Three-Dimensional Nuclear Analysis for the US DCLL TBM

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Background

- DCLL concept uses He to remove heat deposited in FW and structure and flowing PbLi breeder to remove nuclear heat at a high temperature for efficient power conversion
- DCLL is the preferred US blanket concept for commercial fusion plants
- The DCLL TBM went through major design changes with a detailed updated design configuration released in April 2008
- Detailed 3-D analysis performed for the reference design based on detailed CAD model to determine the nuclear parameters

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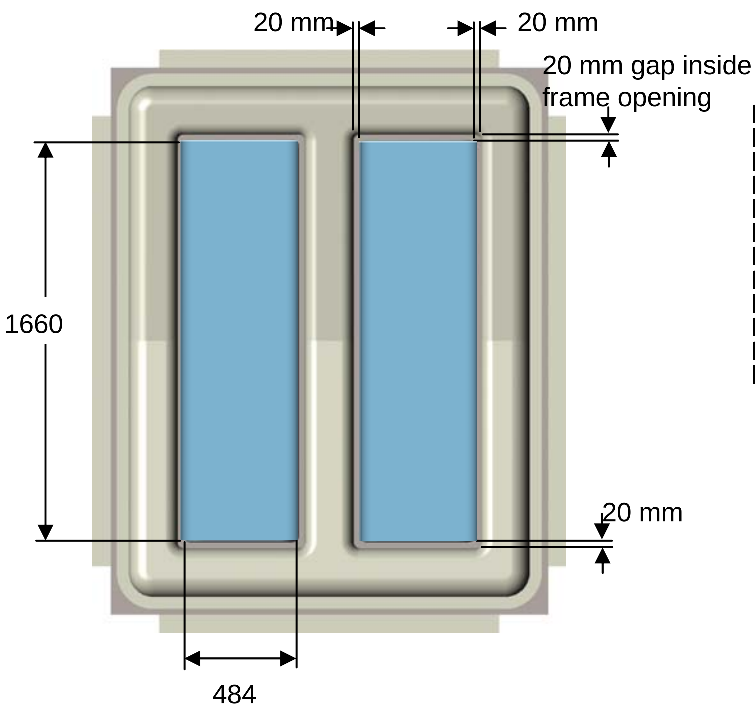
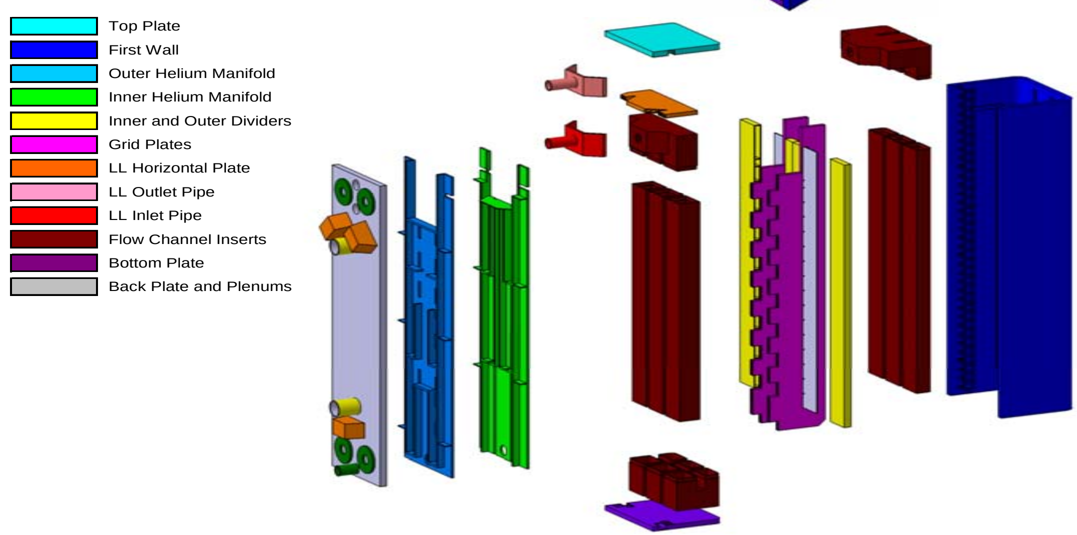
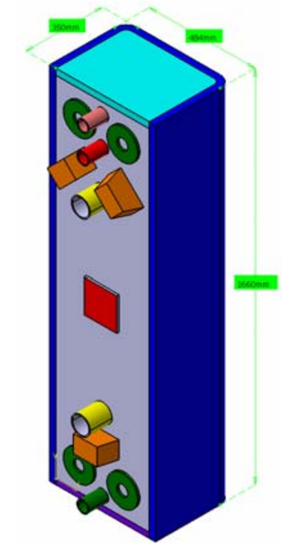
DCLL TBM Design Features

- Frontal dimensions 48.4x166 cm (0.8 m^2)
- Radial depth 35 cm
- Neutron wall loading 0.78 MW/m^2
- 2 mm Be PFC on ferritic steel (F82H) FW
- Lead lithium {$Li_{17}Pb_{83}$} eutectic enriched to 90% Li-6
- 5 mm SiC_f/SiC inserts (FCI) used in all PbLi flow channels
- Geometry is complex requiring detailed 3-D calculations

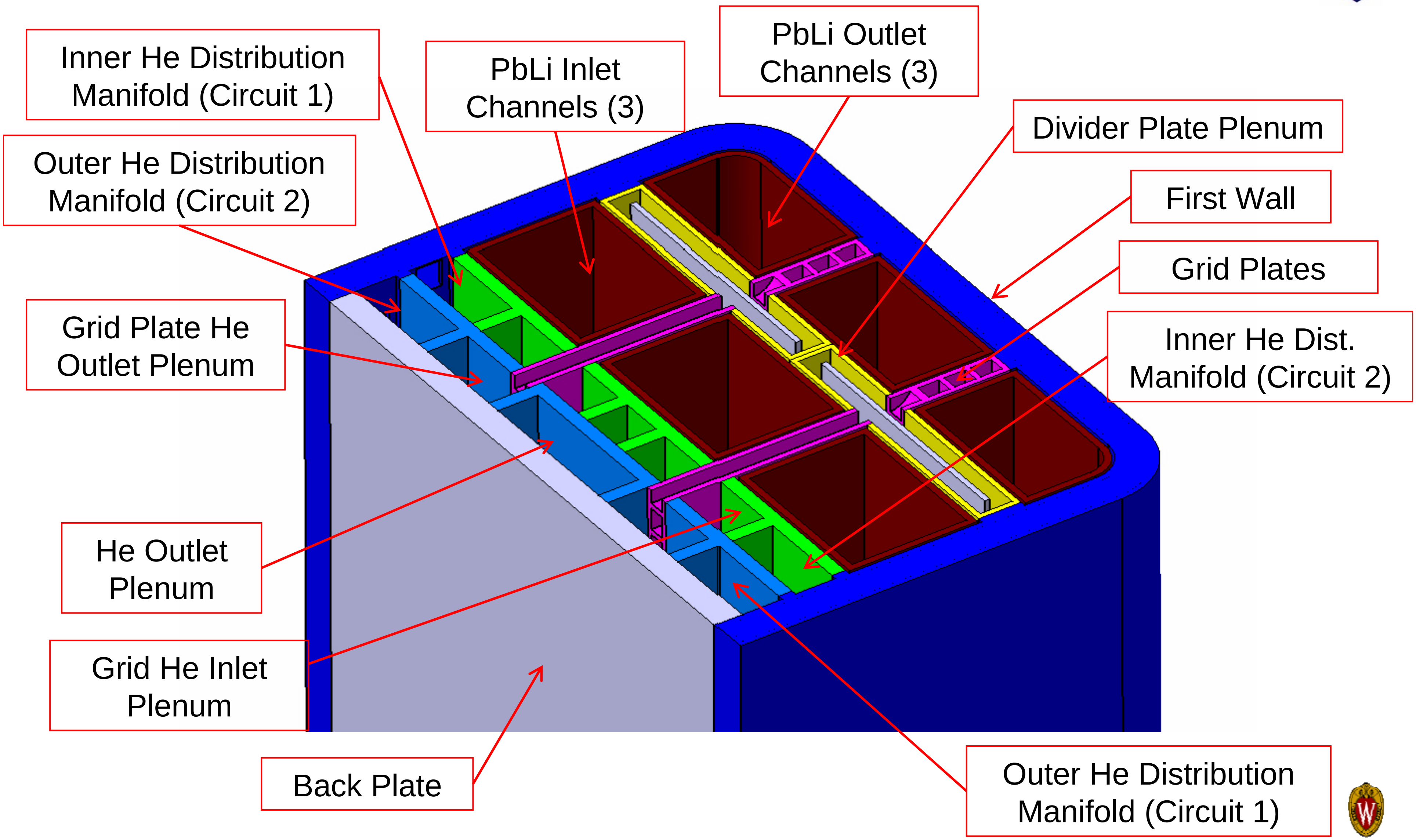




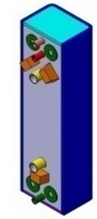


DCLL TBM Assembly Mid-Plane Section

US DCLL TBM

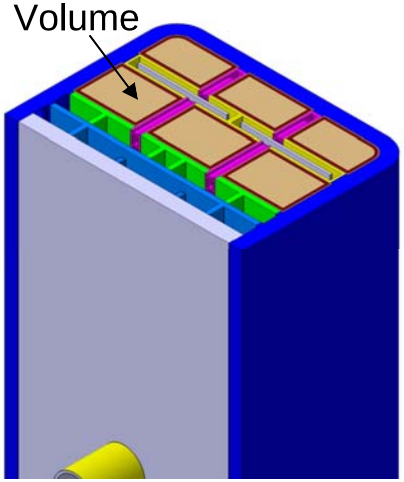


3-D Neutronics Analysis for DCLL TBM

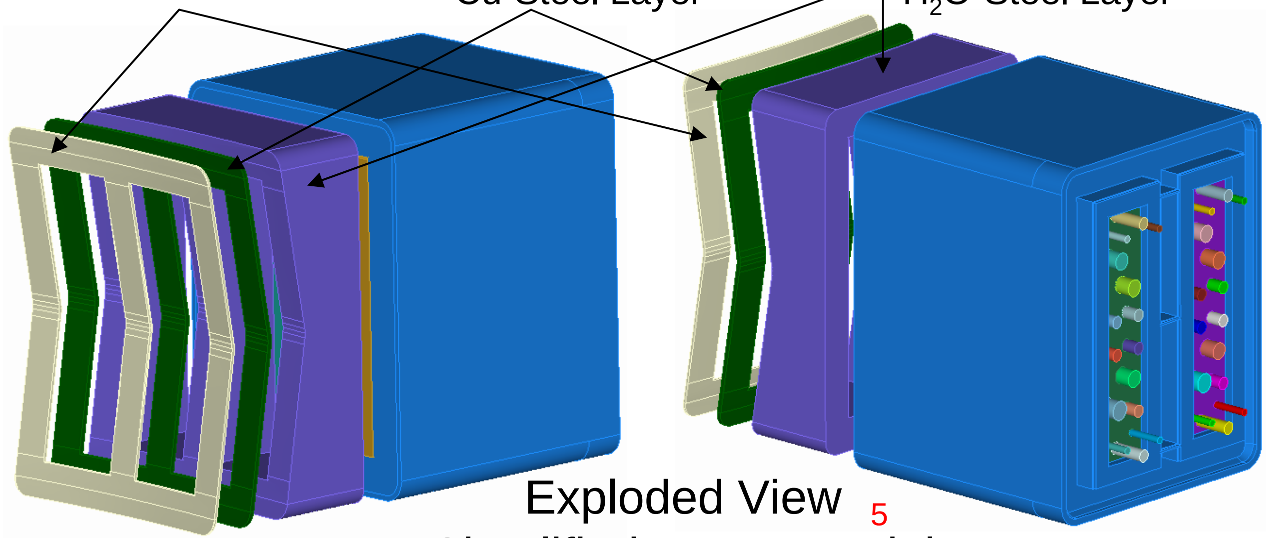


US DCLL TBM

- Calculations using DAG-MCNP where neutronics calculations are performed directly in the CAD model (preserve geometrical complexity without simplification, avoid human error)
- Detailed CAD model for DCLL TBM is utilized
- Helium in the current model is represented by void
- A full PbLi volume has been created for analysis
- A simplified CAD model with homogenized zones was generated for the frame
- TBM and Frame CAD models combined and integrated model used in calculations

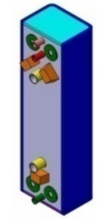


DCLL TBM



Exploded View
Simplified Frame Model

A Surface Source Is Used in The Calculations

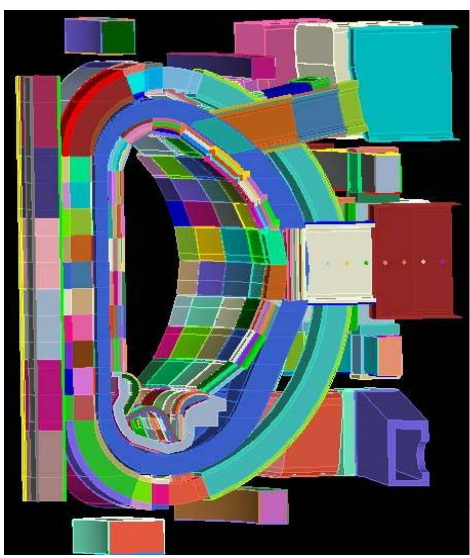


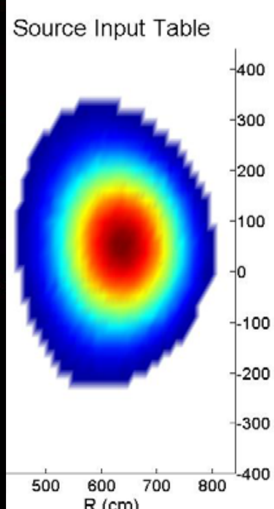
US DCLL TBM

- An extra surface was inserted in front of equatorial port in a 40° sector model of ITER geometry
- All particles crossing this surface were recorded (location, angle, energy, weight)
- Surface crossings into the port is read as a surface source in front of integrated CAD model of frame and TBM
- ***This properly accounts for contribution from the source and other in-vessel components***

2-D calculations for the TBM indicated that the 20 cm thick frame results in neutronics decoupling between TBM and adjacent shield modules with <2% effect. The frame has significant effect on DCLL parameters (up to 30%) and should be

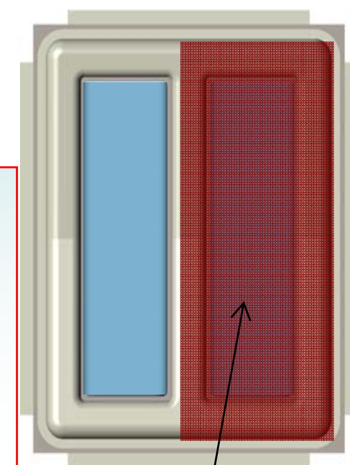
	TBM only	TBM+Frame	TBM+Frame+FWS
Front fast flux	1	0.919	0.895
Back fast flux	1	0.730	0.717
Front FS heating	1	0.976	0.981
Back FS heating	1	0.723	0.706
Front FS dpa	1	0.973	0.964
Back FS dpa	1	0.788	0.779
Front PbLi heating	1	0.983	1.000
Back PbLi heating	1	0.765	0.747
Front PbLi tritium production	1	1.003	1.049
Back PbLi tritium production	1	0.691	0.664





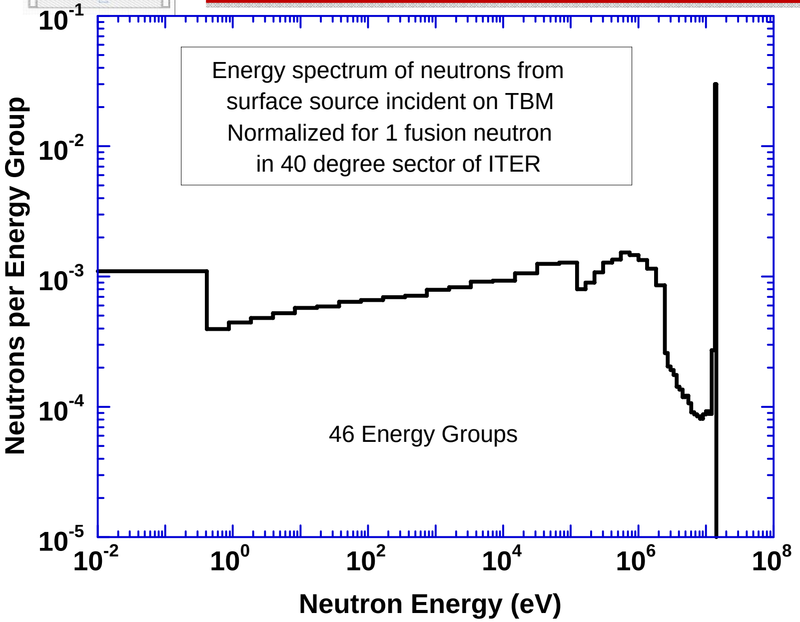
Only half of the frame with a TBM is used in the calculations surrounded on the sides with reflecting boundaries

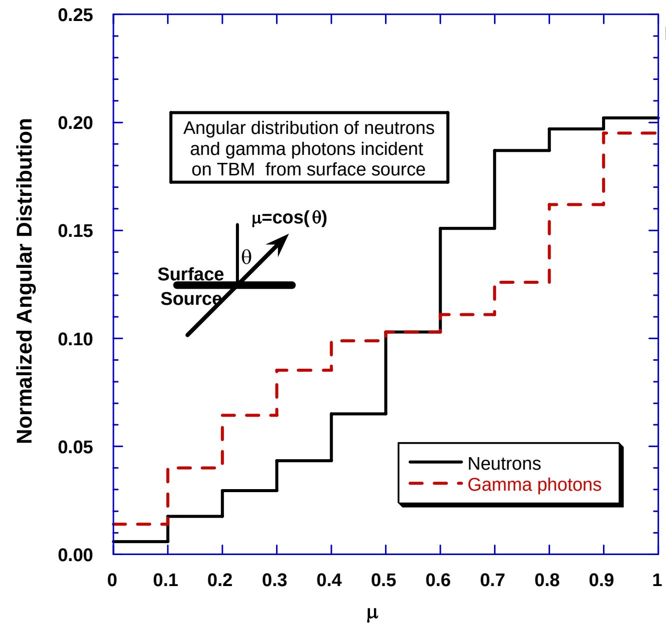
Assessment of surface source utilization indicated that it yields exact results if the surface source is extended at least 10 cm beyond the analyzed module [T.D. Bohn, B. Smith, M.E. Sawan, and P.P.H. Wilson, Assessment of using the surface source approach in 3-D neutronics of fusion systems, University of Wisconsin Fusion Technology Institute, UWFDM-1368 (2009)]



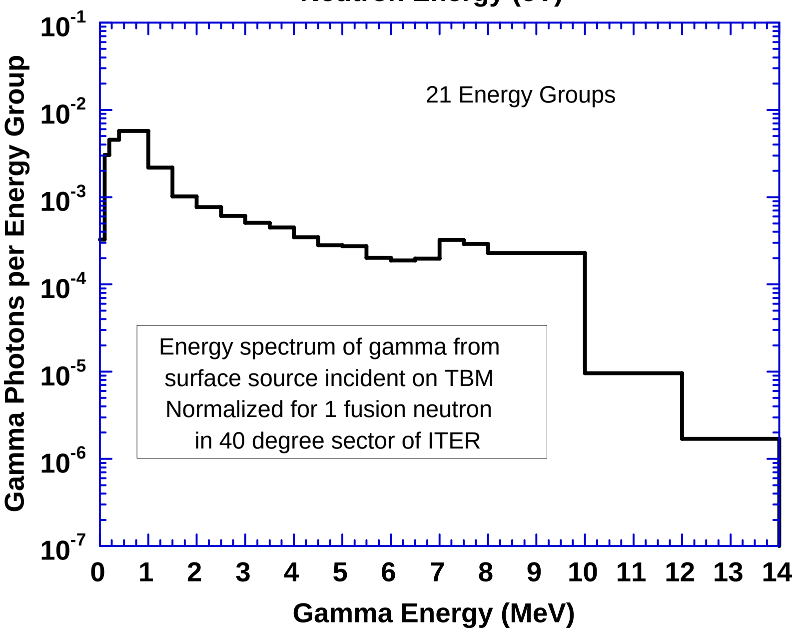
Surface source

Features of Neutron and Gamma Surface Source Incident on TBM





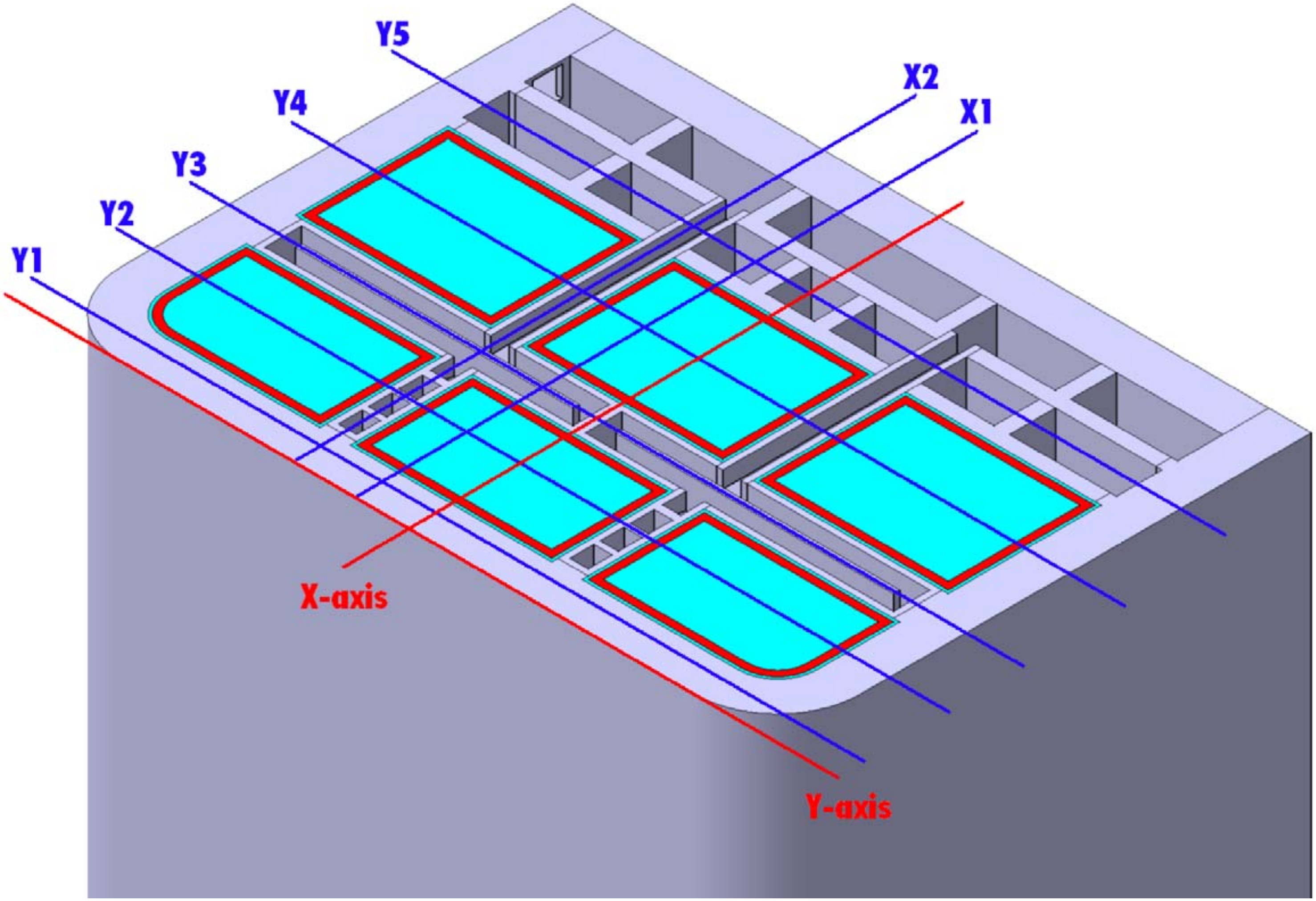
US DCLL TBM



- Only 52% of neutrons incident on TBM are at 14 MeV due to significant secondary component from chamber components. Average neutron energy is 7.75 MeV
- Number of secondary gamma photons incident on TBM is 37% of number of neutrons. Average gamma energy is 1.48 MeV
- Neutrons have more perpendicular angular distribution compared to the mostly tangential secondary gammas

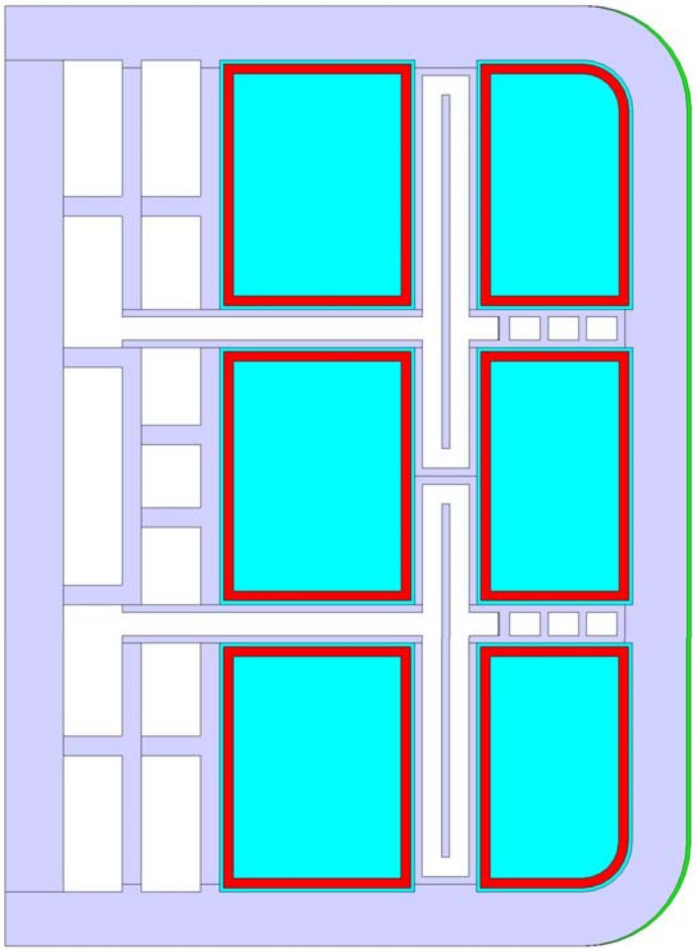
Cross Section in TBM at Mid-plane

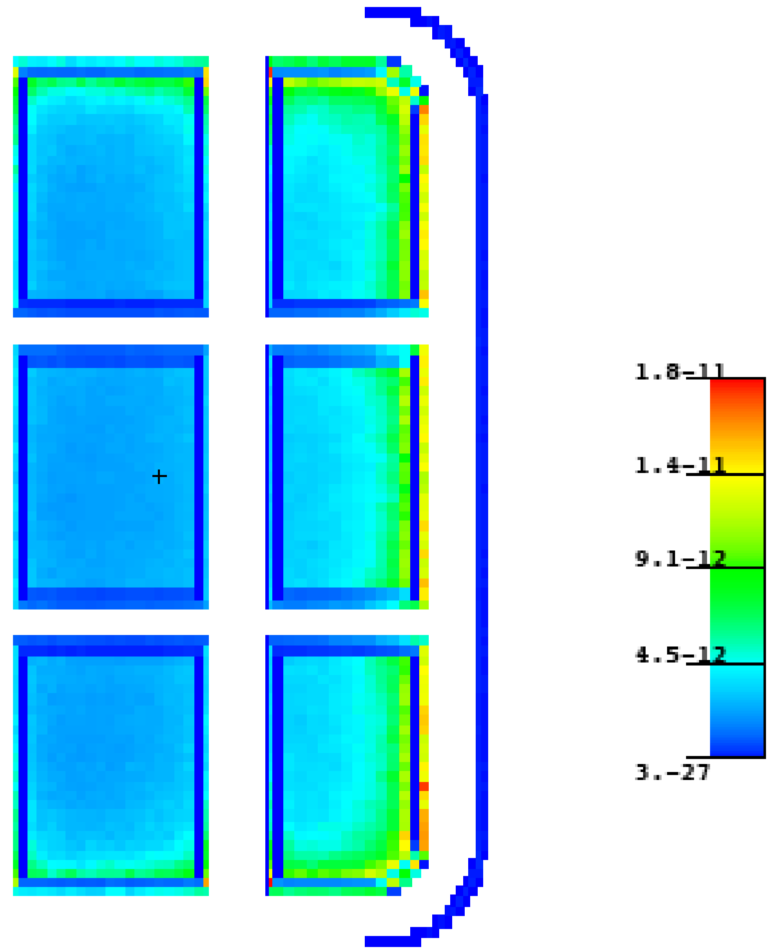
US DCLL TBM



Tritium Production (g T/cm^{3}s) at Mid-Plane of TBM

US DCLL TBM

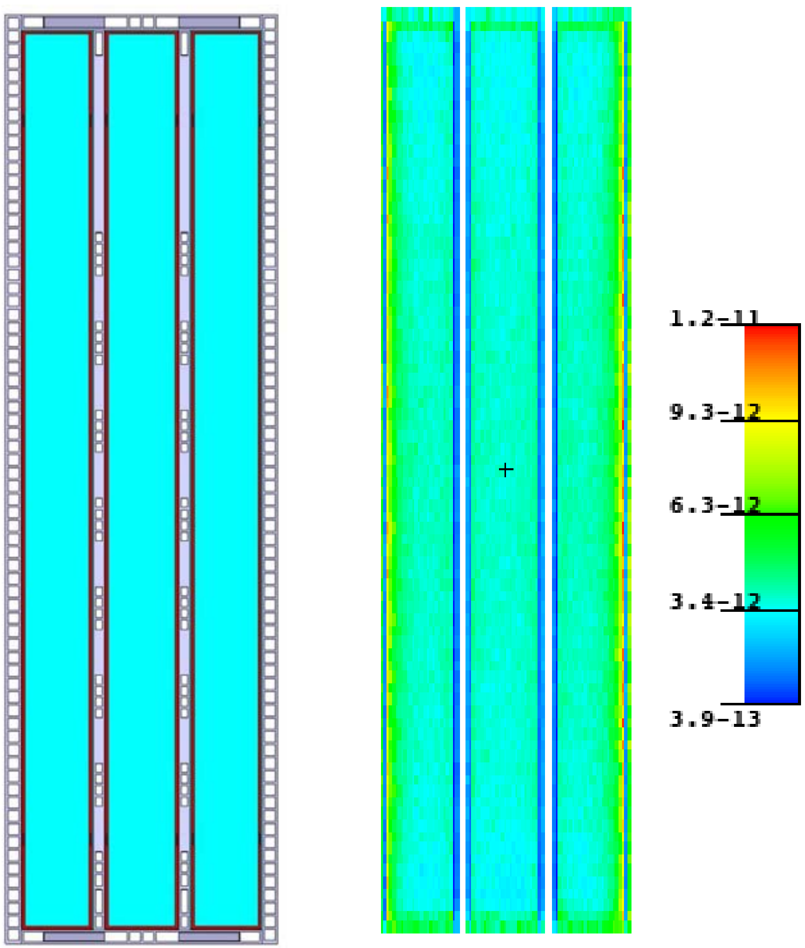




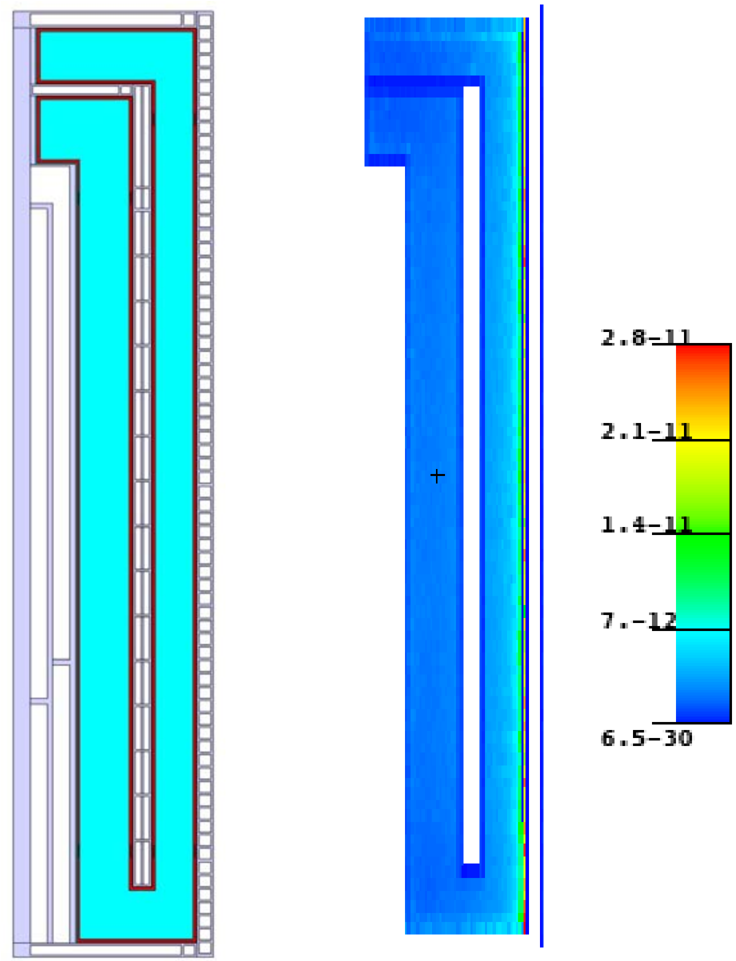
Tritium production is higher at edges of module due to softer neutron spectrum from slowing down in water in surrounding frame leading to higher breeding in Li-6

Tritium Production (g T/cm^{3}s) at Vertical Sections of TBM

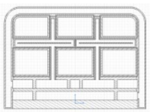
US DCLL TBM



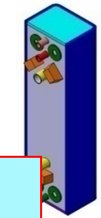
Section Y2



Section X1



Tritium Production in TBM



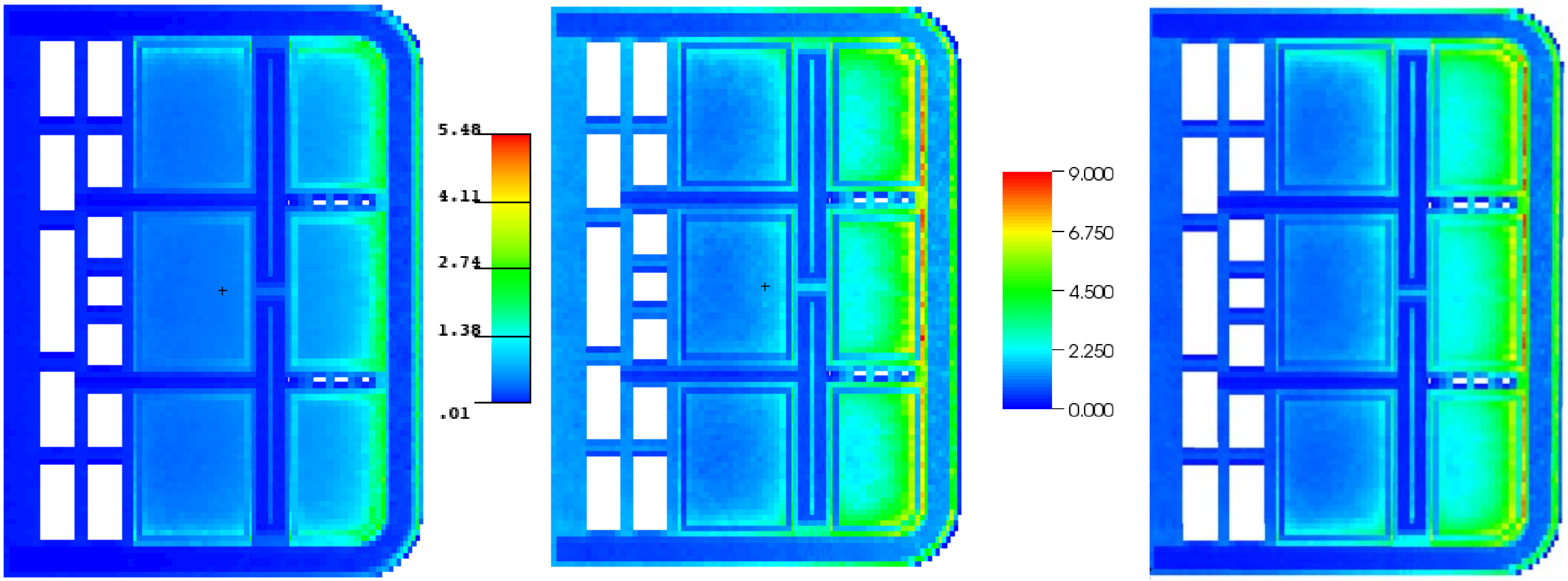
- Tritium generation rate in the PbLi is 4.19×10^{-7} g/s during a D-T pulse with 500 MW fusion power (local TBR is only 0.31)
- For a pulse with 400 s flat top preceded by 20 s linear ramp up to full power and followed by 20 s linear ramp down total tritium generation is 1.76×10^{-4} g/pulse
- For the planned 3000 pulses per year the annual tritium production in the TBM is 0.53 g/year
- Tritium production in the Be PFC is 8.24×10^{-10} g/s $\Rightarrow$ 3.47×10^{-7} g/pulse $\Rightarrow$ 1.04×10^{-3} g/year

Material	Peak Tritium Production (g/cm^3s)
Lead Lithium	2.8×10^{-11}
Be PFC	7.7×10^{-13}

Detailed 3-D analysis of TBM yields total tritium production in the TBM that is 45% lower than the 1-D estimate due to the lower reflection from in-vessel components and additional absorption in frame compared to the 1-D analysis where a DCLL blanket is effectively assumed to replace other chamber components and frame

Nuclear Heating (W/cm^3) at Mid-Plane

US DCLL TBM

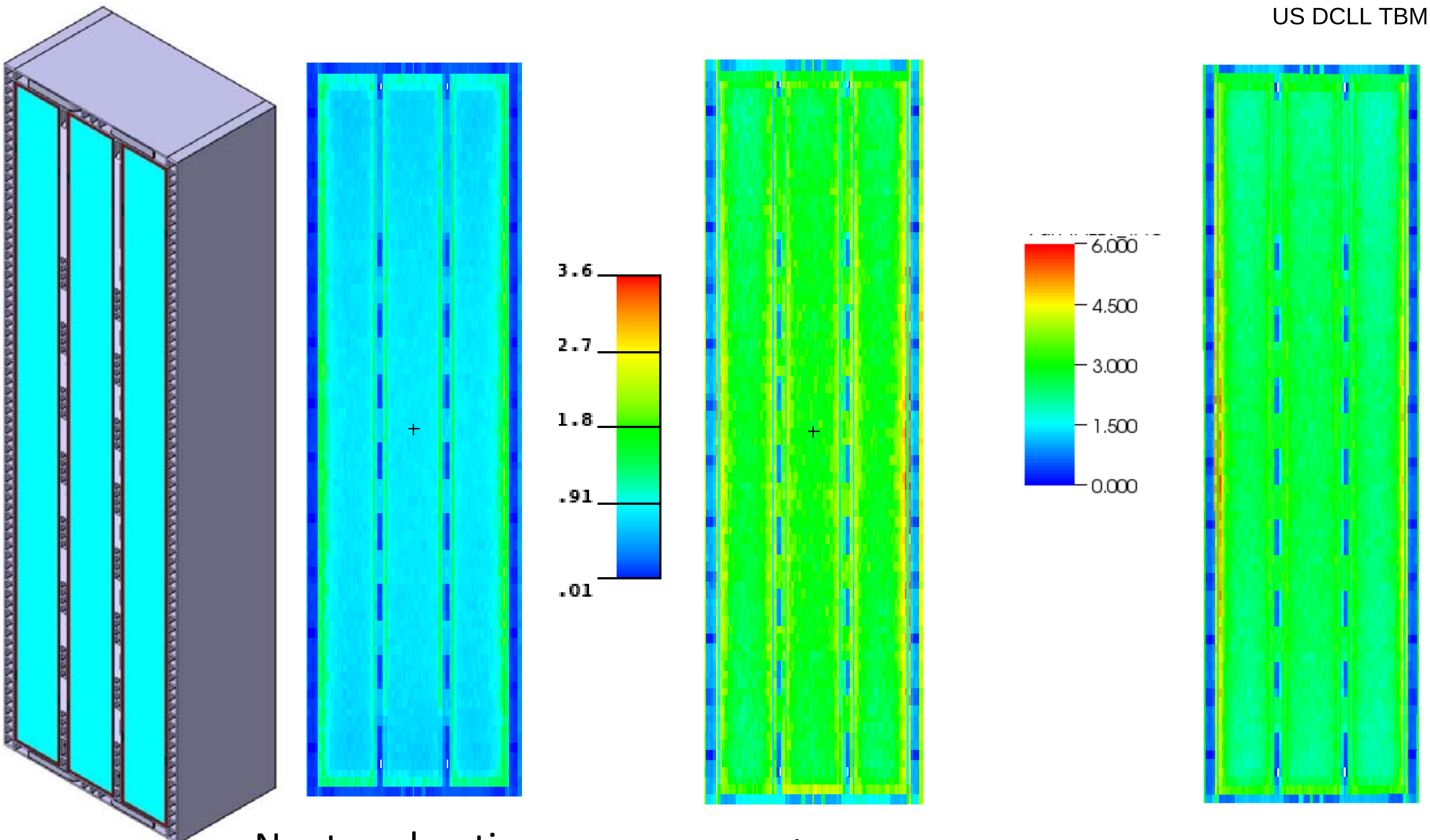


Neutron heating | Gamma heating | Total heating

- Gamma heating in PbLi is higher than in adjacent SiC FCI while neutron heating in SiC is higher than that in PbLi
- Be PFC has lower gamma heating than FS in FW but has higher neutron heating
- Sides of TBM adjacent to water-cooled steel frame show higher gamma heating in PbLi due to gamma generation in steel and water. Neutron heating is also higher due to neutron slowing down in water leading to larger neutron heating in Li-6

Nuclear Heating (W/cm^3) at Section Y2

US DCLL TBM



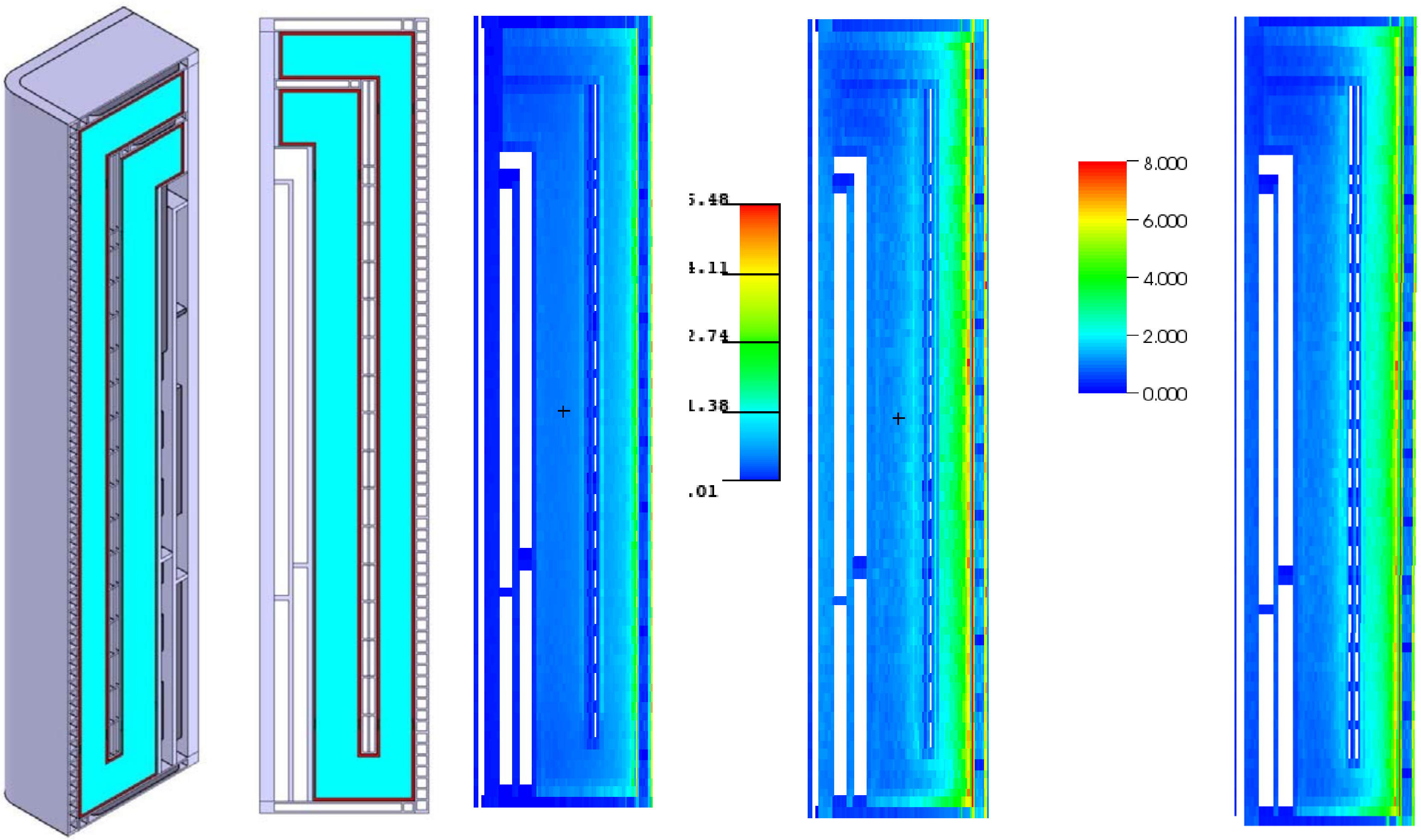
Neutron heating

Gamma heating

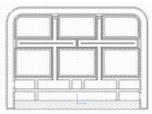
Total heating

Nuclear heating (W/cm^3) at Section X1

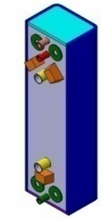
US DCLL TBM



Cross section Neutron heating Gamma heating Total heating



Peak Nuclear Heating in TBM

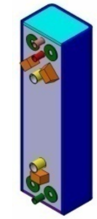


US DCLL TBM

Material	Neutron Heating (W/cm³)	Gamma Heating (W/cm³)	Total Nuclear Heating (W/cm³)	Peak Nuclear Heating from 1-D Calculations
Ferritic Steel	1.38	4.70	***6.08***	9.20
Lead Lithium	4.11	5.48	***9.59***	13.20
SiC FCI	2.74	1.38	***4.12***	4.79
Be PFC	5.48	1.00	***6.48***	8.14

Detailed 3-D analysis of TBM with the surrounding massive water cooled frame and representation of exact source and other in-vessel components yields lower peak nuclear heating values in TBM materials

Total Nuclear Heating in TBM



US DCLL TBM

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

Total TBM thermal power is 0.614 MW that includes 0.24 MW surface heating

- Detailed 3-D analysis of TBM yields total nuclear heating in the TBM that is 35% lower than the 1-D estimate of 0.574 MW
- Reduced total heating is due to less reflection from in-vessel components in 3-D model compared to full coverage with DCLL TBM in 1-D analysis and surrounding water-cooled steel frame acts as a strong sink for neutron

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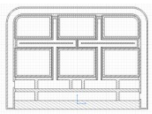
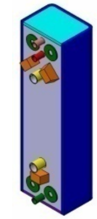
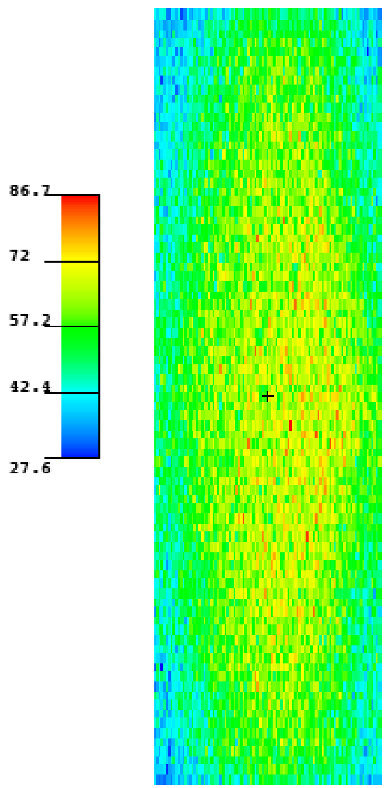


FS Radiation Damage

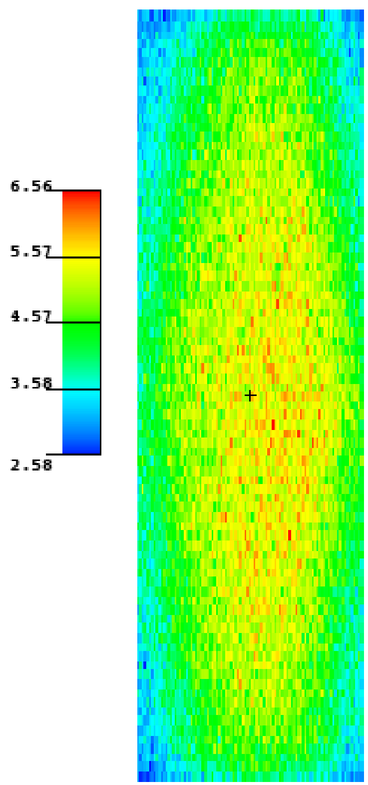


US DCLL TBM

Section Y1

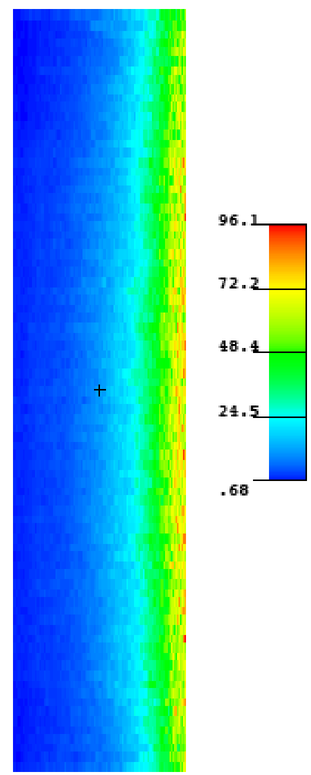


He appm/FPY

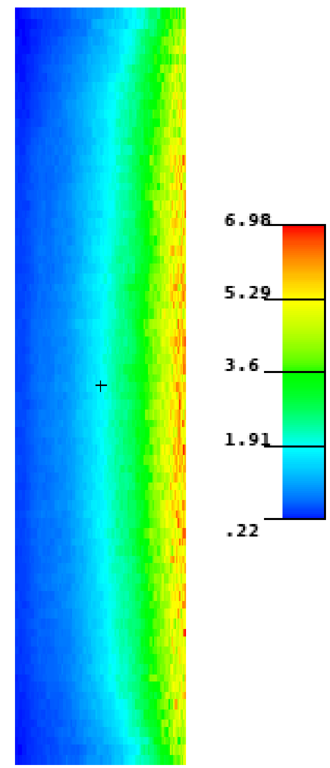


dpa/FPY

Section X1

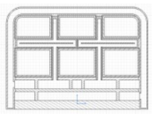


He appm/FPY

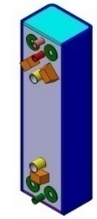


dpa/FPY

- Peak damage parameters in FW occur at center due to enhanced neutron multiplication in PbLi and reduced impact of neutron absorption in frame
- Lower damage parameters occur in outer regions of TBM adjacent to the frame due to neutron absorption and slowing down in the water-cooled steel frame



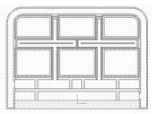
Radiation Damage in FS Structure of TBM



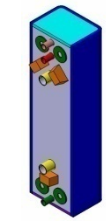
US DCLL TBM

- Peak FS damage rates:
  6.98 dpa/FPY
  96.7 He appm/FPY
- For 0.57 MW/m^2 average NWL and total fluence 0.3 MWa/m^2 total lifetime is 0.526 FPY
- Peak cumulative end-of-life dpa in FW is **3.67 dpa** (vs. 5.1 dpa from 1-D) and He production is **50.9 He appm** (vs. 56.3 appm from 1-D)

- Detailed 3-D analysis of TBM yields 28% lower peak dpa rate and 10% lower peak He production rate in FS compared to the 1-D estimates
- This is due to the more perpendicular angular distribution of incident source neutrons in the realistic 3-D configuration and reduced neutron multiplication and reflection from surrounding frame and other in-vessel components compared to 1-D configuration. Effect on He production is less pronounced since it is produced by higher energy neutrons



Summary and Conclusions



US DCLL TBM

- Detailed 3-D neutronics calculations performed for the US DCLL TBM to accurately account for the complex geometrical heterogeneity and impact of source profile and other in-vessel components
- The neutronics calculations were performed directly in the CAD model using the DAG-MCNP code
- The TBM CAD model was inserted in the CAD model for the frame and the integrated CAD model was used in the 3-D analysis
- Detailed high-resolution, high-fidelity profiles of the nuclear parameters were generated using fine mesh tallies
- The TBM heterogeneity, exact source profile, and inclusion of the surrounding frame and other in-vessel components result in lower TBM nuclear parameters compared to the 1-D predictions
- This work clearly demonstrates the importance of preserving geometrical details in nuclear analyses of geometrically complex components in fusion systems