OBJECTIVES AND DESIGN OF THE QUASI-AXISYMMETRIC NCSX EXPERIMENT

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Designs for a compact quasi-axisymmetric stellarator experiment are being developed and studied, as part of a U.S. compact stellarator initiative. The goals of the experiment are to combine the enhanced confinement and MHD stability of recent tokamak experiments with the demonstrated strengths of stellarators: immunity from disruptions; no need for external current drive (especially off-axis); and external control of the magnetic transform and shear via coils. Quasi-axisymmetric (QA) stellarators [1,2] have a nearly axisymmetric magnetic field strength $|B|$ in Boozer coordinates, with deviations of only a few percent near the plasma edge. Since the drift-orbits are controlled by the variation of $|B|$ in Boozer coordinates [3], they have the same orbit confinement and neoclassical transport as a similar tokamak. In addition, rotation in the quasi-symmetric direction should be undamped, allowing efficient manipulation of the radial electric field shear for turbulent transport control by applied torque. The bootstrap current is the same as for a similar tokamak, raising the magnetic transform (dropping q) as β increases. Quasi-axisymmetric stellarators have been found to have a deep magnetic well and high β limits at low aspect ratios $\overline{A} \sim 3$.

Numerical optimization, discussed in a companion paper [4], is used to search for quasi-axisymmetric stellarators having a high β limit to both ballooning and kink modes, consistency with the bootstrap current, and a radially increasing magnetic transform profile (reversed shear). This shear profile provides neoclassical stabilization of tearing modes and equilibrium islands [5] at finite β. Configurations with 2 to 4 field periods and aspect ratios $\overline{A} \equiv R/\overline{a}$ between 2.1 and 3.9 have been investigated, where R is the major radius and $\overline{a}$ is the average minor radius. Strongly shaped configurations, with high average elongation and triangularity, have been found with calculated β limits due to ballooning and kink modes as high as 7% without an external conducting wall. The fraction of the magnetic transform due to the plasma shaping (from the coils) at the β limit has been varied from 20% to 50%, to provide adequate configuration control with significant bootstrap current. The predicted β limit decreases with increasing aspect ratio, as with tokamaks.

A medium scale experiment is being developed to test whether these attractive configurations can be attained. Its specific goals would be to: (1) demonstrate the ability of a compact stellarator to operate at $\langle\beta\rangle = 4 - 5\ \%$ without disruptions and determine the configuration requirements to avoid disruptions; (2) determine the β limiting mechanisms and their scaling; (3) test the adequacy of the neoclassical transport optimizations; (4) test the ability to control turbulent transport in a QA stellarator and determine its scaling; (5) test neoclassical stabilization of equilibrium islands and tearing modes; and (6) explore methods to control power and particle exhaust in compact stellarators. In order to minimize the expense and development time, we are planning to reuse of existing components of the PBX-M experiment, including heating systems, diagnostics, some of the coils, and the vacuum vessel. This would provide 6 MW of neutral-beam heating into a R = 1.5 m, $\overline{A} \sim 3.3$ plasma with toroidal magnetic field B_T up to 2 T, using the existing toroidal field coils. The heating power could be doubled by using existing ICRF generators.The present neutral-beam pulse length is 0.3 - 0.5 sec, but can be upgraded to several seconds. Representative operating points are shown in Table I. For comparison, PBX-M [6] obtained $\langle\beta\rangle$ = 6.8 % at B_T =1.1 T with 5.5 MW of NBI and a confinement time of 53 ms, corresponding to 3.9 times ISS95 scaling [7].

Two methods for stabilization of the high-β external kink mode are being studied using the TERPSICHORE code [8]. In the first, high magnetic shear at the edge, produced by 3D shaping, provides stability. The second method introduces a poloidally localized low-order helical deformation of the flux surfaces on the low-field side, as shown in Fig. 1. The deformation is similar to that produced by tilted picture-frame or serpentine ("Furth-Hartman") coils [9], though an analytic form for the deformation is currently used for analysis. Initial studies have examined helical perturbations with approximate mode numbers (in coordinate space) of n = 1 per period and $2 < m < 5$, and indicate that m = 3 is most effective. A small amplitude is required to give kink stability with $\langle\beta\rangle$ = 4.4 % in the cases studied, corresponding to approximately 10% of the minor radius, and producing small changes in the magnetic transform, magnetic well, or field ripple. The estimated external currents to produce the deformation are moderate. This method may offer a flexible and attractive means for stabilizing and testing the external kink stability in a high-β stellarator.

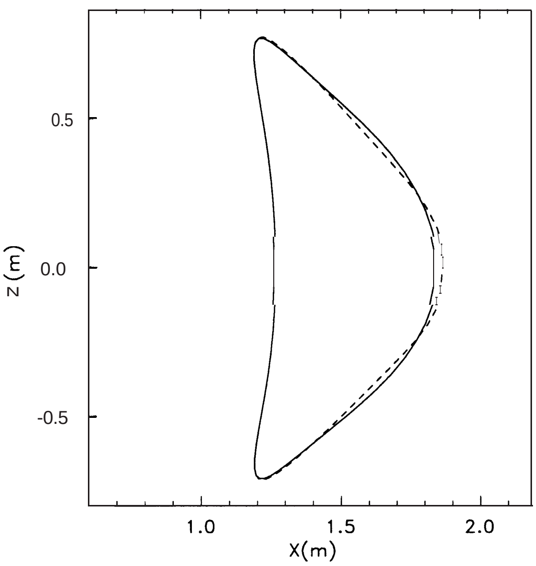

Fig. 1. Deformation of outermost flux surface for kink stability, elongated cross section: unstable (solid) and stable (dashed).

A variety of coil topologies were explored for generating the non-symmetric (in physical space) stellarator equilibrium, using the NESCOIL suite of codes [10]. These codes numerically optimize the coil shapes to minimize the error in the magnetic field perpendicular to the plasma surface [11]. A given stellarator equilibrium can be produced by an infinite number of different coil-set shapes, parameterized by their net poloidal and toroidal currents. The coils vary topologically from distorted TF (modular) coils (only net poloidal current), distorted PF coils (only net toroidal current), helical coils, to saddle coils (no net current), allowing considerable flexibility for design. A complete coil-set may contain coils of only one topology or of several. A broad range of coil-sets has been generated, spanning all the topologies, for the optimized quasi-axisymmetric physics equilibria and examined for engineering attractiveness. For a new facility, modular coils appear most efficient. When reusing an existing facility, making use of existing toroidal field coils and axisymmetric equilibrium coils, it is found that helical coils have the lowest forces and stored energy, while saddle coils have the smallest mass and lower mutual inductances. Both would allow some independent control of the helical and toroidal-average shaping fields, which is advantageous for a flexible experiment. Figure 2 shows an optimized saddle coil configuration for an $\overline{A}$ = 2.1 configuration, making use of axisymmetric toroidal field solenoid and equilibrium coils (not shown). As previously observed [12], saddle coils allow excellent plasma access from the outboard midplane.

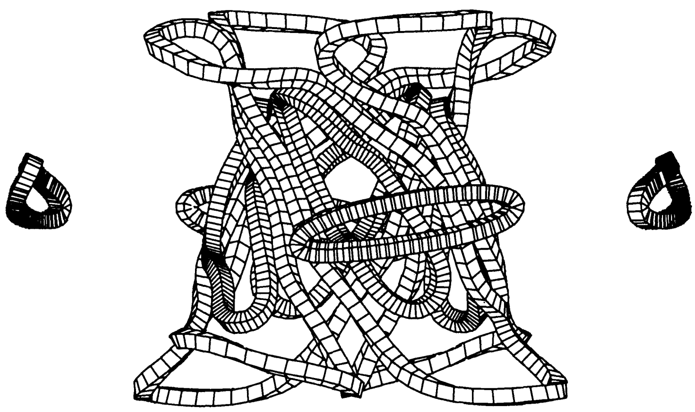

Fig. 2. Optimized saddle coils for A = 2.1, 20% external transform.

Initial investigations of the engineering of stellarator coil modifications for PBX-M have concentrated on a two-field period configuration with 40% of the transform generated externally at $\langle\beta\rangle$ = 4.3 %. Saddle-coils were selected for investigation, since they appear to be easier to wind in place, in addition to the advantages above. A design with (unoptimized)

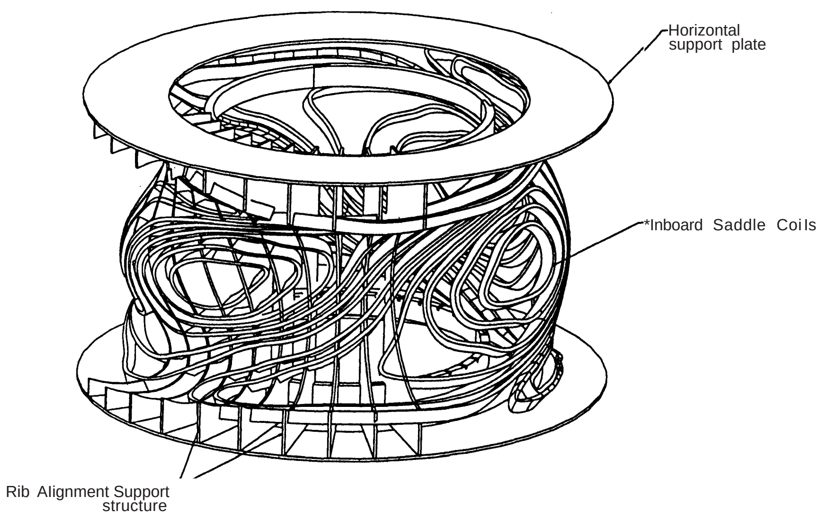

Fig. 3. Inner saddle coils and support structure

saddle coils supported by radial ribs and top and bottom horizontal plates is shown in Fig. 3. Preliminary calculations indicate that the stresses are modest for the nominal 1.25cm thickness. The coils would be wound using flexible conductor in precisely located tracks, vacuum-sealed, and potted in place. Similar techniques were used successfully on PBX-M.

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Table 1. Representative Accessible Plasma Parameters

Toroidal Field, B_T (T)	1	1	1	**2**
Heating Power, P (MW)	6	**12**	6	**12**
Avg. density, n ($10^{19}\,m^{-3}$)	5	6.5	8	20
ISS95 τ_E multiplier	23.	23.	**3.9**	**3.9**
τ_E (s)	0.021	0.016	0.046	0.087
$\langle\beta\rangle$	3.5 %	5.4 %	7.6 %	7.2 %
Central temperature (keV)	1.9	2.0	2.4	3.6

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