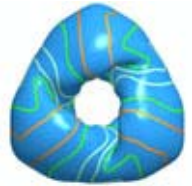


Maintenance Approaches For ARIES-CS Power Core



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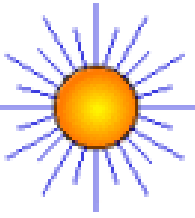
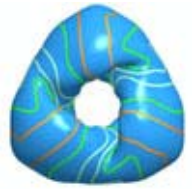
^bFusion Nuclear Technology Consulting, Fliederweg 3, 76351 Linkenheim, Germany

16th ANS Topical Meeting on the Technology of Fusion Energy

September 14-16, 2004

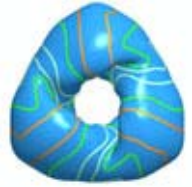
Madison, WI

Outline



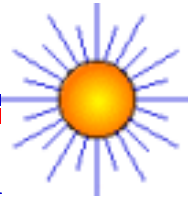
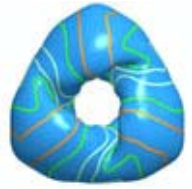
- Introduction
- Reactor parameters
- Maintenance approach based on field-period units
- Modular maintenance approach through selected ports
- Maintenance approach with ports between all the modular coils
- Summary and conclusion

Introduction



- The engineering activities during the phase one of the ARIES-CS study has focused on scoping out maintenance schemes and blanket designs best suited for a compact stellarator configuration.
- Three possible maintenance schemes have been explored in the first phase:
 - *field-period based replacement requiring the disassembly of the coil system;*
 - *modular replacement approach through maintenance ports between each pair of modular coils;*
 - *modular replacement through a small number of designated maintenance port using articulated booms.*
- The study will then down-select to a couple of most attractive combinations of blanket and maintenance scheme for more detailed studies culminating in the choice of a point design for a full system study.

Reactor Parameters



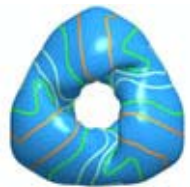
EXAMPLE PARAMETERS ASSUMED FOR INITIAL ARIES-CS SCOPING STUDY

Major radius, R	8.25 m
Minor radius, $\langle a \rangle$	1.85 m
Plasma aspect ratio	4.5
Plasma volume	553 m ³
Plasma boundary surface area	807 m ²
Minimum distance between plasma and center of coil winding, $\Delta_{\min}$	1.2 m
Magnetic field on axis, B	5.3 T
Volume average beta	4.1%
Plasma current, I_p	3.5 MA
Fusion power, P_f	2 GW
Ave. neutron wall loading, Γ_n	2.0 MW/m ²
Max. Neutron wall loading (assumed)	3.0 MW/m ²

NCSX-like plasma and coils were scaled to a size expected to produce a fusion power consistent with a net power output of 1000 MWe.

Maintenance Approach Based on Field-Period Units

Main Challenges for the Design the Configuration to Satisfy the Maintenance Approach



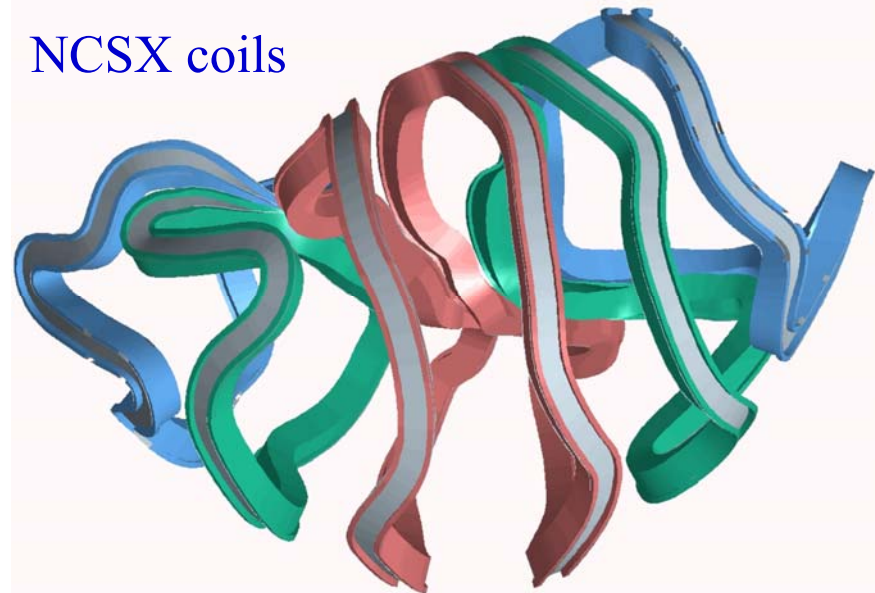
➤ How can the coil system be supported to react the centering force pulling the coil radially towards the center of torus? (up to 350 MN for SPPS stellerator)

➤ How can the force between neighboring coils acting in toroidal direction(out-of-plane force) be reacted?

➤ How can the weight of the “cold” coil system be transferred to the “warm” base structure of the reactor without excessive large heat ingress?

➤ How can the weight of the FW+Blanket+Shields be transferred to the base structure of the reactor?

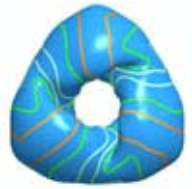
NCSX coils



Three kinds of forces acting on the coils:

- Large centering forces pulling each coil towards the center of the torus;
- Out-of plane forces acting between neighboring coils inside a field period
- Weight of the cold coil system

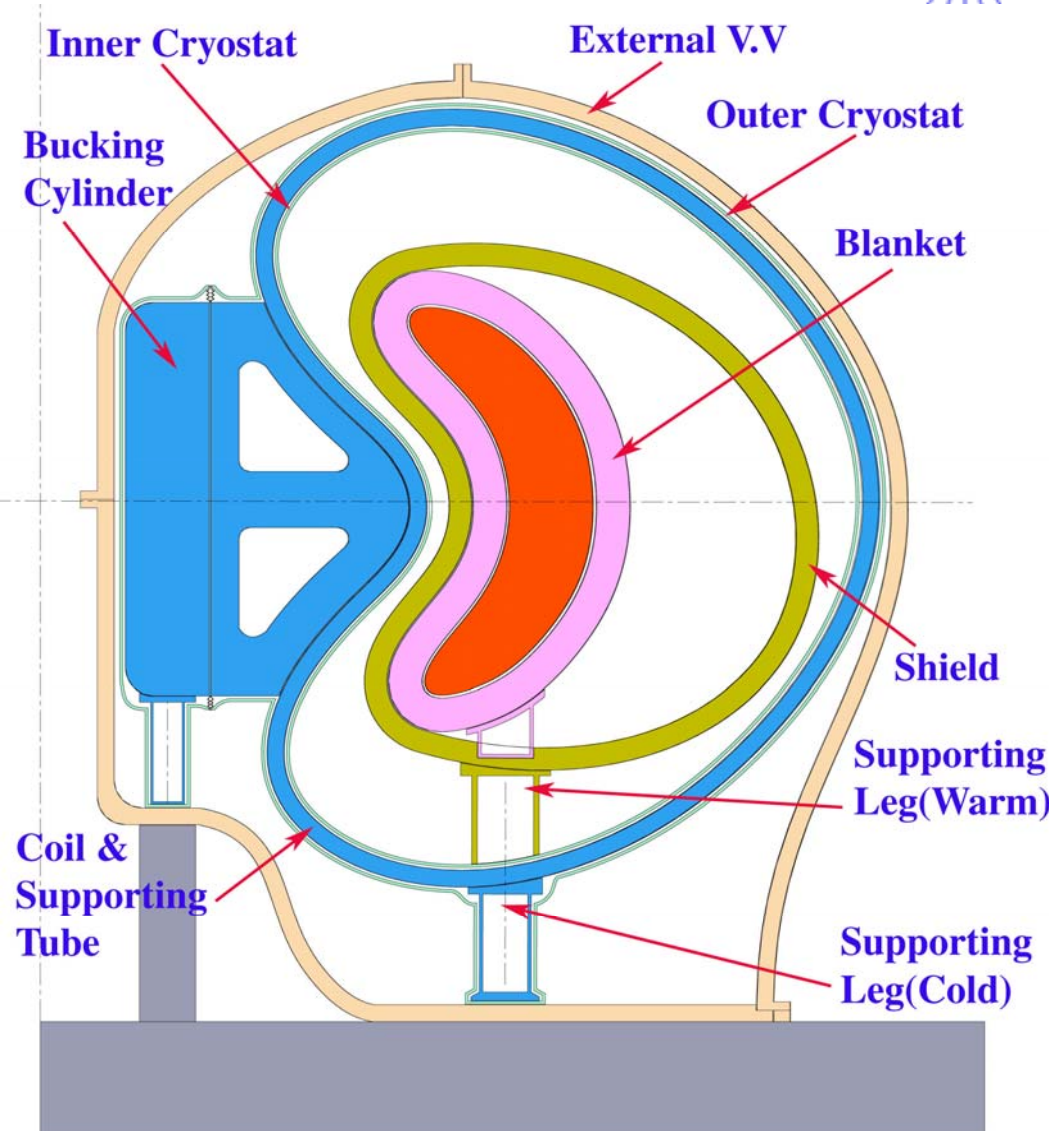
Layout of Coil System, Supporting structure, Cryostats, and External Vacuum Vessel(0 degree)



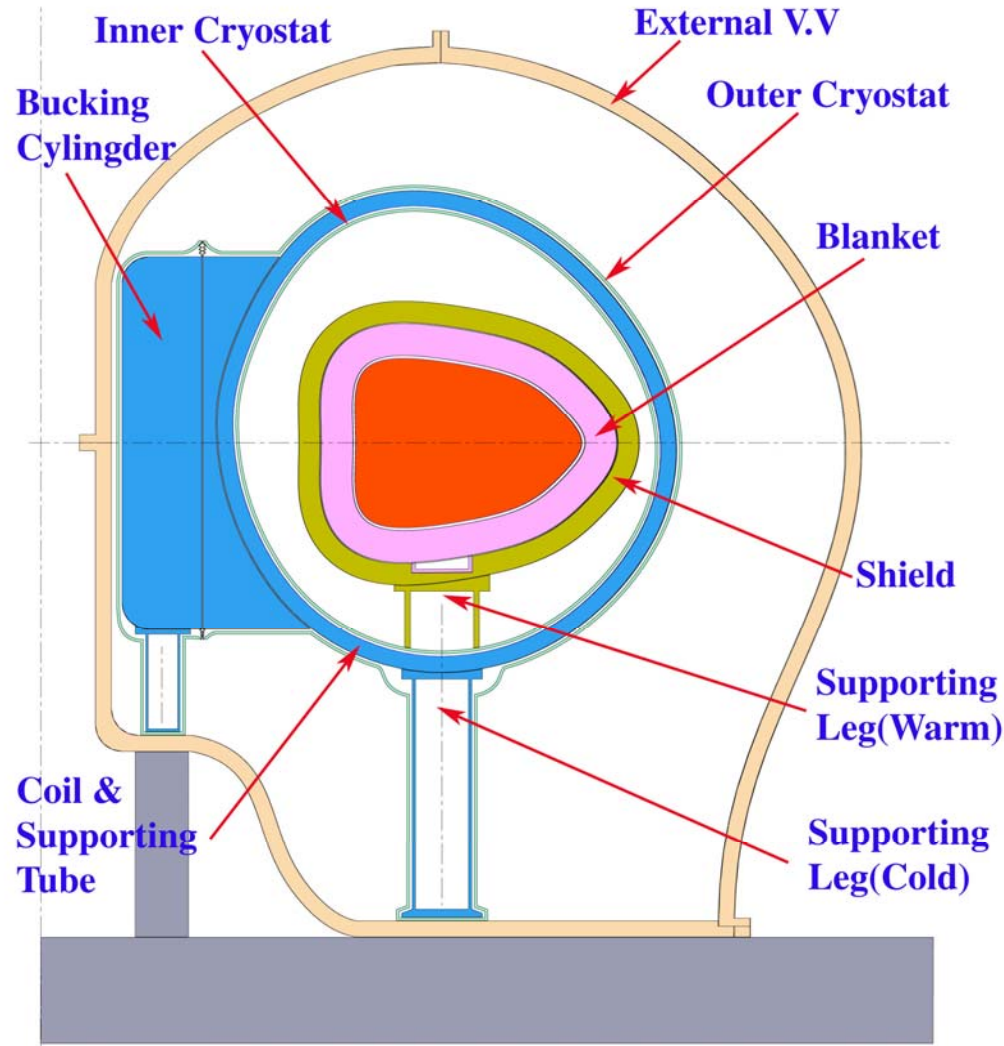
➤ To allow the disassembly of the coil system, the supporting tube of each field period is enclosed by a separate cryostat.

➤ Bucking cylinder to react the centering forces of coils is enclosed by a separate cryostat in order to be maintained at cryogenic temperature.

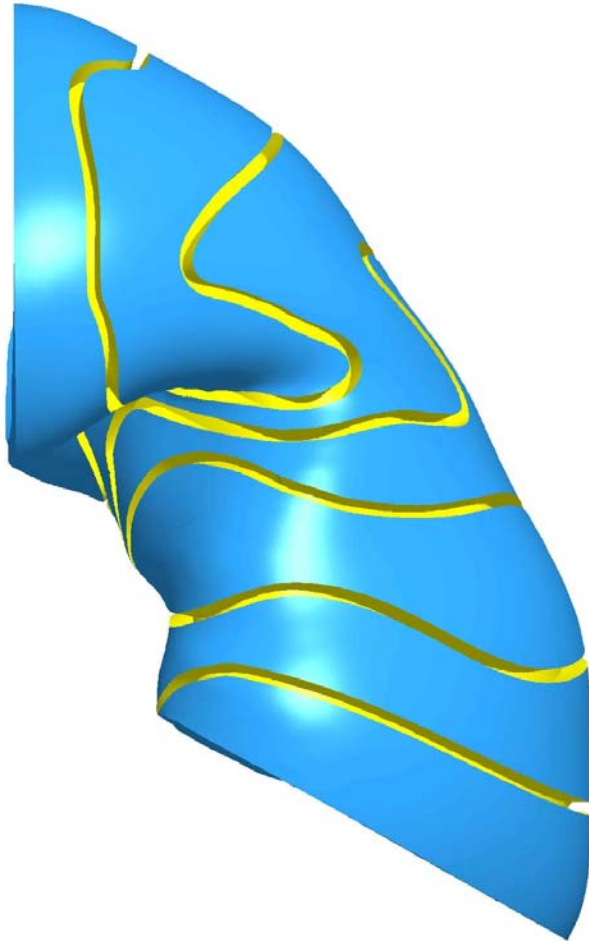
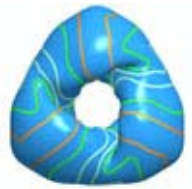
➤ All the individual cryostats containing the entire coil system and the supporting structure are enclosed by an **external vacuum vessel**.



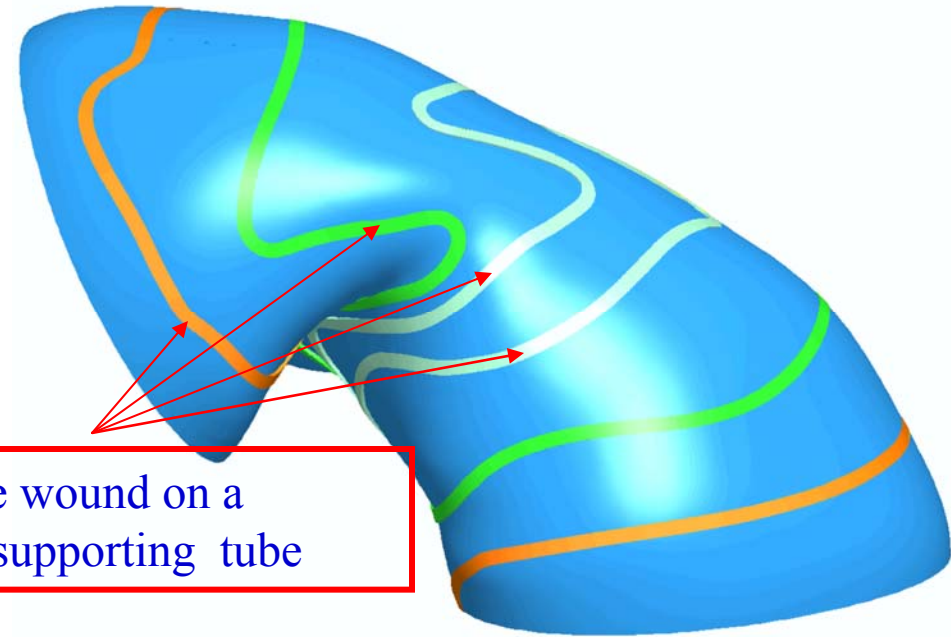
Layout of Coil System, Supporting structure, Cryostats, and External Vacuum Vessel(60 degree)



Arrangement of All Coils of a Field-Period on a Supporting Tube



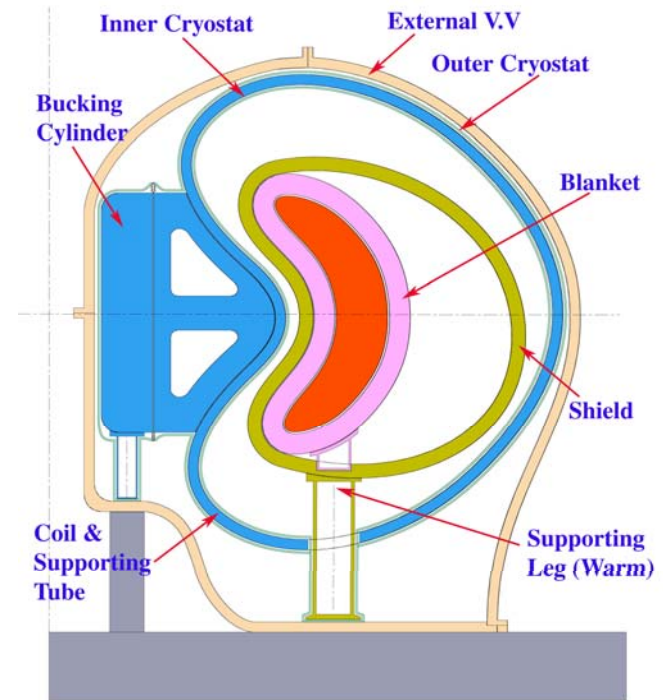
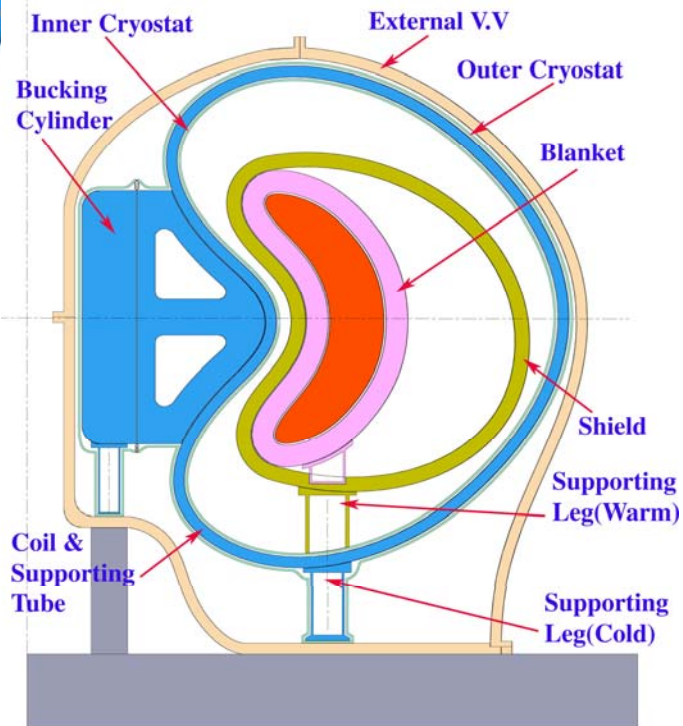
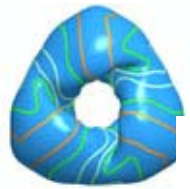
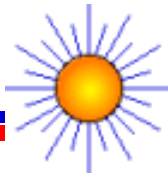
Grooves on the supporting tube(one-field period)



6 coils are wound on a common supporting tube

- **Supporting tube** is composed of inter coil structure, coil cases, and winding pack.
- Coils are wound on a common supporting tube.
- All out-of-plane forces are reacted inside the field-period, and the centering forces are reacted by a strong bucking cylinder in the center of the torus.

Arrangement of Supporting Legs to Support the Weight of Cold Structure and Blanket/Shields



➤ Sufficient large cross section of cold legs required to minimize mechanical stresses.

➤ Small ratio between cross section and length of the legs required to minimize heat ingress.

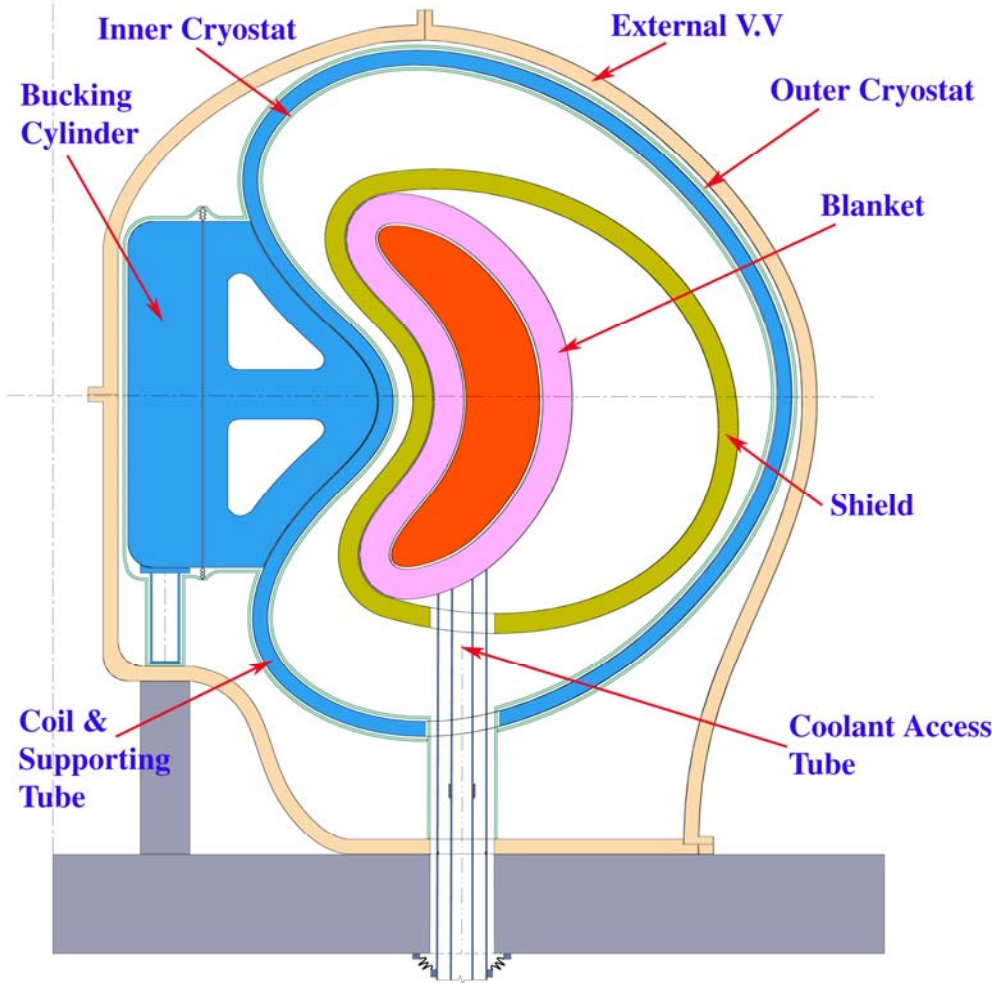
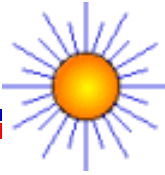
➤ 3x3 long legs required to support the weight of cold supporting tube.

➤ There is nearly no limitation on the cross section of the warm legs because the warm legs are between warm regions.

➤ The shield rests on warm legs, transferring the weight of entire power core (~10,000 tons) to the foundation.

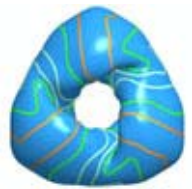
➤ 2x2 strong warm legs are needed each field period (2 units/one period) to support the weight of blanket/shields.

Arrangement of Cooling Access Tubes to FW+Blanket+Shields

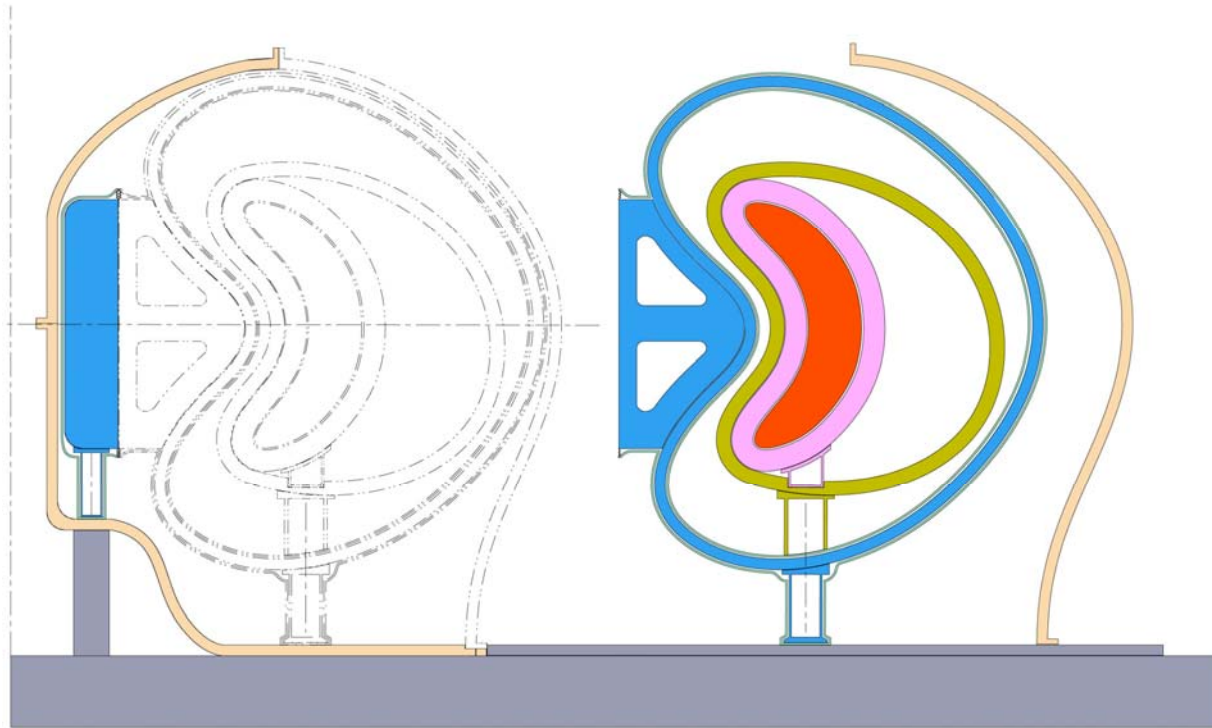


Major Features:

- All the access tubes are from the bottom as concentric tubes.
- Sliding joints can be used at the inner tube.
- Only outer tube has to be cut and re-welded.



Steps to be Performed for an Exchange of Blankets

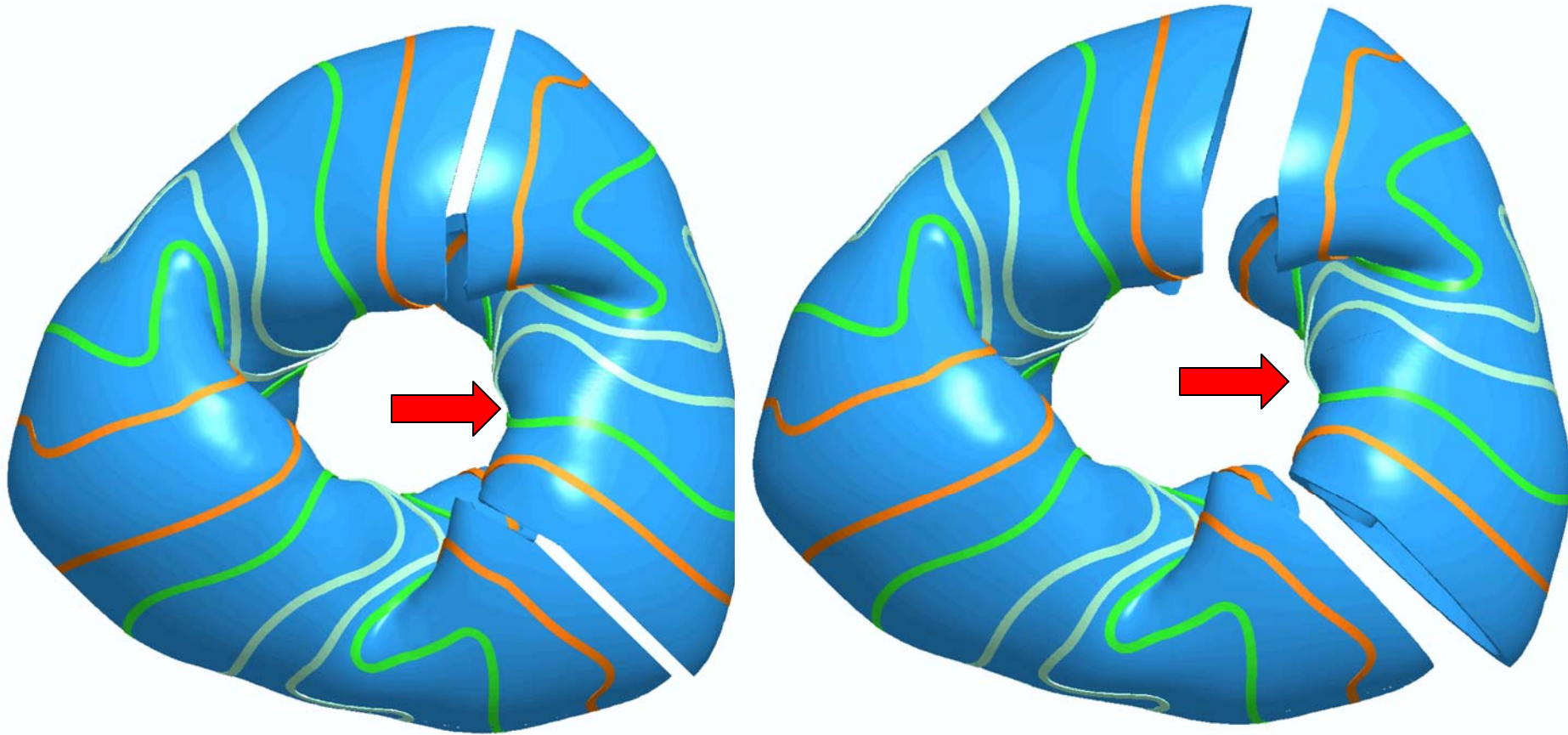


- Warm up the coil system including the mechanical support structure.
- Flood the plasma chamber and the cryostats with inert gas.
- Cut all coolant connections of the field period by using in-bore tools operating from bottom.
- Open the outside of V.V. (one field period).
- Slide the entire field period unit outwards in radial direction on the flat surface at the bottom.
- Cut the access tubes of the blanket to be replaced.
- Slide the replacement unit(**pink**) out from the opening at the both ends on a rail attached to the replacement unit(possibly with an air-cushion system).

Motion Studies Show no Conflicts and Interferences Between Adjacent Coil Field Periods

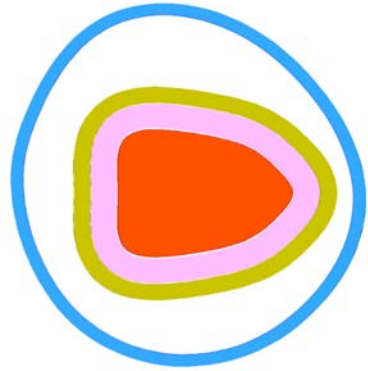
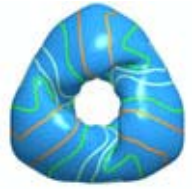


UC San Diego



Clearances have been checked every
10 cm movement.

Verify Clearance for the Replacement Unit in Toroidal Direction



60 °



50 °



40 °



30 °



20 °



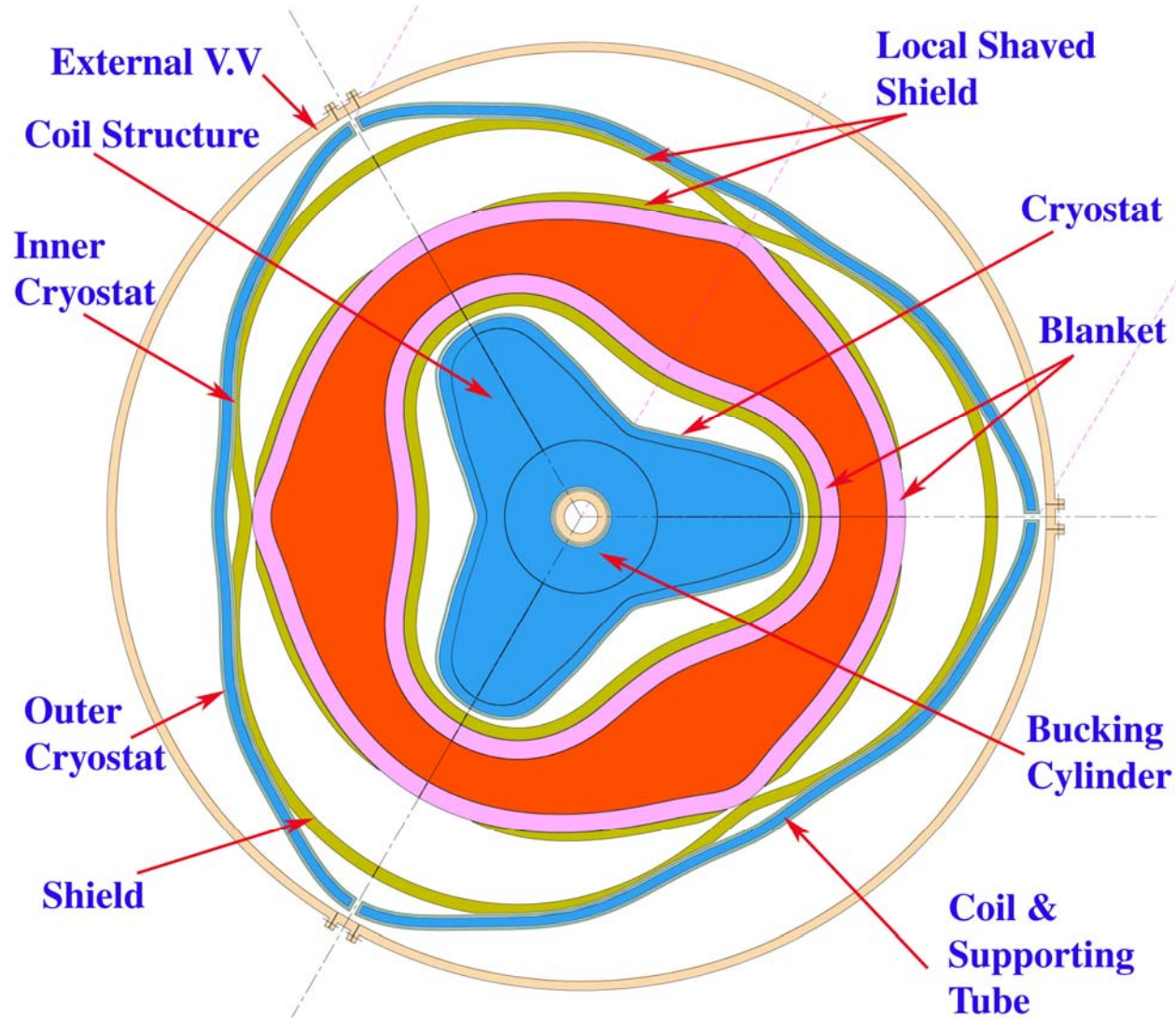
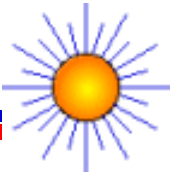
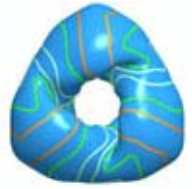
10 °

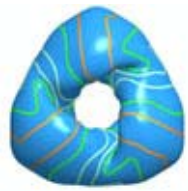


0 °

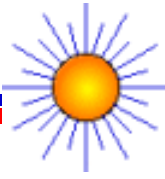
It is feasible to move the replacement unit out in toroidal direction for a combined(blanket+shield) thickness of 100 cm after shaving a minimal shield.

Cross-Section of the Power Core (Cutting Through Middle Plane)





Example Blanket Concept Suited for the Field-Period Based Maintenance



We have evaluated the following blankets concept(in historical order):

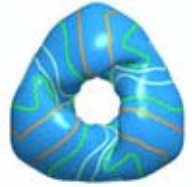
- Self-cooled FLIBE blanket with advanced ferritic steel;
- Self-cooled Pb-17Li blanket with SiC_f/SiC composite as structural material;
- Dual-coolant blanket concept with He-cooled steel structure and self-cooled Li breeding zone;
- Dual-coolant blanket concept with He-cooled steel structure and self-cooled Pb-17Li breeding zone;
- Helium cooled ceramic breeder blanket with ferritic steel structure.

The blanket concept based on dual-coolant blanket with He-cooled FW/structure and self-cooled Li or Pb-17Li breeding zone has been assumed for this maintenance scheme in the first phase CS study. Details on the scoping studies of the different blanket concepts can be found in this issue[1].

[1] A.R. Raffray, L. El-Guebaly, S. Malang, X. Wang and the ARIES Team, “Engineering Study of ARIES-CS Chamber Components”, this issue.

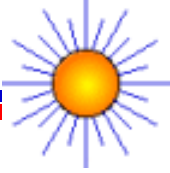
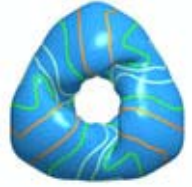
Modular Maintenance Approach Through Selected Ports Based NCSX- like Plasma and Coils

Main Issues for Using Selected Ports with an Articulated Boom



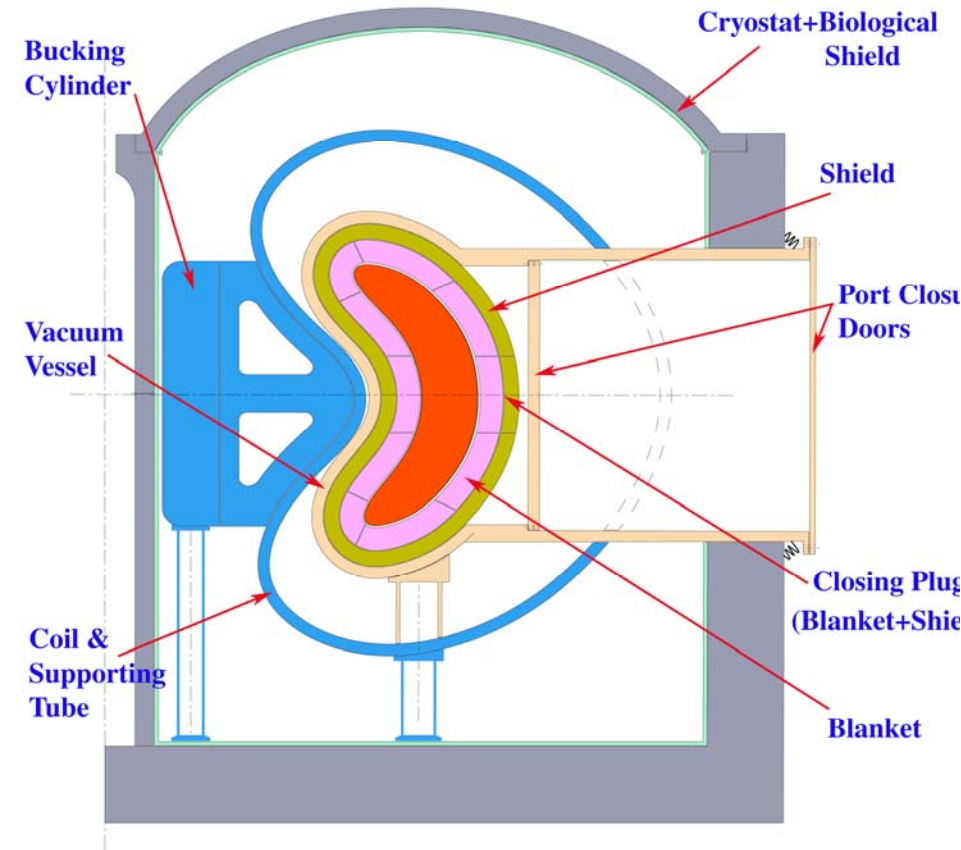
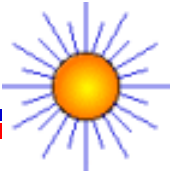
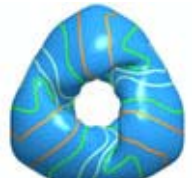
- Space between FW and VV is very restricted at some locations.
- Cutting and re-welding of coolant access tubes must be possible with in-bore tools, inserted from the plasma region.
- Number and geometry of tubes to be cut and re-welded is important for down-time and reliability.
- Load capacity of boom limited to ~ 3 tons.

Vacuum Vessel Arranged Between Shield and Coils

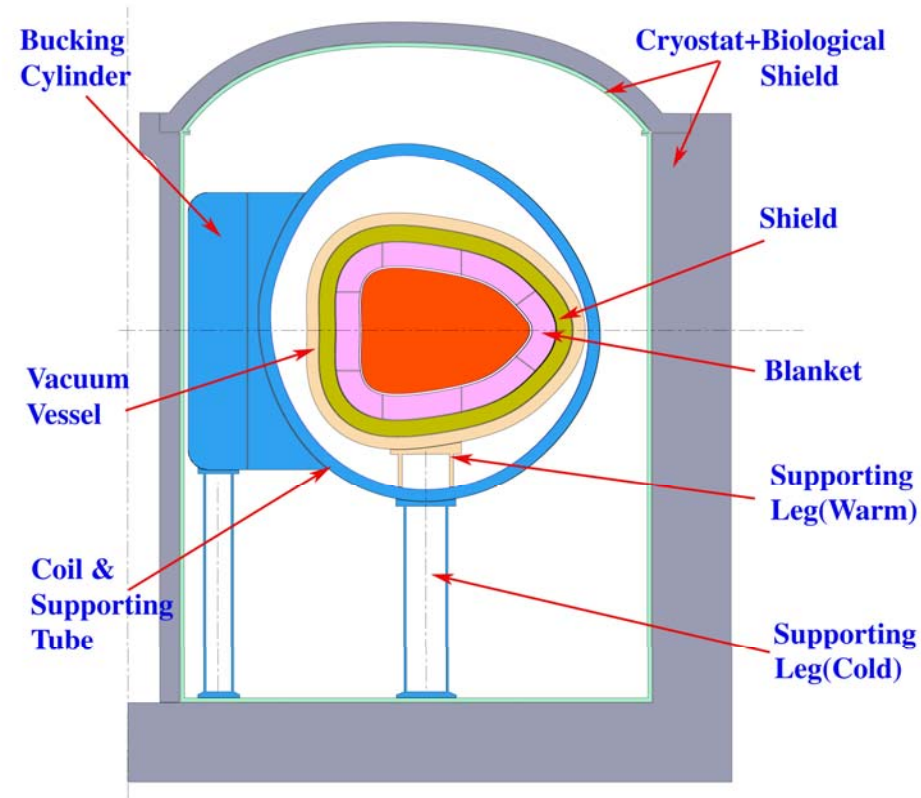


- The VV serves as an additional shield for the protection of the coils from neutron and gamma irradiation. No disassembling and re-welding of the VV is required for blanket maintenance.
- Considering the non-uniform shape and size of the modular coils, each field-period has two VV sectors. The assembly welds are arranged at the largest cross-section (at 0°) and the smallest cross-section (at 60°). This allows sliding the VV sectors into the coils of the field period in toroidal direction.
- There is large freedom in designing the shape of the VV, with the two constraints on cross section:
 1. It must fit into the modular coils with their supporting structure.
 2. The space inside the VV must be sufficient for breeding blankets and shielding modules.

Layout of Coil System, Supporting Structure, Cryostat and Vacuum Vessel



(0 degree)

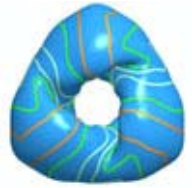


(60 degree)

Major Features:

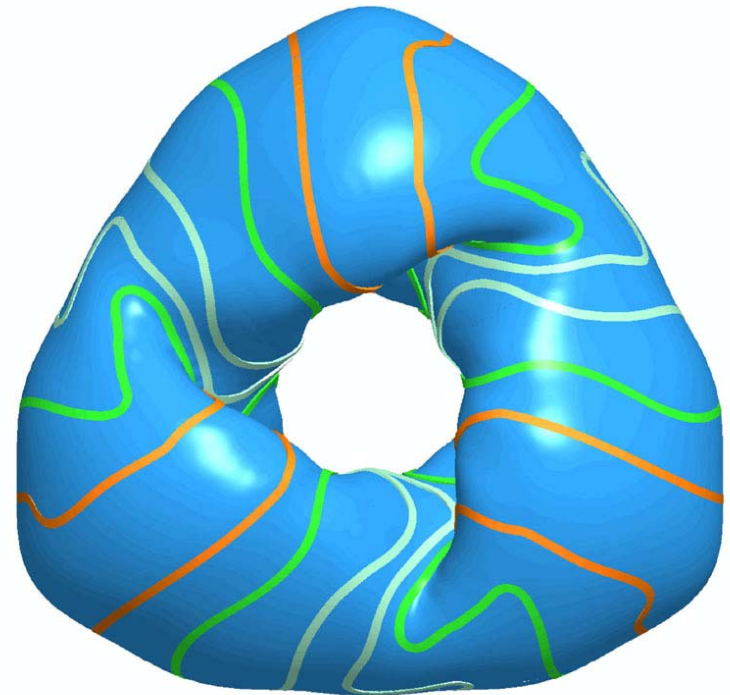
- VV is internal to the coils and serves as an additional shield for protecting the coils.
- No disassembling and re-welding of VV are required for blanket replacement.
- The entire coils system is enclosed in a common cryostat for thermal insulation.

Arrangement of Coils and Supporting Tube

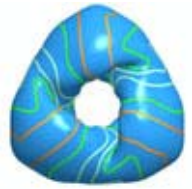


The design principle of coil system has been described already for the maintenance approach based on the field-period units.

- All out-of-plane forces are reacted inside the field period, and the centering forces are reacted by a strong bucking cylinder in the center of the torus.
- No separate cryostats for the different field period coils and the bucking cylinder are required since no disassembly is necessary for a blanket exchange.
- Thermal isolation between the cold coil system and the warm VV has to be provided.

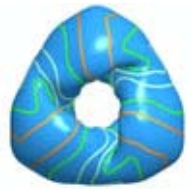


External Cryostat

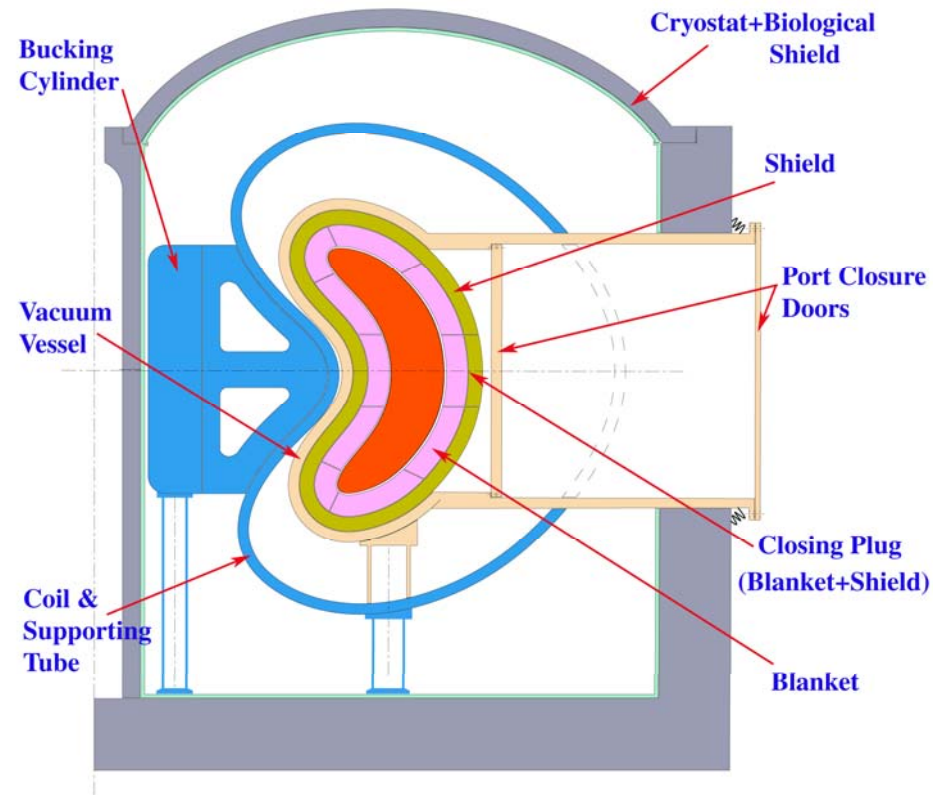


- For thermal insulation, the entire coil system has to be enclosed in a common cryostat(torus).
- This cryostat can serve at the same time as a second containment for the tritium in the VV.
- The most cost effective design maybe to build this large cryostat as a concrete vessel with an internal steel liner, serving as a biological shield in addition.

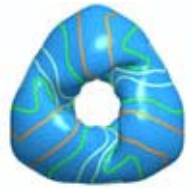
Maintenance Ports Arranged Between Modular Coils at 0°, 120° and 240°



- The optimum locations for these ports are the 0°, 120°, and 240° cross-sections (assuming one port per field period). This enables the maximum height of the ports and the articulated boom for module handling. In this case, the VV sections can be already fabricated with parts of the maintenance ports attached to it.
- The ports have to bridge the space between VV and external cryostat. Bellows at the connections between port and cryostat allow for differential thermal expansion. In order to maintain the containment of tritium, there should be two doors of the port, one at the VV and one at the outside of the cryostat. **Many details of this system are very similar to the solutions proposed in ARIES-RS.**



Blanket Concept Suited for the Modular Maintenance Approach

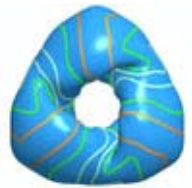


- The blanket options envisaged in combination with this modular maintenance scheme are:
 - (1) *self-cooled liquid metal blankets;*
 - (2) *helium cooled blankets, either with liquid metal breeder or with ceramic breeder;*
 - (3) *blanket concept based on FLiBe and advanced ferritic steel.*
- An important selection criterion for this maintenance scheme is the weight of a module to be replaced, limited by the anticipated capacity of articulated booms to less than 5,000 kg.
- **Lighter-module concepts such as FLiBe/FS and Pb-17Li with SiC_f/SiC (based on ARIES-AT design) are well suited for this modular maintenance scheme.**
- The weight of a typical 2m x 2m x 0.3 m module for these two concepts are ~1500 Kg and ~1000 Kg, respectively.
- Details on the scoping studies of the different blanket concepts can be found in this issue[1].

[1] A.R. Raffray, L. El-Guebaly, S. Malang, X. Wang and the ARIES Team, “Engineering Study of ARIES-CS Chamber Components”, this issue.

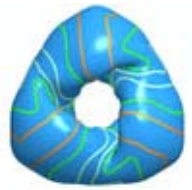
Maintenance Approach with Ports Between All Modular Coils Based on MHH2 Two-Field Period Configurations

Maintenance Approach with Ports Between Each Pair of Adjacent Coils



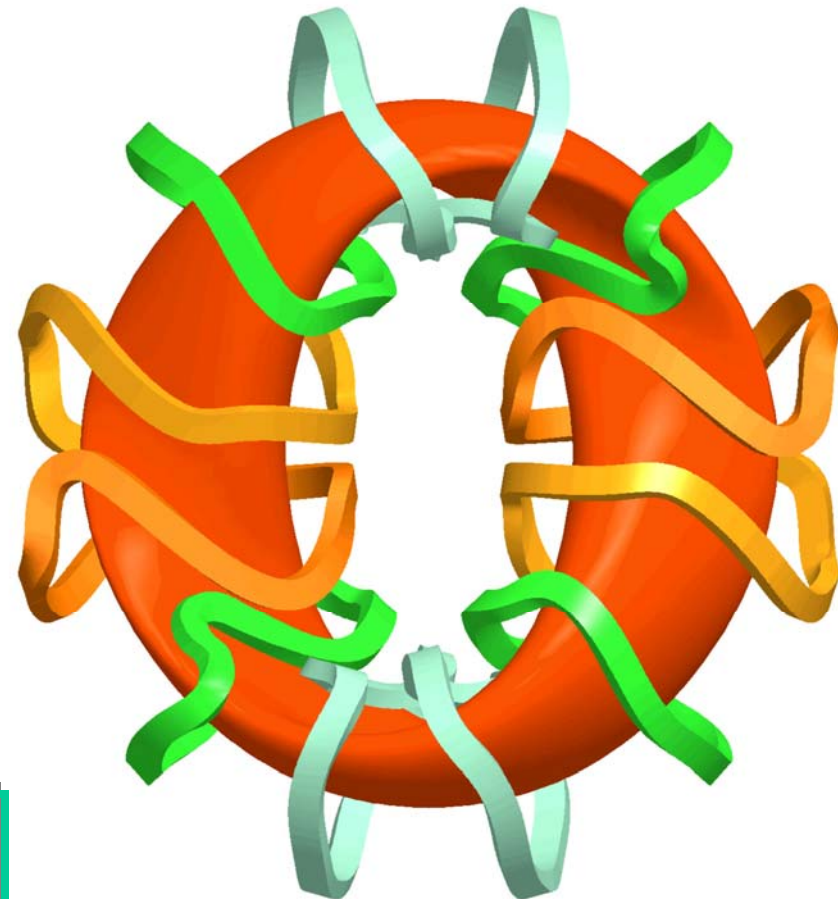
- This maintenance scheme seems marginal for the NCSX-like three-field period configuration because of the minimum port size.
- This maintenance scheme can be viewed as an extension of the previous modular maintenance approach.
- In both cases, blanket replacement is carried out by utilizing articulated booms through the ports, but this maintenance scheme for MHH2 (Modular Helias-like Heliac) two-field period configuration can handle/operate somewhat larger blanket modules through the ports using short booms.
- There are many similarities between the two modular maintenance schemes:
 - Internal vacuum vessel.*
 - Coil supporting tube.*
 - Maintenance ports bridging the region between VV and cryostat.*

MHH2 Configurations Provide More Room for Maintenance Approach with Ports Between all Coils



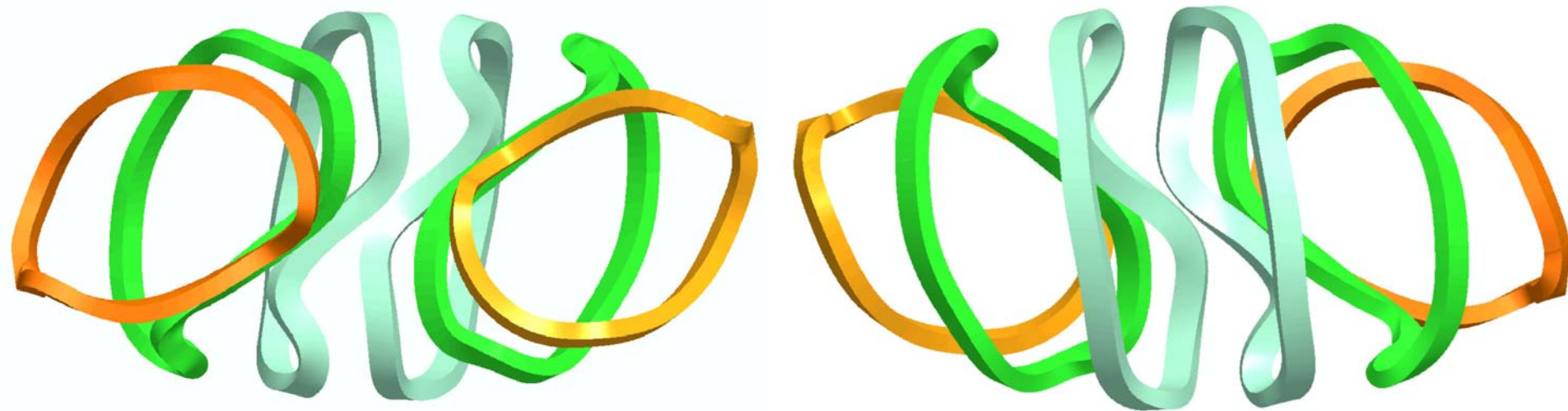
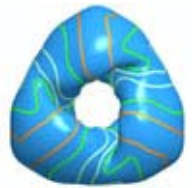
	R=8.25 m (3 FP, 18 coils)	R=7.5 m (2 FP, 12 coils)	R=6.5 m (2 FP, 16 coils)
Port #1	2.5 x 11.0	4.2 x 10.0	3.1 x 8.0
Port #2	1.6 x 10.2	3.9 x 9.4	3.2 x 7.1
Port #3	1.2 x 5.0	4.6 x 7.4	3.4 x 4.3
Port #4	2 x 3.03	5.1 x 4.4	2.4 x 3.7
Port #5	3.5 x 3.6	4.5 x 6.6	3.8 x 4.0
Port #6	2.1 x 10.5	4.1 x 9.6	3.1 x 6.4
Port #7			3.1 x 8.0
Port #8			3.7 x 8.8

Available port sizes are shown. Actual port sizes would depend on coil structure requirement for stress accommodation.



6 coils/field period, 3 type coils

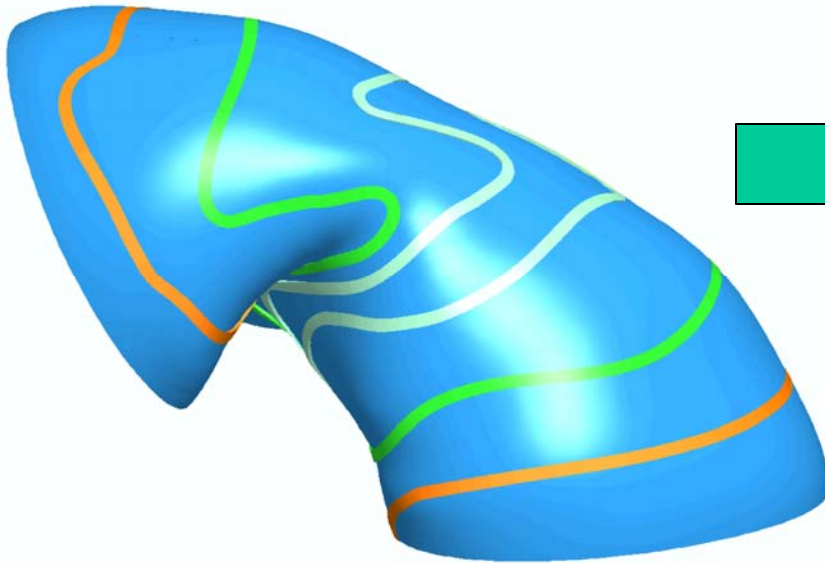
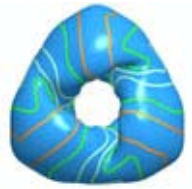
Coil Could be Independently Extracted Radially



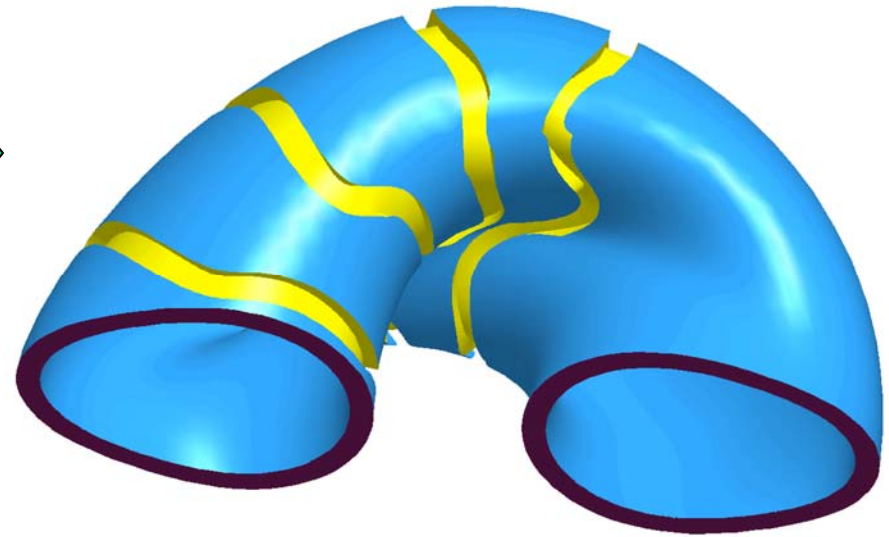
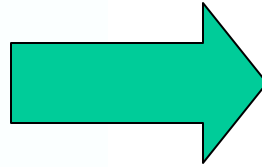
Side view of a field period as viewed from inside Side view of a field period as viewed from outside

- No interferences were found between adjacent coils and better in-reactor access and of shorter articulated boom span requirement.
- Coil can possibly be extracted independently of the others.
- It allows for a large blanket modules than the previous modular approach.

Design Concept of the Coil Supporting Tube for the NCSX-like Configuration Can Be Applied in MHH?



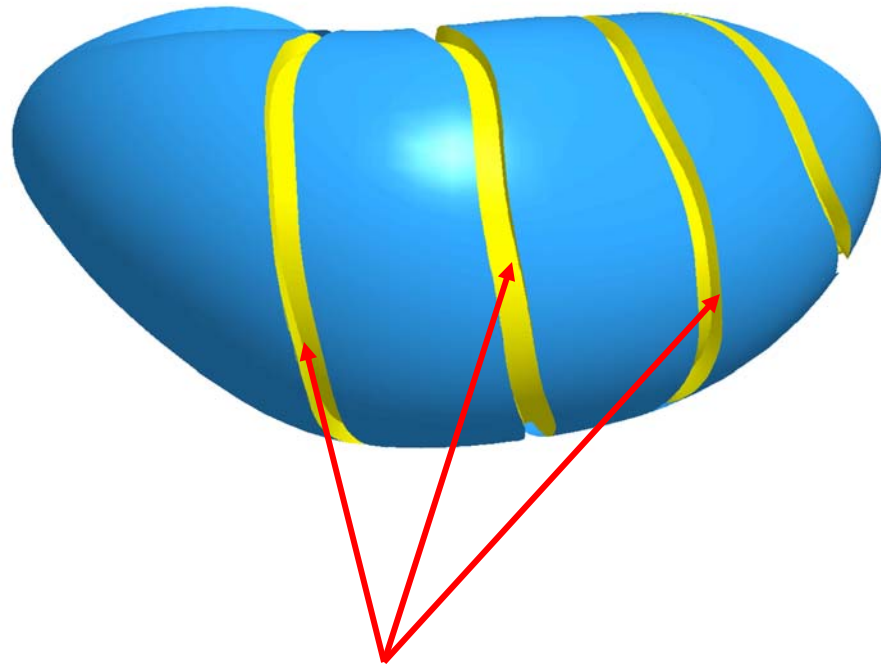
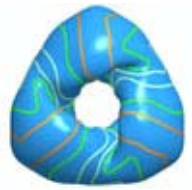
NCSX-like



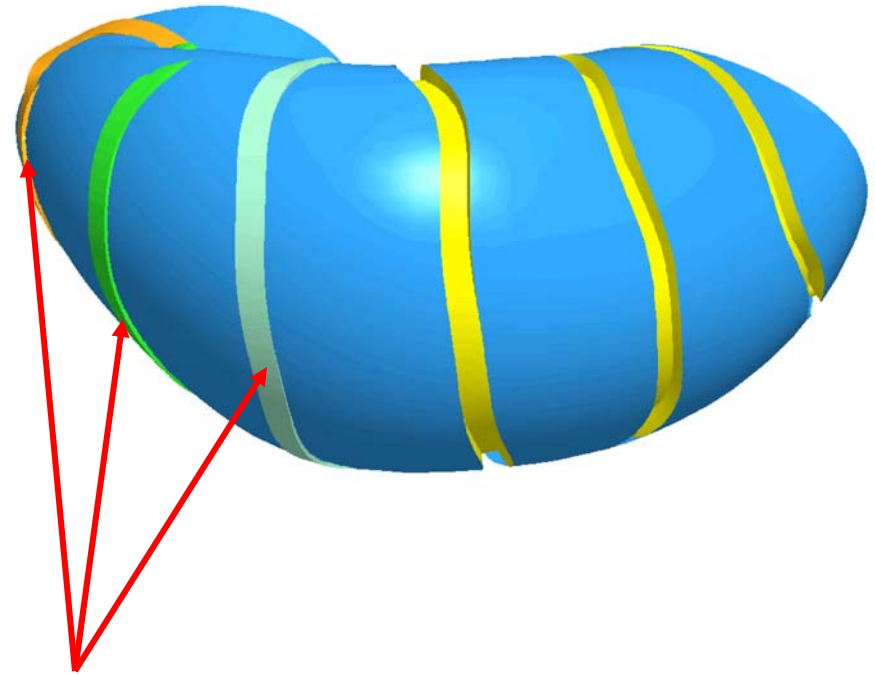
MHH2

- No separate cryostats for the different field period and the bucking cylinder are required since no disassembly is necessary for a blanket exchange.
- Thermal isolation between the cold coil+inter coil structure and the warm VV has to be provided.

Coils of a Field Period Are Wound on a Common Supporting Structure

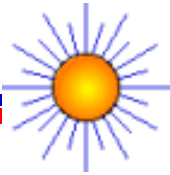
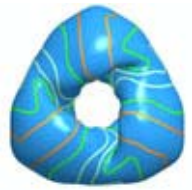


Grooves on a common supporting tube



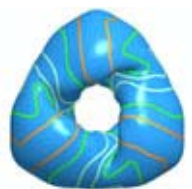
Coils of a field-period are wound on the supporting tube

Blanket Concept Suited for This Modular Maintenance



- This maintenance scheme allows for larger module than in the previous case since the extension arm of the articulated boom would be shorter.
- This scheme could be utilized in combination with the entire blanket concepts considered in the study.
- The helium cooled ceramic breeder blanket designs which is well suited for a modular geometry would particularly benefit from this scheme since the weight of the module would result in rather small modules in the case of modular maintenance through limited number of ports [2].

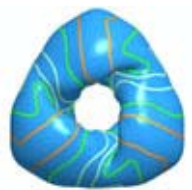
[2] A.R. Raffray, L. El-Guebaly, S. Malang, X. Wang and the ARIES Team, “Ceramic Breeder Blanket for ARIES”, this issue.



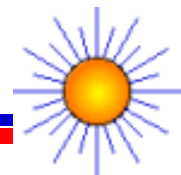
Summary and Conclusions (1)



- Three maintenance schemes for the ARIES-CS compact stellarator have been explored and evaluated based on the NCSX-like three-field period configuration and the two-field period MHH2 configuration.
- The field-period-based maintenance scheme assumes movement of an entire field period composed of blankets, shields, cryostats, coils with inter-coil structure, and all thermal insulation, outward in radial direction after heating up the entire cold structure and opening the outer part of an external vacuum vessel. Then, the two blanket replacement units in the field period can be removed on rails in the toroidal direction.
- Blanket weight is not a limiting factor with the field-period maintenance scheme.



Summary and Conclusions (2)



- The maintenance scheme with a small number of ports would be applicable to a wider range of machine configuration including an NCSX-like three-field period configuration but would impose a more limiting constraints on module weight and size due to the longer required reach of the articulated booms.
- For the initial NCSX-like three-field period configuration considered, the modular maintenance approach with ports between each pair of adjacent coils seems marginal.
- The maintenance scheme with a port between each pair of adjacent coils would be better applicable to cases with fewer coils such as the MHH2 two-field period configuration and would allow for somewhat larger module sizes.