

Effect of Neutral Friction on Parallel Ion Flow in a Quasi-symmetric Stellarator

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ISHW 2019, Madison, WI

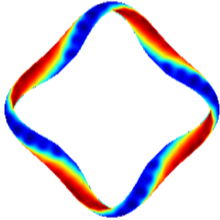


Acknowledgments

T. J. Dobbins, J. N. Talmadge, K. M. Likin, F. S. B. Anderson, D. T. Anderson & HSX team

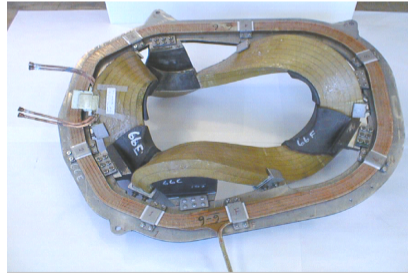
Quasi helically symmetric (QHS) magnetic geometry allows HSX plasmas to exhibit large flows.

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



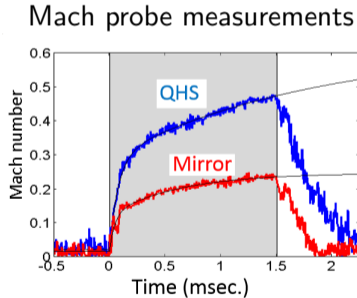
Minimal parallel viscosity is calculated in the helical direction in HSX

Non-planar and planar coils generate QHS and 'Mirror' geometries.



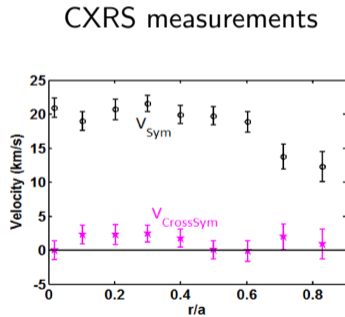
Previous experiments have demonstrated neoclassical properties of QHS in terms of the direction of flows.

Edge biased experiment confirmed reduced flow damping with quasisymmetry ^a.



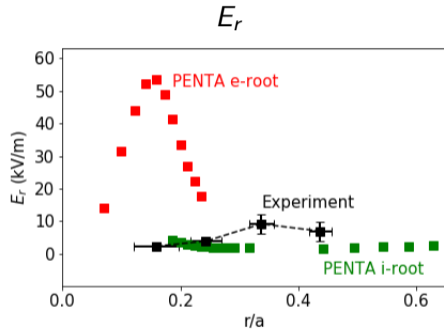
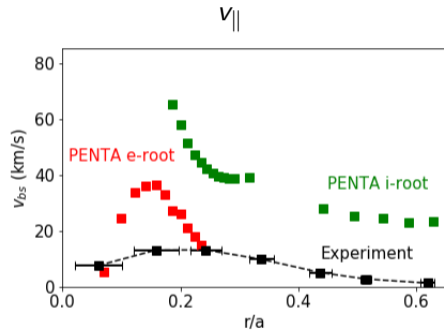
^aGerhardt [2005]

Carbon flow measurements confirmed that flows are predominantly in the symmetry direction ^b



^bBriesemeister [2010]

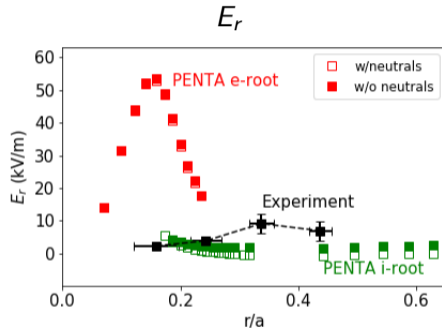
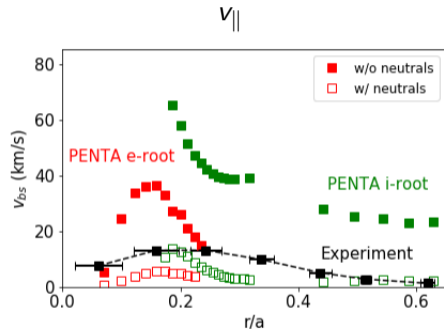
Measured ion parallel flows and E_r are inconsistent with neoclassical calculations. [†]



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

[†]S. Kumar [2017]

The inconsistency is largely resolved by adding neutral friction in the calculation. [†]



Damping due to neutral drag significantly lowered ion-root flow, but E_r is relatively unchanged.

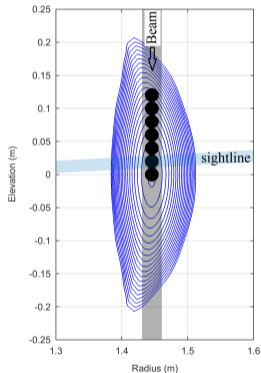
[†]T. Dobbins [2019]

Recent progress with measurements and calculations is presented in this talk.

Outline of the talk:

- ① Parallel flow and E_r measurements
- ② Neutral density measurements/calculation
- ③ Modification to the neoclassical calculation
- ④ Effect of neutral friction on bootstrap current

Flow and E_r measurements are done using charge exchange spectroscopy (CXRS).



- 4A, 30 keV, 3 ms hydrogen neutral beam
- CVI emission at 529.1 nm ($n=8-7$ transition) is measured using a Czerny-Turner spectrometer
- Carbon doping is used get higher signal

Poloidal flow measurements near the core have large uncertainties due to relatively large width of the diagnostic neutral beam.

A new method has been developed to obtain E_r and v_{bs} from parallel flows only, using Pfirsch-Schlüter effect.

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

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

The Pfirsch-Schlüter flows (v_{ps}) arise due to incompressibility.

For ions,

$$\nabla \cdot (\vec{v}_{\perp i} + \vec{v}_{\parallel i}) = 0$$
$$\vec{v}_{\perp i} = \frac{\vec{E}_r \times \vec{B}}{B^2} - \frac{\nabla P_i \times \vec{B}}{en_i Z_i B^2} = - \left(\frac{d\phi}{d\psi} + \frac{1}{en_i Z_i} \frac{dP_i}{d\psi} \right) \left(\frac{\nabla \psi \times \vec{B}}{B^2} \right)$$

A new method has been developed to obtain E_r and v_{bs} from parallel flows only, using Pfirsch-Schlüter effect.

The Pfirsch-Schlüter flow can be written as,

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

where h is a geometrical factor, which is defined by

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

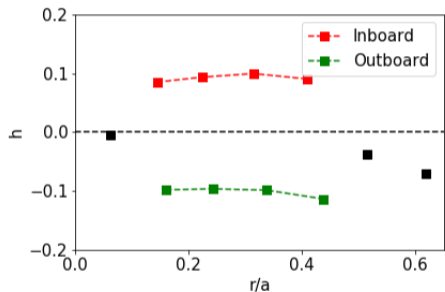
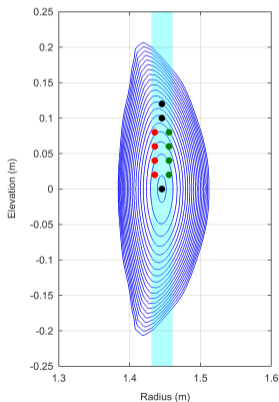
$d\phi/d\psi$ can be written as,

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

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.

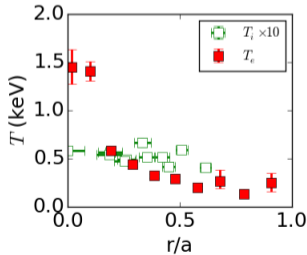
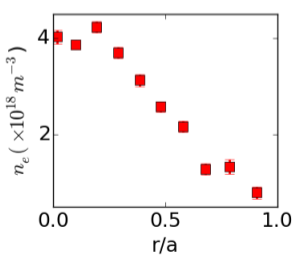
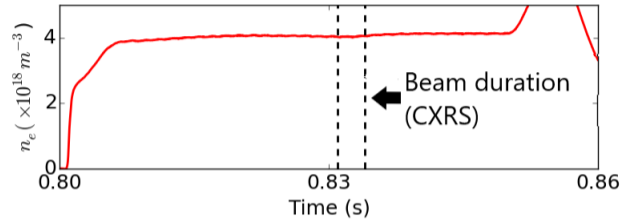
CXRS diagnostic on HSX is modified to measure Pfirsch-Schlüter flows.

Modified to view inboard/outboard side of the beam axis. 11 fibers, measurement spot size radius ~ 1.5 mm



The Pfirsch-Schlüter flows will be counter-streaming at these locations.

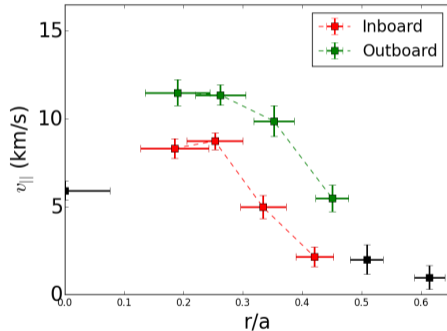
Measurements are made in 100 kW ECH plasma.



- Two 28 GHz gyrotrons, 50 kW each, are used to generate and heat the plasma.
- On-axis field, $B_0 \sim 1$ Tesla
- QHS geometry
- No external momentum injection.

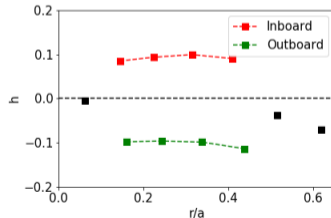
Inboard/outboard flow asymmetry has been observed.

Parallel flow from measured 'toroidal' flow



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

h factor



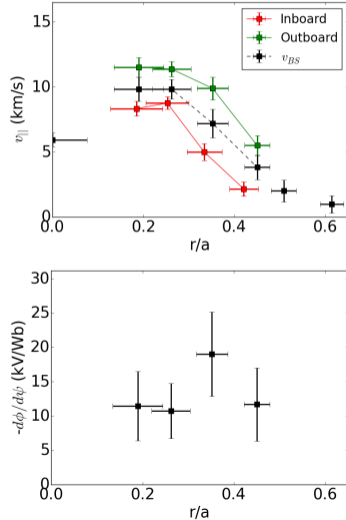
The Pfirsch-Schlüter flows are counter-streaming, direction as expected for a positive E_r .

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

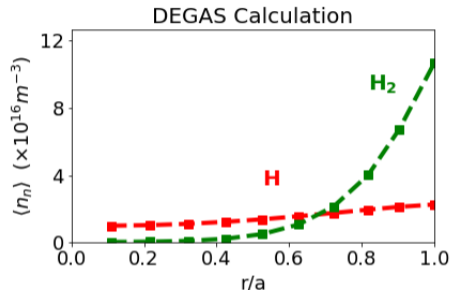
$d\phi/d\psi$ and v_{bs} on both sides of the same flux surface are the same.

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

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



Neutral density is significant throughout the plasma in HSX.



- DEGAS uses Monte-Carlo method to calculate neutral distribution.
- 3D HSX geometry is used in calculations.
- HSX H_α arrays are incorporated.

- Frank-Condon neutrals have long mfp at HSX parameters.
- $\langle n_n \rangle$ profiles are relatively unchanged during a discharge.
- H_2 does not significantly contribute to momentum transfer.

Neoclassical calculations are done using the PENTA code.

Parallel momentum and heat flux balance equations[†]:

$$\langle \mathbf{B} \cdot (\nabla \cdot \Pi_a) \rangle - n_a e_a \langle B E_{||} \rangle = \langle B F_{||a1} \rangle \quad (1)$$

$$\langle \mathbf{B} \cdot (\nabla \cdot \Theta_a) \rangle = \langle B F_{||a2} \rangle \quad (2)$$

- $B F_{||a1}$: Friction between individual species
- $\mathbf{B} \cdot (\nabla \cdot \Pi_a)$: Parallel neoclassical viscosity term
- $n_a e_a \langle B E_{||} \rangle$: Parallel electric field term.
- Momentum conservation using Sugama-Nishimura approach [‡]

[†]D. A. Spong [2005], J. Lore [2010]

[‡]H. Sugama & S. Nishimura [2002]

For this work, neutral friction is included in PENTA parallel momentum and heat flux balance equations.

$$\langle \mathbf{B} \cdot (\nabla \cdot \Pi_a) \rangle - n_a e_a \langle B E_{\parallel} \rangle + \delta_{i,a} F_{i1}^n = \langle B F_{\parallel a1} \rangle \quad (3)$$

$$\langle \mathbf{B} \cdot (\nabla \cdot \Theta_a) \rangle + \delta_{i,a} F_{i2}^n = \langle B F_{\parallel a2} \rangle \quad (4)$$

Ion-neutral friction term [†]:

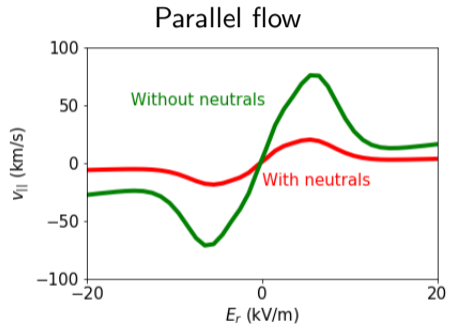
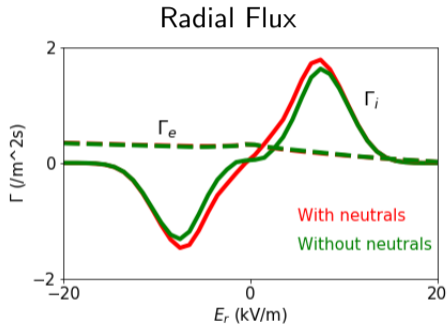
$$\begin{bmatrix} F_{i1}^n \\ F_{i2}^n \end{bmatrix} = -n_i m_i \nu_{in} \begin{bmatrix} 1 & 0 \\ 0 & \frac{E}{T_i} \end{bmatrix} \begin{bmatrix} \langle u_{\parallel a} B \rangle / \langle B^2 \rangle \\ \frac{2}{5p_a} \langle q_{\parallel a} B \rangle / \langle B^2 \rangle \end{bmatrix} \quad (5)$$

$\delta_{i,a}$ is equal to one for ions and zero for electrons.

Collision with impurity ions (carbon) is included in the calculation.

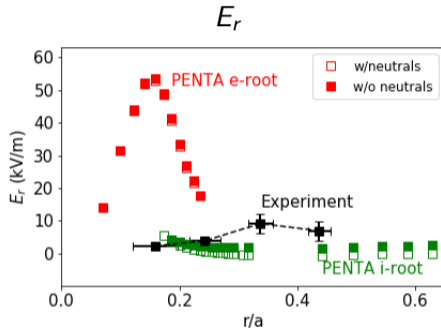
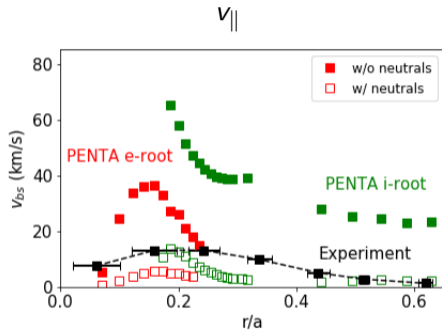
[†]P. Monier-Garbet [1997]

Neutrals significantly reduce ion flow near resonance. Change in radial ion flux is marginal.



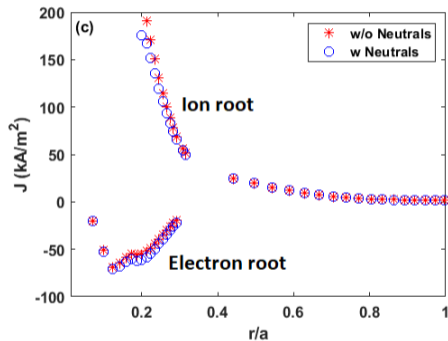
Ambipolar radial electric field calculation is relatively unchanged, but Flow at ambipolar E_r could be significantly different.

Inconsistency between experiment and measurements is largely resolved by including neutral friction.



Damping due to neutral drag significantly lowered ion-root flow, but E_r is relatively unchanged.

Bootstrap current is mostly unchanged with neutral friction.



- Reduction in ion flow is compensated by increase in electron flow due to reduced ion drag.
→ Friction $\propto (v_{||i} - v_{||e})$
- Consistent with previous results that bootstrap current calculated by PENTA agrees with experiment. [†]

[†]J. Schmitt [2014]

Summary

- Improved measurements of E_r and v_{bs} are obtained using Pfirsch-Schlüter flow measurements.
- PENTA code has been modified to include collisions with background neutrals.
- Neutral collisions significantly decrease ion flow. E_r is relatively unchanged.

Inconsistency between experiment and measurements is largely resolved by including neutral friction in the calculation.