INTERNATIONAL ATOMIC ENERGY AGENCY

17th IAEA Fusion Energy Conference
Yokohama, Japan, 19 - 24 October 1998

IAEA-CN-69/
IAEA-F1-CN-69/ICP/06 (R)

Physics Issues in the Design of a High β Quasi-Axisymmetric Stellarator

A. Reiman, L. Ku, D. Monticello, H. Mynick, A. Brooks, G. Fu, R. Goldston, L. Grisham, T. S. Hahm, Z. Lin, D. Mikkelsen, R. Nazikian, G. Neilson, N. Pomphrey, M. Redi, W. Reiersen, J. Schmidt, R. White, M. Zarnstorff, I. Zatz
Princeton Plasma Physics Laboratory, Princeton NJ 08543, USA

W. A. Cooper
CRPP-PPB, CH-1015 Lausanne, Switzerland

M. Drevlak, P. Merkel and C. Nührenberg
IPP-Euratom Association, D-17491 Greifswald, Germany

D. Batchelor, S. Hirshman, J.F. Lyon, R. Sanchez, D. Spong
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-8070, USA

M. Hughes
Advanced Energy Systems, 155 Thoreau Drive, Plainsboro, NJ 08536, USA

A. Boozer
Dept. of Applied Physics, Columbia University, New York, NY 10027, USA

W. Miner and P. Valanju
University of Texas at Austin, Austin, TX 78712-1081, USA

K. Y. Watanabe, N. Nakajima and M. Okamoto
National Institue for Fusion Science, Nagoya, Japan

B. Blackwell and J. Harris
Plasma Research Laboratory, Australian National University, Canberra, Australia

M. Isaev, A. Subbotin and M. Mikhailov
Kurchatov Institute, Moscow, Russia

Physics Issues in the Design of a High β Quasi-Axisymmetric Stellarator

A. Reiman, L. Ku, D. Monticello, H. Mynick, A. Brooks, G. Fu, R. Goldston, L. Grisham, T. S. Hahm, Z. Lin, D. Mikkelsen, R. Nazikian, G. Neilson, N. Pomphrey, M. Redi, W. Reiersen, J. Schmidt, R. White, M. Zarnstorff, I. Zatz
Princeton Plasma Physics Labomtory, Princeton NJ 08543, USA

W. A. Cooper
CRPP-PPB, CH-1015 Lausanne, Switzerland

M. Drevlak, P. Merkel and C. Niihrenberg
IPP-Euratom Association, D-l 7491 Greifswald, *Germany*

D. Batchelor, S. Hirshman, J.F. Lyon, R. Sanchez, D. Spong
Oak Ridge National Laboratory, Oak Ridge, Tennessee 37831-8070, USA

M. Hughes
Advanced Energy Systems, 155 Thoreau Drive, Plainsboro, NJ 08536, USA

A. Boozer
Dept. of Applied Physics, Columbia University, New York, NY 10027, USA

W. Miner and P. Valanju
University of Texas at Austin, Austin, TX 78712-1081, USA

K. Y. Watanabe, N. Nakajima and M. Okamoto
National Institute *for Fusion Science, Nagoya,* Japan

B. Blackwell and J. Harris
Plasma *Research Laboratory, Australian National University, Canberra, Australia*

M. Isaev, A. Subbotin and M. Mikhailov
Kurchatov Institute, MOSCOW, Russia

1 . Introduction

Present day stellarators have aspect ratios large compared to those of tokamaks. The transport optimized stellarators under construction, W7X and HSX, have aspect ratios R/(a) = 11 and 8 respectively. We have been pursuing the design of compact stellarator configurations with aspect ratios comparable to those of tokamaks (R/(a) = 2.1 – 3.5) and good transport and stability properties. To provide good drift trajectories, we focus on configurations that are close to quasi-&symmetric (QA) [1, 2], an approach that is well suited to lower aspect ratios. The plasma can rotate freely in the direction of quasi-axisymmetry, allowing us to apply the same techniques for transport barrier formation that work in tokamaks.

Our near quasi-axisymmetric configurations have drift trajectories similar to those of tokamaks, aspect ratios comparable to those of tokamaks, and bootstrap current as well as average ellipticity and triangularity comparable to that of advanced tokamaks. They therefore tend to look like hybrids between stellarators and advanced tokamaks. Relative to unoptimized stellarators, they have improved neoclassical confinement. They have a much smaller aspect ratio than the drift-optimized stellarators under construction. The bootstrap current, large relative to that of other drift-optimized stellarators, is used to advantage in ameliorating coil design issues and in suppressing magnetic islands. Although the bootstrap current can potentially be used to great benefit, it also brings with it some potential issues. Bootstrap currents may drive instabilities and may reintroduce disruptions into the stellarator. We attempt to minimize this risk by using the results of extensive stability calculations to guide the design, but experimental studies will be needed for a definitive determination of the conditions under which disruptions

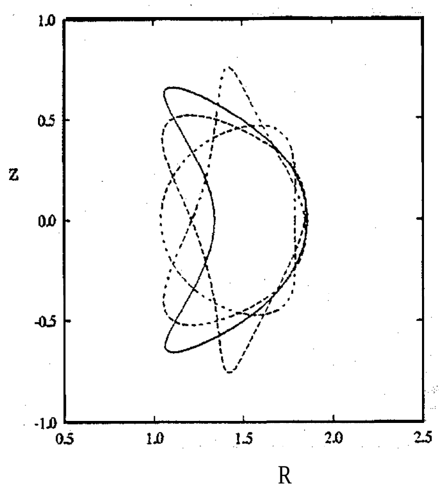

Figure 1: **Plasma cross-sections of a 3-period quasi-axisymmetricstellarator at $\phi = 0$, $\pi/6$, n/3, and $\pi/2$.**

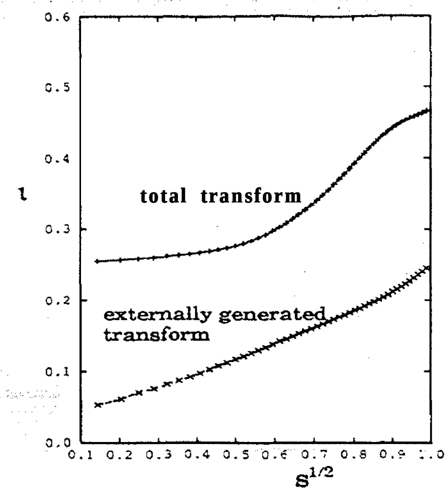

Figure 2: **Rotational transform profile of the configuration shown in Fig. 1.**

are avoided. An experimental study of the potential benefits and dangers of bootstrap currents would be a key focus of a proposed QA stellarator experiment.

Relative to advanced tokamaks the QA configurations we have studied have the potential advantages that the externally generated transform reduces or eliminates the need for rf current drive, and provides control over MHD stability properties. Unlike the tokamak, it is possible to have a monotonically increasing ι profile. (The reversed-shear tokamak has a shear reversal layer at which ideal stability is problematic, and outside of which neoclassical tearing modes are unstable.) A combination of externally generated shear and nonaxisymmetric corrugation of the plasma boundary provides stability to external kink modes even in the absence of a conducting wall. Previous experiments on hybrid tokamak-stellarator configurations on W7A and CLEO found that even a modest level of externally generated transform was sufficient to suppress disruptions.[3, 4].

Figures 1 and 2 show the plasma boundary and the corresponding rotational transform profile for a 3-period configuration with R/(a) $\approx$ 3.4. (The radial variable s in Fig. 2 is the toroidal flux normalized to its value at the plasma boundary.)

2. Physics Issues and Configuration Design

A key problem in designing an attractive QA configuration is the ballooning β limit. Earlier quasi-symmetric configurations display ballooning beta limits in the 1-2% range.[5, 6] We have found that we can solve this problem by imposing a strong axisymmetric (n = 0) component of ellipticity and triangularity on the shape of the outer boundary in our QA configurations. This is similar to the approach used in tokamaks, where it is well known that appropriate shaping of the plasma cross-section can have a strongly stabilizing effect on ballooning modes. This approach has allowed us to open up a previously unexplored regime of low aspect ratio, quasi-axisymmetric configurations with good ballooning stability properties. We have explored the properties of a range of configurations in this regime, with the fraction of the transform generated externally ranging from 20% to about 50%, and with a variety of ι profiles and a range of aspect ratios.

Our initial studies of QA configurations focused on R/(a) $\approx$ 2, an aspect ratio that was regarded as relevant for evaluating the potential attractiveness of the QA stellarator as a reactor concept. More recently we have refocused our studies on somewhat larger aspect ratios, motivated by an interest in converting the PBX tokamak to a stellarator. For $R/\langle a\rangle \approx 2$, our configurations typically have ballooning β limits in the 6% to 7% range, with one configuration found to be ballooning stable at β = 11%. The ballooning β limits are found to be somewhat lower at higher aspect ratio, scaling roughly like $\langle a\rangle/R$. The configuration corresponding to Figs. 1 and 2 is ballooning stable at a β of 4%.

Global ideal MHD stability codes[7] are used to monitor the global MHD stability properties of our configurations and help guide the design. We have found that we can stabilize the external kink mode in our configurations either by imposing adequate externally generated shear or by an appropriate three-dimensional corrugation of the plasma boundary.[8] We have obtained configurations that are stable to external kink modes at a β of 7.5%, with the wall at twice the minor radius, where we believe it has little stabilizing effect on the mode. The configuration of Fig. 1 is stable to external kinks at β = 4%. This is to be contrasted with the situation in reverse-shear tokamaks, which, because of the broadness of the current profile associated with bootstrap driven currents, require a close fitting conducting shell to stabilize the external kink mode. To maintain stability on the L/R time scale of the wall, these devices will either need to rapidly rotate the plasma, raising issues of recirculating power, or they must provide multi-mode feedback stabilization.

The bootstrap current is determined by the Fourier spectrum of mod(B) in Boozer coordinates. In quasi-axisymmetry, the $n \neq 0$ Fourier coefficients vanish, and the bootstrap current looks like that in a tokamak. In particular, the bootstrap current is comparable in magnitude to that in a tokamak, and is in a direction that reinforces the externally generated rotational transform. The bootstrap current can be used to advantage. To the extent that it provides a significant fraction of the rotational transform, it eases coil design. Also, if the shear is designed to have the appropriate sign relative to the direction of the plasma current, the perturbed bootstrap currents suppress magnetic islands. This is the inverse of the neoclassical tearing instability that has been seen in tokamak experiments. An estimate of this effect finds that, for a configuration in which 50% of the rotational transform is supported by the bootstrap current, an island whose width would otherwise be 10% of the minor radius is suppressed by a factor of 20, to about 0.5% of the minor radius.

Our design procedure for quasi-axisymmetric stellarators adopts, as a starting point, advanced tokamak pressure and current profiles in which the current profile is well aligned with the bootstrap current drive. Because the bootstrap current is determined by the n = 0 Fourier components of mod(B), we retain rough consistency of the current with the bootstrap drive. Adjustments are made in the profiles using a three-dimensional bootstrap code[9]. We have verified that adequate external transform entirely eliminates the need for a driven seed current.

To handle the bootstrap currents properly, it is necessary to deal with the issue of resonances. Expressions for the bootstrap current in stellarators commonly given in the literature possess resonances at the rational surfaces, arising from large excursions of toroidally trapped particles in the low collision frequency regime. These resonances are due to a neglect of particle drifts and collisions. A simple detuning function has been derived to broaden the resonances. A Monte-Carlo delta-f technique, used to simulate the bootstrap current, has shown that the detuning function is a good fit to the current near the resonances. Without this resonance broadening term, calculation of equilibria with self-consistent bootstrap current was impossible for most QAS configurations.

The neoclassical transport in our configurations is monitored with Monte-Carlo codes[10] to confirm that the degree of quasi-axisymmetry is adequate. We have verified that the neoclassical transport is dominated by the axisymmetric contribution for the configuration of Fig. 1.

In contrast to conventional stellarators, it is possible to sustain toroidal rotation in a quasi-axisymmetric configuration. For suppression of turbulence, the E x B shearing rate which contains the relevant geometric dependence has been analytically derived:[11]

$$\omega_E = \frac{k_\perp}{k_\psi}\frac{|\nabla\psi||\mathbf{B}\times\nabla\psi|}{B^2}\left|(\iota - N)\frac{\partial}{\partial\psi}\left\{\frac{1}{\iota - N}\frac{\partial}{\partial\psi}\Phi_0(\psi)\right\}\right|. \tag{1}$$

Here, $(\iota - N)\frac{\partial}{\partial\psi}\left\{\frac{1}{\iota-N}\frac{\partial}{\partial\psi}\Phi_0(\psi)\right\}$ is a function of the toroidal flux (ψ) only, $|\nabla\psi||\mathbf{B}\times\nabla\psi|/\mathbf{B}^2$ is the angle (α) dependent form factor, and the first factor describes dependence on the eddy shape. k_ψ and $k_\perp$ are the components of the $\mathbf{k}$ vector of fluctuation in the radial $(\mathbf{e}_\psi)$ and nonradial perpendicular $(\mathbf{b} \times \mathbf{e}_\psi)$ directions. With the assumption of $k_\perp/k_\psi \simeq 1$ which is supported by fluctuation measurements on TFTR, ω_E can be expressed in terms of the equilibrium quantities only.

3. Experimental Implementation

We have been investigating several possible coil configurations capable of producing our design fields.[12] 0 ne option would convert the PBX tokamak to a QA stellarator, retaining the present vacuum vessel and toroidal field coils, adding auxiliary coils (possibly saddle coils) and associated support structure inside the vacuum vessel to produce the desired magnetic field. Another option would use modular coils, supplemented by vertical field coils to adjust the field as the pressure and current vary. The experiment would provide information on transport, MHD β limits, and disruptions in the compact QA stellarator regime, complementing the information that will be received from the W7X and LHD experiments.

This work was supported in part by U. S. DOE Contract No. DE-AC02-76-CH03073.

References

[1] J. Niihrenberg, W. Lotz, and S. Gori, in Theory *of Fusion Plasmas,* E. Sindoni, F. Troyon and J. Vaclavik eds., SIF, Bologna, 1994

[2] P.R. Garabedian, *Phys. Plasmas 3, 2483 (1996).*

[3] W VII-A Team, Nucl. Fusion 20, 1093 (1980).

[4] D. C. Robinson and T. N. Todd, Phys. Rev. Letters 48, 1359 (1982).

[5] J. N. Talmadge and W. A. Cooper, Phys. Plasmas 3, 3713 (1996).

[6] A. Reiman, L. P. Ku, D. Monticello, C. Niihrenberg, and W. Cooper, Plasma Physics Reports 23, 472 (1997).

[7] D.V. Anderson, A. Cooper, U. Schwenn and R. Gruber, *Linear MHD Stability Analysis of Toroidal 3D equilibria with TERPSICHORE* in "Theory of Fusion Plasmas," J. Vaclavik, F. Troyon and E. Sindoni eds. (Soc. Ital. Fisica – Editrice Compositori, Bologna, 1988) pp. 93-102; C. Schwab, Phys. Fluids B 5, 3195 (1993). Equilibria for these calculations, as well as for input to the other codes discussed in this paper, have been generated using VMEC: S. P. Hirshman, J.C. Whitson, Phys. Fluids 26 (1983) 3553.

[8] G. Y. Fu et al, this meeting

[9] Watanabe, K., et al., Nuclear Fusion 35 (1995), 335.

[10] H.E. Mynick, Plasma *Physics* Reports 23, 547 (1997); R. H. Fowler, J. A. Rome, J. F. Lyon, Phys. Fluids 28, 338 (1985).

[11] T.S. Hahm, Phys. Plasmas 4, 4074 (1997).

[12] M. Zarnstorff et al, Proceedings 1998 European Physical Society Meeting.