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Locked Mode and Error Field Physics in NSTX

Results from the 2005 Campaign

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for the NSTX Research Team

2nd Magnetic Error Field Workshop

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Denver, Colorado

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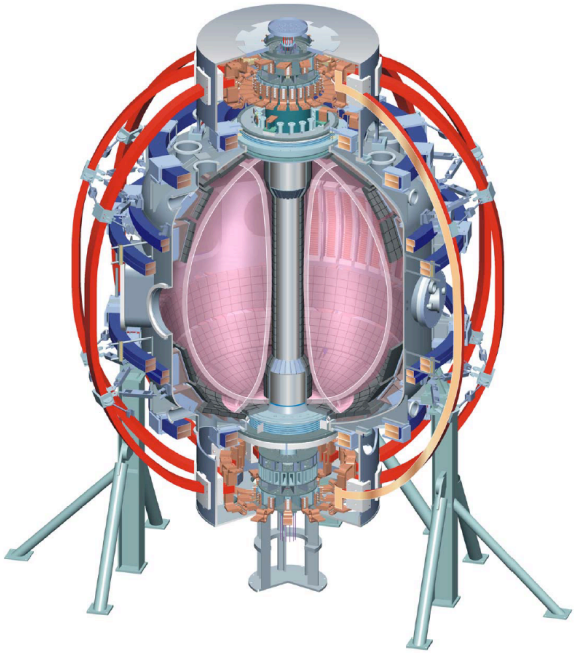

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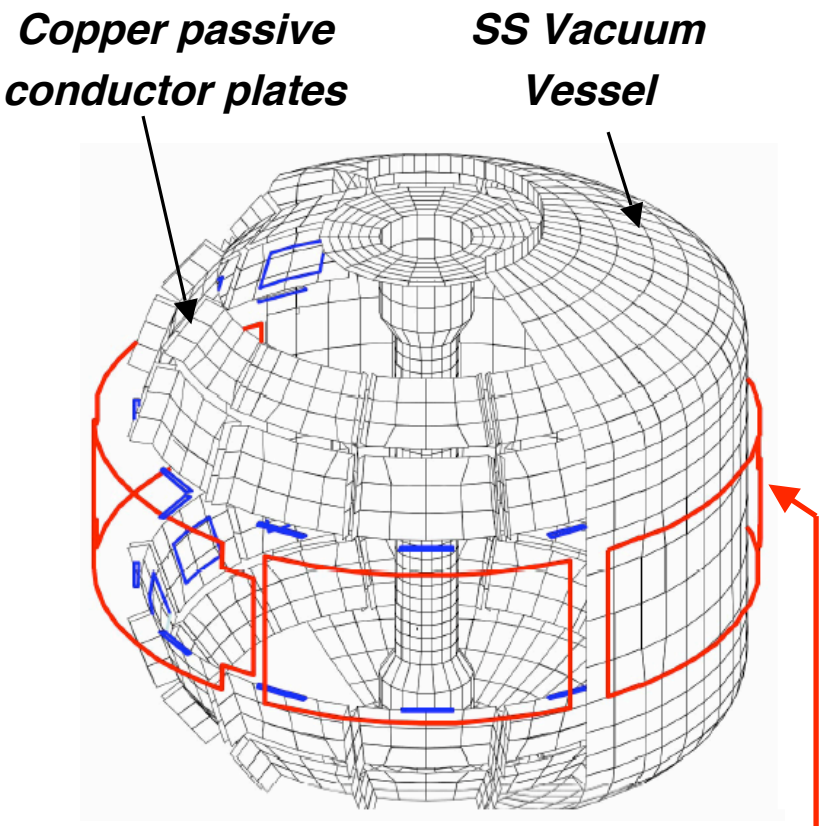
Non-axisymmetric RWM/EF coils and switching power amplifiers (SPA) now being used in experiments

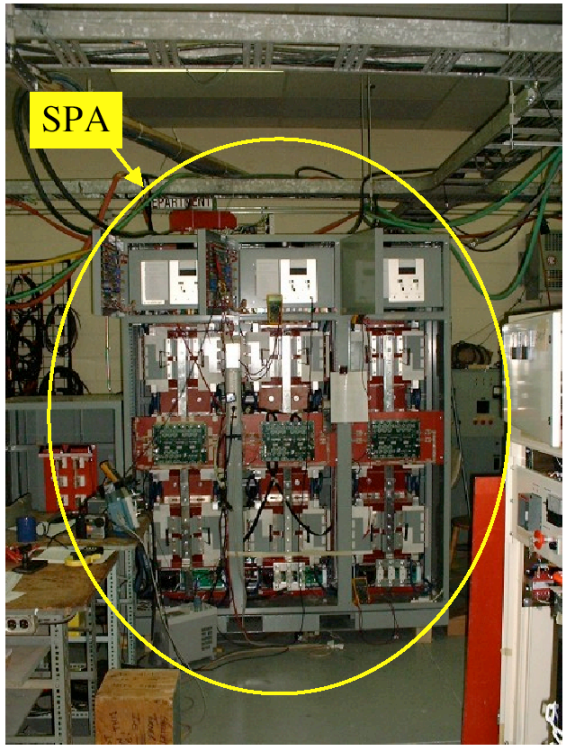


VALEN Model of NSTX (Columbia Univ.)

6 ex-vessel midplane control coils
+ 24 B_R and 24 B_P in-vessel sensors

NSTX RWM/EF coil and SPA capabilities:

- 3 opposing coil pairs in anti-series (n=1, 3)
  - n=2 interconnection also possible
- 3 independent SPA circuits – 3.3kA, 7.5kHz
- Can produce 10-15G n=1 resonant $B_\perp$ at q=2
- Can brake rotation with available fields



Goals of experiments

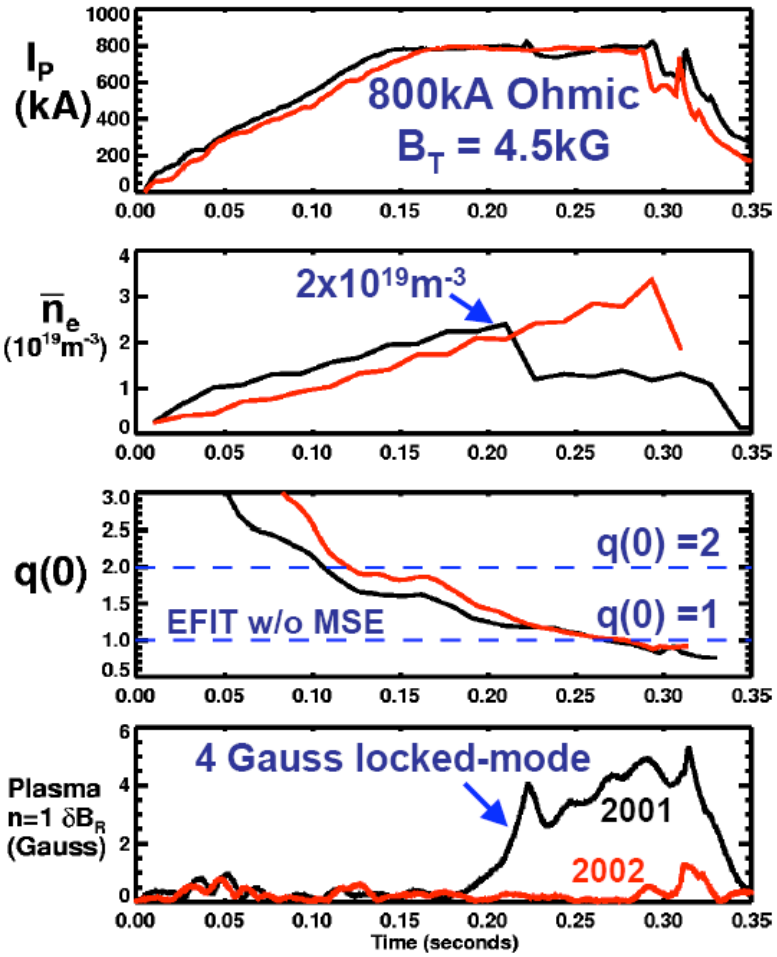
- Study low-b locked-mode threshold during I_P flat-top
  - Contribute low-A data to scaling studies:
    - $a_n \approx 1$, $a_B \approx -1$, **$a_q \approx 0.8 - 1.6$, $a_A \approx 0.4\text{-}0.8$ (MAST)**

$$\frac{b_{pen}}{B_t} \propto n^{\alpha_n} B^{\alpha_B} q^{\alpha_q} (R/a)^{\alpha_A}$$

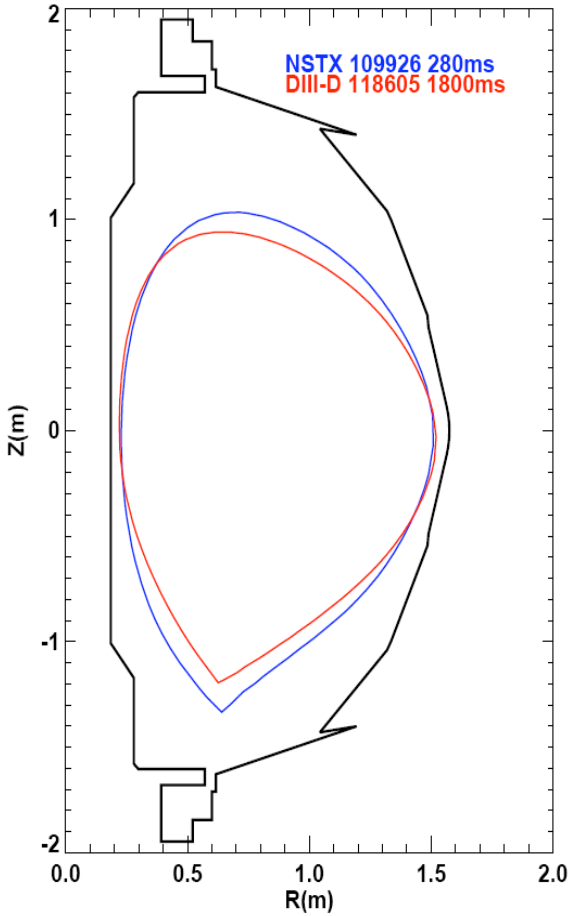
  - Measure threshold for locking vs. phase at fixed *n*, *B*, shape
    - **"Measure" any static intrinsic error field, and correct for it**
  - Determine density scaling of threshold
  - Determine B scaling of penetration threshold
  - Determine elongation scaling of threshold
    - Scan range of k from 1.6 for MDC-6 LSN to typical NSTX k=2
  - Determine q* and q_{95} (triangularity) scaling of threshold

Experiment focuses on moderate d LSN shape

Can compare results to previous NSTX locking data

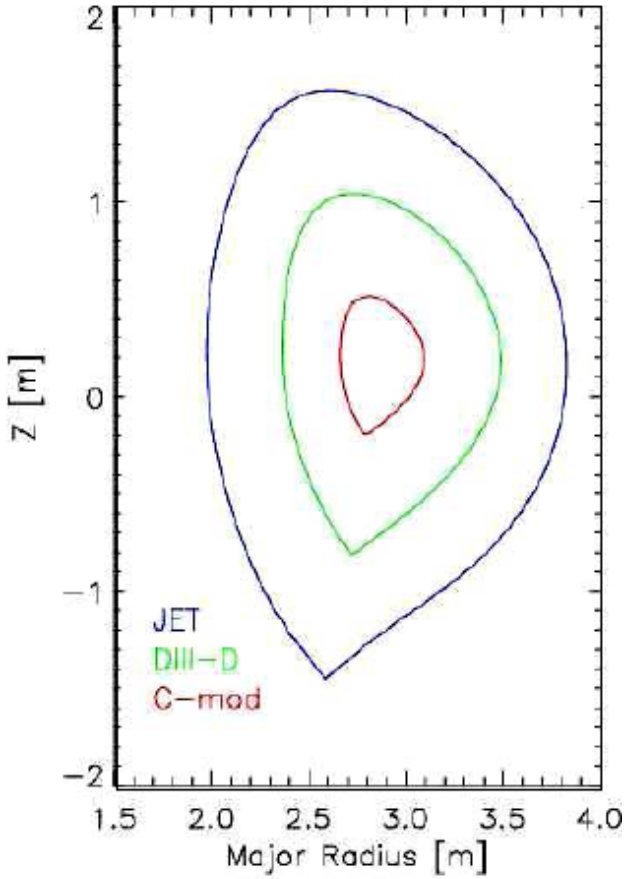


Can compare directly to ITPA Joint-Expt locked-mode results



Relationship to other experiments and results

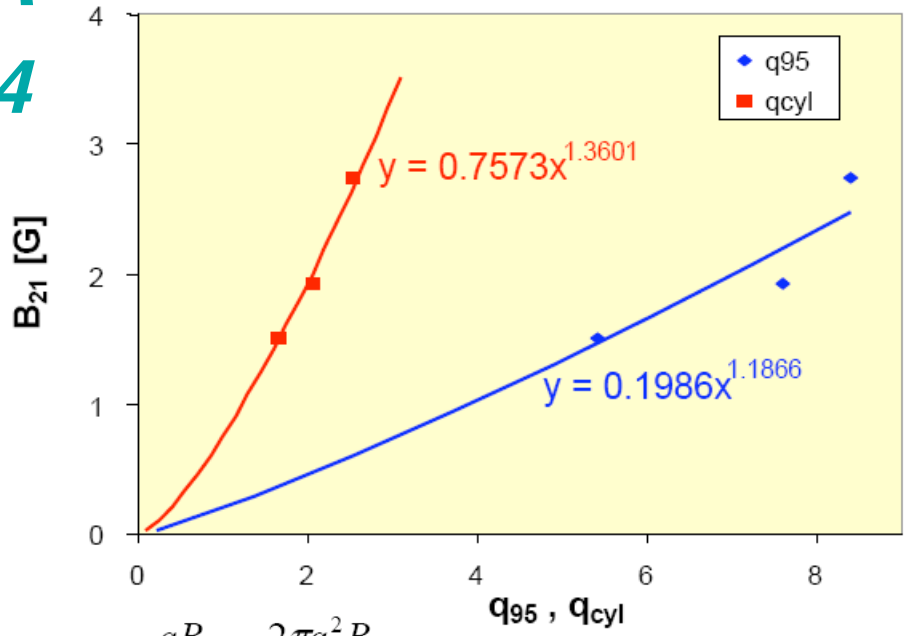
- LSN shape used in high-A identity experiments which matched r * and n*



From ITPA 2004

- Shaping dependence and separation of q_{95}, q^*, q_{cyl} at low-A not considered yet in high-A scaling studies…

MAST Data:

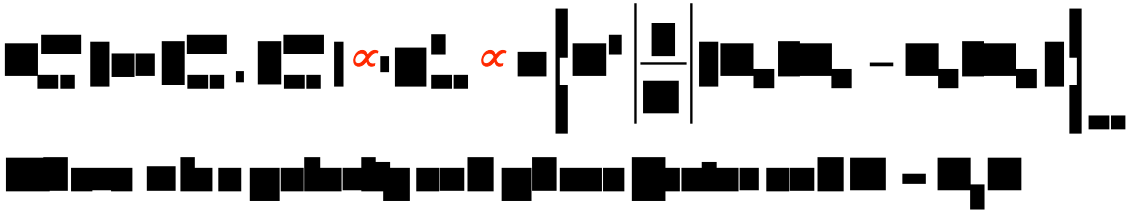


$$q_{cyl} = \frac{aB_t}{RB_\theta} = \frac{2\pi a^2 B_t}{R\mu_0 I_p}$$

Error field definition, and most likely EF sources

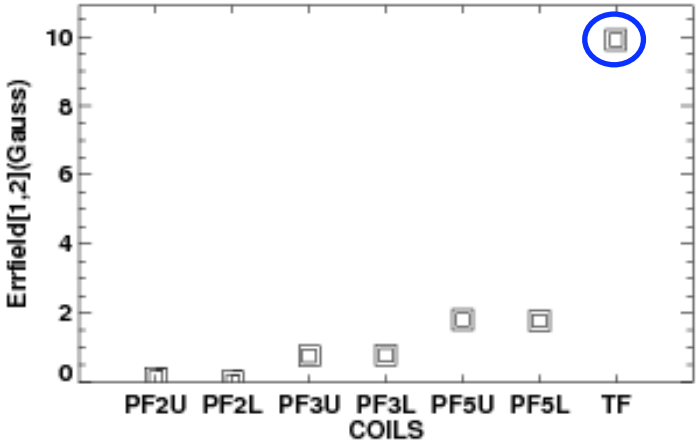
- Work in perturbed helical flux, translate into flux-surface avg. $B_{\perp}$

  - For convenience in this article, EF is defined by

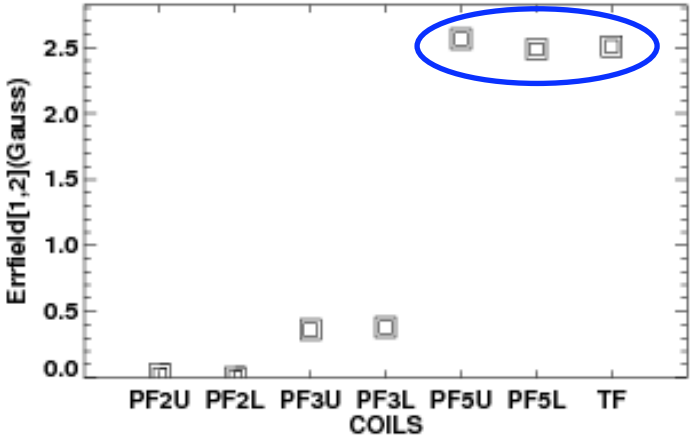


- Shifts and Tilts by PF5 and TF coils are more important than others

By same shift with current weights



By same tilt with current weights

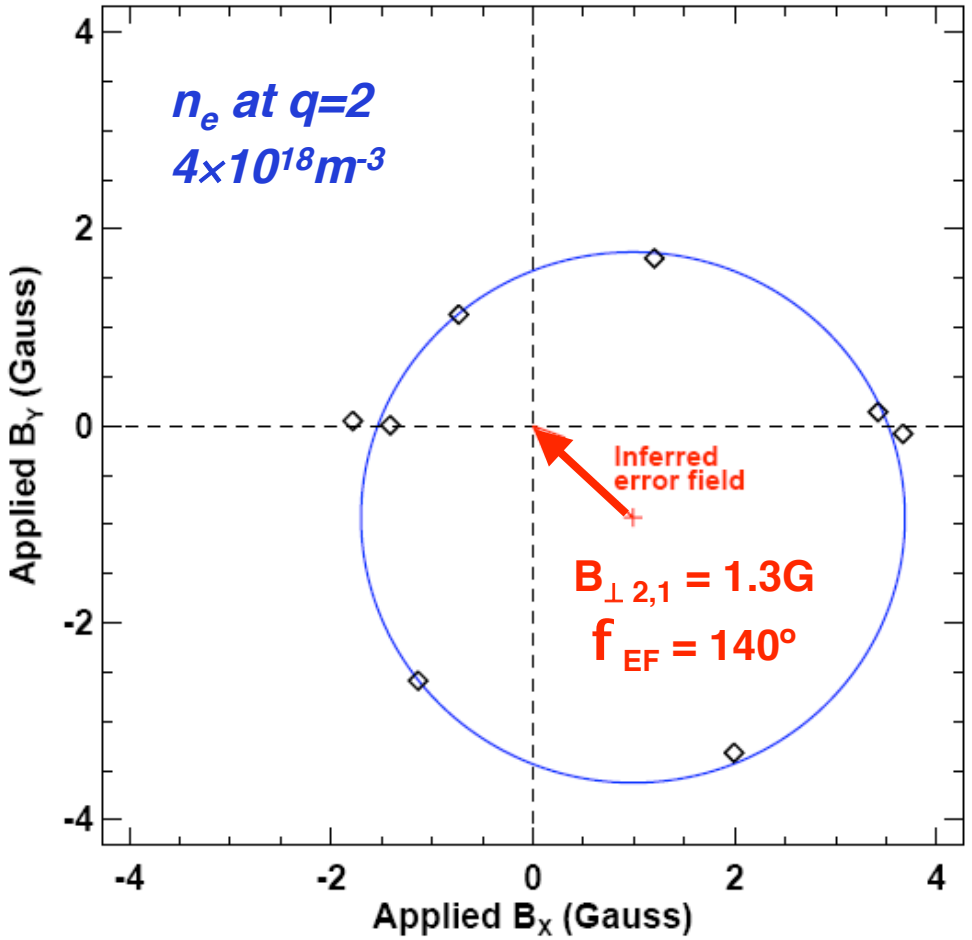


Locking threshold experiments indicate clear asymmetry in response to varied EF direction

- I_P=0.7MA
- B_T = 4.5kG
- q(0) =1.1-1.5

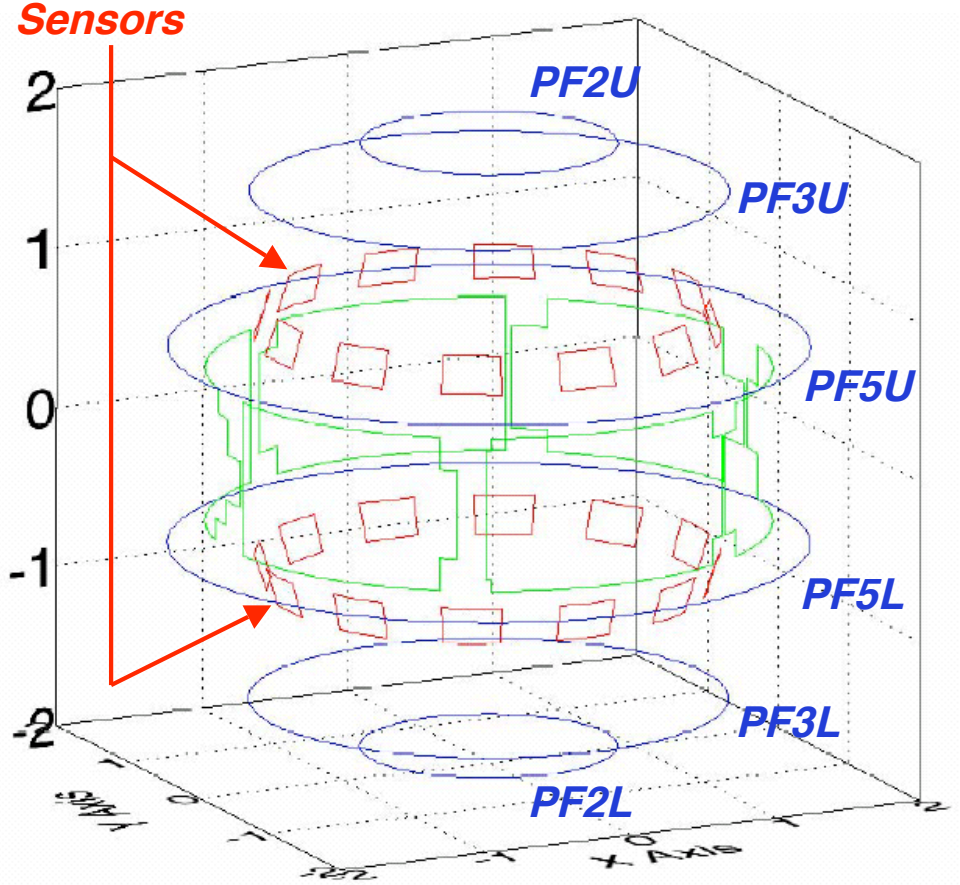
  (no sawteeth)

Inferred amplitude and direction of EF can change 30% and 15º if line-average density is used in place of local n_e

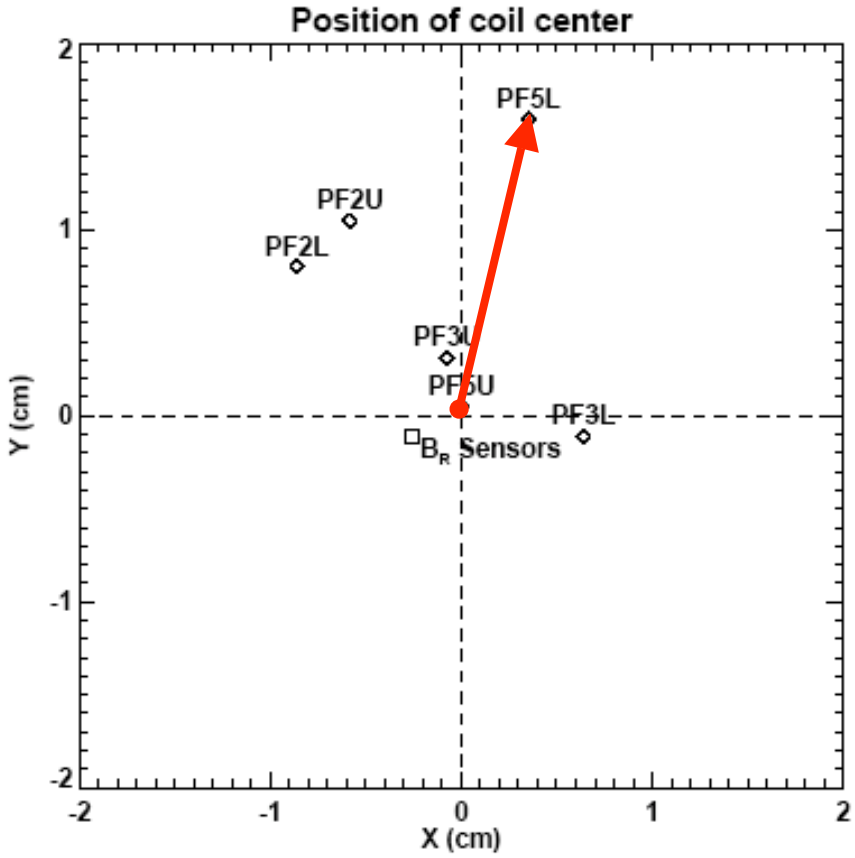


Internal B_R sensors measure up/down asymmetries in PF coil systems → error fields

Filament model of coil/sensor system

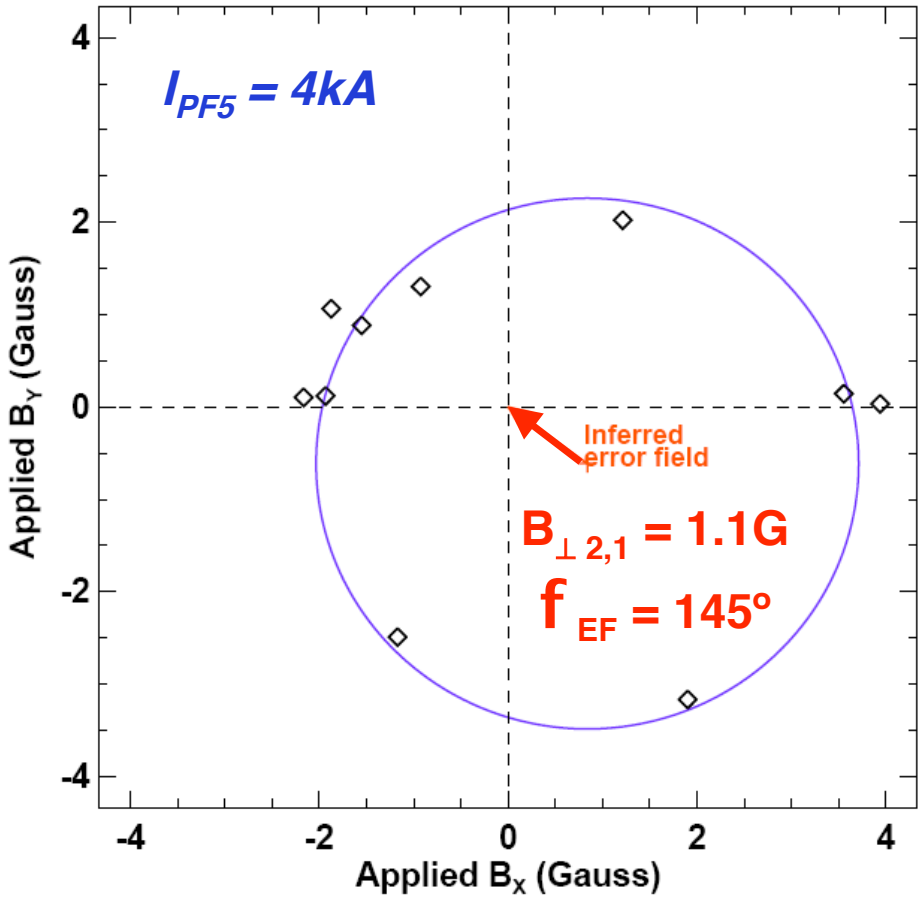


Largest apparent shift occurs in primary vertical field coils (PF5)

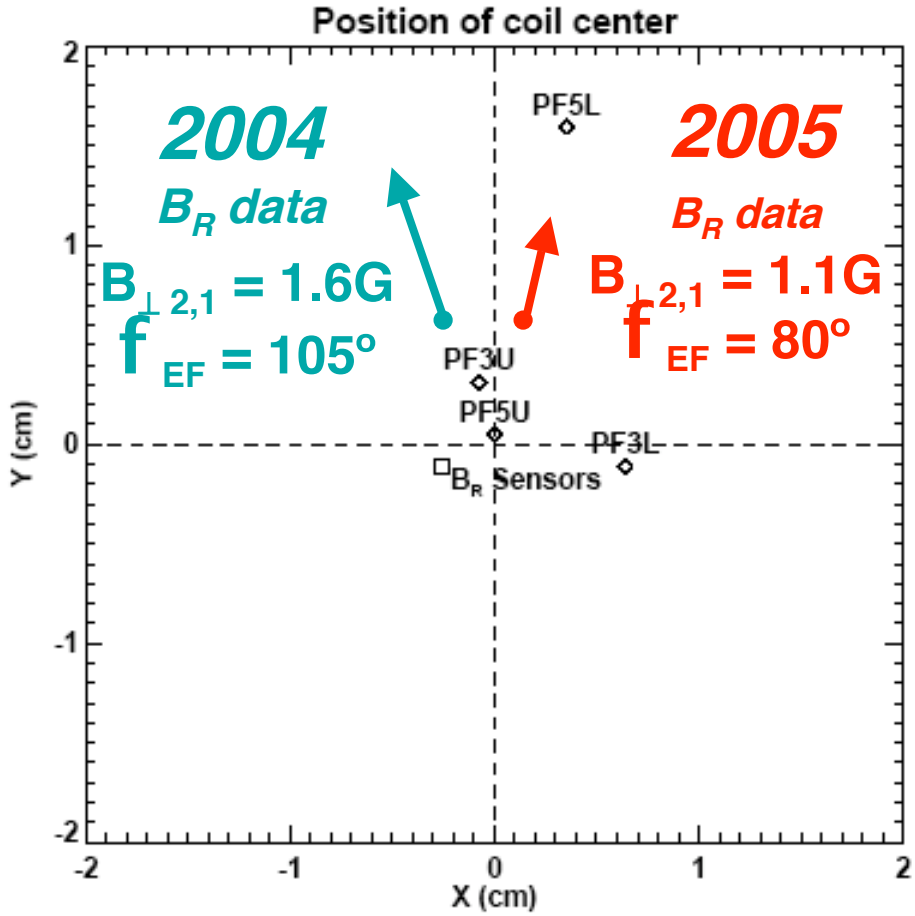


Measured EF amplitude is consistent with PF5 shift model, but EF directions disagree by 35-60º

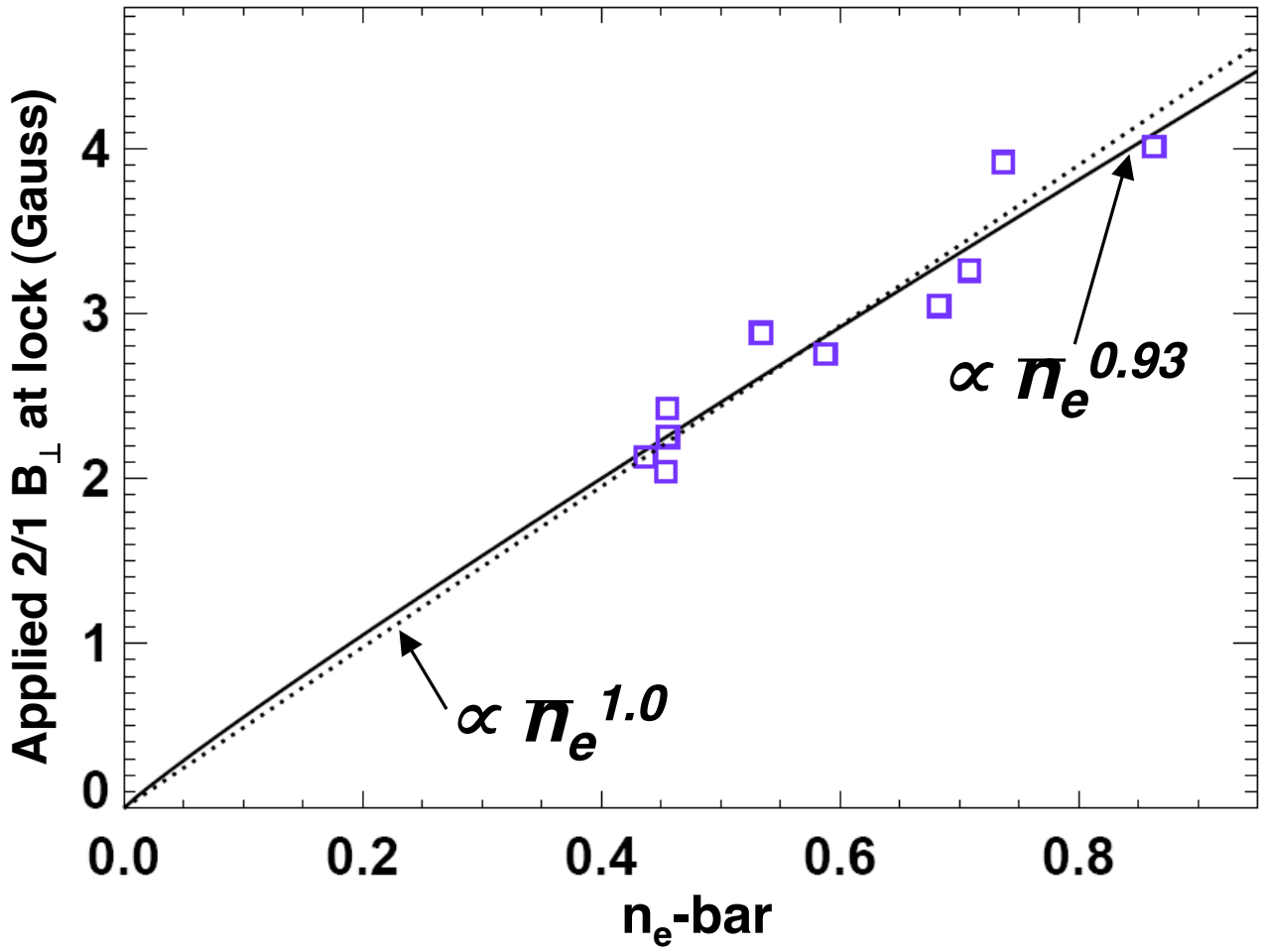
Error field measurements with **additional** data at higher density:



Error field predictions from shifted PF5L model

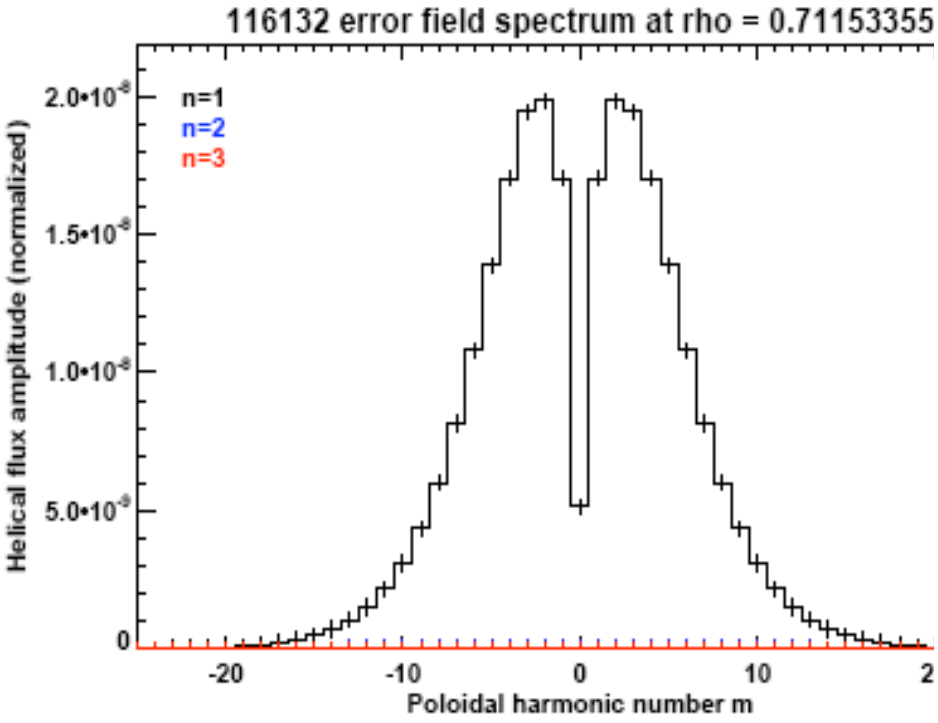


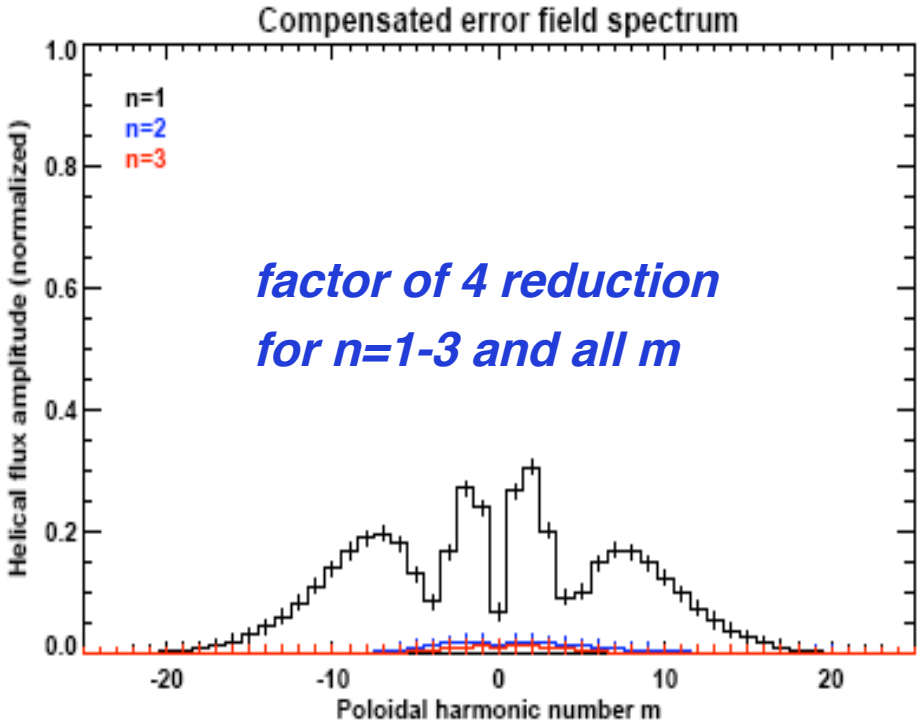
Preliminary density threshold scaling results



Need to widen density scan, and test at other *B* and *q*

Proximity of EF correction coils to PF5 allows good cancellation of PF5 n=1 error fields

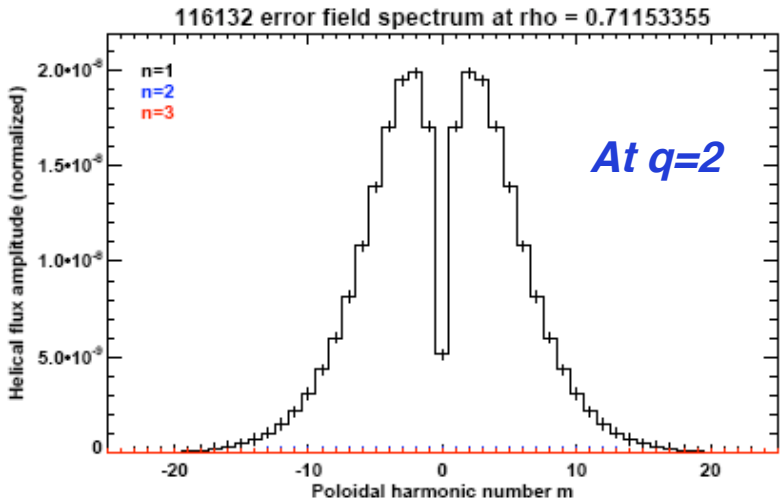


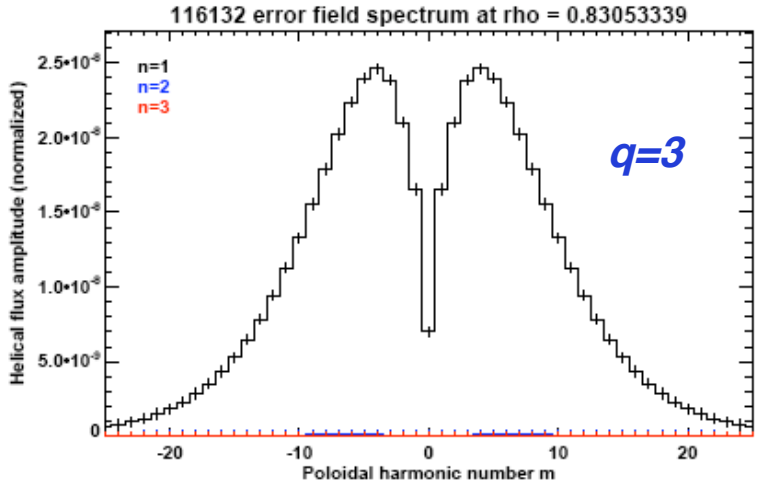


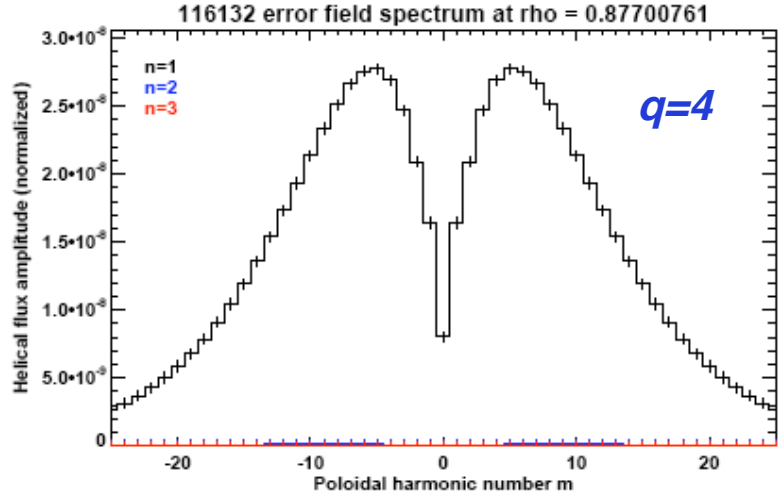
factor of 4 reduction for n=1-3 and all m

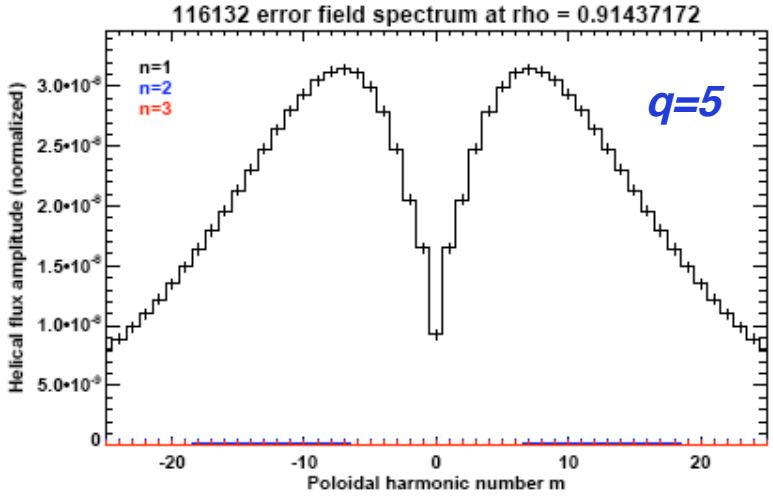
Choose range of m's and n's to minimize vacuum EF helical flux

m-spectrum of n=1 error field (PF5) broadens significantly near the edge of ST plasmas

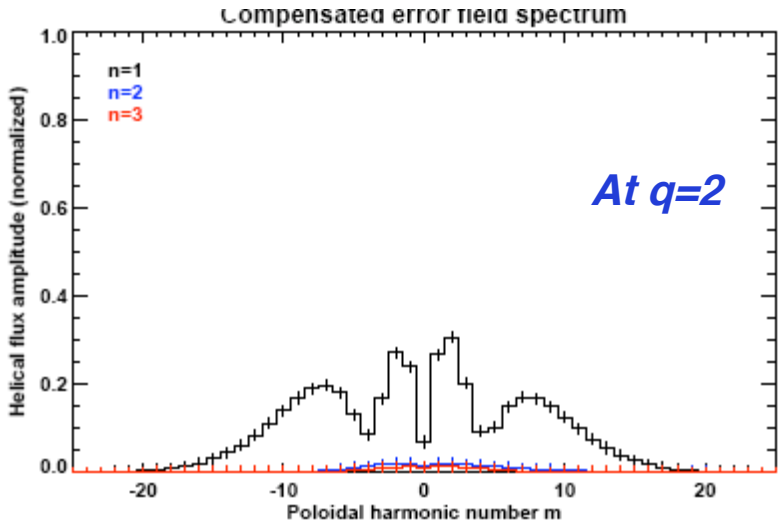


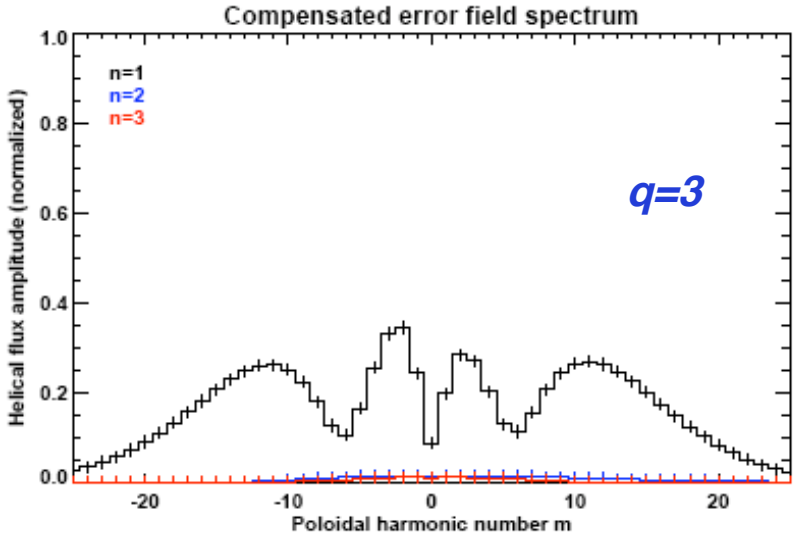


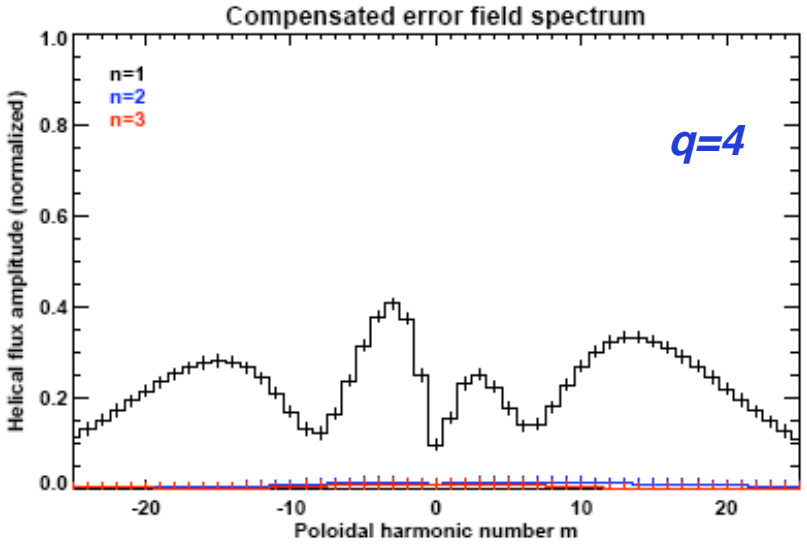


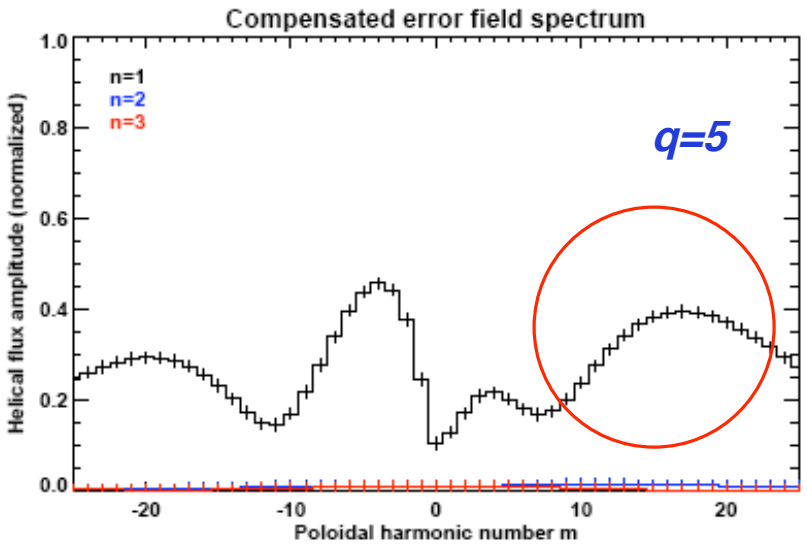


High-m components near edge are not fully compensated when nearly resonant m's are

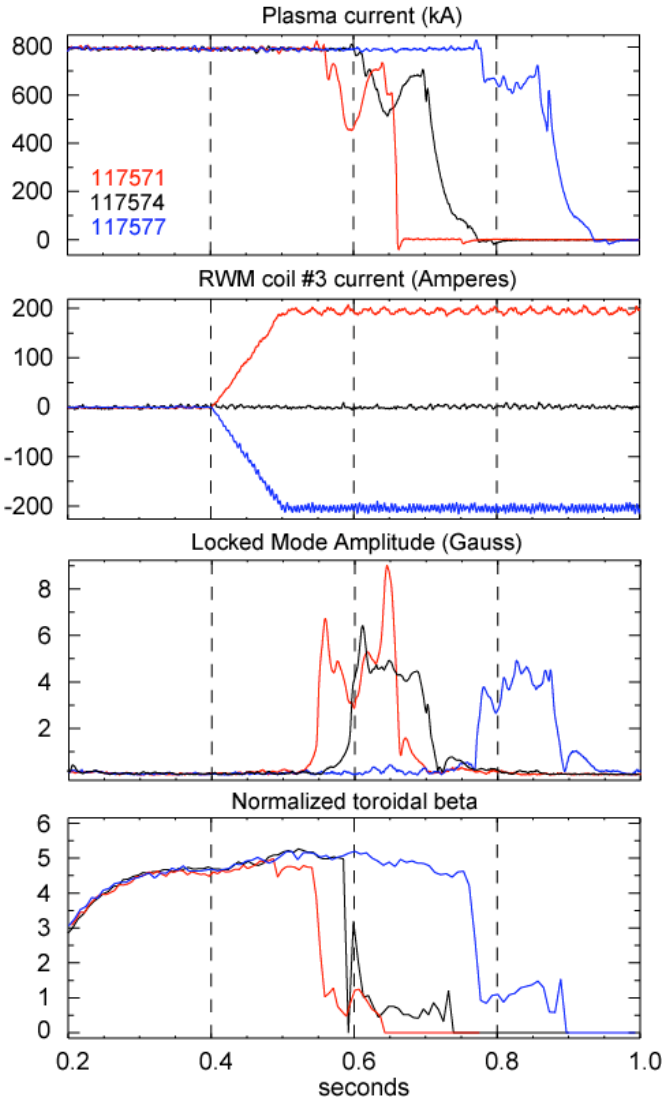


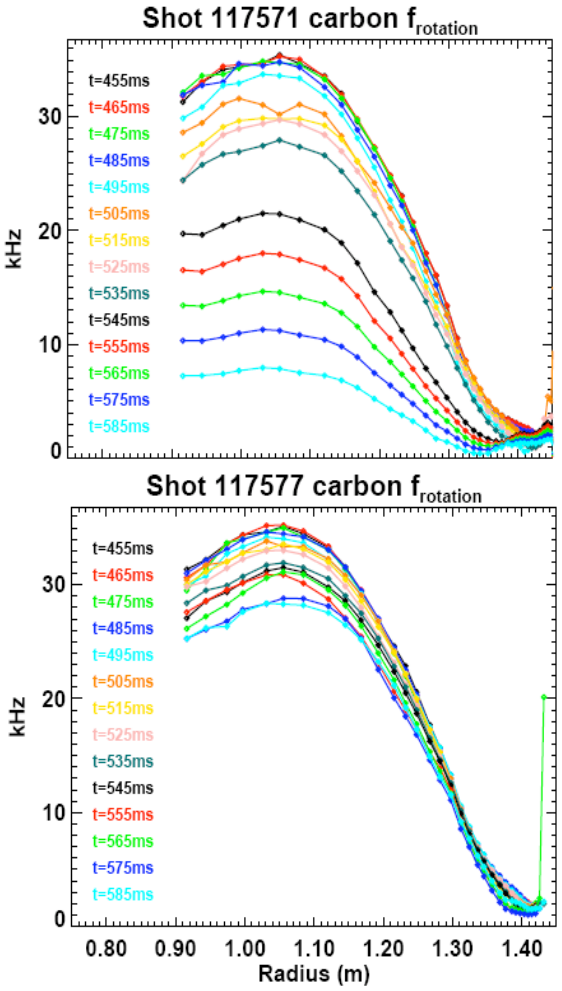






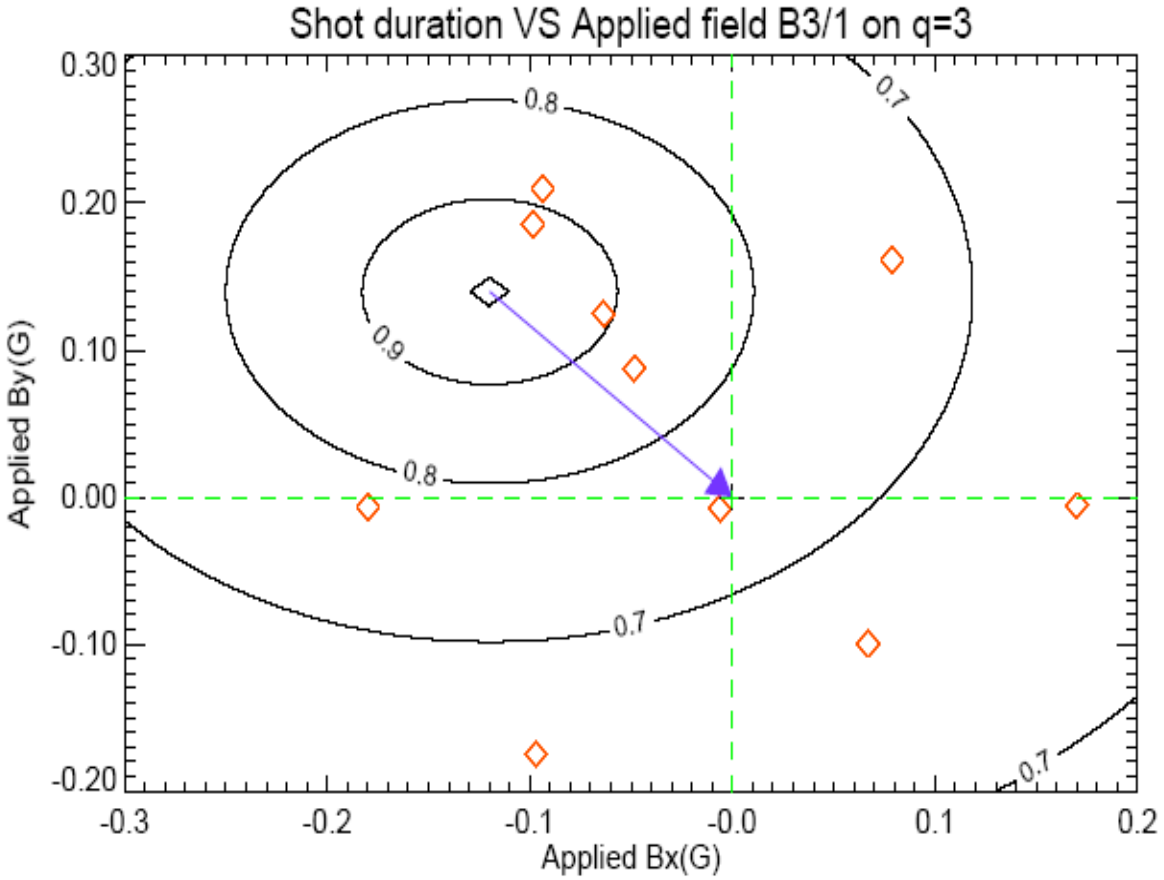
Pulse-lengths have been extended at high b_N using newly installed error-field correction coils





- Rotation is damped in "non-correcting" directions and leads to earlier island locking and/or RWM formation
- Central rotation is sustained & near-edge rotation locking is avoided in "correcting" direction - extending pulse length at high-b

Error-field inferred from high-b experiments has direction opposite to that obtained in low-n_e experiments

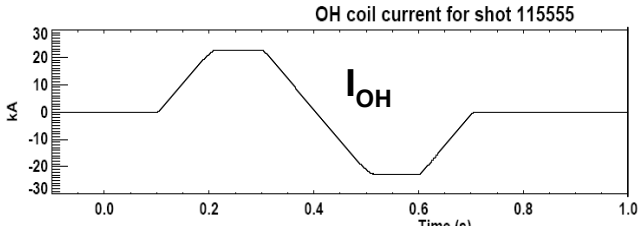


- Shot duration is lengthened for only one particular phase angle and a narrow range of amplitudes of applied n=1 field

Suggests additional EF source is present

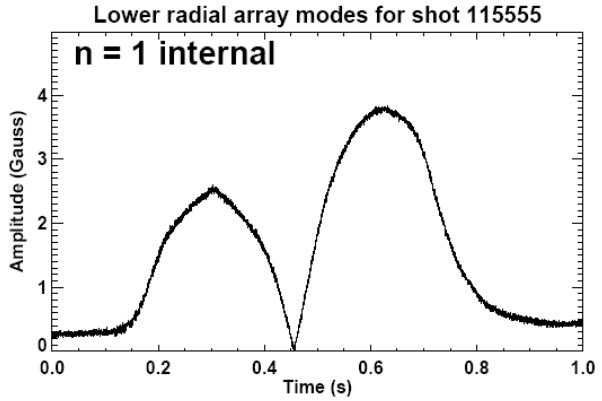
n=1 B_R error field from combination of OH+TF measured, and approximated by pure translation of TF ∝ $I_{OH} \times I_{TF}$

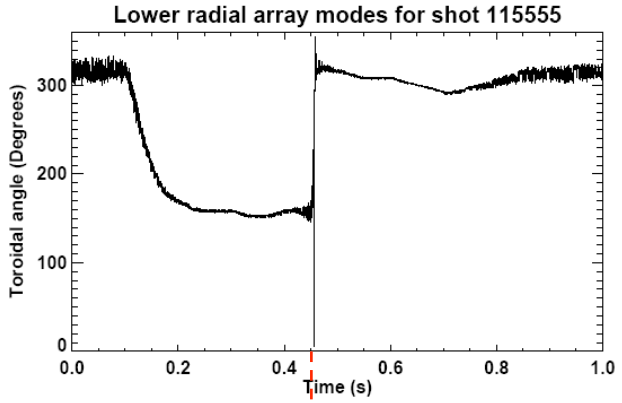
I_{TF} = -40kA flat-top



- Field created is predominantly B_R
- Phase changes 160º after I_{OH} crosses thru zero with 50ms time-lag

Measured error field amplitude at sensors

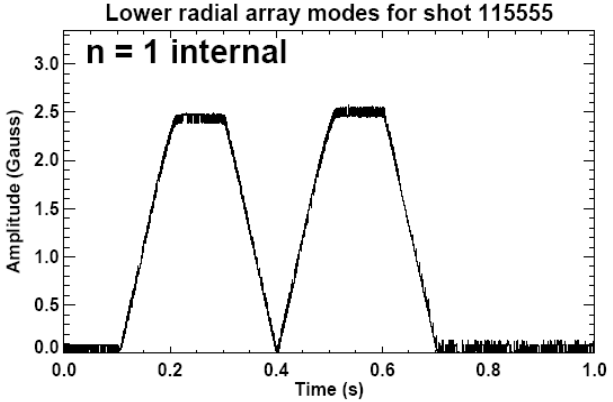


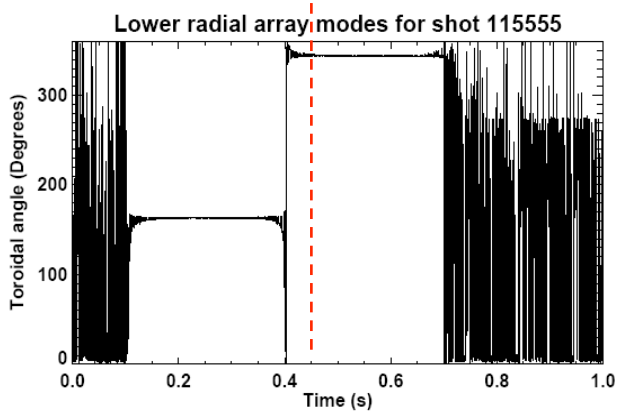


Measured error field phase

MODEL: Entire TF bundle shifts toward Bay I, D= 1.65mm × I_{OH} / 24kA when I_{TF} = -40kA

Simulated error field amplitude at sensors



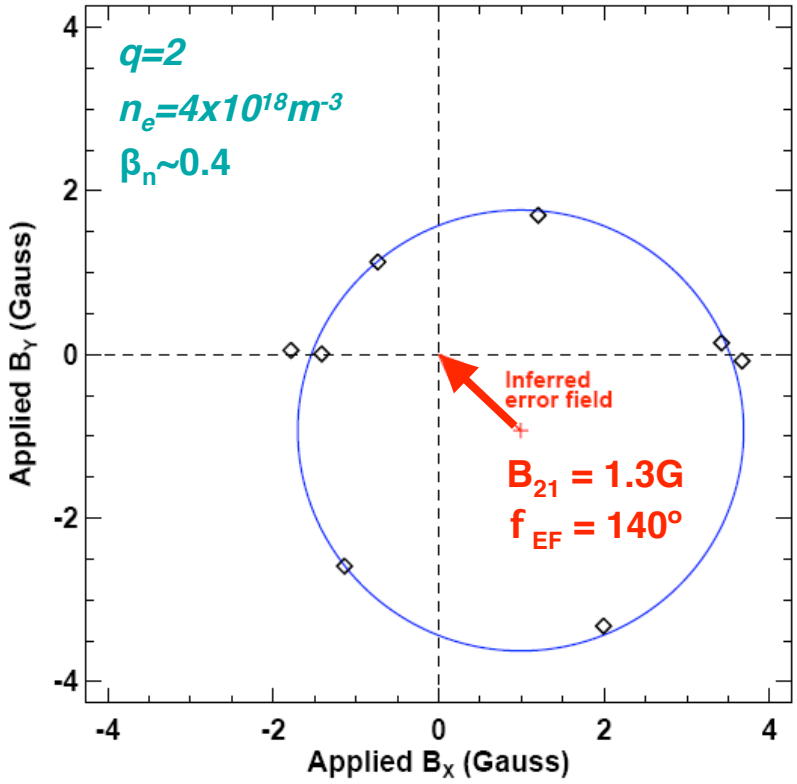


Simulated error field phase

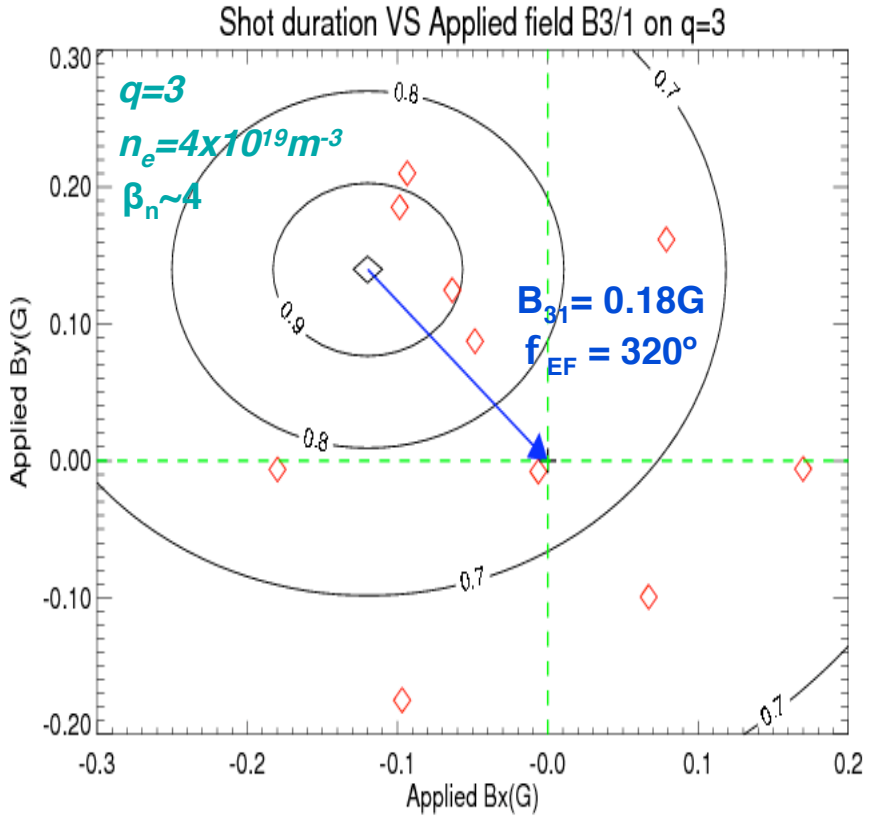
Locking threshold experiments indicate clear asymmetry in response to varied EF direction

- **Inferred Error Fields are observed to be different in low & high-β plasma with assumption of a static error field**

Inferred EF in Low-β



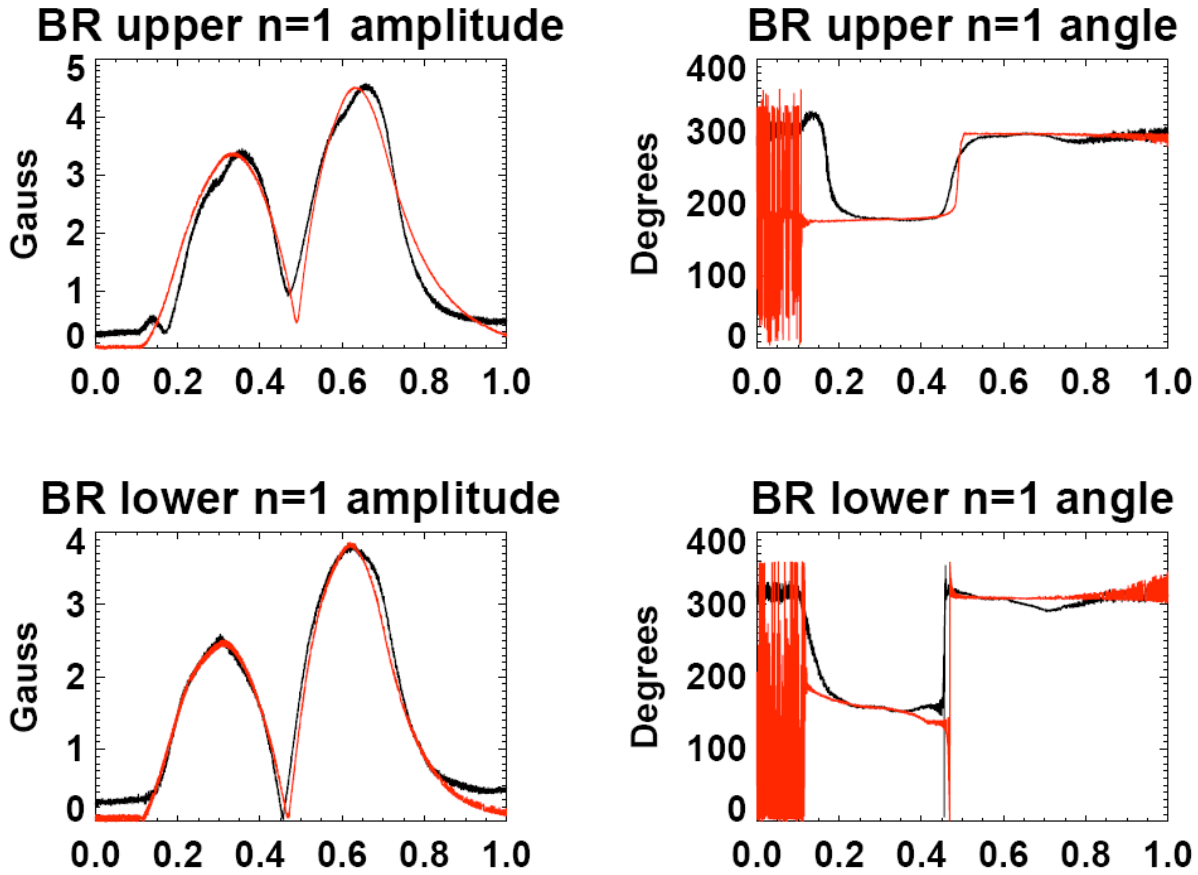
Inferred EF in High-β



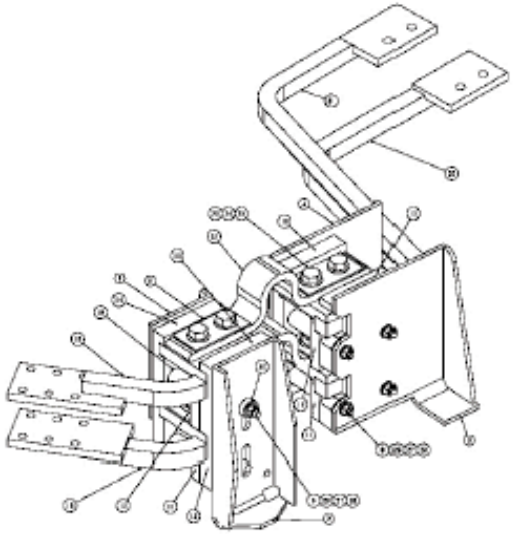
Accurate modeling of n=1 B_R error field from OH+TF requires inclusion of time lag and polarity dependence

- Developed TF model allowing **both shift and tilt**
- Multiple filter time-constants needed to capture time lags
- **Accurate prediction of EF at sensor → hope for predicting EF in plasma**

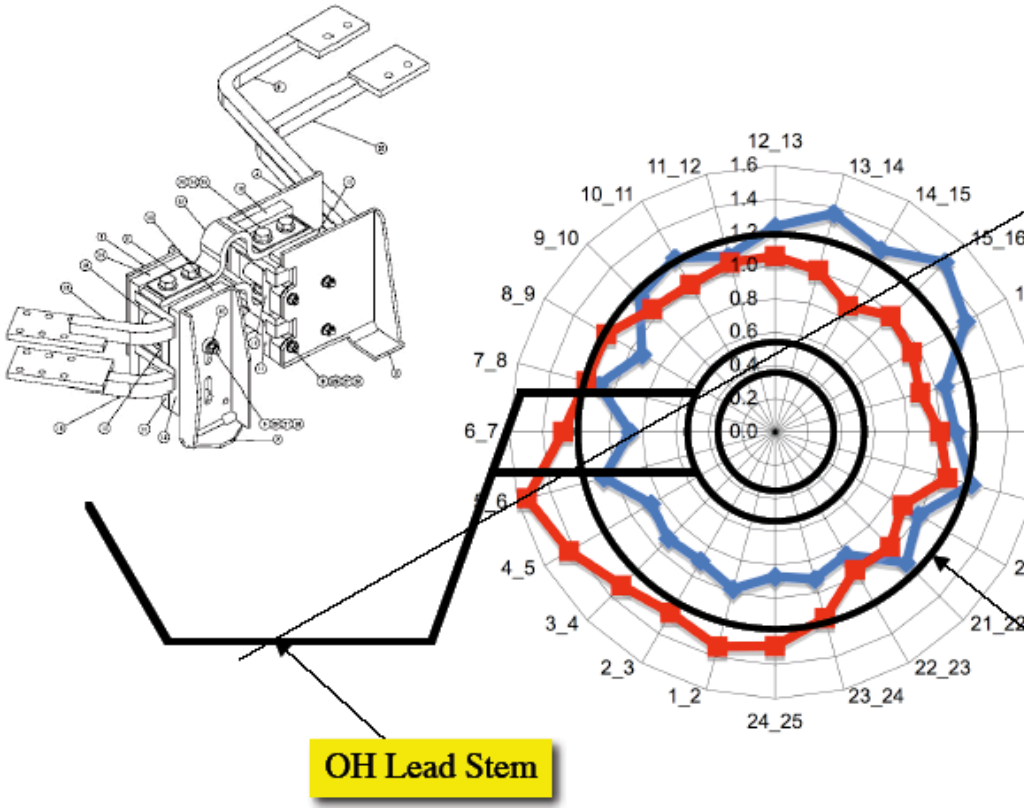
Measured & Simulated error field at sensors

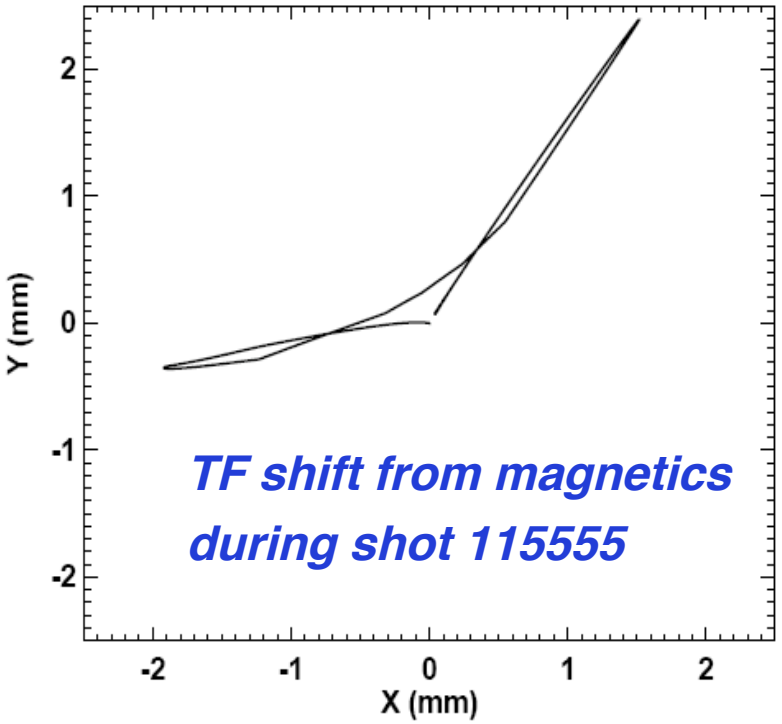


TF flag-joint resistance variation aligns with particular direction consistent with OH lead-stem interaction



TF flag-joint resistance variation direction consistent with direction of translation/shift inferred from magnetics

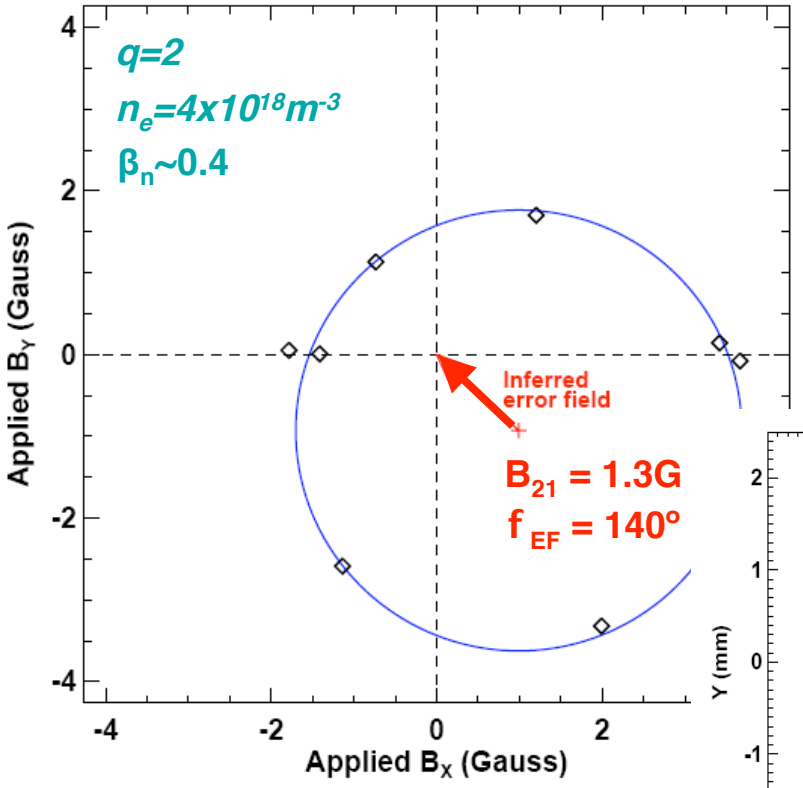




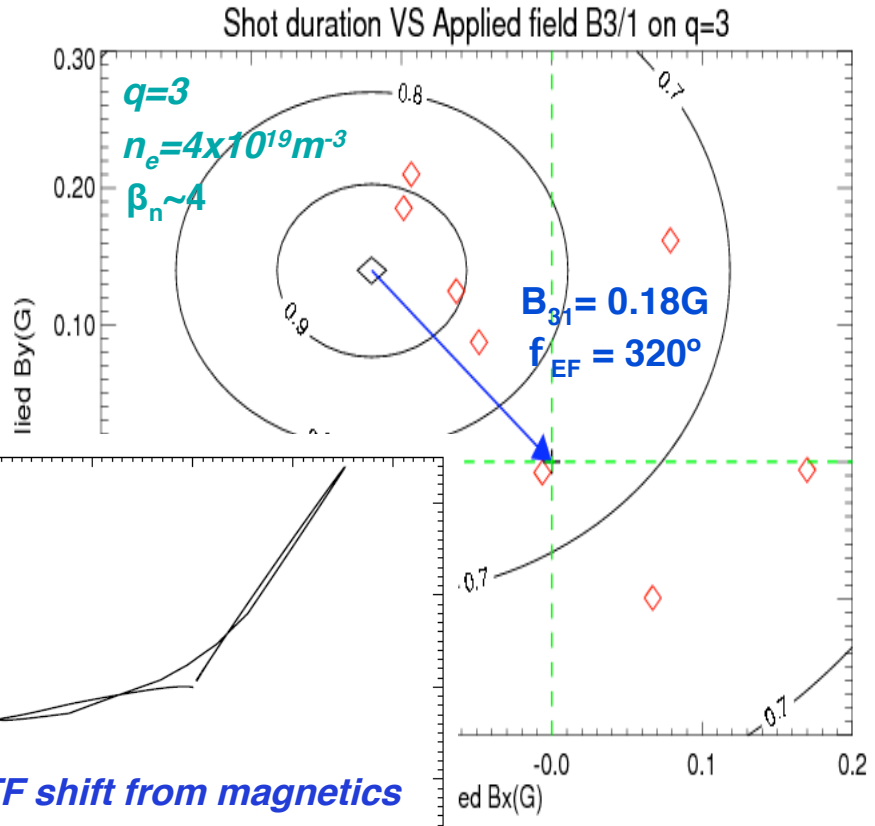
Accumulated data strongly suggests OH/TF interaction creates error field which varies throughout shot even with constant plasma parameters

Error field from TF shift should be orthogonal to shift direction, in reasonable agreement with measurements

Inferred EF in Low-β



Inferred EF in High-β



Low and high-b shots do in fact lock with different OH polarities… Working out signs now…

Summary

- Measured threshold for locking vs. applied error field phase at fixed *B*, shape with varied density
  - Find $a_n \approx 1$
  - Inferred intrinsic error field at low density
  - Inferred intrinsic error field at high-b and high density
- Low b and high b EFC currents have opposite directions
  - PF5 and $I_{OH} \times I_{TF}$ error fields are largest and likely dominate
  - $I_{OH} \times I_{TF}$ EF from TF translation/motion during discharge

Future work

- Expand parameter space for locked mode
  - : n_e, q, B_T and shaping scaling
  - : Low β and High β behavior with sideband effects
- Study sideband effects and mode structure theoretically
  - : DCON/VACUUM code as simulation tools
- Consider multiple resonant and non-resonant EF identification and correction on various surfaces
  - : Multiple EF effects on global plasma behavior
- Implement & test pre-programmed EF correction
  - : Tracking EF during operation by several representative cases such as low/high β
- EF feedback control for locked mode and RWM