Competition between parallel viscosity and ion-neutral friction in damping the parallel flow in a quasisymmetric stellarator

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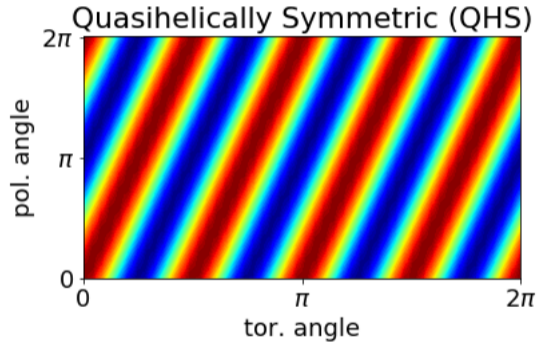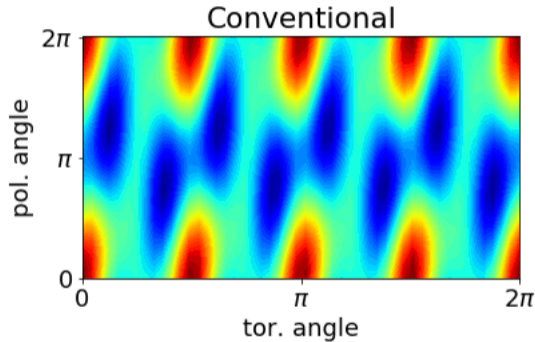APS-DPP, Fort Lauderdale, Florida, October 21-25, 2019

WISCONSIN   HSX

Acknowledgments

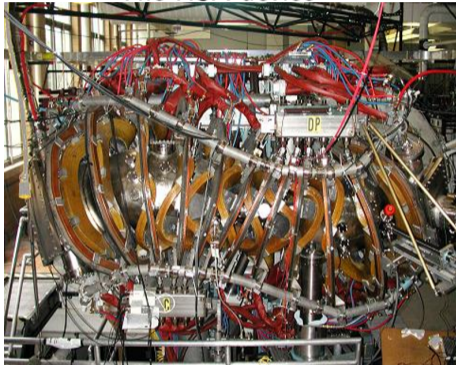# Conventional stellarators have high flow damping.

$|B|$ on a flux surface

Symmetry in $|B|$ leads to reduced viscous damping of plasma flows in quasisymmetric stellarators.
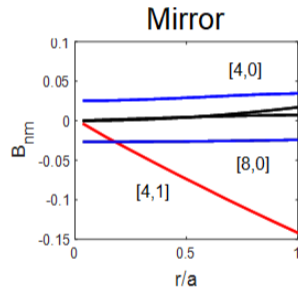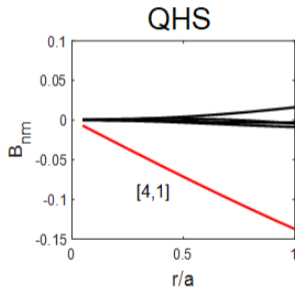
QHS magnetic geometry allows HSX plasmas to exhibit large flows.

The HSX device

Major/Minor radius : 1.2/0.15 m

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

→ Reduced parallel viscosity is calculated for QHS geometry.

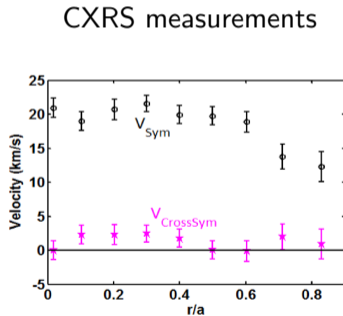→ Flow damping time: $\tau_{QHS} \sim 85ms$, $\tau_{Mirror} \sim 3ms$.

Previous experiments have confirmed reduced parallel viscosity in QHS configuration.

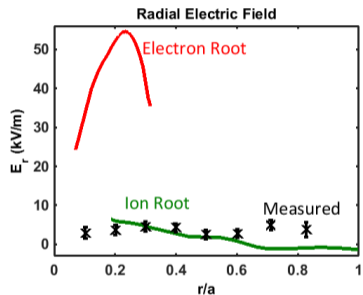Edge biasing experiment confirmed reduced flow damping with quasisymmetry [a].
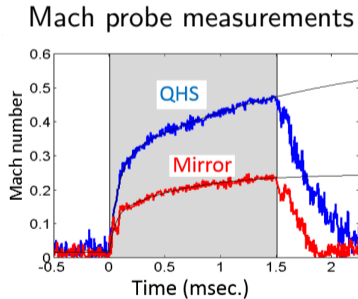
Carbon flow measurements confirmed that flows are predominantly in the symmetry direction [b]

Mach probe measurements

CXRS measurements

[a]Gerhardt [2005]

[b]Briesemeister [2010]

Previously measured ion parallel flows and E_r are inconsistent with neoclassical calculations. [†]
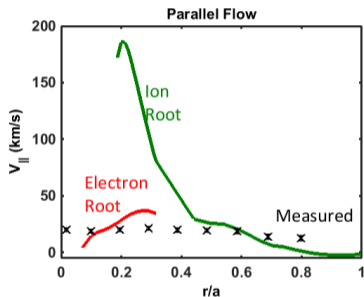
In the core, measured E_r is close to the ion-root, but measured $v_{||}$ is close to the electron-root

[†]Briesemeister, [2010]

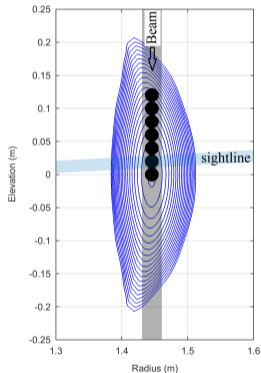# Improvements have been made in measurements and modeling to resolve the inconsistency.

Outline of the talk:

- Improvements in measurements

- Improvements in neoclassical model

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 to 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,

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

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

For ions,

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

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

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

$$\vec{B} \cdot \nabla h = -2\frac{(\vec{B} \times \nabla B) \cdot \nabla \psi}{B^3}, < hB^2 >= 0$$
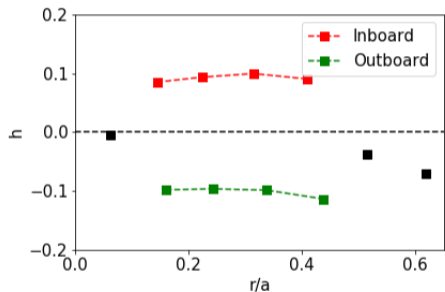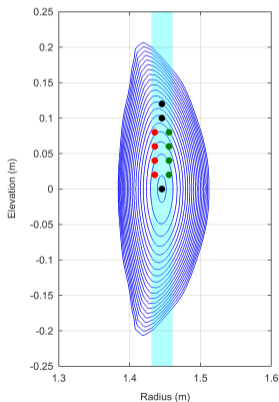
$d\phi/d\psi$ can be written as,

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

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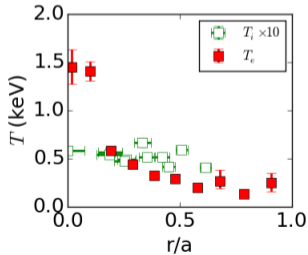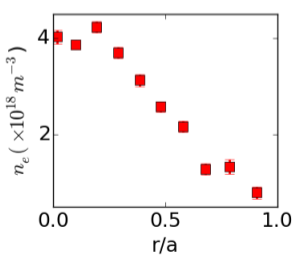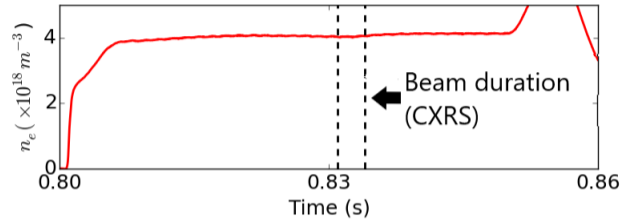
Modified to view inboard/outboard side of the beam axis. 11 fibers, measurement spot size radius ~1.5 mm

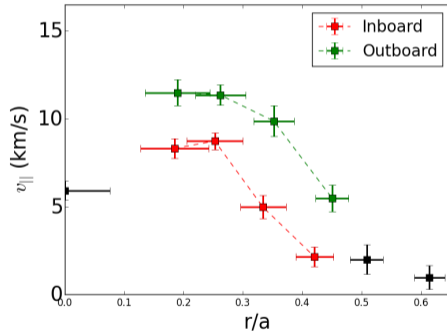The Pfirsch-Schlüter flows will be counter-streaming at these locations.

- 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
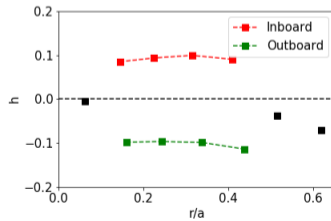
- No external momentum injection.

Parallel flow from measured 'toroidal' flow

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

h factor

Relative direction of Pfirsch-Schlüter flow w/respect to mean flow indicates positive E_r.

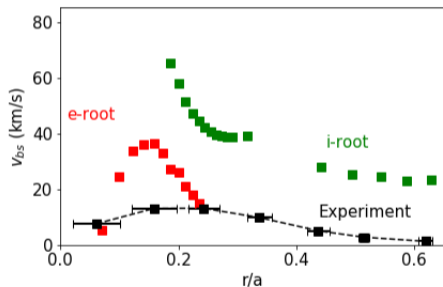$d\phi/d\psi$ and v_{bs} on both sides of the same flux surface are the same.

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

$$\left[\frac{v_{\|i(IN)} - v_{bs}}{(hB)_{(IN)}}\right] = \left[\frac{v_{\|i(OUT)} - v_{bs}}{(hB)_{(OUT)}}\right]$$
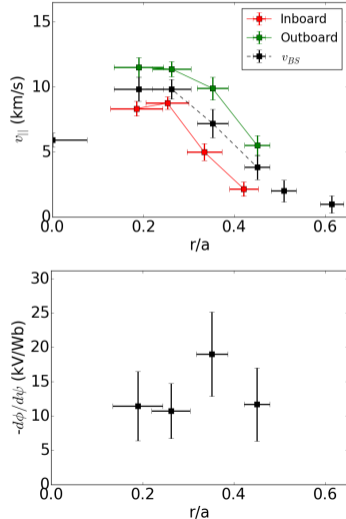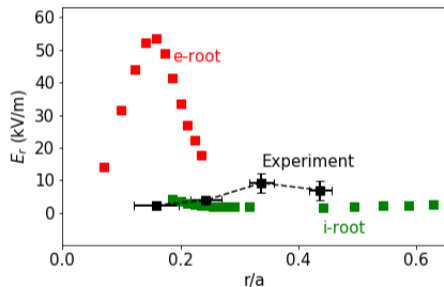
Discrepancy with neoclassical calculations for the QHS geometry still exists.
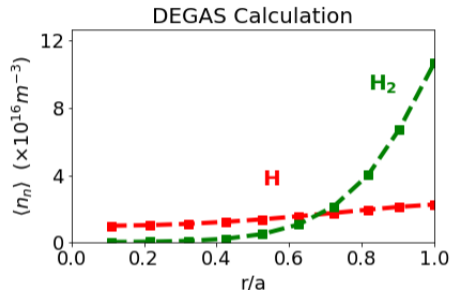

Flow comparison

E_r comparison

E_r agrees with neoclassical ion root, but v_{bs} is closer to the electron root.

Neutral density is significant throughout the plasma in HSX.

DEGAS Calculation

- DEGAS uses Monte-Carlo method to calculate neutral distribution.

- 3D HSX geometry is used in calculations.

- HSX H_α arrays are incorporated.

$\rightarrow$ Frank-Condon neutrals have long mfp at HSX parameters.

$\rightarrow$ $\langle n_n \rangle$ profiles are relatively unchanged during a discharge.

$\rightarrow$ H_2 does not significantly contribute to momentum transfer, but H does.

Neoclassical calculations are done using the PENTA code.

Parallel momentum and heat flux balance equations[†]:

$$\langle \mathbf{B} \cdot (\nabla \cdot \Pi_a)\rangle - n_a e_a \langle BE_{||}\rangle = \langle BF_{||a1}\rangle \tag{1}$$

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

- $BF_{||a1}$: Friction between individual species

- $\mathbf{B} \cdot (\nabla \cdot \Pi_a)$: Parallel neoclassical viscosity term

- $n_a e_a \langle BE_{||}\rangle$: 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.

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

$$\langle \mathbf{B} \cdot (\nabla \cdot \Theta_a) \rangle + \delta_{i,a} F_{i2}^n = \langle B F_{\|a2} \rangle \tag{4}$$
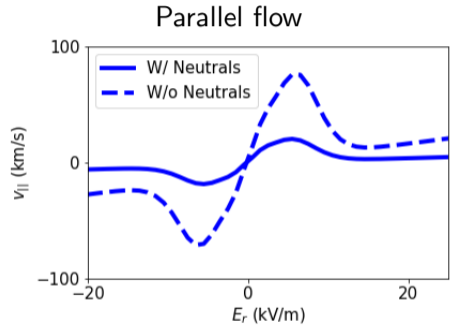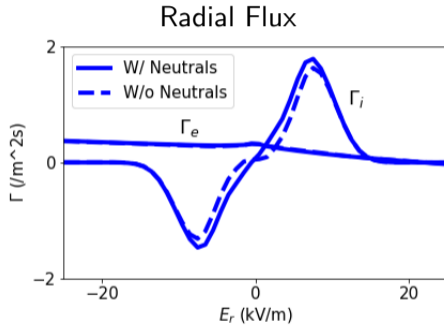
Ion-neutral friction term [†]:

$$\left[\begin{array}{c} F_{i1}^n \\ F_{i2}^n \end{array} \right] = -n_i m_i \nu_{in} \left[\begin{array}{cc} 1 & 0 \\ 0 & \frac{E}{T_i} \end{array} \right] \left[\begin{array}{c} \langle u_{\|a} B \rangle / \langle B^2 \rangle \\ \frac{2}{5 p_a} \langle q_{\|a} B \rangle / \langle B^2 \rangle \end{array} \right] \tag{5}$$

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

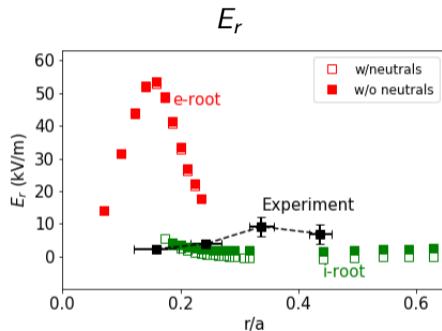Collision with impurity ions (carbon) is included in the calculation.
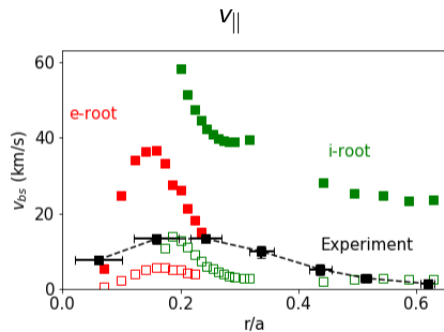

[†]P. Monier-Garbet [1997]

# Neutrals significantly reduce ion flow. 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.

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

In the Mirror geometry, effect of neutral friction is less due to higher neoclassical viscosity.
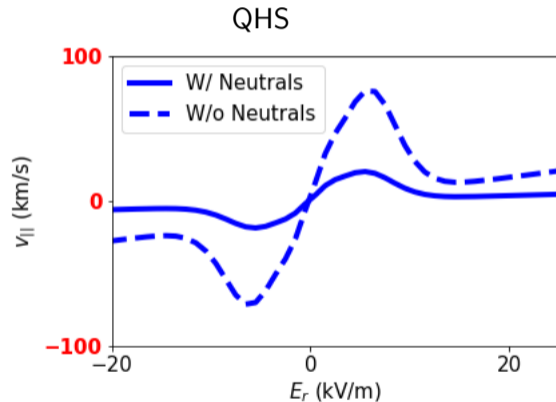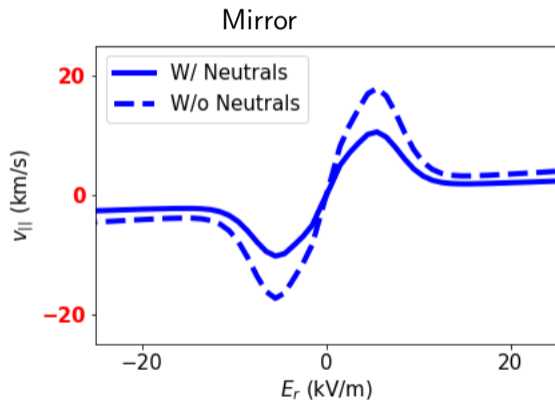
Summary

- 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 damping of ion flow is found to be significant in QHS geometry. E_r is relatively unchanged.

- Neutral friction has lower impact in Mirror geometry than QHS because of higher neoclassical viscosity.
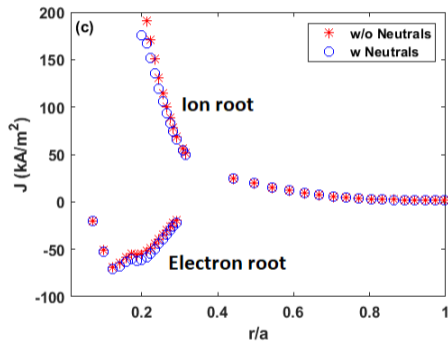
- Reduction in ion flow is compensated by increase in electron flow due to reduced ion drag.

  $\rightarrow$ Friction $\propto (v_{\|i} - v_{\|e})$

- Consistent with previous results that bootstrap current calculated by PENTA agrees with experiment. [†]

[†] J. Schmitt [2014]

r/a = 0.21213