Measurements and neoclassical modelling of radial electric field and flows in HSX

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Acknowledgments

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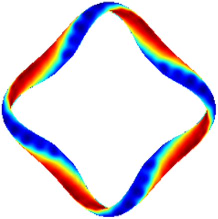
Minimal parallel viscosity is calculated in the helical direction in HSX

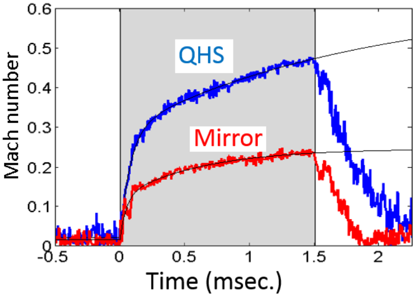
HSX has symmetry of $|\mathbf{B}|$ in the helical direction



The quasi-symmetric magnetic geometry allows HSX plasmas to exhibit large flows in the symmetry direction.

Reduced flow damping in the quasi-helically symmetric (QHS) geometry has been demonstrated in HSX[†]

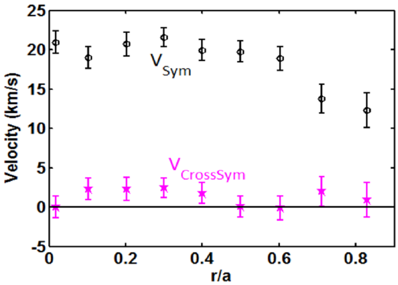
Flow speed



Plasma Edge: Electrode bias induced Flow, measured with probes, is larger and decays slower with quasisymmetry

[†] Gerhardt *et al.*, (2005)

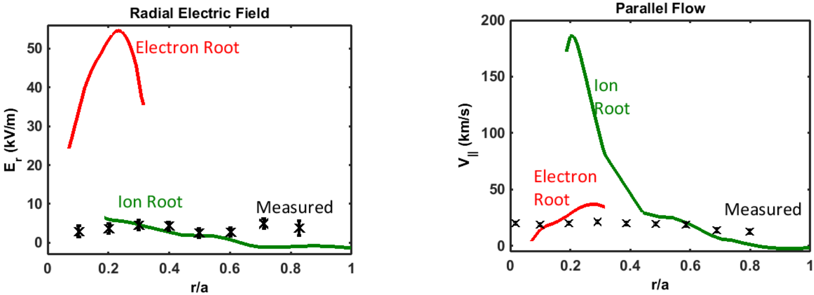
Intrinsic ion flows in HSX are observed to be in the symmetry direction[†]



Carbon ion flows measured using Charge Exchange Recombination Spectroscopy

[†] Briesemeister *et al.*, (2010)

Large discrepancy between the measurements and neoclassical calculations has been observed†



In the core, measured E_r is close to the ion-root, but measured $v_{||}$ is close to the electron-root

†Briesemeister, (2010)

Talk outline

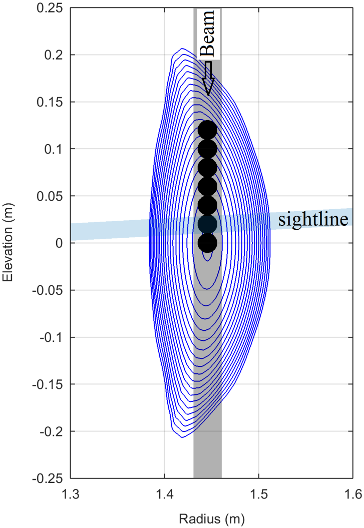
- Improvements in measurements
  - Measurements of E_r and bootstrap flow from **parallel flow** measurements, instead of using **radial force balance equation**

- Measurements in QHS and a broken symmetry configuration, comparison with neoclassical model

Major observations: Broken symmetry configuration exhibits larger flows, agrees better with neoclassical calculations

Talk outline

- Improvement
  - Measure n **parallel flow**
    measure **balance equation**
- Measuremen ry configuration,
  comparison v



Major observati uration exhibits
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- Improvements in measurements
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Major observations: Broken symmetry configuration exhibits larger flows, better agreement with neoclassical calculations

E_r can be determined from Pfirsch-Schlüter effect

The parallel ion flow at any location in the plasma is given by,

$$\vec{v}_{||i} = \underbrace{\vec{v}_{bs}}_{\text{flux function}} + \underbrace{\vec{v}_{ps}}_{\text{local}}$$

The Pfirsch-Schlüter flows (v_{ps}) are flows parallel to the magnetic field lines that arise due to incompressibility. For ions,

$$\nabla \cdot \left(\vec{v}_{\perp i} + \vec{v}_{||i}\right) = 0$$

$$\vec{v}_{\perp i} = \frac{\vec{E}_r \times \vec{B}}{B^2} - \frac{\nabla P_i \times \vec{B}}{en_i Z_i B^2} = -\left(\frac{d\phi}{d\psi} + \frac{1}{en_i Z_i}\frac{dP_i}{d\psi}\right)\left(\frac{\nabla \psi \times \vec{B}}{B^2}\right)$$

E_r can be determined from Pfirsch-Schlüter effect

The Pfirsch-Schlüter flow can be written as,

$$\vec{v}_{ps} = \left(\frac{d\phi}{d\psi} + \cancel{\frac{1}{en_i Z_i} \frac{dP_i}{d\psi}} \right) h\vec{B}$$

where h is a geometrical factor, which is defined by

$$\vec{B} \cdot \nabla h = -2 \frac{(\vec{B} \times \nabla B) \cdot \nabla \psi}{B^3}, < hB^2 >= 0$$

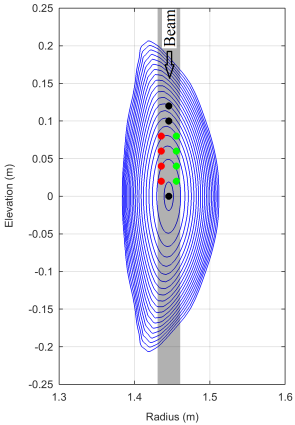
$d\phi/d\psi$ can be written as,

$$\frac{d\phi}{d\psi} = \frac{v_{ps}}{hB} = \frac{v_{||i} - v_{bs}}{hB}$$

Therefore, the flux surface function $d\phi/d\psi$ can be obtained by measuring the parallel flow for at least 2 locations on a flux surface.

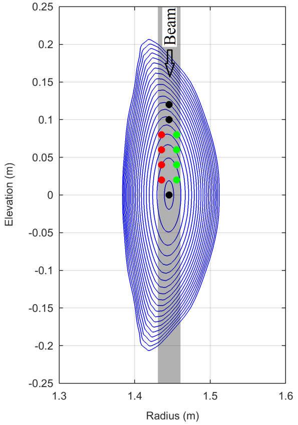
Charge Exchange Spectroscopy diagnostic on HSX is modified to measure Pfirsch-Schlüter effect

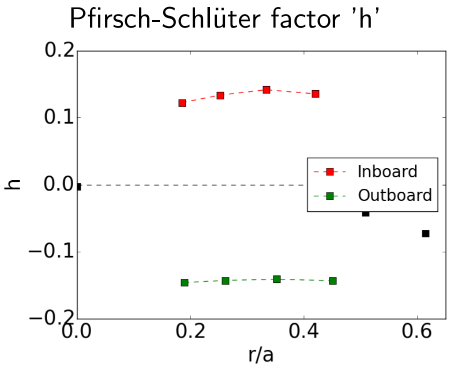
'Toroidal' view has been modified to view inboard/outboard side of the beam axis.



- 4A, 30 keV, 3 ms hydrogen neutral beam
- 11 fibers, measurement spot size radius ~1.5 mm
- CVI emission at 529.1 nm (n=8-7 transition) is measured using a Czerny-Turner spectrometer
- Methane is used as the working gas instead of hydrogen

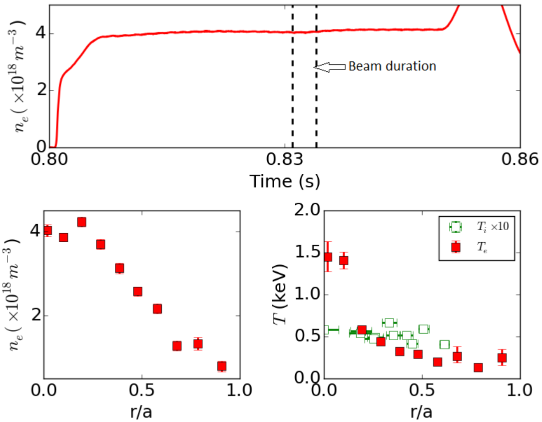
Pfirsch-Schlüter geometric factor at the measurement locations has been calculated





The Pfirsch-Schlüter flows manifest in the form of an inboard/outboard asymmetry in the measured parallel flows

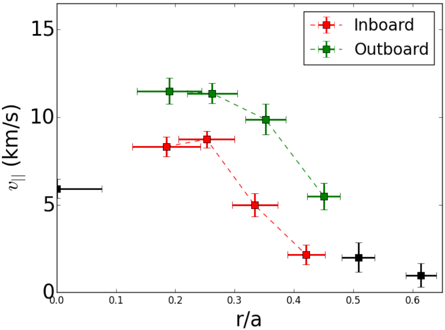
Measurements are made in 100 kW methane plasma



- 100 kW electron cyclotron heating
- QHS magnetic geometry
- On-axis B $\sim$ 1 Tesla
- No external momentum injection

Inboard/outboard flow asymmetry has been observed

Parallel flow from measured 'toroidal' flow



The Pfirsch-Schlüter flows are counter-streaming, with a direction as expected for a positive E_r.

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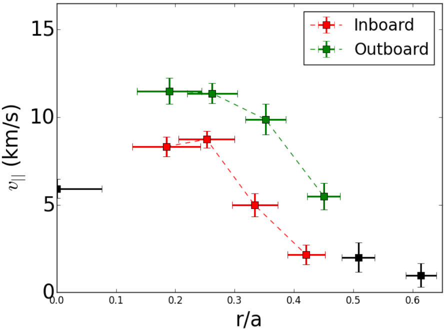
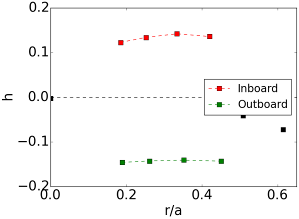
Parallel flow from measured 'toroidal' flow



$$\frac{d\phi}{d\psi} = \frac{v_{ps}}{hB}$$

h factor



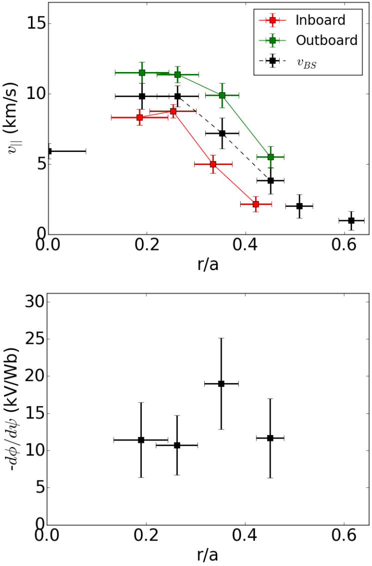
The Pfirsch-Schlüter flows are counter-streaming, direction as expected for a positive E_r.

The bootstrap flow (v_{bs}) and $\frac{d\phi}{d\psi}$ are calculated from the measured inboard/outboard flows

$d\phi/d\psi$ and v_{bs} on both sides of the same flux surface are the same.

$$\left[\frac{d\phi}{d\psi}\right]_{IN} = \left[\frac{d\phi}{d\psi}\right]_{OUT}$$

$$\left[\frac{v_{||i(IN)} - v_{bs}}{(hB)_{(IN)}}\right] = \left[\frac{v_{||i(OUT)} - v_{bs}}{(hB)_{(OUT)}}\right]$$

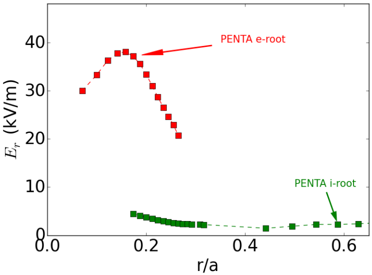


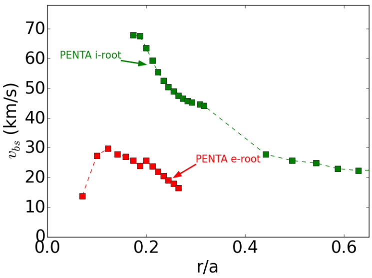
Neoclassical calculations are done using the PENTA code

- ADAS[a] calculation of fractional abundance of carbon, scaled to methane proportion is used
- PENTA[b] uses radial coordinate system based on toroidal flux
- Measured E_ψ is converted to a PENTA variable by,

$$\frac{d\phi}{dr_{PENTA}} = \frac{d\phi}{d\psi} \times 2\sqrt{\psi B_T \pi}$$

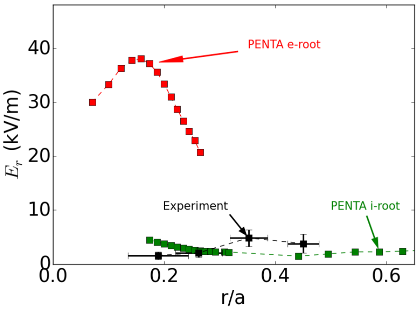
[a] Summers H. P. (2004)
[b] Spong D. A. (2005)



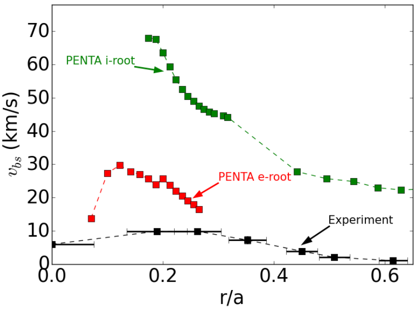


Discrepancy with neoclassical calculations for the QHS geometry still exists

E_r comparison



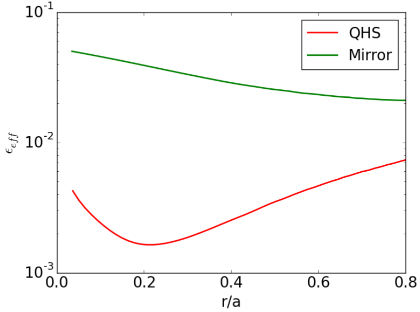
Flow comparison



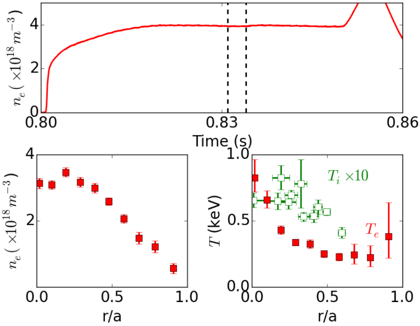
E_r qualitatively agrees with PENTA electron root, but v_{bs} lower than both roots.

A similar experiment has been conducted in broken symmetry ('mirror') geometry

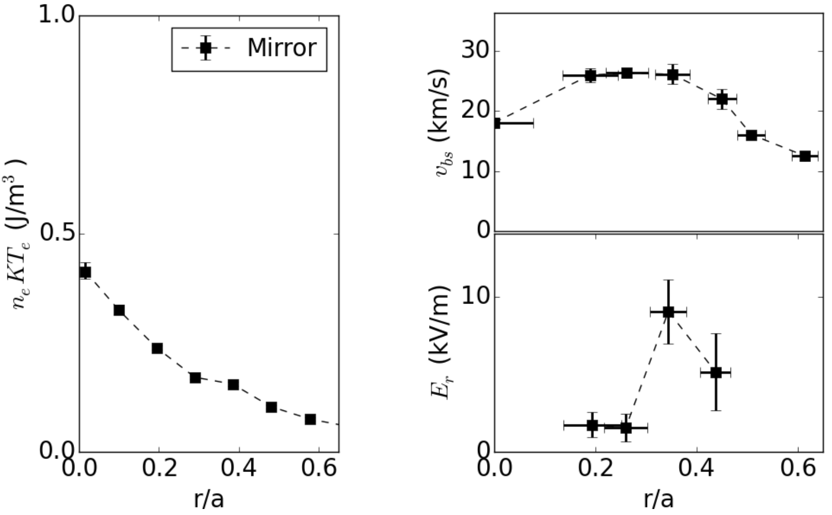
Effective ripple is much higher for broken symmetry



Lower T_e, gradients in mirror geometry for the same injected ECH power (100 kW)



Higher E_r and significantly larger flows are observed in broken symmetry configuration



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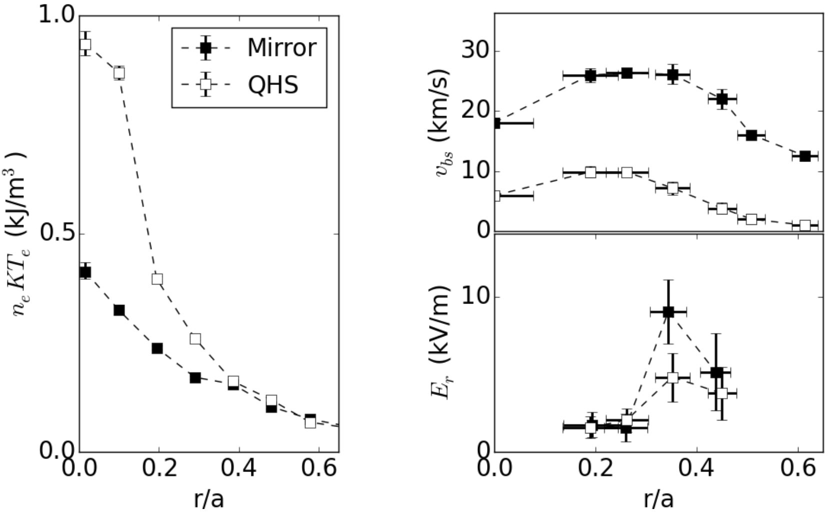
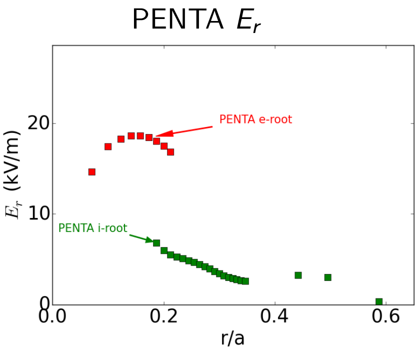
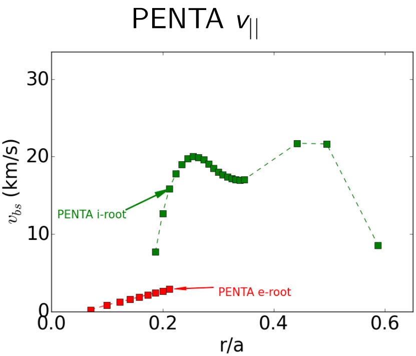


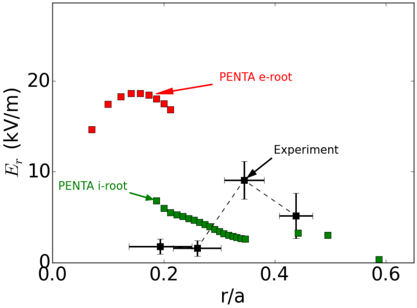
Calculated flows and Er are smaller in the mirror geometry



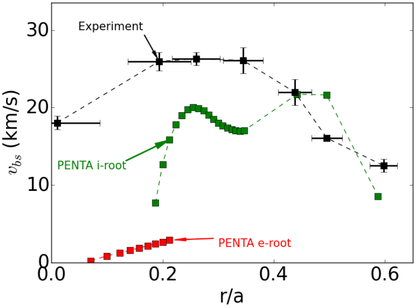


Mirror case agrees better with the neoclassical calculation

E_r comparison



Flow comparison



E_r and flow measurements are both consistent with ion root electric field.

E_r and flows in QHS configuration may be governed by non-neoclassical processes near the core

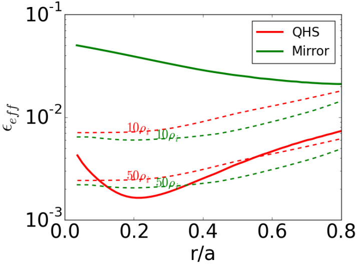
- [a]Over a radial distance of Nρ_i, the nonambipolar current exceeds that driven by Reynolds stress, if

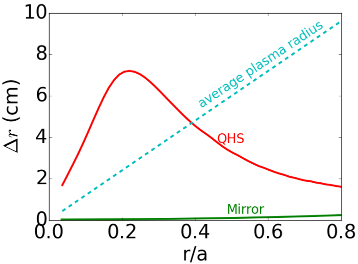
$$\epsilon_{eff} > \left(\frac{L}{N\lambda_{MFP}}\right)^{2/3}$$

- The radial width over which non-neoclassical processes dominate,

$$\Delta r = N\rho_i = \frac{L}{\epsilon_{eff}^{3/2}\lambda_{MFP}}\rho_i$$

[a]Helander&Simakov, (2008)





Summary

- The counter-streaming Pfirsch-Schlüter flows have been observed
- E_r and bootstrap flows are obtained from Pfirsch-Schlüter effect
- Large discrepancy with neoclassical calculation is observed for QHS geometry
- Broken symmetry configuration exhibits larger flows and E_r, agrees better with neoclassical model

Observations indicate that flows and E_r in QHS configuration may be governed by non-neoclassical processes in the core.