Recent Advances in Development of Fusion Neutronics Predictive Capabilities

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Nuclear Data Development for Fusion

- US fusion neutronics community represented in the Cross Section Evaluation Working Group (CSEWG)
- Make sure that nuclear data needs for US fusion neutronics community are addressed satisfactorily
- Support development of updated FENDL-3 through participation in the IAEA sponsored Coordinated Research Project (CRP) and identification of issues from the user's perspective

FENDL-2.1 Background

- Revision to FENDL-2.0 (1995/96)
- Compiled November 2003, INDC(NDS)-451
- 71 elements/isotopes
- Working libraries prepared by IAEA/NDS, INDC (NDS)-467 (2004)
- Reference data library for nuclear analysis of ITER and other fusion systems

Data Source for FENDL-2.1

No.	Library	NMAT	Materials
1	ENDF/B-VI.8 (E6)	40	^{2}H, ^{3}H, ^{4}He, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B, ^{16}O, ^{19}F, $^{28-30}Si$, ^{31}P, S, $^{35,37}Cl$, K, $^{50,52-54}Cr$, $^{54,57,58}Fe$, ^{59}Co, $^{61,62,64}Ni$, $^{63,65}Cu$, ^{197}Au, $^{206-208}Pb$, ^{209}Bi, $^{182-184,186}W$
2	JENDL-3.3 (J33)	18	^{1}H, ^{3}He, ^{23}Na, $^{46-50}Ti$, , ^{55}Mn, $^{92,94-98,100}Mo$, ^{181}Ta,V
3	JENDL-3.2 (J32)	3	Mg, Ca, Ga
4	JENDL-FF (JFF)	4	^{12}C, ^{14}N, Zr, ^{93}Nb
5	JEFF-3 (EFF) JEFF3	4	^{27}Al, ^{56}Fe, ^{58}Ni, ^{60}Ni
6	BROND-2.1 (BR2)	2	^{15}N, Sn

- Majority (40) of materials taken from ENDF/B-VI.8
- Investigated effect of recently released ENDF/B-VII.0 (December 2006) on results for ITER calculational benchmark and four FNG ITER relevant integral experiments

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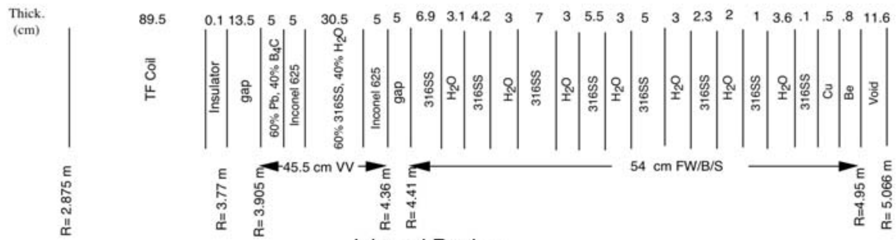
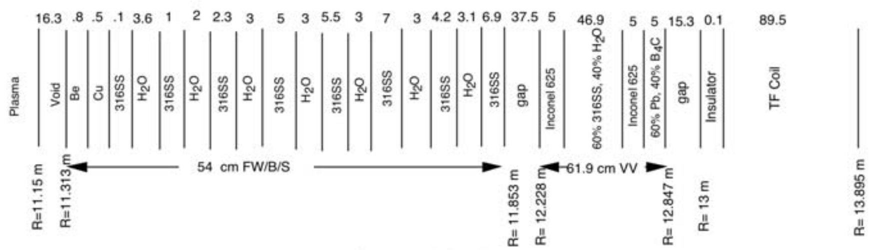
Calculational and Experimental Benchmarks

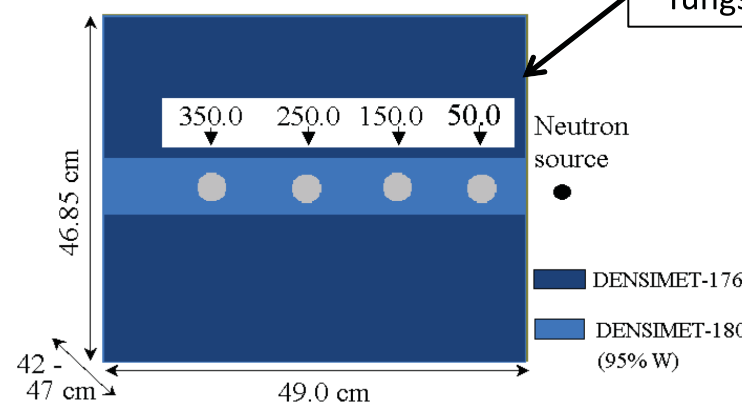


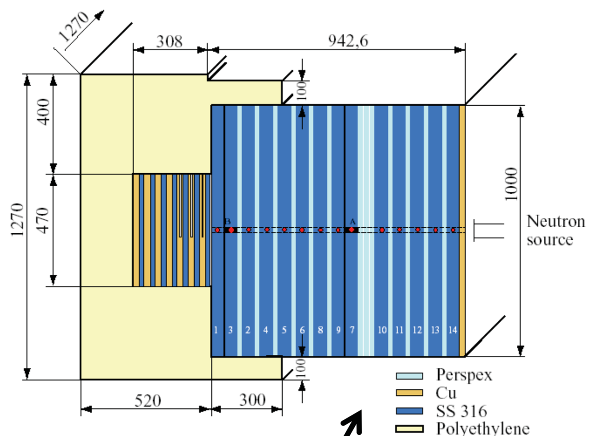
Inboard Region



Outboard Region

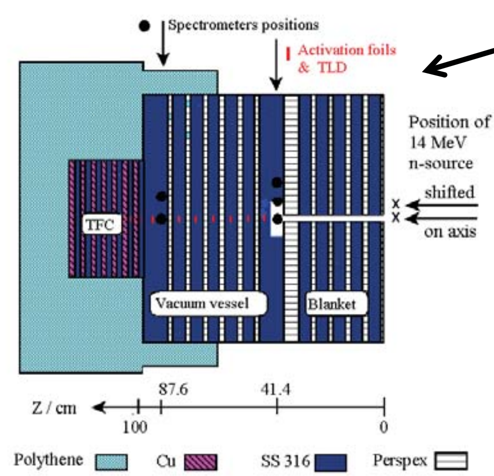
Tungsten

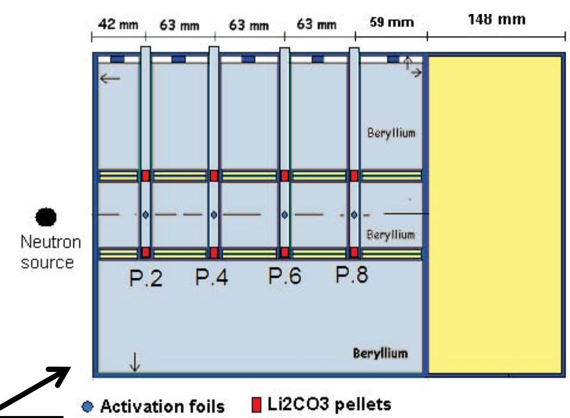




Bulk shielding

Streaming





HCPB breeder

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FENDL-3 Development

(http://www-nds.iaea.org/fendl3/)

- An effort was initiated by the IAEA in 2008 to update the FENDL library to improve status of nuclear databases for fusion devices including IFMIF
- The library (FENDL-3) is a substantial extension of FENDL-2.1 library toward higher energies, with inclusion of incident charged particles and the evaluation of related uncertainties (covariance data)
- FENDL-3 will be released at the end of the 3 years of the Coordinated Research Project (CRP) activities [end of 2011]

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FENDL-3/SLIB Starter Library

- A starter library (FENDL-3/SLIB) was generated based on several agreed upon rules of creation
  - Replace present evaluations with updates
  - Adopt evaluations from libraries with standards (H-1 from ENDF)
  - Use isotopic evaluations where available
- The library includes 88 isotopes with updated evaluations from ENDF/B-VII.0, JENDL-HE, JEFF-3.2, and RUSFOND
- Only evaluation switch occurred for H-1 and He-3 (JENDL-3.3 → ENDF/B-VII.0)
- Sn is the only material with elemental rather than isotopic evaluation
- Using FENDL-3/SLIB instead of FENDL-2.1 in ITER relevant calculations gives 1.5-3.5% higher nuclear parameters in regions heavily shielded with water-cooled SS (VV, magnets)

A. Trkov, R. Forrest and A. Mengoni, "Summary Report from 1st RCM on Nuclear Data Libraries for Advanced Systems – Fusion Devices (FENDL-3)," INDC(NDS)-547, IAEA (March 2009)

Expanded FENDL-3 General Purpose Neutron Library

- During the 2nd RCM held in March 2010, a decision was made to nearly double the number of materials in the library and the source of evaluation for each material was agreed on
- ***Materials added to the library*** were based on input obtained from the fusion neutronics community. These are 23 elements with their constituent isotopes:

  Re, Zn, Ag, Ba, Y, Cd, Ce, Ar, Er, Sb, Rh, Sc, Br, Ge, I, Lu, La, Cs, Pt, Hf, Gd, U, Th

- ***Only 3 actinide isotopes*** will be added as they are needed for neutron measurement by fission chambers (U-235, U-238) or exist in the ITER concrete (Th-232)
- Total number of isotopes in library increased to ***166***
- Evaluations to be utilized for these materials were selected

M.E. Sawan, "Summary Report from 2nd RCM on Nuclear Data Libraries for Advanced Systems – Fusion Devices (FENDL-3)," INDC (NDS)-567, IAEA (June 2010)

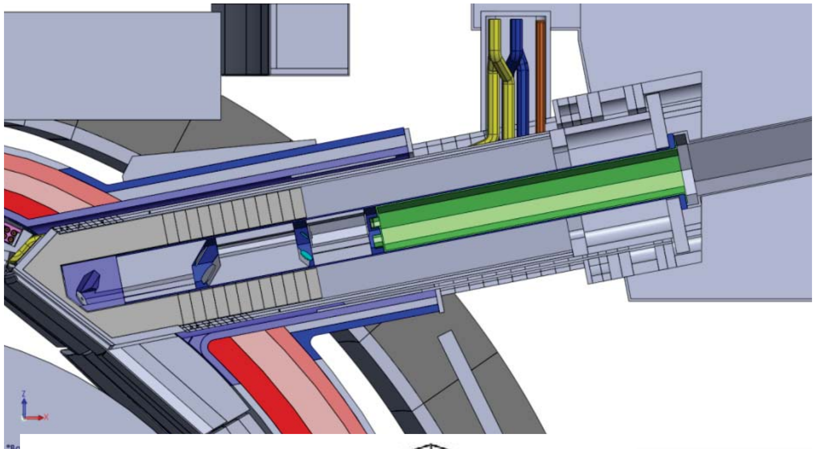
Neutronics Codes

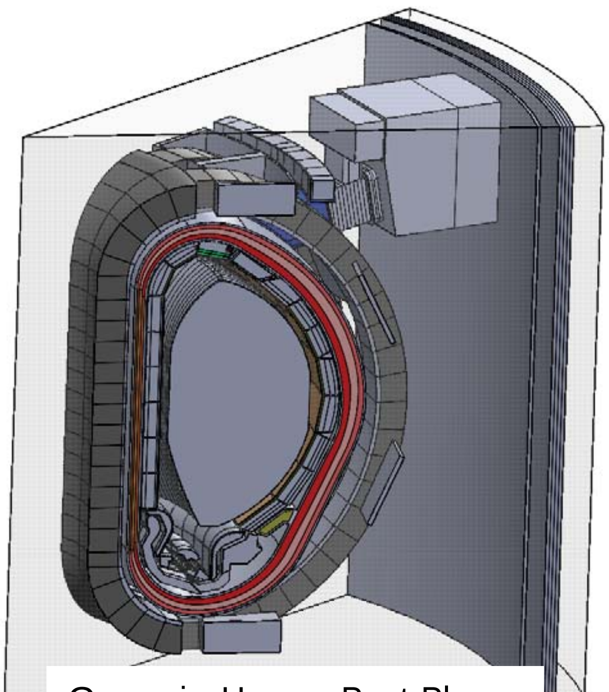
- Deterministic
  - PARTISN, DOORS, DENOVO, ATTILA (Transpire)
- Monte Carlo
  - MCNP, TRIPOLI
  - CAD-based
    - Translators: MCAM (ASIPP), McCAD (KIT), GEOMIT (JAEA)
    - Direct coupling: DAGMC (being developed at UW)

Generic Diagnostic Upper Port Plug Neutronics

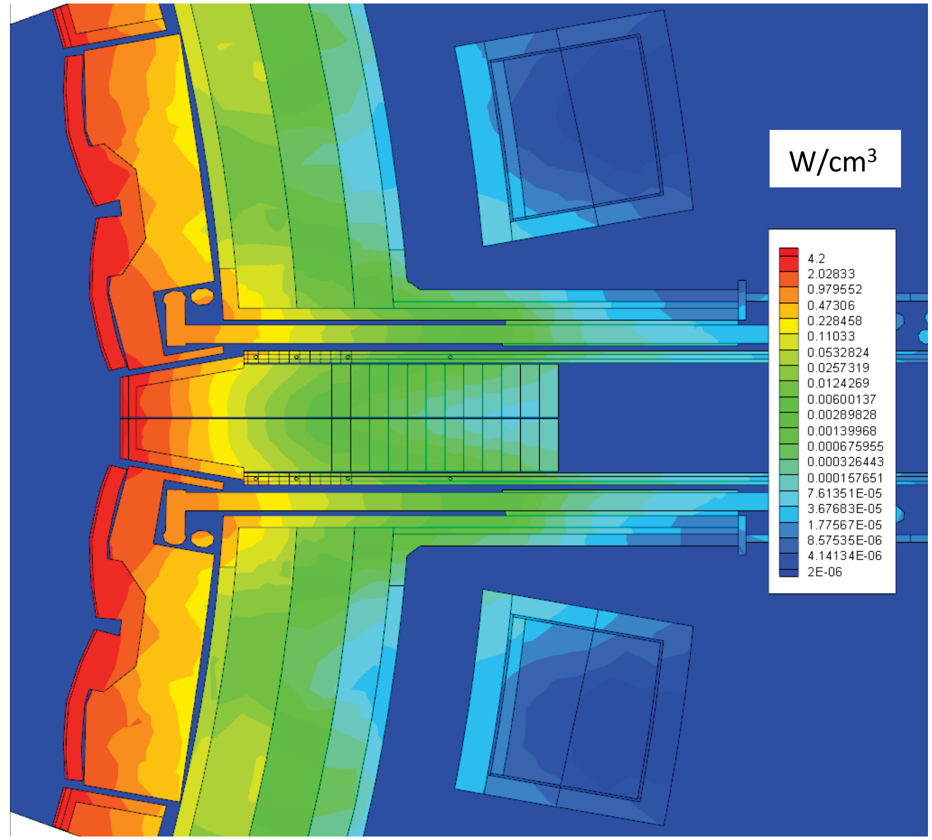
ATTILA

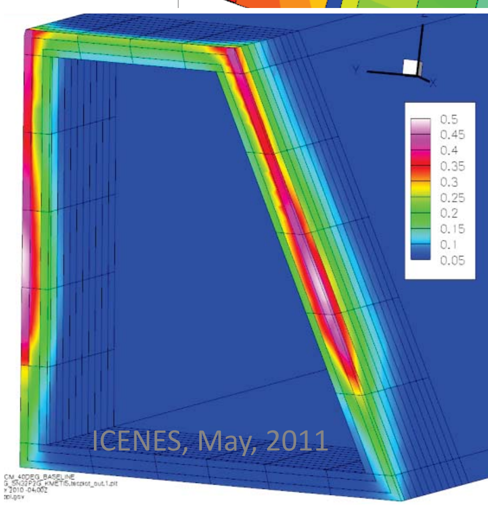
Section Through Upper Port
Showing the Visible/IR Camera Labyrinth





Generic Upper Port Plug
SolidWorks Analysis Model





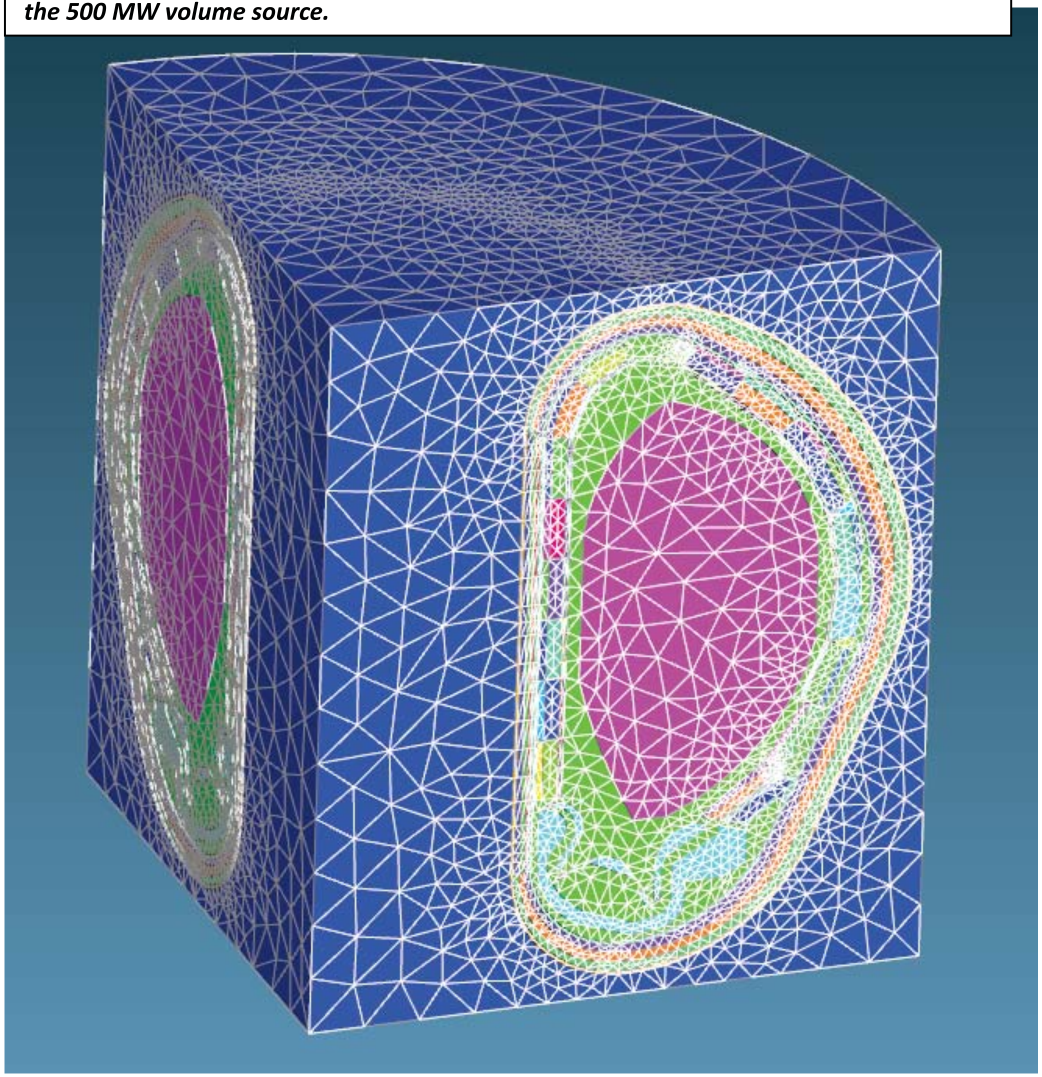
Generic Upper Port Nuclear Heating

Total: 316 kW
First Wall + Diagnostic Shield: 309 kW
GUPP Structure: 7 kW

PPPL PRINCETON PLASMA PHYSICS LABORATORY
UCLA

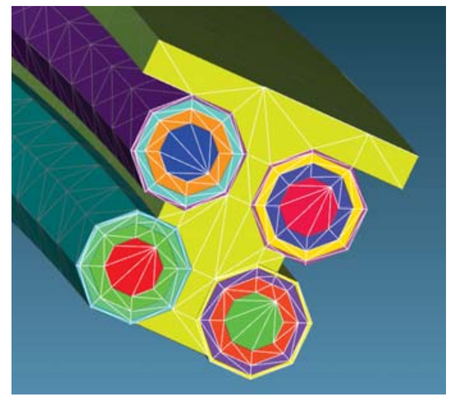
Upper and Lower VS Neutronics Analysis Model

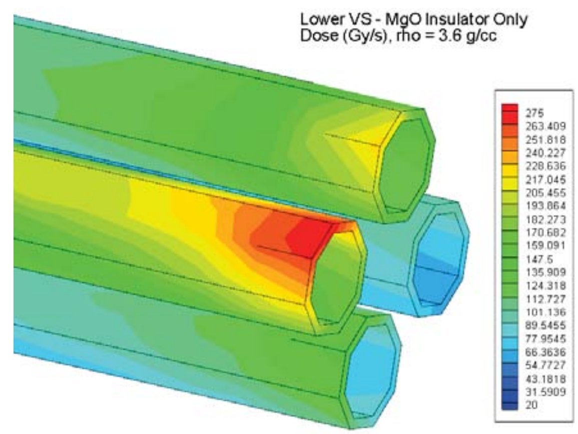
This is a view of the meshed ATTILA model. The dark blue and light green volumes are the "Void" parts. The plasma region is also void but is modeled separately for applying the 500 MW volume source.



Mesh: 1.6M Cells
Sn32, P3
46-neutron, 21-gamma
reflecting-reflecting B.C.

This is a section through the Upper VS coil model showing the ATTILA mesh. Round objects are modeled as octogons to help resolve the mesh.





Direct Accelerated Geometry Monte Carlo (DAGMC)
Motivations

- **Cheaper**
  - Reduce human effort
- **Better**
  - Avoid human error in conversion
  - Preserve geometrical details
  - **Include higher-order surface descriptions in analysis**
- **Faster**
  - Reduce human effort – faster design iteration
  - **Provide common domain for coupling to other analyses**

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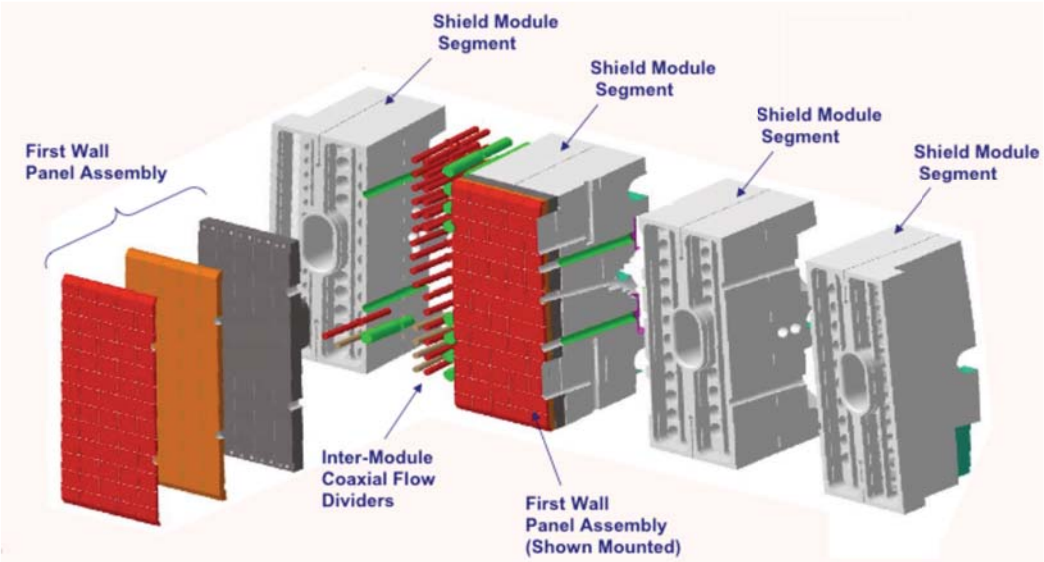
Accelerations

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

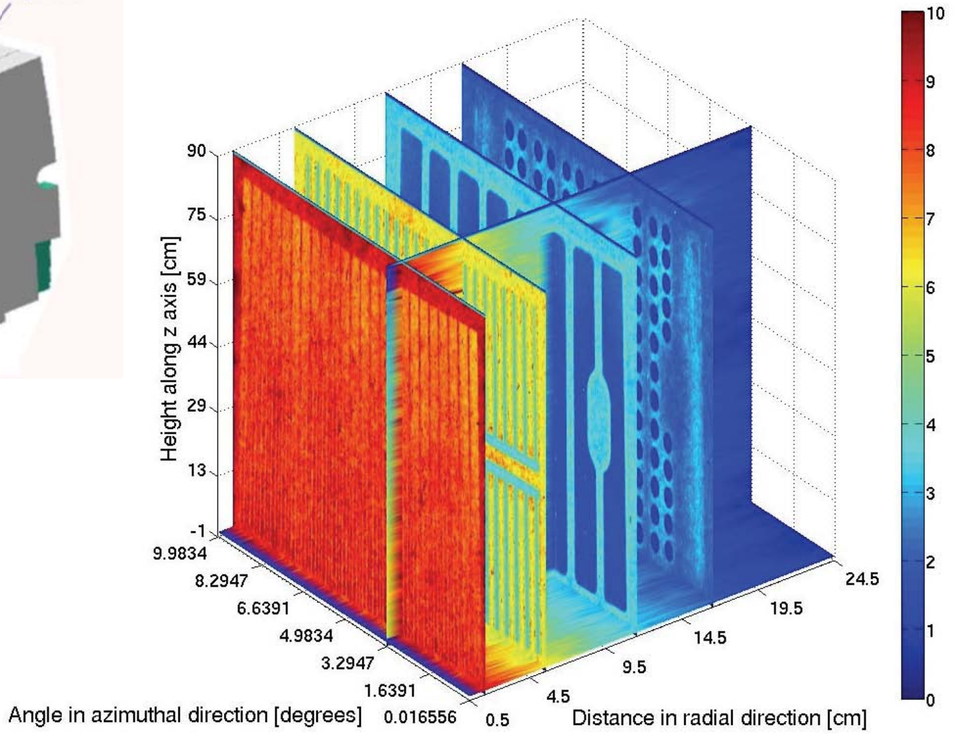
Enhanced Performance

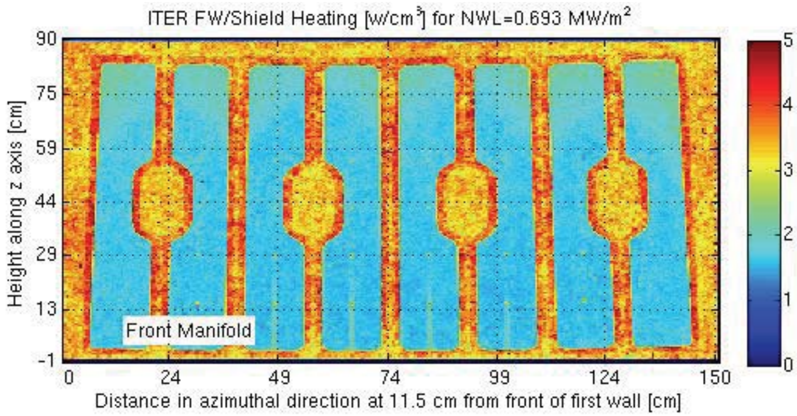
- *Implicit complement*
- *Overlap tolerance*
- *Conforming Mesh Tallies*

Detailed High-Resolution, High-Fidelity Calculations with DAG-MCNP in CAD Model of ITER Blanket Module 13

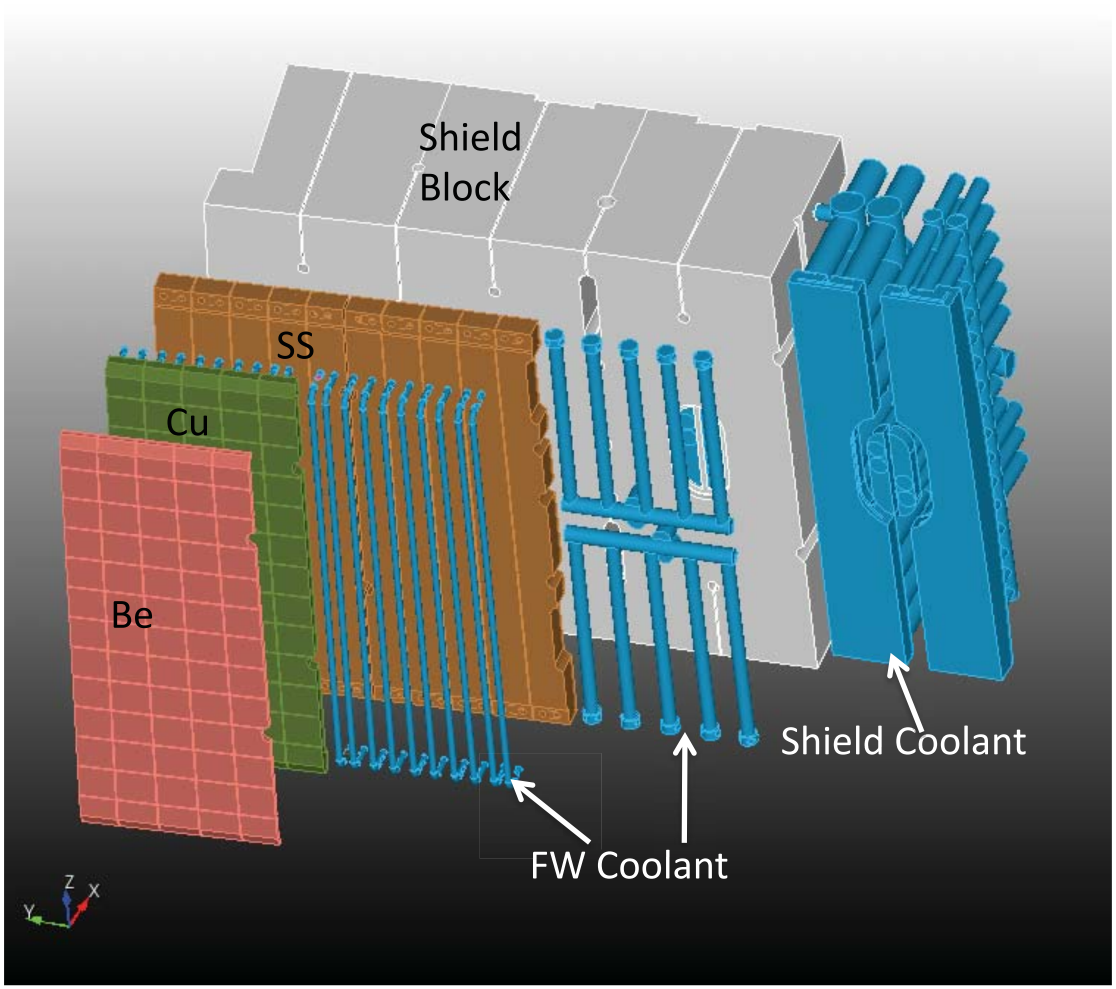


Interesting heterogeneity effects revealed





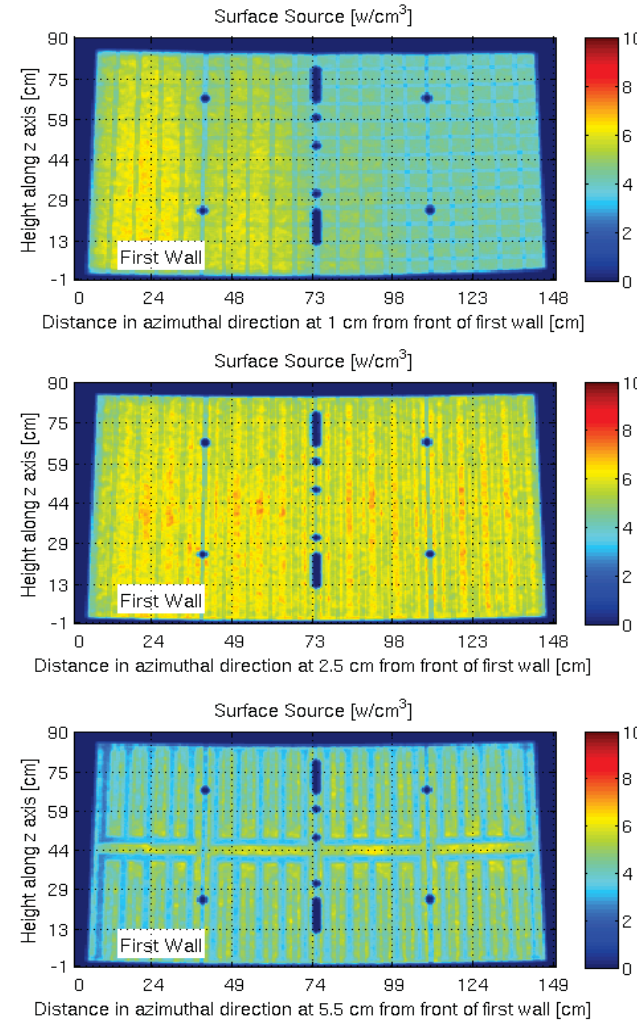
Detailed Calculations with DAG-MCNP for Revised Blanket Module Design



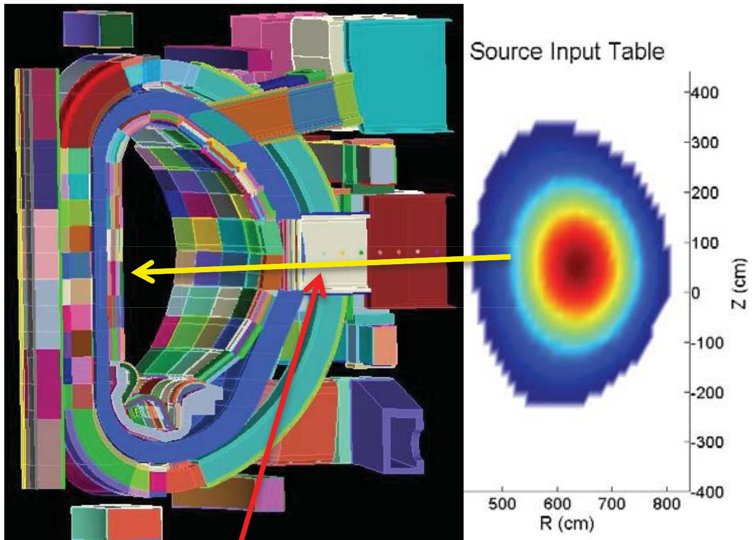
Be Layer

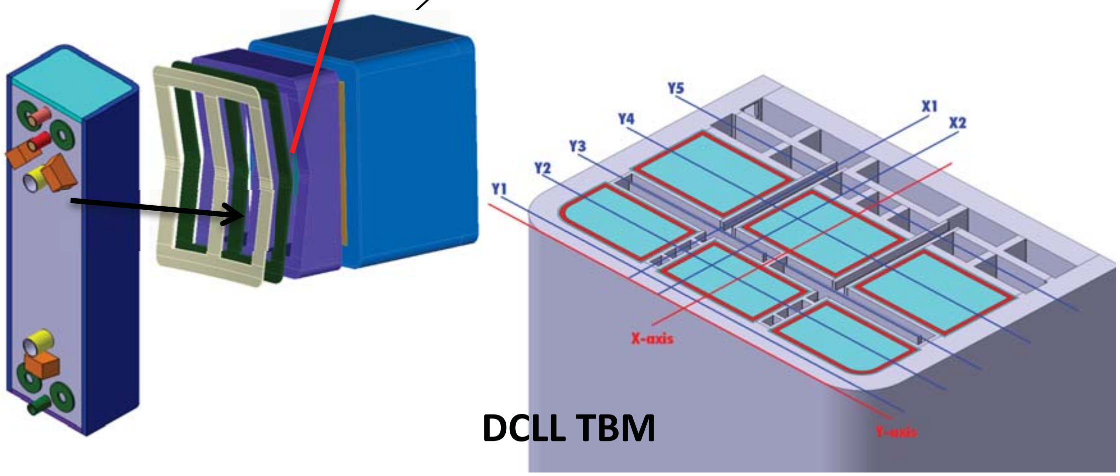
Cu Layer

SS Layer

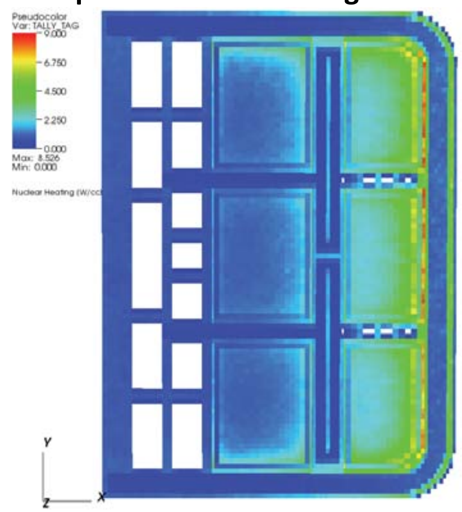


Detailed 3-D Neutronics for DCLL TBM

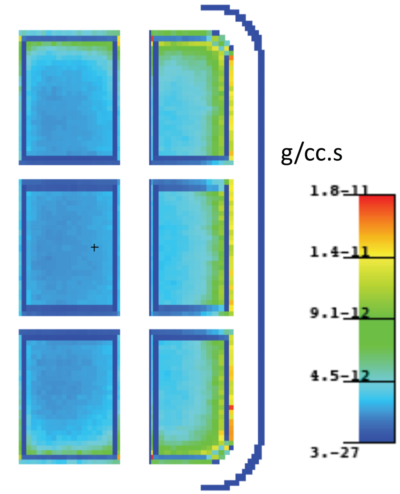




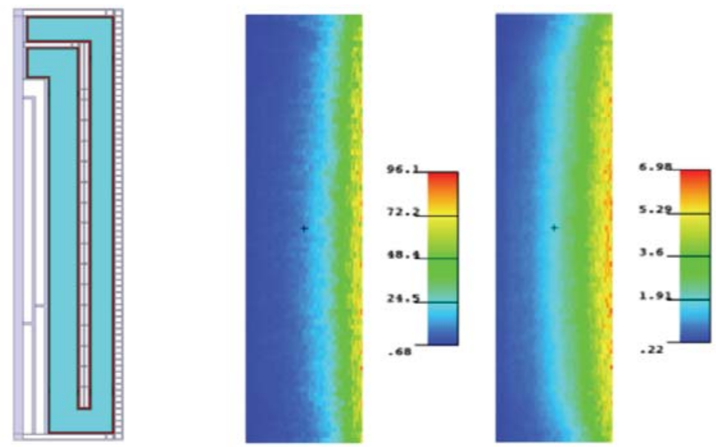
Mid-plane nuclear heating



Mid-plane T production

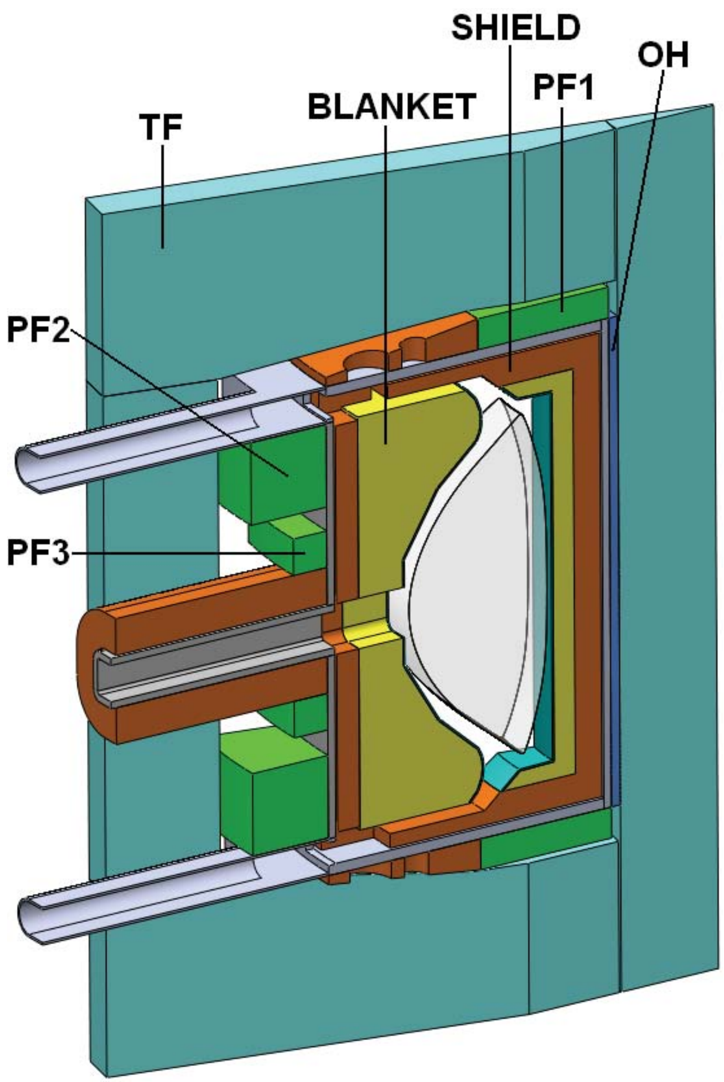


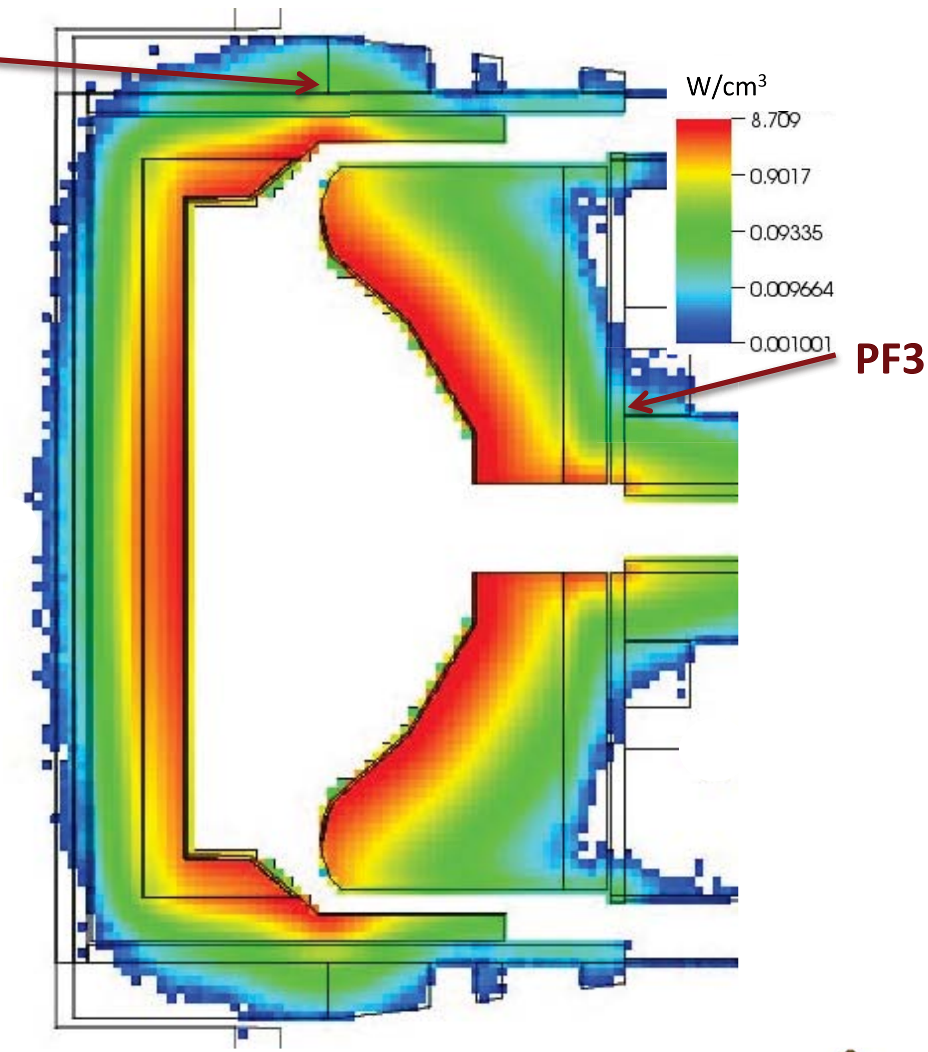
Steel damage at section X2



Cross section He appm/FPY dpa/FPY

3-D Neutronics for FNSF-AT





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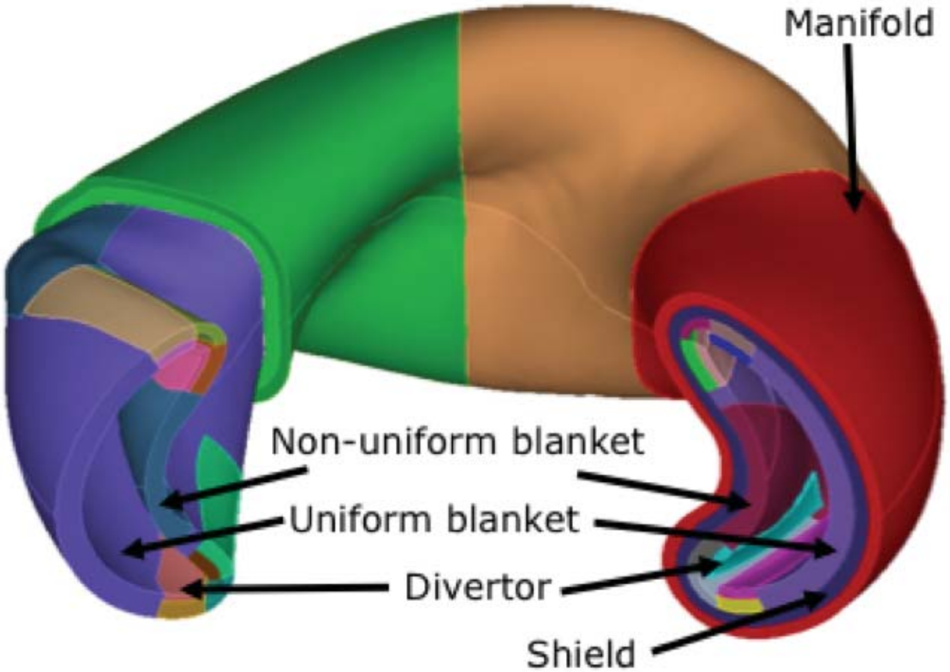
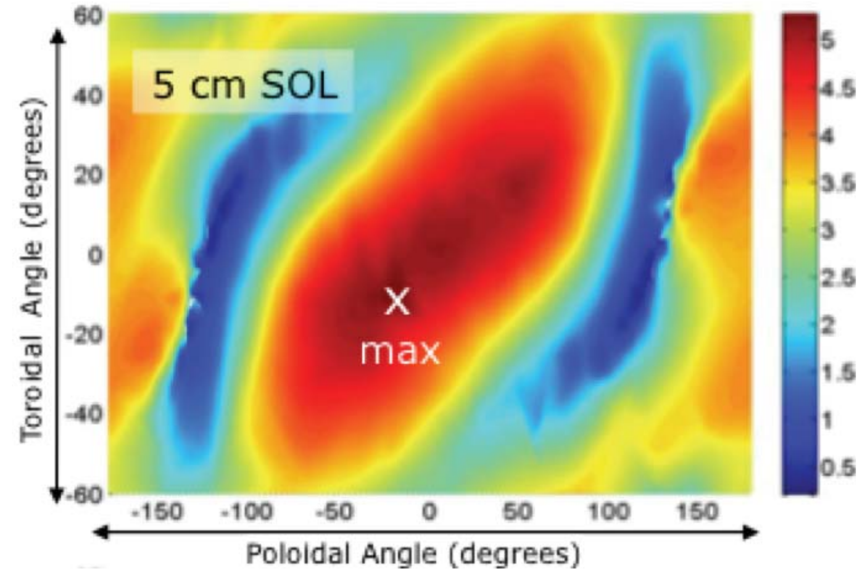
Application to ARIES-CS Compact Stellarator

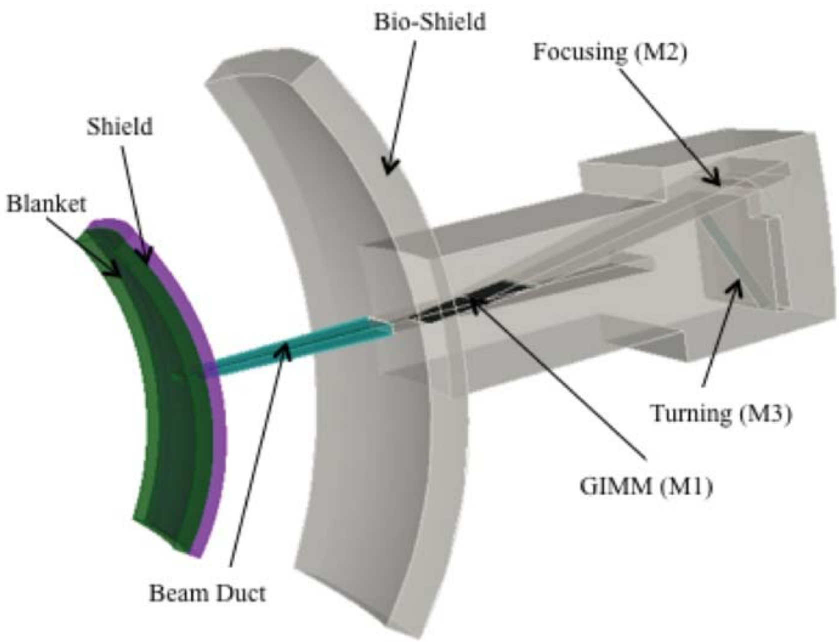


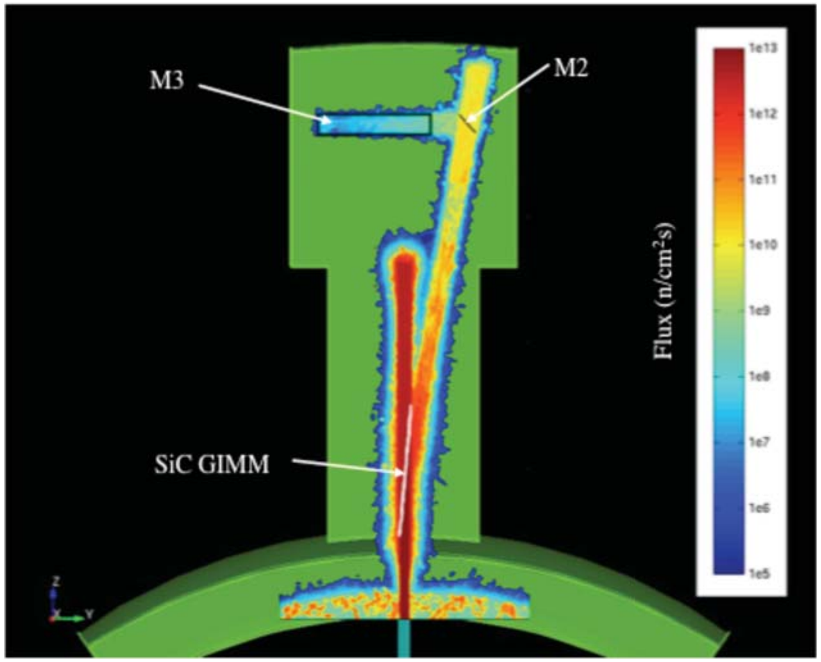
- Geometry and source complex
- Cannot be modeled by standard MCNP



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

HAPL Final Laser Optics





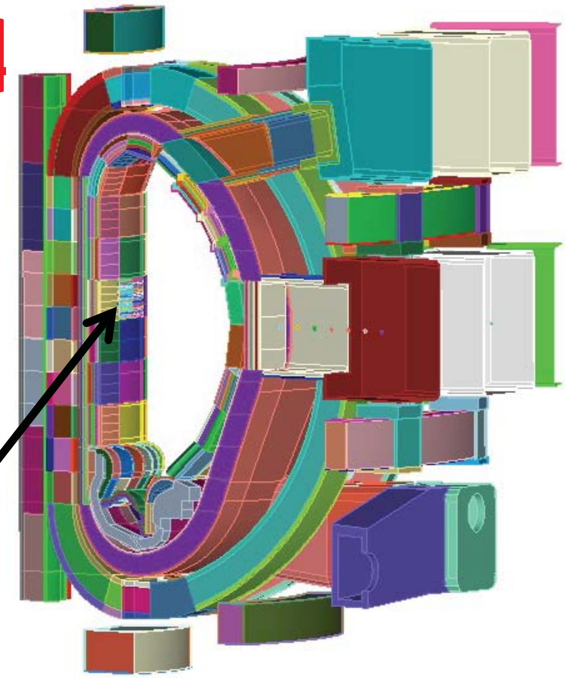
- Fast neutron flux at dielectric optics depends on material choice for the GIMM and total GIMM areal density
- AlBeMet GIMM results in highest flux level (factor of ~1.6 higher than with lightweight SiC GIMM)
- Significant drop in nuclear environment occurs as one moves from the GIMM to dielectric focusing and turning mirrors

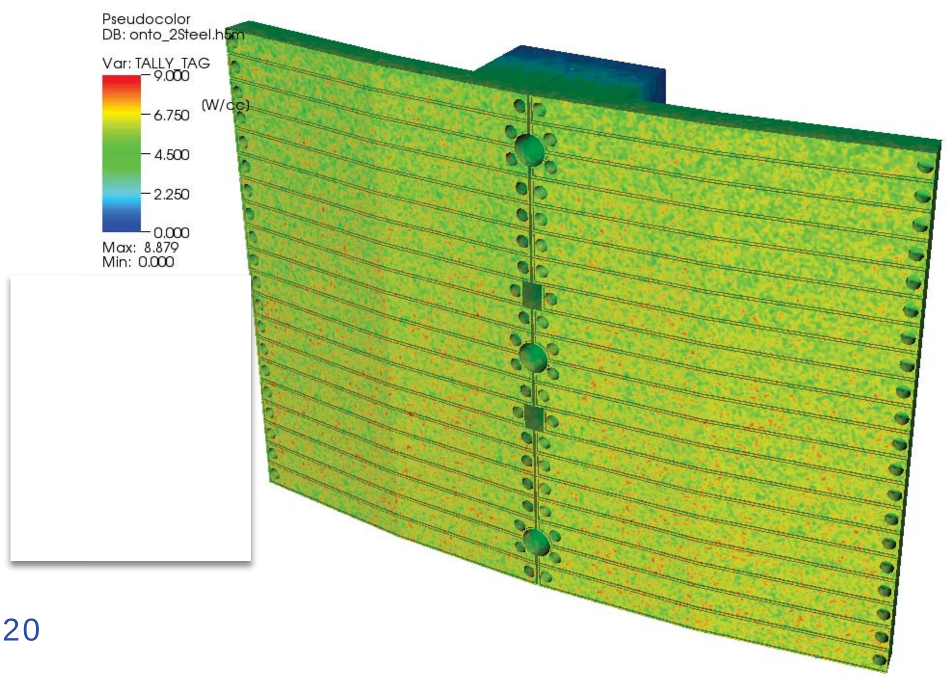
Multi-Physics: Coupling to CFD

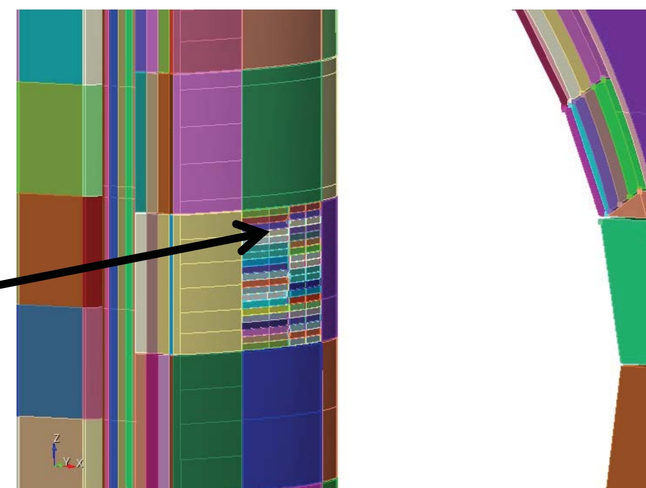
- Fine mesh DAG-MCNP5 results
  - 1-3 mm Cartesian mesh overlay
  - Total nuclear heating
- Arbitrary mesh on CAD geometry
  - Tetrahedral
  - Polyhedral (Star-CCM+)
- Automated interpolation using MOAB

DAGMC Simulation BM04

- Module 4 CAD model inserted into full ITER CAD model
- 500 M source particles simulated using 3-D ITER source profile
- 240 computer-days on 30 2.66 GHz Intel Core2 processors
- Couple nuclear heating to CFD using Star-CCM+

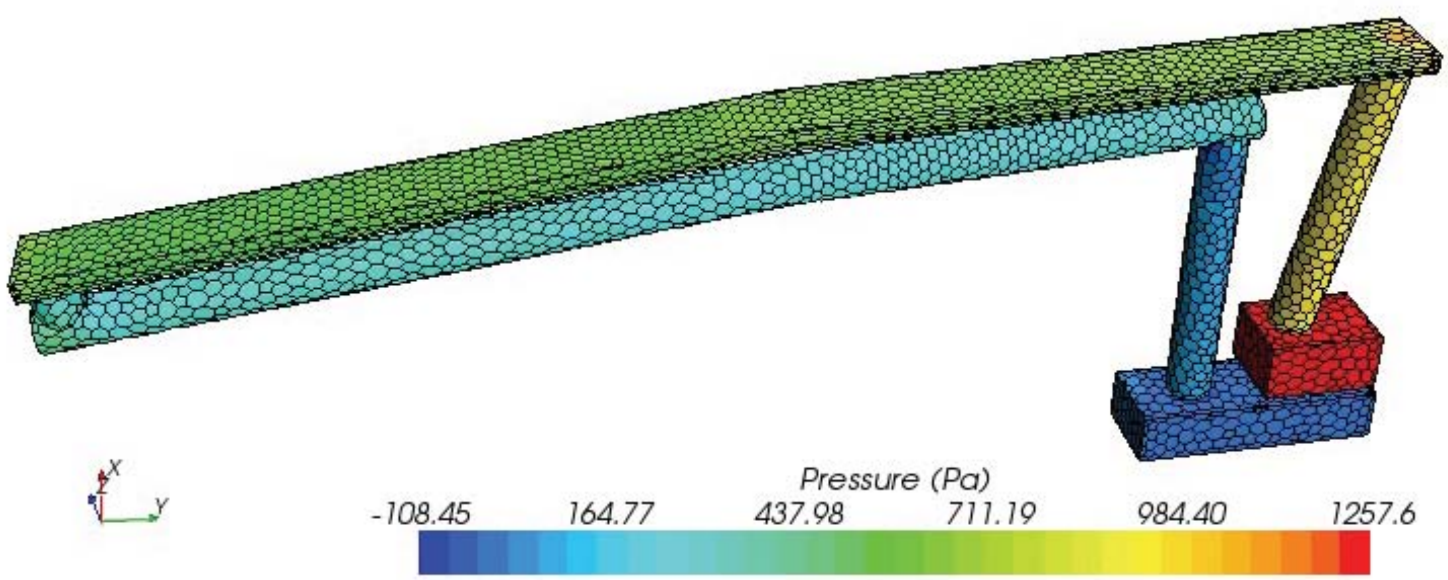






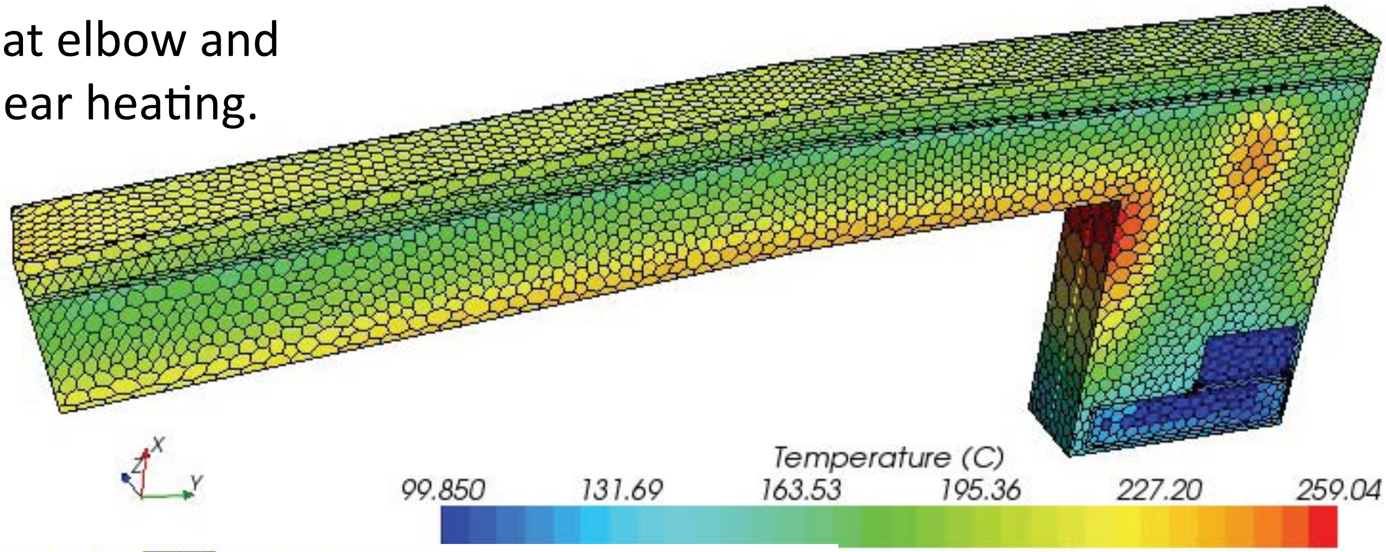
Multi-Physics: Coupling to CFD

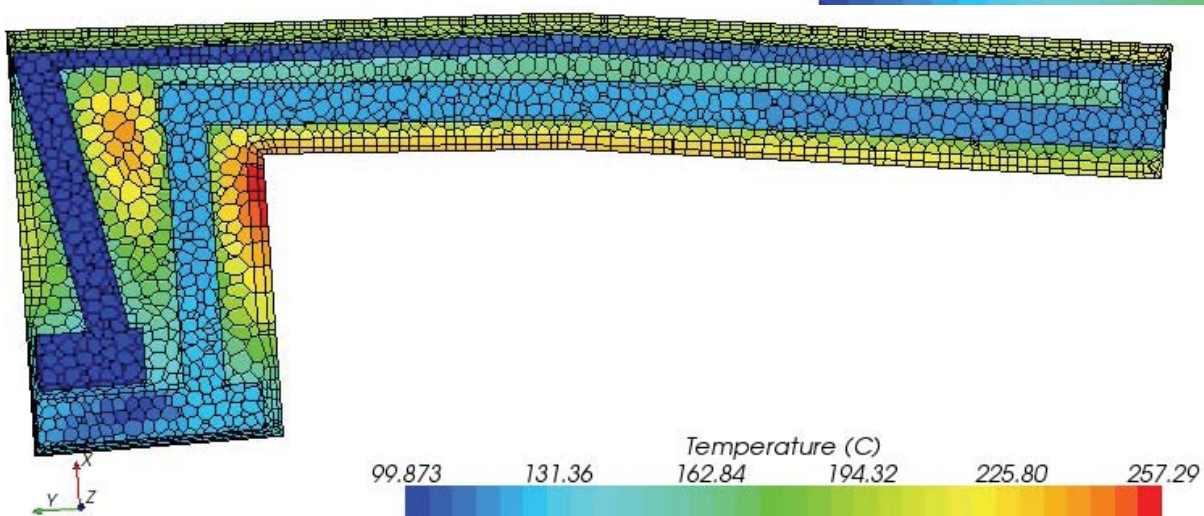
- 1 of 40 fingers in ITER First Wall concept
- Beryllium plasma facing component
- CuCrZr heat sink into pressurized water
- Steel backing for structural support
- 0.2 MW/m^2 heat flux onto Beryllium
- Inlet: 0.2 kg/s water, 373 K, 3 MPa



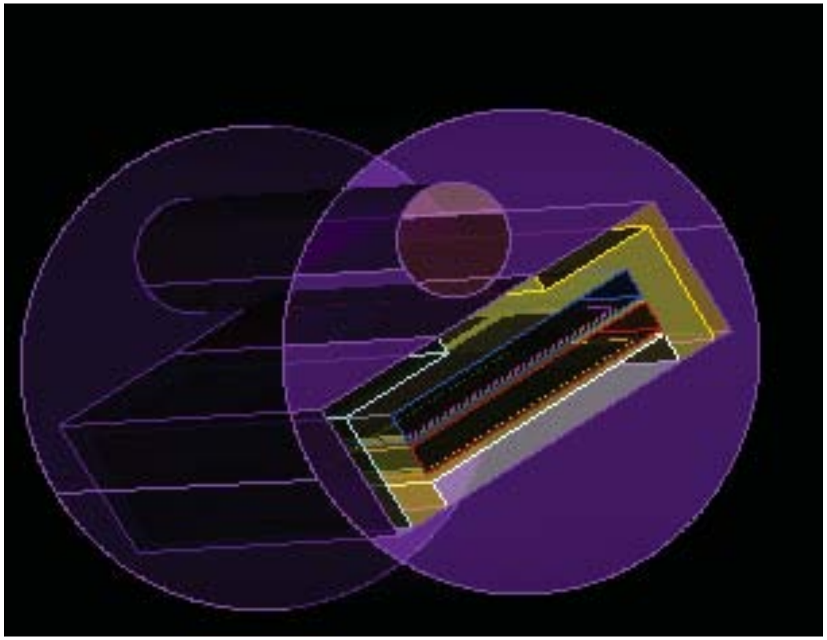
Neutronics+CFD Coupling

Notice "hot spot" at elbow and center due to nuclear heating.

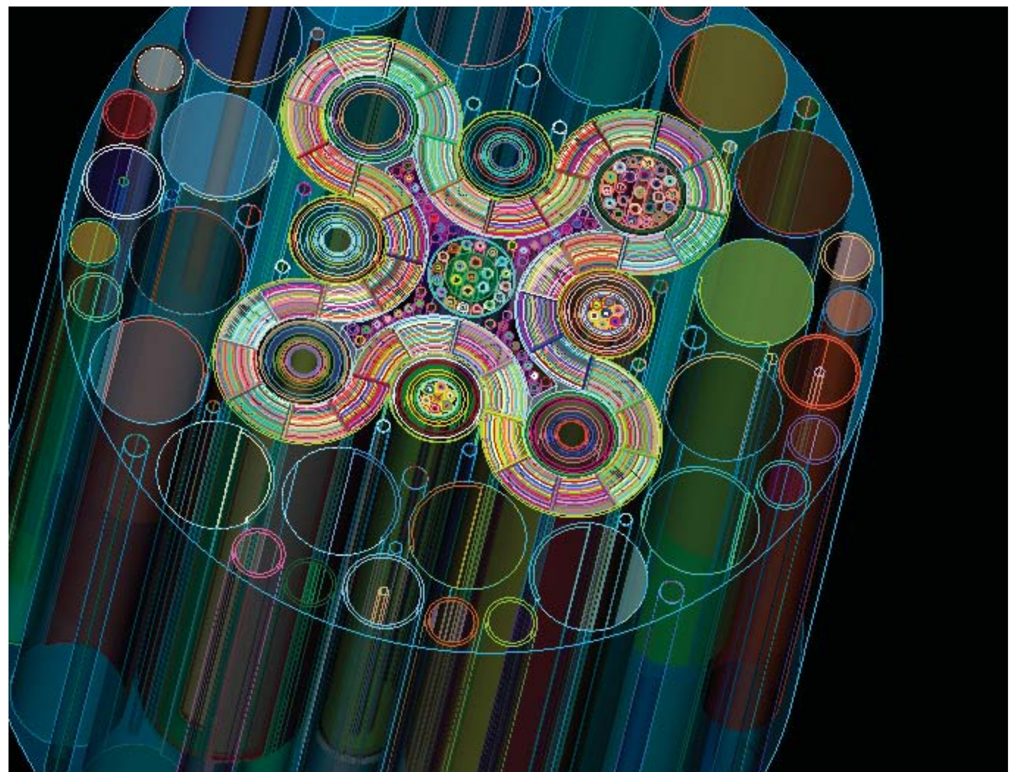




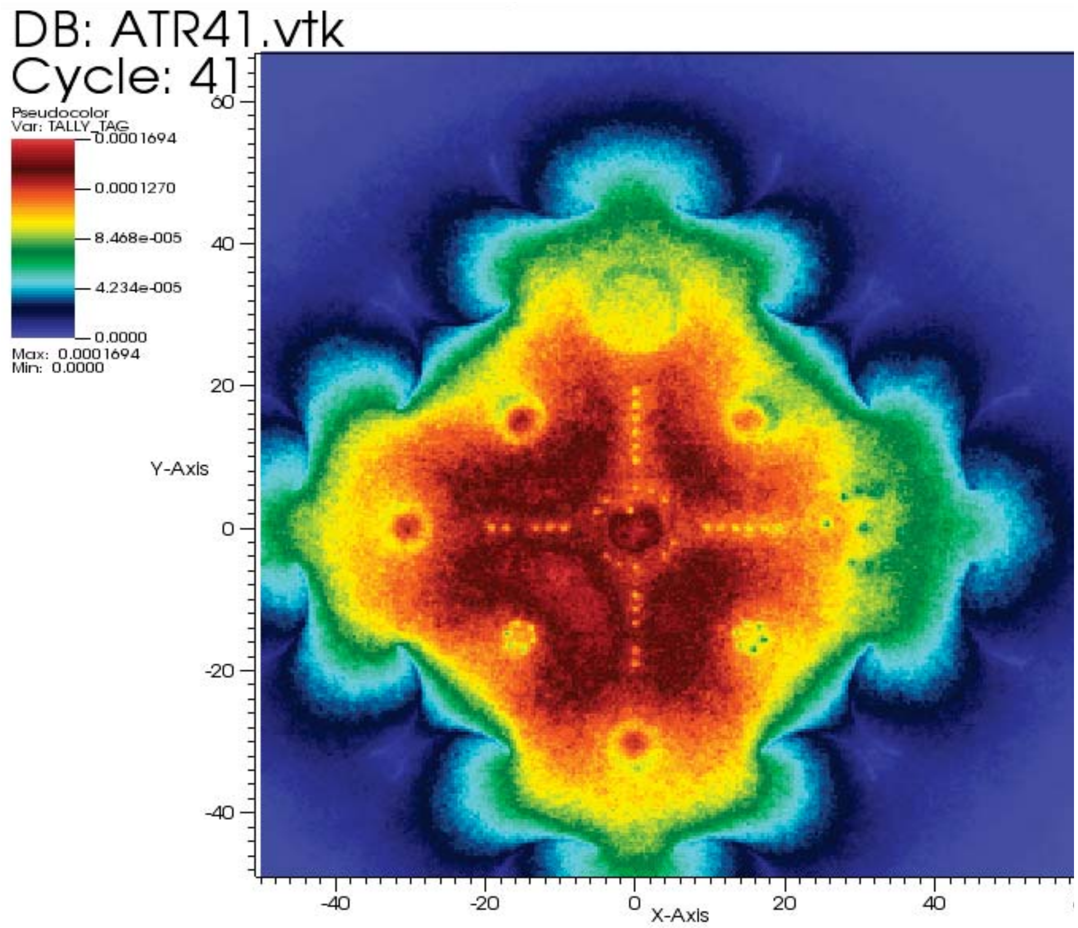
Fission Applications
ATR National Science User Facility

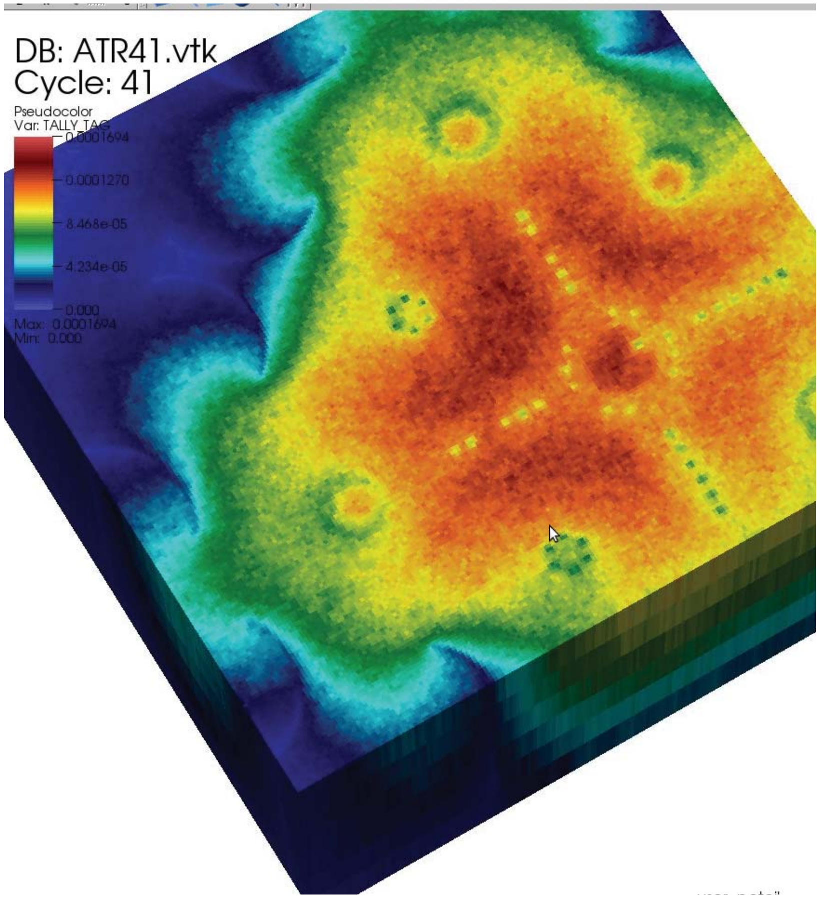


AFIP Experiment In CFT



ATR Neutron Flux Distribution





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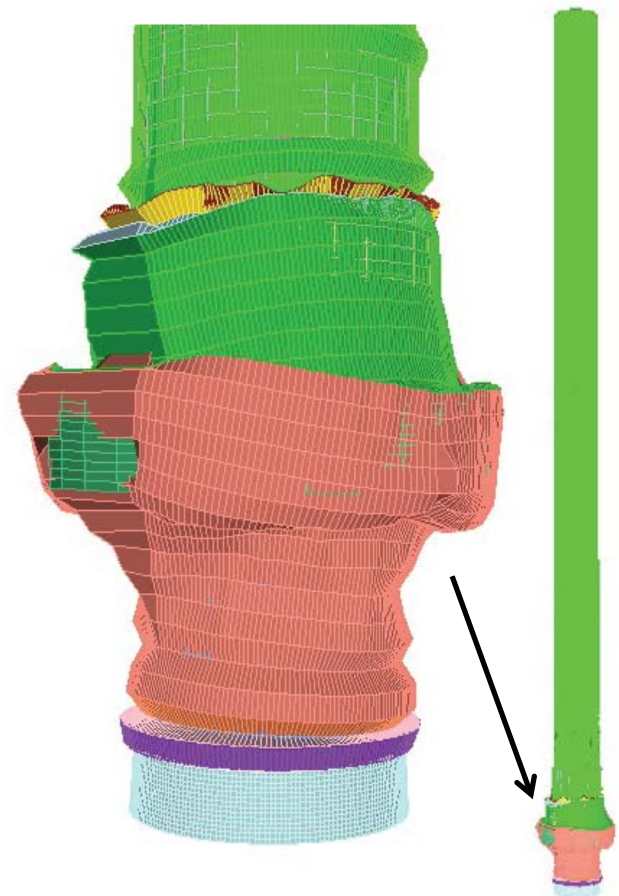
Research Directions

Analysis of Deformed Systems

- Thermal response can lead to structural/geometric changes
- Nuclear analysis on deformed system will help understanding the feedback on performance parameters
- Not applied yet for fusion but used for deformed fission reactors



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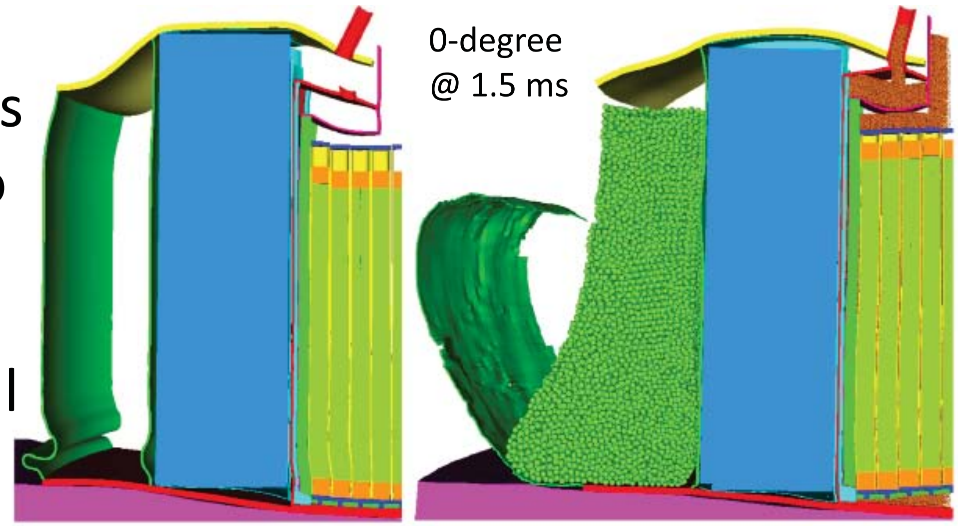
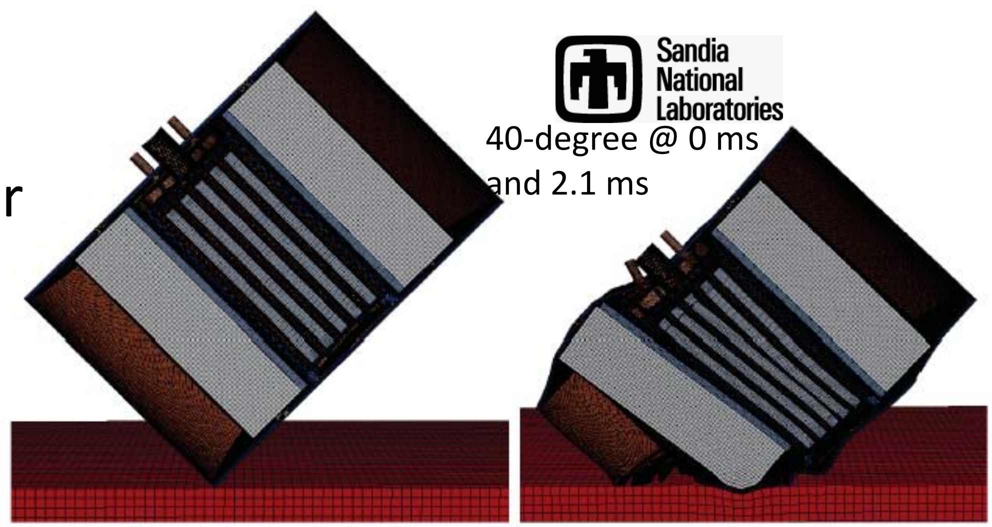
Neutron Transport in Deformed Geometries

- Space reactor launch accidents may result in reactor return to earth
- Criticality of intact reactor well understood
- 100 m/s impact on concrete
- Impact likely to deform reactor
- Is criticality possible?





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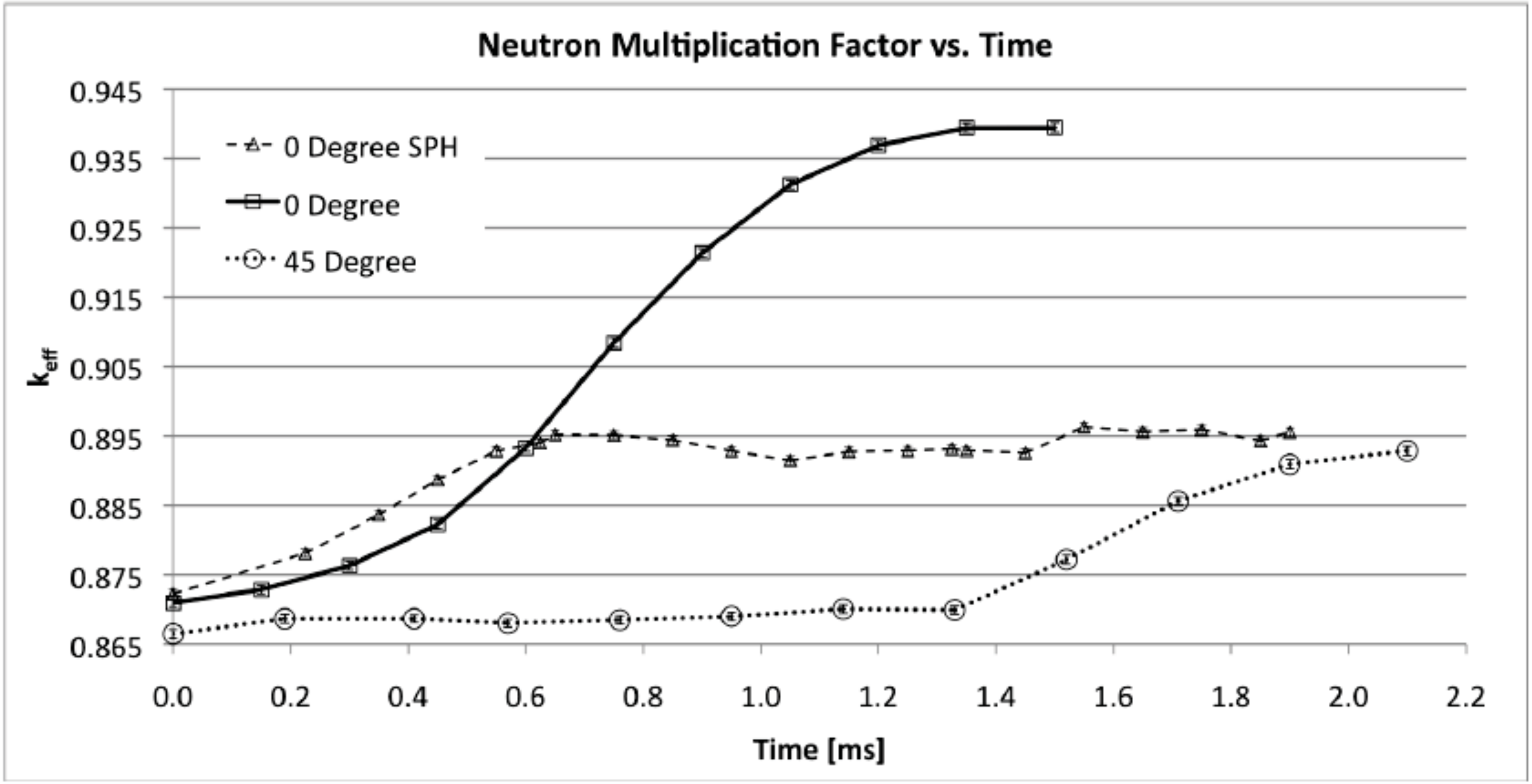
Neutron Transport:
85-Pin Full-Scale Space Reactor Impact



Research Directions

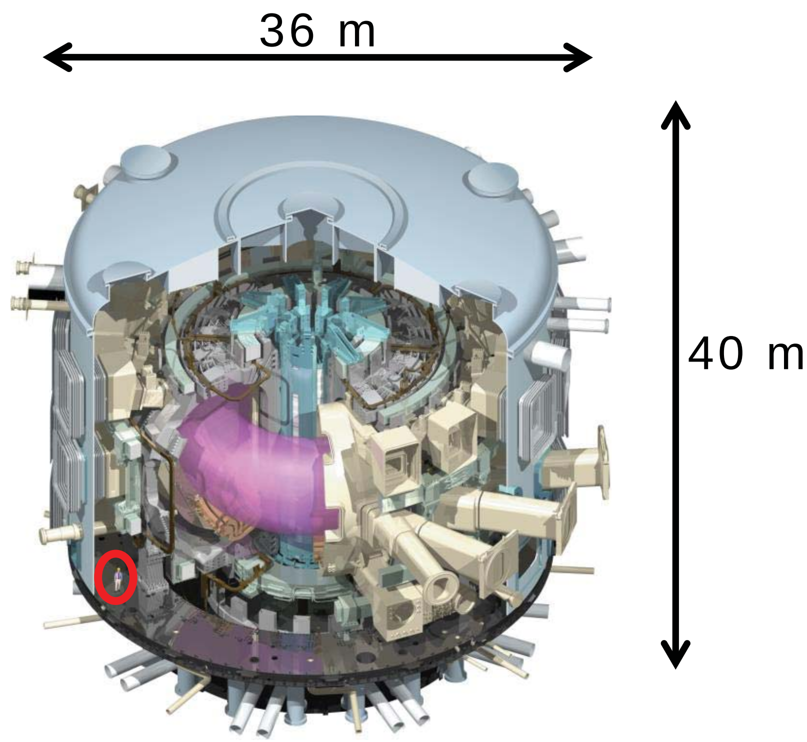
Advanced Mesh Tallies

- Perform tallies on arbitrary polyhedral mesh
  - Prototype exists for tetrahedral mesh
- Get detailed isotopic compositions after activation/transmutation
- Solve separate activation problem in millions of mesh elements
- Use previous source sampling capability to represent distributed photon source

Research Directions

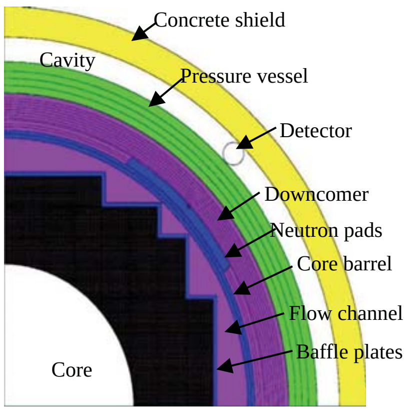
Hybrid Methods

- Monte Carlo not well-suited to deep penetration problems
- Deterministic methods not well suited to gap streaming problems
- Use deterministic methods to develop importance maps for Monte Carlo problems

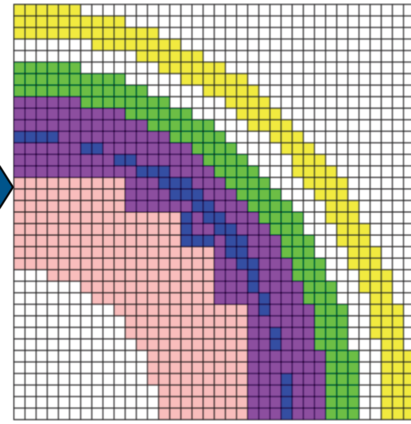


•Large size
•Complex geometry
•Massive shielding

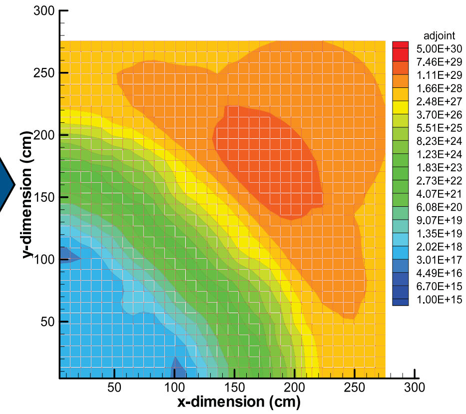
ADVANTG dramatically speeds up calculation



MC model



Deterministic model



Adjoint flux

CADIS calculation of VR parameters

Source biasing

$$\hat{q}(\bar{r},E) = \frac{\phi^{+}(\bar{r},E)\,q(\bar{r},E)}{R}$$

Weight windows

$$w_{\ell}(\bar{r},E) = \frac{R}{\phi^{+}(\bar{r},E)}$$

MC

Results

Case	CPU time (hr) for 1% uncertainty	Speed up
No VR	8.86E+4 (10.1 yrs)	1
Manual VR	13.6	6500*
ADVANTG	**1.02**	**87000**

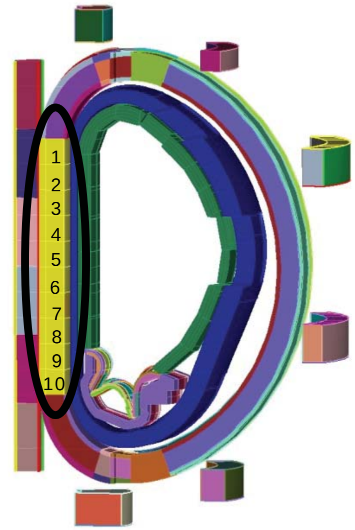
* Required ~3 weeks by an experienced MC practitioner using all applicable MCNP4C VR capabilities

- **Automatic** creation of deterministic input file
- Only approximate deterministic fluxes- Coarse mesh
- **Minimal penalty from deterministic calculations**

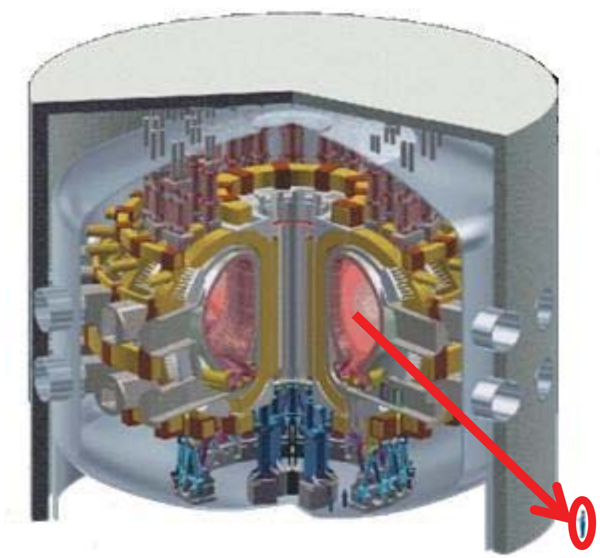
ORNL hybrid methods (CADIS, FW-CADIS) suitable for fusion applications

ITER magnet heating

	Time (day)	Max. uncertainty	Normalized FOM
Analog	**121.3**	**5.9%**	**1**
WWG	**11.0**	**3.6%**	**30**
FW-CADIS	**0.8**	**4.5%**	**275**



ITER prompt dose

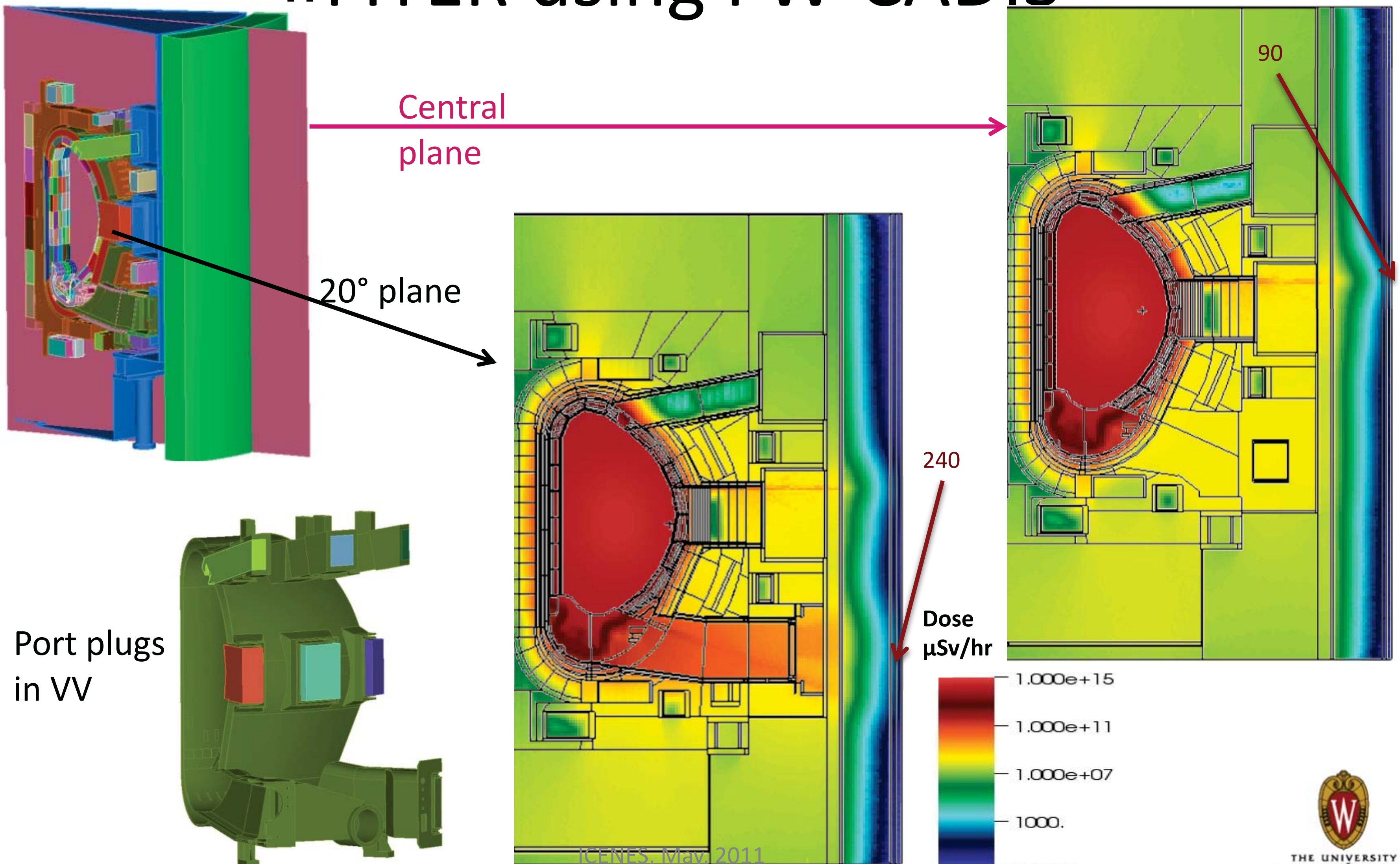


	Dose (µSv/hr)	Relative uncertainty (RU)	Time (day)	Speed up
MC(no CADIS)	**4.8**	**76.7%**	**610.0**	**1**
MC (CADIS)	**2.7**	**3.8%**	**8.6**	**29,000**

Requires 393 years to reach 5% RU

16 orders of magnitude attenuation

Global Evaluation of Prompt Dose Rate in ITER using FW-CADIS



Summary

- An updated comprehensive (ns to 150 MeV, activation, p, d, covariance) fusion evaluated nuclear data library FENDL-3 that is suitable for all fusion systems will be developed, validated, and released by the end of 2011
- Significant progress made on improving fusion neutronics predictive capabilities for accurate and fast analysis of the large geometrically complex fusion systems
- CAD-based neutronics tools allow efficient automated integration with other multi-physics analyses

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