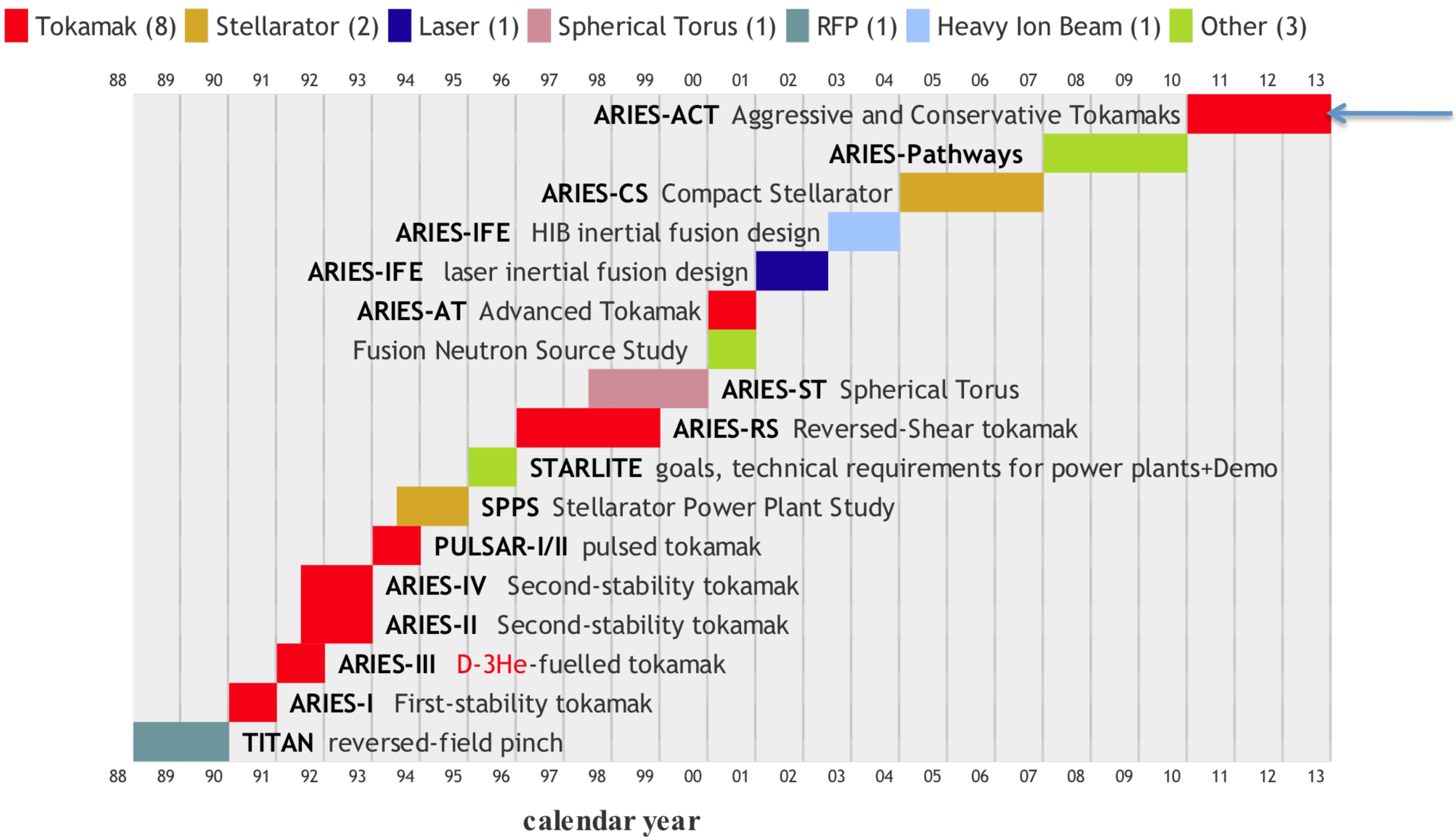
New Advances in Computing TBR and Application to ARIES Power Plants

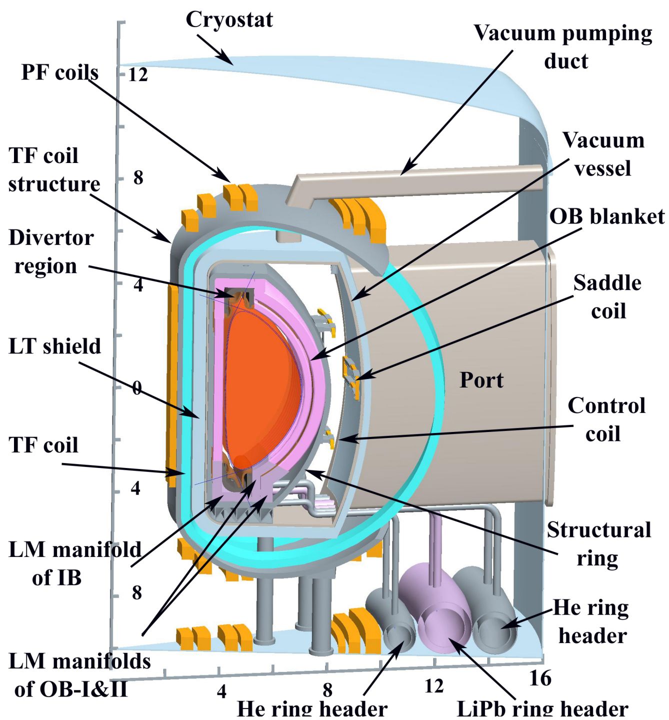
L. El-Guebaly
Fusion Technology Institute
University of Wisconsin-Madison
http://fti.neep.wisc.edu/UWNeutronicsCenterOfExcellence

VLT Conference Call
September 19, 2012

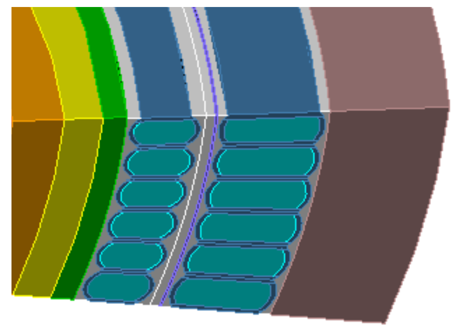
ARIES Designs (1988 – 2012)



ARIES-ACT Design

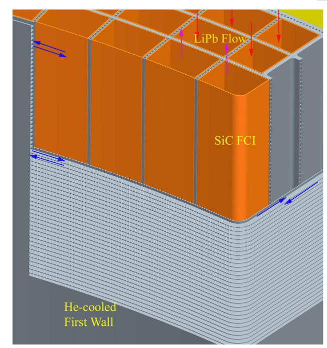


Two Blanket Designs



SiC/LiPb

$\eta_{th} \sim 60\%$



DCLL

$\eta_{th} \sim 45\%$

R= 5.5 m; a= 1.375 m; A= 4; P_f~1800 MW; 16 TF magnets; 16 Toroidal modules; SiC/LiPb blanket.
No blanket behind divertor (only LiPb manifolds for inboard blanket).

ARIES breeding requirements* : calculated TBR = 1.05 with ^{6}Li enrichment < 90%.

- L. El-Guebaly, A. Jaber and S. Malang, "State-of-the-Art 3-D Assessment of Elements Degrading the TBR of the ARIES DCLL Blanket," Fusion Science and Technology 61, #4 (May 2012) 321-331.

We Addressed Several Breeding-Related Questions that Puzzled Fusion Community for Decades

Breeding-related questions:

- How does blanket structure (first wall, side, and back walls, cooling channels, etc.) degrade TBR?
- Which change to blanket thickness and/or Li enrichment is more enhancing to TBR?
- How does advanced physics (that requires embedding stabilizing shells within blanket) degrade breeding?
- Could required TBR be achieved in presence of several design elements (such as plasma heating and current drive ports) that compete for best available space for breeding?
- Does blanket offer flexible approach to handle any shortage and surplus of T?

- Past studies answered some questions by addressing individual issues – one at a time.

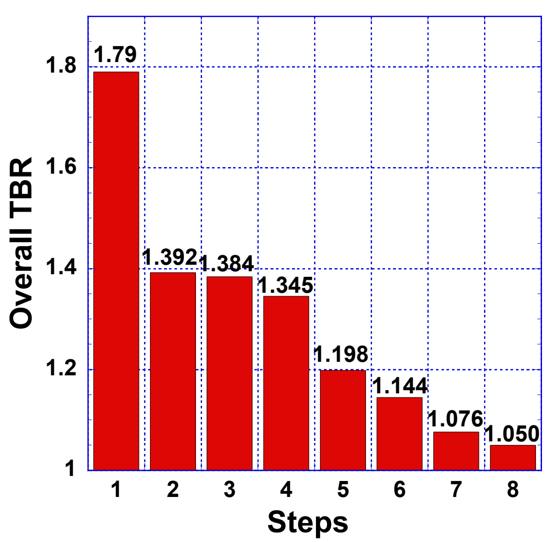
- Our state-of-the-art 3-D analysis examined all questions collectively in integral fashion to account for inter-dependence and synergistic effects.

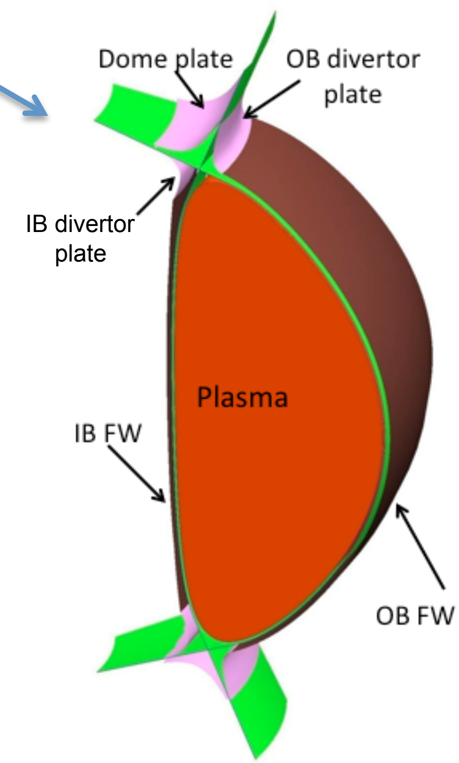
Questions Addressed with Sophisticated 3-D Neutronics Codes

- UW Computational Nuclear Engineering Research Group (CNERG) developed most innovative computational tool in recent years.
- DAGMC code permits fully accurate modeling of complex devices by integrating CAD geometry directly with 3-D MCNP code.
- To point out terms that contribute to decrease/increase in TBR, we also developed a novel stepwise approach that allows adding various blanket components "step-by-step."
- This unique capability allows fully accurate presentation of blanket geometry with high fidelity in 3-D TBR results. Note that 1% less TBR means T shortage of ~1 kg/y, costing $30-100M to purchase annually from external sources.

Stepwise Approach

- Build CAD model from scratch, starting with FW/divertor skeleton
- Couple CAD with MCNP using DAGMC code
- No homogenization within breeding zones
- Model each individual component using CAD, import CAD model into neutronics code, then add in multiple steps:
  - FW and other walls for blanket
  - Other design elements (shield, assembly gaps, stabilizing shells, penetrations, etc.)
- Record impact of **7** individual design elements on TBR
- Vary Li enrichment from natural to 90% to determine operating enrichment.





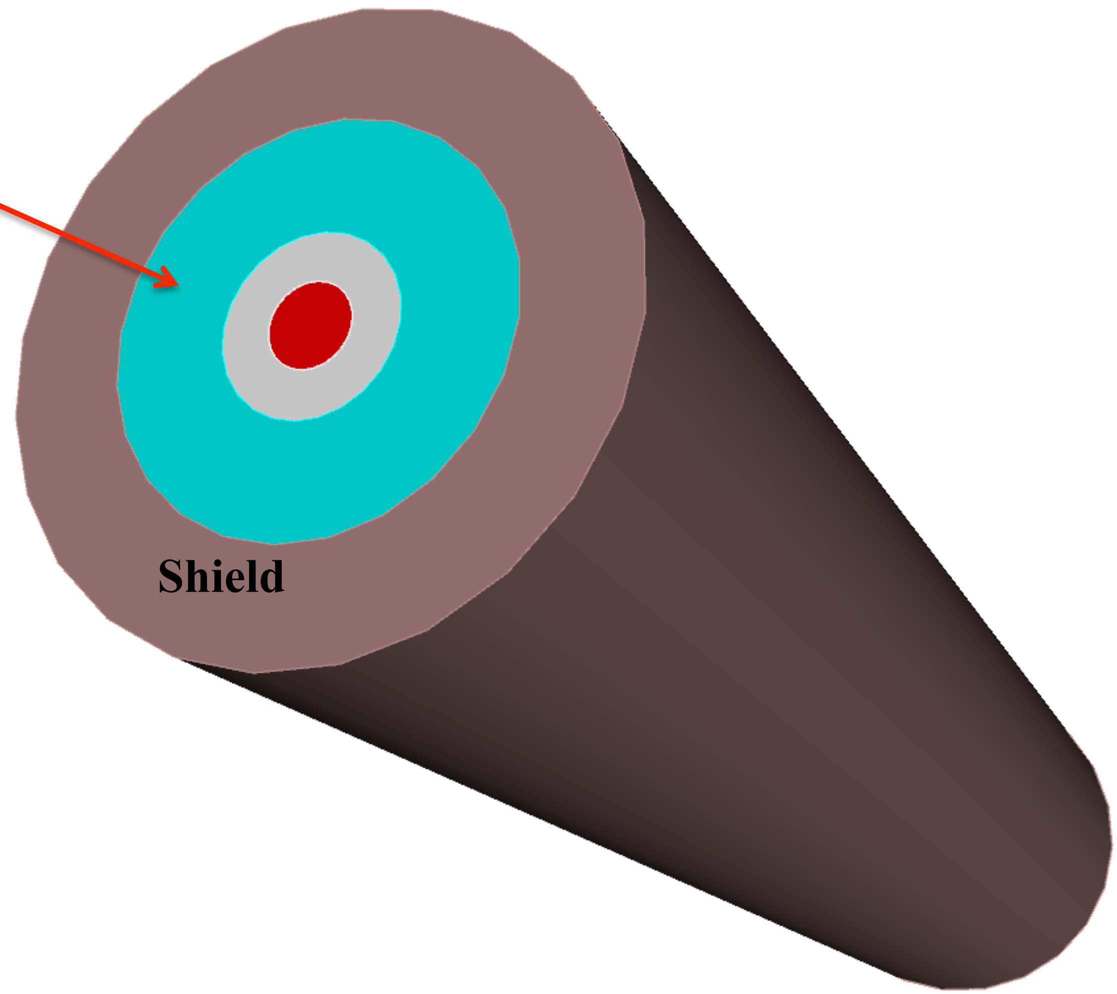
ARIES-ACT-SiC
One module (22.5°)

1-D Infinite Cylinder

(to estimate maximum achievable TBR for 100 % LiPb; 90% Li enrichment; no structure)

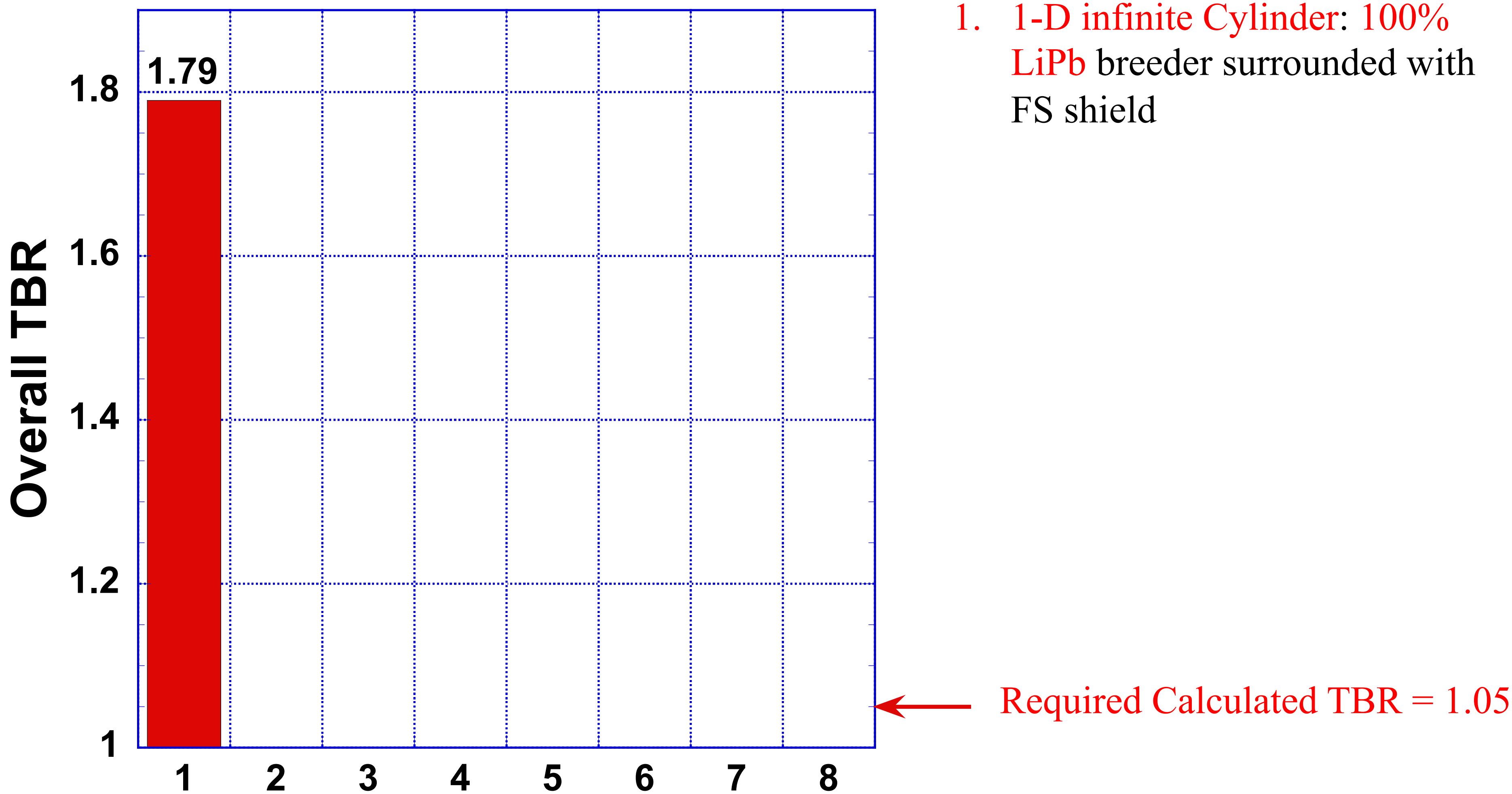
2 m thick LiPb Breeder

$Li_{15.7}\ Pb_{84.3}$



1-D Infinite Cylinder

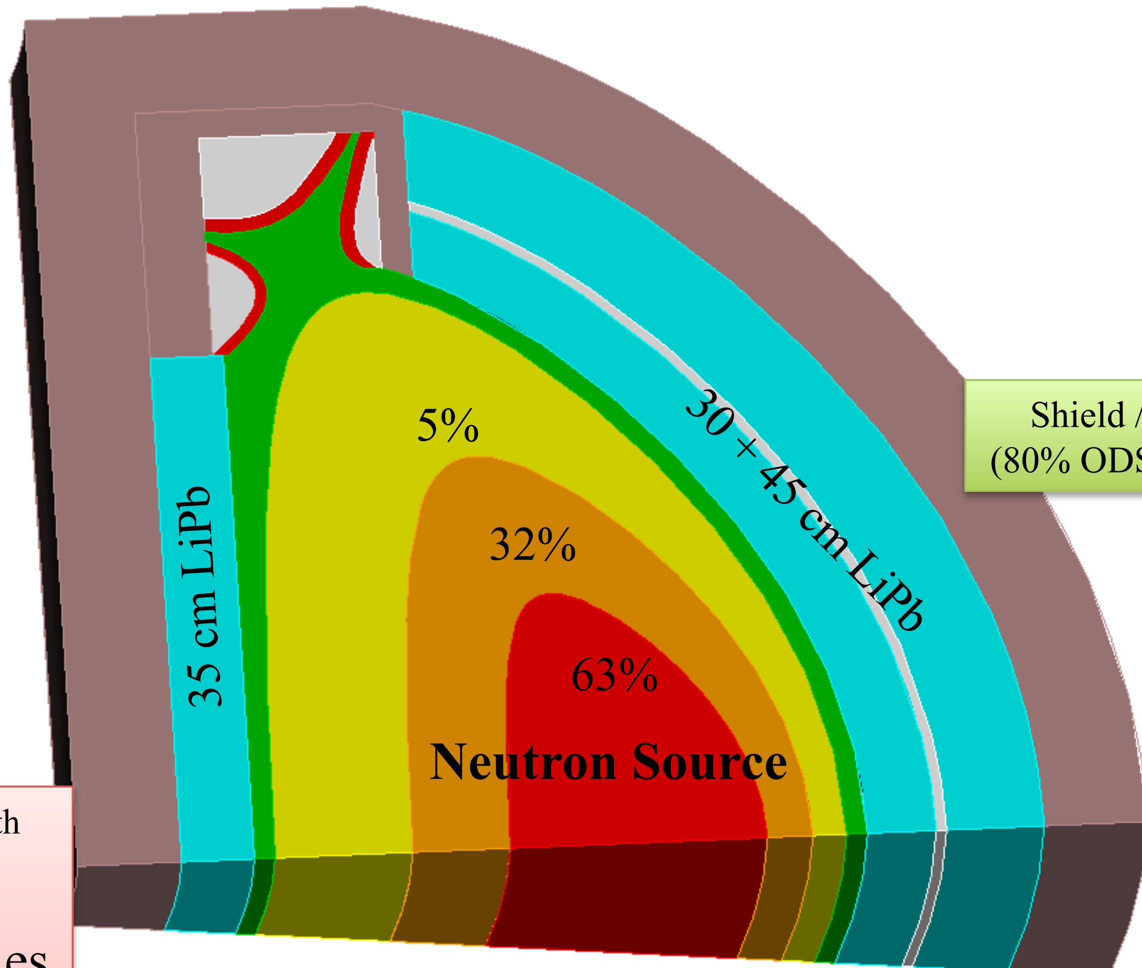
(to estimate maximum achievable TBR for 100 % LiPb; 90% Li enrichment; no structure)



90% Enriched Li-6

1. 1-D infinite Cylinder: 100% LiPb breeder surrounded with FS shield

3-D Toroidal Model: $Li_{15.7}Pb_{84.3}$ Confined Radially/ Vertically to Blanket. Shield and Divertor Added

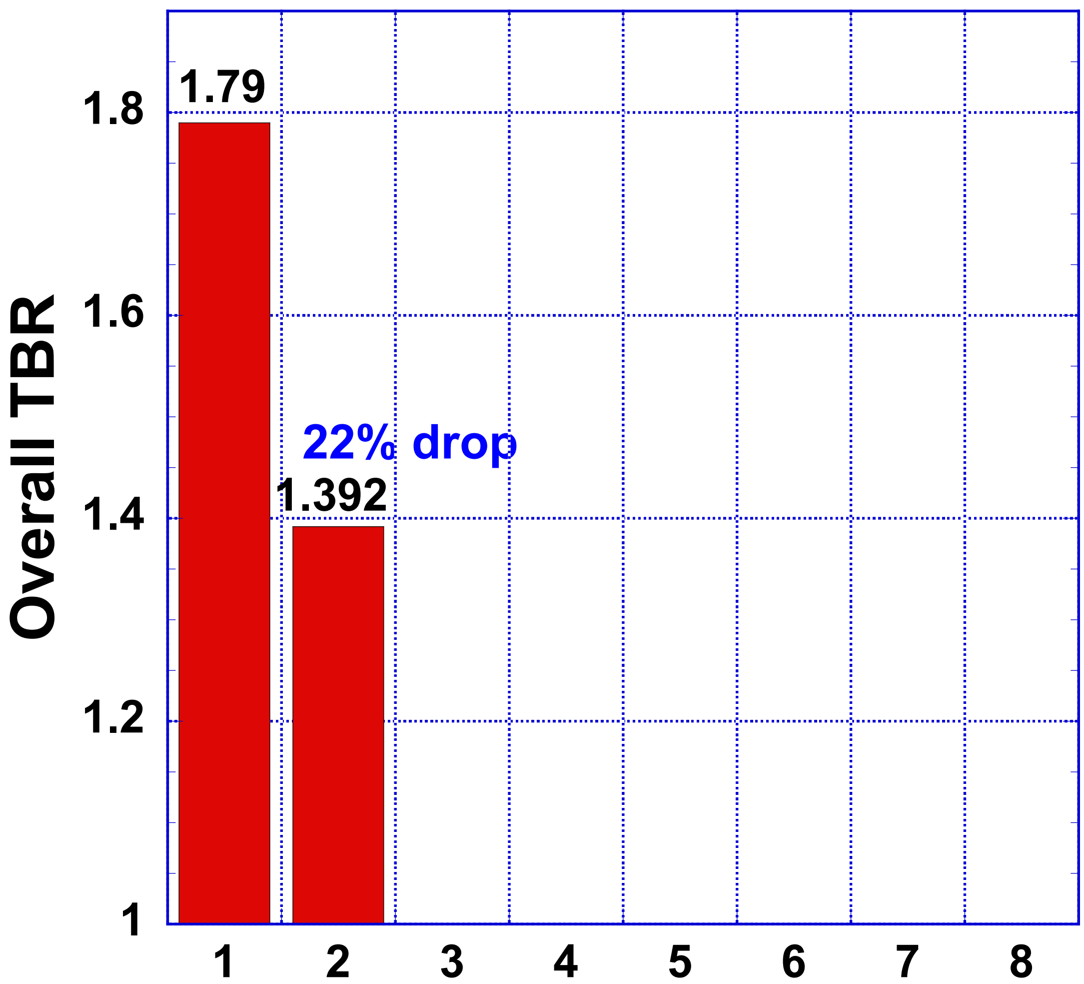


Shield / Steel Ring
(80% ODSFS, 20% He)

Upper half of 1/32[th] module with three reflecting boundaries at both sides and at midplane

1/64[th] of ARIES-ACT-1 torus

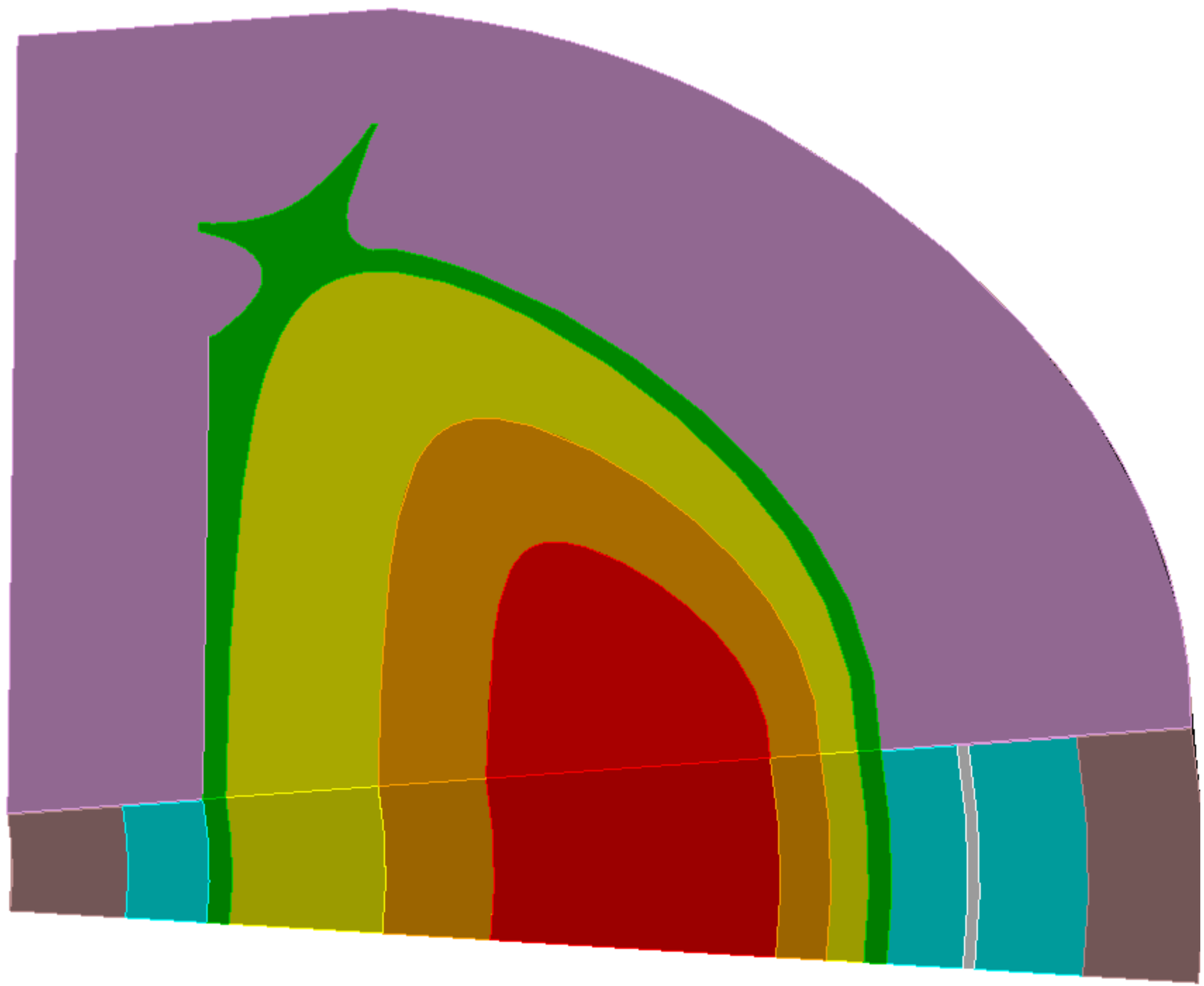
3-D Toroidal Model: $Li_{15.7}Pb_{84.3}$ Confined Radially/ Vertically to Blanket. Shield and Divertor Added



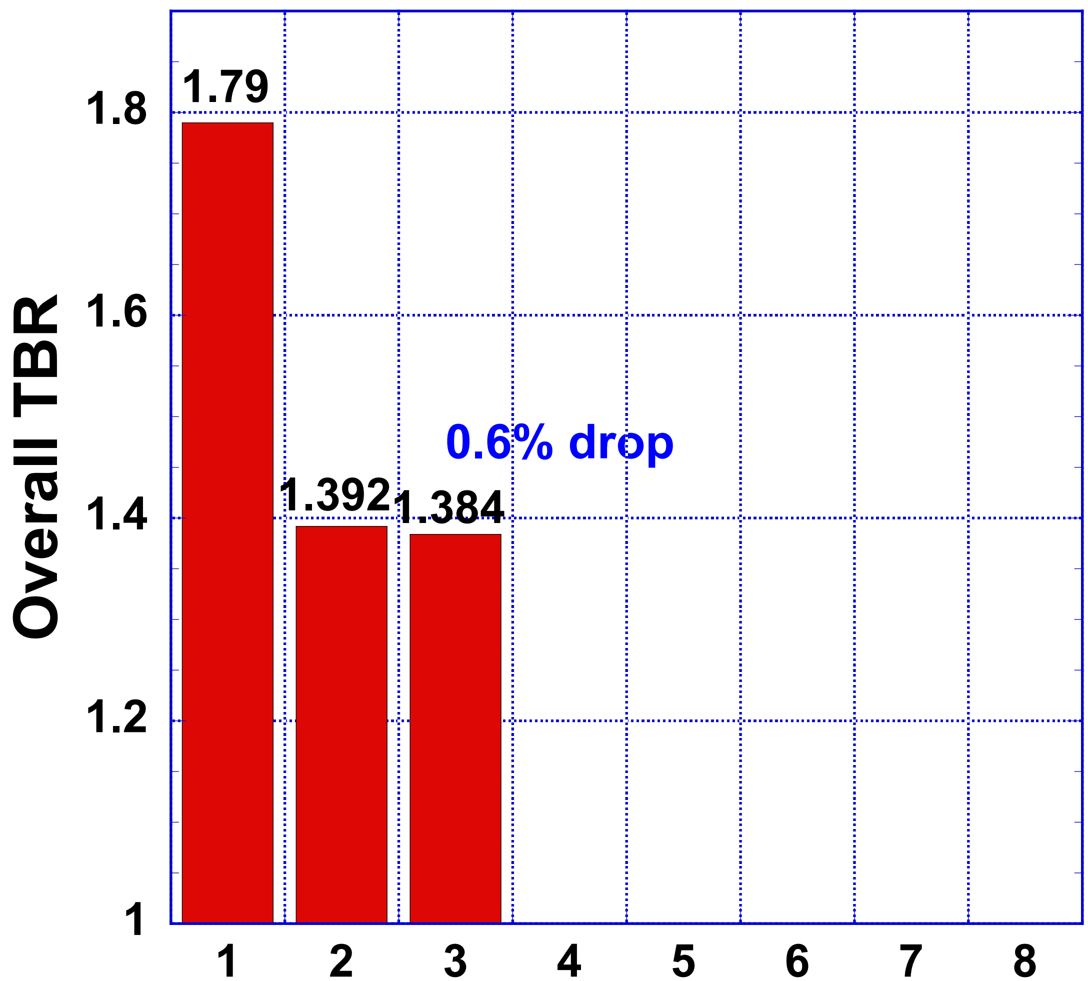
90% Enriched Li-6

1. 1-D infinite Cylinder: 100% LiPb breeder surrounded with FS shield
2. 3-D Toroidal Model: LiPb confined to 35 cm IB blanket and 30+45 cm OB blanket

2 cm Wide Assembly Gaps Between Modules (purple)



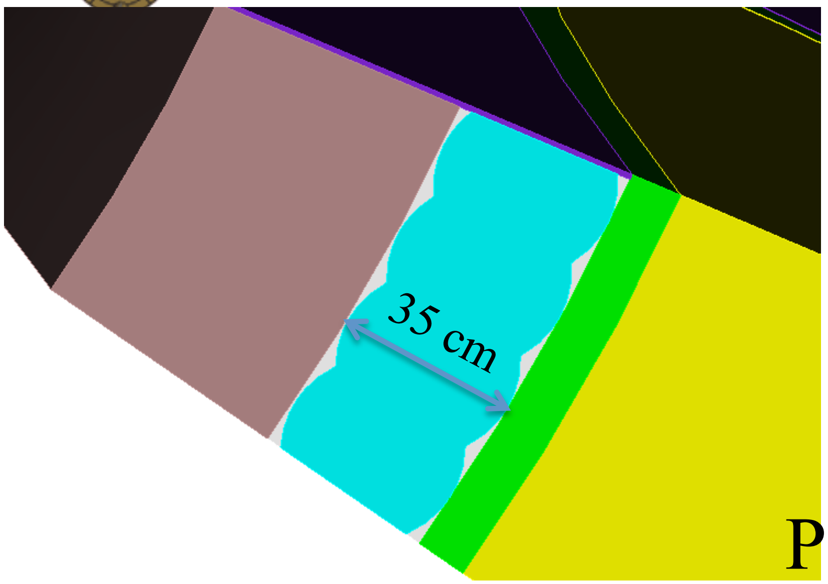
2 cm Wide Assembly Gaps Between Modules



90% Enriched Li-6

1. 1-D infinite Cylinder: 100% LiPb breeder surrounded with FS shield
2. 3-D Toroidal Model: LiPb confined to 35 cm IB blanket and 30+45 cm OB blanket
3. Add assembly gaps between blanket modules

Segment Blankets into Sectors and Curve FW and BW of each Sector



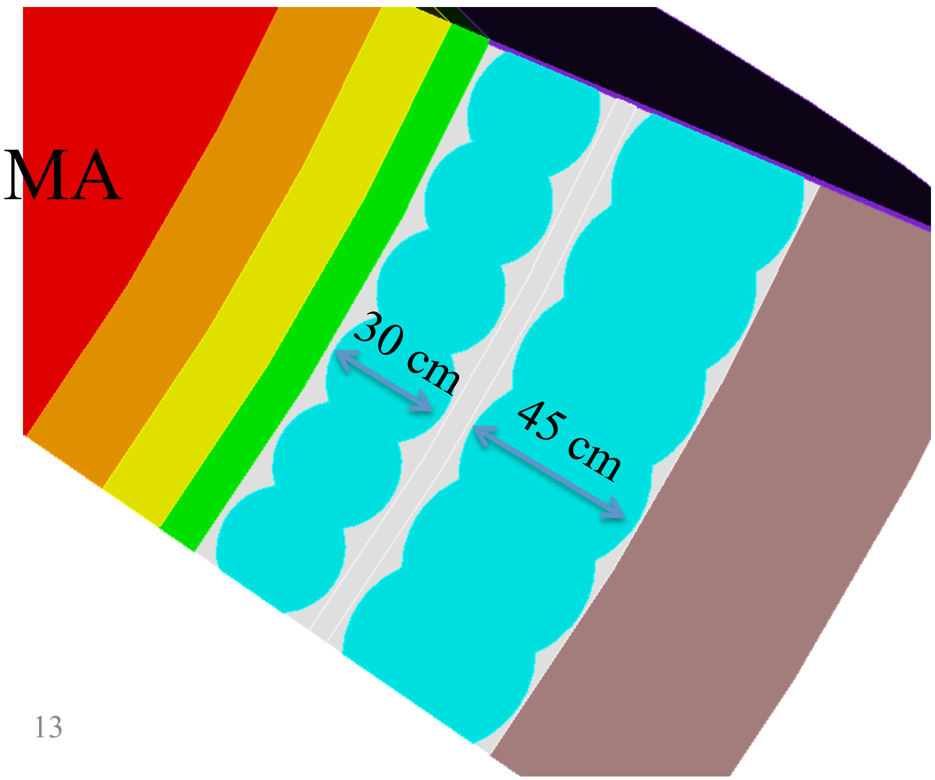
PLASMA

IB

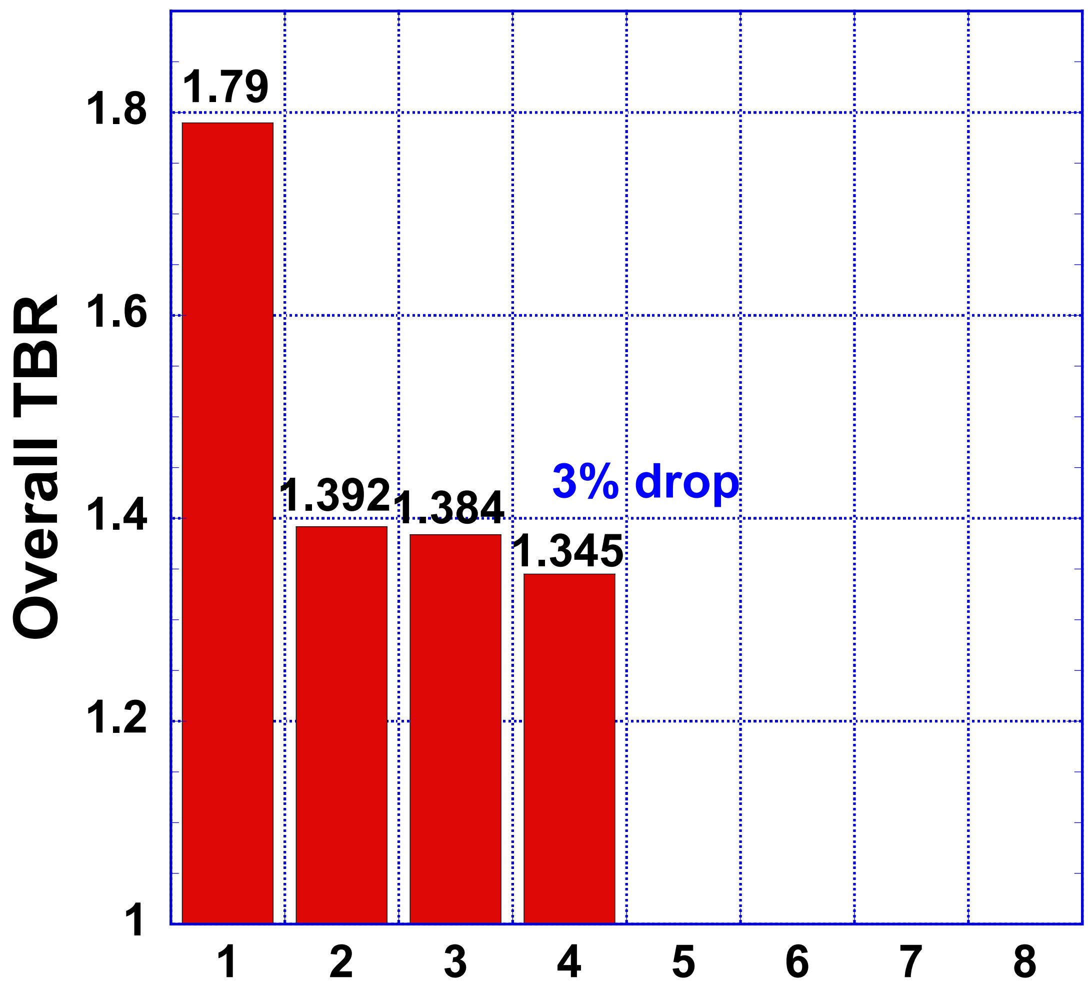
Maximum radial blanket thickness = 35 cm

OB

Max OB-I radial blanket thickness = 30 cm
Max OB-II radial blanket thickness = 45 cm



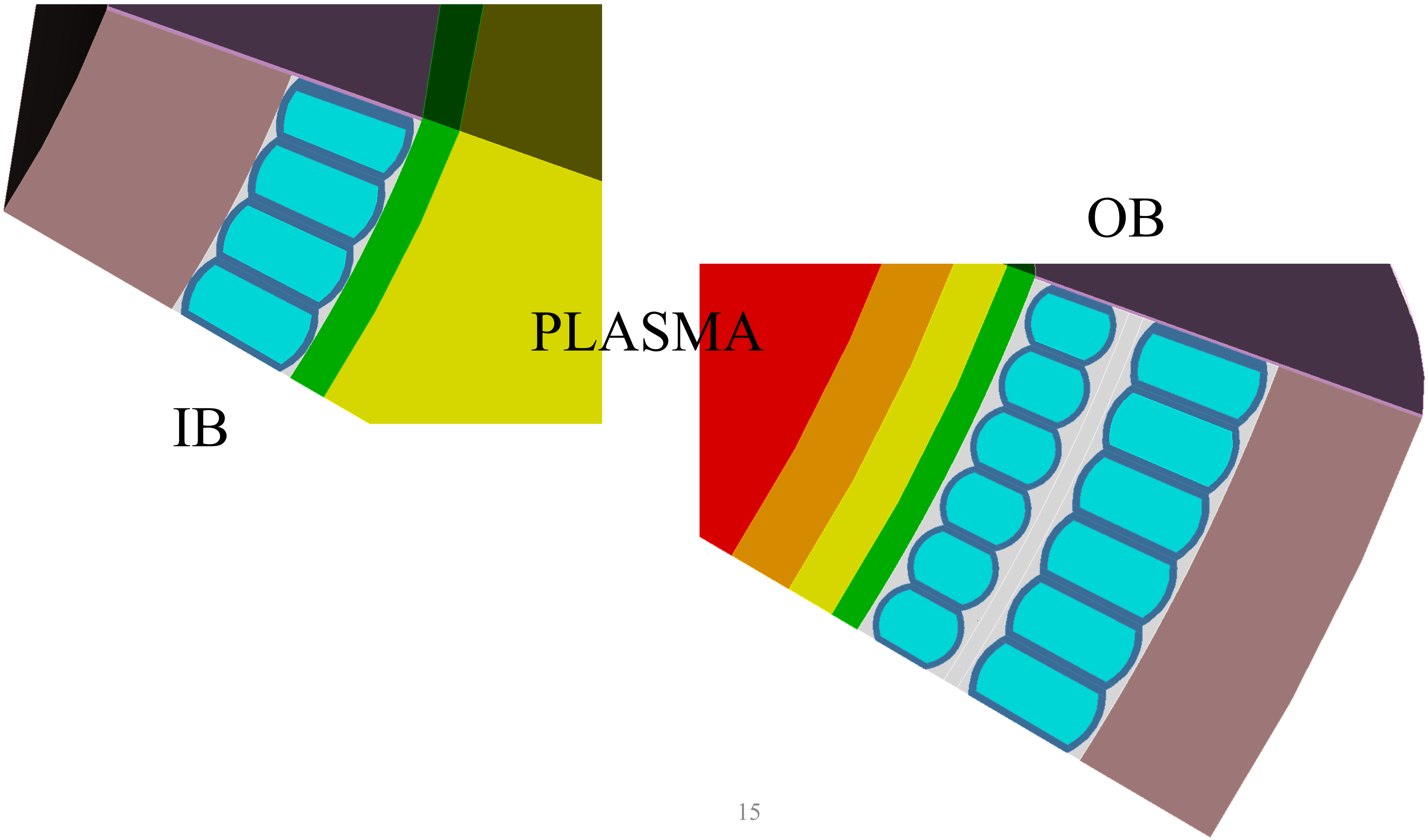
Segment Blankets into Sectors and Curve FW and BW of each Sector



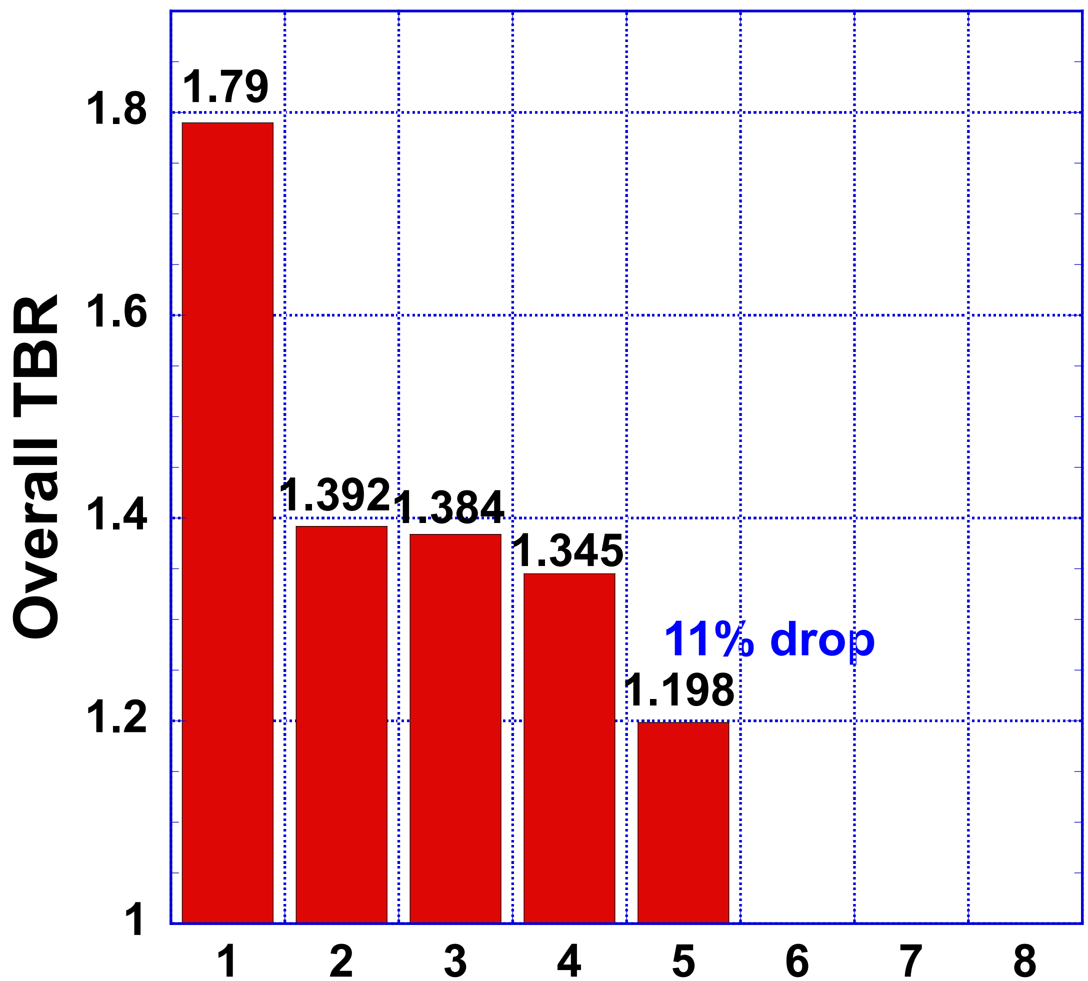
90% Enriched Li-6

1. 1-D infinite Cylinder: 100% LiPb breeder surrounded with FS shield
2. 3-D Toroidal Model: LiPb confined to 35 cm IB blanket and 30+45 cm OB blanket
3. Add assembly gaps between blanket modules
4. Curve IB and OB blanket sectors

SiC/LiPb Materials Assigned to Walls



SiC/LiPb Materials Assigned to Walls



90% Enriched Li-6

1. 1-D infinite Cylinder: 100% LiPb breeder surrounded with FS shield
2. 3-D Toroidal Model: LiPb confined to 35 cm IB blanket and 30+45 cm OB blanket
3. Add assembly gaps between blanket modules
4. Curve IB and OB blanket sectors
5. Add blanket walls

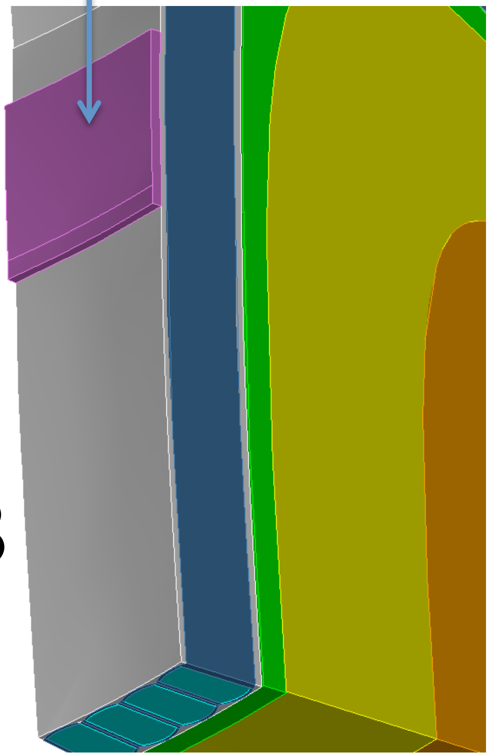
W Stabilizing Shells Added to IB & OB (purple)

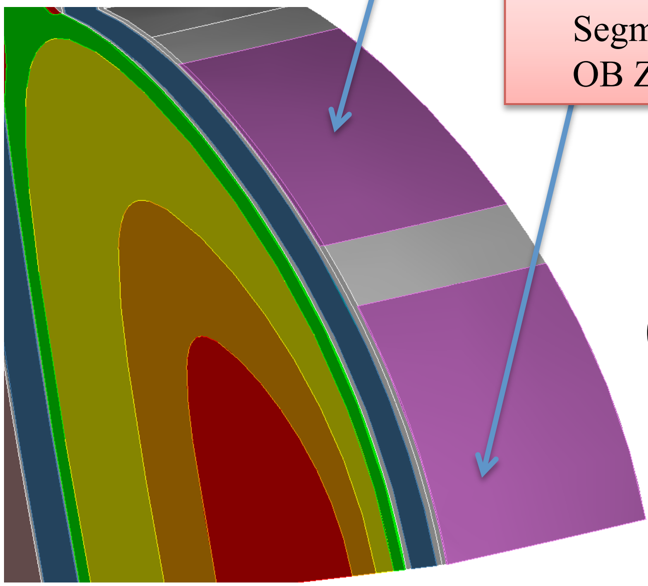
4 cm thick IB Vertical Stabilizing shell.
Continuous toroidally.
100% W-TiC.

4 cm thick OB Vertical Stabilizing (VS) shell.
Continuous toroidally.
100% W-TiC.
OB Z = 1.76 – 2.81 m.

1 cm thick OB Kink shell.
Segmented toroidally.
OB Z = 0 – 1.42 m.

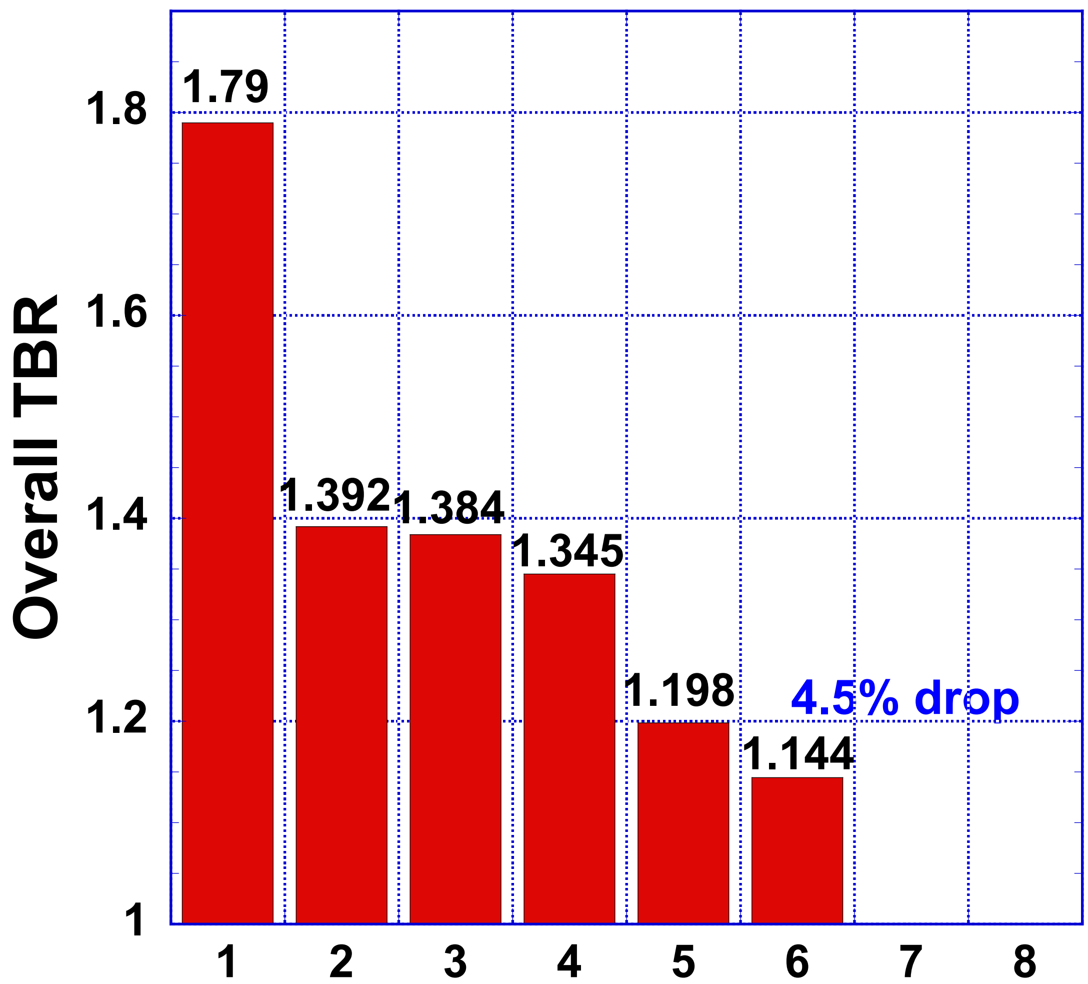
IB





OB

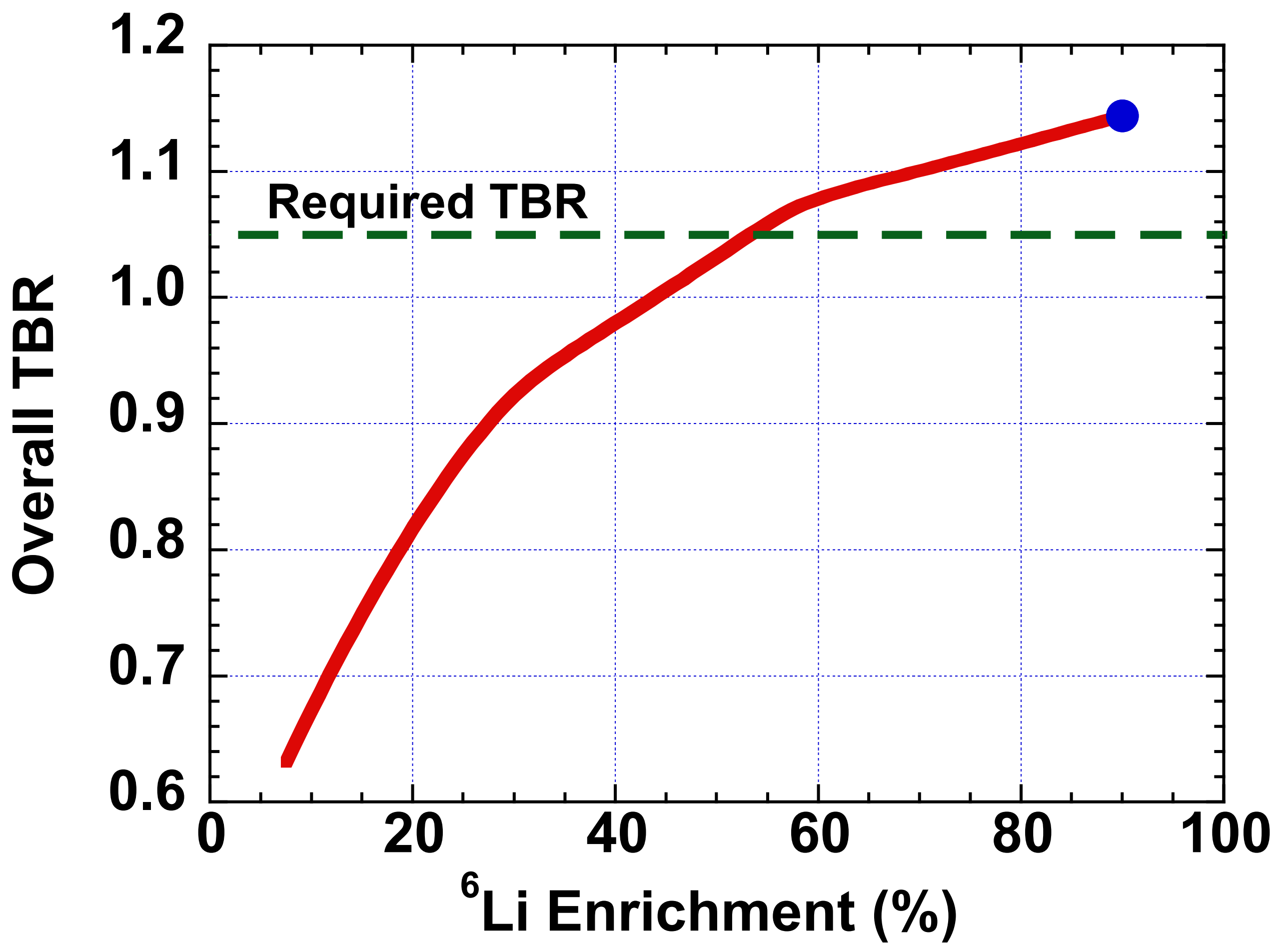
W Stabilizing Shells Added to IB & OB



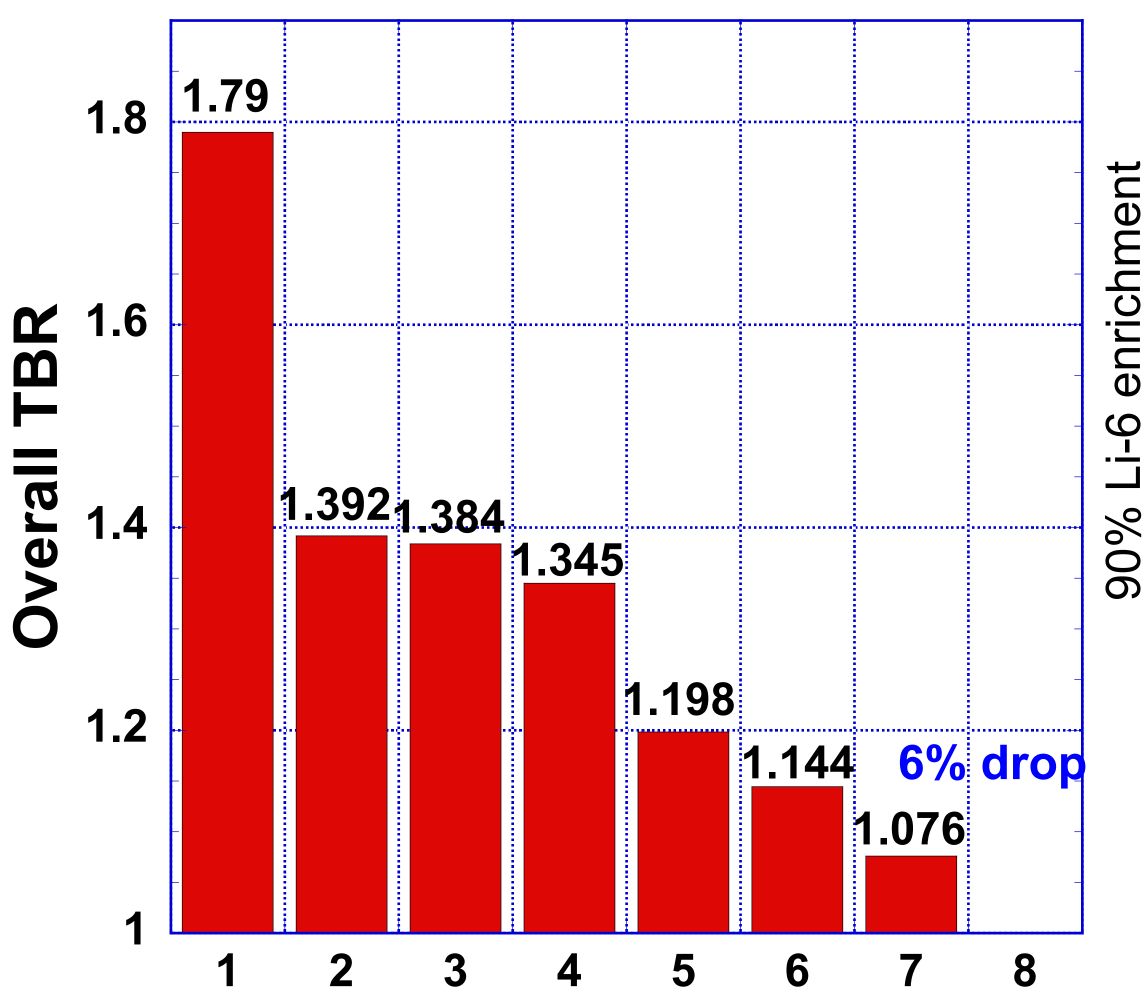
90% Enriched Li-6

1. 1-D infinite Cylinder: 100% LiPb breeder surrounded with FS shield
2. 3-D Toroidal Model: LiPb confined to 35 cm IB blanket and 30+45 cm OB blanket
3. Add assembly gaps between blanket modules
4. Curve IB and OB blanket sectors
5. Add blanket walls
6. Add stabilizing shell

Vary Li-6 Enrichment



Vary Li-6 Enrichment



1. 1-D infinite Cylinder: 100% LiPb breeder surrounded with FS shield
2. 3-D Toroidal Model: LiPb confined to 35 cm IB blanket and 30+45 cm OB blanket
3. Add assembly gaps between blanket modules
4. Curve IB and OB blanket sectors
5. Add blanket walls
6. Add stabilizing shell

7. 58% Li-6 enrichment

Penetrations

Footprints at FW:

Plasma control, heating, and fueling:

	2 m^2 ICRF (or 0.5 m^2 EC)
	2 m^2 LH
	0.008 m^2 fueling ducts
Diagnostics:	3 m^2

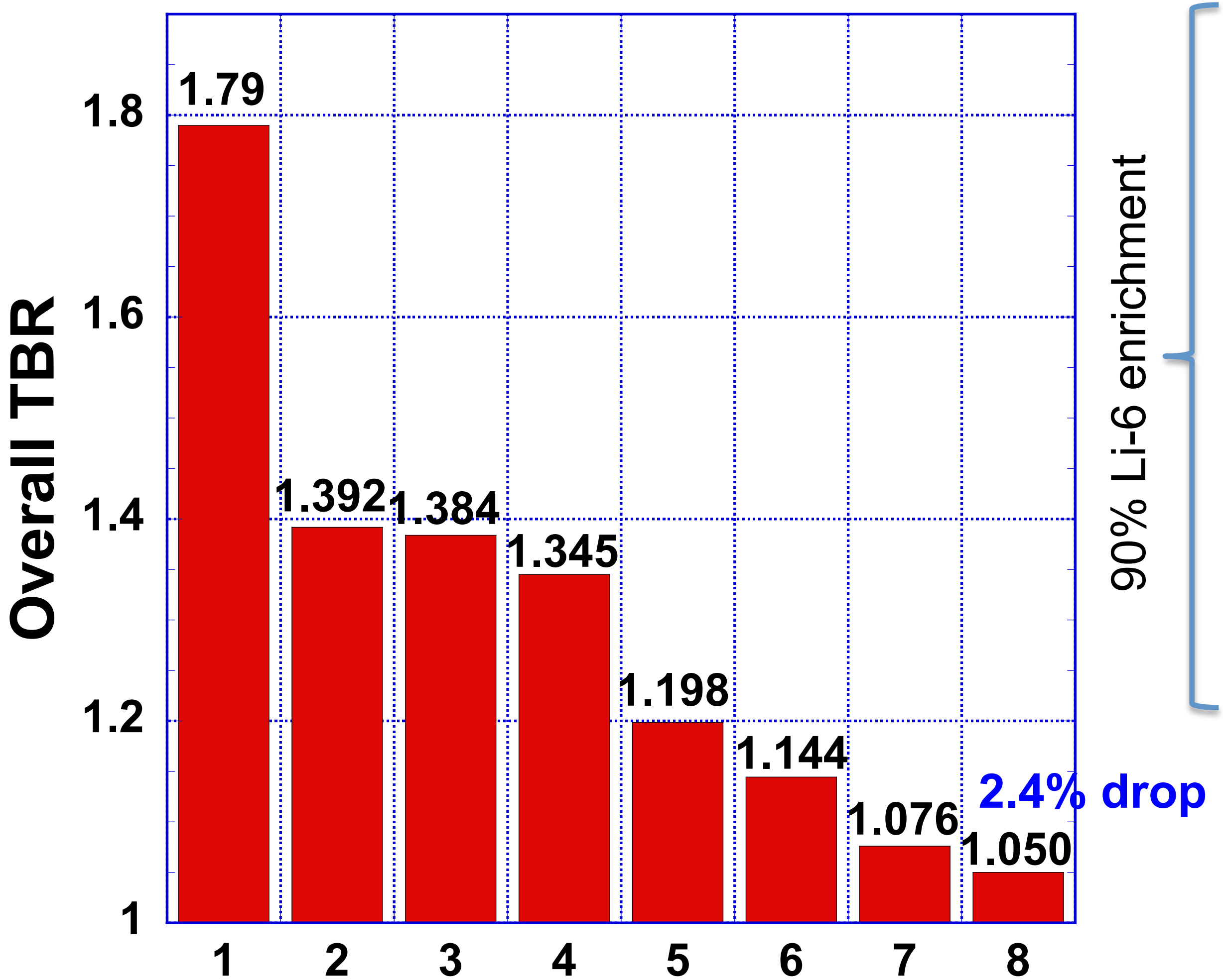
Total	7.0 m^2 (or 5.5 m^2)

Fraction of OB surface area = $\frac{\sim 7.0 \text{ m}^2}{313 \text{ m}^2} \approx 2.24\%$

Maximum fraction could reach 4% of OB area.

We considered 4% of OB FW area (12 m^2)
for ARIES-ACT penetrations

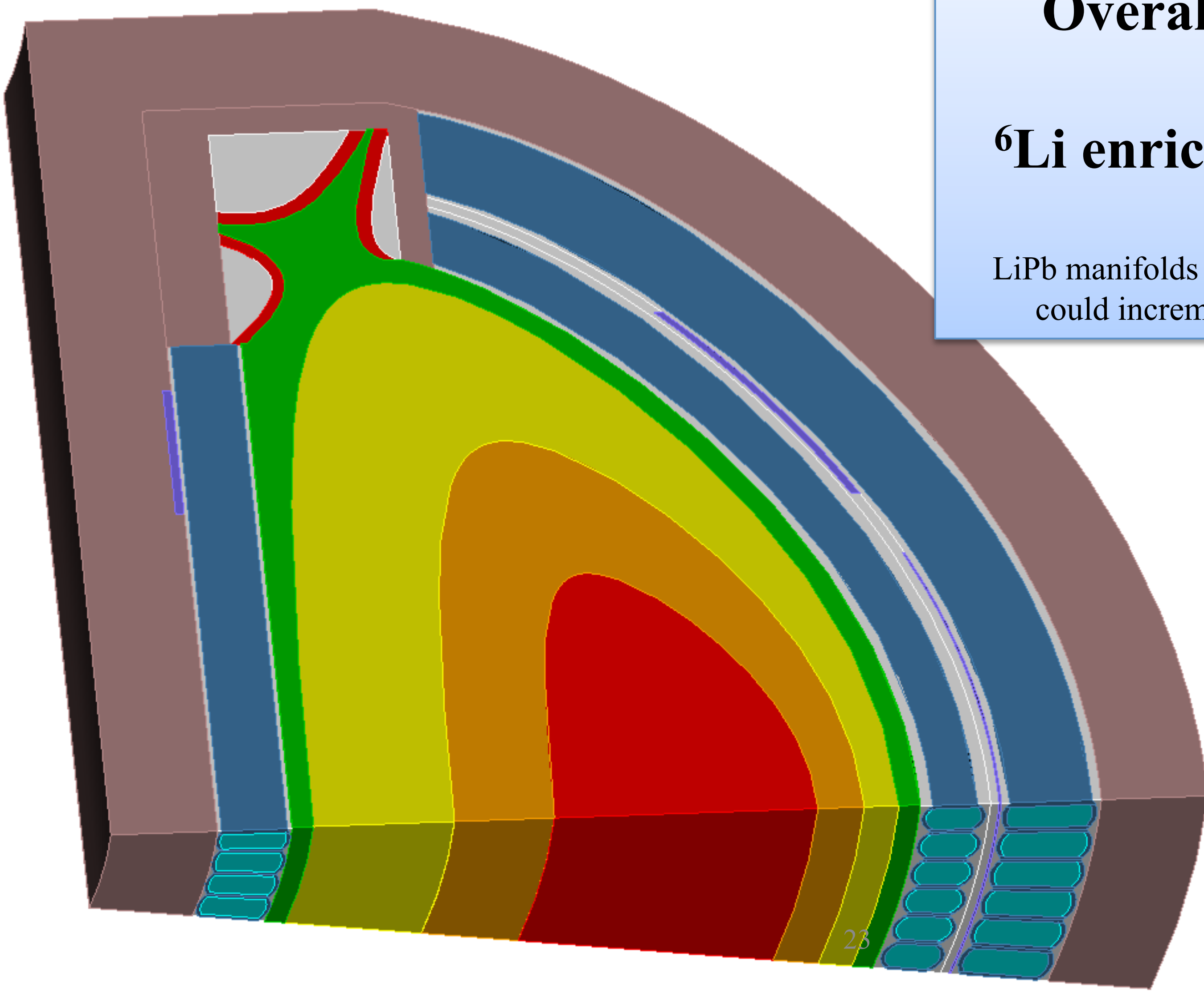
Including Penetrations



1. 1-D infinite Cylinder: 100% LiPb breeder surrounded with FS shield
2. 3-D Toroidal Model: LiPb confined to 35 cm IB blanket and 30+45 cm OB blanket
3. Add assembly gaps between blanket modules
4. Curve IB and OB blanket sectors
5. Add blanket walls
6. Add stabilizing shell
7. 58% Li-6 enrichment
8. Add penetrations (4% of OB FW area)

Isometric View of Detailed Blanket

(Upper half of 1/32th (11.25^{o}) toroidal module)



Overall TBR = 1.05

^{6}Li enrichment = ~ 60%

LiPb manifolds behind upper/lower divertor could increment TBR by few percent.

Conclusions and General Observations

- 3-D analysis showed progressive reduction of theoretical TBR (~1.8) down to more realistic TBR (1.05) when real geometry of LiPb/SiC blanket is addressed.
- **Main findings and results**:
  - ARIES-ACT-SiC blanket complies with ARIES breeding requirements (calculated TBR of 1.05 with 60% ^{6}Li enrichment (< 90%))
  - Limiting the blanket coverage radially and vertically has the largest impact on TBR (22%)
  - Shaping the blanket and adding the SiC structure have 14% reduction in TBR
  - Inclusion of stabilizing shells has ~5% impact on TBR
  - Adding penetrations and assembly gaps has smaller (3%) but still significant impact on TBR.
- **TBR verification**:
  - Achievable TBR will not be verified till after Demo operation **with fully integrated blanket and T extraction and processing systems.**
- Because many uncertainties in operating system govern achievable TBR during plant operation, it is a must requirement for any blanket design to have flexible approach.
- Most attractive scheme for LiPb breeder is to operate with ^{6}Li enrichment < 90% and increase or decrease ^{6}Li enrichment online shortly after plant operation*.
- This scheme helps mitigate concerns about danger of placing plant at risk due to T shortage as well as problem of handling and safeguarding any surplus of T.

• L. El-Guebaly and S. Malang, "Toward the Ultimate Goal of Tritium Self-Sufficiency: Technical Issues and Requirements Imposed on ARIES Advanced Fusion Power Plants," Fusion Engineering and Design 84 (Dec 2009) 2072-2083.