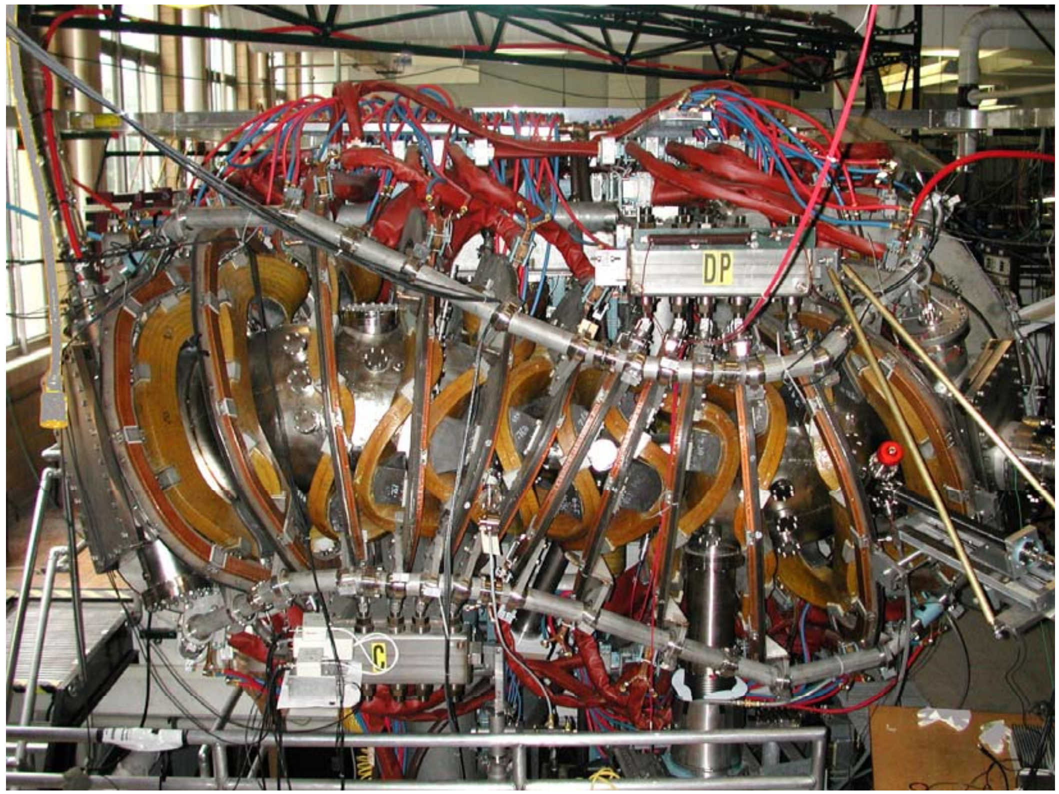
Measurement, Reconstruction and Modeling of Equilibrium Currents in the HSX Stellarator



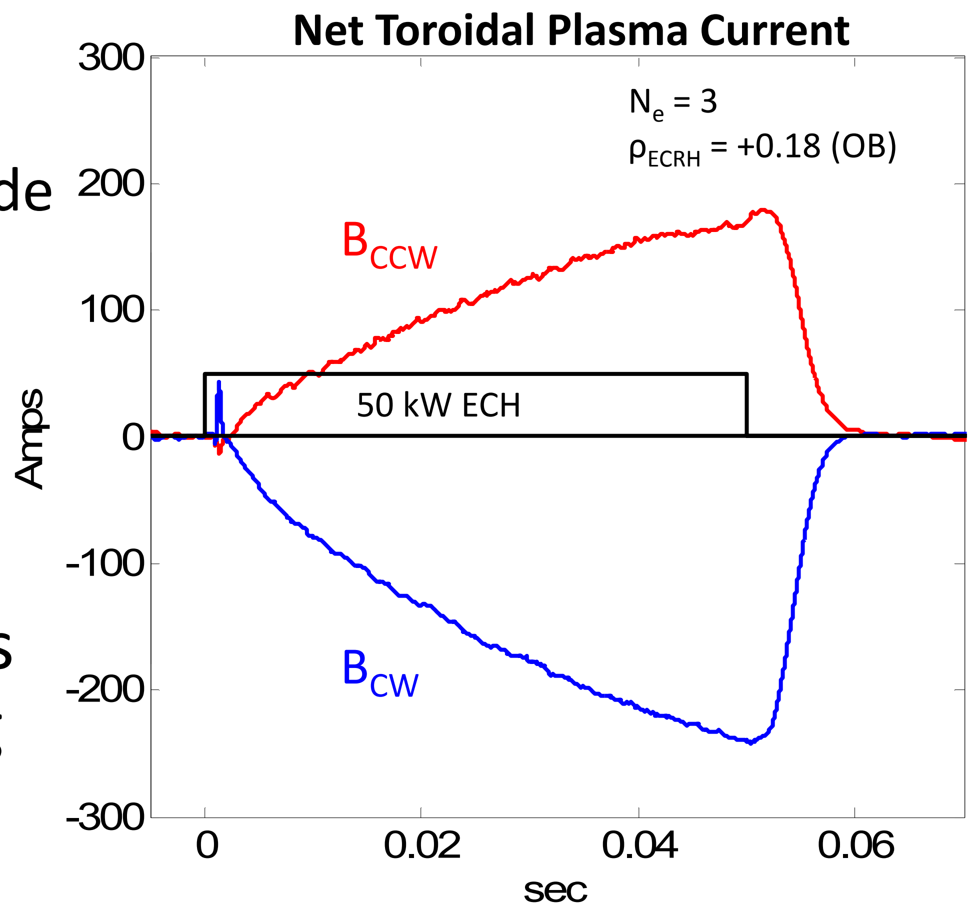
J.C. Schmitt, J.N.Talmadge, J.Lore

15TH WORKSHOP ON MHD STABILITY CONTROL

15-17 November, 2010 Madison, WI

Toroidal current is predominantly bootstrap-driven

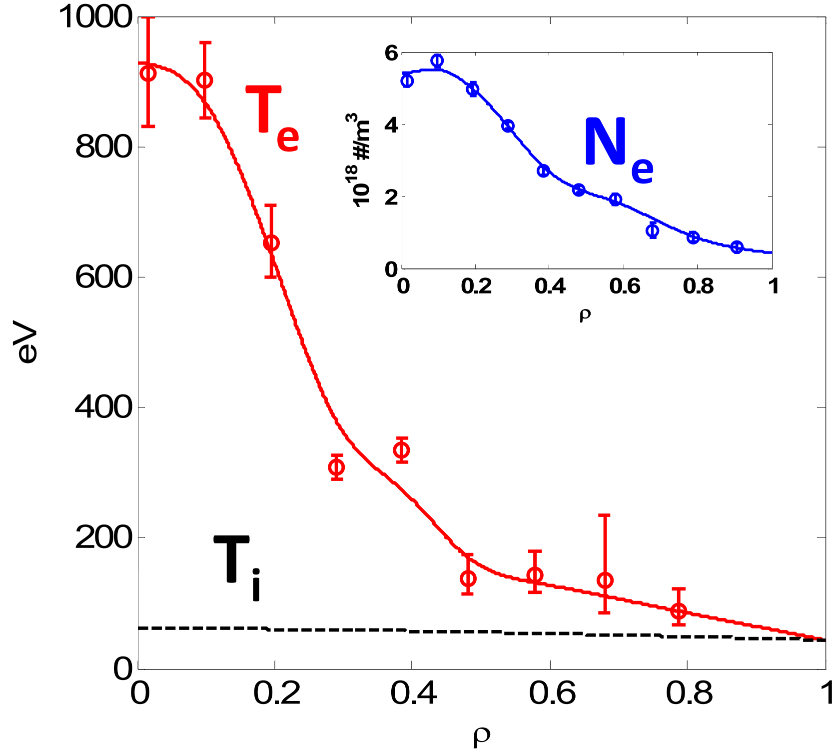
- Electron Cyclotron Resonance Heating
  - 1^{st} Harmonic Ordinary-mode
  - Perpendicular launch
- No ohmic drive
- Toroidal current reverses with B-field direction
- Bootstrap current induces toroidal current with long decay times: $\tau_{\eta_{||}/\mu_0} \geq \tau_{EXP}$

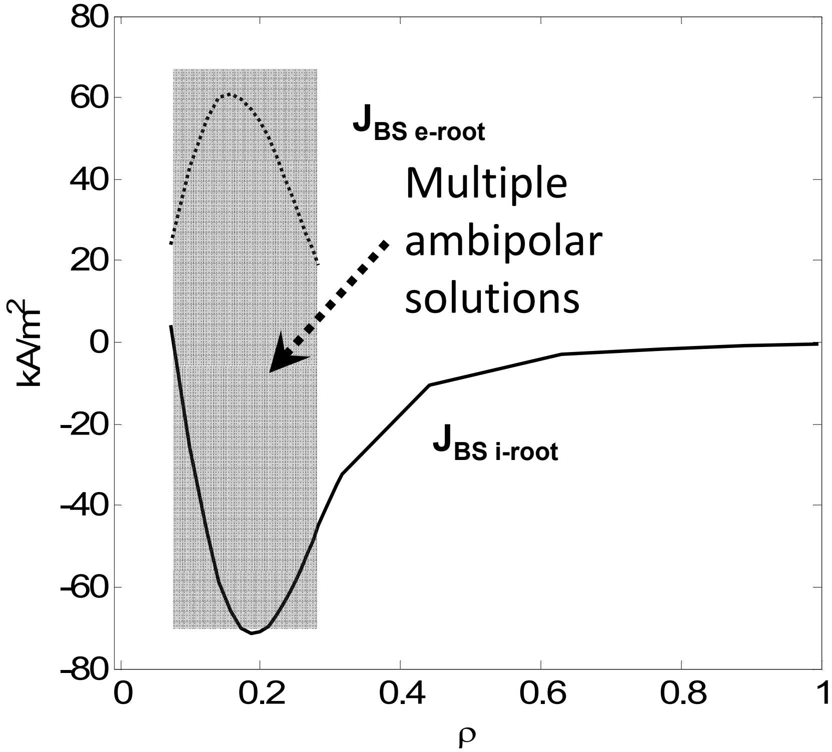


Equilibrium Currents with Quasi-Helical Symmetry

- 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.
- V3FIT reconstructs the pressure and current profiles based on the magnetic diagnostics signals.

Bootstrap current depends on E_r

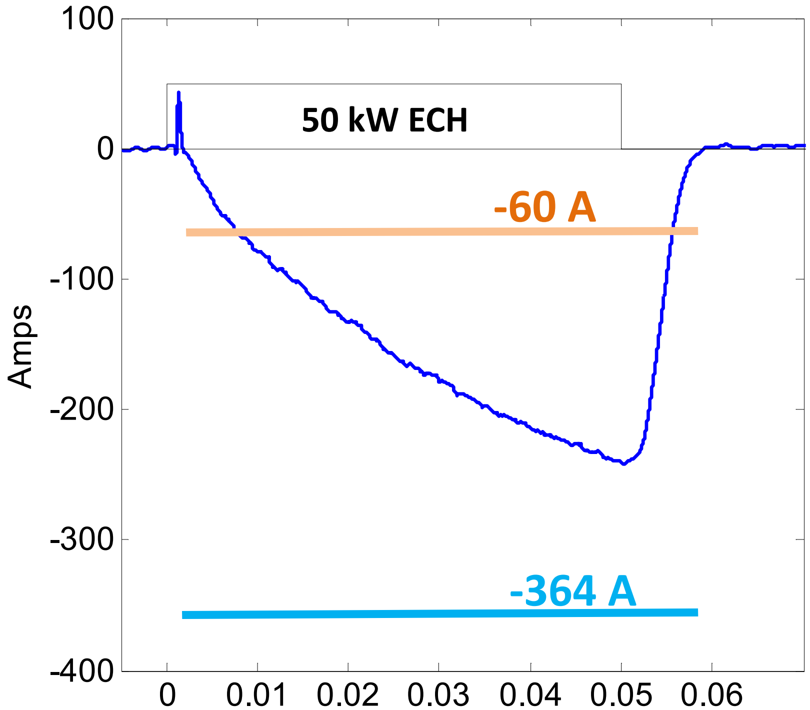




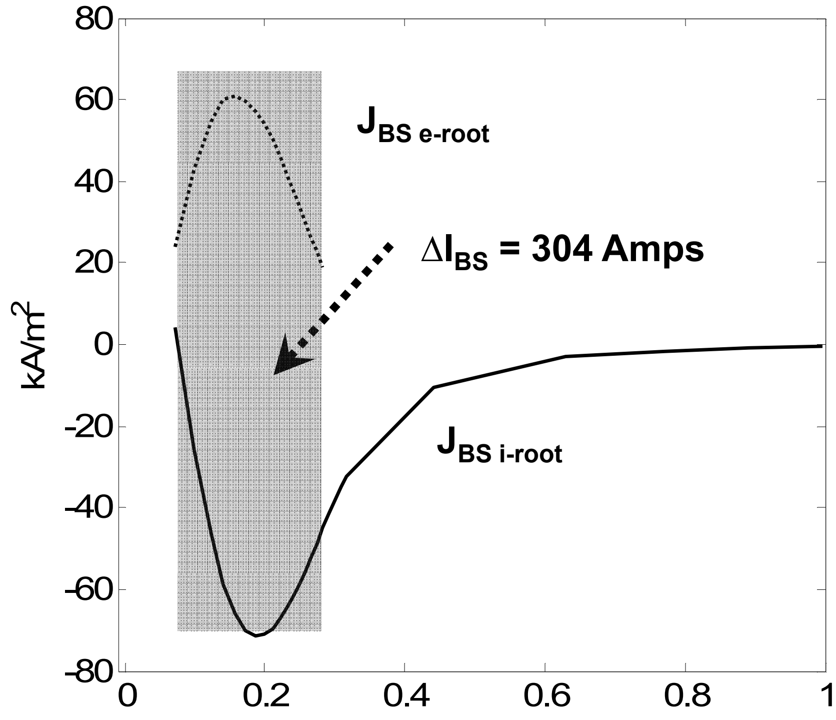
- T_e, N_e from Thomson Scattering.
- T_i from ChERS. $Z_{eff} \approx 1$ from Bremsstrahlung radiation (ChERS optics).
- PENTA[1] calculates the fluxes. E_r is determined by ambipolarity.
- The electron-root reverses the direction of the bootstrap current.

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

Toroidal current evolves during shot



If electron-root dominates: I_{BS} = -60 A



If ion-root dominates: I_{BS} = -364 A

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

The extrapolated steady state value is -345 A. $\tau_{L/R}$ ~ 40ms. $$I_{tor}(t) = I_{\infty} \cdot \left[1 - e^{-t/\tau_{L/R}}\right]$$

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

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

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

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

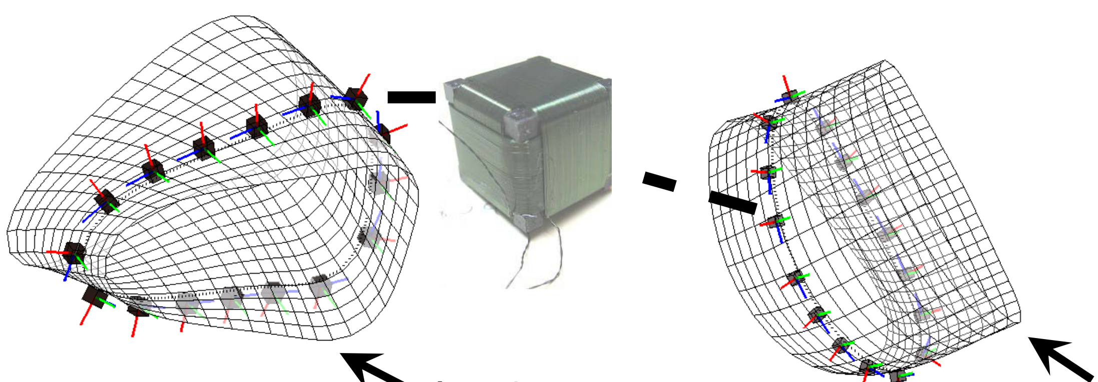
V3FIT[3] Calculates the Magnetic Diagnostics Signals

- Diagnostic set includes two Rogowski coils, two flux loops , 32 d**B**/dt sensors and the limiter location.
- VMEC is the equilibrium solver. The plasma pressure, toroidal current profile and net toroidal flux are specified with up to 9 free parameters.

$$p(s) = presscale \cdot \left[\frac{1}{N_0} \left(\left(1 + \left(\frac{s}{a_2^2} \right)^{a_3} \right)^{-a_4} - c_0 \right) \right]; N_0 = 1 - c_0 \; ; c_0 = \left(1 + \left(\frac{1}{a_4^2} \right)^{a_3} \right)^{-a_4} \qquad I_{enclosed}(s) = curtor \frac{2}{\pi} \arctan\left(\frac{a_2 s^{a_3}}{(1-s)^{a_4}} \right)$$

- For reconstruction, V3FIT adjusts the parameters to minimize the difference between the measured and modeled signals.

$$\chi^2(p) = \sum_i \kappa_i \left(\frac{\mathrm{S}_{\mathrm{o,i}} - \mathrm{S}_{\mathrm{m,i}}(\mathrm{p})}{\sigma_{\mathrm{i}}} \right)^2$$



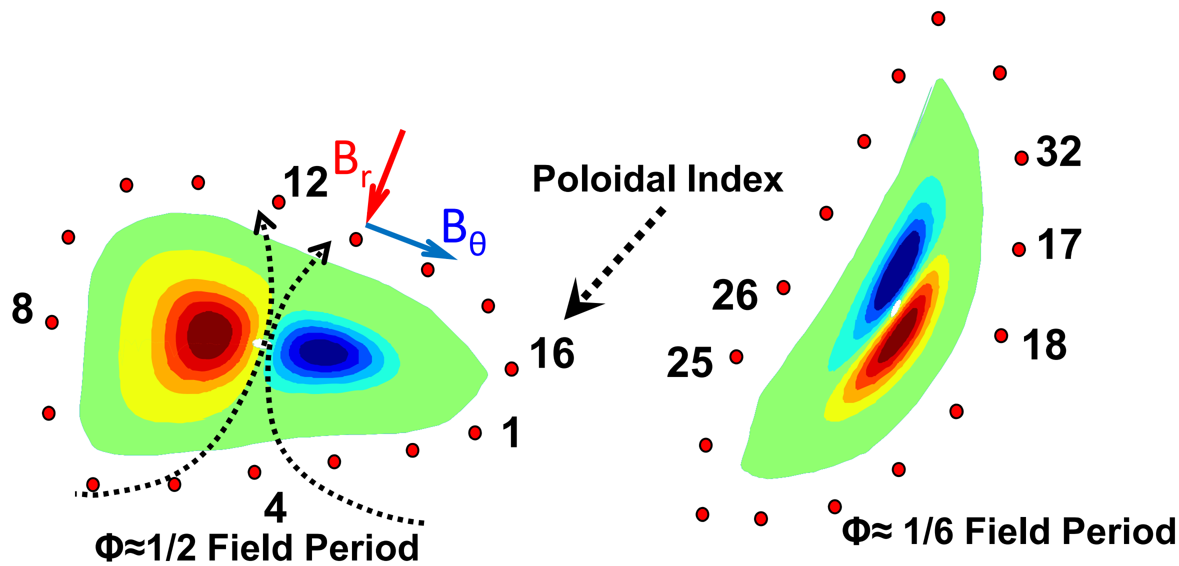
Thanks to James Hanson and Steve Knowlton for the assistance in using V3FIT

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

The Pfirsch-Schlüter current rotates helically

Red Contours: J_{PS} OUT OF PLANE

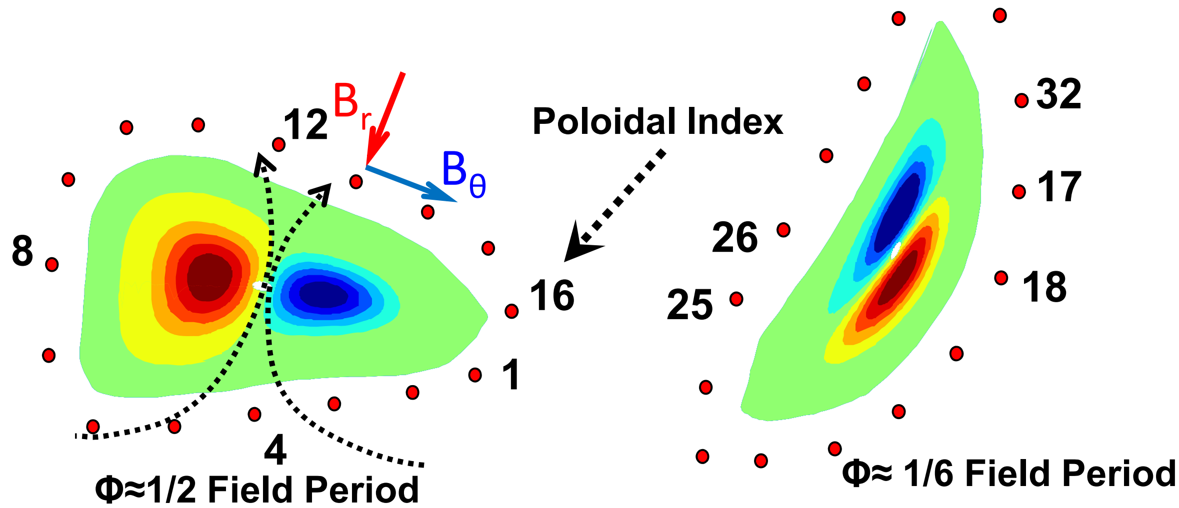
Blue Contours: J_{PS} IN TO PLANE

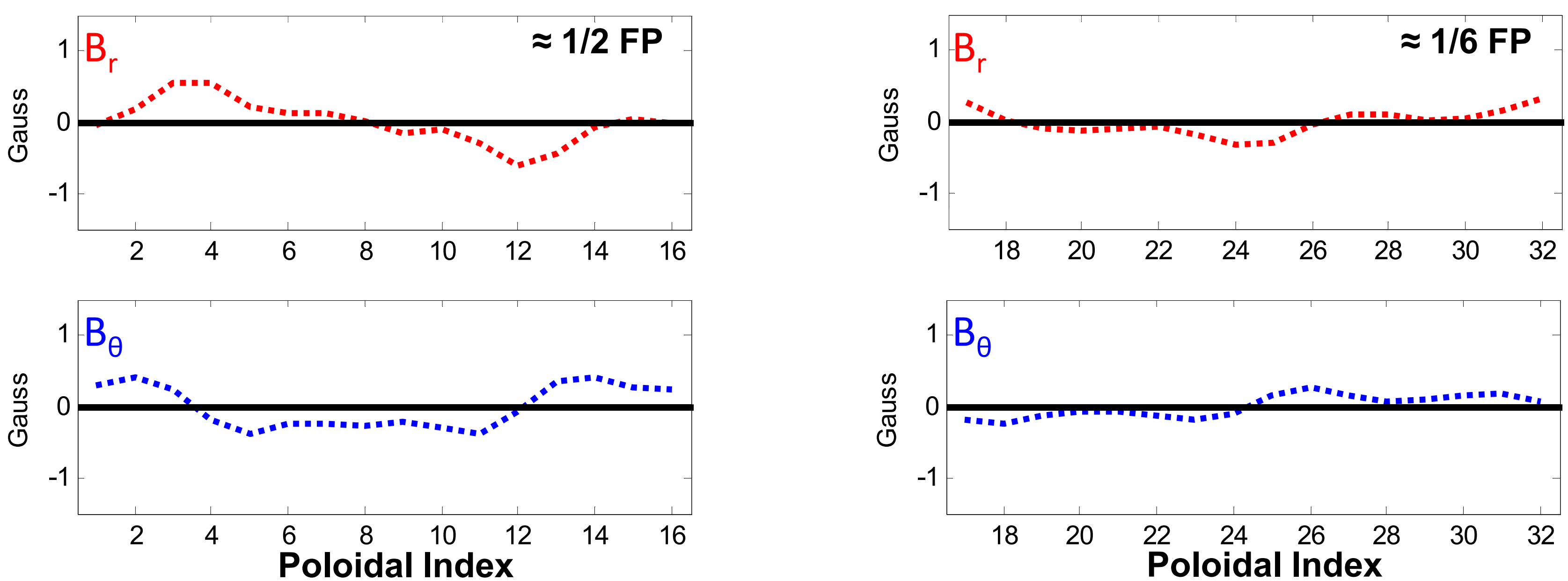


- The plasma pressure profile is calculated and used in V3FIT to find the magnetic response due to the Pfirsch-Schlüter current.
- The net toroidal current is set to 0.

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

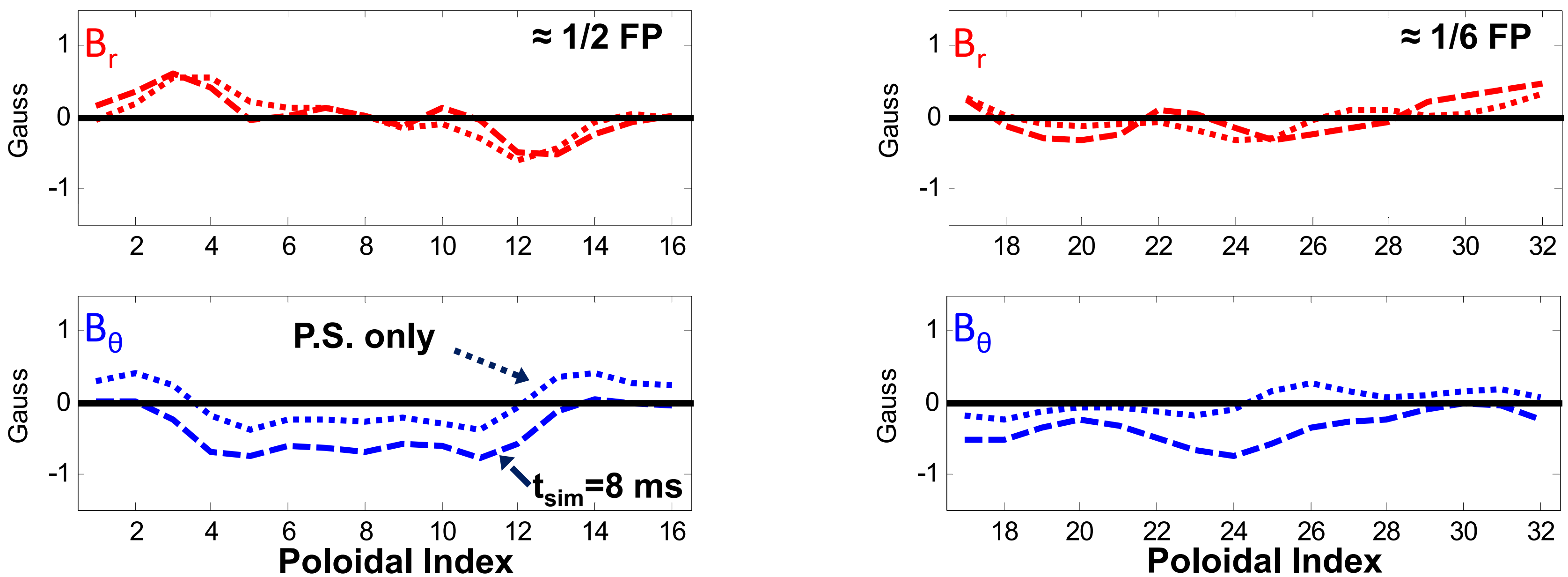
The sign of the signals at the two toroidal locations demonstrate a phase shift showing the helical rotation.





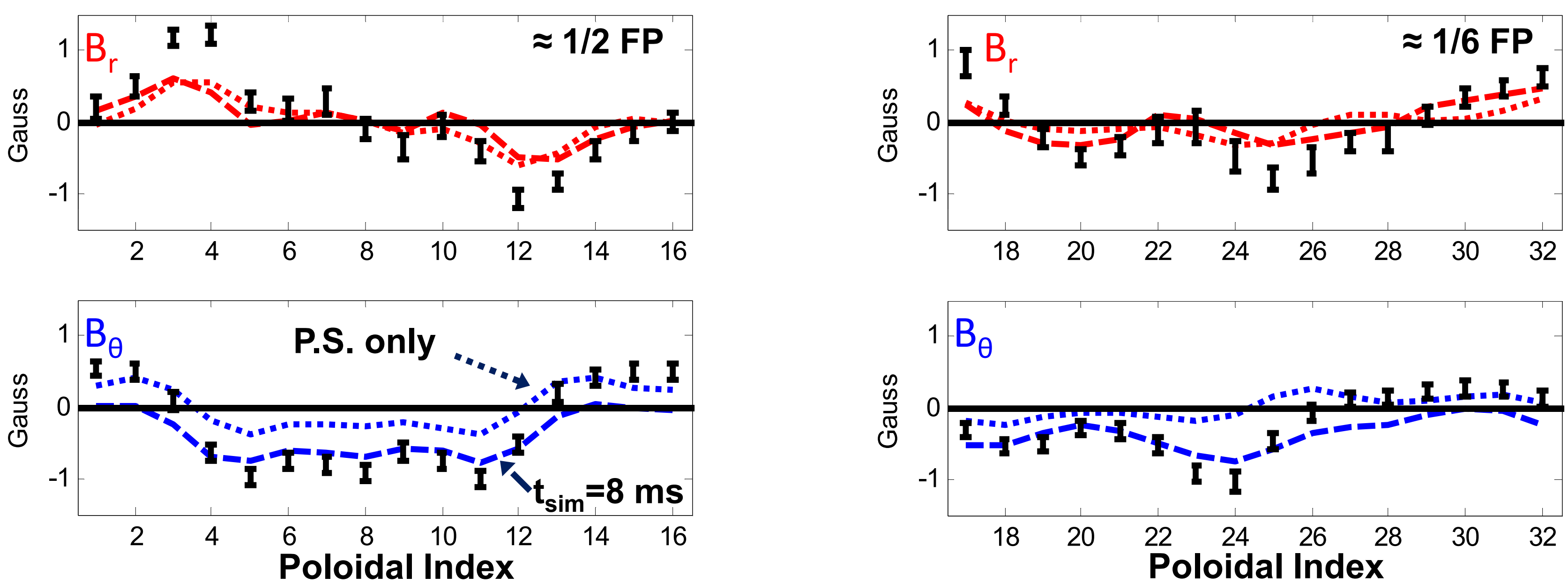
Bootstrap Current Contributes Little to B_r Early in Shot

- The toroidal current profile is simulated in time and the diagnostic response is predicted with V3FIT.
- A small net toroidal current (40 A) contributes to the B_θ component.



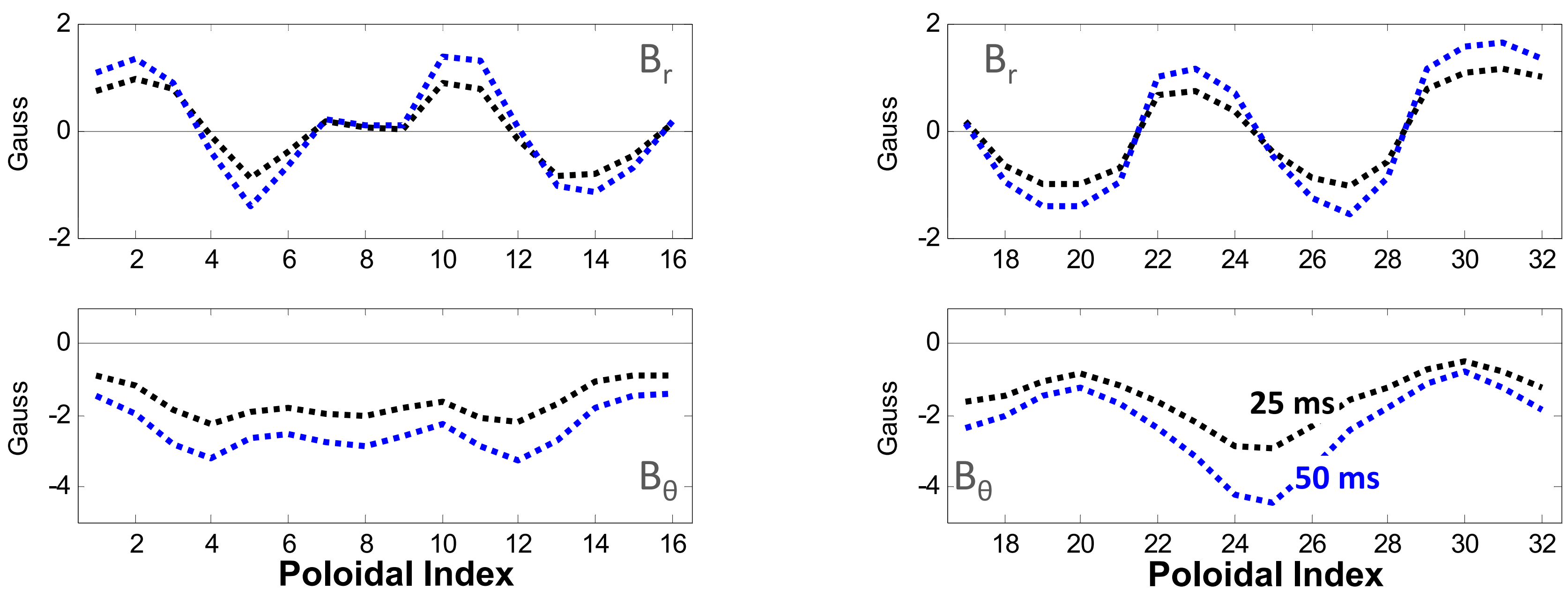
Confirmation of the Helical Rotation of the Pfirsch-Schlüter Current

- The experimental signals at t=8ms 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

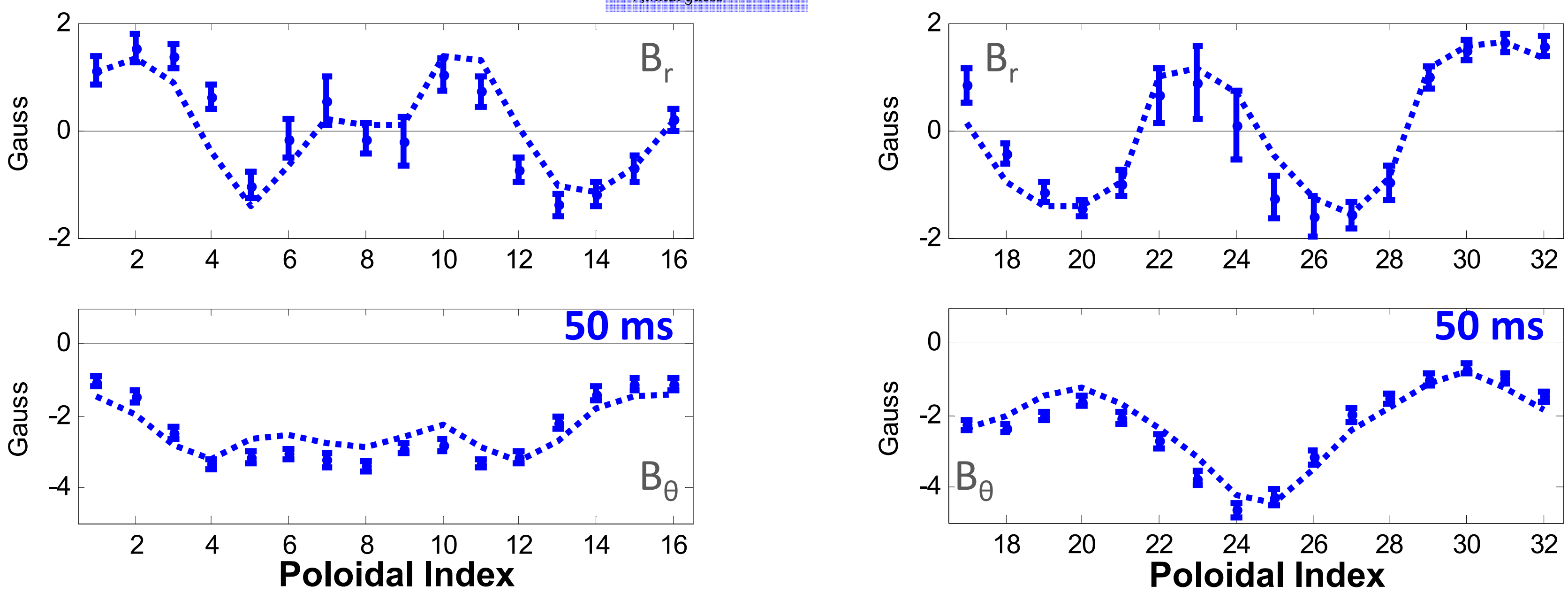
- Simulated profiles at 25ms and 50ms.
- B_θ has large unidirectional contribution from <J·B>.
- B_r is dominated by the m=2 structure of the vacuum vessel.



Measured signals are close to the simulated ones

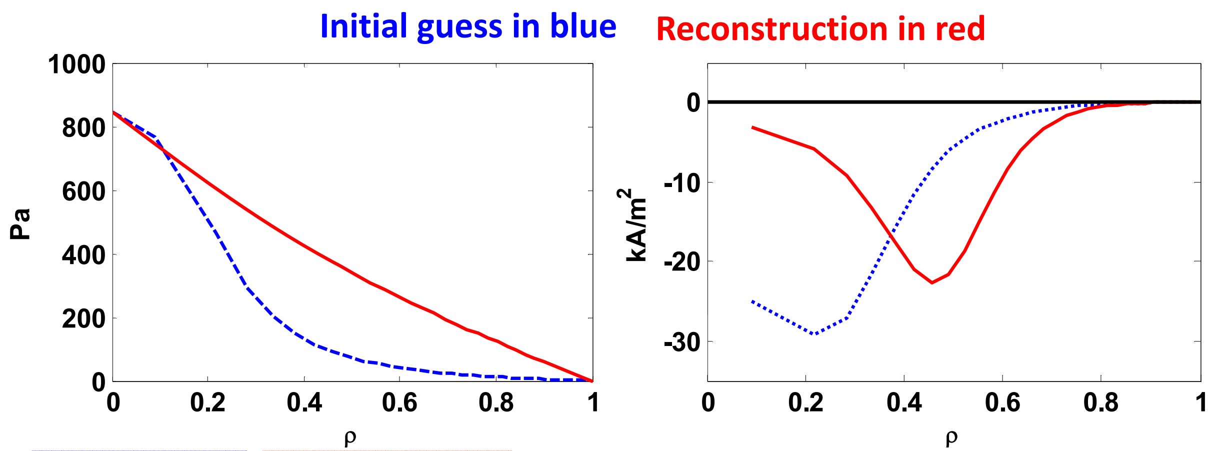
- Measurement evolves slightly faster than simulated values.
- Possible sources of error: Z_{eff}, initial plasma profiles, neoclassical calculation of bootstrap current.
- The pressure profile and evolved current profile serve as an 'initial guess' in the V3FIT reconstruction attempt.

$$\chi^2_{\nu,\,inital\ guess} = 5.6$$

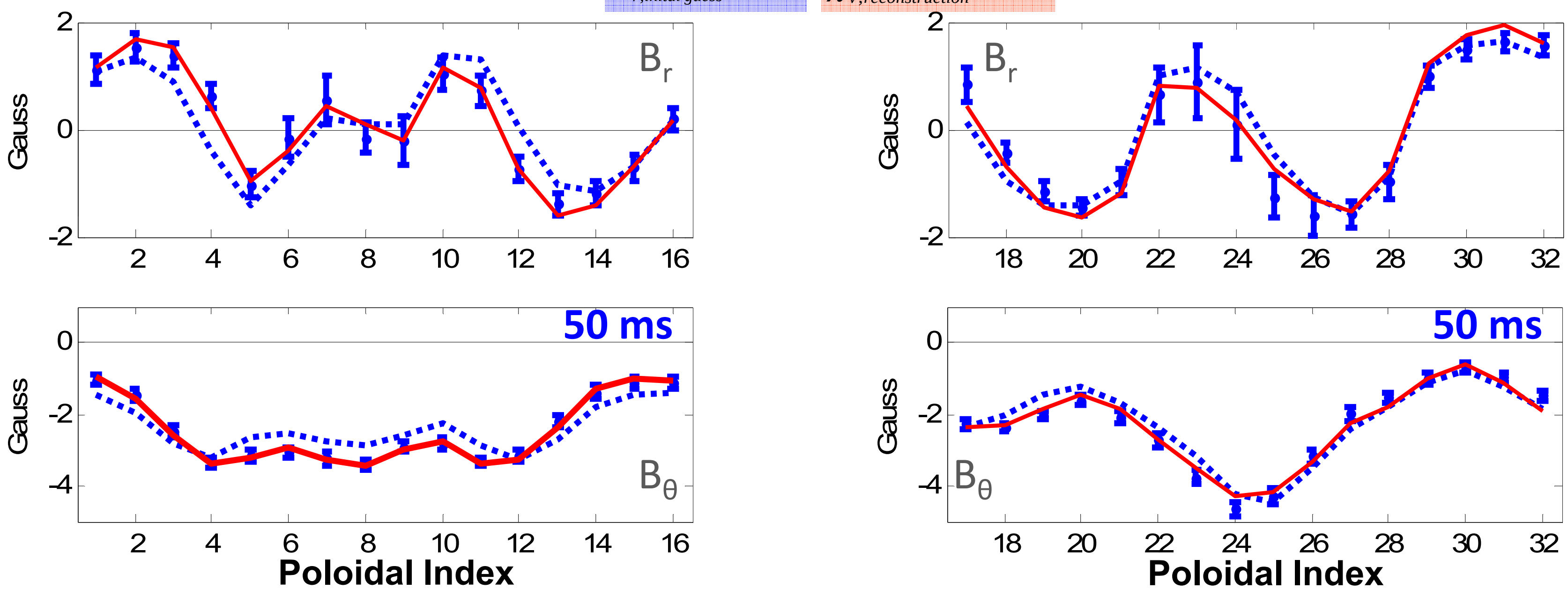


The reconstruction minimizes the mismatch between the measured and modeled signals

- Pressure profile becomes wider; Current density is shifted radially outward.
- Posterior sigmas are large: Need to reduce the # of free parameters in the model.



$\chi^2_{\nu,\text{inital guess}} = 5.6$ $\chi^2_{\nu,\text{reconstruction}} = 1.7$



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 Pfirsch-Schlüter current rotates with |B| contours and is reduced by ~1/3 compared to a tokamak, demonstrating the lack of toroidal curvature.

- The evolving current profile is modeled with a diffusion equation using a 3D susceptance matrix. Expected magnetic diagnostic signal are calculated with V3FIT.

- Continue to improve the V3FIT reconstruction. e.g., Reduce the # of free parameters in the reconstruction to achieve reasonable uncertainties in the profiles.