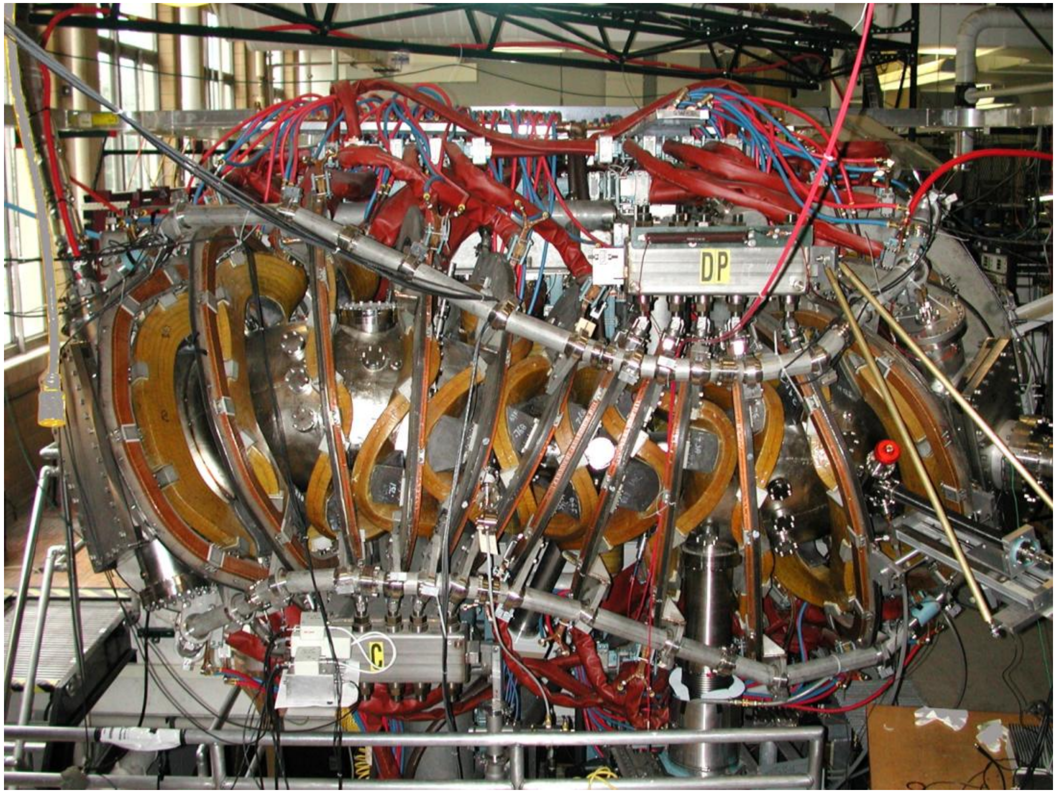
Modeling and Measurement of Toroidal Currents in the HSX Stellarator



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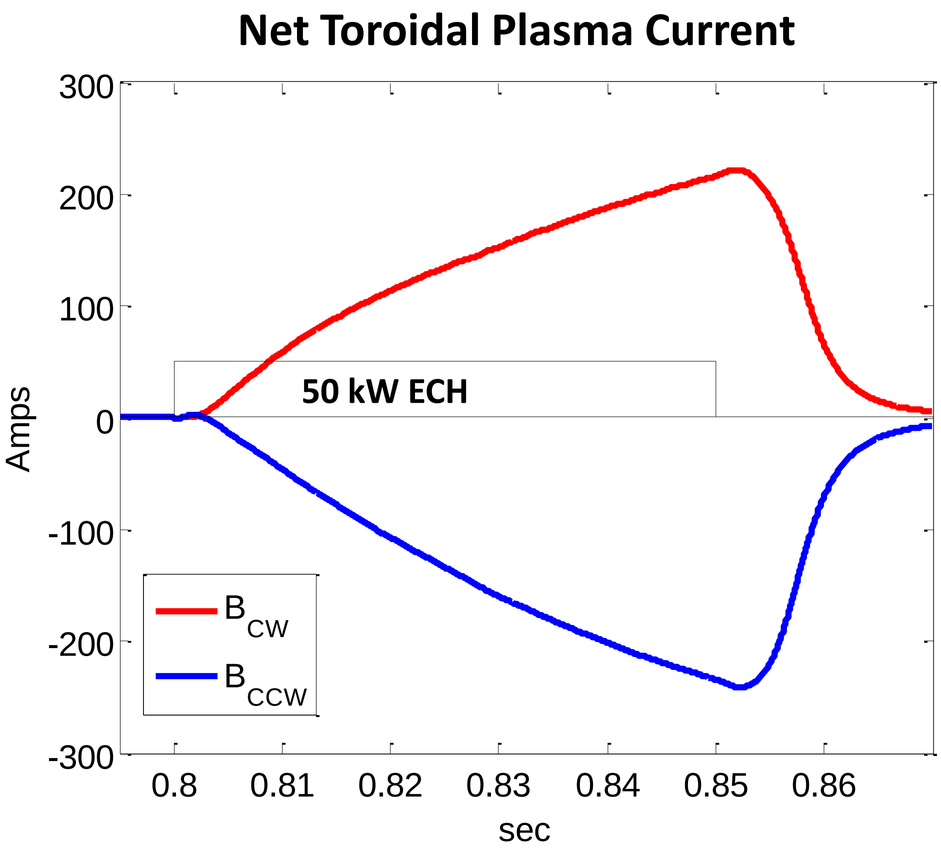
Toroidal current is bootstrap-driven

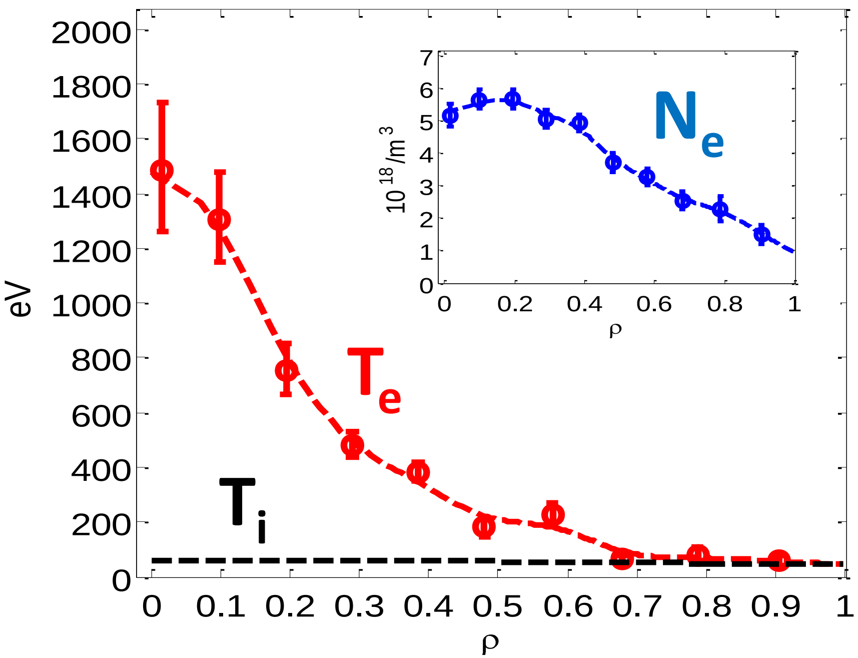
- Electron Cyclotron Resonance Heating
  - 1st Harmonic Ordinary-mode
  - Perpendicular launch
  - Little to no current drive seen during 1 Tesla campaign
- No ohmic drive
- Bootstrap current reverses with B-field direction
- Bootstrap current induces toroidal current with long decay times: $\tau_{\eta_{||}/\mu_0} \geq \tau_{EXP}$

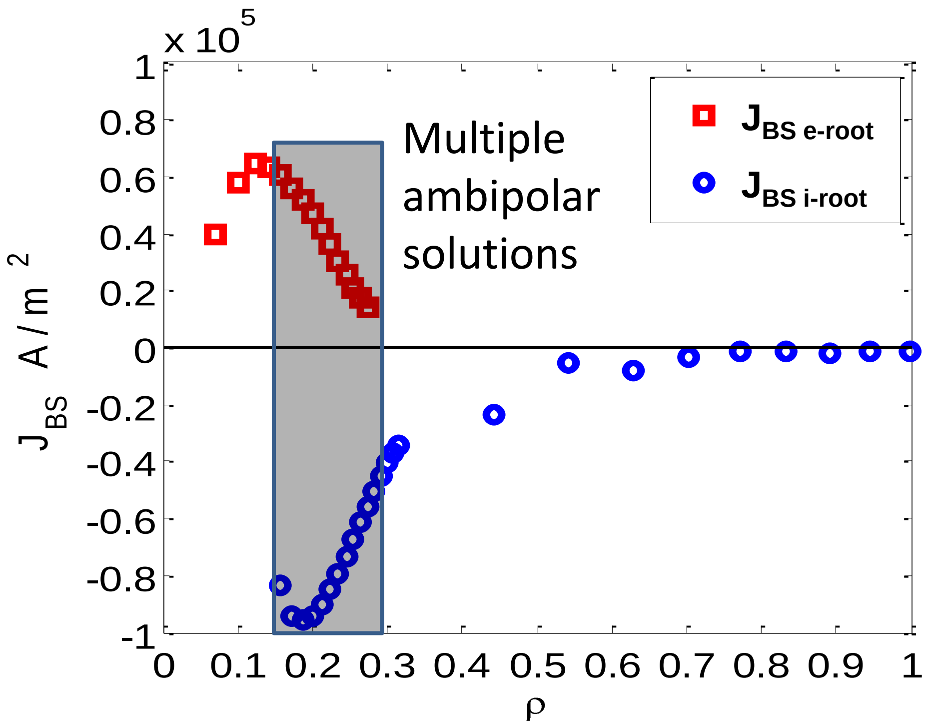


Equilibrium Currents with Quasi-Helical Symmetry

- Pfirsch-Schlüter current rotates with the |B| contours
- Bootstrap current is in the opposite direction and reduced compared to a tokamak
- The evolving current profile is modeled with a diffusion equation using a 3d susceptance matrix
- V3FIT calculates the expected signal response for an array of magnetic diagnostics. Next step includes using V3FIT for equilibrium reconstruction of HSX plasmas.

Bootstrap current depends on E_r

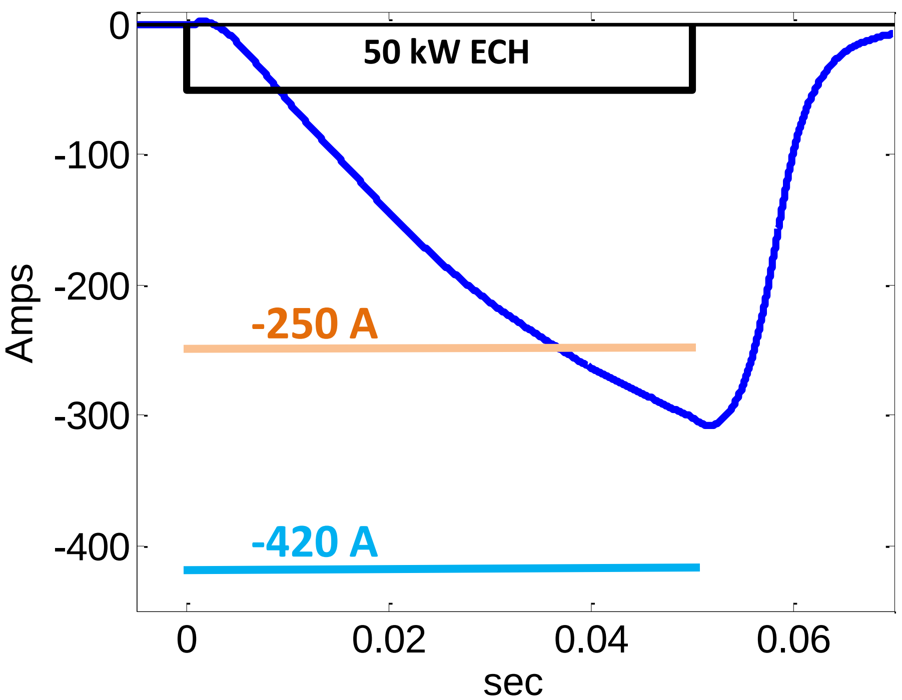


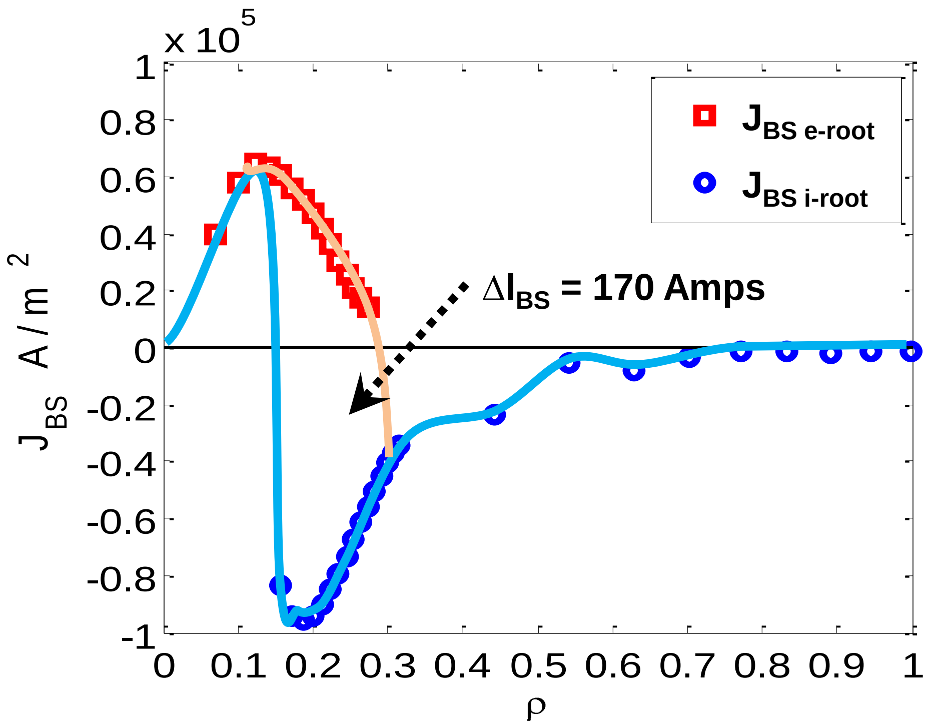


- Te, Ne from Thomson Scattering.
- Ti from ChERS. Zeff ≈ 1 from Bremsstrahlung radiation (ChERS optics).
- PENTA[1] calculates the fluxes. E_r is determined by ambipolarity.
- The electron-root reverses the direction of the bootstrap current

[1] D.A. Spong, Phys. Plasmas 12, 056114 (2005).

Toroidal current evolves during shot





If electron-root dominates: I_{BS} = -250 A

If ion-root dominates: I_{BS} = -420 A

The measured net current is between the predicted limits of the ion- and e-roots.

Modeling the Evolution of the Toroidal Current

- 3d susceptance matrix links toroidal and poloidal currents and magnetic fluxes[2]
  - $S_{12} = S_{21} = 0$ for Tokamaks
  - $S_{11} \approx S_{12} \approx S_{21}$ for HSX

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

- 1-D diffusion equation for rotational transform

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

Any non-inductive source

- Boundary conditions

Finite current density on axis: $\left.\frac{d\iota}{ds}\right|_{s=0} = 0$

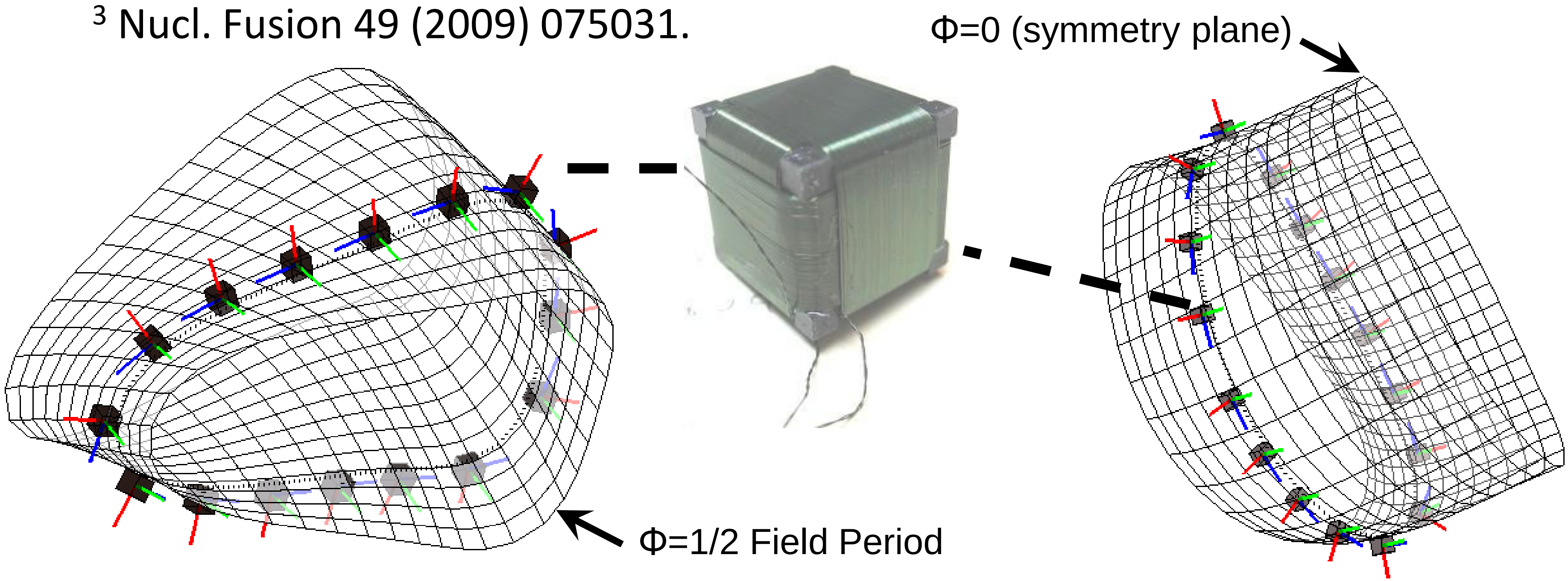
iota @ LCFS set by measurement: $\iota_{s=1} = \left(\frac{\mu_0 \mathrm{I}}{S_{11}\Phi'} - \frac{S_{12}}{S_{11}}\right)_{s=1}$

[2] P. I. Strand and W. A. Houlberg, Phys. Plasmas 8, 2782 (2001).

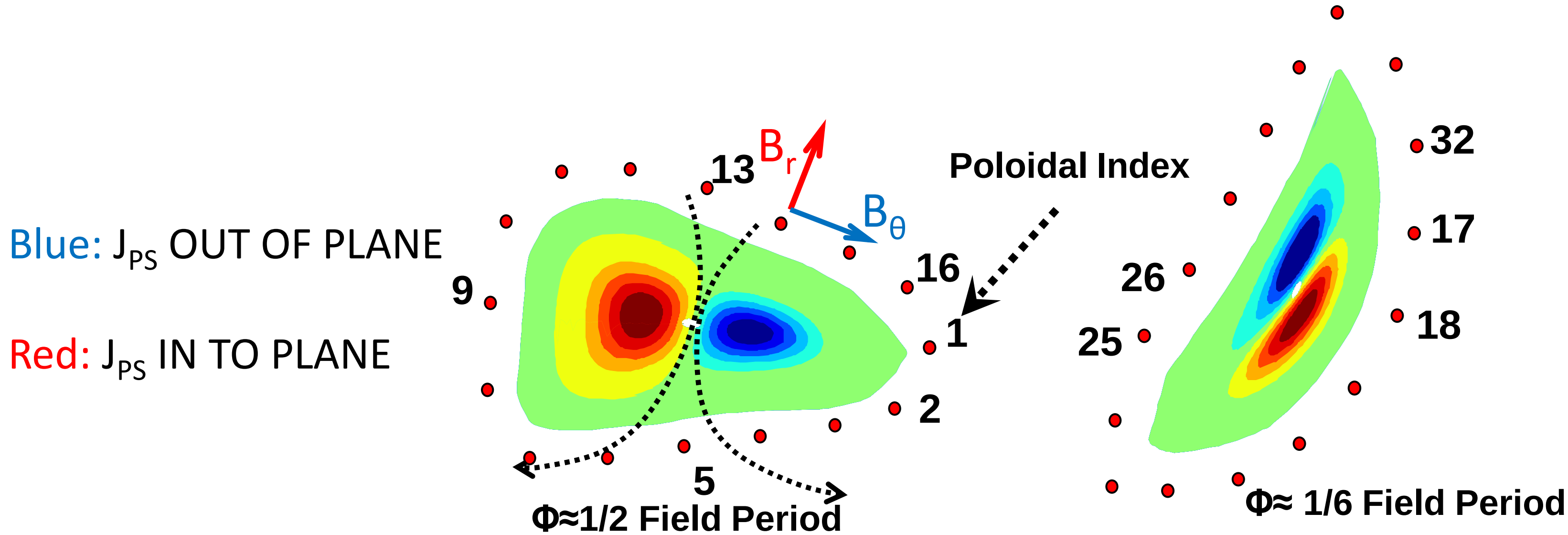
V3FIT[3] is Used to Calculate the Magnetic Diagnostics Signals

- Diagnostic set includes two Rogowski coils, two flux loops and 32 d**B**/dt sensors
- Thanks to James Hanson and Steve Knowlton for the assistance in using V3FIT
- See J.Hanson, I14, Tuesday 11:15, “Three-dimensional Equilibrium Reconstruction: the V3FIT Code.”

[3] Nucl. Fusion 49 (2009) 075031.



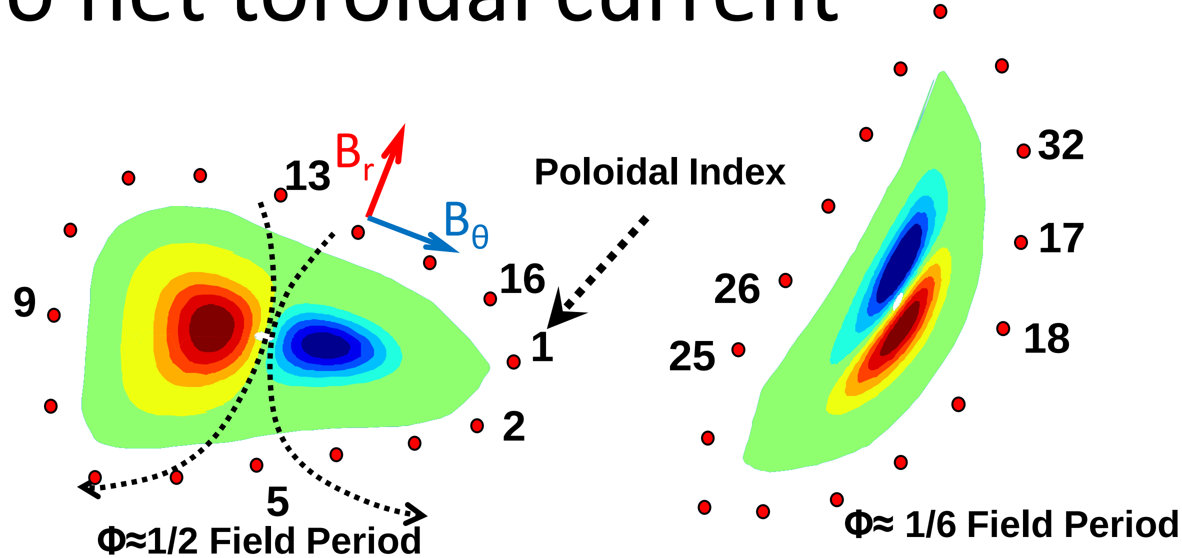
The Pfirsch-Schlüter current rotates helically

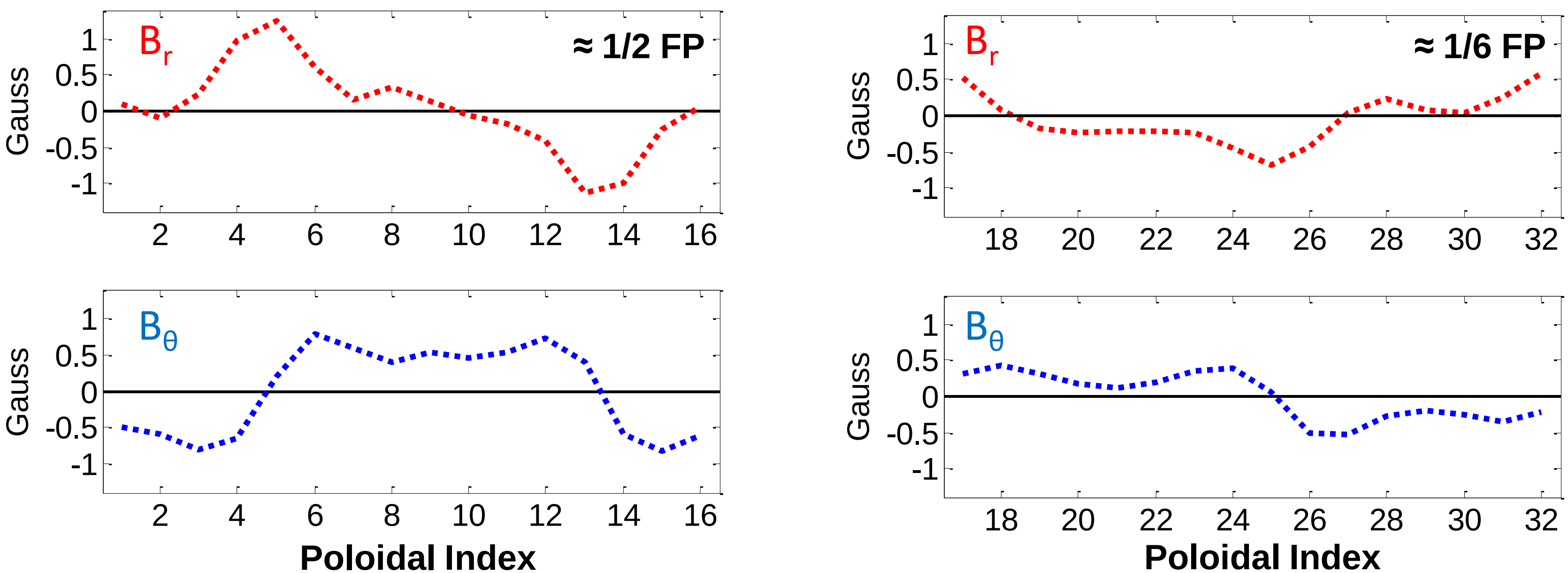


- The plasma pressure profile is calculated and used in V3FIT to find the magnetic response due to the Pfirsch-Schlüter current.
- The net toroidal current is set to 0.

A ‘dipole-like’ response is predicted for the case of no net toroidal current

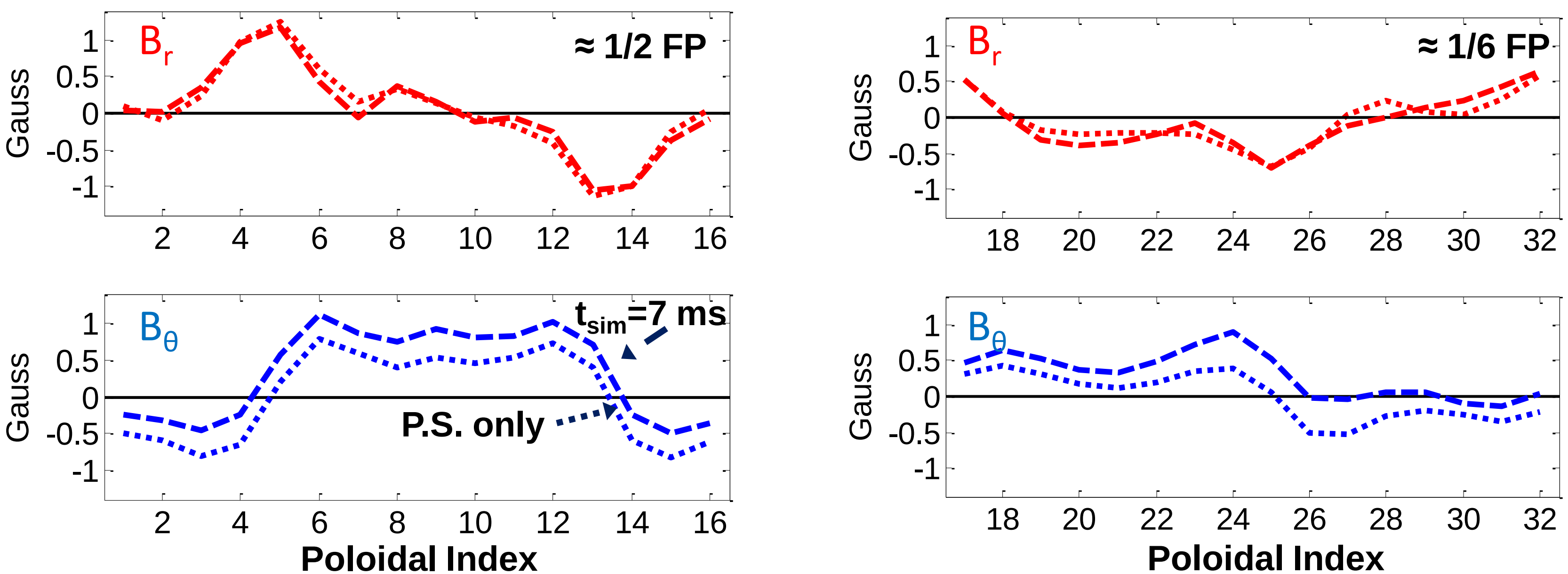
The sign of the signals at the two toroidal locations demonstrate a phase shift showing the helical rotation.





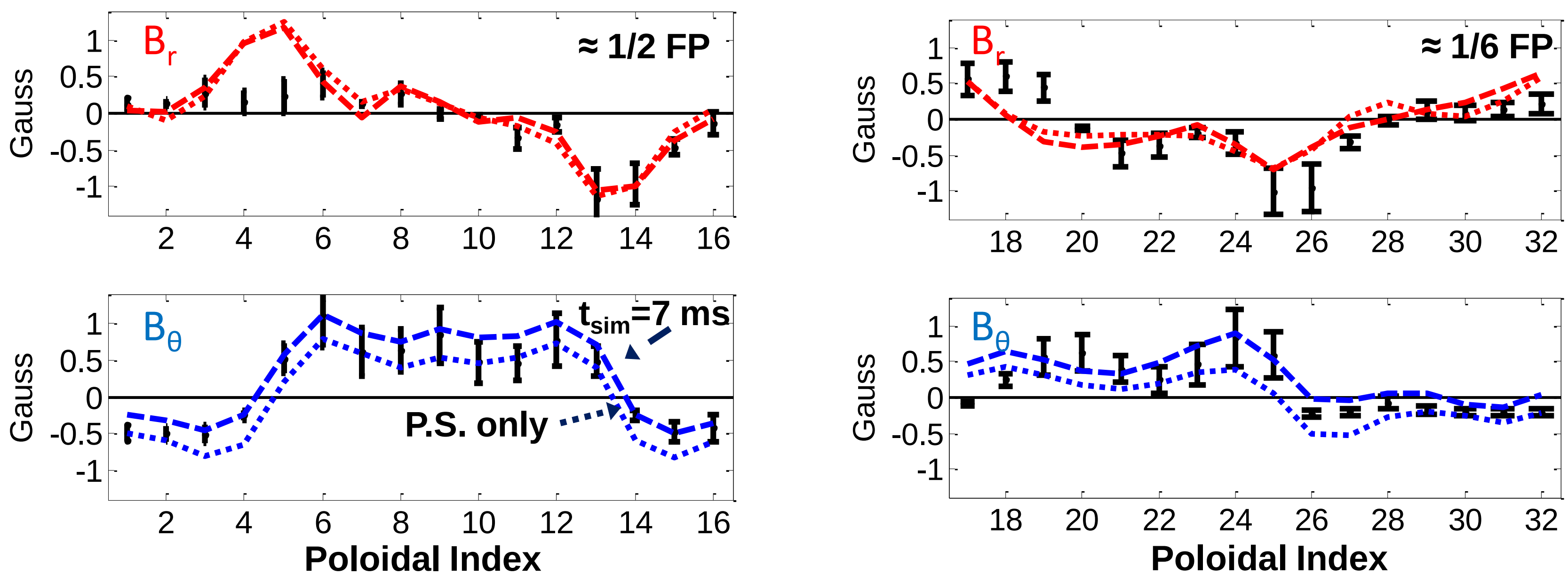
Bootstrap Current Contributes Little to B_r Early in Shot

- The toroidal current profile is simulated in time and the diagnostic response is predicted with V3FIT
- A small net toroidal current (30 A) contributes to the B_θ component



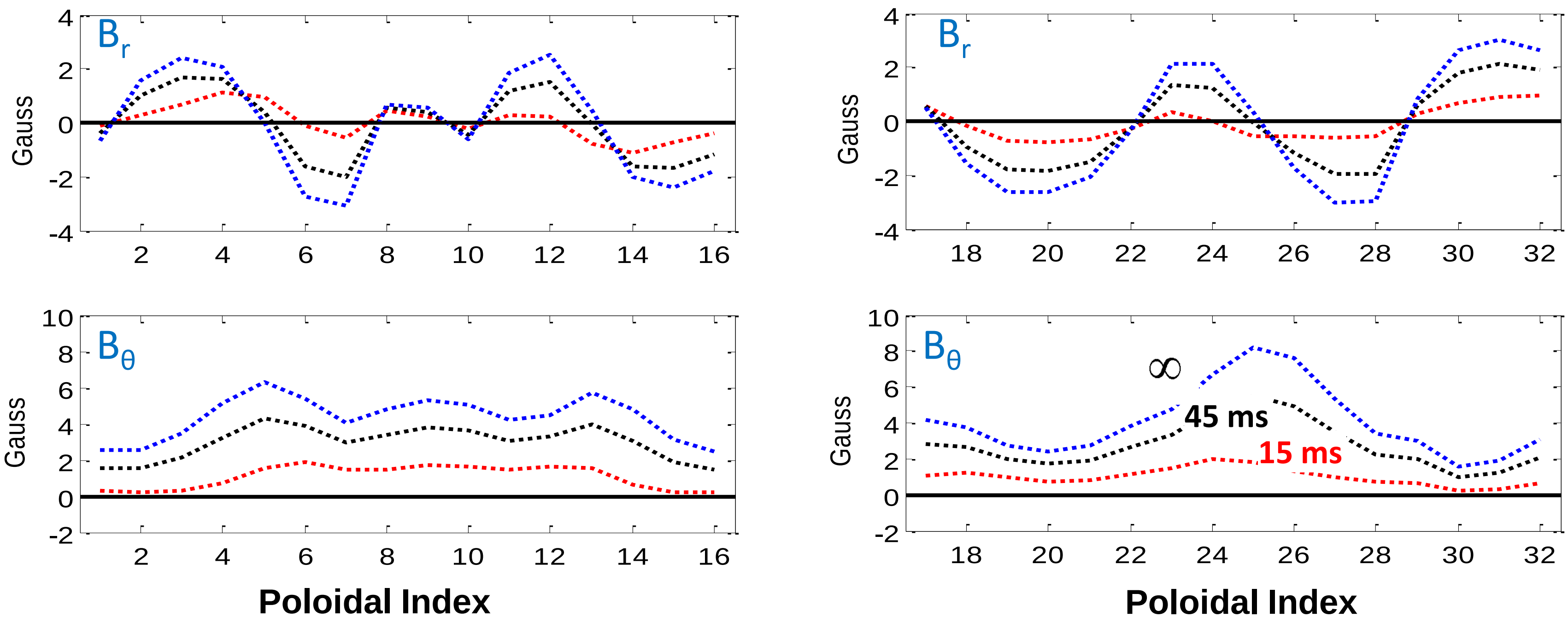
Confirmation of the Helical Rotation of the Pfirsch-Schlüter Current

- The experimental signals from t_{ave}=(3ms–7ms) agree well with theory in terms of the sign and phase.
- Good agreement in magnitude. Reconstruction with V3FIT may resolve the differences.



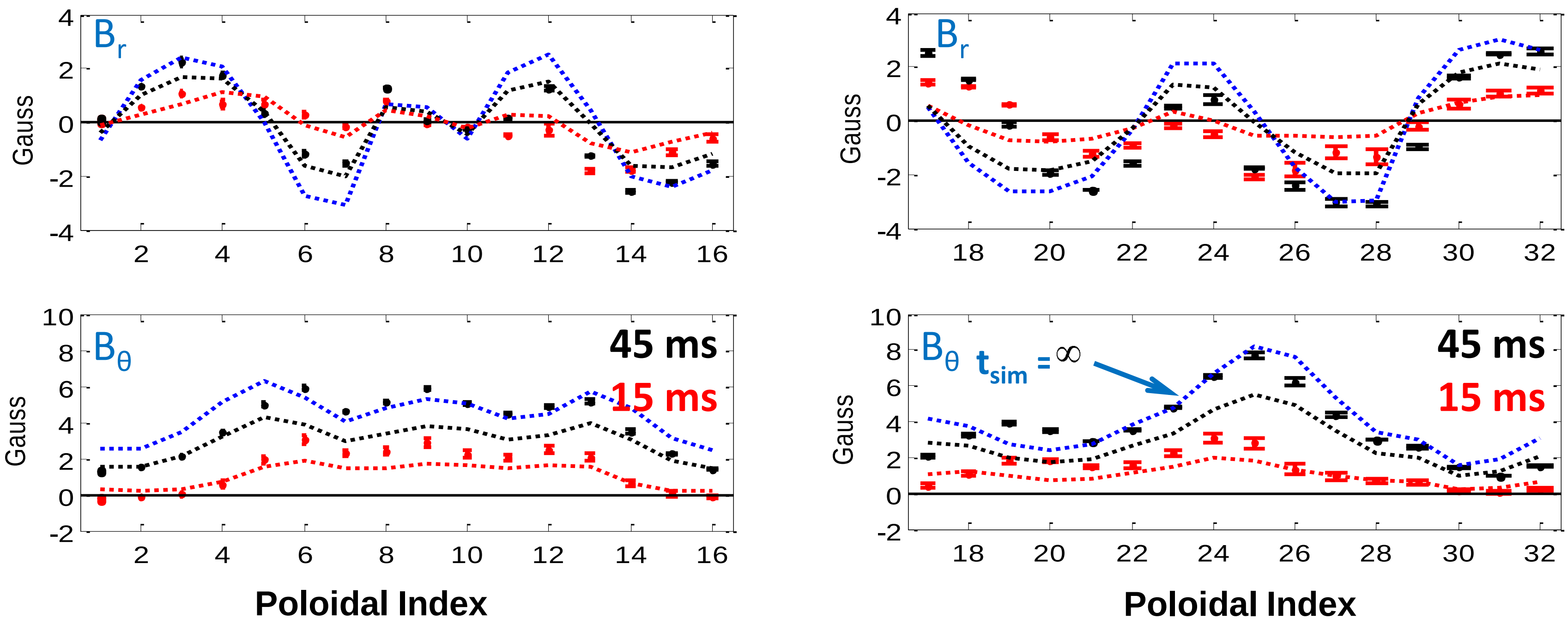
Later in Time, the Largest Signals are from Bootstrap Current

- Simulated profiles at 15ms, 45ms and ∞ are used in V3FIT
- B_θ has large unidirectional contribution from <J·B>
- B_r is dominated by the m=2 structure of the vacuum vessel



Measured B_θ shows increasing offset due to bootstrap current evolution

- Measurement evolves slightly faster than simulated values
- Possible sources of error: Zeff, initial plasma profiles, neoclassical calculation of bootstrap current



Toroidal Currents with Quasi-Helical Symmetry

- The direction of the bootstrap current is reversed and reduced by ~1/3 compared to an equivalent tokamak (same iota, R_{major}, r_{minor}). This results in a reduction in rotational transform.
- The evolving current profile is modeled with a diffusion equation using a 3d susceptance matrix
- Expected magnetic diagnostic signal are calculated with V3FIT
- The Pfirsch-Schlüter current rotates with |B| contours and is reduced by ~1/3 compared to a tokamak, demonstrating the lack of toroidal curvature.
- Future work includes using V3FIT for equilibrium reconstruction