Characteristics of Edge Turbulence in HSX


U. of Wisconsin, Madison
Abstract

Langmuir probes have been used to measure electrostatic fluctuations in the edge plasma of the University of Wisconsin-Madison Helically Symmetric eXperiment (HSX) stellarator. The measured floating potential and transport profiles display a complex dependence on line averaged density. At densities below \( \sim 1.7 \times 10^{12} \text{ cm}^{-3} \), transport is measured to be inward at the edge. Above this density, the measured transport is outward, with the direction change experimentally explained by the direction change in measured phase velocity. Floating potential profiles indicate a change in radial electric field from positive to negative above this density threshold. Data has also been acquired with a probe that has access to the high field side of the plasma edge in a region of good curvature. Initial measurements with this probe (below the threshold density stated above).
Outline of this Poster

• Description of probes and measurement locations
• HSX plasma operation

• Density dependence of measured profiles and transport
• Comparison of low field side and high field side data

• Conclusions
**HSX Uniquely Allows Probe Access to Regions of Good and Bad Curvature**

- Fluctuation probes located:

  1. on the low field side (LFS) near a box port,
  2. on the high field side (HFS) near a joint flange.

![Diagram showing probe locations on HSX](image-url)
Probes Used

- Four tungsten probe tips (3.2 mm × 0.74 mm) separated poloidally by 3.2 mm
- Fourth tip recessed radially 6.4 mm.
- Three of four probe tips are roughly aligned on a vacuum flux surface.
Estimation of Particle Transport

- Particle flux from electrostatic fluctuations is estimated via

\[ \Gamma(t) = \langle n'(t)V_r'(t) \rangle = \langle n'(t)E_\theta'(t) \rangle / B_\phi \]

where \( E_\theta = -\nabla V_{\text{float}} = (V_{f2} - V_{f1})/d \)

\[ n = I_{\text{sat}} / (0.6eA_{\text{probe}} c_s) \]


\[ \Gamma(f) = \text{Re}\{N^*(f)E_\theta(f)\}/B = |P_{nE_\theta}(f)| \cos[\alpha_{nE_\theta}(f)] / B \]

- or -

\[ \Gamma(f) = k_\theta(f) \gamma_{n\phi}(f)|N(f)||\Phi(f)| \sin(\alpha_{n\phi}(f)) / B \]

- \( T_e \) fluctuations have been neglected.
HSX Plasma

- HSX |B| spectrum is quasi-helically symmetric (n=4, m=1), resulting in a predicted reduction of neoclassical transport.
- Anomalous transport is expected to dominate.
- A n=4, m=0 mirror field can be added to break the symmetry.

- Typical line averaged density between $3 \times 10^{11} - 2.5 \times 10^{12} \text{ cm}^{-3}$.
- Stored energies ~20 J for QHS and Mirror configurations (50 kW of 28 GHz ECH).

**Typical discharge parameters**

- Stored Energy
- Density
- $H_\alpha$

**Edge parameters**

- $T_e \sim 40 \text{ eV}$
- $B \sim 0.45 \text{ T}$
- $\rho_s \sim 1.5 \text{ mm}$
Raw Probe Data Displays Large Fluctuation Amplitudes and Fast Time Scales

- Time series similar to other magnetic toroidal experiments
- Electrostatic transport bursty in nature
- Power spectra indicate broad frequencies.

\[ \frac{\Gamma(t)}{\Gamma(t)} \]

-5 spectral index (for reference)
Mean $\Phi_{\text{float}}$ & $\Gamma$ Profiles Display Complex Dependence on Density

- $I_{\text{sat}}$ profiles roughly overlap when normalize by density.

- Floating potential profiles indicate $E_r$ transitions from positive to negative at some density.

- Measured particle transport is inward at lower densities.
Mean $\Phi_{\text{float}}$ & $\Gamma$ Display Complex Dependence on Density

- Density scan performed with probe located at $r/a \sim 0.8$

- Floating potential continuously drops $\rightarrow$ reduction in $E_r$.

- Measured particle transport is inward at line averaged densities below $\sim 1.7 \times 10^{12}$ cm$^{-3}$. 
**Change in Transport Direction**

Corresponds With Phase Velocity ($k_\theta$)

- Power weighted $n$-$\phi$ phase remains negative.

- Power weighted poloidal wavenumber changes direction, indicating change in phase velocity direction.

- $\alpha_{n\phi}$ sign remains same
  $k_\theta$ changes sign

\[ \Rightarrow \Gamma \sim k_\theta \sin(\alpha_{n\phi}) \text{ changes sign} \]
Phase Velocity is Correlated with the Local $E_r$ Measured by $\Phi_{\text{float}}$

- Two tips measuring floating potential radially separated 6 mm to estimate $E_r$ (no $T_e$ dependence included).

$$V_{\text{phase}} = \sum_{\omega, k_\theta} (\omega/k_\theta) S_l (k_\theta, \omega)$$

$S_l(k,\omega)$

$V_{\text{phase}}$ vs. $E_r = \langle V2 \rangle - \langle V3 \rangle$

Estimated $E\times B$ velocity

$E_r = \langle V2 \rangle - \langle V3 \rangle$ (V/cm)
Evidence for a Non-thermal Electron Population

- Comparison of ECE and TS data suggests the existence of non-thermal electrons at lower density plasmas.
- Discrepancy disappears near line averaged densities of \( \sim 1.7 - 2.0 \times 10^{12} \text{ cm}^{-3} \).
- See K. Likin’s poster for more information on ECE, and K. Zhai for Thomson Scattering.
How Does the Existence of Non-thermal Electrons Complicate the Interpretation of Langmuir Probe Data?

• Why the change in fluctuation induced electrostatic transport direction?

• Does the population of super-thermal electrons complicate probe interpretation via:
  – Non-saturated \( I_{\text{sat}} \) measurement
  – Secondary electron emission contaminating the floating potential measurement
  – Phase relation of \( I_{\text{sat}} \) and \( V_{\text{float}} \) (e.g., \( T_e \) fluctuations)

• Or do the super-thermals affect the equilibrium \( E_r \rightarrow V_{\text{ph}}/k_\theta \rightarrow \Gamma \)

• These are currently unanswered questions.
A Comparison of Low Field Side and High Field Side Probe Data

- This data is at a “lower” density - $1.0 \times 10^{12}$ cm$^{-3}$.
- $I_{\text{sat}}$ profiles overlap in r/a coordinates (determined by flux surface mapping and experimentally choosing a separatrix).
- Floating potentials agree outside r/a $\sim 0.8$.
- Because of expanded flux surfaces, the high field side probe is more perturbative for r/a $< 0.8$.
- Transport is similar, but smaller in magnitude at high field side.
Fluctuation Amplitudes Differ Between LFS & HFS probes at the Edge

- In the edge region \((0.85 < r/a < 1.0)\), fluctuation amplitudes differ between LFS and HFS data.

- \(I_{\text{sat}} < I_{\text{sat}}\) reduced about 25% on HFS, \(V_f\) reduced a factor of \(\sim 2\).

- HSX has a low % hill outside \(r/a \sim 0.8\).

- Within \(r/a = 0.8\), \(I_{\text{sat}} < I_{\text{sat}}\) deviates substantially – HFS probe perturbation?
At \( r/a \sim 0.85, \)

- Fluctuations are distributed over lower frequencies on the high field side – less Doppler shift due to reduced \( E_r \) (expanded flux surfaces) and therefore smaller \( E \times B \) drift.
- This is evident in \( V_{ph} \) & \( k_\theta \).
- Two peaks apparent on the HFS measurements, \( f \sim 45 \) & 90 kHz.
Phase Velocities on High Field Side are Reduced

- Because of expanded flux surfaces on the high field side, $E_r = \frac{dV}{dr}$ is smaller $\rightarrow V_{\text{phase}}$ is smaller.
Conclusions
Continuing Work

• Further characterize the more thermal plasmas at densities \( \geq 2 \times 10^{12} \text{ cm}^{-3} \).
• Investigate the effects of biased electrode discharges on turbulent fluctuations and ES particle transport.
• With the flexibility of the auxiliary coil set, measure the effect of magnetic well depth on electrostatic fluctuation amplitudes and transport.
Fluctuation Amplitudes and Spectra Also Change with Density

- $V_{\text{float}}$ and $I_{\text{sat}}$ fluctuation amplitudes decrease above $\sim 1.7 \times 10^{12} \text{ cm}^{-3}$.
- A large reduction in high frequencies ($f>200 \text{ kHz}$) for $I_{\text{sat}}$. 

\[ \frac{n}{<n>} \sim \frac{1}{k_{\theta} L_n} \sim 0.2 \]
$V_{\text{phase}}$ profiles

![Graph showing $V_{\text{phase}}$ profiles](image)