High-Beta Quasi-Poloidally Symmetric Stellarator Configurations

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I. Introduction

High-energy density, compactness, and steady-state operation are all attractive features for a fusion reactor. While a stellarator reactor allows for steady-state operation, the poor confinement of present day stellarators relative to axisymmetric devices seems to preclude a compact stellarator reactor. Moreover, stability limits of ideal magnetohydrodynamic interchange modes can limit the obtainable β in three-dimensional magnetic configurations, thus impacting the achievable energy-density. Here, β is the ratio of the plasma pressure to the magnetic pressure, $\beta = p/B^2$, and $\langle\beta\rangle$ indicates the volume average β.

The designs of a number of recent stellarator experiments have incorporated quasi-symmetry in the magnetic spectrum in order to achieve improved neoclassical confinement. The improved confinement has allowed the design of more compact stellarator experiments. Among these quasi-symmetric configurations, the most compact stellarator design is that of the Quasi-Poloidal Stellarator (QPS, a proposed quasi-poloidal symmetric device) [1]. Quasi-poloidal symmetry is defined as the magnetic field strength, $|B|$, being independent of the poloidal angle, $\partial|B|/\partial\theta = 0$, in flux coordinates. QPS is a two-field period device with a race-track shape and very small aspect ratio, $A < 3$, where A is the ratio of the average major radius to the average minor radius. A reference QPS configuration is described in the next section.

The focus of this work is the stability properties of QPS plasma at high-β. While the planned experimental program for QPS calls for operation at $\langle\beta\rangle \sim$ 1-2%, the similarities in the magnetic spectrum between QPS and a class of tokamak-stellarator hybrid configurations which have very-high MHD stability β limits [2] have led us to examine the properties of high-β QPS plasma. In particular, second-stability access in the QPS configuration is explored. Second ballooning stability is a region of interchange stability for large pressure gradients [3]. While there has been some concern that a region of second stability does not

exist for stellarators [4], more recent work indicates that a second stability does exist for a variety of stellarator configurations at very large pressure gradients [2,5]. In this work, we show that a region of second stability exists in QPS at moderate plasma β.

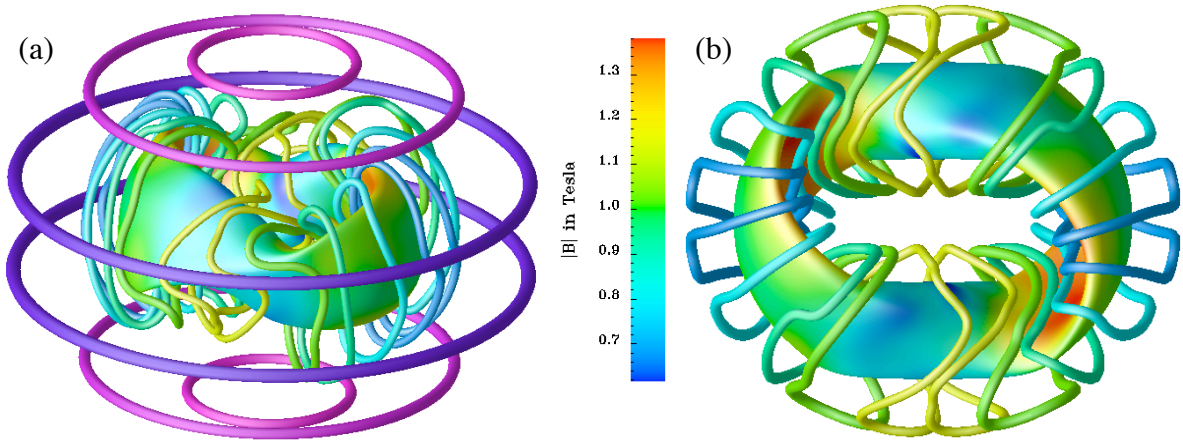

Figure 1. (a) Reference QPS coil set (toroidal field coils not shown) with the last-closed-flux surface, color on the surface indicating $|B|$ and (b) a portion of the last-closed-flux surface with a cutaway showing a cross-section of nested surfaces.

II. The QPS Configuration

The coils and outer plasma surface for the reference QPS configuration are shown in Figure 1. The coil set includes 20 modular coils with 5 distinct coil types, 3 pairs of circular vertical field coils, and 12 toroidal field coils (the toroidal field coils are not shown are the toroidal field coils). The plasma current profile for the reference configuration is consistent with the predicted bootstrap current profile. QPS will also have the capacity to drive Ohmic current. The impact of different current profiles on ballooning stability in QPS is discussed in a later section.

III. Second Ballooning Stability in QPS

The VMEC code [6] is used to obtain an equilibrium and infinite-n ballooning mode stability is analyzed using the Code for Ballooning Rapid Analysis for VMEC coordinates (COBRAVMEC) [7]. For the reference configuration, a quadratic pressure profile, $p(S) = p_0(1 - S)^2$, was chosen for simplicity. Ballooning growth rates as a function of the normalized flux, S, are shown in Figure 2a. As the plasma pressure is increased, the plasma first becomes ballooning unstable at $\beta \sim 2\%$. The region of instability grows until $\beta \sim 6\%$, where a region of second stability appears as shown in Figure 2b. Optimization for stability via variation of the plasma current profile, pressure profiles, and the currents in the external coils can minimize the gap between first and second stability to $\beta = 2.5 - 5.5\%$.

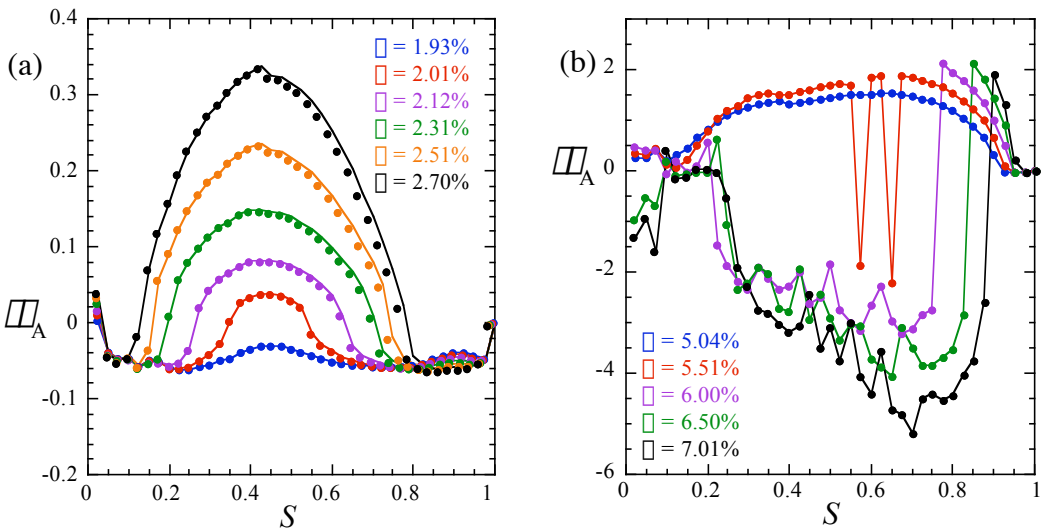

Figure 2. Ballooning growth rates from COBRAVMEC as a function of the normalized flux, *S*, for various indicating (a) the first stability boundary and (b) the onset of second stability.

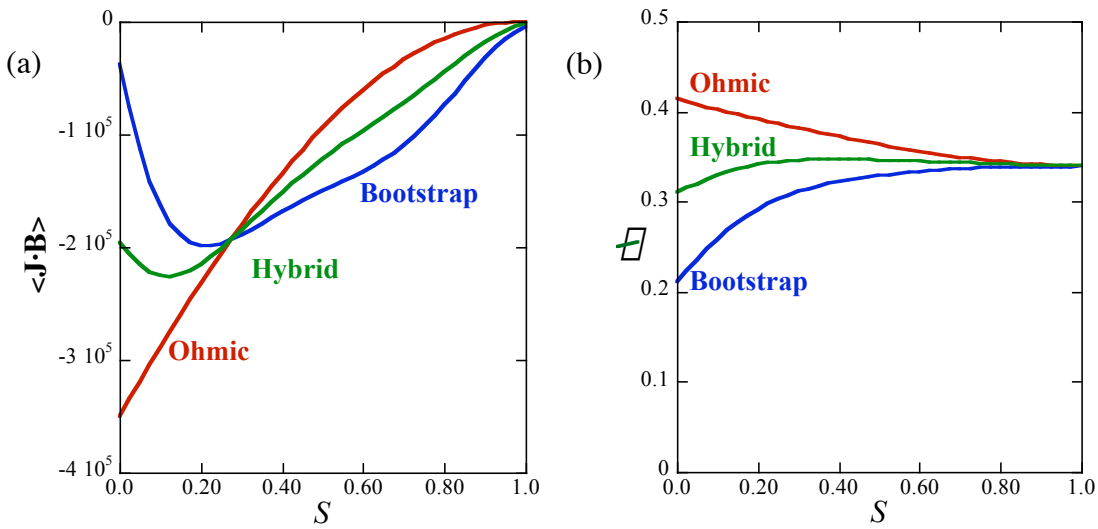

Figure 3. (a) Three field-aligned current profiles used to test the impact of the plasma current profile on access to second stability and (b) the respective rotational transform profiles for these current profiles.

IV. Impact of the Plasma Current Profile on Ballooning Stability

Three plasma current profiles used for testing the impact of the plasma current profile on ballooning stability in QPS are shown in Figure 2a. These consist of a bootstrap profile which has been optimized to match the predicted bootstrap current, an Ohmic profile peaked on axis, and a hybrid profile corresponding to an average of the Ohmic and bootstrap profiles. The corresponding rotational transform profiles for a QPS plasma with = 2% and a total plasma current of 41 kA. The Ohmic current results in a reverse-shear rotational transform profile even for this small amount of current.

The ballooning stability results from COBRAVMEC are shown in Figure 3 as contour plots of the growth rate versus normalized flux, S, and volume average β. The gap between first and second stability is largest for the Ohmic current profile and smallest for the bootstrap current profile. For the bootstrap current profile, the plasma becomes unstable at β > 2% and exhibits regions of second stability for β > 5.5%.

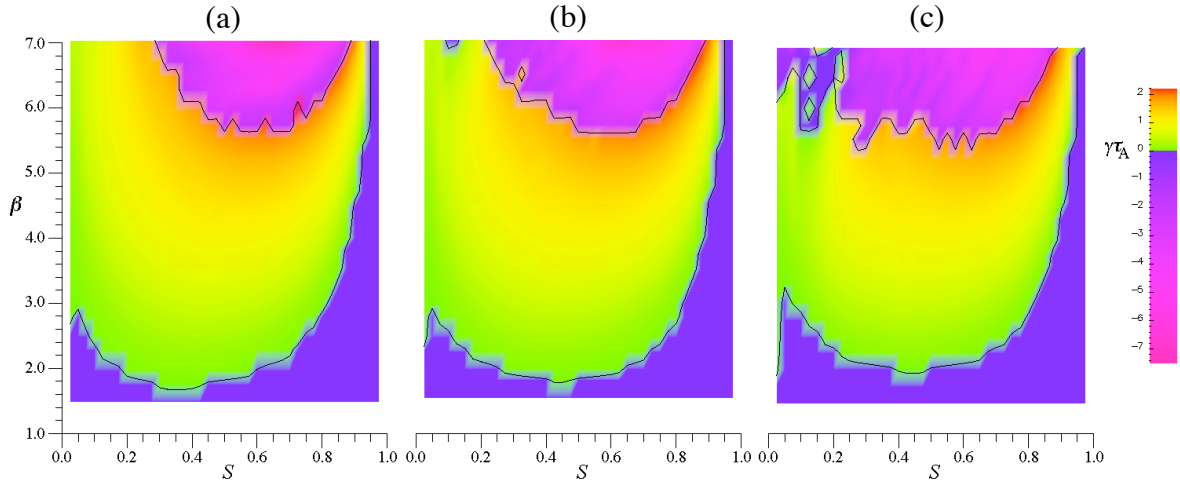

Figure 3. Contours of ballooning growth rates from COBRA as a function of the volume-average β and the normalized flux, S, for (a) Ohmic, (b) hybrid, and (c) bootstrap current profiles.

V. Conclusions

A region of second ballooning stability exists in QPS with a large region of the plasma becoming second stable for β > 6%. The plasma current profile impacts the gap between first and second stability with a bootstrap current profile resulting in the smallest gap.

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