Comparison of Plasma Flows and Currents in HSX to Neoclassical Theory

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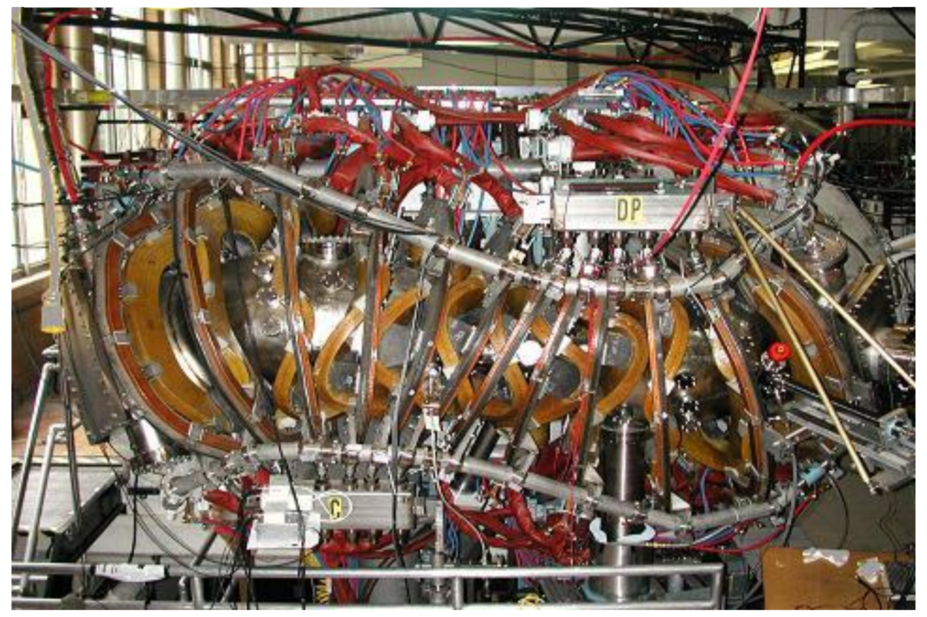
EX/P3-30

Overview

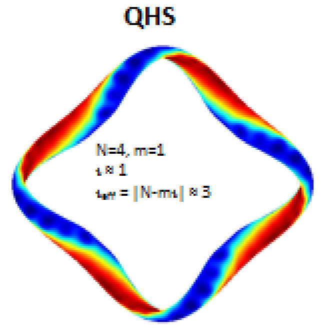
- HSX was designed with a helical symmetry direction in the magnetic field strength (quasisymmetry)
- This symmetry, unlike previous stellarators, offers the possibility for large flows with positive impacts on confinement as in the tokamak.
- Large flows in the symmetry direction have been observed in HSX without external momentum input.
- Calculations with the PENTA code demonstrate the importance of including momentum conservation to get agreement with the measured parallel flows.
- The bootstrap current and its evolution will have significant impact on the magnetic configuration in high performance devices.
- The bootstrap and Pfirsch-Schluter currents have been estimated with external flux loop signals modeled with PENTA and V3FIT.
- V3FIT has been used to reconstruct equilibria from the diagnostic signals with improved agreement between signals and predictions
- The results confirm the unique helical nature of the Pfirsch-Schluter current in HSX and the reduction in magnitude of both Pfirsch-Schluter and bootstrap currents due to the high effective transform.



The Quasi-Helically Symmetric HSX Stellarator

- HSX has already demonstrated reduced flow damping and improved neoclassical transport due to quasisymmetry [Gerhardt PRL 2005; Canik PRL 2007]

QHS



$B = B_0[1-\varepsilon_h \cos(N-m\iota)\phi]$

<R>	1.2 m
<a>	0.12 m
ι	1.05 →1.12
B₀	1.0 T
ECRH 28 GHz	100 kWx2

Typical plasma parameters (100 kW)

$\langle n_e\rangle \leq 6\times10^{12}$ cm^{-3}

$T_e \sim 0.5$ - 2.5 keV ; $T_i \sim 30$-60 eV

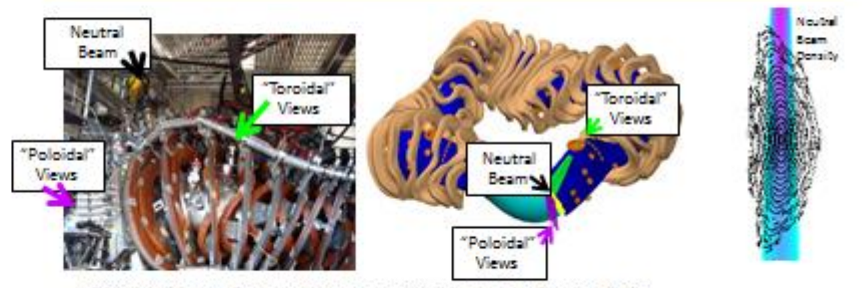
No external momentum source; all flows and currents discussed are intrinsic

The Total Flow is Comprised of Perpendicular and Parallel Components

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

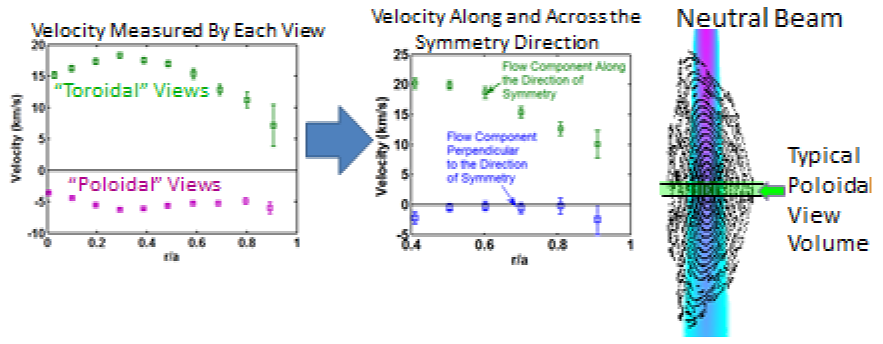
- E_r is determined by neoclassical transport
- Diamagnetic flow small for higher Z ions like carbon
- V_{PS} is the Pfirsch-Schlüter flow that varies on a surface, causes the total flow to satisfy incompressibility
- All flow components change direction if $\vec{B}$ is reversed

Charge Exchange Recombination Spectroscopy 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 ccd's image the spectra
- Frames integrated for 5ms are taken before, during and after the beam fires

Flows Move Primarily Along the Helical Direction of Symmetry



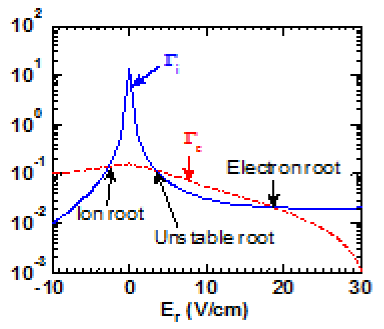
- Geometric factors are used to relate the measured velocities to the average flow in the symmetry and cross symmetry directions within the view
- Near the axis the flow direction changes significantly across the beam/view volume leading to an unacceptable level of uncertainty in the geometric factors

Determining the Radial Electric Field in a Stellarator

- Fluxes in a stellarator are not intrinsically ambipolar; E_r is determined by enforcing ambipolarity.

$$\sum_s e_s\Gamma_s(E_r,D(E_r))=0$$

- LMFP with $T_e > T_i$ results in three roots
  - **Ion root:** ion flux reduced from E_r=0 level
  - **Electron root**: both species flux reduced from E_r=0 level
  - **Unstable root:** any perturbation drives toward either electron or ion root



Historically, Stellarator Transport Coefficients are Calculated Numerically Using DKES

- The NC transport coefficients are calculated by the DKES[1] code.
- DKES solves the linearized drift kinetic equation (DKE) via a variational method using a pitch angle scattering (PAS) collision operator
- Advantages
  - Allows DKE of each species to be decoupled
  - Conserves speed v, reducing dimensionality of problem
  - Leads to fast computation for arbitrary B, collisionality
- Disadvantages
  - Does not conserve momentum
  - Intrinsic ambipolarity in (quasi)symmetric limit not recovered

1) W.I. van Rij and S.P. Hirshman, Phys. Fluids B 1, 563 (1989), S.P. Hirshman, *et al.*, Phys. Fluids 29, 2951 (1986).

PENTA Restores Momentum Conservation

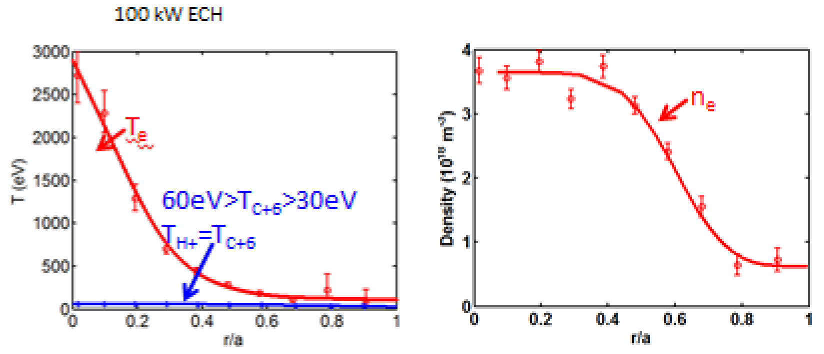
- Originally developed by Don Spong (ORNL)
  - Uses DKES coefficient calculations
  - Corrects for momentum conservation with method of Sugama and Nishimura
- Has been expanded at HSX (J Lore now at ORNL) for
  - Multiple ion species of arbitrary mass, charge, temperature (HSX impurity transport)
  - Arbitrary expansion order (improves accuracy, allows for convergence checks)
  - Particularly important experimental comparisons of flow (ChERS) and bootstrap current
- Effects of parallel flow, interspecies collisions included
- Expressions used analytically reproduce intrinsic ambipolarity in symmetric limit
- In principle, this method can be applied to the full range of configurations:

tokamaks → rippled tokamaks → quasi-symmetric → conventional stellarators

Increasing effective ripple →

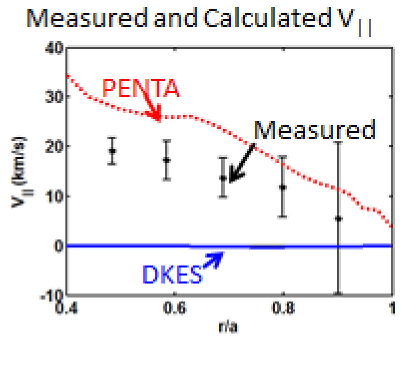
H. Sugama and S. Nishimura, Phys. Plasmas 9, 4637 (2002).

Measured Density and Temperature Profiles Input to PENTA



- T_e and n_e measured using Thomson scattering
- Penta is able to handle multiple ion species
- Ions are collisional and Penta predicts majority ions and impurities have the same temperature and $V_{||}$

Flows predicted by PENTA, including momentum conservation, much closer to experimental values



- DKES predicts a parallel flow near zero

Key Points

•Intrinsic flows of up to 20 km/s have been observed in HSX

•These flows are in the direction of symmetry of the quasisymmetric field

•Momentum conservation is required for modeling to predict flows of this level

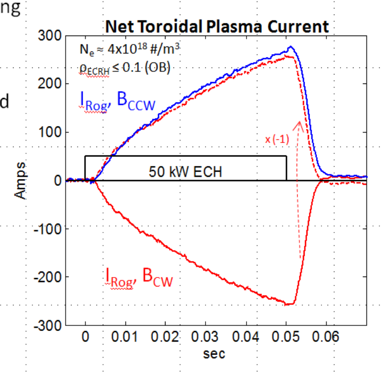
Equilibrium Currents in HSX are Unique Due to Symmetry

- The predicted Pfirsch-Schluter and bootstrap currents in HSX are reduced by a factor of three due to the high effective transform
- The Pfirsch-Schluter current has a helical structure due to the quasihelical symmetry.
- The bootstrap current is in the opposite sense to a tokamak (in that it reduces the rotational transform)

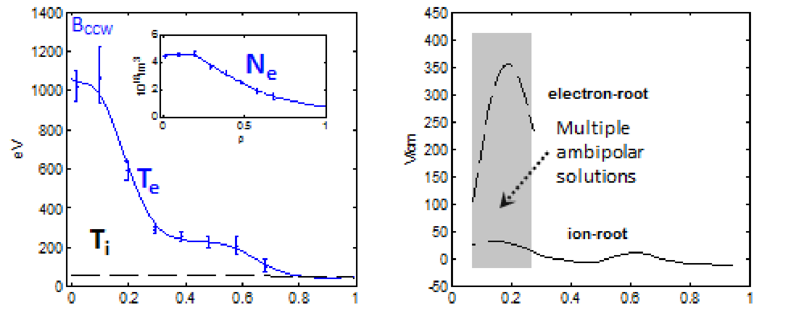
- Currents have been measured in HSX through analysis of a set of external magnetic flux loop signals.
- Early in time, the Pfirsh-Schluter currents (which are set up on equilibrium timescale) show the expected helical rotation.
- The bootstrap current evolves over the discharge duration due to the low resistivity.
- The signals are analyzed using the V3FIT code and the bootstrap current is calculated with the PENTA code.

Net toroidal current is predominantly bootstrap-driven

- ➢ Electron Cyclotron Resonance Heating
  - 1st Harmonic Ordinary-mode
  - No ECCD
- ➢ Toroidal current reverses with B-field direction
- ➢ Current diffusion time long; comparable to shot length
- ➢ $\tau_{\eta_{||}/\mu_0} \geq \tau_{EXP}$

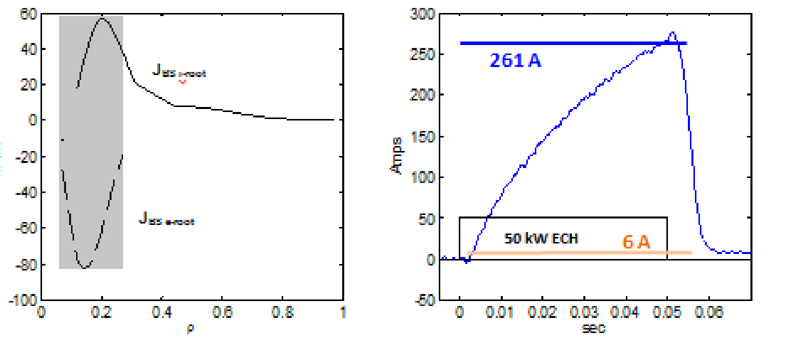


PENTA calculates E_r based on measured plasma profiles



- Current measurements performed at reduced power to lower the electron temperature and decrease current diffusion time
- T_e, N_e from Thomson Scattering.
- T_i from ChERS. $Z_{eff} \approx 1$ from Bremsstrahlung radiation (ChERS optics).
- PENTA calculates the fluxes. E_r is determined by ambipolarity.

The Extrapolated Value of the Bootstrap Current Depends on the Ambipolar Root in the Core Plasma



If e-root is chosen for ρ ≤ 0.3 : I_{BS} = 6 A

If ion root is chosen for ρ ≤ 0.3 : I_{BS} = 261 A

The measured net current is close to the predicted limit of the ion-root solution.
The extrapolated steady state value is 386 A. $\tau_{L/R}$ ~ 50ms.

$$I_{tor}(t)=I_\infty\cdot\left[1-e^{-t/\tau_{L/R}}\right]$$

Modeling the Toroidal Current Evolution

- 1-D diffusion equation for rotational transform (Strand-Houlberg, 2001)

$s=\Phi/\Phi_{LCFS}$

Any non-inductive source

$$\frac{d\iota}{dt}=\frac{1}{\Phi_{LCFS}^2}\frac{d}{ds}\left(\eta_\|V'\left[\frac{\langle B^2\rangle}{\mu_0}\frac{d}{ds}(S_{11}\iota+S_{12})+p'(S_{11}\iota+S_{12})-\langle\mathbf{J}\cdot\mathbf{B}\rangle\right]\right)$$

$$\mu_0\begin{pmatrix}I\\F\end{pmatrix}=\begin{pmatrix}S_{11}&S_{12}\\S_{21}&S_{22}\end{pmatrix}\begin{pmatrix}\Psi'\\\Phi'\end{pmatrix}$$

$-S_{11} \approx S_{12} \approx S_{21}$ for HSX

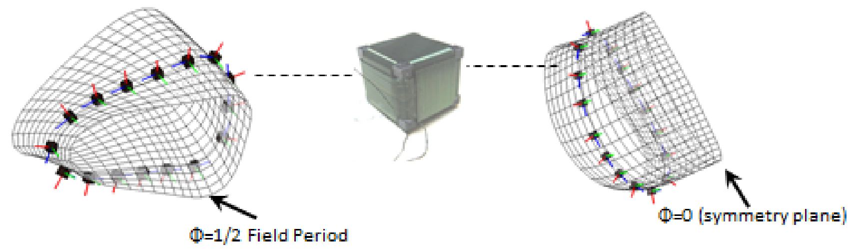
$S_{12} \approx 0$, $S_{21} \approx 0$ for Tokamaks

- Transform related to enclosed toroidal current $\iota=\left(\frac{\mu_0 I}{S_{11}\Phi'}-\frac{S_{12}}{S_{11}}\right)$
- Boundary conditions

$$\left.\frac{d\iota}{ds}\right|_{s=0}=0 \qquad \iota|_{s=1}=\left(\frac{\mu_0 I}{S_{11}\Phi'}-\frac{S_{12}}{S_{11}}\right)_{s=1}$$

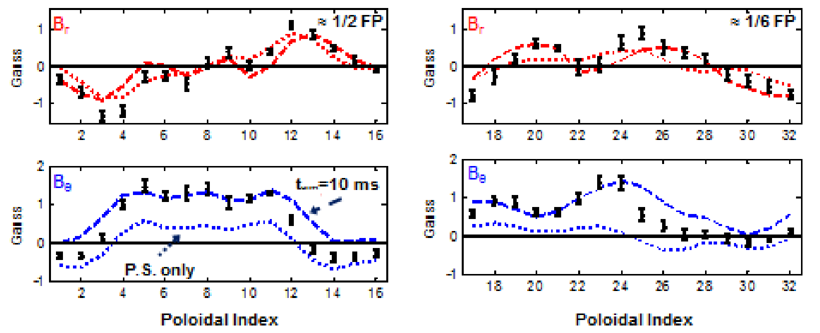
V3FIT Calculates the Magnetic Diagnostics Signals

- V3FIT uses the equilibrium PS currents and the evolved bootstrap current to get a time evolution of the total signals
- Diagnostic set includes two Rogowski coils, 32 external d**B**/dt sensors, and 15 internal coils
- Each d**B**/dt sensor measures the change in the local magnetic field vector
- Internal coils measure only the (approx) B_θ component



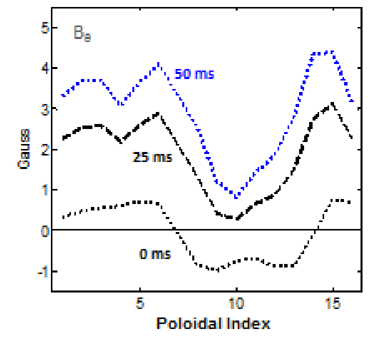
Confirmation of the Helical Rotation of the Dipole Pfirsch-Schlüter Current

- The experimental signals at t=10ms agree well with simulation in terms of the sign and phase.
- Rotation seen mostly clearly by inspecting the phase difference in the B_θ component.
- Offset in B_θ due to small but non-zero bootstrap at 10 ms



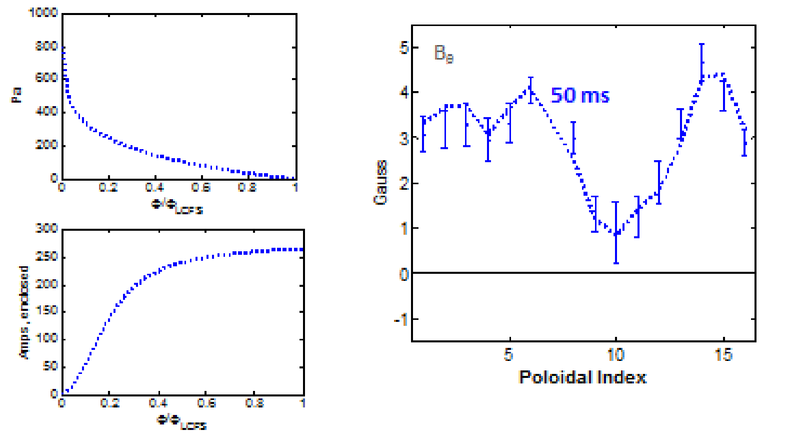
Later in Time, the Largest Signals are from Bootstrap Current

- Simulated profiles at 0 ms, 25ms and 50ms
- Internal coils measure B_θ–component of field: Large unidirectional contribution from <J·B>
- Triangular shape of vacuum vessel leads to additional variation



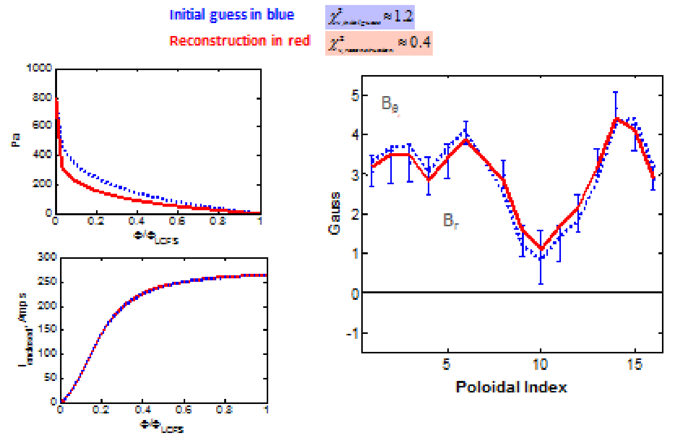
Simulated signals are close to the measured ones

- Good agreement across the internal diagnostic set.
- The pressure profile and evolved current profile serve as an 'initial guess' for V3FIT reconstruction



The reconstruction reduces the mismatch between the measured and modeled signals

- Reconstructed pressure and current profiles are close to the model.



- V3FIT has been used in the forward direction to interpret magnetic signals from external diagnostics.
- In the reconstruction mode, it has been used to modify profiles to improve agreement between predictions and measurements
- With only external magnetic diagnostics, there are a broad range of profiles which can account for the signals, pointing to a need for further constrains on the reconstruction from other data.
- Improvements have and continue to be made in this regard by the V3FIT team (inclusion of Thomson scattering, ECE, MSE data).

Summary

•Intrinsic plasma flows and currents have been measured in HSX and compared to calculations from the PENTA and V3FIT codes

•Large flows are observed in the direction of symmetry

•Momentum conservation is needed to correctly model the flows (through use of PENTA).

•First 3D reconstructions of the bootstrap current have been made.

•Bootstrap current calculated with PENTA

•Diffusion model has been applied to calculate the evolution of the bootstrap current over time

•V3FIT in a forward mode shows good agreement between predicted signals and those measured by external magnetic diagnostics.

•The helical nature of the Pfirsch-Schluter current and the direction of the bootstrap current in a quasihelically symmetric system has been confirmed.

•The current magnitudes are reduced by the high effective transform.

PENTA and V3FIT can be applied across a broad spectrum of toroidal systems

2012 IAEA Fusion Energy Conference, October 8-13, 2012, San Diego, CA, USA