Experimental Tests of Quasisymmetry in HSX

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Outline

• Quasihelically symmetric with no toroidal curvature ➔ high effective transform
  - Small deviation from flux surface; Parallel currents reduced in magnitude
  - Helical Pfirsch-Schlüter current
  - Bootstrap current reduces transform
    ➔ Good agreement of V3FIT code to diagnostic coil data
• Good confinement of trapped particles ➔ MHD instability
  ➔ First reflectometer measurements shows core localization of mode
• B = 0.5 T: Reduction of neoclassical momentum, particle and heat transport with anomalous component dominant in QHS
• B = 1.0 T: Thermal plasmas, $T_e$ up to 2.5 keV
• 1D transport model ➔ Large curvature, short connection length drives TEM and anomalous transport
  - Good model for temperature profile and confinement scaling
• Future Plans and Conclusions
Quasihelical stellarators have high effective transform

Quasihelical: Fully 3-D, BUT

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

In straight line coordinates $\theta = t\phi$, so that

$$B = B_0[1 - \varepsilon_h \cos(N - m t)\phi]$$

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

$$t_{\text{eff}} = N-m \ t \sim 3$$

With $t \geq 1$ and $n = 4$ periodicity of the quasisymmetric field, modulation of $|B|$ on field line $t_{\text{eff}} \sim 3$
Lack of toroidal curvature verified by passing orbit measurements

• Grad B drift in HSX confirms lack of toroidal curvature
• Small orbit shift confirms large effective transform of $N-m_l$
High effective transform reduces Pfirsch-Schlüter and bootstrap current

**Pfirsch-Schlüter current:**
- reduced in magnitude
- helical in HSX due to lack of toroidal curvature
- dipole currents are opposite of tokamak where field in HSX is tokamak-like (grad B drift is opposite).

**Bootstrap current:**
- reduced in magnitude
- opposite direction to tokamak
- reduces transform but confinement improves slightly due to \( N-\ell t \) factor

\[
J_{PS} = \frac{1}{B_0} \frac{dp}{d\psi} \sum_{n,m} \frac{n I + mg}{n-m \ell} \delta_{nm} \cos(n\phi-n\theta)
\]

\[
J_B \sim 1.46 \sqrt{b_{nm}} \frac{m_g}{n-m \ell B_0} [\text{gradients}]
\]

Boozer, ’82 ‘92
3 axis coils measure current evolution at two toroidal locations

- 16 3-axis pick-up coils mounted in a poloidal array
- Two sets of measurements separated by <1/2 field period.
- From Pfirsch-Schlüter current: $B_\theta \sim \cos \theta$ and $B_r \sim \sin \theta$
Rogowski confirms bootstrap current unwinds transform

- For on-axis heating, bootstrap current rises during 50 ms ECH
- Colder plasmas with off-axis heating show saturation
- Good agreement with BOOTSJ (ORNL) for extrapolated currents
- Current direction consistent with lack of toroidal curvature
Coil array shows Pfirsch-Schlüter current dominant early in time

- Early time $t = 10$ ms $\Rightarrow I_B = 0$ in model
- Bootstrap current probably underestimated

*** Special thanks to Steve Knowlton and V3FIT team! ***
Bootstrap current shows up later in time

- Bootstrap current shows up as DC offset in $B_\theta$
- Later in time $t = 50$ ms $\Rightarrow I_B = \text{BOOTSJ}$ value (overestimated)
- Helical PS current evident in reversal of $B_r$
Bootstrap current decreases transform in HSX

- Pressure profile from TS; current density profile from BOOTSJ
- Pressure and Current density profiles in VMEC → transform profile
- With 500 A, iota is just above one → no instability signatures observed
Symmetry is broken with auxiliary coils

- Phasing currents in auxiliary coils breaks quasihelical symmetry (n=4, m = 1) with n = 4 & 8, m = 0 mirror terms
- Neoclassical transport and parallel viscous damping increased

\[ + + + - - - \quad \text{‘Old’ Mirror} \]
\[ - + + + - - \quad \text{‘New’ Mirror} \]

Minimal displacement of magnetic axis at ECH and TS ports
New mirror configuration increases effective ripple while keeping magnetic axis stationary

\[ \varepsilon_{\text{eff}} \text{ increases by factor of 8 at } r/a \sim 2/3 \]

New Mirror Configuration allows for both on-axis heating and on-axis Thomson profiles

Thomson Scattering Laser Path (separated by 1 field period)

ECRH Beam
…. while transform, well depth and volume remain almost fixed

<table>
<thead>
<tr>
<th>Rotational Transform</th>
<th>Well Depth</th>
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<tbody>
<tr>
<td><img src="image1.png" alt="Graph" /></td>
<td><img src="image2.png" alt="Graph" /></td>
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<table>
<thead>
<tr>
<th>Parameter</th>
<th>QHS</th>
<th>‘New’ Mirror</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transform $(r/a = 2/3)$</td>
<td>1.062</td>
<td>1.071</td>
</tr>
<tr>
<td>Volume $(m^3)$</td>
<td>0.384</td>
<td>0.355</td>
</tr>
<tr>
<td>Axis location (m)</td>
<td>1.4454</td>
<td>1.4447</td>
</tr>
<tr>
<td>$\varepsilon_{\text{eff}} (r/a = 2/3)$</td>
<td>0.005</td>
<td>0.040</td>
</tr>
</tbody>
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< 1% 
< 10% 
< 1 mm shift 
factor of 8
Good confinement of trapped particles

- Collector plate in direction of electron \( \nabla B \) drift shows large negative potential when quasisymmetry broken.
- Larger HXR flux in QHS configuration.
BUT … global coherent mode observed at 0.5 T

- Fluctuation observed on interferometer and magnetic coils. Absent at B = 1.0 T
- Frequency scaling with mass density consistent with Alfvenic mode
- Propagates in electron diamagnetic direction
- Amplitude decreases as quasisymmetry is degraded
First results from Reflectometer

- Extraordinary mode at $B = 0.5$ T
- Coherent mode in QHS localized to core region
- Mode is absent at high symmetry-breaking
- Broad turbulent spectrum observed in Mirror mode
HSX has demonstrated benefits of quasisymmetry

- Reduction in momentum, particle and heat transport: $B = 0.5$ T
- Neoclassical is reduced BUT anomalous contribution now dominates

**Momentum**

Larger flows in QHS with equivalent torque

- Lower parallel viscous damping

**Particle**

Peaked density profiles in QHS

- Reduced thermodiffusion

**Heat**

Higher $T_e$ in QHS with same absorbed power

- Lower $\chi_e$
Off-axis Heating Confirms Thermodiffusive Flux in Mirror

- With off-axis heating, core temperature is flattened
- Mirror density profile becomes centrally peaked
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![Graph showing ECH Resonance and On-axis heating](image-url)
Electron temperature profiles can be well matched between QHS and Mirror

- To get the same electron temperature in Mirror as QHS requires 2.5 times the power
  - 26 kW in QHS, 67 kW in Mirror \( \rightarrow \) large nonthermal population at 0.5 T
  - Density profiles don’t match because of thermodiffusion in Mirror
Thermal Diffusivity is Reduced in QHS

- QHS has lower core $\chi_e$
  - At $r/a \sim 0.25$, $\chi_e$ is 2.5 m²/s in QHS, 4 m²/s in Mirror
  - Difference is comparable to neoclassical reduction (~2 m²/s)

- Two configurations have similar transport outside of $r/a \sim 0.5$
Anomalous conductivity is difference between experimental and neoclassical

- Little difference in anomalous transport between QHS and Mirror
• Good agreement between kinetic and diamagnetic stored energy
  ➔ minimal nonthermal contribution
• Core $T_e$ about twice as large in QHS as Mirror configuration
• Mirror density profile more hollow as $T_e$ gradient increases
Minimum difference profiles to compare transport at $B = 1.0 \, \text{T}$

- More than twice the power in Mirror configuration to approximate the temperature profile
- Density profile still slightly more peaked in QHS than Mirror
Electron thermal conductivity lower in QHS than Mirror

- Ray-tracing code calculates power deposition profiles
- Total power scaled to diamagnetic loop measurement of stored energy
- QHS experimental thermal conductivity ~ 3 times lower than Mirror:
- Neoclassical calculation is being redone using Spong’s PENTA code
Can we model anomalous transport in HSX?

- Rewoldt ’05 using FULL code showed HSX had largest linear growth rate to ITG/TEM modes compared to LHD, W7-X, NCSX, QPS
- Goal is to apply predictive transport modeling to HSX using multi-mode approach
- Neoclassical transport based on DKES, anomalous transport based on Weiland analytic model
Microstability estimates using axisymmetric models with “quasisymmetric” approximation

- 3D stability calculations find most unstable eigenmodes (ITG/TEM) ballooning in the low field, bad curvature region in HSX

- Dominant particle trapping comes from helical ripple, $\varepsilon_H (0.14 \cdot r/a = 1.4 \cdot r/R)$

- Reduced connection length, $L_c = q_{\text{eff}} R = R/|N-m_\perp| \approx R/3$, leads to very low collisionality electrons across the minor radius $\rightarrow$ TEM ($T_e >> T_i$)

- Normal curvature rotates helically, with bad curvature following the location of low field strength

- $\kappa_{N,\text{max}} \sim 1/45 \text{ cm}^{-1} \neq 1/R$ (R=120 cm)

- To account for toroidal drifts in drift wave models, $R/L \rightarrow (R/3)/L$
Weiland model with simplified assumptions benchmarked against GS2 code

- Linear growth rates from Weiland and 3D GS2 are in agreement near experimental gradients \((a/L_n, a/L_{Te} = 2 \rightarrow 5\), largest difference \(\sim 30\%\))

- Weiland growth rates 2\(\times\) smaller without “quasisymmetric” approximation
Model predicts gross features of $T_e$ profile and confinement scaling

• Weiland model, with geometry approximations, gives reasonable fit to temperature profile.

• Captures the scaling and magnitude of confinement times at $B = 1.0$ T
Near Term Plans

• Emphasis in near term will be to measure flows and radial electric field and compare to neoclassical modeling ➔ diagnostic neutral beam mounted on HSX for CHERS

• Compare experimental data to Spong’s PENTA code. How important is it to solve 2 momentum balance equations on flux surface for a quasisymmetric plasma? How do changes in effective ripple affect $E_r$?

• Compare reflectometer measurements of turbulence at plasma core for QHS versus Mirror at 1 T. How important are differences in trapped particle fraction and $E \times B$ shear?

• Novel low-cost HIBP system being developed with RPI

• Model time evolution of neoclassical currents and compare to measurements for different magnetic geometries.

• Obtain ion root plasma for Mirror to maximize differences with QHS configuration of neoclassical and possibly anomalous transport
Conclusions

• Lack of toroidal curvature verified by
  • grad-B drift of passing particle
  • helical Pfirsch-Schlüter current
  • bootstrap current that decreases transform
• High effective transform verified by
  • small drift of passing particles from flux surface
  • reduced magnitude PS and bootstrap currents
• Good confinement of trapped particles with quasisymmetry ➔ MHD mode observed
  • first reflectometer results shows mode localized to core
  • broad density fluctuation spectrum in Mirror compared to QHS
Conclusions

• ECH at B = 0.5 T
  • Reduction of particle, momentum and heat transport with quasisymmetry
  • Large themodiffusive flux in Mirror yields hollow density profiles, reduction of neoclassical in QHS results in peaked density profile.

• ECH at B = 1.0 T
  • Nonthermal component is small
  • $T_e$ up to 2.5 keV is observed
  • Multi-mode model of neoclassical + modified Weiland for anomalous agrees well with temperature profile and confinement time.

⇒ Quasihelically symmetric configuration improves neoclassical transport. Initial results suggests anomalous transport may be high.