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Goals and Status of HSX: a Helically Symmetric Stellarator

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Abstract

The Helically Symmetry Experiment (HSX) is a quasi-helically symmetric (QHS) stellarator being constructed at the University of Wisconsin-Madison Torsatron Stellarator Laboratory, and the first experimental test of the QHS approach. HSX has a single dominant helical component to the magnetic field spectrum, with neoclassical transport 1–2 orders of magnitude lower than conventional stellarators in the low collisionality regime. Auxiliary coils will be used to add a toroidal mirror mode to destroy the symmetry, with only small changes in the rotational transform profile. The ASTRA code predict factors of two between $T_e(0)$ for these two spectral cases. The mirror mode also causes a large increase in direct loss orbits and increases viscous damping as compared to the QHS mode.

Keywords:

HSX, quasi-helically symmetric, neoclassical transport, direct loss orbits, plasma rotation, viscous damping

1. Introduction

Quasi-helically symmetric (QHS) stellarators [1] are fully toroidal systems that possess a single dominant (helical) component in the magnetic field spectrum. This is directly analogous to the tokamak which possesses a dominant term due to the toroidal curvature ($m=1$, $n=0$; m and n the poloidal and toroidal mode numbers, respectively). Neoclassical transport, outside of scale factors, depends only upon this spectral content [2]. Neoclassical transport is algebraically equivalent between the two systems with the substitutions:

$$\varepsilon_t => \varepsilon_h$$

$$q => 1/|N-m\iota| \quad \text{HSX: } N=4,\ m=1,\ \iota \sim 1$$

Thus, HSX looks like a $q=1/3$ currentless tokamak. In the above, ε_t and q are the toroidal field modulation and safety factor in the tokamak, and ε_h is the helical field amplitude, N is the number of field periods, and ι is the rotational transform in the QHS system. HSX [3,4] will be the first experimental test of a quasi-helically symmetric configuration. The toroidal curvature has been reduced to 0.0023 at the edge as compared to 0.125 expected in an equivalent $R/a=8$ toroidal device; a conventional torus would need an aspect ratio >400 to attain this level.

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2. Experimental Goals and the HSX Device

Conventional stellarators, with a myriad of ripple structures in the magnetic field strength along a field line, have strongly increasing neoclassical transport at low collisionalities (the so-called ν^{-1} regime), high direct losses of trapped particles, and strong damping of plasma rotation in all directions. The primary objectives of HSX are:

- Investigate the reduction of neoclassical transport in QHS configurations and the role of anomalous transport
- Demonstrate a reduction in the direct loss of deeply trapped particles due to QHS
- Show QHS leads to decreased viscous damping of rotation on a flux surface

The first objective requires the ability to get the plasma into a low-collisionality regime. HSX has a major radius of 1.2 m, an average plasma minor radius of 0.15 m and a maximum magnetic field strength of 1.37 T. With 100 kW of absorbed power (from a 200 kW peak power, 100 ms pulse duration, 28 GHz gyrotron system), LHD scaling [5] gives peak electron temperatures of ~1 keV at a density of 5×10^{18} m^{-3}, giving collisionalities of $\nu_e^* < 0.1$. HSX actually enters the low collisionality regime sooner than a conventional system due to the $|N - m\iota|$ factor.

3. Experimental Flexibility

The standard QHS configuration in HSX is produced by a set of 48 main modular coils. Surrounding each of these main modular coil is a planar (although non-circular) coil which can introduce variations in the rotational transform, magnetic well and spectral content. Different current directions and magnitudes in these planar coils accomplish these variations. Two key cases are termed the "well" configuration where the magnitude of the magnetic well is increased and the "mirror" configuration where asymmetries are introduced into the magnetic field spectrum. The well configuration is formed with 10 % of the ampere-turns of the main coils flowing in the auxiliary to reduce the toroidal field produced by the main modular coils. For the mirror mode, half of the coils increase the toroidal field component and the other half oppose this field.

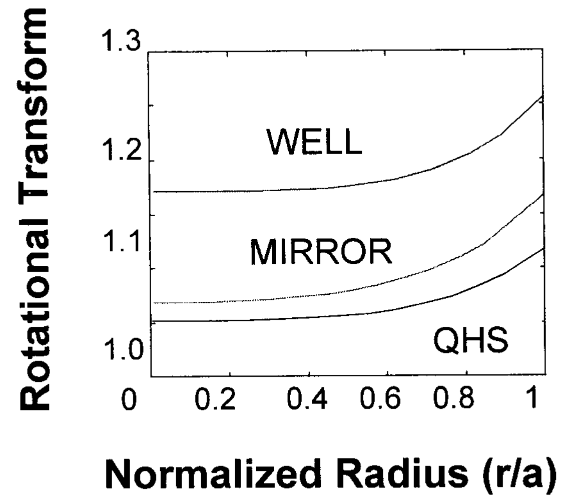

Fig. 1 Rotational transform profiles in HSX for the QHS, mirror mode and magnetic well configurations.

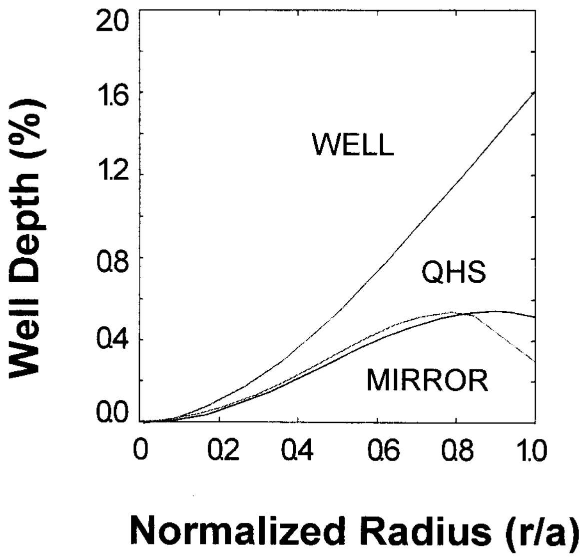

Fig. 2 Magnetic well depth profiles in HSX for the QHS, mirror mode and magnetic well configurations.

Figure 1 shows the rotational transform in HSX for the base (QHS) configuration compared with that of these two other modes of operation. Dangerous resonances (of the form $\iota = 4\ n/m$ for natural islands) are avoided in all three cases. The rotational transform profile is similar between the QHS and mirror modes. The magnetic well depth for these three cases is plotted in Figure 2. Here again, there is not a large variation between the QHS and mirror modes, but in the well configuration there is a three-fold increase in the well depth out to the plasma edge. The magnetic field spectrum is:

$$\frac{B}{B_0} = \sum_{n,m} b_{nm} \cos(n\phi - m\phi)$$

where n is the toroidal mode number in one field period. Figure 3 compares the magnetic field spectrum between the QHS, mirror and well modes of operation,

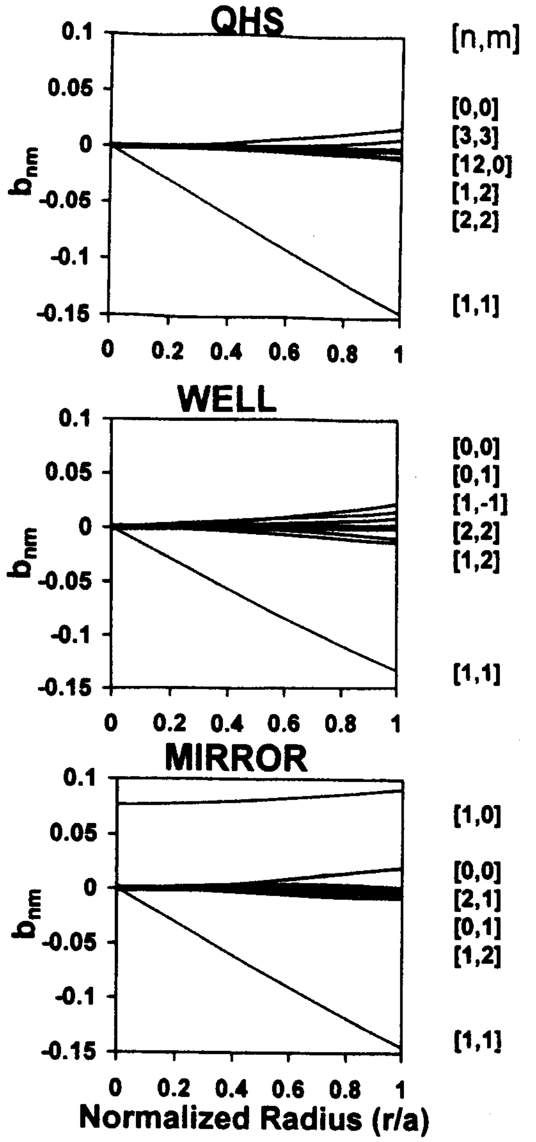

Fig. 3 Spectrum of the magnetic field strength for the QHS, magnetic well and mirror modes in HSX. The central value of b_{00} is subtracted for clarity on that mode.

where the six largest modes are plotted. These spectra are based on vacuum magnetic fields, but generated by a full finite-size coil model including the separate turns, crossovers and coil feeds. Symmetry-breaking terms are below 1% and the toroidal curvature term does not appear on the plot for the QHS case. The introduction of a stronger magnetic well gives rise to symmetry breaking terms on the order of 1–2%; the toroidal curvature is the dominant symmetry-breaking term. In the mirror mode, the b_{10} term is 2/3 that of the dominant helical (b_{11}) component, producing a strong breaking of the quasi-helical symmetry.

In the magnetic well case, the rotational transform and well depth are increased without a major change to the magnetic field spectrum. This offers some interesting possibilities for stability studies [6]. In the mirror mode, the magnetic field spectrum and neoclassical transport can be significantly changed without large associated changes in the rotational transform and magnetic well. The mirror case forms the basis for the initial experimental program aimed at the transport goals previously discussed.

4. Experimental Program

Neoclassical electron thermal conductivity is more sensitively dependent upon the magnetic field spectrum than is particle transport at low collisionalities and it can dominate the anomalous contribution. The ASTRA [7] one-dimensional transport code was used to compare the expected T_e profiles for the QHS and mirror modes of operation in HSX. The electron thermal conductivity was assumed to be the sum of a neoclassical and an anomalous component. The neoclassical component was based on a model by Beidler [8] and the anomalous component was based on ASDEX L-mode scaling [9]. The density profile was constant in time with a fairly flat spatial profile and central density of 6×10^{18} m^{-3}. Power deposition of 100 kW was centrally peaked, consistent with ray tracing calculations. $T_e(0)$ goes from approximately 1 keV in the QHS case to ~600 eV for mirror mode operation. Other simulations showed clearly visible changes for densities as high as 1×10^{19} m^{-3} and powers as low as 50 kW. In the QHS mode, transport is certainly dominated by the anomalous contribution while in the mirror mode the neoclassical transport dominates in the center. There exists the possibility of a reduction in the anomalous transport level (by this factor $|N-m\iota|$) if Lackner scaling [10] is applicable.

The presence of symmetry-breaking terms in the spectrum can give rise to particle orbits that leave the confinement region very rapidly. Large trapped particle loss could be a significant problem for stellarators as reactors, and present difficulties for heating methods which couple energy preferentially into the perpendicular direction. Direct loss orbits can play an important role in determining density profiles, the radial electric field and plasma rotation. Direct loss orbits can be controlled in HSX by manipulating the magnetic field spectrum with the auxiliary coils. In the mirror mode, deeply trapped 25 keV electrons quickly leave the confinement volume, whereas they are well confined for the

QHS case. Second harmonic ECH heating will be used to produce plasmas with energetic electrons, as was done on Heliotron DR [11].

In a conventional stellarator, plasma rotation can be strongly damped away from the magnetic axis because of the strong variation of the magnetic field in all directions on a magnetic surface [12]. However, in a QHS stellarator the near-axis of symmetry in the helical direction decreases the damping of the rotation due to parallel viscosity in this direction. Calculations of the flow damping rate in HSX indicate a 1–2 order of magnitude decrease for the QHS configuration compared to the mirror mode. Biased electrode-induced rotation will be used to examine damping in the plateau regime.

5. Status of HSX

Final assembly of the HSX components on the support structure is in progress with completion expected in early 1998. Beam mapping and magnetic field measurements will determine the attained field structure in the device. First plasma operation will focus on second harmonic ECH and direct loss orbits. Operations will then shift to $B = 1$ T to address the lower collisionality investigations of thermal conductivity.

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