ARIES-CS Maintenance Scheme and Blanket Design for Modular Approach

Presented by A. R. Raffray
University of California, San Diego

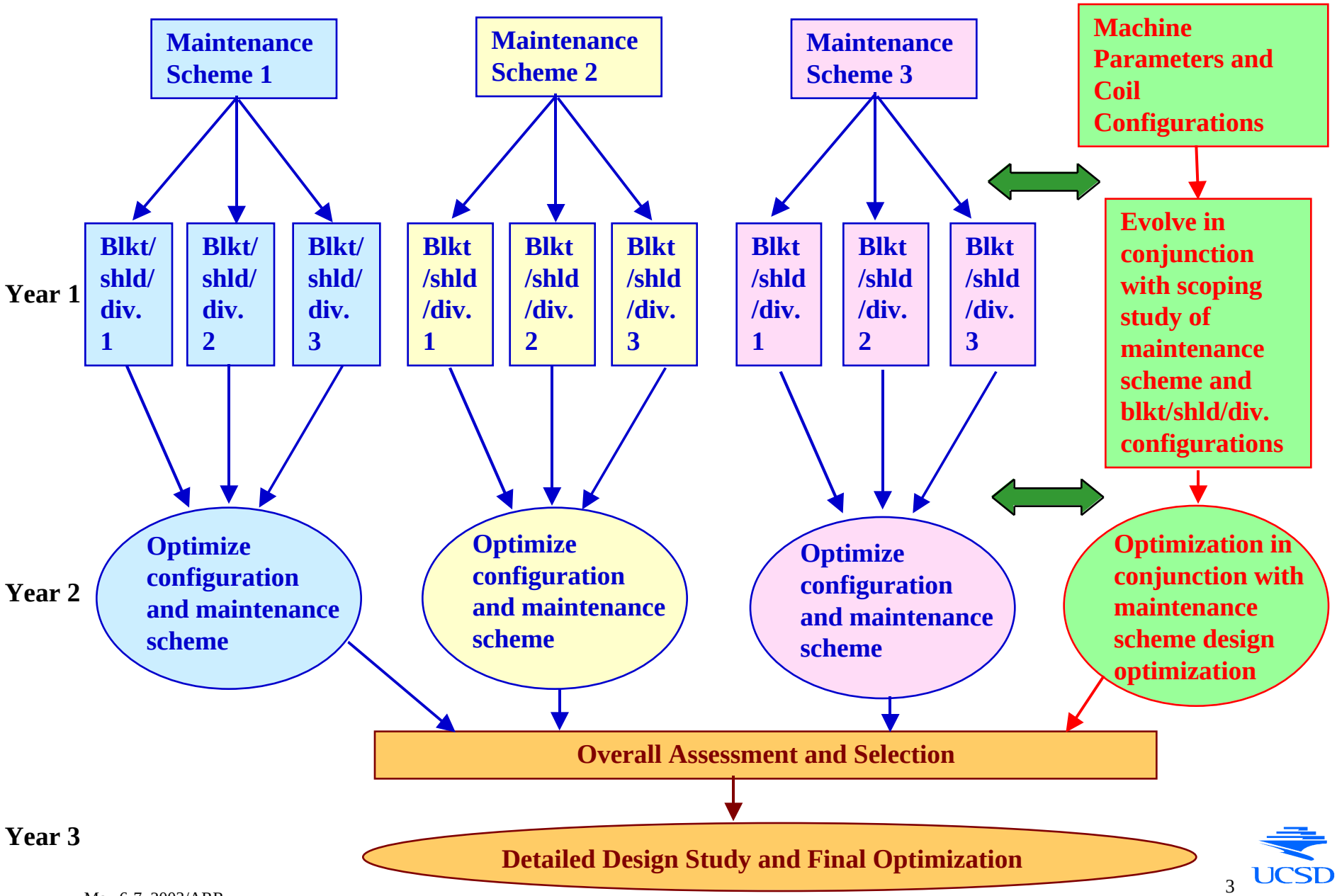
L. El-Guebaly
S. Malang
D. K. Sze
X. Wang
and the ARIES Team

ARIES Meeting
Hilton Garden Inn, Livermore, CA
May 6-7, 2003

Outline

- **Summarize engineering plan of action**
- **Modular maintenance approach**
- **Modular design with SiC_f/SiC and Pb-17Li**
- **Preliminary discussion of other maintenance approaches**
- **Future work**

Proposed Plan for Engineering Activities



Engineering Activities: Year 1

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

  - **Three Possible Maintenance Schemes:**

    1. **Sector replacement including disassembly of modular coil system (e.g. SPPS, ASRA-6C)** ***Some initial thoughts for discussion***
    2. **Replacement of blanket modules through maintenance ports arranged between all modular coils (e.g. HSR)** ***Preliminary port size evaluation***
    3. **Replacement of blanket modules through small number of designated maintenance ports (using articulated boom)** ***Current focus***

  - **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(LiPb) (might need He-cooled divertor depending on heat flux)** ***This presentation***
     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**
  3. **Flibe-cooled ferritic steel blanket (might need He-cooled divertor depending on heat flux)** ***Presented at last meeting***
- **Evolve coil configuration(s) (PPPL, MIT)**
  - **Material and thicknesses**
  - **Radius of curvature, shape**
  - **Space and shielding requirements**

Proposed Analysis Procedure

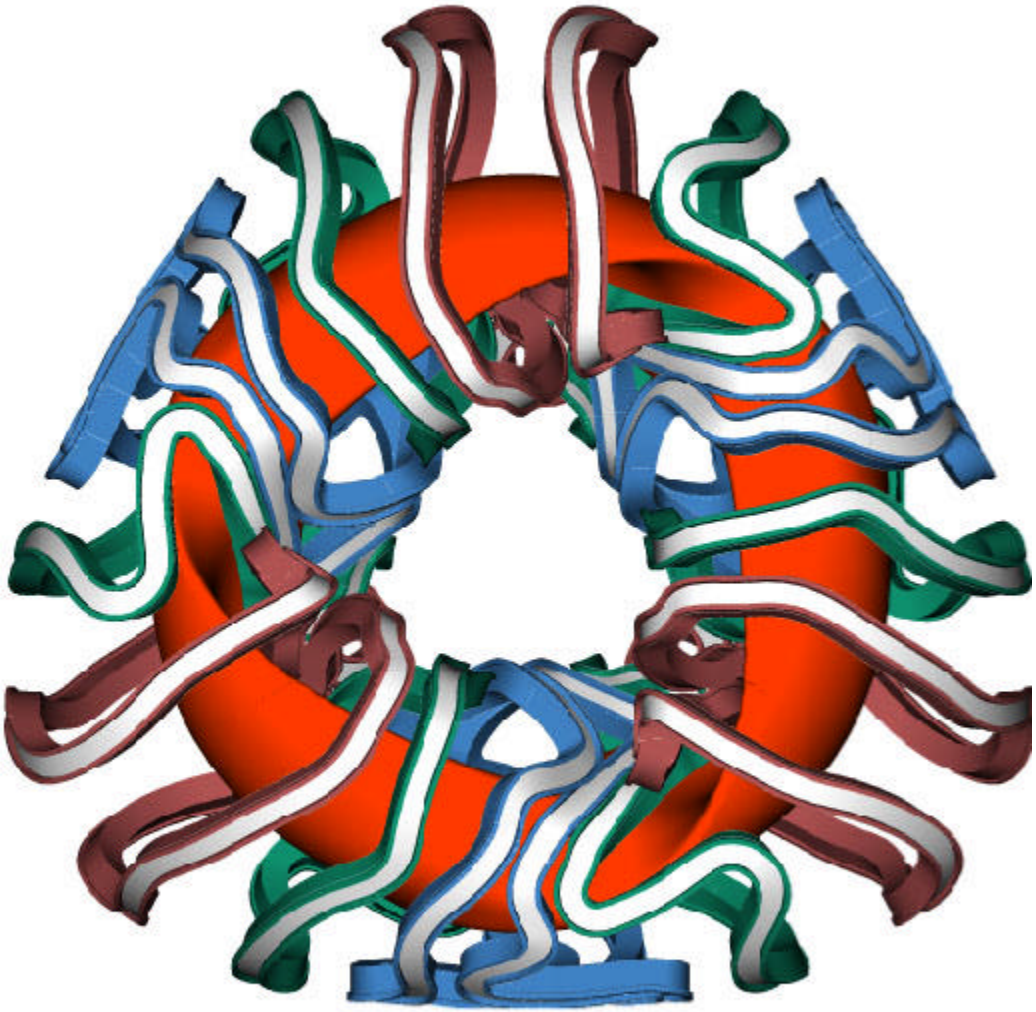
- **Start with NCSX-based coil and plasma shape with 3-field period (From Long-Poe Ku's memo)**
- **Perform scoping maintenance scheme & configuration analysis**
- **Need divertor guidelines (heat load, geometry)**

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

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

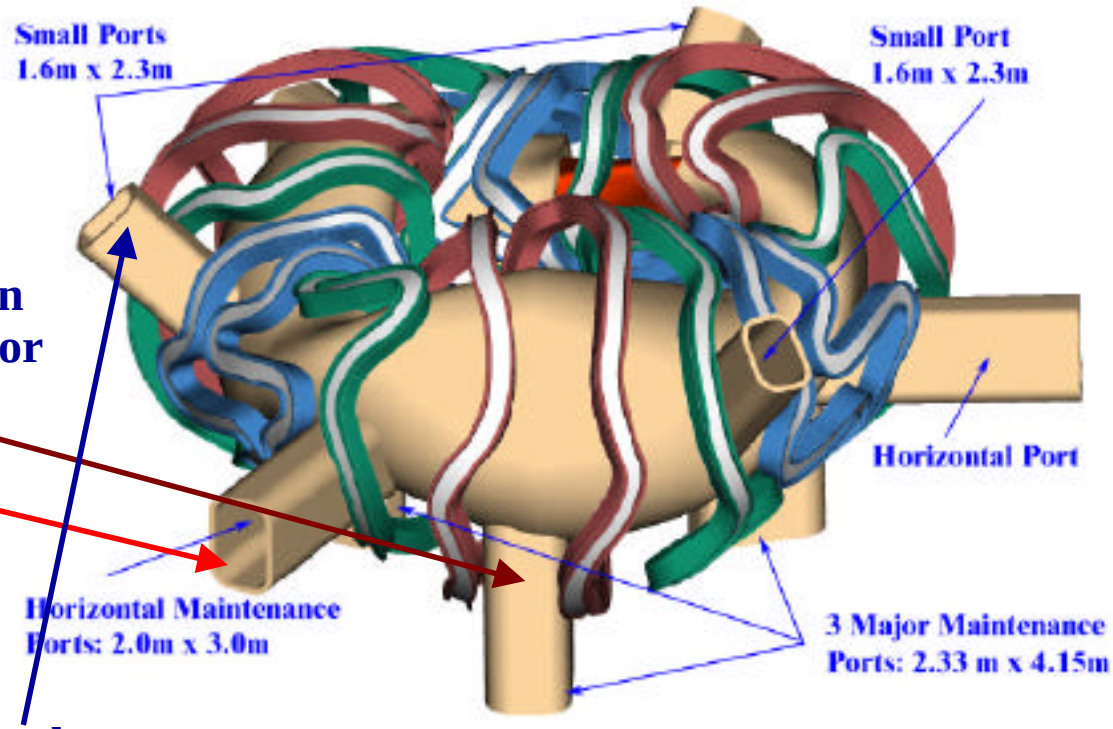
- **ITER modular maintenance approach**
  - **Rail system**
  - **Transporter from port to ~module plane on rail**
  - **Articulated boom to replace module**

- **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

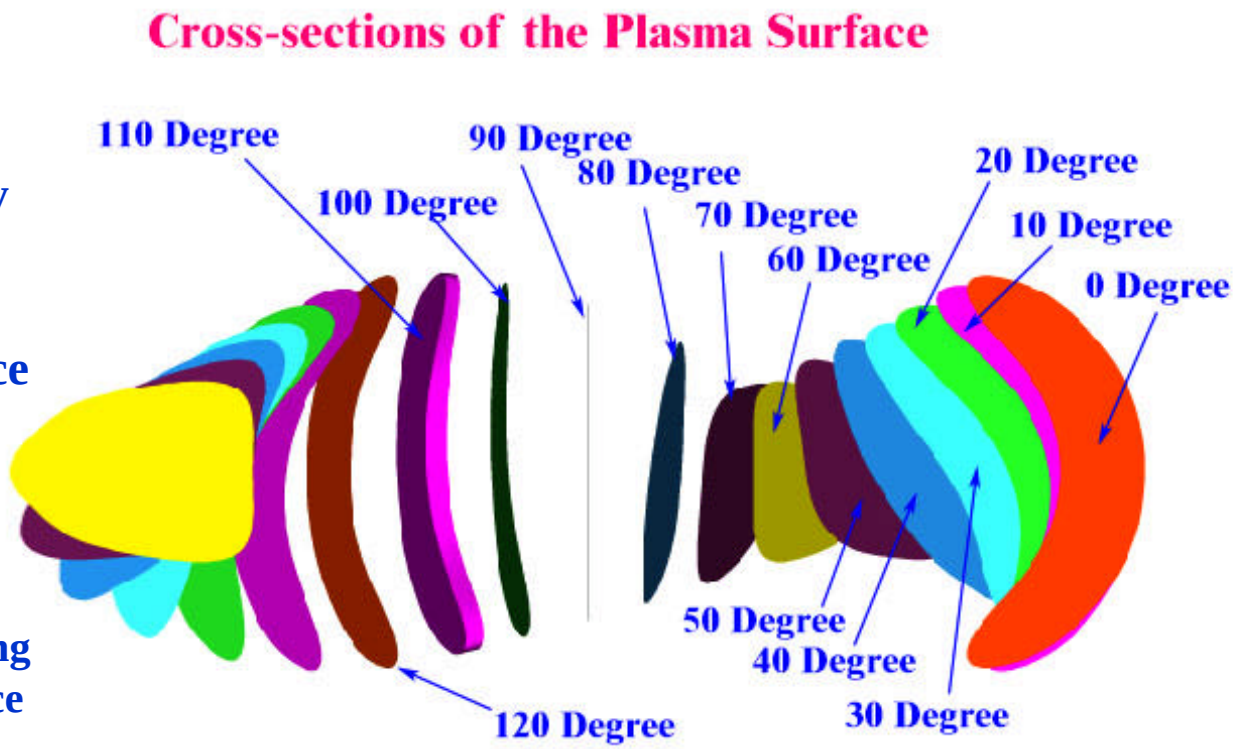
- **From EDITH-system*, boom built with:**
  - a total length of ~ 10m
  - a reach of +/- 90° in NET
  - pay load of 1 ton
  - maximum height of 2 m
- **Current ARIES-CS modular design based on comparable parameters for 3 ports (horizontal or vertical)**
  - half field period length ~ 9 m
  - minor radius =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



*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**



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

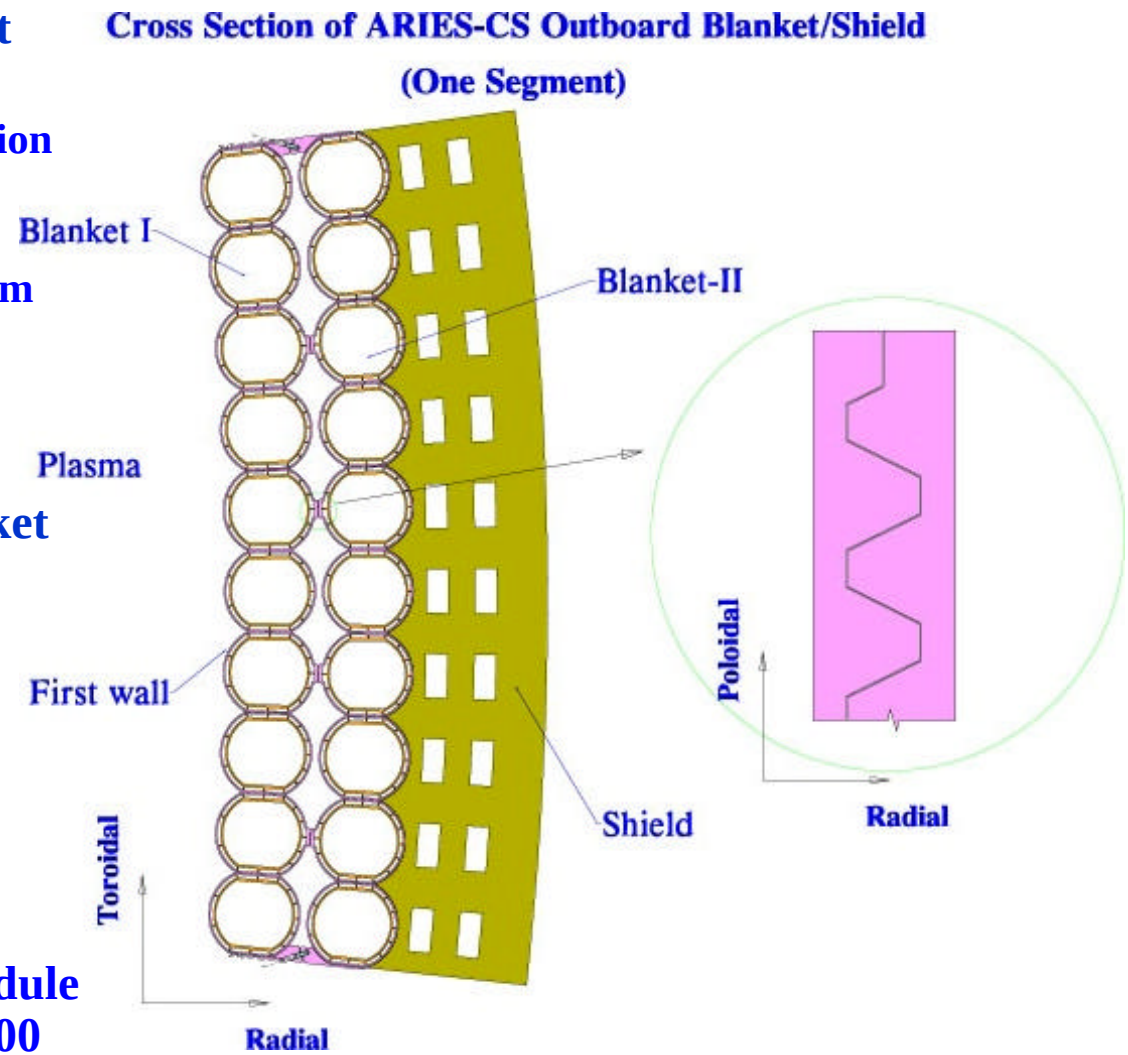
Based on ARIES-AT concept

- **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)**

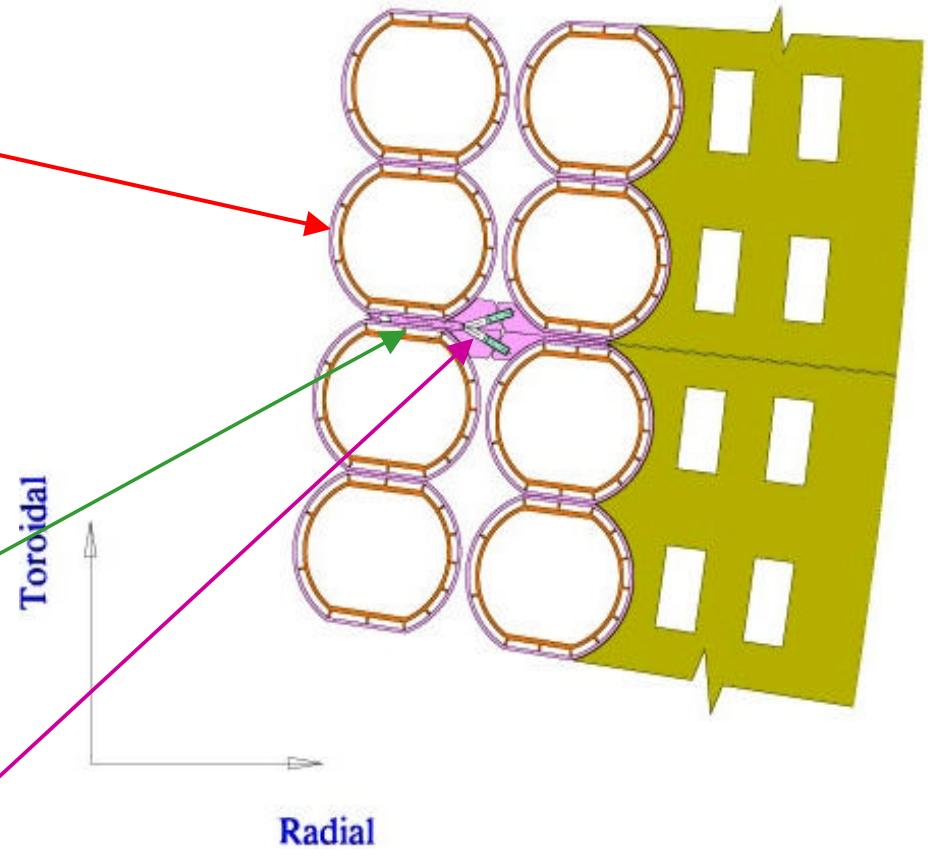
- **Example replaceable blanket module size ~2 m x 2 m x 0.25m (~ 500-600 kg when empty) consisting of a number of submodules (here 10)**



Blanket Module Configuration Consists of a Number of Submodules

Submodule configuration

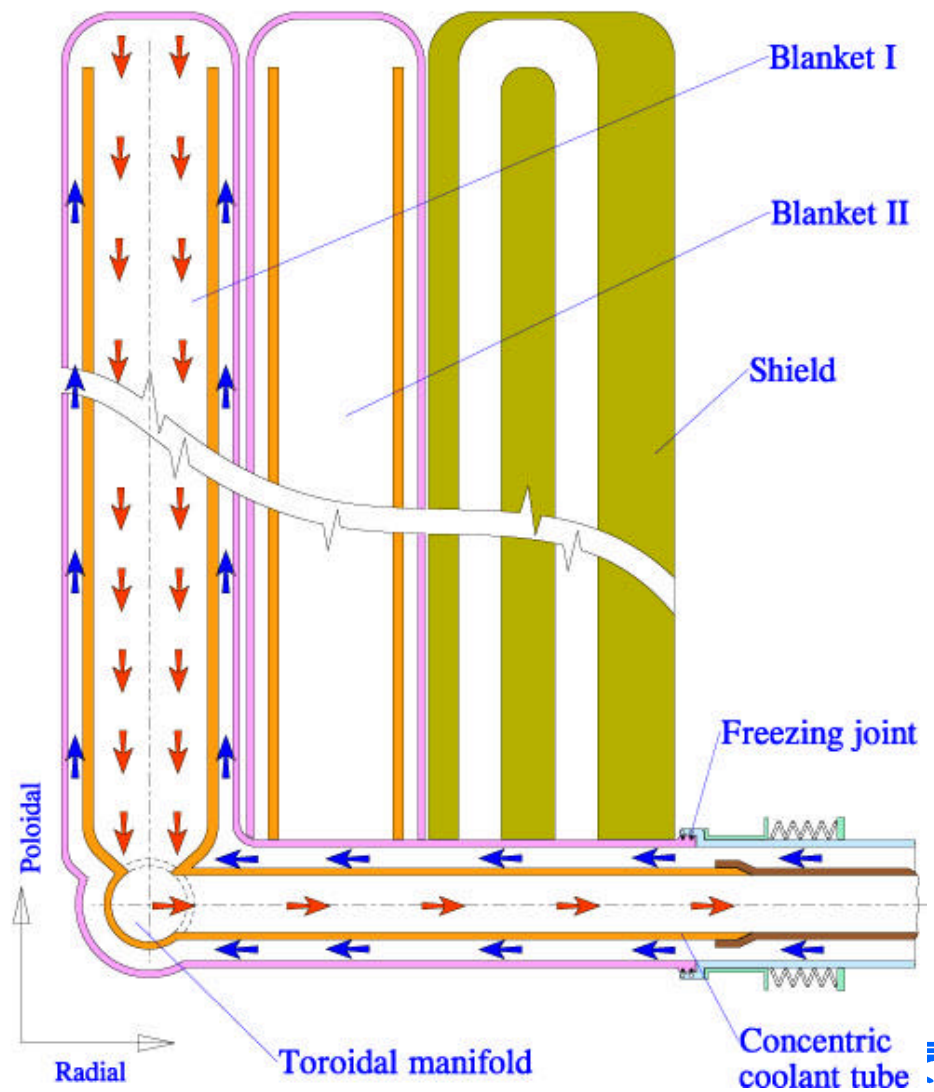
- Curved first wall for better Pb-17Li pressure (<~2 MPa) accommodation
- 4 mm thick SiC_f/SiC first wall with 1 mm CVD SiC coating
- Hoop stress ~ 60 MPa
- Side wall of adjacent submodules pressure balanced, except for each end submodule where thicker side walls are required to accommodate the pressure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



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

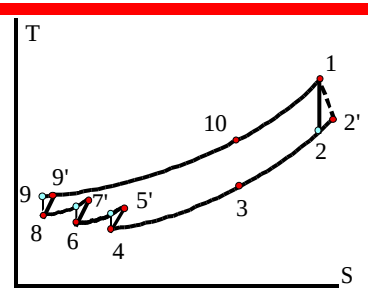
- **Two-pass flow through submodule**
  - **First pass through annular channel to cool the box**
  - **Slow second pass through large inner channel**
- **Helps to decouple maximum SiC_f/SiC temperature from maximum Pb-17Li temperature**
  - **Maximize Pb-17Li outlet temperature (and cycle efficiency)**
  - **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**

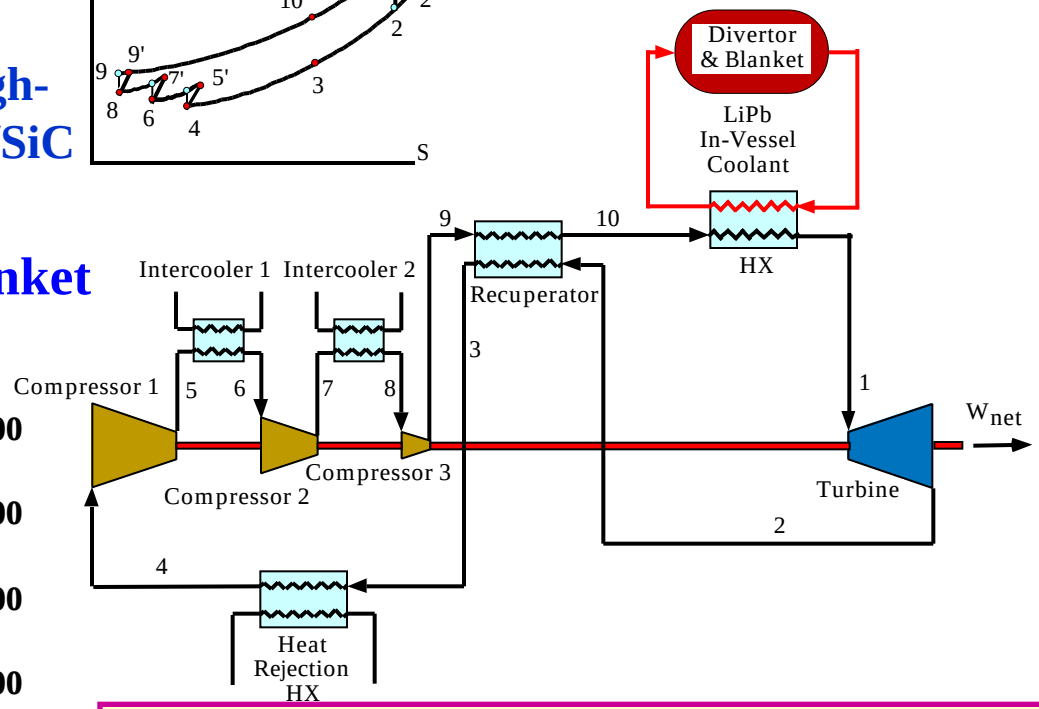
Cross-section Showing Coolant Flow Path and Access Tube

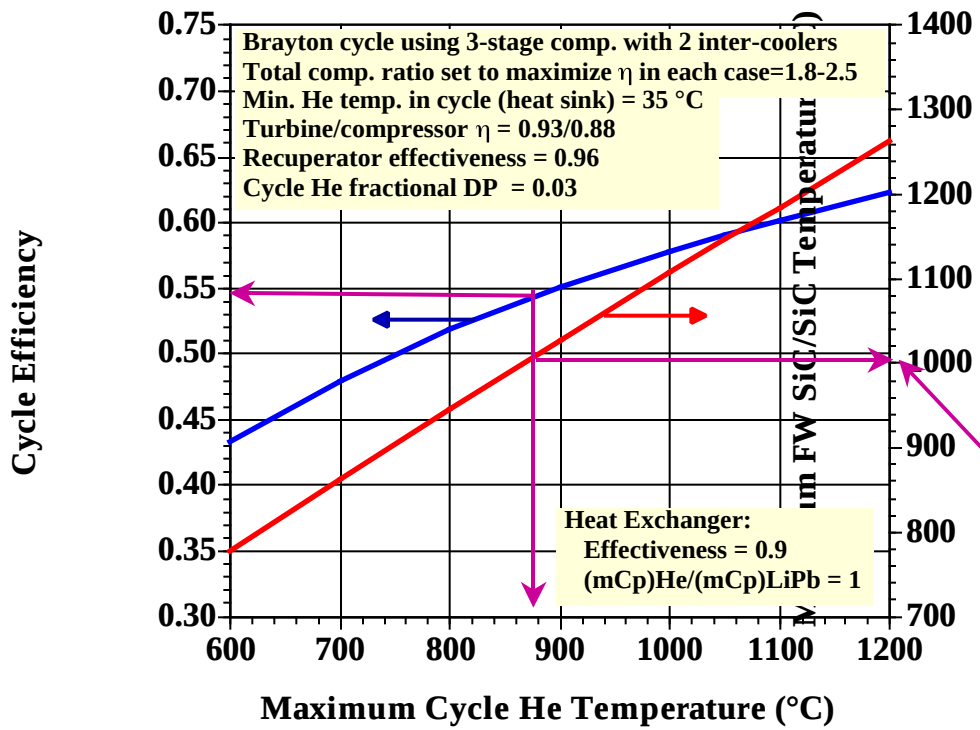


Pb-17Li Coolant Coupled with Brayton Power Cycle

- **Best near-term possibility of power conversion with high efficiency**
  - **Maximize potential gain from high-temperature operation with SiC_f/SiC**
- **Compatible with liquid metal blanket through use of HX**



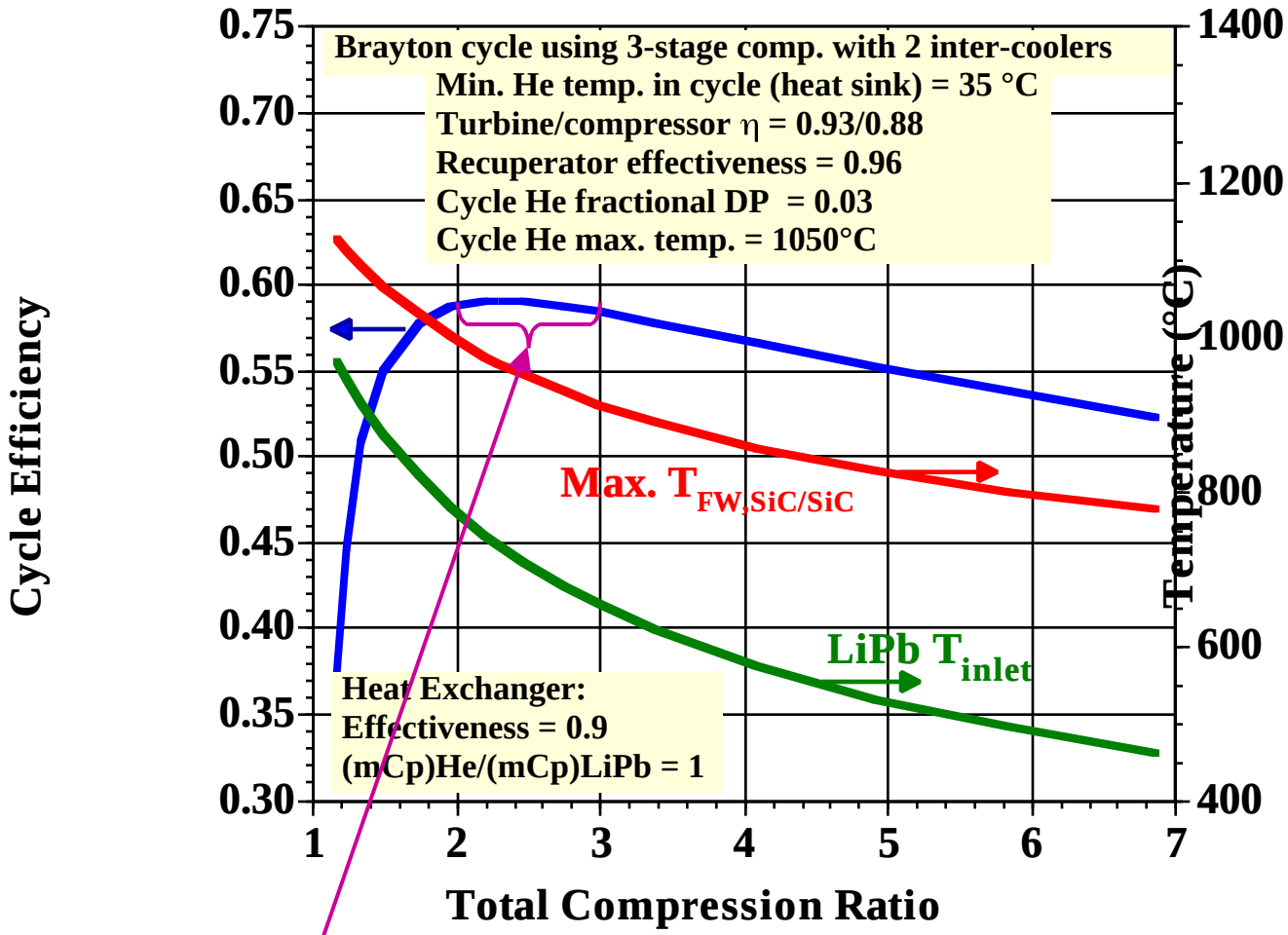




Cycle Efficiency Increases with Maximum Cycle He Temperature

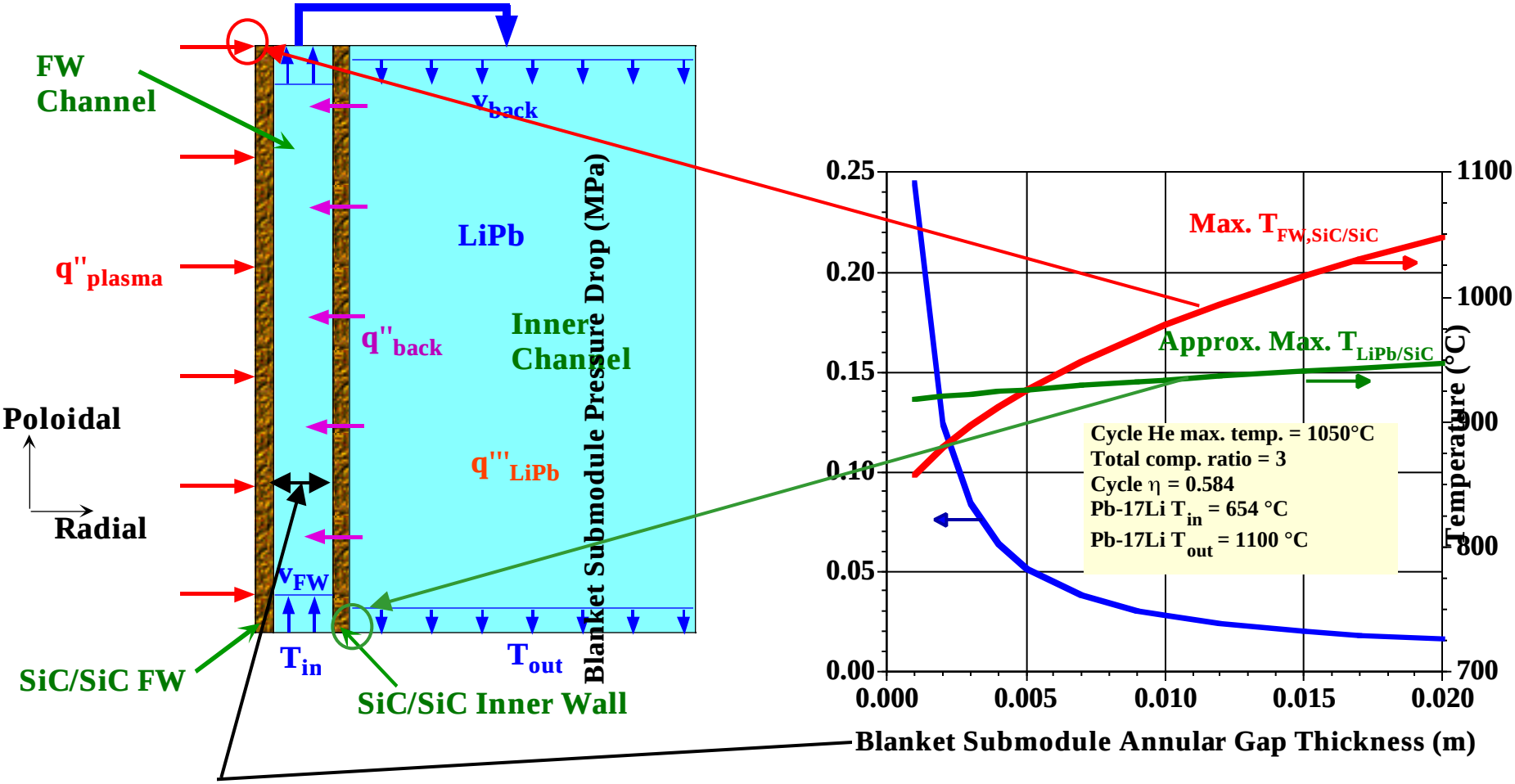
- **Compression ratio set to maximize cycle efficiency in each case**
- **For $T_{SiC/SiC}$ < 1000°C, Max. $T_{He,cycle}$ ~ 900°C and η_{cycle}~ 0.55**
- **Compression ratio is additional control knob**

HX Inlet He Temperature (and, hence, Power Core Pb-17Li Inlet Temperature) Can Be Set by Adjusting Cycle Compression Ratio



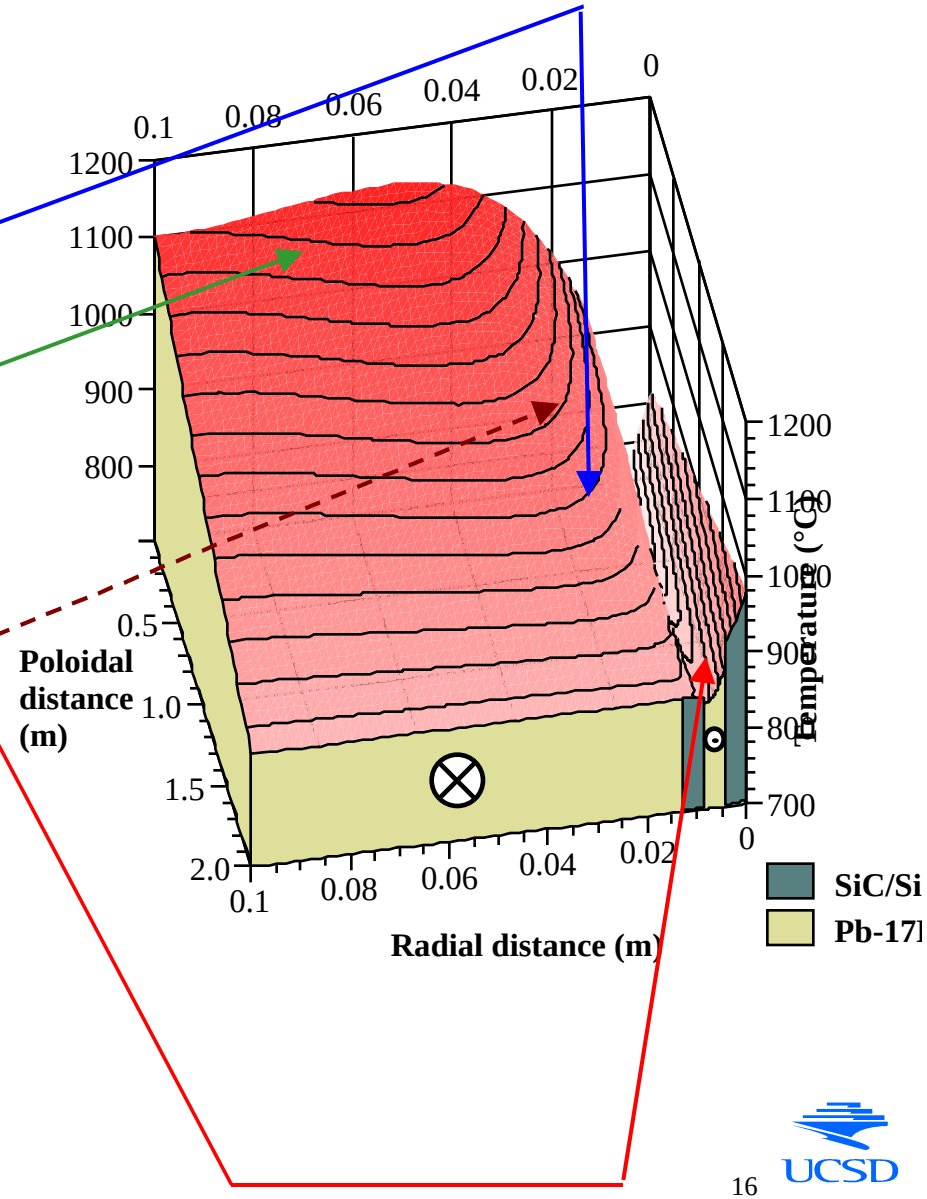
Some flexibility in setting cycle compression ratio, and inlet HX He temp. (dictating inlet blanket Pb-17Li inlet and max. SiC_f/SiC temp.) with minimal decrease in cycle efficiency temperature

Maximum SiC/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**



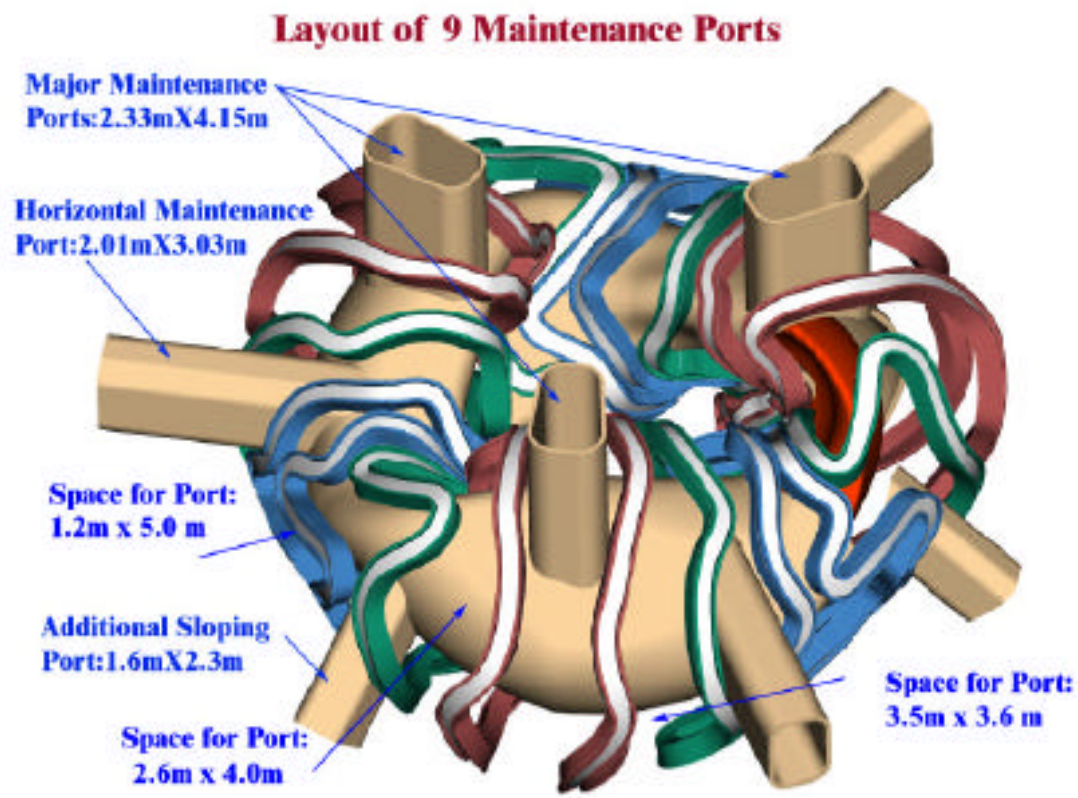
Typical Parameters for Example ARIES-CS Blanket Design with SiC_f/SiC and Pb-17Li (Not fully optimized yet)

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

Modular Maintenance Approach with Ports Between Each Coil

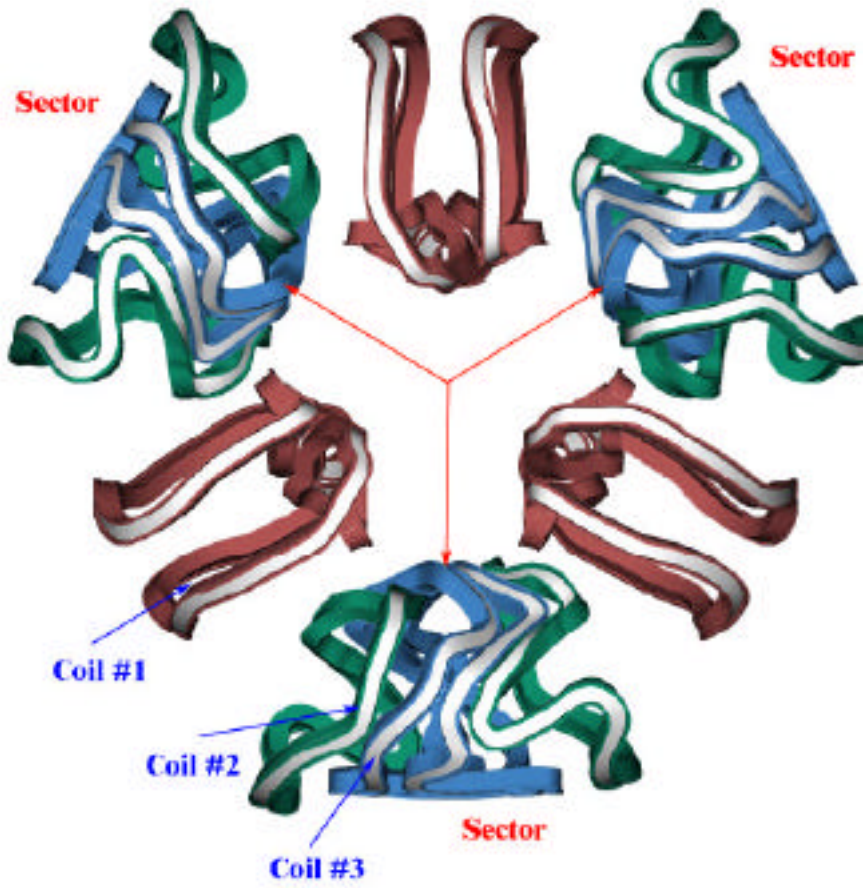
- **Minimum Port Sizes**
  - 1.6 m x 2.3 m and 1.2 m x 5.0 m
  - Quite limiting constraint on size of module
  - Desirable to accommodate ~2 m x 2 m x 0.25 m module

- **Unless reactor size (and port size) is increased, this maintenance scheme seems marginal and a modular maintenance scheme through fewer larger ports is preferable**



Sector-Like Maintenance Approach

- **Based on current example machine configuration, the following sector removal seems possible**
  - 3 sectors consisting of 4 coils each
  - 3 sectors consisting of 2 coils each
  - Must remove two larger sectors first and then smaller sector
  - Complex maintenance process
  - Size and number of maintenance sectors would change based on several parameters including:
    - size of machine
    - toroidal protrusion of coil on adjacent coil
    - size coil + casing
  - Guidance needed on these, e.g.
    - confirmation of smaller size coil + casing (20 cm?)
    - physics wise how much do we lose with ~10's cm less toroidal coil protrusion?



Some Initial Thoughts for Sector-Like Maintenance Approach Based on Disasembling the Modular Coil System (S. Malang)

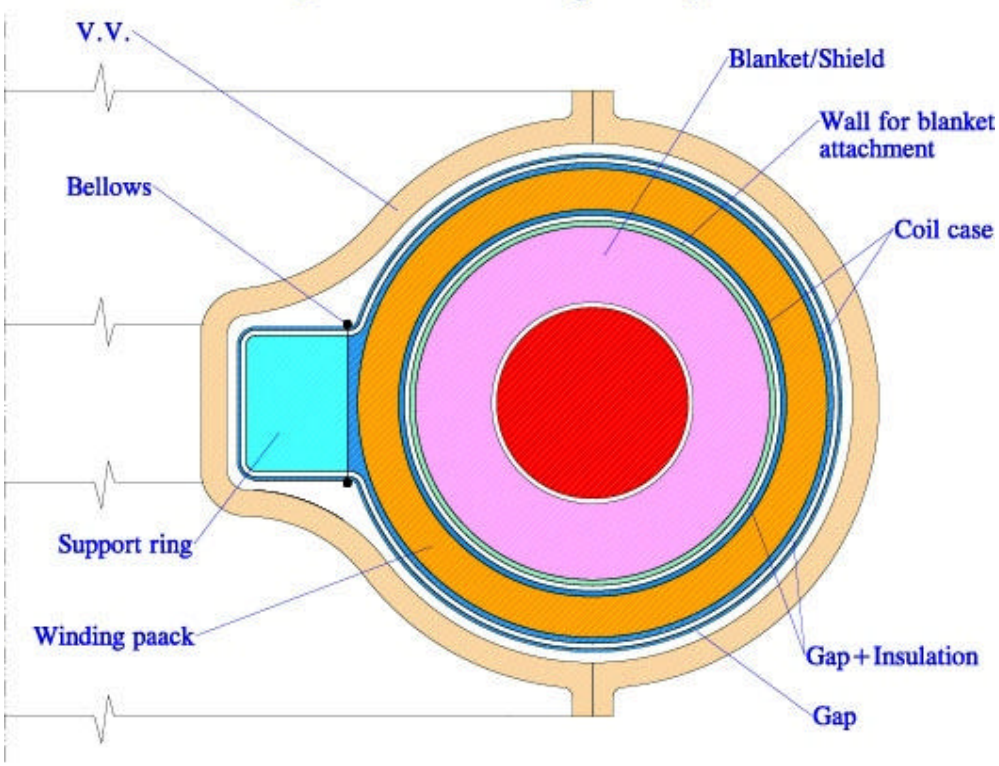
1. **Is it feasible to heat up the coil system prior to disassembly or is it necessary to design the coil system for "cold" maintenance**
   - **If heating up the system is feasible (for blanket replacement), how much additional time would be required for such an operation?**
   - **Impact of this additional time will depend on frequency of blanket replacement**
   - **e.g. a cool-down period of ~1 month years would probably be acceptable for blanket replacement (~3MW/m^2, 0.85 load factor-->200 dpa steel) every ~8 years of operation (~1% impact on availability)**

2. **Which kind of connections between the cold coil system and a support at ambient temperature can be designed to carry the total weight of coils + supporting structure?**
   - **The issue here is the heat flow to the cold system through the supporting legs.**
   - **More serious problem for LTSC's**
   - **Is a requirement for the cryogenic plant of ~1 MW acceptable (corresponding to ~1000W of heat removal)?**

Some Initial Thoughts for Sector-Like Maintenance Approach Based on Disasembling the Modular Coil System (cont.)

3. **How can the coil system be supported to react the radial forces pulling it toward the centre of the system?**
   - **These are by far the largest forces acting on the coils.**
     - **Up to 350MN per coil for the SPPS-Stellarator, reacted by a ring with a 5-m inner radius of and a 3-m wall thickness**
   - **Such large forces cannot be transferred from a cold to a warm component (through an insulation).**
   - **Therefore, the coil winding, housing, and the supporting ring in the centre have to be operated at a uniform cryogenic temperature.**

Cross-section of Showing a Torus with Circular Plasma and Planar Coil
(Vertical Cut Through Torus)



- **Already challenging to design such a system without the requirement to allow for disassembling the coils for blanket replacement.**
- **This issue needs more attention than previously paid by a number of Stellarator reactor studies.**

Some Initial Thoughts for Sector-Like Maintenance Approach Based on Disasembling the Modular Coil System (cont.)

4. How large are the forces between neighboring coils, and how can they be reacted?

- **For planar coils with equal current flow these forces are balanced, but if one coil fails, large forces would act on the neighboring coils.**
- **For a system with non-planar coils, forces between neighboring coils exist but are balanced within each field period in the case of a Stellarator .**
- **All coil windings of a field period could be placed in grooves of a common support tube strong enough to balance the lateral forces of the coils.**
- **If this is feasible, these support tubes would be "stand-alone elements" not requiring force transfer between field periods.**
- **This would be advantageous for blanket maintenance but at the expense of having to move a huge unit for blanket replacement (the size would be reduced if it could be done over half a field period)**

5. How can the weight of the blanket+neutron shield be transferred to the base structure of the reactor?

- **For the above-mentioned case with a strong supporting tube per field period, the weight of the cold elements (winding + supporting tube, ~ 5000 tonnes) must be transferred to the vacuum vessel through supporting legs with minimum heat conduction area**
- **The weight of the "warm" components surrounding the plasma (FW, breeding blanket, reflector, neutron shield, ~ 10,000 tonnes)) must be transferred to the fundament of the vacuum vessel via "warm" leg, reaching through openings in the "cold" support tubes of the coils.**
- **There has to be insulation around these legs, and the legs can be used to house the coolant access tubes for the blankets.**

Guidance Needed on Several Questions, Including:

1. **Coil: HTSC or LTSC**
2. **Coil: Confirm thickness of windings+casing**
3. **Coil: Demountable or not**
4. **Coil/Physics: What is the penalty of shaving off ~10 cm's radially to facilitate access for sector maintenance**
5. **Coil/Physics: What is the penalty of changing the number of field periods (e.g. going from 3-field to 2-field or 4-field periods)**
6. **Divertor: Location, heat loads, particle fluxes?**
7. **Starting Point Configuration: Need revised consistent set of power density, machine size, plasma parameters and magnetic field**