Measuring and Predicting the Flow Velocity in the HSX Stellarator

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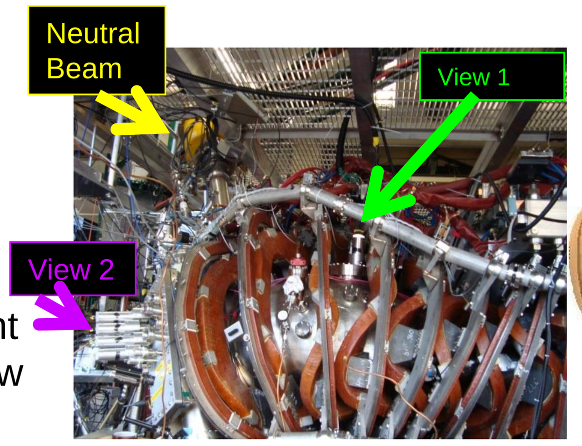
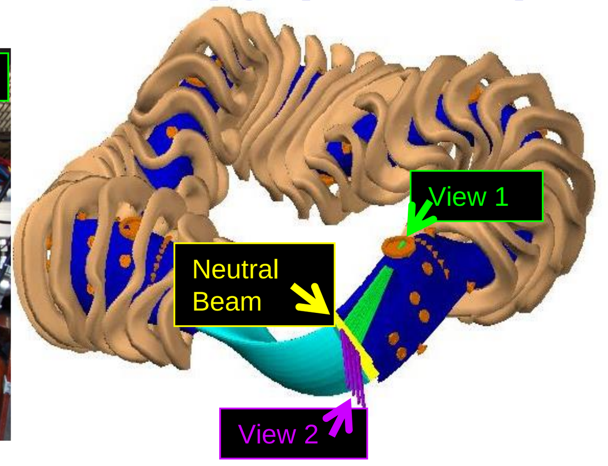
Overview

- CHERS has been used to measure C^{+6} flow velocity, temperature and density.
- The PENTA code has been used to calculate the neoclassical value of the radial electric field and parallel flow.
- Ion flows are measured to increase with increasing electron heating power.
- PENTA predicts an increase in E_r in the core and an increase in the pressure gradient driven flow in the outer half of the plasma for the higher power case.
- The flow direction is measured and predicted to be predominantly along the helical direction of symmetry in the outer half of the plasma where flows are predicted to be predominantly driven by the pressure gradient.
- Agreement is seen between measured and neoclassically predicted $V_{||}$ in the outer half of the plasma
- Flow direction and magnitude changes significantly within the core of the plasma, complicating interpretation of the CHERS measurements near the axis
- Improvements to the CHERS views are planned

Charge Exchange Recombination Spectroscopy (CHERS)

- 30keV 4Amp 4ms hydrogen diagnostic neutral beam
- Two 0.75m Czerny-Turner spectrometers with EMCCDs
- 10 radial locations are viewed from two different directions.
- Flows will not have a component in the radial direction, so the flow velocity vector is uniquely determine by the two velocity measurements



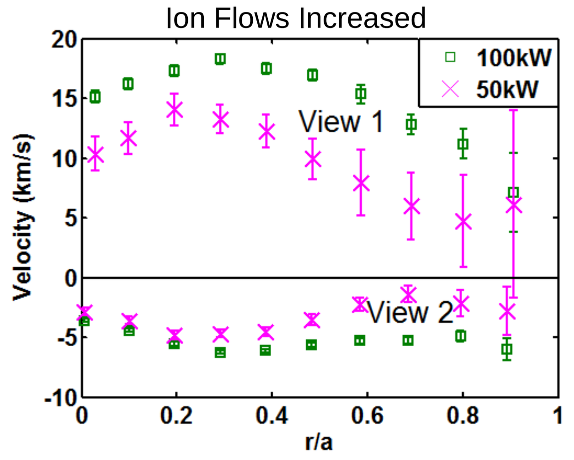


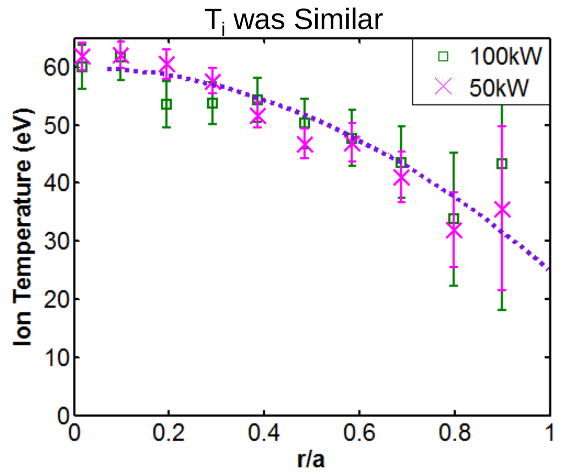
- Beam atoms charge exchange with plasma ions, causing spatially localized photon emission.
- The Doppler shift, Doppler broadening and strength of the emission are used to calculate velocity, temperature and density respectively.
- A series of shots are taken with the magnetic field in the clockwise direction and then the counter clockwise direction in order to reverse the flow. This essentially doubles the measured Doppler shift and eliminates uncertainty in the position of the unshifted wavelength.
- For typical HSX ion temperatures (~50eV) the ion-ion collision times are short. ($\tau_E^{C+6/p}$~3.0μs and $\tau_E^{p/C+6}$~40μs) Proton temperatures should be similar to the measured C^{+6} temperatures.

PENTA Calculations

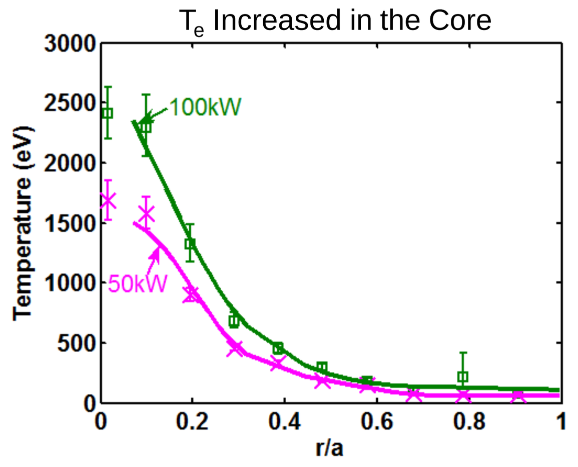
- The PENTA code [1][2] is used to calculate neoclassical particle fluxes, radial electric field, and parallel flow velocities.
- Monoenergetic transport coefficients are calculated using the Drift Kinetic Equation Solver (DKES).
- DKES [3][4] uses a non-momentum conserving collision operator, which was previously assumed to be sufficiently accurate for calculations in stellarators, which do not posses a direction of symmetry.
- PENTA can reintroduce the effects of momentum conservation, making the calculations applicable to devices with a variety of levels of symmetry in their magnetic field structure.
- PENTA can also include the effects of multiple ion species.

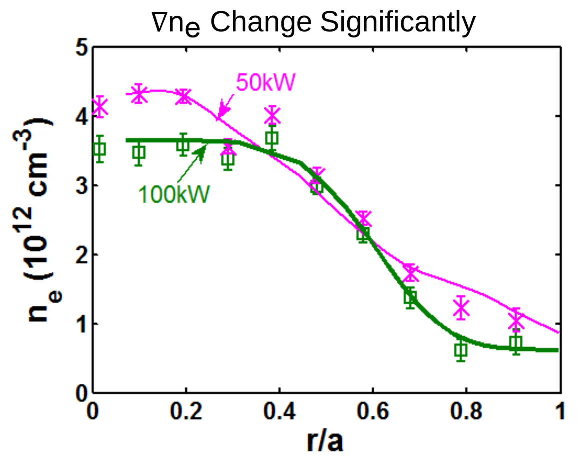
Flows Increase with ECRH





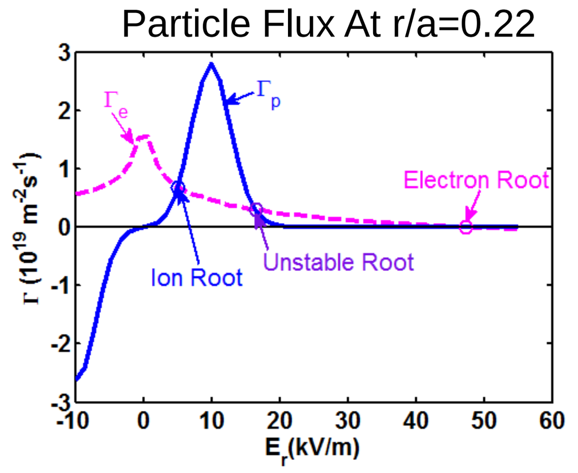
- The measured ion flow velocity was significantly faster in the case where 100kW of electron cyclotron resonance heating (ECRH) was used.
- All flows are intrinsic (no external momentum sources).
- Ion temperatures did not measurably change.





- The electron temperature and temperature gradient in the core of the plasma increased with ECRH
- The density profile for the 100kW had a smaller gradient in the core, but a larger gradient near r/a=0.6

E_r is Determined by the Ambipolarity Condition for Particle Flux

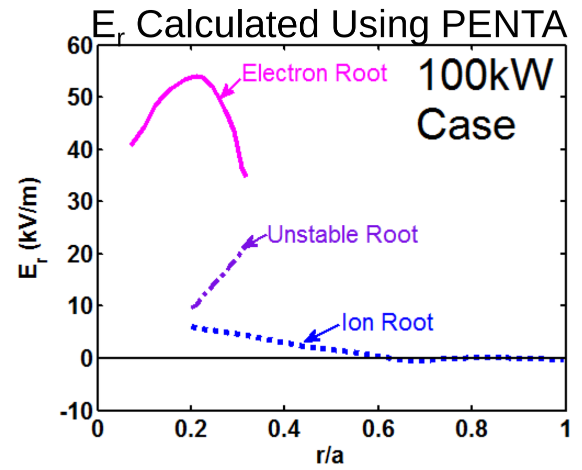


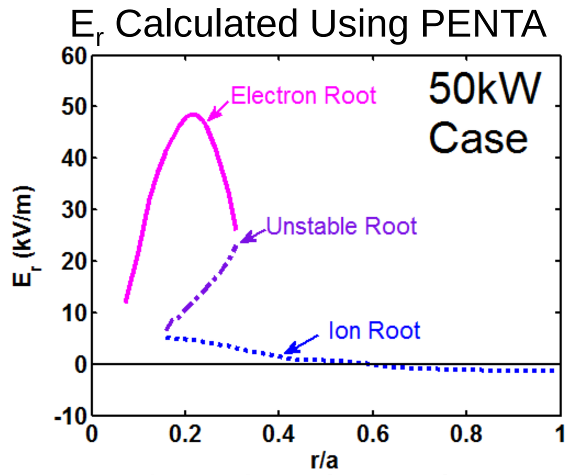
Electron root: Larger positive E_r associated with reduced neoclassical transport

Ion root: Smaller, sometimes negative E_r

Unstable root: Not a stable solution

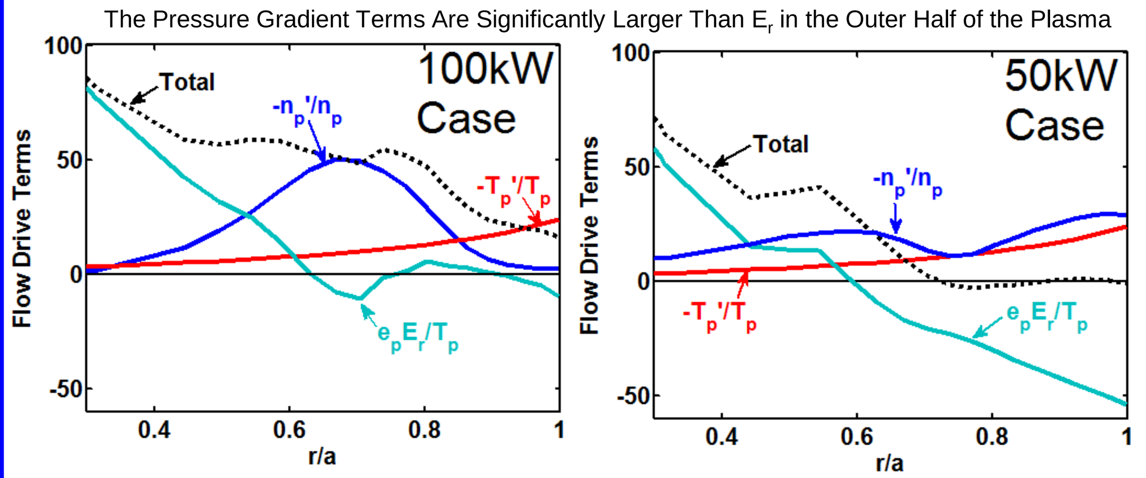
- Particle flux is not inherently ambipolar in devices with significant non-symmetric magnetic field components .
- E_r is determined from the ambipolarity condition: $\Gamma_e(E_r) = \sum_s Z_s\,\Gamma_s\,(E_r)$.
- This equation can have multiple solutions (roots).
- The peak in the electron flux at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



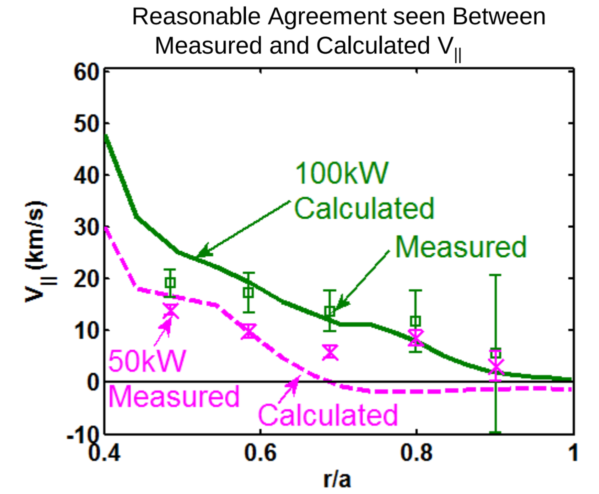


- In both the 100kW and 50kW cases near the axis only an electron root is predicted, from r/a~0.2 to r/a~3 multiple roots are predicted, for the outer half of the plasma only the ion root is predicted.
- E_r is predicted to be slightly lower in the 50kW case for most locations in the plasma

∇p Drives $V_{||}$ for r/a>0.5



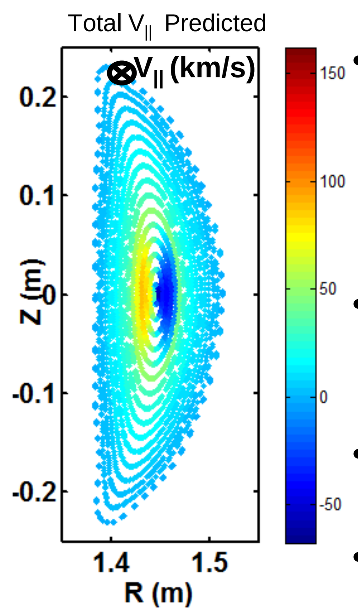
$V_{||}$ for the protons is predicted to have a similar dependence on all the thermodynamic drive terms: $\frac{e_pE_r}{T_p}, -\frac{T_p'}{T_p}$, and $-\frac{n_p'}{n_p}$.



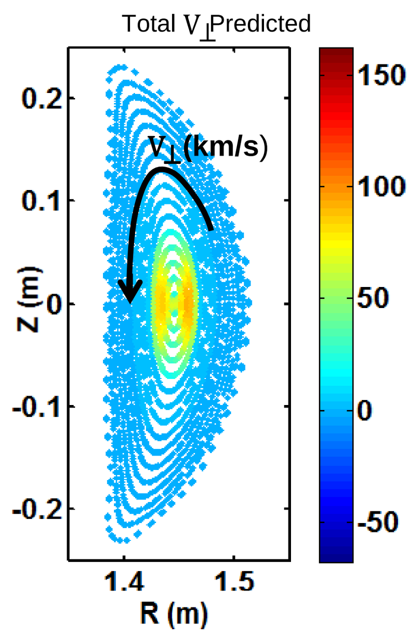
- In the outer half of the plasma E_r is small and in some regions negative, which in the absence of the pressure gradient terms would drive a negative parallel flow.
- Reasonable agreement is seen between the measured and calculated $V_{||}$ when all terms are included.

Flow Direction and Magnitude Predicted to Vary Significantly Near the Axis

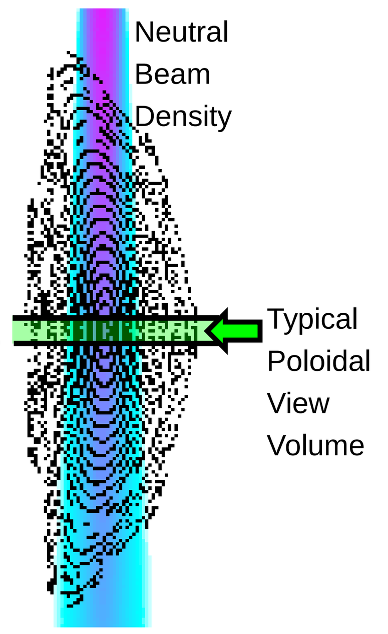
$$\vec V_{\parallel i} = \left(\frac{1}{en_iZ_i}\frac{\partial p_i}{\partial\Psi}+\frac{\partial\Phi}{\partial\Psi}\right)V_{PS}\hat b + \frac{\langle V_\parallel B\rangle}{\langle B^2\rangle}\vec B \qquad \vec V_{\perp i} = \left(\frac{1}{en_iZ_i}\frac{\partial p_i}{\partial\psi}+\frac{\partial\Phi}{\partial\Psi}\right)\left(\frac{\vec B\times\nabla\Psi}{B^2}\right)$$



- The magnitude of the plasma flow velocity components are plotted for the toroidal location where CHERS measurements are made.
- Flows shown were calculated using profiles for the 100kW case.
- The electron root was chosen in the multi root region
- The total $V_{||}$ is dominated by the Pfirsch-Schlüter component

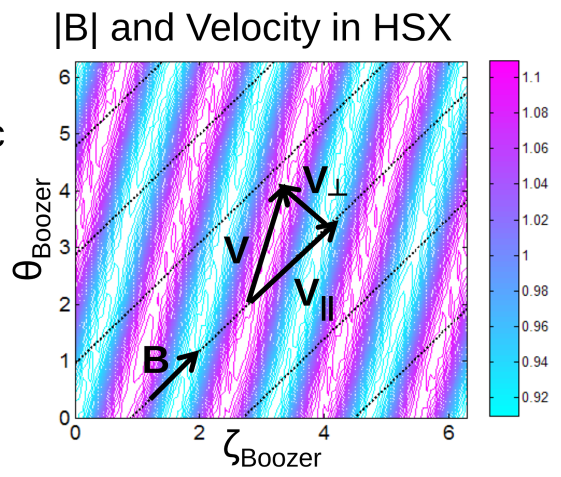


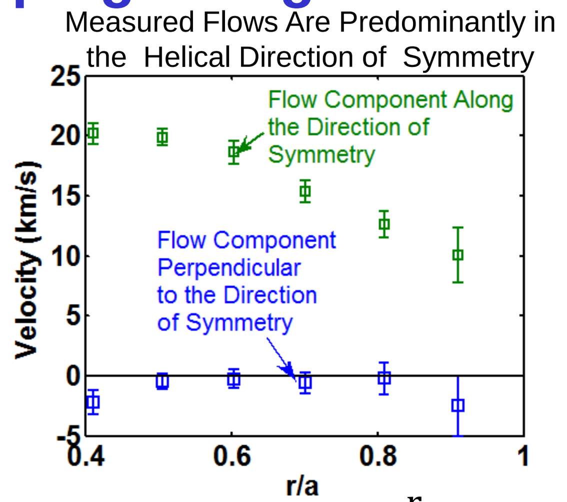
- The magnitude of $v_\perp$ has a minima in the middle of the neutral beam
- $v_\perp$ changes direction across the view/beam intersection volume measured by the CHERS views of the core.
- New views are being developed to measure the Pfirsch-Schlüter flow to better resolve E_r in the core.



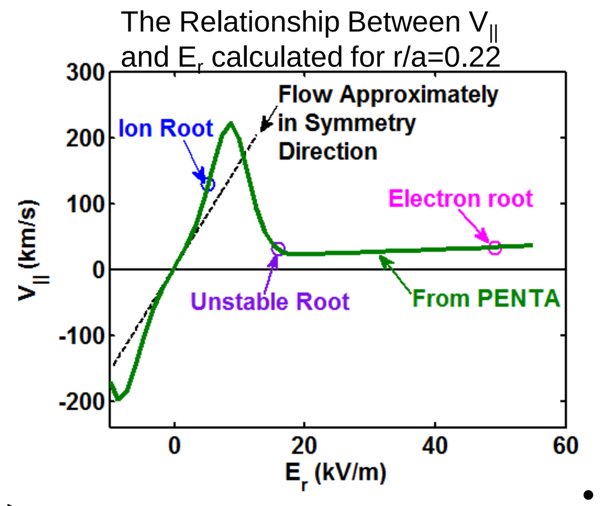
Reduced Flow Damping Along the Helical Direction of Symmetry Leads to Parallel Flow

HSX was optimized to have a direction of symmetry in its magnetic field strength. This has been predicted and measured to cause reduced flow damping in the n=4, m=1 helical direction [5].



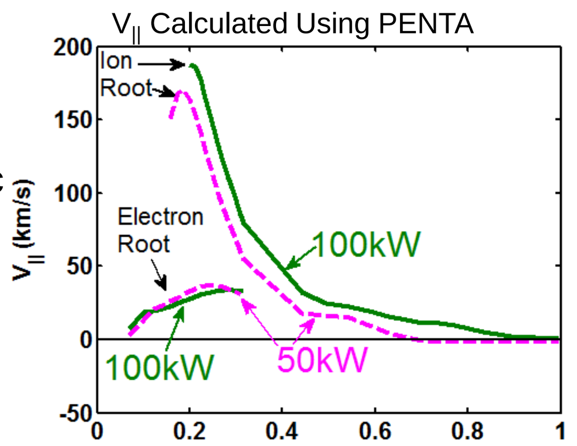


- For small values of E_r parallel flows will arise that cause the total flow direction to be along the direction of symmetry, on average.
- In the outer half of the plasma, where E_r is predicted to be small, the direction is along direction of symmetry.



- When $V_\perp \propto -\frac{r}{R}V_{||}$ (ι−4) the total flow will move approximately along the symmetry direction.
- For small values of E_r PENTA predicts flows will move in the direction of symmetry.

For large perpendicular flow drives, such as the electron root radial electric field, ions which caused the plasma viscosity are de-trapped and parallel flow will be reduced



- For both the 100kW and the 50kW cases a small $V_{||}$ is predicted near the core as a result of the large electron root E_r
- The peak flows are larger than the ion thermal velocity, no experimental evidence of supra-thermal flows has been found

References

1) D.A. Spong, Phys. Plasmas 12, 056114 (2005).
2) J. Lore, Phys. Plasmas 17 056101 (2010).
3) Hirshman et al., Phys. Fluids 29, 2951 (1986).
4) van Rij et al., Phys. Fluids B 1, 563 (1989).
5) S.P. Gerhardt *et al*., Phys. Plasmas 12, 05116 (2005).

Thanks to MST for loaning us the neutral beam.

53rd Annual Meeting of the Division of Plasma Physics, November 14 - 18, 2011, Salt Lake City, Utah