Development of Nuclear Analysis Predictive Capabilities for Fusion Energy Systems

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Nuclear Fusion

- Unlike fission where uranium splits generating energy, fusion occurs when two hydrogen nuclei fuse together and release energy
- Two approaches:
  - Magnetic confinement
  - Inertial confinement

D-T Fusion Represents a Nearly Inexhaustible Energy Source

Fuels: **Deuterium**: abundant in sea water

Tritium: Half-life~12 years…must be produced?

Reaction		Ignition Temperature		Output Energy
Fuel	Product	(millions of °C)	(keV)	(keV)
D + T	^{4}He + n	45	4	17,600

^{6}Li + n --> T + ^{4}He + 4.8 MeV + others

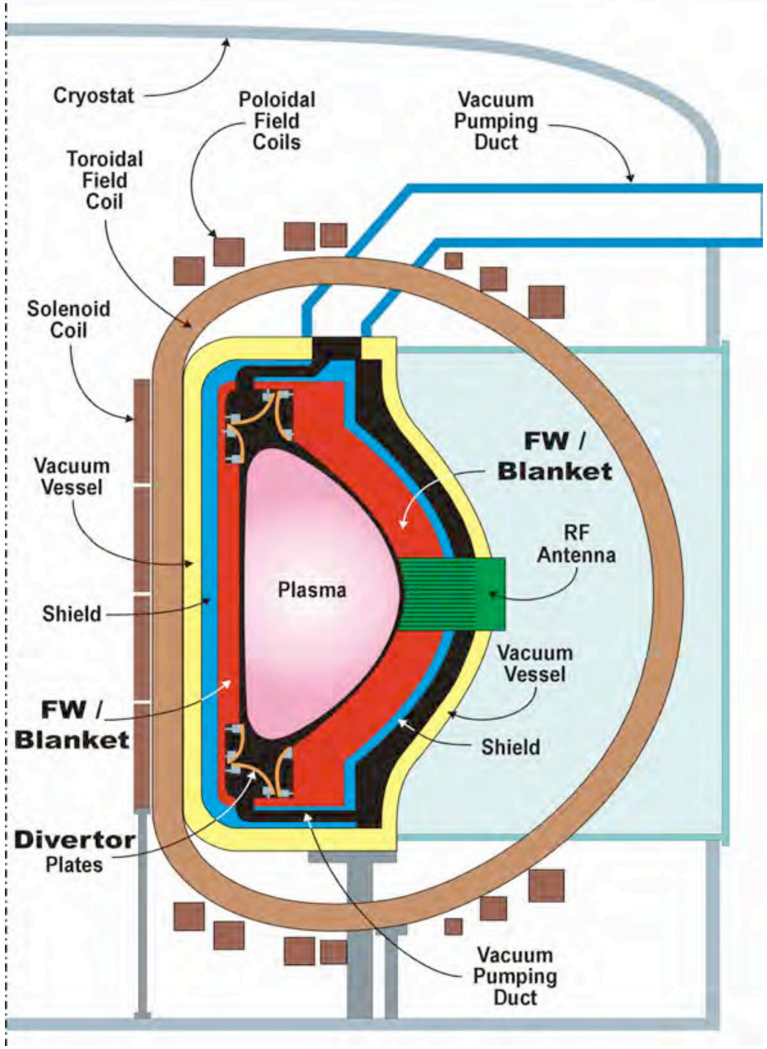
T_{bred} / T_{burned} > 1

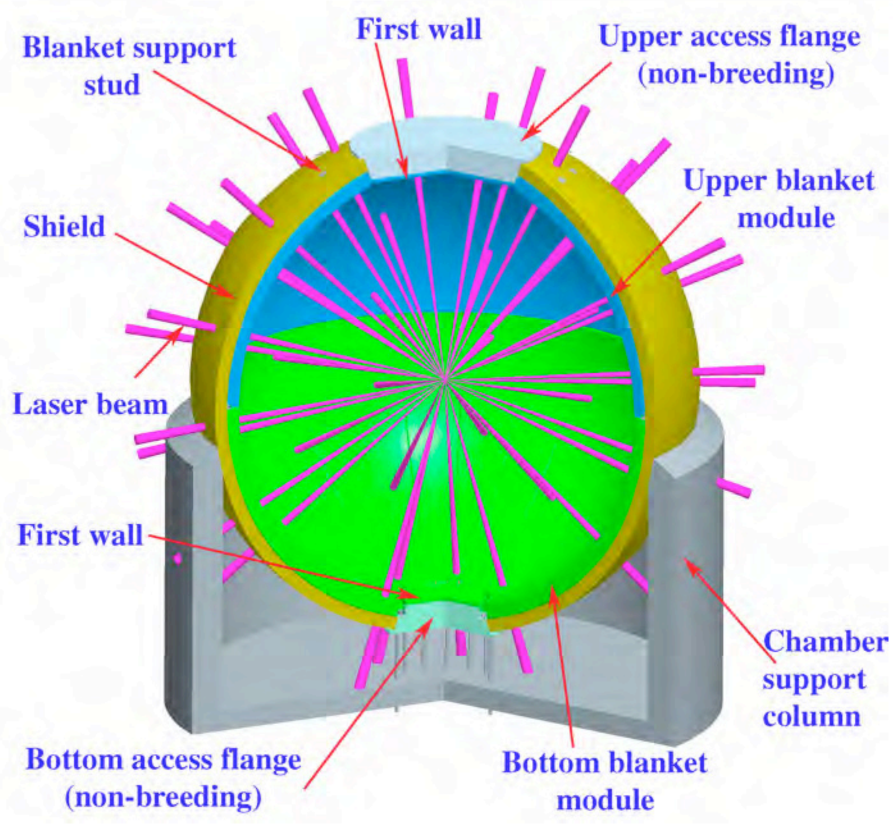
"Real" fusion fuel cycle:

^{6}Li + D = 2^{4}He + 22.4 MeV

30 Million years of world energy demand in oceans

Fusion Reactors are Complex with Many Components





ITER

1^{st} Integrated Fusion Test Reactor

Central Solenoid

Nb_3Sn, 6 modules

Outer Intercoil Structure

Toroidal Field Coil

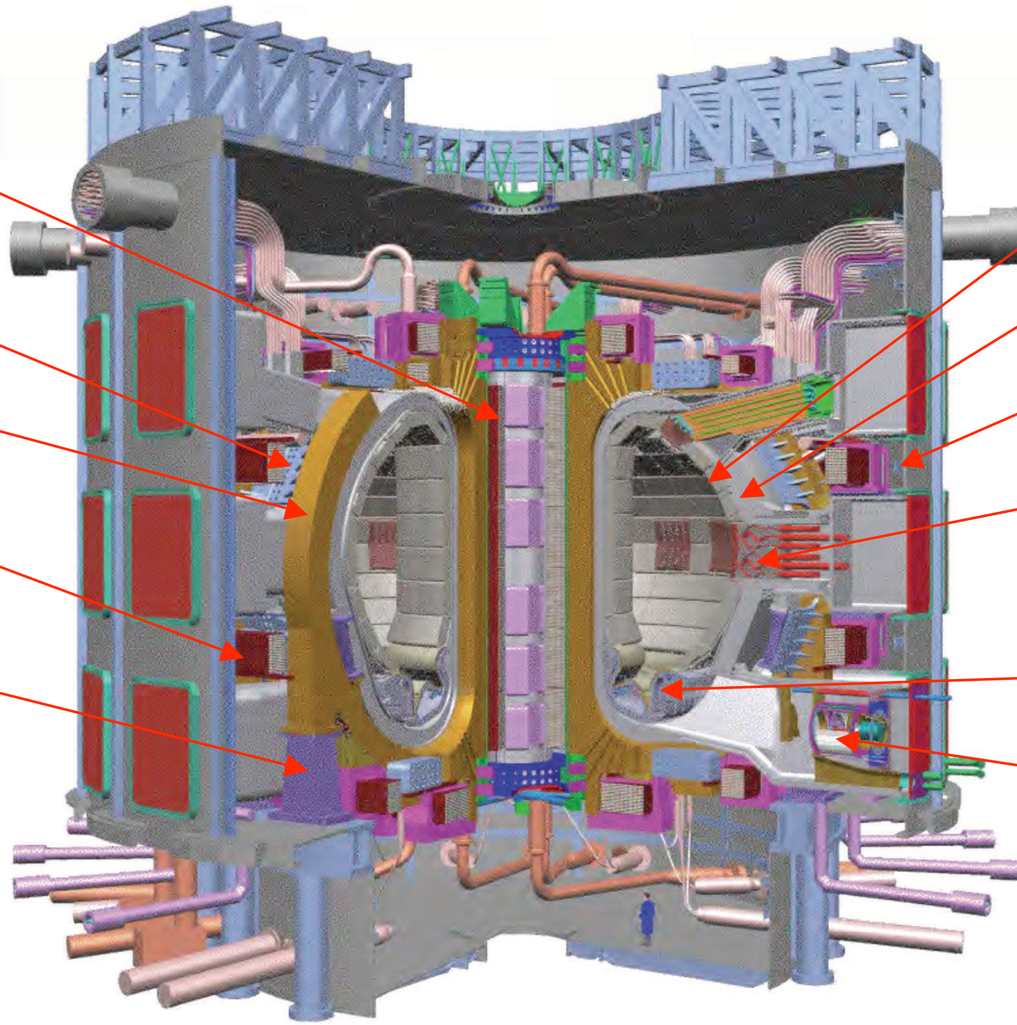
Nb_3Sn, 18, wedged

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

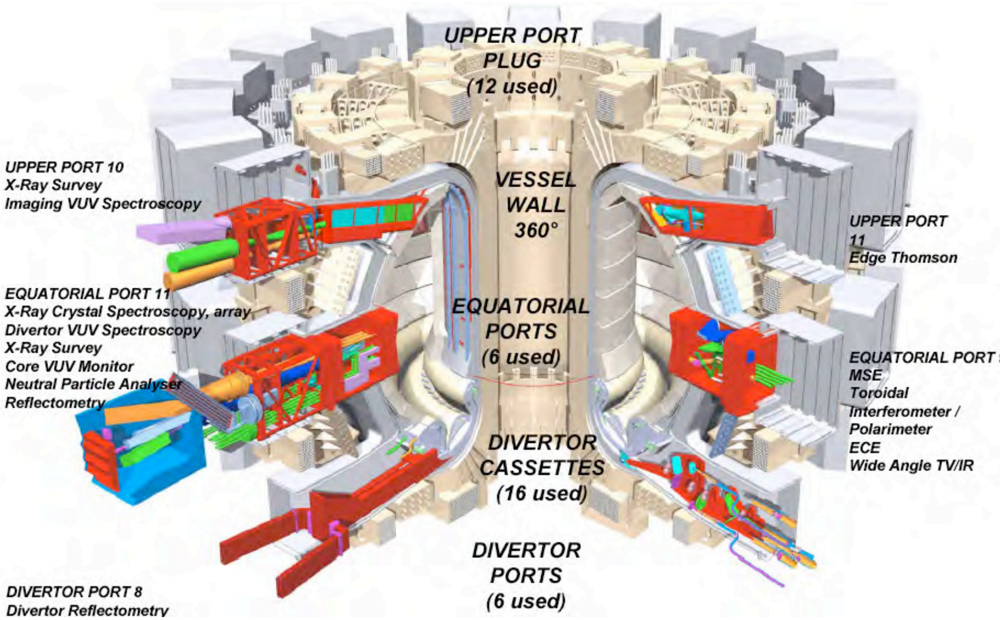
Torus Cryopump

8, rearranged

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 Design

- Energetic 14 MeV neutrons are emitted in plasma and slowed down and absorbed by surrounding components
- Nuclear analysis for components surrounding the plasma is essential element of fusion nuclear technology
  - 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
- State-of-the-art predictive capabilities (codes and data) are needed to perform required nuclear analyses

Calculation Methods

- There are several numerical methods and codes available to solve the Boltzmann transport equation
- The methods can be broken down into two groups
  - -***Deterministic method***:
    Directly solves the equation using numerical techniques for solving a system of ordinary and partial differential equations
  - -***Statistical based method***:
    Solves the equation using probabilistic and statistical techniques
- Each method has its strengths and weaknesses

Deterministic Approach

The phase space (space, angle, energy) is discretized

Angle

S_n - Discrete Ordinates P_l - Moment expansion

Energy

Multi-group (175n-42g)

Spatial discretization

Finite Element (un-structured meshes)

Finite Difference (structured equal fine meshes)

Advantages

- Spatial Resolution
- Flux evaluated at a large number of points

Disadvantages

- Angular Quadrature approximation
- Legendre Polynominal expansion of cross- sections
- Ray-Effects for streaming problem
- Group treatment of energy variable
- Require large storage space for multi-dimensional calculations

Codes

DANTSYS, DOORS. PARTISN code systems (1D, 2D, 3D finite difference)

ATTILA (3D finite element with CAD coupling)

Statistical Monte Carlo Approach

Method

- Use probabilistic and statistical approach to solve transport equation
- The particle travel distance and interaction physics are converted to probabilistic and cumulative distributions, that are sampled using a random number

Advantages

- Exact Geometrical representation
- Exact treatment of the transport process
- Exact source-modeling capability
- Continuous (pointwise) energy treatment of the cross-sections

Disadvantages

- Require variance reduction techniques to improve accuracy
- Usually cannot generate accurate results at all locations
- Many particle histories and large CPU time to obtain accurate results

Codes

MCNP, MCNPX, MORSE, TRIPOLI, TART

Activation Codes

Method

Solve rate equations for radioactive nuclide production and decay to determine radioactive inventory, decay heat, biological dose, and radwaste

Codes

ALARA
DKR-PULSAR
REAC2
RACC
FISPACT
ORIGN2
ANITA
ACAB
ACT4

Nuclear Data

Evaluated nuclear data include raw data that needs processing to produce working libraries for use with nuclear analysis codes

US: ENDF/B-IV, -V, -VI, -VII

ENDF/B-VII released Dec 15, 2006

Japan: JENDL-3.2, JENDL-3.3

EU: JEFF-3.1

RF: BROND-2.1

Processing Codes: NJOY, TRANSX, AMPX

- Process data in either Multi-group or continuous energy format
- In addition to basic transport and scattering cross sections, special reaction cross sections are generated
  - -Kerma factors- for nuclear energy deposition
  - -Damage energy cross sections- for atomic displacement (dpa)
  - -Gas production (tritium, helium, hydrogen)

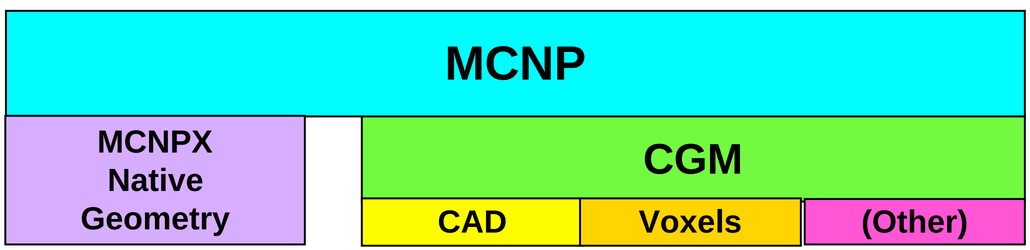
FENDL-2.1 is Reference International Fusion Nuclear Data Library

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

Developed Innovative Monte Carlo 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

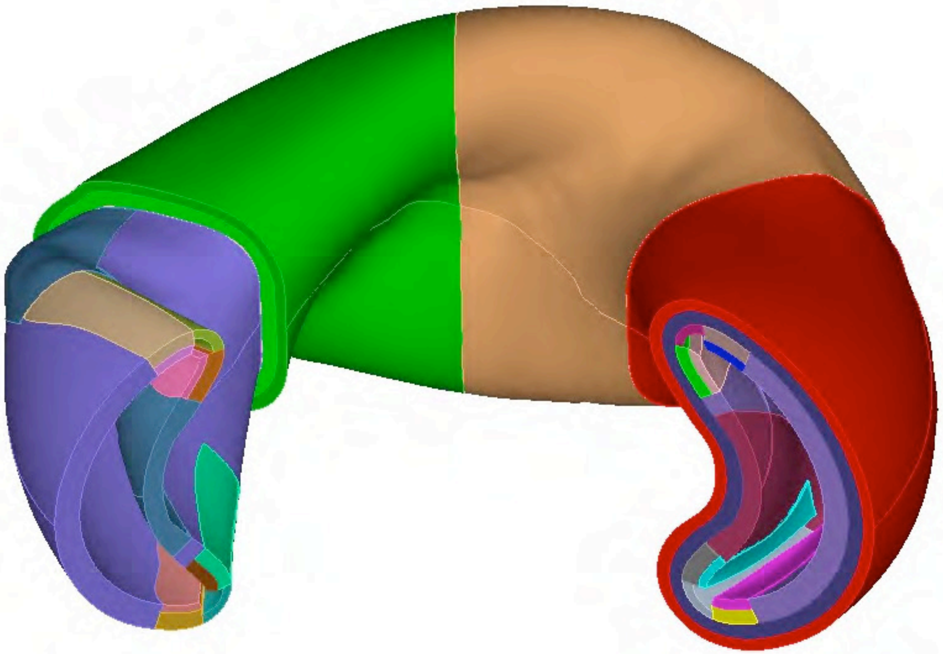


- Production experience
  - ARIES-CS
  - HAPL
  - ITER FWS

Motivations

- Reduce impacts of manual conversion of 3-D model data
  - Time
  - Simplifications
  - Errors
- Extend richness of geometric representation

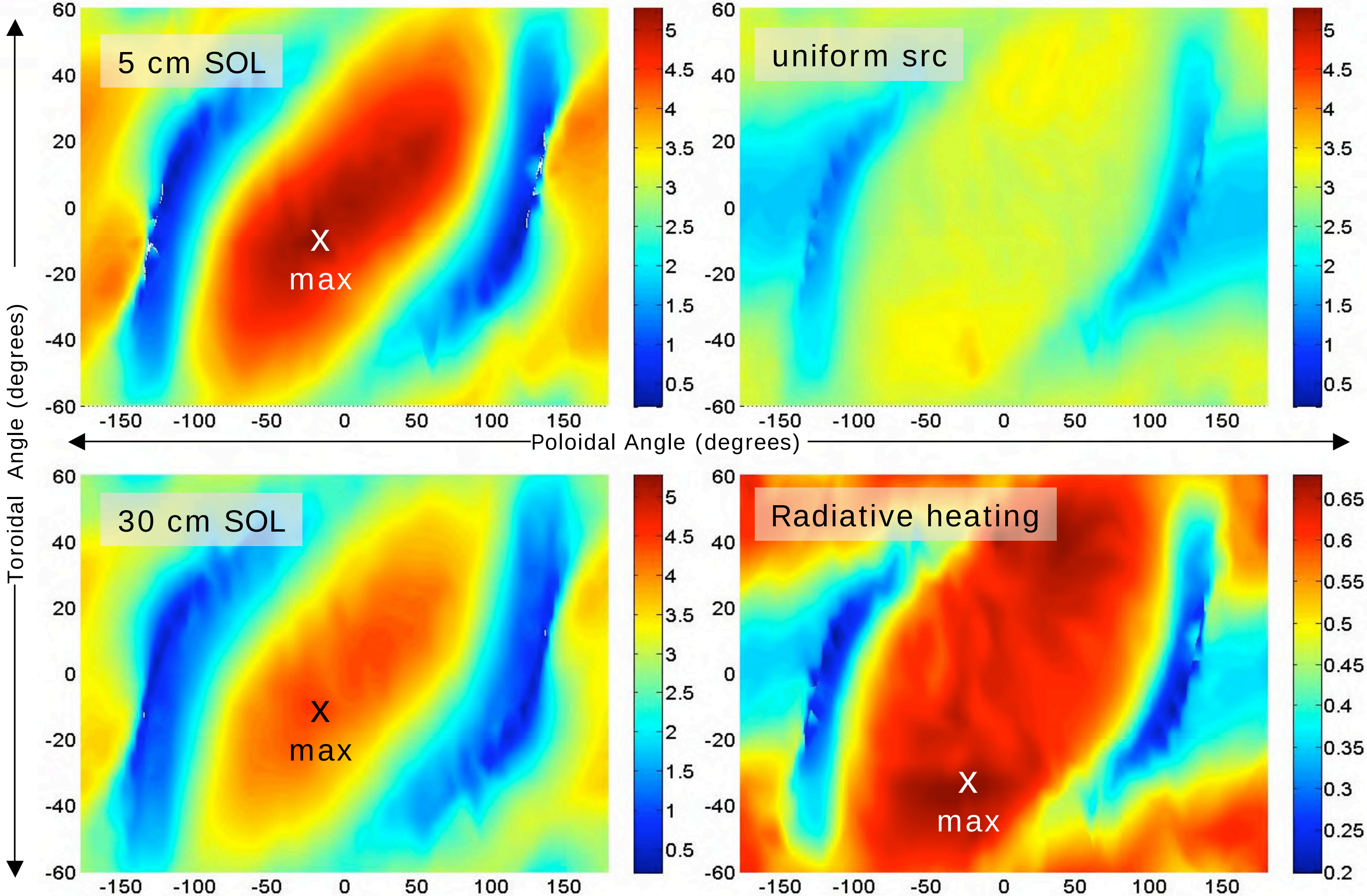
Application to ARIES-CS Compact Stellarator



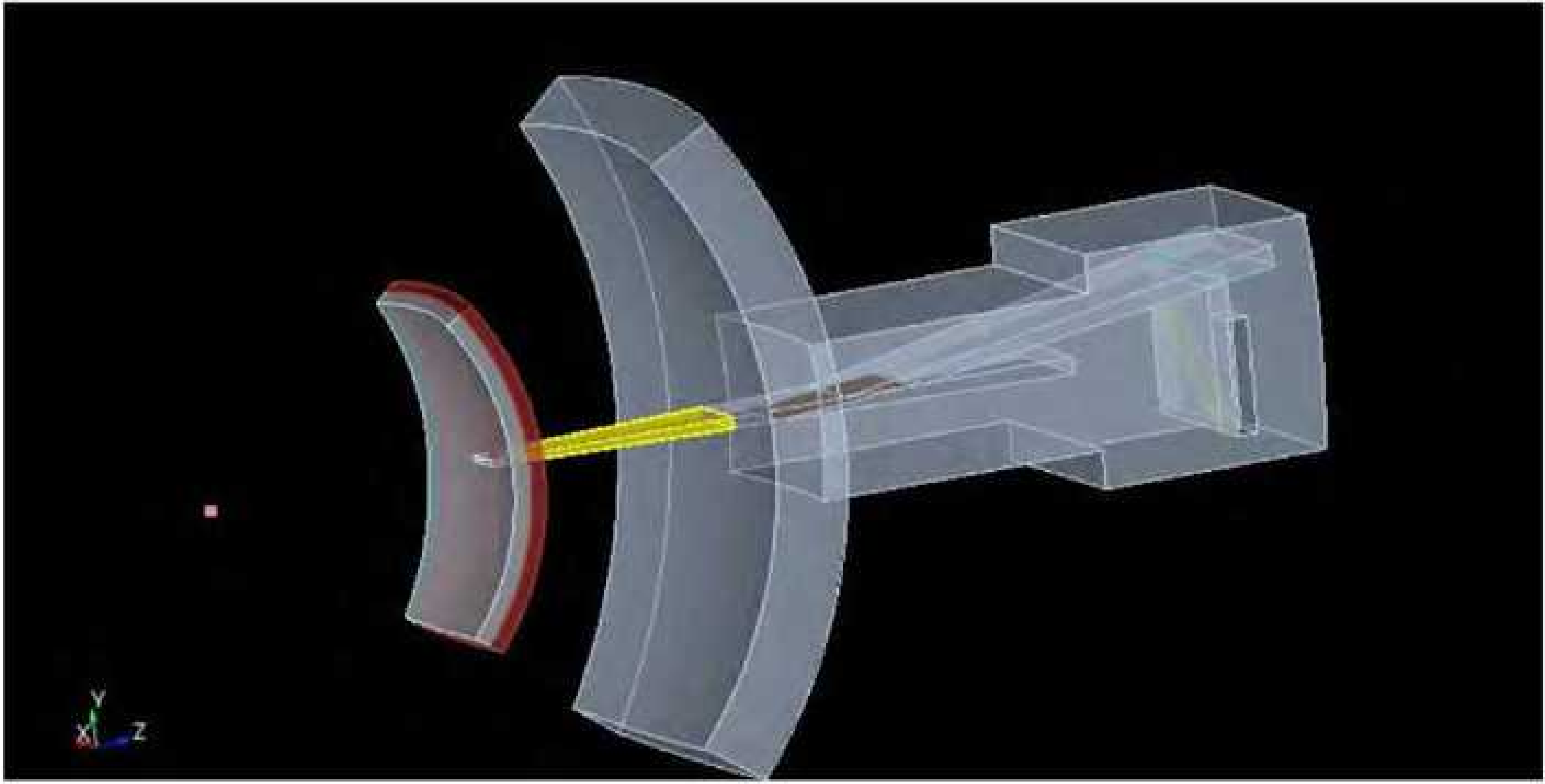
- Geometry complex varying in both poloidal and toroidal directions
- Cannot be modeled by standard MCNP

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

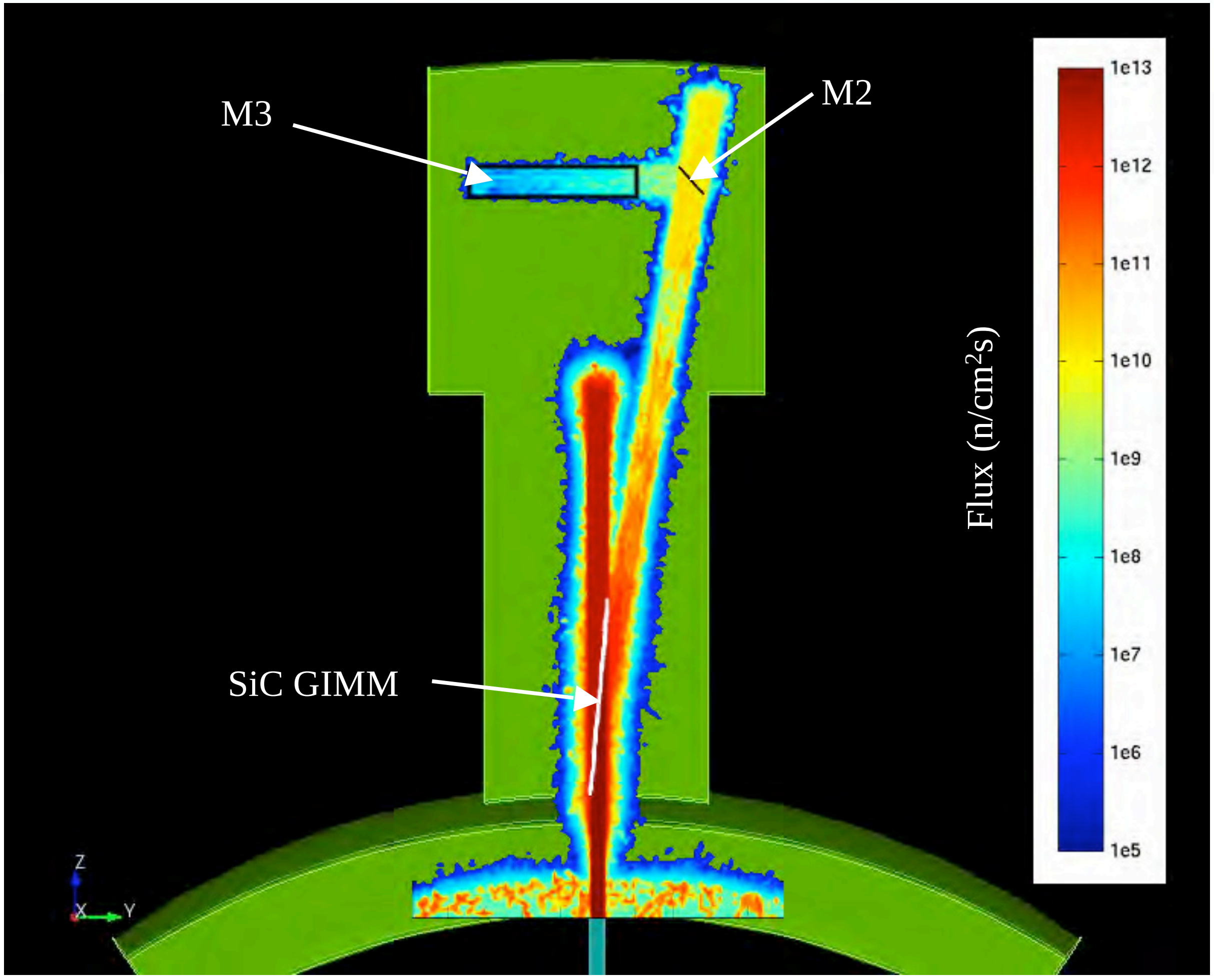
NWL Maps (colormaps in MW/m^2)



HAPL Final Laser Optics

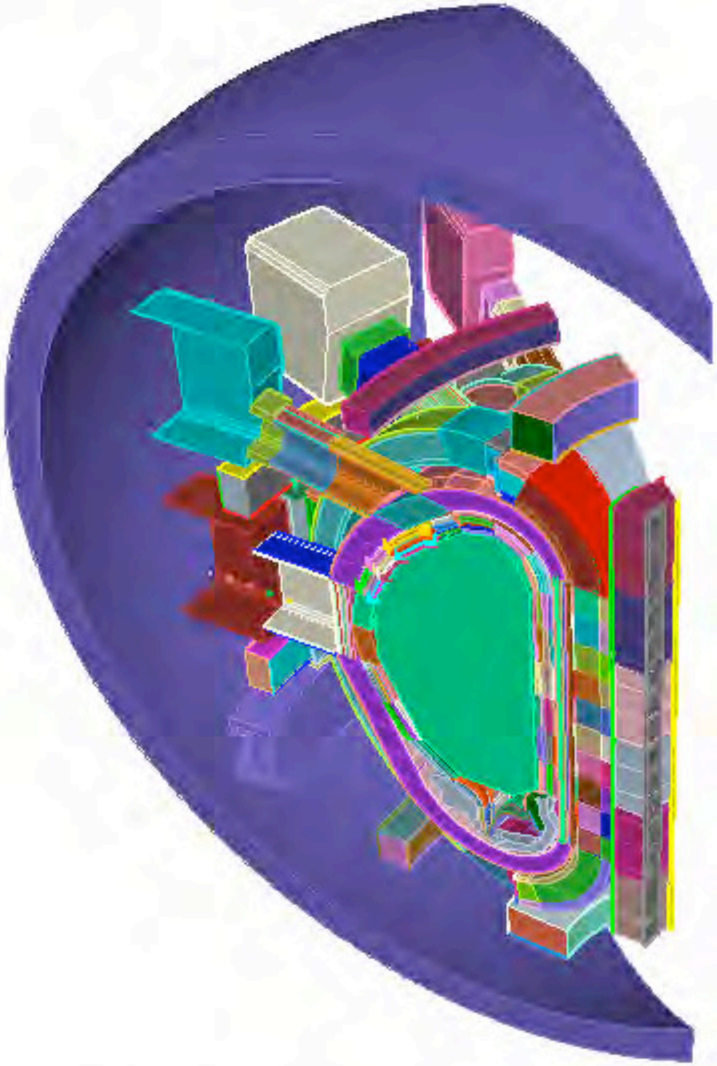


Neutron Flux in Laser Beam Duct



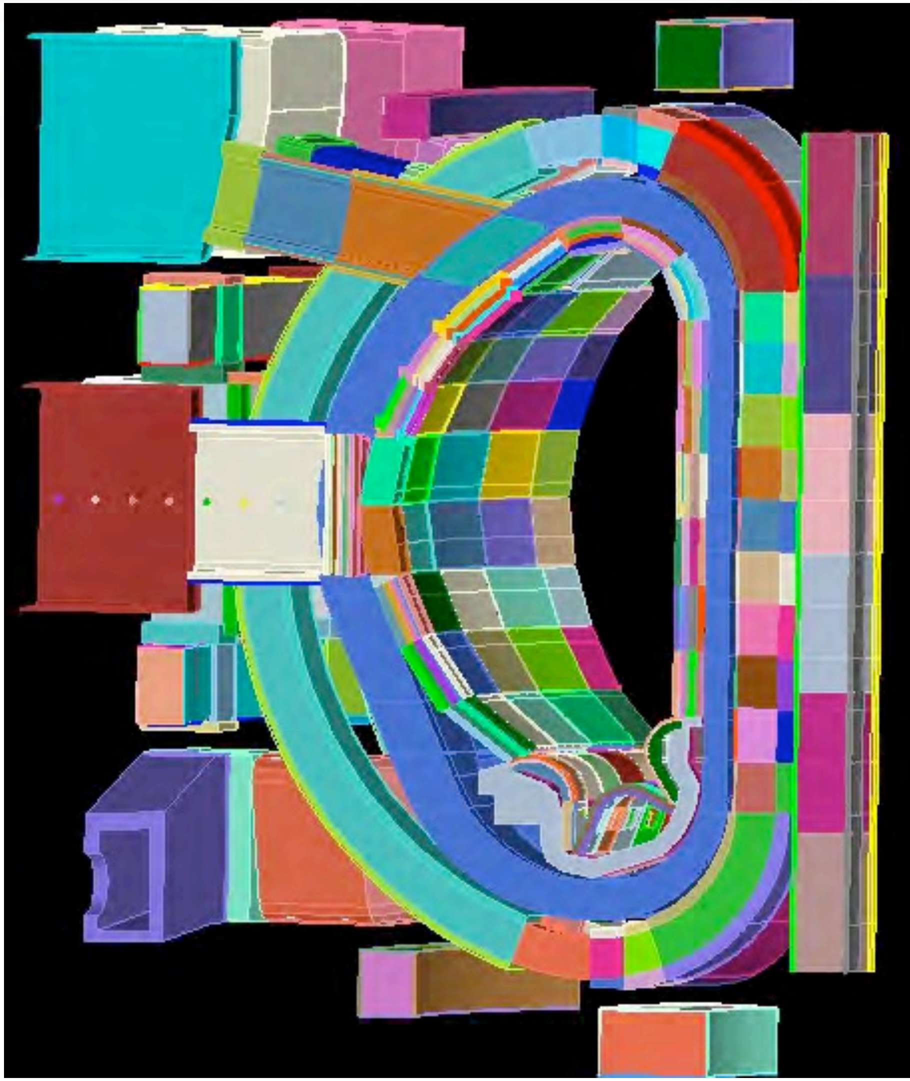
ITER Benchmark

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

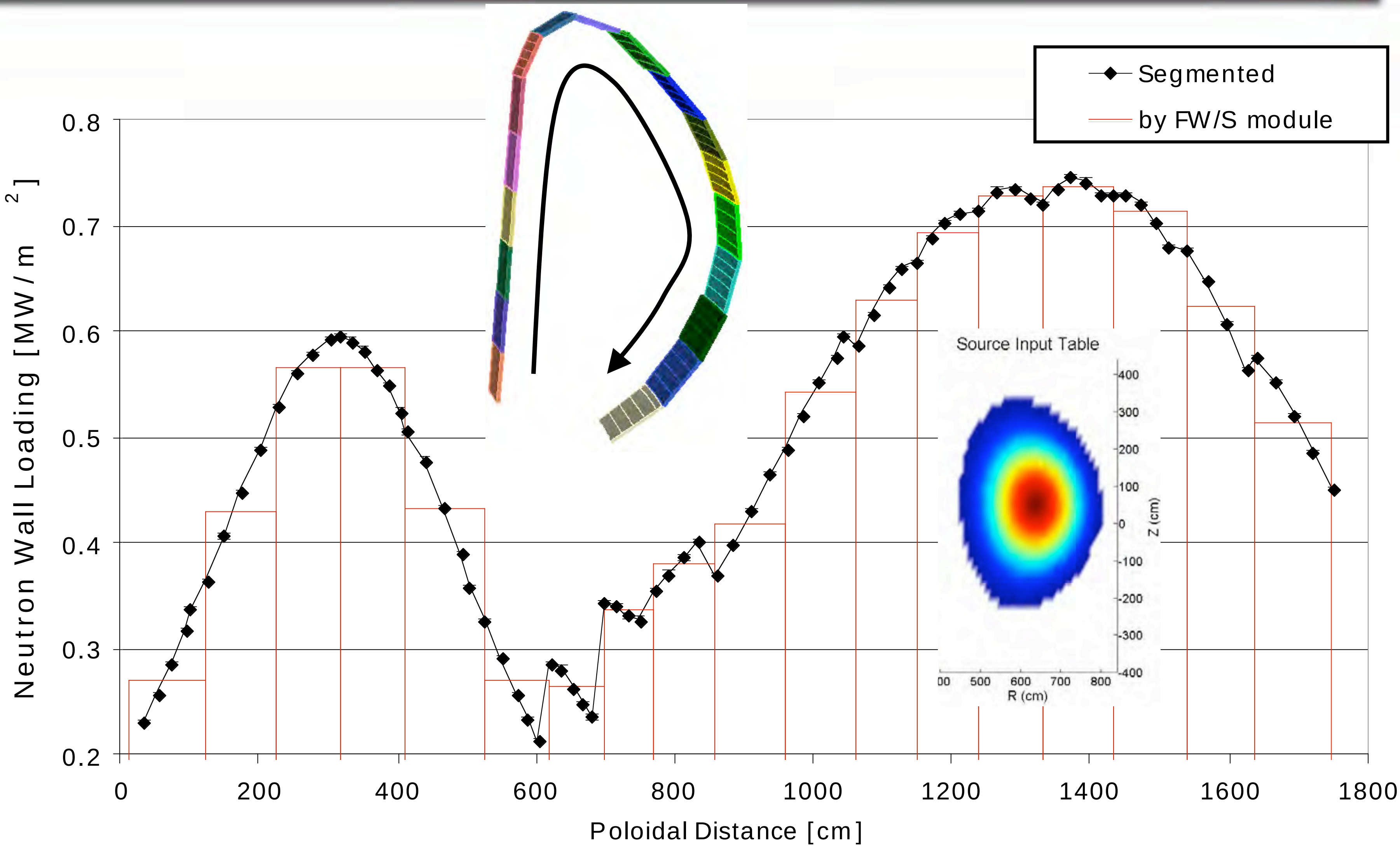


ITER Benchmark

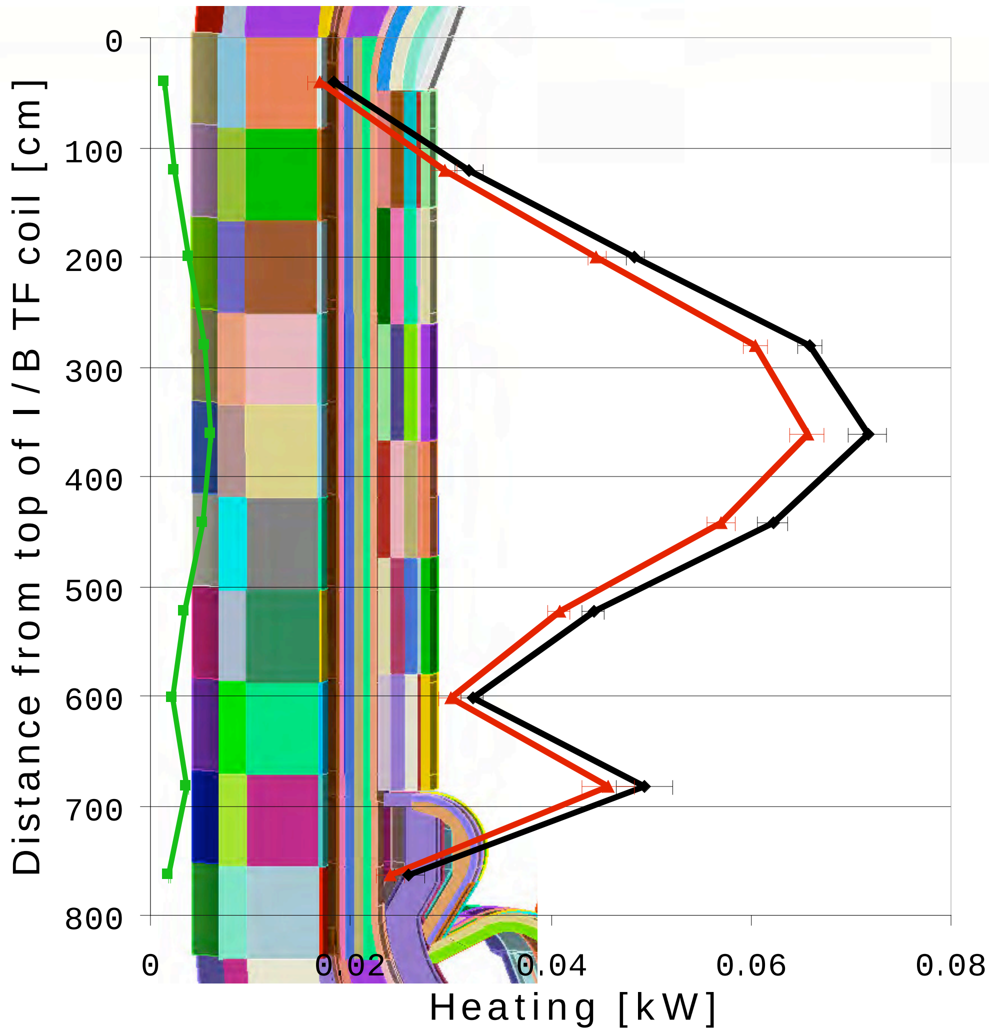
- Comparing 4 results
  - Neutron wall loading
  - Divertor fluxes and heating
  - Magnet heating
  - Midplane port shielding/streaming
- Participants
  - UW, FZK, ASIPP, JAEA



Neutron Wall Loading : results



TF Coils : results



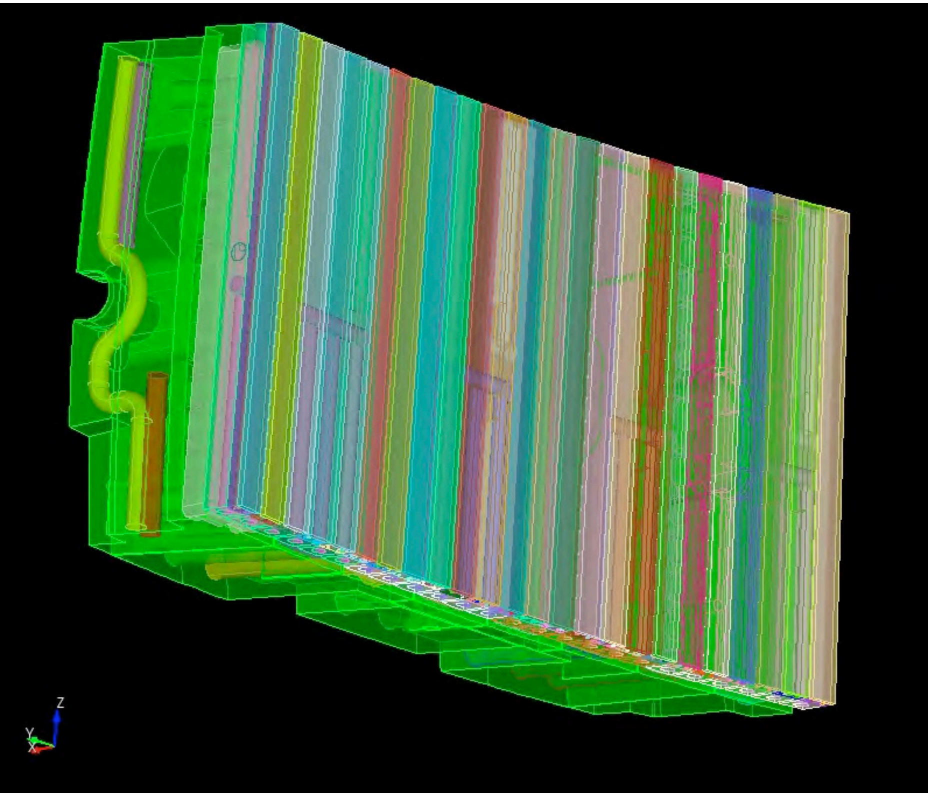
Nuclear Heating (W)

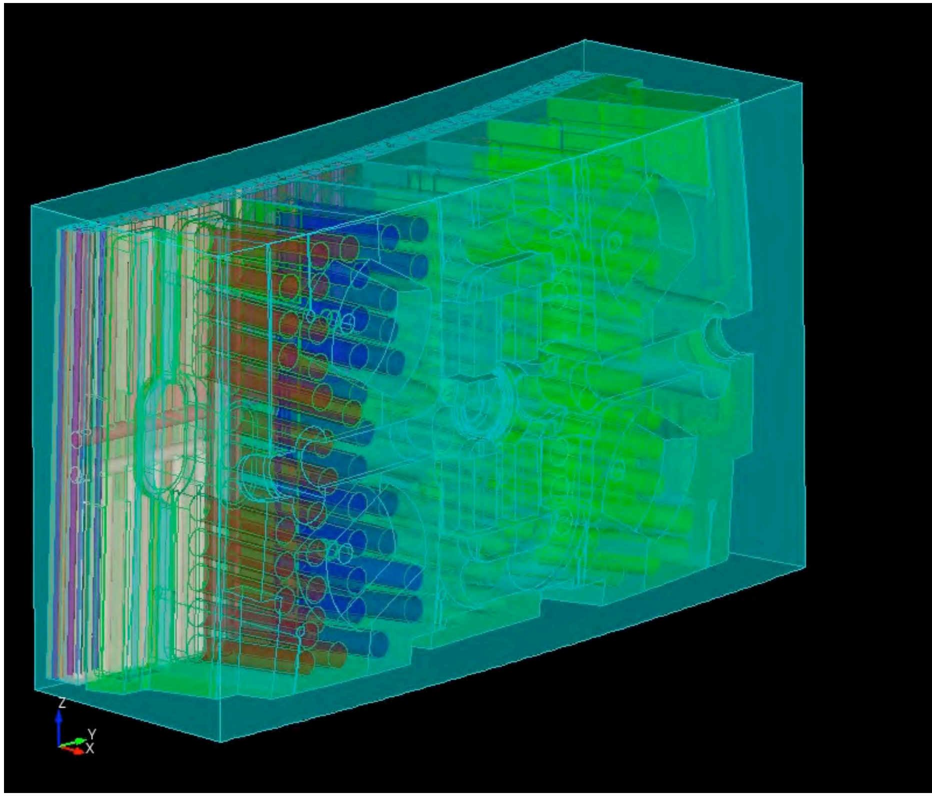
Neutron	Photon	Total
1.39 ± 0.05	17.0 ± 0.6	18.4 ± 0.6
2.47 ± 0.06	29.4 ± 0.6	31.8 ± 0.7
3.82 ± 0.04	44.6 ± 0.4	48.4 ± 0.5
5.41 ± 0.05	60.4 ± 0.6	65.8 ± 0.6
6.03 ± 0.12	65.6 ± 0.9	71.6 ± 1.0
5.16 ± 0.08	57.0 ± 0.7	62.2 ± 0.8
3.38 ± 0.04	40.9 ± 0.5	44.3 ± 0.6
2.27 ± 0.04	29.9 ± 0.5	32.2 ± 0.6
3.66 ± 0.08	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

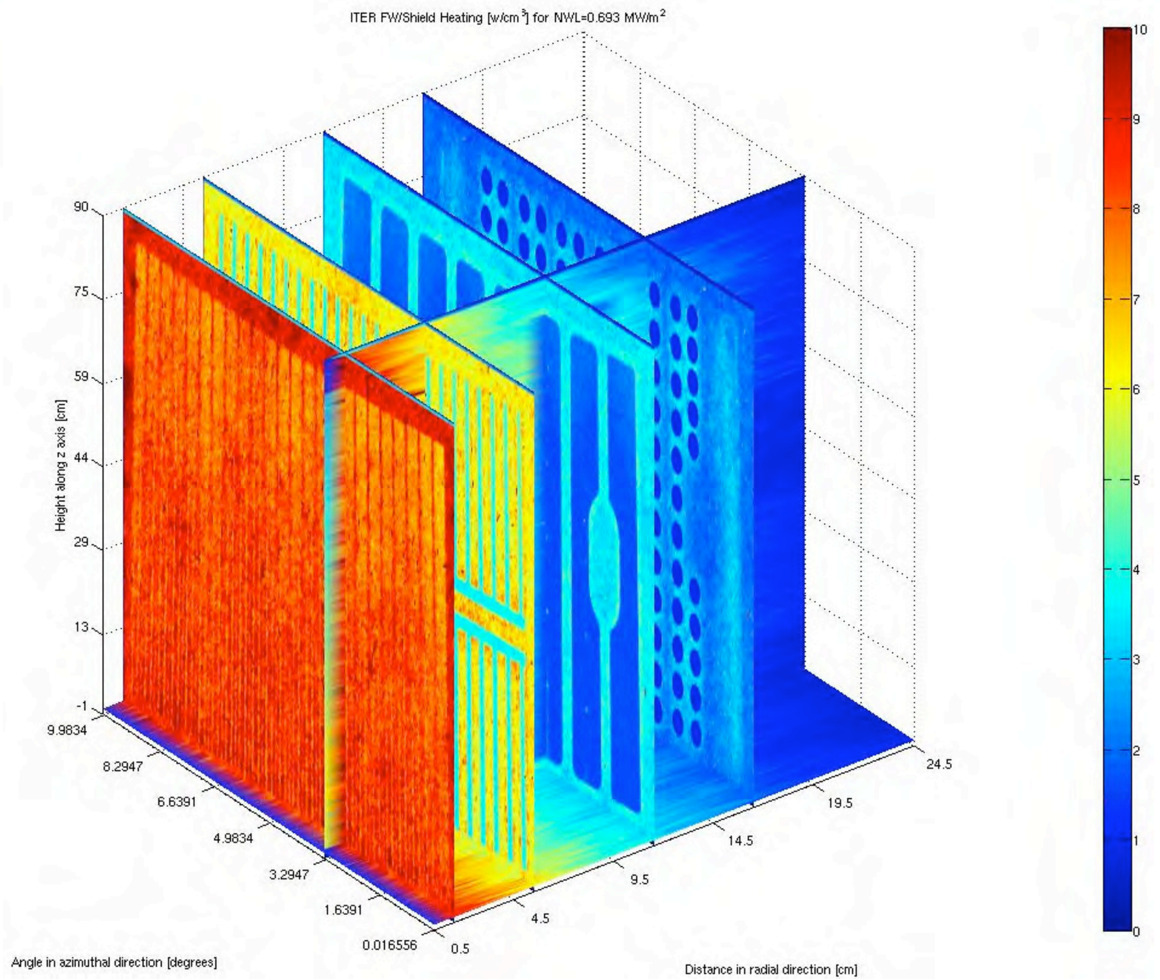
ITER First Wall/Shield
Module 13 Mockup

Model generated by designers using common tools facilitates analysis





FWS results



ITER FW/Shield Heating [w/cm^3] for NWL=0.693 MW/m^2
Height along z axis [cm]
90
75
59
44
29
13
-1
9.9834
8.2947
6.6391
4.9834
3.2947
1.6391
0.016556
Angle in azimuthal direction [degrees]
0.5
4.5
9.5
14.5
19.5
24.5
Distance in radial direction [cm]
10
9
8
7
6
5
4
3
2
1
0

Summary

- 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

Questions?

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