*29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-4.110 (2002)*

QPS Plasma and Coil Optimization

D.J. Strickler[1], D.A. Spong[1], L.A. Berry[1], G.Y. Fu[2], S.P. Hirshman[1], J.F. Lyon[1], R. Sanchez[3], A.S. Ware[4]

[1]*Oak Ridge National Laboratory, P.O. Box 2009, Oak Ridge, TN 37831-8073*
[2]*Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08502*
[3]*Universidad Carlos III de Madrid, Madrid, Spain*
[4]*Department of Physics and Astronomy, University of Montana, Missoula, MT, 59812*

Abstract. The optimization of compact stellarators is a challenging physics and engineering problem whose solution has required the development of new computational tools. These include: rapidly evaluated transport and 3D ballooning targets, a bootstrap current consistency condition, and an upgraded version of the VMEC equilibrium code with improved convergence; these components are immersed in an optimization algorithm that has been adapted to utilize multi-processor parallel computing architectures. Following the physics optimization of the outer flux surface, a set of coils is developed (COILOPT code) by directly adjusting the coil geometry and currents so as to minimize the normal component of magnetic field on the outer flux surface in conjunction with coil engineering constraints. Based on these methods, new stellarator hybrid configurations have been developed with quasi-poloidal symmetry at very low aspect ratios ($\langle R\rangle/\langle a\rangle \sim 2.7$) that achieve low levels of neoclassical transport and good stability properties, including access to high β second stability states.

I. Introduction

The QPS[1] (Quasi Poloidal Stellarator) is a compact (A = 2.7) two field period device that has been developed through a systematic optimization procedure that balances physics requirements (confinement quality, plasma stability to pressure and current-driven modes, bootstrap current consistency), design goals (low aspect ratio, adequate minimum plasma width for good neutral shielding, avoidance of low order rational surfaces, rotational transform provided predominantly from coils and engineering constraints (adequate coil-plasma and coil-coil separation, minimum bend radius, and sufficient space in the center for Ohmic current and toroidal field coils). The successful optimization of low aspect ratio devices has been possible due to a number of past scientific advances: (a) the identification of an appropriate coordinate system[2] within which magnetic field symmetries leading to improved particle orbit confinement could readily be identified; (b) demonstration that numerical optimizations of three-dimensional systems could lead to good equilibrium, transport, and stability properties[3]; (c) numerical design[4] of coils to accurately produce these configurations; and (d) the increasing availability of massively parallel computers with capacities of 1 teraflop and higher coupled with the development of efficient algorithms to take advantage of this resource.

II. Plasma Optimization

Our plasma optimization technique, known as the STELLOPT-COILOPT code, has evolved to include a range of physics and engineering targets. Confinement measures include: the alignment of drift surfaces with flux surfaces, minimization of local diffusive transport both in the plateau regime (using the DKES transport coefficients) and the low collisionality regime (using $\varepsilon_{eff}^{3/2}$ from NEO[5] code). Levels of $\varepsilon_{eff}^{3/2}$ ranging from 2×10^{-4} (center) to 1.5×10^{-3} (edge) have been achieved; at these levels, neoclassical transport is expected to remain subdominant to anomalous levels for all regimes. Bootstrap consistency is targeted using an evaluation of the collisionless bootstrap current which then can be reduced by a scale factor to model collisional effects. Levels of bootstrap current that are reduced by a factor of 3 – 4 from the equivalent tokamak are targeted to significantly reduce the drive for tearing and kink instabilities.

A ballooning stability target is included using the COBRA[6] code. This provides a rapid, but accurate, evaluation based on VMEC coordinates of 3D ballooning stability. Targets for Mercier stability and the presence of a magnetic well are also evaluated. The ballooning growth rates are targeted on multiple flux surfaces and can be reduced by the optimizer either through changes to the outer flux surface shape or via plasma pressure profile modifications. Our configurations typically have first stability ballooning limits of $\langle\beta\rangle \sim 2\%$. QPS devices also have second stability regimes to ballooning modes; this becomes possible when the outward equilibrium flux surface shift is significant, leading to enhanced poloidal fields and shorter connection lengths on the outboard side of the plasma. Near term QPS configurations, with stellarator-like shear, have second stability regimes, provided the bootstrap current can be suppressed from collisionless levels. QPS devices with tokamak-like shear,[7] which are possible reactor candidates, also have such regimes; ballooning and kink stable cases have been found for $\langle\beta\rangle$'s up to 15%.

Finally, the optimization of the outer flux surface shape is coupled to several coil-related figures of merit (e.g., complexity, curvature, and current density); these are approximated using the NESCOIL[4] surface current model. These targets help guide the choice of plasma shapes into regions of parameter space where realizable coils will exist.

IV. Coil Optimization

Discrete coil geometries that reconstruct the magnetic surface shapes derived from the above physics optimization are developed using the COILOPT[8] code. This approach solves for the optimal parameters (using spline representations) of modular coils on a toroidal winding surface that is well separated from the plasma boundary. The primary target for this optimization is the reduction of the normal component of magnetic field on the outermost magnetic flux surface; in addition, a number of coil geometry and engineering penalty functions are included; examples are plasma-coil, coil-coil separation, coil current density and coil curvature.

We have chosen a QPS coil optimization model based on 16 coils (four unique coil types) with no coils on the symmetry planes, equal modular coil currents, four pairs of vertical field coils with fixed position and variable current, and 12 TF coils. We are able to obtain good flux surface reconstruction and preserve the physics properties for QPS devices with average field errors on the outer surface [$\delta B_{avg} = (1/A)\oint\!\!\oint dA|\mathbf{B}\cdot\mathbf{n}|/|\mathbf{B}|$] of ~ 0.58%.

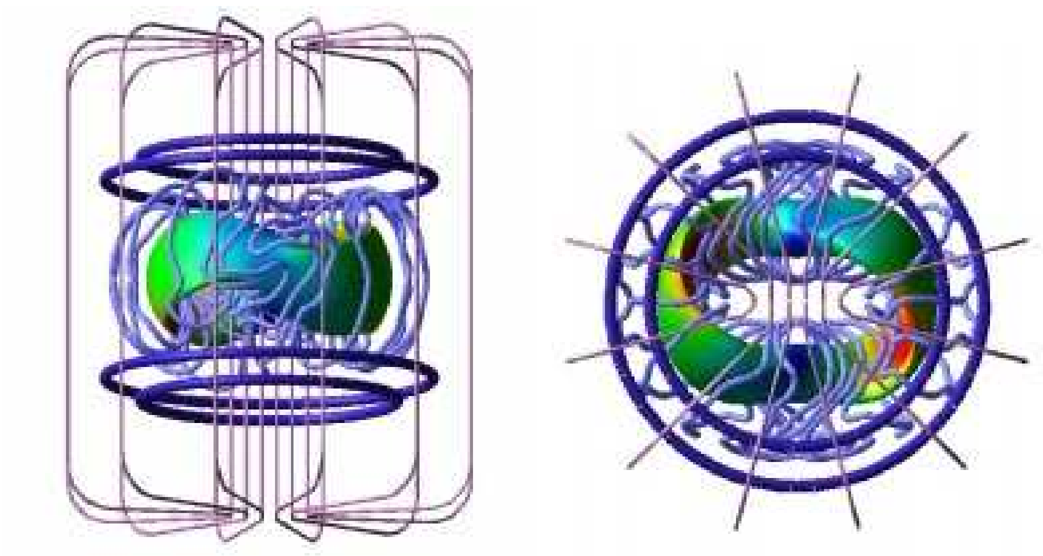

Fig. 1. (a) Side and (b) top views of outer magnetic flux surface and the three coil sets (modular, vertical, toroidal) with color contours showing magnetic field strength.

Two views of the QPS outer magnetic surface along with the three coil sets (the modular coils, the vertical field coils and the toroidal field coils) are shown in Figures 1(a) and 1(b). These combined modular, TF and VF coils meet a variety of QPS-specific plasma and device constraints, such as adequate space in the center of the device for Ohmic solenoid and TF coils (~ 18 cm), sufficiently large minimum radius of curvature (~ 10 cm) and adequate coil-plasma spacing (~ 15 cm).

Recently, the STELLOPT and COILOPT codes have been merged together to form an optimization tool that simultaneously targets physics and coil engineering criteria. This merged optimizer allows the designer to identify nearby neighboring equilibria that have close to the same physics properties as the initial one, but with significantly better coils (i.e., lower field errors, easier to build). It has also, in some cases, been of use in identifying nearby equilibria whose outer flux surface shapes have a smoother structure than those that are initially reconstructed from coils based only on the COILOPT calculation.

VI. Conclusions

A systematic plasma optimization and modular coil synthesis procedure has been developed and applied toward the development of low aspect ratio stellarators with quasi-poloidal symmetry. This effort has lead to the QPS device which has two field periods, A = 2.7, levels of neoclassical transport that are substantially suppressed from the stellarator ISS95 scaling, first stability limits around $\langle\beta\rangle \sim 2\%$ and second stability regimes up to $\langle\beta\rangle \sim 15\%$. Using the COILOPT code, modular coils have been developed for this device that have good engineering feasibility, yet preserve the flux surface integrity and physics characteristics of the original plasma optimization.

Acknowledgements: This work was supported by U.S. Department of Energy under Contract DE-AC05-00OR22725 with UT–Battelle, LLC.

---

[1] D. A. Spong, S. P. Hirshman, et al., Nuclear Fusion **41**, 711 (2001).
[2] Boozer, A. H., Phys. Fluids **24,** 1999 (1981).
[3] J. Nührenberg and R. Zille, Phys. Lett. A **114,** 129 (1986).
[4] P. Merkel, Nucl. Fusion **27**, 867 (1987).
[5] Nemov, V. V., et al., Phys. Plasmas **6**, 4622 (1999).
[6] Sanchez, R., Hirshman, S. P., Whitson, J. C., Ware, A. S., J. Comput. Phys. **161**, 576 (2000)
[7] Ware, A., submitted to Phys. Rev. Lett., 2002.
[8] Strickler, D. J., Berry, L. A. , Hirshman, S. P., accepted for publication in Fusion Science and Technology, Vol. **41** 2002.