Development of a Robust Class of Quasi-Poloidal Compact Stellarator Configurations[1]

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The stellarator optimization code STELLOPT [1] has been used in low aspect ratio Quasi-Poloidal Stellarator (QPS) [2] design to determine the shape of the outer magnetic flux surface, together with internal plasma pressure and current profiles, that produce desirable physics properties such as confined particle drift trajectories and plasma MHD stability at $\langle\beta\rangle \approx 2\%$. The integration of the COILOPT [3] model, based on explicit representations for modular coils and coil geometry constraints, into the stellarator optimization package STELLOPT, provides a unique and important computational tool [4] for the design of compact stellarators. This self-consistent analysis ensures that physics and engineering criteria are simultaneously targeted in the full-pressure, full-current plasma/coil configuration. In this paper we describe a method that is based on including, in addition to the usual plasma confinement and stability properties at the full value of beta, a vacuum condition that drives the combined optimization of the plasma and coil configuration into a region of parameter space with improved flexibility and robustness.

In the STELLOPT code, the optimization is formulated as a least-squares minimization of a target $\chi^2 = \Sigma\, \chi_i(\mathbf{x})^2$, where the individual components, χ_i, are nonlinear functions of the system state-vector $\mathbf{x}$. Prior to merging with COILOPT, the state-vector $\mathbf{x}$ included coefficients describing the MHD plasma equilibrium pressure and current profiles, as well as either 1) Fourier coefficients of the plasma shape, in the case of a fixed-boundary optimization, or 2) coil currents, if the optimization is to be executed in free-boundary mode. The functions χ_i include both stellarator physics and coil engineering figures-of-merit evaluated numerically using a set of models that are dependent on a 3D plasma

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MHD equilibrium solution provided by the VMEC [5] code. Neoclassical transport, for example, is optimized using the NEO [6] code to evaluate a function χ_{NEO} returning values of the effective ripple factor ($\varepsilon_{eff}^{\ 3/2}$) on several magnetic flux surfaces. Subroutines interface each physics and engineering model (e.g., NEO, COBRA [7], TERPSICHORE [8]) with the optimization code through system calls. In the merged plasma/coil optimization code, the state-vector **x** consists of the independent variables from COILOPT, including the coefficients of the coil winding law, winding surface, and the coil currents, together with internal plasma profile coefficients from STELLOPT. Here COILOPT is executed in a "single-step" mode from within STELLOPT to evaluate the coil-engineering penalty functions χ_{COIL} (**x**). A solution is achieved by targeting the physics parameters of the reference plasma and the geometric properties necessary for engineering coil design, while allowing the plasma boundary shape to vary in accordance with a free-boundary MHD equilibrium response to the external coils and currents.

Implementation of the Robustness (Vacuum Field) Constraint

Plasma flexibility and robustness [9] are important components of stellarator coil design. Of particular interest to QPS is the ability to obtain a vacuum field configuration having a large fraction of nearly integrable surfaces. In this work, a vacuum field term $\chi_{VAC} = \omega_{VAC}|\mathbf{B}\cdot\mathbf{n}|/|\mathbf{B}|$ is added to the STELLOPT objective function. Here, **n** is the normal to the full-pressure plasma boundary and **B** is the *vaccum* magnetic field due to the coils. During optimization, this term is minimized to force the last closed vacuum magnetic flux surface to enclose the same volume as the full-pressure plasma. Experience shows that to obtain a class of quasi-poloidal solutions ($\partial|\mathbf{B}|/\partial\theta \approx 0$, where θ is the poloidal angle in Boozer coordinates) with plasma volume, bounded by good vacuum flux surfaces, that is comparable to the high beta equilibrium requires an average vacuum field error $\langle\delta B\rangle = (1/A)\int_{\partial P}|\mathbf{B}\cdot\mathbf{n}|/|\mathbf{B}|\, dA \leq 1.3\%$ at the full-pressure plasma boundary ∂P.

Application to the Design Optimization of QPS

The QPS is a concept exploration experiment to investigate the effects of three-dimensional shaping and quasi-poloidal symmetry on neoclassical confinement at moderate beta in a very low aspect ratio ($A \leq 2.7$) compact stellarator. The QPS plasma has two field periods, average major radius <R> = 0.9 m, magnetic field <B> = 1 T, and infinite-n ballooning stable limit <β> = 2%. The QPS coil system includes 20 modular coils, 12 TF coils (capable of changing the toroidal field on axis by ±0.2 T), and 3 pairs of circular VF coils.

The modular coils (Fig. 1) consist of a winding pack containing multiple turns of multi-strand flexible copper conductor wound on a machined winding form. In this study, each coil is modeled with a single central filament. A recent change in the QPS coil configuration is to wind pairs of coils on a single winding form with a variable web structure, including the pair of coils nearest to the v = 1/2 symmetry plane. This implies that coils near v = 0 are wound on different forms, leaving a large space in the v = 0 plane for diagnostic access to the plasma. A major cost-related significance of this arrangement is that only 3 winding form shapes are required for the 5 distinct coil types.

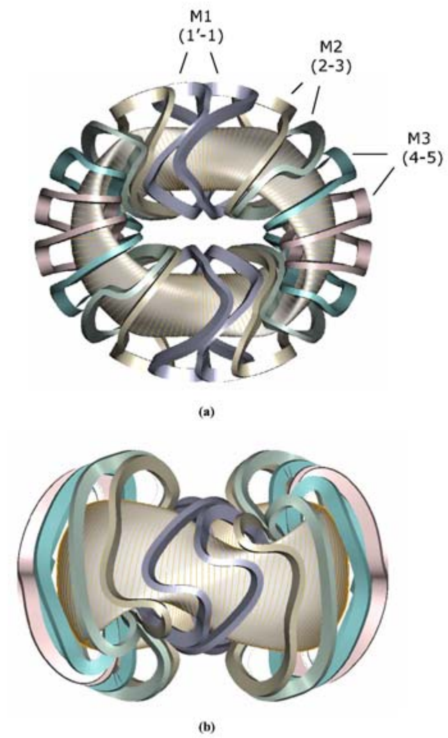

Figure 1. Top (a) and side view in the v=1/2 plane (b) of QPS modular coils. Pairs of coil types 1' and 1, 2 and 3, and 4 and 5 are on the same winding form and connected by a structural web (not shown).

Vacuum magnetic surfaces for the new configuration are shown in Fig. 2 for the v = 1/2 symmetry plane. The targeted vacuum normal field error has been significantly reduced (from <δB> = 1.82% for the configuration presented in Ref. [2] to 1.27% in the present design) at the location of the VMEC s = 1 full beta boundary. The coil currents are the same as those for the full beta case and not optimized for low beta. This leads to a plasma volume in vacuum that is comparable to that of the full-beta case and which exhibits a large fraction of closed magnetic surfaces (compared to islands). The small n = 2, m = 9 island chain (Fig. 2) may be targeted through the variation of coil currents and, if necessary, the addition of small correction coils.

The coil engineering features of the new configuration are also significantly improved over the design presented in Ref. [2]. Minimum plasma-coil separation, important for allowing adequate plasma scrapeoff distance and divertor operation, is greater than 15 cm at β=2%. The minimum distance across the central region of the torus, ΔY, a critical parameter related to the design of TF coil inner legs and the central solenoid is 40 cm (measured from coil centerlines). Increasing the minimum centerline separation (to > 12 cm) between coils on different winding forms, and the minimum coil radius of curvature (to ~ 12.5 cm), has greatly improved the feasibility of the coil engineering design, allowing for both easier coil manufacture as well as larger experimental excursions in coil currents. The new vacuum field constraint, together with the recent reconfiguration the coil model, has resulted in a robust Quasi-Poloidal Stellarator with improved engineering design properties.

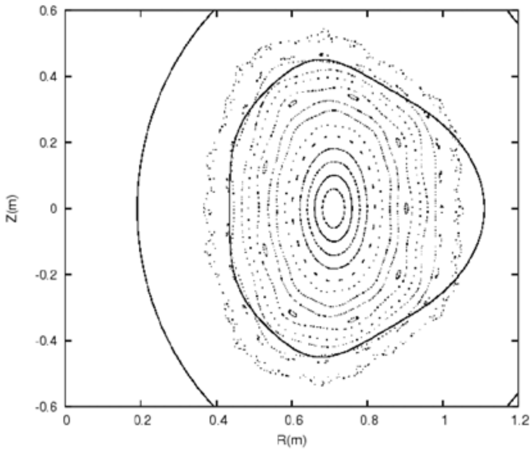

Figure 2. Vacuum magnetic surfaces in the v = 1/2 symmetry plane after applying the vacuum constraint. The outer solid line is the coil winding surface and the inner solid line is the full-beta VMEC plasma boundary.

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