Measured and Neoclassically Predicted Intrinsic Plasma Flows and Radial Electric Field in the HSX Stellarator

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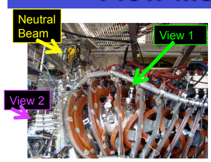
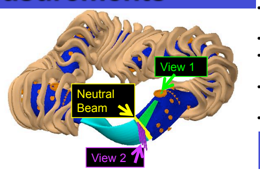
Overview

- HSX is a quasi-helically symmetric stellarator with a single dominant n=4, m=1 helical magnetic field spectrum component
- B_o=1T, up to 100kW ECRH, No direct ion heating, $T_e >> T_i$
- Ion flows up to ~20km/s have been measured using a CHERS (Charge Exchange Recombination Spectroscopy) system
- Neoclassical calculations were performed using PENTA, the most comprehensive code available for fully 3D magnetic configurations
- Agreement is only seen between measured and predicted $V_{||}$ when momentum conservation is included
- Increasing carbon content increases T_e in the core of the plasma
- C^{+6} ions have been included in the neoclassical calculations and are predicted to have approximately the same $V_{||}$ as the protons.
- Measured flow velocity did not change appreciably when m=0 magnetic perturbations were introduced.

Flow Measurements





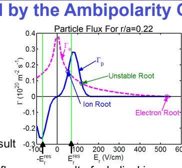
Charge Exchange Recombination Spectroscopy is used to measure C^{+6} ion temperatures, densities, and flow velocities

- Measurements are made at 10 radial locations from 2 viewing directions
- View 1 is an approximately toroidal view while view 2 is approximately poloidal. The views are not orthogonal to each other.
- 30keV neutral H beam and two 0.75m Czerny-Turner spectrometers with EMCCD's are used to stimulate and image photons from the 529nm C^{+5} line
- Spectral calibration is performed every shot using a Ne pencil-style calibration lamp
- C^{+6} ion temperatures are measured to be ~50eV, at these temperatures and relevant densities all ion temperatures are predicted to equilibrate quickly ($\tau_E^{C+6/p}$~0.003ms and $\tau_E^{p/C+6}$~0.04ms)

Neoclassical Calculations

E_r is Determined by the Ambipolarity Condition for Particle Flux

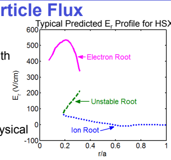
- Particle flux is not inherently ambipolar in devices with significant non-symmetric magnetic field components
- E_r is determined from the ambipolarity condition: $\Gamma_e(E_r) = \sum_s Z_s \Gamma_s(E_r)$
- This equation can have multiple solutions (roots)
- The peak in the electron flux at E_r=0 is a result of $1/\nu$ transport



Electron root: Larger positive E_r associated with reduced neoclassical transport

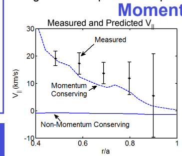
Ion root: Smaller, sometimes negative E_r

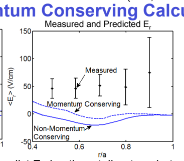
Unstable root: Non-physical

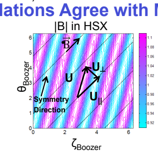


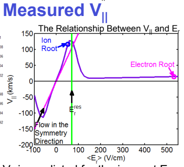
- The positive and negative peaks in the ion flux are a result of a helical ion resonance
- The effects of the resonance peak at: $E_r^{res} = \pm\left(1 - \frac{n}{m\iota}\right) V_{th} B_\theta$
- n and m describe the poloidal and toroidal variation of the component of the magnetic field spectrum responsible for the resonance (n=4, m=1 for HSX)
- V_{th} is the thermal velocity of the resonating ion
- For a given ion temperature, more massive ions will resonate at lower values of E_r and the effects of the resonance on transport and $V_{||}$ will be smaller

Momentum Conserving Calculations Agree with Measured $V_{||}$



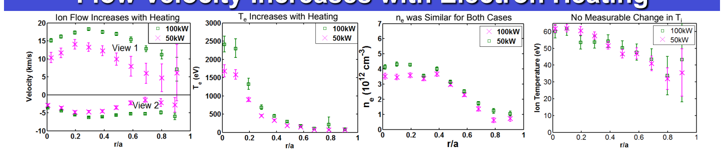






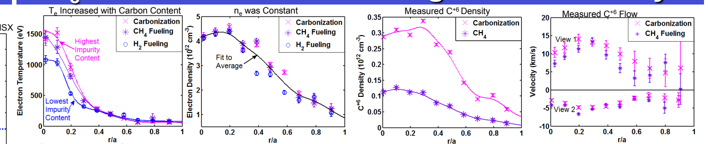
- DKES [2, 3] has been used to predict E_r in other stellarators, but uses a non-momentum conserving collision operator
- PENTA [1] includes flow effects and momentum conservation
- Calculations that neglect momentum conservation predict a $V_{||}$ that is significantly smaller than the measured flow
- Both methods appear to under-predict E_r, but the disagreement is on the order of the measurement error
- Measurements of $V_{||}$ and E_r for r/a<0.4 are complicated by Pfirsch-Schlüter flows
- Large positive $V_{||}$ is predicted for the ion root E_r because of a peak in the relationship between $V_{||}$ and E_r
- Despite having a much larger E_r, the electron root is associated with a significantly smaller $V_{||}$.
- Large values of E_r prevent particle trapping in local |B| minima, reducing the viscosity that would direct flows in the direction of symmetry

Flow Velocity Increases with Electron Heating



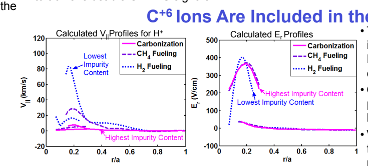
- The measured flow velocity increased with increasing heating at all radial locations
- T_e and ∇T_e increased significantly, especially in the core of the plasma

T_e Increases with Increasing Carbon Density

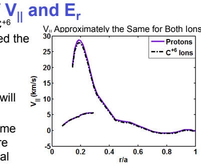


- Carbonization of the vessel led to a high carbon ion density.
- Boronization reduced carbon content.
- Carbon content is increased by fueling the plasma with methane to achieve usable CHERS signals
- Only small differences in the flows were measured in the cases where CHERS measurements were available
- Future work will attempt to separate the effects of changing E_r and $V_{||}$ on the measured velocity

C^{+6} Ions Are Included in the Calculations of $V_{||}$ and E_r

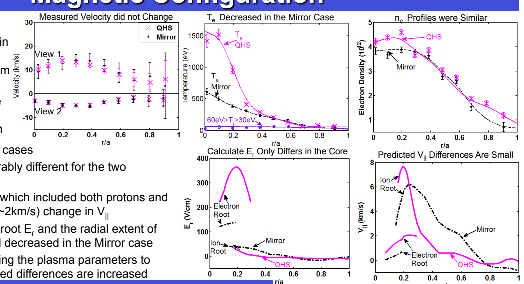


- The measured density of C^{+6} impurities has been included the PENTA calculations for the cases where it is available
- Other ion species may be present in the plasma and will be included in future work
- $V_{||}$ is predicted to be the same for all ions because they are relatively cold and collisional



Magnetic Configuration

- HSX can be run in a magnetic configuration known as Mirror in which m=0 components are added to the magnetic spectrum
- T_e in the core is lower in the Mirror configuration than in the optimized, quasi-helically symmetric (QHS) configuration



- 50kW ECRH was used in both cases
- The ion flows were not measurably different for the two configurations
- The neoclassical calculations, which included both protons and C^{+6} ions, predict only a small (~2km/s) change in $V_{||}$
- The magnitude of the electron root E_r and the radial extent of the region where it is predicted decreased in the Mirror case
- Future work will include changing the plasma parameters to see if predicted and/or measured differences are increased

References

1) D.A. Spong, Phys. Plasmas 12, 056114 (2005).
2) S. P. Hirshman, K.C. Shaing, et al., Phys. Fluids 29, 2951 (1986).
3) W.I. van Rij and S.P. Hirshman, Phys.Fluids B 1, 563 (1989).

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