# MAINTENANCE APPROACHES FOR ARIES-CS COMPACT STELLARATOR POWER CORE

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*Abstract: The key issues associated with the three maintenance approaches envisaged for the Compact Stellarator (CS) power core have been identified and addressed, and the layout of coil system, coil supporting structure, cryostats, vacuum vessel and maintenance ports have been conceptually defined. These are summarized in this paper. Blanket concepts compatible with the three maintenance approaches have been investigated, and will be reported in separate papers. State-of-art CAD tools have been used in this study to verify clearances for blanket movements during maintenance operations and to determine the maximum size of the blanket replacement units.*

## I. INTRODUCTION

The configuration and maintenance approaches for a power plant based on a compact stellarator are very different than for one based on the tokamak concept. Compared to a tokamak, the replacement of the power core in a stellarator is considerably more challenging because the access to the blanket is strongly limited by the shape of the modular coils. The engineering effort during the first phase of the ARIES-CS study has focused on scoping out different compact stellarator design configurations and maintenance schemes to determine the key issues and to better understand the parametric design windows and the engineering constraints [1,2]. Three possible maintenance approaches for the ARIES-CS compact stellarator have been considered during this scoping phase: (1) field-period based replacement requiring the disassembly of the coil system; (2) modular replacement approach through maintenance ports arranged between each pair of adjacent modular coils; (3) modular replacement through a small number of designated maintenance ports using articulated booms [3].

Individually, there are interactions between physics configuration of the compact stellarator and the most suitable maintenance schemes. For example, the field-period based replacement scheme tends to be more suited for configurations with three (e.g. NCSX [4]) or more field periods. The modular replacement approach through maintenance ports arranged between each pair of adjacent modular coils requires adequate port space between the coils and tends to be better suited for a two-field period configuration. However, as a whole, these choices of maintenance schemes provide a sufficiently broad range of possibilities to accommodate the physics optimization on the machine configuration and size (including the number of coils and number of field periods).

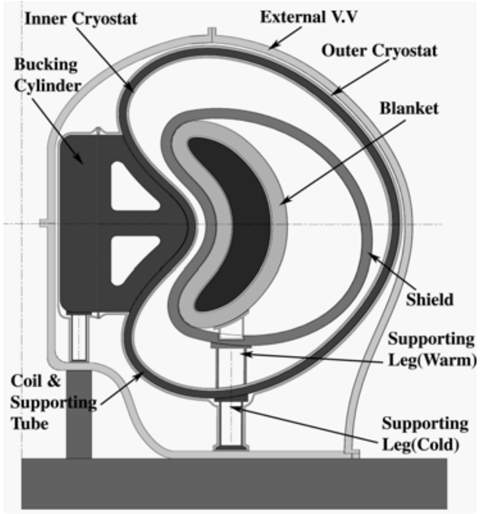
## II. FIELD-PERIOD BASED MAINTENANCE APPROACH

### II. A. Reactor Parameters

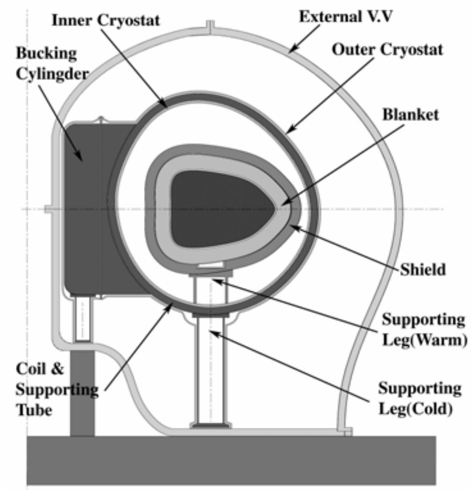
The first phase of physics studies on a stellarator involves scoping out different physics configurations including a Modular Helias-like Heliac (MHH2) with two-field period and three-field period (NCSX) options. For an initial scoping study of a NCSX-like coil and plasma shape with three-field periods, the modular coils, the M50 configuration, and the related reference plasma were scaled to a size expected to produce a fusion power consistent with a net power output of 1000 MWe. This provided a starting point for the ARIES team to begin the engineering studies. One caveat is that the M50 coil design is based on copper conductors cooled with $LN_2$ as opposed to super-conducting or high temperature super-conducting coils. The design parameters are $R = 8.25$ m, $A = 4.5$, $B = 5.3$ T, Beta = 4.1%, and $Ip = 3.5$ MA. This configuration would yield a mid-coil to plasma distance ($\Delta$) of 1.2 m and an average neutron wall loading of 2 $MW/m^2$. These values were used as the starting point with the understanding that they will evolve as the optimization to a power plant configuration proceeds.

### II.B. Power Core Layout

The field-period based maintenance approach requires disassembling the modular coil system in order to remove the replacement components. This approach assumes an external vacuum vessel. It is similar to the maintenance method in the ARIES SPPS study [5] as well as in the ASRA6C study performed jointly by IPP Garching, FZK Karlsruhe and UW Madison [6]. The main challenges for the design of this maintenance approach include: (1) How can the coil system be supported to react a centering force pulling the coil radially towards the center of the torus, and an out-of-plane force between neighboring coils? (2) How can the connections between the cold coil system and a support at ambient temperature be designed to carry the total weight of coils and coil structure? (3) How can the weight of the blanket and shield be transferred to the base structure of the reactor?



(a). Cross-section at 0 degree.



(b). Cross-section at 60 degree.

Fig. 1. Layout of power core based on field-period maintenance approach

Fig. 1 shows a layout of the coil system, supporting structure, cryostat and an external vacuum vessel at toroidal angles of 0 and 60 degree. A possible solution to support the weight of the coils is to rest the cold coils on the “warm” foundation via long legs with high thermal resistance in order to keep the heat ingress into the cold system to tolerable limits. This implies that all coils (at least per field period) are enclosed in a common cryostat which facilitates the design of the inter coil structure. However, there is a strong bucking cylinder in the central bore of the torus to react the centering forces of the coils, and this ring has to be maintained at cryogenic temperature to avoid transfer of forces through an insulator. Fig. 2 is a plan view of showing the layout of the power core components.

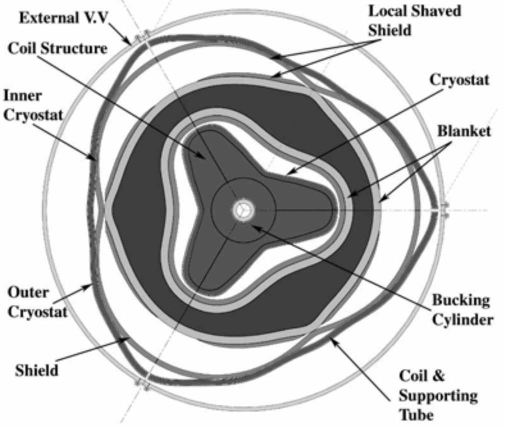


Fig. 2. A plan view

To facilitate the disassembly of the coil system, the coils of each field period and its inter coil structure are enclosed in a separate cryostat, providing thermal insulation at all surfaces with the exception of the surface touching the bucking cylinder. All the individual cryostats containing the entire coil system and the supporting structure are enclosed in an external vacuum vessel. The overall coil-to-coil forces are balanced within each field period but can be large between adjacent coils in a field period. To react these forces inside a field period it is suggested to wind the coils into grooves of a thick-walled supporting tube as shown in Fig. 3, operated at cryogenic temperature.

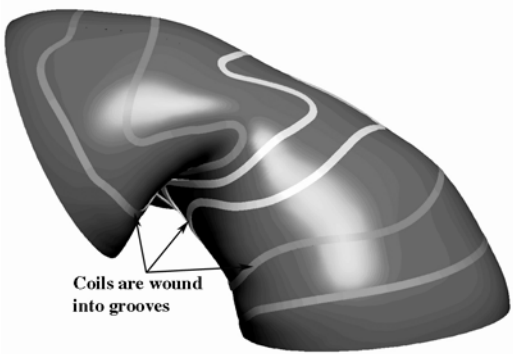


Fig. 3. Arrangement of all coils of a field period on a supporting tube

This tube reacts all forces and momentums between neighboring coils, and is supported on the inboard side by the bucking cylinder. Tube and coils are enclosed by a common cryostat with thermal insulation between “cold” structure and “warm” cryostat walls. The coils and the entire support structure is maintained at LHe temperature, the cryostat walls will probably be cooled by $LN_2$ (“warm”) in order to minimize heat flow to the low cryogenic temperature and, in turn, the power consumption of the total cryogenic system. As shown in

Fig. 1, there is free access to the vacuum vessel. This simplifies the blanket replacement. An additional advantage for this power core layout is that the vacuum vessel is shielded from nuclear heating or radiation damage. With this concept it is possible to remove a cryostat containing the coils and the inter coil structure of one field period without opening any cryostat or removing any thermal insulation. Shielding the SC coils against the fast neutrons from plasma requires thick heavy shields made of steel or tungsten carbide. A very rough estimate is that a shield with a total thickness of 1.0 m is required with a total weight in the order of 10,000 tons. This weight has to be transferred to the foundation by strong legs as shown in Fig. 1. It can be seen in this figure that these legs fit through openings in the cryostat (“warm bore”).

### II.C. An Example Blanket Concept for the Field-Period Based Maintenance Approach

Ref. [2] discusses the different blanket concepts considered during the first phase of the ARIES-CS study. Each maintenance concept imposes particular requirements in regard to the choice of blanket concept. For example, port maintenance utilizing articulated booms imposes constraints on the size and weight of the modules. In contrast, the field period based maintenance scheme enables the use of very large blanket units nearly without weight limitations but requires large blanket fabrication sizes. The idea is to minimize the number of coolant connections to be cut/rewelded for a blanket replacement, and to locate these connections close to the points of mechanical support in order to avoid problems due to differential thermal expansion. An example blanket concept based on dual coolant blanket with helium cooled FW/structure and self-cooled Li or Pb-17Li breeding zone has been assumed in the scoping study of this maintenance scheme during the first phase of the ARIES-CS study.

A replacement unit is composed of FW, breeding zone and a structural ring (which also serves as a first neutron shield). The high temperature shield outside the replacement unit as well as the surrounding low temperature shields are life-time components and do not have to be moved for a blanket replacement. It is suggested to have all these access tubes coming from the bottom as concentric tubes. The following major steps have to be performed for the replacement of blankets, either if they have failed or at the end of their life times: (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 vacuum vessel in the range of the field period to be moved; (5) slide the entire field period, composed of blankets, shields, cryostats, coil system, and all thermal insulation, outward in the radial direction on the flat surface at the bottom, possibly using an air-cushion system for this movement; (6) cut the coolant access tubes to the blanket to be replaced; (7) slide toroidally out from the openings at both ends the unit being replaced (FW, breeding zone, and a structural ring). The replacement unit is moved on a rail attached to the low temperature shield section of the replacement zone. State-of-art CAD tools have been used to verify clearances for blanket movements during maintenance operations and to determine the maximum size of the blanket replacement units**.** The CAD assessment indicates that such a movement is feasible not only for the idealistic case of circular, planar coils but also for the real geometry of a modular compact stellarator. When applying this method to different blanket concepts, measures (aside from the last resort of increasing the reactor size) can be taken to avoid local interferences such as shaving off the shield and increasing the blanket thickness locally.

## III. MODULAR MAINTENANCE THROUGH A SMALL NUMBER OF DESIGNATED PORTS

### III.A. Power Core Layout

For module maintenance through ports, only the blanket module has to be moved through the opening of a port with an articulated boom. This enables a completely different design of the vacuum vessel and cyrostat. In this case the vacuum vessel is internal to the coils and serves as an additional shield for the protection of the coils from neutron and gamma irradiation. No disassembling and re-welding of the vacuum vessel are required for blanket maintenance. Provisions for cutting and re-welding of the vacuum vessel have to be made only for the very unlikely case that coils have to be replaced or the vacuum vessel itself fails. Considering the non-uniform shape and size of the modular coils, the vacuum vessel for a compact stellarator with three field periods is assembled from six sectors. The assembly welds are arranged at the largest cross-section (at 0 deg.) and the smallest cross-section (at 60 deg.). This allows sliding the vacuum vessel sectors into the coils of a field period in the toroidal direction. There is large freedom in designing the shape of the vacuum vessel, with the two limitations on the cross section: (1) it must fit into the modular coils with their supporting structure; (2) the space inside the vacuum vessel must be sufficient for breeding blankets and shielding modules. Breeding blankets and shielding modules have to be attached to the vacuum vessel, and provisions for the arrangement of coolant access tubes and manifolds have to be made. The arrangement of the vacuum vessel inside the coil system is illustrated in Fig. 4.

The design principle of the coil system has been previously described for the maintenance method based on the removal of an entire field period. 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. However, no separate cryostats for the different field period and the bucking cylinder are required since no disassembly is necessary for a blanket exchange. Certainly, thermal isolation between the cold coil+inter-coil structure and the warm vacuum vessel has to be provided. For thermal insulation the entire coil system has to be enclosed in a common cryostat. This cryostat can serve at the same time as a second containment for the tritium in the vacuum vessel. The most cost effective design may be to build this large cryostat as a concrete vessel with an internal steel liner, which would also serve as a biological shield.

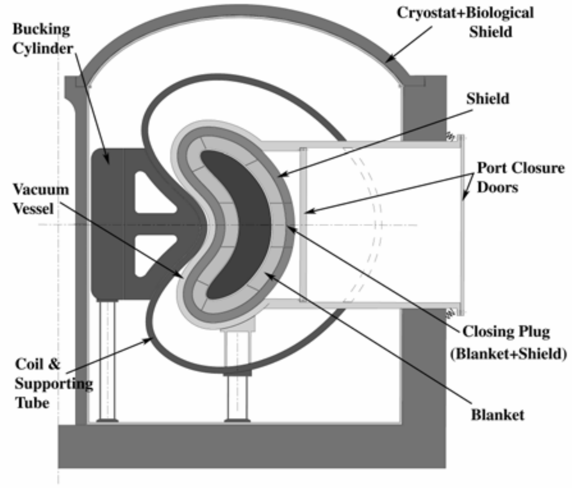


Fig. 4. Layout of power core based on modular maintenance though a small number of designated ports

For the initial NCSX-like configuration assumed for the scoping study, the optimum locations for these ports are the 0, 120, 240 degree 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 vacuum vessel sections can be fabricated with parts of the maintenance ports already attached to it. In order to design these components compatible with the articulated boom approach, the replacement units are composed of FW and breeding zone only. There is no additional shielding required to make the region behind a lifetime component. The ports have to bridge the space between vacuum vessel and external cryostat. Bellows at the connections between port and cryostat allow for differential thermal expansion. In order to maintain the double containment of tritium, there should be two doors of the port, one at the vacuum vessel and one at the outside of the cryostat. Many details of this system are very similar to the solutions proposed in ARIES-RS [7].

### III.B. Blanket Concept 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 [8]) 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 being ~1500 Kg and ~1000 Kg, respectively. Details on the scoping studies of the different blanket concepts can be found in ref. [2].

## IV. MODULAR MAINTENANCE THROUGH PORTS BETWEEN EACH PAIR OF COILS

### IV.A. Power Core Layout

This maintenance approach can be viewed as an extension of the previous modular maintenance approach but with replacement of somewhat larger blanket modules through a larger number of ports arranged between each pair of adjacent coils, using shorter boom for installing, inspecting, removing and minor repairs of the module inside plasma chamber. There are many similarities between the two modular maintenance schemes, including an internal vacuum vessel, maintenance ports bridging the region between vacuum vessel and external cryostat, the possibility to keep the modular coils cold and at a fixed location during blanket replacement. The layout of the coil system, the coil supporting structure, and vacuum vessel are the same as shown in the Fig. 4. The advantage is that all blanket modules are adjacent to the maintenance ports and do not require other modules to be removed for replacement. This approach uses shorter booms with much higher load capabilities. The disadvantage is that more ports are required and they are larger in size, which places more geometry constraints on the coil configuration. This maintenance method has been suggested in all IPP Gaching Stellarator studies [9] but seems marginal for the NCSX-like three-field period configuration because the available room between coils limits the size of blanket module when compared to desirable module dimensions of at least 2.0 m x 2.0 m x 0.30 m. It seems better suited for a configuration with fewer coils such as MHH2 two-field period configuration shown in Fig. 5 for a case with 12 coils. The MHH2 two-field period configuration provides more room for maintenance ports between the individual coils than the NCSX three-field period configuration, therefore this approach would allow for larger modules than the previous modular approach. The coil support and winding scheme for the three-field period configuration is also applicable to this two-field period configuration.

Fig. 5. MHH2 plasma and coils

### IV.B. Blanket Concept Suited for This Modular Maintenance Approach

This maintenance scheme allows for larger modules 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 [1,10] 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.

## VI. Summary and conclusion

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 the 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 this maintenance scheme. However, it is with the two port-based modular maintenance schemes that were considered. The first assumed a small number of maintenance ports (perhaps 1 or 2 per field period); the second assumed maintenance ports between each pair of adjacent coils. In both cases, blanket replacement is carried out by utilizing articulated booms through the ports. This maintenance scheme can also be used for the replacement of high power divertor target plates as the arrangement of such plates is facilitated by the modular blanket concept. The maintenance scheme with a small number of ports would be applicable to a wider range of machine configurations including an NCSX-like three-field period configuration but would impose more limiting constraints on module weight and size due to the longer required reach of the articulated booms. The maintenance scheme with a port between each pair of adjacent coils would be more applicable to cases with fewer coils such as the MHH2 two-field period configuration and would allow for somewhat larger module sizes.

## ACKNOWLEDGEMENTS

This work was supported under U.S. Department of Energy Grant No. DE-FC03-95-ER54299.

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