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MHD EQUILIBRIUM AND STABILITY OF THE QPS DEVICE

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Abstract. The MHD equilibrium and stability properties of the proposed Quasi-Poloidal Stellarator (QPS) experiment are discussed. This work examines the equilibrium properties, bootstrap current alignment, equilibria with Ohmic current profiles, and the ideal MHD stability of Mercier, ballooning, kink, and vertical modes in QPS**.** The proposed QPS device is a low aspect ratio ($\langle R\rangle/\langle a\rangle$=2.7) stellarator with a $|B|$ spectrum that exhibits quasi-poloidal symmetry. The existence of vacuum flux surfaces from filamentary coils based on a modular coil design has been tested numerically. The reference coil set for QPS reproduces the physics properties of the fixed-boundary MHD equilibrium at finite β (the fixed-boundary configuration was optimized for both physics properties and engineering constraints at very-low aspect ratio). The QPS experiment has been designed to run with a bootstrap aligned current profile (a total current of ~40 kA at β = 2%) but will also have the capacity for Ohmic current. The issue of bootstrap alignment for the reference configuration is discussed. The QPS configuration has stellarator-like rotational transform [$\iota(0)$~0.2 to $\iota(a)$~0.3] with a magnetic well across the profile. The configuration has good Mercier stability except at isolated resonances. The reference configuration has ballooning stability limits at β ~ 2.5%. Due to the small amount of plasma current, QPS is robustly stable to kink and vertical modes. Kink and vertical modes are stable at β ~ 5% without feedback or close conducting walls.

I. Introduction

Theoretical and numerical studies on compact three-dimensional magentic equilibria has led to the design of a proposed experiment: the Quasi-Poloidal Stellarator (QPS) [1]. QPS is a very-low-aspect ratio (A = 2.7) stellarator with a $|B|$ spectrum which exhibits quasi-poloidal symmetry. The QPS experiment will test the concept of quasi-poloidal symmetry as a pathway for obtaining adequate neoclassical confinement at very-low aspect ratio and in addition will explore the physics of MHD stability and anomalous transport in a quasi-poloidal symmetric device. A crucial aspect in the design of the QPS experiment has been the development of an optimized MHD equilibrium and its confinement and stability properties. Here, we present a detailed numerical analysis of the MHD equilibrium and stability properties of a reference QPS configuration.

II. Equilibrium

The design of the QPS experiment incorporated a current profile fully compatible ("aligned") with the bootstrap current. The issue of bootstrap *alignment* and *consistency* (i.e., where the bootstrap current is computed self-consistently from the rotational transorm and pressure profiles, and the $|B|$ spectra) is esserntial in a current-carrying stellarator. The 3D

equilibrium code VMEC [2] is used to obtain the finite-β equilibria. The refernce coil set and last closed flux surface of the reference configuration at $<\beta> = 1.9\%$ are shown in Fig. 1. The VMEC equilibrium current and the predicted bootstrap current profiles for the reference configuration are shown in Fig. 2a for $\beta = 1.9\%$. The degree of agreement between the equilibrium and bootstrap currents is quite good. Also shown in Fig. 2a is the predicted bootstrap current for an equivalent tokamak which is a factor of 2-3 larger than the bootstrap current in the QPS configuration. The pressure and rotational transform profiles are shown in Figures 2b and 2c, respectivley.

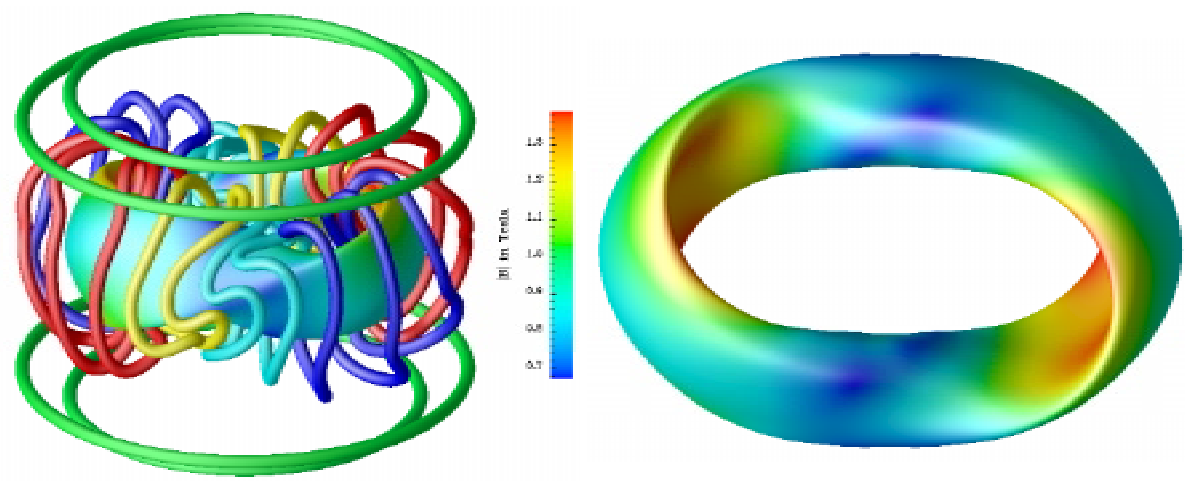

Figure 1. (a) Modular and vertical coils for a reference QPS configuration and (b) last-closed flux surface of a QPS plasma with $\beta = 1.9\%$, $I_{plasma} = 40$ kA, and coil currents of $I_{mod} = 374$ kA, $I_{VF} = -205$ kA, and $I_{TF} = -341$ kA (toroidal field coils not shown).

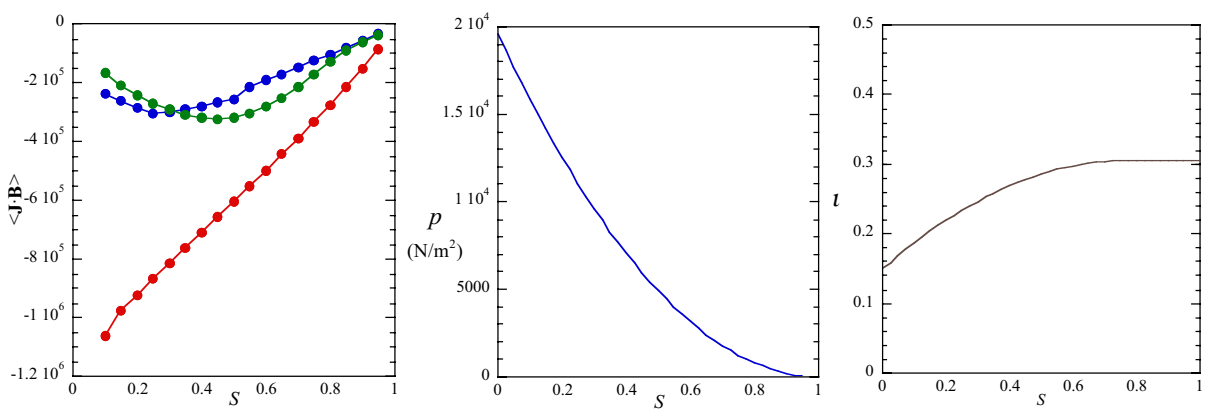

Figure 2. Profiles of (a) the equilibrium current (green circles), the predicted bootstrap (blue circles), the bootstrap current in an equivalent tokamak (red circles), (b) the pressure profile, and (c) the rotational transform profile for a reference QPS configuration.

The direction of the bootstrap current in the QPS configuration is such that it adds to the existing external rotational transform arising from coils. Because the relationship $j_{BS} d\ln|\iota|/d\phi > 0$ is satisfied, the effect of bootstrap current should be to reduce (heal) magnetic island widths for finite-β QPS equilibria. Part of the QPS experimental program will be to investigate neoclassical healing (or its reverse, island enhancement) by altering the sign of the rotational transform through changes in the external coil currents.

III. MHD Stability Properties

The primary modes of concern for stellarators are Mercier (global interchange) and ballooning modes (local interchange). For QPS, the nonzero plasma current makes kink or vertical mode instability a possibility. The numerical analysis of all of these modes in QPS is discussed below.

The QPS reference configuration is stable to Mercier (global interchange) modes over the entire plasma cross-section except for a few isolated resonances as shown in Fig. 3a. This configuration has a substantial well over the entire plasma cross section due to a combination of helical curvature and a small Shafranov shift (see Fig. 3b). It is stabilized primarily by the well rather than the shear (bending) terms in the Mercier criterion. This applies everywhere except near the edge, where the destabilizing geodesic curvature is small anyway. The terms arising from the net parallel bootstrap current are stabilizing but small. The strong well stabilization implies that high-n resistive modes should also be stable in this configuration.

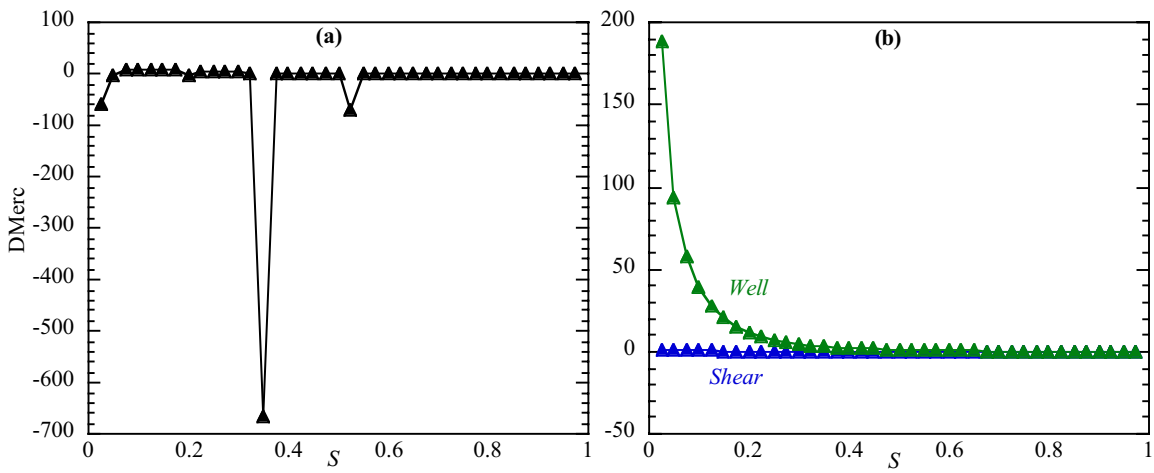

Figure 4. (a) Mercier stability criteria for the QPS reference configuration and (b) the well (green diamonds) and shear (blue diamonds) stabilizing contributions to the criteria.

The QPS reference configuration is sensitive to ballooning modes as analyzed by the Code for Ballooning Rapid Analysis (COBRA) [3]. These set the β MHD stability limits for the reference configuration. The field line-bending term is weakened as a result of the small number of field periods (the connection length R/N is relatively long). This seems to be the dominant adverse effect on stability in QPS. The pressure profile for the reference configuration has been optimized for ballooning stability at $\beta = 2\%$, with the constraint $dp/d\psi = 0$ at the plasma edge to avoid edge currents. As β is increased above 2% (by scaling the pressure profile and increasing the plasma current to maintain bootstrap alignment), a region of instability appears in the outer half of the plasma. For a coil configuration similar to the reference case, free boundary equilibria with higher β limits were obtained by allowing an edge pressure pedestal. Those configurations had a β limit of > 2.5%. This class of profiles may develop naturally as a result of H-mode physics.

The finite current in the QPS configuration makes it necessary to address the issue of low-n ideal MHD modes which can be destabilized by current and pressure gradients. The TERPSICHORE stability code [4] was used to analyze vertical ($n = 0$) and kink ($n = 1$) mode stability of the reference configuration. This configuration is stable to both vertical and kink modes at $\beta = 2\%$. The vertical and kink stability of QPS configurations with plasma beta up to $\beta = 5\%$ were also analyzed. All the cases were stable to vertical modes. Only the $\beta = 5\%$ case with a bootstrap-aligned current of 112 kA was unstable to kink modes with a kink

eigenvalue of 5.4×10^{-4} (in units of an Alfven time). Thus, kink and vertical modes are not an issue for QPS.

The vertical stability is due primarily to the external rotational transform. An analytic stability criterion for vertical mode in a large aspect ratio current-carrying stellarator has been developed (for constant current density and constant external rotational transform) [5]. The stability criteria relates the fraction of edge rotational transform, $F = \iota_{external}/\iota_{total}$, to the axisymmetric elongation, κ: $F \geq (\kappa^2 - \kappa)/(\kappa^2 + 1)$. The external transform is stabilizing because the external poloidal flux enhances the field line bending energy relative to the current-driven term for the vertical instability. For the reference configuration, we have $F = 0.697$, $\kappa = 2.765$, and $(\kappa^2 - \kappa)/(\kappa^2 + 1) = 0.565$, resulting in the condition being well-satisfied. This criterion is met for all of the QPS reference plasmas and is consistent with stability to vertical modes for all of these.

IV. Conclusions

The proposed QPS experiment is a very-low apsect ratio stellarator with moderate, bootstrap-aligned plasma current. The MHD stability limits are set by ballooning modes rather than kink or vertical modes. The ballooning beta limit is approximately ~2%. The experimental ballooning beta limit may be higher than this if pressure profiles with edge pedestals are obtained. QPS is stable to Mercier modes up to $\beta \sim 2.5\%$. Kink and vertical modes are not an issue for the QPS configuration due to the low plasma current (~40 kA of neoclassical bootstrap current at $\beta = 2\%$). QPS plasmas are stable to kink and vertical modes up to $\beta = 2\%$.

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