Neutronics Evaluation and Updates for ARIES-DB-DCLL

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ARIES-Pathways Project Meeting

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UW - Madison

Objectives

- Redefine ARIES-Database-DCLL radial builds using ARIES-AT design parameters (R, a, and NWL) with:
  - DCLL blanket and shield:
    - 70% Li enrichment
    - 0.5 cm low-density Ultramel SiC inserts
    - No LiPb/He manifolds behind blanket/shield*
    - No stabilizing shells (to be added later)
  - LT magnets (instead of HT magnets).

- Develop 3 Options for IB radial build based on survivability of shield and/or reweldability of VV

- JK2LB or Incoloy-908 steel for magnet?

- New W alloys for EU divertor and FW armor (and ARIES stabilizing shells!)

- Comparison of SiC/LiPb and DCLL Systems and economic trend.

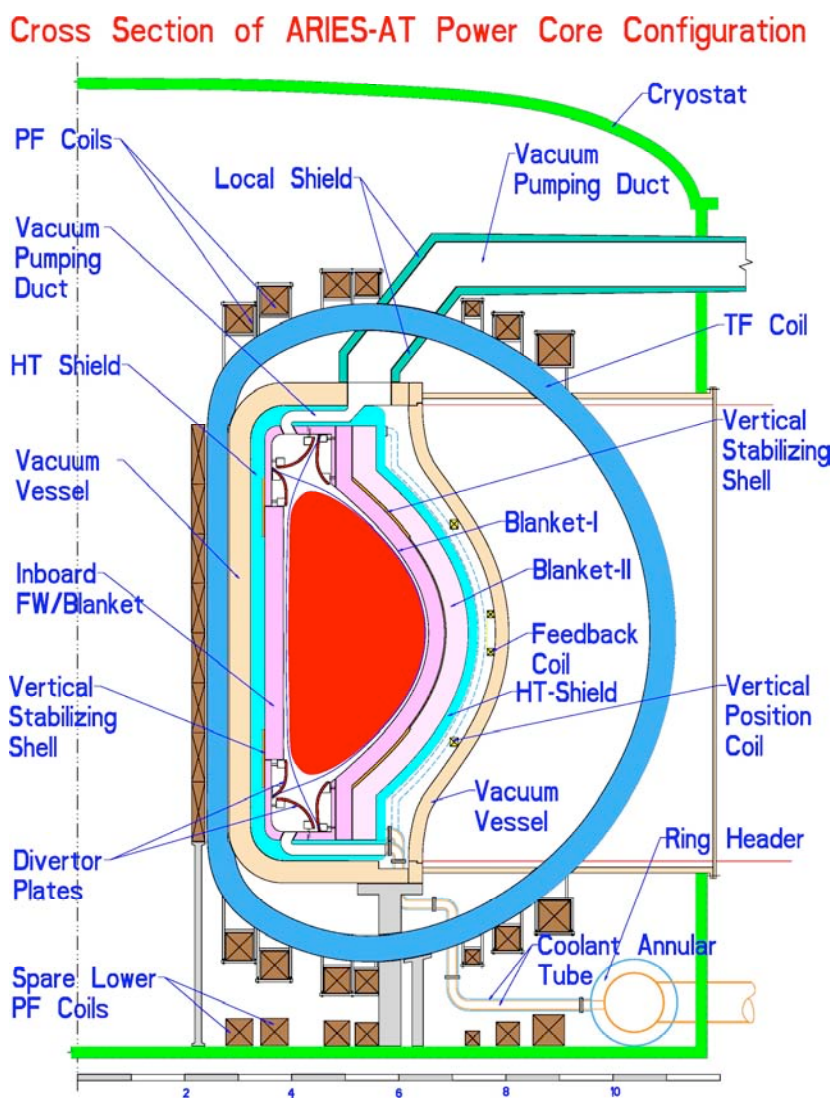
* To reduce radial build standoff, as originally proposed by L. El-Guebaly (12/07 and 3/08 presentations) and recently confirmed by S. Malang.

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/m²**
	3.4
SiC/SiC Composite Structure	
LiPb/SiC Blanket	
Discrete LiPb Manifolds	
HT S/C Magnet @ 70-80 K	
No W on FW	
Calculated Overall TBR	1.1
η_{th}	~ 60%
Availability	85%

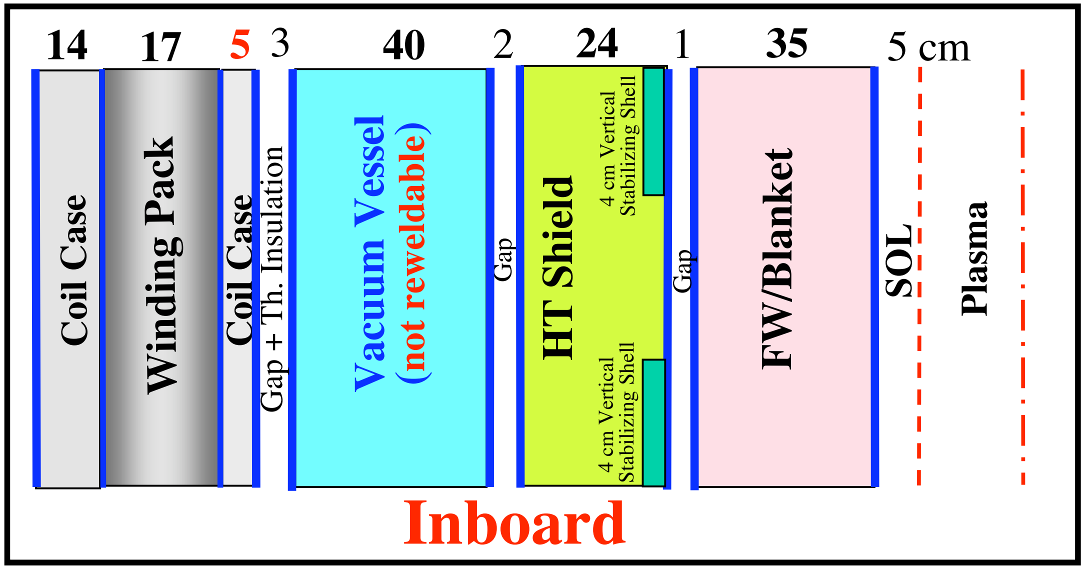
Plasma Control:

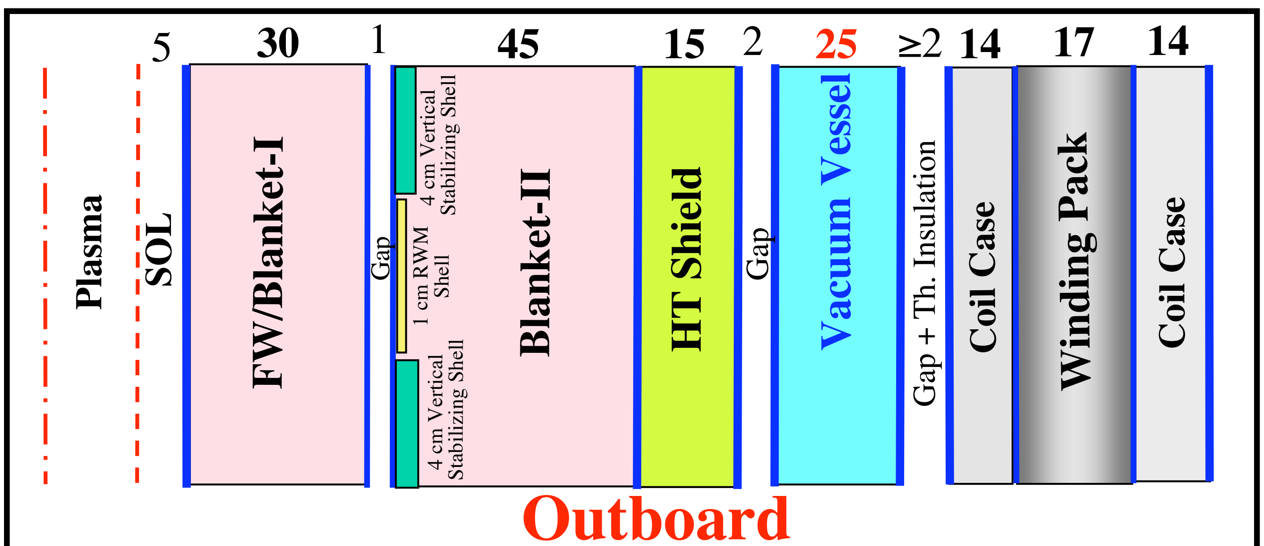
- 5 Tungsten Shells on IB and OB
- 2 Vertical Position Coils
- 2 Feedback Coils

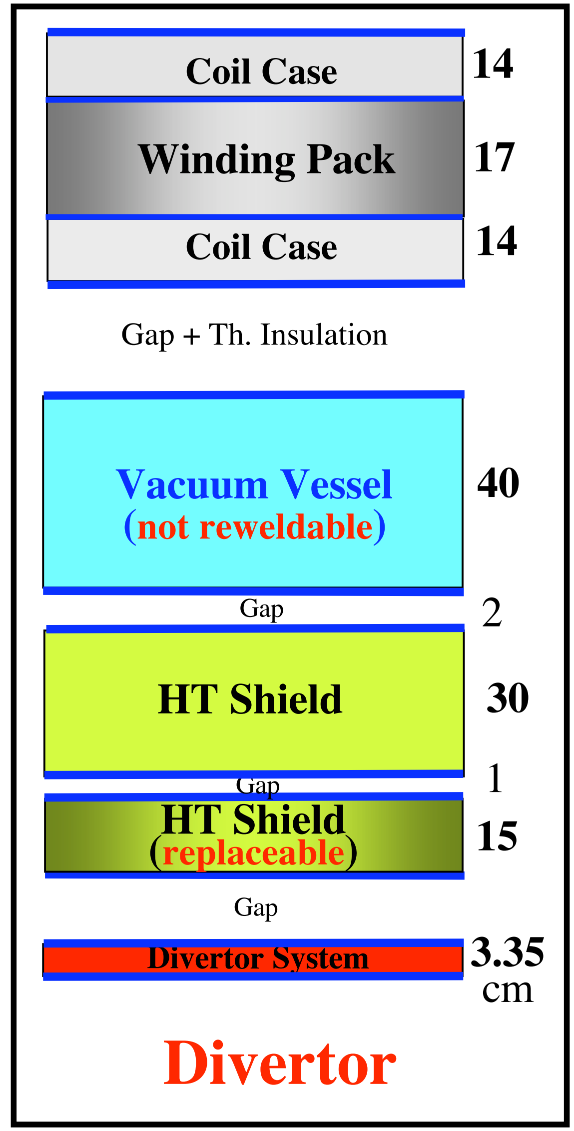


ARIES-AT Radial Builds: IB, OB, Div

(SiC Structure; HT Magnets)



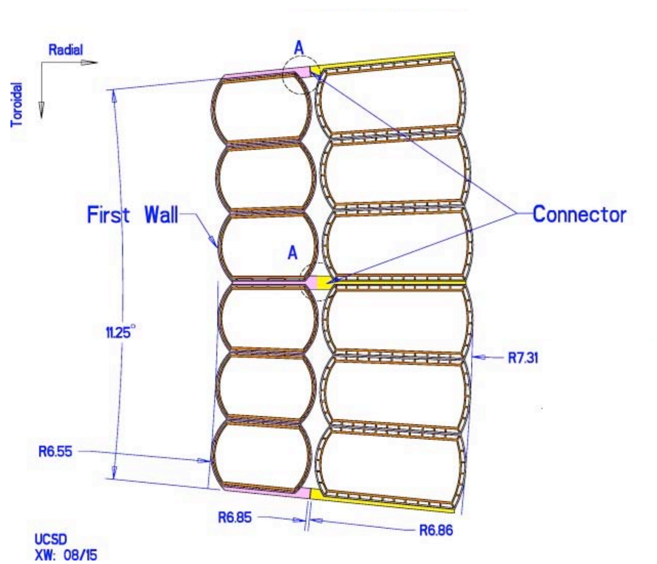




Blanket Options

ARIES-AT OB Blanket

SiC Structure

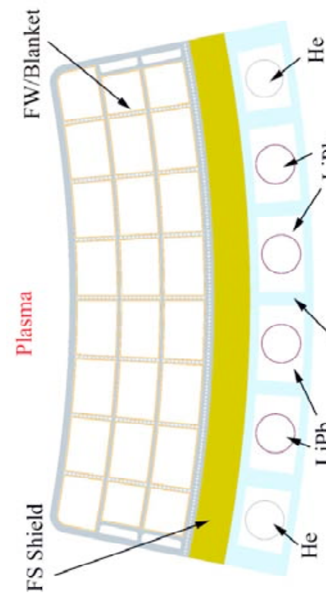


Breeder	LiPb
Coolant	LiPb
LiPb T_{out}	~1100 °C
η_{th}	~60%

ARIES-DB-DCLL OB Blanket

(a la ARIES-CS)

FS Structure



with or without manifolds?

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

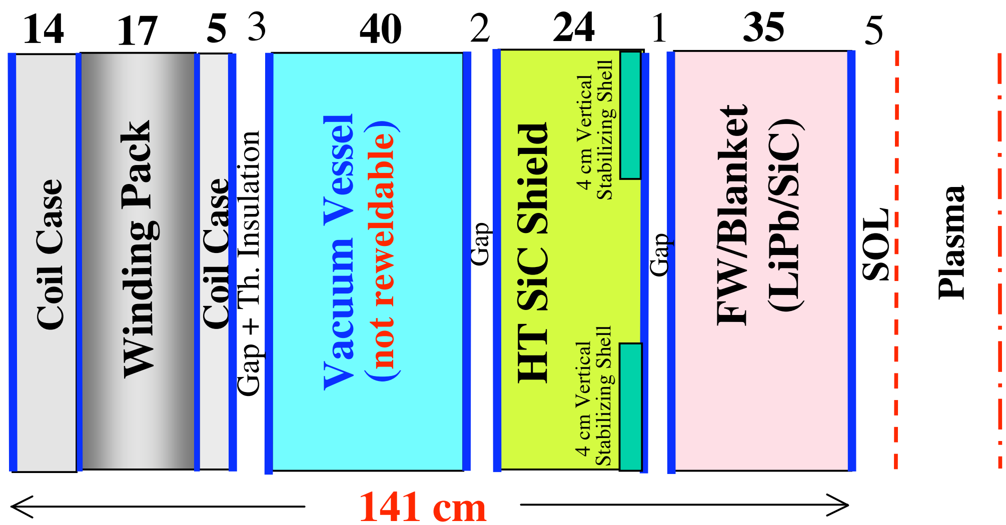
ARIES-DB-DCLL Radiation Limits and Key Parameters

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 @ VV#	1	He appm
(for reweldability of FS)		
LT S/C 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

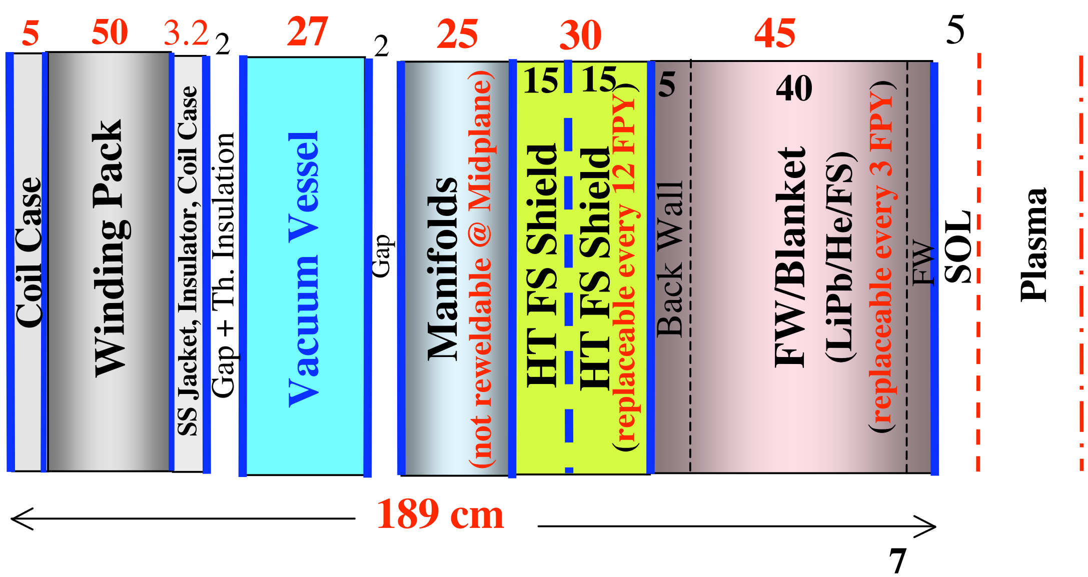
* For divertor plates, W stabilizing shells, and W armor, if needed.

\# IB VV need not to be reweldable.

ARIES-DB-DCLL IB Radial Build with Manifolds (1/09 presentation)



ARIES-AT



ARIES-DB-DCLL with Manifolds

$\Delta = 48$ cm

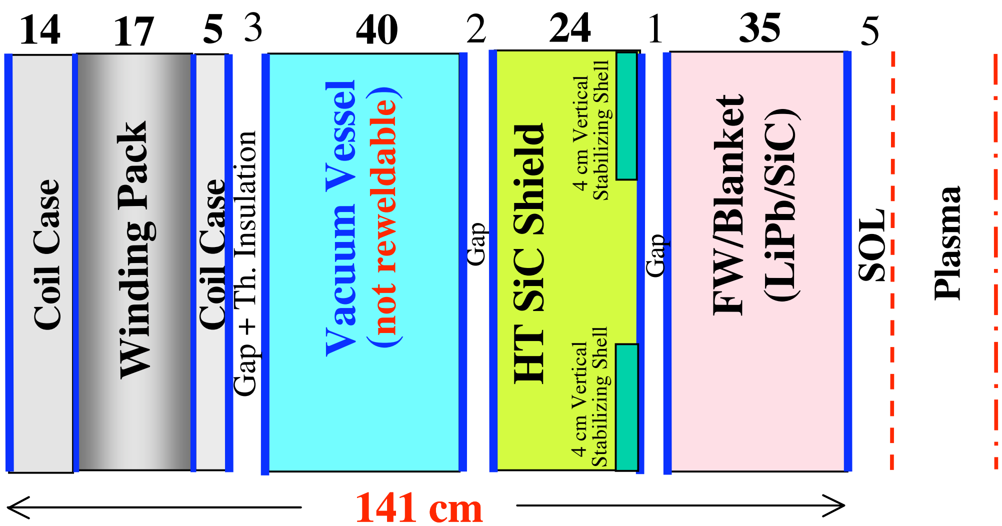
Main features:

- Thick radial build
- Half shield is replaceable
- Manifolds not reweldable near midplane
- Reweldable VV

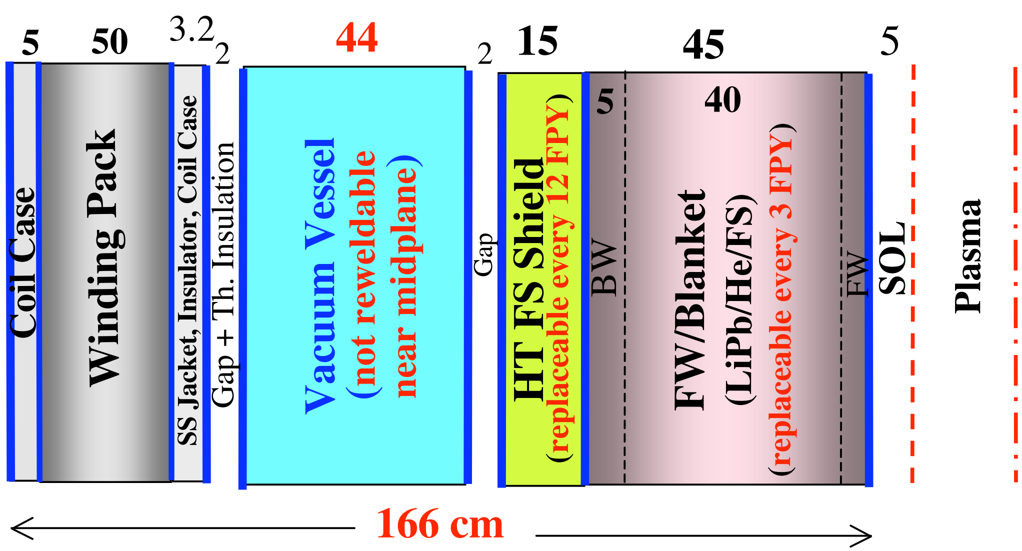
Variations to ARIES-DB-DCLL
IB Radial Build
without Manifolds

(based on reweldability of VV or He-access pipes to back of shield)

ARIES-DB-DCLL IB Radial Build-I without Manifolds



ARIES-AT



ARIES-DB-DCLL-I
without Manifolds

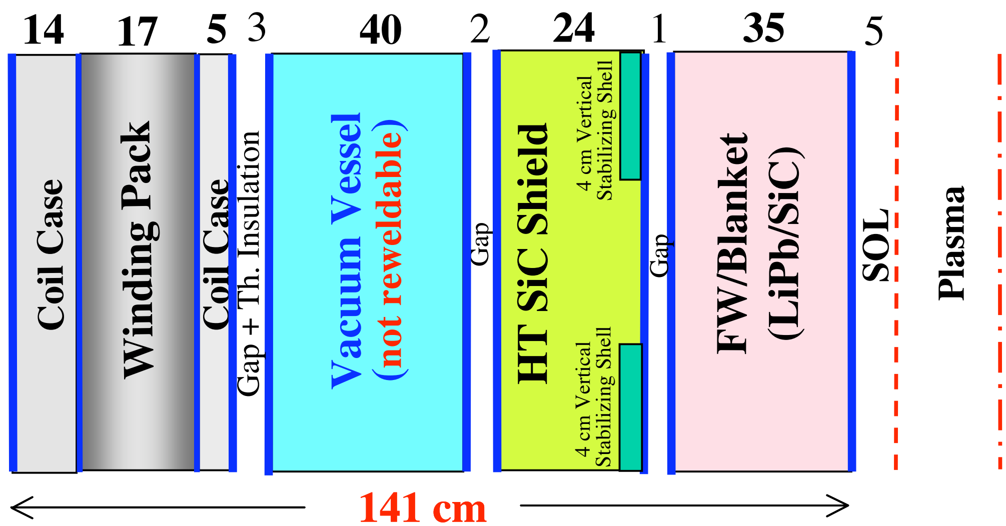
Δ = 25 cm
(vs 48 cm w/ mnflds)

Breakdown:
- 10 cm He/void
- 22 cm Δ magnet
- -2 cm gaps
- -5 cm better shielding materials

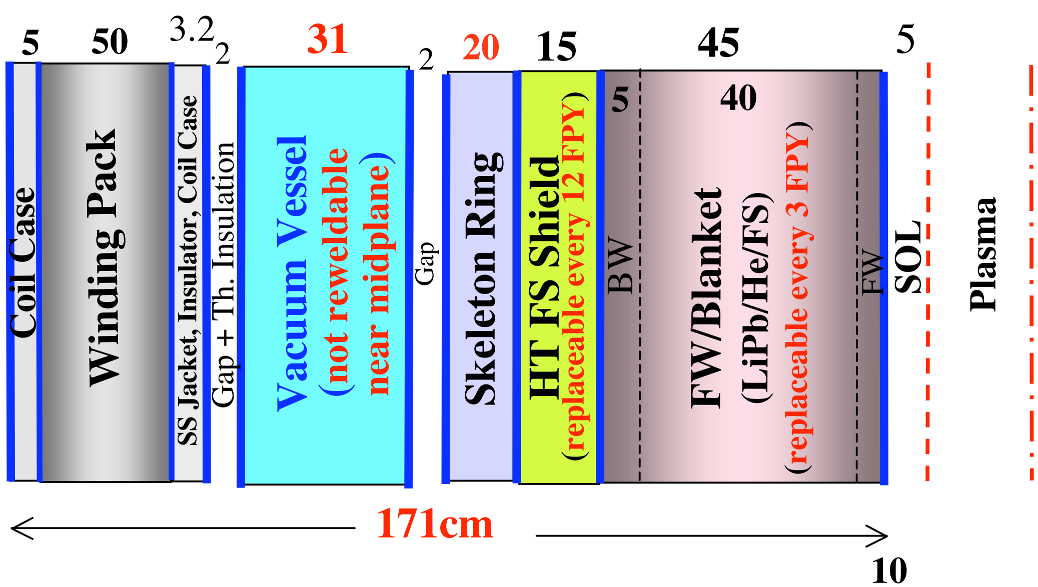
Main features:
- **Thinnest possible radial build**
- TBR ~1.1 (w/o shells)
- 15 cm replaceable shield
- **Thick VV** - not reweldable

ARIES-DB-DCLL IB Radial Build-II without Manifolds

Preferred IB Option



ARIES-AT



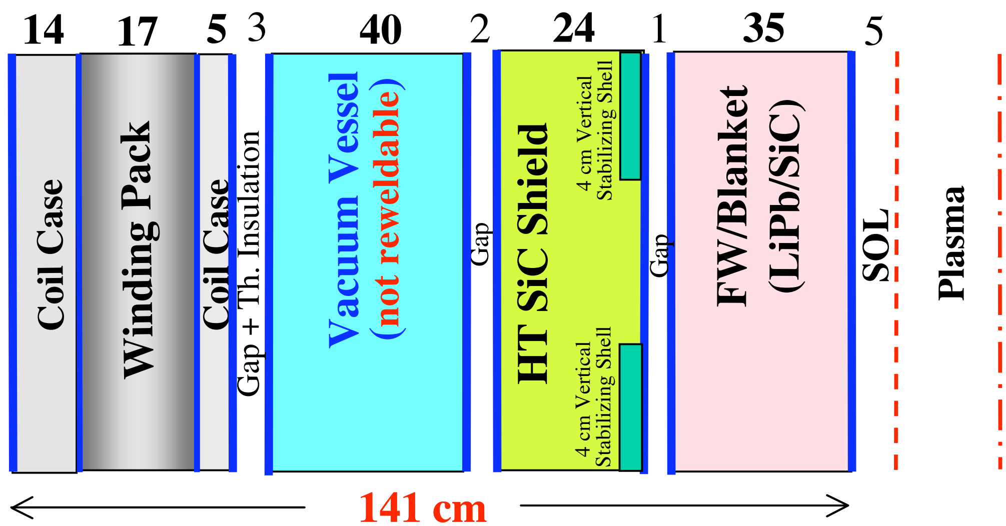
ARIES-DB-DCLL-I without Manifolds

Δ = 30 cm
(vs 48 cm w/ mnflds)

Breakdown:
- 12 cm He/void
- 22 cm Δ magnet
- -2 cm gaps
- -2 cm better shielding materials

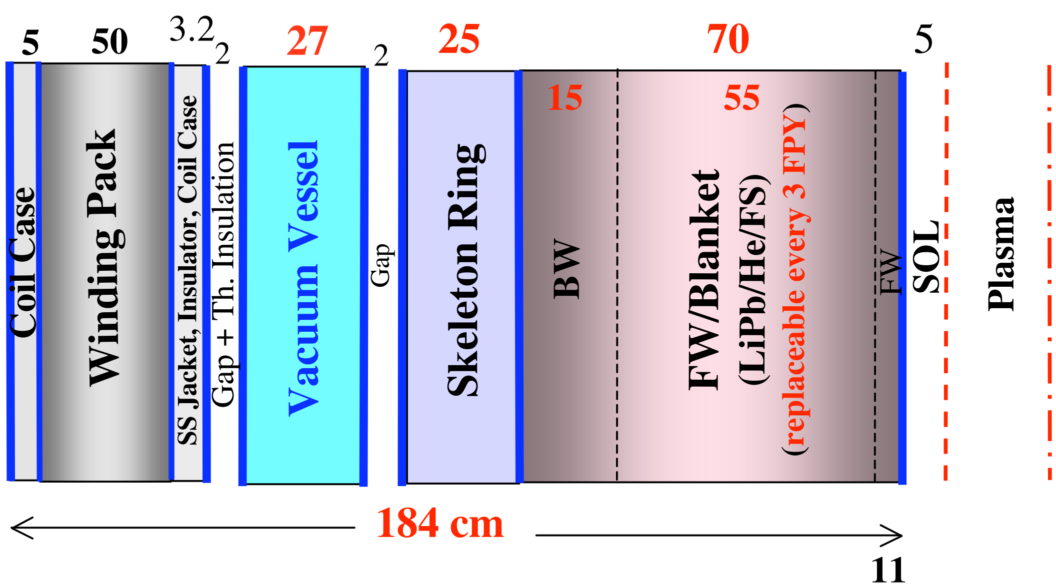
Main features:
- 15 cm replaceable shield
- **20 cm Skeleton Ring**, per Malang
- **Not reweldable VV**

ARIES-DB-DCLL IB Radial Build-III without Manifolds



ARIES-AT

ARIES-DB-DCLL-II without Manifolds



Δ = 43 cm
(vs 48 cm w/ mnflds)

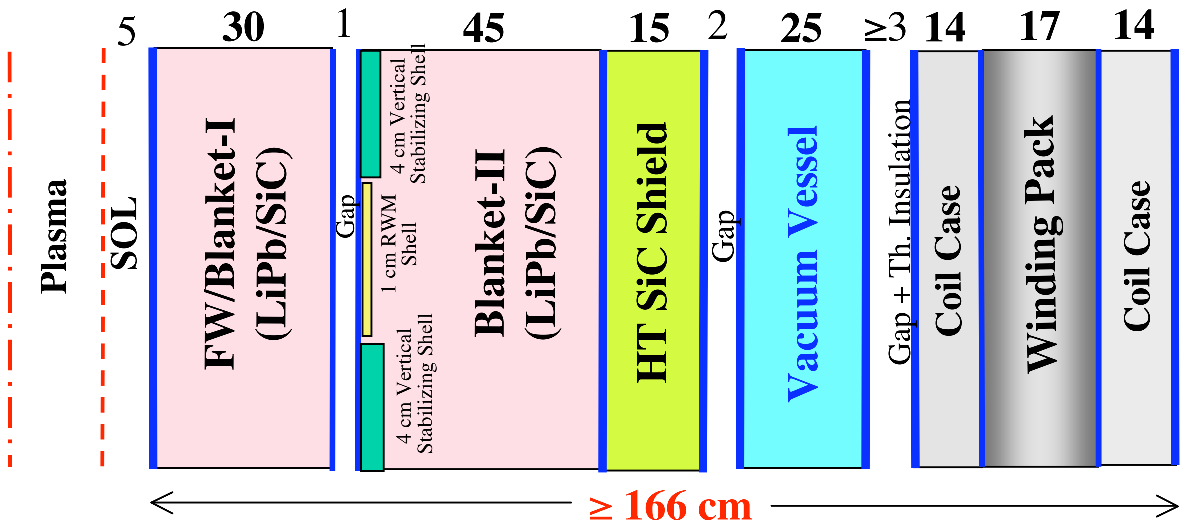
Breakdown:
- 14 cm He/void
- 22 cm Δmagnet
- -2 cm gaps
- 9 cm for less efficient shielding components (thicker blanket/BW/Ring and thinner VV)

Main features:
- **Sizable radial build**
- **Thick IB blanket**
- Higher **TBR ~1.14** (w/o shells)
- **No replaceable shield**
- **25 cm Skeleton Ring**
- **Reweldable VV / back of Ring**

ARIES-DB-DCLL OB Radial Build

ARIES-DB-DCLL OB Radial Build with Manifolds (1/09 presentation)

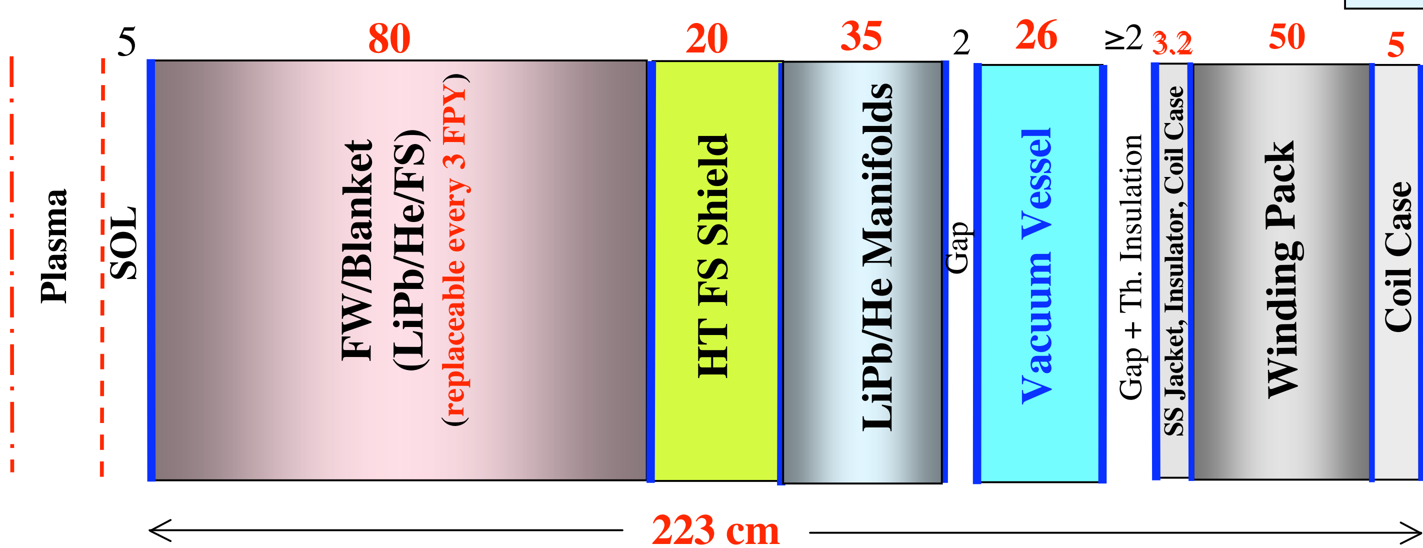
(Radial Xn Underneath Magnet)



ARIES-AT

ARIES-DB-DCLL with Manifolds

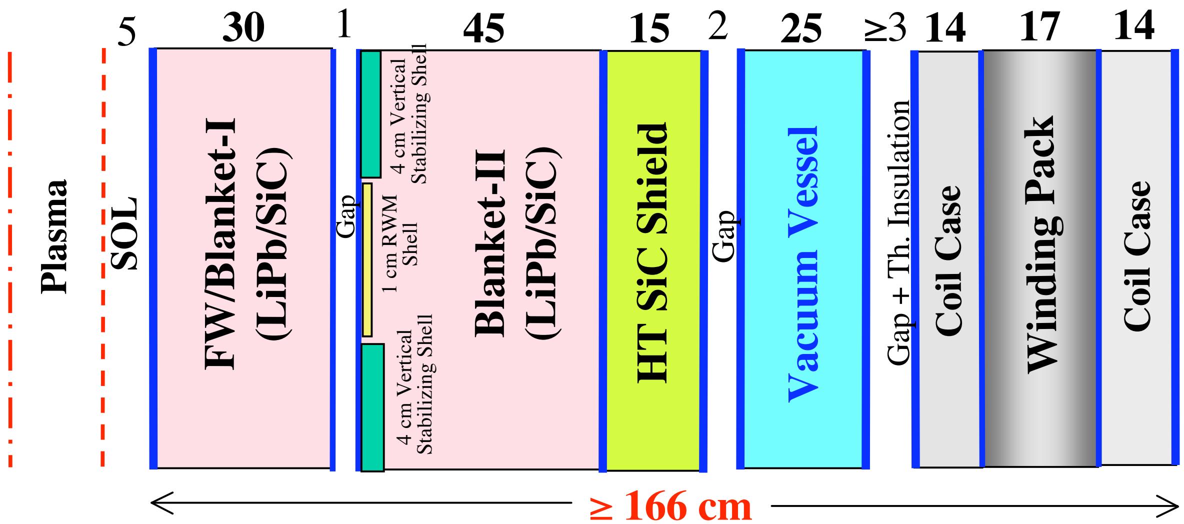
No Shells



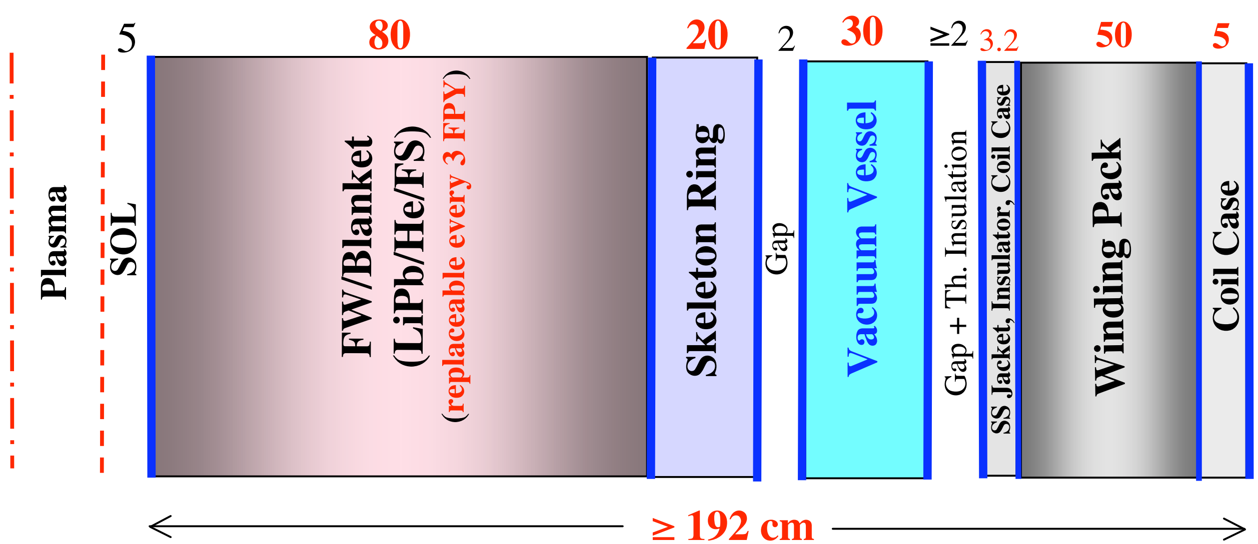
Δ = 57 cm

ARIES-DB-DCLL OB Radial Build
without Manifolds
(Radial Xn Underneath Magnet)

Preferred OB Option



ARIES-AT



ARIES-DB-DCLL without Manifolds

Δ = 26 cm
(vs 57 cm w/ mnflds)

No Shells

Breakdown:
- 14 cm He/void
- 13 cm Δ magnet
- -2 cm gaps
- 1 cm others

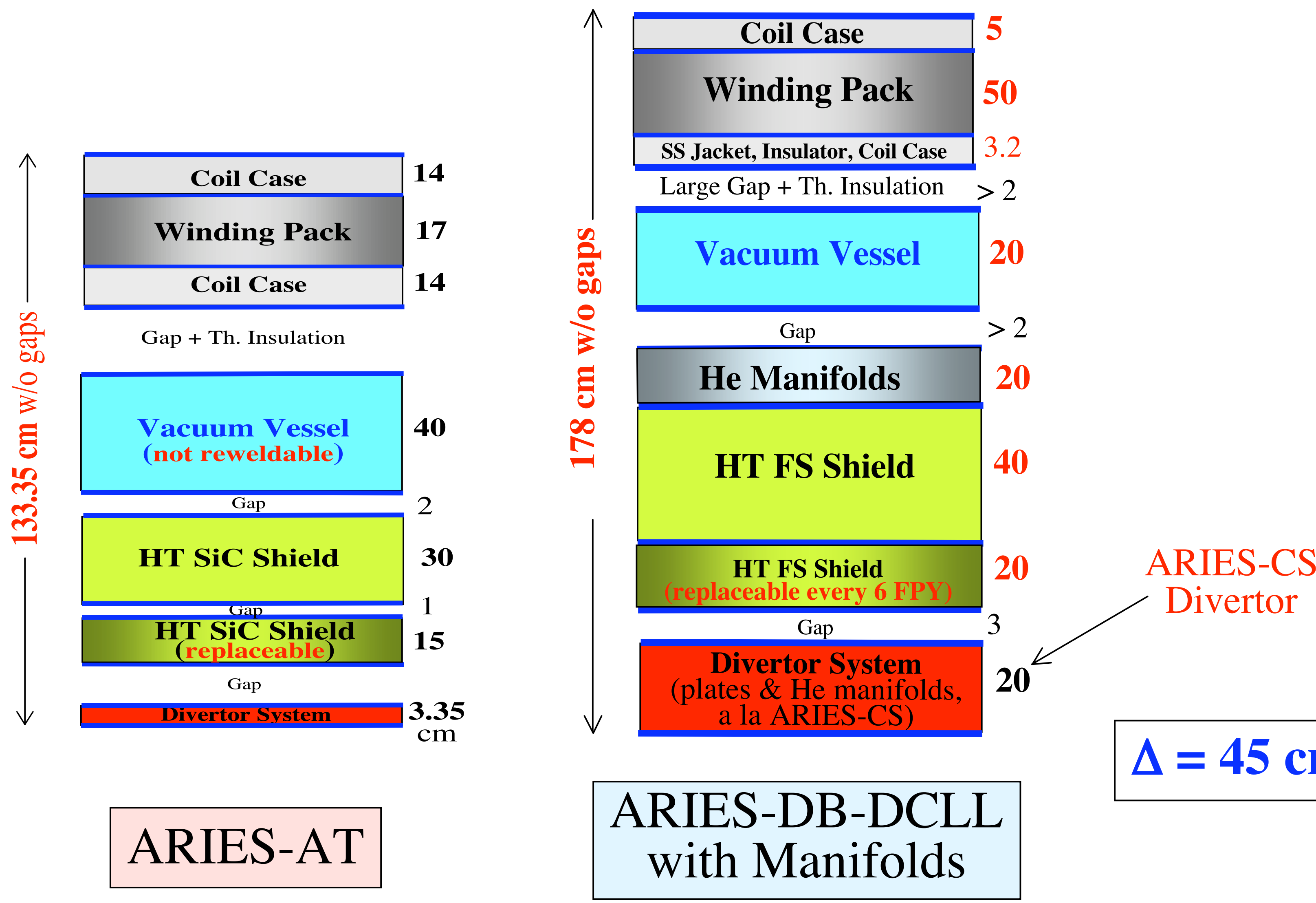
Main features:
- **Single piece, thick OB blanket**
- **20 cm Skeleton Ring**, per Malang
- **Reweldable VV / back of Ring**

ARIES-DB-DCLL

Upper/Lower Radial Build

(most challenging because of large vacuum pumping ducts)

ARIES- DB-DCLL Div Radial Build with Manifolds (1/09 presentation)



Δ = 45 cm

ARIES- DB-DCLL Div Radial Build without Manifolds

Preferred Div Option

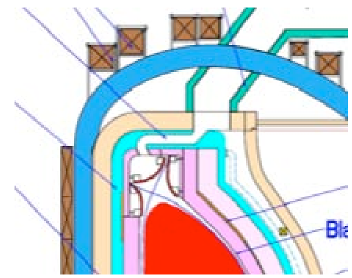
Div **pumping ducts** present streaming problem. 3-D analysis will be performed to check reweldability of He-access pipes to back of Ring.

ARIES-AT (133.35 cm w/o gaps)

Coil Case	14
Winding Pack	17
Coil Case	14
Gap + Th. Insulation	
Vacuum Vessel (not reweldable)	40
Gap	2
HT SiC Shield	30
Gap	1
HT SiC Shield (replaceable)	15
Gap	
Divertor System	3.35 cm

ARIES-DB-DCLL without Manifolds (158 cm w/o gaps)

Coil Case	5
Winding Pack	50
SS Jacket, Insulator, Coil Case	3.2
Large Gap + Th. Insulation	> 2
Vacuum Vessel	25
Gap	
Skeleton Ring	45
HT FS Shield (replaceable every 6 FPY)	20
Gap	
Divertor Plates	10



Reweldable (in absence of n streaming)

New Div Design

Δ = 25 cm (vs 45 cm w/ mnflds)

Breakdown:
- 12 cm He
- 13 cm Δ magnet

Compositions

	ARIES-AT-LiPb/SiC 90% Li-6 enrichment	ARIES-DB-DCLL* 0.5 cm Ultramet SiC, No Shells, 70% Li-6 enrichment
Inboard:		
FW		34% FS, 66% He
Blanket / Breeding Zones	81% LiPb, 19%SiC (includes FW)	76% LiPb, 13% He/void, 7% FS, 4%SiC
Back Wall	---	80% FS, 20% He
HT Shield / Skeleton Ring	15%SiC, 10% LiPb, 70% B-FS Filler , **5% W shells**	15%FS, 10% He, 75% B-FS Filler
VV	13% FS, 22% H_2O, 65% WC	15% FS, 35% H_2O, 50% WC
Outboard:		
FW		34% FS, 66% He
Blanket-I / Breeding Zones	80% LiPb, 20%SiC (includes FW)	77% LiPb, 12% He/void, 7% FS, 4%SiC
Blanket-II	77% LiPb, 20%SiC, **3% W shells**	---
Back Wall	---	80% FS, 20% He
HT Shield / Skeleton Ring	15%SiC, 10% LiPb, 75% B-FS Filler	15%FS, 10% He, 75% B-FS Filler
VV	30% FS, 70% H_2O	28% FS, 52% H_2O, 20% B-FS
Top/Bottom:		
Divertor System	40%SiC, 50% LiPb, 10% W	25% FS, 25% W, 50% He
Replaceable HT Shield	15%SiC, 10% LiPb, 75% FS Filler	15%FS, 10% He, 75% B-FS Filler
Permanent HT Shield / Skeleton Ring	15%SiC, 10% LiPb, 75% B-FS Filler	15%FS, 10% He, 75% B-FS Filler
VV	13% FS, 22% H_2O, 65% WC	19% FS, 50% H_2O, 31% B-FS

1-D Estimate for Radiation Damage Includes Safety Factor of 3

- Based on 1-D analysis, all radiation limits are met for ARIES-DB-DCLL preliminary design, except at:
  - **IB shield** ⇒ Replace front layer of IB shield every 12 y
  - **IB VV** ⇒ Locate cut/weld points at top/bottom of IB VV, away from midplane (as in ARIES-AT).
  - **Divertor shield** ⇒ Replace front layer of div shield every 6 y.

- Estimated 1-D radiation levels at shield, VV, and magnet include **Safety Factor of 3*** that accounts for:
  - Neutron streaming through "zigzag" assembly gaps (factor of ~2).
  - Uncertainty in nuclear data (factor of ~1.5).

- Safety Factor will be updated and adjusted for individual components according to recent 3-D streaming analysis (see T. Bohm's presentation).

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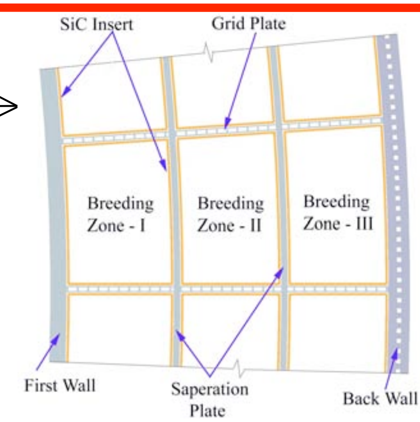
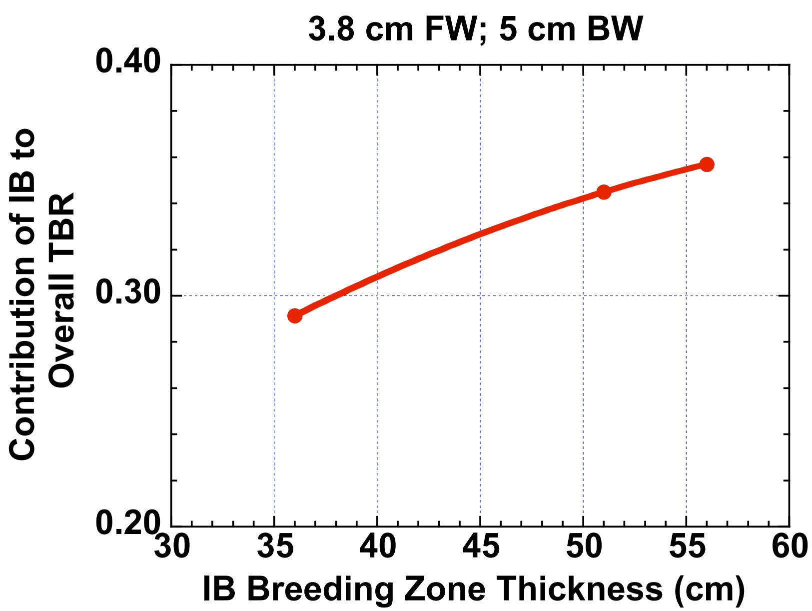
* L.A. El-Guebaly and M.E. Sawan, "Shielding Analysis for ITER with Impact of Assembly Gaps and Design Inhomogeneities," Proceedings of 8th International Conference on Radiation Shielding, Arlington, Texas, 1047 (April 1994).

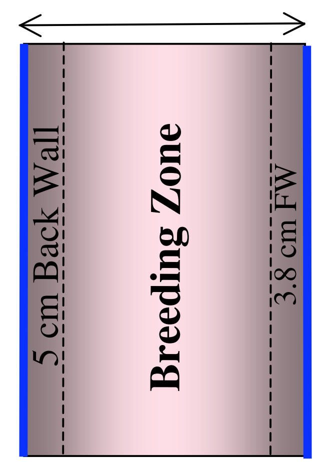
TBR will be Reevaluated for ARIES-DB-DCLL Blanket with Stabilizing Shells

Assumptions for TBR calculations:
- DCLL blanket with He cooling channels
- 70% Li-6 enrichment
- 0.5 cm thick low-density Ultramet SiC inserts
- Penetrations cover 2% of **OB** FW area
- No W armor on FW





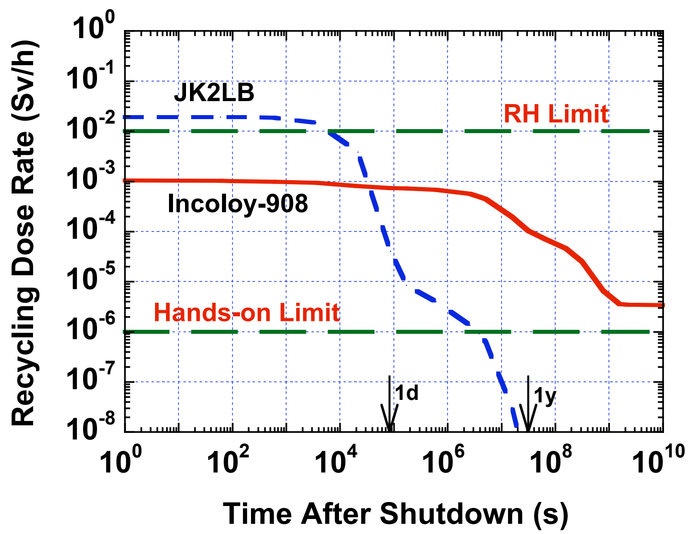
IB Blanket Thickness

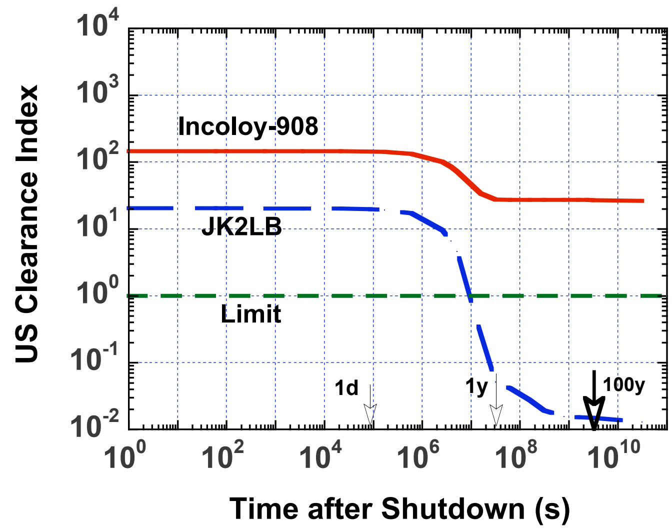


60 cm IB blanket could provide ~5% more breeding, but impact on magnet shielding should be assessed

JK2LB or Incoloy-908 for Magnet?

(ARIES-CS Study; 4/06 Presentation)





	Incoloy	JK2LB
Nb content	3 wt%	---
Class A WDR	0.1	0.0003
Recyclable?	**remotely** because of ^{94}Nb	with **hands-on**
Clearable?	**no** because of ^{94}Nb	**yes** after 1 y

Recommendation: for environmental reasons, use JK2LB structure in future magnet designs

JK2LB or Incoloy-908 for Magnet? (Cont.)

Quotes from ARIES-CS final papers:

El-Guebaly:

- The rationale for selecting the JK2LB steel over Incoloy-908 relates to the activation characteristics of the two candidate alloys.
- The activation assessment limited the material choices for one of ARIES-CS components. It provided a definitive answer to "what is the best structural material for ARIES-CS magnet: JK2LB or Incoloy-908?" The superior recycling and clearance characteristics of the JK2LB Japanese steel provided a strong incentive to use it as the reference magnet structure.

Bromberg:

- There are two drawbacks for choosing Incoloy-908:
  - In terms of the response of the different alloying materials to neutron irradiation, the high 3 wt% Nb content makes Incoloy 908 less environmentally attractive than JK2LB.
  - Because of the high Ni content, this material is substantially more expensive than specialty steels.
- It was decided to select JK2LB as the baseline material for the structure of the ARIES-CS magnets, and to keep Incoloy-908 as an alternative.

European W alloys for Divertor and FW Armor

(J.Pamela et al., “Key R&D Issues for DEMO: an analysis based on functional requirements,” JET Seminar, Feb. 2009)

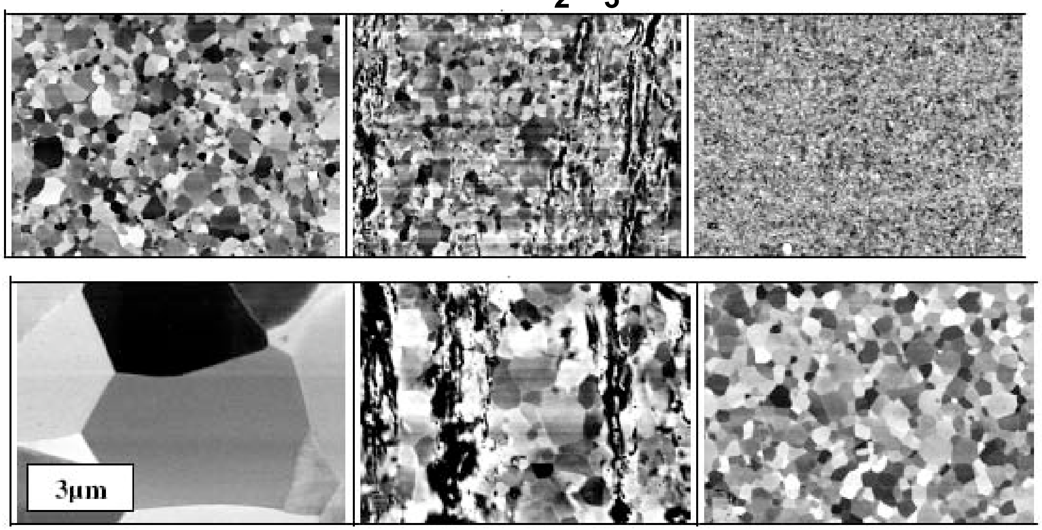
New alloys are being developed : **W-Ti, W-V** for structural applications,
W-Y_2O_3, W-Si-Cr, W-TiC for armour.

Behaviour under irradiation to be tested in a second stage

Severe Plastic Deformation & Alloying: To Improve the Fracture Toughness of W and W-alloys

Loss of Fracture Toughness

W | **W-La_2O_3** | **W-26%Re**



Annealing 1 hour

835 ^{0}C
Initial Microstructure Non-Affected

1200 ^{0}C
Unacceptable Recrystallisation

Recrystallisation resistance is unacceptably affected

UW Recommendation: Avoid using W-Re alloys for two reasons:

- Re generates high-level waste
- Transmutation of Re to Os adversely affects W properties, per R. Kurtz (PNL).

Comparison of SiC/LiPb and DCLL Systems and Economic Trend

	ARIES-AT-LiPb/SiC (Reference)	ARIES-DB-DCLL	Cost of ARIES-DB-DCLL
IB, OB, Div radial standoff*	135, 160, 133 cm	167, 188, 158 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 $ in 2008 $	 **48 mills/kWh** **70 mills/kWh**	 **> 60 mills/kWh** **> 90 mills/kWh**	↑

* Excluding gaps.
# in 2008$.
@ in 1992$.

Observations and Recommendations

Observations:

- Relocating He/LiPb manifolds helps reduce radial standoff.
- Compared to ARIES-AT, DCLL system increases radial build by ~30 cm

  ⇒ Larger and more costly ARIES-DB-DCLL design.
- Adding stabilizing shells may degrade breeding by few percent, depending on location.
- Divertor pumping ducts will increase radiation level behind divertor shield where reweldability of coolant pipes is essential.

Recommendations:

- Replace front layers of IB and div shields every 6-12 years.
- Avoid rewelding VV around IB midplane.
- Segment OB blanket as it offers design advantages (refer to1/09 presentation):
  - Alleviate impact of shells on breeding
  - Reduce radwaste stream.
- Use JK2LB steel for magnet.
- Adjust Safety Factor according to 3-D streaming results.

Qs and needs:

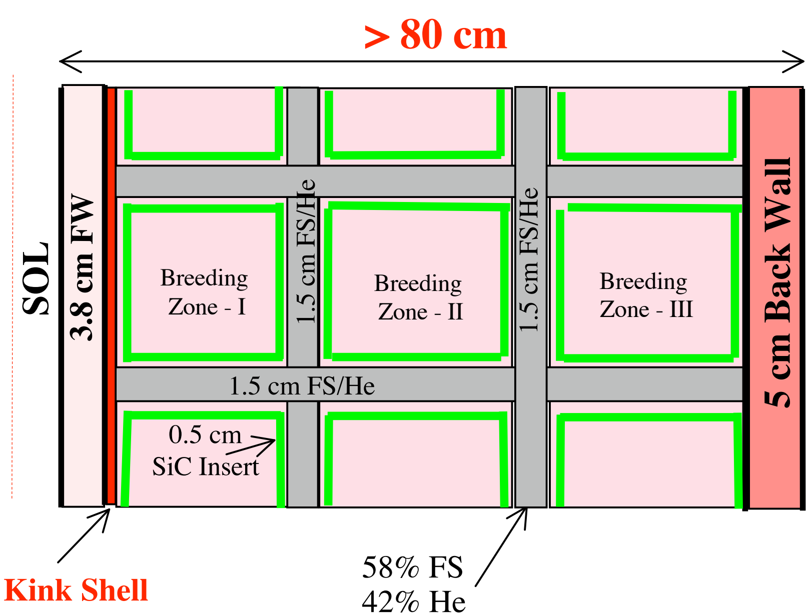
- Blanket composition and dimension (assure TBR ≥ 1.1).
- Locations of kink shells, vertical stabilizing shells, and feedback coils. Impact on TBR?
- Divertor plate dimension and composition.
- Divertor pumping ducts: size and location.
- VV design and FS content.
- W armor for FW?

To be considered:

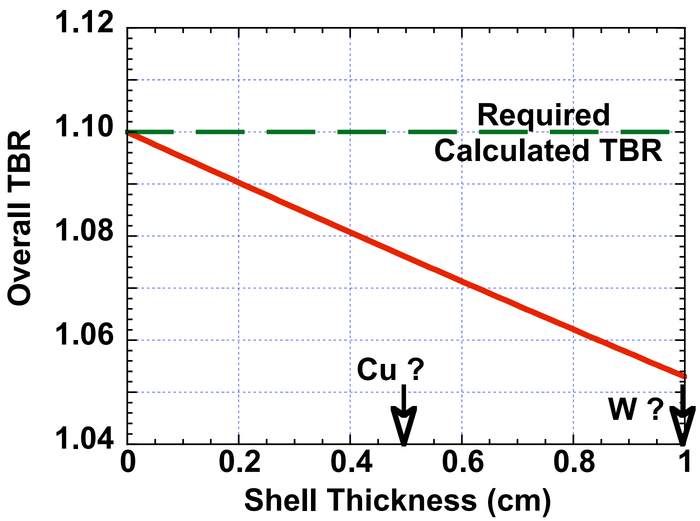
- Change of SiC electric conductivity with neutron irradiation.
- Change of electric conductivity of stabilizing shells with neutron irradiation.

Kink Shell Behind OB FW ?

- **Could Cu (or W) kink shell be placed behind OB FW?**
- Integration of kink shell with blanket?
- Impact on breeding?



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



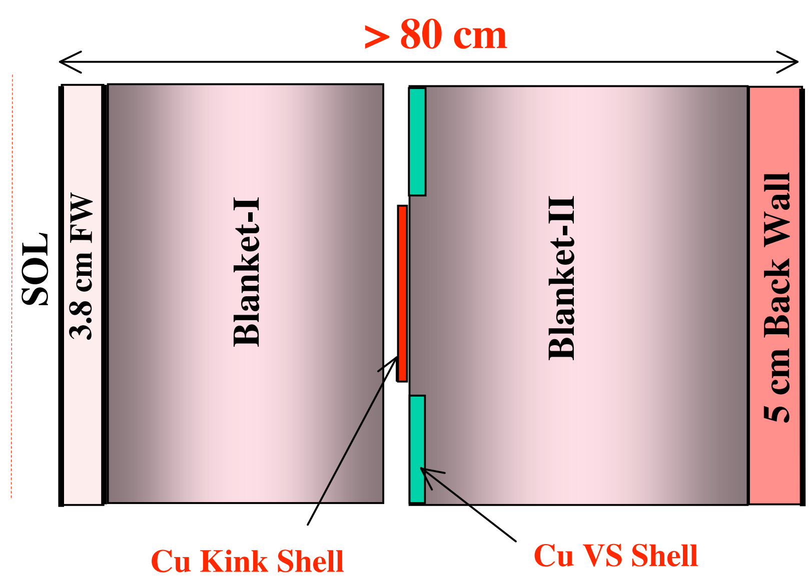
IB and/or OB Blanket
should be thickened to compensate
for losses in breeding

Shells Between OB Blanket Segments ?

- **Could OB blanket be segmented into two segments?**

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

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



Isometric View of OB Blanket with Manifolds