Modeling and Measurement of Toroidal Currents in the HSX Stellarator

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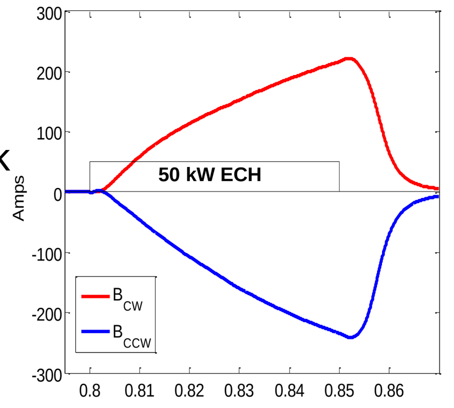
Overview

- The Helically Symmetric eXperiment
  - Quasi-Helically Symmetric and almost no toroidal curvature
  - B_0 = 1 Tesla
  - 26 kW – 100 kW ECR Heating (1st Harmonic)
    - Perpendicular launch
    - Little to no current drive seen during 1 Tesla campaign

- Pfirsch-Schlüter current rotates with the |B| contours with toroidal angle and is reduced by a factor of 1/3 compared to a conventional stellarator

- Bootstrap current
  - Is in the opposite direction and reduced compared to a tokamak
  - Reduces the rotational transform in HSX
  - Reverses with B-field direction
  - Induces toroidal current with long decay times: $\tau_{\eta_{\|}/\mu_0} \geq \tau_{EXP}$



- Evolving current profile is modeled by a diffusion equation with a 3d susceptance matrix

- V3FIT[1] calculations of magnetic signals are compared to diagnostic signals
  - Special thanks to Steve Knowlton, Jim Hanson, and the V3FIT team

Diagnostic System

2x Rogowski coils (I_{tor})
- External -- Low-frequency response ≤ 3kHz
- Internal -- High-frequency ≤ 200kHz

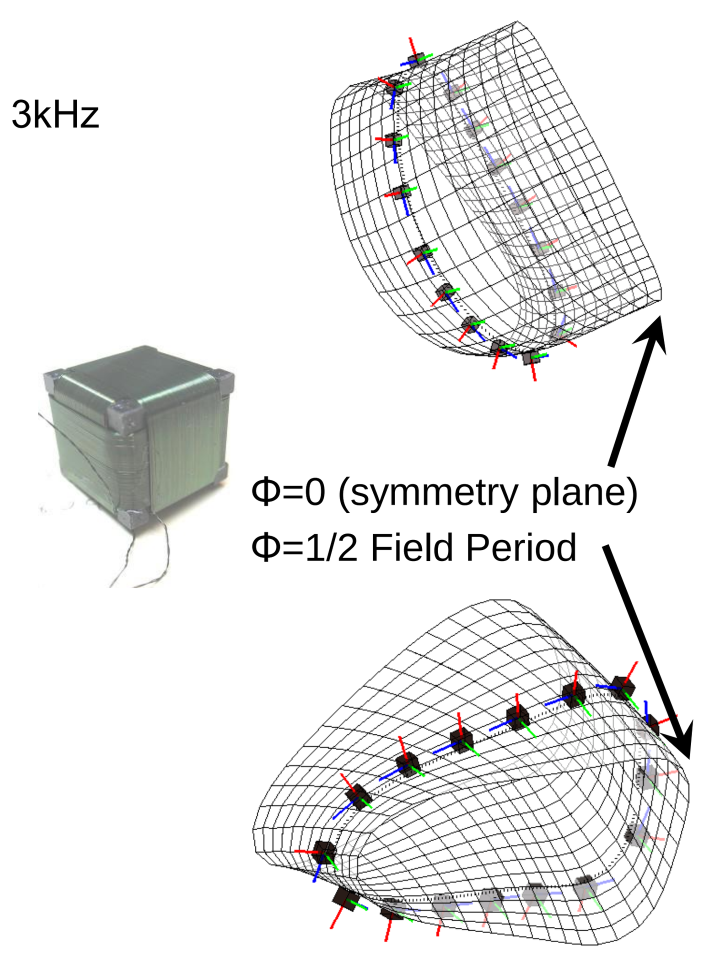
2x Diamagnetic Loops (W_{Kin})
- Internal – High-frequency ≤ 125kHz

2x dB/dt triplet array – 32 external triplets
- MHD and bootstrap currents
- Low-frequency response

High-frequency Mirnov array inside vessel
- 36 coils: 26 poloidal, 10 toroidal
- Frequency response ≤ 200kHz

ChERS Diagnostic
- T_i and Z_{eff} estimate

10-chord Thomson Scattering
- $T_e(\rho)$ and $n_e(\rho)$ profiles

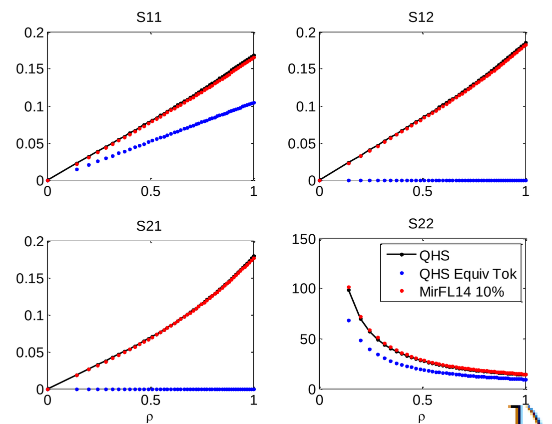


Evolution of Toroidal Current

3d susceptance matrix links toroidal and poloidal currents and magnetic fluxes[2]

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

$S_{12} = S_{21} = 0$ for Tokamaks
$S_{11} \approx S_{12} \approx S_{21}$ for HSX



1-D diffusion equation for rotational transform

$$s = \Phi/\Phi_a \qquad \frac{d\iota}{dt} = \frac{1}{\Phi_a^2}\frac{d}{ds}\left(\eta_{\|} V'\left[\frac{\langle B^2\rangle}{\mu_0}\frac{d}{ds}(S_{11}\iota + S_{12}) + p'(S_{11}\iota + S_{12}) - \langle J_{NI}\cdot B\rangle\right]\right)$$

Any non-inductive source

Boundary conditions

On axis: finite current density

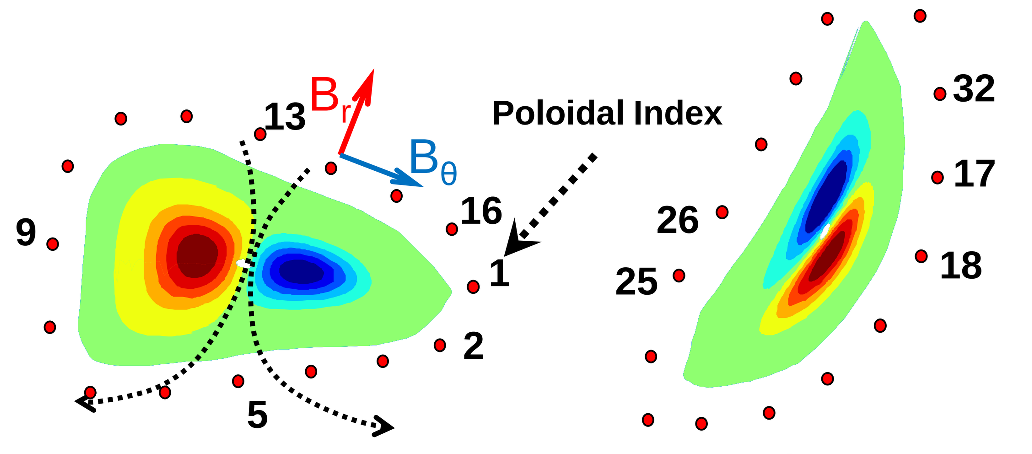
$$\left.\frac{d\iota}{ds}\right|_{s=0} = 0$$

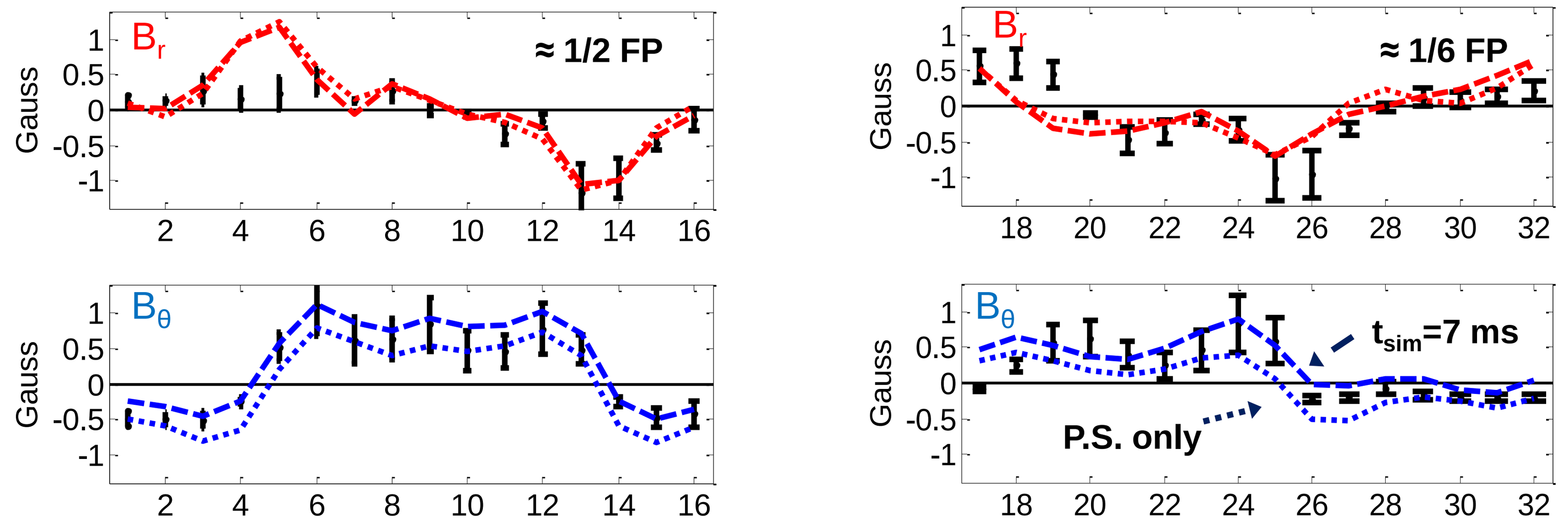
@ LCFS :set by measurement

$$\iota_{s=1} = \left(\frac{\mu_0 I}{S_{11}\Phi'} - \frac{S_{12}}{S_{11}}\right)_{s=1}$$

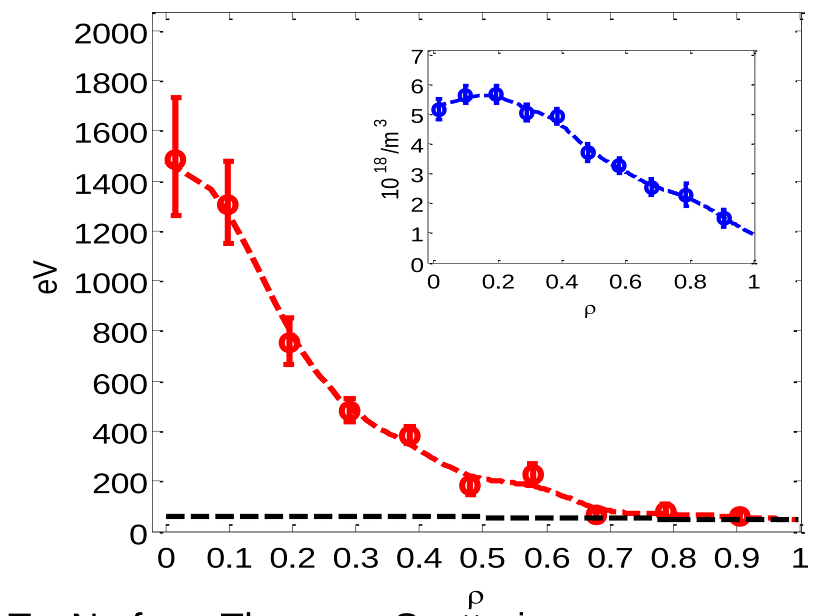
Pfirsch-Schlüter Current Rotates Helically

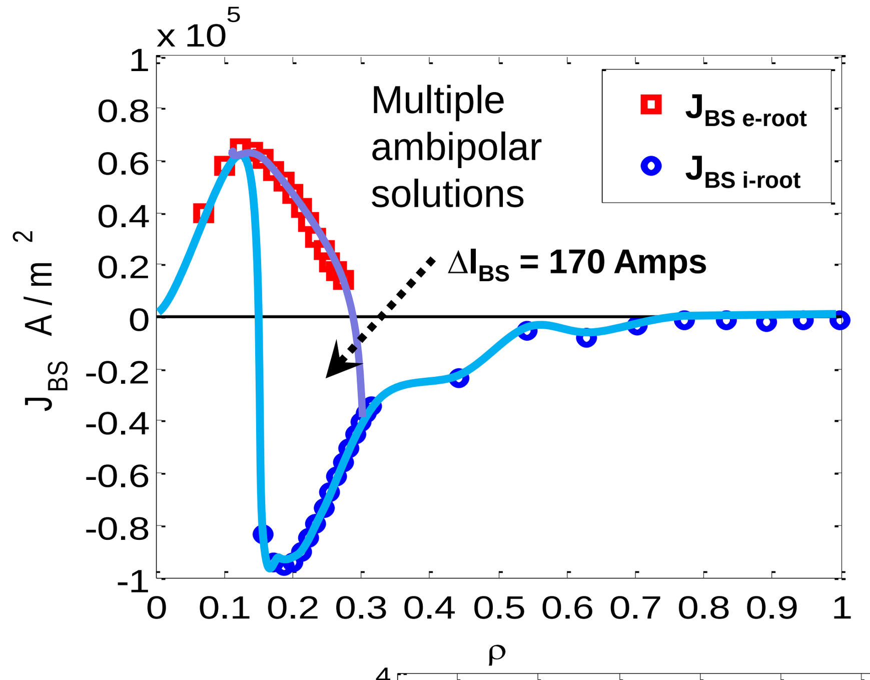
- Pfirsch-Schlüter current exhibits dipole behavior and rotates with |B| contours
- Sign of signals at two toroidal locations demonstrate a phase shift showing the helical rotation.
- Toroidal curvature is effectively eliminated in HSX

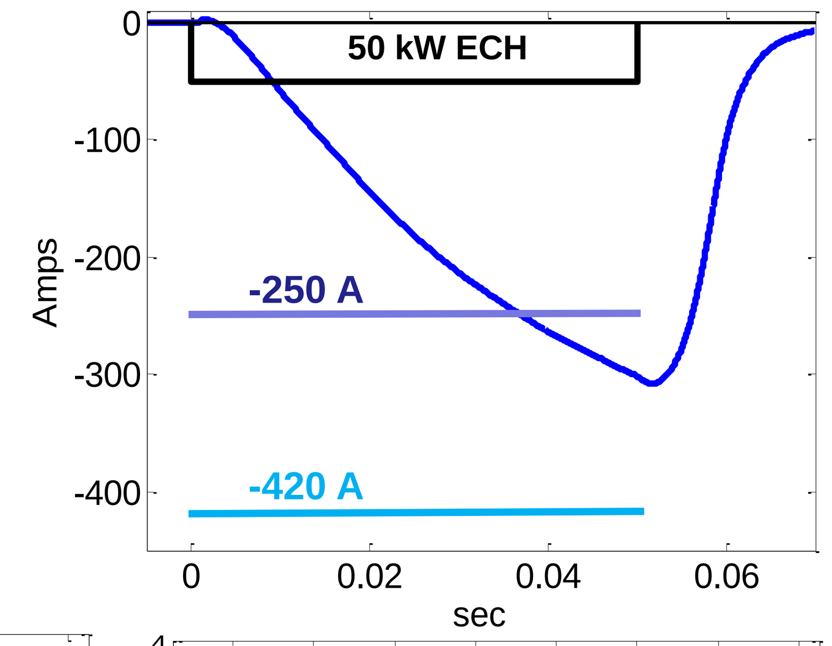




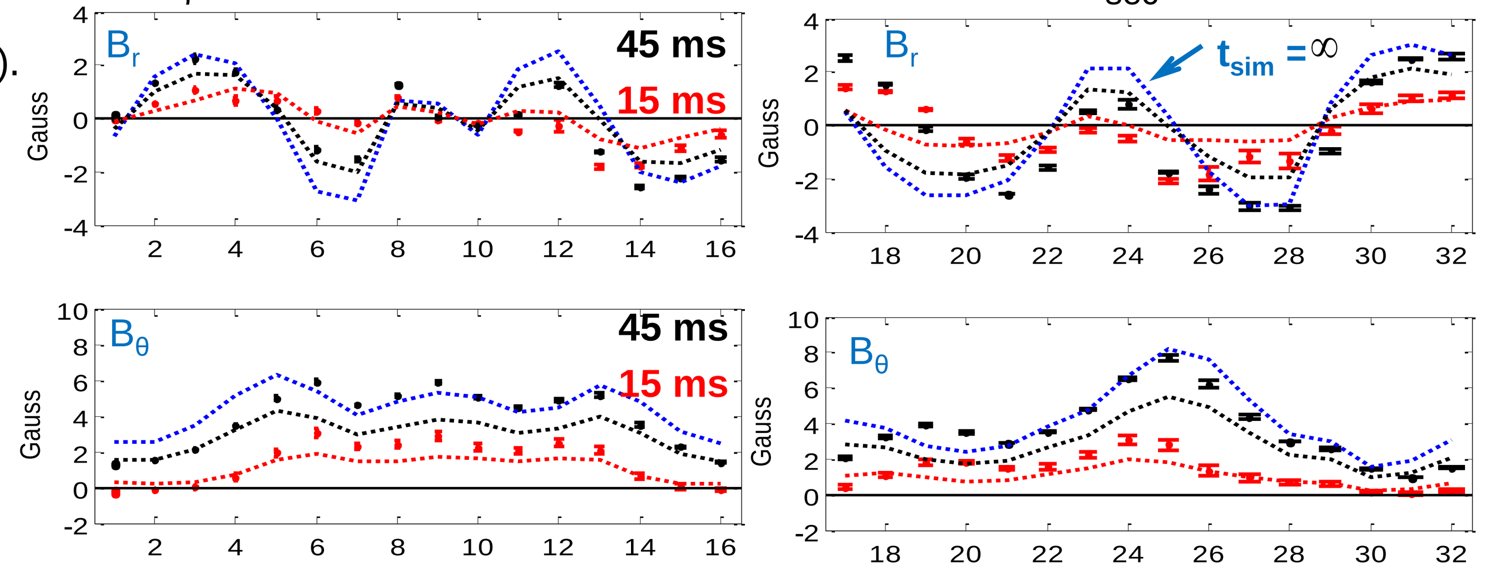
Bootstrap Current







- Te, Ne from Thomson Scattering.
- Ti from ChERS. Zeff ≈ 1 from Bremsstrahlung radiation (ChERS optics).
- PENTA[3] calculates the fluxes. E_r is determined by ambipolarity.
- The electron-root reverses the direction of the bootstrap current
- B_θ has large unidirectional contribution from <J·B>
- B_r is dominated by the m=2 structure of the vacuum vessel
- Measurement evolves slightly faster than simulated values
- Possible sources of error: Z_{eff}, initial plasma profiles, neoclassical calculation of bootstrap current



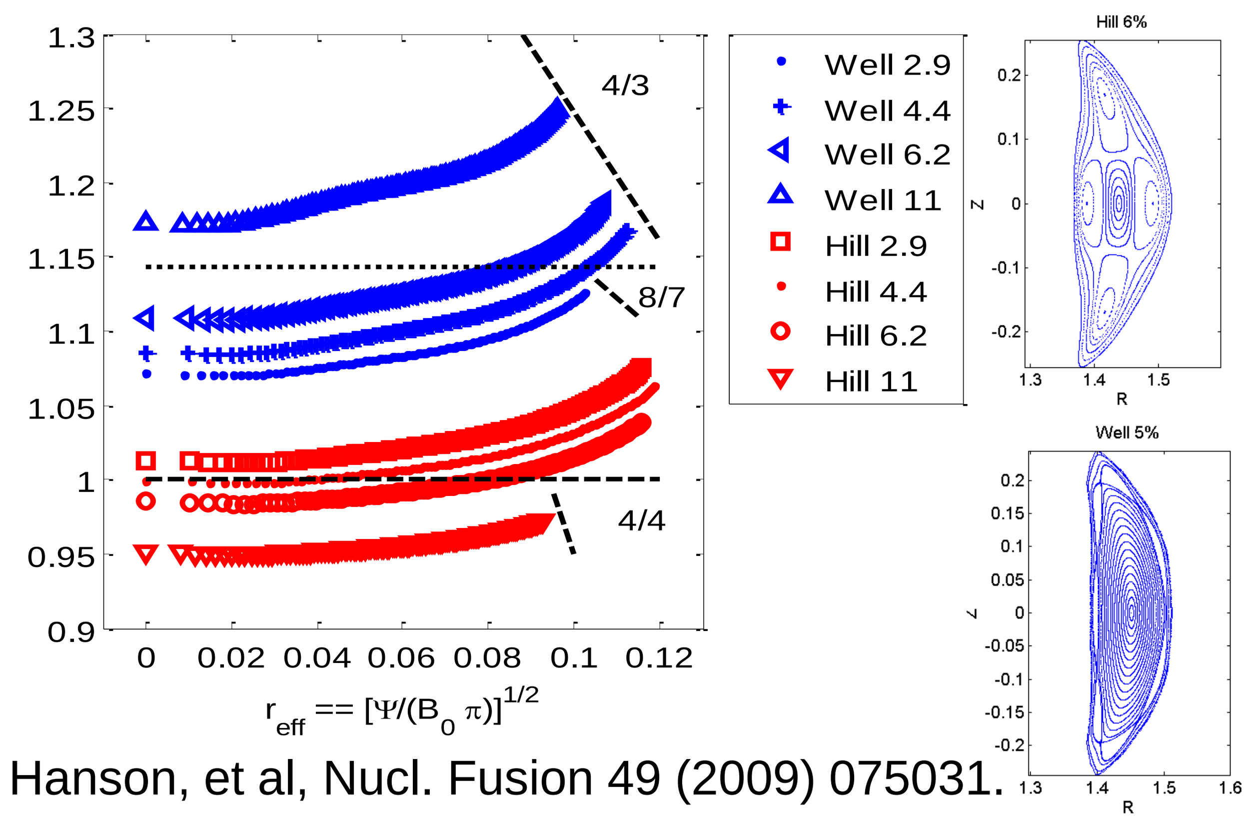
Summary + Future Plans

- The direction of the bootstrap current is reversed and reduced by ~1/3 compared to an equivalent tokamak. This results in a reduction in rotational transform.
- Evolving current profile is modeled by a diffusion equation with a 3d susceptance matrix.
- The Pfirsch-Schlüter current rotates with |B| contours and is reduced by ~1/3 compared to a tokamak, demonstrating the lack of toroidal curvature.

- V3FIT for equilibrium reconstruction of HSX plasmas.
- HSX can alter the magnetic spectrum with a set of auxiliary coils

  Mirror: The helical symmetry is spoiled by introducing (n,m) = (4,0) component (and harmonics) into magnetic spectrum, affecting equilibrium, bootstrap currents

  Well/Hill: Rotational transform profile may be raised/lowered, adjusting the location of rational surfaces, vacuum islands



[1] J.D. Hanson, et al, Nucl. Fusion 49 (2009) 075031.
[2] P. I. Strand and W. A. Houlberg, Phys. Plasmas 8, 2782 (2001).
[3] D.A. Spong, Phys. Plasmas 12, 056114 (2005).

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