29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-2.111 (2002)

High-Beta Quasi-Poloidally Symmetric Stellarator Configurations

S. P. Hirshman, D. A. Spong, L. A. Berry, A. J. Deisher, G. Fu, J. F. Lyon, R. Sanchez

[a]*University of Montana, Missoula MT 59812, USA*
[b]*Oak Ridge National Laboratory, P.O. Box 2009, Oak Ridge TN 37831-8070, USA*
[c]*Universidad de Carlos III de Madrid, Madrid, Spain*
[d]*Princeton Plasma Physics Laboratory, P.O. Box 451, Princeton, NJ 08502 USA*

Abstract. Compact stellarator configurations have been obtained with good neoclassical confinement that are stable to both pressure- and current-driven modes for high values of β. These configurations are drift-optimized tokamak-stellarator hybrids with a high shear tokamak-like rotational transform profile primarily from a self-consistent bootstrap current. The role of the modular coils is to reduce the bootstrap current to only 1/3-1/5 of that in an equivalent tokamak. Self-consistent bootstrap current profiles have been obtained for plasma pressures in the range 2% < β < 23%. These configurations have strong magnetic wells and consequently high interchange stability beta limits up to β = 23%. Because of the reduced bootstrap current, these configurations are stable to low-*n* ideal MHD kink modes with no wall stabilization for values of β (~ 11%) significantly larger than in an equivalent advanced tokamak. The combination of high beta limits and low bootstrap current in this hybrid device yields a Troyon factor (~19) that is much larger than that for advanced tokamaks. The $|B|$ spectrum exhibits approximately poloidally symmetry which results in good neoclassical confinement. Surfaces of constant $|B|$ become more aligned with flux surfaces and the neoclassical bootstrap current transport coefficient decreases as beta increases. This results in a unique form of configurational invariance in which the bootstrap current becomes nearly independent of β at higher values of β.

I. Introduction

Three-dimensional magnetic configurations are often limited in the obtainable β due to stability limits of ideal magnetohydrodynamic interchange modes. Here, β is the average ratio of the plasma pressure to the magnetic pressure, $\beta = \langle p/B^2 \rangle$. Both ballooning and Mercier modes are of concern in the design of stellarator experiments. In contrast, β values above the limit set by first ballooning stability are obtainable in axisymmetric configurations due to the existence of a region of second stability [1]. A second stability regime for three-dimensional configurations would make operation at high-β possible in a stellarator fusion reactor. Hegna and Hudson, however, have suggested that a second-stability region does not exist in general three-dimensional equilibria [2] due to the overlap of regions of minimum magnetic shear and maximum unfavorable curvature. Here, evidence for a second stability region in a compact, high-β stellarator is presented.

Recent progress in the numerical codes used to design and optimize stellarator configurations has been outstanding. These tools have been developed in the process of designing three-dimensional magnetic configurations which exploit approximate symmetry in the magnetic field in order to achieve improved neoclassical confinement [3]. These developments enable the simultaneous optimization of equilibrium, stability, and transport properties [4]. Among the goals used in designing the recently proposed Quasi-Poloidal Stellarator (QPS, a proposed quasi-poloidally symmetric device) are a compact configuration ($A < 3$), bootstrap current alignment (i.e., the equilibrium current is matched to the predicted bootstrap current), excellent neoclassical confinement, stability to interchange modes, and enhanced quasi-poloidal symmetry [5]. Quasi-poloidal symmetry (qps) is defined as the magnetic field strength, $|B|$, being independent of the poloidal angle in Boozer coordinates [6].

The optimization of qps configurations which have bootstrap consistent field-aligned current led to the discovery of a new class of configurations which have very-high MHD stability β limits [7]. 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 β ~ 11%. These configurations have extremely high second stability ballooning limits (β > 23%). They have been optimized for improved neoclassical transport by both enhancing the degree of qps and by using the a transport code in a stellarator optimization routine. The equilibrium and MHD stability properties, including the second stability region, are elaborated upon in the following sections.

II. High-β Equilibrium

The last closed flux surface of 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 is shown in Figure 1a. A two-field period, A = 2.7, β = 7% plasma which has an equilibrium current of 152 kA when the magnetic field strength is set to $\langle B \rangle$ = 1 T is shown in Figure 2a. The predicted bootstrap current provides the majority of the plasma current in both cases and is a factor of ~4 less than the bootstrap current in an equivalent tokamak. This plasma current produces the majority of the tokamak-like rotational transform [ι(0) ~ 0.4 to ι(a) ~ 0.1]. The extent of quasi-poloidal symmetry in these configurations is not readily apparent from the variation of $|B|$ on the outer surfaces shown in Fig. 1. However, the degree of quasi-symmetry of these configurations has previously been examined [7]. The quasi-symmetry results in improved neoclassical confinement in these configurations, especially for alpha particle confinement [4].

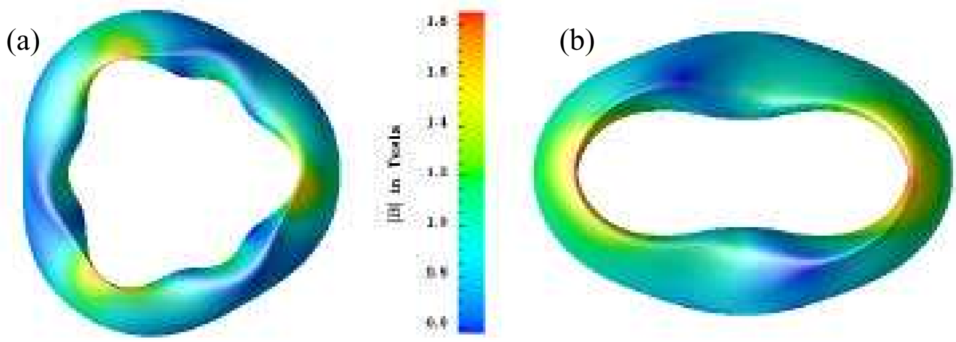

Figure 1. Last closed flux surface of (a) three-field period, β =15% and (b) two-field period, β =7%, quasi-poloidal symmetric stellarator configurations.

III. Second Stability

These configurations exhibit regions of second stability. The optimization of these configurations for high-β ballooning stability was done using the COBRA stability code [9]. 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 configuration optimized for high-β (e.g., the β = 15% case shown in Fig. 1a) and lowering the pressure without changing the boundary shape leads to the onset of ballooning instability in these configurations. Figure 2a shows pressure profiles used to determine ballooning stability at different values of β. Contours of the ballooning growth rates as a function of β and the normalized toroidal flux, *S*, are shown in Figure 2b. This configuration is stable on all surfaces at β = 15% and is stable for higher β as well. As β is lowered to 13%, a single surface near the edge becomes unstable. The edge region of instability broadens and the maximum growth rate becomes larger as β is lowered to 9%. As β is further lowered to 3%, the edge region of instability increases, but the peak growth rate decreases. If β is lowered even further, the region of instability spreads over the majority of the plasma cross section. The plasma finally becomes ballooning stable again for β < 0.5%.

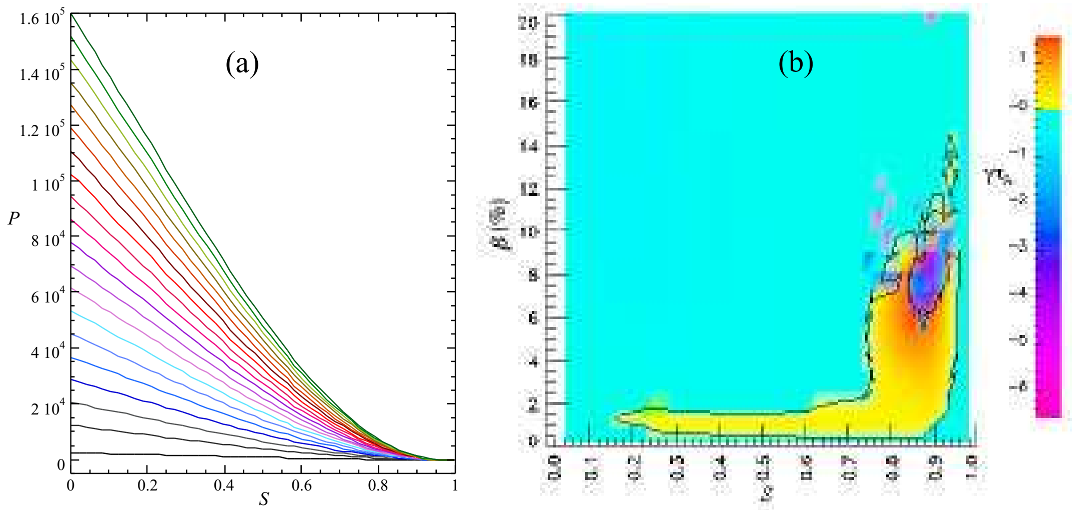

Figure 2. (a) Some of the pressure profiles for the equilibria used to calculate (b) contours of ballooning growth as a function of β and the normalized toroidal flux, *S*. The solid line indicates the stability boundary, yellow indicates unstable regions, and blue are stable regions.

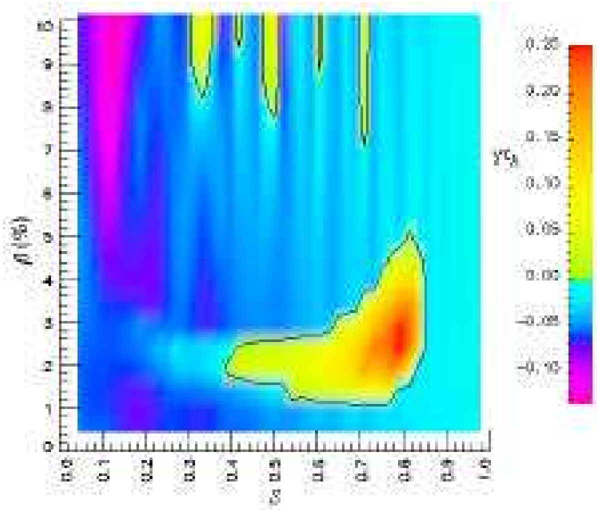

Figure 3. Contours of ballooning growth as a function of β and *S* for the two-field period configuration.

The two-field period configuration also exhibits a region of second stability. This configuration was optimized for ballooning stability at β = 7%. Using a scaled version of the same pressure profile, ballooning mode stability was examined as a function of β. Contours of the ballooning growth rates as a function of β and *S* are shown in Figure 3. This configuration is stable on all surfaces at β = 7%. As β is lowered to 5%, a region of weak ballooning instability enters in the edge plasma. As β is further lowered to below 1%, the plasma becomes stable again. In addition, the plasma becomes ballooning unstable at higher β > 7%.

This stability behavior as a function of β indicates that these plasmas are in the second-stable ballooning regime. We note that relatively small shape and profile modifications can produce stable plasmas at all values of $\beta < 23\%$. A consistent pathway from lower β configurations to these high-β cases is currently under investigation.

IV. Kink and Vertical Stability

The plasma current in these 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 [10]. In spite of the finite plasma current and high β, the three-field period configuration 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 $\beta_N = 19$. This is a significantly larger value ofβ (for kink-stability) than in the equivalent tokamak with no wall stabilization.

The two-field period configuration is susceptible to vertical mode instability [11]. The ideal MHD β limit for the vertical mode in these configurations is ~7%. Feedback stabilization of the vertical mode may allow access to these higher values of β in the two-field period configurations.

V. Conclusions

Quasi-poloidal symmetry allows a pathway to a second stable regime in a three-dimensional magnetic configuration. 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 b 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.

Acknowledgements: This research was supported by the U.S. DOE under Grant No. DE-FG 03-97ER54423 at the University of Montana and under contract DE-AC05-00OR22725 at Oak Ridge National Laboratory, managed by UT-Battelle, LLC.

References

[1] Hazeltine, R. D., and Meiss, J. D., *Plasma Confinement* (Addision-Wesley, Redwood City, 1992), pp. 309-312.
[2] Hegna, C. C., and Hudson, S. R., Phys. Plasmas **9**, 2014 (2002).
[3] Grieger, G., et al., Plasma Physics and Controlled Nuclear Fusion Research, Proceedings 13th International Conference, Washington, 1990, Vol. **3**, p. 525 (International Atomic Energy Agency, Vienna, 1991).
[4] Spong, D. A., Hirshman, S. P. et al., Nucl. Fusion **41**, 711 (2001).
[5] Lyon, J. F. and the QPS team, "QPS, A Low Aspect Ratio Quasi-Poloidal Concept Exploration Experiment", http://qps.fed.ornl.gov/, April 2001.
[6] Boozer, A. H., Phys. Fluids **23**, 904 (1980).
[7] Ware, A. S., Hirshman, S. P., et al., "High β Equilibria of Drift Optimized Compact Stellarators", submitted to Phys. Rev. Lett., (2002).
[8] Nührenberg, J., et al., Trans. Fusion Technology **27**, 71 (1995).
[9] Sanchez, R., Hirshman, S. P., Whitson, J., Ware, A. S., J. Comp. Phys. **161**, 576 (2000).
[10] Cooper, W. A., Singleton, D. B., Dewar, R. L., Phys. Plasmas **3**, 275 (1996).
[11] Fu, G. Y., Phys. Plasmas **7**, 1079 (2000).