Key Physics & Technology Issues for Compact Stellarator Power Plants

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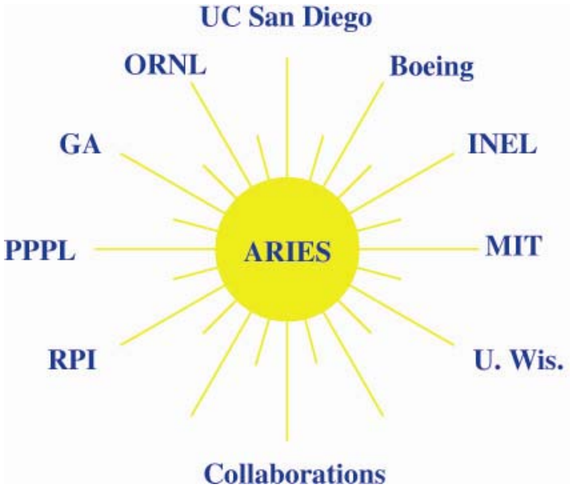
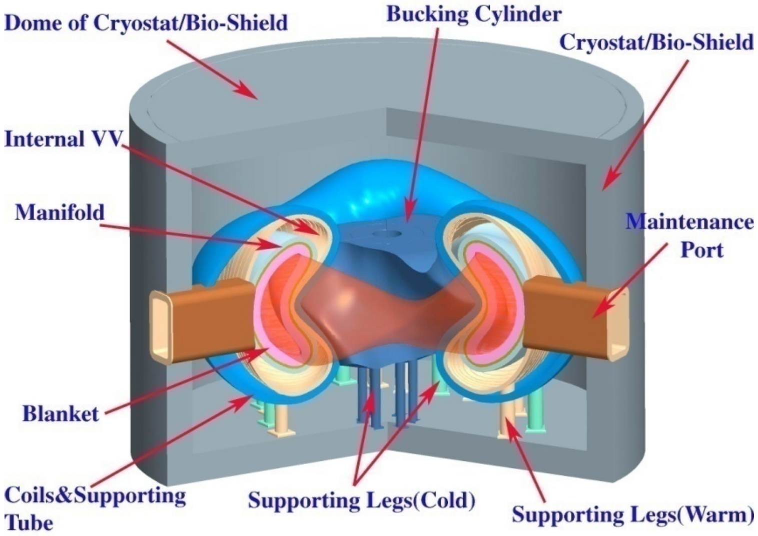


Key R&D Issues – Observations from the ARIES-CS study

- ARIES-CS study was completed in 2007. Final report is published in J. Fusion Science & Technology 2008.
- ARIES CS was the first integrated design of a compact stellarator; designs was pushed in many areas to uncover difficulties.
- Many issues were identified.



<R> = 7.75 m,

$<B_o>$ = 5.7 T,

FPC Mass = 11,000 tonnes

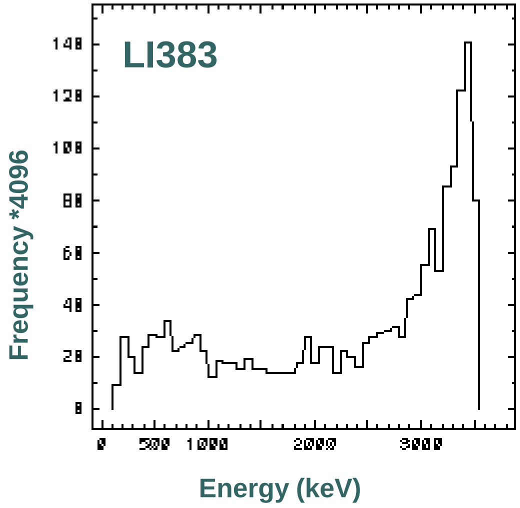
(size & mass comparable to advanced tokamaks)

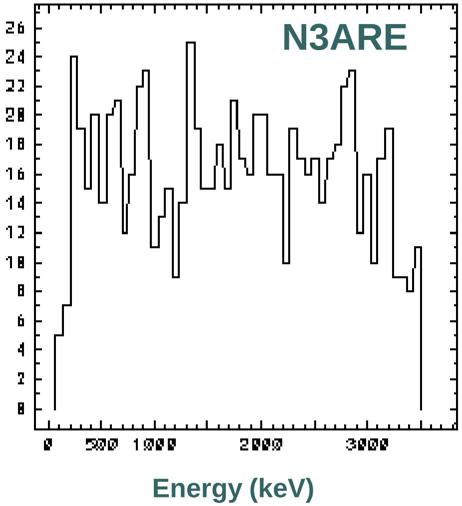
Goals of the ARIES-CS Study

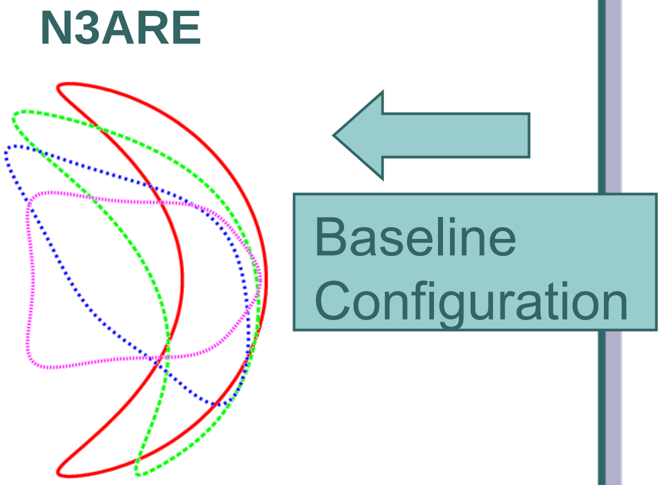
- Can compact stellarator power plants be similar in size to advanced tokamak power plants?
  - ✓ **Physics:** Reduce coil aspect ratio, $A_c = \langle R\rangle/\Delta_{min}$ while maintaining “good” stellarator properties (focused on QA configuration)
  - ✓ **Engineering:** Reduce the required minimum coil-plasma distance.
- What is the impact of complex shape and geometry?
  - ✓ Complex 3-D analysis (e.g., CAD/MCNP interface for 3-D neutronics)
  - ✓ Complexity-driven constraints (e.g., superconducting magnets)
  - ✓ Configuration, assembly, and maintenance
  - ✓ Manufacturability (feasibility and Cost)

Optimization of NCSX-Like Configuration: Improving α Confinement

- ➢ A bias was introduced in the magnetic spectrum in favor of B(0,1) and B(1,1):
- ✓ A substantial reduction in α energy loss (from ~18% to ~ 4-5%) is achieved.







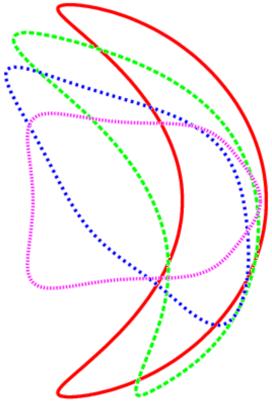
Baseline Configuration

- ➢ α loss may be too high (localized heating and exfoliation concerns)

Optimization of NCSX-Like Configuration: Increasing Plasma-Coil Separation

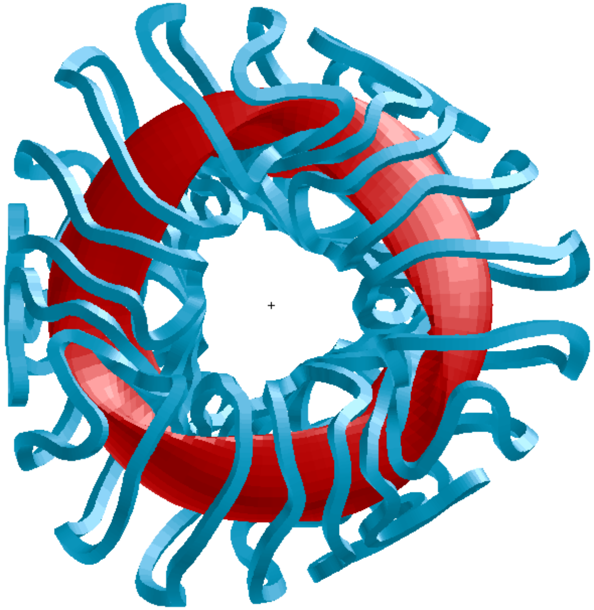
- A series of coil design with **A_c=<R>/Δ_{min}** ranging 6.8 to 5.7 produced.
  - ✓ Large increases in B_{max} /B_o only for A_c < 6.

N3ARE



A_c=5.9

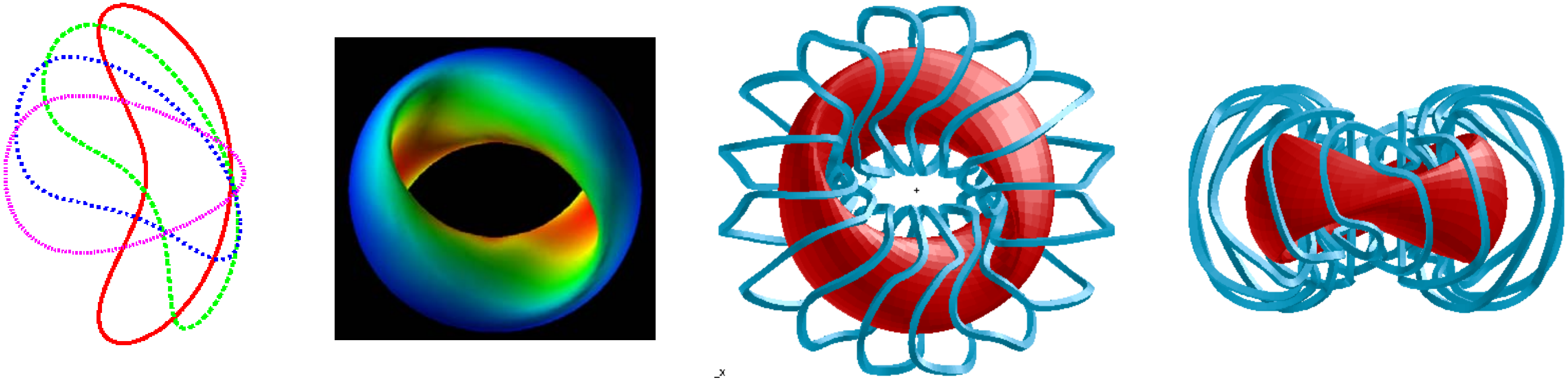
For <R> = 7.75m:
Δ_{min}(c-p)=1.32 m
Δ_{min}(c-c)=0.8 m



Many attractive QA configurations exists!

Example: MHH2

- Low plasma aspect ratio ($A_p \sim 2.5$) in 2 field period.
- Excellent QA, low effective ripple (<0.8%), low α energy loss ($\leq$ 5%) .
- Less complex coils with a relatively large coil to coil spacing



Stellarator Configuration Space is rich with interesting configurations

- Typical configuration optimization process includes criteria on transport, equilibrium, stability, etc. Each criterion is assigned a threshold and a weight in the optimization process. In-depth understanding of relative importance of these criteria on overall performance system is needed.

- Understanding of β limits in stellarators is critical.
- Configurations with reduced α-particle loss should be developed.
- Demonstration of profile control in compact stellarators (e.g., QA) to ensure the achievement and control of the desired iota profile, including bootstrap current effects.

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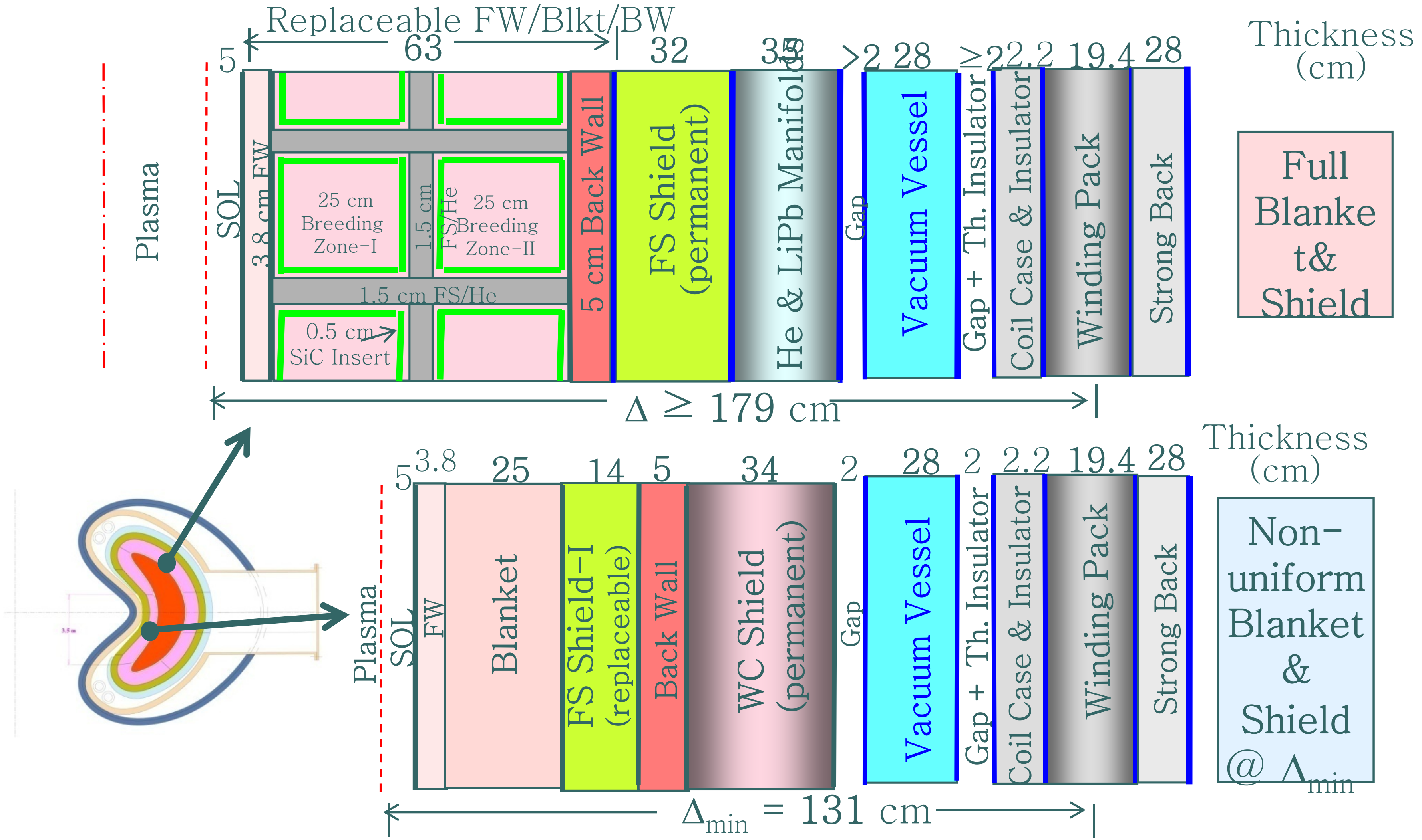
Minimum Coil-plasma Stand-off Can Be Reduced By Using Tapered-Blanket Zones



Replaceable FW/Blkt/BW

Thickness (cm): 5 | 63 | 32 | 35 | >2 | 28 | ≥2 | 2.2 | 19.4 | 28

Plasma | SOL | 3.8 cm FW | 25 cm Breeding Zone-I | 1.5 cm FS/He | 25 cm Breeding Zone-II | 1.5 cm FS/He | 0.5 cm SiC Insert | 5 cm Back Wall | FS Shield (permanent) | He & LiPb Manifolds | Gap | Vacuum Vessel | Gap + Th. Insulator | Coil Case & Insulator | Winding Pack | Strong Back

$\Delta \geq 179$ cm

Full Blanket & Shield

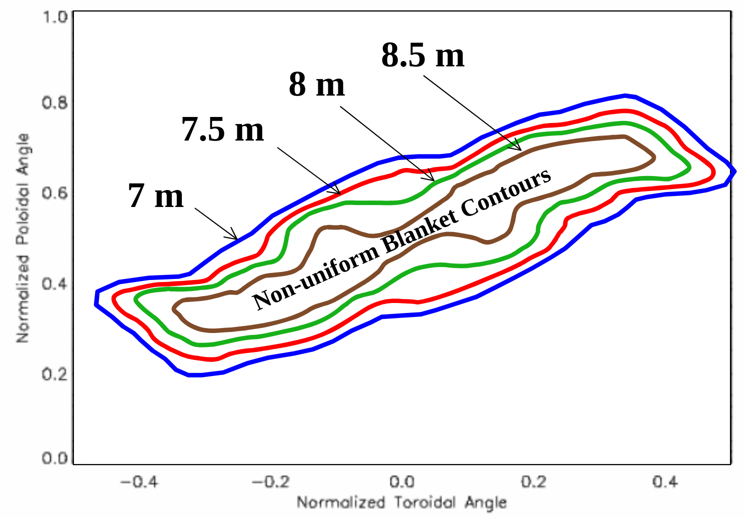
Thickness (cm): 5 | 3.8 | 25 | 14 | 5 | 34 | 2 | 28 | 2 | 2.2 | 19.4 | 28

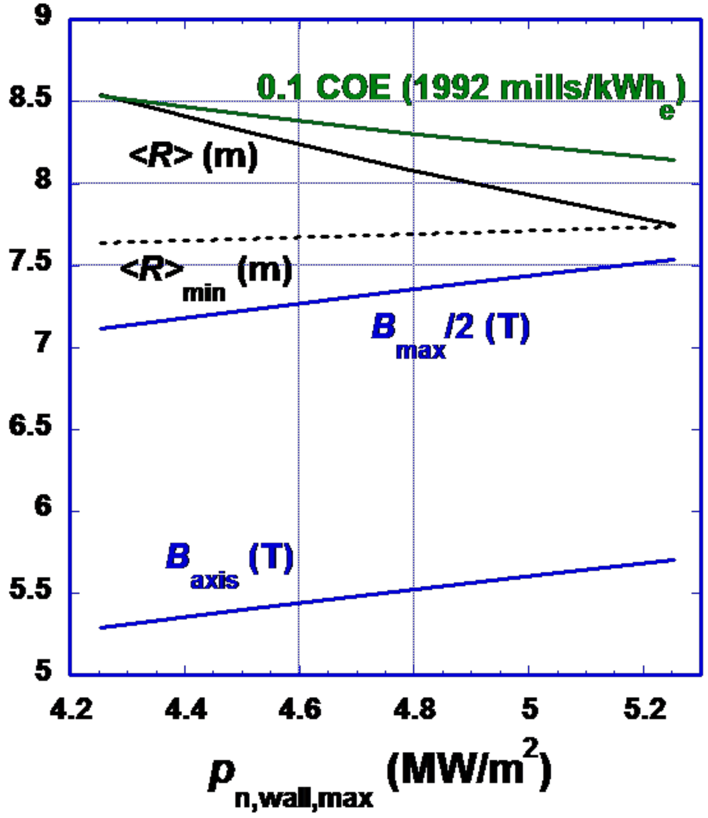
Plasma | SOL | FW | Blanket | FS Shield-I (replaceable) | Back Wall | WC Shield (permanent) | Gap | Vacuum Vessel | Gap + Th. Insulator | Coil Case & Insulator | Winding Pack | Strong Back

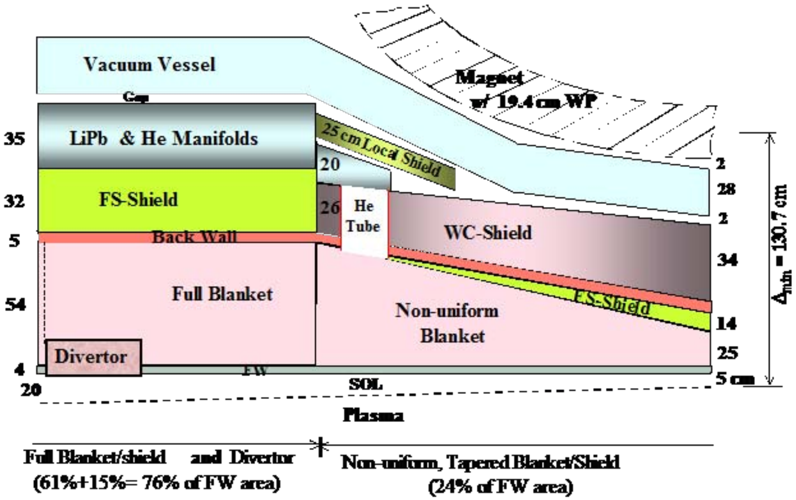
$\Delta_{min} = 131$ cm

Non-uniform Blanket & Shield @ Δ_{min}

Major radius can be increased to ease engineering difficulties with a small cost penalty







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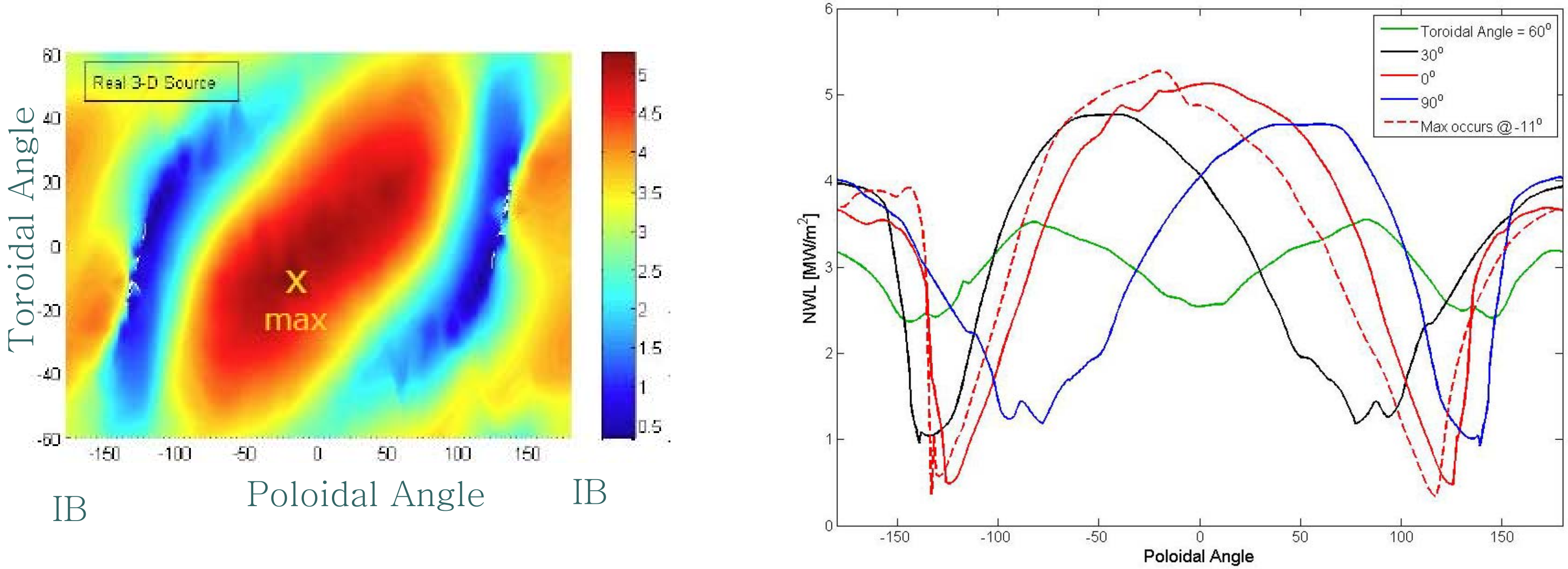
First ever 3-D modeling of complex stellarator geometry for nuclear assessment using CAD/MCNP coupling

- Detailed and complex 3-D analysis is required for the design
  - ✓ Example: Complex plasma shape leads to a large non-uniformity in the loads (e.g., peak to average neutron wall load of 2).

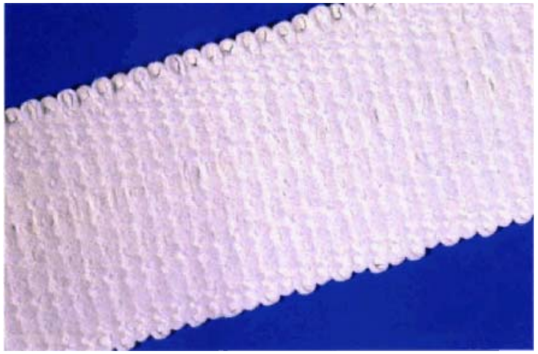
Distribution of Neutron wall load



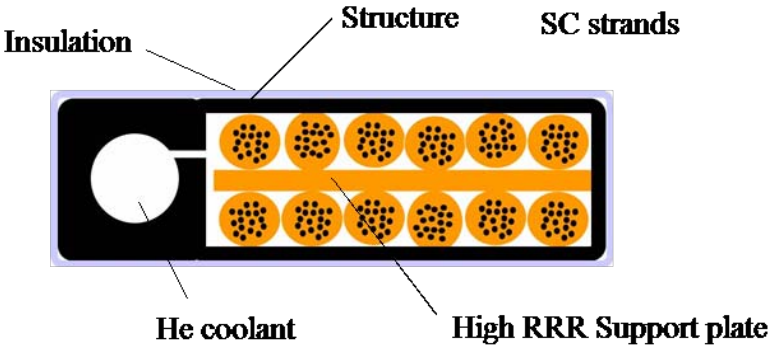
Coil Complexity Impacts the Choice of Superconducting Material

- Strains required during winding process is too large.
  - ✓ NbTi-like (at 4K) ⇒ B < ~7-8 T
  - ✓ NbTi-like (at 2K) ⇒ B < 9 T, Potential problem with temperature margin
  - ✓ Nb_3Sn ⇒ B < 16 T, Conventional technique does not work because of inorganic insulators

Option 1: Inorganic insulation, assembled with magnet prior to winding and capable to withstand the heat treatment process.



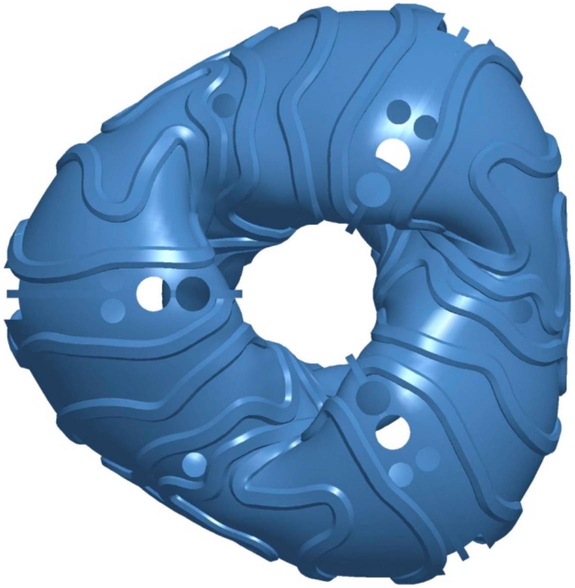
Option 2: conductor with thin cross section to get low strain during winding. (Low conductor current, internal dump).

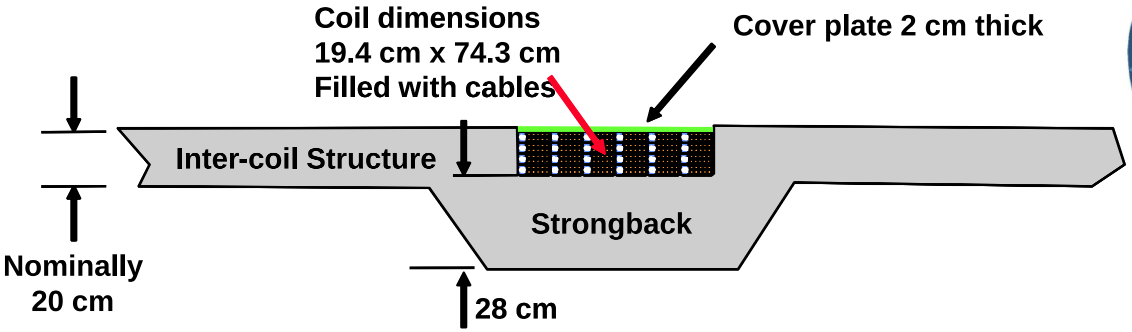


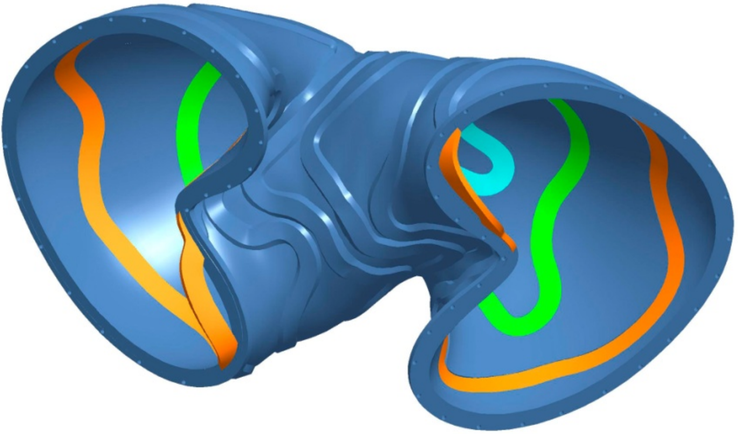
Option 3: HTS (YBCO), Superconductor directly deposited on structure.

Coil Complexity Dictates Choice of Magnet Support Structure

- It appears that a continuous structure is best option for supporting magnetic forces.
- Net force balance between field periods (Can be in three pieces)
- Superconductor coils wound into grooves inside the structure.

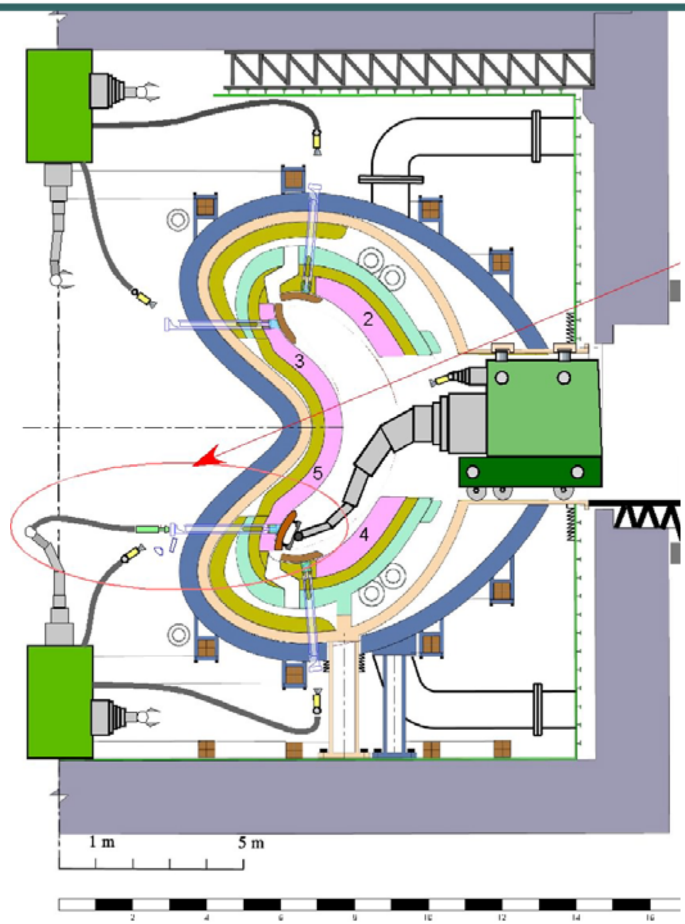


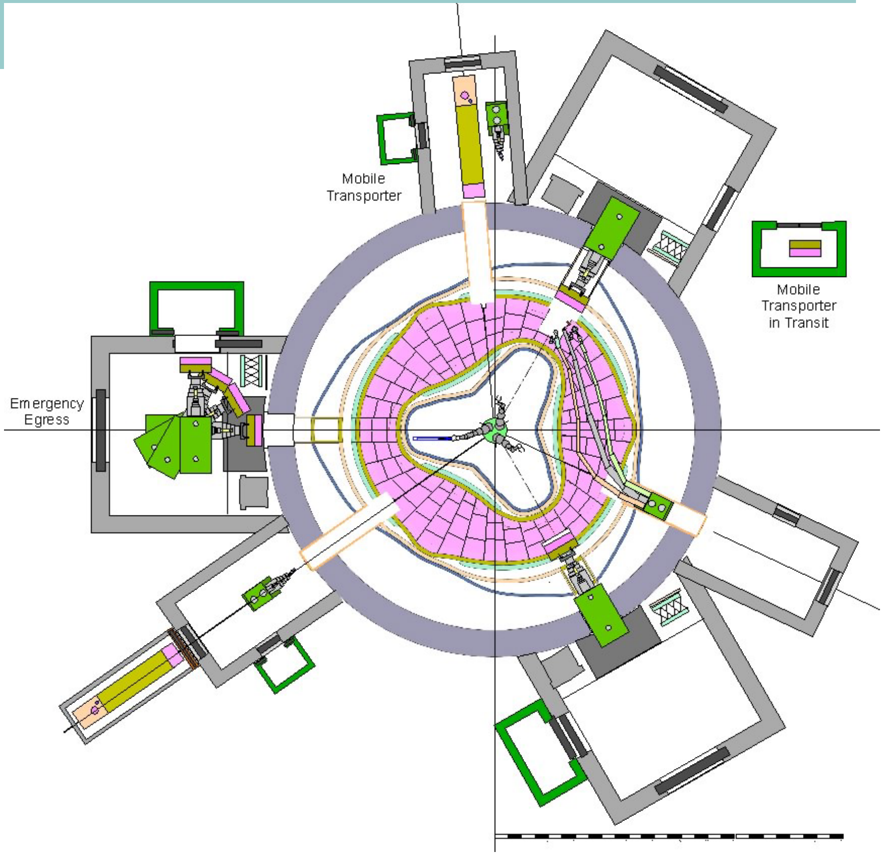




Components are replaced Through Ports

- Modules removed through three ports using an articulated boom.



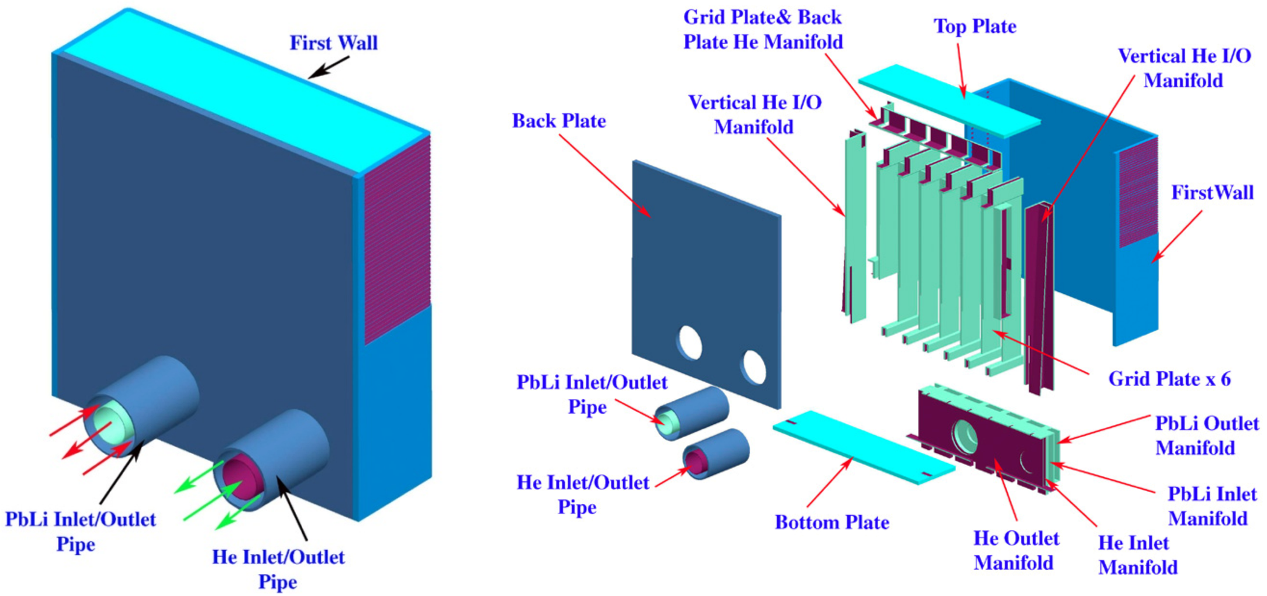


Drawbacks:

- ✓ Coolant manifolds increase plasma-coil distance.
- ✓ Very complex manifolds and joints
- ✓ Large number of connect/disconnects

Manufacturing of blanket modules is challenging

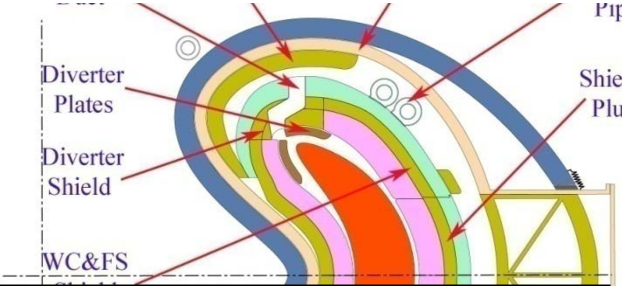
- Dual coolant with a self-cooled PbLi zone and He-cooled RAFS structure and SiC insert:

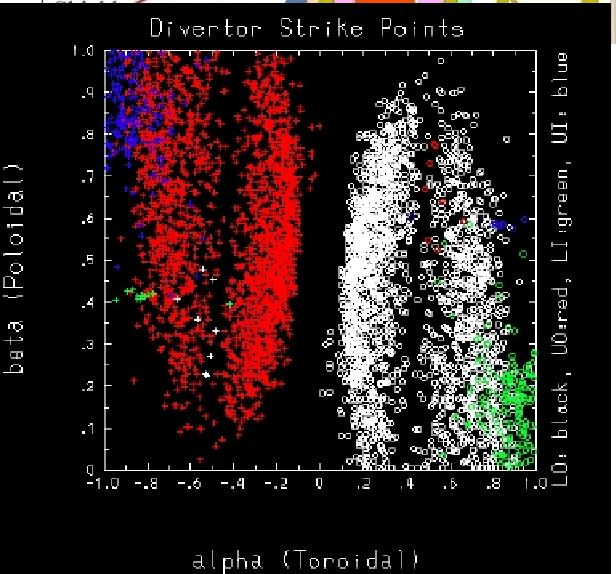


- The complex internal components should be manufactured with the desired 3-D shape.
- Impact of Ferritic material on the stellarator configuration is unknown.

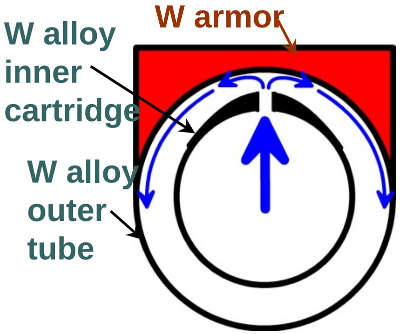
A highly radiative plasma is needed for divertor operation

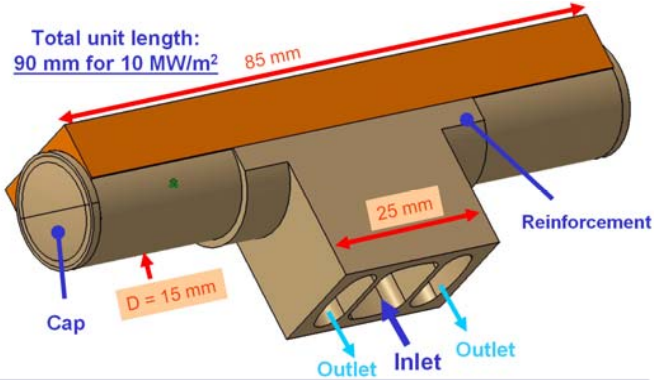
- Heat/particle flux on divertor was found by following field lines outside LCMS.
  - Because of 3-D nature of magnetic topology, location & shaping of divertor plates require considerable iterative analysis.





Top and bottom plate location with toroidal coverage from -25° to 25°.





- T-Tubes divertor module is based on W Cap design (FZK) extended to mid-size (~ 10 cm) with a capability of 10 MW/m^2

In Summary:

- ➢ Understanding of β limits in stellarators is critical.
- ➢ Configurations with negligible α-particle loss should be developed.

- ➢ Configuration, assembly, and maintenance drives the design
  - ✓ Component replacement through ports appears to be the only viable method. This leads to many non-identical modules, large coolant manifolds (increased radial build), large number of connects and disconnects, complicated component design for assembly disassembly.
- ✓ 3-D analysis of components is required for almost all cases, New tools may have to be developed for component optimization.
- ✓ Feasibility of manufacturing of component should be included in the configuration design as much as possible. For ARIES-CS, manufacturing of many components is challenging and/or very expensive.

- ➢ **Stellarator configuration optimization should include “strong” penalties for complex plasma (and coil) shape.**

Thank you!
Any Questions?