Radial Build Definition for LiPb/FS and Li/FS Systems

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With Input from:

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http://fti.neep.wisc.edu/FTI/ARIES/SEP2003/lae_radialbuild.pdf

ARIES-CS Project Meeting
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Atlanta, GA

Candidate Blanket Concepts

Breeder	Multiplier	Structure	Blanket/Shield Coolant	VV Coolant	VV Location
ARIES-CS:					
Flibe	Be	FS	Flibe	H_2O	Inside Magnet
LiPb	–	SiC	LiPb	H_2O	Inside Magnet
LiPb	–	FS	He	H_2O	Inside Magnet
LiPb	–	FS	He	He	Outside Magnet
Li	–	FS	He/Li	He	Outside Magnet
SPPS:					
Li	–	V	Li	He	Outside Magnet

Initial Parameters
(1/31/03 Strawman - L.P. Ku)

Net Electric Power	1000 MW_e
Fusion Power	2000 MW
# of Field Periods	3
A	4.5
< R >	8.25 m
< a >	1.85 m
Average Neutron Wall Loading (Γ)*	2 MW/m^2
FW Area	~ 800 m^2
Toroidal Length of Field Period	~ 9 m
Minimum Plasma to Mid-Coil Distance (Δ_{min})	1.2 m
# of Δ_{min} per Field Period	2
FW Coverage Fraction# for Shield-only Zones	8%

* Peak Γ is ~3 MW/m^2.

Sensitive to difference between Δ_{min} and nominal Δ .

Design Requirements and Radiation Limits

Overall TBR (for T self-sufficiency)	1.1	
dpa to FS Structure (for structural integrity)	200	dpa
Helium Production @ VV (for reweldability of FS)	1	appm
LT S/C Magnet (@ 4K):		
n **fluence** to Nb_3Sn (E_n > 0.1 MeV)	10^{19}	n/cm^2
Dose to polyimide insulator	10^{11}	rads
Nuclear **heating**	2	mW/cm^3
dpa to Cu stabilizer	6×10^{-3}	dpa
Biological dose outside building (dose during operation for workers and public protection)	2.5	mrem/h

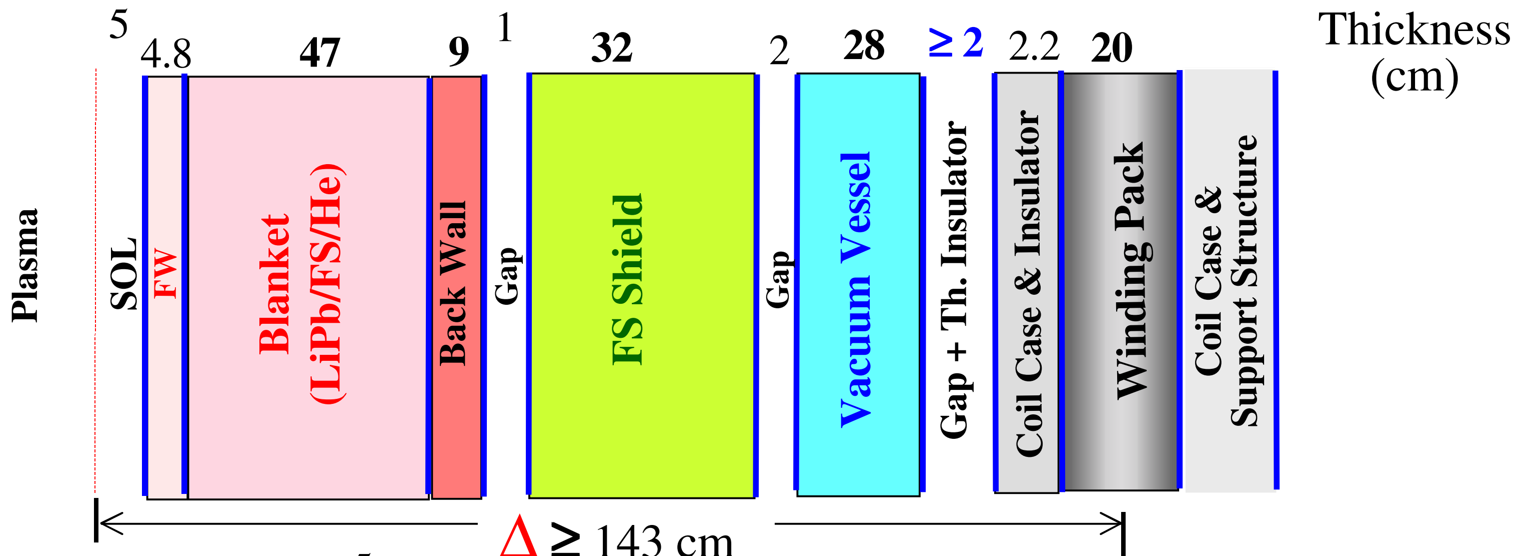
Assumptions

- Peak to average $\Gamma = 1.5$
- RF Penetrations and assembly gaps occupy 2% of FW area.
- Divertor plates/baffles:
  - 5 cm thick
  - 50% structure and 50% He coolant
  - Cover 15% of FW area.
- SPPS magnet composition.
- **8% FW coverage fraction** of shield-only zones used **for all blanket concepts.**
- **1-D** poloidal neutronics model with av. a = 1.85 m.

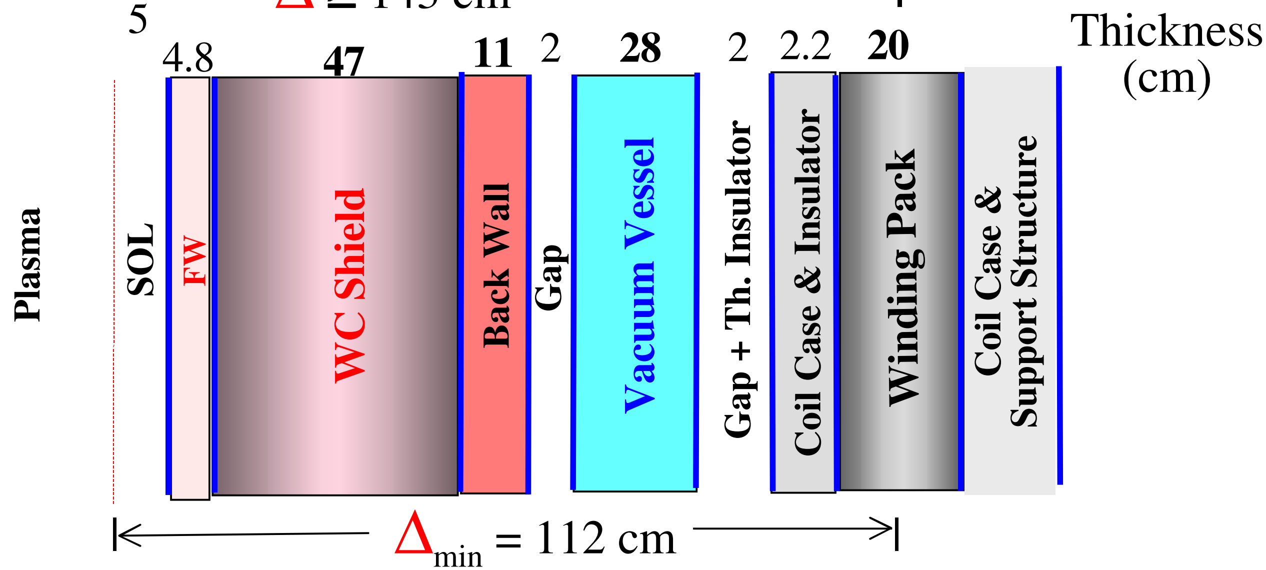
Recommended LiPb/FS/He Radial Build

(water-cooled **internal** VV)

Blanket Zones



Shield Only Zones



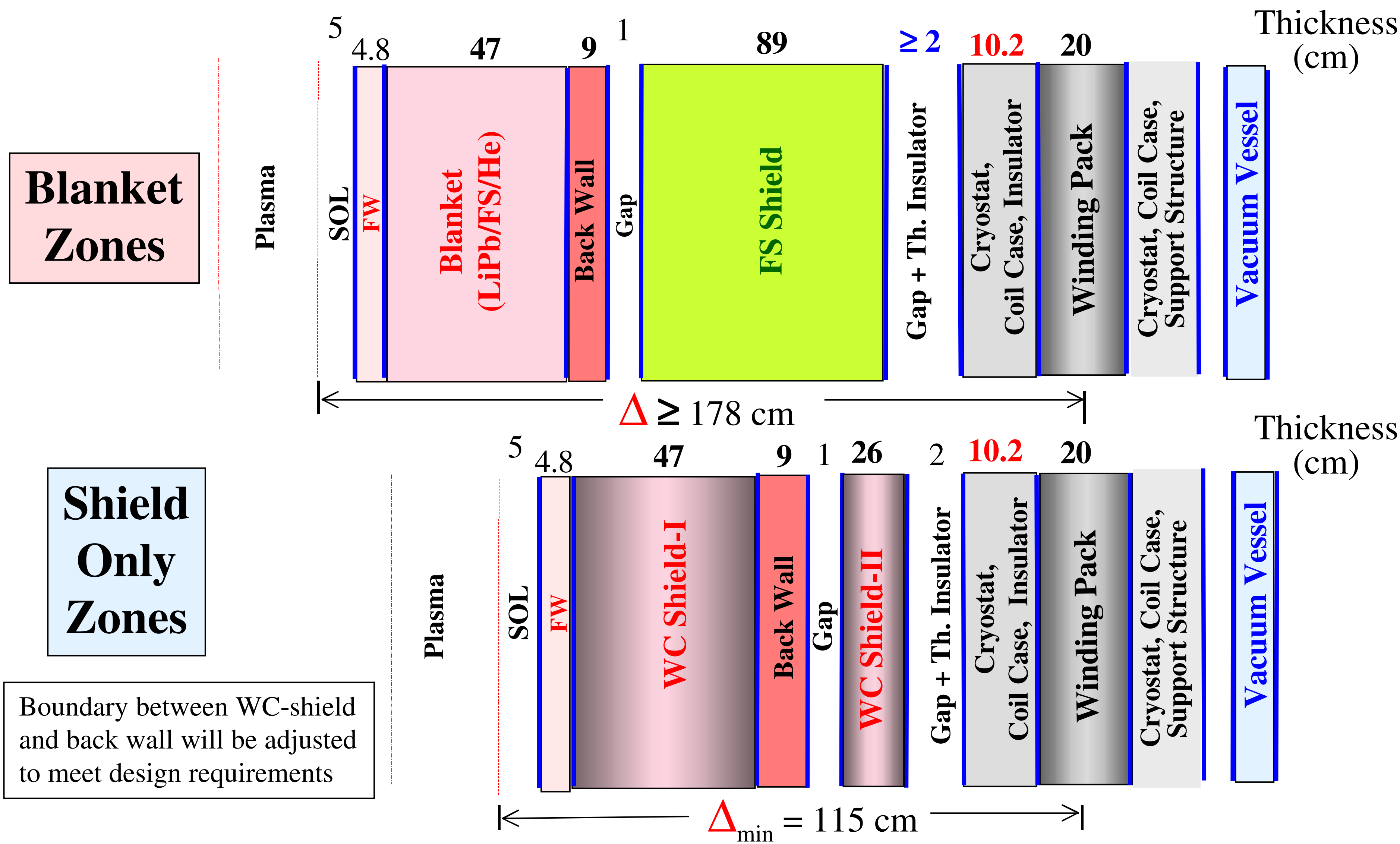
Boundary between WC-shield and back wall will be adjusted to meet design requirements

LiPb/FS/He System
(water-cooled **internal** VV)

Components	Composition
FW	31% FS Structure 69% He Coolant
Blanket	90% LiPb with 90% enriched Li 3% FS Structure 7% He Coolant
WC Shield*	90% WC Filler 3% FS Structure 7% He Coolant
FS Shield	15% FS Structure 10% He Coolant 75% Borated Steel Filler
VV	28% FS Structure 49% **Water** 23% Borated Steel Filler
Winding Pack (Composition not available. Used SPPS')	25% Incoloy Structure 20% Cu Stabilizer 15% Nb_3Sn + Conduit 25% GFF Polyimide 15% LHe

* Same constituents for blanket with WC replacing LiPb.

Recommended LiPb/FS/He Radial Build
(He-cooled **External** VV)



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(He-cooled **External** VV)

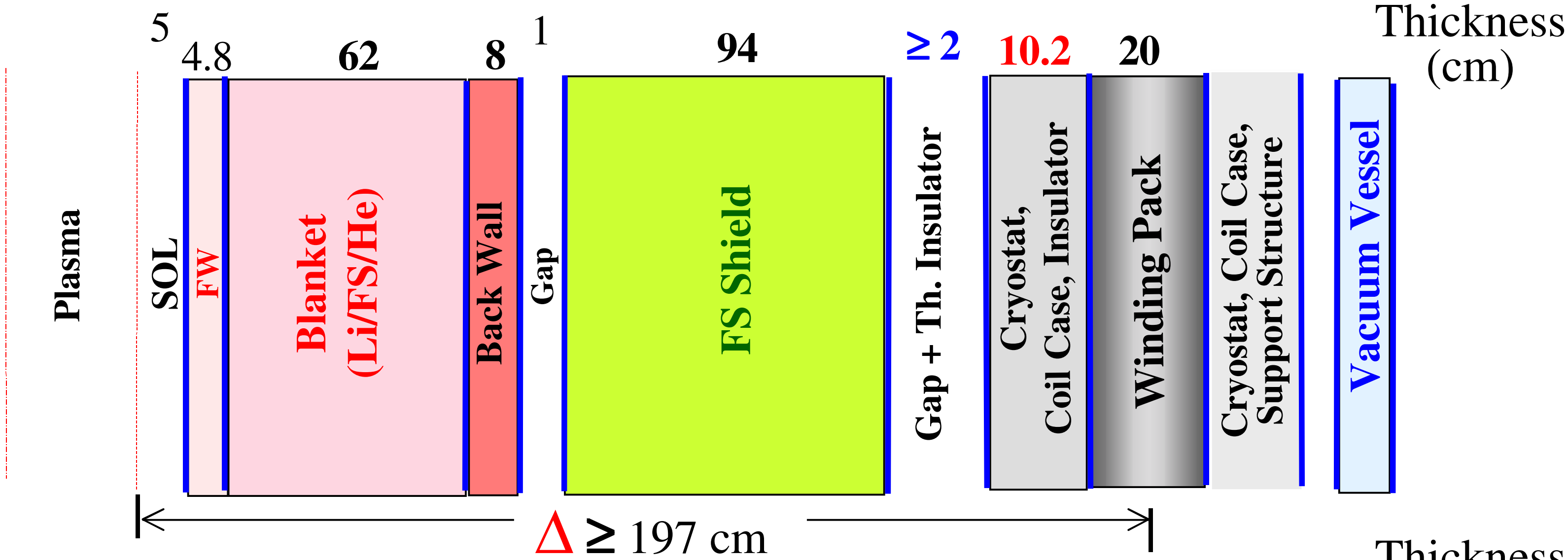
Components	Composition
FW	31% FS Structure 69% He Coolant
Blanket	90% LiPb with 90% enriched Li 3% FS Structure 7% He Coolant
WC Shield-I*	90% WC Filler 3% FS Structure 7% He Coolant
WC Shield-II#	15% FS Structure 10% He Coolant 75% WC Filler
FS Shield	15% FS Structure 10% He Coolant 75% Borated Steel Filler
Winding Pack (Composition not available. Used SPPS')	25% Incoloy Structure 20% Cu Stabilizer 15% Nb_3Sn + Conduit 25% GFF Polyimide 15% LHe
VV	30% FS Structure 70% He

* Same constituents for blanket with WC replacing LiPb.

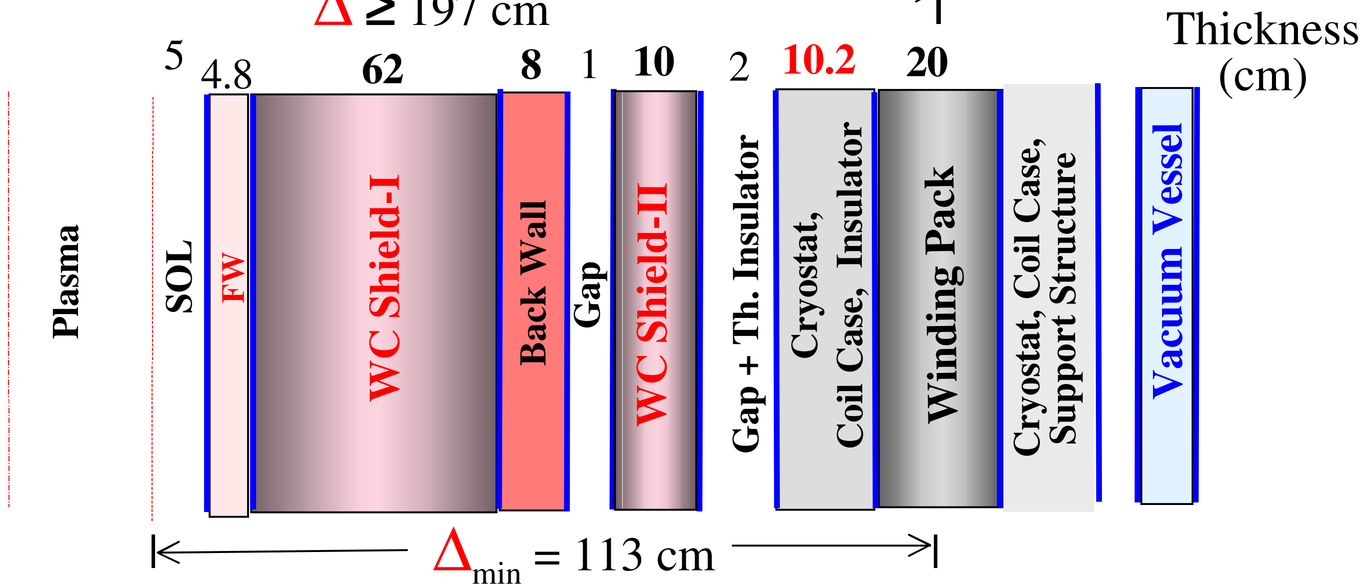
Same constituents for FS-shield with WC replacing B-FS filler. $ZrH_{1.7}$ filler could save 2-3 cm in radial build.

Recommended Li/FS/He Radial Build
(He-cooled **External** VV)

Blanket Zones



Shield Only Zones



Boundary between WC-shield and back wall will be adjusted to meet design requirements

Li/FS/He System
(He-cooled **External** VV)

Components	Composition
FW	31% FS Structure 69% He Coolant
Blanket	90% Li (natural) 3% FS Structure 7% He Coolant
WC Shield-I*	90% WC Filler 3% FS Structure 7% He Coolant
WC Shield-II#	15% FS Structure 10% He Coolant 75% WC Filler
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VV	30% FS Structure 70% He

* Same constituents for blanket with WC replacing LiPb.

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Nominal Blanket and Shielding Components

	ARIES-CS					SPPS
	Internal VV			External VV		External VV
Blanket Concept	Flibe/FS/Be	LiPb/SiC	LiPb/FS/He	LiPb/FS/He	Li/FS/He	Li/V
Thickness (cm):						
FW/Blanket-I	33	25	52	52	67	36
Gap	–	1	–	–	–	–
FW/Blanket-II	–	25	–	–	–	–
FS Back Wall	–	–	9	9	8	–
Gap	1	–	1	1	1	2
HT Shield	45	35	32	89	94	45
Gap	2	2	2	–	–	2
LT Shield	–	–	–	–	–	35
VV	25	25	28	–	–	–
Total B/S/VV	**106**	**113**	**124**	**151**	**170**	**120**
Net Change (compared to SPPS)	**- 14**	**- 7**	**+ 4**	**+ 31**	**+ 50**	**–**

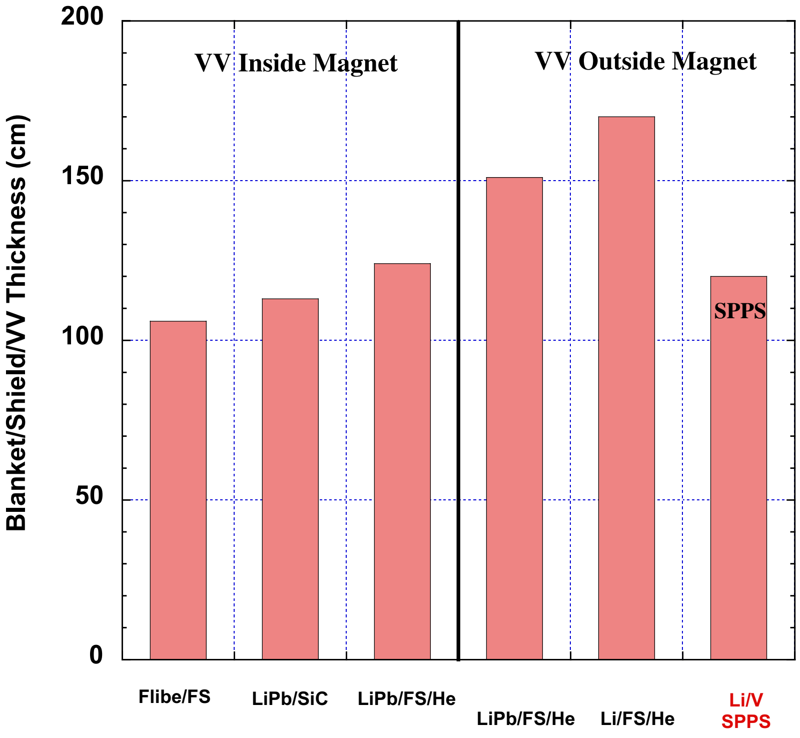
Nominal Plasma to Mid-Coil Distance

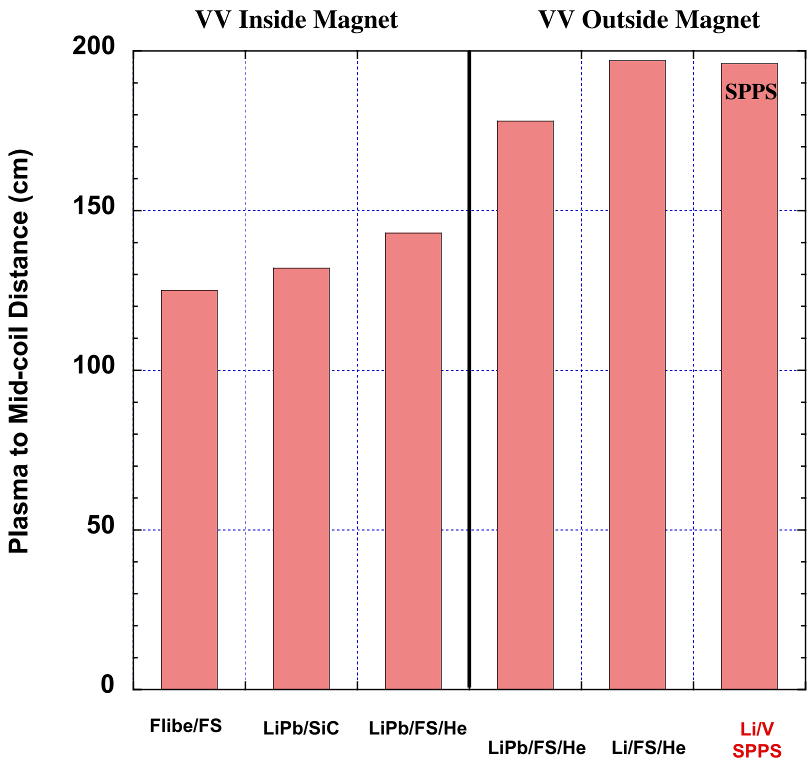
	ARIES-CS					SPPS
		Internal VV		External VV		External VV
Blanket Concept	Flibe/FS/Be	LiPb/SiC	LiPb/FS/He	LiPb/FS/He	Li/FS/He	Li/V
Thickness (cm):						
SOL	5	5	5	5	5	15
FW/B/S/VV	**106**	**113**	**124**	**151**	**170**	**120**
Gap + Th. Insl.	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	≥ 8
Cryostat*	2.2	2.2	2.2	10.2	10.2	15
1/2 Winding Pack	10	10	10	10	10	38
Δ	**125**	**132**	**143**	**178**	**197**	**196**
Net Change (compared to SPPS)	**- 71**	**- 64**	**- 53**	**- 18**	**+ 1**	**–**

* Includes coil case and electric insulator.

Flibe system offers most compact radial build

Comparison Between Nominal Radial Builds





Water-cooled internal VV helps reduce nominal radial build

Recommended Shield-Only Zones for Δ_{min}

	ARIES-CS					SPPS
	Internal VV			External VV		External VV
Blanket Concept	Flibe/FS/Be	LiPb/SiC	LiPb/FS/He	LiPb/FS/He	Li/FS/He	Li/V
Thickness (cm):						
WC Shield-I	33	25	52	52	67	–
FS Back Wall	–	–	11	9	8	–
Gap	1	1	–	1	1	–
WC Shield-II	25	36	–	26	10	–
Gap	2	2	2	–	–	–
LT Shield	–	–	–	–	–	–
VV	25	25	28	–	–	–
Total FW/S/VV	86	89	93	88	86	

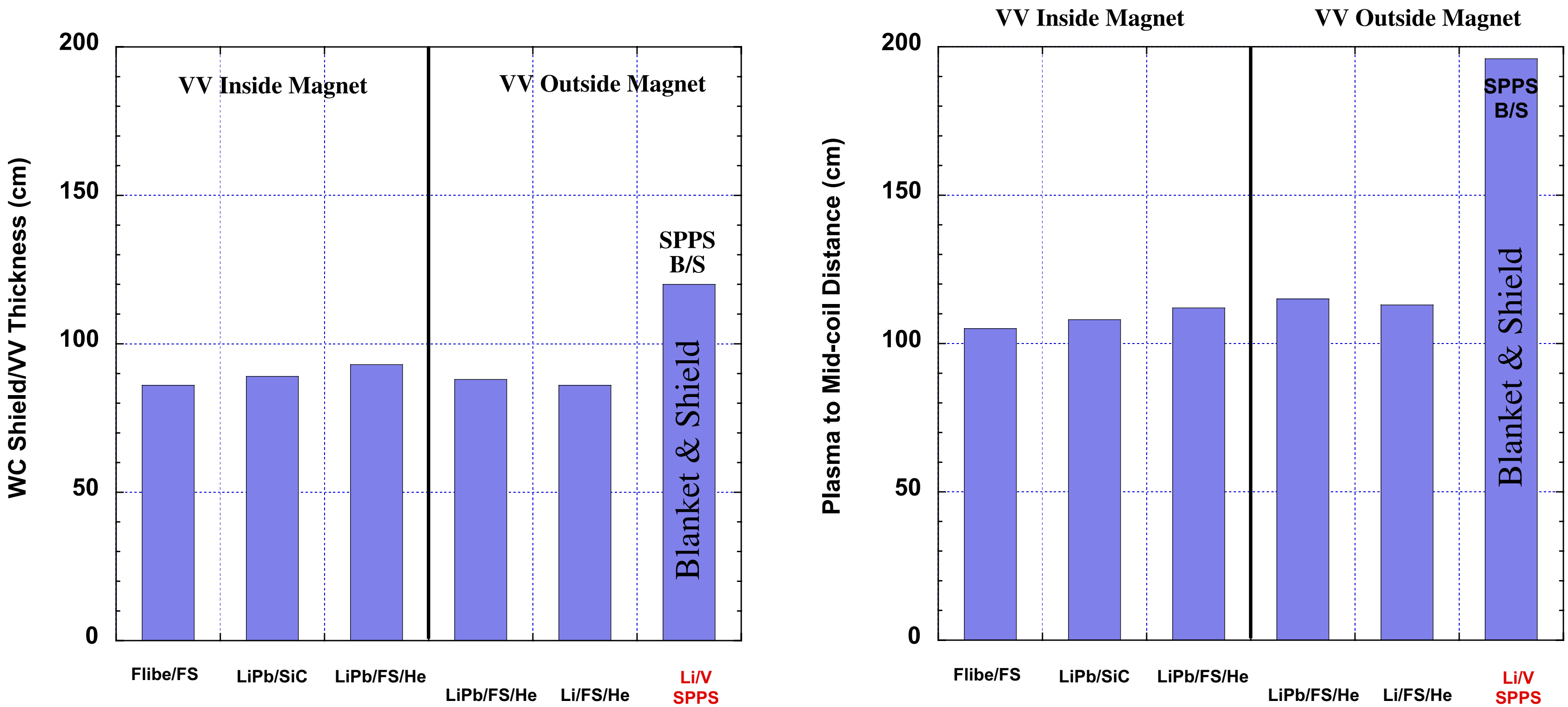
Dimensions of Δ_{min} Shielding Components (no Blanket)

	ARIES-CS					SPPS
	Internal VV			External VV		External VV
Blanket Concept	Flibe/FS/Be	LiPb/SiC	LiPb/FS/He	LiPb/FS/He	Li/FS/He	Li/V
Thickness (cm):						
SOL	5	5	5	5	5	–
FW/S/VV	**86**	**89**	**93**	**78**	**86**	**–**
Gap + Th. Insl.	≥ 2	≥ 2	≥ 2	≥ 2	≥ 2	–
Cryostat*	2.2	2.2	2.2	10.2	10.2	–
1/2 Winding Pack	10	10	10	10	10	–
Δ_{min}	**105**	**108**	**112**	**115**	**113**	

* Includes coil case and electric insulator.

Δ_{min} varies slightly with blanket concept

Comparison Between Δ_{min} (Shield-Only Zones, no Blanket)

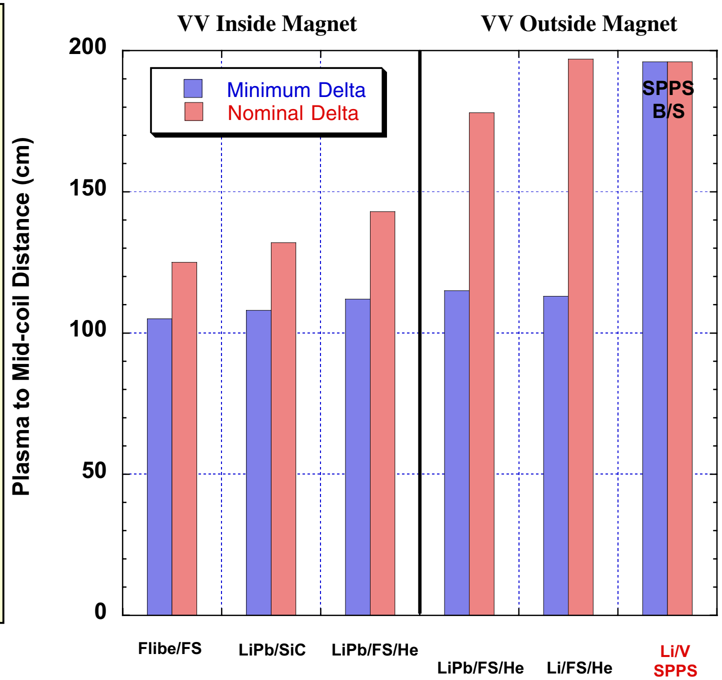


VV location has negligible impact on Δ_{min}

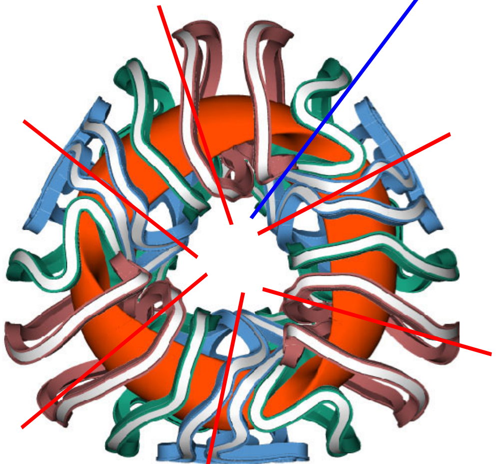
Comparison Between Radial Builds

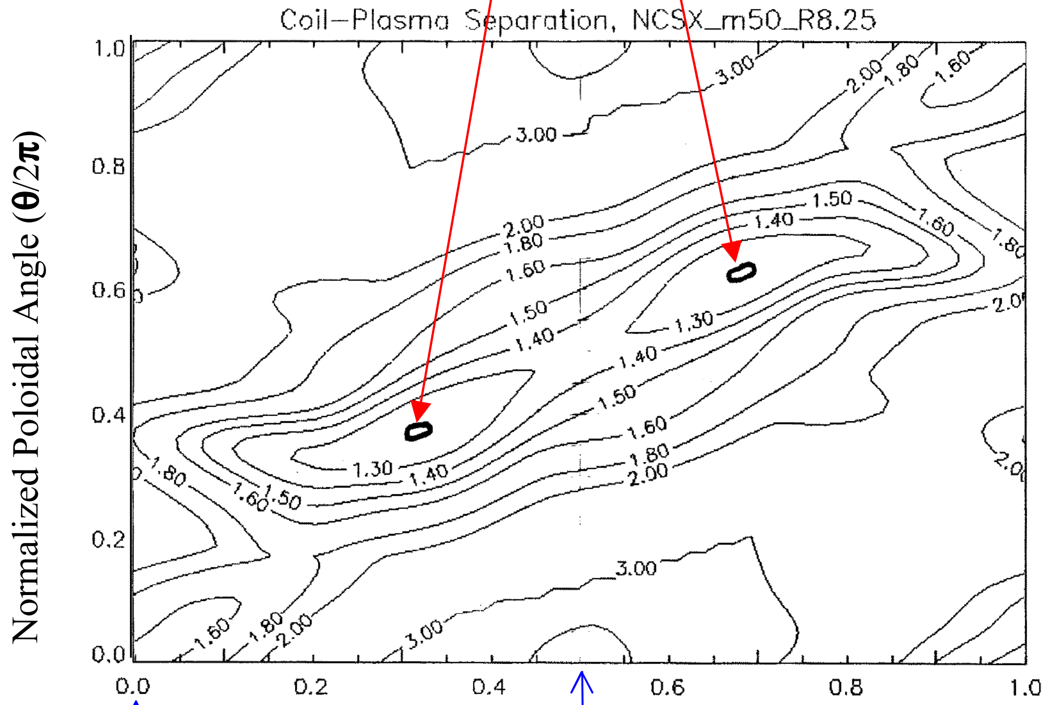
	ARIES-CS					SPPS
	Internal VV			External VV		External VV
Blanket Concept	Flibe/FS/Be	LiPb/SiC	LiPb/FS/He	LiPb/FS/He	Li/FS/He	Li/V
Thickness (cm):						
Nominal Δ	125	132	143	178	197	196
Δ_{min}(shield-only)	105	108	112	115	113	–
Net Saving	20	24	31	63 ?	84 ?	–

- Shield-only zones could offer 20 - 84 cm (16 - 43%) reduction in radial build.
- Net saving exceeding 20 cm calls for shield-only zones with FW coverage > 8%, meaning overall TBR < 1.1.
- It is impossible to achieve TBR of 1.1 for LiPb and Li systems if shield-only zones cover 30-40% of FW area.
- Potential solutions:
  - For internal VV case, thicken LiPb blanket
  - For external VV case, install LiPb (or Li) blanket everywhere with uniform or variable thickness.



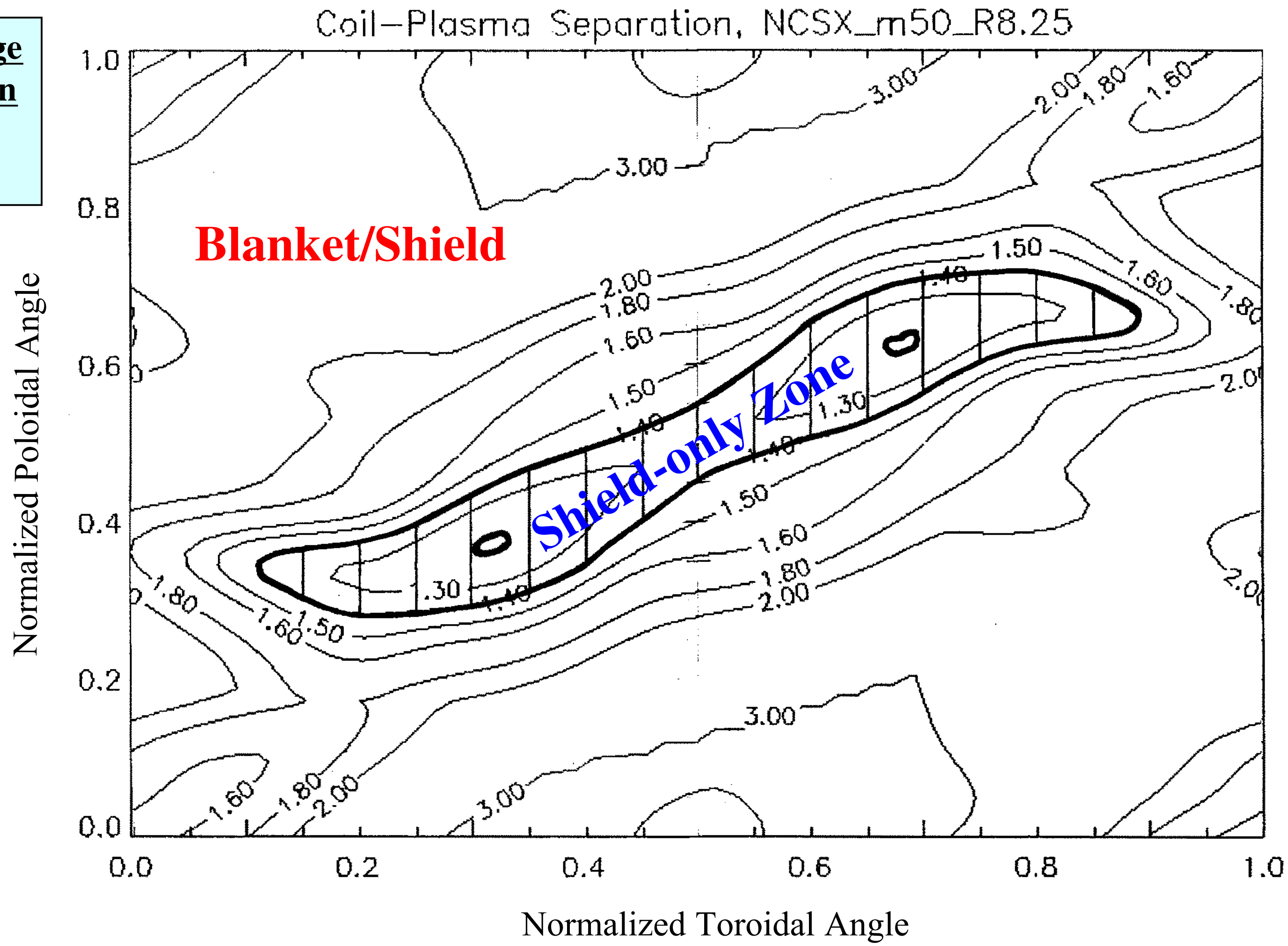
Δ_{min} Occurs Twice per Field Period





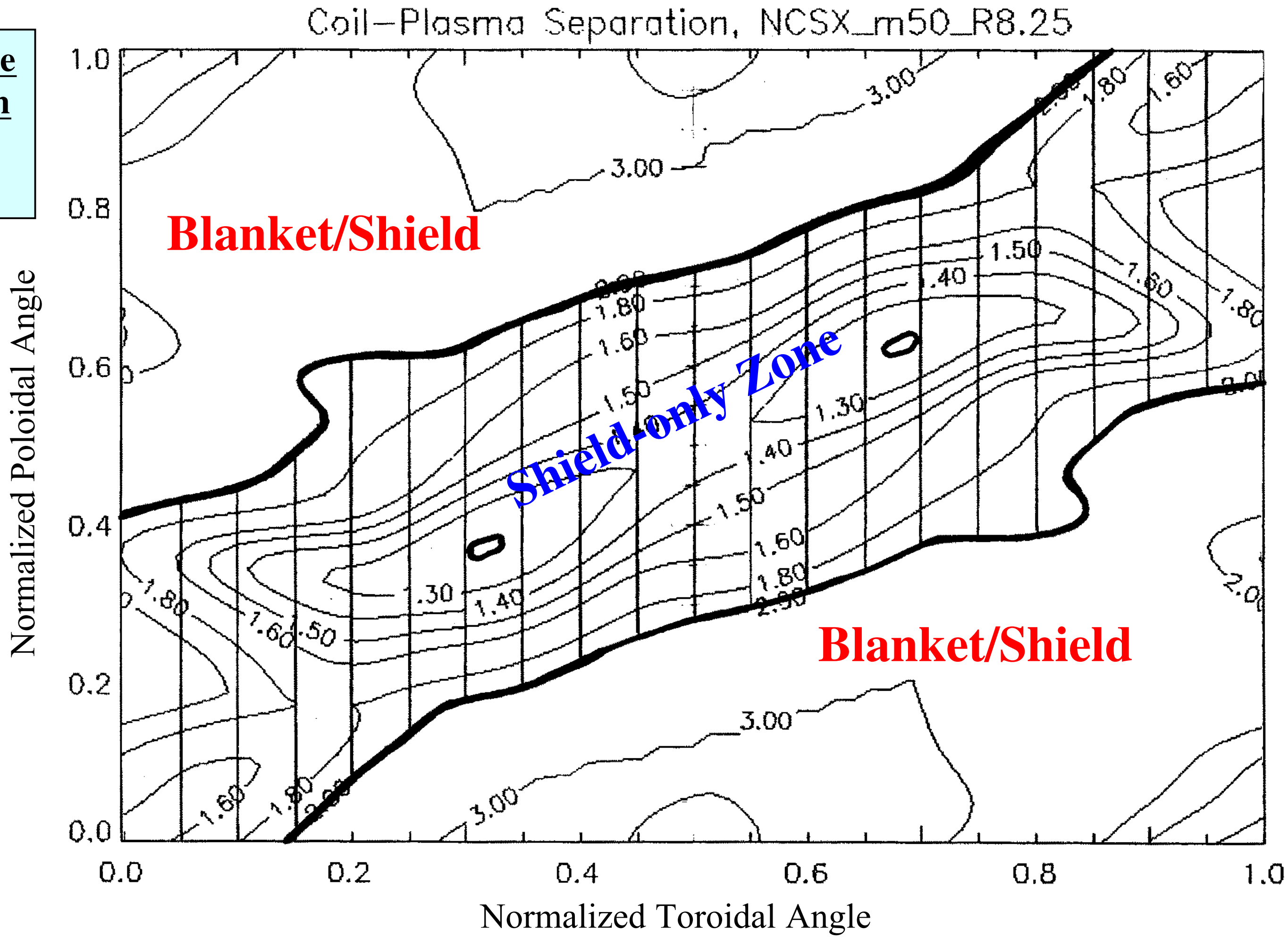
Transition Region for Δ of 1.2-1.4 m Covers ~8% of FW Area

	Coverage Fraction
Shield-only zone	8%
Blanket/Shield	92%



Transition Region for Δ of 1.2-2.0 m Covers ~40% of FW Area

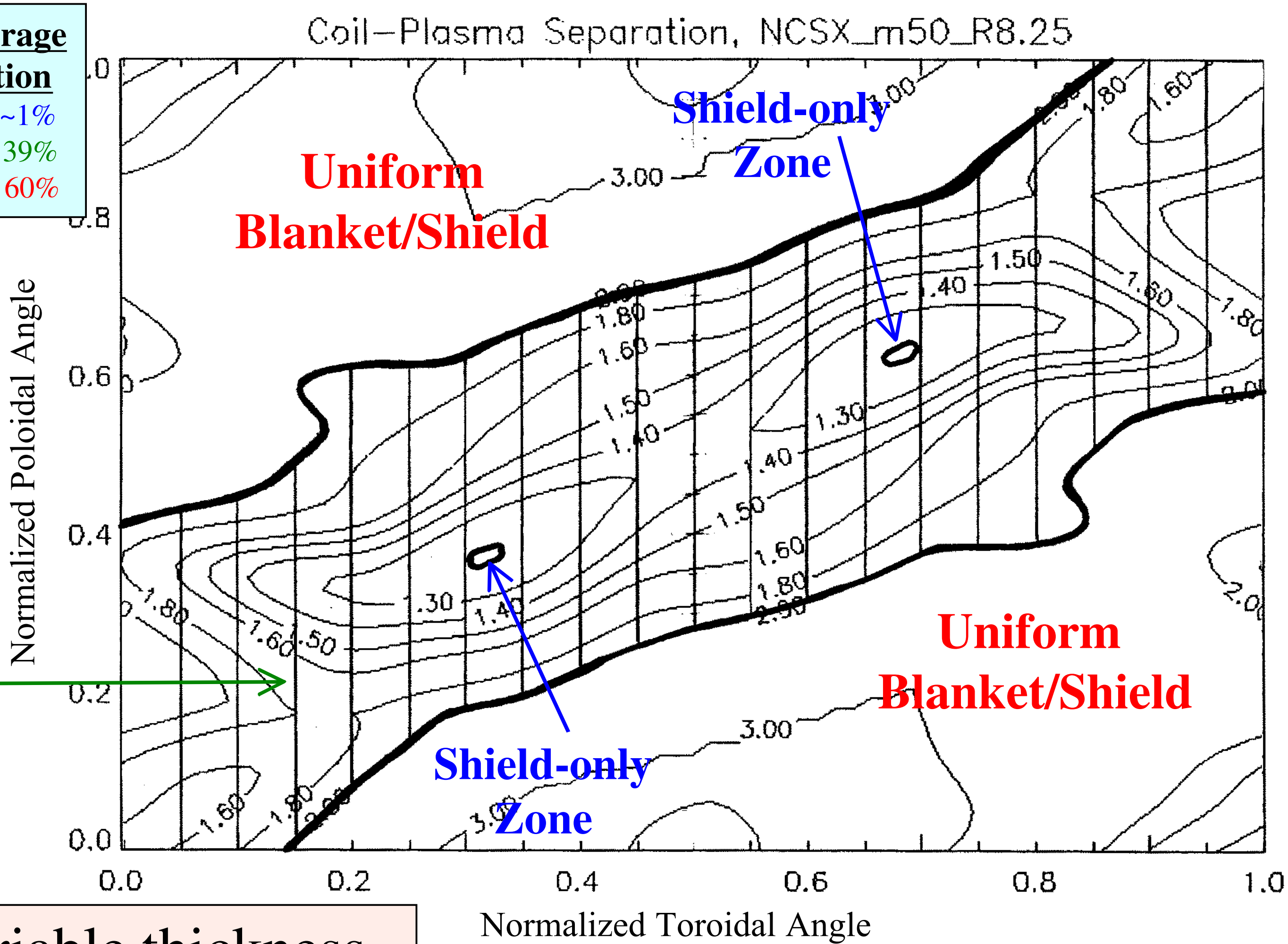
	Coverage Fraction
Shield-only zone	40%
Blanket/Shield	60%



Blankets may not provide TBR ≥ 1.1 if coverage fraction drops below 70%

Potential Solution for Sizable Transition Regions

	Coverage Fraction
Shield-only zone	~1%
Non-uniform Blanket/Shield	39%
Uniform Blanket/Shield	60%



Non-uniform Blanket/Shield

Blanket with variable thickness could meet breeding requirement

WC-Shield-Only Zones for Δ_{min} Introduce Engineering Problems

- Benefits:
  - Compact radial build
  - Smaller R and lower B_{max}
  - Lower COE

- Potential engineering problems:
  - Integration of WC-shield with blanket system
  - Accommodation of WC decay heat removal loop
  - Heavy WC shield $\Rightarrow$ many small modules, if weight-limited
  - Any WC high level waste?

Key Parameters for ARIES-CS System Analysis

	Flibe/FS/Be	LiPb/SiC	LiPb/FS	Li/FS
TBR	1.1	1.1	1.1* ?	1.1* ?
Energy Multiplication (M_n)	1.2	1.1	1.15	1.13
Thermal Conversion Efficiency (η_{th})	45%	55-60%	~45%	~45%
FW Lifetime (FPY)	6.5	6	5	7
System Availability	~80%	~80%	~80%	~80%

* Based on 8% FW coverage fraction for shield-only zones.

Integrated system analysis could assess impact of M_n and η_{th} on COE for comparable Δ_{min}

Conclusions

- Radial standoff controls COE, a unique feature for stellarators.
- Employ expensive, highly efficient **local** shield at Δ_{min} and combine **blanket with variable thickness** and cheap shield elsewhere.
- Blankets should breed extra tritium to compensate for losses due to non-breeding shield-only zones.
- To reduce Δ_{min}, use:
  - WC-shield
  - Liquid breeder to cool HT shield
  - Water to cool LT shield (or internal VV)
  - No He coolant for shield.
- Shield-only Δ_{min} varies slightly (2-7 cm) with blanket concept.
- External VV increases Δ_{min} by few cm.
- Economic impact of shield-only zones needs to be assessed and innovative solutions to WC problems should be developed.

Conclusions (cont.)

- For water-cooled internal VV case, Flibe system offer most compact radial build, followed by LiPb.
- For external VV case, LiPb and Li blankets should be installed everywhere to meet breeding requirement.
- Water is superior shielding material that helps reduce nominal radial build and minimize radwaste volume

  ⇒ **Exclude breeders incompatible with water**.

- **3-D nuclear analysis is needed** to:
  - Generate neutron wall loading profile using CAD-MCNP interface*
  - Assess 3-D impact of shield-only zones on breeding
  - Determine 3-D effect of penetrations, assembly gaps, and divertor system on TBR
  - Evaluate overall TBR for blankets with variable thickness
  - Confirm key nuclear parameters (M_n, lifetime, Δ_{min}, etc)
  - Determine boundary between replaceable and permanent components.

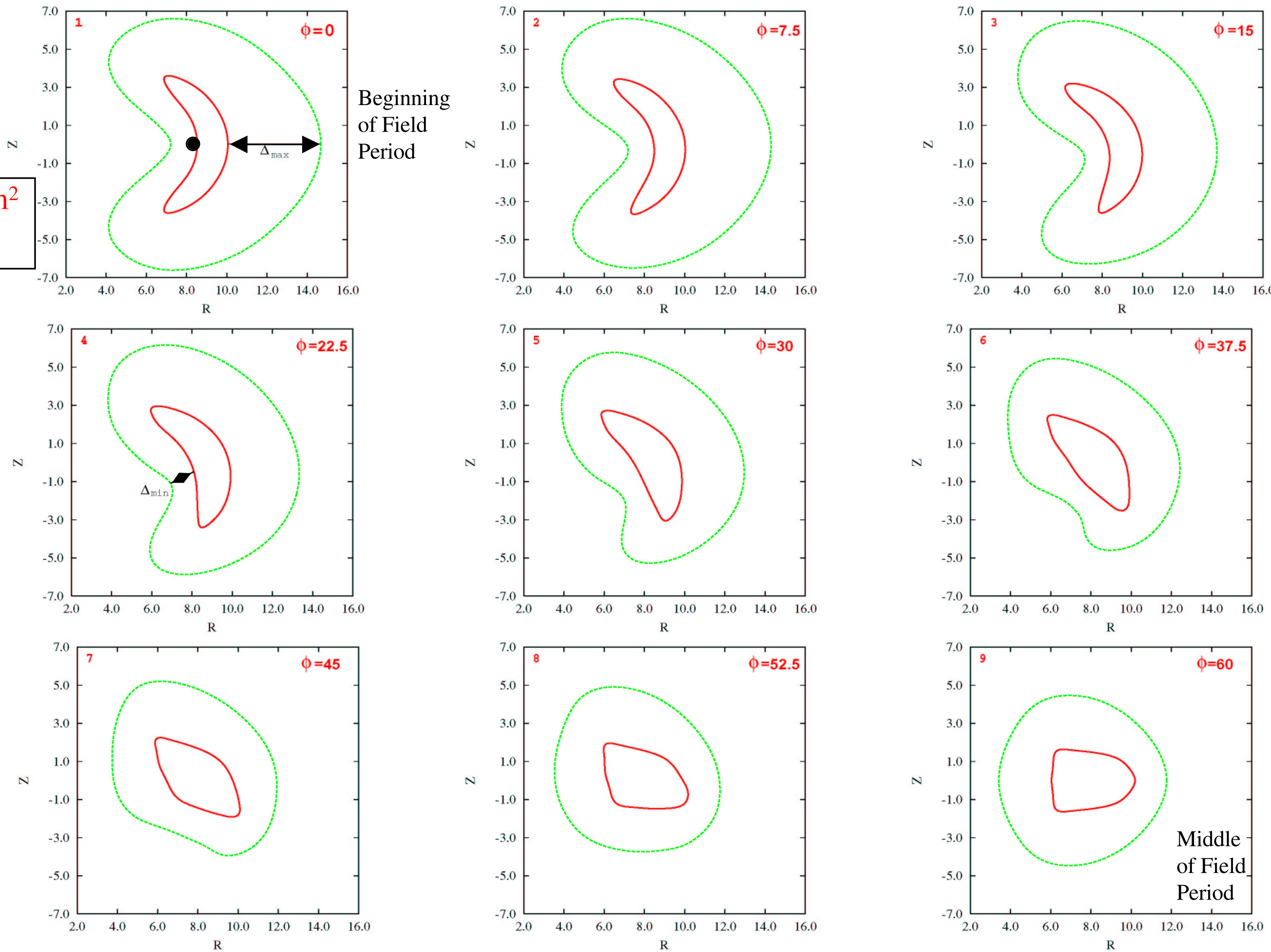
* Under development at UW.

9 Xns of Plasma Boundary (red) and WP Center (green) Covering Half Field Period (~9 m)

Δ_{max}~ 4.6 m

Γ peaks @ ~3 MW/m^2 at black dot

Δ_{min}= 1.2 m



Transition Region Between Δ_{min} and Δ_{min}+ 0.2 m Covers ~8% of FW Area

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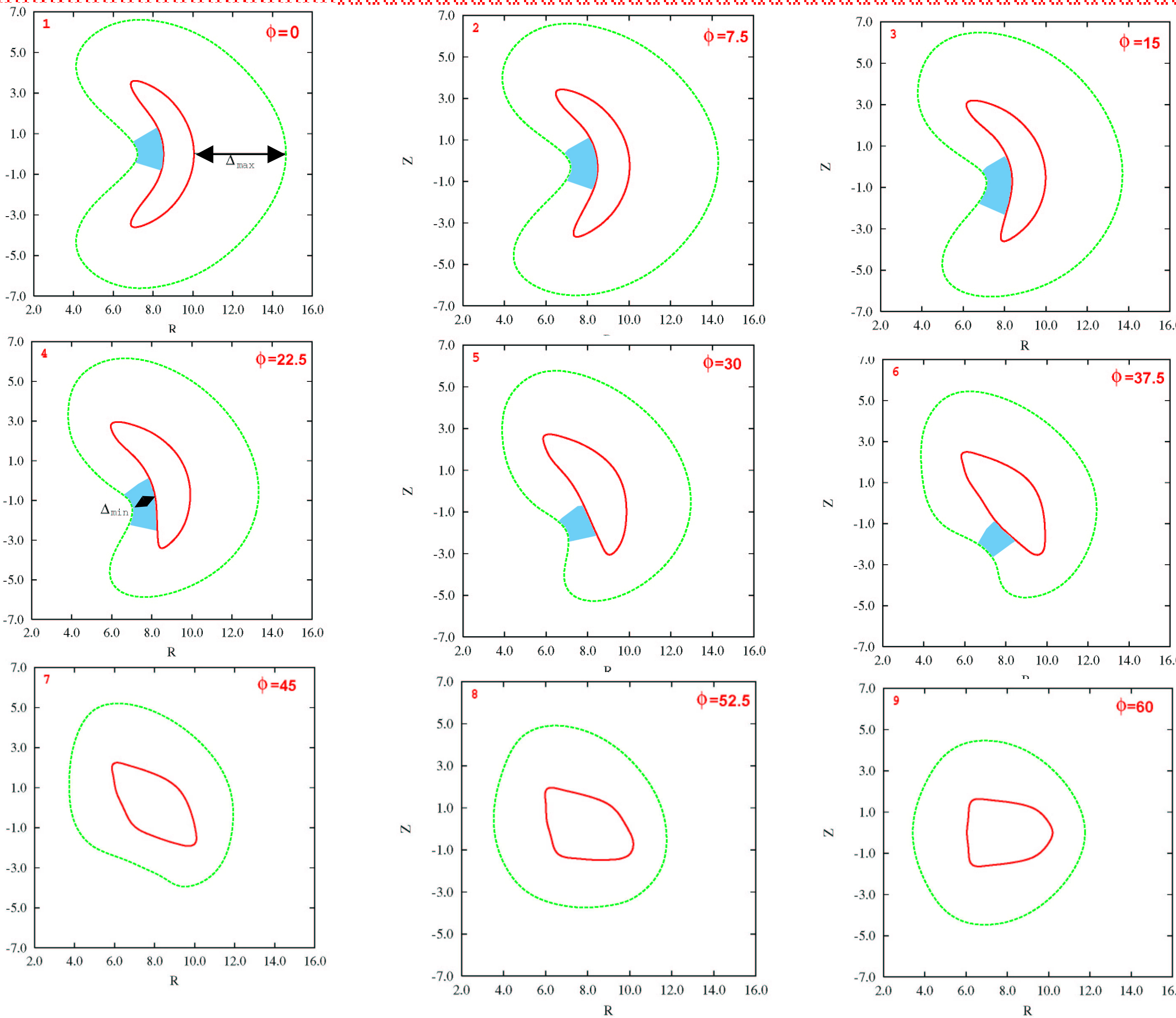
Beginning of Field Period



Middle of Field Period

Δ_{min}= 1.2 m

Blue areas:
~2 m Poloidal extent
~5.5 m Toroidal extent
~8% of FW area