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HIGH β QUASI-POLOIDALLY SYMMETRIC COMPACT STELLARATOR CONFIGURATIONS

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Abstract. This paper concerns a class of compact tokamak-stellarator hybrid configurations with a $|B|$ spectrum which exhibits approximate poloidal symmetry. These configurations are low aspect ratio devices (A = 2.5-4) with a low number of field periods (2-4). They are hybrids in the sense that the plasma current provides the majority of the rotational transform. The role of the modular coils is to reduce the bootstrap current (which is typically 1/3 -1/5 that in the equivalent tokamak) as well as to provide a small amount of vacuum transform. Self-consistent bootstrap current profiles (in which the bootstrap current provides the equilibrium current) have been obtained in the range $2\% \leq \beta \leq 23\%$. These configurations have a high shear, tokamak-like rotational transform profile [$\iota(0) \sim 0.4$ to $\iota(a) \sim 0.1$] with strong magnetic wells and high Mercier and ballooning stability β-limits. Due to the low bootstrap current, these configurations are stable to low-n ideal MHD kink modes for high values of β, significantly larger values (7-11% for kink and vertical stability) than in an equivalent tokamak with no wall stabilization. These configurations have good neoclassical confinement which improves with β as surfaces of constant $|B|$ become more aligned with flux surfaces. The small external transform and low number of field periods result in relatively simpler modular coils compared with conventional, lower current, compact stellarators.

I. Introduction

Recent work on stellarator design theory has focused on configurations with approximate symmetry of the $|B|$ spectrum in order to achieve improved neoclassical confinement [1]. This work has led to quasi-symmetric configurations such as the National Compact Stellarator Experiment (NCSX, a proposed quasi-axisymmetric device) [2], the Helically Symmetric Experiment (HSX, a quasi-helically symmetric stellarator) [3], and the Quasi-Poloidal Stellarator (QPS, a proposed quasi-poloidally symmetric device) [4]. This last quasi-symmetry, quasi-poloidal symmetry (qps), has many beneficial properties. In the limit of *exact* poloidal symmetry, the canonical angular momentum $p_\theta = mv_\theta + eA_\theta$ is conserved and orbit excursions would be limited to the gyroradius in the *toroidal* field, which is usually much smaller than the *poloidal* gyroradius (banana width) characteristic of quasi-axisymmetric devices (e.g., NCSX or tokamaks). This reduction in orbit size implies a concomitant reduction in the bootstrap current compared to tokamaks. Thus devices with qps tend to operate either with significantly smaller bootstrap current than in axisymmetric devices (for the same ι, or $1/q$, the potential reduction is $\sim\iota/N$) and/or at lower ι (higher q). Note that the implied smaller poloidal flux in these devices does not necessarily lead to increased neoclassical losses because the limiting toroidal gyroradius remains quite small.

The optimization of qps configurations which have bootstrap consistent field-aligned current (i.e., the equilibrium current is matched to the predicted bootstrap current) has led to

the discovery of a new class of configurations which have very-high MHD stability β limits and good confinement properties [5]. These configurations are compact (A = 2.5–4) tokamak-stellarator hybrid configurations: the bootstrap consistent field-aligned current provides the majority of the rotational transform (>90%) while the role of the non-axisymmetric components of $|B|$ is to reduce the bootstrap current relative to an axisymmetric device. The predicted bootstrap current is 1/3-1/5 that in an equivalent axisymmetric device. The lower current (for the same ι) enables these configurations to be stable to kink and vertical modes up to $\beta \sim 11\%$. These configurations have extremely high second stability ballooning limits ($\beta >$ 23%). They have been optimized for improved neoclassical transport by both enhancing the degree of qps and by using the DKES transport code in a stellarator optimization routine [4]. The equilibrium, MHD stability, and confinement properties are elaborated upon in the following sections.

II. Equilibrium

The prototypical high β, qps configuration is shown in Figure 1. This is a three field period, A = 3.7, β = 15% plasma which has an equilibrium current of 172 kA when the magnetic field strength is set to $\langle B \rangle$ = 1 T. The equilibrium current is consistent with that predicted by a low-collisionality bootstrap code. This plasma current produces the majority of the tokamak-like rotational transform [$\iota(0) \sim 0.4$ to $\iota(a) \sim 0.1$]. The profiles of pressure, rotational transform, and field-aligned current are shown in Figure 2. In addition to the equilibrium current, Fig. 2c also shows the predicted bootstrap current and the bootstrap current in an equivalent tokamak which is a factor of ~4 larger (note that the field-aligned current is anti-parallel to the magnetic field direction).

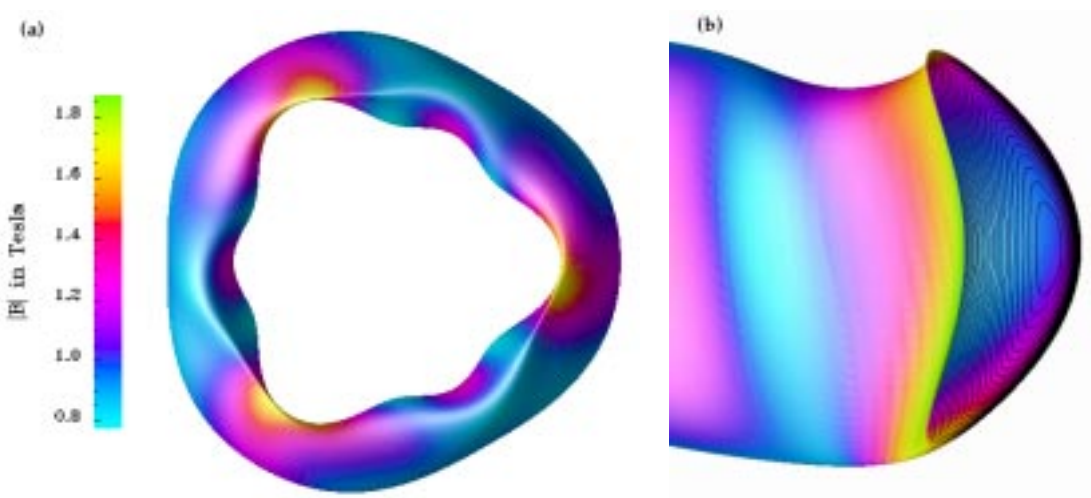

Figure 1. (a) Last closed flux surface and (b) partial last closed flux surface with a cutaway showing cross sectional surfaces for a three-field period, β=15%, qps configuration.

The extent of qps in these configurations is not readily apparent from the variation of $|B|$ on the outer surface as shown in Fig. 1. Since these configurations have been optimized for low aspect ratio, the toroidicity induced, m = 1, n = 0, Fourier component of $|B|$ is nonnegligible and reduces the degree of qps at larger r. The profiles of the ten largest Fourier coefficients of $|B|$ in Boozer coordinates are shown in Figure 3a. While the two largest are the lowest poloidally symmetric terms, the m = 1, n = 0 component is the next largest. A more quantitative measure of qps, shown in Figure 3b, is the ratio of the sum of all $B_{m\neq 0,n}$ components to the sum of all $B_{m=0,n\neq 0}$ components. Using this measure of qps, these configurations are roughly 50% more symmetric than the proposed lower-current QPS experiment and a factor of 2 more QP symmetric than W7-X [6]. Efforts to further enhance

the degree of qps of these configurations led to configurations with highly elliptical cross sections that were not desirable.

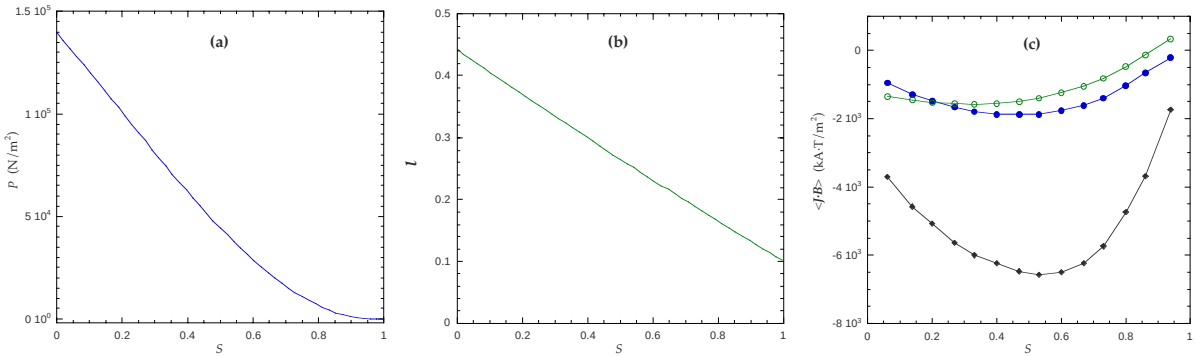

Figure 2. Profiles of (a) pressure, (b) rotational transform, and (c) field-aligned current for a qps, high-β configuration. In (c), open green circles is equilibrium current, closed blue circles is the bootstrap current, and black diamonds is the bootstrap current in an equivalent tokamak.

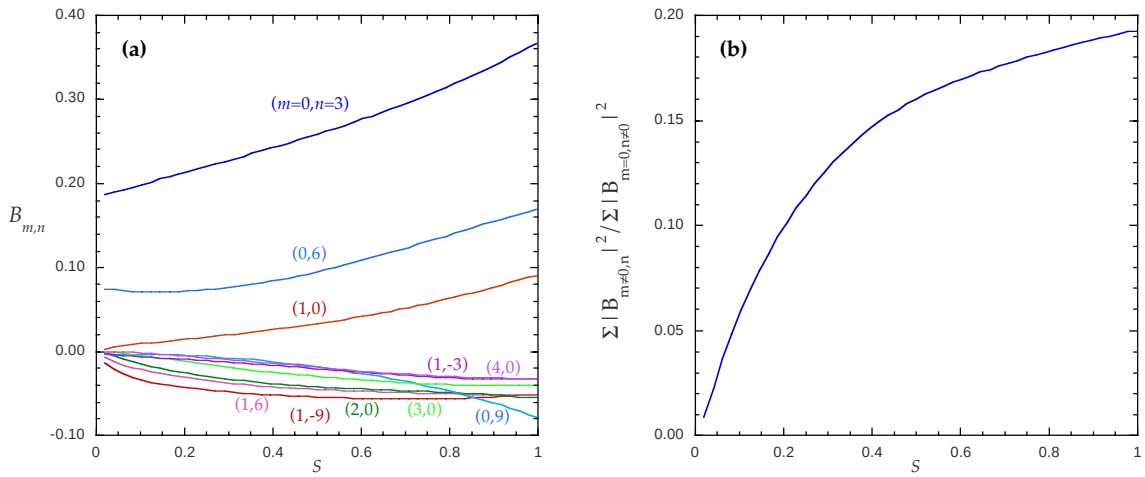

Figure 3. Profiles of (a) the largest 10 Fourier coefficients of $|B|$ in boozer coordinates and (b) the ratio of the sum of all the poloidally asymmetric modes to the sum of all the poloidally symmetric modes (excluding the 0,0 mode).

III. Stability

The optimization of these configurations for high-β ballooning stability was done using the COBRA stability code [7]. By optimizing the shape of the plasma boundary along with small variations in the pressure profile, ballooning stable configurations with bootstrap aligned current were found in the range 2% < β < 23%. However, starting with a high-β case (β = 15%) and lowering the pressure without changing the boundary shape did lead to the onset of ballooning instability in these configurations. These configurations are in a second stable ballooning regime. A consistent pathway from lower β configurations to these high-β cases is currently under investigation.

The plasma current in these qps configurations is large relative to conventional stellarators which makes them potentially susceptible to vertical and kink modes. The stability of these configurations to kink and vertical modes was analyzed using the TERPSICHORE code [8]. In spite of the finite plasma current and high β, the configuration discussed above is stable to vertical modes and only weakly unstable to an external kink mode. Keeping the same shape but scaling β down to ~11% (but without modifying the rotational transform) leads to stabilization of the kink mode. At this β, the Troyon factor ($\beta_N = \beta(\%)[a(\mathrm{m})B(\mathrm{T})/I(\mathrm{MA})]$) is β_N = 19. This is a significantly larger value of β (for kink-

stability) than in the equivalent tokamak with no wall stabilization. In combination with the lower current compared with a tokamak, this feature gives rise to a Troyon factor exceeding 10, which is much larger than the typical value ~3 for achieved for advanced tokamaks.

IV. Transport

The high degree of qps in these configurations also results in acceptable neoclassical confinement times despite the relatively low rotational transform. Ion and electron neoclassical confinement times were calculated using a Monte Carlo calculation. For $\langle B \rangle = 1$ T, $\langle R \rangle = 0.86$ m, and in the moderate collision frequency regime, we find $\tau_{Eneo} = 58$ ms and $\tau_{Eneo}/\tau_{ISS95} = 3.6$ for expected values of the radial electric field and with a confinement enhancement factor of $H = 1$ (here, τ_{Eneo} is the global neoclassical energy confiement time and τ_{ISS95} is the confinement time predicted by the ISS95 empirical scaling law [9]). Under these conditions, anomalous processes should dominate the thermal transport. The transport was also tested using the DKES transport code. Confinement was further enhanced by using DKES directly in the optimization. Factors of 2 improvement in τ_{Eneo} were obtained by minimizing the local transport coefficients at several surfaces without sacrificing ballooning and kink stability. Furthermore, as β increases, the drift and flux surfaces approach omnigeneity (achieve better alignment), so that alpha particle confinement is found to improve with increasing β.

V. Conclusions

Quasi-poloidal symmetry allows a pathway to ideal MHD stable, high-β hybrid configurations. The rotational transform in these configurations is produced primarily by plasma current; the role of the nonaxisymmetric components of $|B|$ is to reduce the self-consistent bootstrap current, thus maintaining MHD stability at higher β than in a tokamak at the same rotational transform. Ongoing research includes optimizing these configurations for improved confinement, exploring access to these second stability regimes, and testing the link between these configurations and the lower-β QPS experiment.

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