Progress Toward Attractive Stellarators *

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Abstract. The quasi-axisymmetric stellarator (QAS) concept offers a promising path to a more compact stellarator reactor, closer in linear dimensions to tokamak reactors than previous stellarator designs. Concept improvements are needed, however, to make it more maintainable and more compatible with high plant availability. Using the ARIES-CS design as a starting point, compact stellarator designs with improved maintenance characteristics have been developed. While the ARIES-CS features a through-the-port maintenance scheme, we have investigated configuration changes to enable a sector-maintenance approach, as envisioned for example in ARIES AT. Three approaches are reported. The first is to make tradeoffs within the QAS design space, giving greater emphasis to maintainability criteria. The second approach is to improve the optimization tools to more accurately and efficiently target the physics properties of importance. The third is to employ a hybrid coil topology, so that the plasma shaping functions of the main coils are shared more optimally, either with passive conductors made of high-temperature superconductor or with local compensation coils, allowing the main coils to become simpler. Optimization tools are being improved to test these approaches.

1. Introduction

Stellarators offer robust physics solutions for overcoming major challenges facing MFE—maintenance of the poloidal field without current drive, elimination of most of the causes and effects of disruptions and other transients, and operation at densities above the Greenwald limit. Successful development of stellarator reactors requires a balanced approach which simultaneously takes into account physics performance requirements and engineering characteristics compatible with favorable economics. Two factors which are important for reactor economics, and which are emphasized in stellarator reactor design studies, are device size and availability.

2. Stellarator Reactor Studies

The HELIAS family of reactor designs [1] is based on scale-ups of the five-period, physics-optimized Wendelstein 7-X experiment, currently under construction in Germany. Straightforward extrapolation to a fusion power 3 GW reactor leads to a large (plasma major radius R = 22 m) five-period, plasma aspect ratio of 12 design, HSR5/22. A four-period, aspect ratio 9 variant, HSR4/18 has been investigated and leads to a more compact (R = 18 m) reactor. Recent HELIAS magnet system studies have found that substituting more advanced superconductor technology (Nb_3Sn or Nb_3Al) for NbTi in the five-period design allows higher magnetic fields, which can provide increased physics margins [2]. In terms of availability, the HELIAS designs are found to have longer component lifetimes when compared to tokamaks due to lower average neutron wall loading (< 1 MW/m^2). A drawback, however, is their large number (10) of coils per period, which requires the blanket to be subdivided into a large number of small segments which must fit through small ports between coils.

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The FFHR reactor family [3, 4] follows from the heliotron research line and the Large Helical Device (LHD) experiment, currently operating in Japan. Conceptual studies have focused on designs with ~2 GW of fusion power, R ≈ 15 m, 10 field periods, plasma aspect ratio ~8, and a continuous helical coil. A 3-GW variant has R = 17.3 m, similar to the HSR4/18 HELIAS design. The FFHR reactors are designed for 1.5 MW/m^2 average neutron wall load. Availability considerations include the use of thick layers of C and Be_2C tiles in front of the first wall to extend the lifetime of the first wall and blanket structure by reducing the incident fast neutron flux. The tiles, however, are subject to irradiation damage and swelling and would have to be replaced more frequently. Large port openings between the helical coils and an efficient structure design facilitate maintenance access to the in-vessel components.

The ARIES-CS (compact stellarator) design [5] is based on a three-period quasi-axisymmetric stellarator (QAS) configuration similar to that of the partially-constructed National Compact Stellarator Experiment (NCSX) in the United States. The QAS concept permits a lower plasma-aspect-ratio (4.6) and more compact (R = 7.8 m for 2.4 GW fusion power) design than previous stellarator reactor designs, one that is closer to tokamak reactor dimensions. However, the relatively high neutron wall load (2.6 MW/m^2 average, 5.4 MW/m^2 peak) and limited space are challenging. A novel tapered blanket design, in which an efficient WC shield permits a thinner, reduced-breeding module in the most space-constrained zones while maintaining an overall tritium breeding ratio > 1, is a key solution enabling the compact design. The ARIES-CS adopted a port-based maintenance scheme using long articulated booms to replace blanket modules. [6] Due to limitations on port number and total area resulting from the coil and structure geometries, a large number (~200) of blanket modules is required and their replacement may be excessively time-consuming.

In terms of stellarator reactor size, the QAS approach offers promise of a compact design closer to tokamaks in its linear dimensions than the HELIAS or FFHR lines. However none of the stellarator reactor designs has been optimized for high availability despite its importance as an economic factor. Achieving designs compatible with short replacement times and high availability requires that maintainability criteria be imposed as optimization targets, along with physics targets such as stability and alpha particle confinement, at the fundamental configuration design level. We are investigating the feasibility of several such strategies for the QAS stellarator line, using the ARIES-CS design as a starting point.

3. Engineering Criteria for High Availability

In order to realize a large improvement in availability over the ARIES-CS design, the configuration must be modified to allow a small number of large components to be removed through widened openings on the outboard (large major radius) side between the modular coils. To examine the engineering implications of this criterion, a configuration was developed based on the ARIES-CS design but with the outboard legs of the modular coils straightened, with no re-optimization, to provide access to internal components. (Approaches to satisfy this criterion consistently with plasma requirements are discussed in Section 4.) In the modified configuration, only two of the three ARIES-CS modular coil types (A and B) were modified. The third (Type C), which exhibits the most extreme geometry, was unchanged in the expectation that compensating magnetically for straightened Type C coils would be more difficult than moving some of the in-vessel components toroidally to an adjacent opening for extraction. The in-vessel blanket-shield components were reshaped to provide simpler, two-dimensionally shaped sections at the top, bottom and outboard regions, while retaining 3-D shapes conformal to the plasma on the inboard region where close proximity to the magnets is critical. This simplification (Figure 1) is intended to reduce component costs and to facilitate large-segment removal through the inter-coil openings. Figure 2 shows the current status of the modified ARIES-CS configuration, incorporating larger openings as well as a vertical maintenance scheme that allows the heavy duty cranes needed to assemble the machine to be used to maintain it.

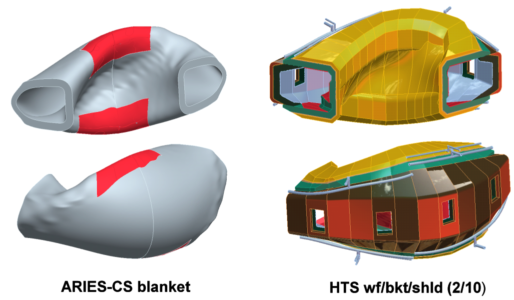

Figure 1. Modification of the ARIES-CS blanket / shield system to improve manufacturing and maintenance feasibility.

4. Design Strategies to Realize Availability Criteria

Several strategies are being investigated for simplifying the geometry of QAS coils. The aim is to assess the feasibility of addressing the availability criteria of Section 3 while simultaneously retaining required QAS physics properties and compactness.

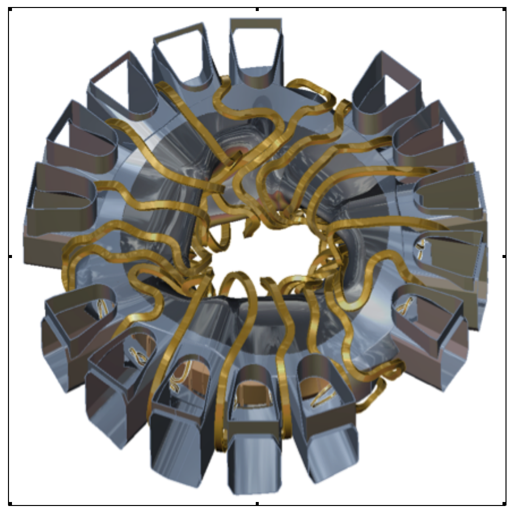

Figure 2. Modified ARIES-CS machine configuration to improve maintenance feasibility

4.1. Configuration Trade Study

A systematic study of the QAS design space in the neighborhood of the ARIES-CS configuration has been carried out, examining variations in the characteristics of modular coils that are related to the rotational transform, plasma aspect ratio, number of field periods and distance separating coils from the plasma. [7] Plasma configurations in two, three and four field periods and two different levels of rotational transform, but having similar magnetohydrodynamic (MHD) stability and symmetry properties, were developed. Filamentary modular coils were then constructed from a current potential solution on a conformal winding surface displaced from the plasma by a chosen distance. The current potential solution minimizes the root-mean-square value of the normal magnetic fields on the plasma surface. [8] Comparisons of coil characteristics were made on the basis of the same plasma volume, plasma β (ratio of the plasma pressure to the magnetic pressure), magnetic fields and rotational transform per field period.

It was found that, for a given plasma aspect ratio per field period at the same coil-plasma separation, coil characteristics are similar, particularly with respect to the winding excursion in the toroidal direction. Reducing the toroidal excursion of coil winding improves reactor assembly and maintenance properties for both port and sector access schemes. It was also found that, for a given plasma aspect ratio and a fixed coil-plasma separation, coil complexities tend to increase with the number of field periods. Figure 3 provides a comparison between 3- and 4-field-period configurations with rotational transform ι~0.15 per field period, plasma aspect ratio of 6 and coil-plasma separation Δ=1.4 m for plasma volume 1000 m^3. For a given number of field periods, the toroidal excursion of coil winding is reduced as the plasma aspect ratio is increased. Figure 4 shows an aspect-ratio scan with ι=0.1 per field period and Δ=2.1 m for a plasma volume of 1000 m^3. Finally, it is clear that the larger the coil-plasma separation is the more complex the coils become. The precise definition of coil complexity depends on many factors, such as the systems size, required magnetic field strength, etc. The most desirable configuration will ultimately be determined by the systems analysis when all the requirements are defined.

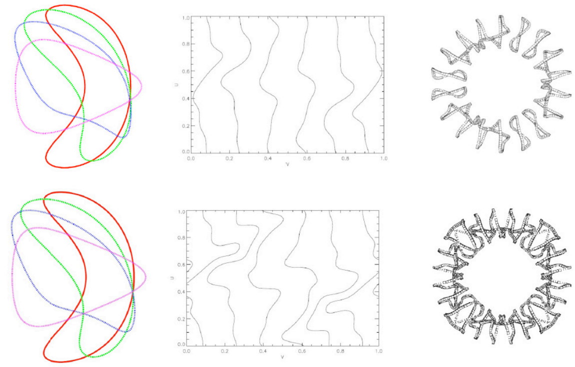

Figure 3. Comparison of modular coil characteristics for 3- (top row) and 4- (bottom row) period configurations. Shown are the plasma cross section shapes at four toroidal angles (left), coil contours on the winding surface in normalized toroidal and poloidal angles, v and u (center), and top views of the coils in Cartesian coordinates (right). The major radii of the configurations have been scaled to make all plots about the same size.

4.2. Improved Physics Targeting

Since coil design is driven by the physics properties targeted in the optimization process, it is important to target, as efficiently as possible, only properties according to their importance for performance.

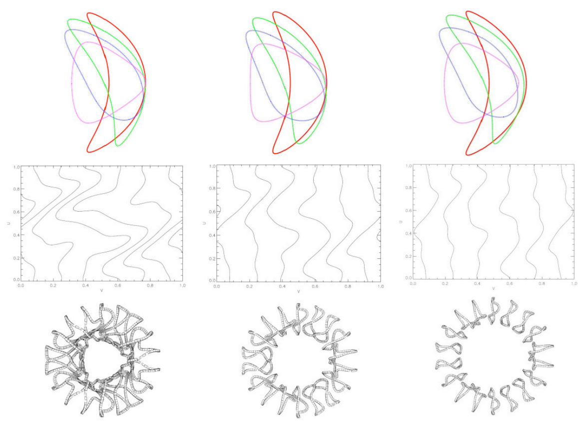

Figure 4. Comparison of modular coil characteristics for 3 field period configurations with A_p=4, 6, and 8 (left to right). Shown are the plasma cross section shapes at four toroidal angles (top), coil contours on the winding surface in normalized toroidal and poloidal angles (middle), and top views of the coils in Cartesian coordinates (bottom).

Sensitivity of plasma properties. The rich information contained in the plasma response to external magnetic perturbations can provide the basis for new design methods leading to improved stellarator optimization and better coils [9]. To demonstrate the feasibility of such an approach, a numerical method has been developed in which small perturbations are applied to the plasma boundary and the resulting perturbed equilibria evaluated. A plasma response matrix is constructed that gives changes in the plasma properties, such as the MHD stability to the kink and ballooning modes and the quality of quasi-symmetry, due to perturbations of different modes in the external magnetic fields. The plasma sensitivity information is used to determine the spatial distributions of external normal magnetic field at the location of the unperturbed plasma boundary to which the plasma properties are most sensitive, and to determine the distributions of external normal magnetic field that can be produced most efficiently by distant coils. A method for choosing the ratios of the magnitudes of the efficiently produced magnetic distributions was developed so that sensitive plasma properties can be controlled. A proof-of-principle application has been given for NCSX. It was found that for both the kink mode and the effective helical ripples the plasma responds most sensitively to external magnetic perturbations in outboard regions. New sets of modular coils have also been found that are either smoother than those derived using the traditional method or can be located farther from the plasma boundary than those of the present design.

Targeting reduced anomalous transport. Up to now, a transport optimized stellarator has meant one optimized to reduce neoclassical transport, while the task of also reducing turbulent transport (usually the dominant transport channel in such designs) has not been addressed. However, with the advent of gyrokinetic codes valid for 3D geometries such as GENE [10, 11], and stellarator optimization codes such as STELLOPT [12], designing stellarators to also reduce turbulent transport has become a realistic possibility.

Since the use of radial heat flux Q_{gk} from GENE runs as a measure of turbulent transport would be computationally too expensive for STELLOPT runs, we employ a "proxy function" in place of Q_{gk}. The proxy function Q_{prox} is a quickly-evaluated function of key input geometric quantities, based on theory and on the geometry dependences of Q_{gk} found from earlier GENE studies. [13] Using Q_{prox} and beginning with the NCSX baseline design, STELLOPT has produced two initial proof of principle configurations with substantially reduced Q_{prox}. As the decisive test of whether the turbulent transport has been diminished, GENE has been applied to the derived configurations and finds transport levels a factor of 2 to 2.5 below that of NCSX [14]. For one of these configurations, the neoclassical transport is actually reduced below that of NCSX. However, the configurations were evolved without applying other targets needed to make them fully satisfactory, for example, kink stability and adequate rotational transform.

The proof of principle configurations found have demonstrated an effective method of targeting anomalous transport, opening many further avenues for further exploration. The proxy function needs to be refined and extended, for example, to improve the modeling of ITG transport, and to encompass the transport from other channels, such as those from trapped-electron and electron temperature gradient modes. Moreover, the same method applied to other interesting toroidal designs in addition to NCSX, (e.g., tokamaks and other stellarators) may lead to new classes of turbulence-optimized devices.

4.3. Alternative Technologies and Topologies

Passive shaping by superconducting tiles provides a new design option that can be used to simplify the coils and improve availability. By placing multiple, discrete magnetic controlling tiles properly aligned on a surface, it is possible to modify the background magnetic field. If such materials can be attached to the in-vessel structure of a stellarator, it could allow the coils to be made simpler and improve maintenance access.

To assess the potential benefits, a configuration scoping study was developed around the ARIES-CS design point, using high temperature superconducting monoliths for passive field shaping. In this design (Figure 5) a background toroidal magnetic field is provided by six planar toroidal field (TF) coils, arranged and sized to allow each of the three field periods to be assembled with a straight radial motion. The tiles are pre-attached to a shell structure that is modularized, with a semi-permanent interior structure and a removable external structure to facilitate assembly. The HTS monoliths are charged as the background field is raised; poloidal breaks in the structure allow the background field to penetrate it. The removable structure would require cold-to-warm transition members that would be removed prior to extracting the replaceable first-wall/blanket/shield component. The conclusion is that the stellarator engineering characteristics can be improved through the use of HTS monoliths, provided it can be shown that passive field shaping with such materials is effective. It is expected that the design could be optimized by varying the number of TF coils or deforming them to a limited degree so as share in the 3D plasma shaping function instead of relying entirely on the tiles; this is a subject for future study.

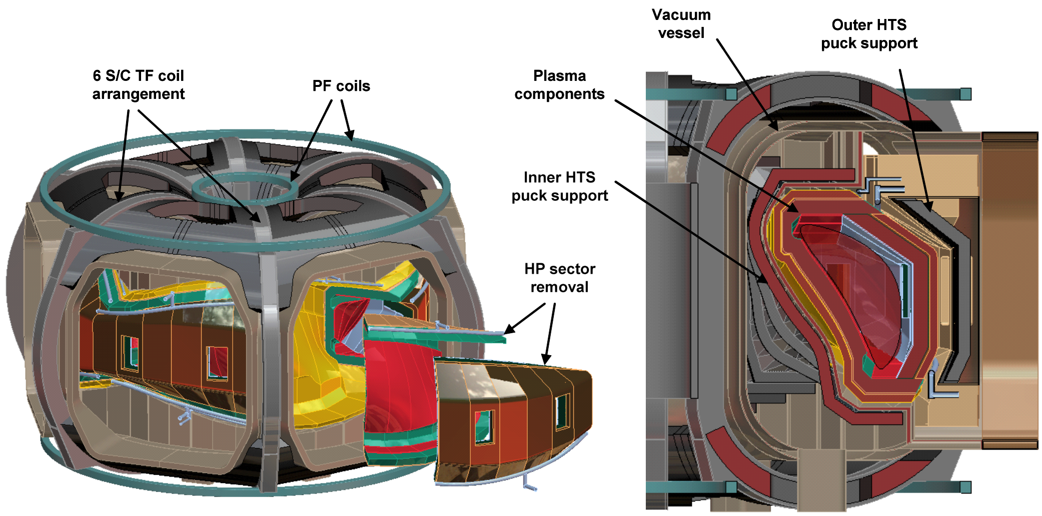

Figure 5. Stellarator machine configuration using HTS monoliths for passive shaping. Left: isometric view showing retracted internal components. Right: section view.

High temperature superconductors (HTS) exist in bulk form, with monoliths of the materials relatively easy to fabricate using conventional crystal growing methods. Materials (e.g., ReBCO) with attractive properties at temperatures up to 60-65 K are available. Because of their high critical temperatures and, consequently, high energy margins, HTS materials are not as prone as low-temperature superconductors to instabilities where the field propagates into bulk material (flux jumping). Additional advantages of HTS materials operating at elevated temperatures (> 30 K) include higher radiation limits and more efficient nuclear heat removal. At the same time, there are challenging issues, such as mechanical support and cooling of the monoliths, performance and lifetime limitations in the fusion environment, field creep, superconducting stability of the monoliths, and cryostat design.

The field-shaping capability by superconducting elements has been calculated for tokamaks [15] where it was shown that by appropriately placing HTS monoliths (overlapping, tilted tiles), it was possible to cancel a substantial toroidal ripple. In this section, proof-of-principle calculations for a straight stellarator are presented. As a simplifying assumption, the monoliths are treated as perfect superconductors (diamagnetic elements). Although the real problem is non-linear due to the interaction between the fields and currents in the superconductor, this is a good approximation provided the critical current is large enough that the surface currents do not penetrate very deep within the superconductor. The treatment of the monoliths as realistic superconductors is left for future work.

Analytical expressions for the last closed flux surface of a straight $l = 2$ stellarator (adapted from [16]), with minor radius of 0.3 m, pitch length of 2 m, and an applied axial magnetic field (the background field) of 1 T, are used to generate a control surface. When the control surface is treated as a continuous superconducting wall, a stellarator configuration with flux surfaces and a rotational transform of 1.81 per pitch length. The calculated magnetic field agrees with that of the analytical solution and has same value of rotational transform.

Next the control surface was covered with discrete flat tiles, axially overlapping and tilted for the purpose of reducing flux leakage through inter-tile gaps. The tilting algorithm was developed to provide complete coverage of the surface when looked along the axial direction, but this choice of tile overlap and orientation is not necessarily optimal magnetically. The result (Figure 6) is that most of the tile surfaces have a field of about 1 T (same as the

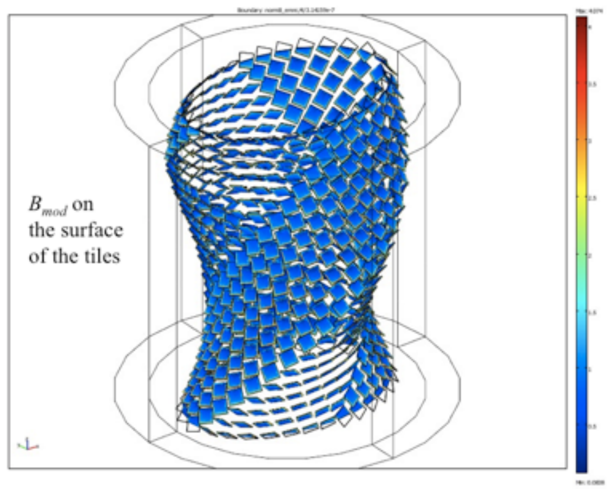

Figure 6. Arrangement of HTS tiles on control surface. Color indicates magnetic field strength on the tile surface.

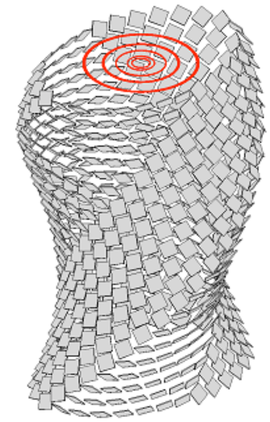

Figure 7. Calculated magnetic surfaces generated by HTS tiles.

background), although the field can be more than twice as high near the edges of the tiles. The peak surface current density for this case is around 3×10^6 A/m. Assuming the current density in the monolith is 10^9 A/m^2, the thickness of the surface current is around 3 mm. Since the tiles are on the order of 1 cm thick, the assumption of magnetic insulating boundary condition is justified. If the tiles operated at critical current density throughout their volume, the minimum required tile thickness is 6 mm. since there is current flowing both sides of the tiles. The force on the tiles is about 20 N and the torques, assuming 4.5 cm squares, are about 1 N-m. The forces and torques will scale as B^2L^2, and B^2L^3, respectively, where L is the side of the square and B is the background magnetic field. With a tile length of about 0.4 m and a B field 5 T (i.e., ARIES-CS scale), the force is relatively small (resulting in pressures around 10 MPa). The torques would be in the range of 10,000 N-m, also relatively small because adjacent tiles balance the edge forces. The corresponding flux surfaces for the tile case are shown in Figure 7. The value of the rotation transform is 0.33 per pitch length, or a factor of 5 lower than for the ideal case. Some of the field is escaping through the tiles, and as was found for the case of toroidal field ripple, it may be possible to substantially decrease this leakage (and thus increase the rotational transform per pitch length) by appropriately arranging the tiles (overlap, pitch and yaw of the tiles). Future work includes optimizing the arrangement to achieve desired plasma properties.

A more conventional approach may be to use local compensating coils to relax the shaping requirements on the main coils. As described in Section 3, engineering scoping activities indicate that straightening the outboard legs of the modular coils and moving them radially outward, while preserving the geometry on the inboard leg, facilitates access to in-vessel components. The difference in magnetic fields between each original coil and its modification can be exactly represented by a twisted saddle loop formed from the eliminated segments of each original coil and that of the modified coil. The twisted saddle is then approximated by one or more saddles that can be separately removed by radial extraction. To improve upon this simplistic approach, a coil design code with the capability to re-optimize the coil geometry to recover the desired physics properties with the added geometric constraints will be developed.

5. Summary

Compact size may be favorable for minimizing the capital cost of a reactor. The QAS concept offers the possibility of a compact stellarator power plant design, closer in its linear dimensions to tokamaks than previous stellarator reactor designs. The overall economic attractiveness of fusion power plants also requires high availability. A basic machine design that is compatible with rapid removal and replacement of limited-life components is a necessary condition for achieving high ability. For stellarators, this means that engineering criteria for maintainability must be targeted, together with required physics properties, in the numerical optimization of the coil configuration. By modifying the ARIES-CS power plant design so as to make the outboard legs of the majority of the modular coils straight and provide large openings, a sector maintenance scheme becomes possible, greatly improving its potential for high availability. Several design strategies that would allow such engineering criteria to be achieved, while simultaneously realizing plasma configurations with required physics properties, have been investigated and found to be feasible.

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