Scoping Assessment of Advanced Tokamak with DCLL Blanket: Design Challenges and Economic Implications

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Objectives

- Scoping assessment of ARIES-AT* with Dual-Coolant LiPb (DCLL) blanket (previously developed for ARIES-ST@ in 1997 and ARIES-CS# in 2003)
  ⇒ redefine ARIES-AT radial builds with:
  - DCLL blanket and shield system
  - < 90% Li enrichment
  - LiPb/He Manifolds (tentative composition/dimension/location)
  - No stabilizing shells (will be added later)
  - Low-temperature magnets (replacing high-temperature magnets).

- Impact of SiC inserts on TBR:
  - **Reference**: 100% dense, 0.5 cm thick SiC inserts
  - **Alternative**: 0.5-0.7 cm thick, less dense SiC inserts (0.3-0.5 cm 10% dense SiC foam sandwiched between 1 mm 100% dense impermeable CVD-SiC face sheets; 0.23-0.25 cm equivalent SiC thickness).

- Compare reference ARIES-AT-SiCLL design with proposed ARIES-AT-DCLL design, highlight impact of DCLL system on overall design, and recommend improvements for final ARIES-AT-DCLL design.

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* F. Najmabadi, A. Abdou, L. Bromberg, T. Brown, V.C. Chan, M.C. Chu et al., "The ARIES-AT Advanced Tokamak, Advanced Technology Fusion Power Plant," Fusion Engineering and Design 80, 3-23 (2006).

@ F. Najmabadi, "Spherical Torus Concept as Power Plants–the ARIES-ST Study," Fusion Engineering and Design 65 (2) (2003) 143-164.

F. Najmabadi, A.R. Raffray, S. Abdel-Khalik, L. Bromberg. L. Crosatti, L. El-Guebaly et al., "The ARIES-CS Compact Stellarator Fusion Power Plant," Fusion Science and Technology 54, No. 3 (2008) 655-672.

ARIES-AT Reference Design

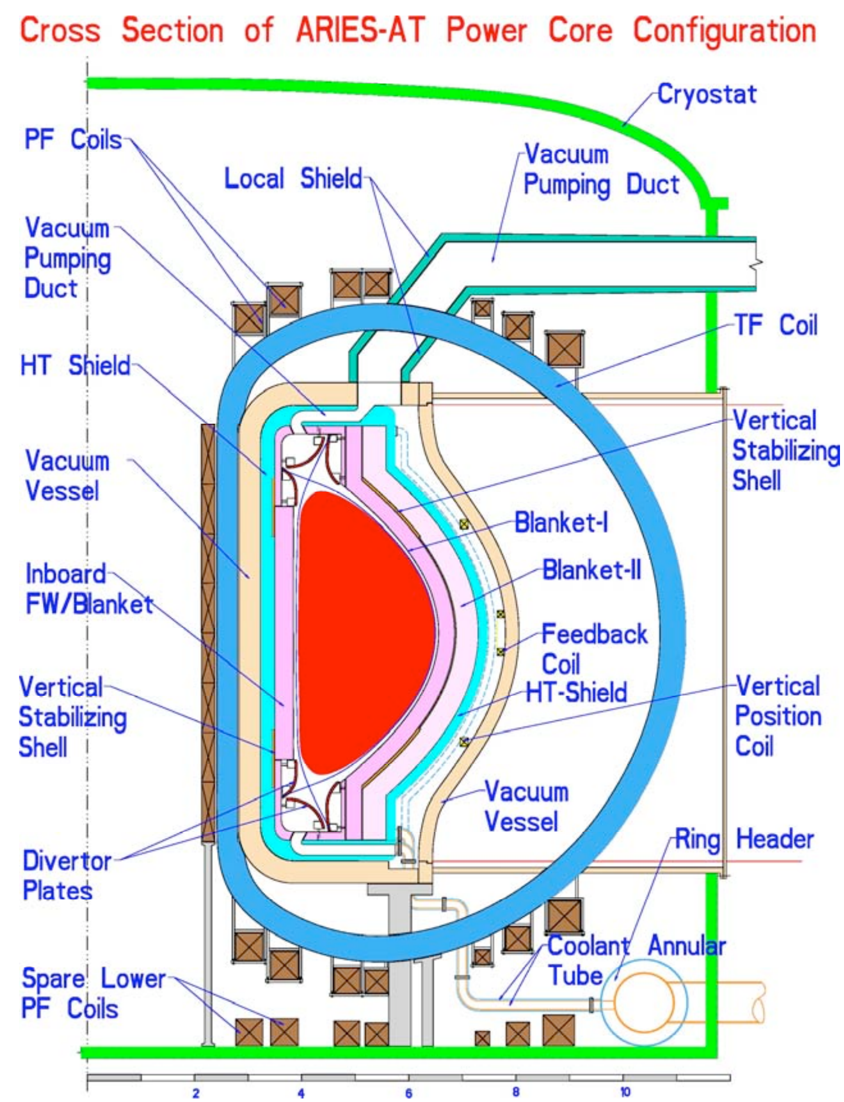
Fusion Power	1755 MW
Major Radius	5.2 m
Minor Radius	1.3 m
Peak Γ @ IB, OB, Div	3.1, 4.8, 2 MW/m^2

SiC/SiC Composite Structure
LiPb/SiC Blanket
Discrete LiPb Manifolds
High Temperature S/C Magnet @ 70-80 K
No W on FW

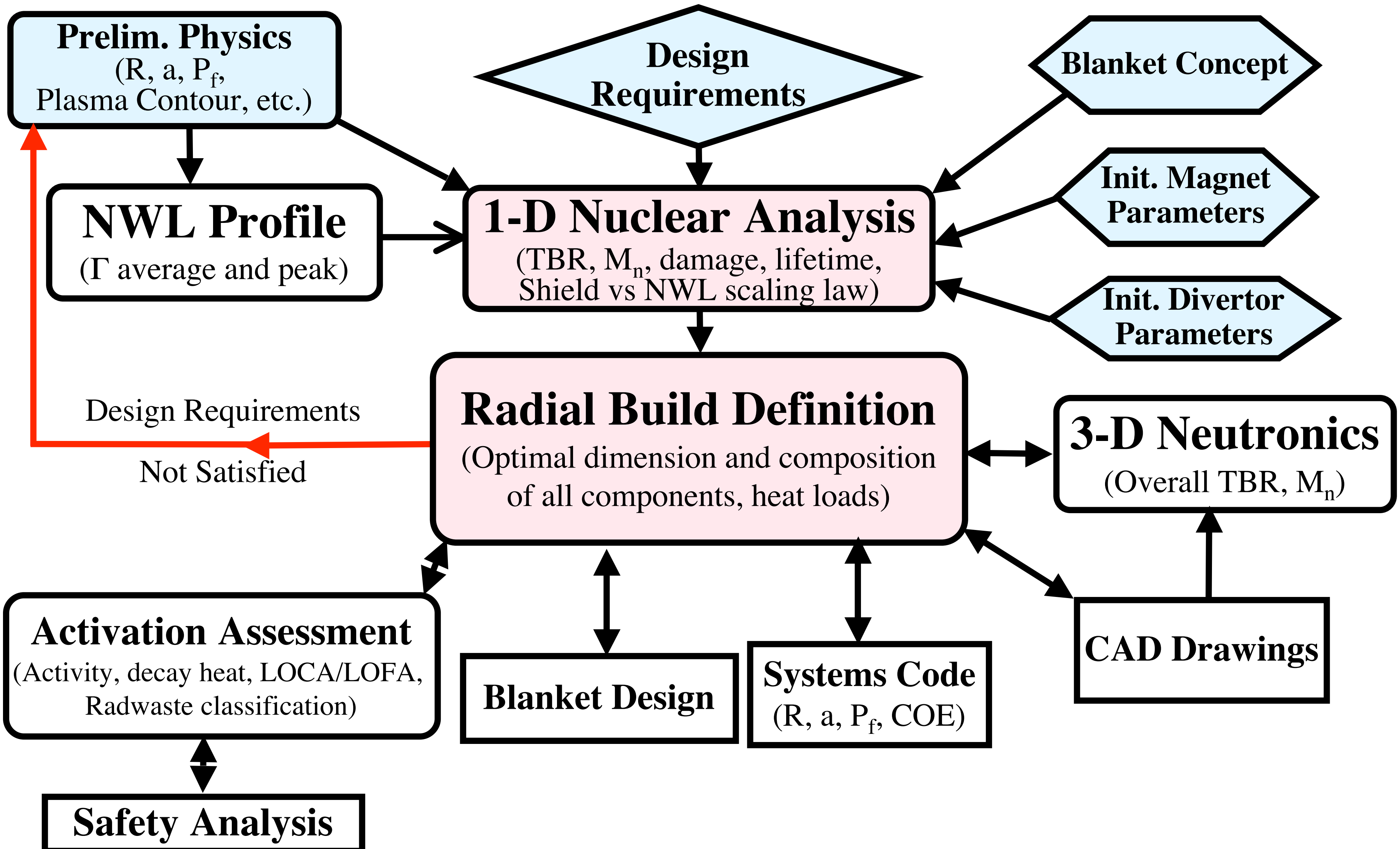
Calculated Overall TBR	1.1
η_{th}	~ 60%
Availability	85%

Plasma Control:

- 5 **Tungsten** Shells on IB and OB
- 2 Vertical Position Coils
- 2 Feedback Coils

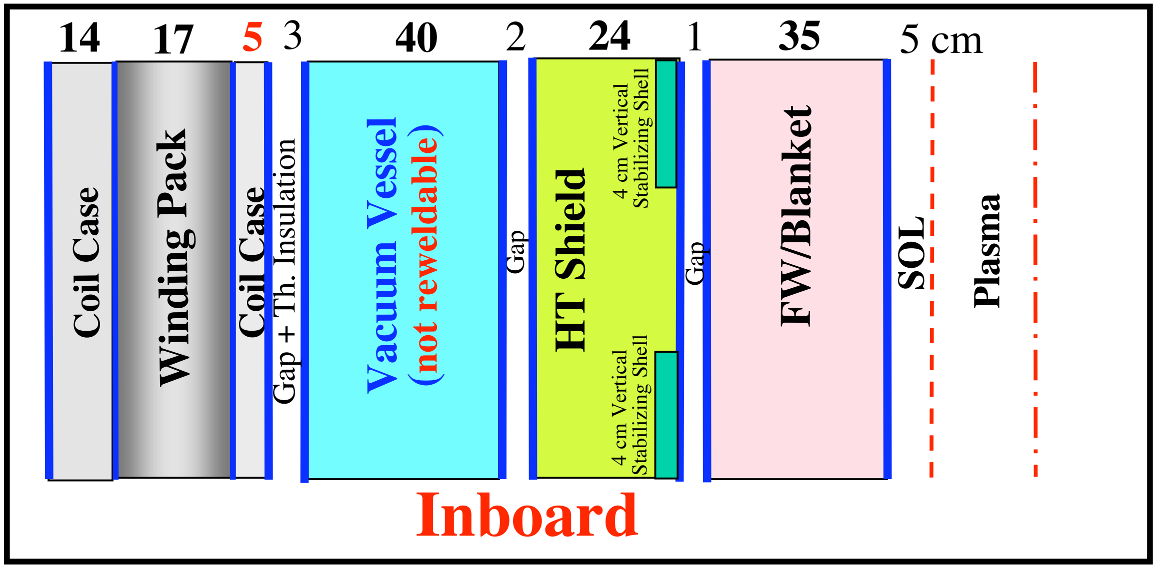


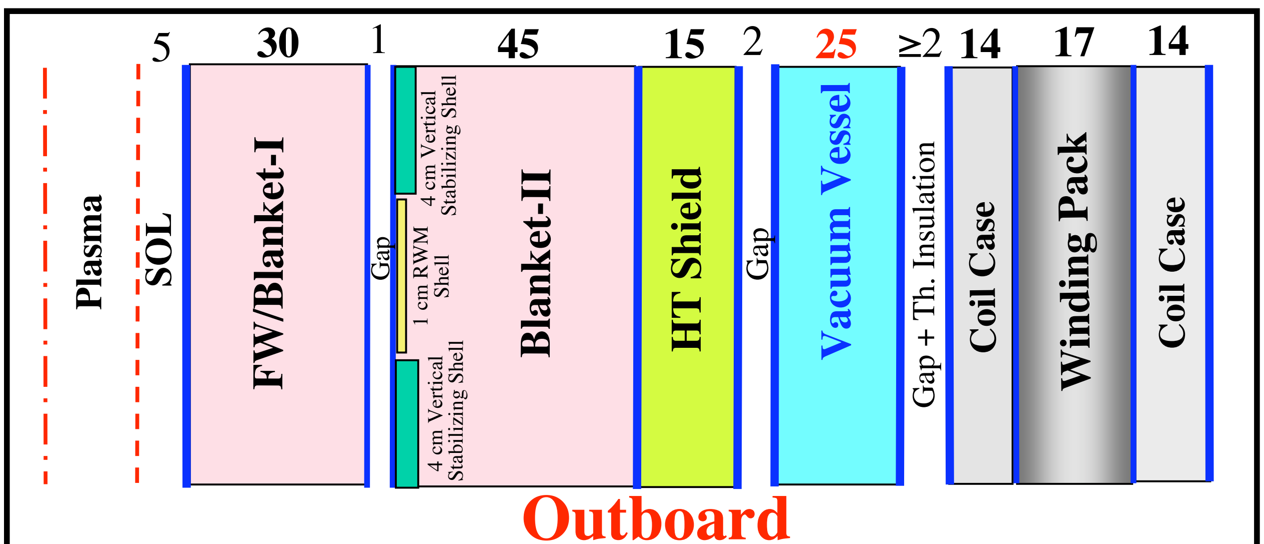
Radial Build Definition Involves Active Interaction with many Disciplines

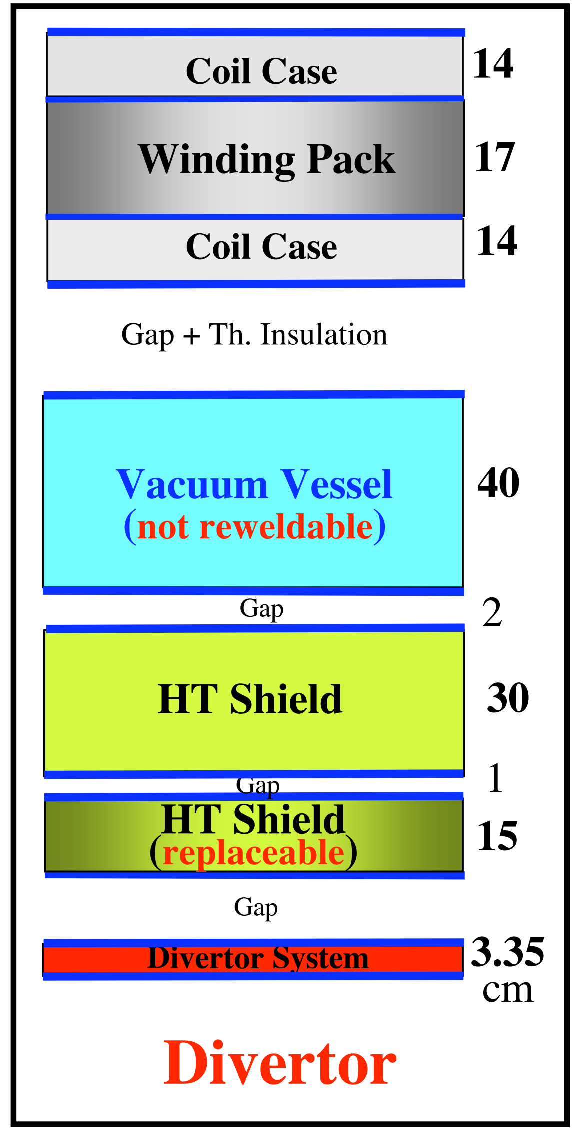


ARIES-AT Radial Builds: IB, OB, Div

(SiC Structure; HT Magnets)



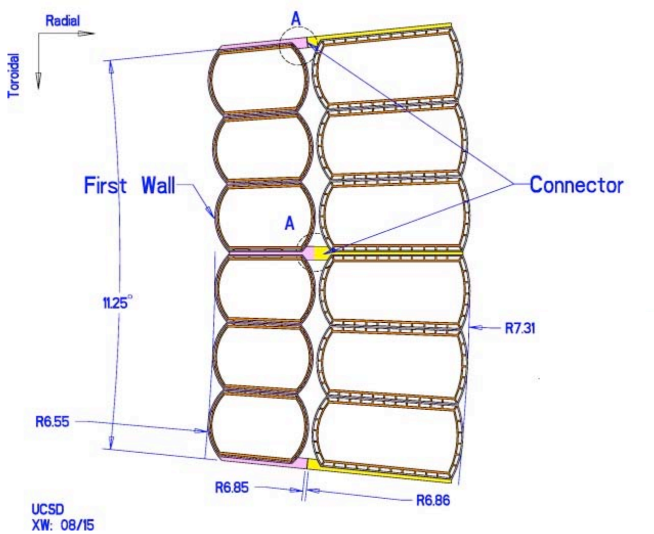




ARIES-AT Blanket Options

Reference
ARIES-AT OB Blanket

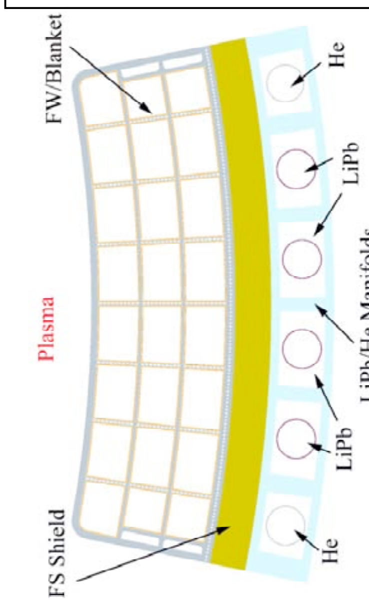
SiC Structure



Breeder	LiPb
Coolant	LiPb
LiPb T_{out} Temp	~1100 °C
η_{th}	~60%

New
ARIES-AT-DCLL OB Blanket
(a la ARIES-CS)

FS Structure



Breeder	LiPb
Dual Coolant	LiPb and He
LiPb T_{out} Temp	~700 °C
η_{th}	40-45%

ARIES-AT Compositions

	ARIES-AT-LiPb/SiC (Reference Design)	ARIES-AT-DCLL* 0.5 cm Ultramet SiC, No Shells
Inboard:		
FW/Blanket	81% LiPb, 19%SiC	79% LiPb, 12% He/void, 6% FS, 3%SiC inserts
HT Shield	15%SiC, 10% LiPb, 70% B-FS Filler , **5% W shells**	15%FS, 10% He, 75% B-FS Filler
Manifolds	---	50%FS, 25% He, 24% LiPb, 1%SiC
VV	13% FS, 22% H_2O, 65% WC	17% FS, 34% H_2O, 49% WC
Outboard:		
FW/Blanket-I	80% LiPb, 20%SiC	79% LiPb, 12% He/void, 6% FS, 3%SiC inserts
FW/Blanket-II	77% LiPb, 20%SiC, **3% W shells**	---
HT Shield	15%SiC, 10% LiPb, 75% B-FS Filler	15%FS, 10% He, 75% B-FS Filler
Manifolds	---	50%FS, 25% He, 24% LiPb, 1%SiC
VV	30% FS, 70% H_2O	30% FS, 50% H_2O, 20% B-FS
Top/Bottom:		
Divertor System	40%SiC, 50% LiPb, 10% W	33% FS, 4% W, 63% He
Replaceable HT Shield	15%SiC, 10% LiPb, 75% FS Filler	15%FS, 10% He, 75% B-FS Filler
Permanent HT Shield	15%SiC, 10% LiPb, 75% B-FS Filler	15%FS, 10% He, 75% B-FS Filler
Manifolds	---	50%FS, 25% He, 24% LiPb, 1%SiC
VV	13% FS, 22% H_2O, 65% WC	22% FS, 48% H_2O, 30% B-FS

* Tentative compositions. Will change as design evolves.

ARIES-AT-DCLL Radiation Limits and Key Parameters

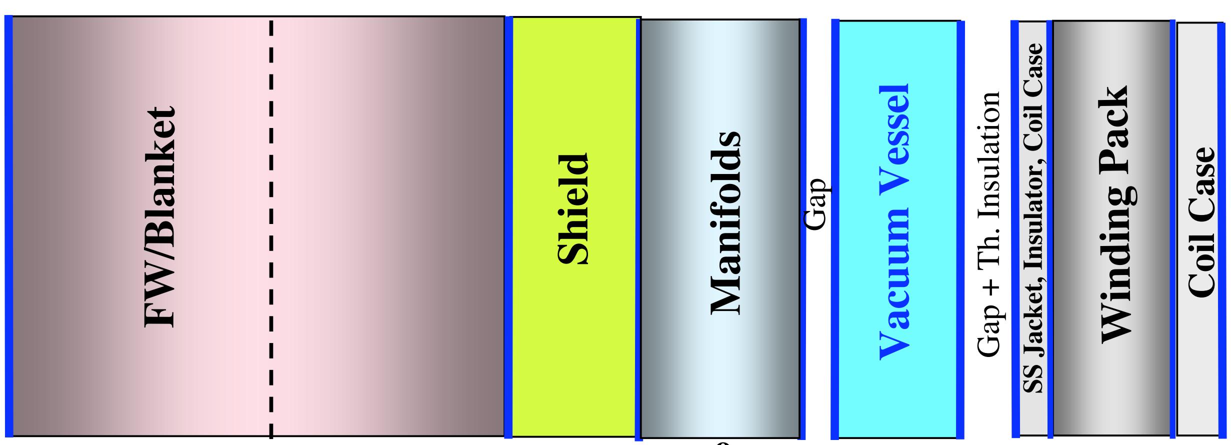
Calculated Overall TBR	1.1	
Net TBR (for T self-sufficiency)	~1.01	
Damage to Structure	200	dpa - advanced FS
(for structural integrity)	???	W structure
Helium Production @ Manifolds and VV (for reweldability of FS)	1	He appm
LT S/C TF & PF Magnets (@ 4 K):		
Peak Fast n **fluence** to Nb_3Sn (E_n > 0.1 MeV)	10^{19}	n/cm^2
Peak Nuclear **heating**	2	mW/cm^3
Peak **dpa** to Cu stabilizer	$6x10^{-3}$	dpa
Peak **Dose** to GFF Polyimide insulator	$< 10^{11}$	rads
Plant Lifetime	40	FPY
Availability	85%	
Operational Dose to Workers and Public	< 2.5	mrem/h

Radial Build Optimization Criteria

- **Adjust blanket dimension to provide overall TBR of 1.1**
  - Check impact of less dense SiC inserts on breeding

- **Maximize number of permanent components to minimize radwaste stream:**
  - Segment OB blanket into replaceable and permanent components
  - Protect external components (shield, manifolds, VV, and magnets) to serve for entire plant lifetime

- **All in-vessel components should provide shielding function**:
  - Blanket protect shield for plant life (40 FPY)
  - Blanket and shield protect manifolds and VV
  - Blanket, shield, manifolds, and VV protect magnets



Ultramet SiC Inserts

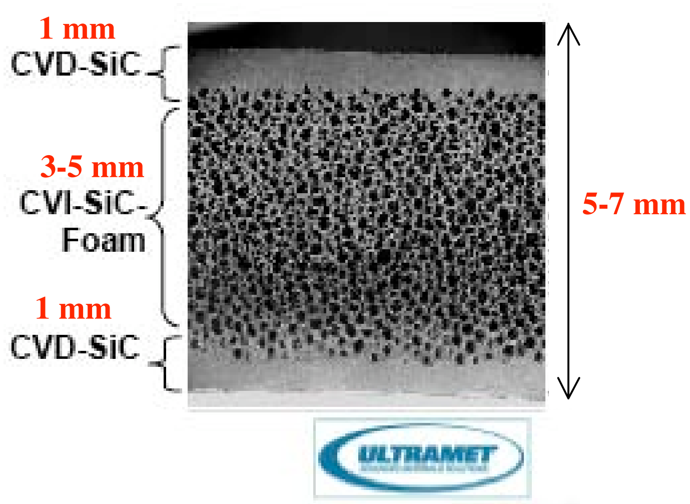
(Ref: S. Sharafat, Development Status of Flow Channel Inserts for the U.S.-ITER DCLL TBM; 18th TOFE, 2008)

Main features and advantages:

- 3-5 mm 10% dense foam ⇒ Low SiC content (to alleviate impact on TBR)
- Fully dense CVD SiC face sheets prevent LiPb ingress into foam
- Construction of long segments (> 75 cm) seems feasible
- Low-cost manufacturability
- Good strength, stiffness, and thermal stress resistance
- Low thermal and electrical conductivity.

Testing is underway.

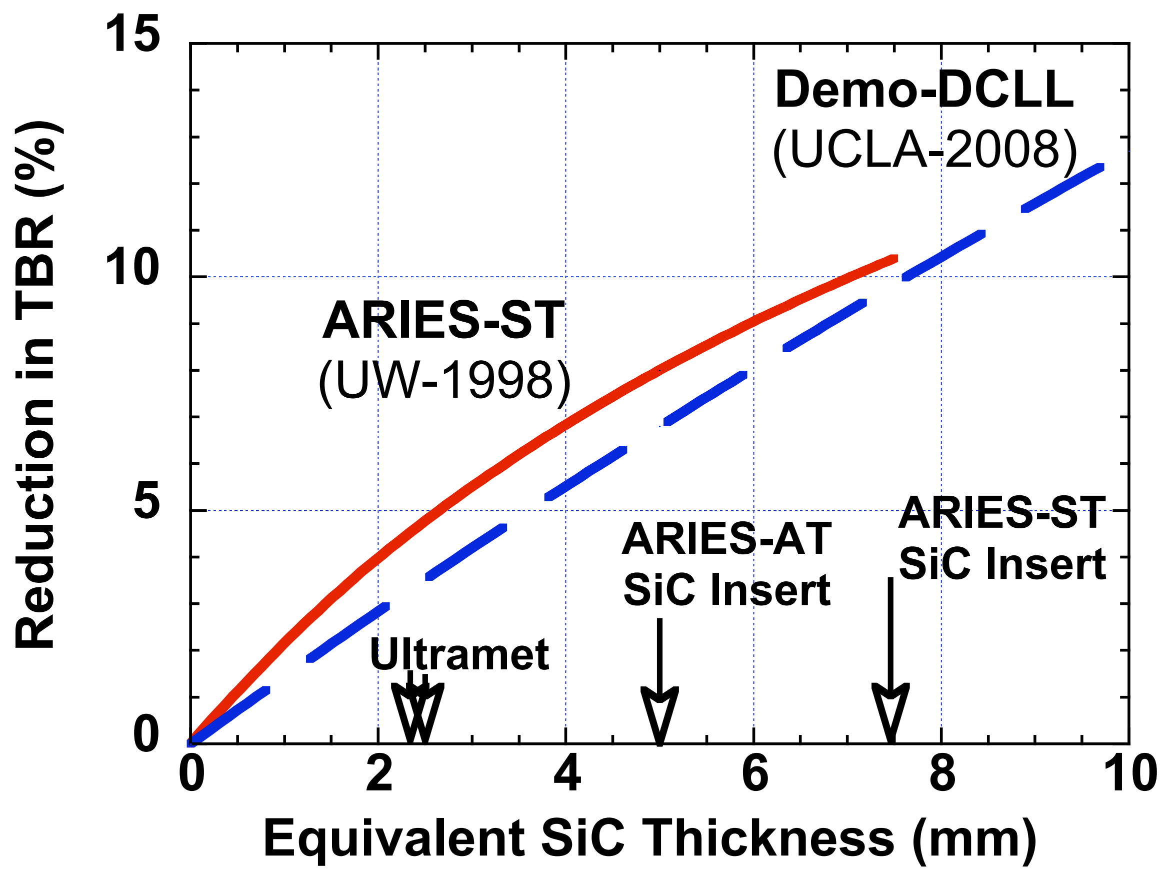
Results so far are promising.



For any type of SiC inserts:

Change of <u>electrical conductivity</u> with neutron irradiation could be significant (0.4 atom% Mg @ 3 FPY for 6 MW/m^2 NWL, per Sawan (UW)).

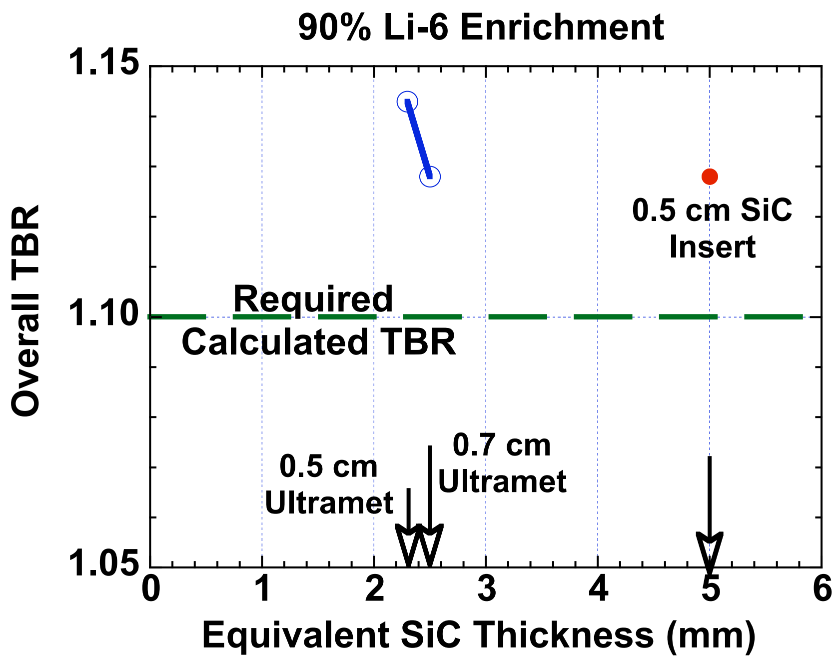
SiC Inserts Degrade Tritium Breeding

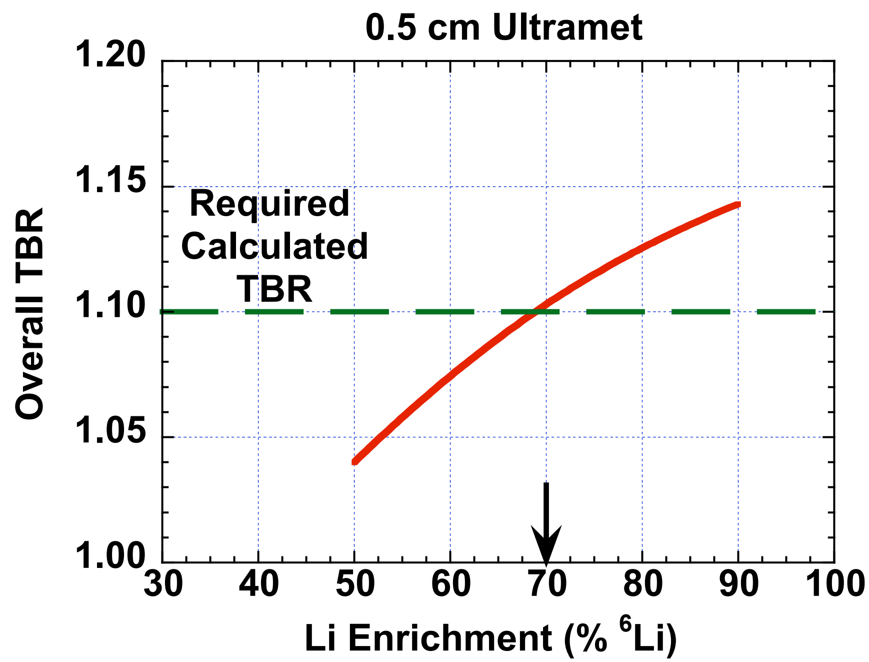


Less dense Ultramet alleviates impact of SiC on TBR, allowing lower enrichment (< 90%) and/or thinner blanket

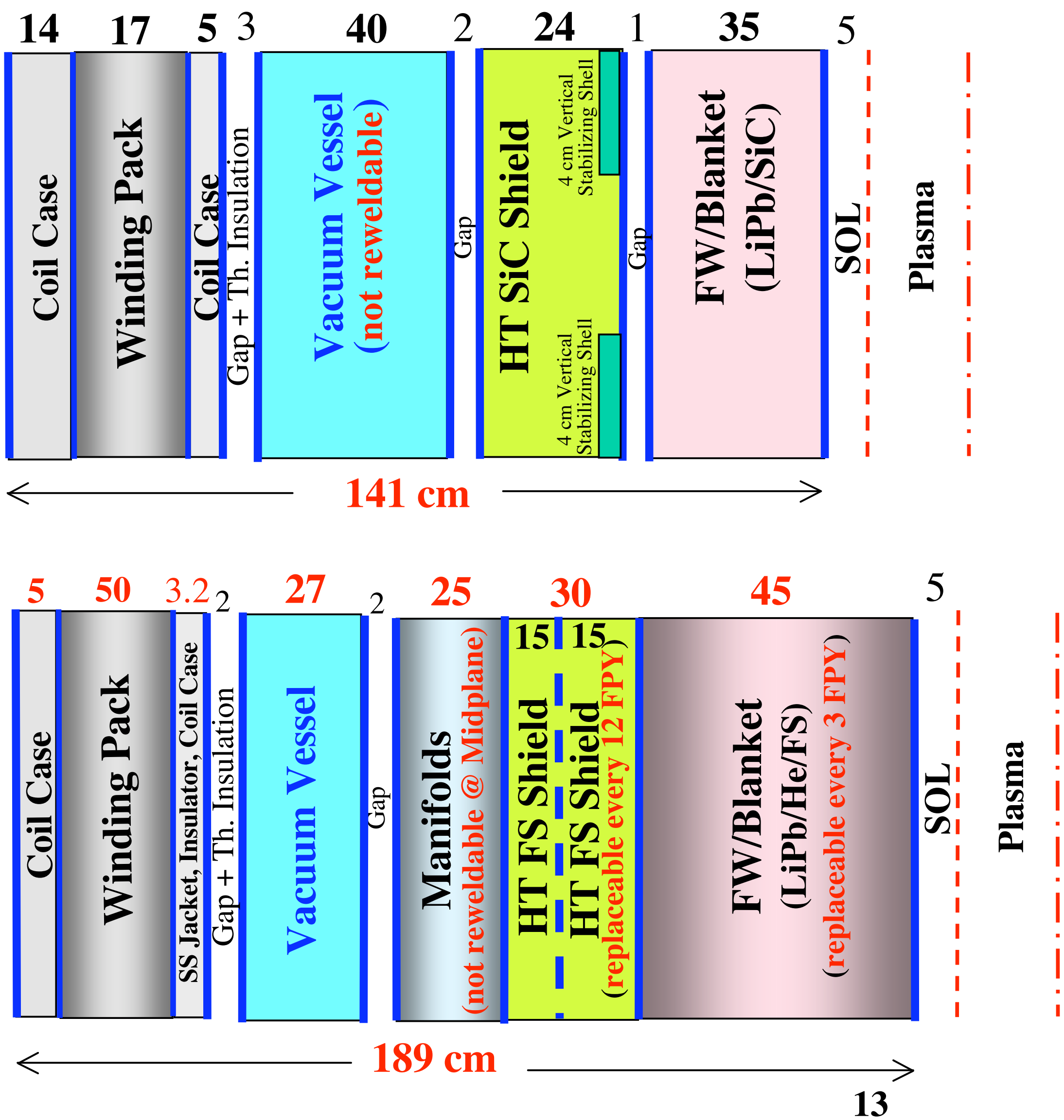
ARIES-AT-DCLL TBR

45 cm IB FW/Blanket/Back Wall
80 cm OB FW/Blanket/Back Wall
No Shells





ARIES-AT IB Radial Build



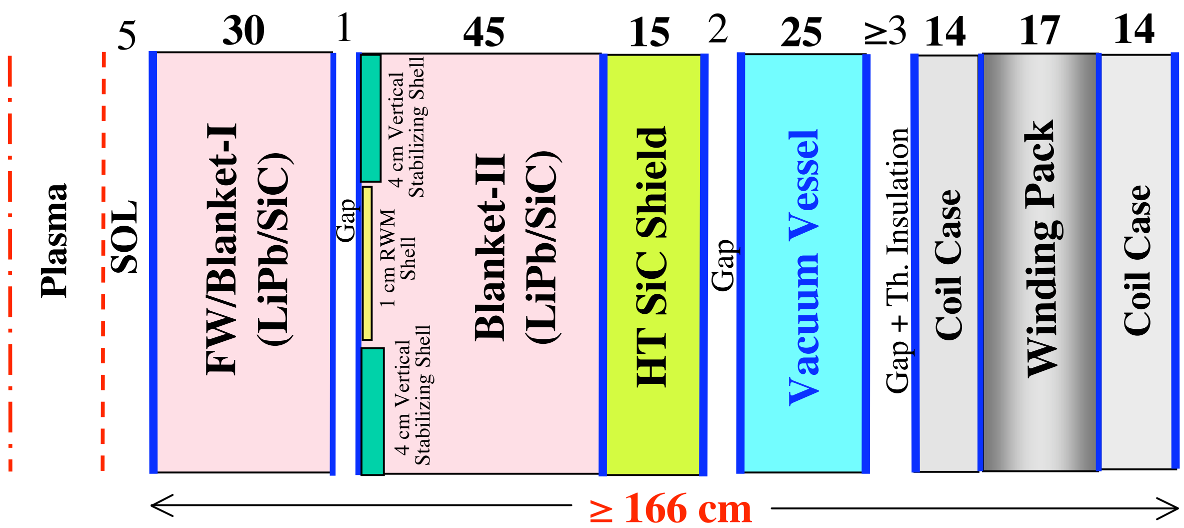
Reference

Proposed
ARIES-AT-DCLL

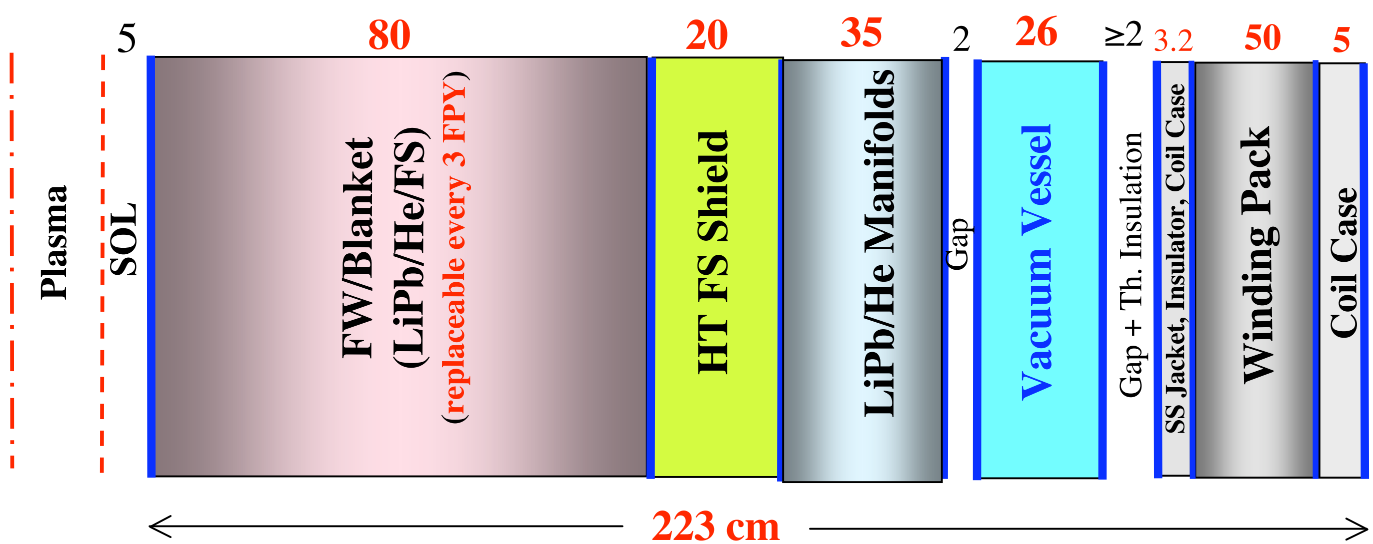
0.5 cm Ultramet
70% ^{6}Li Enrichment
No Shells

Δ = 48 cm

ARIES-AT OB Radial Build



Reference

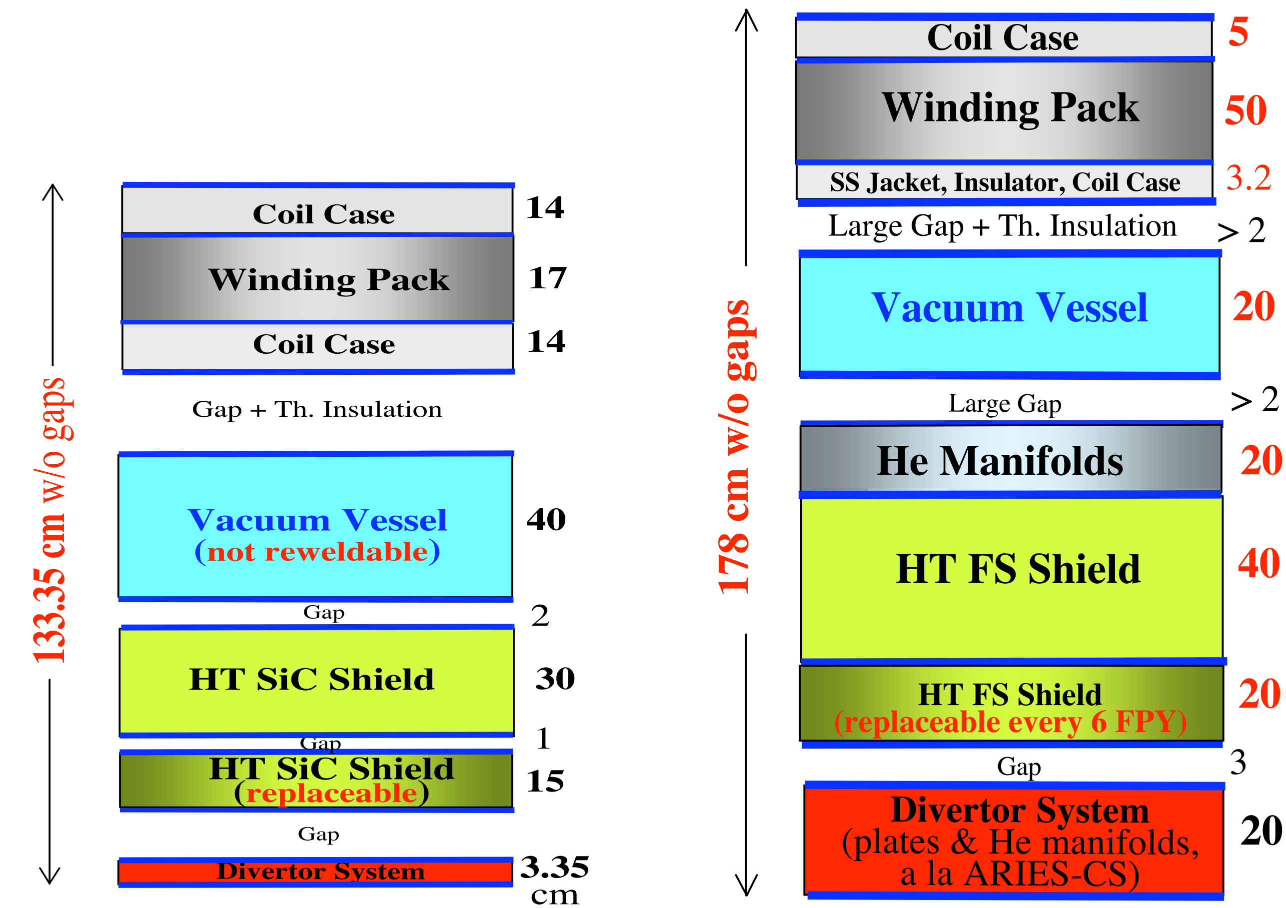


Proposed
ARIES-AT-DCLL

0.5 cm Ultramet
70% ^{6}Li Enrichment
No Shells

Δ = 57 cm

ARIES-AT Divertor Radial Build



Reference

Proposed
ARIES-AT-DCLL

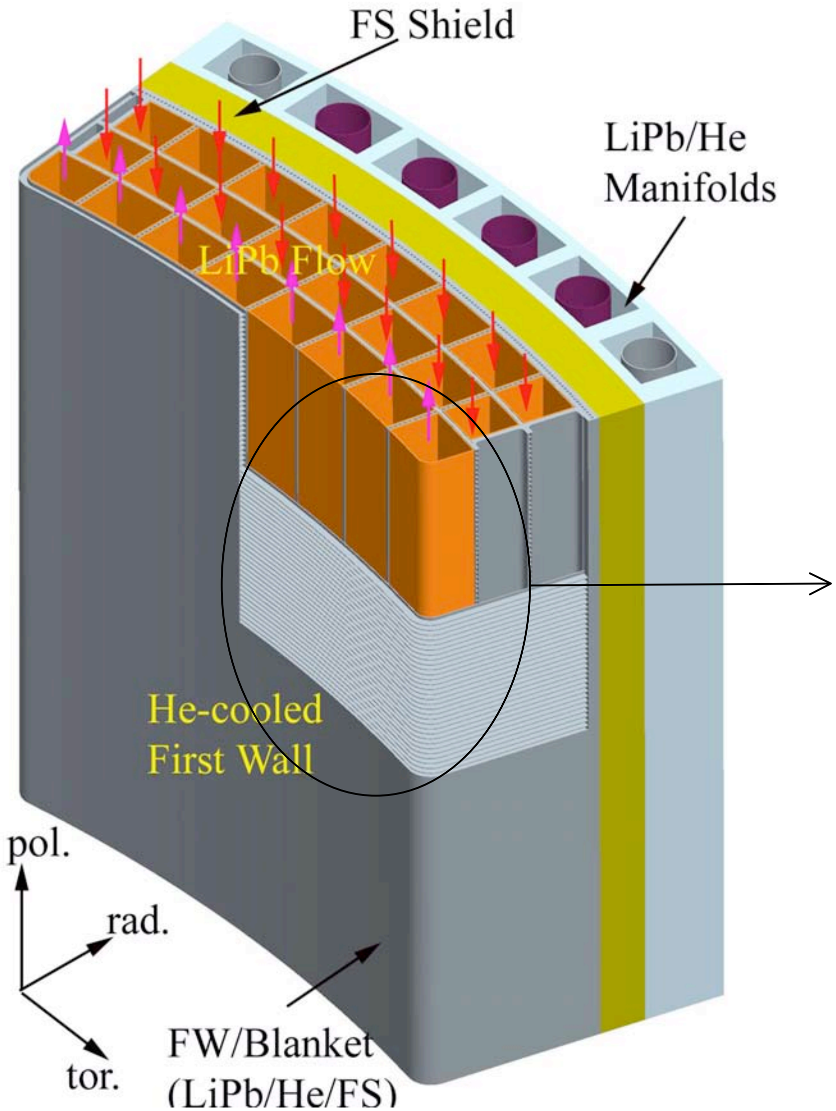
Δ = 45 cm

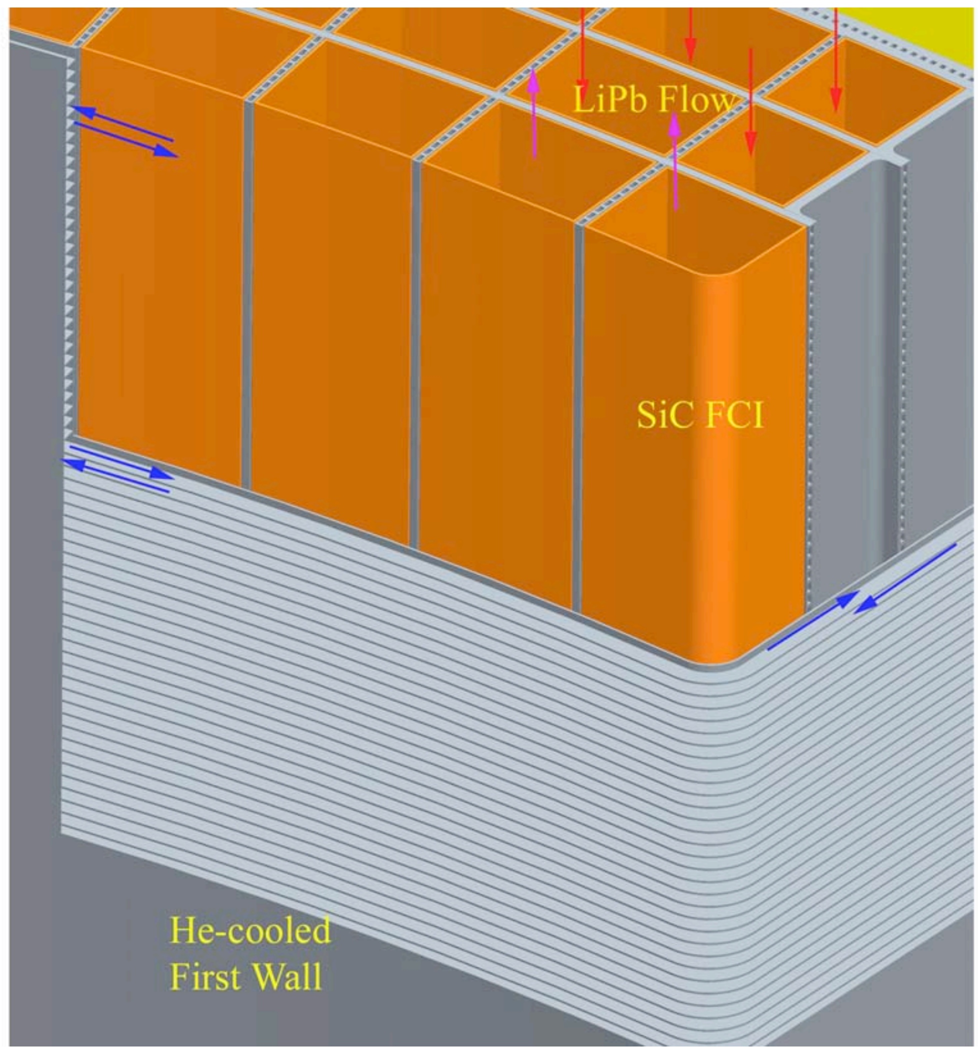
Radiation Level

	IB	OB	Div.	Limit
Peak NWL (MW/m^2)	3.4	4.8	2	
Peak atomic displacement @ FW and W of div:				
dpa / FPY	68	73	7.4	
FW dpa @ 2.8 FPY	190	200		200
dpa at W of Div @ 2.8 FPY			20	???
dpa at shield (dpa @ 40 FPY):				200
Replaceable	640	---	1080	
Permanent	160	109	160	
He production at manifolds (He appm @ 40 FPY)	5*	1	0.8	1
He production at VV (He appm @ 40 FPY)	1	0.2	0.1	1
LT Magnet @ 4 K:				
Fast neutron **fluence** (10^{19} n/cm^2 @ 40 FPY)	1	0.5	0.7	1
Nuclear **heating** (mW/cm^3)	0.6	2	1	2

* Rewelding allowed at top/bottom, not around midplane.

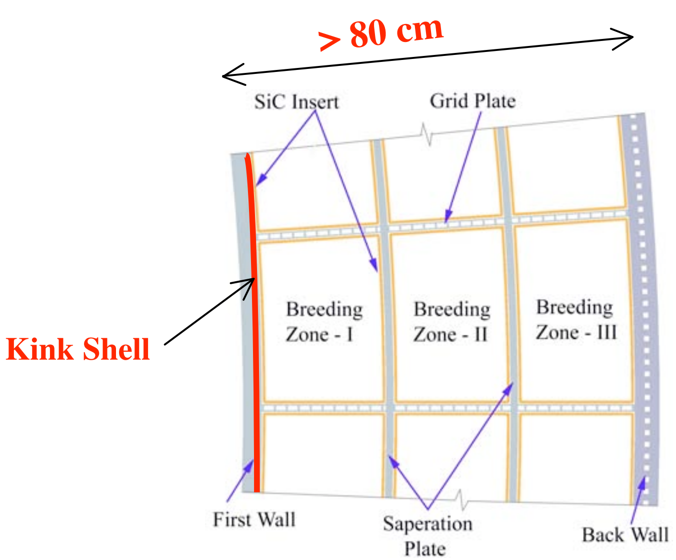
Isometric View of Proposed DCLL Blanket



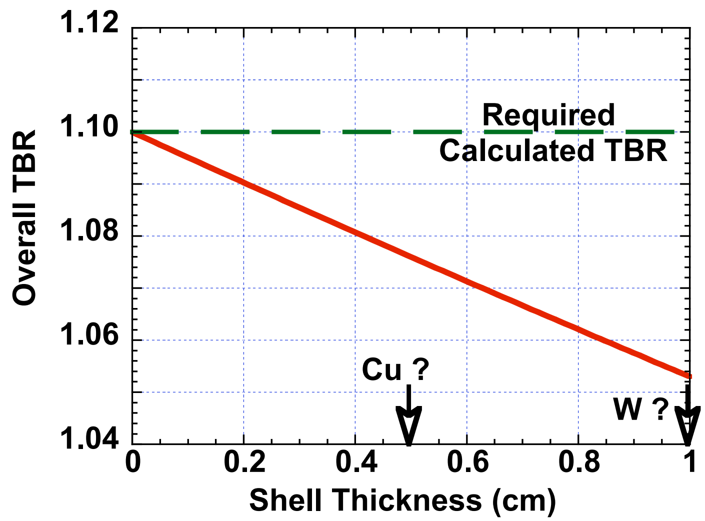


Kink Shell Behind OB FW ?

- **Could Cu or W kink shell be placed behind OB FW?**
- Could Cu operate at 700 °C? Is W the only option?
- Integration of kink shell with blanket?
- Impact on breeding?



ARIES-AT-DCLL OB Blanket
with kink shell behind FW



IB and/or OB Blanket
should be thickened to compensate
for losses in breeding

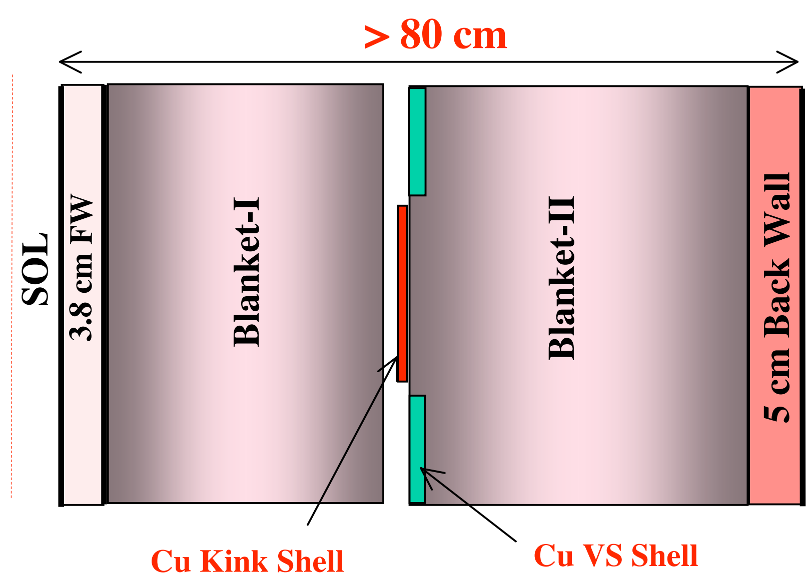
Shells Between OB Blanket Segments ?

- **Could OB blanket be segmented into two segments to accommodate shells** (al la ARIES-AT)**?**

- **Advantages**:
  - Less integration problems
  - Less impact of shells on breeding
  - Lifetime of back blanket segment > 3 FPY (~15 FPY)
  - Notable reduction in lifecycle radwaste volume.

- **Need**:
  Innovative method to support and cool both blanket segments.

ARIES-AT-DCLL OB Blanket
with Cu kink and VS shells
between OB blanket segments
(blanket temp < 700 ^{o}C)



Economic Trend

	ARIES-AT-LiPb/SiC (Reference)	ARIES-AT-DCLL	Cost of ARIES-AT-DCLL
IB, OB, Div radial standoff*	135, 160, 133 cm	185, 219, 178 cm	↑
Limit on max. NWL (MW/m^2)	~6	< 5.5	
Major radius	5.2 m	> 5.2 m	↑
Calculated overall **TBR**	1.1 w/ 90% ^{6}Li enrichment	1.1 w/o shells w/ 70% ^{6}Li enrichment	
FW/blanket **lifetime**	~4 FPY ⇒ 18 MWy/m^2	~2.8 FPY ⇒ 13 MWy/m^2	↑
Overall **energy multiplication**	1.1	~1.15	↓
Structure unit cost#	~620 $/kg	~95 $/kg	↓
η_{th}	~ 60%	40-45%	↑
Cost of **heat transfer/transport system#**	~$160M	> $300M	↑
He **pumping power**	---	> 100 MW_e	↑
Level of Safety Assurance (**LSA**) factor	1	2	↑
COE:			↑
in 1992 $	48 mills/kWh	> 60 mills/kWh	
in 2008 $	70 mills/kWh	> 90 mills/kWh	

* Excluding gaps.
\# In 2008 $.

Observations and Recommendations

Observations:

- DCLL system increases ARIES-AT radial standoff by 50-60 cm
  - ⇒ Larger and more costly ARIES-AT-DCLL machine
- Less dense SiC inserts lessen -ve impact on breeding
- Adding stabilizing shells will degrade breeding, requiring thicker IB/OB blankets, if effective.

To enhance ARIES-AT-DCLL design:

- Investigate means to reduce radial build standoffs, machine size, and cost (e.g., relocate manifolds at top/bottom*, lower He pumping power, etc.)
- Thicken IB blanket to protect IB shield for plant life (40 FPY)
- Segment OB blanket to accommodate stabilizing shells, alleviate impact of shells on breeding, and reduce radwaste stream.

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* As suggested by El-Guebaly @ Dec-07 ARIES meeting: DCLL Blanket for ARIES-AT: Major Changes to Radial Build and Design Implications.