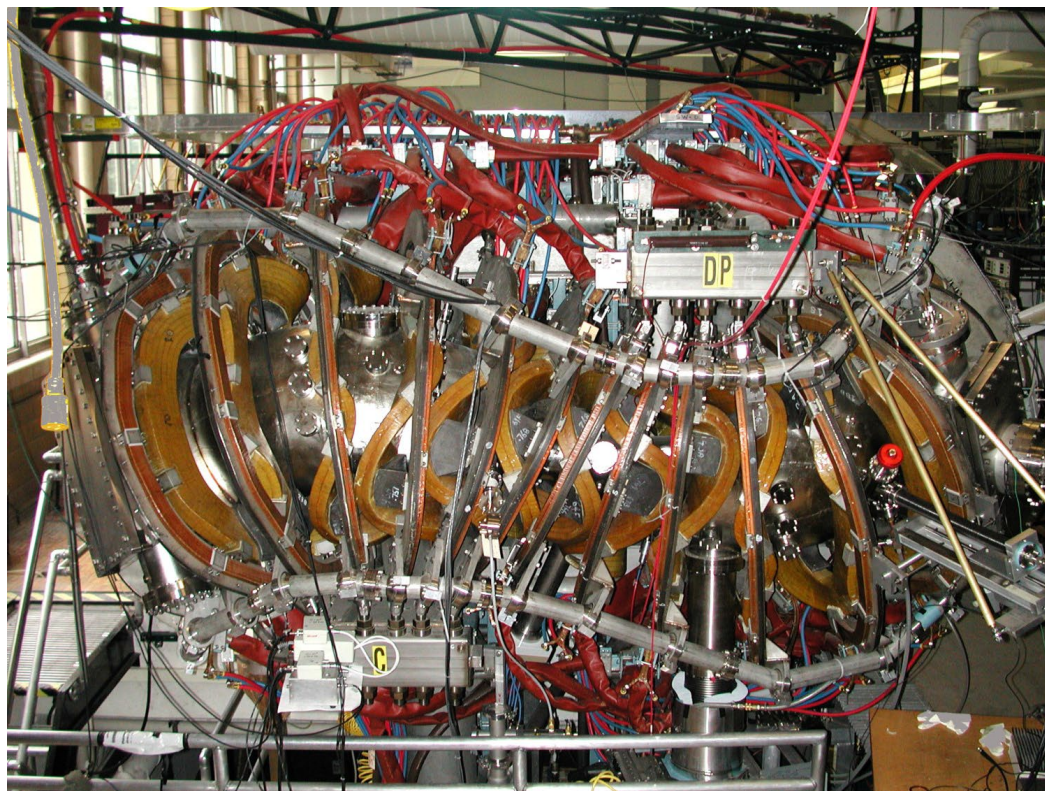


Modeling and Measurement of Toroidal Currents in the HSX Stellarator



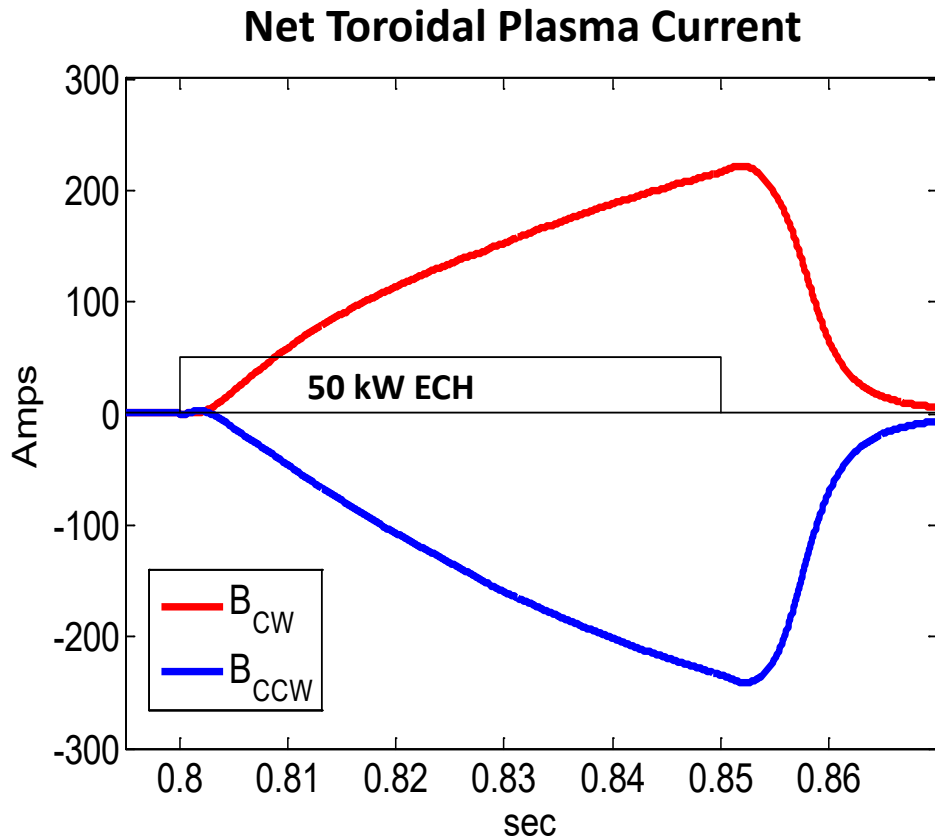
J.C. Schmitt, J.N. Talmadge, J.Lore

17th International Stellarator/Heliotron Workshop

12-16 October, 2009 Princeton, New Jersey

Toroidal current is bootstrap-driven

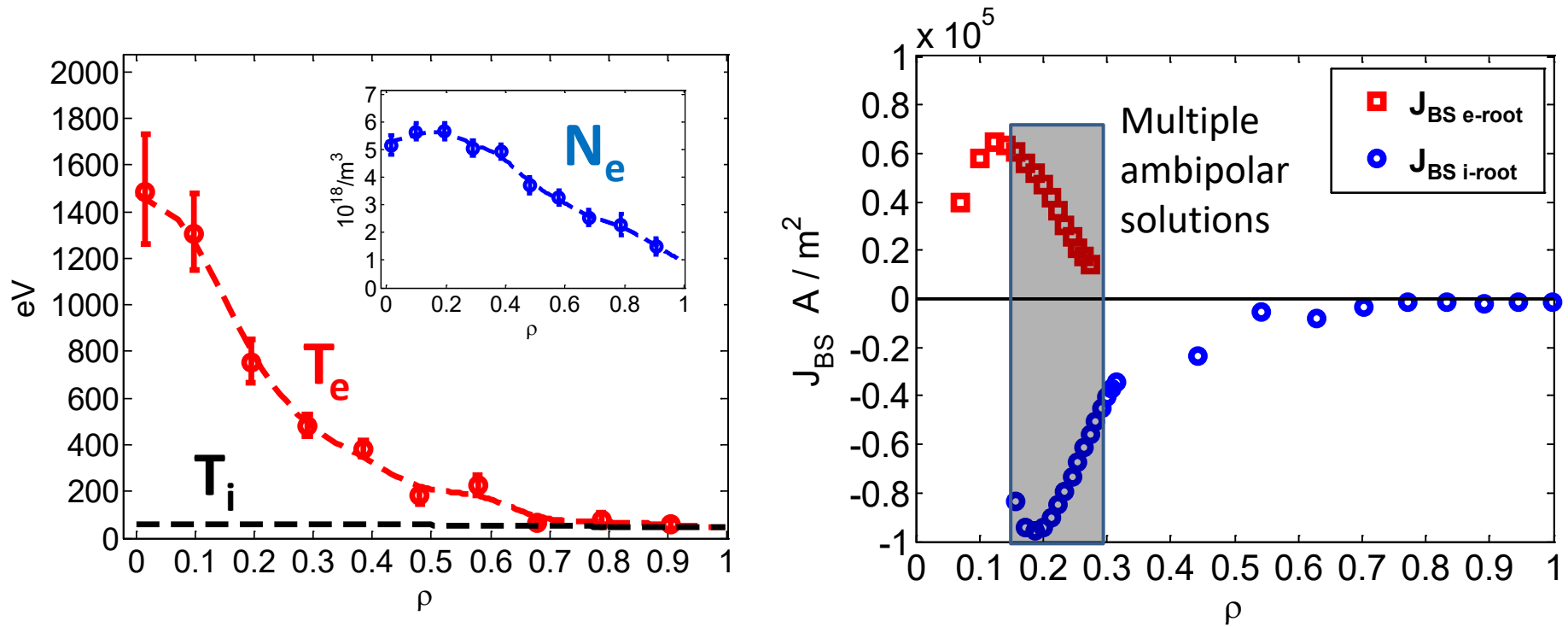
- Electron Cyclotron Resonance Heating
 - 1st Harmonic Ordinary-mode
 - Perpendicular launch
 - Little to no current drive seen during 1 Tesla campaign
- No ohmic drive
- Bootstrap current reverses with B-field direction
- Bootstrap current induces toroidal current with long decay times: $\tau_{\eta_{||}}/\mu_0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



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.

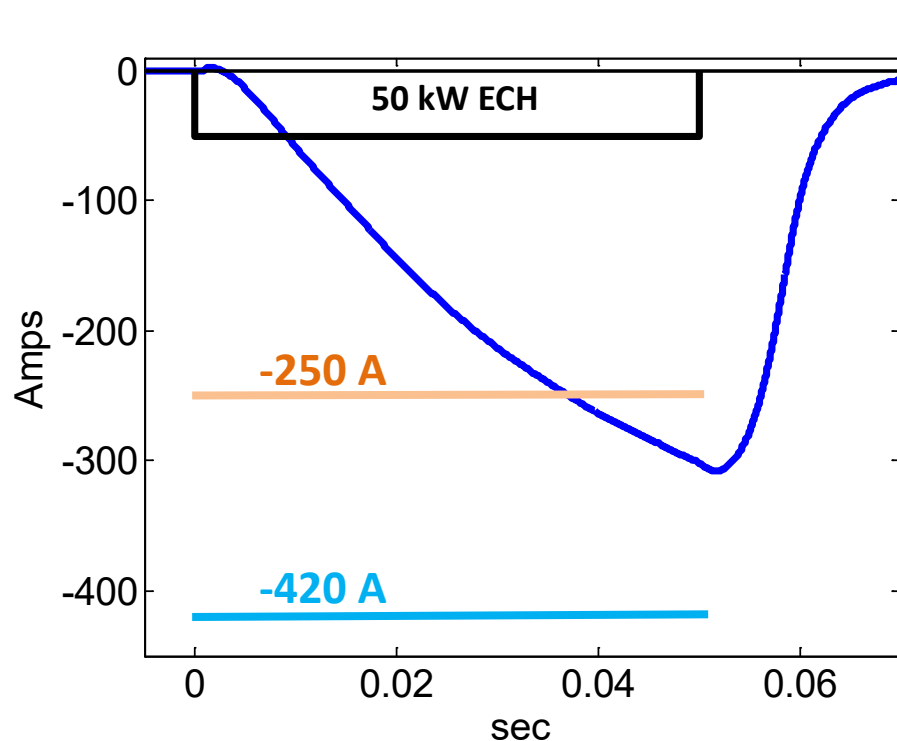
Bootstrap current depends on E_r



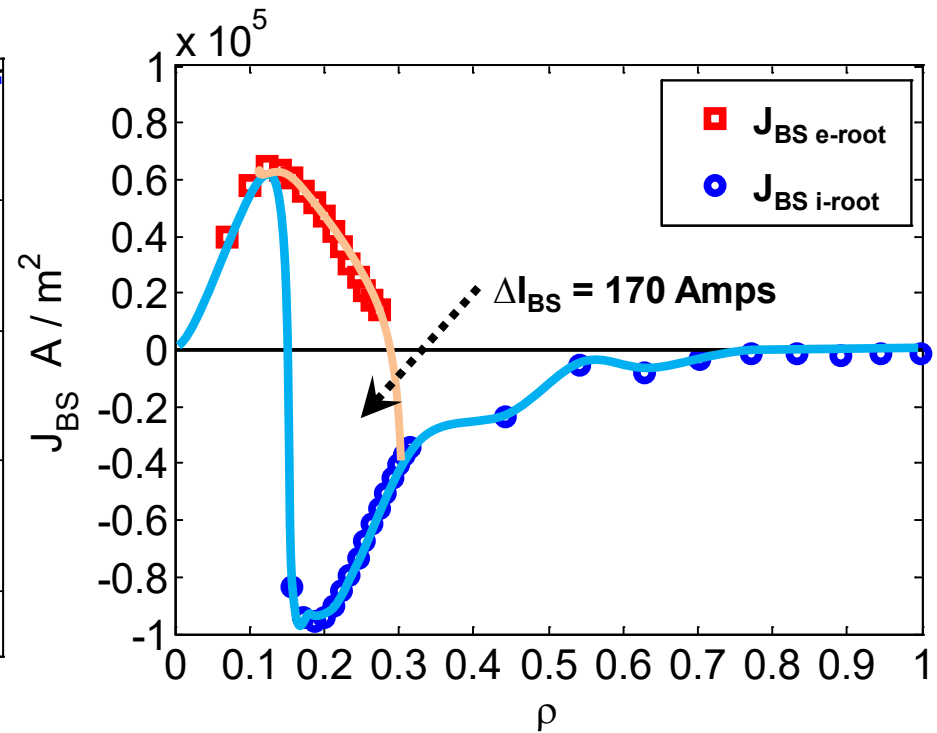
- T_e , N_e from Thomson Scattering.
- T_i from ChERS. $Z_{eff} \approx 1$ from Bremsstrahlung radiation (ChERS optics).
- PENTA¹ calculates the fluxes. E_r is determined by ambipolarity.
- The electron-root reverses the direction of the bootstrap current

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 fluxes²

– $S_{12} = S_{21} = 0$ 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

$$s = \Phi / \Phi_a \quad \frac{dt}{ds} = \frac{1}{\Phi_a^2} \frac{d}{ds} \left(\eta_{\parallel} V' \left[\frac{\langle B^2 \rangle}{\mu_0} \frac{d}{ds} (S_{11}t + S_{12}) + p' (S_{11}t + S_{12}) - \langle \mathbf{J}_{NI} \cdot \mathbf{B} \rangle \right] \right)$$

- Boundary conditions

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

Any non-inductive source

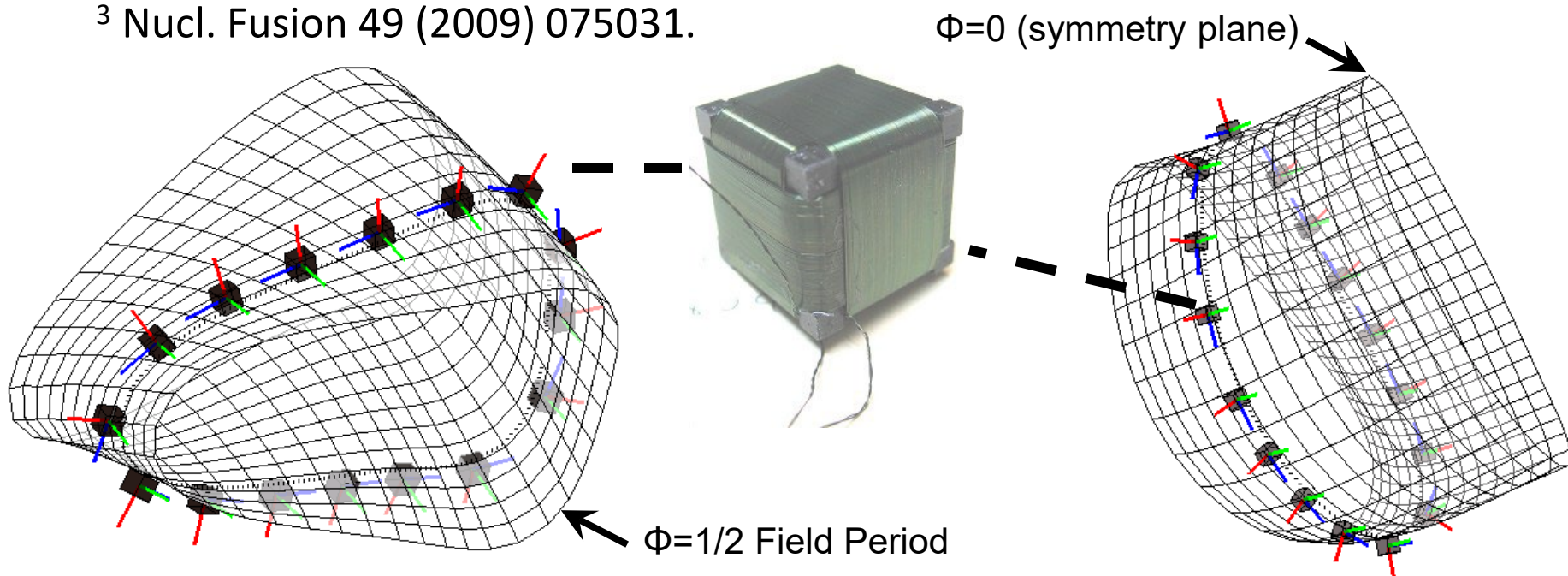
iota @ LCFS set by measurement: $t_{s=1} = \left(\frac{\mu_0 I}{S_{11} \Phi'} - \frac{S_{12}}{S_{11}} \right)_{s=1}$

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

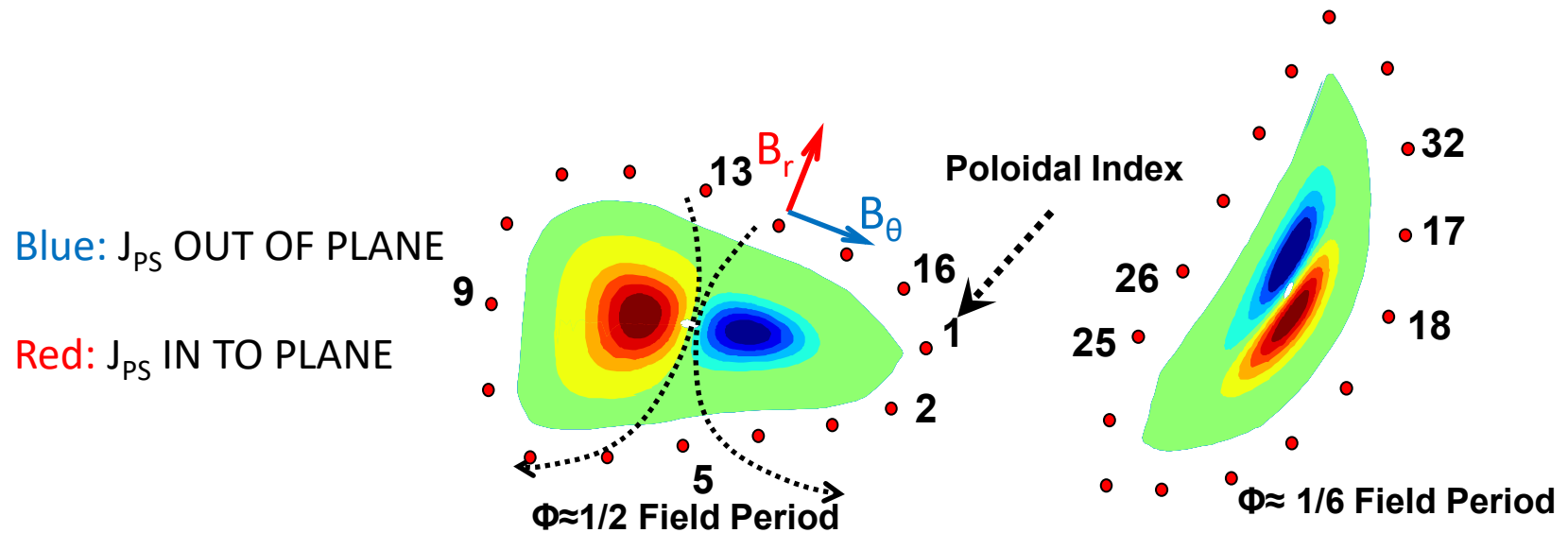
V3FIT³ is Used to Calculate the Magnetic Diagnostics Signals

- Diagnostic set includes two Rogowski coils, two flux loops and 32 $d\mathbf{B}/dt$ 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.



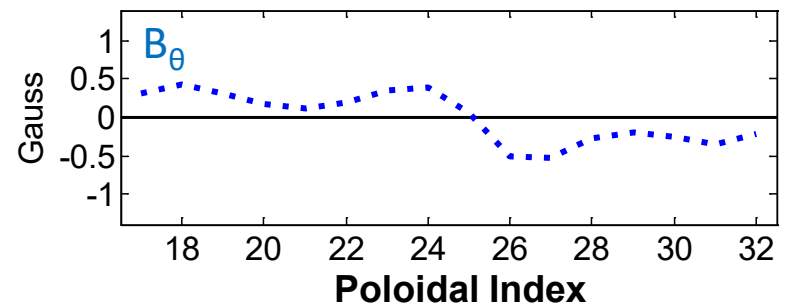
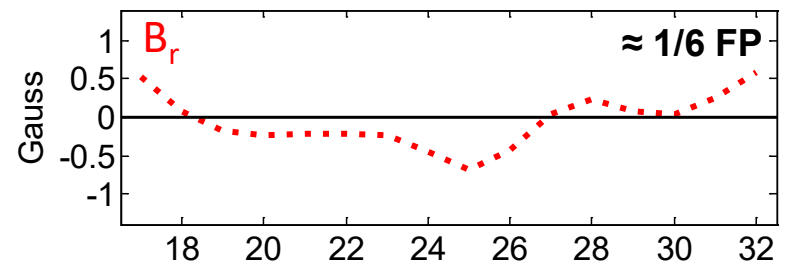
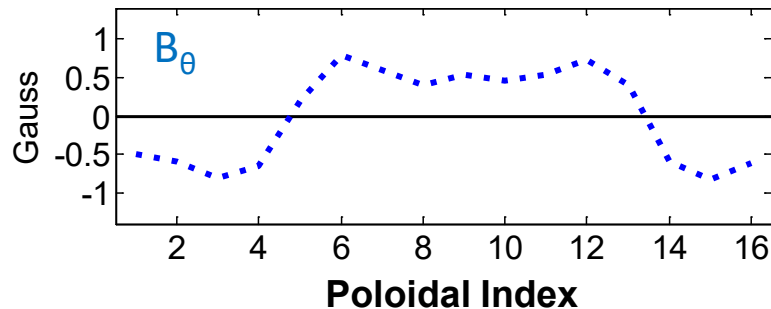
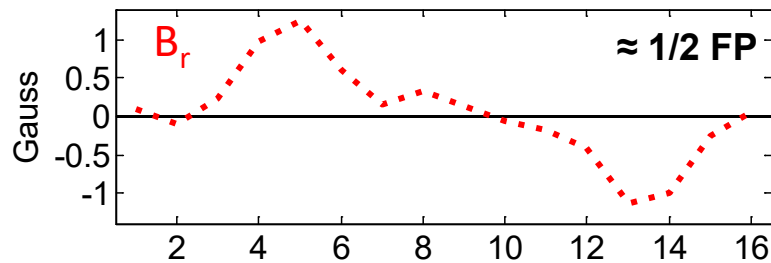
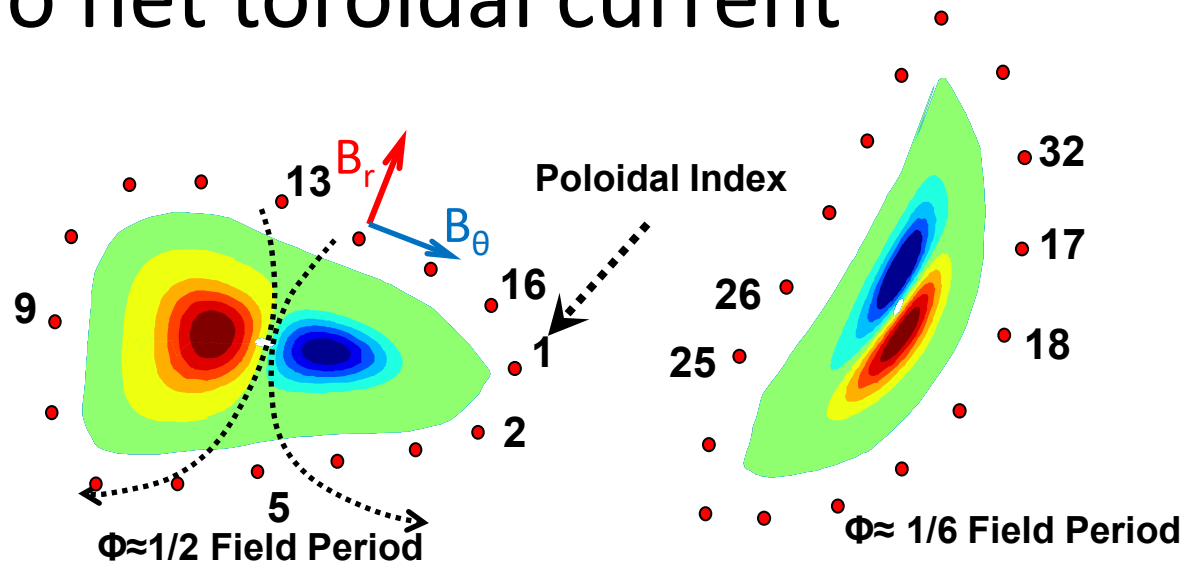
The Pfirsch-Schlüter current rotates helically



- 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.

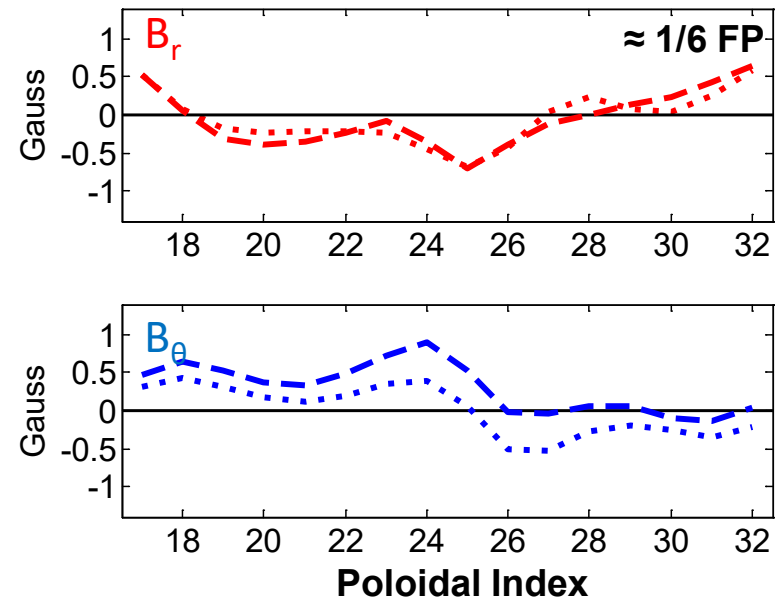
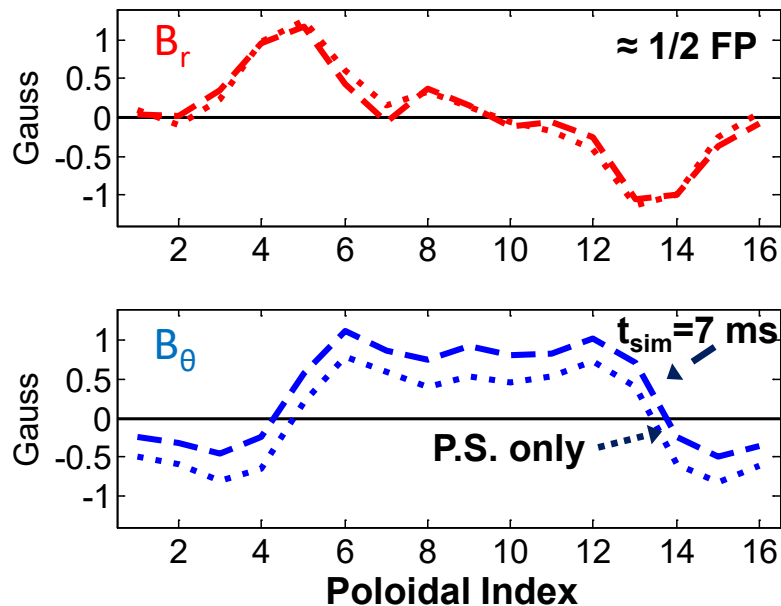
A 'dipole-like' response is predicted for the case of no net toroidal current

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



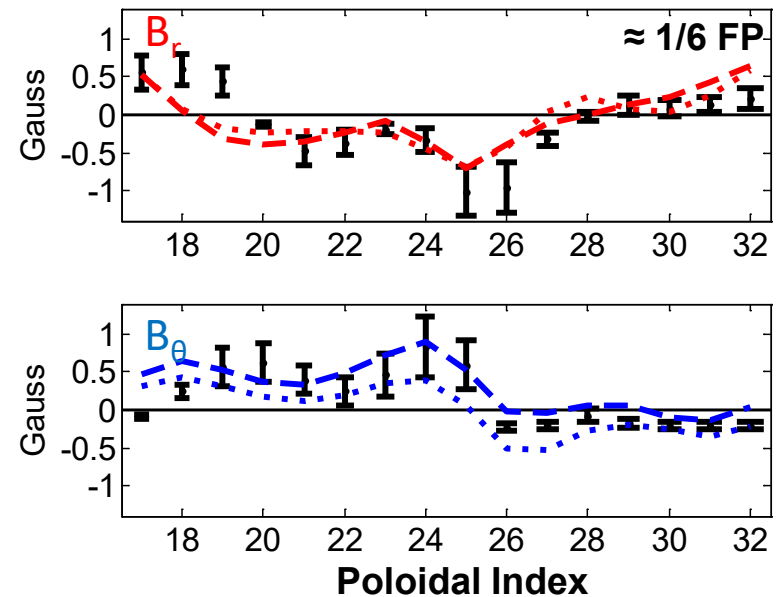
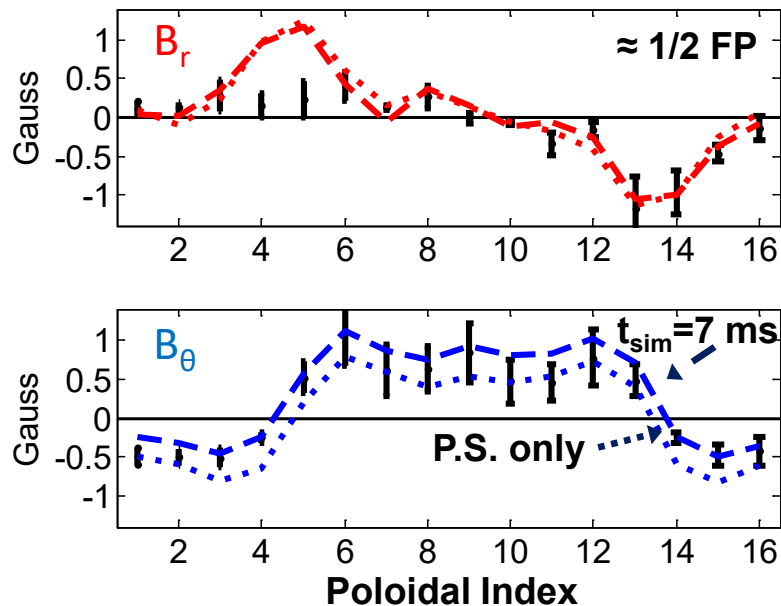
Bootstrap Current Contributes Little to B_r Early in Shot

- 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



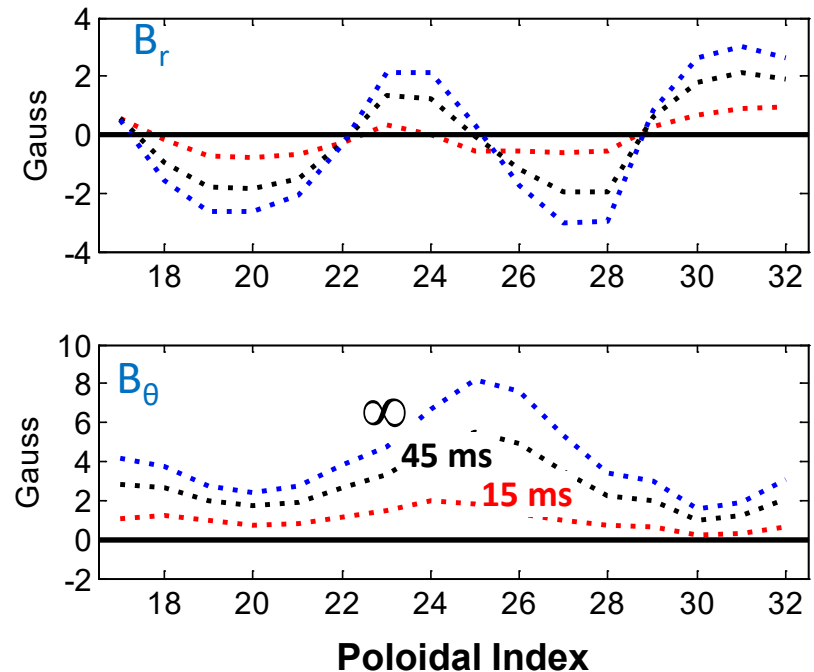
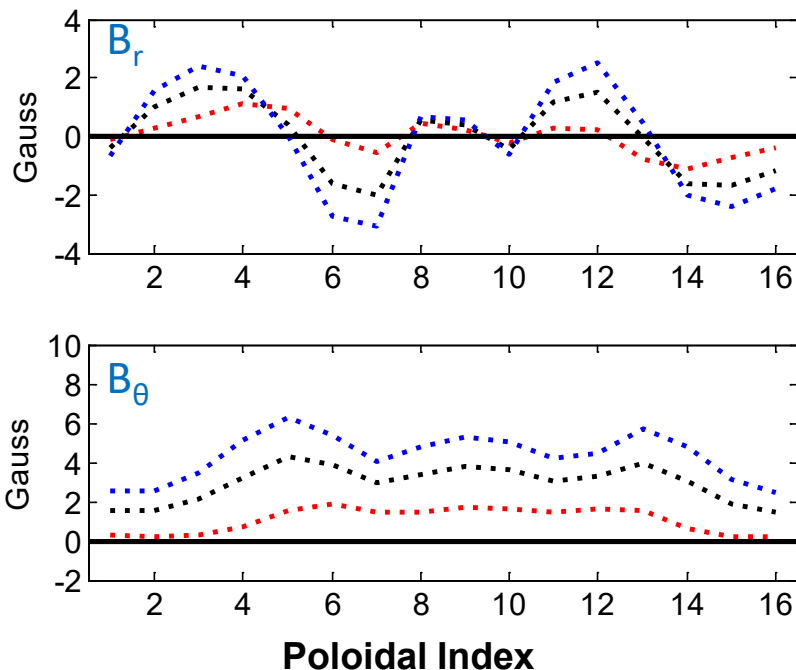
Confirmation of the Helical Rotation of the Pfirsch-Schlüter Current

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



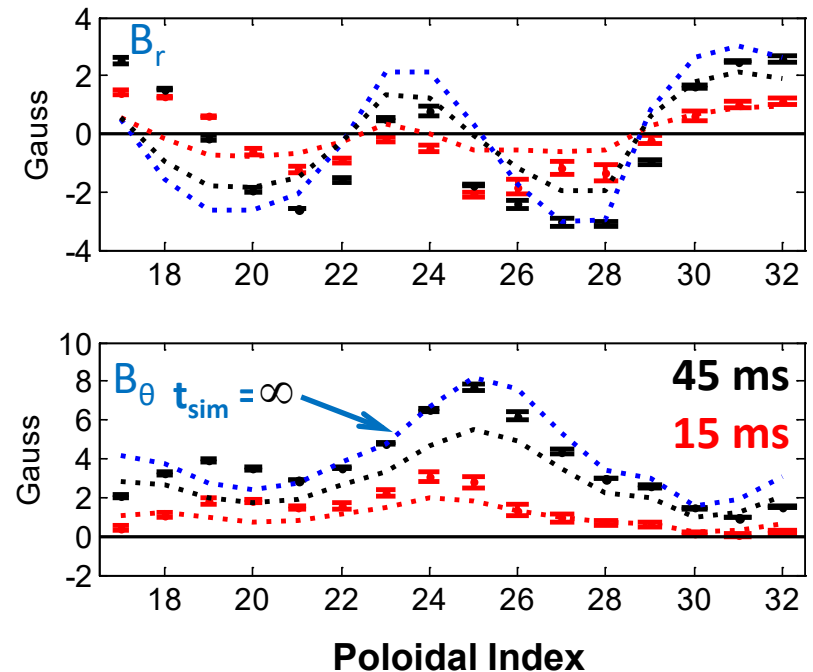
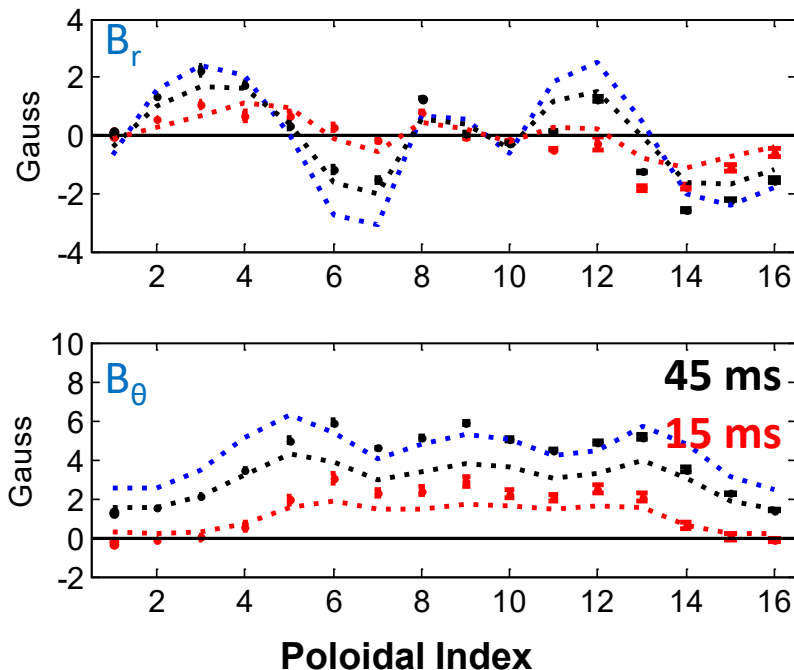
Later in Time, the Largest Signals are from Bootstrap Current

- Simulated profiles at 15ms, 45ms and ∞ are used in V3FIT
- B_θ has large unidirectional contribution from $\langle J \cdot B \rangle$
- 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: Z_{eff} , 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 $\sim 1/3$ compared to an equivalent tokamak (same i_{ota} , 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 signals are calculated with V3FIT
- The Pfirsch-Schlüter current rotates with $|B|$ contours and is reduced by $\sim 1/3$ compared to a tokamak, demonstrating the lack of toroidal curvature.
- Future work includes using V3FIT for equilibrium reconstruction