Overview of Recent Results from HSX

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HSX is a Quasihelically Symmetric Stellarator

Magnitude of B

B=0.5-1.0 T

28 GHz ECH

Up to 100 kW

HSX has a helical axis of symmetry in |B| and a resulting very low level of neoclassical transport
Neoclassical Transport Can Be Increased with Mirror Field

- Mirror configurations in HSX are produced with auxiliary coils in which an additional toroidal mirror term is added to the magnetic field spectrum.

- **In Mirror mode** the term is added to the main field at the location of launching antenna.
- **In anti-Mirror** it is opposite to the main field.
Trapped particles in QHS are well-confined.

By the ECH antenna, orbits are poor in Mirror configuration;

Even worse in anti-Mirror.
Anomalous Transport Should Dominate Thermal Plasmas Under Present Operation

• How does anomalous transport scale in HSX?
  – Evidence that $X_e$ scales like $1/n$ (vs $T_e^{3/2}$)

• In lower density operation strong evidence for energetic tail population
  – Well-confined in QHS

• What are the benefits of QHS in more thermal plasmas?
  – Good absorption of ECH
  – Reduced rotation damping
  – Eventually, good confinement of thermal plasmas in lmfp regime
ASTRA is Used to Model Transport

- The power deposition profile comes from measurements of the radiation pattern from an ellipsoidal mirror and a ray-tracing calculation of the energy deposition profile.

- To model neoclassical transport, a 6-parameter fit to the monoenergetic diffusion coefficient allows for quick solution of the ambipolarity condition to solve for $E_r$.

$$
D_{EX} = \frac{\sqrt{\pi}}{2} \varepsilon_t^2 C_6 V_d^2 \frac{\tilde{v}}{\omega^2}
$$

$$
\omega^2 = C_1 \tilde{v}^2 + C_2 (\omega_E + \omega_B)^2 + C_3 \omega_B^2 + C_4 |\omega_B| \tilde{v}
$$

$$
\omega_B = C_5 V_d
$$

$$
V_d = \frac{K}{eBr} \quad \omega_E = \frac{E}{rB}
$$

$$
\tilde{v} = \frac{\nu}{C_6}
$$


Full details on transport modeling and experimental measurements this afternoon in poster by Talmadge.
ASDEX L-mode Anomalous Model

- In addition to the neoclassical transport, we assume that there is an anomalous electron thermal conductivity:

\[ \chi_e = \chi_{e, neo} + \chi_{e, anom} \]

- Previously we used an anomalous thermal conductivity based on ASDEX L-mode scaling:

\[ \chi_{e, anom} \sim \frac{T_{e}^{3/2}}{RB^2} \left[ \frac{1}{1.1 - (r/a)^2} \right]^4 \]

- If \( \tau \sim 1/ T_{e}^{3/2} = nT/P \), then:

\( T \sim (P/n)^{0.4} ; \quad \tau \sim (n/P)^{0.6} ; \quad W \sim n^{0.6}P^{0.4} ; \quad \text{ISS95-like} \)
Modeling Anomalous Transport II

- ASDEX L-mode model did not agree with scaling dependencies of experimental data.

- A better model of anomalous transport in HSX is an Alcator-like dependency ($n_e$ in units of $10^{18}$ m$^{-3}$):

$$\chi_{e,\text{anom}} = \frac{10.35}{n_e} \text{m}^2/\text{s}$$

- If $\tau \sim n = nT/P$, then:

$$T \sim P \text{ (independent of } n) \;; \quad \tau \sim n \;; \quad W \sim nP;$$

which is more in agreement with experiment.
H\textsubscript{\alpha} Measurements Consistent with Model

- See poster by J. Canik
- H\textsubscript{\alpha} toroidal and poloidal data analyzed using DEGAS code for 3 different line average densities and 4 different power levels
- Dependence of diffusion coefficient on \( n \) and \( P \):
  \[ D_{\text{anom}} \sim \frac{P^{0.09}}{n^{0.6}} \]
- Negligible dependence on power!
Experimental Diffusion Coefficients Larger than Neoclassical Values

ASTRA calculations of neoclassical diffusion coefficients with ambipolar $E_r$ (solid) and $E_r = 0$ (dashed)

$D$ from equilibrium analysis in rough agreement with modulated gas puff
Central Electron Temperature is Independent of Density

- QHS thermal conductivity is dominated only by anomalous transport.
- $T_e(0)$ in Mirror is calculated with self-consistent $E_r$ (solid line) and $E_r = 0$ (dashed).

- Except for lowest densities, $T_e(0)$ from Thomson scattering is roughly independent of density,
- Consistent with $\chi \sim 1/n$ model.
Thomson Data shows $T_e(0)$ Increases Linearly with Power

- Fixed density of $1.5 \times 10^{18} \text{ m}^{-3}$.
- ASTRA calculation is consistent with Thomson measurements for QHS and Mirror.
- $T \sim P$ is supportive of $\chi \sim 1/n$ model.
At Lower Density, TS Disagrees with Model

- Fixed density of $0.7 \times 10^{18}$ m$^{-3}$.
- Does Thomson data overestimate $T_e(o)$ compared to model because of poor statistics at low density or because of nonthermal electron distribution?
Stored Energy Increases Linearly with Power

- Fixed density of $1.5 \times 10^{18} \text{ m}^{-3}$.
- Difference in stored energy between QHS and Mirror reflects 15% difference in volume.
- $W \sim P$ in agreement with $\chi \sim 1/n$ model.

At the "Cross-roads"; higher-power and higher-density operation will be interesting!
At Lower Density, Stored Energy is Greater than Predicted

• Fixed density of $0.7 \times 10^{18} \text{ m}^{-3}$.

• Data shows stored energy even greater than ISS95 scaling.

• However, still $W \sim P$ in agreement with $\chi \sim 1/n$ model.

• Are nonthermal electrons responsible for large stored energy?
Stored Energy Does Not Have Linear Dependence on Density

• Fixed input power, 40 kW.
• For $\chi \sim 1/n$ model, $W \sim n$ for fixed power. Data clearly does not show this.
• Are nonthermal electrons causing stored energy to peak quickly at low density?
Stored Energy Goes Up Linearly with Density when Confinement is Poor

- Resonance is on low-field side of Mirror configuration where confinement of trapped particles is degraded
- $W \sim n$ in this configuration is now consistent with $\chi \sim 1/n$ model.

- Stored energy of 7 J at $n= 0.7 \times 10^{18} \text{ m}^{-3}$ now in agreement with ASTRA prediction
Hard X-rays Have Similar Dependence on Density as Stored Energy for \( n < 1 \times 10^{18} \text{ m}^{-3} \)

- Shielded and collimated CdZnTl detector with 200 \( \mu \)m stainless steel filter.
- Fixed input power: 40 kW.
- Hard X-ray intensity peaks at \( 0.5 \times 10^{18} \text{ m}^{-3} \), as does stored energy.

- Hard X-ray intensity falls off sharply beyond \( 1 \times 10^{18} \text{ m}^{-3} \), while stored energy remains roughly constant.
Hard X-rays Greater in QHS than Mirror

- Intensity increases till gyrotron turn-off, then decreases with 13 ms time constant for QHS, 5 ms for Mirror; virtually no hard x-ray counts for anti-Mirror
$T_{\text{rad}}$ by ECE Shows Large Non-Thermal Component at Low Densities

- $T_{\text{rad}}$ as high as 6 keV in QHS; less than 3 keV in Mirror
- At densities of $1.5 \times 10^{18}$ m$^{-3}$ emission is thermal in both QHS and Mirror plasmas
QHS Central Resonance
Thomson Scattering Profile

Central line averaged density: $1.6 \times 10^{12}$/cm$^3$

Thomson scattering and ECE in agreement for densities where non-thermals not playing a significant role.
Differences Appear Between QHS and Mirror Modes for Thermal Plasmas

Two time scales for flow rise
(This is QHS case)

Talk by Gerhardt this session
Stable, Thermal Discharges Are Achieved with QHS at Higher Density

$T_e(0) \sim 600$ eV, line averaged density $\sim 1.8 \times 10^{12}$ m$^{-3}$

$W \sim 25$ J, $P_{\text{rad}} \sim 17$ kW (50 kW injected)
In Low Density QHS Discharges, ‘Crashes’ Are Observed in Stored Energy and $T_{\text{rad}}$

Trapped electron modes; electron velocity anisotropy?
Concluding Remarks

• Central $T_e$ and stored energy increase linearly with power, in agreement with $\chi \sim 1/n$ model.
• For constant power, $T_e$ is roughly independent of density, also in accord with $\chi \sim 1/n$ model.
• Model is consistent with $H_{\alpha}$ measurements that show D is roughly independent of power, but depends on $1/n^{0.6}$
• At low density, increases in stored energy are commensurate with energetic trapped population
  – Hard x-ray data
  – Non-thermal ECE emission
  – Outboard resonance mirror returns to proper scaling
• QHS shows higher absorption efficiency and higher X-ray flux than Mirror at low density. At high density, absorbed power falls off at $n > 2 \times 10^{18} \text{ m}^{-3}$.
• Hence, superthermal electrons at low density and degraded absorption at high density account for discrepancy of stored energy with $\chi \sim 1/n$ model.
• For thermal plasmas, ECE and Thomson scattering are in good agreement with central electron temperature of \(~600\) eV at a line averaged density of \(~1.5 \times 10^{18}\) m\(^{-3}\)
  – Centrally peaked electron temperature profile (QHS)
• Differences in flows and damping have been observed for thermal plasmas between QHS and Mirror; two timescales
  – QHS slower damping, faster flow, for less drive than mirror
• Superthermal electrons may be drive in stored energy energy drops observed in low density QHS operation

Differences are observed between QHS and Mirror Modes for both thermal and non-thermal plasmas

Near term goals are increasing heating power and plasma density to further understanding of the role and modeling of anomalous transport in quasi-symmetric configurations