Recent Advances in Stellarator Optimization

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Abstract. Computational optimization has revolutionized the field of stellarator design. To date, optimizations have focused primarily on optimization of neoclassical confinement and ideal MHD stability, although limited optimization of other parameters has also been performed. One of the criticisms that has been leveled at existing methods of design is the complexity of the resultant field coils. Recently, a new coil optimization code - COILOPT++, which uses a spline instead of a Fourier representation of the coils, - was written and included in the STELLOPT suite of codes. The advantage of this method is that it allows the addition of real space constraints on the locations of the coils. The code has been tested by generating coil designs for optimized quasi-axisymmetric stellarator plasma configurations of different aspect ratios. As an initial exercise, a constraint that the windings be vertical was placed on large major radius half of the non-planar coils. Further constraints were also imposed that guaranteed that sector blanket modules could be removed from between the coils, enabling a sector maintenance scheme. Results of this exercise will be presented. New ideas on methods for the optimization of turbulent transport have garnered much attention since these methods have led to design concepts that are calculated to have reduced turbulent heat loss. We have explored possibilities for generating an experimental database to test whether the reduction in transport that is predicted is consistent with experimental observations. To this end, a series of equilibria that can be made in the now latent QUASAR experiment have been identified that will test the predicted transport scalings. Fast particle confinement studies aimed at developing a generalized optimization algorithm will also be discussed.

1. Introduction

The stellarator concept, like its symmetric cousin the tokamak, is a toroidal magnetic confinement device which holds promise for confining plasmas with sufficient efficiency to reach the plasma parameters required to generate fusion energy. Because stellarators use external magnets to generate nearly all the confining fields they are generally free of the plasma terminating instabilities frequently found in tokamaks. Additionally, the use of mostly-external fields for confinement obviates the need for external current drive for configuration sustainment, which is a major impediment to achieving steady state in a tokamak. Steady-state maintenance of the magnetic configuration provides additional advantages: 1) no possibility of the loss of positional equilibrium, which is associated with disruptions, and 2) no requirement to have a plasma current greater than 5MA, where the problem of runaway electrons becomes severe. An important property, which reduces the cost and time for fusion energy development, is that stellarator plasmas are subject to external control rather than being in a self-organized state. This removes many uncertainties in the extrapolation from smaller experiments to the reactor scale.

In the early years of stellarator research energy confinement was severely limited by neoclassical ion losses, caused by the asymmetry associated with the 3D nature of the fields. However, beginning in the 1980s, design concepts were developed that addressed neoclassical losses. The technique that was employed involved a conceptual change in the stellarator design process. Early stellarator designs were developed by first creating a coil set, and then, investigating the resultant plasma properties. In the new paradigm, a plasma equilibrium is designed to have (for example) good neoclassical confinement properties and then a coil set is designed to generate that equilibrium.

The primary drivers for this new design paradigm were advances in theoretical understanding of the sources of the large neoclassical losses in traditional stellarator designs. Numerous publications on the topic of enhanced neoclassical stellarator confinement are very well summarized in Reference [1]. Of particular note are the references by Boozer which show 1) the guiding-center equations of motion in flux coordinates depend only on the magnitude of the magnetic field, and not on its individual components [2], and 2) that if two systems are both symmetric in flux coordinates, the orbits and transport coefficients in one system may be gotten from those of the other by a simple parameter mapping between the two [3], regardless of their physical shape. These ideas led shortly thereafter the first stellarator design based on the idea of "quasi-symmetry" [4].

Three types of stellarators appear to have the potential for reactors. (1) Quasi-Axisymmetric (QA), which in design space is continuous with the tokamak, (2) Quasi-Helical (QH), which tends to have better energetic particle confinement, and (3) Quasi-Omnigeneous (QO), which has properties that are essentially independent of the plasma pressure and can be designed to have no plasma current. Stellarators have approximately an order of magnitude more degrees of freedom in external magnetic fields than tokamaks in the number of externally produced magnetic field distributions that can be used for plasma control. The number of degrees of freedom is far too large to be explored empirically; design points must be chosen through well-organized computations which exploit this freedom to address issues in fusion development.

In addition to the optimization of neoclassical confinement the newest systems are also optimized relative to ideal MHD stability such that they are absolutely stable to all ideal MHD perturbations. The procedure for guaranteeing MHD stability is described in detail in Reference [5] and [6]. The capabilities for the neo-classical + MHD stability optimization are contained within the STELLOPT suite of codes which is described in detail in Reference [7].

This paper describes advances to the computational tools attempts to utilize these advances to demonstrate that major design improvements can be made in areas such as simplified coil designs, improved divertor options, better confinement of alpha particles to reduce damage to the chamber walls, and reduced micro-turbulent transport.

2. Areas for advanced optimization studies.

Improved coil design: We show examples of the use of modernized coil design tools STELLOPT/COILOPT++ to address the issue of coil complexity in stellarators and also investigate the engineering feasibility of these designs.

Turbulent transport studies: We present a brief summary of an exciting new area for stellarator design - the optimization of turbulent transport. We also present an experimental strategy to test directly comparable theoretical predictions from the GENE code so as to place the concept of turbulent transport optimization on a sufficiently firm footing that it can be confidently used to design turbulence optimized configurations.

Fast particle optimization: We discuss capabilities to optimize the confinement of fast particles within the context of the simplified stellarator coil design tools STELLOPT/COILOPT++ described above.

Divertor Design: We describe a method to incorporate divertor plate design options into the STELLOPT code and incorporate useful engineering constraints into the design process.

2.1.Improved coil design

Dramatic improvements to the coil design features of the STELLOPT code, embodied in a new code called COILOPT++, have been used to develop coil designs that are compatible with a large sector maintenance scheme [8]. The process involves coupling explicit engineering constraints into the optimization, which was modified to operate with spline representation of the coils instead of Fourier modes. High-T_c superconducting tapes, which permit much higher current density and higher magnetic field than the conventional superconductors, while also providing much greater flexibility for the cooling systems hold promise for reducing the size of the coil windings. The new conductors offer additional unique advantages for non-axisymmetric plasmas. For example the minimum local radius of curvature is often a constraint for stellarator coils, but the increased current density in the new conductors enables coils to be thinner, relaxing the curvature constraint.

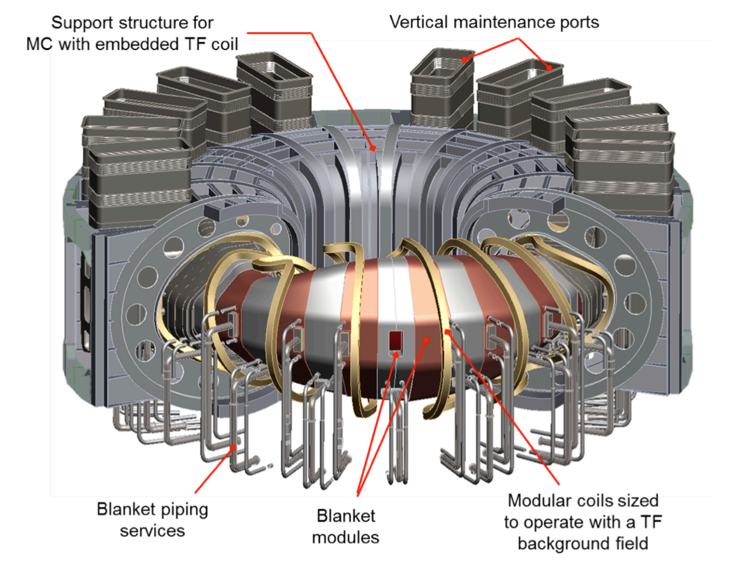

Figure 1 *Cut-away view of a maintainable stellarator with the outer half of the modular coils constrained to be vertical for sector maintenance access.*

As an initial exercise, A=6.0 quasi-axisymmetric stellarator plasma was considered, based on the baseline ARIES-CS N3ARE configuration [4]. 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 [9], and scaled appropriately.

The resultant stellarator coil design with a large sector maintenance scheme is shown in Figure 1. The coil optimization was sufficiently successful with modular coils only, that it was not necessary to add trim coils, although the COILOPT++ code supports that possibility. The ideas described in this section are the first attempt to include constraints on the physical location of the coils for an optimized stellarator. Given the ease with which an attractive solution was found, it seems clear that additional physical constraints could be added if it is deemed advantageous.

A second important aspect of stellarator coil complexity is the fact that stellarator coils typically need to be relatively close to the plasma, much more so than the coils in a tokamak. The reason for this small plasma-coil separation in stellarators is that the shaping components of the magnetic field created by coils decay through space, so for a given stellarator plasma shape, the non-planar excursions of modular coils must grow exponentially as the plasma-coil separation is increased. The issue of small plasma-coil separation becomes even more important in a reactor, because a blanket and neutron shielding must fit between the plasma and coils. Indeed, in the ARIES-CS reactor study, plasma-coil separation was identified as "the most influential parameter for the stellarator's size and cost" [10]. However, the maximum feasible plasma-coil separation is a strong function of the plasma shape. For example, plasma shapes with concave regions tend to require very close coils, whereas plasma shapes with convex cross-sections permit the coils to be more distant. recently, Landreman & Boozer [11] defined and explored several new magnetic field 'efficiency' metrics, called the efficiency sequence and feasibility sequence. These metrics can be used to define "efficient shapes" to help guide shape optimization which in turn can decrease the need for small plasma coil separation.

2.2.Turbulent transport studies

A major development in stellarator physics in recent years is the ability to simulate microturbulence with a first-principles model, nonlinear gyrokinetics. Several gyrokinetic codes that allow nonaxisymmetric geometry are newly available, including GKV [12], GENE [13], and GS2 [14]. Calculation is now feasible not only of linear stability but also of saturated nonlinear turbulence over entire flux surfaces. At the same time, analytic understanding of microstability in stellarators has also developed. For example, it was realized that stellarators can be immune to a range of trapped particle instabilities [15]. These advances, if validated, open new possibilities for stellarator design optimization that urgently need to be exercised and experimentally tested.

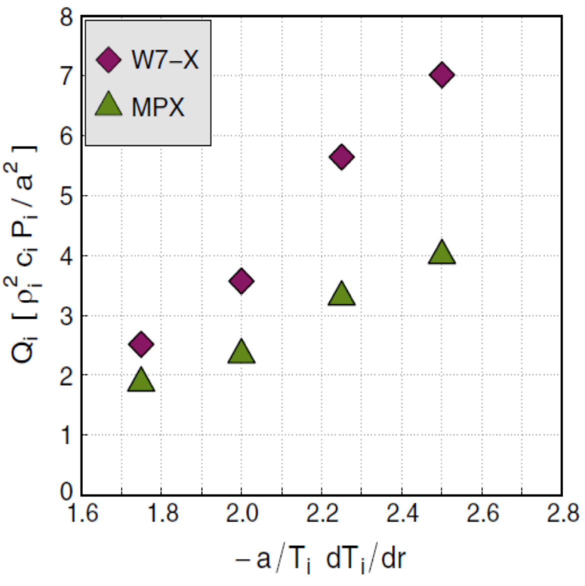

Figure 2 *From Xanthopoulos et al PRL 113, 155001 (2014). Demonstration that the turbulent heat flux predicted by nonlinear gyrokinetic simulation can be reduced in a W7-X-like stellarator design using optimization. W7-X points indicate the heat flux prior to the turbulence optimization; MPX points indicate the optimized design.*

With understanding of turbulence in stellarators comes the possibility of choosing the nonaxisymmetric shaping to minimize turbulent transport. In a proof of concept, Mynick et al. [16, 17] demonstrated it was possible to further optimize several stellarator designs, substantially reducing the turbulent transport predicted in nonlinear gyrokinetic simulations. The authors also applied the method to a tokamak equilibrium, demonstrating in a direct way that stellarator optimization tools can benefit tokamak design and performance. In these studies and in subsequent work, it has not been computationally feasible to run nonlinear gyrokinetic simulations at each iteration of the optimization. Instead, the optimization targeted various proxy functions that were much less expensive to evaluate. The proxy functions took the form of a mixing-length estimate for the heat flux, using a simplified analytic model for the linear growth rate of the ion temperature gradient (ITG) mode. The magnetic geometry enters the proxy functions through quantities such as the "bad" curvature and the local separation between flux surfaces. Full nonlinear gyrokinetic simulations were run before and after the optimization to verify that their more accurate prediction of heat flux was actually reduced. It has also been shown that [18, 19] applied the same methodology the W7-X design can be further optimized to reduce turbulent transport, without increasing (and actually decreasing) neoclassical transport (Figure 2).

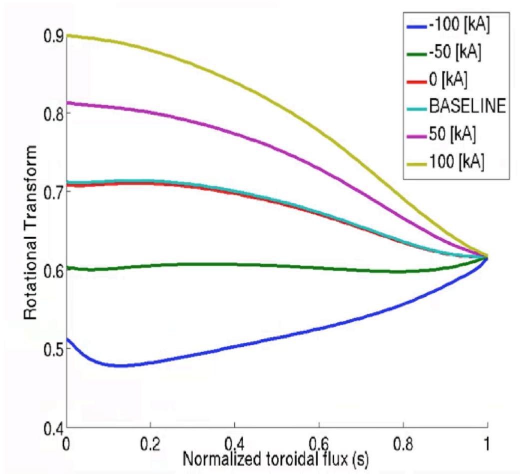

Figure 3 *iota profiles for QUASAR shear scan. Legend indicates current in toroidal field coils.*

In order to validate predictions of ITG turbulence reduction in QUASAR, a shear scan was performed using the STELLOPT code. Six free boundary configurations with Ohmic current profiles were developed. The iota profiles are shown in Figure 3. These 2% beta configurations would be experimentally realizable in the QUASAR facility. These configurations showed little variation in neoclassical transport, although 'prox1d' used for ITG optimization indicated up to a factor of 2 variation in predicted turbulence. Non-linear ITG flux calculations also show significant variation and will be presented in a future publication.

2.3. Energetic ion confinement

Any viable magnetic fusion reactor will need to confine alpha particles long enough for them to transfer most of their energy to the main species. Meeting this requirement is more challenging for nonaxisymmetric schemes than for axisymmetric ones. Axisymmetry implies conservation of canonical angular momentum, which implies that all particle trajectories are confined (within a poloidal gyroradius of a given magnetic surface) in the absence of collisions and turbulence. However in nonaxisymmetric plasmas, the absence of such a conservation law means that trapped particle trajectories are not necessarily confined. For thermal particles, the problem is mitigated by collisionless detrapping associated with poloidal *ExB* drift, but for fast particles this helpful process is weak due to the smaller ratio of ExB to parallel speed. The scale of the fast-particle confinement problem is clearly shown in [20], which found all trapped alpha particles to be lost in ~ 10^{-4}-10^{-3}s in simulations of a conventional (not optimized) l=2 stellarator and of W7-AS. For comparison, the required alpha confinement time for typical reactor parameters can be estimated as >= 0.1 s. Fast particle confinement in modern optimized designs such as W7-X and NCSX is much improved compared to conventional stellarators [21], but remains one of the main challenges for the concept. For instance, alpha confinement remained one of the most serious concerns expressed in the ARIES-CS reactor study [22]. Even though the ARIES design was able to reduce alpha losses to 5% over a slowing-down time.

Neoclassical optimization naturally leads to improvement in the confinement of fast particles, but while confinement of thermal and fast particles is related, some considerations are different. Targets for neoclassical optimization (e.g. effective helical ripple, [23]) are typically derived using a "radially local" analysis, in which an expansion is made in the smallness of the particle orbit width compared to equilibrium scale lengths. For fast particles, this ratio is often not small, so the finite orbit width must be taken into account. Moreover, alpha particles are likely to be born close to the magnetic axis, making finite-orbit-width effects especially important. Also, neoclassical transport computations assume a nearly Maxwellian distribution function, whereas the fast particle distribution function is often very far from Maxwellian. Collisions are central to neoclassical confinement but unimportant for fast-particle confinement, whereas the opposite is often true for poloidal magnetic drift. Thus, separate figures of merit for fast particle confinement should ideally be included in stellarator optimization in addition to the neoclassical targets that have been used to date.

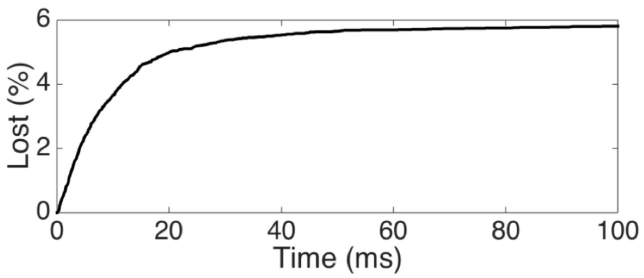

Figure 4 *Particle loss fraction as a function of time as calculated by the BEAMS3D code*

Given improvements in computing power, as well as code development efforts in the past year, it is more feasible than ever before to directly optimize the confinement of fast particle trajectories. STELLOPT has recently been coupled to the gyro-center following parts of the BEAMS3D code [24] allowing massively parallel computations. Initial tests have been carried out using this pair of codes on as many as 10,000 processors on the Hydra supercomputer in Garching, Germany [25]. In this work 12,000 particles were followed until losses appeared to reach an asymptote (approximately a slowing down time, see Figure 4). Losses for this case were dominated by particles with small pitch angles (large perpendicular energies). These computations also indicated the need for fast proxies if computations are to be carried out using more modest computational resources. Thus development of proxy functions for energetic particle confinement may still play a key role in energetic particle confinement optimization.

2.4.Divertor design

In reactor-relevant conditions, the divertor has to guarantee an effective particle and energy exhaust for a wide range of plasma and magnetic parameters. The divertor offers a protection to the vacuum vessel on the higher loaded areas, and decouples the main confined plasma from the wall, generating a private plasma region. In this way, most of the plasma-material interactions concentrates close to the target plates and near the pumping gap, without much affecting or contaminating the fusing plasma core. While the two-dimensional poloidal divertor of tokamaks offer a clear and distinct plasma private region separate from the main plasma, the three-dimensional magnetic topology of stellarators forces also the divertor to be three-dimensional, with a more complicated pattern of connection lengths outside the separatrix and an ergodic or stochastic behavior in the private plasma region.

There are two basic strategies for divertors in stellarators: (1) resonant or island divertors as in W7-X and (2) a non-resonant divertor, which takes advantage of the strong plasma shaping that is characteristic of all optimized stellarators. Only the non-resonant type appears relevant to Quasi-Axisymmetric and Quasi-Helical stellarators, which have their transform changed significantly by the bootstrap current. Resonant divertors generally take the least room in the plasma chamber, but this also implies the divertor strike points are very close to the plasma, which might make shielding the plasma difficult.

From a design standpoint, the divertor is tightly connected to all previous areas of our work, namely coil geometry, turbulent transport, and fast particles exhaust. In order to be effective, the design of the divertor has to be embedded in the optimization loop, and be an integral part of it. The divertor geometry, and eventually the divertor chamber (e.g. LHD) deeply affects the shape of the vacuum vessel, and consequently of the coil geometry, magnetic topology, plasma transport, etc. In addition, several divertor components must necessarily be hosted inside the vacuum vessel, including all plasma facing components (divertor targets, baffles), cooling ducts, cryo-pumps, and eventually additional divertor control coils.

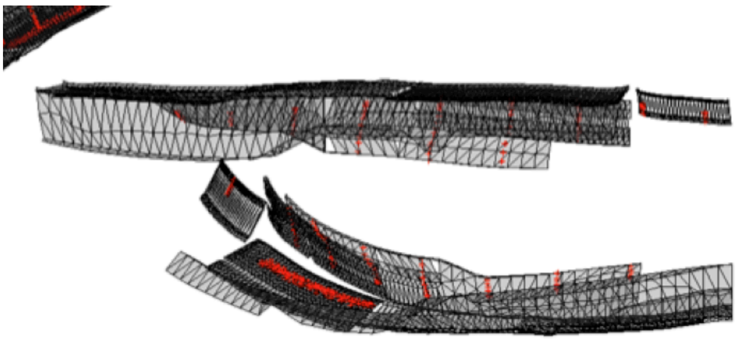

Figure 5 *FIELDLINES modeling of divertor strike points in W7-X. Red marks indicate strike points.*

Inclusion of divertor design in stellarator optimization requires that codes capable of addressing divertor heat loads be included into the STELLOPT code along with their associated figures of merit. The fastest and most obvious method is to use field line tracing with diffusion to model the path taken by particles as they head toward the divertor plates. This method has been used with some success already in the modeling of heats loads for W7-X (see Figure 5). Moreover, a parallelized field line tracing code exists (FIELDLINES) which is already part of the STELLOPT family of codes. Wall loading and plate loading figures of merit will soon be developed for the optimizer. The resulting optimized configuration could undergo a more detailed analysis with codes such as EMC3/EIRENE.

3. Summary

The objective of stellarator optimization is to address gaps in developing the stellarator concept as a reactor. This paper has summarized the following topics:

- Simplification of stellarator magnets which allow improved maintenance access
- Development of experimental scenarios for validating turbulence computations in stellarators to gain confidence in using turbulence optimization as a design criterion
- Creation of tools and designs for achieving reactor-relevant alpha particle confinement
- Mitigation of the materials challenge by integrating divertor design into the framework of stellarator optimization.

Successful inclusion of these optimization concepts as part of a concerted design effort could help solve many of the problems of fusion energy development.

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