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ENGINEERING OPTIMIZATION OF STELLARATOR COILS LEAD TO IMPROVEMENTS IN DEVICE MAINTENANCE

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ENGINEERING OPTIMIZATION OF STELLARATOR COILS LEAD TO IMPROVEMENTS IN DEVICE MAINTENANCE

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Abstract

As part of an early PPPL pilot plant study an engineering exercise was undertaken to straighten the stellarator modular coil (MC) back legs to provide greater access to plasma components. Saddle coils were located within separate enclosures and configured to reconstitute changes in the magnetic fields caused by straightening the MC back legs. A follow on lab directed research study looked to further improve stellarator maintenance by considering higher aspect ratio plasmas along with improving the MC defining metrics by adding engineering maintenance requirements to the physics code used in defining the modular coil winding configuration. The physics design code (COILOPT) was upgraded to provide coil solutions with straightened MC back legs and to receive inputs of engineering constraints on the MC surface geometry and winding centers.

Several improvements and extensions of COILOPT++ were made which include: the ability to target coil penalties and freeze coil geometry for individual coils; adding torsion constraints on the geometry of the space curve defining the MC winding; allowing freedom to straighten MC back legs over asymmetric distances above and below the outboard mid-plane; the inclusion of nested saddles with enforced minimum coil-to-coil separation distances and adding the ability to accept coil winding surface geometry from Pro-E. These changes along with a number of other features have substantially improved our ability to achieve better self-consistency between engineering maintenance requirements and plasma surface reconstructions with targeted physics. Using the new COILOPT++ code, a first pass design of an improved maintenance stellarator device has been developed. The code details and the ensuing device design will be presented.

I. BACKGROUND

Within the NCSX project (2001-2008) a 1.4-m, 3-period, quasi-axisymmetric stellarator was designed where physics codes established winding characteristics of discrete modular coils (MC's) to meet plasma performance requirements. The primary engineering input for the low aspect ratio (4.4) device included modular coil-to-coil spacing, minimum bend radius, tangential NBI access and coil-to-plasma space requirements. NCSX was designed as a physics experiment and in principle needed no requirements to meet any specified maintenance plan for in-vessel components. The NCSX modular coil winding design was later used in the definition of a power plant in the ARIES-CS study (2004 – 2006). Within the ARIES studies additional space was added around the plasma, particularly in the outboard, top and bottom regions to meet size requirements for blankets, shielding, engineering gaps and maintenance area – but the basic NCSX modular coil winding topology and plasma aspect ratio remained the same. The ARIES-CS device configuration followed a maintenance approach similar to the design of ITER; that is a large number of small in-vessel components would be extracted through a small number of medium sized horizontal midplane ports (see Figure 1). When compared with ITER, the NCSX modular coil winding topology further complicates the maintenance process. ARIES-CS reported an availability of 85% could be achieved for a tenth of a kind stellarator power plant [1] assuming the maintenance approaches and procedures adopted in the study; however, a comparable European tokamak study looking at an equivalent ITER configured DEMO design found an operating availability barely above 50% could be achieved, which is unacceptable [2].

As part of a 2009-2010 pilot plant study the stellarator topology was allowed to change to improve the prospects of operating with high availability. A common consensus from most fusion power plant studies is that high availability performance can best be achieved when the device is configured with a small number of large in-vessel components are removed through large openings on the outside of the device. The pilot plant stellarator effort was primarily an engineering exercise to define a concept to increase the in-vessel component access space to enhance the ability to achieve high availability operations. This was accomplished in a design that employed straightened modular coil back legs to provide the access with the inclusion of saddle coils located within separate enclosures configured to reconstitute changes in the magnetic fields caused by straightening the MC back legs. Figure 2 shows the developed reactor concept and improvements made in the 3-D shaping of the in-vessel

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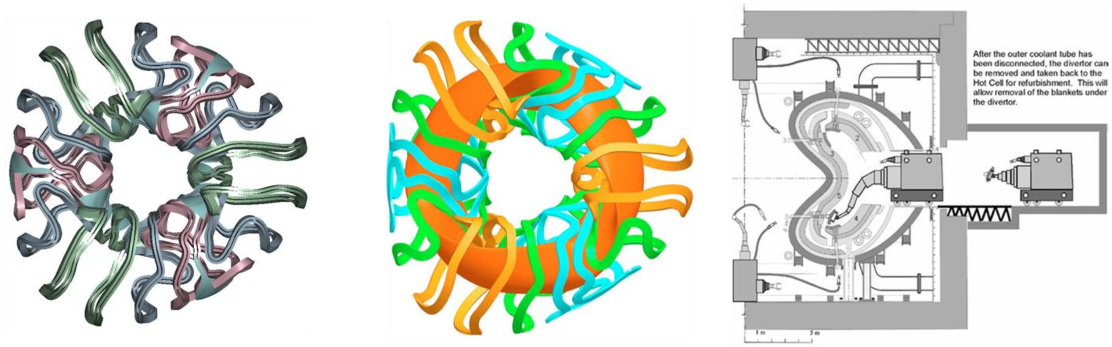


Figure 1. Modular coil winding topology used on NCSX and ARIES-CS design leads to a small component, port based maintenance approach

components. Other than a small effort in defining a few representative saddle loops no physics involvement was included in defining the MC themselves. In looking at options to improve access for stellarator maintenance a review of past work carried out by L-P. Ku and A. Boozer was investigated [3]. This report showed that higher aspect ratio plasmas offered simplification of the modular coil winding along with increased coil-to-coil spacing. The sensitivity of moving to higher aspect ratio with respect to degrading the physics performance was well documented; however, striving to find a balance between physics performance and a viable engineering configuration with acceptable availability characteristics was a worthy challenge to pursue. The aspect ratio 6 plasmas looked to be an interesting place to start, but was left to later study.

A 2013-14 LDRD stellarator study provided the opportunity to look into greater detail at the prospects of moving to a higher aspect ratio design and make a concerted effort to add engineering maintenance metrics to the physics code used in defining the modular coil winding configuration. Several facets of the COILOPT++ design code were upgraded to improve its ability to provide coil solutions with straightened MC back legs and to receive input of engineering constraints on MC surface geometry and MC winding centers. The next section provides details of the A=6 plasma configuration used in the reactor design study, and a brief description of improvements that were made to COILOPT++. It also provides the output solution for the MC windings that support the plasma. Section 3 presents engineering design details. Section 4 provides a discussion of follow-on activities that would be needed to complete the work.

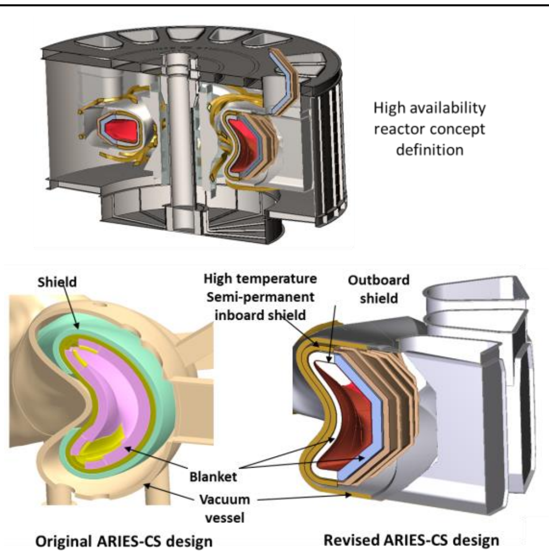


Figure 2. Revision of the ARIES-CS maintenance approach

II. PHYSICS DETAILS AND CODE IMPROVEMENTS

The A=6.0 quasi-axisymmetric stellarator plasma considered is based on the baseline ARIES-CS N3ARE configuration [4] and expressed in Long-Poe Ku's VMEC input file **input.n3are_R7.75B5.7**. In moving from ARIES-CS parameters (A=4.5, R = 7.75m, B = 5.7T) to an aspect ratio A=6.0 configuration while retaining the values for fusion power, beta, plasma volume, and toroidal magnetic field leads to a major radius of 9.39m. The plasma current, I_p, is scaled to keep I_p / RB = 0.045, leading to I_p = 2.6MA. Plasma beta is assumed to be 4.0%. Fourier coefficients describing the target plasma boundary of the A=6.0 configuration are taken from Table 1 of ref [3], and scaled appropriately. Cross sections of the plasma boundary are displayed as red curves in Fig. 3.

Several improvements and extensions of COILOPT++ were made during execution of the 2013-14 LDRD study. Among these were: 1) a careful benchmark with NESCOIL which led to the identification and elimination of an important bug in the primary target **B.n** cost function that had hitherto compromised the ability to

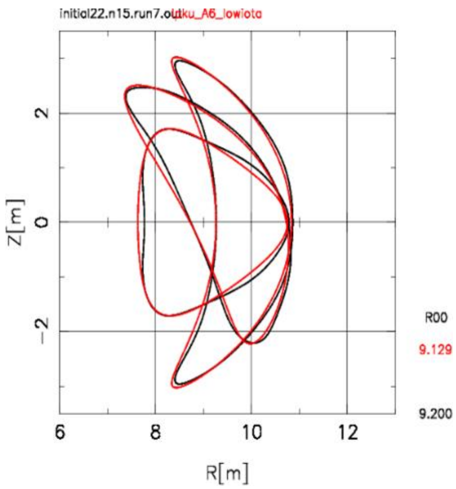


Figure 3. Plasma reconstruction

drive residual **B.n** fitting errors on the plasma boundary to small values; 2) the ability to target coil penalties and freeze coil geometry for individual coils was implemented; 3) torsion was added as a constraint on the geometry of the space curve defining the MC winding; 4) freedom to straighten MC back legs over asymmetric distances above and below the outboard mid-plane was implemented; 5) unnecessary clamping of spline control points for both straightened modular and saddle geometries was removed; 6) the inclusion of nested saddles with enforced minimum coil-to-coil separation distances was implemented; 7) self-symmetric saddles, necessary if saddles are to straddle toroidal symmetry planes, were included; 8) saddles can now be constrained to lie within a chosen u-v patch on the control winding surface and finally, 9) coil winding surface geometry can be accepted from Pro-E. The extensions listed here have substantially improved our ability to achieve better self-consistency between engineering maintenance requirements and plasma surface reconstructions with targeted physics.

COILOPT++ was run with three distinct MC coil shapes per half-period initialized as toroidal field coils lying on equally spaced toroidal planes on an engineering designed winding surface (Sec. 3). The primary minimization cost function target was a combination of R.m.s and Max dB/B over the desired plasma boundary, with B the normal component of magnetic field from the plasma, and dB the difference between this and the normal component of magnetic field produced by the coils. Auxiliary targets were coil length, coil-to-coil spacing, coil curvature, and coil torsion. Differential evolution was our optimization algorithm of choice, which evolves a population of candidate solutions through a sequence of generations until a candidate solution is deemed to be satisfactory. This occurs when the dB/B fitting errors is considered low enough. How low is ultimately determined by performing a VMEC free-boundary reconstruction of the plasma using the coil shapes and currents predicted by COILOPT++, and comparing the reconstructed plasma boundary with the desired shape. Cross sections of the target plasma (red) and reconstructed plasma (black) are shown in Fig. 3 corresponding to R.m.s dB/B = 2.27e-2 and Max dB/B = 5.28e-2.

III. DESIGN RESULTS

Figure 4 shows the general arrangement of the device core highlighting some of the key component details. The 3-period stellarator developed is a 9.39-m average major radius, aspect ratio 6 device with all modular coil back legs located in a near vertical plane, except for the type-C coil which is further tilted off vertical (shown in more detail in the Figure 5 plan view). Although initial COILOPT++ runs included saddle coils in expectation of being needed to compensate the straightening of MC back legs, improvements in the code allowed us to achieve a MC solution without the need to add saddle coils. This was a welcomed result.

The blanket system is subdivided into 36 blanket segments, twelve per field period (shown with striped color in Figures 4 and 5). The gray shaded segments can move straight out to an attached vertical port whereas the copper colored segments need to move first in a toroidal direction prior to a radial extraction through the nearest vertical port. Figure 5 further illustrates the blanket segmentation and the access for extraction through vertical ports. With adjacent space still available, an updated design would expand the overall width of the vertical ports to provide additional space for support equipment to aid in extracting the blanket modules.

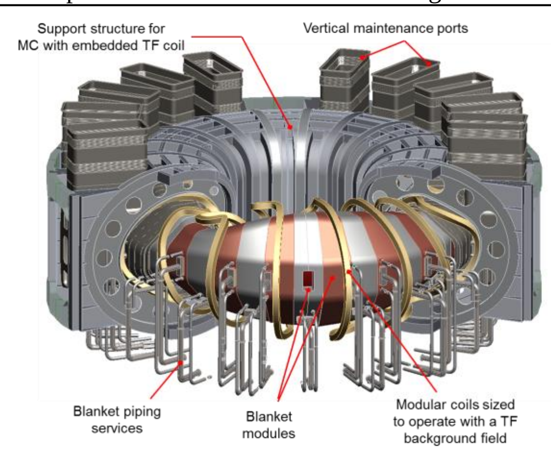


Figure 4. General arrangement

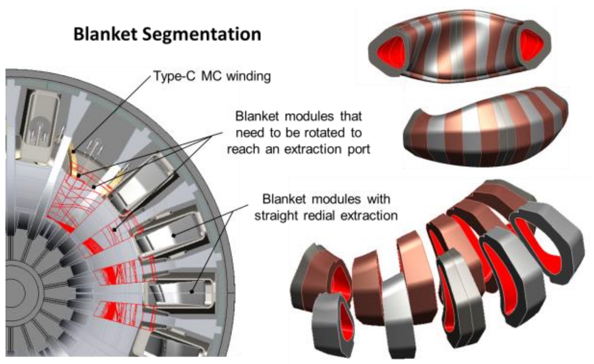


Figure 5. Views showing blanket module segmentation

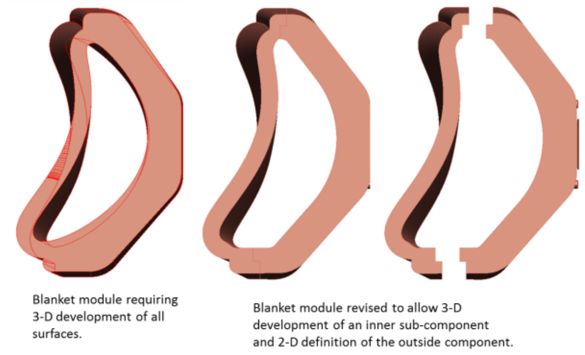


Figure 6. Blanket sector design simplification

One major design driver in setting up the device configuration was defining the piping services for the blanket modules. As shown in Figure 4 blanket services were located on the outside of each sub-module. The assumed piping included a pair of helium pipes and a high temperature multi-feed, concentric piping system that would supply PbLi for a DCLL blanket or water for the solid breeding blanket option that is being developed on K-DEMO. A tokamak design includes PF coils which place restrictions on the radial extent of a vertical access port, requiring a front-to-back split of the blanket modules to size them to fit within the allotted space for a vertical port maintenance approach. Splitting a blanket module requires adding a separate piping system, one for the outside blankets and one for the inside blanket. This will work in a tokamak design with plainer TF coils as space beneath or above the blankets is available to add additional piping supplies. This is more problematic in a stellarator design with non-plainer modular coils. For this reason blankets were subdivided into full sectors and the vertical port elongated to accept the full extent of the blanket sector. In the first pass design a rectangular vertical port was defined although in later revisions this shape would be altered to provide greater width in the outboard region to allow more space for lift tooling. Another detail not fully developed at this time is the shaping of a blanket module. In this first pass a blanket period was created using 3-D surfacing of all features. This is an involved process and would imply that complex processes would be needed to fabricate the blanket components. An option that needs to be evaluated in more detail is illustrated in Figure 6 where an inner segment was developed with 3-D surfacing and the outer segment developed with standard planer geometries. The two segments would be joined and function as a unit with one piping supply system. It is expected that a lower fabrication cost could be realized as only the inner region would require construction using complex manufacturing methods.

Another focus of the design study was the development of the structural arrangement of the modular coil support system, the influence of including toroidal field windings in sizing the modular coils and the impact of including TF coils on the device design. Figure 7 shows the structural arrangement established for two options; the left figure includes TF windings enclosed in the structure surrounding the MC's, and the right figure

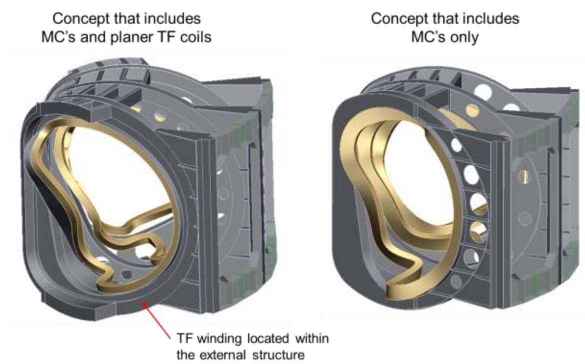
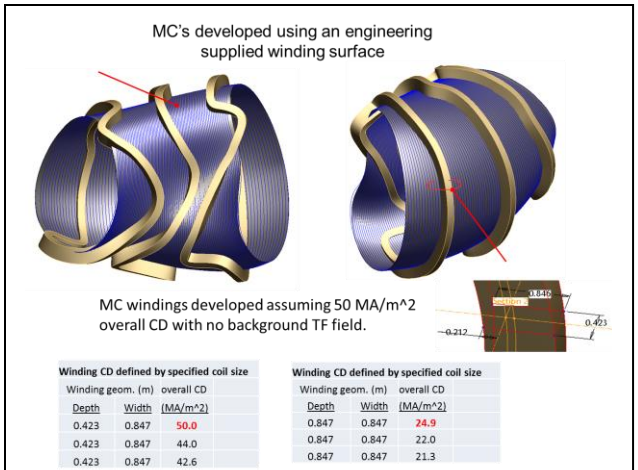


Figure 7. Structural support concept

includes structure with no TF windings. The basic design, regardless of including TF coils, defines a structure that surrounds all modular coils, forming a common shaped structure. The Type-A MC establishes the internal vertical height of the structure opening and typically the Type-B or Type-C modular coil defines the inner radial extent of the internal space. The engineering defined MC winding surface (shown in Figure 8) defines the outer extent of the support structure, where space is allocated on the outside for the assembly of the MC and blanket system. With the vertical maintenance scheme adopted and the plan to extract a full blanket module, the outer radial extent of the support structure in the shadow of the straightened MC legs is set. As the MC change in size (from Type-A to C) the surrounding structure outer surface is unchanged. Local structure will be included to support the MC winding and beam the load to the outer shell structure. The inclusion of TF windings will result in a slight increase in the outer boundary of the support structure but has little impact on the design of the support structure. The major reason that TF windings are being considered is in their ability to unload the current being carried by the modular coils. An early COILOPT++ run assuming an infinite TF found that the total current of the MC's could be cut in half, albeit with MC windings having greater toroidal extent in the inboard corners. It is too early to make an final assessment in this approach, however if feasible within physics and engineering there could be a cost advantages by developing smaller, high field MC's along with low field TF coils. A two-winding, low field, high field design is being developed on K-DEMO where it was found that one-billion dollar cost savings over to a single winding TF system could be realized. Another factor that will need to be addressed is the operating current density of the MC. At this stage of the design low temperature superconductors (LTS) would be designed with an upper limit of 25 MA/m^2. Employing high temperature superconductors (HTS) would allow the overall current to increase to 50 MA/m^2 or higher. There are ramifications with either option. Inclusion of TF windings may allow a LTS system to operate within the symmetry of the winding surface with reduced currents in the MC's. Further design and analysis is needed.

An engineering defined MC winding surface (Figure 8) was developed using a physics supplied A=6 plasma configuration (see Sec 2) along with engineering estimates of component build dimensions and assembly requirements. Surface details are represented by a set of points located on a series of curves that is compatible for input into the COILOPT++ code. A few iterations can be expected to arrive at a self-consistent design point that satisfies both physics and engineering requirements. The design detail of this device was developed with a vertical maintenance approach in mind. However, with a stellarator requiring limited heating on the outside may afford better device sizing of the external cryostat if horizontal maintenance is employed with local vertical maintenance chambers located on the outside of the main cryostat – this needs to be evaluated in a follow-on study.



Winding CD defined by specified coil size		
Winding geom. (m)		overall CD
Depth	Width	(MA/m^2)
0.423	0.847	50.0
0.423	0.847	44.0
0.423	0.847	42.6

Winding CD defined by specified coil size		
Winding geom. (m)		overall CD
Depth	Width	(MA/m^2)
0.847	0.847	24.9
0.847	0.847	22.0
0.847	0.847	21.3

Figure 8. Engineering supplied MC winding surface

Finally, it is interesting to make a comparison between the tokamak and stellarator fusion options. Moving to higher aspect ratio along with enhancements to the COILOPT++ physics code with new engineering metrics has resulted in a stellarator design with improved maintenance characteristics. Figure 9 show a size comparison between K-DEMO and the new stellarator device developed in this LDRD study. With this new stellarator design – is the maintenance of in-vessel components now similar or simpler than the maintenance approach found within a tokamak design? Further study is needed.

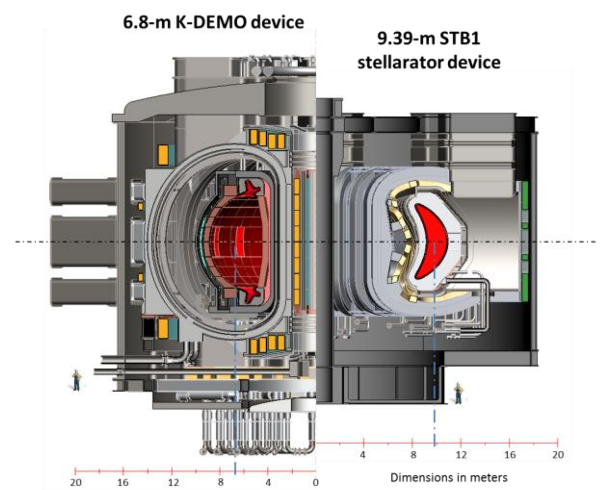


Figure 9. Comparison of a 9.39-m, AR 6 stellarator device with the 6.8-m K-DEMO design

IV. SUMMARY

More physics assessments are needed to substantiate the quality of the plasma surface reconstruction and the ability of the windings to produce the plasma properties. Performing STELLOPT++ calculations with optimized coil currents for the derived windings may allow us to obtain performance parameters comparable to NCSX. Additional physics / engineering collaboration can be made by further optimizing the engineering supplied winding surface with a specified vertical range (Z_{top} to Z_{bottom}) for which straightening is necessary. This would alleviate the tight bend radius occurring in some windings without compromising the physics by invoking engineering specified high bend radius values. Straight outer legs were developed for all MC type windings with the exception of Type-C coil where a somewhat off normal shape was allowed. Some latitude can be provided to allow off normal outer leg geometries at all locations which may further improve the winding details and physics quality. This study was specifically done for a device design with an aspect ratio 6. Applying the new COILOPT++ code and design process to evaluate lower aspect devices would help to optimize the device size, balancing requirements between physics and engineering. Further evaluation of the impact of including TF windings need to be assessed from both a physics and engineering standpoint. The initial assessment developed only included a background 1/R toroidal field to provide 50% of the total toroidal flux of the plasma. As a next step, analysis of "real" discrete TF coils is needed since the ripple they produce can contribute to the quality of the alpha particle confinement and QAness of the plasma. The goal is to determine if a lower cost solution can be realized with the inclusion of TF coils, operating as a graded two coil winding system similar to the approach developed in the K-DEMO tokamak design. An initial first pass was made in developing some of the device configuration details. Additional details are needed to underpin the design and assure that all configuration driving features are adequately defined and sufficient space is allocated for in-vessel blanket maintenance – this work is needed to ensure that a credible modular coil winding surface is passed on to physics.

V. REFERENCES

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