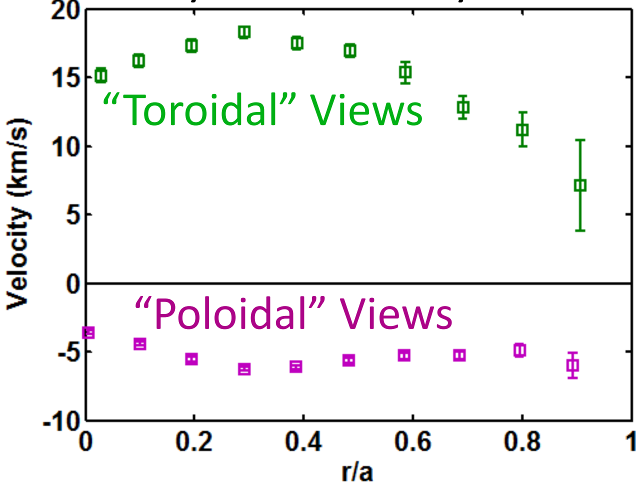
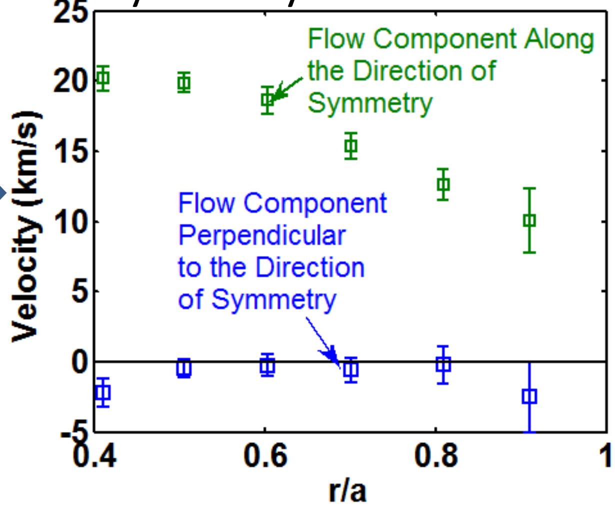
Flows Move Primarily Along the Helical Direction of Symmetry

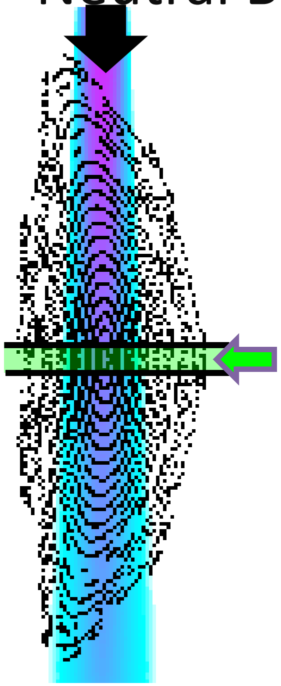
Velocity Measured By Each View



Velocity Along and Across the Symmetry Direction



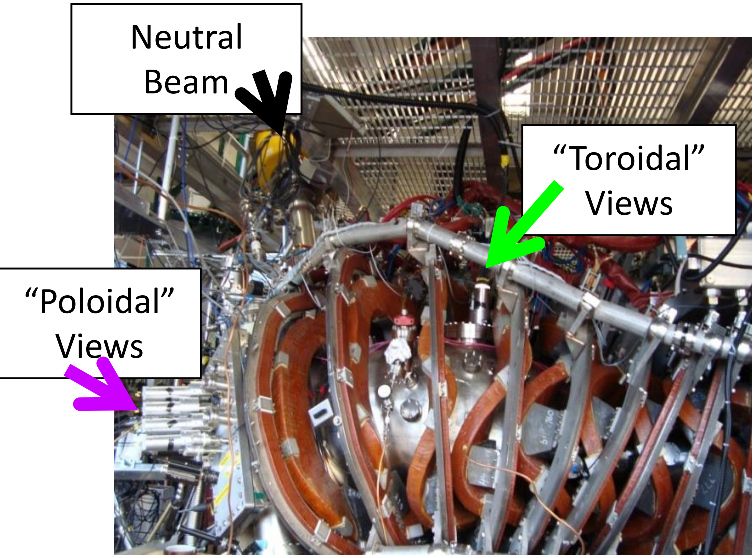
Neutral Beam

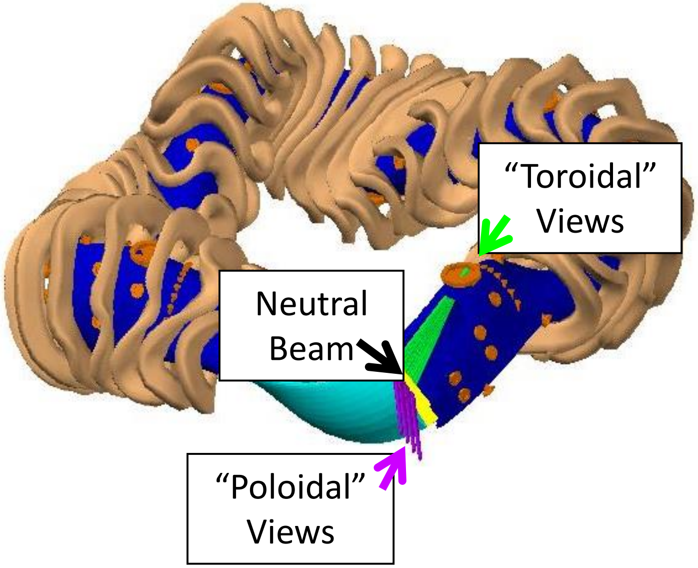


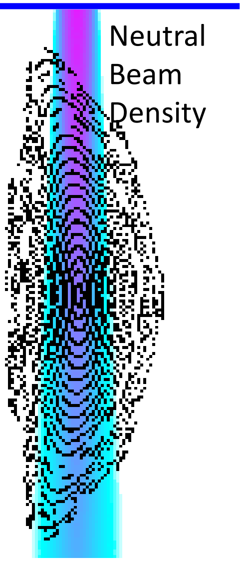
Typical Poloidal View Volume

- Geometric factors are used to relate the measured velocities to the average flow in the symmetry and cross symmetry directions within the view
- Near the axis the flow direction change significantly across the beam/view volume

Charge Exchange Recombination Spectroscopy (CHERS) On HSX



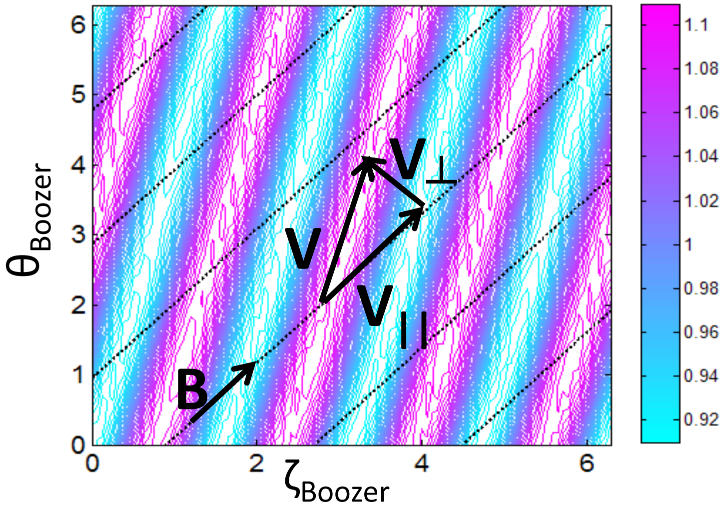


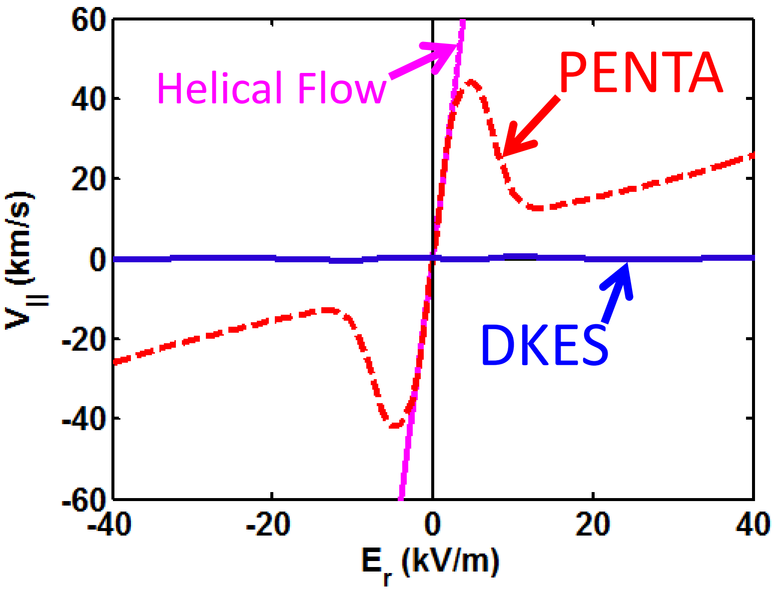


- 30keV, 4Amp, 3ms hydrogen neutral beam is fired radially
- C^{+6} ions charge exchange with the neutral beam
- 529nm light from the C^{+5} ions is collected
- Two 0.75m imaging Czerny-Turner spectrometers with electron multiplying ccds image the spectra
- Frames integrated for 5ms are taken before, during and after the beam fires

$V_{||}$ is Determined by and Viscosity

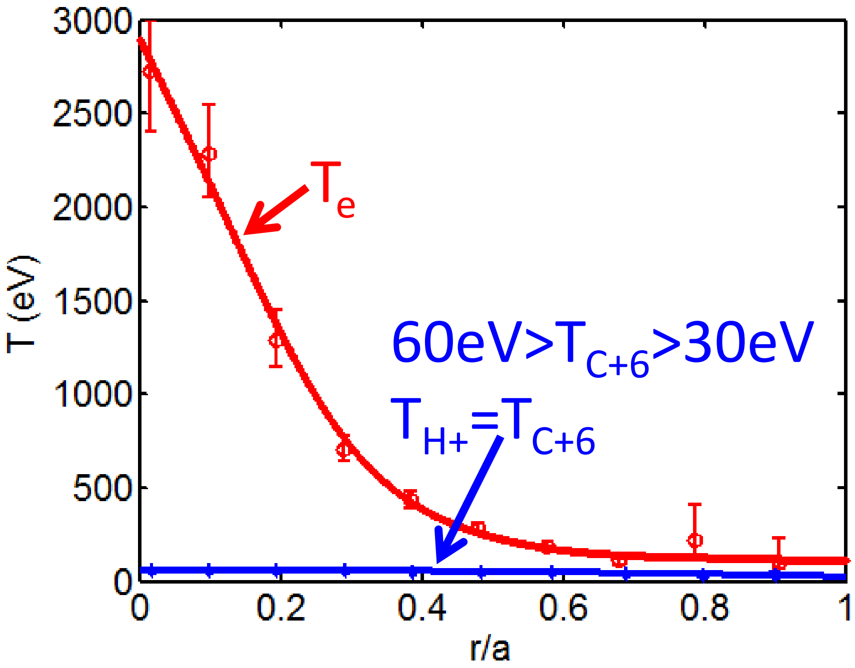
|B| and Velocity in HSX

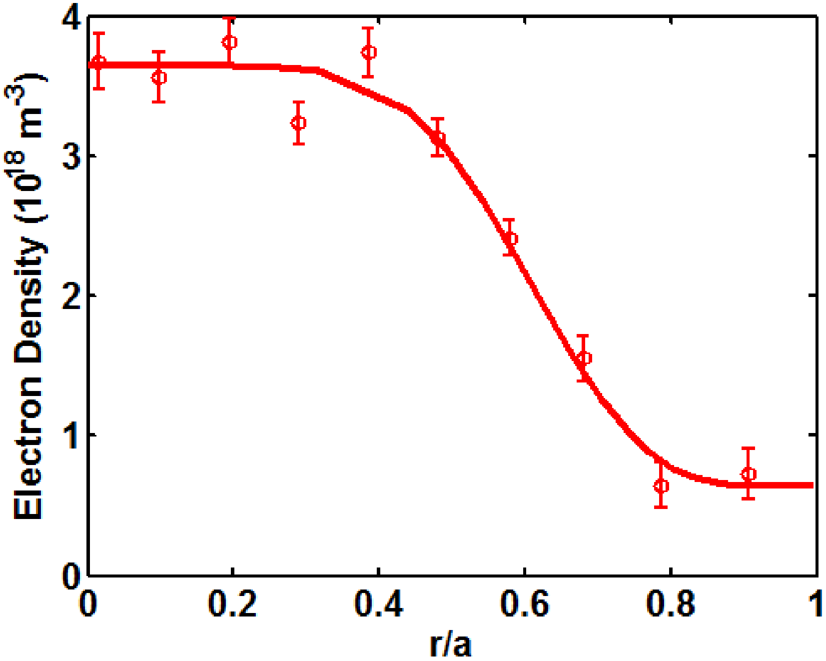




DKES predicts ~0 $V_{||}$ for all values of E_r because it does not account for momentum conservation in collisions

The Measured Density and Temperature Profiles Input to PENTA

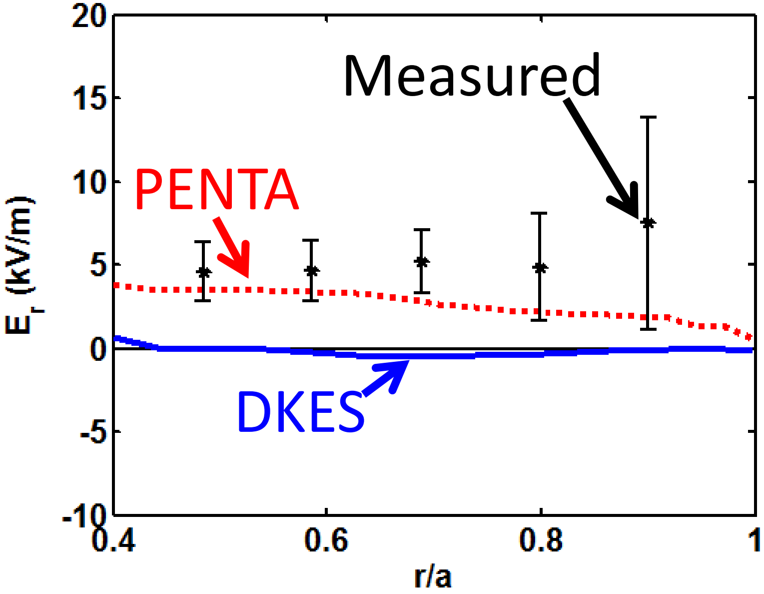




- T_e and n_e measured using Thomson Scattering
- Ions are collisional and have the same temperature and $V_{||}$

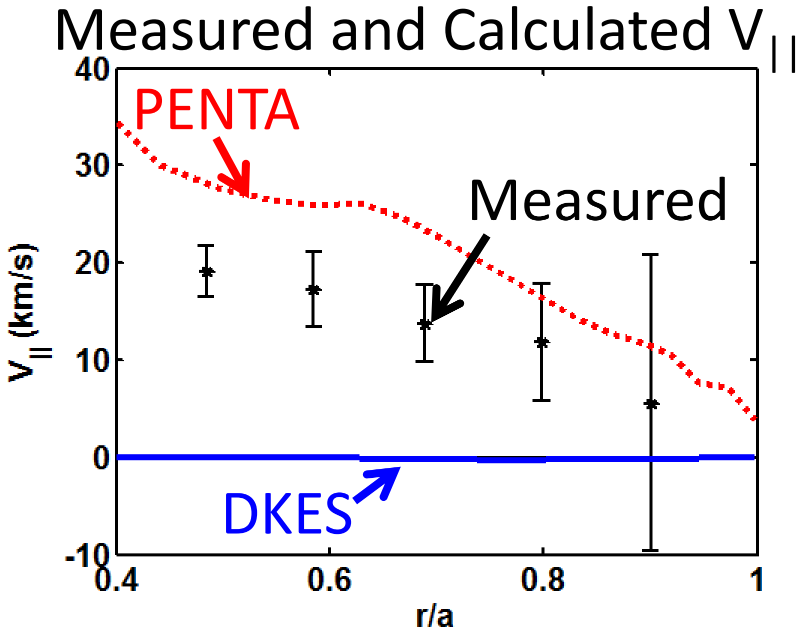
Agreement Seen Between Measured E_r and The PENTA Value

Measured and Calculated E_r



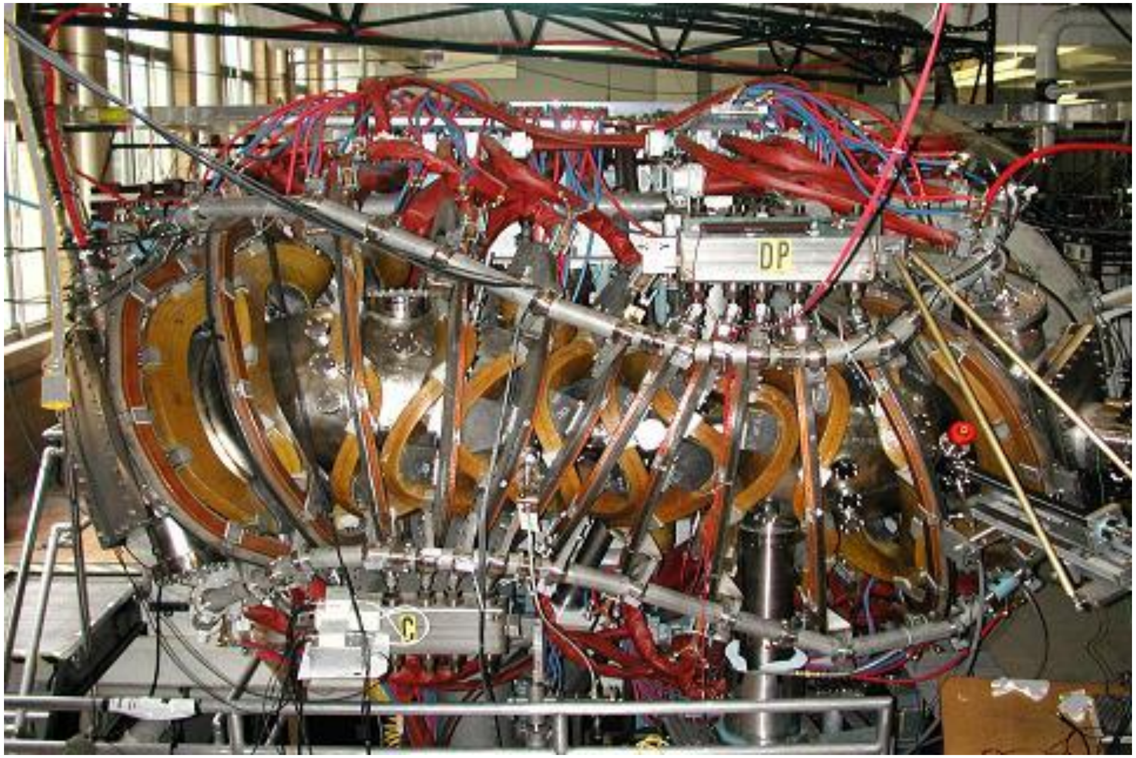
- PENTA predicts a small positive E_r at the edge
- Differences between the E_r predicted by PENTA and DKES become significant when there are multiple ion species in the calculations

Flows Predicted PENTA, Including Momentum Conservation Show better Agreement



- DKES under-predicts $V_{||}$ by more than an order of magnitude
- Better agreement is seen with the PENTA code which accounts for momentum conservation

Measurement and Modeling of Large Helical Flows in the HSX Stellarator



Alexis Briesemeister

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Electrical & Computer Engineering, UW-Madison

54th Annual Meeting of the APS-DPP, Providence, Rhode Island October 31, 2012

Motivation

- Quasi-symmetry allows large intrinsic flows in stellarators, which typically have large flow damping
  - HSX was optimized for quasi-helical symmetry
- Flows improve plasma confinement and stability
  - Using neutral beams to drive flows is impractical for larger devices, intrinsic flows become important
- This is the first test of the PENTA code which can calculate intrinsic flows in devices with any level of symmetry
  - Non-symmetric fields can increase flow drive, but damp plasma rotation

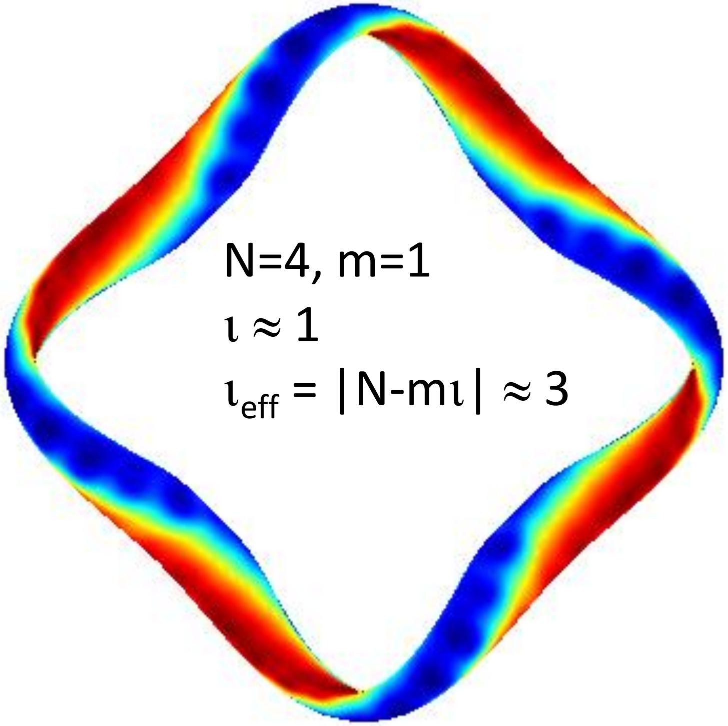
Outline

- The quasi-symmetric HSX stellarator
  - Charge exchange recombination spectroscopy (CHERS) used to measure flow speed and direction
  - Flows move in the helical direction with speed 20km/s
- PENTA code is used to calculate neoclassical transport, E_r and parallel flow
  - The ambipolar constraint determines E_r in configurations with significant non-symmetric field components
  - Includes momentum conservation and multiple ion species
- Measured and predicted flows agree only when momentum conservation is accounted for

The Quasi-Helically Symmetric HSX Stellarator

- Quasihelical symmetry (QHS) reduces neoclassical transport [Canik PRL, 2007] and flow damping in the helical direction [Gerhardt PRL, 2005]

QHS



N=4, m=1

$\iota \approx 1$

$\iota_{eff} = |N - m\iota| \approx 3$

<R>	1.2 m
<a>	0.12 m
ι	1.05 → 1.12
B_0	1.0 T
ECRH 28 GHz	100 kW
$\langle n_e \rangle$	$\leq 6 \times 10^{12}$ cm^{-3}
T_e	0.5 to 2.5 keV
T_i	30 to 60 eV

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

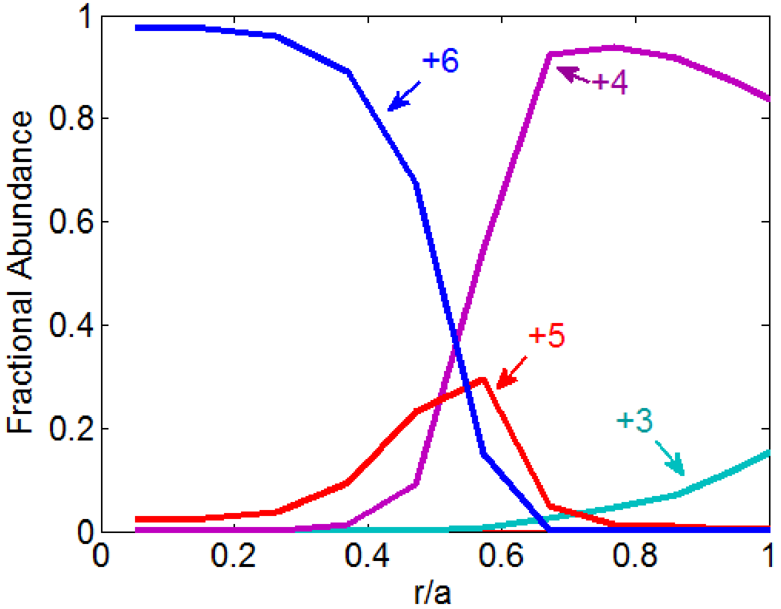
no external momentum source, all flows shown are intrinsic

The Total Flow has Perpendicular and Parallel Components

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

- E_r is determined by neoclassical transport
- Diamagnetic flow small for higher Z ions like carbon
- V_{PS} is the Pfirsch-Schlüter flow that varies on a surface, causes the total flow to satisfy incompressibility
- All flow components change direction if is reversed
  - Using the flow reversal with eliminates error from uncertainty in the unshifted line position

Coronal Equilibrium Used to Find Abundance of Other Carbon Ionization States

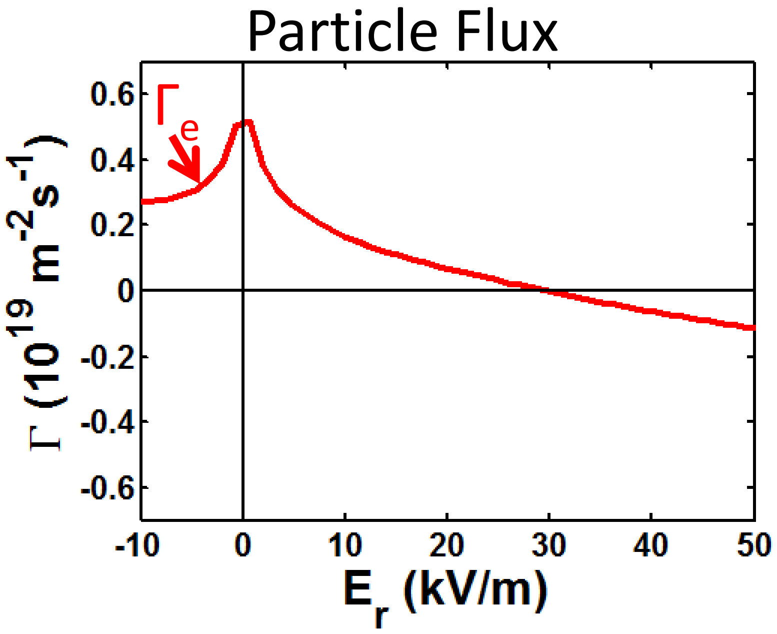


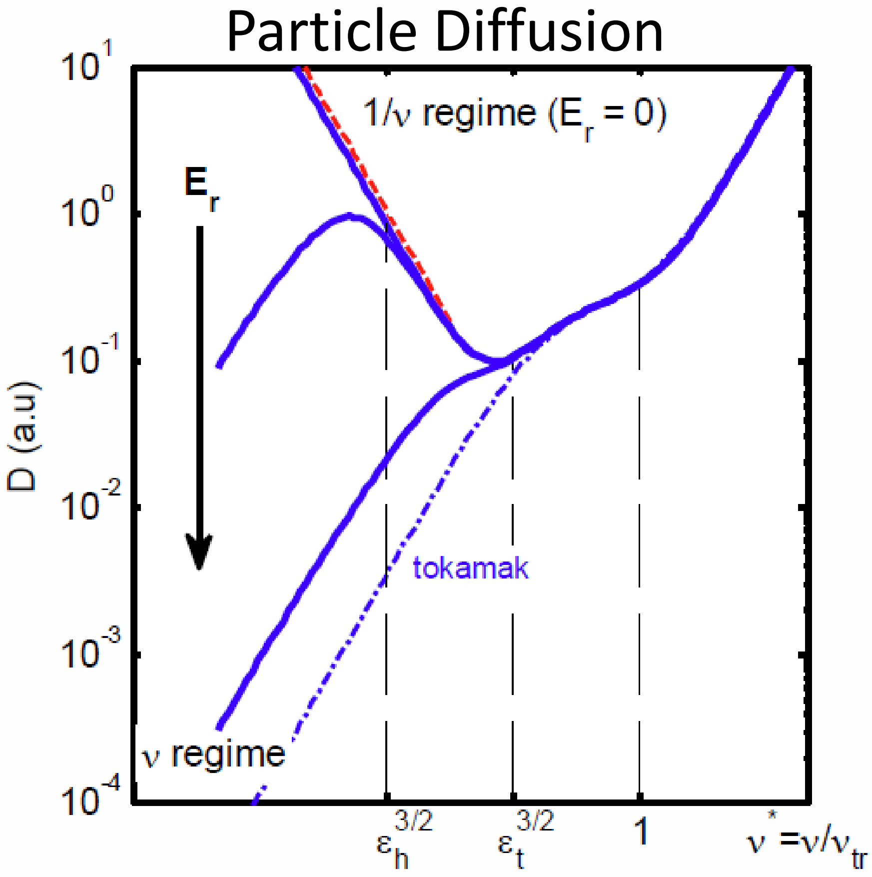
- Electron impact ionization, recombination, and charge exchange are included [ADAS: Summers (2004)]
- No measurement of all ionizations states is currently available
- Carbon to hydrogen ratio taken to be 1 to 4, methane

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 mono-energetic diffusion coefficients
  - Uses a non-momentum conserving collision operator
  - Developed for conventional stellarators with large flow damping
- The PENTA code[Spong PoP 2005] corrects the mono-energetic diffusion coefficients from DKES for momentum exchange
  - This correction makes PENTA valid for devices with any level of symmetry from ideal tokamaks to conventional stellarators
  - Can include multiple ion species

Electron's Are in the 1/nu Regime In The Core

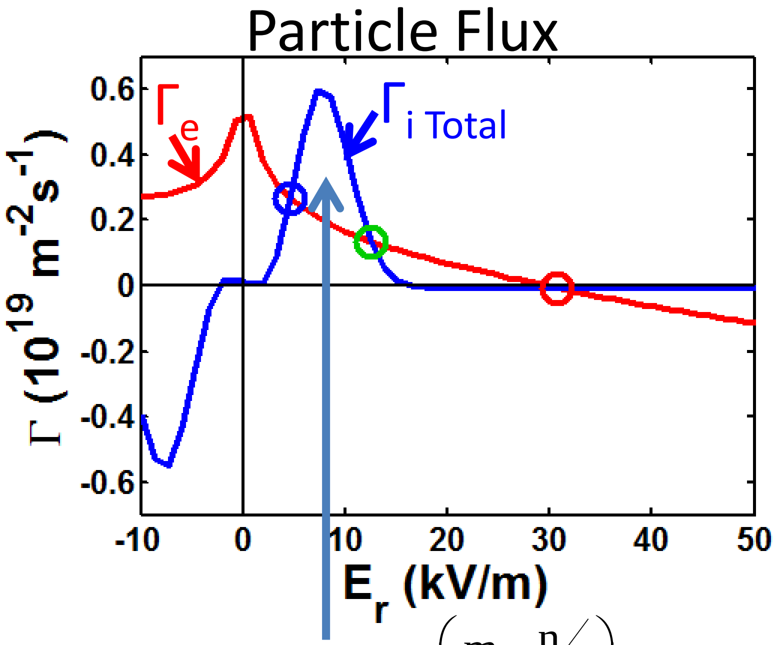




[Lore Thesis 2010]

- The hotter electrons are in the $1/\nu$ regime
- Their flux peaks at E_r=0

Multiple Roots are Predicted As a Result of the Helical Proton Resonance



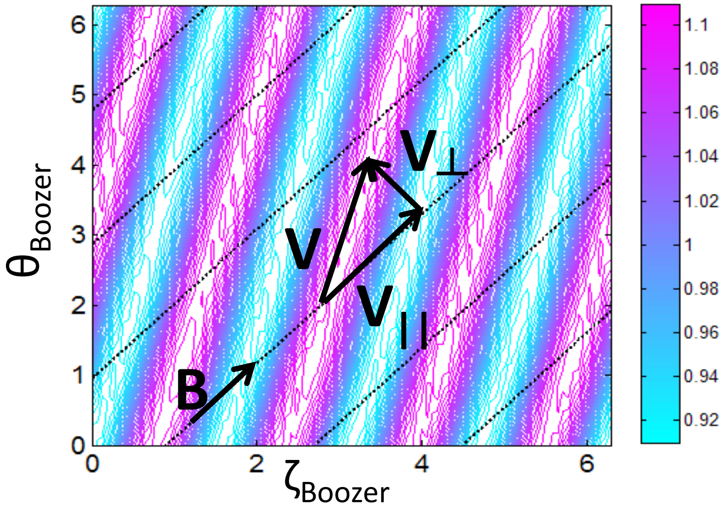
$$E_r^{res} = \pm\left(\frac{m - n/\bar{\iota}}{m}\right) V_{th} B_\theta$$

$$\Gamma_e(E_r) = \sum_s Z_s\, \Gamma_s(E_r) = \Gamma_{i\ \mathrm{Total}}$$

- E_r is found by enforcing ambipolarity
- Multiple roots of the ambipolarity condition are predicted in the core because of a peak in the Γ_{H+} near the helical proton resonance

$V_{||}$ is Determined by and Viscosity

|B| and Velocity in HSX

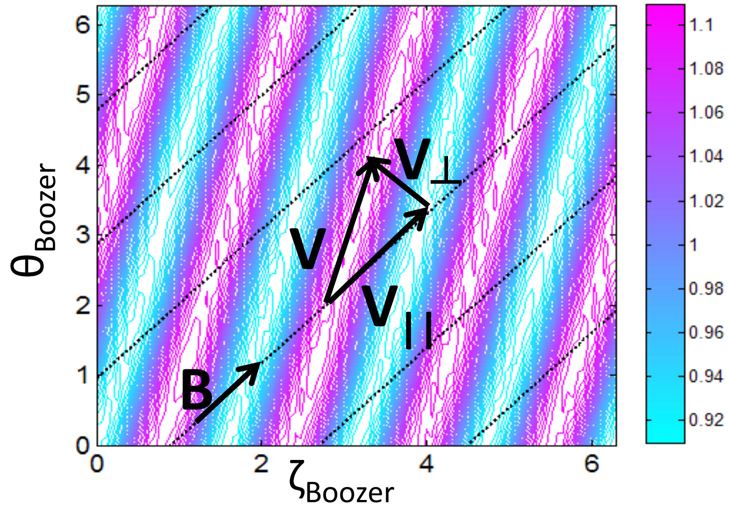


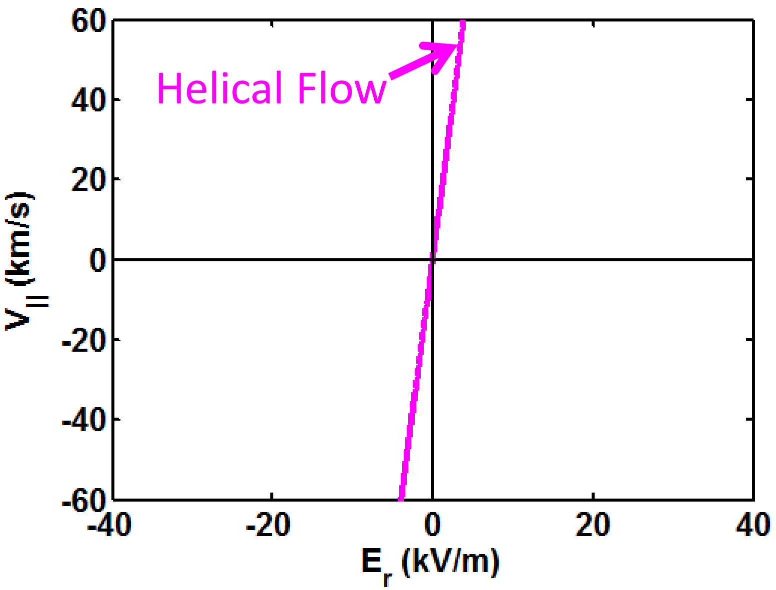
$$\vec{V}_i = \underbrace{\left(\frac{\vec{E}_r \times \vec{B}}{B^2} - \frac{\nabla p_i \times \vec{B}}{n_i Z_i e B^2}\right)}_{\vec{V}_{\perp}} + \underbrace{V_{PS}\hat{b} + \frac{\langle V_{\|i} B \rangle}{\langle B^2 \rangle}\vec{B}}_{\vec{V}_{\|}}$$

- $V_{\perp}$ driven by ExB and diamagnetic flows
- $V_{||}$ proportional to $V_{\perp}$ will arise to cause the total flow to move along HSX's helical direction of symmetry

$V_{||}$ is Determined by and Viscosity

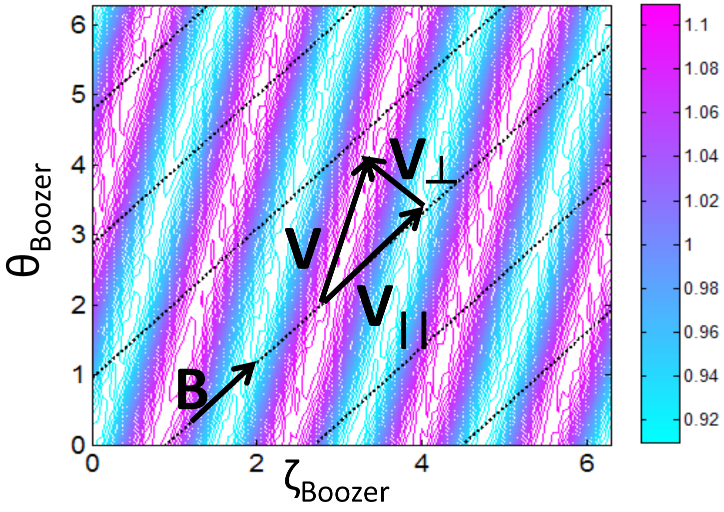
|B| and Velocity in HSX

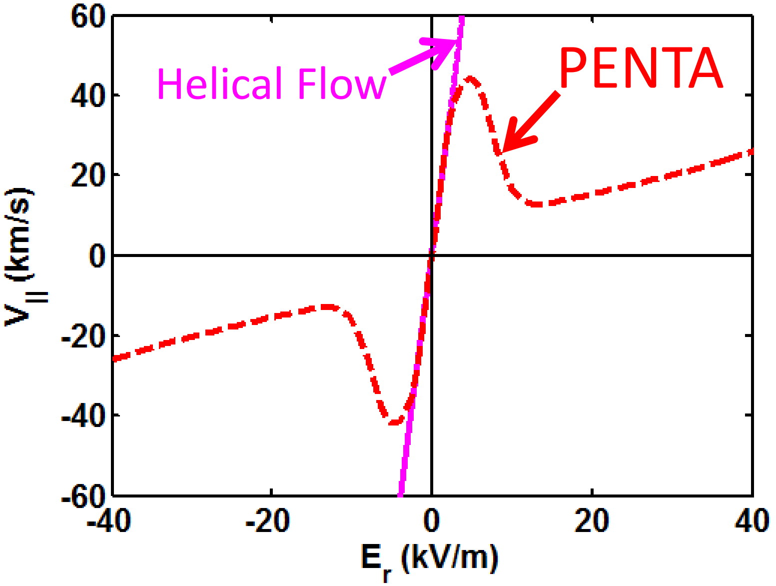




With all else held constant, $V_{||}$ should increase linearly with E_r to cause the to total flow to move along the helical direction of symmetry

$V_{||}$ is Determined by and Viscosity


|B| and Velocity in HSX

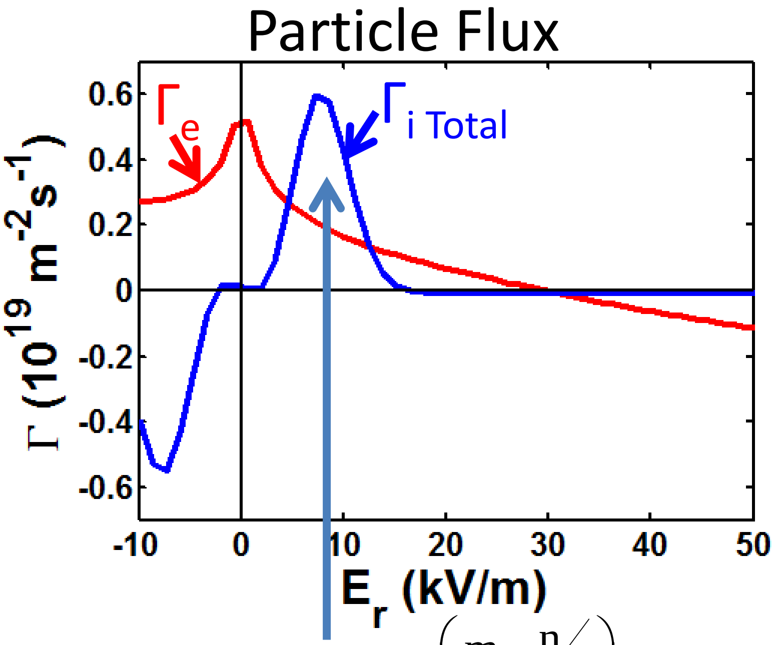


- For small (ion root) values of E_r PENTA predicts the protons will move in the direction of symmetry
- Large values of E_r detrap the particles responsible for the plasma viscosity, reducing $V_{||}$

Conclusion

- The intrinsic plasma flow follows HSX's helical direction of symmetry
- Reasonable agreement between the measured and calculated flow is only seen when the effects of momentum conservation are included in the calculation
- PENTA successfully predicts flows in a system that is largely symmetric

Multiple Roots are Predicted As a Result of the Helical Proton Resonance



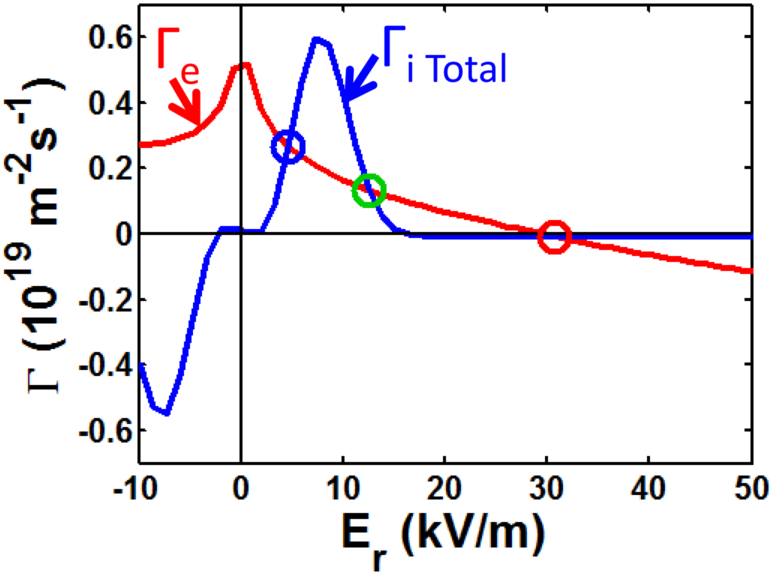
$$E_r^{res} = \pm\left(\frac{m - n/\iota}{m}\right) V_{th} B_\theta$$

$$\Gamma_e(E_r) = \sum_s Z_s \Gamma_s(E_r) = \Gamma_{i\ Total}$$

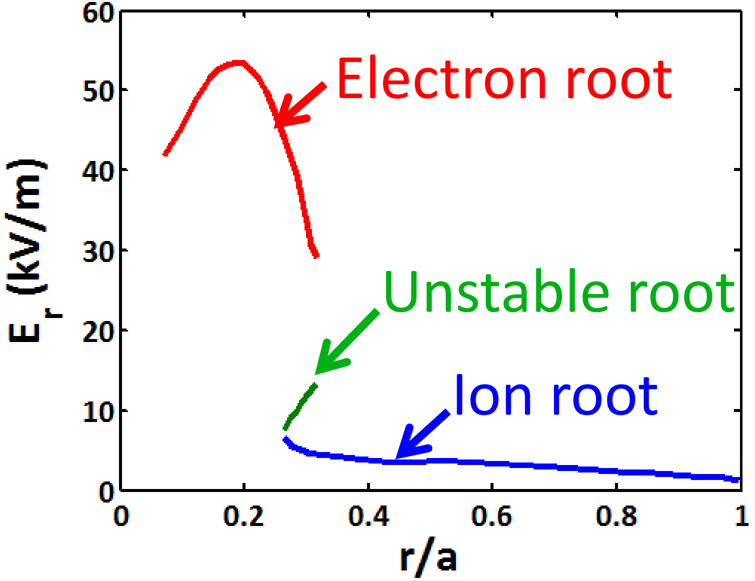
- E_r is found by enforcing ambipolarity
- Multiple roots of the ambipolarity condition are predicted because of a peak in the Γ_{H+} near the helical proton resonance

Multiple Roots are Predicted As a Result of the Helical Proton Resonance

Particle Flux



Calculated E_r Profile



$$\Gamma_e(E_r)=\sum_s Z_s\,\Gamma_s\,(E_r)=\Gamma_{i\ Total}$$

Electron root: Larger positive E_r associated with reduced neoclassical transport

Ion root: Smaller, sometimes negative E_r

Unstable root: Not a stable solution

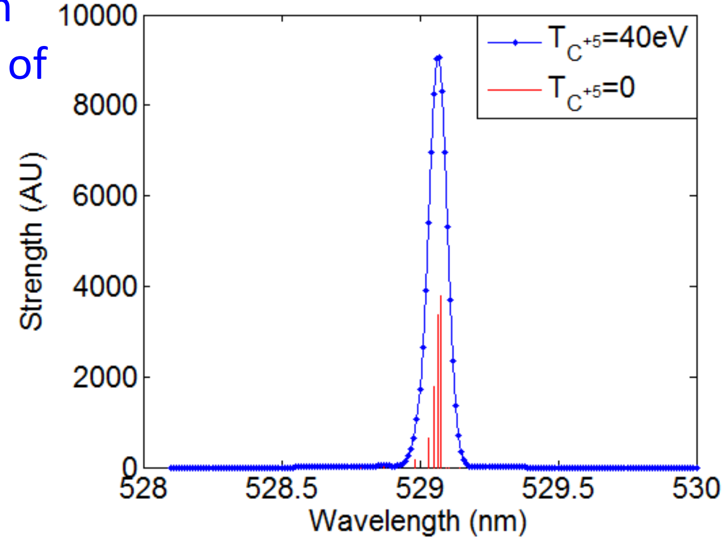
PENTA Accounts for Momentum Conservation

- HSX’s quasi-helical symmetry allows large flows to develop
- The DKES (Drift Kinetic Equation Solver) code uses a non-momentum conserving collision operator
- The parallel momentum conserving moments method techniques developed by Sugama and Nishimura[PoP 2002], and Maasberg, Beidler, and Turkin [PoP 2009] and Taguchi[Phys. Fluids 1992] were implemented by Spong and Lore in the PENTA code [Spong 2005] to correct the DKES coefficients
- These techniques are valid for devices with any level of effective ripple, from tokamaks to conventional stellarators

Atomic Data and Field Reversal Used To Find Density, Temperature and Velocity

Thermal motion of the ion causes Doppler broadening of the spectral line

Fine Structure Broadening
Comparable to Thermal Broadening



Doppler shift is determined by flow velocity along the viewing direction

$$\Delta\lambda = \frac{529nm*Velocity}{c}$$~0.04nm

- The charge exchange cross section used to find the C^{+6} density and the fine structure of the line used to correct the line width is taken from the Atomic Data Analysis Structure ADAS [Summers 2004]
- Reversing the magnetic field reverses the flows, doubling the measured Doppler shift
- Spectral calibration performed each shot to account for instrumental drift using a Neon lamp

Local Flow Velocity Can Be Calculated from PENTA Profiles and Magnetic Geometry

- PENTA calculates : $\frac{\langle V_{\|i} B \rangle}{\langle B^2 \rangle}$ and $E_{rPENTA} = -\frac{\partial \Phi}{\partial r_{PENTA}}$

  where $r_{PENTA} \equiv \sqrt{\frac{\Psi}{\pi B_o}}$

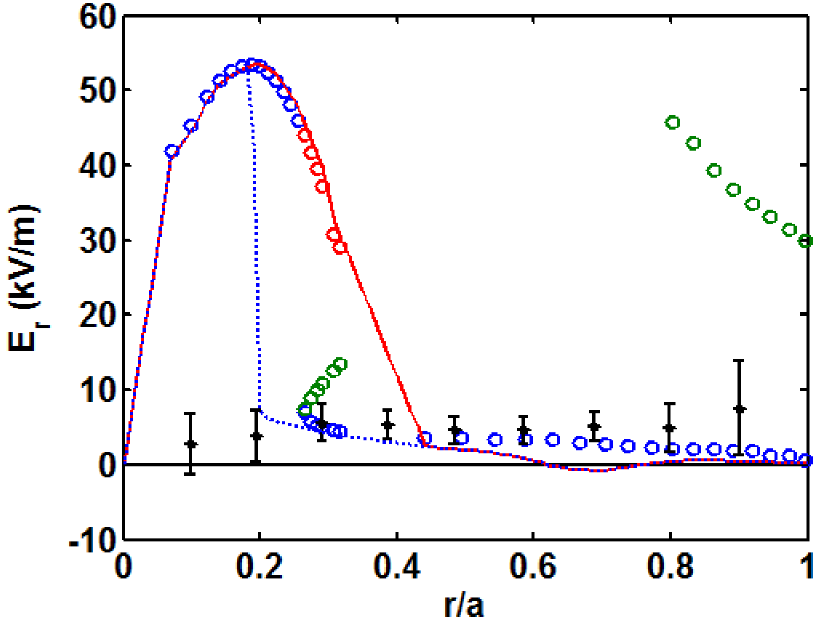
- The local flow is calculated on a grid of points throughout the beam/view intersection volumes:

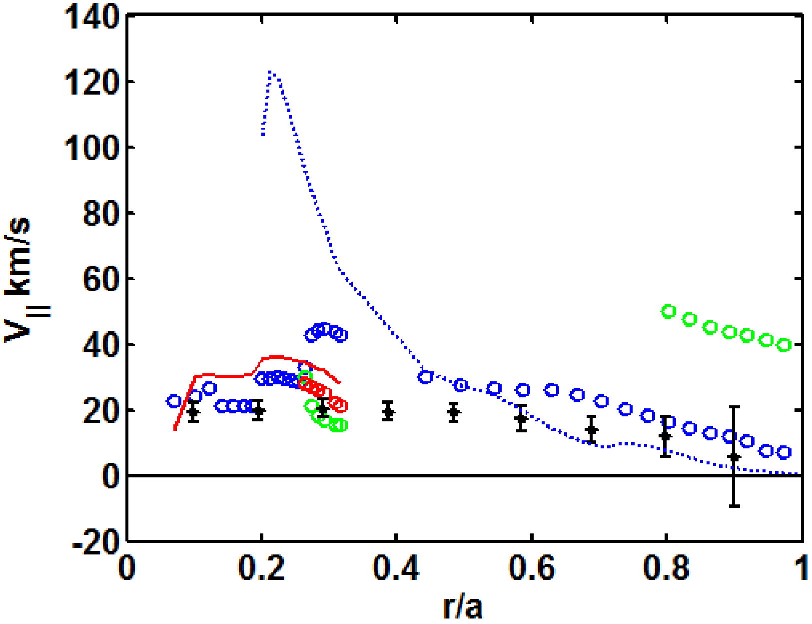
$$\vec{V}_i = \left(\frac{E_{rPENTA} \partial r_{PENTA}}{\partial \Psi} - \frac{1}{e n_i Z_i} \frac{\partial p_i}{\partial \Psi} \right) \left(\frac{\nabla \Psi \times \vec{B}}{B^2} + G_{PS} \hat{b} \right) + \frac{\langle V_{\|i} B \rangle}{\langle B^2 \rangle} \vec{B}$$

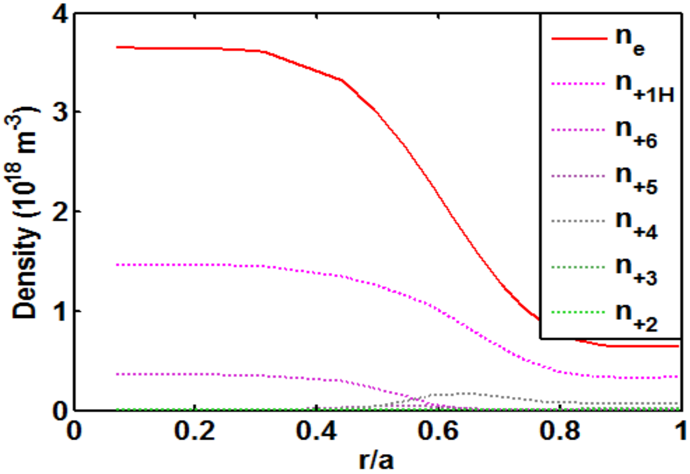
G_{ps} =geometry factor for the Pfirsch-Schlüter flow

- The calculated neutral beam density is used to create a weighted average of the velocity that would be “seen” by each view

Including All Ions


Circles=New Calculations With all Ions


Circles=New Calculations With all Ions


Coronal Equilibrium with 4H to 1C Ratio

- Lines are old calculations with just protons and C^{+6}

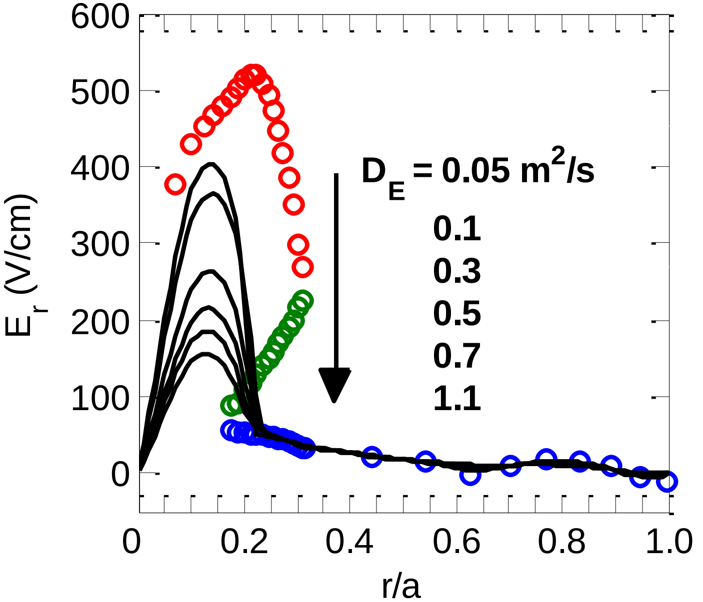
I stole this from J. Lore’s Dissertation, Do we now have a better calculation for D_E?

Solving the Diffusion Equation for E_r

$$\frac{\partial E_r}{\partial t} - \frac{\partial}{\partial V}\left[\langle \nabla V \rangle D_E \left(\frac{\partial E_r}{\partial r} - \frac{E_r}{r}\right)\right] = \frac{e}{\varepsilon_\perp}\left(\Gamma_e - \Gamma_i\right)$$

- The radial electric field profile can be determined by solving a diffusion equation[1]
- D_E (related to perpendicular viscosity) is generally not known[2]
  - Solutions for different D_E show a region of strong E_r shear at r/a~0.25

1) Shaing (1984), Maassberg *et al* (1993). 2) Hastings (1985, 1986)



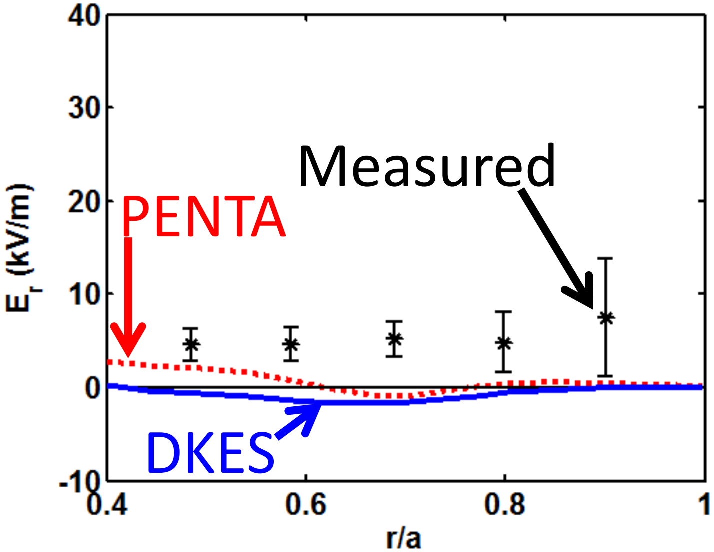
In the Core Flow Direction Changes Across the Beam/View Intersection Volumes

- The CHERS system can only measure a weighted average of the local plasma flow within each beam/view intersection volume
- The measured flows are much smaller (~20km/s) than the flows predicted by PENTA (~50 to 100km/s) in the core
- A synthetic diagnostic was developed to better understand the relationship between E_r and $V_{||}$ predicted by PENTA and the velocities seen by each view

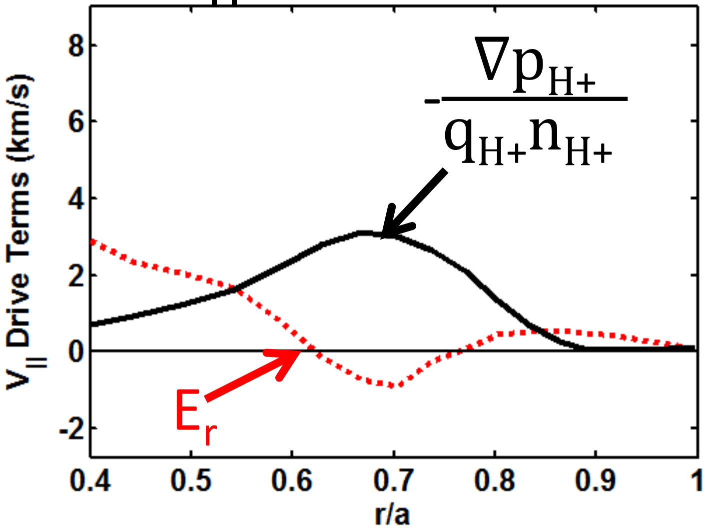
DKES and PENTA Predict Low E_r for r/a>0.5, Total Flow Determined by Diamagnetic Flow

- E_r measured by CHERS is ~5kV/m larger than the predicted E_r profile in the outer half of the plasma
- E_r larger than the calculated values were also measured using probes [*See Poster R. Wilcox on Thursday*]
- The predicted $V_{||}$ does not change direction in the regions where E_r is negative because of the positive diamagnetic flow

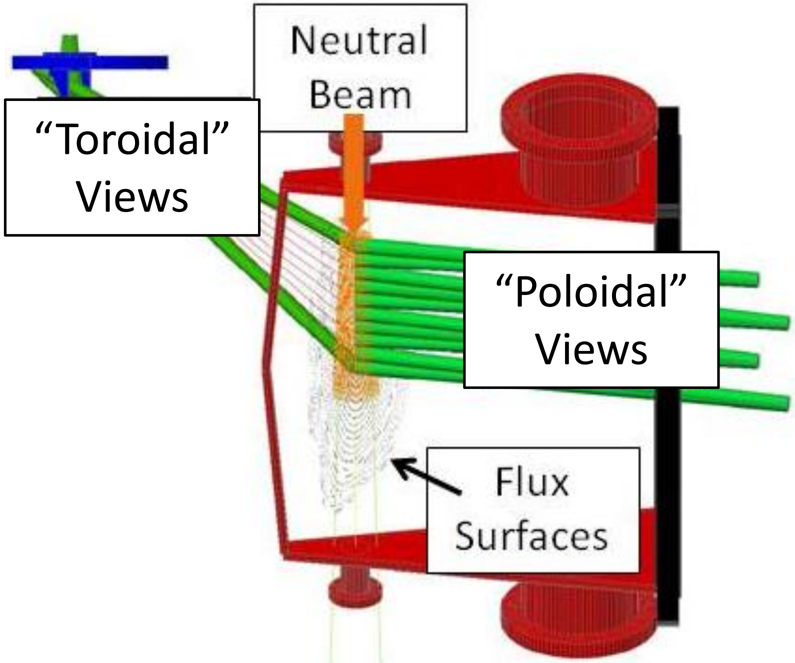
Measured and Calculated E_r



$V_{||}$ Drive Terms



Two Viewing Angles Needed To Find Flow Direction

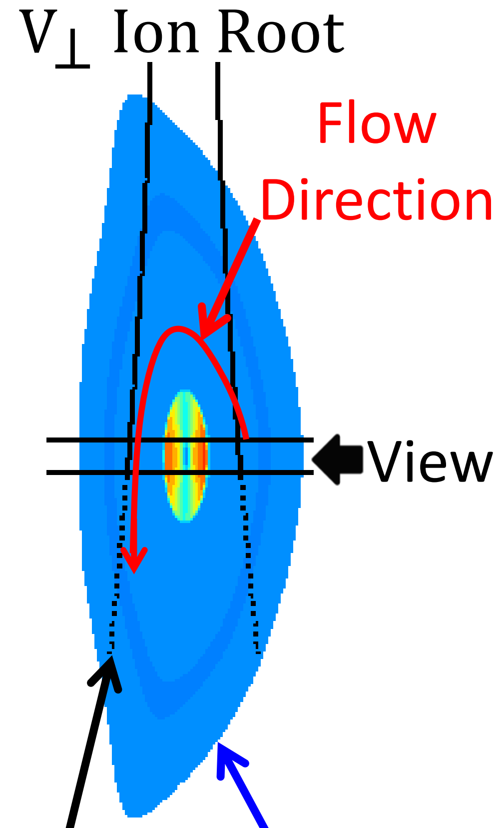


Three Constraints Used to Determine the Local Flow Speed and Direction:

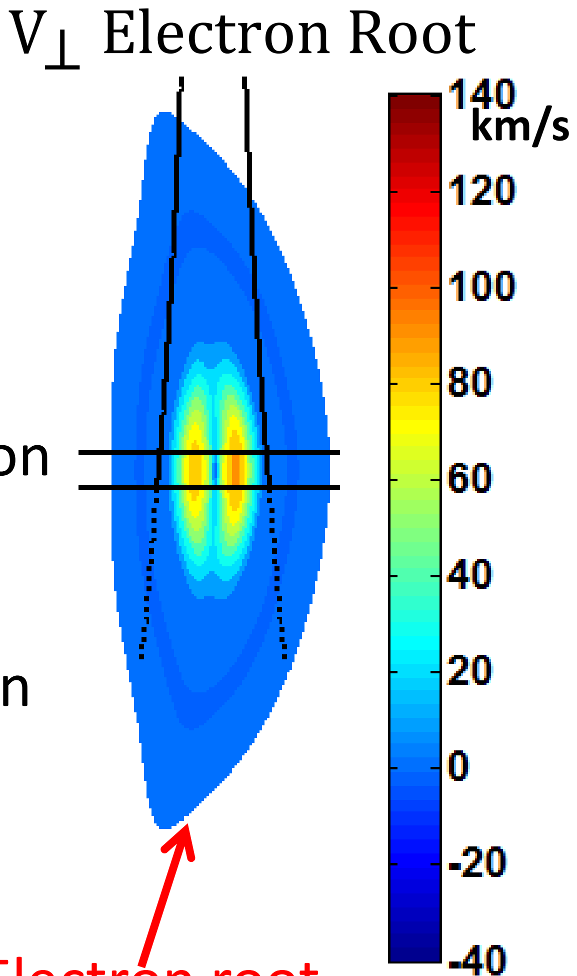
$$V_{Measured\ Poloidal} = \hat{u}_{View\ Poloidal} \cdot \vec{V}_{local}$$
$$V_{Measured\ Toroidal} = \hat{u}_{View\ Toroidal} \cdot \vec{V}_{local}$$
$$\nabla\Psi \cdot \vec{V}_{local} = 0$$

- Measurements made at 10 radial locations from 2 different viewing directions ($\hat{u}_{View\ Poloidal}$ and $\hat{u}_{View\ Toroidal}$)
- The direction of $\nabla\Psi$ is used as the third constraint on the flow vector
- The average local flow velocity is found from the flows measured by the two views and the geometric constraints

The Flow Perpendicular to the Magnetic Field Changes Speed and Direction in View Volume

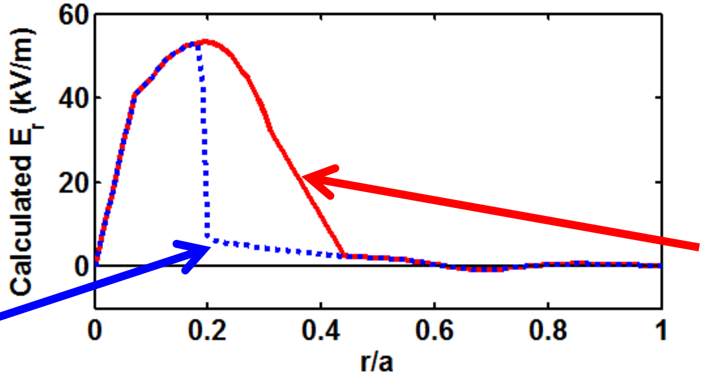


- $V_\perp$ changes direction and magnitude within the beam/view intersection volumes
- The radial extent of the region predicted to have large $V_\perp$ will depend on which root exists in the multi-root region



Neutral beam width

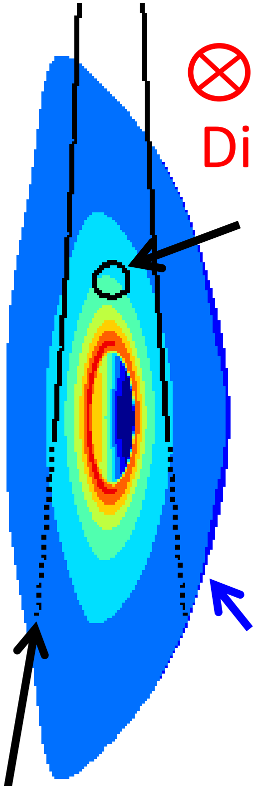
Ion root chosen in multi-root region



Electron root chosen in multi-root region

The Flow Along the Magnetic Field is Dominated by the Pfirsch-Schlüter Flow For Electron Root E_r

$V_{||}$ Ion Root



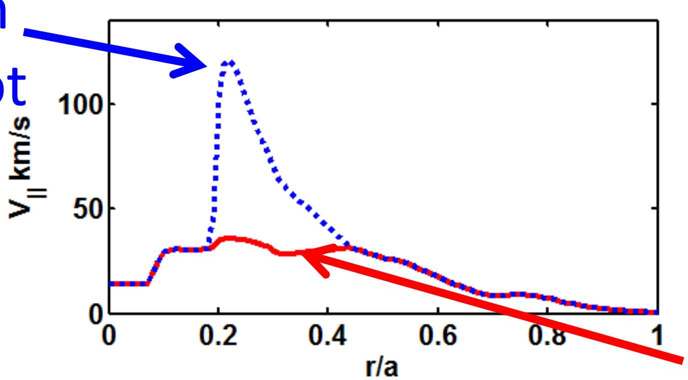
⊗Flow Direction

View

Neutral beam width

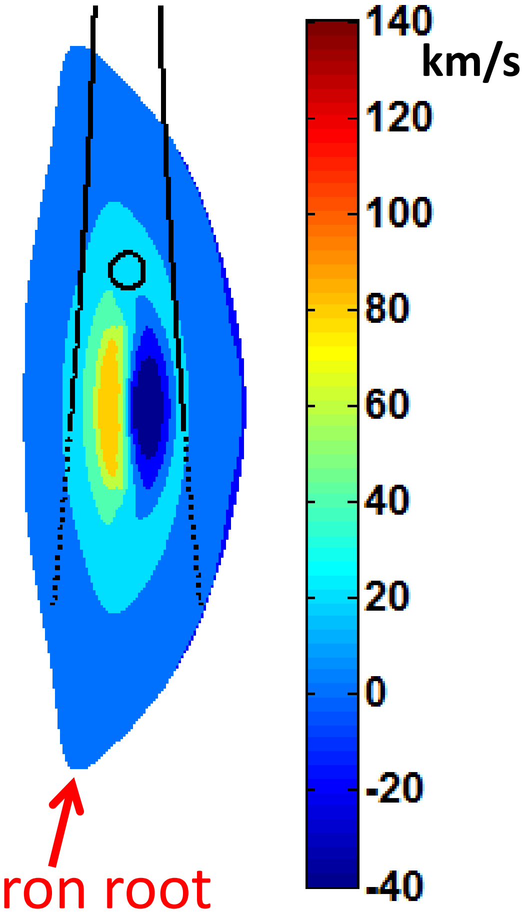
Ion root chosen in multi-root region

- In the multi-root region the smaller, ion root, E_r produces a larger net $V_{||}$
- When the electron root is chosen the Pfirsch-Schlüter flow, which changes direction across the "toroidal" views dominates the total $V_{||}$



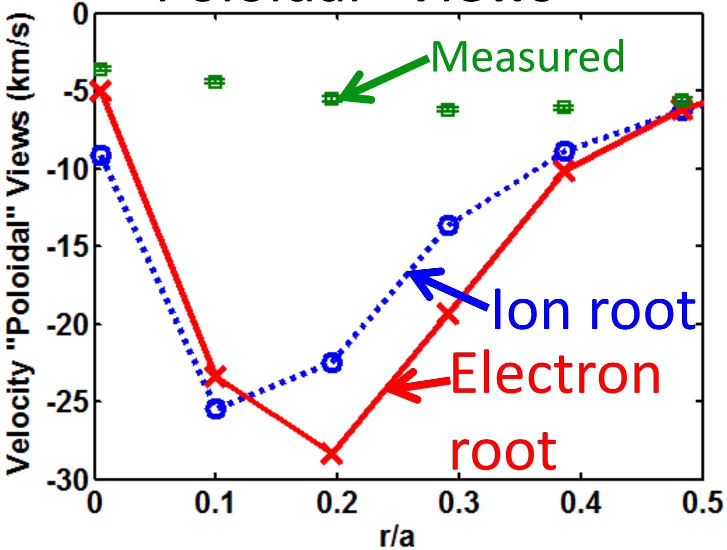
Electron root chosen in multi-root region

$V_{||}$ Electron Root

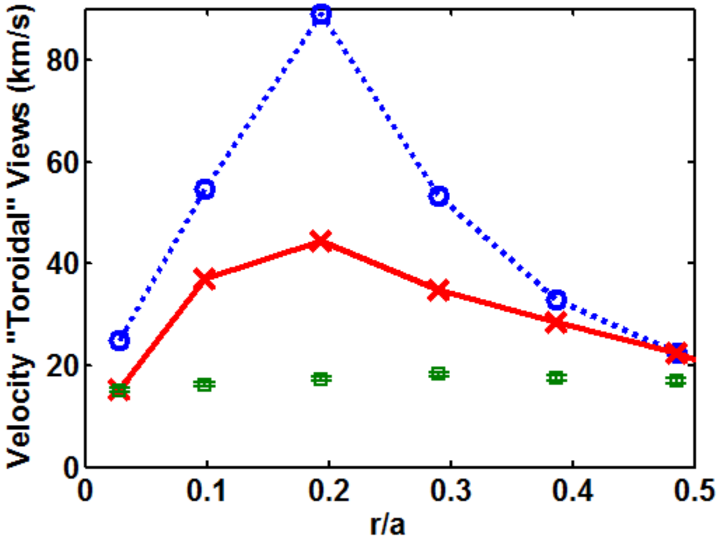


Synthetic Diagnostic Shows Flows Predicted by PENTA Larger Than Measured Flows for r/a<0.5

Velocity Seen By
“Poloidal” Views



Velocity Seen By
“Toroidal” Views



- The velocity that would have been measured by each view for a given profile is calculated using the synthetic diagnostic
- In the core the measured velocity is more than 20km/s less than that predicted by PENTA when either the electron or ion root is chosen where both are predicted
- V_{thH+}~100km/s; V_{thC+6}~30km/s

Neoclassical Fluxes Are Not Intrinsically Ambi-Polar in Non-Symmetric Configurations

- Neoclassical electron and ion fluxes are non-linear independent functions of radial electric field
- Turbulent fluxes are assumed to be ambipolar
- In steady state the radial electric field is determined by enforcing ambipolarity $\Gamma_e(E_r) = \sum_s Z_s \, \Gamma_s \, (E_r)$

Motivation

- Flows improve plasma confinement and stability by
  - Healing vacuum islands in stellarators
  - Stabilizing resistive wall and tearing modes
- Using neutral beams to drive flows is impractical for larger devices, intrinsic flows become important
- Non-symmetric magnetic field components damp flows, but can in some cases increase flow drive
  - Symmetry breaking terms are being added to tokamaks
  - Non-symmetric fields in stellarators determine E_r, but damp large flows
  - HSX's direction of symmetry allows for large flows