ARIES-CS Engineering Approach

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ARIES Meeting
Princeton Plasma Physics Laboratory, Princeton, GA
December 3-4, 2003

Outline

- Objectives of ARIES-CS study
- Summary of engineering plan of action
- Example field period-based maintenance approach and blanket design
- Example modular maintenance approach and blanket design
- Conclusions and future work

Background

- **Assessment of Compact Stellarator option as a power plant to help:**
  - **Advance physics and technology of CS concept and address concept attractiveness issues in the context of power plant studies**
  - **Identify optimum CS configuration for power plant**
    - **NCSX and QSX plasma/coil configurations as starting point**
    - **But optimum plasma/coil configuration for a power plant may be different**

ARIES-CS Program is a Three-Year Study

FY03: Development of Plasma/coil Configuration Optimization Tool

1. Develop physics requirements and modules (power balance, stability, α confinement, divertor, *etc.)*
2. Develop engineering requirements and constraints.
3. Explore attractive coil topologies.

FY04: Exploration of Configuration Design Space

1. Physics: β, aspect ratio, number of periods, rotational transform, shear, *etc.*
2. Engineering: configurationally optimization, management of space between plasma and coils.
3. Choose one configuration for detailed design.

FY05: Detailed system design and optimization

Overall Design Process Requires Close Interaction among Physics, System and Engineering Studies

Proposed CS Configuration(s) from Physics Analysis (plasma shape + coil configuration)

- Start with NCSX based configuration
- Explore alternate concepts that might better extrapolate to power plant
- 2-field period configuration (from P. Garabedian)
- Others

Calculate Consistent Machine Parameters Based on System Studies (J. Lyon)

- Physics parameters (B, β, α loss, etc..) and reactor size (aspect ratio, major radius) for ignition for given:
  - Space between coils
  - Minimum plasma edge to coil distance
  - Fusion power

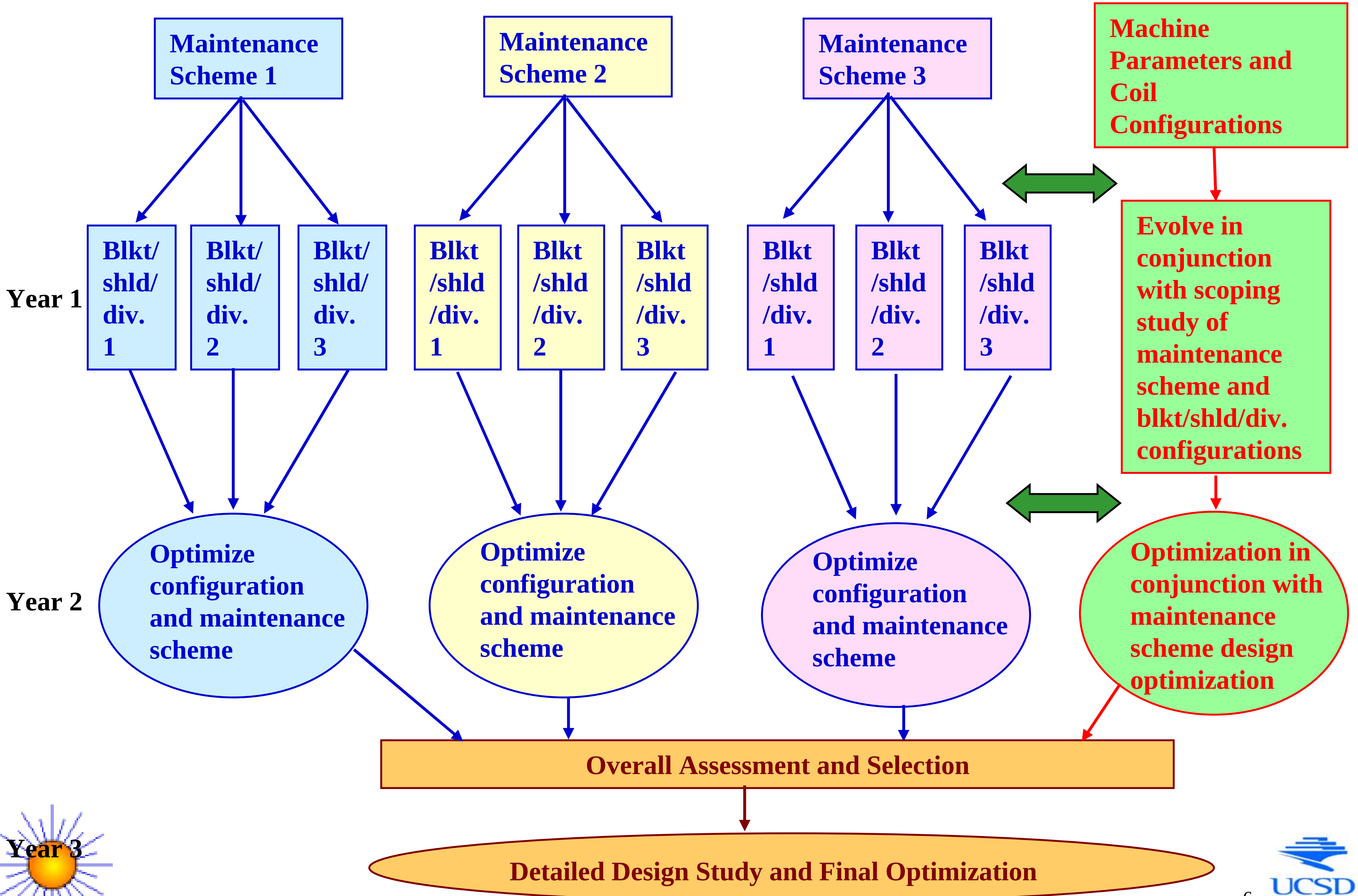
Develop Engineering Design Configuration

- Blanket, Shield, Vacuum Vessel, Divertor
- Maintenance Scheme

Analysis of Design Requirements and Performance Parameters

- Tritium breeding
- Shielding requirements
  - Magnet configuration and heating limits
  - Reweldability
- Thermal efficiency
- Maintenance requirements
  - Size and weight of blanket unit
  - Access
- Safety requirements

Plan for Engineering Activities



Engineering Activities: Year 1

- **Perform Scoping Assessment of Different Maintenance Schemes and Consistent Design Configurations (coil support, vacuum vessel, shield, blanket)**

  - **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:**

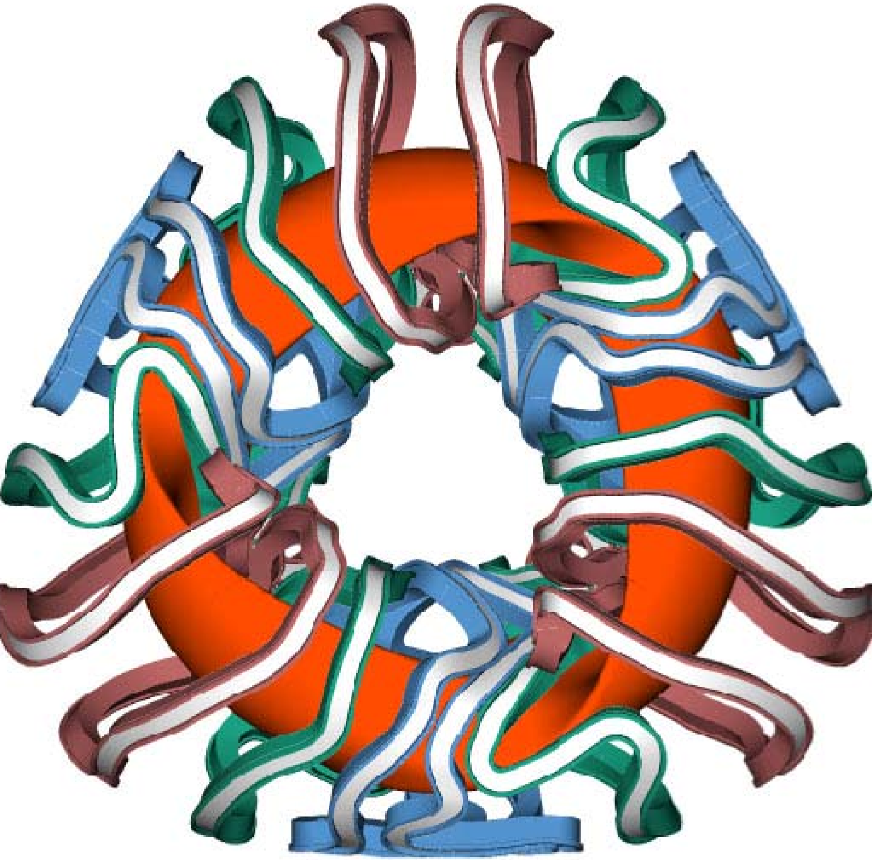
1. **Self-cooled liquid metal blanket(Pb-17Li) (might need He-cooled divertor depending on heat flux)**
   a) **with SiC_f/SiC** ✓
   b) **with insulated ferritic steel and He-cooled structure**

2. **He-cooled liquid breeder blanket (or solid breeder) with ferritic steel and He-cooled divertor** ***In progress***

3. **Flibe-cooled ferritic steel blanket (might need He-cooled divertor depending on heat flux)** ✓

Example field period-based maintenance approach and blanket design

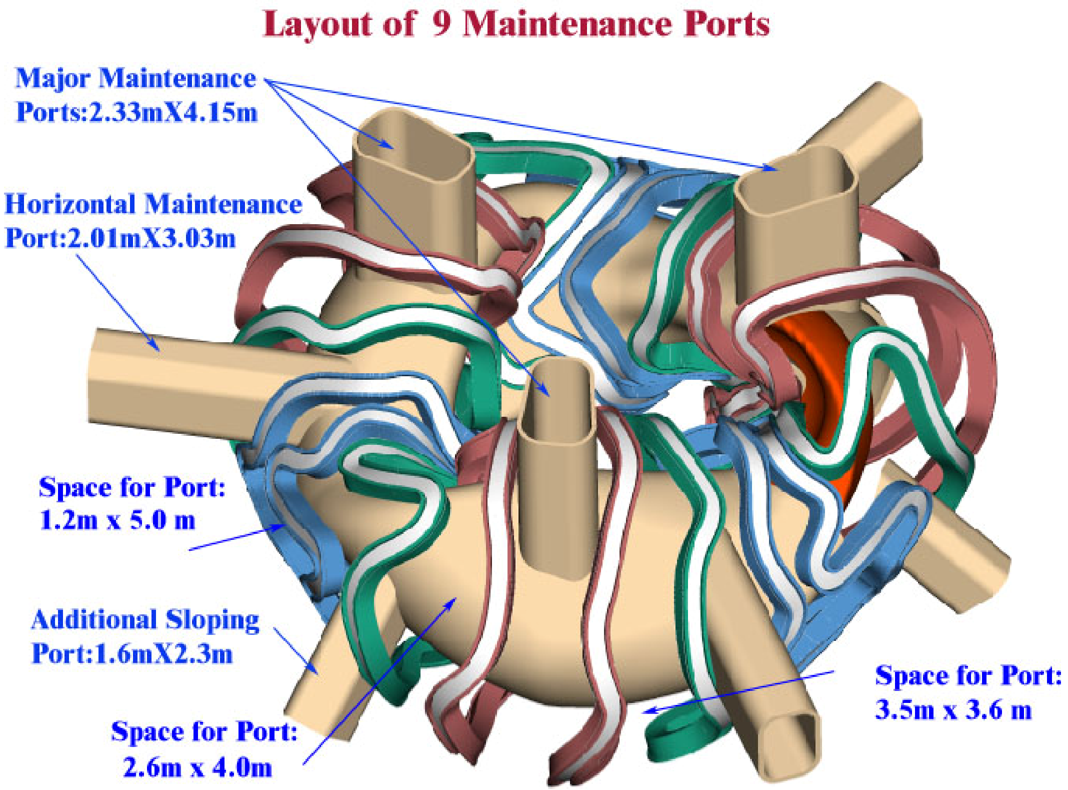
Example Scoping Analysis of Maintenance Scheme and Engineering System Design for NCSX-Based Coils and Plasma Shape with 3-Field Period



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	5.3 T
Volume Averaged Beta	4.1%
Plasma Current, I_p	3.55 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

Maintenance Approaches for NCSX-Like Power Plant

- **For blanket module-based maintenance scheme**
  - **Desirable to accommodate ~2 m x 2 m x 0.25 m module**
  - **Modular maintenance scheme with limited number of ports and articulated boom seems possible**
  - **Not suited for maintenance scheme with ports between each pair of adjacent coils unless reactor size is increased and/or 2-field period is considered (resulting in larger individual port sizes)**



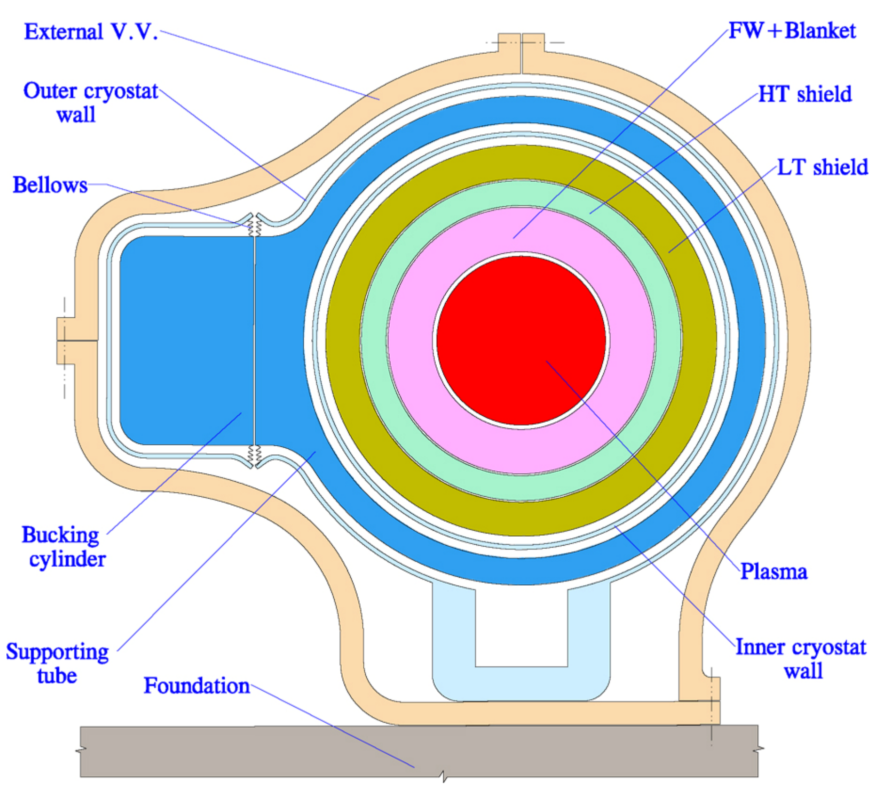
- **Seems best suited for field period-based maintenance**

Example Design Approach for Field-Period Based Maintenance Scheme

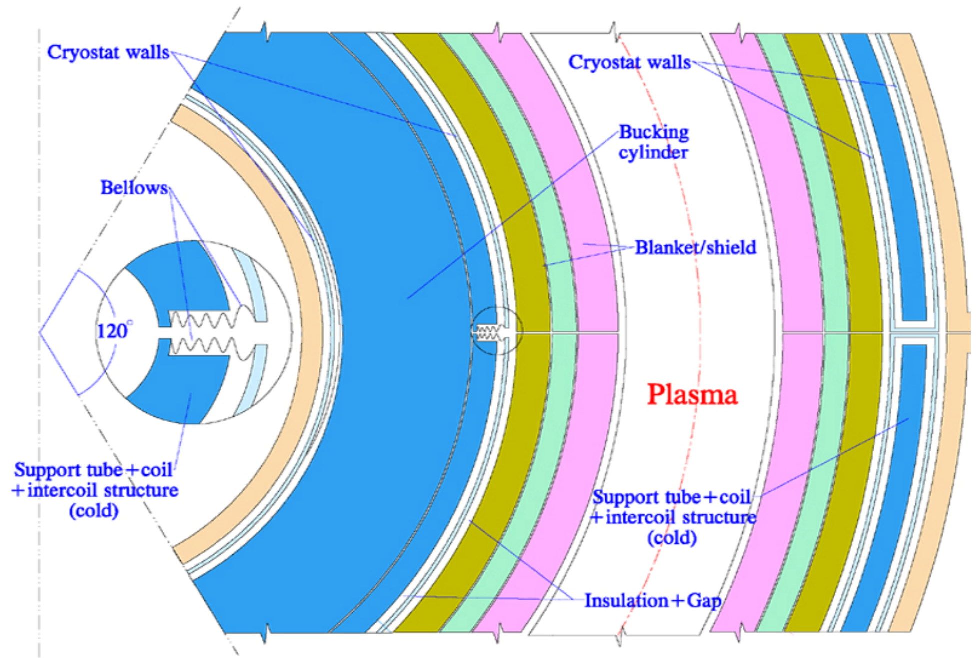
- **Need to Design Coil Support Structure to Accommodate the Three Kinds of Forces Acting on Coils while Being Compatible with Maintenance Scheme**
  - **Large centring forces need to be reacted by strong bucking cylinder.**
  - **No net forces between coils from one field period to the other.**
  - **Out-of plane forces acting between neighbouring coils inside a field period require strong inter-coil structure.**
  - **Weight of the cold coil system has to be transferred to the "warm" foundation without excessive heat ingress.**
  - **The radial 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 unacceptably long down time.**
  - **Transfer of large forces within a field period and between coils and bucking cylinder is not possible between "cold" and "warm" elements. This means that the entire support structure has to be operated at cryogenic temperature.**
  - **To facilitate opening of the coil system for maintenance, separate cryostats for the bucking cylinder in the centre of the torus and for every field period are envisaged.**

Proposed Solution: Enclose the Individual Cryostats in a Common External Vacuum Vessel

Vertical Cut Through Torous (Principle Arrangement)



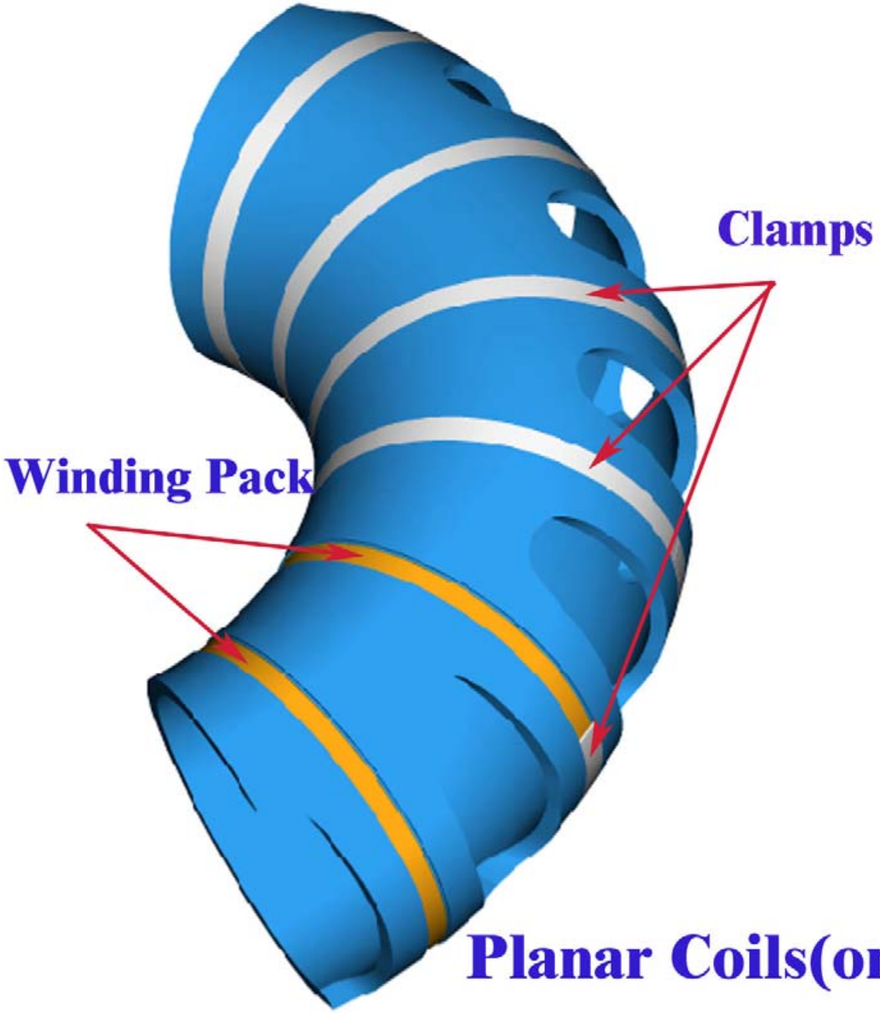
Horizental Cut Through Torus (One Field Period)



- **Minimize fabrication costs and mass of waste by separating regions requiring replacement (“replacement units”) from the life-time components (“permanent zone”).**

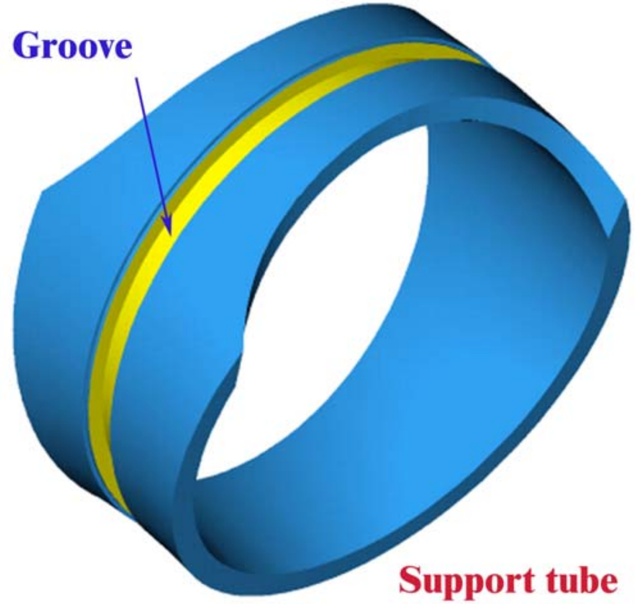
- **Divide neutron shielding into high temp. and low temp. regions for two reasons:**
  - **to enable passive low temperature cooling in the outer shield region for safety reasons,**
  - **to minimize low temperature heat (“waste heat”) to <1% of total heat**

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



Planar Coils(one period)

Winding of Coils into Grooves in the Supporting Tube

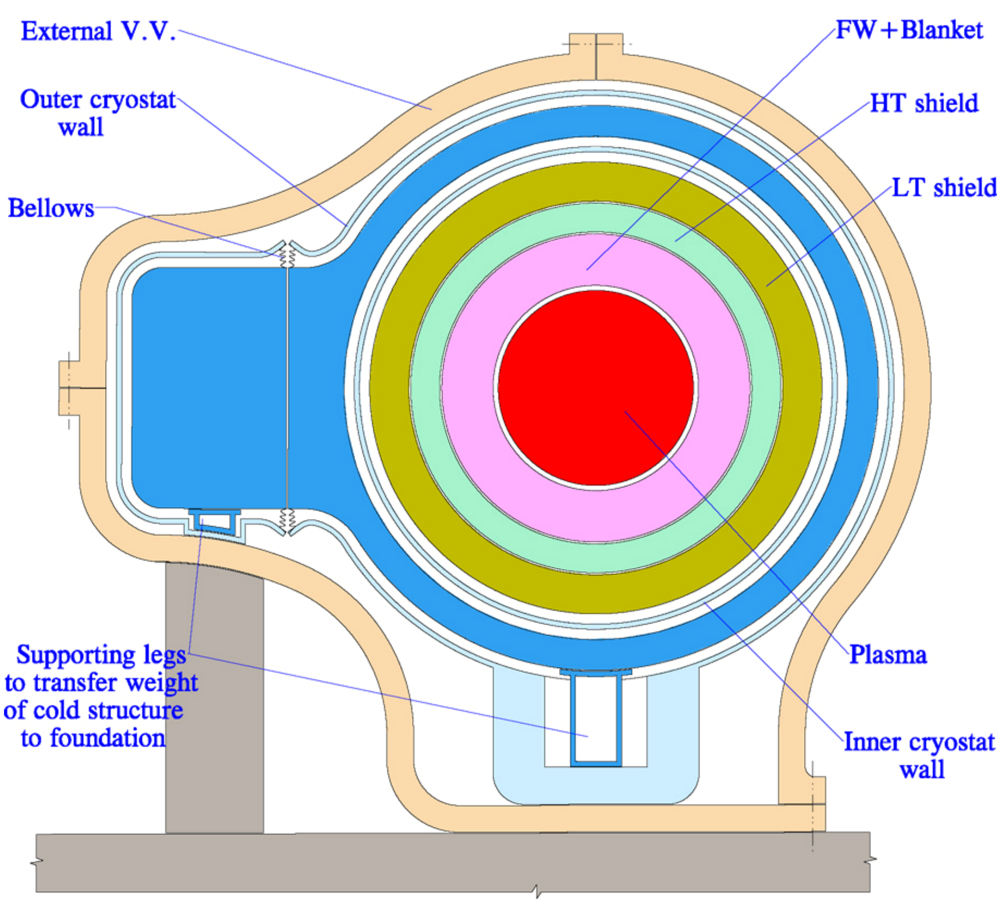


Arrangement of Long Legs to Support the Weight of the Cold Structure

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
- e.g. for a total cold structure weight of 1,800 tons and 3x3 legs
  - required cross section of one cylindrical tube leg: 100mm diameter and 3 mm wall thickness
  - corresponding heat flow between 300 K and 4 K through 0.5 m long legs ~ 500 watt for all legs *(Much longer legs shown in sketch)*

Supporting Legs for Cold Structure

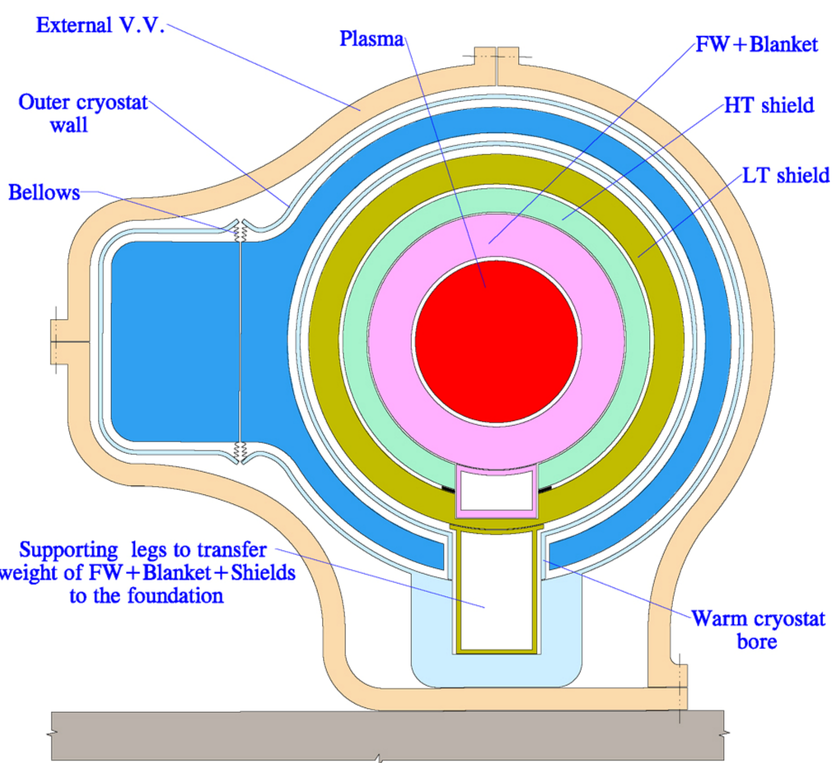


Arrangement of Legs Supporting the Weight of FW+Blanket+Shields and of Coolant Routing

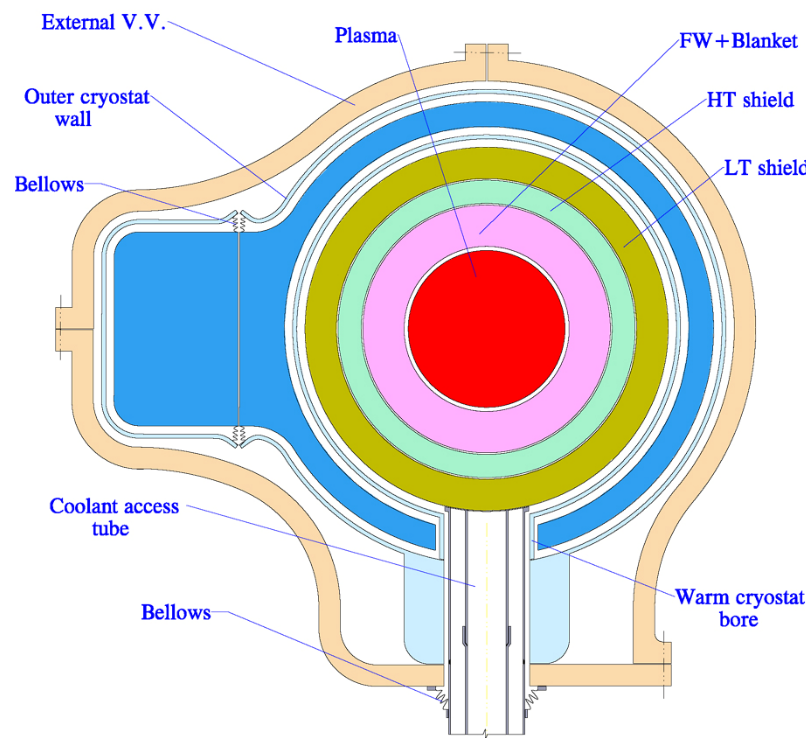
- **Much larger weight to be supported than for cold structure but legs are between "warm" regions and there is nearly no limit on cross section.**
  - ***e.g. 4 legs in each field period, 500 mm diameter, 35 mm wall thickness***

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

Supporting Legs for FW/Blanket/Shields



Arrangement of Coolant Access Tube to FW/Blanket/Shield



Steps to be Performed for an Exchange of Blankets (at end of life or because of failure)

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 the outer side of the external VV in the range of the field period to be moved.

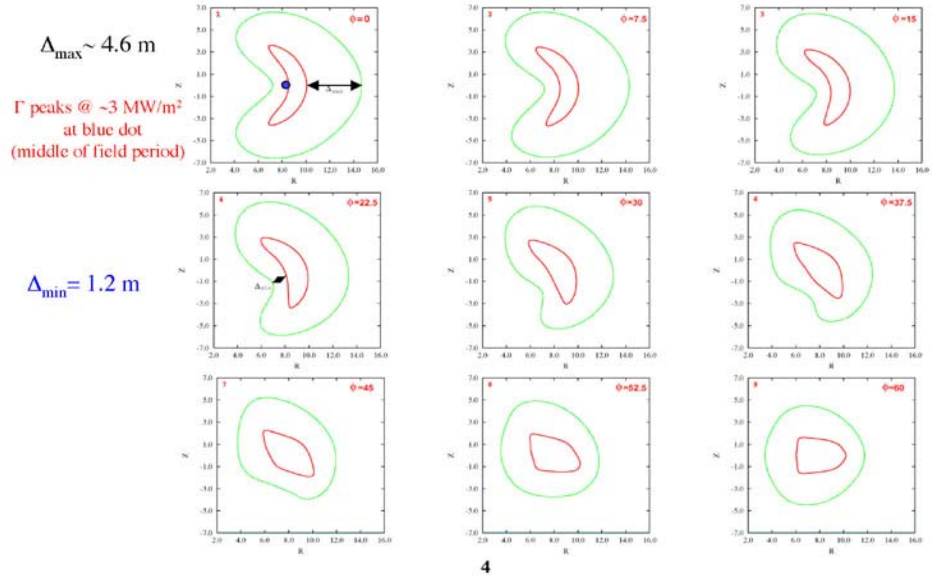
5. Slide the entire field period, composed of blankets, shields, cryostats, coils with inter coil structure, and all thermal insulation, outward in radial direction an the flat surface at the bottom. It should be possible to use an air-cushion system for this movement.

6. Cut the coolant access tubes to the blanket to be replaced.

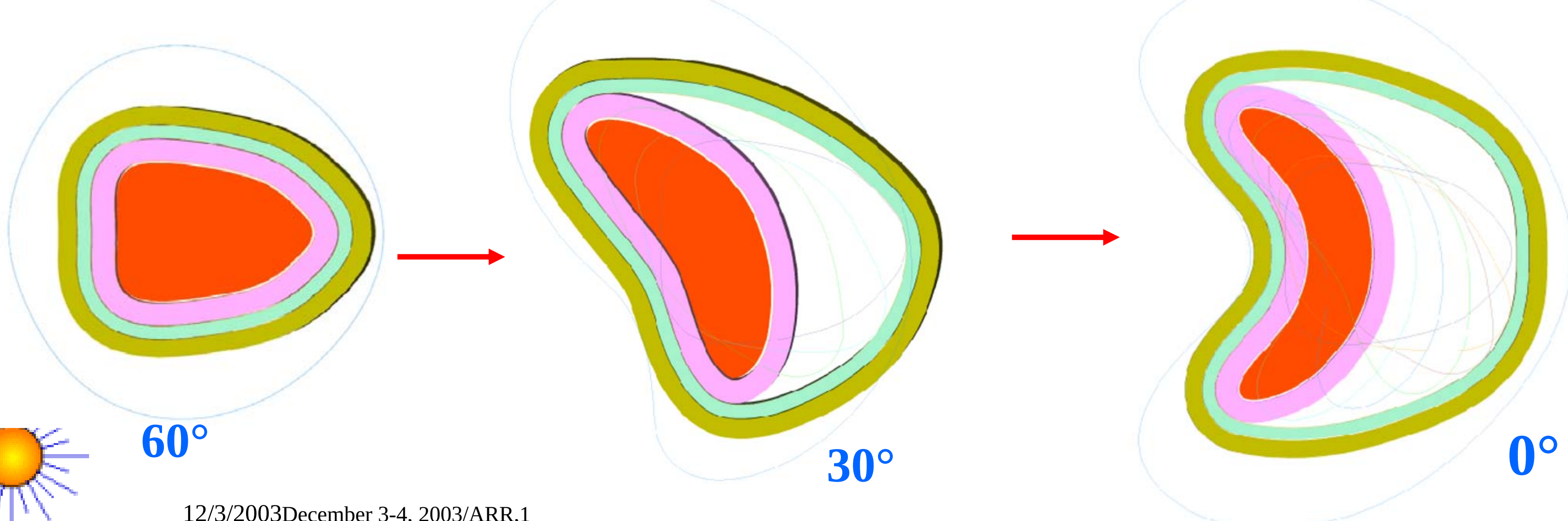
7. Slide out from the openings at both ends the replacement units, composed of FW, breeding zone, and a structural ring (serving at the same time as a first high temperature shield). The replacement unit is moved outwards in the toroidal direction on a rail attached to the replacement zone, and sliding on the low temperature shield (possibly with an air-cushion system).

Extrapolation of the Maintenance Scheme to a CS

- For simplicity, the design and maintenance scheme have been illustrated for a circular plasma with uniform cross-section.
- They have to be adapted to the particular geometry of a CS
- In particular, can a replacement unit be extracted toroidally in a CS geometry?

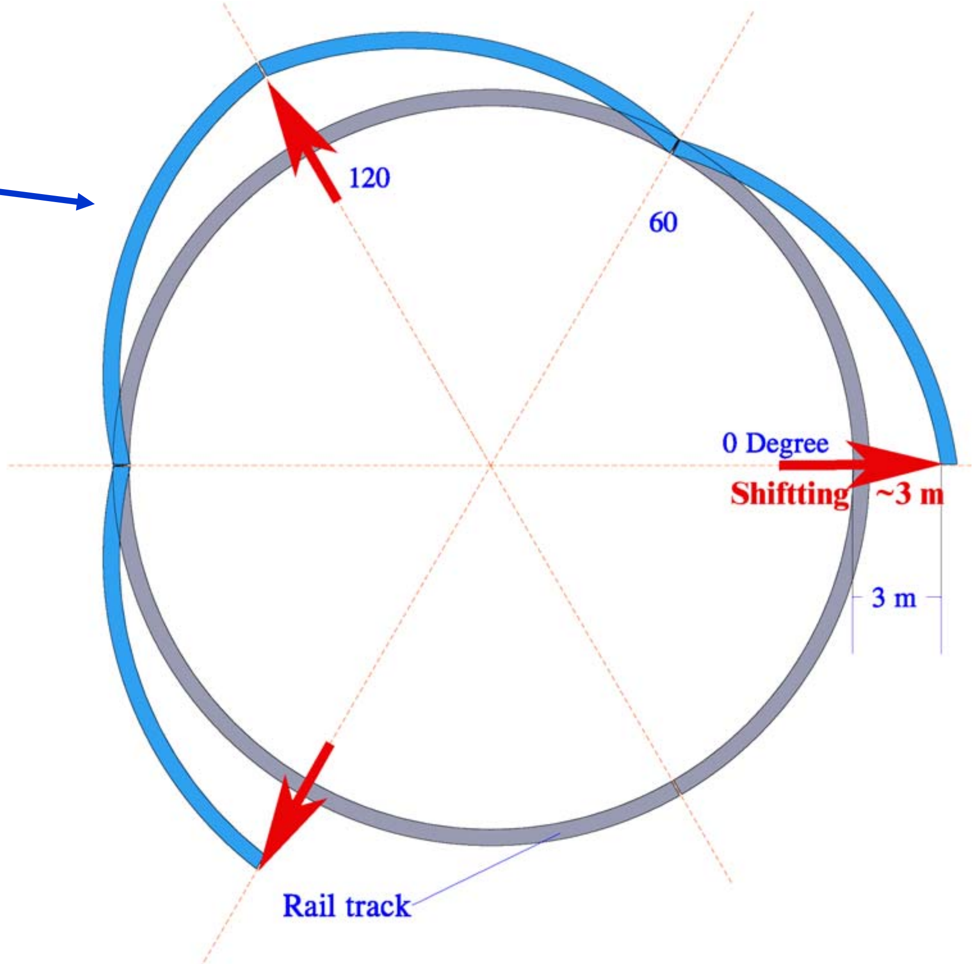


- Replacement unit in pink (blanket)
- Permanent components: hot shield in blue and cold shield in green

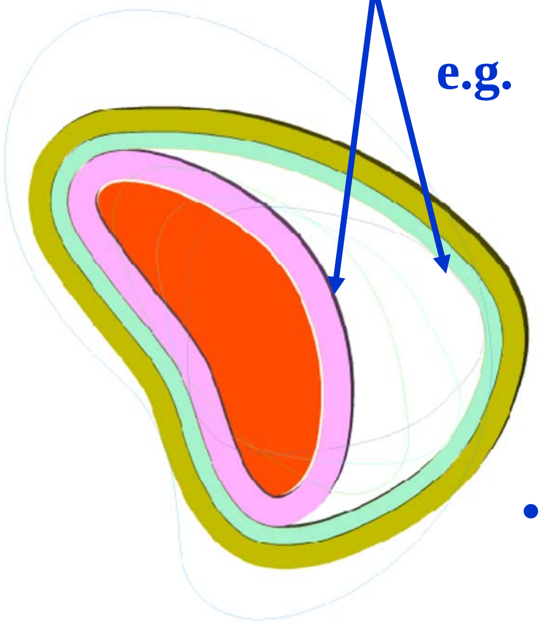


Removal Blanket Replacement Unit under Proposed Maintenance Scheme is Possible for CS

- **Replacement unit can be removed toroidally by:**
  - **using off-axis track system**
  - **locally decreasing shield and correspondingly increasing blanket to provide a minimum of 100 cm shield**



e.g.



- **Removal would be easier for geometries with smaller variation of the plasma cross section, and coils with smaller deviations from circular shape.**

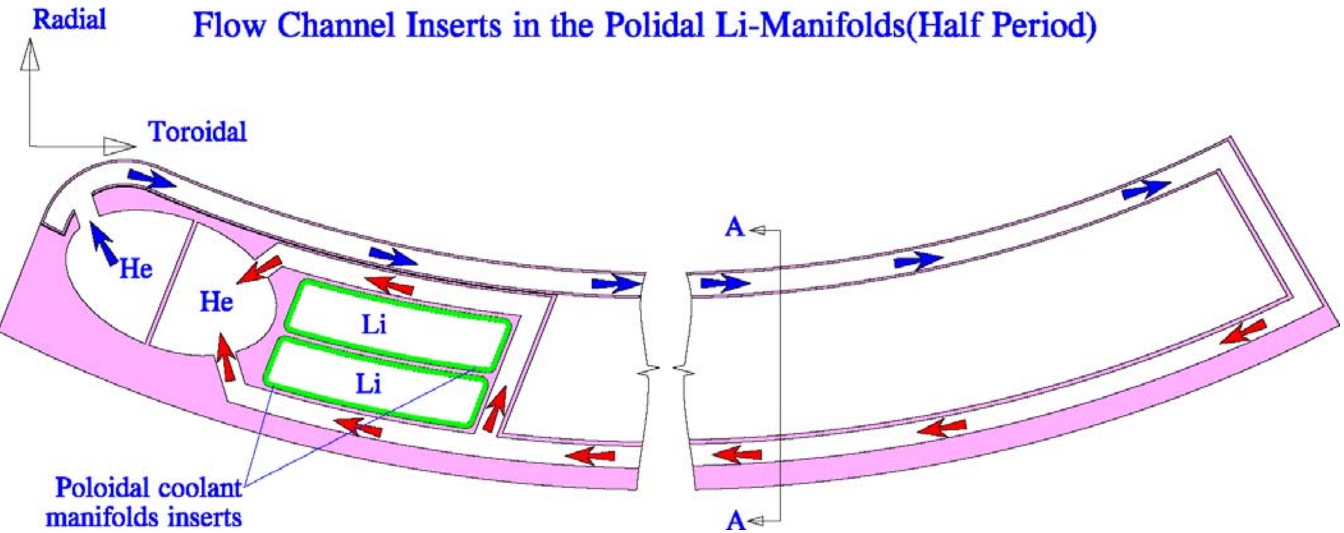
Example of a Blanket Concept Suitable for Field Period-Based Maintenance

- **This maintenance scheme allows for very large blanket units with virtually no weight limit.**

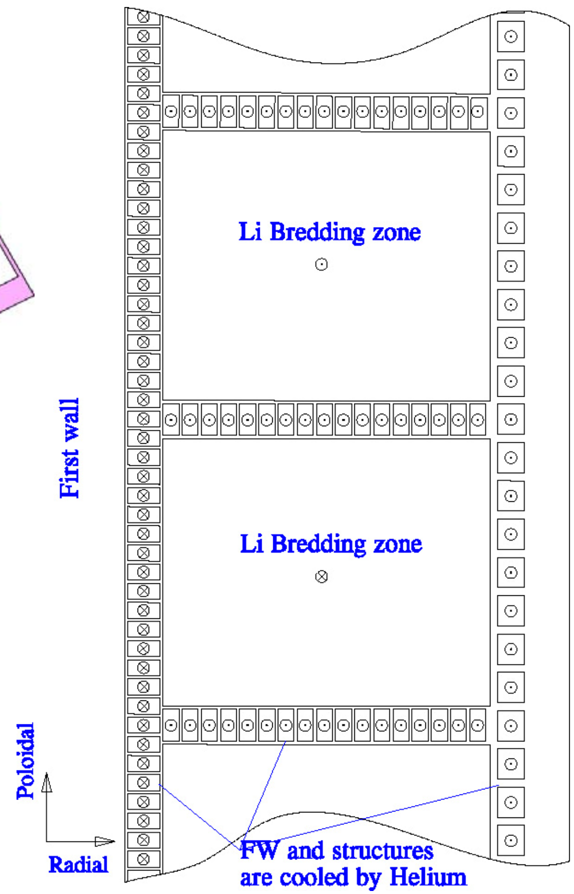
- **Self-cooled liquid breeder (Li, Pb-17Li)or dual-coolant concept would be good candidates**

- **Dual coolant Li/He concept with ferritic steel as structural material used as example**
  - **no need for additional neutron multipliers as in solid breeder or FLiBe blankets.**
  - **no need for large internal heat transfer surfaces as in solid breeder blankets.**
  - **volumetric heating of the breeder/coolant provides the possibility to set the coolant outlet temperatures beyond the maximum structural temperature limits.**
  - **FW and the entire steel structure cooled with helium.**
  - **Li flowing slowly toroidally (parallel to major component of magnetic field) to minimize MHD pressure drop used as breeder/coolant in the breeding zone.**
  - **electrically insulating coating between Li and FS not required but thermal insulating layer might be needed to maintain Li/FS temp. within its limit (~600°C)**

Schematic of Blanket Concept Showing Cooling Arrangement



Cross section of toroidal cooling channels



Example Blanket Parameters for 2 GW Fusion Power Plant

- **For one replacement unit (1/6 of entire machine):**
  - **Total thermal power to be removed** — **400 MW**
  - **Heat to be removed with Li/He** — **~300/100 MW**

- **Helium cooling of FW**
  - **Pressure** — **8MPa**
  - **Inlet/outlet temperature** — **400/500°C**
  - **Velocity** — **70 m/s**
  - **Heat transfer coefficient** — **4,200 W/(m^2-K)**
  - **Pressure drop** — **0.1 MPa**

- **Lithium cooling of breeding zone**
  - **Inlet/outlet temperature** — **500/800°C**
  - **Velocity** — **0.12 m/s**
  - **Heat transfer coefficient** — **450 W/(m^2-K)**
  - **Pressure drop** ***(assuming perpendicular B=1T)*** — **0.1 MPa**

- **Tritium self-sufficiency has been estimated with breeding zones ~ 47-62 cm**

- **Shielding of the S/C coils requires a steel shield of ~ 95 cm**

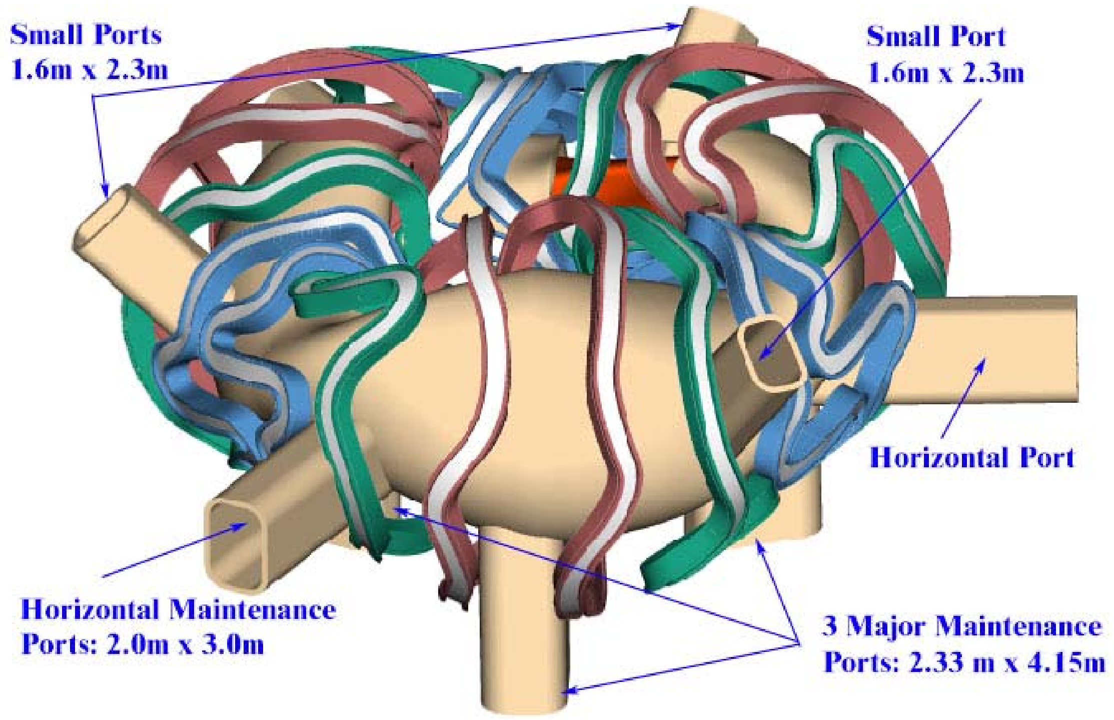
Example modular maintenance approach and blanket design

Modular Maintenance Approach

- **ITER-like rail system + articulated boom extremely challenging in CS geometry due to "roller coaster effect" and to non-uniform plasma shape and space**
- **Preferable to design maintenance based on articulated boom only**

- **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**

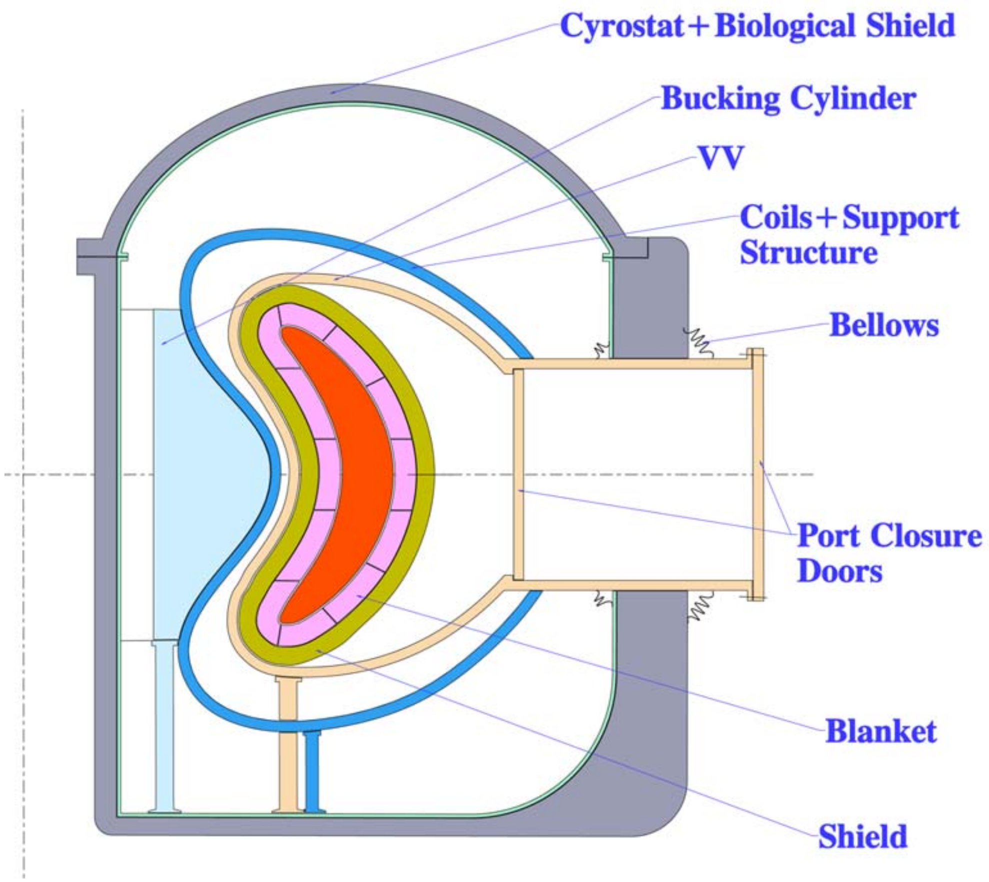
- **Current ARIES-CS modular design based on comparable parameters for 3 horizontal ports**
  - **half field period length ~ 9 m**
  - **minor radius =1.85 m (local plasma height varies over about 1.5-3.5 m)**
  - **weight of empty module < 1 ton**



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

Vacuum Vessel Arranged Between Blankets and Coils for Module-Based Maintenance Scheme through Limited Number of Ports

- **The VV serves as an additional shield for the protection of the coils**
- **No disassembling and re-welding of the VV is required for blanket maintenance.**
- **There are 2 VV sectors per field period welded at the largest and smallest cross-sections. This allows for toroidally sliding the VV sectors through the coils of the field period.**
- **For thermal insulation, the entire coil system has to be enclosed in a common cryostat, serving also at as a secondary containment for tritium in the VV.**
- **Similar coil structure design as for the field-period based maintenance scheme.**
- **Design could be adapted for maintenance scheme with a port between each pair of adjacent coils**



1 Port per field period (for 3 field period configuration) at 0°

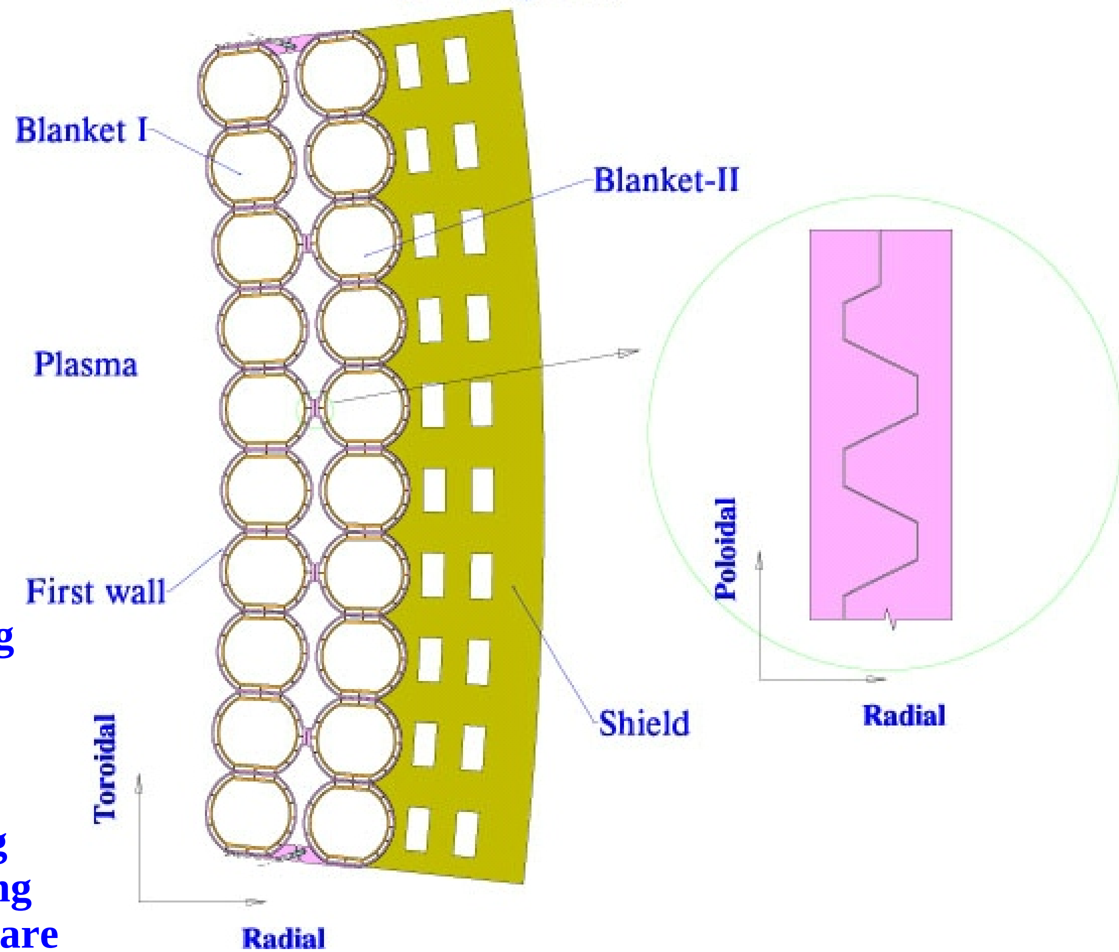
Example Blanket Modular Design Approach: SiC_f/SiC as Structural Material and Pb-17Li as Breeder/Coolant

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)**
- **Thicknesses of breeding and shielding regions for acceptable tritium breeding (~1.1 net) and shielding performance are scaled from ARIES-AT study**

Cross Section of ARIES-CS Outboard Blanket/Shield

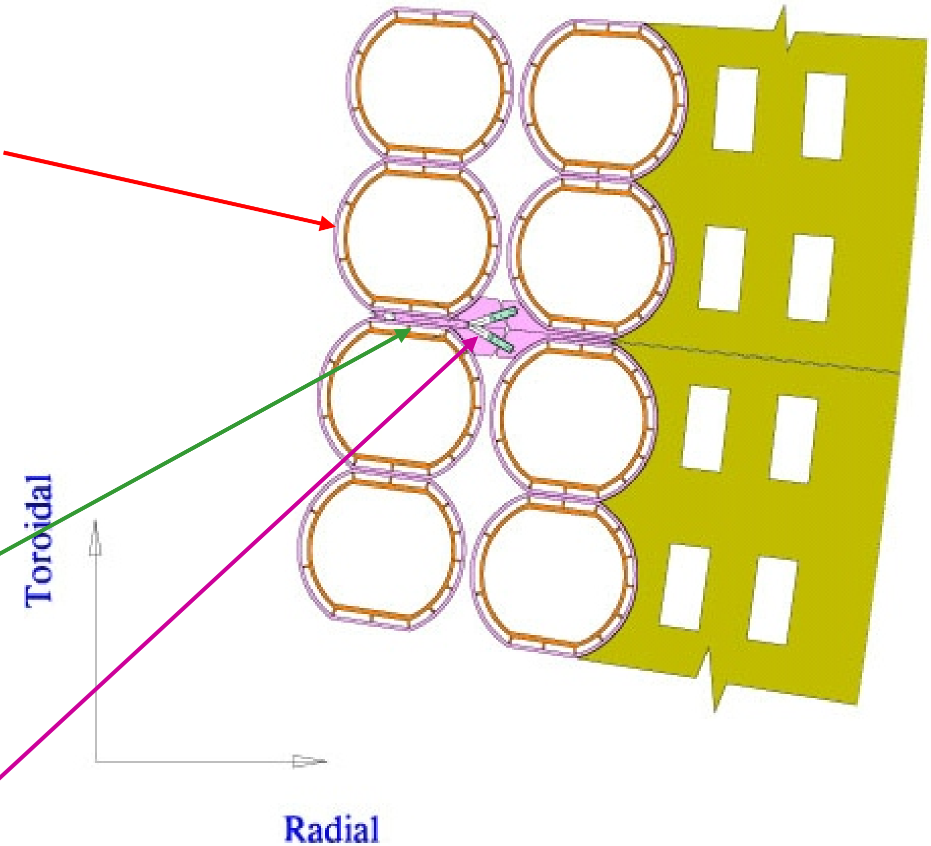
(One Segment)



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

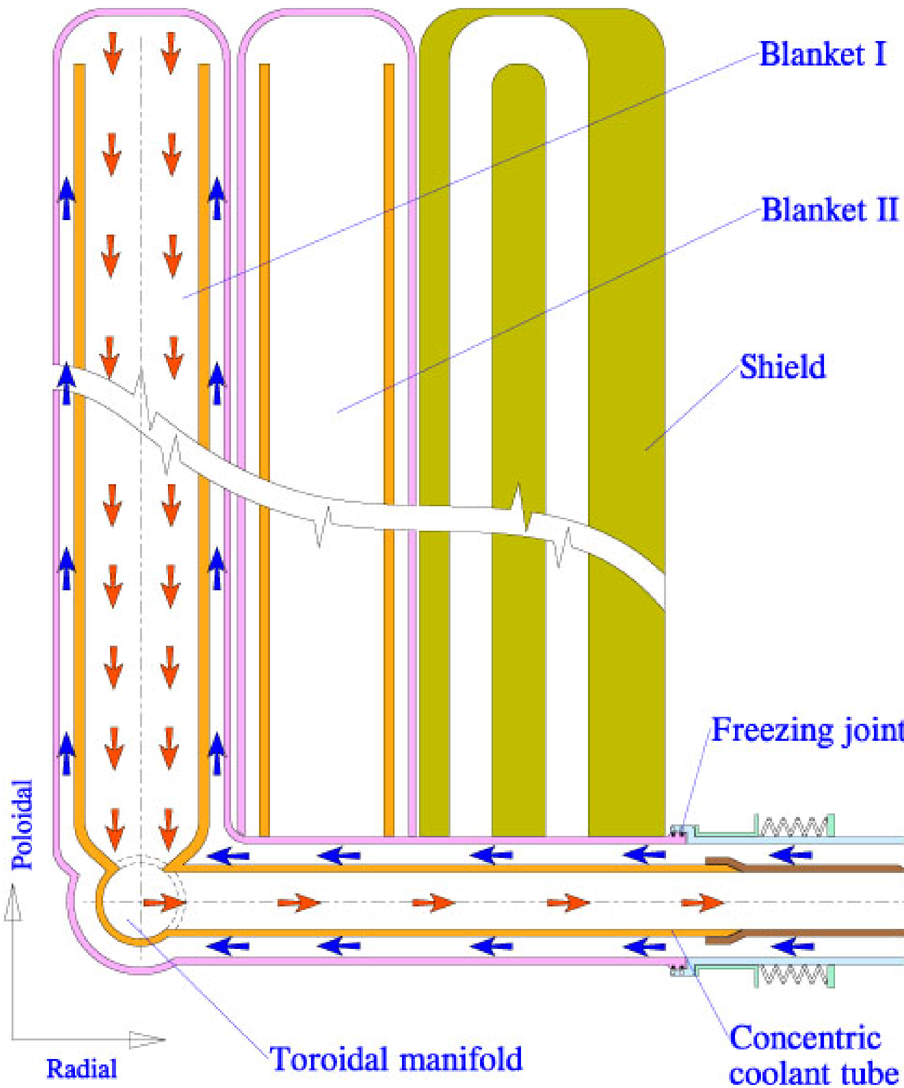
Coolant Flow and Connection for ARIES-CS Blanket Modular Design Using SiC_f/SiC and Pb-17Li

- **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)
  - Maintain SiC_f/SiC temperature within limits

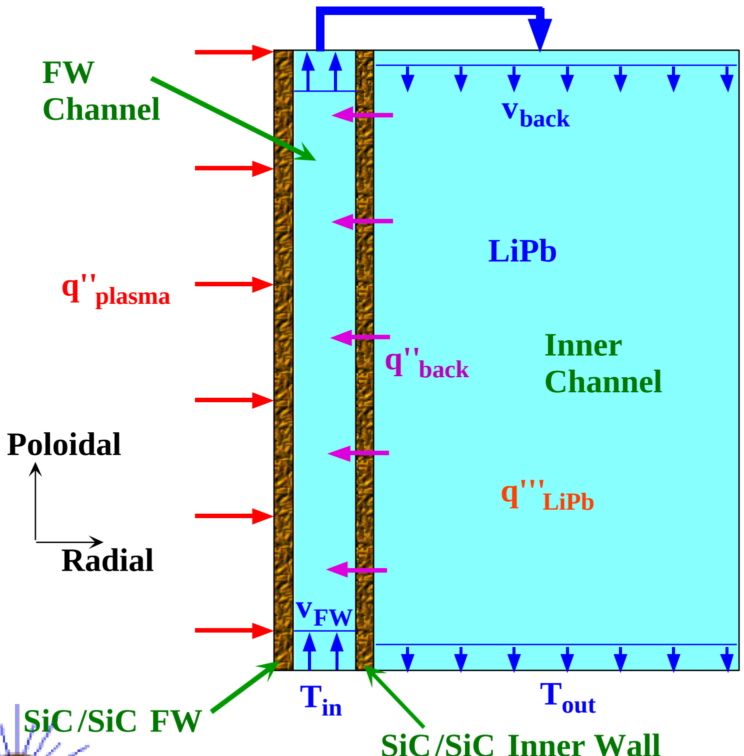
- **Use of freezing joint behind shield (and possibly vacuum vessel) for annular coolant pipe connection**
  - Inlet in annular channel, high temp. outlet in inner channel

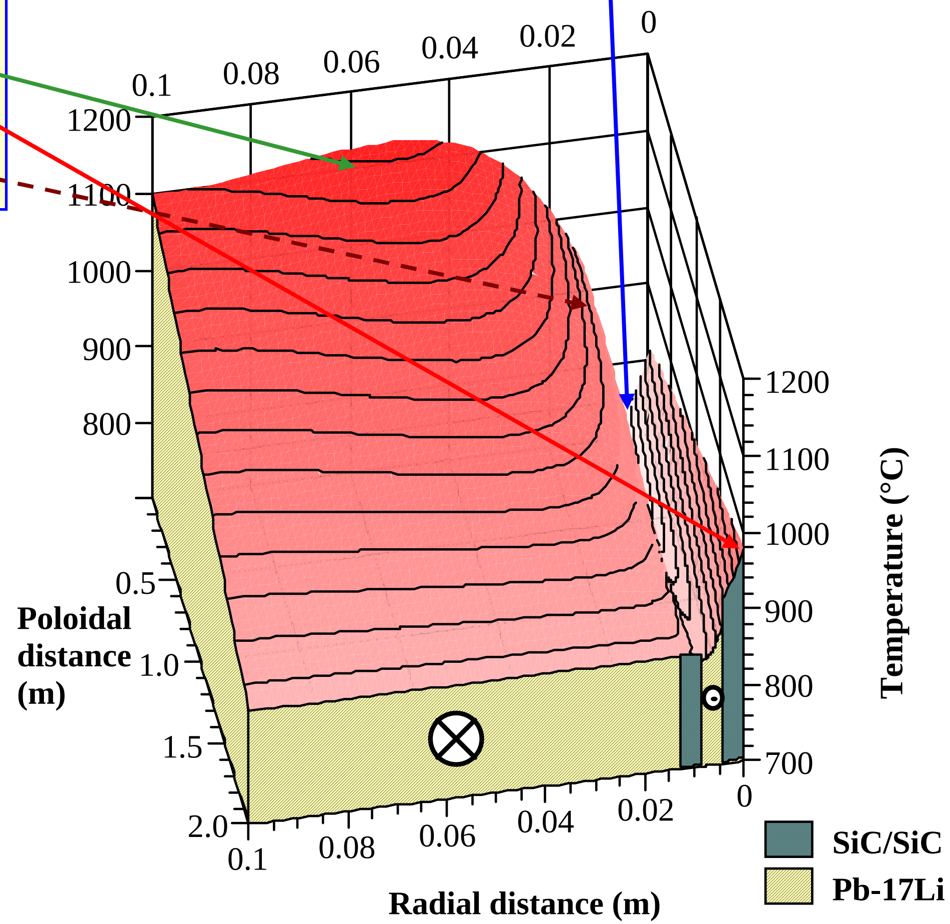
Cross-section Showing Coolant Flow Path and Access Tube



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 Design with SiC_f/SiC and Pb-17Li (Not fully optimized yet)

Brayton cycle & Coolant Parameters	
Cycle He Maximum T emperature	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

2-Field Period Configuration (from P. Garabedian) Results in More Space for Maintenance Ports that Could Allow for Maintenance Scheme with Ports Between each Pair of Adjacent Coils

<u>Initial Assumed Parameters</u>

R = 8 m
<a> = 2.3 m
A = 3.5
16 coils (8 per period)
Thickness = 57 cm.
Aspect ratio = 2
Coil-plasma min. distance = 1.5 m

<u>Example of Some of the Latest Parameters from System Study</u>

R = 6.62 m
B (axis) = 6.55 T
<β> = 4.47%
16 coils (8 per period)
Coil pack dimension = 40 cm x 40 cm
Fusion power = 2 GW
Plasma aspect ratio = 3.75

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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

Horizontal space available between coils, 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	2.3 x 11.0	1.5 x 10.2	1.2 x 5.0	2.0 x 3.0	3.5 x 3.6	2.2x10.5		
R=9.68 m	2.8 x 12.8	1.8 x 11.9	1.4 x 5.9	2.4 x 3.6	4.1 x 4.2	2.6x12.3		
R=6.1 m	1.8x8.3	1.1x7.7	0.9x3.8	1.5x2.3	2.6x2.7	1.7x7.9		
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 10.0	4.7 x 10.9
R=6.62 m	3.2 x 8.2	3.4 x 7.4	3.5 x 4.5	2.5 x 3.8	3.9 x 4.1	3.3 x 6.5	3.3 x 8.3	3.9 x 9.0
R=6.34 m	3.0 x 7.9	3.2 x 7.0	3.4 x 4.2	2.4 x 3.6	3.7 x 3.9	3.1 x 6.2	3.1 x 7.9	3.7 x 8.6

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

Engineering Activities

Year 2: Configuration Optimization Including Plasma/Coil Space Management

- Assess and select best maintenance scheme/configuration pairings
- Optimize each selection including integration of machine/coil parameters and geometry
- Select most attractive integrated pairing(s) for detailed design study
- Develop compatible divertor design based on guidelines to be provided (heat load, geometry)

Year 3: Perform Detailed Design Study and Optimization for ARIES-CS Power plant

Conclusions from First Year Scoping Studies

- **Engineering work is on schedule**
  - Scoping analysis of 3 different maintenance schemes and of different blanket concepts
  - Consistent design at a scoping level of coil support structure, vacuum vessel and cryostat
  - Study done at a preliminary level but with enough detail to provide some confidence as to credibility of concept and scheme (engineering, maintenance, safety, performance)
  - However, region of localized heat loads as well as divertor not included yet

- **Physics configuration**
  - 3-field period (better suited for field period based maintenance design)
  - 2-field period (better suited for modular maintenance scheme)
  - New physics configurations welcome (sooner better than later)

- **Close interaction with system studies**
  - Our study focused on the initial sizes (~ 8 m)
  - We are now evaluating the impact of smaller sizes, ~ 6 m (really putting the C in CS) on shielding and breeding, and on maintenance requirements
  - Size of coil winding pack important. We have assumed 20-50 cm. We will need to firm up the numbers based on the final analysis

- **Goal this year is to focus on 2-3 combinations of maintenance scheme/blanket design for more detailed study**