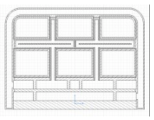
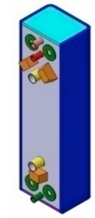




Updated DCLL TBM Neutronics Analysis

Mohamed Sawan[1]

with Input from

Mo Dagher[2], Edward Marriott[1], Brandon Smith[1], and Clement Wong[3]

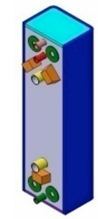
[1]UW – Madison, Fusion Technology Institute

[2]University of California – Los Angeles

[3]General Atomics

FNST Meeting
UCLA
August 12-14, 2008

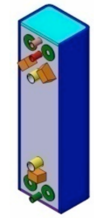
DCLL TBM Updated Neutronics Analysis



US DCLL TBM

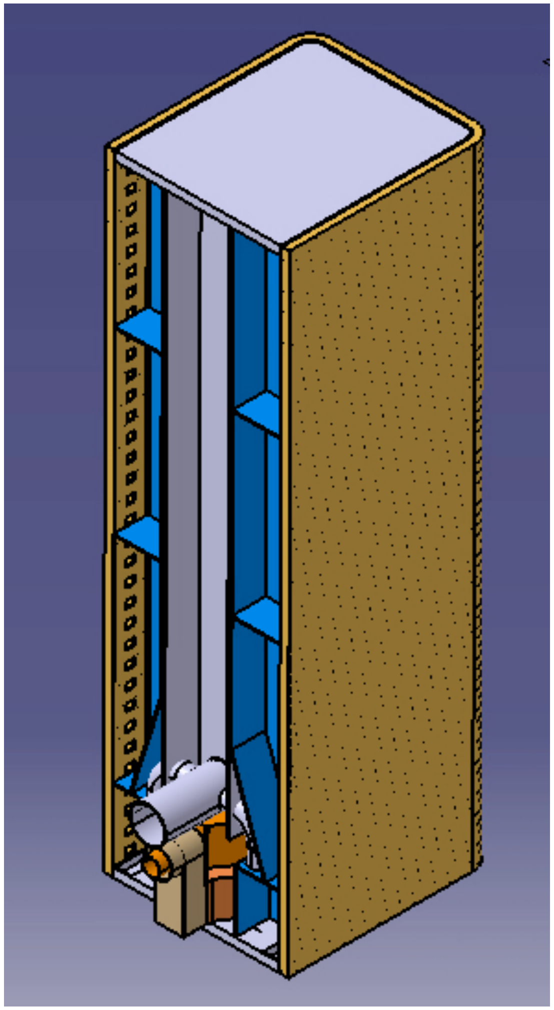
- The DCLL TBM went through major design changes since the last time a technical design review was held in August 2006
- Detailed updated design configuration was released in April 2008
- The nuclear parameters for the DCLL TBM were updated for the current design
- Initial 1-D calculations performed for ITER mid-plane radial build that includes the inboard FWS module
- Calculations performed for configurations at the different vertical zones of TBM
- Started 3-D analysis for the detailed CAD model using the DAG-MCNP code

DCLL TBM Design Design Change Highlights



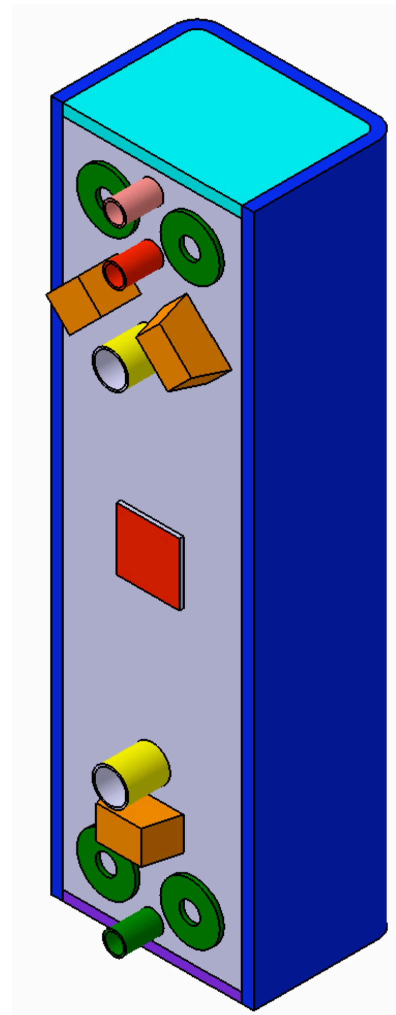
US DCLL TBM

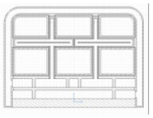
Original Design Concept



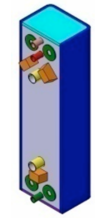
1. Reversed PbLi Flow
    1. Starting at the top
    2. PbLi Inlet in back Channel with Downward flow
    3. PbLi Outlet flow in Front channel Upward Flow
    4. Replaced PbLi concentric pipe concept with two individual I/O Pipes
2. He Flow in FW is Un-Changed, 2 circuits, 7 passes per circuit
3. He Flow in Grid Plate is Modularized.
4. He Flow in Grid plate in radial direction
5. Multi-layered back plate design Configuration.

Current Design Concept

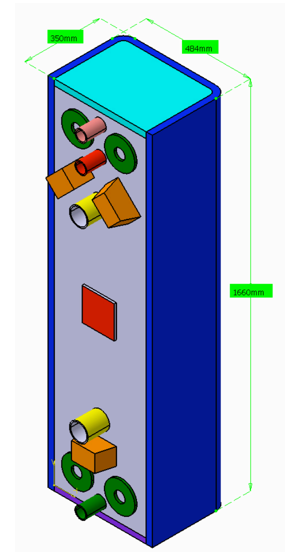


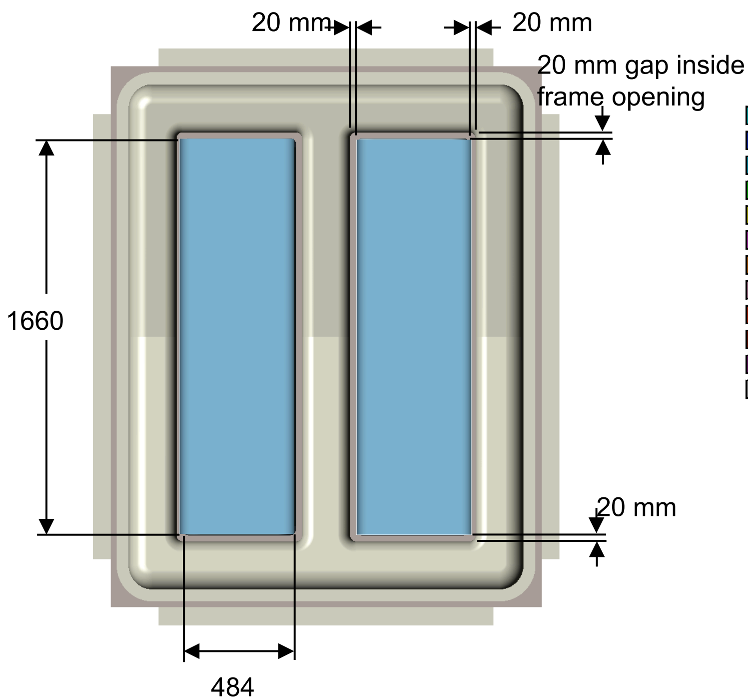


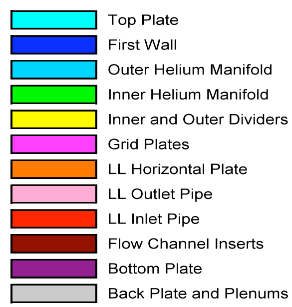
DCLL TBM Design Features

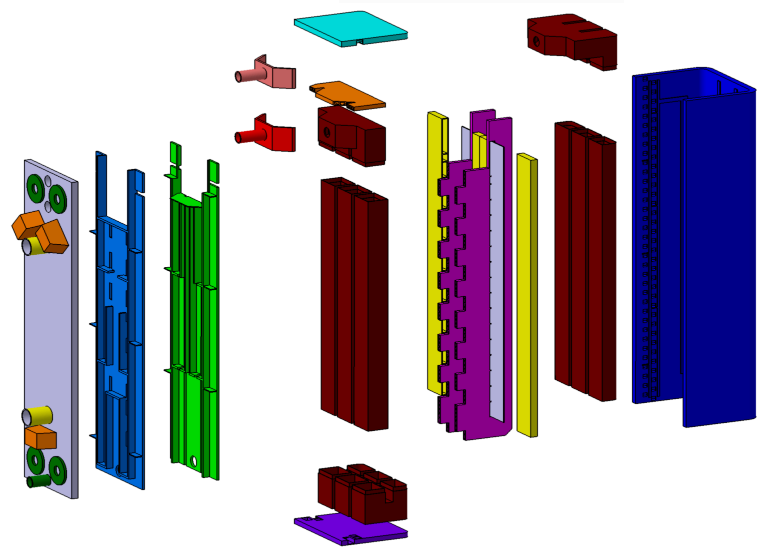


- Frontal dimensions 48.4x166 cm (0.8 m^2)
- Radial depth 35 cm
- Neutron wall loading 0.78 MW/m^2
- 2 mm Be PFC on ferritic steel (F82H) FW
- Lead lithium $\{Li_{17}Pb_{83}\}$ eutectic enriched to 90% Li-6
- 5 mm SiC_f/SiC inserts (FCI) used in all PbLi flow channels





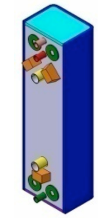




DCLL Radial Build and Material Composition

- A radial build is the homogenization of the material composition along the radial direction of the TBM starting from the FW
- The TBM is divided into seven vertical layers each representing a poloidal section of the TBM
- These sections are determined based on the internal design configuration of the TBM, in order to maintain a uniform vertical configuration in each vertical layer
- For each poloidal layer the radial zones are homogenized by determining the volume fractions of each material in the zone
- The material volume fractions for each zone were then used in neutronics calculations to determine the power density distribution throughout the corresponding poloidal layer

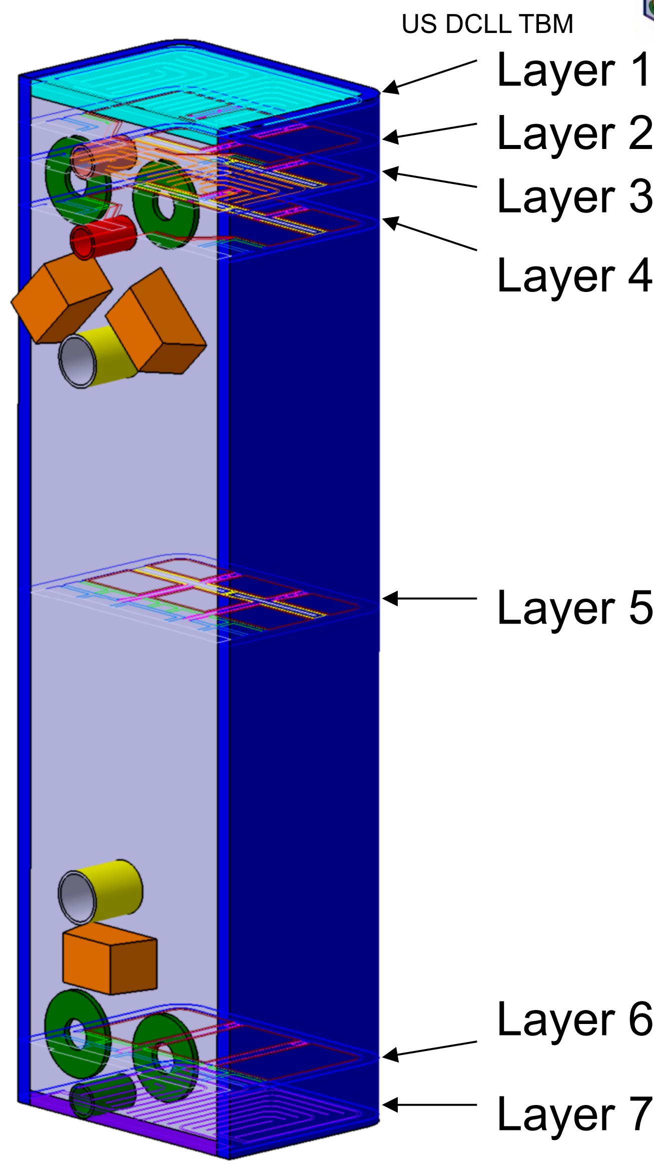
Radial Build Layer Positions

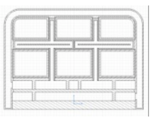


Seven Layers were used

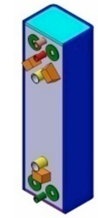
(Layer height shown in parentheses):

1) Top Plate (28mm)
2) PbLi Outlet (100mm)
3) Horizontal Grid Plate (20mm)
4) PbLi Inlet (120mm)
5) Midplane (1275mm)
6) Bottom Zone (93mm)
7) Bottom Plate (24mm)





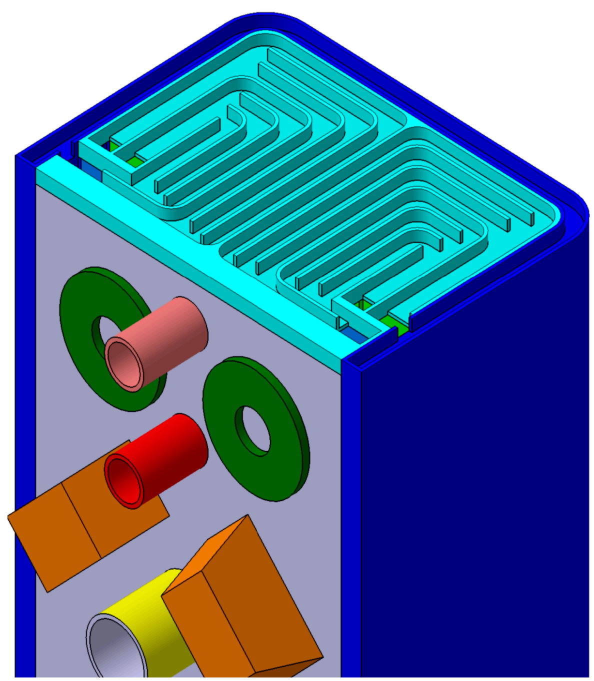
Layer 1 – Top Plate (28mm)

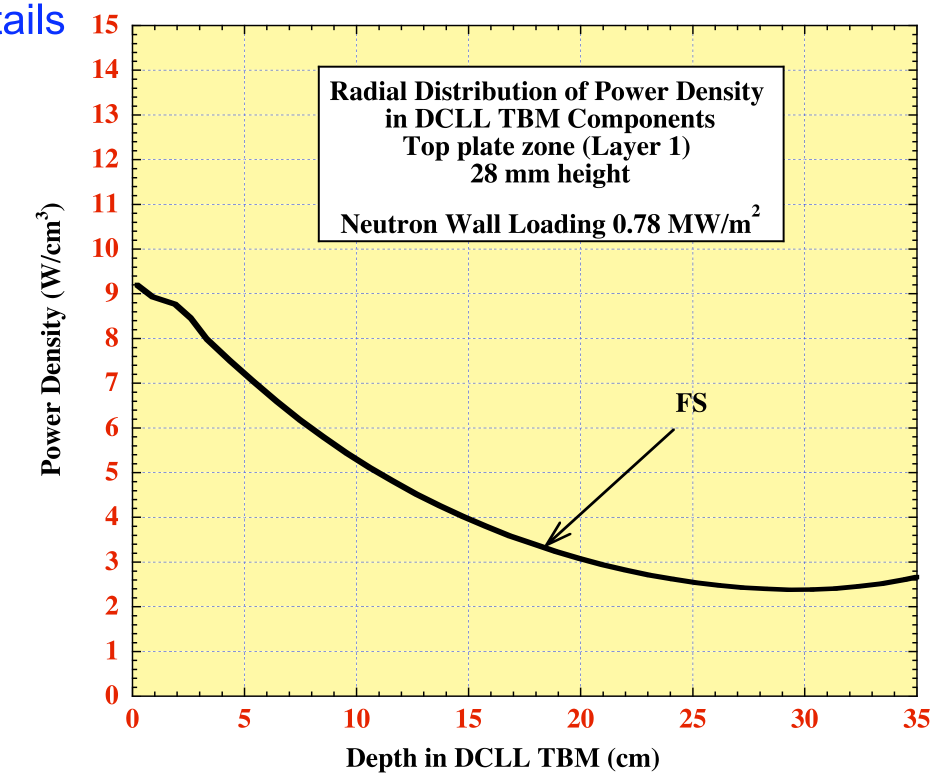


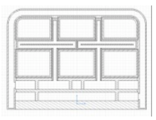
US DCLL TBM

Zone	Description	Thickness [mm]	% Be	% FS	% LL	% SiC	% He
1	PFC	2	100	0	0	0	0
2	Front wall of FW	4	0	100	0	0	0
3	FW cooling channel	20	0	17	0	0	83
4	Back wall of FW	4	0	100	0	0	0
5	Top/Bottom plate layer	322	0	42.8	0	0	57.2

View Showing Top Plate internal Details

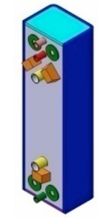






Layer 2 – PbLi Outlet Manifold (100mm) Material Composition

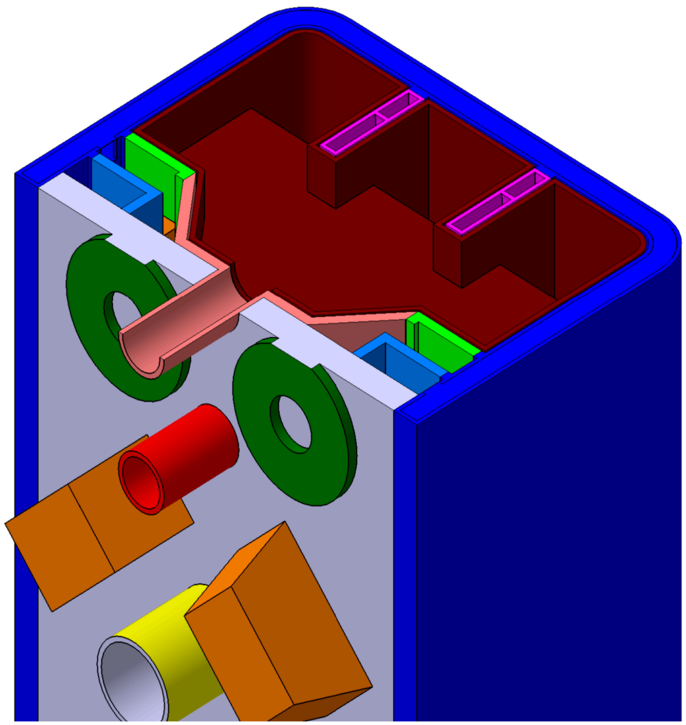
US DCLL TBM

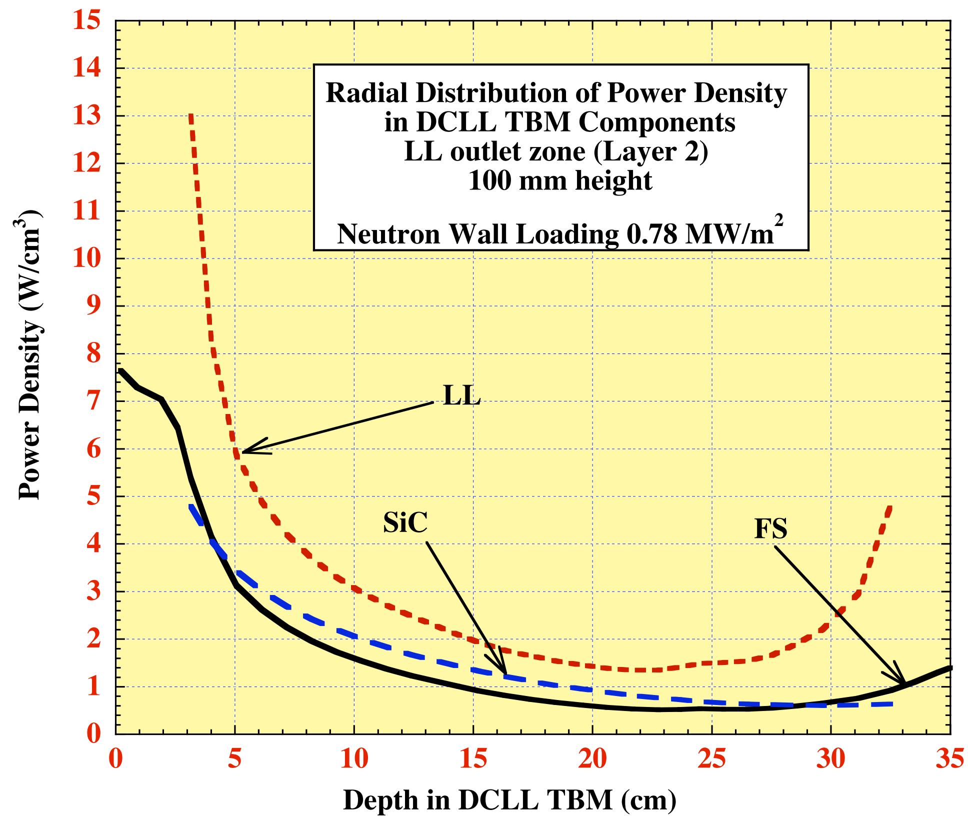


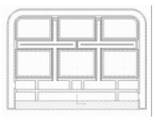
Zone	Description	Thickness [mm]	% Be	% FS	% LL	% SiC	% He
1	PFC	2	100	0	0	0	0
2	Front wall of FW	4	0	100	0	0	0
3	FW cooling channel	20	0	17	0	0	83
4	Back wall of FW	4	0	100	0	0	0
5	FCI layer 1	7	0	6.3	24.7	55.4	13.6
6	Breeding channel	105	0	6.3	73.9	6.2	13.6
7	FCI layer 2	7	0	2	74	14.4	9.6
8	Breeding channel	86	0	2	86.3	2.1	9.6
9	FCI layer 3	7	0	2	64.8	23.6	9.6
10	Inner He manifold	10	0	37.1	51.2	2.1	9.6
11	Inner He channel	30	0	10.2	41.3	2.1	46.4
12	Outer He manifold	10	0	39.1	37.2	2.1	21.6
13	Outer He channel	13	0	10.2	33.1	2.1	54.6
14	Outer He channel with LL component	17	0	10.2	11.4	21.6	56.8
15	Back plate	30	0	87.8	2.6	0	9.6

Layer 2 – PbLi Outlet Manifold, Power Density Distribution

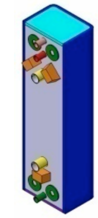
US DCLL TBM







Layer 3 – Horizontal Grid Plate (20mm) Material Distribution

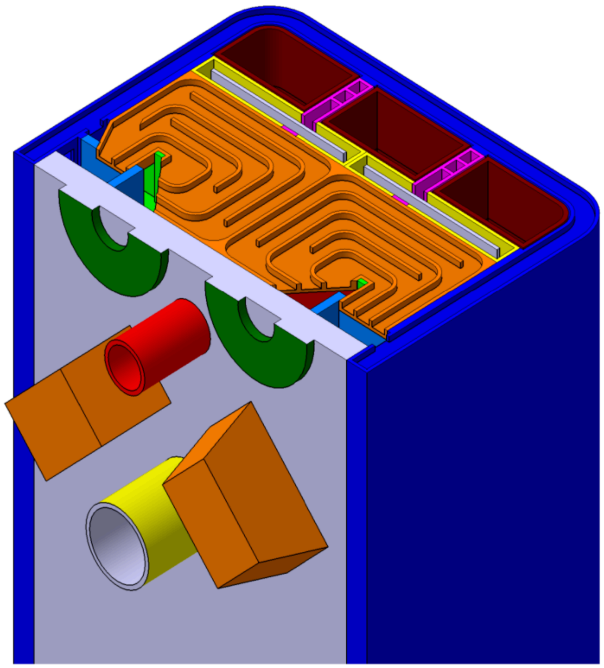


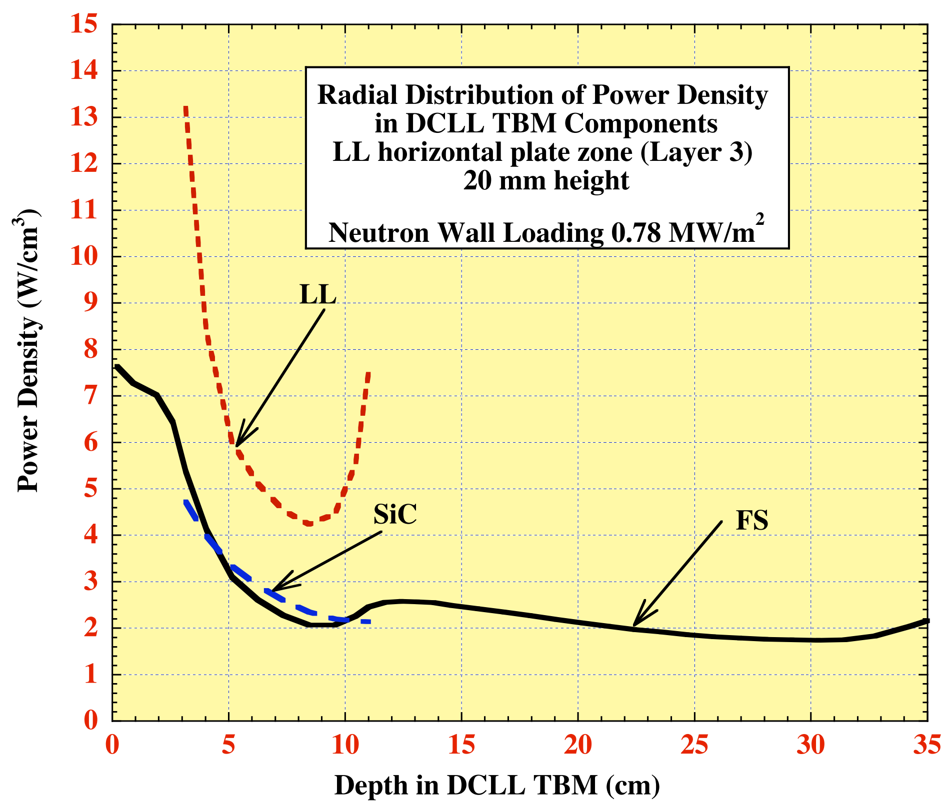
US DCLL TBM

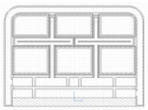
Zone	Description	Thickness [mm]	% Be	% FS	% LL	% SiC	% He
1	PFC	2	100	0	0	0	0
2	Front wall of FW	4	0	100	0	0	0
3	FW cooling channel	20	0	17	0	0	83
4	Back wall of FW	4	0	100	0	0	0
5	FCI layer 1	7	0	6.3	24.7	55.4	13.6
6	Front breeding channel	66	0	6.3	73.9	6.2	13.6
7	FCI layer 2	7	0	6.3	24.7	55.4	13.6
8	Front wall of divider	4	0	86.4	0	0	13.6
9	Divider gap 1	10	0	31	0	0	69
10	Plenum layer	4	0	82.1	0	0	17.9
11	Divider gap 2	10	0	31	0	0	69
12	Back wall of divider	4	0	90.4	0	0	9.6
13	LL Horizontal plate region	180	0	42.4	0	0	57.6
14	Back plate	30	0	90.4	0	0	9.6

Layer 3 – Horizontal Grid Plate, Power Density Distribution

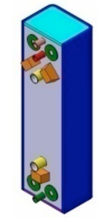
US DCLL TBM







Layer 4 – PbLi Inlet Manifold (120mm) Material Composition

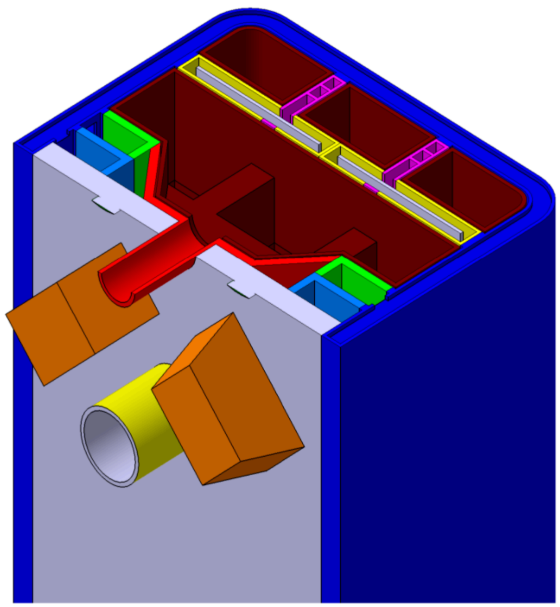


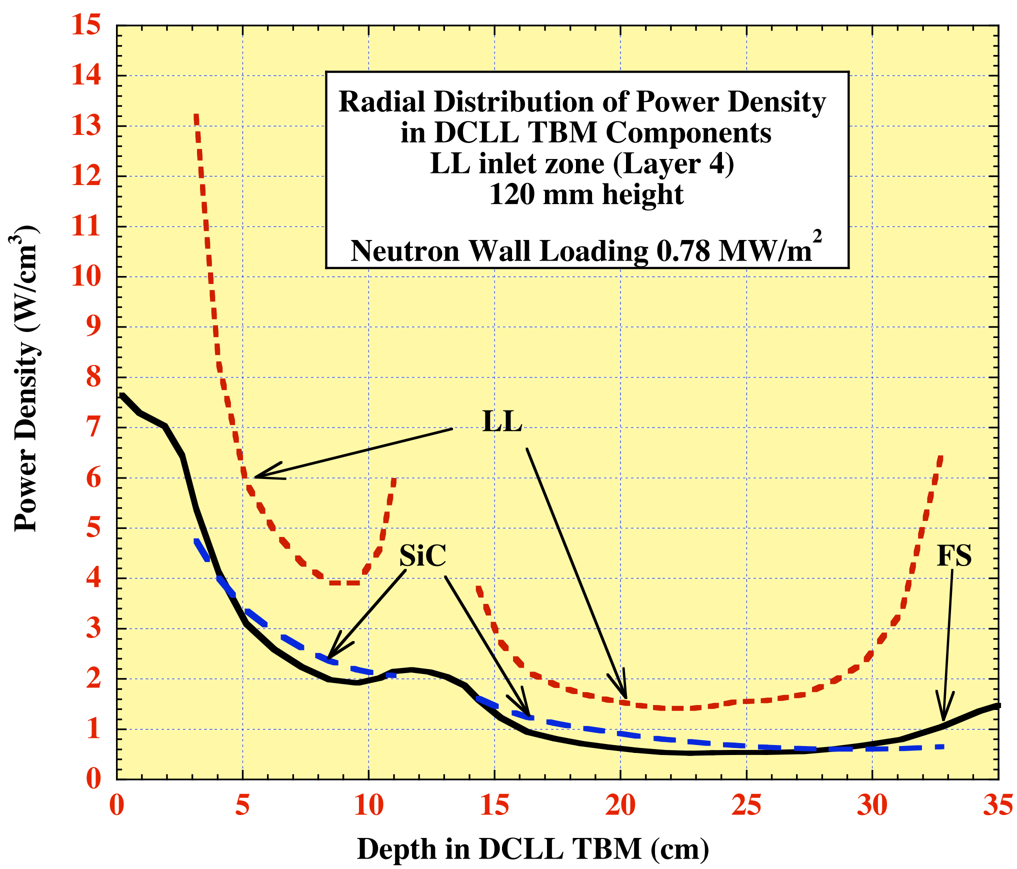
US DCLL TBM

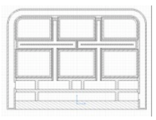
Zone	Description	Thickness [mm]	% Be	% FS	% LL	% SiC	% He
1	PFC	2	100	0	0	0	0
2	Front wall of FW	4	0	100	0	0	0
3	FW cooling channel	20	0	17	0	0	83
4	Back wall of FW	4	0	100	0	0	0
5	FCI layer 1	7	0	6.3	24.7	55.4	13.6
6	Front breeding channel	66	0	6.3	73.9	6.2	13.6
7	FCI layer 2	7	0	6.3	24.7	55.4	13.6
8	Front wall of divider	4	0	86.4	0	0	13.6
9	Divider gap 1	10	0	31	0	0	69
10	Plenum layer	4	0	82.1	0	0	17.9
11	Divider gap 2	10	0	31	0	0	69
12	Back wall of divider	4	0	90.4	0	0	9.6
13	FCI layer 3	7	0	2	25.8	62.6	9.6
14	Back breeding channel	86	0	2	86.3	2.1	9.6
15	FCI layer 4	7	0	2	64.8	23.6	9.6
16	Inner He manifold	10	0	37.1	51.2	2.1	9.6
17	Inner He channel	30	0	10.2	41.3	2.1	46.4
18	Outer He manifold	10	0	39.1	37.2	2.1	21.6
19	Outer He channel	13	0	10.2	33.1	2.1	54.6
20	Outer He channel with LL component	17	0	10.2	11.4	21.6	56.8
21	Back plate	30	0	87.8	2.6	0	9.6

Layer 4 – PbLi Inlet Manifold (120mm), Power Density Distribution

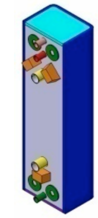
US DCLL TBM



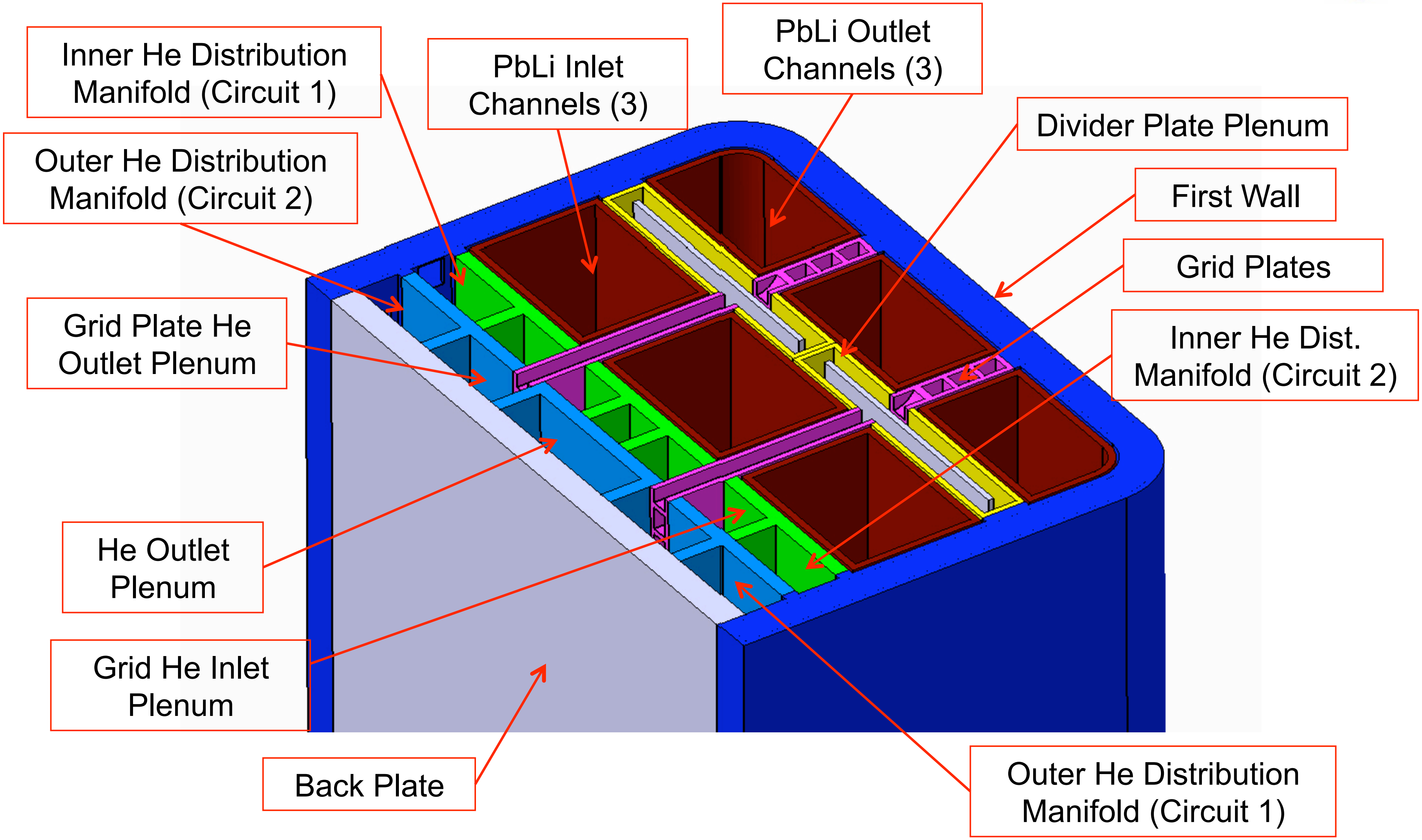


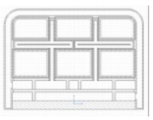


DCLL TBM Assembly Mid-Plane Section

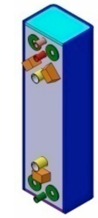


US DCLL TBM

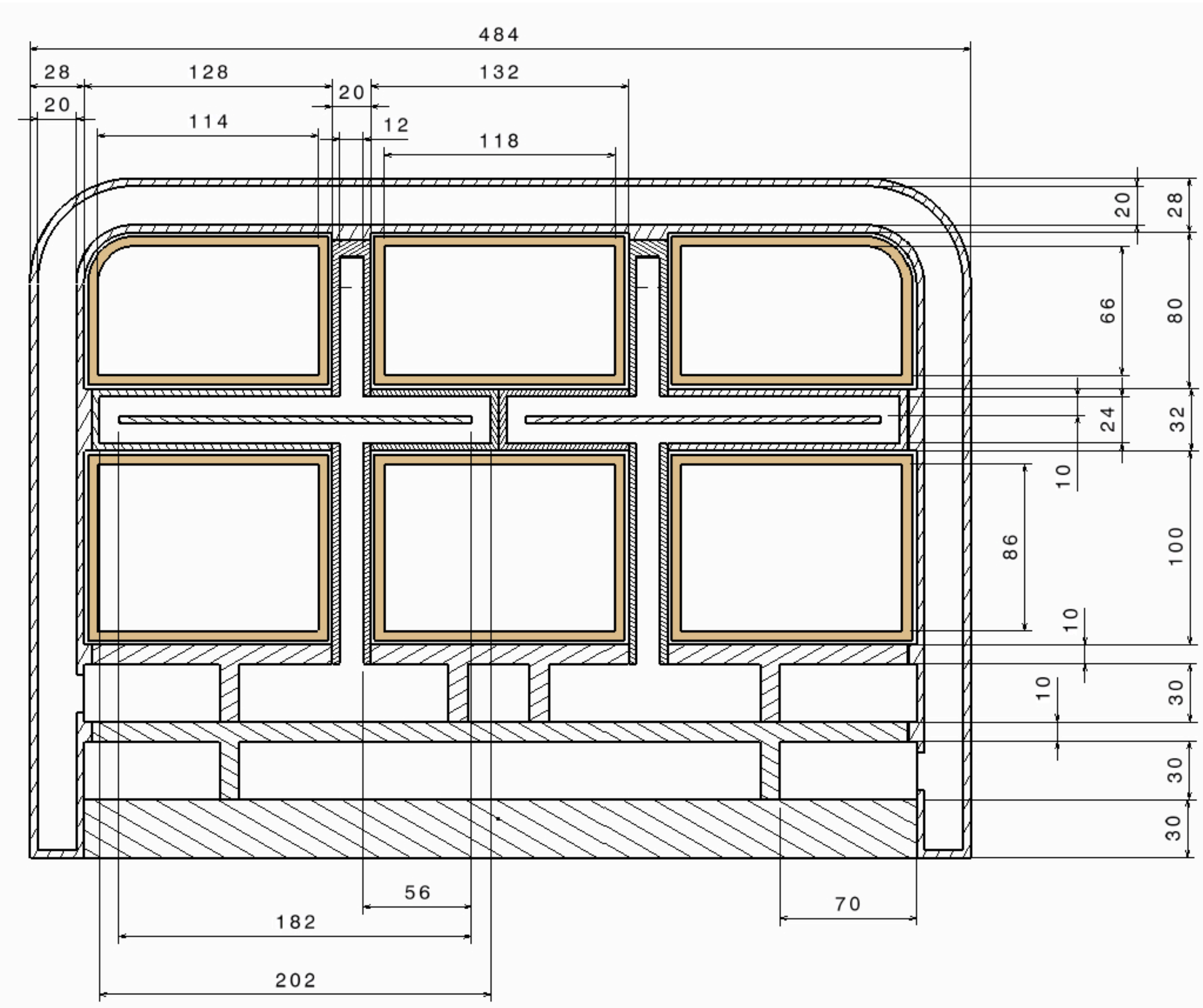


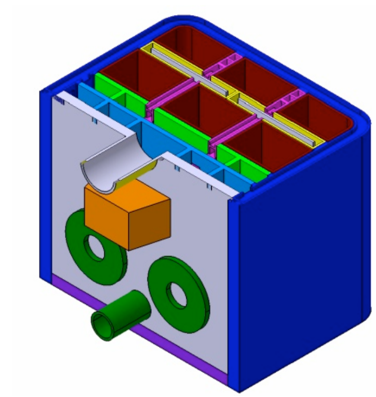


Mid-Plane Section View

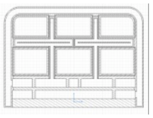


US DCLL TBM

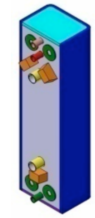




Represents 77% of TBM



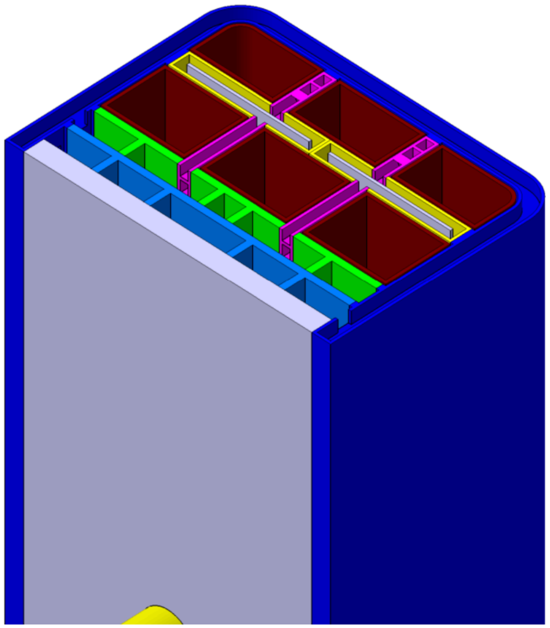
Layer 5 – Mid-Plane (1275mm) Material Composition

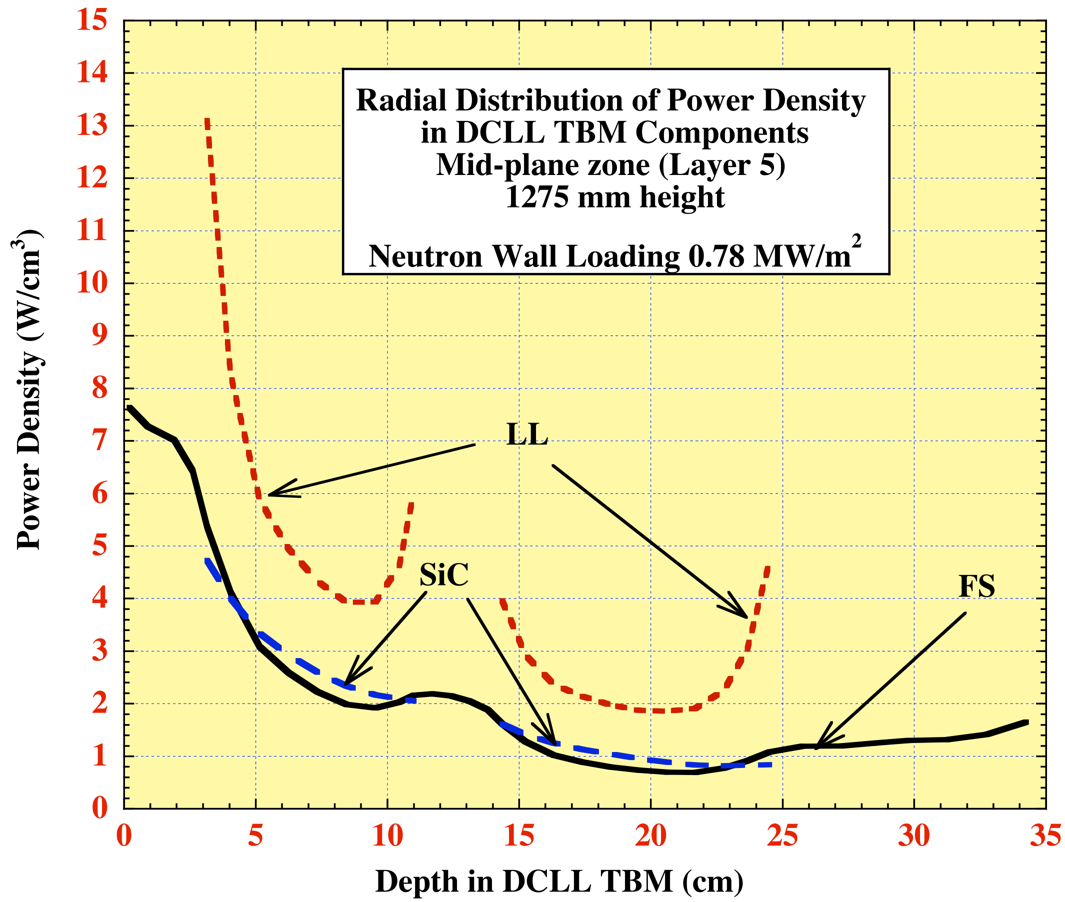


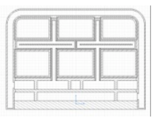
US DCLL TBM

Zone	Description	Thickness [mm]	% Be	% FS	% LL	% SiC	% He
1	PFC	2	100	0	0	0	0
2	Front wall of FW	4	0	100	0	0	0
3	FW cooling channel	20	0	17	0	0	83
4	Back wall of FW	4	0	100	0	0	0
5	FCI layer 1	7	0	6.3	24.7	55.4	13.6
6	Front breeding channel	66	0	6.3	73.9	6.2	13.6
7	FCI layer 2	7	0	6.3	24.7	55.4	13.6
8	Front wall of divider	4	0	86.4	0	0	13.6
9	Divider gap 1	10	0	31	0	0	69
10	Plenum layer	4	0	82.1	0	0	17.9
11	Divider gap 2	10	0	31	0	0	69
12	Back wall of divider	4	0	86.4	0	0	13.6
13	FCI layer 3	7	0	6.3	24.7	55.4	13.6
14	Back breeding channel	86	0	6.3	73.9	6.2	13.6
15	FCI layer 4	7	0	6.3	24.7	55.4	13.6
16	Inner He manifold	10	0	86.4	0	0	13.6
17	Inner He channel	30	0	12.6	0	0	87.4
18	Outer He manifold	10	0	88.4	0	0	11.6
19	Outer He channel	30	0	10.2	0	0	89.8
20	Back plate	30	0	90.4	0	0	9.6

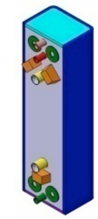
Layer 5 – Mid-Plane (1275mm), Power Density Distribution







Layer 6 – Bottom Zone (93mm) Material Composition

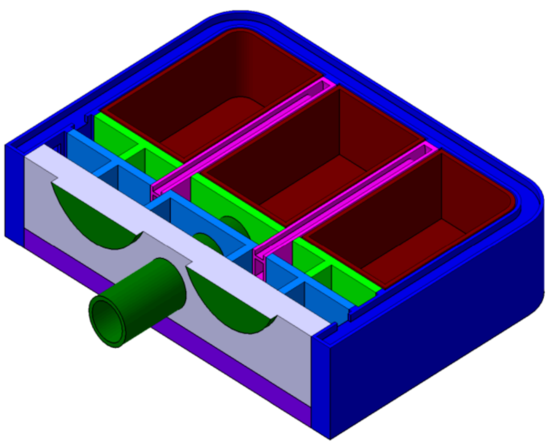


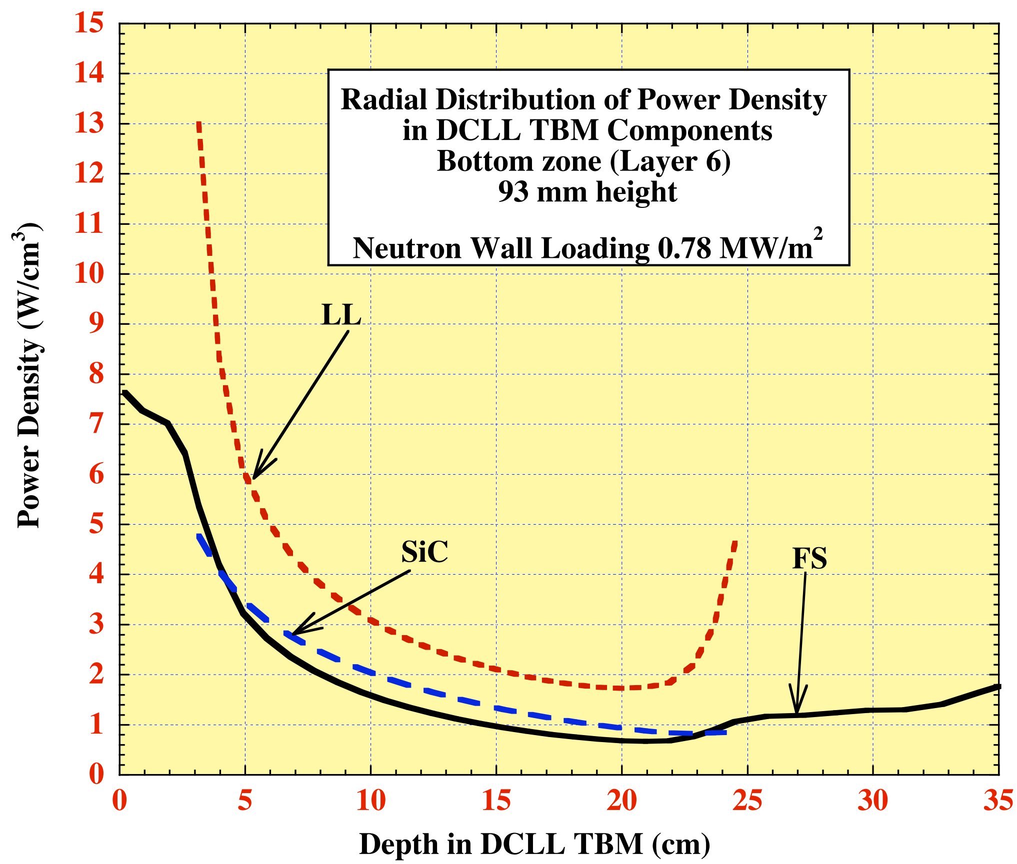
US DCLL TBM

Zone	Description	Thickness [mm]	% Be	% FS	% LL	% SiC	% He
1	PFC	2	100	0	0	0	0
2	Front wall of FW	4	0	100	0	0	0
3	FW cooling channel	20	0	17	0	0	83
4	Back wall of FW	4	0	100	0	0	0
5	FCI layer 1	7	0	6.3	24.7	55.4	13.6
6	Breeding channel	198	0	6.3	73.9	6.2	13.6
7	FCI layer 2	7	0	6.3	24.7	55.4	13.6
8	Inner He manifold	10	0	86.4	0	0	13.6
9	Inner He channel	30	0	12.6	0	0	87.4
10	Outer He manifold	10	0	88.4	0	0	11.6
11	Outer He channel	30	0	10.2	0	0	89.8
12	Back plate	30	0	90.4	0	0	9.6

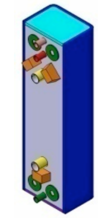
Layer 6 – Bottom Zone (93mm), Power Density Distribution

US DCLL TBM



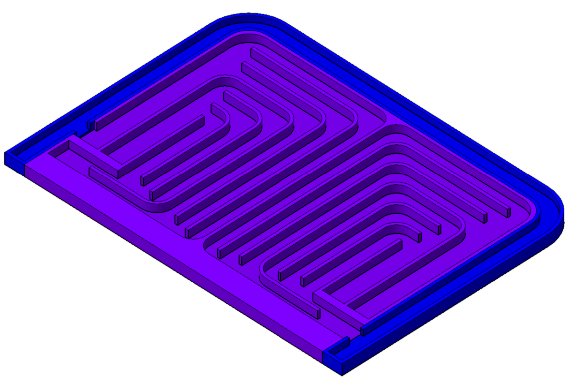


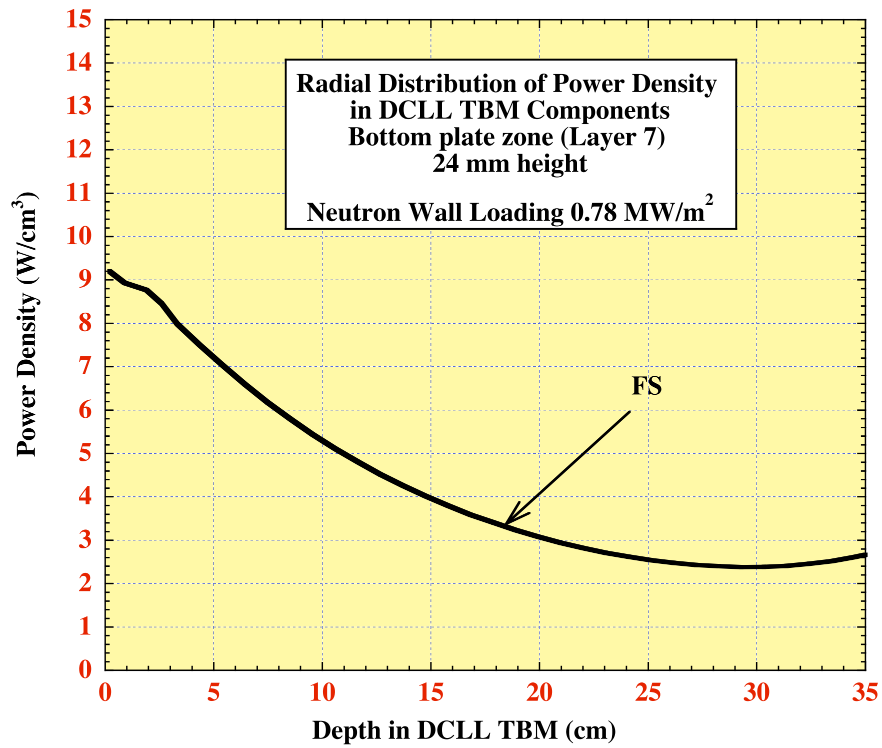
Layer 7 – Bottom Plate (24mm)



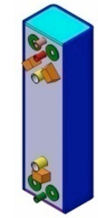
US DCLL TBM

Zone	Description	Thickness [mm]	% Be	% FS	% LL	% SiC	% He
1	PFC	2	100	0	0	0	0
2	Front wall of FW	4	0	100	0	0	0
3	FW cooling channel	20	0	17	0	0	83
4	Back wall of FW	4	0	100	0	0	0
5	Top/Bottom plate layer	322	0	42.8	0	0	57.2





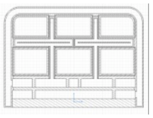
Total Nuclear Heating in TBM



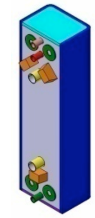
US DCLL TBM

- Power density in Be PFC
  8.14 W/cm^3 in layer 2
- Peak power density in FS structure
  9.20 W/cm^3 in layers 1,7
- Peak power density in PbLi
  13.20 W/cm^3 in layer 3
- Peak power density in SiC FCI
  4.79 W/cm^3 in layer 2

Vertical Layer	Height (mm)	Nuclear Energy Mult. (M_n)	Nuclear Heating (MW)
1	28	0.857	0.009
2	100	0.935	0.035
3	20	0.904	0.007
4	120	0.939	0.042
5	1275	0.920	0.441
6	93	0.917	0.032
7	24	0.857	0.008
Total	**1660**	**0.920**	**0.574**



Tritium Production in TBM

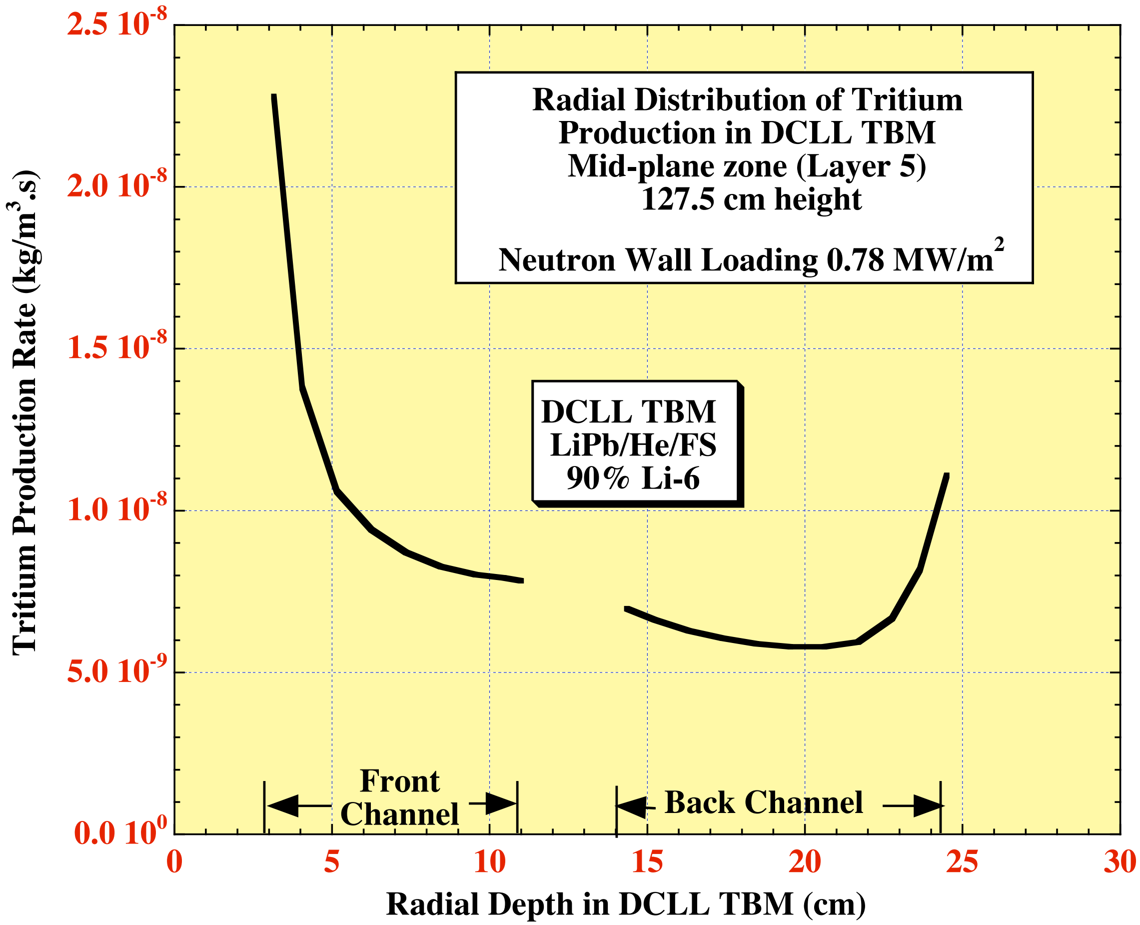


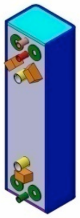
US DCLL TBM

- Local TBR in the 35 cm thick DCLL TBM is only 0.561
- Tritium generation rate in the TBM is 1.55×10^{17} atom/s (7.73×10^{-7} g/s) during a D-T pulse with 500 MW fusion power
- 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 3.25×10^{-4} g/pulse
- For the planned 3000 pulses per year the annual tritium production in the TBM is 0.97 g/year
- Tritium production in the Be PFC is 1.54×10^{-9} g/s $\Rightarrow$ 6.47×10^{-7} g/pulse $\Rightarrow$ 1.94×10^{-3} g/year

Vertical Layer	Height (mm)	Local TBR	Tritium Prod. (g/s)
1	28	0	0
2	100	0.733	$6,08 \times 10^{-8}$
3	20	0.338	5.61×10^{-9}
4	120	0.662	6.59×10^{-8}
5	1275	0.560	5.92×10^{-7}
6	93	0.625	4.82×10^{-8}
7	24	0	0
Total	**1660**	**0.561**	**7.73×10^{-7}**

Tritium Production Distribution in TBM

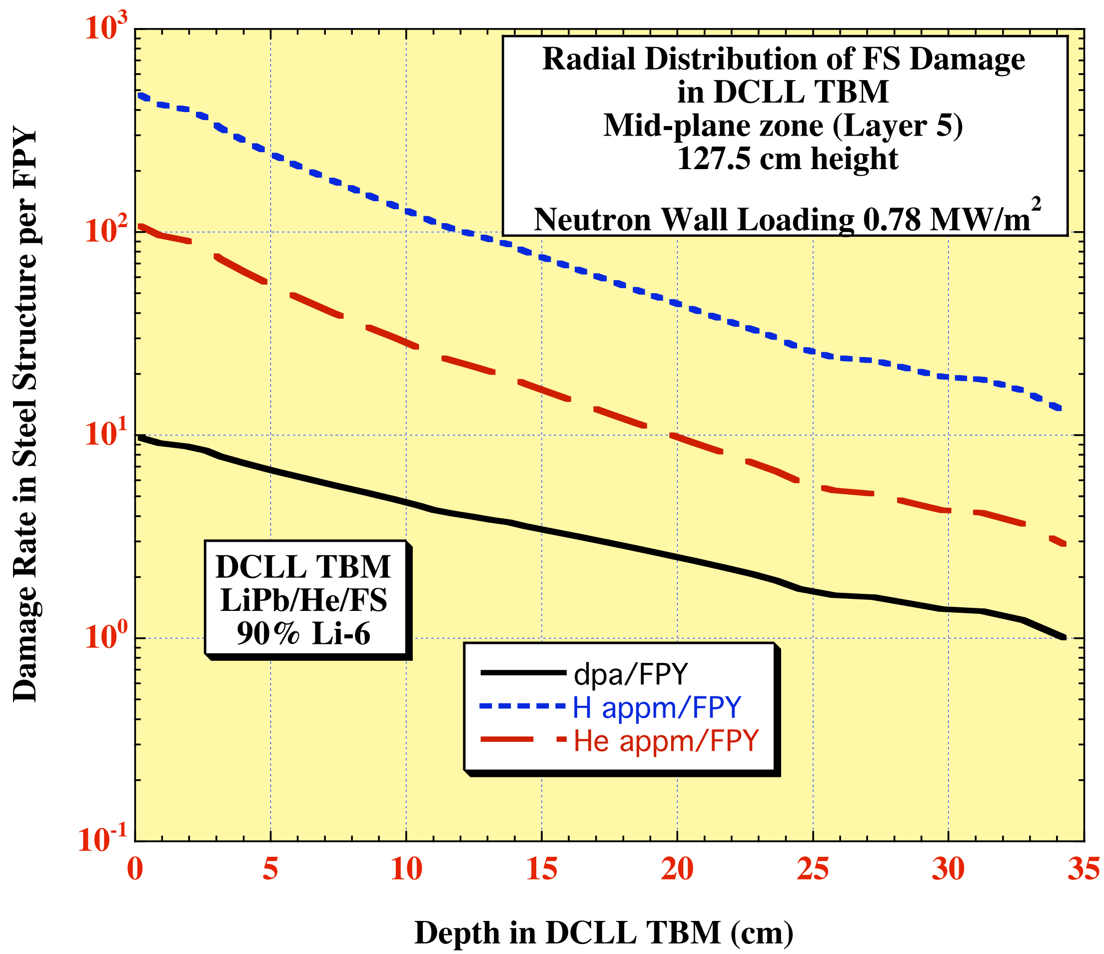




- Peak tritium production rate in PbLi is 2.3×10^{-8} kg/m^{3}s/year during the 500 MW D-T pulse

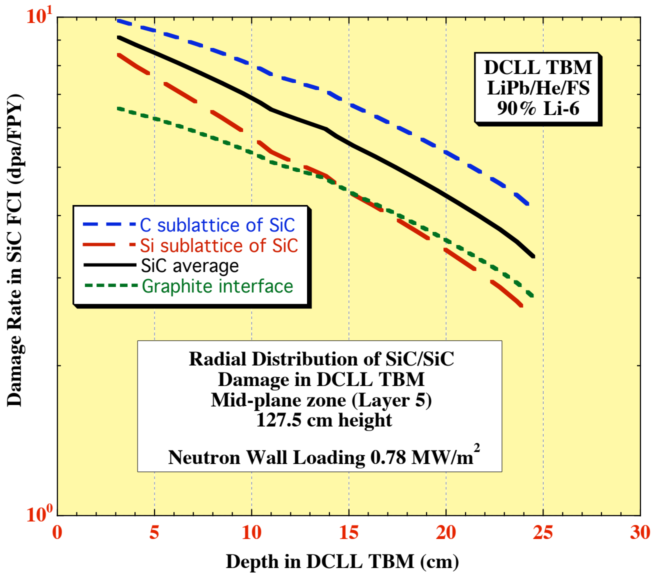
Radiation Damage in Steel Structure

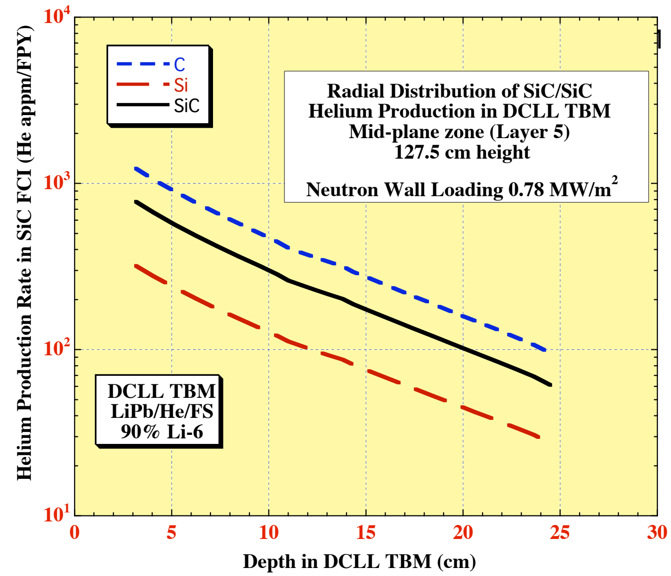
US DCLL TBM

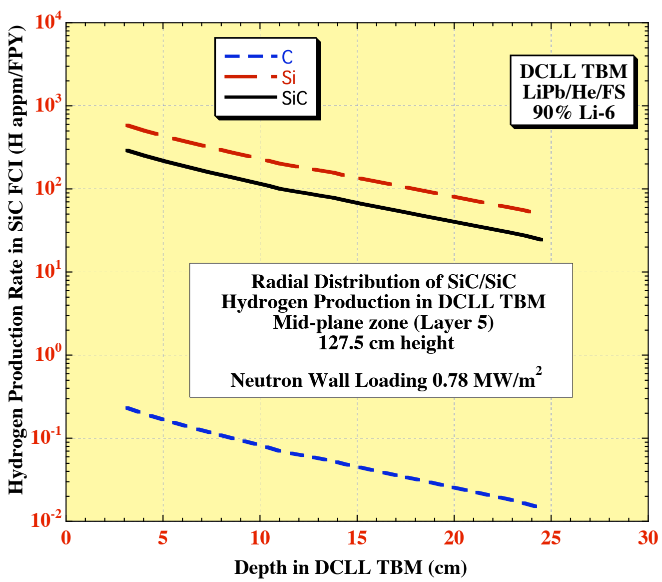


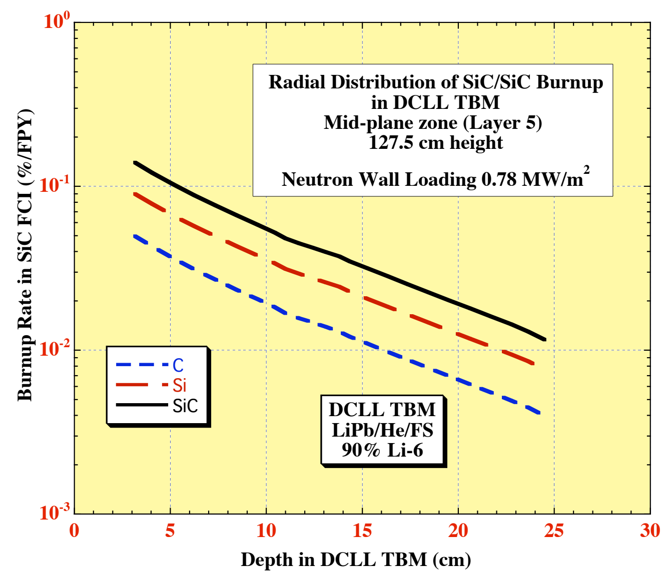
- Peak FS damage rates:
  9.73 dpa/FPY
  107 He appm/FPY
  472 H appm/FPY
- For 0.57 MW/m^2 average NWL and total fluence 0.3 MWa/m^2 total lifetime is 0.526 FPY
- Peak cumulative end-of-life dpa in FW is **5.1 dpa** and He production is **56.3 He appm**

Radiation Damage in SiC_f/SiC FCI

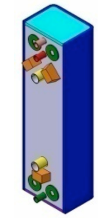






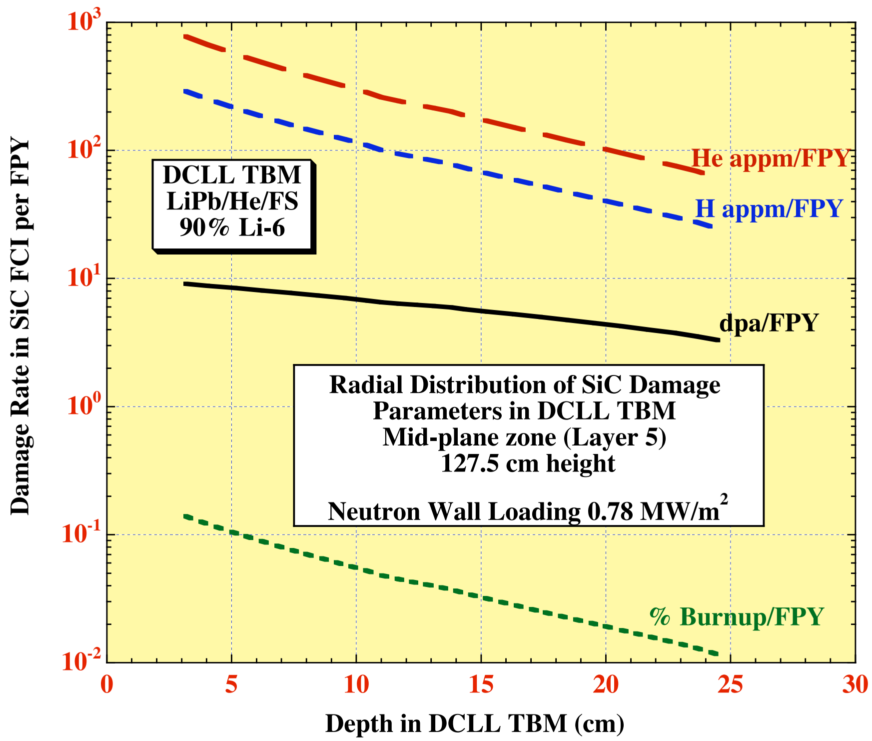


Peak Radiation Damage in SiC_f/SiC FCI



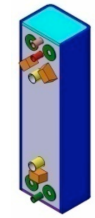
US DCLL TBM

	C Sublattice	Si Sublattice	SiC	Graphite Interface
dpa/FPY	9.86	8.41	9.14	6.57
He appm/FPY	1,235	320	777	1,235
H appm/FPY	0.2	583	291	0.2
% Burnup/FPY	0.05	0.09	0.14	0.05



- Peak SiC damage rates:
  9.14 dpa/FPY
  777 He appm/FPY
  291 H appm/FPY
  0.14% burnup/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 FCI is **4.8 dpa**, He production is **409 He appm,** H production is **153 H appm** burnup is **0.073%**

Observations on Radiation Damage in SiC$_f$/SiC FCI

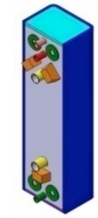


US DCLL TBM

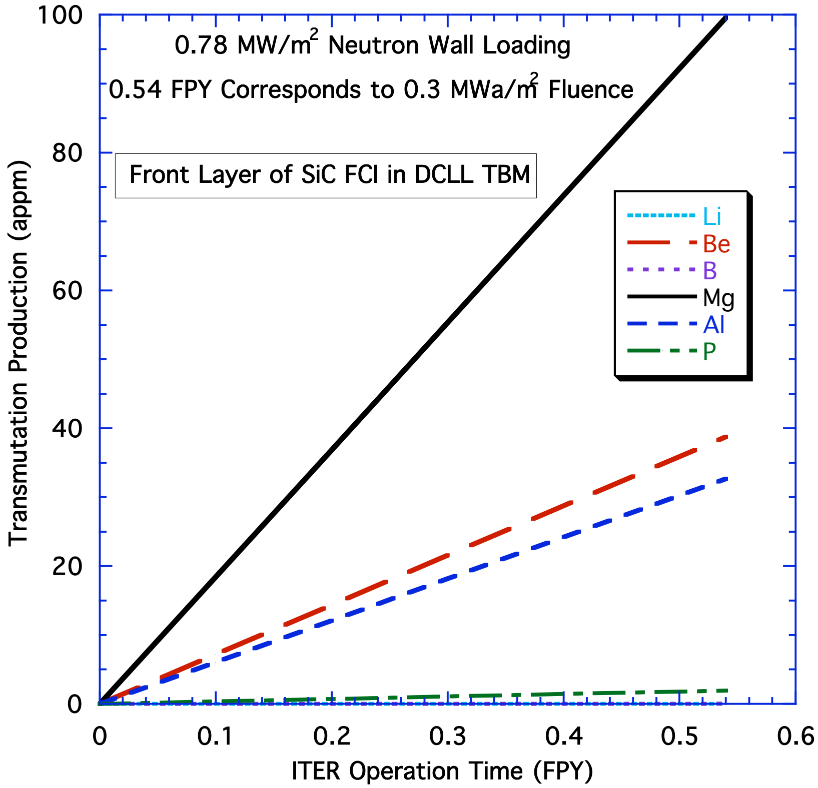
- Higher atomic displacement damage rates occur in C sublattice
- He production in C is about a factor of 4 larger than in Si due to the (n,n´3α) reaction
- Significant H production occurs in Si with negligible amount in C
- Burnup of Si is about twice that of C
- He production rate in graphite interface is ~60% higher than in SiC
- The issue of lifetime was addressed in a recent paper:

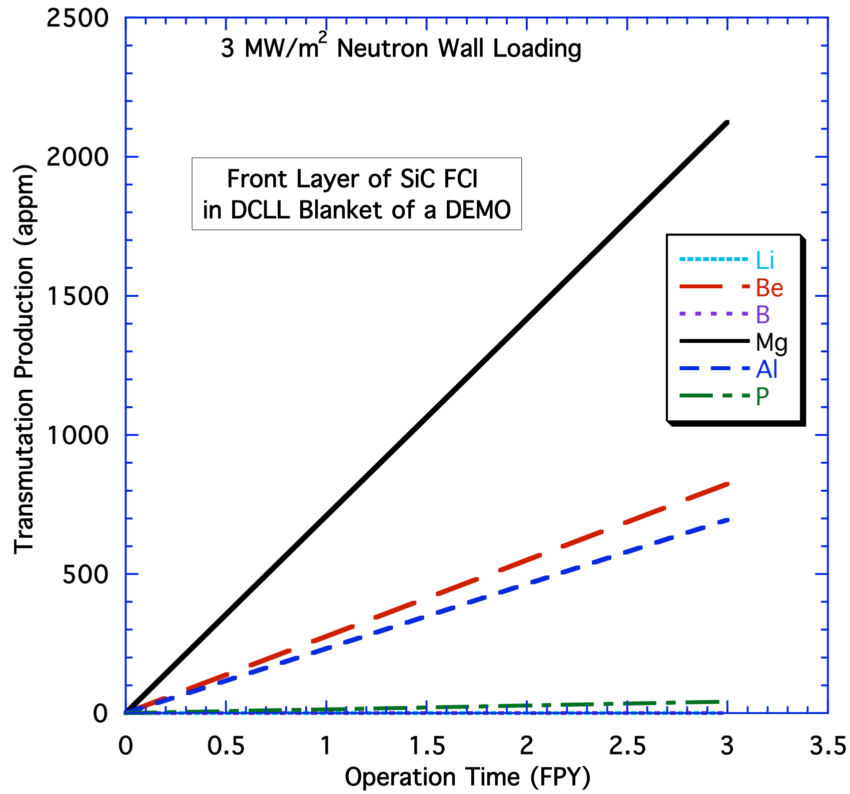
  M. Sawan, L. Snead, and S. Zinkle, “Radiation onentDamage Parameters for SiC/SiC Composite Structure in Fusion Nuclear Environment,” Fusion Science & Technology, vol. 44, pp 150 – 154 (2003).
- The FCI is not a structural comp and main concern is change in resistivity resulting from transmutations
- Transmutation of Si produce Mg and Al with smaller amount of P. The main transmutation product for C is Be with smaller amount of B and Li. This might not be a concern for the ITER low fluence but is important for a DEMO or power plant

Transmutation Products in SiC_f/SiC FCI



US DCLL TBM



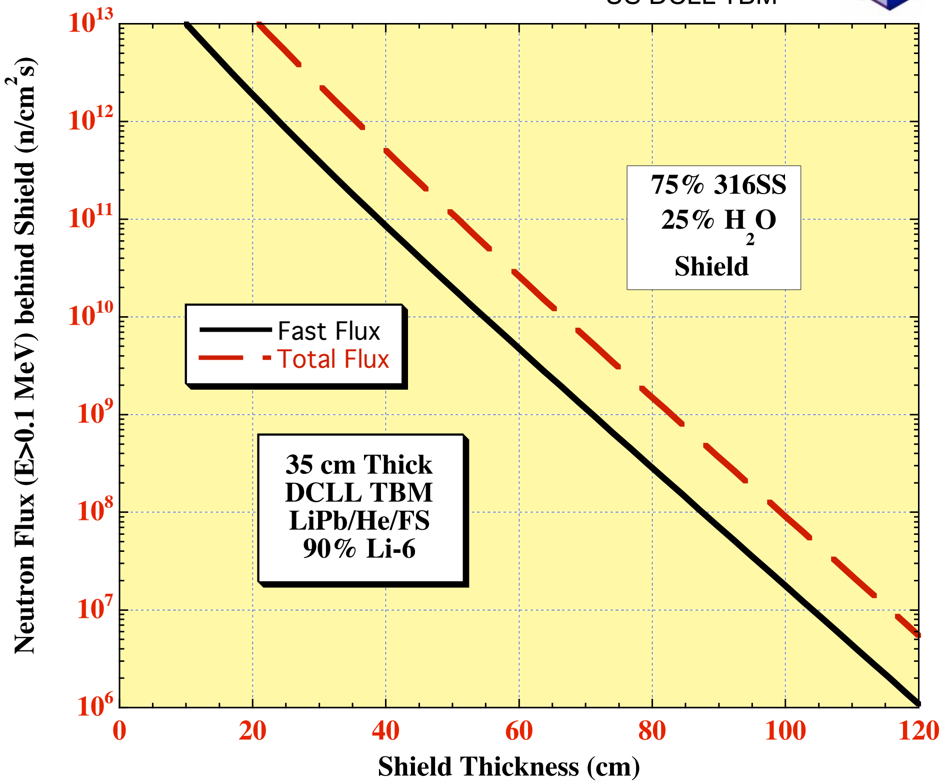


- Dominant metallic transmutation product is Mg
- When DCLL blanket is used in a power reactor with 6 MW/m^2 NWL, Mg concentration in SiC FCI at end-of-life of blanket (3 FPY) is 0.43 at%
- Impact on conductivity should be addressed

Shielding Required Behind TBM

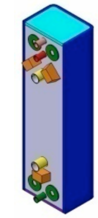
- Criterion for maintenance access used in ITER is dose rate <100 μSv/h at 10^6 s after shutdown
- Rules of thumb used to relate dose after shutdown from decay gamma of activated material to fast neutron flux
- Formulas used in the ITER Nuclear Analysis Report, G 73 DDD 2 W 0.2, July 2004, relate the dose rate @10^6 s after shutdown to the fast neutron flux during operation
- DR(μSv/h) ~ 1-3x10^{-5} FF(n/cm^{2}s)
- To be conservative we use the factor of 3x10^{-5} and assume the fast flux component with E>0.1 MeV
- To satisfy the ITER guidelines for maintenance accessibility the fast neutron flux during operation should be <3x10^6 n/cm^{2}s (E>0.1 MeV)

US DCLL TBM



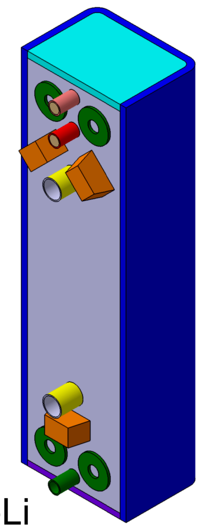
~1.2 m thick shield is required behind DCLL TBM

3-D Neutronics Analysis for DCLL TBM

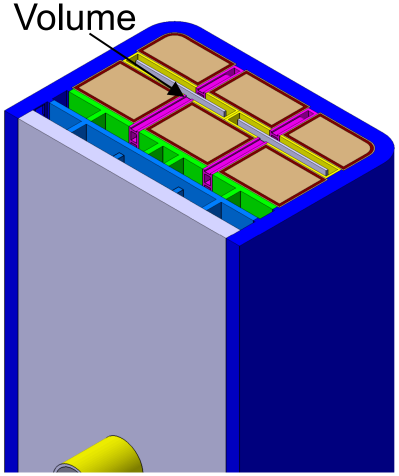


US DCLL TBM

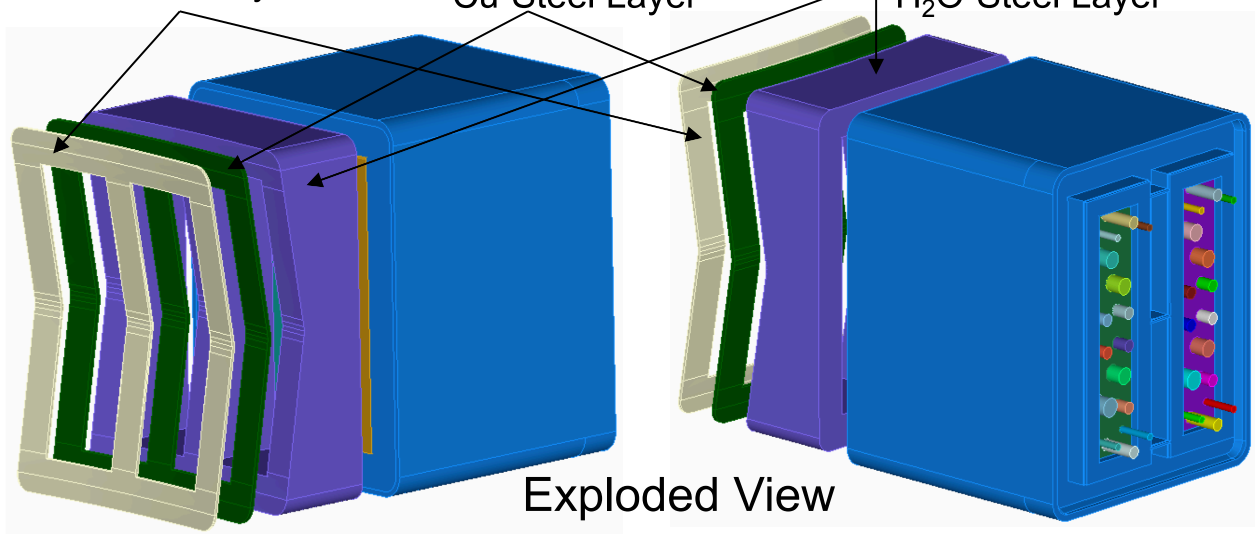
- Calculations started using DAG-MCNP
- Detailed CAD model for DCLL TBM is utilized
- Helium in the current model is represented by void
- A full PbLi volume has been created for analysis
- A simplified CAD model with homogenized zones was generated for the frame (FW and shield regions)
- TBM and Frame CAD models will be combined and the integrated model will be used in the calculations



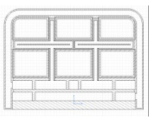
PbLi Volume



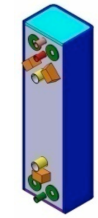
DCLL TBM



Exploded View
Simplified Frame Model



A Surface Source Is Used in The Calculations

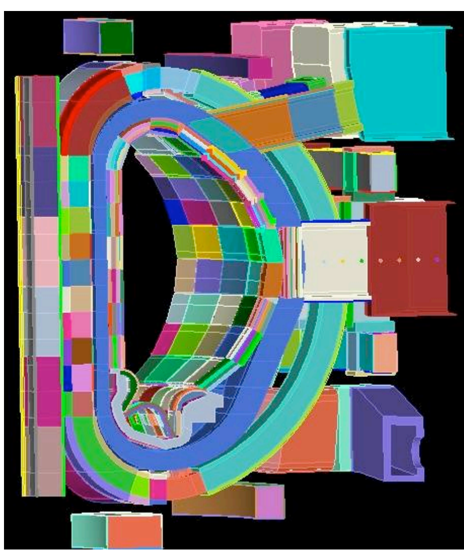


US DCLL TBM

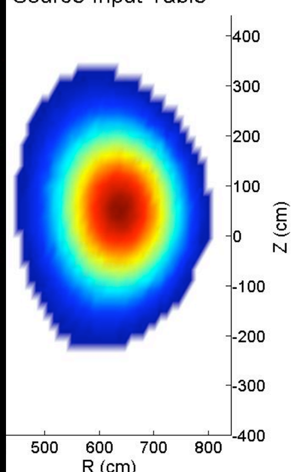
- An extra surface was inserted in front of equatorial port in the 40° sector model of ITER geometry
- All particles crossing this surface were recorded (location, angle, energy, weight)
- Surface crossings will be read as a surface source in front of integrated CAD model of frame and TBM
- ***This properly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

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 included

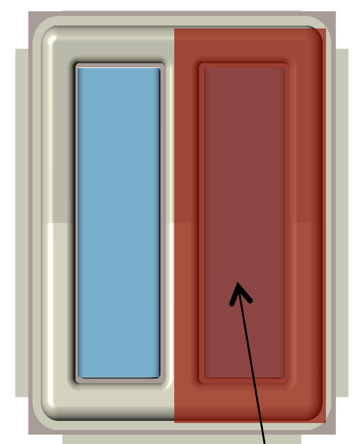
	TBM only	TBM+Frame	TBM+Frame+FWS
Front fast flux	1	0.919	0.895
Back fast flux	1	0.730	0.717
Front FS heating	1	0.976	0.981
Back FS heating	1	0.723	0.706
Front FS dpa	1	0.973	0.964
Back FS dpa	1	0.788	0.779
Front PbLi heating	1	0.983	1.000
Back PbLi heating	1	0.765	0.747
Front PbLi tritium production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



Source Input Table

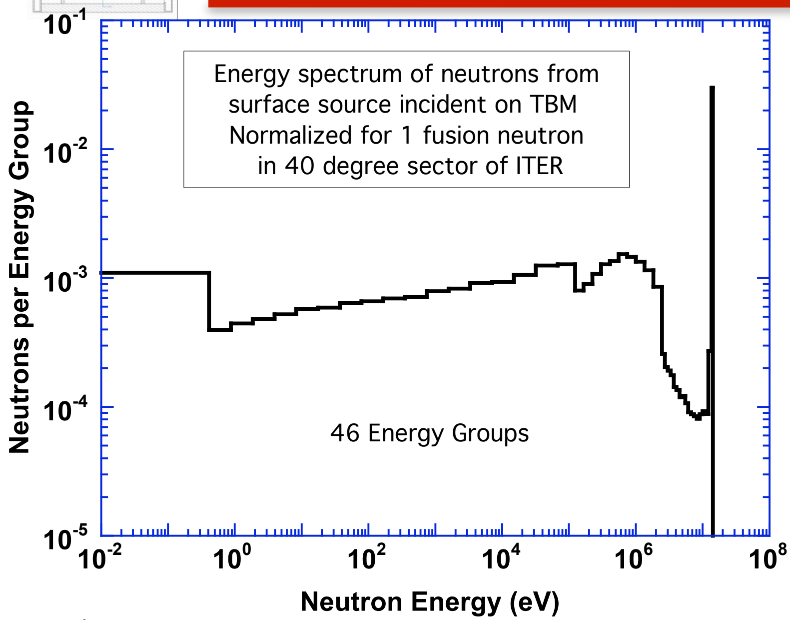


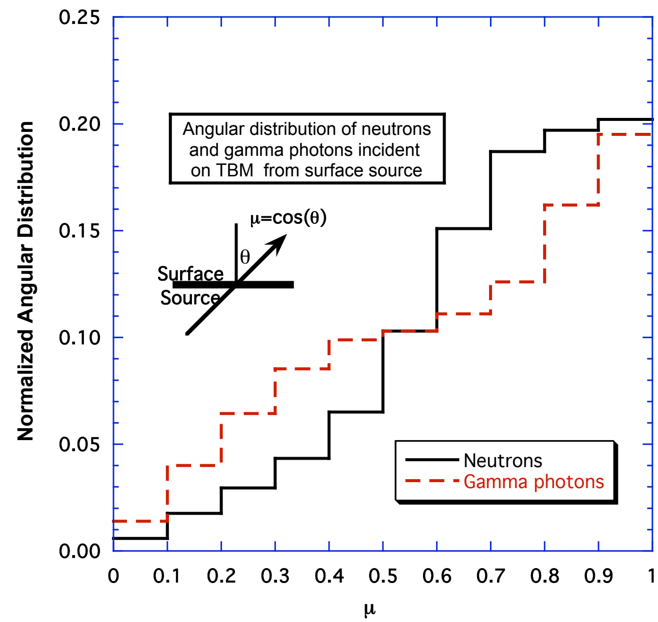
Only half of the frame with a TBM is used in the calculations surrounded on the sides with reflecting boundaries



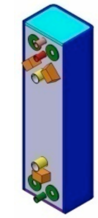
Surface source

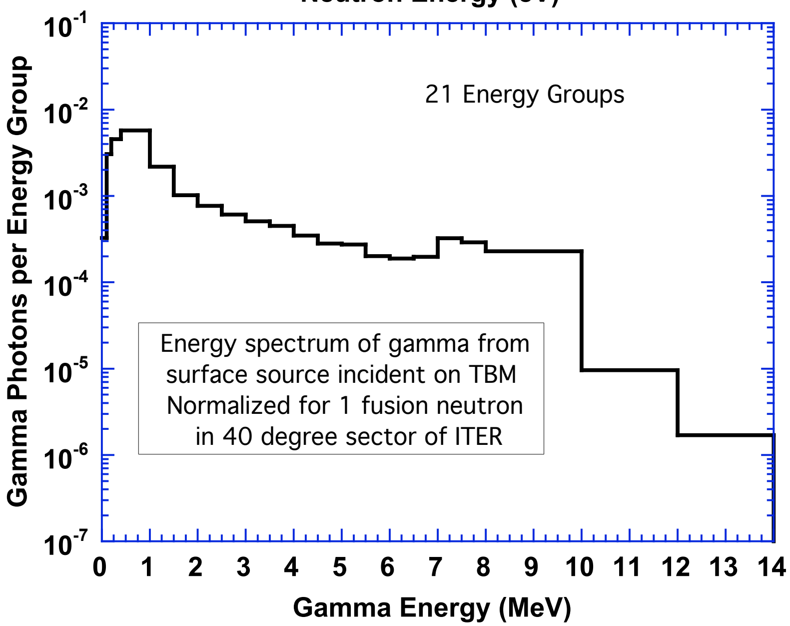
Features of Neutron and Gamma Surface Source Incident on TBM





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