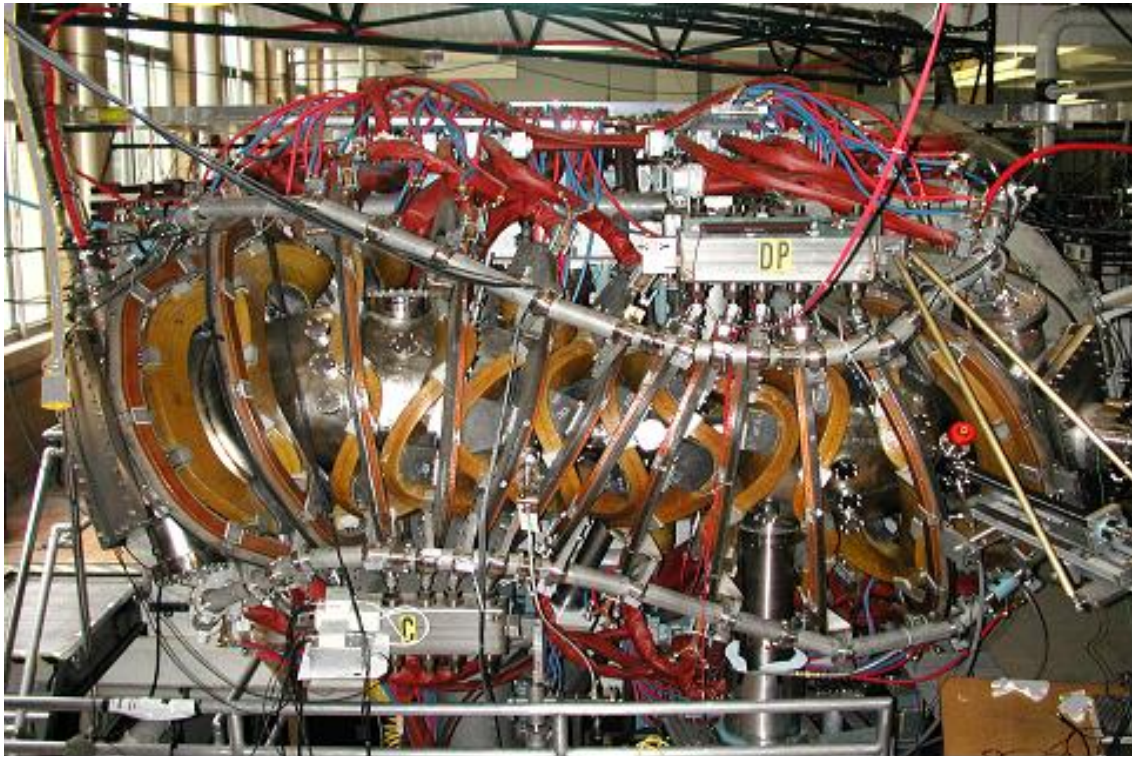
Measurement and Modeling of the Flows and Radial Electric Field in the HSX Stellarator



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Motivation For Measuring Radial Electric Field

- Large radial electric fields can develop in stellarators as a result of their non-ambipolar neoclassical particle flux
- Radial electric fields reduce neoclassical transport
- Radially sheared ExB flow can break apart turbulent eddies reducing anomalous transport
- Radial electric fields drive intrinsic plasma rotation

Motivation For Measuring Flows

- Flows improve plasma confinement and stability
  - Using neutral beams to drive flows is impractical for larger devices, intrinsic flows become important
- Quasi-symmetry allows large intrinsic flows in stellarators, which typically have large flow damping
  - HSX only operational quasi-symmetric stellarator
- The PENTA code can calculate intrinsic flows in devices with any level of symmetry
  - Non-symmetric fields can increase flow drive, but damp plasma rotation
  - Flows in HSX provide an important test case

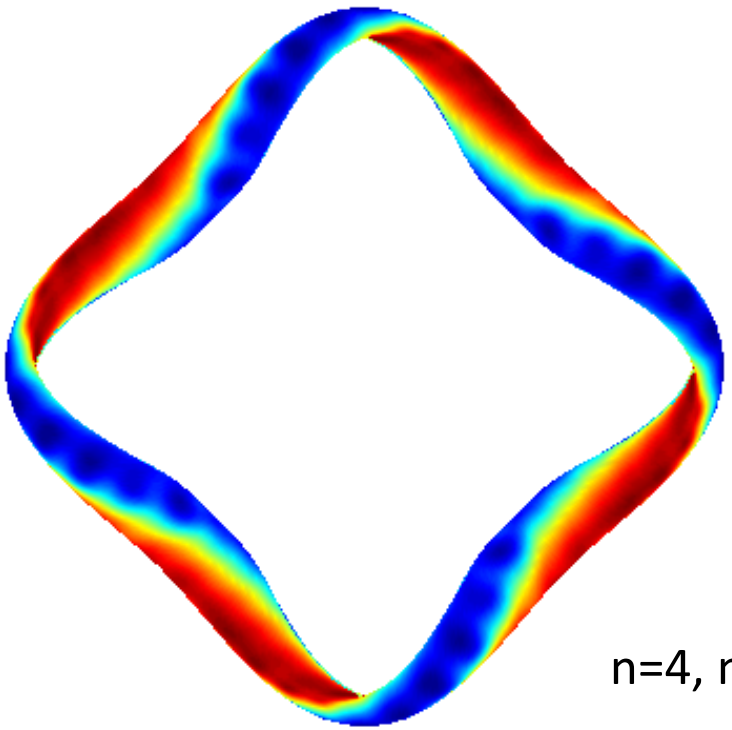
Outline

- The quasi-helically symmetric HSX stellarator
- Charge exchange recombination spectroscopy (CHERS) used to measure C^{+6} temperature, density and velocity
  - Velocity measured from 2 viewing directions to allow flow speed and direction to be determined
  - Flows move approximately in the helical direction with speed of up to 20 km/s
- The PENTA code is used to calculate neoclassical transport, E_r and parallel flow, including momentum conservation
- Comparison of PENTA calculations and measurements
  - Small positive E_r measured across the plasma<<electron root value
  - Measured parallel flow similar to the flow calculated at the edge, but smaller than the value calculated in the care
  - The highest measured parallel flows measured in the cases with the highest neoclassical fluxes in the core

HSX is a Quasi-Helically Symmetric Stellarator

<R>	1.2 m
<a>	0.12 m
ι	1.05 →1.12
B_0	1.0 T
ECRH 28 GHz	100 kW
$\langle n_e \rangle$	$\leq 6 \times 10^{18}$ m^{-3}
T_e	0.5 to 2.5 keV
T_i	30 to 60 eV

QHS



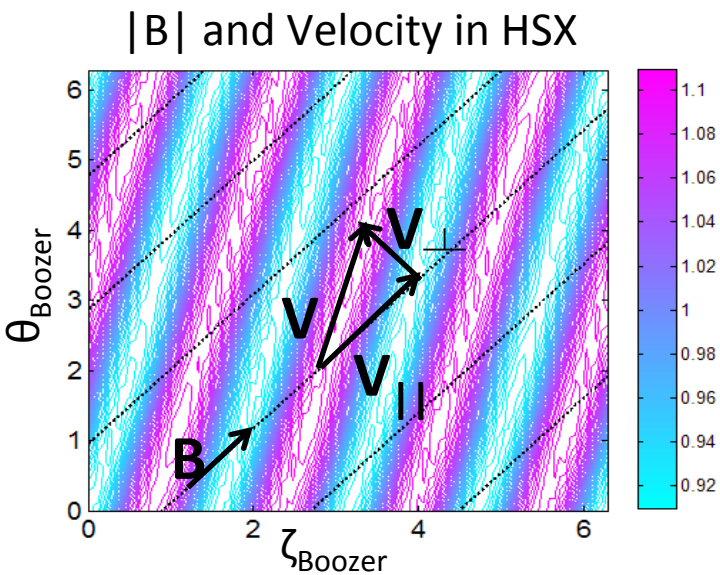
n=4, m=1

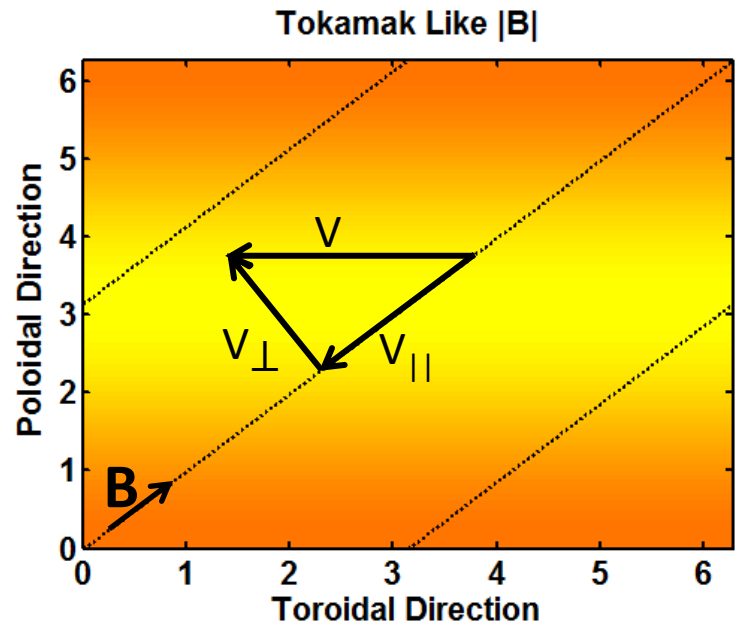
$$|B| = B_0\left[1 - \varepsilon_h \cos(n - m\iota)\varphi\right]$$

No external momentum sources

- Flows expected to follow helical direction of symmetry

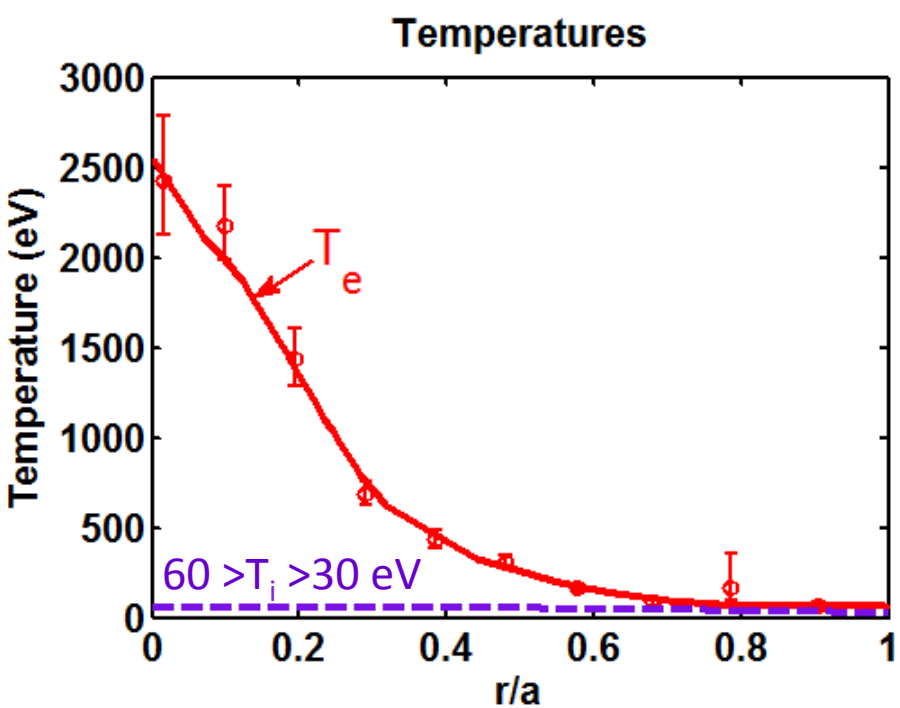
Magnetic Field Spectrum Determines Flow

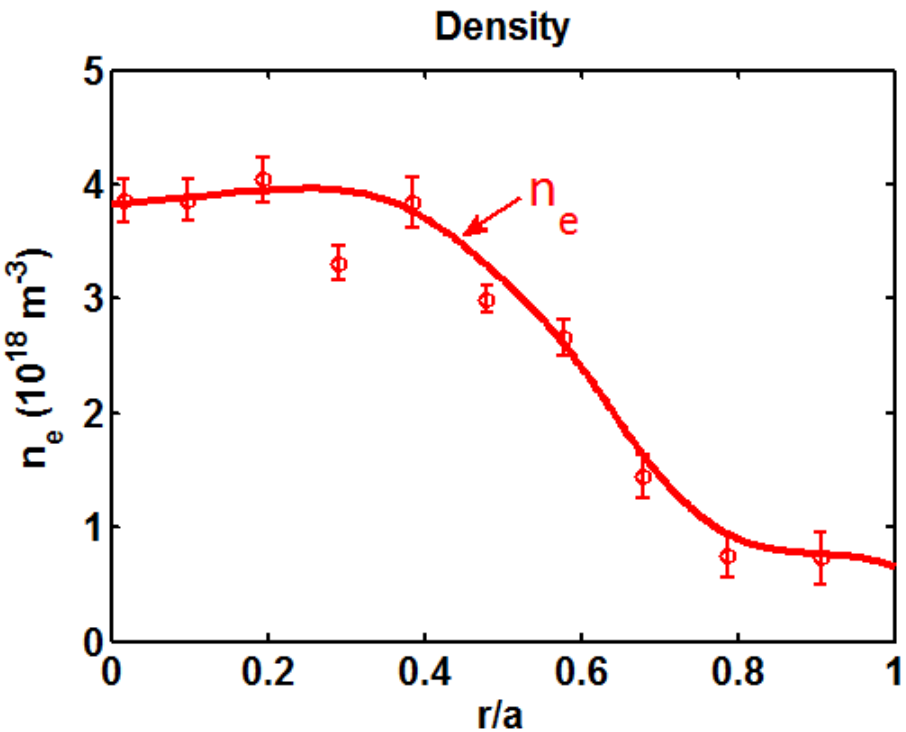




- $V_\perp$, flow perpendicular to $\vec{B}$, is driven by $\vec{E}\times\vec{B}$ and ∇p
- $V_{||}$, flow parallel to $\vec{B}$, is a result of viscosity
- The dominant magnetic component determines the direction of $V_{||}$
- The magnitude of $V_{||}$ is determined by the full magnetic field spectrum

HSX Plasma Profiles for Highest Heating Case

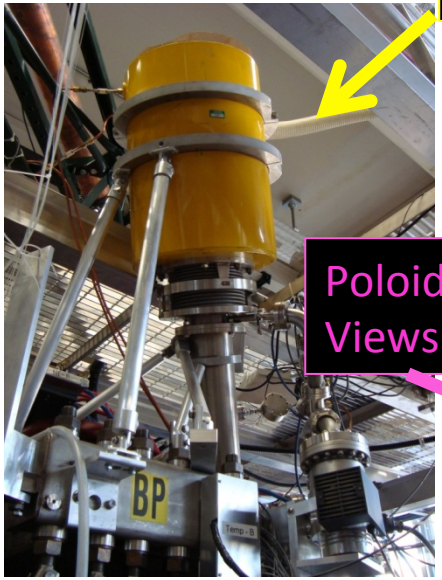




- 100 kW launched electron cyclotron resonance heating (ECRH) was used
- Strongly peaked electron temperature profiles were measured by Thomson scattering
- No direct ion heating
- These profiles will be used throughout this work

Charge Exchange Recombination Spectroscopy (CHERS)

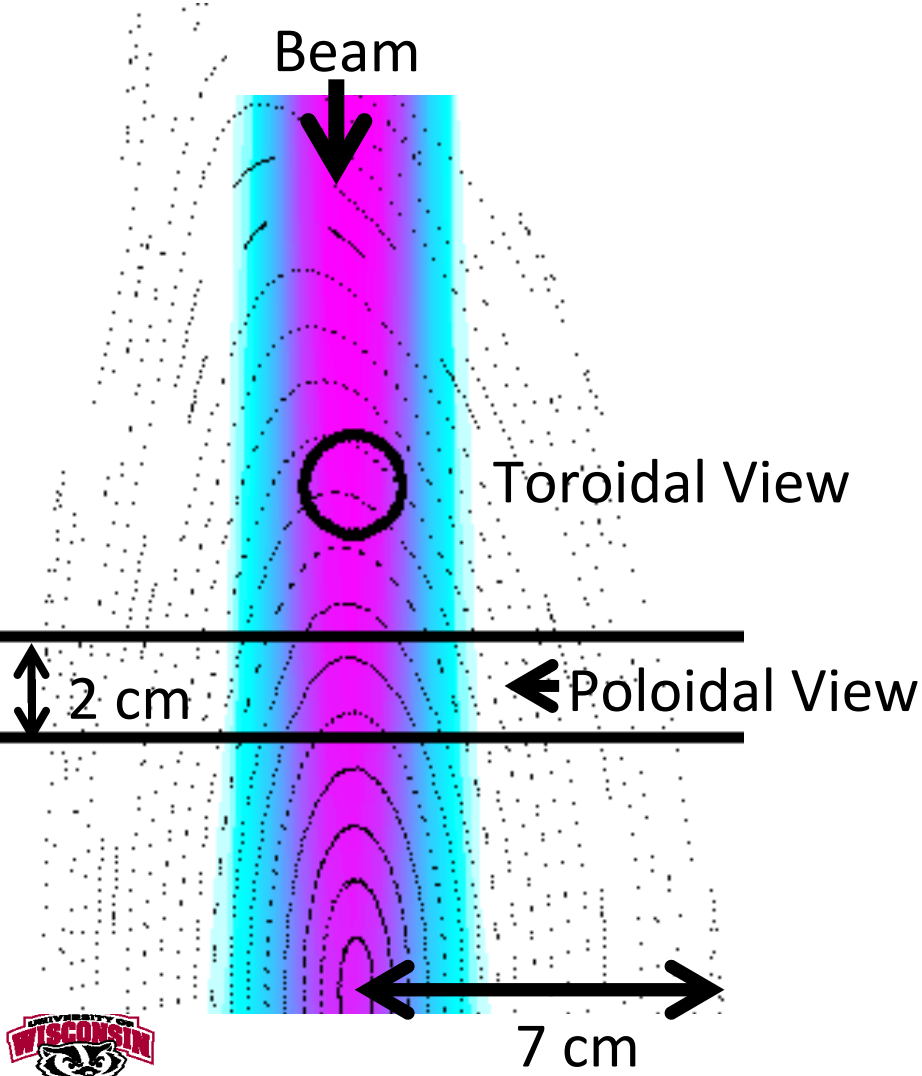
A CHERS system has been installed on HSX to measure impurity ion flow velocity, temperature and density. The E_r can be inferred from these measurements.



Spectral Measurements

- 0.75 m imaging Czerny Turner Spectrometers, which can be used for wavelengths below 600 nm
- Princeton Instruments PhotonMax 512B electron multiplying CCDs, sensitivity decreases for wavelengths below 400 nm
- The 529 nm C^{+5} line falls within the optimum wavelength range of the system
- Carbon was the dominant impurity ion when the walls were carbonized, it is now added by methane doping
- Light from a neon glow is used to measure the broadening of the spectral lines caused by the instrumental function
- Light from a neon lamp is used to calibrate the spectral alignment on every shot to remove spectral drift

Neutral Beam Stimulates the Emission of Spatially Localized Light

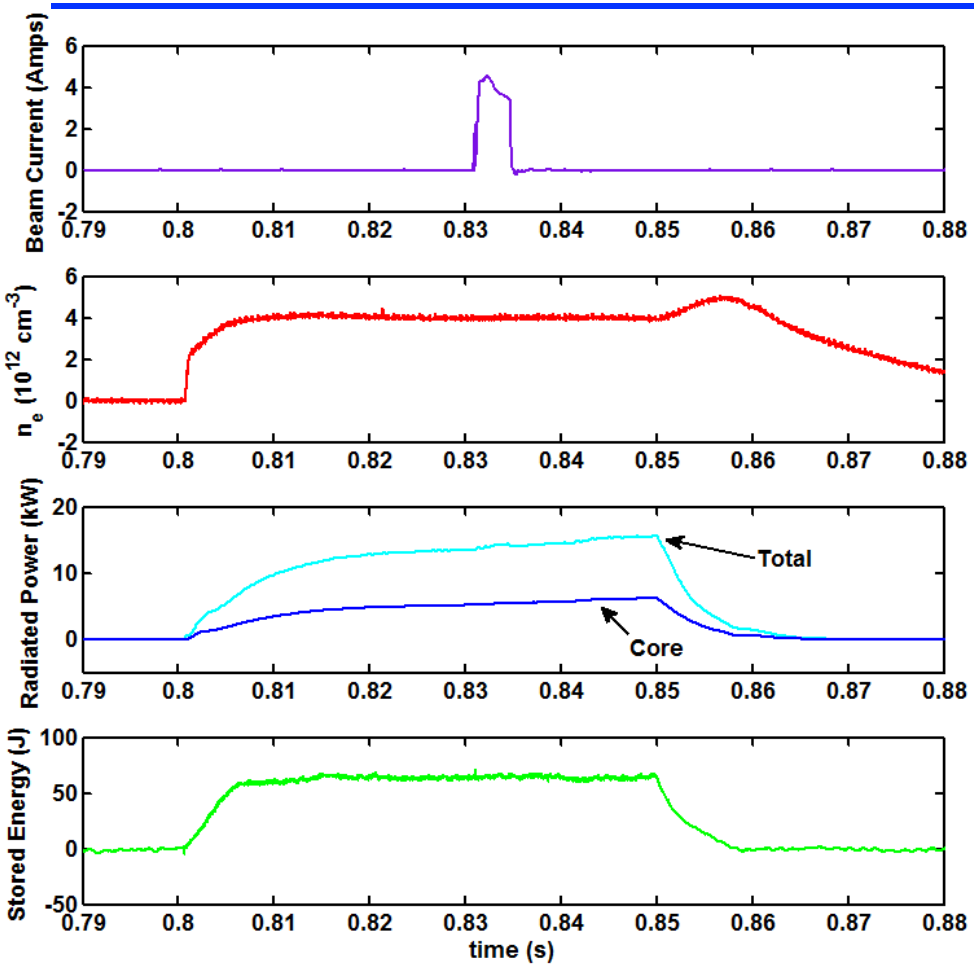


- A high energy neutral hydrogen beam launched through the plasma
- Some of the beam atoms will charge exchange with ions in the plasma

$$H^0 + C^{+6} \rightarrow H^+ + C^{+5}$$

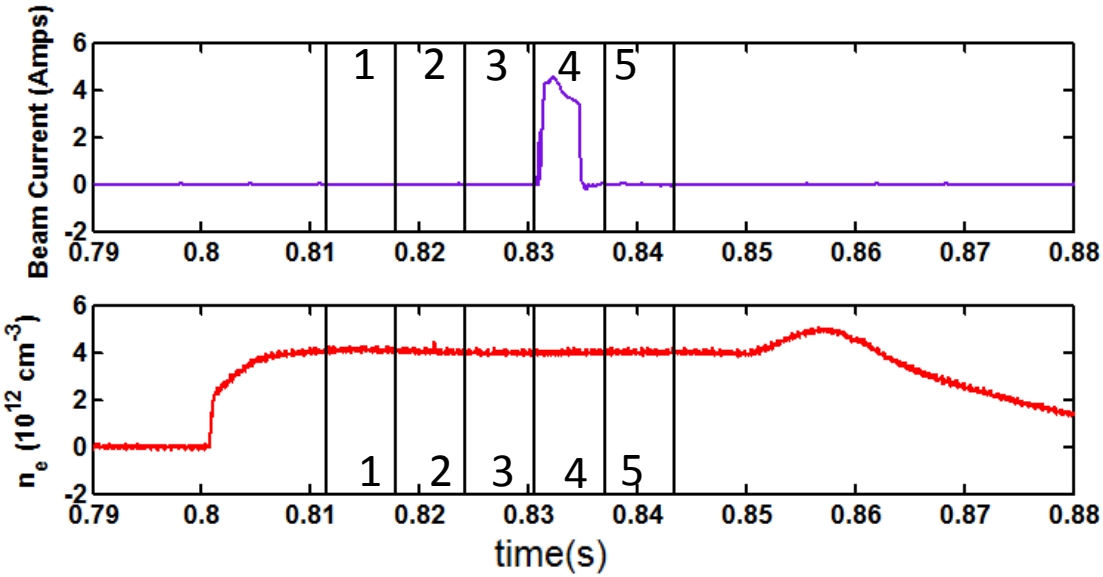
- The electrons exchanged into an excited energy level promptly decay, emitting a photon
  - Doppler Shift→Velocity
  - Doppler Broadening→Temperature
  - Intensity→Density

The Beam Does Not Perturb the Plasma



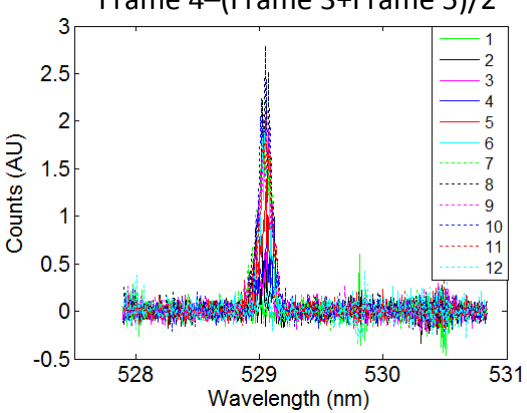
- 30 keV, 4 Amp-equivalent, 4 ms neutral hydrogen beam
- Line averaged density and stored energy do not change when the beam is fired.
- A small increase in radiated power is measured while the beam is firing
- No measurable perturbations are seen in the electron density and temperature profiles measured using the Thomson scattering system.

Images of the Background Light are used to Remove the Background Plasma Light

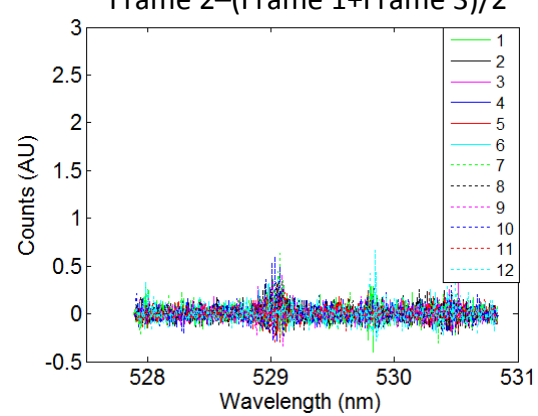


- Spectra taken before and after the beam is fired are averaged and subtracted from the image taken during the time the beam is firing
- This will remove any background signal captured by the CCD's
- When this technique is applied to frames where the beam was not fired only noise remains in the spectra
- When this technique is used the beam stimulated emission remains in the spectra.

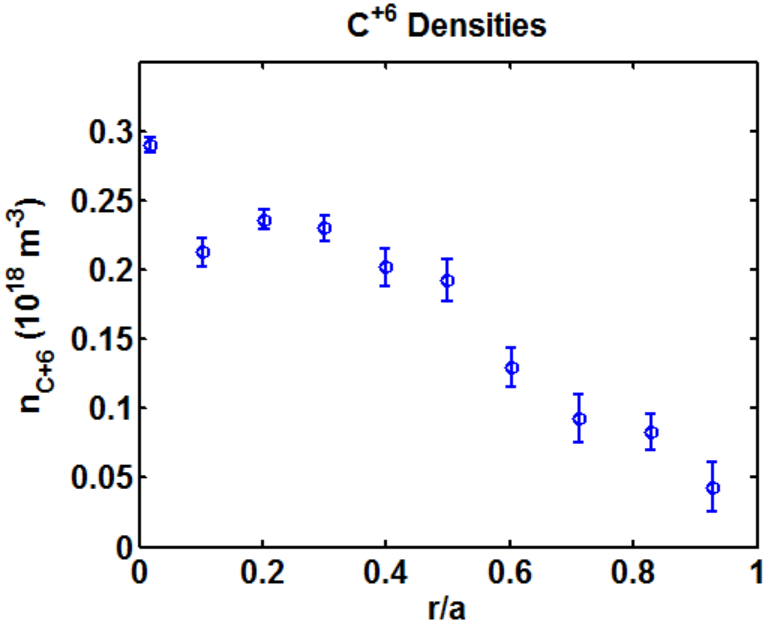
Frame 4–(Frame 3+Frame 5)/2

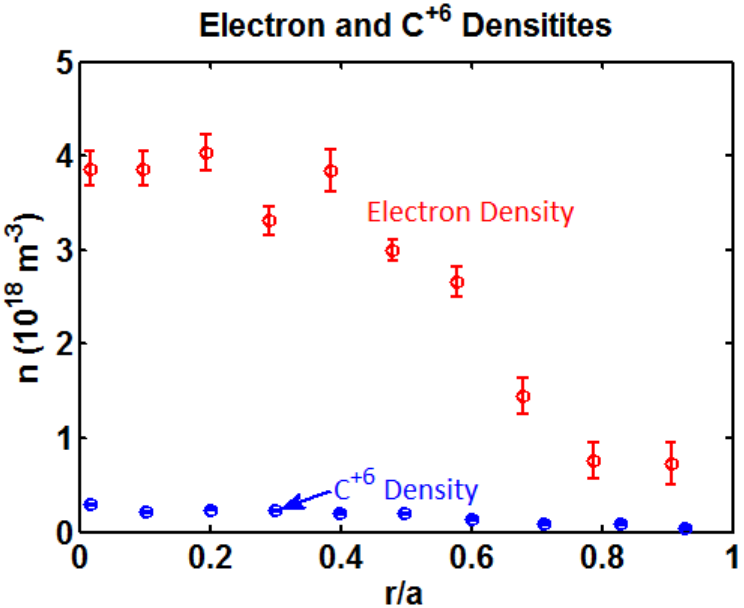


Frame 2–(Frame 1+Frame 3)/2



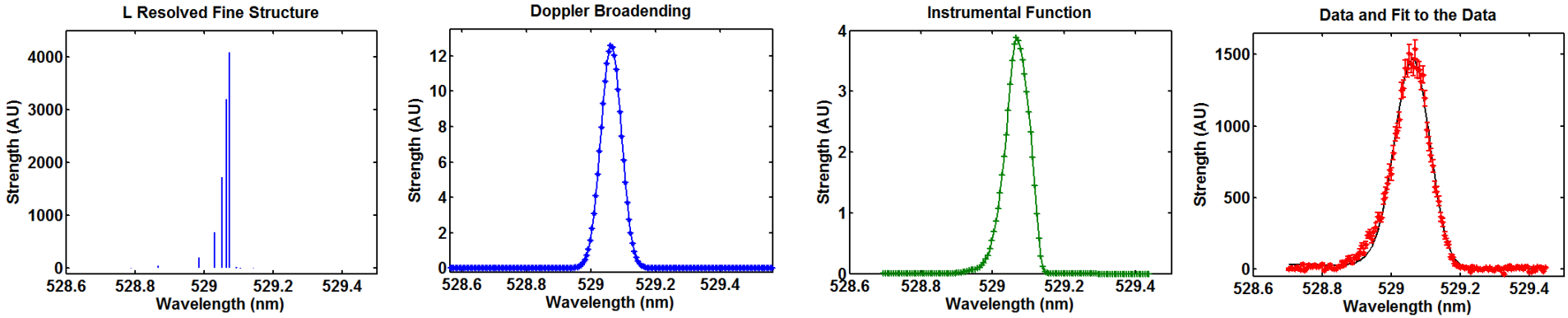
C^{+6} Density Determined From Total Emission Strength





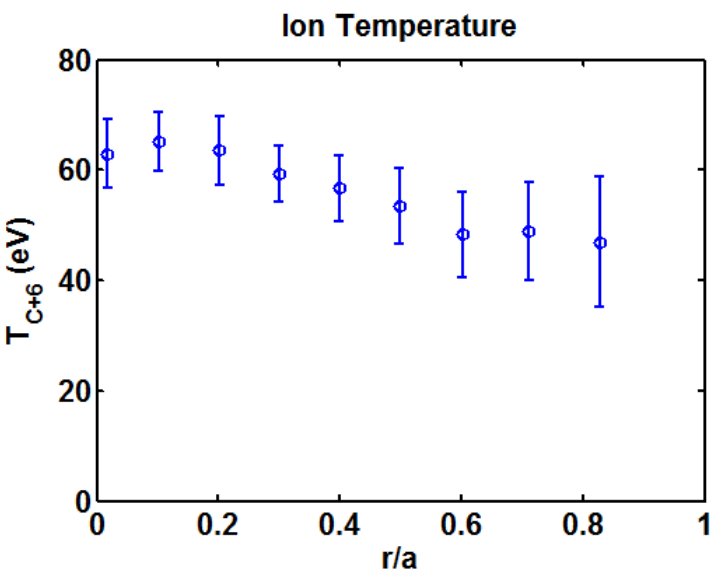
- The total CHERS signal is proportional to the neutral beam current and the C^{+6} density
- Emission coefficient used to related measured signal to C^{+6} density calculated by the Atomic Data Analysis Structure code (ADAS) [Summers 2004]
- C^{+6} density is much smaller than the electron density

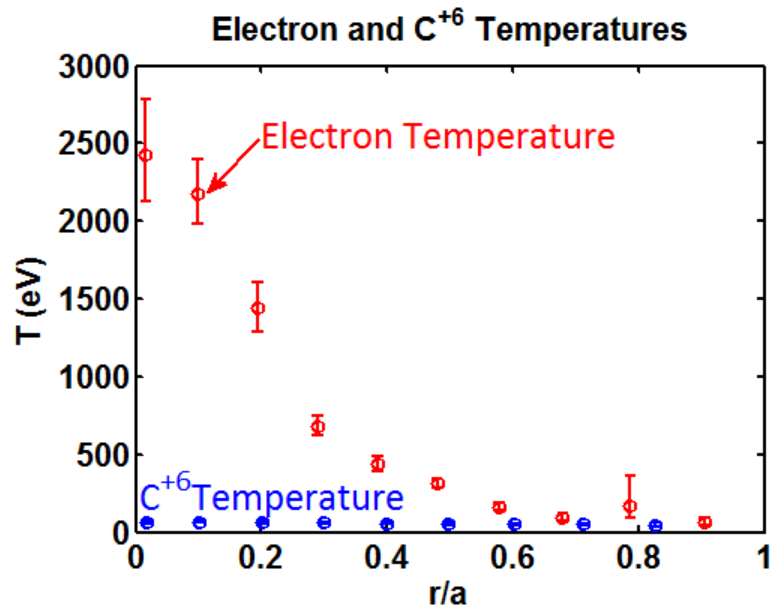
Fine Structure, Instrumental Function and Doppler Broadening Contribute to Line Width



- Fine structure is several closely spaced emission lines from the sub-levels of the principal energy levels
- The fine structure is calculated using ADAS
- Each component of the fine structure is Doppler broadened by the thermal motion of the ions
- Instrumental function of each view measured using Ne light
- The measured line is the convolution of the shifted and broadened fine structure with the instrumental function

Ion Temperature Much Lower Than the Electron Temperature

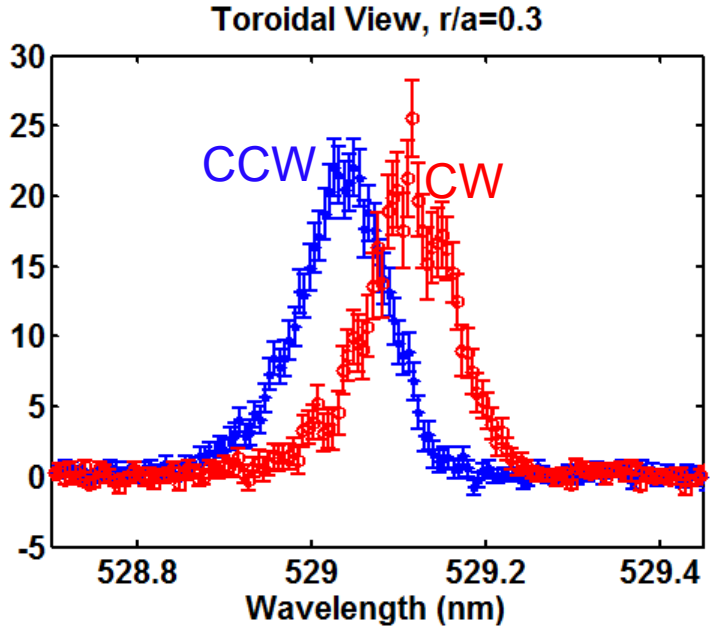


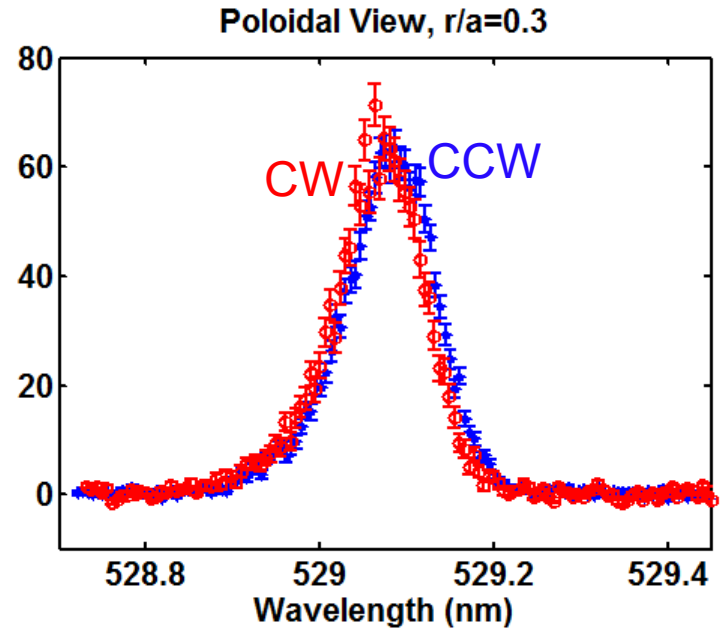


- Energy equilibration time for all the ion species is fast
- Carbon temperature is a good proxy for the temperatures of all the ion species

Flow Velocity and Doppler Shift Reverse Direction When the Magnetic Field is Reversed

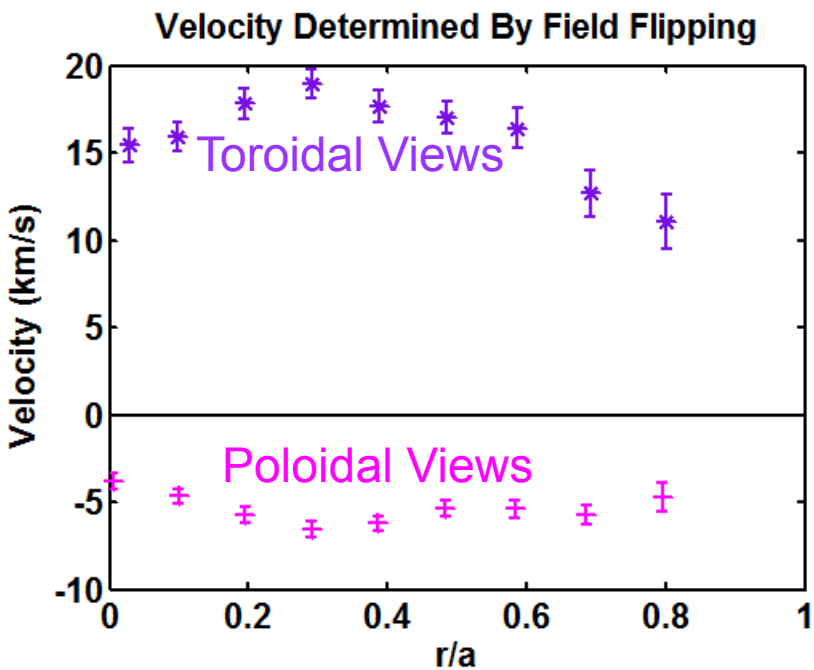
Spectra Measured With a CW and CCW Magnetic Field





- Eliminates the need to precisely calculate the unshifted line position
- Effectively doubles the measured shift
- 1 pixel shift = 3 km/s

Flow Velocity Along Each Viewing Direction Determined from Measured Doppler Shift



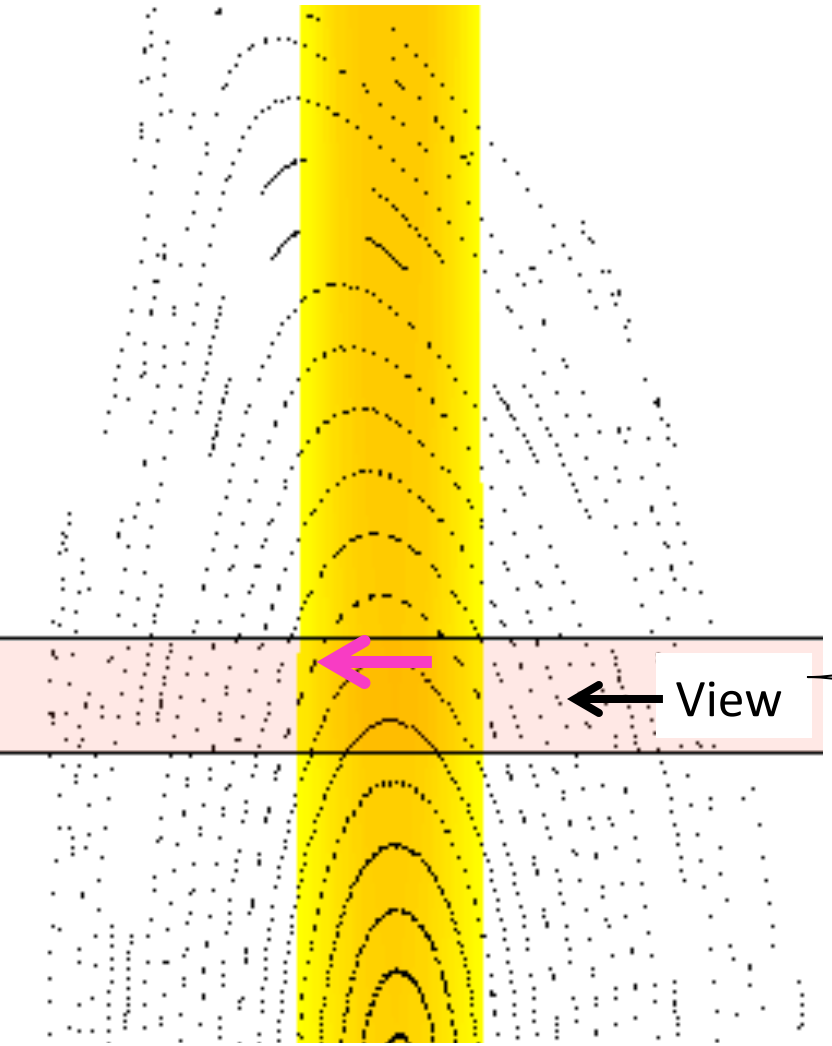
- Toroidal views typically see a velocity which is about 3 times larger than the velocity measured by the poloidal views
- Views are not orthogonal

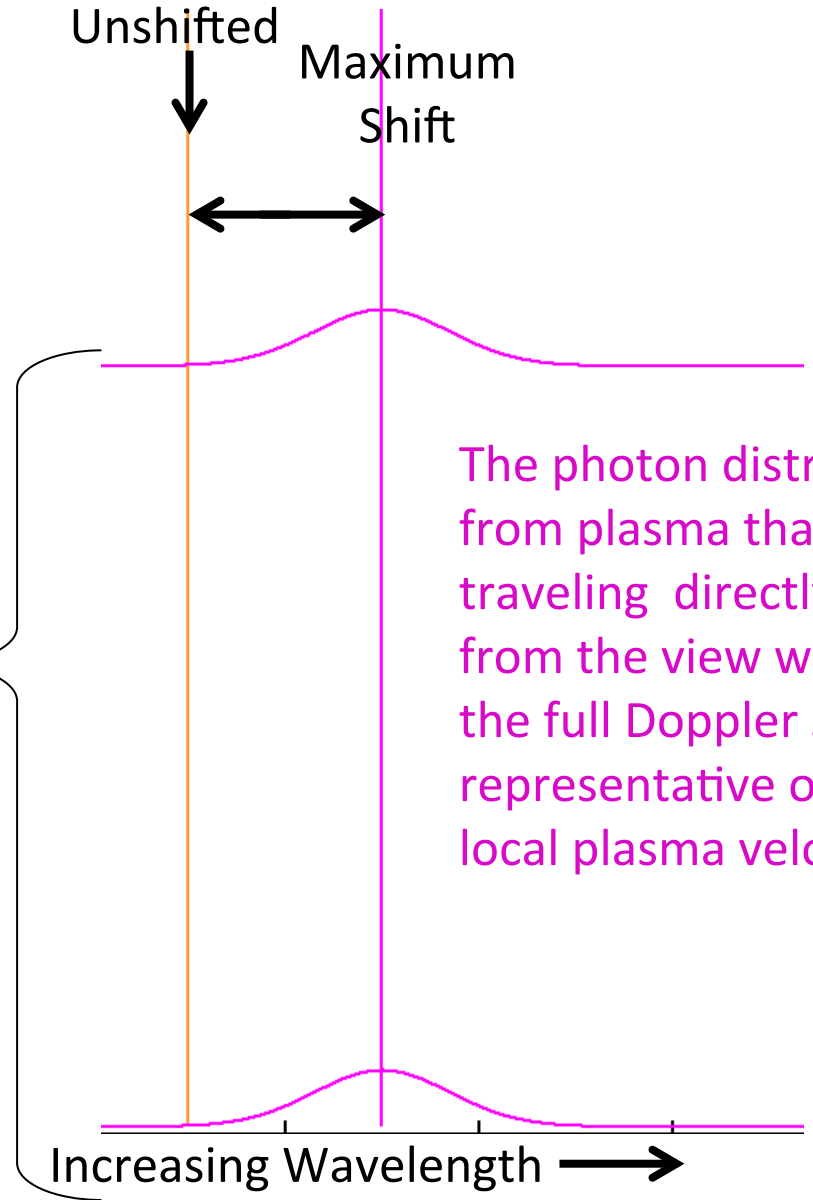
Flow Magnitude and Direction Varies Within a Surface

$$\vec{V}_i = \underbrace{\left(\frac{\vec{E}_r \times \vec{B}}{B^2} - \frac{\nabla p_i \times \vec{B}}{n_i Z_i e B^2}\right)}_{\vec{V}_\perp} + \underbrace{V_{PS}\hat{b} + \frac{\langle V_{||i} B\rangle}{\langle B^2\rangle}\vec{B}}_{\vec{V}_{||}}$$

- ∇p driven flow is small for higher Z ions like carbon
- Pfirsch-Schlüter flow V_{PS} ensures incompressibility
- The variation of the flow velocity within a surface accounted for when comparing measured and calculated E_r and $V_{||}$

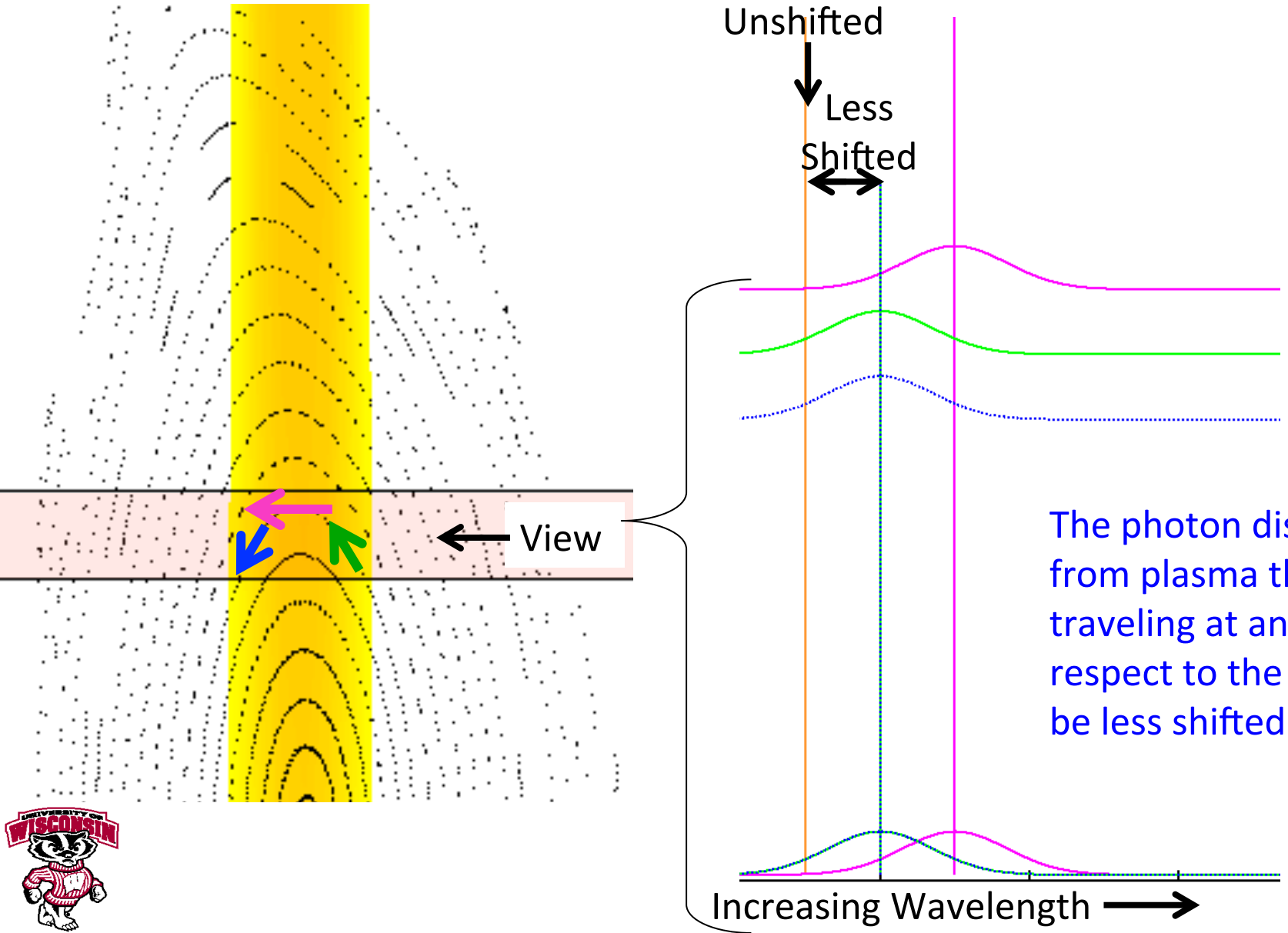
Measured Flow Depends on Angle of the Local Flow with Respect to the View Direction





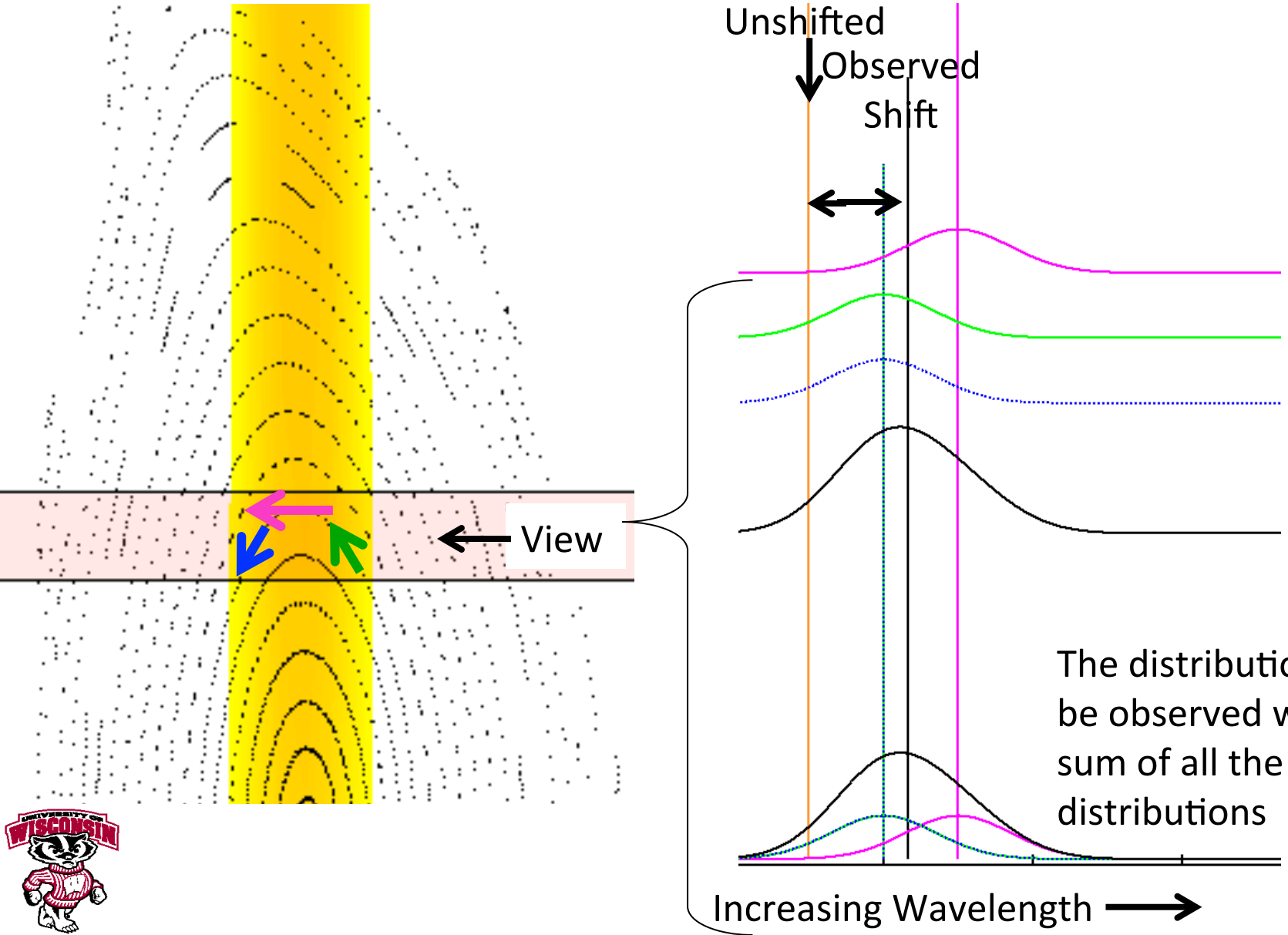
The photon distribution from plasma that is traveling directly away from the view will have the full Doppler shift, representative of the local plasma velocity

Measured Flow Depends on Angle of the Local Flow with Respect to the View Direction



The photon distribution from plasma that is traveling at an angle with respect to the view will be less shifted

Measured Flow Depends on Angle of the Local Flow with Respect to the View Direction



The distribution that will be observed will be a sum of all the different distributions

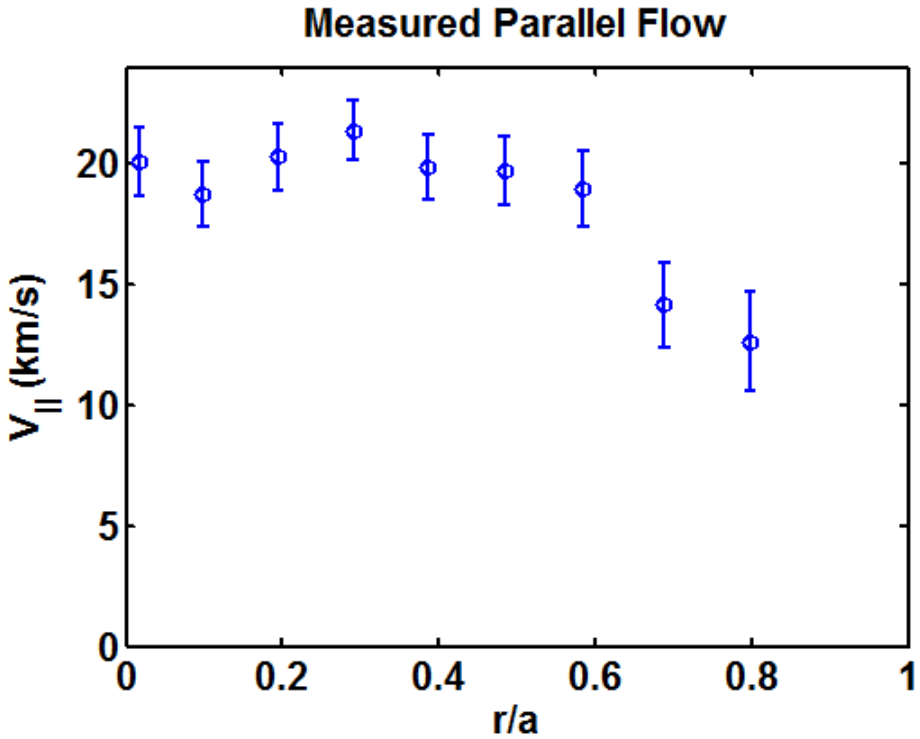
Average Magnetic Geometry of HSX used to Determine $V_{||}$ and $V_{\perp}$ from Measured Velocities

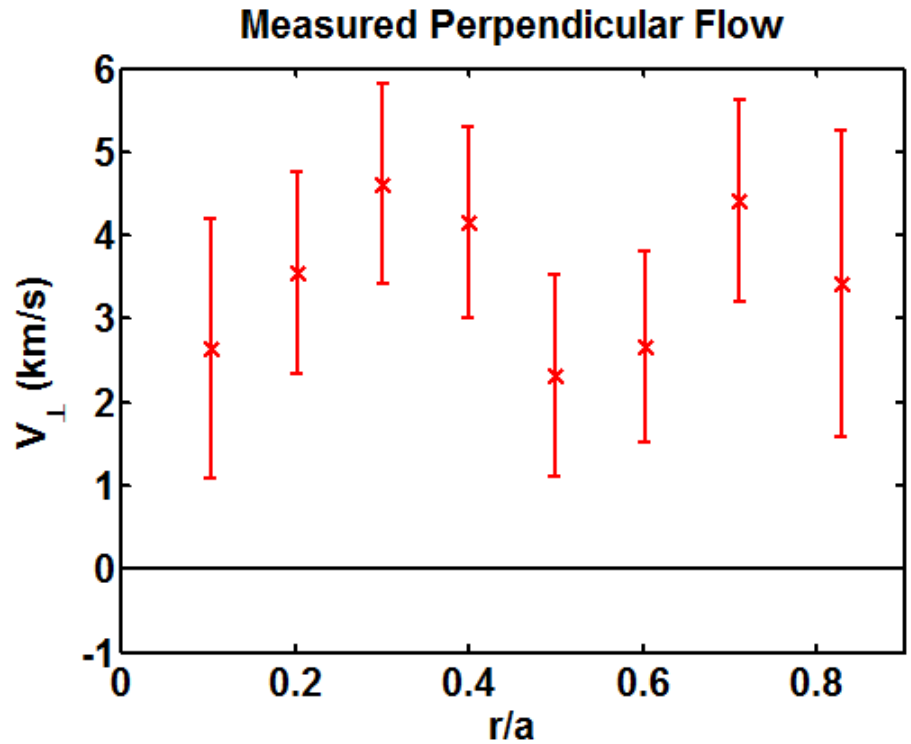
- The beam density weighted average of the local magnetic geometry is used to create a single matrix equation for each radial location

$$\begin{bmatrix} G_{||\ Tor} & G_{\perp\ Tor} \\ G_{||\ Pol} & G_{\perp\ Pol} \end{bmatrix} \begin{bmatrix} V_{||} \\ V_{\perp} \end{bmatrix} = \begin{bmatrix} V_{M\ Tor} \\ V_{M\ Pol} \end{bmatrix}$$

- This equation is then inverted to find the perpendicular and parallel flow velocities
- This equation can also be formulated to find the flow velocities along and normal to the helical direction of symmetry within a flux surface

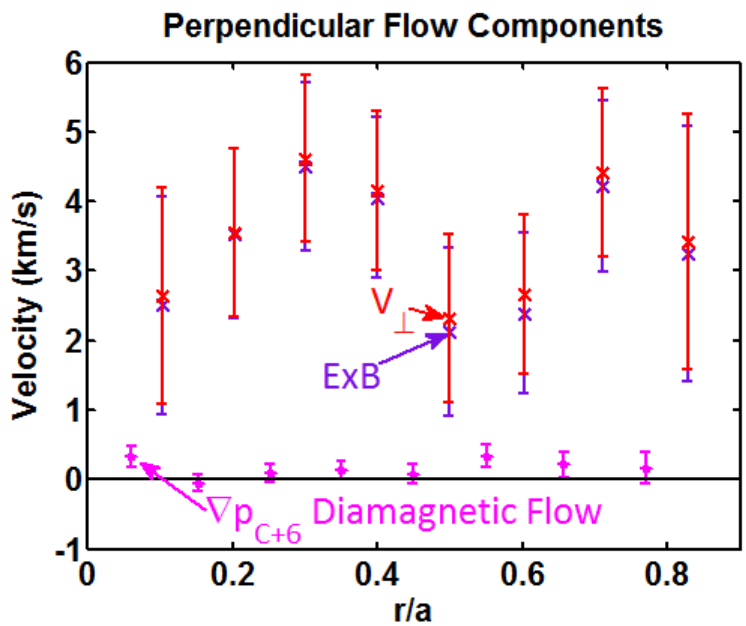
Measured Parallel Flow Much Larger than the Perpendicular Flow





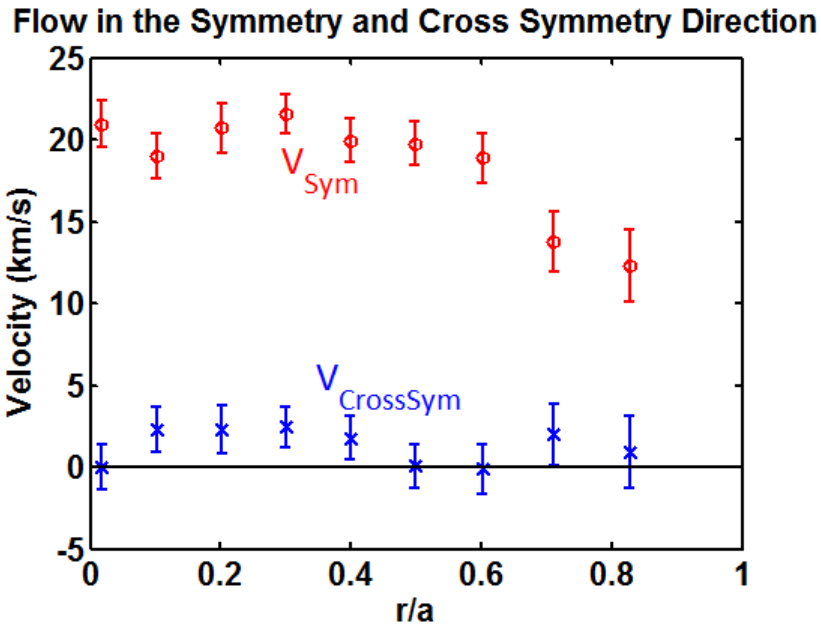
- Measure parallel flow is approximately constant in the inner half of the plasma and only decreases slightly towards the edge of the plasma
- Changes in the magnitude of $V_{\perp}$ across the plasma are small

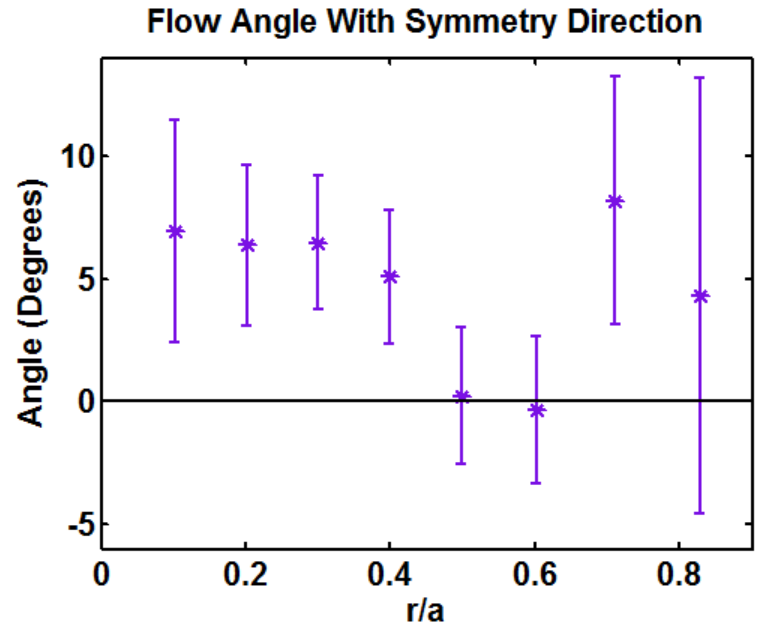
Pressure Gradient Driven Flow For C^{+6} Makes a Negligible Contribution to $V_\perp$



- The measured perpendicular flow is given by: $\vec{V}_{\perp i} = \frac{\vec{E}\times\vec{B}}{B^2} - \frac{\nabla p_i \times \vec{B}}{e n_i Z_i B^2}$
- The ∇p driven flow is calculated from the C^{+6} temperature and density profiles measured by CHERS
- The ∇p driven flow is subtracted from the measured $V_\perp$ to find the ExB flow
- B=1 Tesla for these plasmas

The Flow Direction Diverges Only Slightly From The Helical Direction of Symmetry





- Since $V_{||} >> V_{\perp}$ the total flow direction is approximately along the helical direction of symmetry
- The angle between the flow direction is about 5°

Neoclassical Particle Flux and Flows are Calculated using the PENTA Code

- The DKES (Drift Kinetic Equation Solver) code [Hirshman PoF 1986] is used to find the monoenergetic radial transport coefficients
  - Uses a simplified pitch angle scattering collision operator
  - Applicable to conventional stellarators with large flow damping
- The PENTA code[Spong PoP 2005] corrects the transport coefficients from DKES for momentum exchange
  - This correction makes PENTA valid for devices with any level of symmetry, ideal tokamaks ➡conventional stellarators

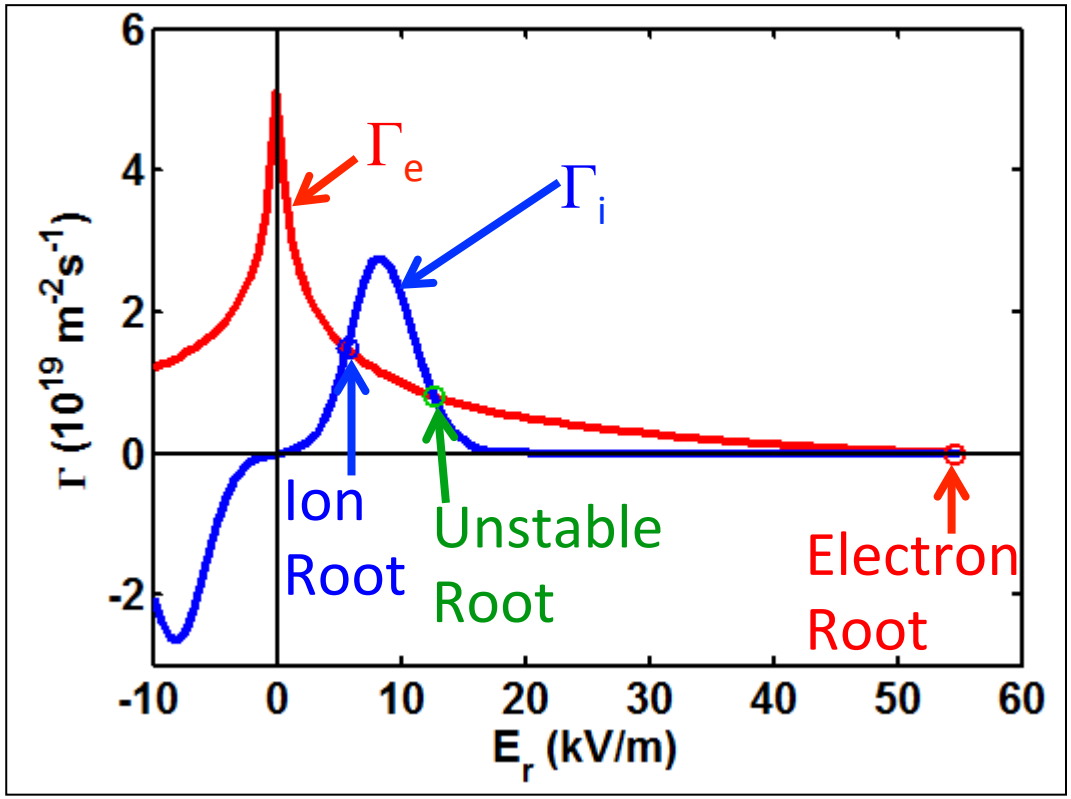
Calculating E_r from Neoclassical Transport

- Particle flux is not inherently ambipolar in devices with significant non-symmetric magnetic field components

- E_r can be determined from the ambipolarity condition:

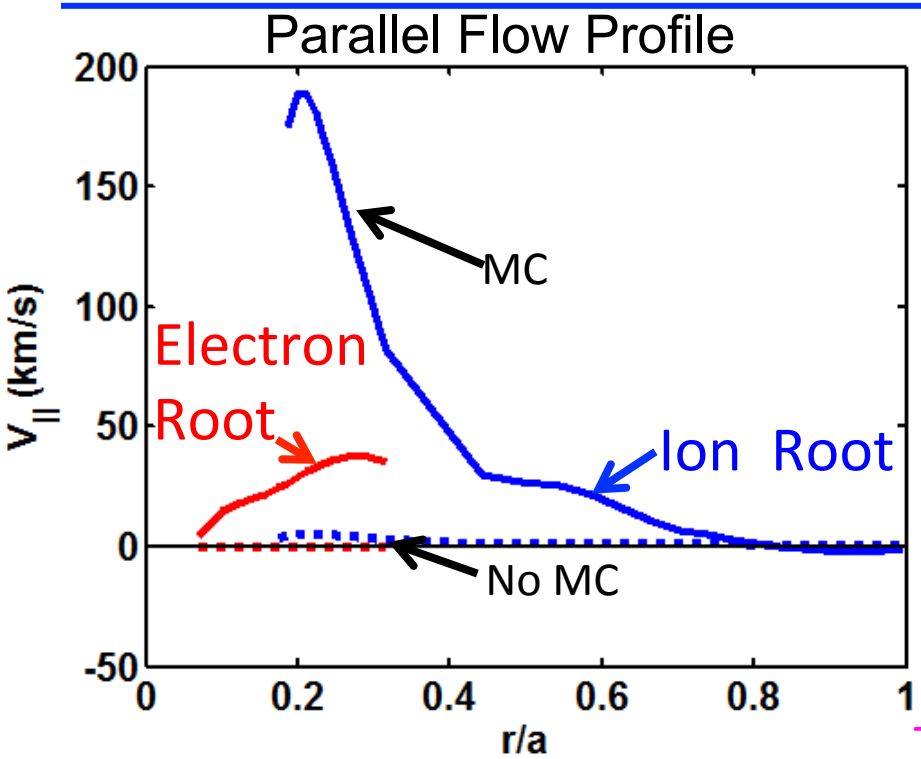
$$\Gamma_e(E_r) = \sum_s Z_s \, \Gamma_s \, (E_r)$$

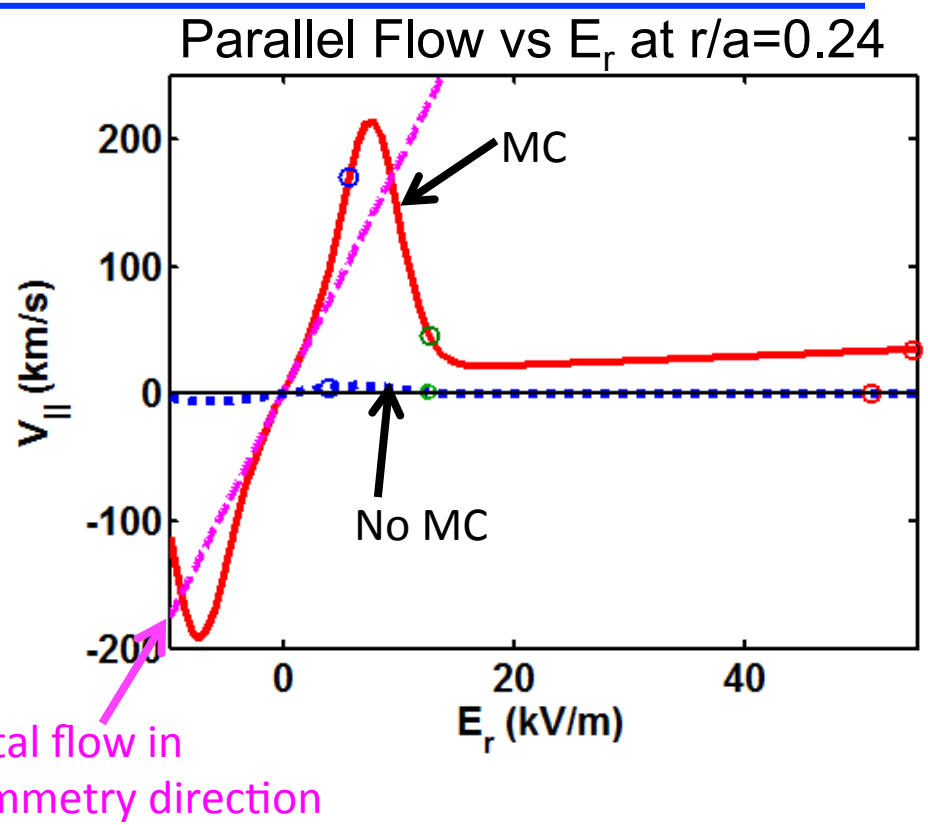
- Multiple solutions (roots) to the ambipolarity condition can exist



- **Electron root**: Larger positive E_r associated with reduced neoclassical transport
- **Ion root**: Smaller, sometimes negative E_r
- **Unstable root**

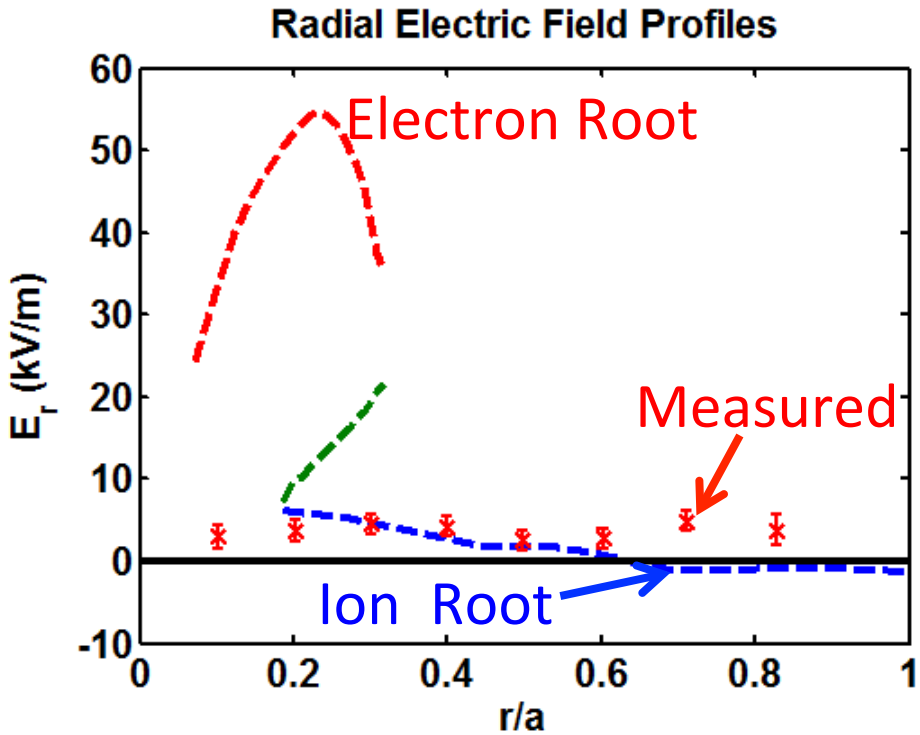
The Momentum Correction Significantly Increases the Calculated Parallel Flow





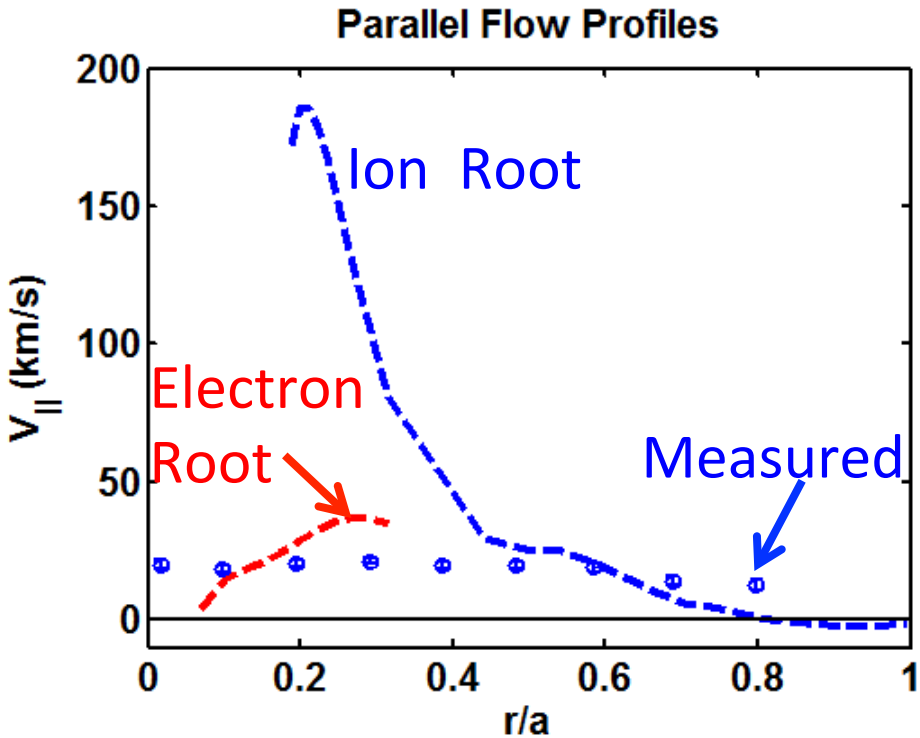
- The non-momentum conserving calculations predict an extremely small (<5 km/s) flow, for all values of E_r
- With momentum correction, for low E_r, the total flow is calculated to be along the helical direction of symmetry

Measured E_r Much Smaller than Electron Root Value, but Comparable to Ion Root



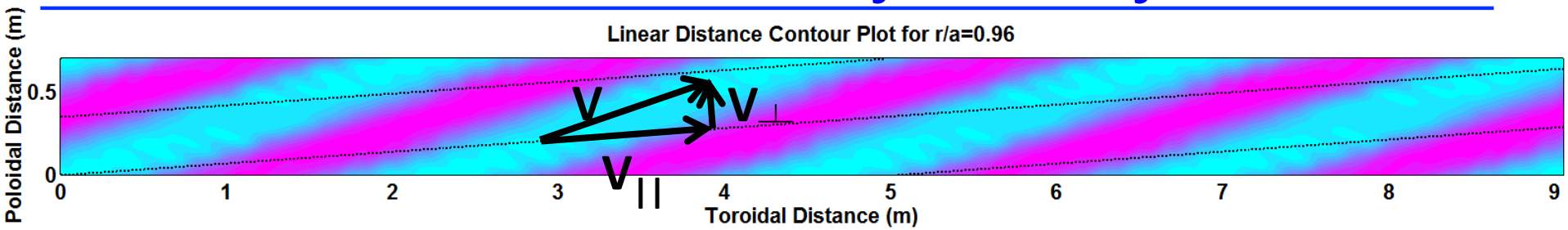
- Measured E_r close to the ion root value near the mid-radius
- Small positive E_r measured at the edge where PENTA calculates negative E_r

$V_{||}$ Associated with Ion Root E_r is Much Larger the Measured $V_{||}$ in the Core



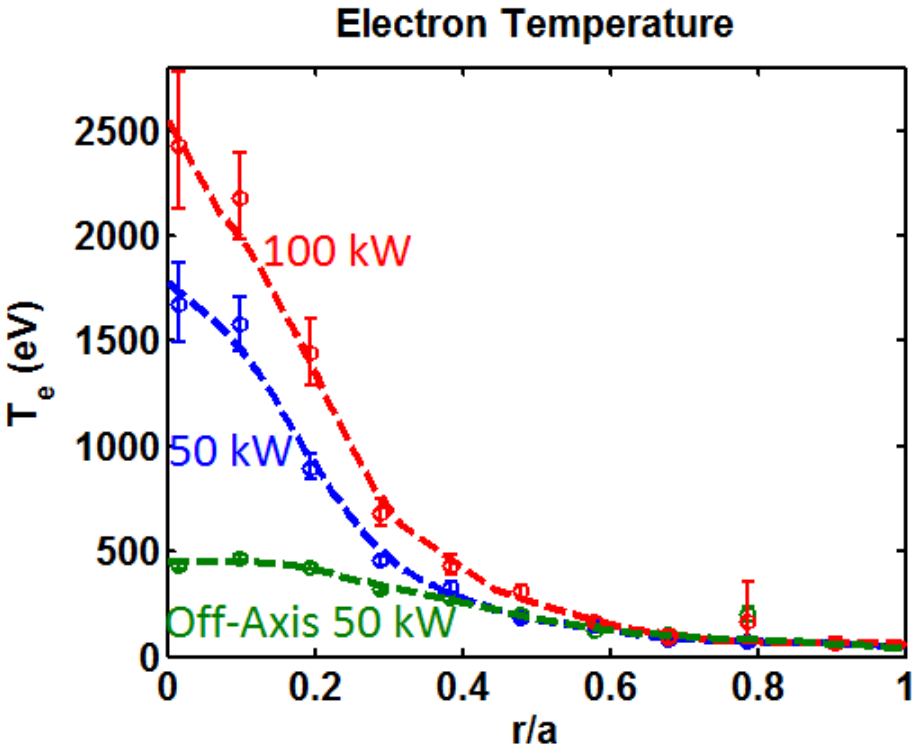
- In the outer regions, where E_r is calculated to be negative, $V_{||}$ is measured to be larger than the calculated value
- The calculated $V_{||}$ increases sharply towards the core, while the measured $V_{||}$ is approximately constant

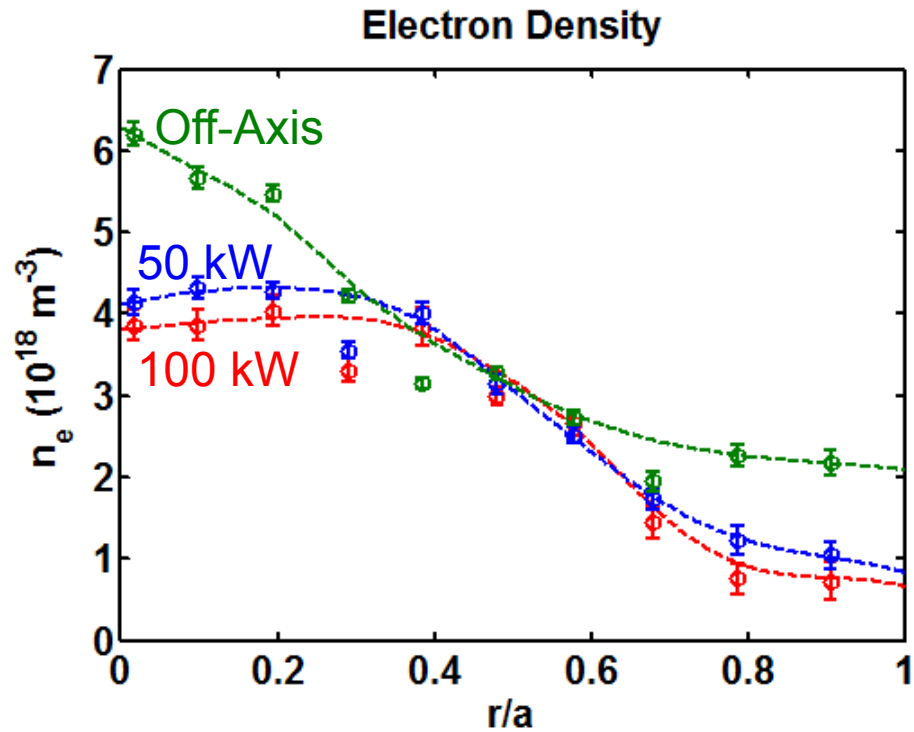
$V_{||} \gg V_{\perp}$ for the Flow to Follow the Helical Direction of Symmetry



- The Hamada toroidal and poloidal angles can be converted into approximate toroidal and poloidal distances around a flux surface using the major and minor radii
- Even on the outer most flux surfaces the poloidal distance around a flux surface is much smaller than the toroidal distance
- The rotational transform is approximately constant in HSX
- The ratio of parallel to perpendicular flow increases like 1/r towards the axis

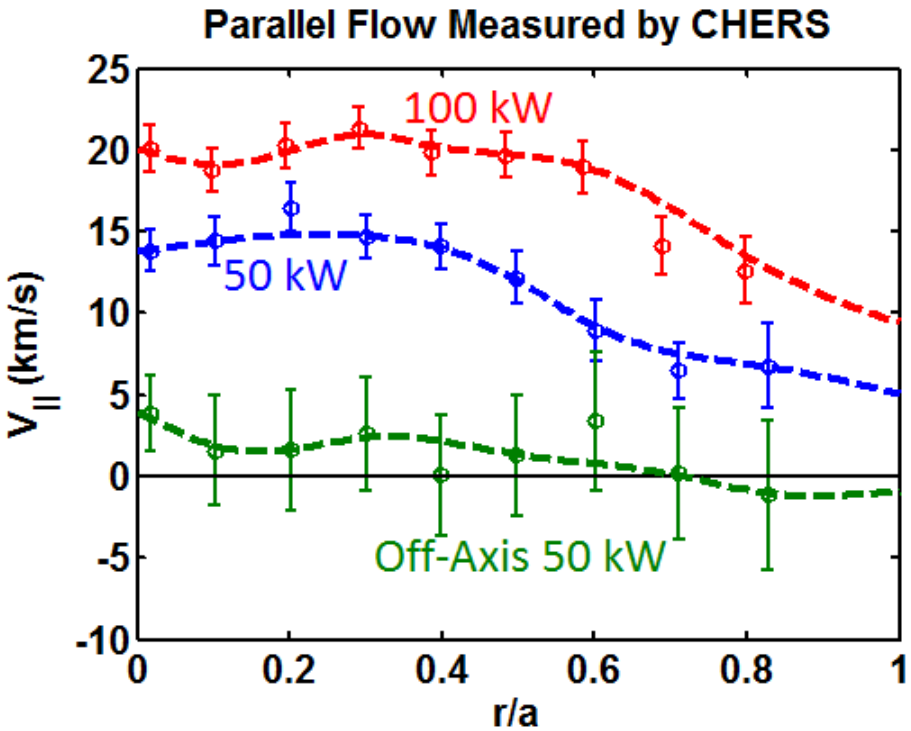
The Analysis of 3 Different Electron Heating Scenarios

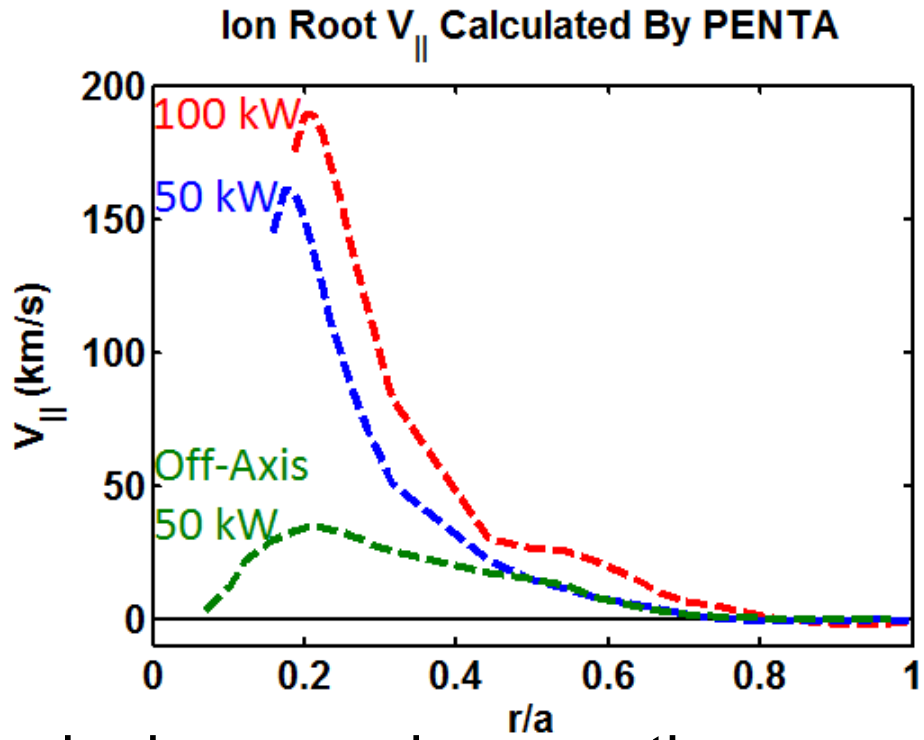




- The electron temperature was reduced by reducing the launched ECRH power
- The temperature was further reduced by moving the heat deposition to r/a~0.3

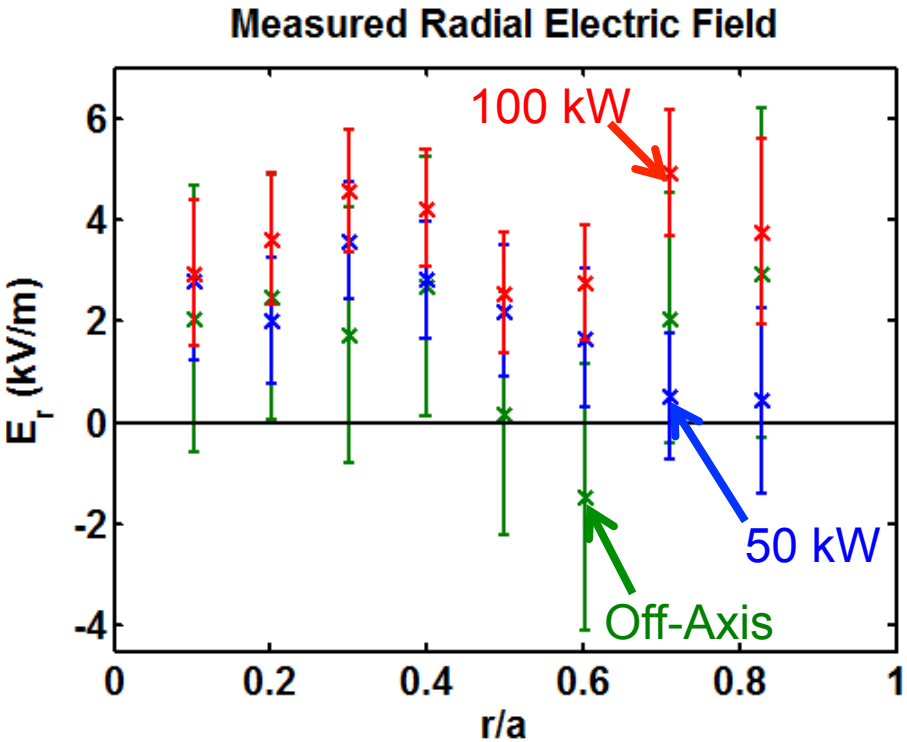
A Reduction in $V_{||}$ is both Calculated and Measured with Reduced T_e

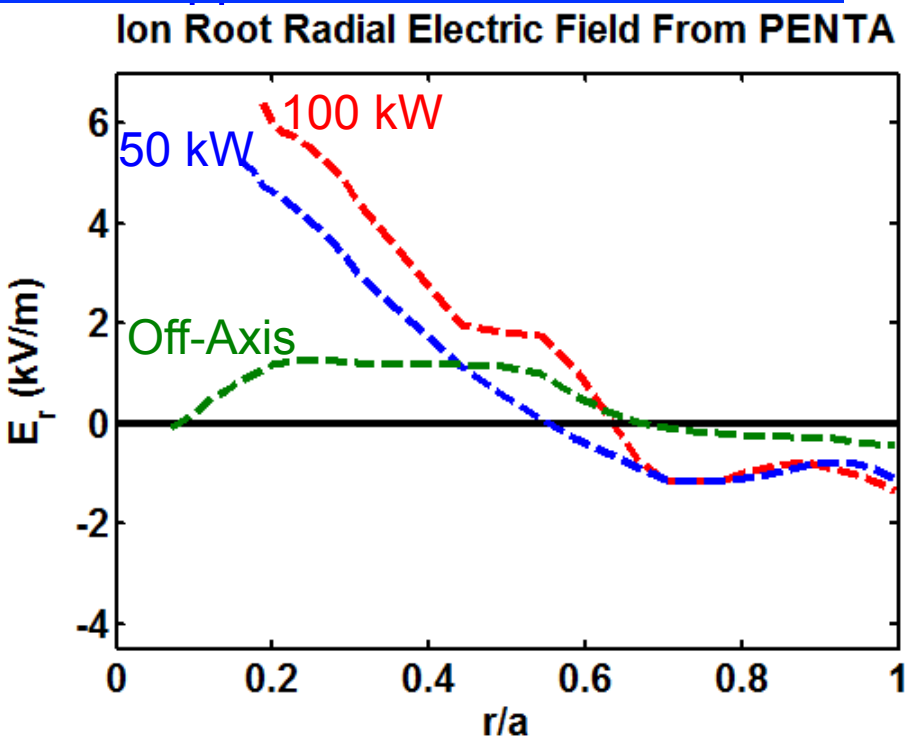




- The measured parallel flow is decreased across the entire radius when T_e is reduced
- The calculated parallel flow is much larger than the measured parallel flow in the core for all cases

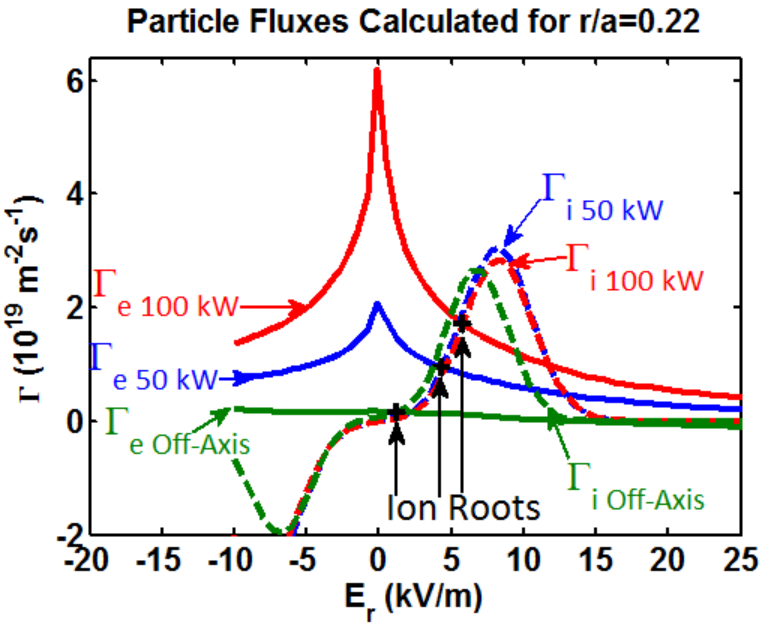
Small Changes in E_r Drive Changes in the Calculated $V_{||}$





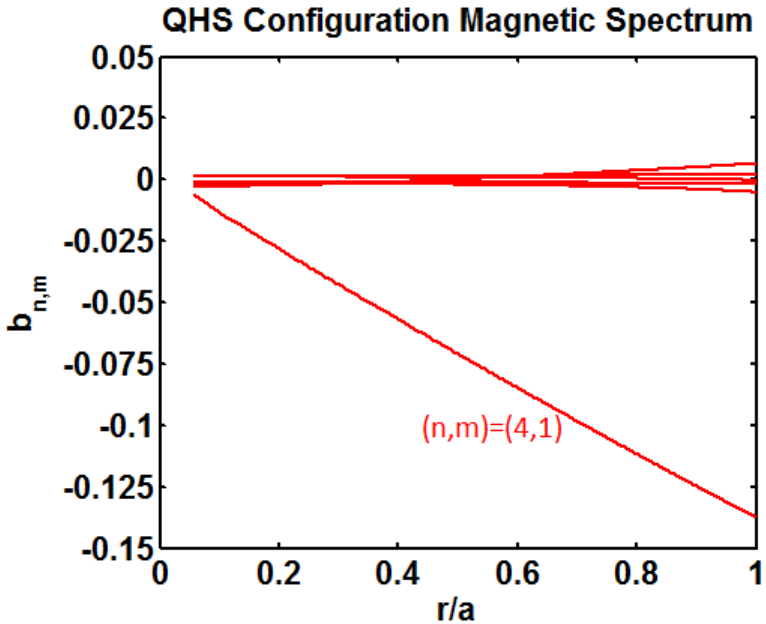
- The calculated ion root electric field is comparable to the measured E_r
- A small reduction, which is comparable to the uncertainty in the measured E_r, is calculated in the core when T_e is reduced

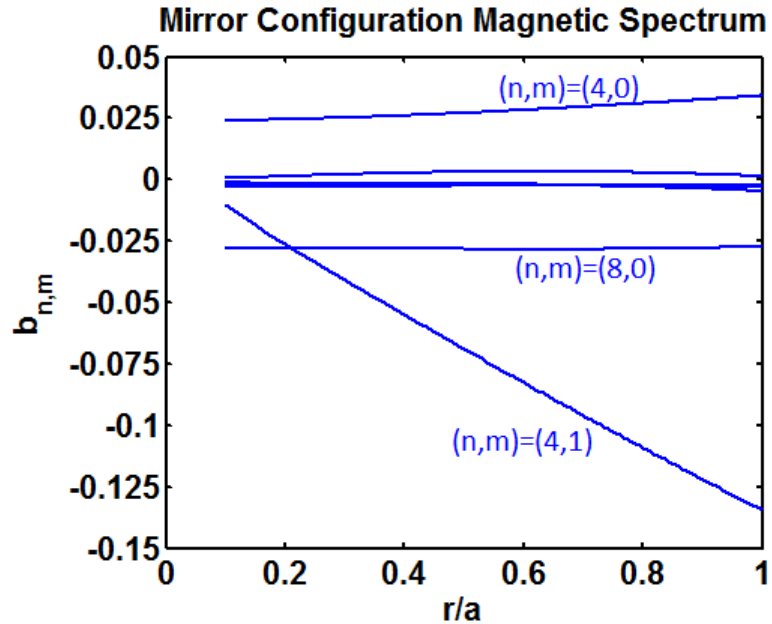
Changes in Particle Flux cause Changes in the Calculated E_r in the Core



- The calculated ion root electric field is comparable to the measured E_r
- A small reduction, which is comparable to the uncertainty in the measured E_r, is calculated in the core when T_e is reduced

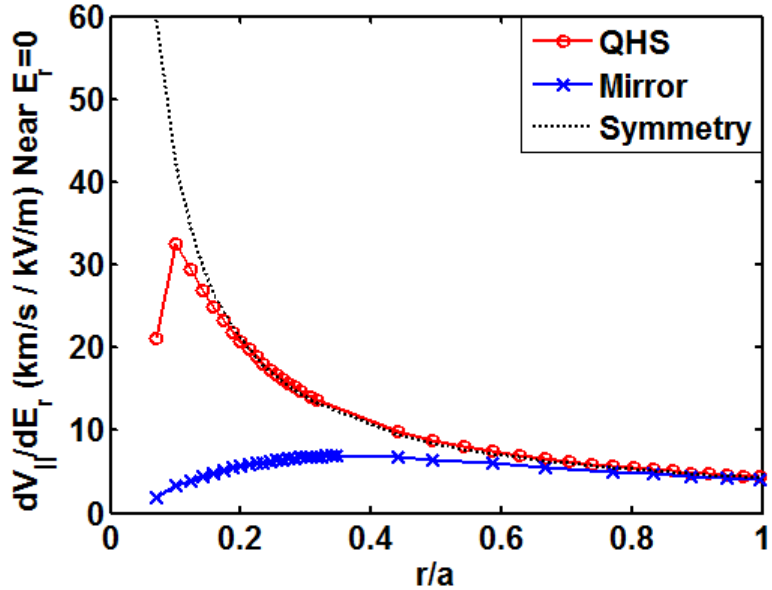
Mirror Magnetic Configuration Has Additional Magnetic Spectrum Components





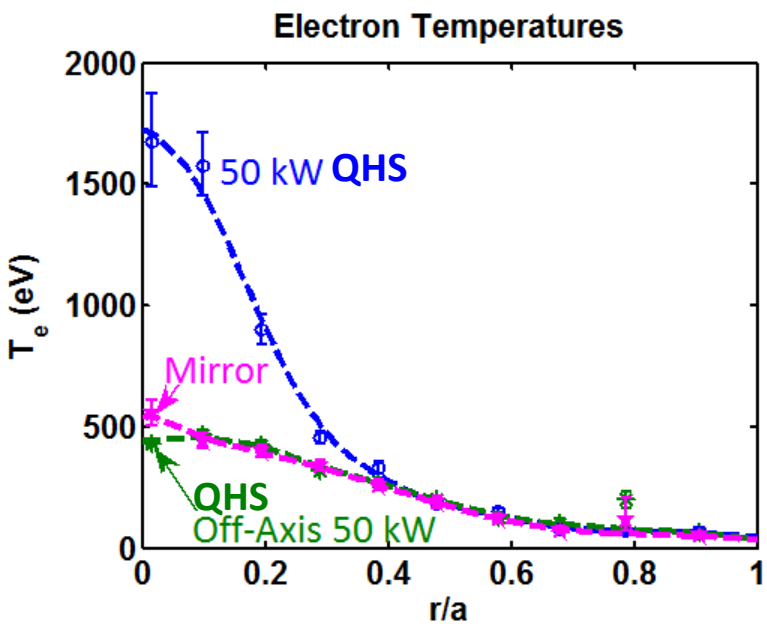
- By energizing the auxiliary coils of HSX, symmetry breaking terms can be added to the magnetic field spectrum
- This Mirror magnetic configuration has been shown to have higher neoclassical transport than the QHS configuration [Canik PRL 2007]

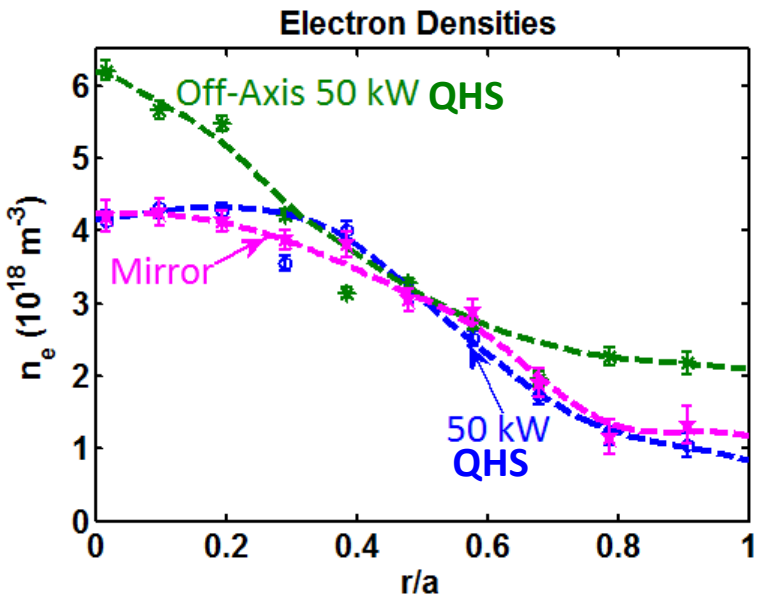
These Additional Terms Are Calculated By PENTA to Reduce $V_{||}$ in the Core



- For the same E_r PENTA calculates that the Mirror configuration will have lower $V_{||}$ than the QHS configuration as a result of higher parallel flow damping

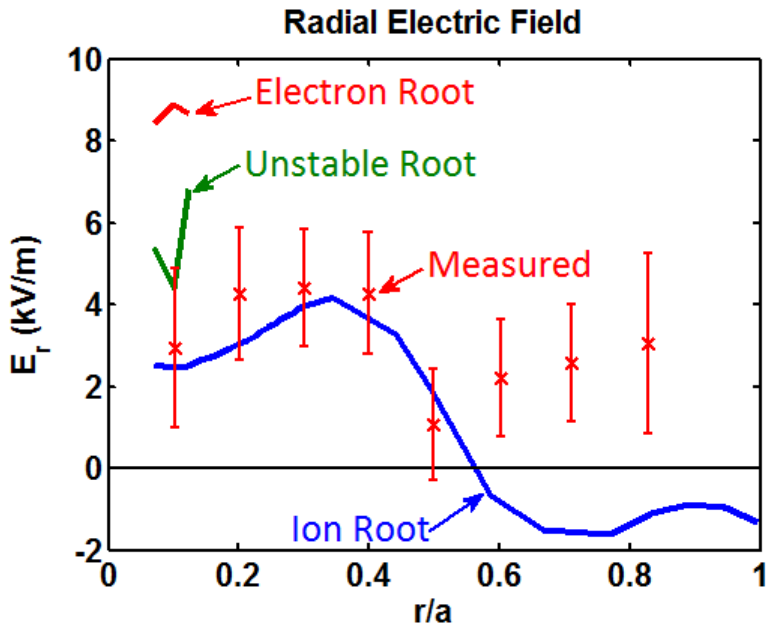
Electron Temperature for Mirror Case Similar to Off-Axis Heating Case

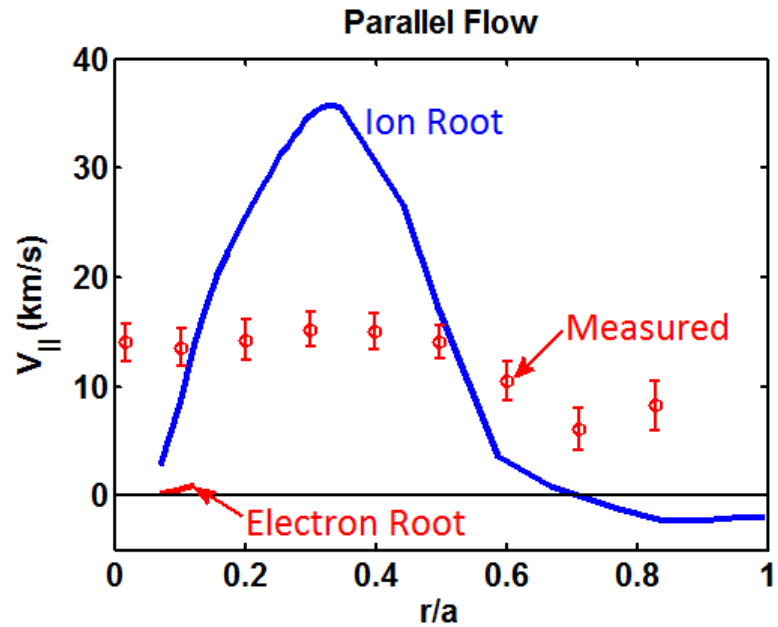




- 50 kW, on-axis heating was used for the Mirror case
- The core electron temperature in the Mirror case was much lower than the 50 kW, on-axis heating QHS case
- The electron density in the Mirror case was similar to that for the 50 kW on-axis case

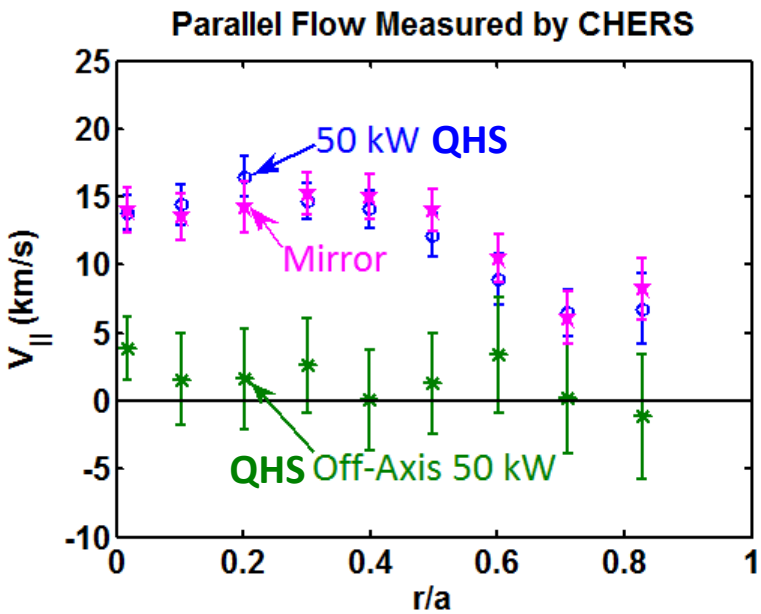
$V_{||}$ Calculated by PENTA Smaller for Mirror Than For QHS but Still Larger than Measured $V_{||}$

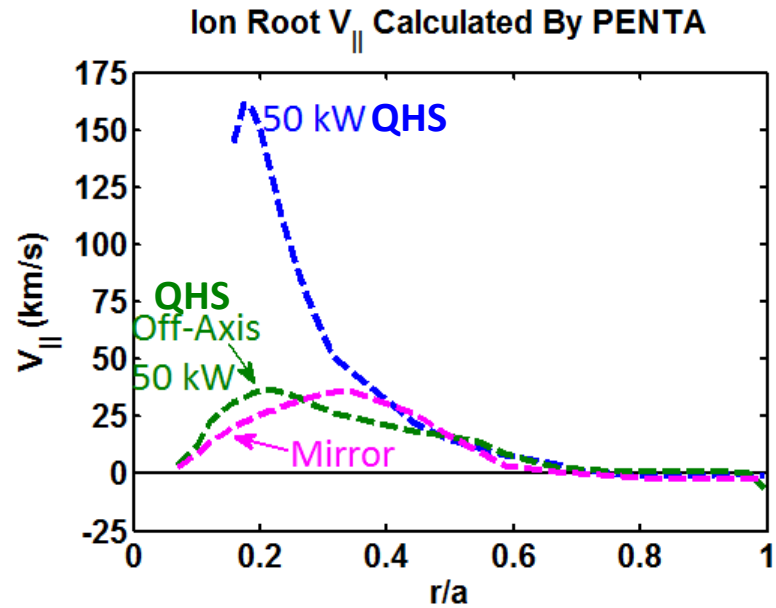




- An ion root solution for E_r is calculated across the entire plasma
- The electron root E_r smaller for Mirror than it was for the QHS case
- The calculated $V_{||}$ peaks at a value more than twice the maximum measured $V_{||}$

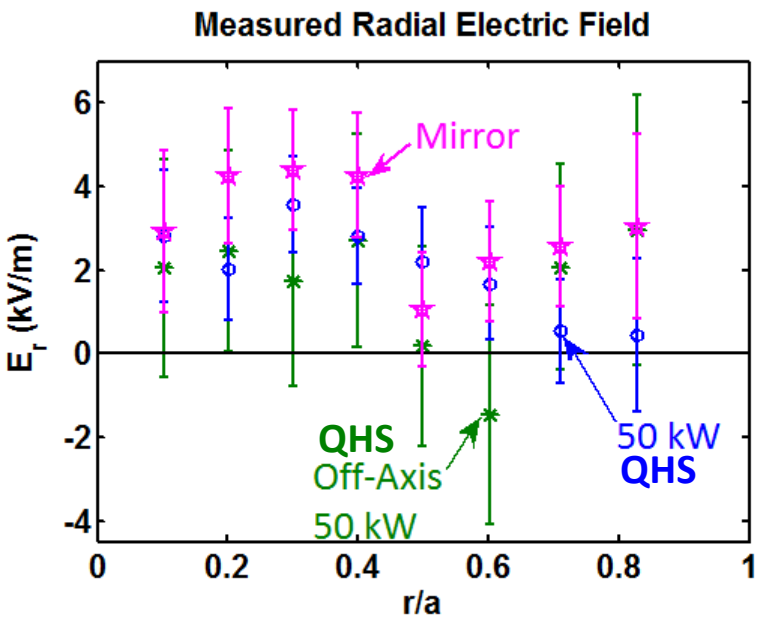
The Measured $V_{||}$ for Mirror Case was Similar to Higher T_e QHS Case

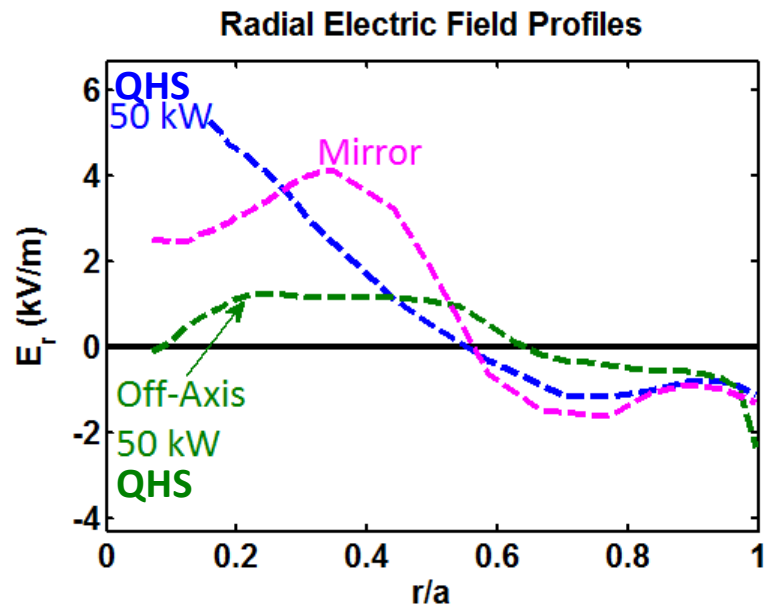




- Measured $V_{||}$ was nearly identical to $V_{||}$ measured for the QHS case in which on-axis heating was used
- The $V_{||}$ calculated by PENTA was closer to that of the off-axis heating case

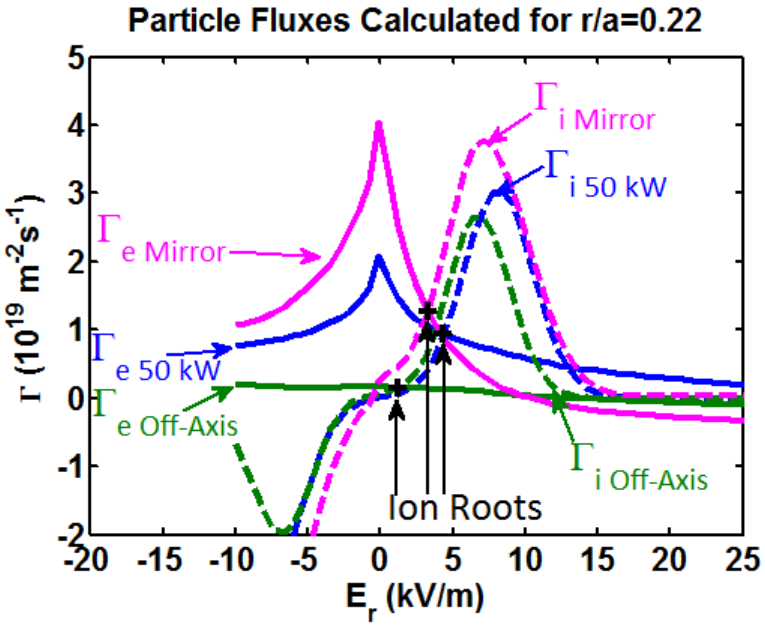
E_r For the Mirror Case Similar to Other Cases





- Any differences in E_r between the 3 cases are small when compared to the uncertainties in the measurements
- PENTA calculates that the 50 kW and Mirror cases have higher E_r in the core than the off-axis case

PENTA Calculates a Higher E_r for Mirror As a Result of its Higher Neoclassical Particle Flux



- Even though the Mirror case had lower core electron temperatures than the QHS case it has higher electron particle flux

Conclusion

- The intrinsic plasma flow in HSX approximately follows the helical direction of symmetry
- No evidence of the large electron root radial electric field is measured by CHERS
- Measured E_r is comparable to ion root value where it is calculated to be positive
- Larger flows measured in cases which have higher neoclassical electron fluxes which are calculated to cause higher radial electric fields in the core