Effects of Symmetry-Breaking on Plasma Formation and Stored Energy in HSX

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Outline

Principles of Quasi-helical Symmetry

The HSX Device and Goals

2nd Harmonic ECH Breakdown

Effects of Magnetic Field Spectrum on Stored Energy

Plasma Rotation with Electrode Biasing

Posters on HSX website http://hsxa.ece.wisc.edu
The Helically Symmetric Experiment

Quasihelical: Fully 3-D, BUT

Symmetry in $|B|$: $B = B_0[1 - \varepsilon_h \cos(N\phi - m\theta)]$

In straight line coordinates $\theta = \eta \phi$, so that $B = B_0[1 - \varepsilon_h \cos(N - m\eta)\phi]$

In HSX: $N=4$, $m=1$, and $\eta \sim 1$

$\tau_{\text{eff}} = N - m \tau = 1/q_{\text{eff}} \sim 3$
High Effective Transform and Quasi-helical Symmetry Lead to Unique Properties

• Low neoclassical transport
  
  Small deviations from magnetic surfaces, small banana widths
  Minimal direct loss particles, reduction in ‘1/v’ transport, very small neoclassical thermal conductivity

• Plasma currents are small
  
  Small Pfirsch-Schluter and bootstrap currents
  Robust magnetic surfaces, high $\beta_{eq}$ limit

• Low parallel viscosity in the direction of symmetry
  
  Possibility of high E x B shear to reduce turbulence

• Lower anomalous transport (?)
  
  L-2 experimental results $\chi_{e,anom} \sim 1/1$
The HSX Device

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major Radius</td>
<td>1.2 m</td>
</tr>
<tr>
<td>&lt;r&gt;</td>
<td>0.15 m</td>
</tr>
<tr>
<td>Volume</td>
<td>~.44 m³</td>
</tr>
<tr>
<td>Field periods</td>
<td>4</td>
</tr>
<tr>
<td>𝑙_{axis}</td>
<td>1.05</td>
</tr>
<tr>
<td>𝑙_{edge}</td>
<td>1.12</td>
</tr>
<tr>
<td>Coils/period</td>
<td>12</td>
</tr>
<tr>
<td>B₀ (max.)</td>
<td>1.25 T</td>
</tr>
<tr>
<td>Pulse length</td>
<td>0.2 s</td>
</tr>
<tr>
<td>Auxiliary Coils</td>
<td>48</td>
</tr>
</tbody>
</table>

ECH heating at 28 GHz to investigate low collisionality electron transport

Experiments to date utilize 2nd harmonic heating at B=0.5 T to generate hot trapped electron population
Designed Magnetic Structure Confirmed Experimentally

Low energy electron beams and fluorescent mesh used to map the magnetic surfaces

- Well-formed nested magnetic surfaces observed
- Rotational transform within 1% of design value
Passing Particle Orbits Contain Information about \( m \neq 0 \) Spectral Components of \( B \)

High energy passing electron orbits, measured at several toroidal angles, mapped into Boozer space using neural network

**Shifts from flux surface**

\[
r^2 = r_0^2 + \frac{2Mv_g}{eB_0^2} \sum b_{nm} \frac{m}{n-m} [\cos(n\phi - m\theta) - \alpha_{nm}]
\]

Method ideal for measurement of nearly resonant spectral components which cause large deviation of orbit from flux surface.

Details can be found in Physics of Plasmas (Dec., 2001)

Results in HSX confirm that:

- Toroidal curvature is very small
- Very large effective transform results in small excursions of passing particles from flux surface

**Mapping and Drift Orbit Studies Confirm the Designed HSX/QHS Structure Has Been Achieved**
## Auxiliary Coils Provide Flexibility for HSX

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Auxiliary Coil Currents</th>
<th>Dominant Feature</th>
</tr>
</thead>
<tbody>
<tr>
<td>QHS</td>
<td>None</td>
<td>Best transport; symmetry</td>
</tr>
<tr>
<td>MIRROR</td>
<td>3 coils on ends add to main; center 6 opposite</td>
<td>Transport similar to conventional stellarator</td>
</tr>
<tr>
<td>ANTI-MIRROR</td>
<td>Opposite phasing to mirror; same global transport</td>
<td>Deep ripple on low-field side at ECH launcher</td>
</tr>
<tr>
<td>WELL</td>
<td>All currents opposite to main coil currents</td>
<td>Well depth and stability increase</td>
</tr>
</tbody>
</table>
The Breakdown Time is a Function of Spectrum and Resonance Location

- 2nd Harmonic ECH (B=0.5T)
- \( P_{\text{RF}} = 50 \text{ kW} \)
- Constant puff (1 x 10^{-6} torr)
- Breakdown time defined as time to \( <n_e> = 2 \times 10^{11} \text{ cm}^{-3} \)

- **QHS** symmetric about on-axis heating
- **Increased** \( \tau_b \) for **mirror** on outboard side; longer for **anti-mirror**
Particle Orbits at ECH Launch ($\phi=0$): QHS

Inboard launch

Outboard launch
Particle Orbits at ECH Launch ($\phi=0$) : Mirror Mode

Inboard launch

Outboard launch
Particle Orbits at ECH Launch ($\phi=0$) : Anti-Mirror

Inboard launch

Outboard launch
Line-Density Signals and Profiles for QHS and Mirror-Mode Plasmas; Central Heating

- QHS has density rise for ~5 ms after ECH turn-off
- Density decay comparable after initial rise (cold afterglow)
- Line-density profiles insensitive to heating location
Higher Stored Energies Can be Achieved in the QHS Mode of Operation

With similar densities, large variations are observed in the stored energies measured by a diamagnetic loop

- Variations with magnetic field spectrum, resonance location, and line-averaged density
Clear Reduction in Stored Energy at Constant Density and $P_{RF}$ as Anti-Mirror Term is Increased

All data for scans taken with $P_{RF}=50\text{ kW}$ input
Gas programmed to maintain $<n_e>$ constant
Low stored energy observed uniformly for anti-mirror mode

Subsequent data presented for QHS/Mirror modes
Role of direct loss for anti-mirror under investigation
The QHS Mode has Higher Stored Energies than the Mirror Mode at Low Densities

- Central Heating
- QHS stored energy drops with increasing density while mirror increases below $1 \times 10^{12}$ cm$^{-3}$
- Stored energy independent of density above this value
Stored Energy in the Mirror Mode Falls Rapidly with Outboard Heating

\[ <n_e> \sim 1.0 \times 10^{12} \text{ cm}^{-3} \]

* 10% Mirror

+ QHS
QHS Mode Effectively Absorbs Power for all $<n_e>$

Absorbed power inferred from $\Delta W_p$ at ECH turn-off

Absorbed power increases with density in the mirror mode

Increases in confinement time observed in low density QHS plasmas
Mirror and High Density QHS Follow ISS95 Scaling
Initial Measurements of Plasma Flow Induced Using a Biased Electrode

- QHS plasmas should have low parallel viscous damping in the direction of symmetry
- Biased electrode used in edge region to drive flow
- Flow measured with a six-element Mach probe
The Measured Induced Plasma Flow is in the Direction of Quasi-symmetry
QHS Has a Larger Flow Velocity Change for Less Drive than the Mirror Mode

ΔU ~ 50% larger for QHS; slower rise

Higher radial conductivity observed for mirror mode
Damping Due to Parallel Viscosity for QHS 1-2 Orders on Magnitude Less Than Mirror

Factor of two difference in damping rates near the plasma edge explained by damping due to neutrals
Concluding Remarks

• Stellarators can be designed for targeted physics properties

• Specifically for quasi-helical symmetry
  - Virtual elimination of toroidal curvature
  - $|N - m|$ reduction of orbit shifts (high $\lambda_{\text{eff}}$)

• Quasi-Symmetry Matters!
  • Shorter breakdown times
  • Higher stored energy/better absorption
  • Reduced rotation damping
What is $T_e$ in HSX?

Stored energies of 30 J routinely attained at $\langle n_e \rangle \sim 1 \times 10^{12} \text{ cm}^{-3}$

$$\frac{3}{2} n k T_e V = 30 \Rightarrow T_e \sim 300 \text{ eV}$$

Density profile peaked; with $T_e$ peaking, factor of 3-4 in $T_{e0}$ possible $\Rightarrow$

$$T_{e0} \sim 900-1200 \text{ eV}$$

SX, calibrated against MST Thomson system, gives $\sim 1500 \text{ eV}$

Resolution awaits additional diagnostics: HSX Thomson (mid 2002), fast electron diagnostics and ECE (soon!) and time-resolved spectroscopy (now)