magnet heating
  - Midplane port shielding/streaming
- Participants
  - UW, FZK, ASIPP, JAEA, UCLA



Neutron Wall Loading : results



TF Coils : results

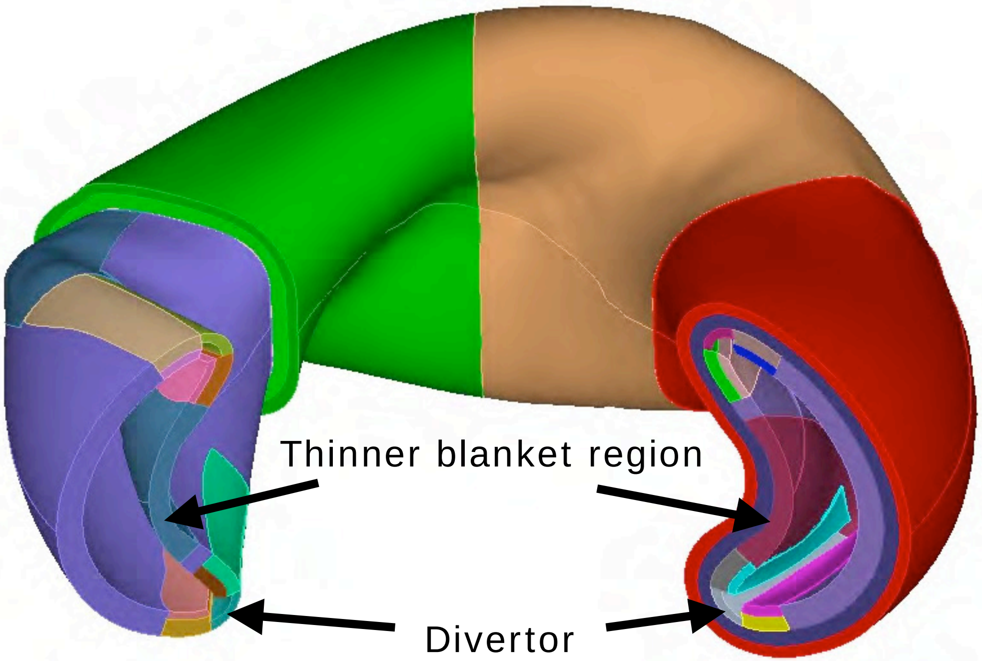


Nuclear Heating per Coil (W)

Neutron	Photon	Total
1.39 ± 0.05	17.0 ± 0.6	18.4 ± 0.6
2.47 ± 0.06	29.4 ± 0.6	31.8 ± 0.7
3.82 ± 0.04	44.6 ± 0.4	48.4 ± 0.5
5.41 ± 0.05	60.4 ± 0.6	65.8 ± 0.6
6.03 ± 0.12	65.6 ± 0.9	71.6 ± 1.0
5.16 ± 0.08	57.0 ± 0.7	62.2 ± 0.8
3.38 ± 0.04	40.9 ± 0.5	44.3 ± 0.6
2.27 ± 0.04	29.9 ± 0.5	32.2 ± 0.6
3.66 ± 0.08	45.7 ± 1.3	49.4 ± 1.4
1.88 ± 0.05	24.0 ± 0.7	25.9 ± 0.7
35.5 ± 0.2	415 ± 2.3	450 ± 2.5

8.1 kW in all TF I/B legs

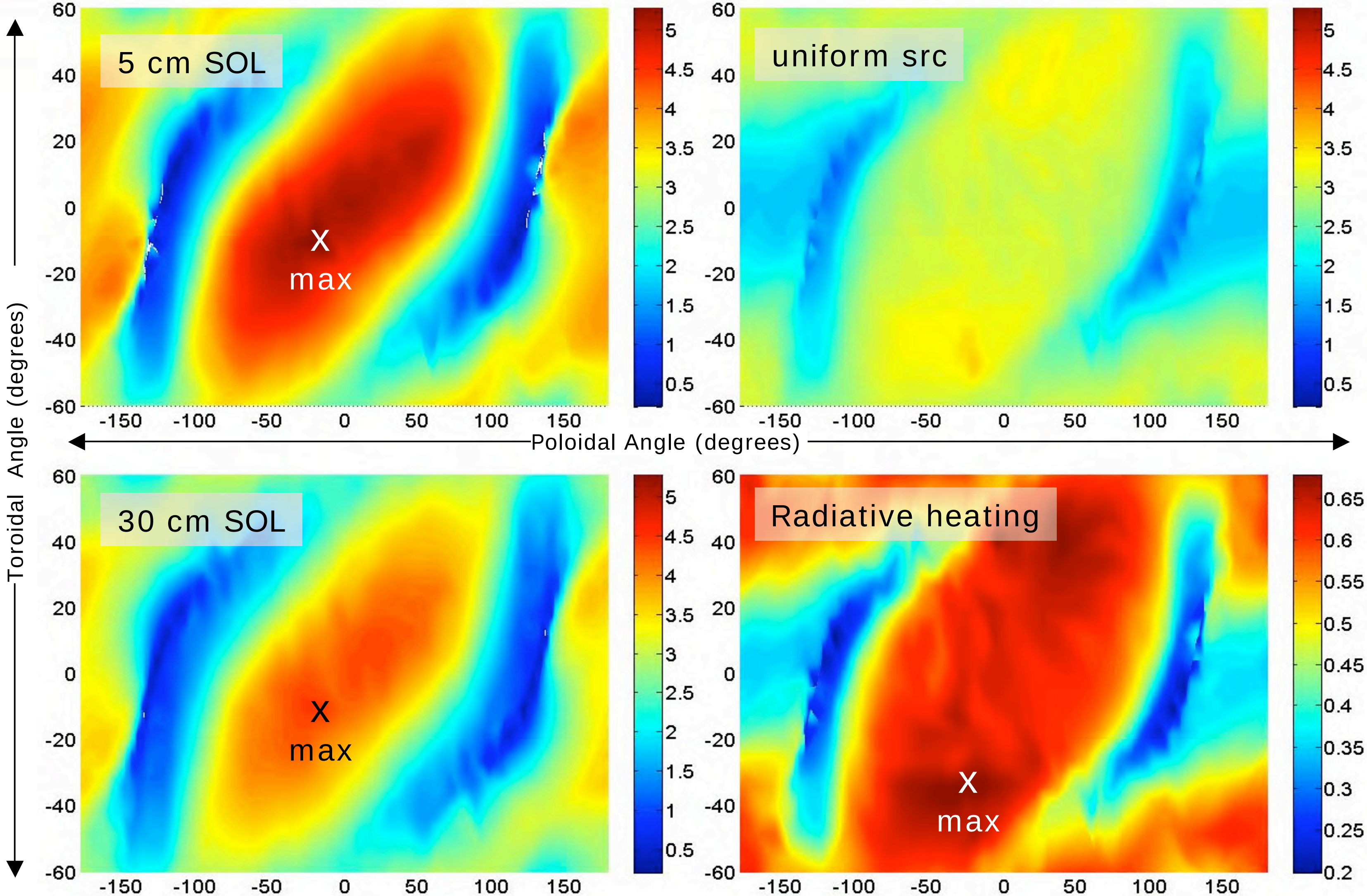
Application to ARIES-CS Compact Stellarator



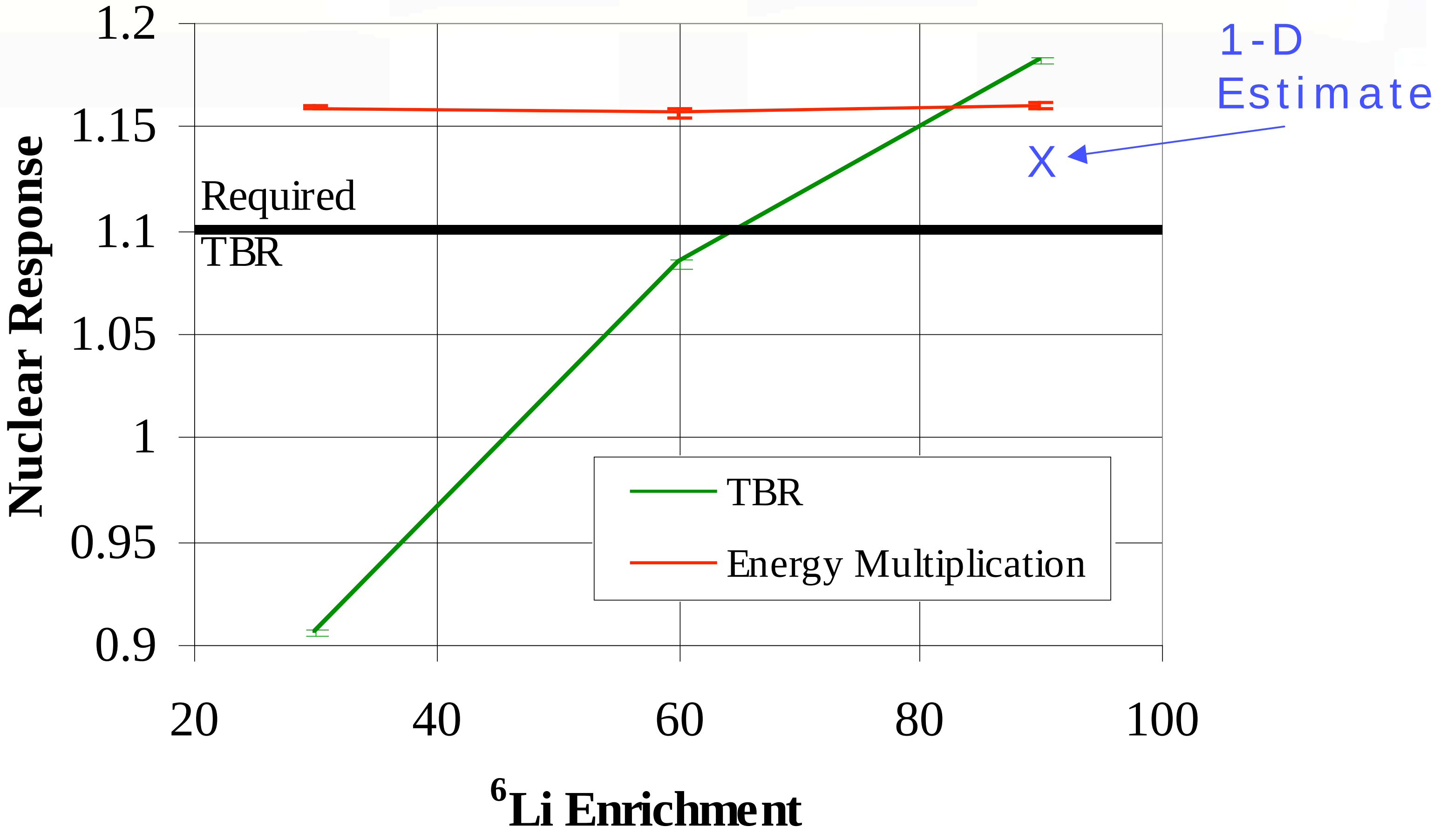
- Geometry complex
- FW shape and plasma profile vary toroidally within each field period
- Cannot be modeled by standard MCNP

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

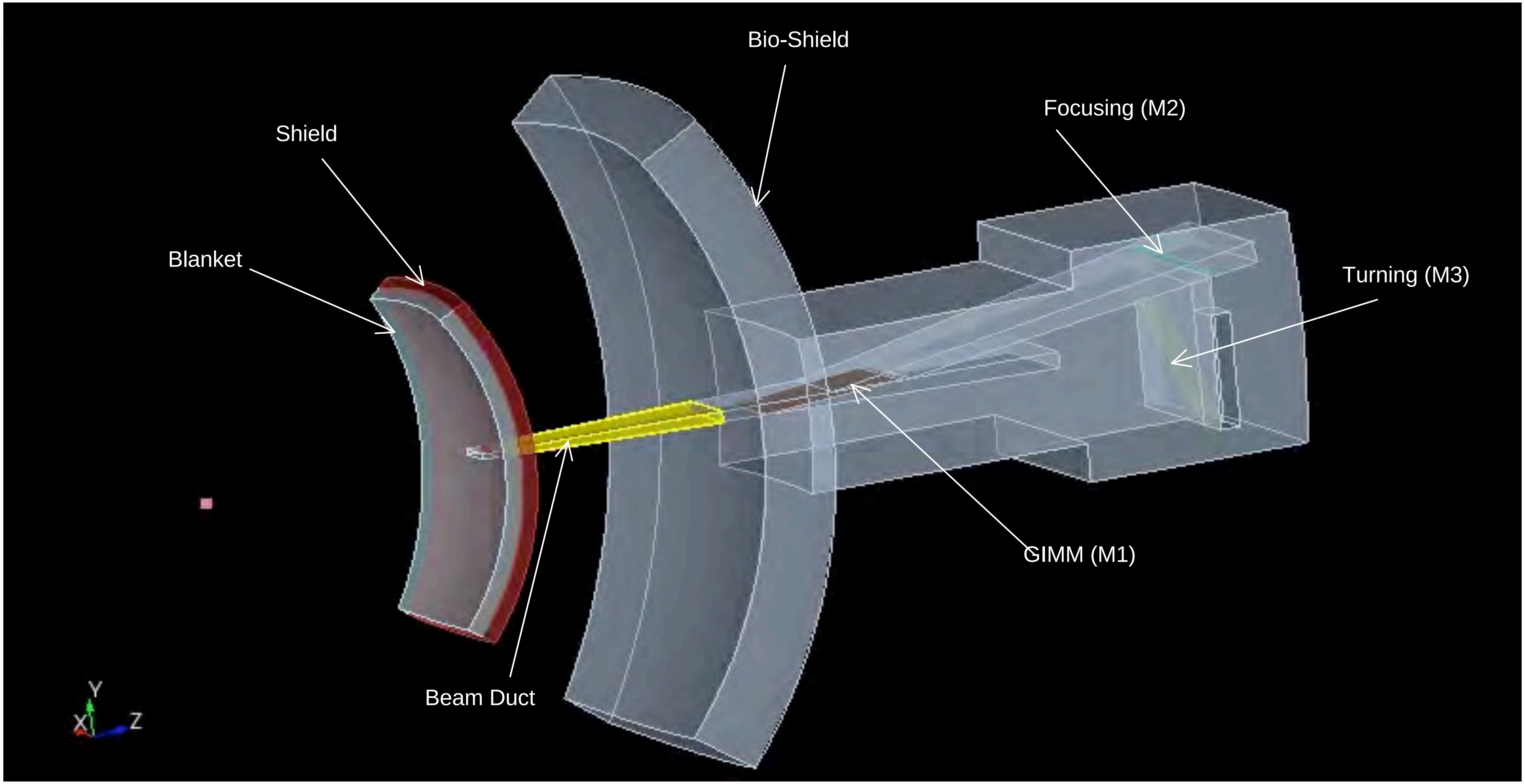
NWL Maps (colormaps in MW/m^2)



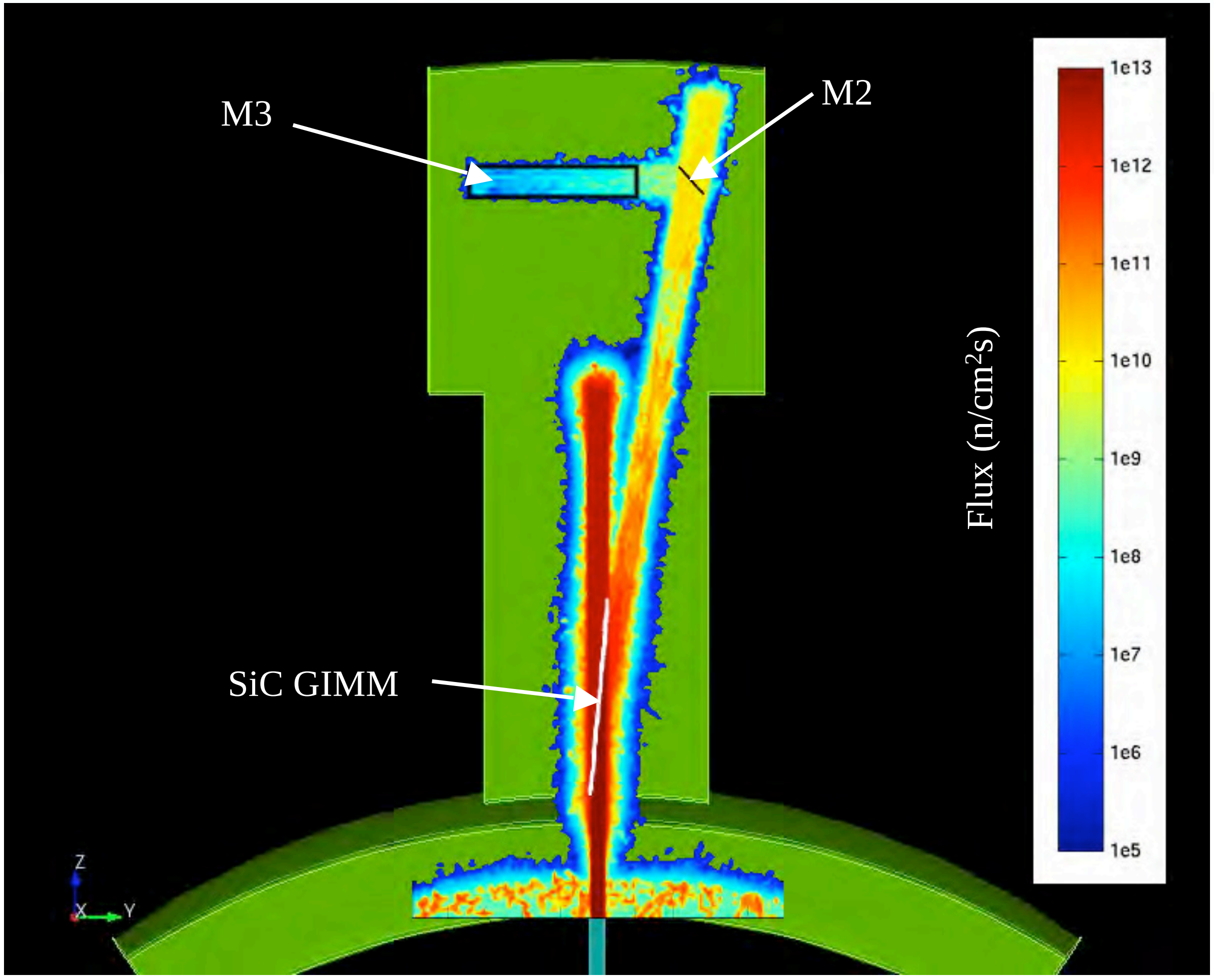
TBR: 3-D Results Differ from 1-D



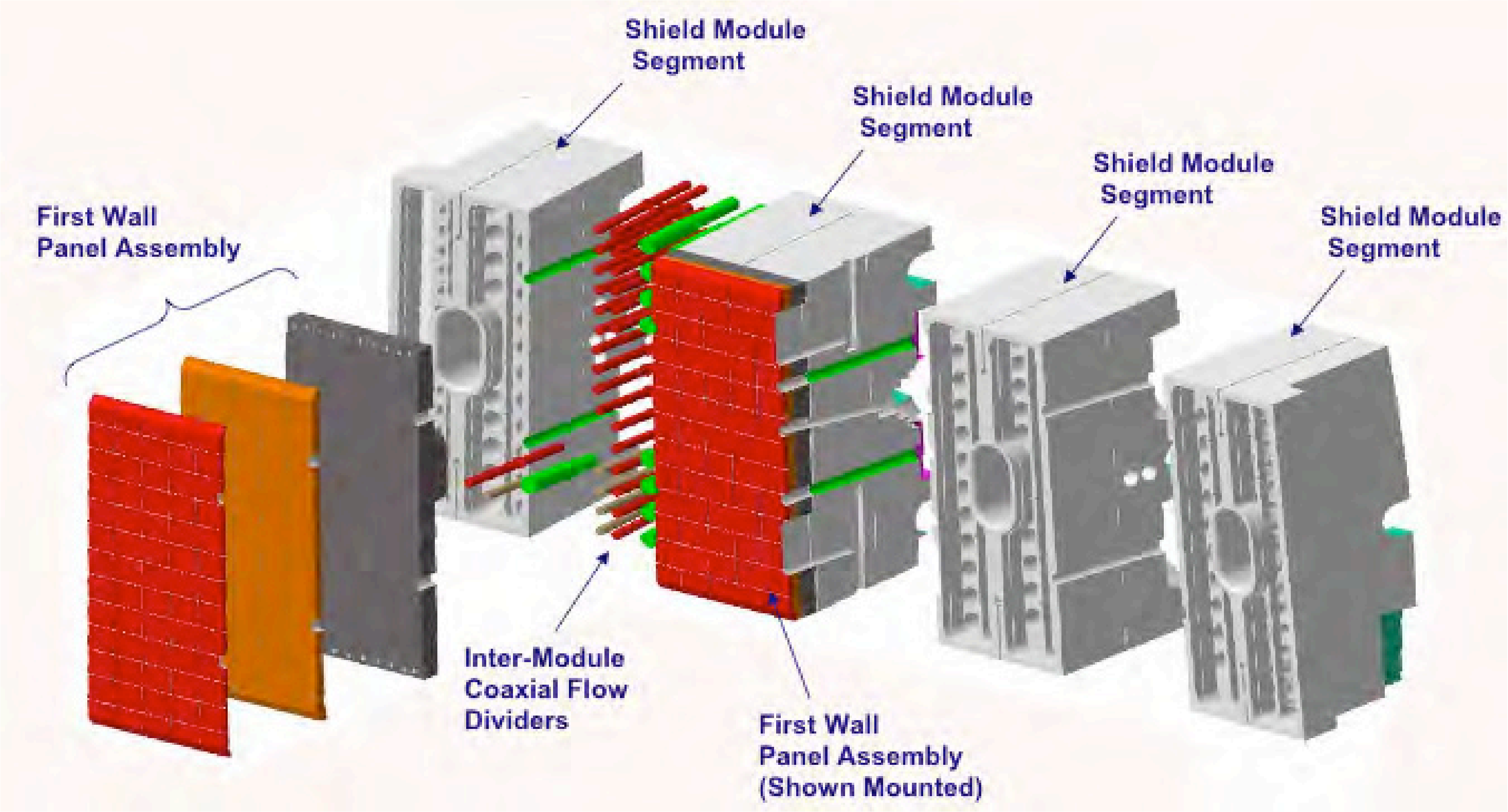
HAPL Final Laser Optics



Neutron Flux in Laser Beam Duct

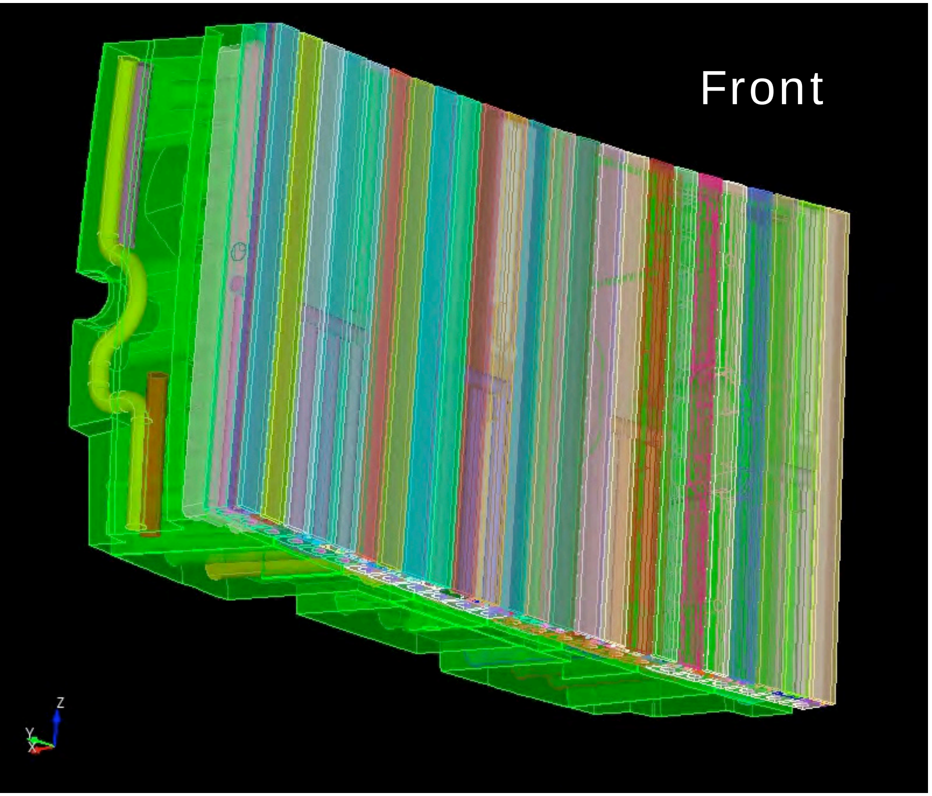


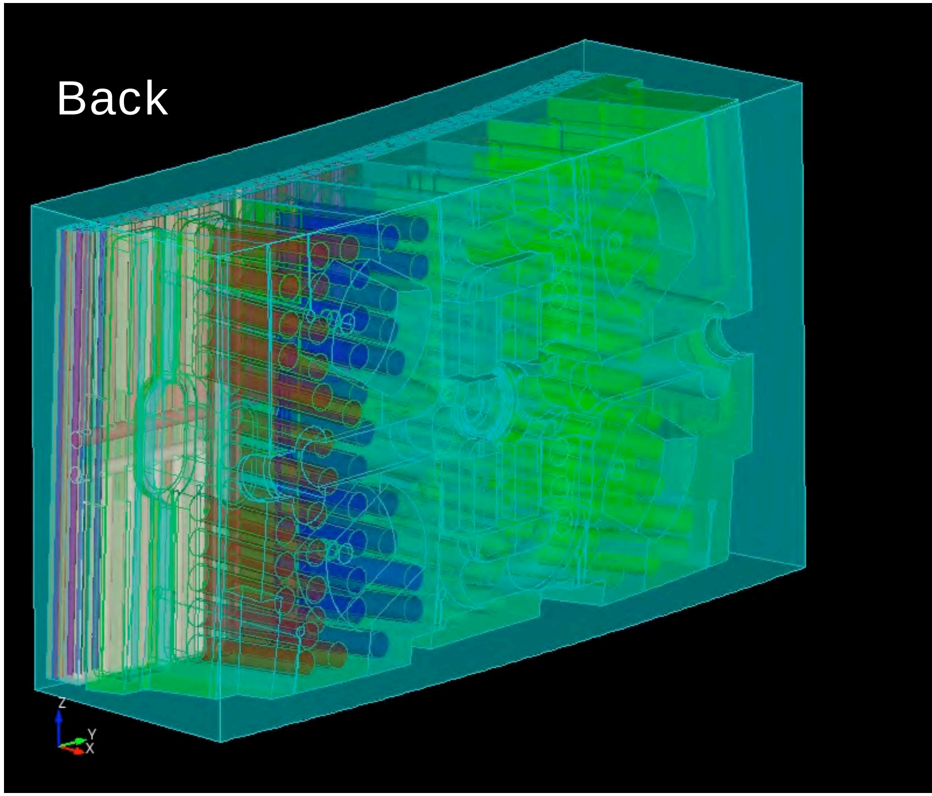
ITER FWS Module Elements



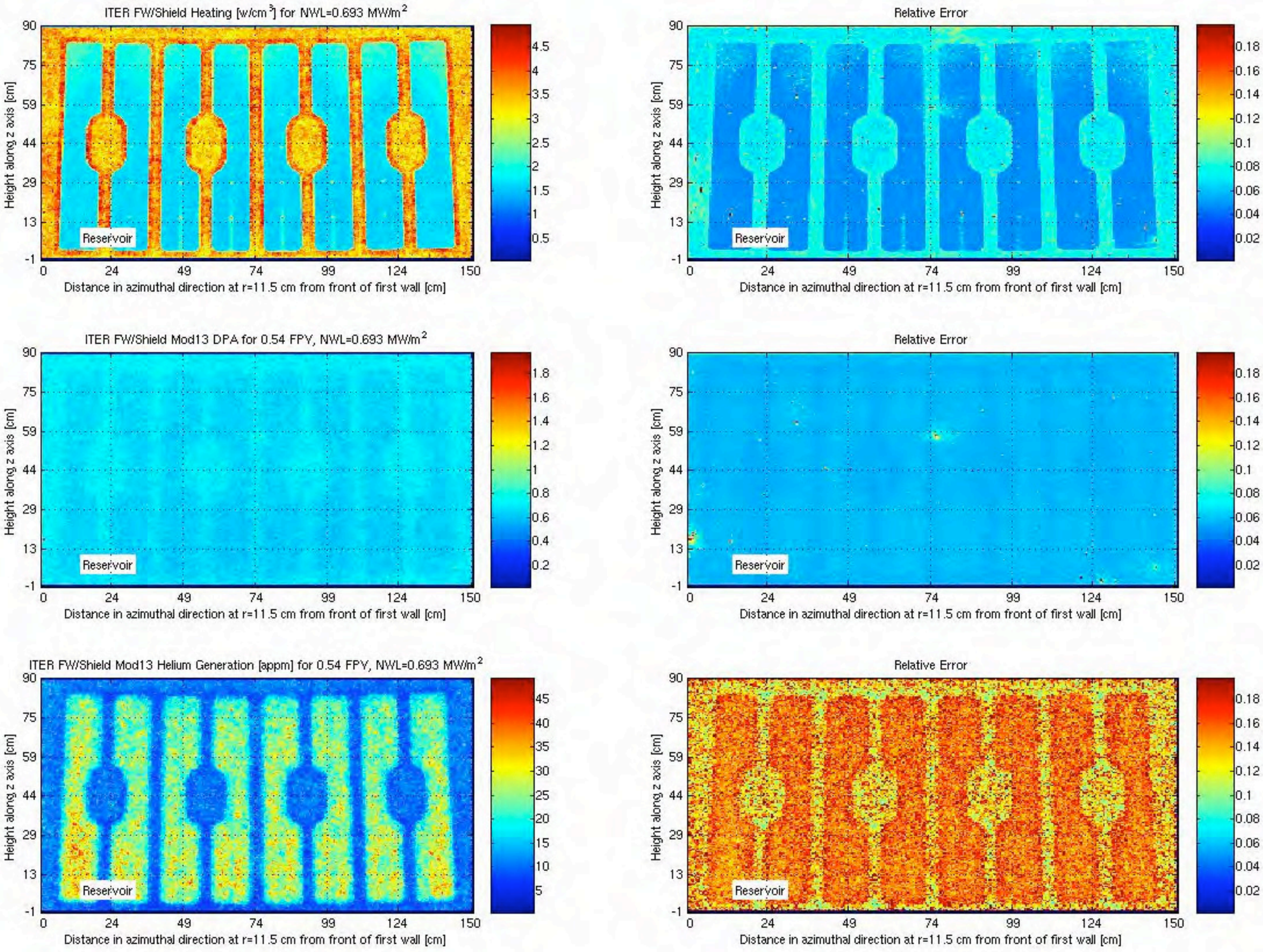
ITER First Wall/Shield
Module 13 Mockup

Model generated by designers using standard tools (CATIA/CUBIT)

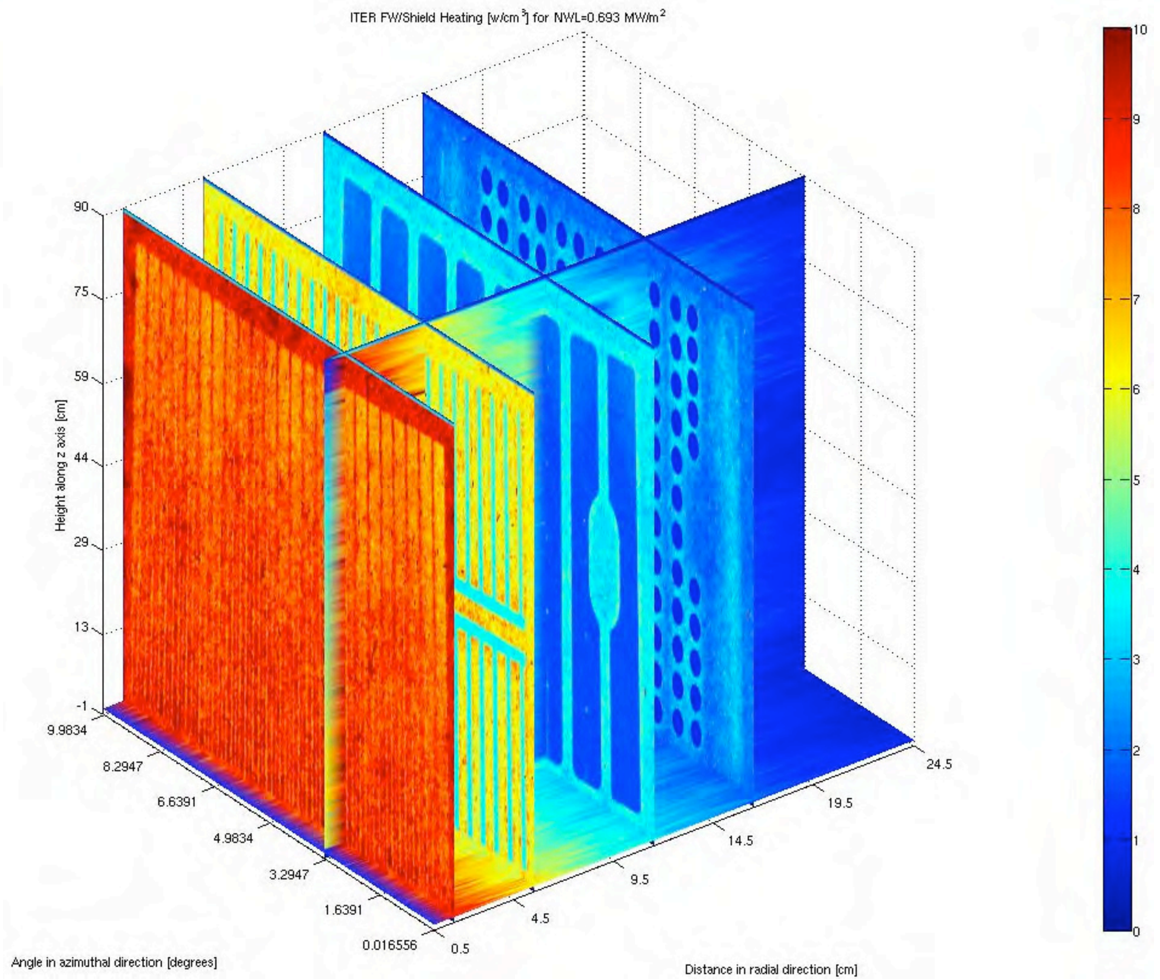




Nuclear responses at reservoir (11.5 cm from front of FW)



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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