Scoping Studies of Fusion Power Core Engineering and Maintenance Options for ARIES-CS

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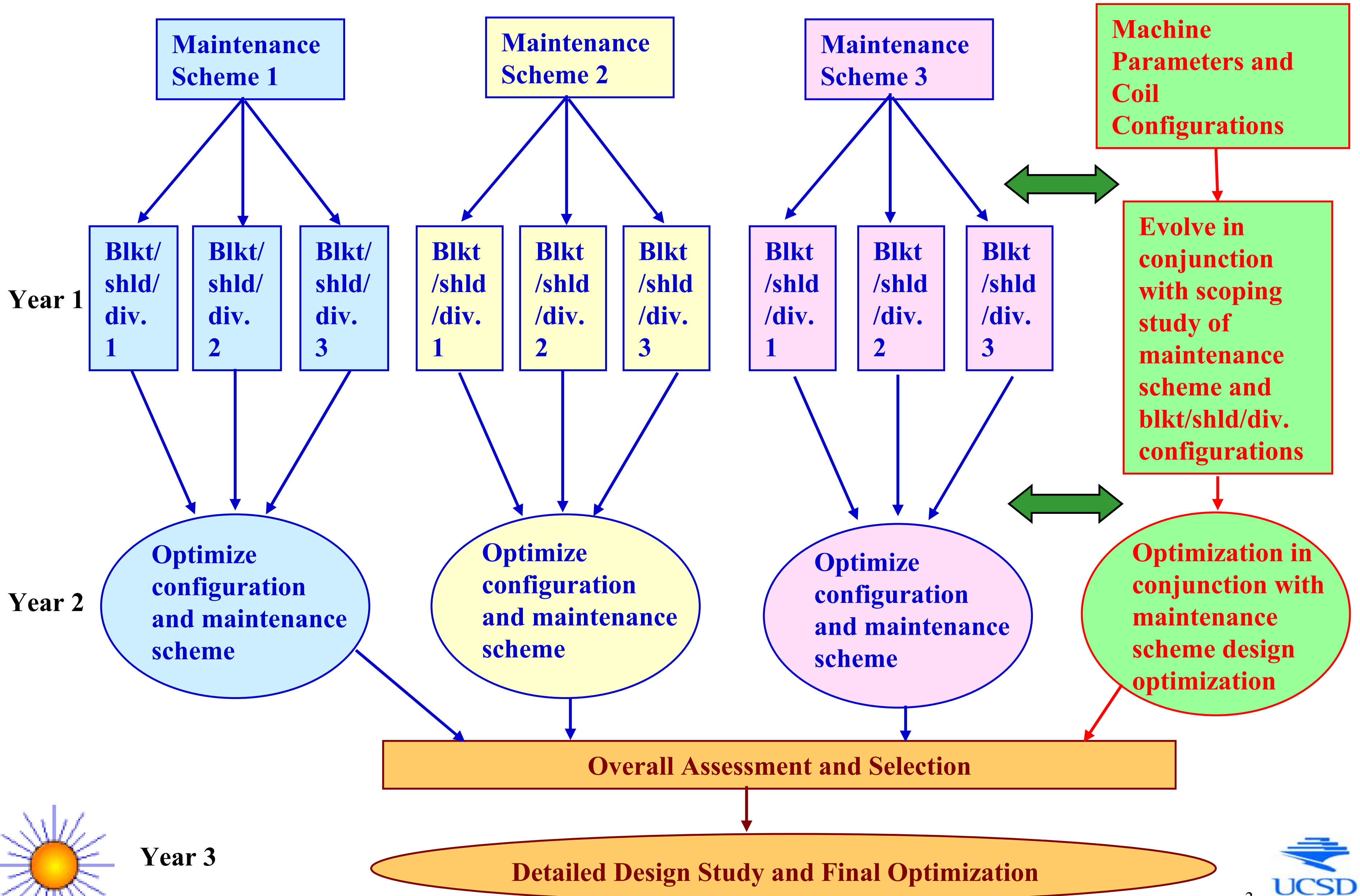
Outline

- Engineering plan of action
- Initial example reactor configuration (3-field period)
- Field-period based maintenance approach
  - Example blanket design
    - FS and dual coolant (Li+He)
- Modular maintenance approach with limited number of ports
  - Example blanket modular designs
    - SiC_f/SiC and Pb-17Li
    - FS and flibe
- Modular maintenance approach with ports between each pair of adjacent coils
  - Initial scoping study for 2-field period configuration
- Conclusions
  - Where we are now and what still needs to be done

Proposed Plan for Engineering Activities



Engineering Activities: Year 1

- **Perform Scoping Assessment of Different Maintenance Schemes and Design Configurations**

  - **Three Possible Maintenance Schemes:**

    1. **Field-period based replacement including disassembly of modular coil system (e.g. SPPS, ASRA-6C)**

    2. **Replacement of blanket modules through small number of designated maintenance ports (using articulated boom)**

    3. **Replacement of blanket modules through maintenance ports arranged between each pair of adjacent modular coils (e.g. HSR)**

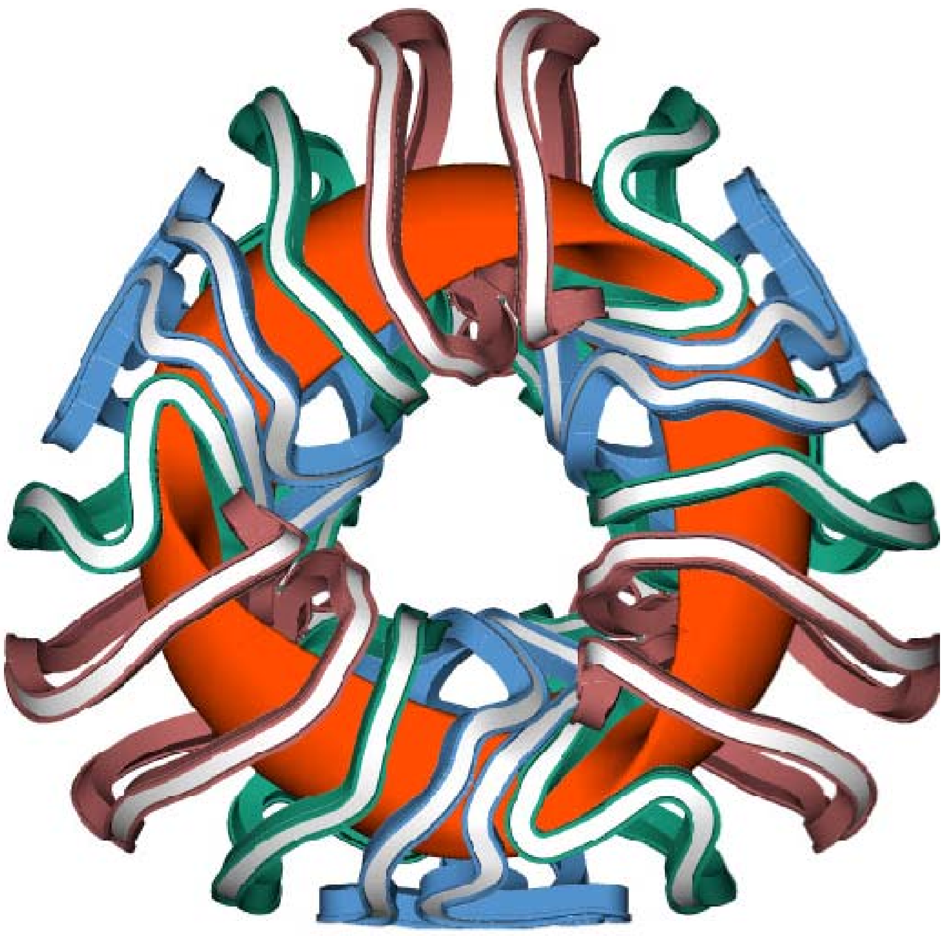
  - **Each maintenance scheme imposes specific requirements on machine and coil geometry**

Engineering Activities: Year 1

- **Scoping analysis of possible blanket/shield/divertor configurations compatible with maintenance scheme and machine geometry, including the following three main classes:**
  1. **Self-cooled liquid metal blanket (might need He-cooled divertor depending on heat flux)**
     a) **Pb-17Li with SiC_f/SiC**
     b) **Pb-17Li or Li with insulated ferritic steel and He-cooled structure**
  2. **Flibe-cooled ferritic steel blanket (might need He-cooled divertor depending on heat flux)**
  3. **He-cooled liquid breeder blanket (or solid breeder) with ferritic steel and He-cooled divertor**

- **Evolve coil configuration(s)**
  - **Material, shape and thicknesses**
  - **Space and shielding requirements**

Start with NCSX-Based Coil and Plasma Shape with 3-Field Period (from PPPL) for Initial Maintenance and Blanket Design Scoping Analysis



Geometry	
Major Radius, R	8.3 m
Minor Radius, <a>	1.85 m
Plasma Aspect Ratio	4.5
Plasma Volume	550 m^3
Plasma Boundary Surface Area	780 m^2
Minimum Distance between Plasma Boundary and Center of Coil Winding, Δ_{min}	1.2 m
Plasma Parameters	
Magnetic Field on Axis, B	6.4 T
Volume Averaged Beta	4.08%
Plasma Current, I_p	5.15 MA
Power	
Fusion Power, P_f	2 GW
Ave. Neutron Wall Loading, Γ_n	2 MW/m^2
Max. Neutron Wall Load (assumed)	~3 MW/m^2

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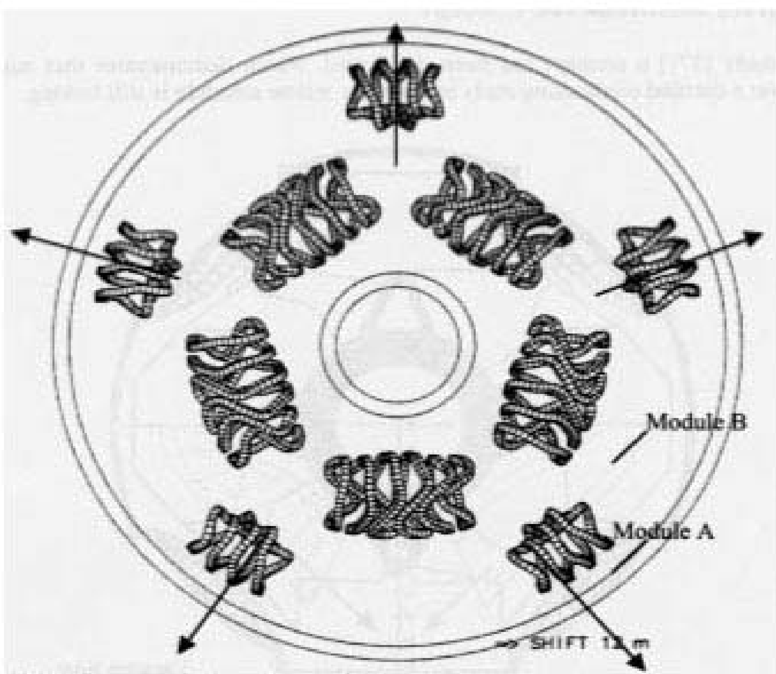
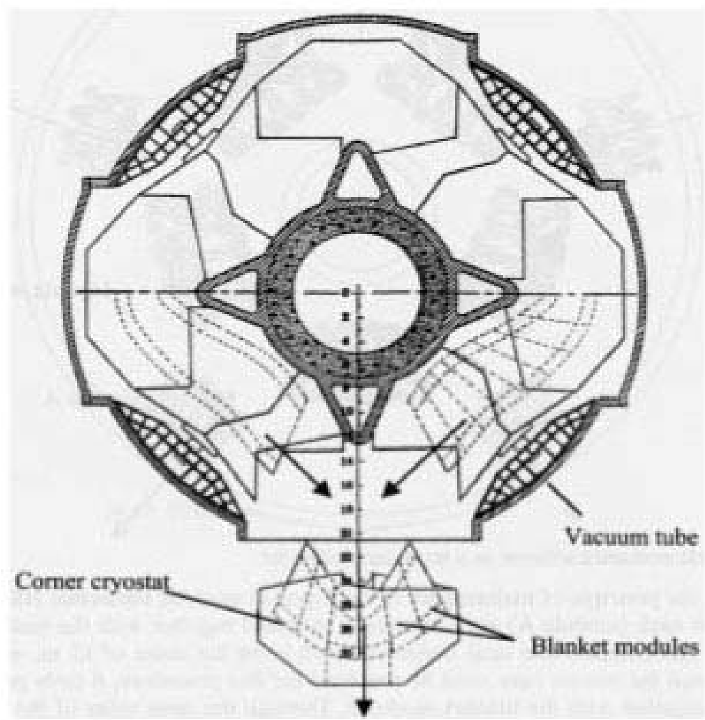
Field-period based maintenance approach

Field Period Maintenance Approach Involves Radial/Toroidal Movement of Large Modules, such as for:

ASRA6C



SPPS



Design of the Coil Support Structure is Challenging

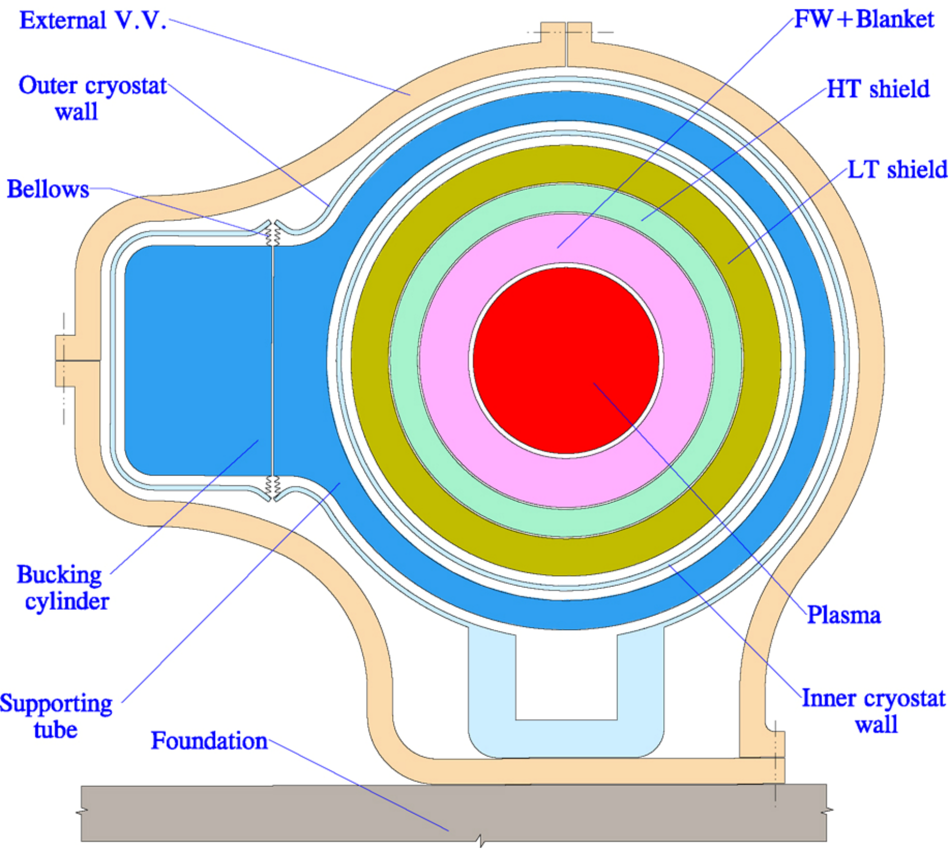
- **The movement of a field period as required for blanket replacement should be possible without disassembling coils, inter-coil structure and thermal insulation in order to avoid unacceptable long down time.**

- **However, transfer of large forces within a field period and between coils and bucking cylinder is not possible between “cold” and “warm” elements.**
  - **Entire support structure has to be operated at cryogenic temperature.**

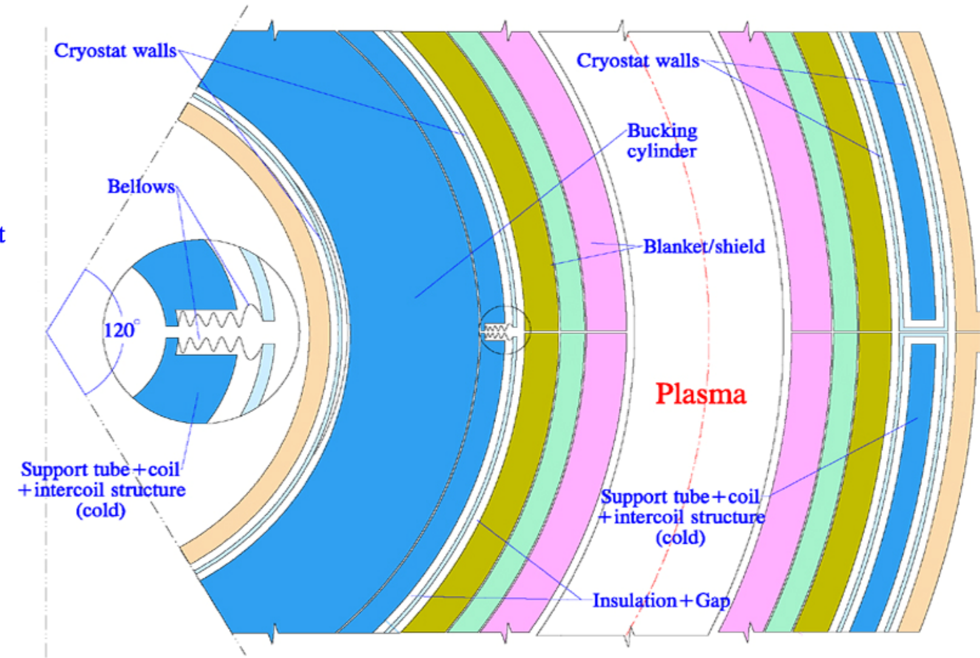
- **To facilitate fast opening of the coil system, it is suggested to have separate cryostats for the bucking cylinder in the center of the torus and for every field period.**

Possible Solution is to Enclose Individual Cryostats in a Common External Vacuum Vessel

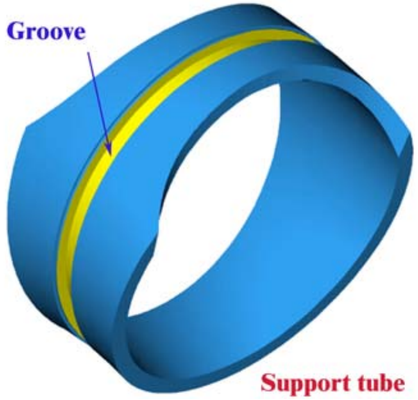
Vertical Cut Through Torous (Principle Arrangement)



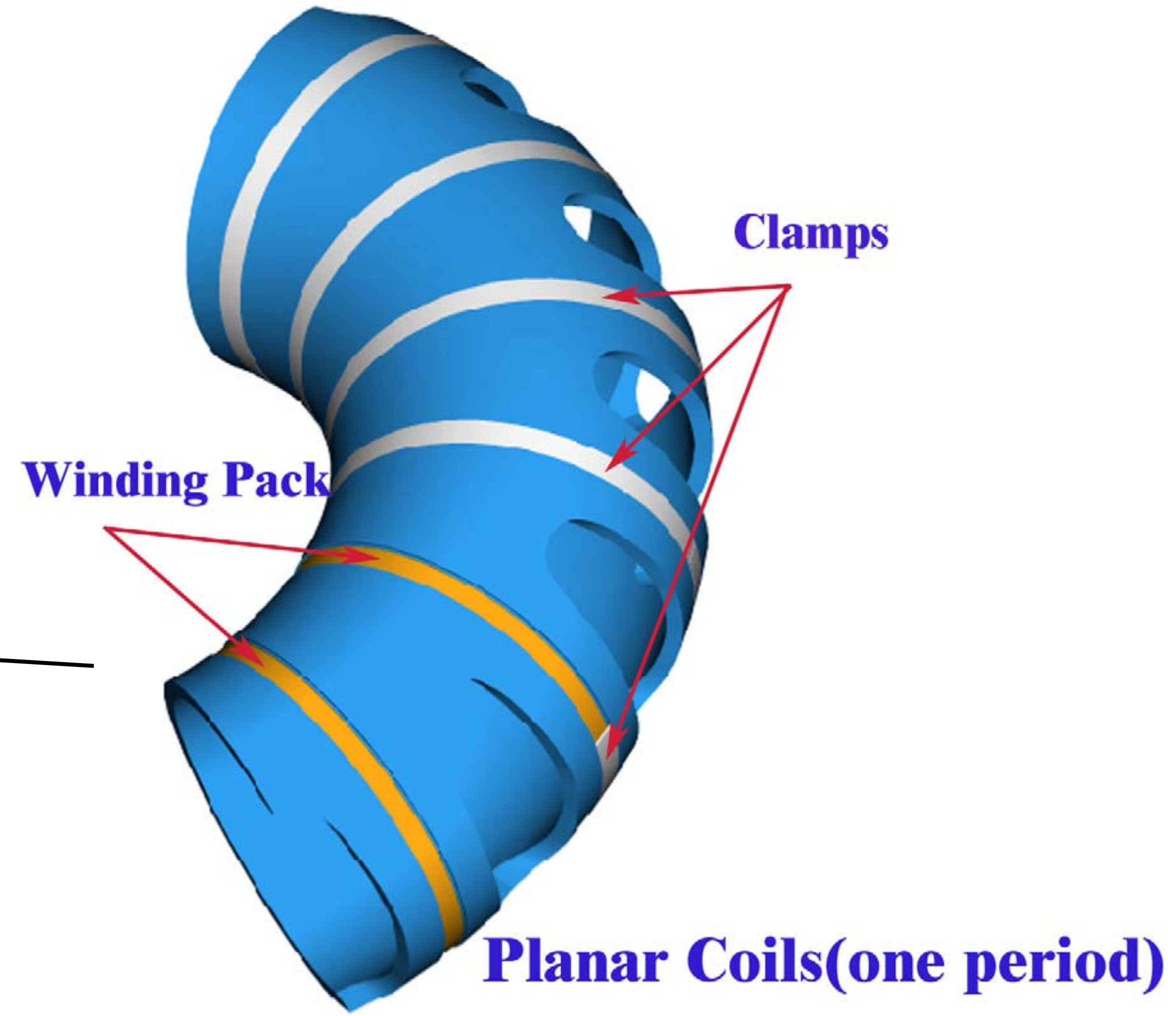
Horizontal Cut Through Torus (One Field Period)



Schematic of Arrangement of all Coils of a Field Period on a Supporting Tube



Winding of Coils into Grooves in the Supporting Tube

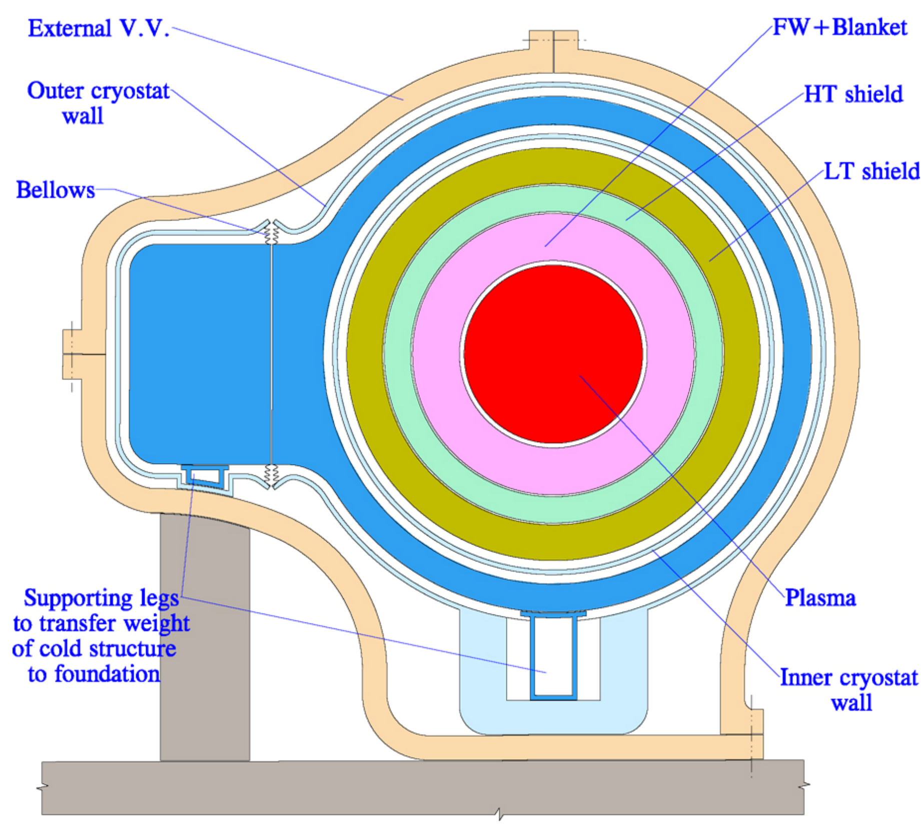


Arrangement of Long Legs to Support the Weight of the Cold Structure

Conflicting requirements:

- **Sufficiently large cross section of legs required to minimize mechanical stresses**
- **Small ratio between cross section and length of the legs required to minimize heat ingress → long legs**
- **Example**
  - **total weight of cold structure ~ 1,800 tons**
  - **total number of legs 3x3**
  - **required cross section of one leg: for example cylindrical tube with 100mm diameter, 3 mm wall thickness q (300 K-->4 K) with 0.5m long legs ~ 500 W for all legs**

Supporting Legs for Cold Structure



(Much longer legs shown in the sketch)

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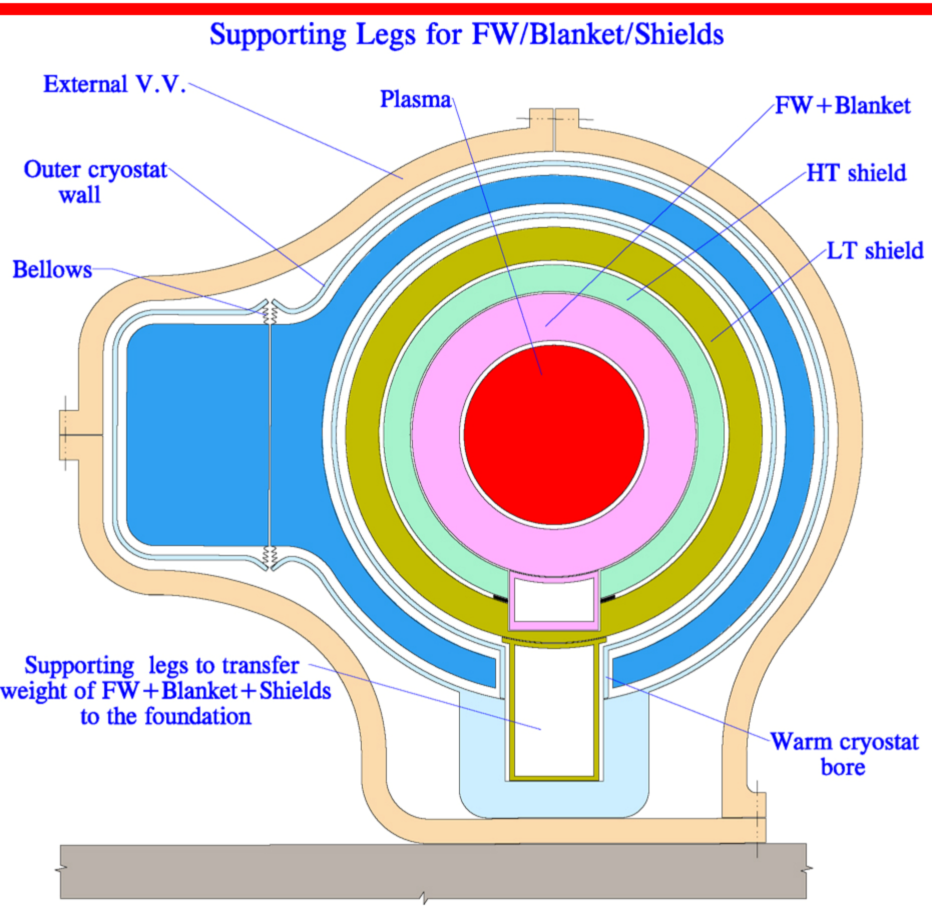
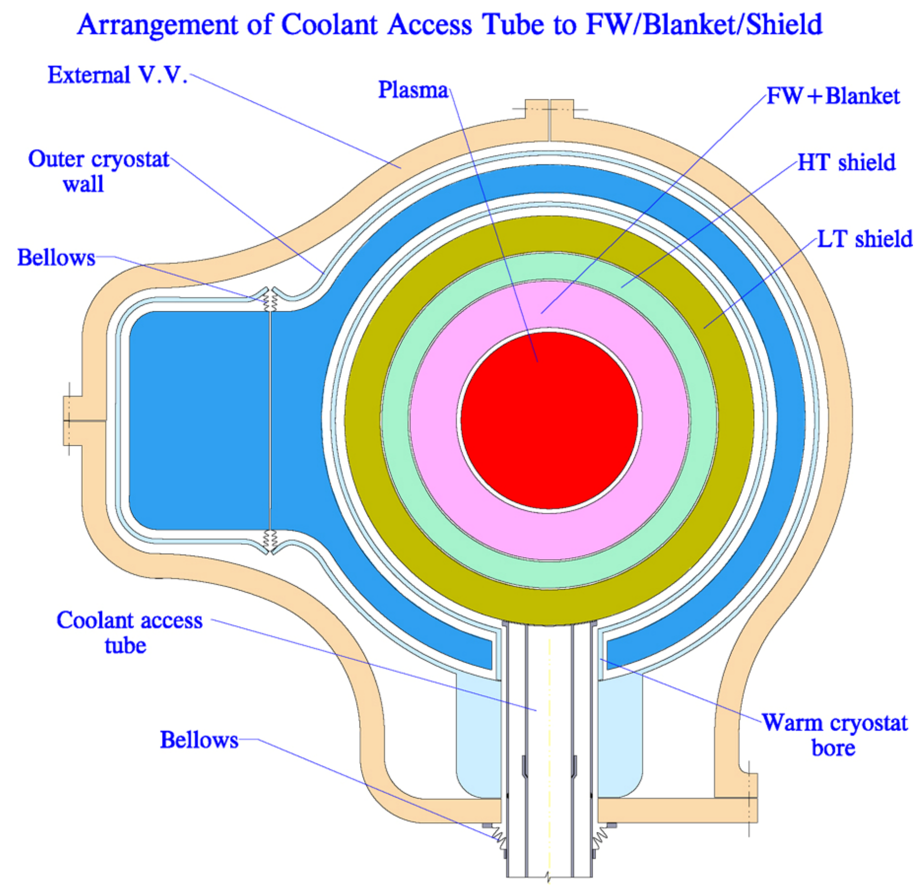
Arrangement of Supporting Legs and Coolant Access Tubes for FW+Blanket+Shields





Large weight to be supported, but legs are between "warm" regions and therefore nearly no limitation on cross section.

- **4 legs in each field period, 500 mm dia., 35 mm wall thickness**

- **All access tubes are coming from the bottom.**
- **Location of the access tubes close to points of mechanical support.**
- **Concentric tubes with inlet flow in the annulus and outlet flow in the centre tubes allow for sliding seals in the centre tube.**

Subdivision of FW, Breeding Blanket, and Shields

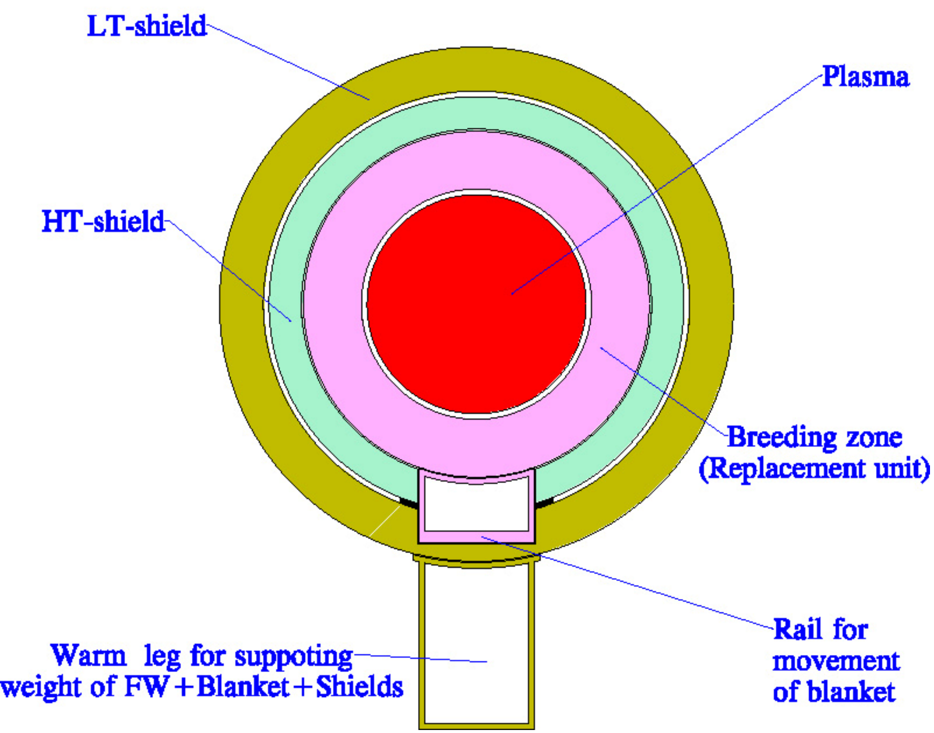
- **Minimize fabrication costs and waste by separating regions requiring frequent replacement ("replacement units") from the life-time components ("permanent zone").**

- **Choose an overall geometry allowing the removal of a replacement unit without disconnecting life-time components.**

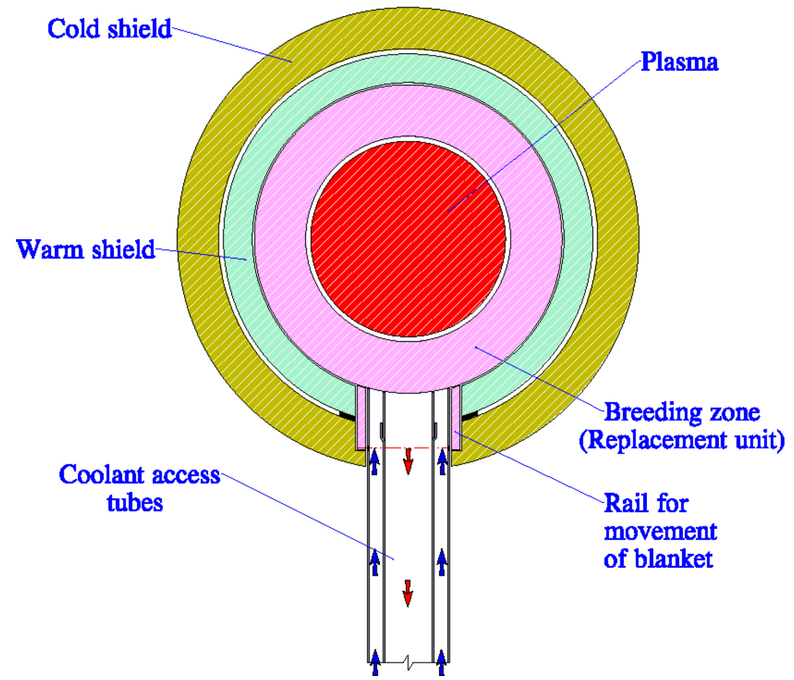
- **Split the required neutron shielding into high temperature and low temperature shield to:**
  1. **enable passive low temperature cooling in the outer shield region for safety reasons,**
  2. **minimize low temperature heat ("waste heat") to <1% of total heat**

Mechanical Support and Coolant Access for Different FW/Blanket/Shield Components

Principle Arrangement of Blanket/HT-Shield/LT-Shield



Coolant Access Tubes to Breeding Zone+First Wall



- **Cold shield rests on warm legs, transferring the entire power core weight to foundation.**
- **Hot shield rests at the bottom only on the cold shield, allowing free differential thermal expansion.**
- **FW+Breeding zone+support ring ("Replacement Unit") slides on a rail located inside cold shield.**

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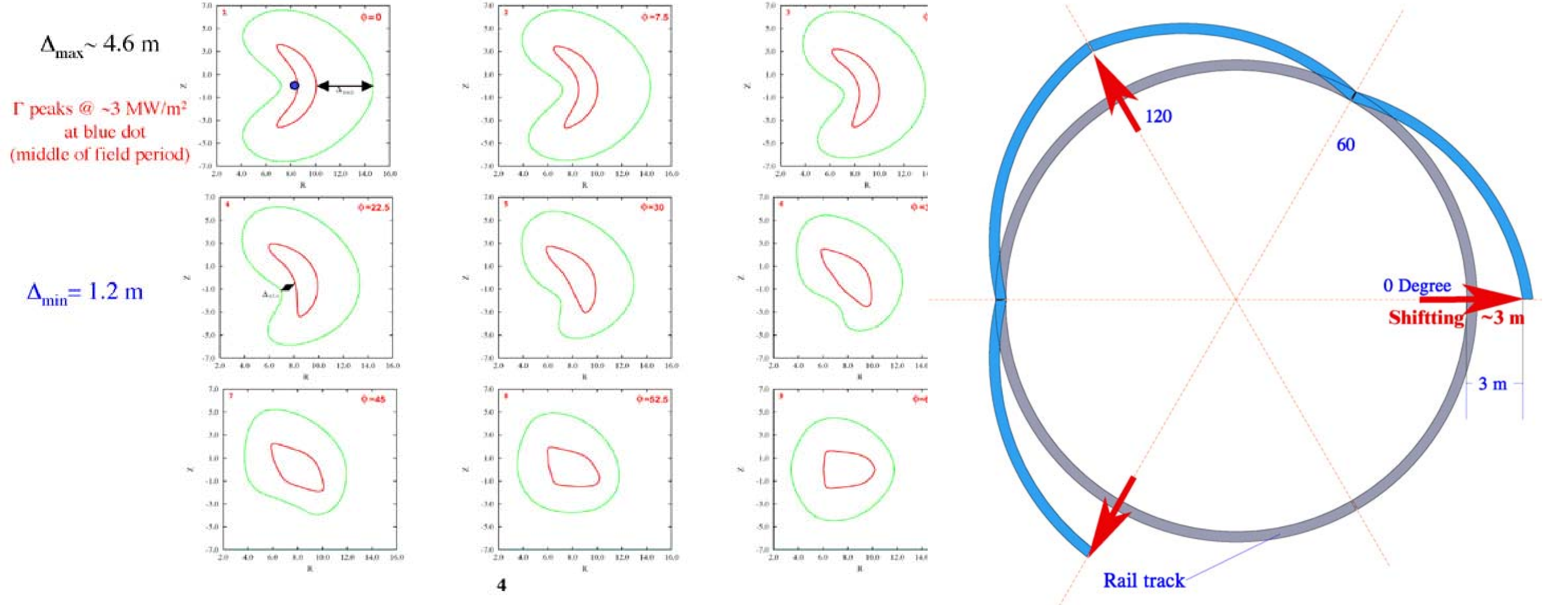
Steps to be Performed for an Exchange of Blankets (due to failure or for end-of-life replacement)

1. Warm up the coil system including the mechanical support structure.
2. Flood the plasma chamber and the cryostats with inert gas.
3. Cut all coolant connections to the field period to be moved, using in-bore tools operating from the bottom.
4. Open outer side of external VV over field period to be moved.
5. Slide entire field period components (blankets, shields, cryostats, coils and all thermal insulation) outward in radial direction on flat bottom surface (possibly with an air-cushion system).
6. Cut the coolant access tubes to the blanket to be replaced.
7. Slide out toroidally from the openings at both ends the 2 replacement units (FW, breeding zone and a structural ring). This replacement unit slides on a rail attached to the low temperature shield (again possibly with an air-cushion system with pressure ~0.6 MPa).

Although, For Illustration Purposes, Maintenance Approach Was Shown For Simple Cylindrical Geometry, It Can Be Extrapolated to a CS



- For example, the replacement units can be removed long off-axis rails but the thickness of blanket and shield regions must be reduced to ~0.82 cm
- Need to increase minimum distance between coil and plasma (1.2 m for present example) and/or to modify locally some coils to facilitate access to allow for thicker blanket and shield regions
- Extrapolation would be easier for geometries with smaller variation of the plasma cross section, and coils with smaller deviations from circular shape.

Example Blanket Concepts for Field-Period Based Maintenance Approach

- **This maintenance scheme allows for very large blanket units virtually without weight limitations.**

- **It is desirable to minimize the coolant connections to be cut/rewelded for blanket replacement, and to locate these connections close to the points of mechanical support in order to avoid differential thermal expansion problems.**

- **A self-cooled liquid metal breeder blanket is an example of a simple concept for this maintenance scheme (with main flow in toroidal direction to minimize MHD effects).**

  - **Self-cooled blanket with Li flowing in FW and breeding one.**

  - **Dual coolant blanket with helium cooled FW/structure and self-cooled Li-breeding zone.**

  - **Dual coolant blanket with helium cooled FW/structure and self-cooled Pb-17Li-breeding zone.**

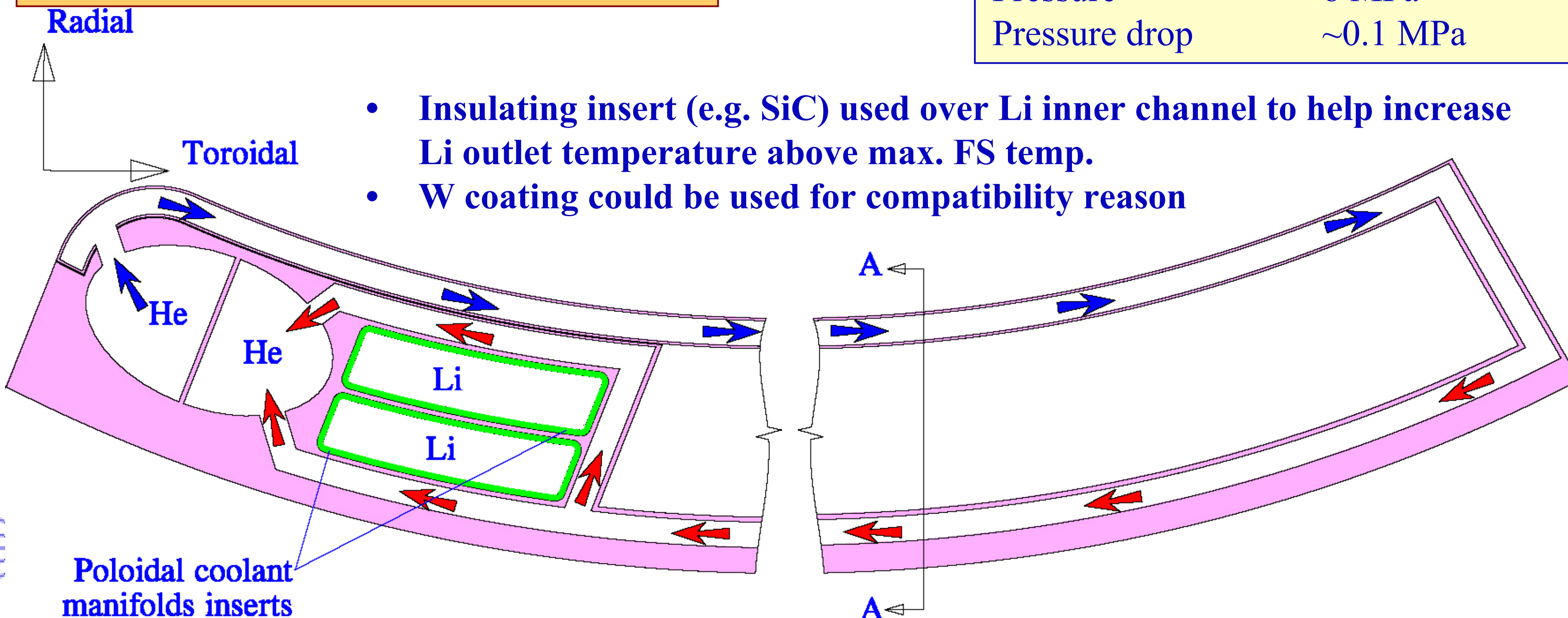
Dual-Coolant Li/He/FS Blanket

- Total thermal power to be removed per replacement unit (1/6 of entire machine): 400MW
- Heat to be removed with Li ~300MW, and with He ~100 MW
- Tritium self-sufficiency estimated with breeding zones ~47cm and 62cm thick.
- For sufficient shielding of the S/C coils, the steel shield has to be around 95 cm thick (challenging for example configuration)

Lithium cooling of breeding zone	
Velocity	0.12 m
Inlet temperature	500°C
Temperature rise	300°C
Heat transfer coef.	450 W/(m^2-K)
Pressure drop	~0.1 MPa
(assuming perpendicular B=1T)	

Helium cooling of FW and Box	
Velocity	70 m/s
Heat transfer coef.	4,200 W/m^2-K
Inlet temperature	400 °C
Temperature rise	50 °C
Pressure	8 MPa
Pressure drop	~0.1 MPa

- Insulating insert (e.g. SiC) used over Li inner channel to help increase Li outlet temperature above max. FS temp.
- W coating could be used for compatibility reason

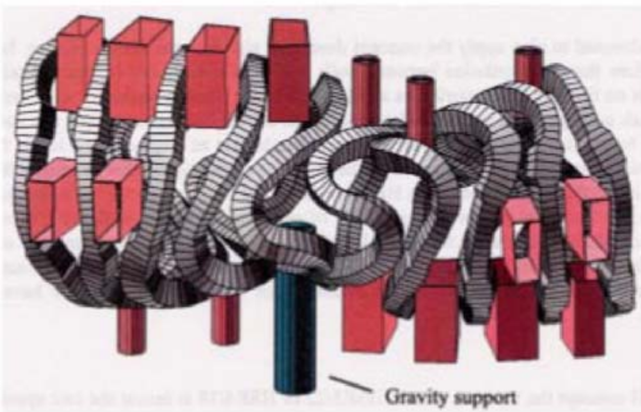


Modular maintenance approach through selected ports

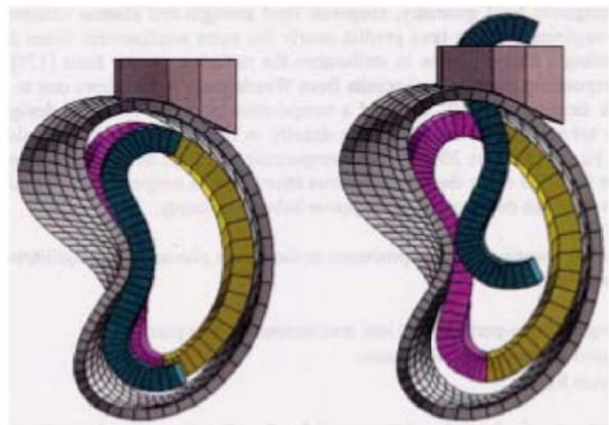
Modular Maintenance Approach Involves Replacement of Smaller Modules (weight limitation based on handling system) through Dedicated Ports, such as for:

HSR Maintenance Concept

- HSR5/22: small modules thru ports



One field period of the coil system with ports

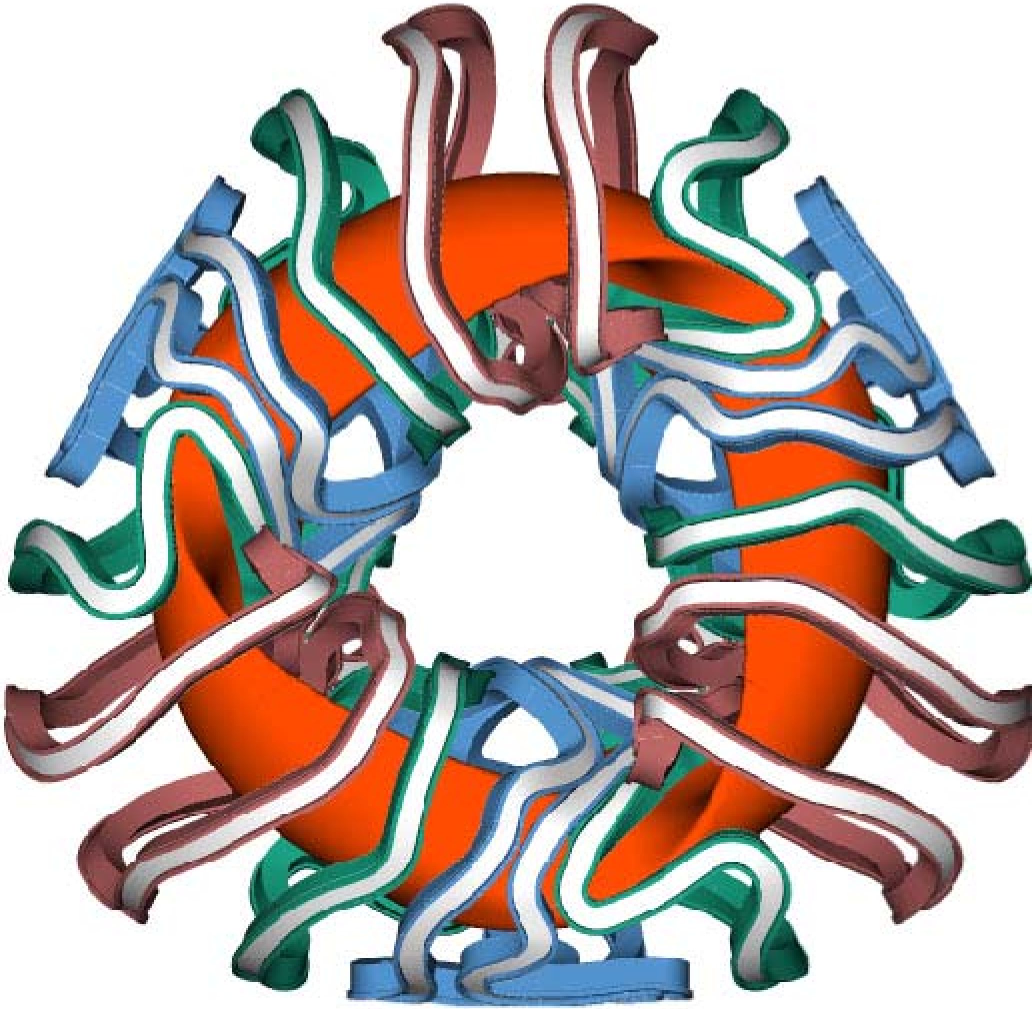


Maintenance scheme for blanket segments

Plasma Access for Articulated Boom Between Ports for Modular Maintenance Approach With Limited Number of Ports

- **ITER modular maintenance approach**
  - Rail system
  - Transporter from port to module plane on rail
  - Articulated boom to replace module

- **CS configuration makes a rail system very challenging**
  - "Roller coaster" system
  - Perhaps single rail but only to provide support for boom when extended, not for transporter to carry module to and from port
  - Preferable to design for module replacement using articulated boom only if possible

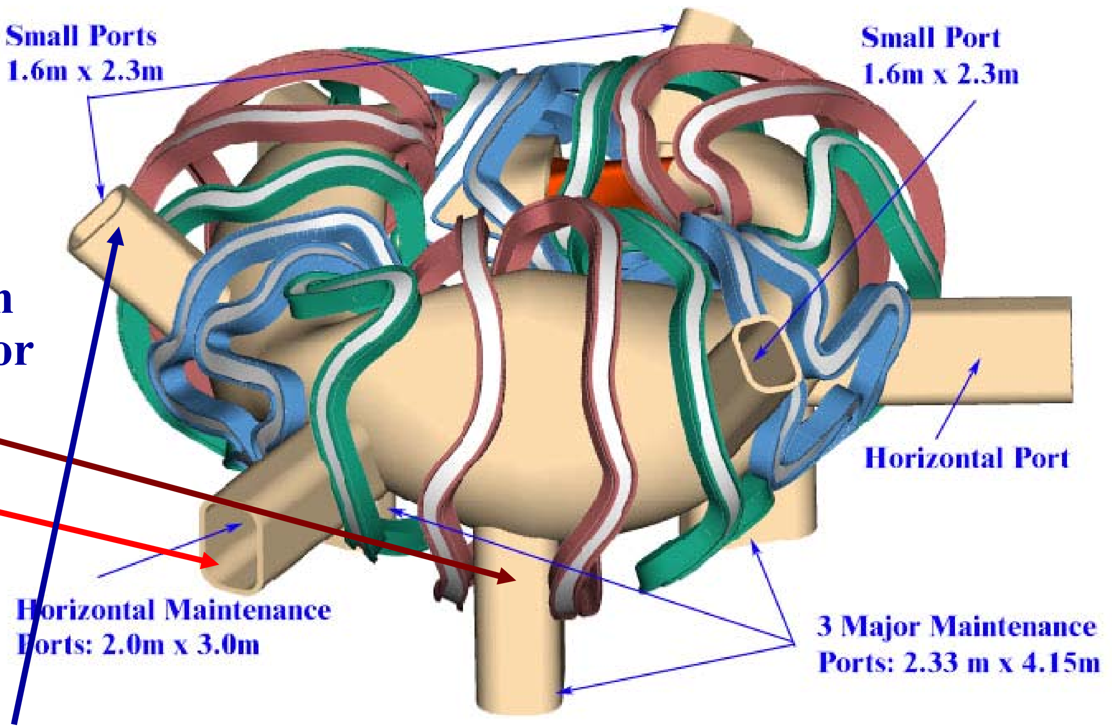


Modular Design Approach Using Articulated Boom

- **From EDITH-system*, boom built with:**
  - a total length of ~ 10m
  - a reach of +/- 90° in NET
  - pay load of 1 ton
  - maximum height of 2 m

- **Current ARIES-CS modular design based on comparable parameters for 3 ports (horizontal or vertical)**
  - half field period length ~ 9 m
  - minor radius =1.85 m (local plasma height varies over about 1.5-3.5 m)
  - Weight of empty module < ~1 ton

- **Could use additional ports if required**
  - Depending on access for module removal in toroidal direction over region serviced by port

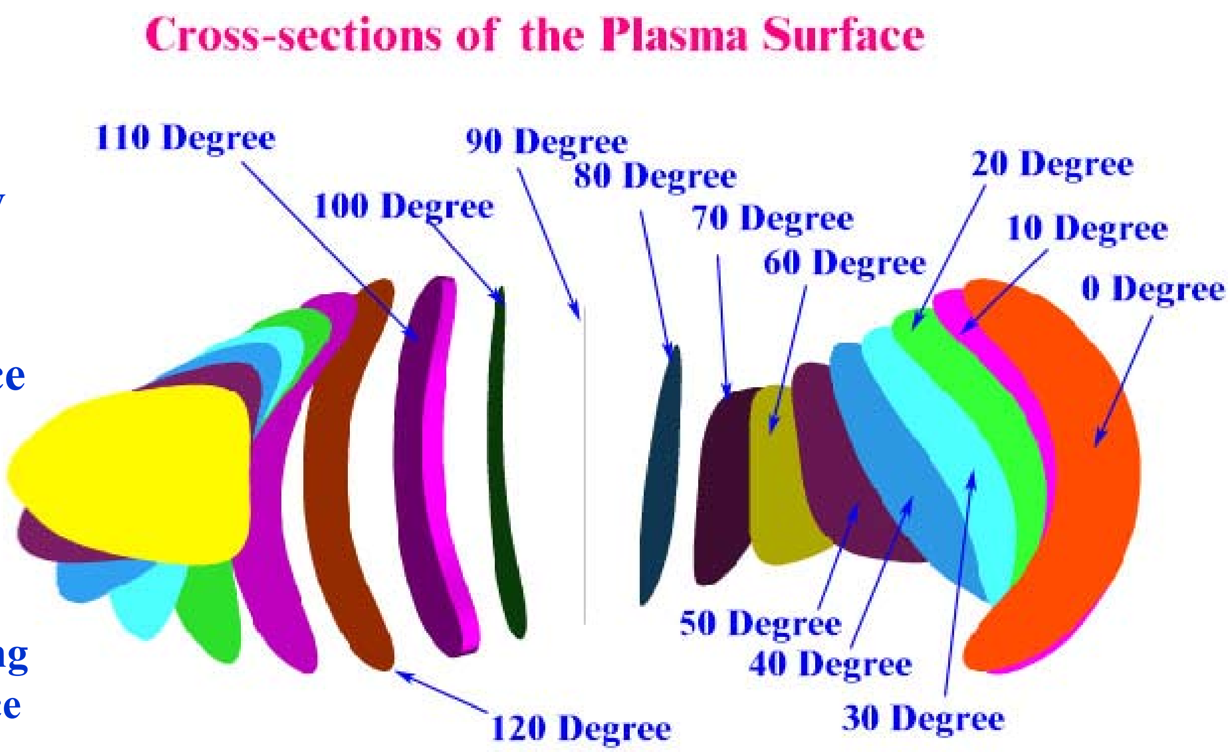


Maintenance boom can be also usedy for the replacement of high power divertor target plates.

*Experimental -In-Torus Maintenance System for Fusion Reactors, FZKA-5830, Nov. 1966.

Plasma Access for Articulated Boom Between Ports for Modular Maintenance Approach With Limited Number of Ports

- **Final number of ports, largest module size and degree of freedom of articulated boom (probably with at least 3-4 "elbows") would depend on toroidal access through plasma space between port and furthest serviced region**
  - **If required, optimization between penalty of increasing reactor size and maintenance and module design considerations**



Example Blanket Concepts for Modular Maintenance Approach

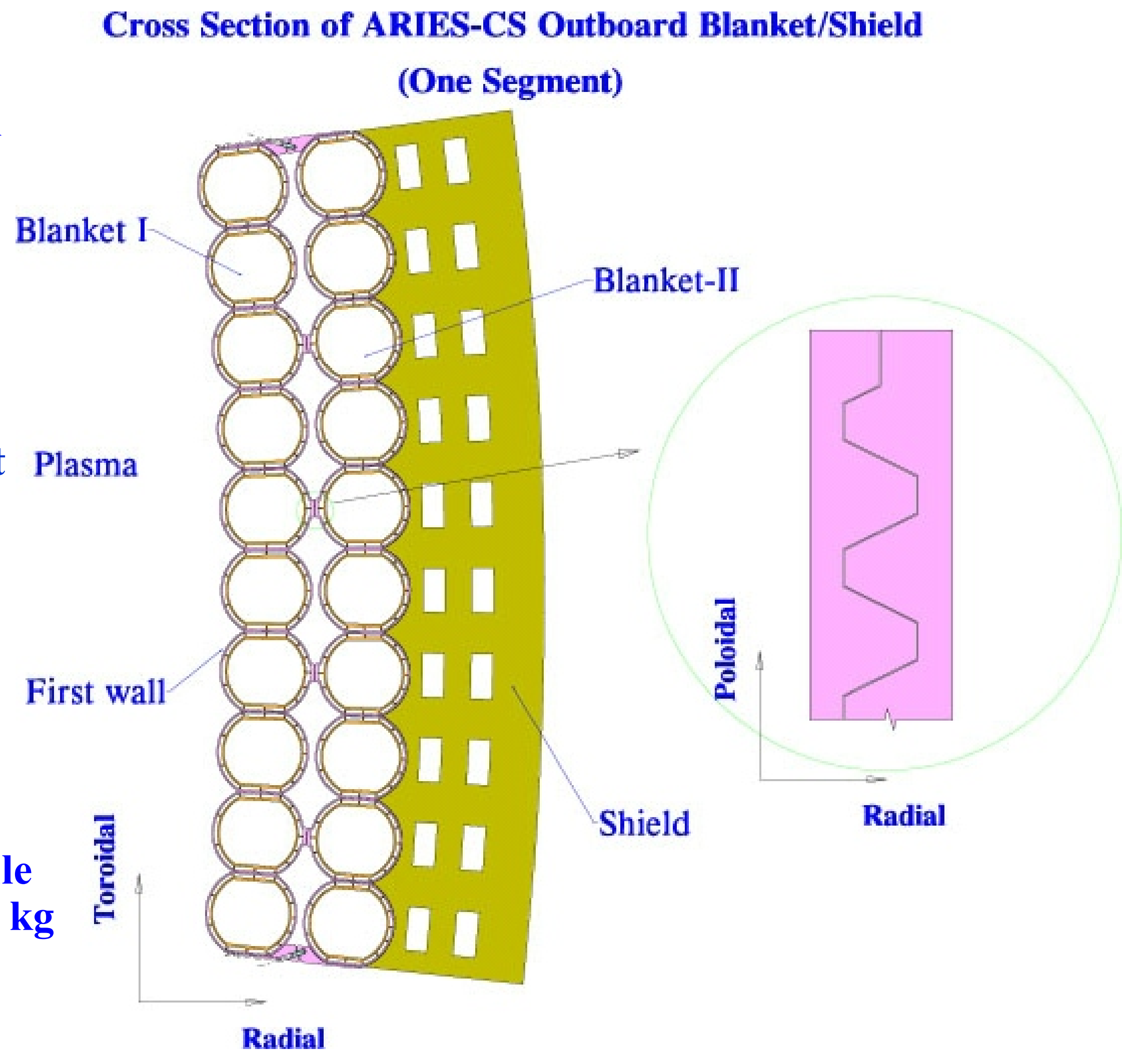
- **For this maintenance scheme where blanket modules are replaced with articulated booms through ports in the VV, the size of the modules and their weight are severely limited.**

- **The following concepts were considered in this initial scoping study:**
  - **Self-cooled Pb-17Li blankets with SiC-composites (lower density structural material)**
  - **Self-cooled Flibe blankets with advanced ferritic steel as structural material (low pressure --> thinner walls --> lighter modules)**
  - **These choices were based also on making sure to cover the different blanket options to be evaluated in this initial phase of the study**
  - **A He-cooled ceramic breeder blanket will be considered next**

Blanket Modular Design Approach Using SiC_f/SiC as Structural Material and Pb-17Li as Breeder/Coolant

Based on ARIES-AT concept

- High pay-off, higher development risk concept
  - SiC_f/SiC: high temperature operation and low activation
  - Key material issues: fabrication, thermal conductivity and maximum temperature limit
- Replaceable first blanket region
- Lifetime shield (and second blanket region in outboard)
- Mechanical module attachment with bolts
  - Shear keys to take shear loads (except for top modules)
- Example replaceable blanket module size ~2 m x 2 m x 0.25m (~ 500-600 kg when empty) consisting of a number of submodules (here 10)



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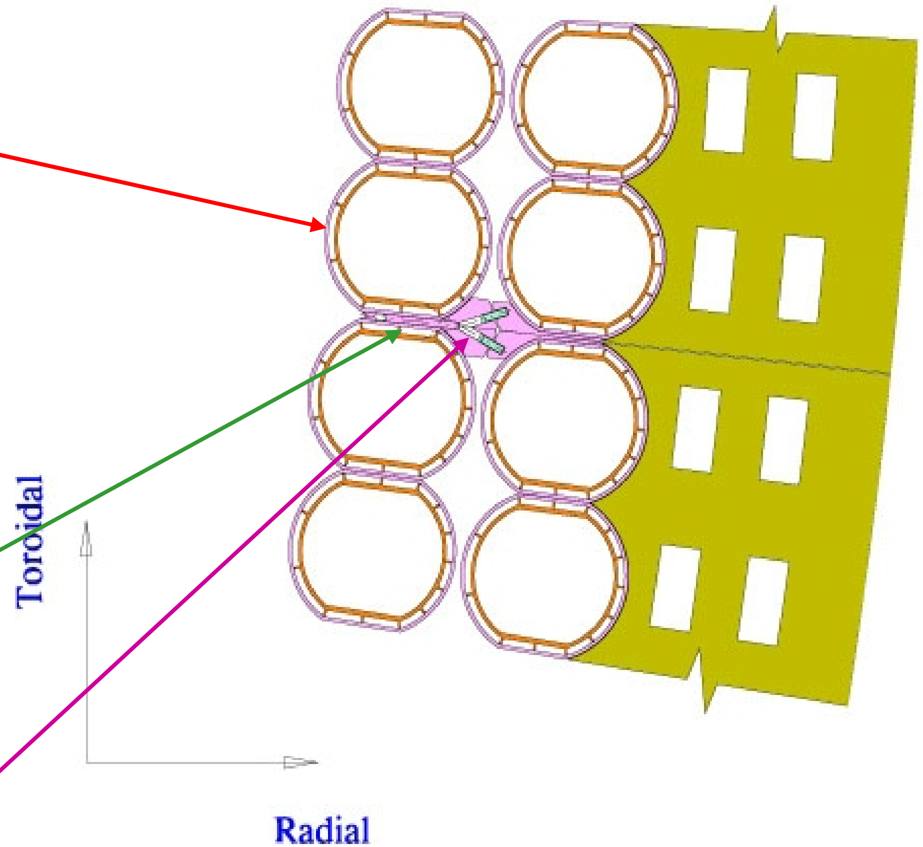
Blanket Module Configuration Consists of a Number of Submodules

Submodule configuration

- Curved first wall for better Pb-17Li pressure (<~2 MPa) accommodation
- 4 mm thick SiC_f/SiC first wall with 1 mm CVD SiC coating
- Hoop stress ~ 60 MPa
- Side wall of adjacent submodules pressure balanced, except for each end submodule where thicker side walls are required to accommodate the pressure
- Mechanical attachment between two modules also shown



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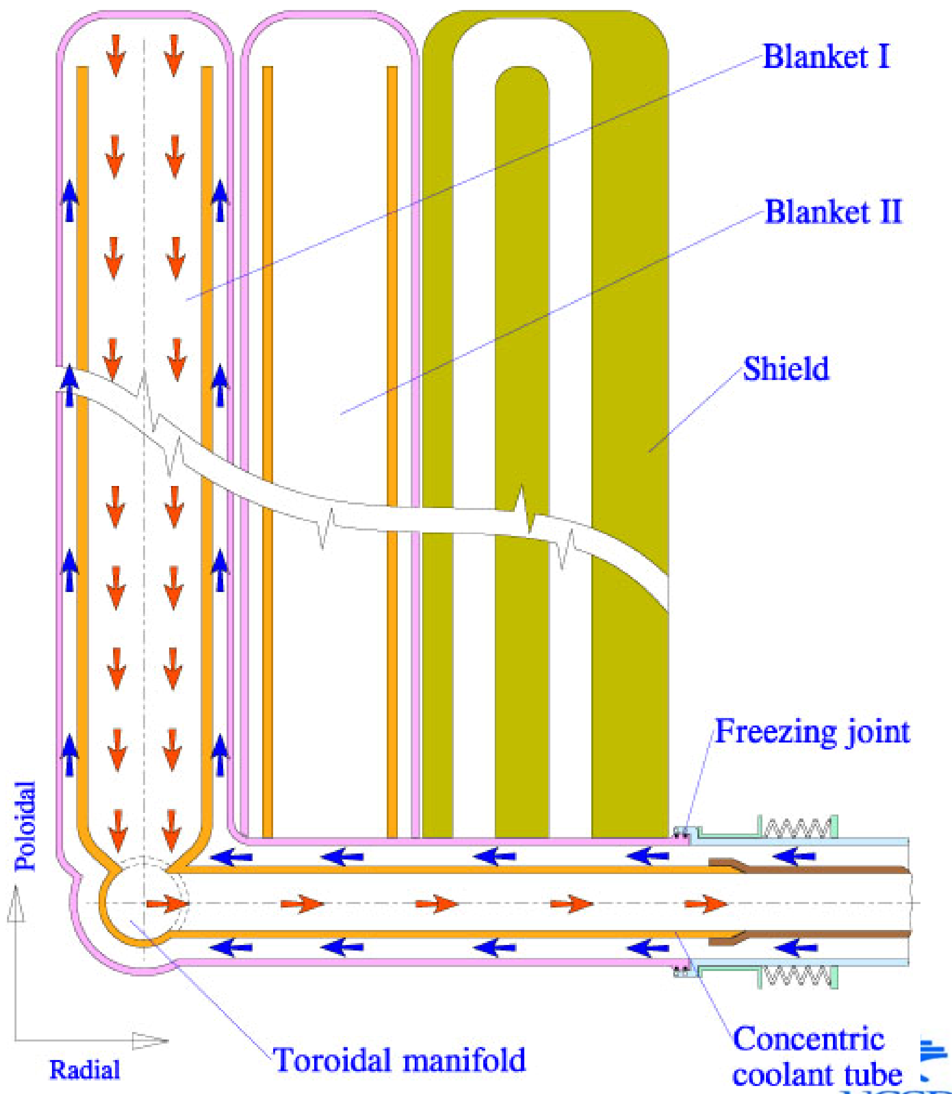
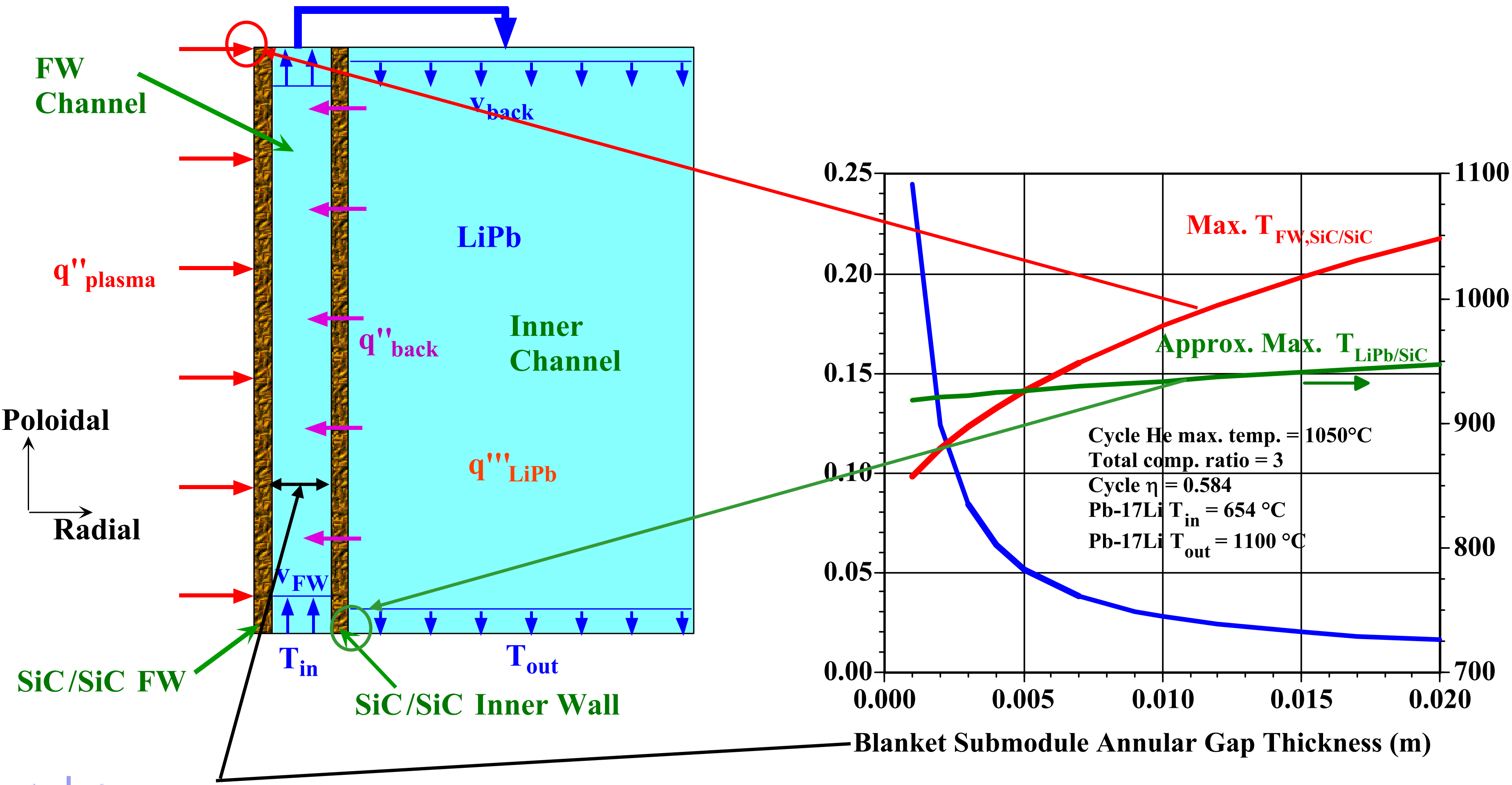
Coolant Flow and Connection for ARIES-CS Blanket Modular Design Using SiC_f/SiC and Pb-17Li

- **Two-pass flow through submodule**
  - First pass through annular channel to cool the box
  - Slow second pass through large inner channel
- **Helps to decouple maximum SiC_f/SiC temperature from maximum Pb-17Li temperature**
  - Maximize Pb-17Li outlet temperature (and Brayton cycle efficiency, ~0.55)
  - Maintain SiC_f/SiC temperature within limits
- **Possible use of freezing joint behind shield (and possibly vacuum vessel) for annular coolant pipe connection**
  - Inlet in annular channel, high temp. outlet in inner channel

Cross-section Showing Coolant Flow Path and Access Tube

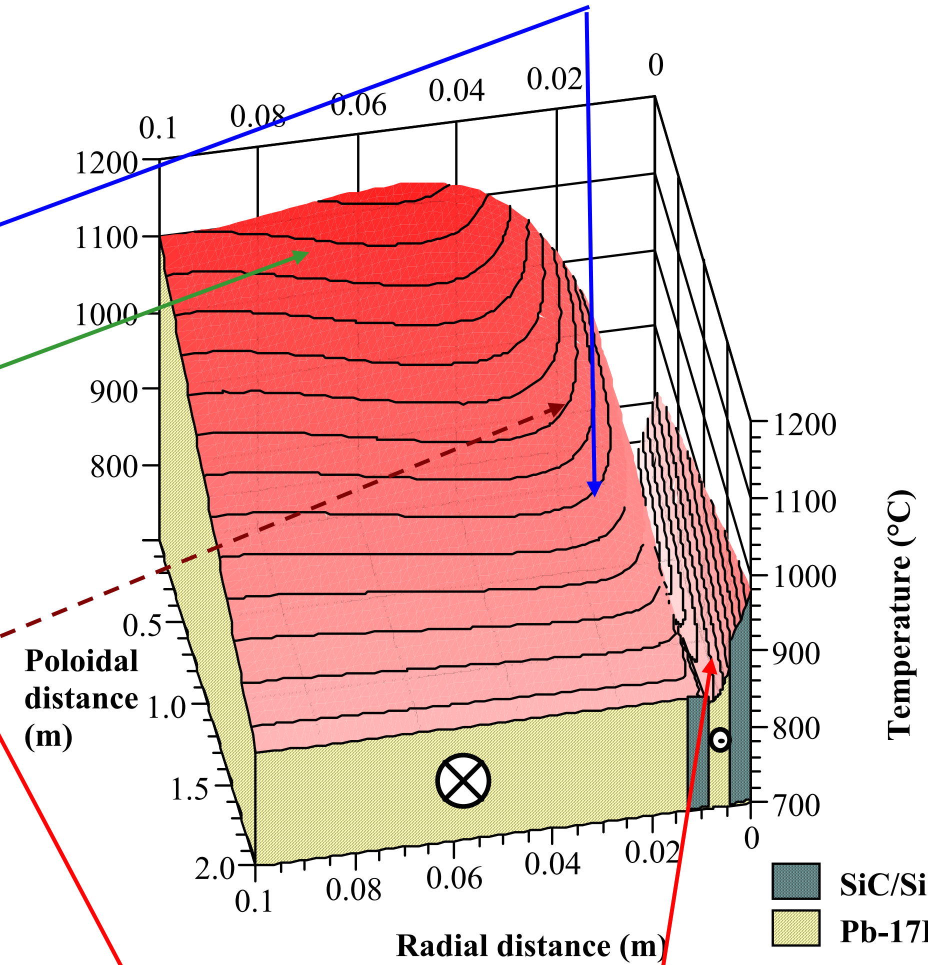


Maximum SiC_f/SiC Temperature Can be Reduced by Decreasing the Annular Channel Thickness, but with a Pressure Drop Penalty



Temperature Distribution in Example ARIES-CS Blanket Modular Design Using SiC_f/SiC and Pb-17Li

- Pb-17Li Inlet Temperature ~ 699°C
- Pb-17Li Outlet Temperature ~ 1100°C
- Maximum SiC/SiC Temperature ~ 970 °C
- Maximum SiC/LiPb Temperature ~ 900 °C



Typical Parameters for Example ARIES-CS Blanket Concept with SiC_f/SiC and Pb-17Li (Not fully optimized yet)

Cycle & Coolant Parameters	
Cycle He Maximum Temperature	1050°C
Total Compression Ratio	3
Efficiency	0.584
Cycle T_{He} at Recuperator Exit	604°C
LiPb Inlet Temperature to Divertor	654°C
LiPb Inlet Temperature to Blanket	699°C
LiPb Outlet Temperature	1100°C
LiPb Inlet Pressure	2 MPa
Outboard Blanket Module	
Module Poloidal Dimension	2 m
Module Toroidal Dimension	2 m
Module Radial Dimension	0.25 m
Number of Submodules per Module	10
Submodule Toroidal Dimension	0.2 m
Outboard FW Annular Channel Thickness	4 mm
LiPb Average Velocity in Annular Channel	0.7 m/s
LiPb Velocity in FW Annular Channel	1.6 m/s
LiPb Average Velocity in Large Inner Channel	0.05 m/s
SiC_f/SiC FW Thickness	4 mm
CVD SiC_f/SiC Armor Thickness	1 mm
Maximum CVD SiC Temperature	~970°C
Max. SiC/LiPb Temperature at Submodule Outlet	~900°C
FW MHD Pressure Drop	0.063 MPa
SiC_f/SiC Hoop Stress	60 MPa

Blanket Modular Design Approach Using FS as Structural Material and Flibe as Breeder/Coolant

Pros:

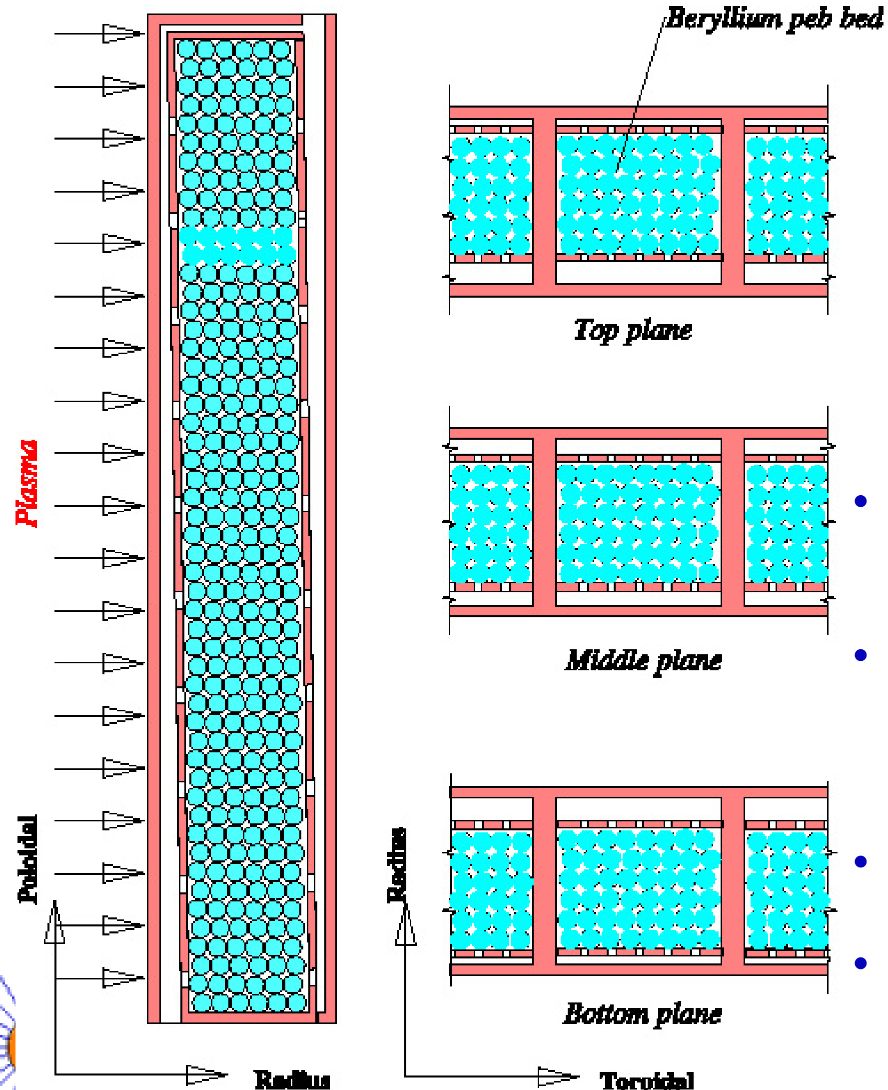
- Electrical conductivity of flibe low enough to avoid need for insulating coatings
- Thinner breeding zones are required for tritium self-sufficiency and shielding compared to other breeder materials
- Low pressure (<0.5 MPa) minimizes the weight of structure
- Only one concentric tube required as coolant access tube for each module
- Flibe can be used as shield coolant without the need for an additional neutron moderator

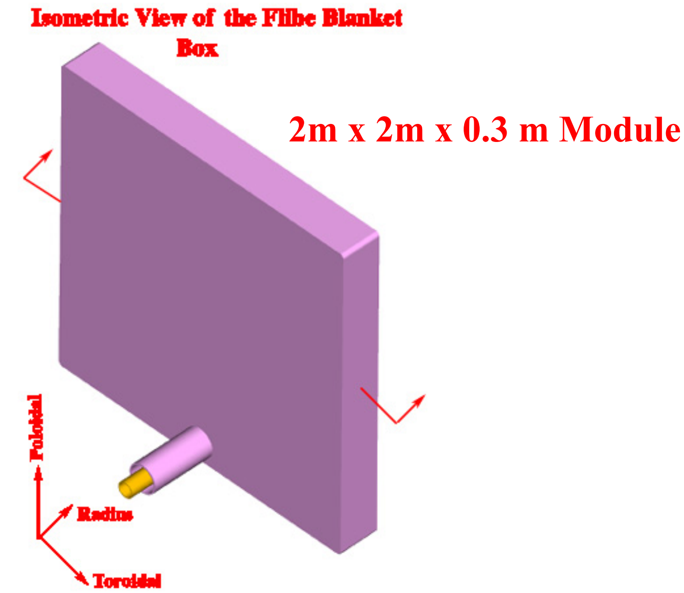
And Cons:

- Low thermal conductivity of flibe (~1 W/m-K) and high viscosity requires high velocity in FW channel for turbulent flow and acceptable h
  - Maximum NWL up to 5 MW/m^2 seems feasible with proposed concept.
- Breeding capability of flibe is limited; neutron multiplier (Be) is mandatory.
- High melting point of flibe (459°C for $(LiF)_2(BeF_2)$) requires a structural material with high temperature range
  - Flibe/steel interface < 700° C

Example Self-Cooled Flibe Blanket Modular Concept with FS as Structural Material

Cross-Section Showing First Wall and Multiplier Region

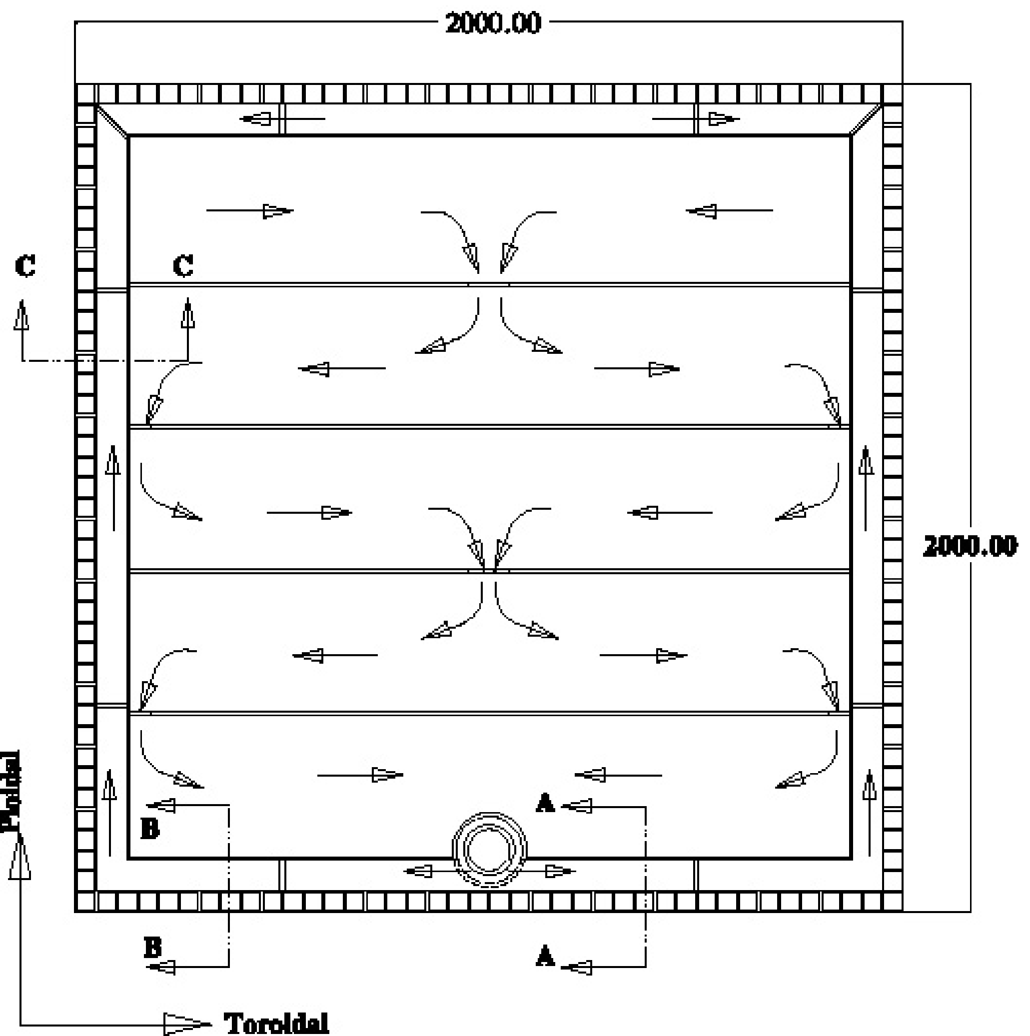




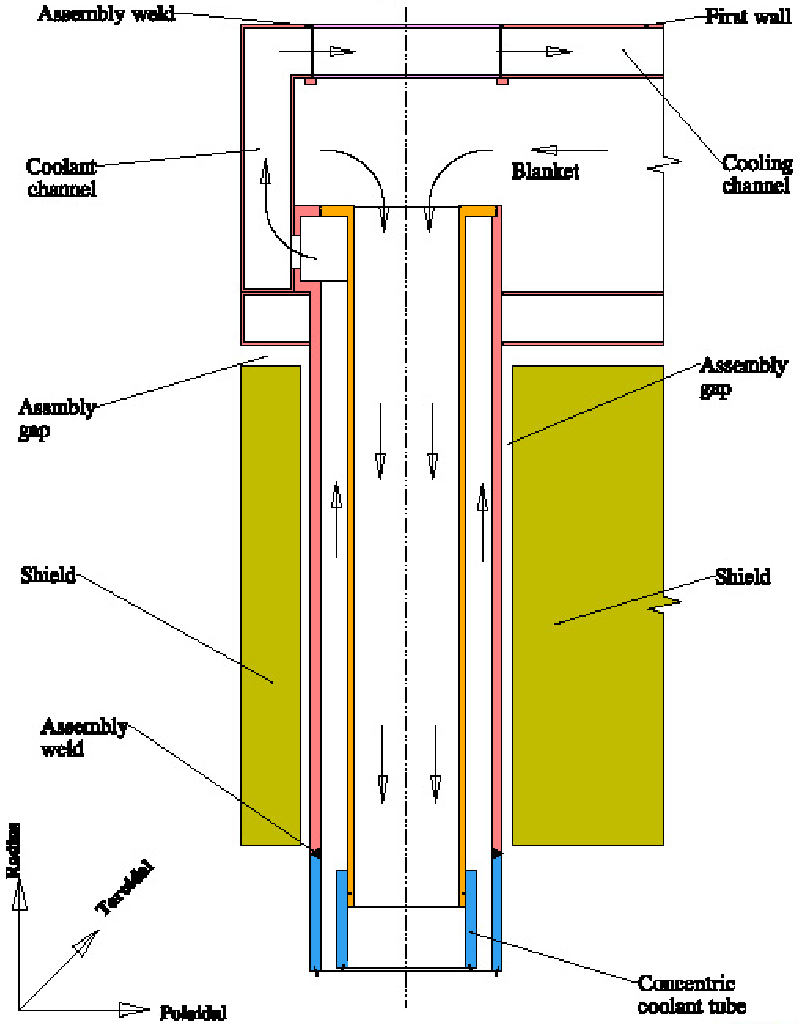
- Cold inlet flow cools the entire structure. (T_{in}=550°C; T_{out}=700°C)
- Then, slowly flowing flibe in the large central ducts is heated up to a temperature equal or higher than the max. interface temperature.
- Coupled with Brayton cycle ($\eta > 0.45$)
- Arrangement of ~ cm's thick Be pebble bed between perforated plates in FW region (for neutron multiplication and for Flibe chemistry control

Example Self-Cooled Flibe Blanket Modular Concept with FS: Details of Flow Path (high velocity at walls, low velocity in center channel) and of Coolant Access Tube

Cross-section of the Flibe Blanket Box (View From Back Side)



Cross-section Showing the Access Coolant Tube



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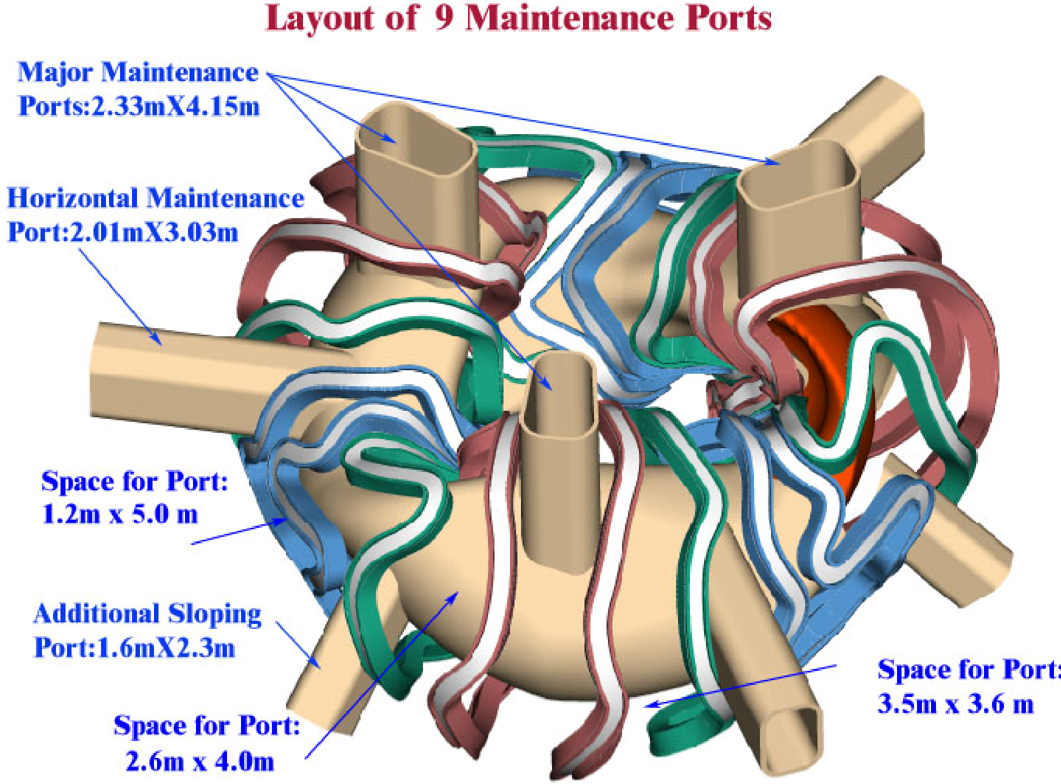
Modular maintenance approach with ports between each pair of adjacent coils

(initial observations for example CS configuration)

Modular Maintenance Approach with Ports Between Each Coil

- Minimum Port Sizes for 3-Period Configuration
  - 1.6 m x 2.3 m and 1.2 m x 5.0 m
  - Quite limiting constraint on size of module
  - Desirable to accommodate ~2 m x 2 m x 0.25 m module

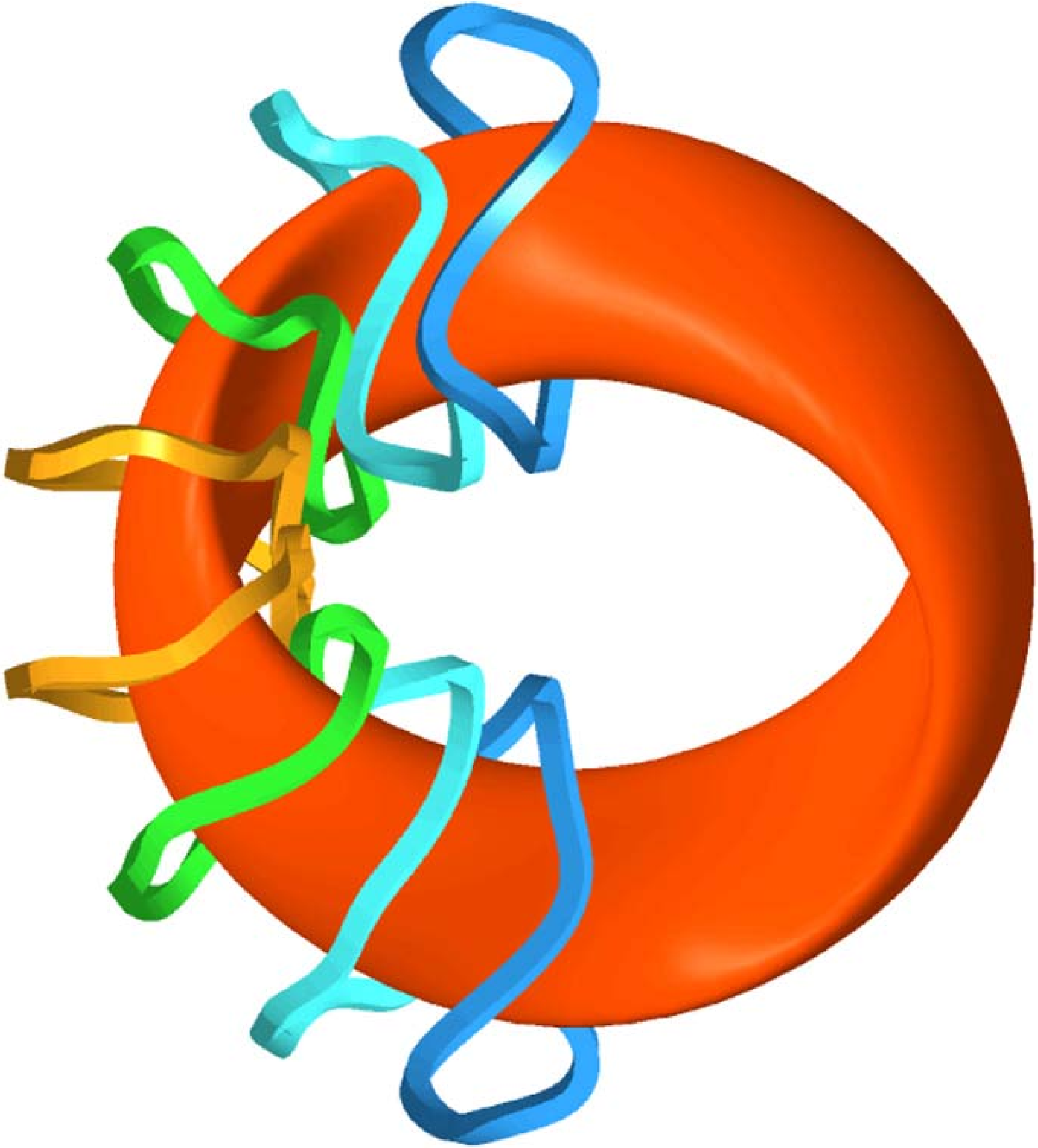
- Unless reactor size is increased and/or 2-field period is considered (resulting in larger individual port sizes), this maintenance scheme seems marginal and a modular maintenance scheme through fewer larger ports is preferable



Initial parameters for an Example 2-Field Period CS Configuration (from P. Garabedian)

Major radius = 8 m
Minor radius = 2.3 m
Aspect ratio = 3.5
16 coils (8 per period)
Coil thickness = 57 cm
Aspect ratio = 2
Coil-plasma min. distance = 1.5 m

(These parameters are currently being revisited and should be considered as example only for preliminary port size estimates)



Comparison of Port Access Area Between Adjacent Coils for 3 Different Configurations

Port toroidal dimension x poloidal dimension (m x m)

Port / Configuration	Port #1	Port #2	Port #3	Port #4	Port #5	Port #6	Port #7	Port #8
NCSX-like 3-field period R=8.25 m	2.6 x 4.0	1.6 x 2.3	1.2 x 5.0	2.0 x 3.0	3.5 x 3.6	2.3 x 4.2		
NCSX-like 3-field period R=9.68 m	3.1 x 4.7	1.9 x 2.7	1.4 x 5.9	2.4 x 3.6	4.1 x 4.2	4.0 x 4.7		
2-field period R=8 m*	3.9 x 10	4.1 x 8.9	4.3 x 5.4	3.8 x 4.6	4.7 x 5.0	3.9 x 7.9	3.9 x 10	4.7 x 10.9

* Assuming a coil cross-section of 0.57 m x 1.15 m

2-Field Configuration Provides Substantially More Space for Ports Between Each Pair of Adjacent Coils

Need further study to confirm dimensions and configuration

- System study for physics and configuration parameters
- Confirmation of coil cross-section
- Benefit of larger blanket modules
  - Scoping analysis of example blanket concept(s)
- Details of maintenance scheme

Conclusions from the Initial ARIES-CS Engineering Effort

- **Engineering Plan of Action is on Schedule**

- **Scoping study of different maintenance schemes and of different blanket options in full swing**

- **Field-period based maintenance more suited for configuration with 3 (or more) field periods**
  - **However, iteration needed between physics and engineering to provide enough space for blanket unit removal**

- **Modular maintenance could be done through:**
  - **Selected ports (would require articulated boom with longer reach, and smaller modules)**
  - **Ports between each pair of adjacent coils (would allow for larger modules, best suited for larger reactor or for 2-field period configuration)**

- **Different blanket options considered for the different maintenance schemes**
  - **Dual coolant (Li+He) + FS**
  - **Self-cooled Pb-17Li + SiC_f/SiC**
  - **Self-cooled Flibe + FS**
  - **Ceramic breeder + He to be considered next**

- **At the scoping level these blanket options seem possible but differ in term of issues and performance, which will be carefully considered in the final evaluation**

Future ARIES-CS Engineering Effort Will Include:

Over the next year

- Complete maintenance scheme evaluation and blanket option scoping study
- Perform evaluation
- Converge on a few (perhaps 2-3) combinations of maintenance scheme and blanket option for more detailed study
- Scoping design analysis of divertor concept once more information becomes available on location and loads from physics analysis

Over Following Year(s)

- Choose one combination for full design study