PRINCETON PLASMA PHYSICS LABORATORY

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NSTX Error Fields & Locked Modes

from the 2005 campaign

Jong-kyu Park, Jonathan Menard, Russell Feder, Christiane Ludescher, Aaron Sontag, Christina Tcheyan

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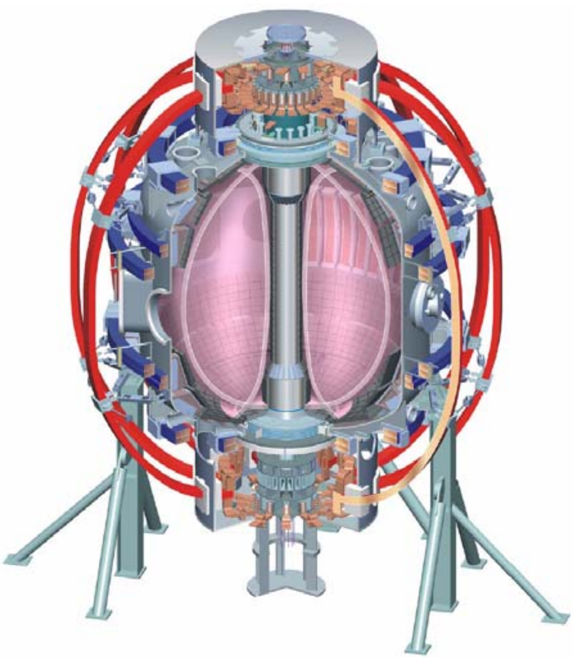

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Abstract (original)

The full set of six mid-plane external error field and RWM control coils has now been installed and utilized on NSTX. Locked-mode threshold experiments performed with these coils imply that a few Gauss resonant 2/1 intrinsic error field(B_{21}^{EF}) is present in NSTX. The in-vessel B_R sensor array and direct measurements of PF coil shapes indicate the presence of an effective shift of the lower primary vertical field coil (PF5) relative to the nominal machine centerline. The error field magnitude predicted by this shifted PF5 model is consistent with the results from locked-mode experiments, but the toroidal phase angle differs by as much as 60 degrees. Thus far, the 2/1 resonant error field threshold(B_{pen21}) for mode locking has been measured as a function of plasma density in NSTX, and locking as a function of q, B_T, and elongation in LSN will be investigated in the near term. These studies will allow comparison to the threshold scaling derived from higher aspect ratio experiments. Plans for error field studies extended to higher-β plasmas will also be discussed. Simultaneously, magnetic field characteristics of external error field coils are investigated in the context of how a desired and pure (n=1, 3) compensating field can be produced. This preliminary study will continue on more efficient pre-programmed and dynamic control of error fields in NSTX.

Goals of research

- **Study low-β locked mode thresholds during I_P flat-top**
  - **Contribute low-A data to scaling studies of locked mode**
    α_n~1, α_B~-1, α_q~0.8-1.6, α_A~0.4-0.8(MAST)

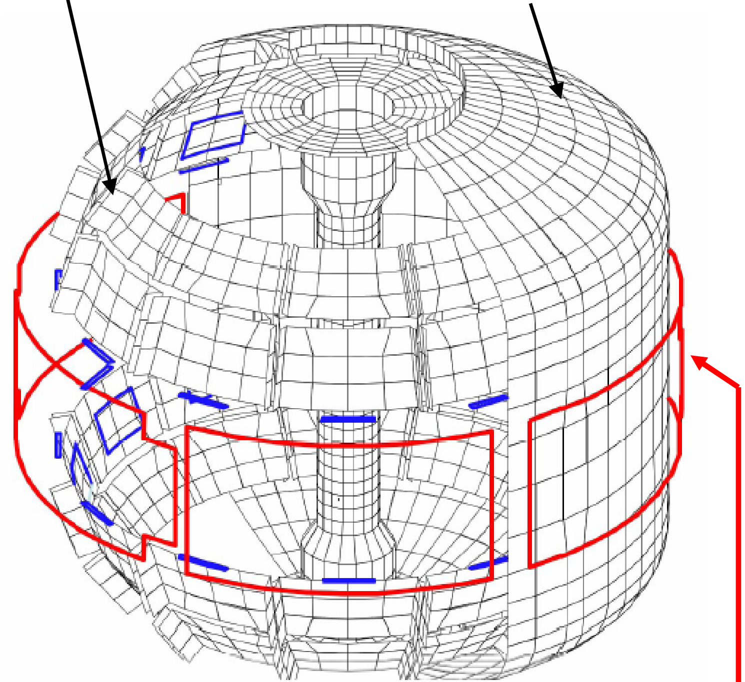
$$\frac{b_{pen}}{B_t} \propto n^{\alpha_n} B^{\alpha_B} q^{\alpha_q} (R/a)^{\alpha_A}$$

  - **Investigate Shaping scaling of threshold**
    κ~1.6-2.0, q* and q_{95}(Triangularity)
- **Study for control of locked mode by using RWM coils**
  - **Measure and predict all possible external error field sources**
    Static and Dynamic error fields from PF or TF coil Shift/Tilt
  - **Correct error fields and study locking behavior by RWM coils**
    Focus on resonant fields on surfaces (B2/1 on q=2, B3/1 on q=3)
  - **Comparison predictions with low/high β experiments**
    Study for possibility of Internal error fields and error amplifications
    Study for possible way to make feed back control for locked mode

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

Copper passive conductor plates

SS Vacuum Vessel

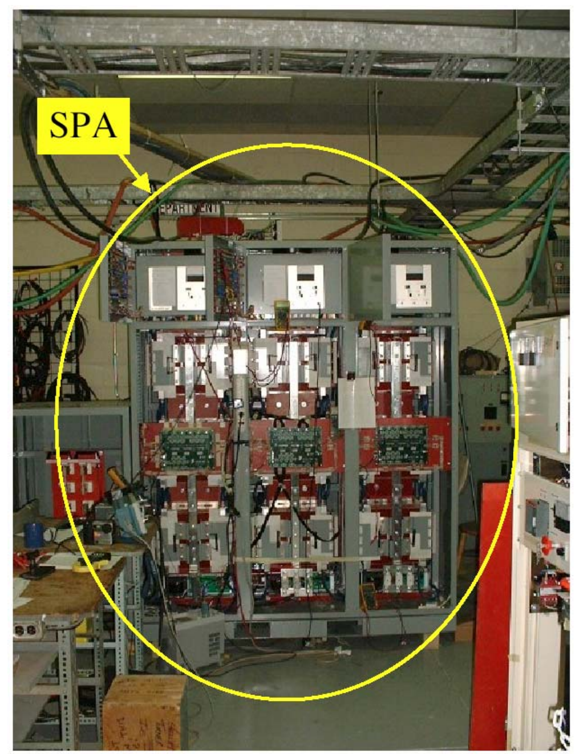


VALEN Model of NSTX (Columbia Univ.)

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

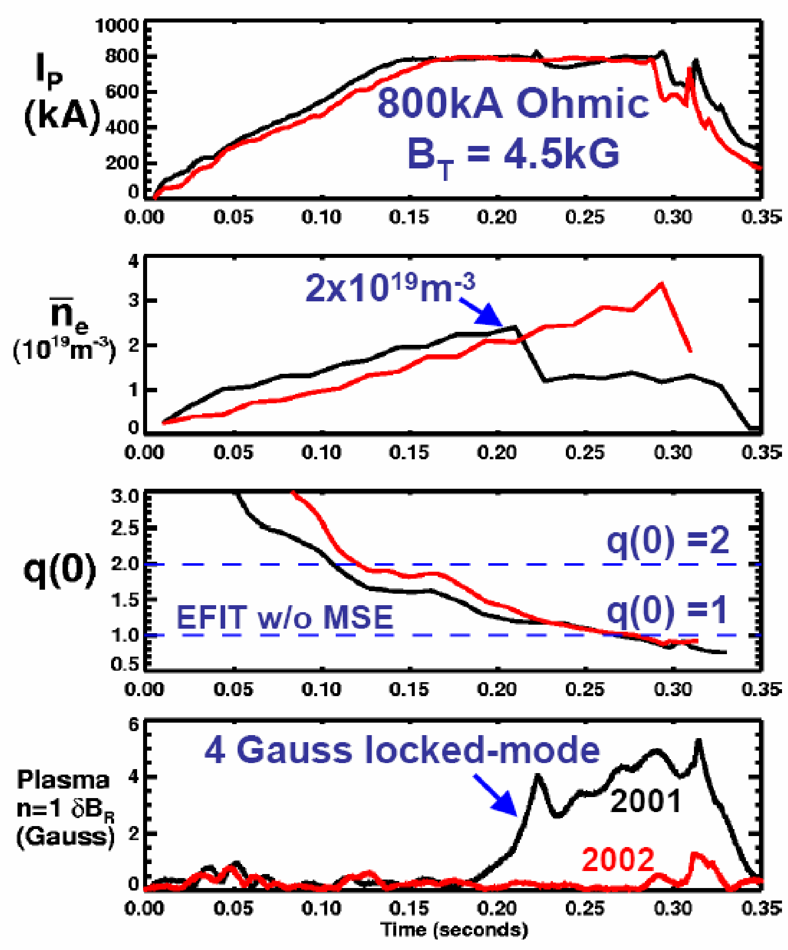
NSTX RWM/EF coil and SPA capabilities:

- 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

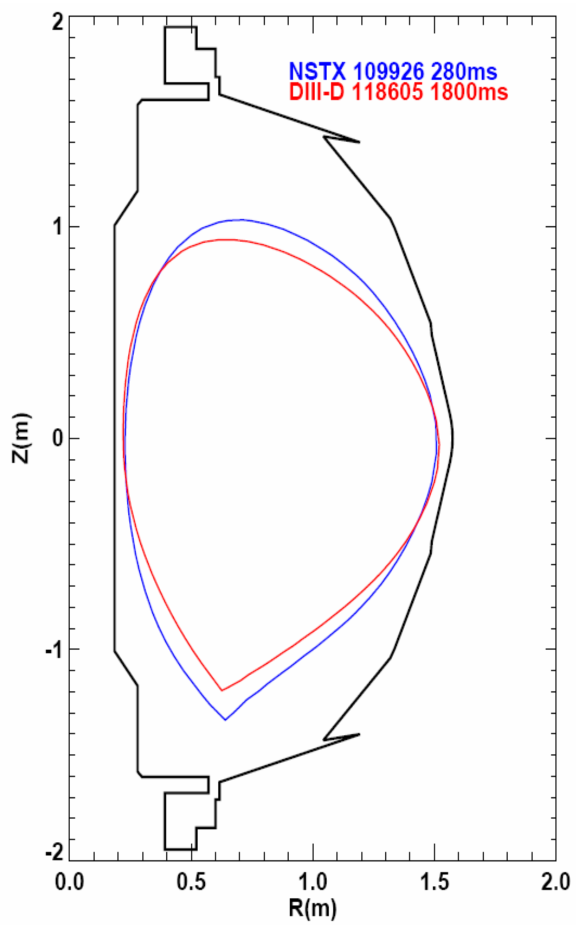


Experiment focuses on moderate δ LSN shape

Can compare results to previous NSTX locking data

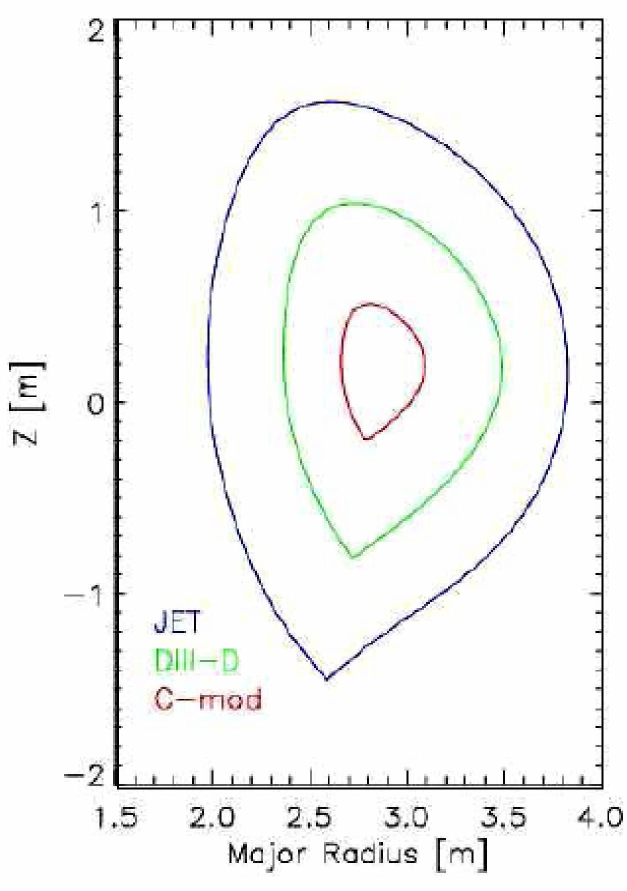


Can compare directly to ITPA Joint-Expt locked mode results

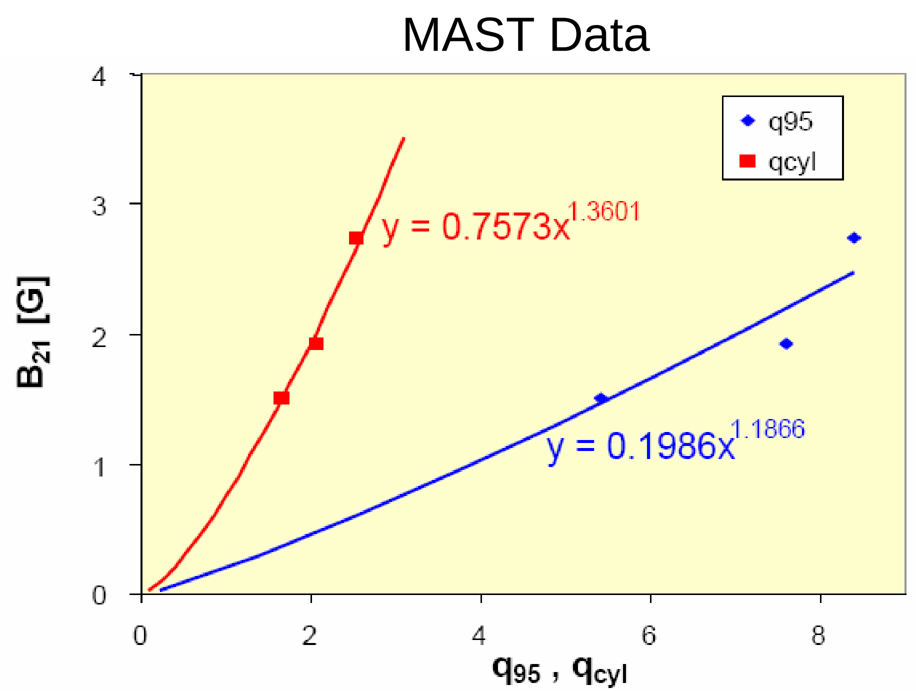


Relationship to other experiments and results

LSN shape used in high-A identity experiments which matched ρ^* and ν^*



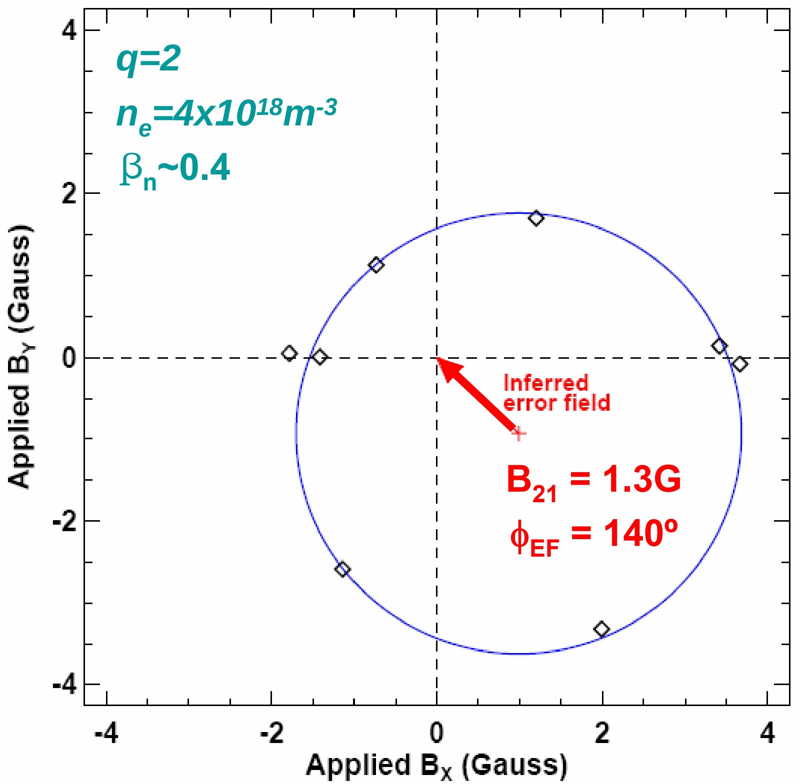
Shaping dependence and separation of q_{95}, q^*, q_{cyl} at low-A not considered yet in high-A scaling studies



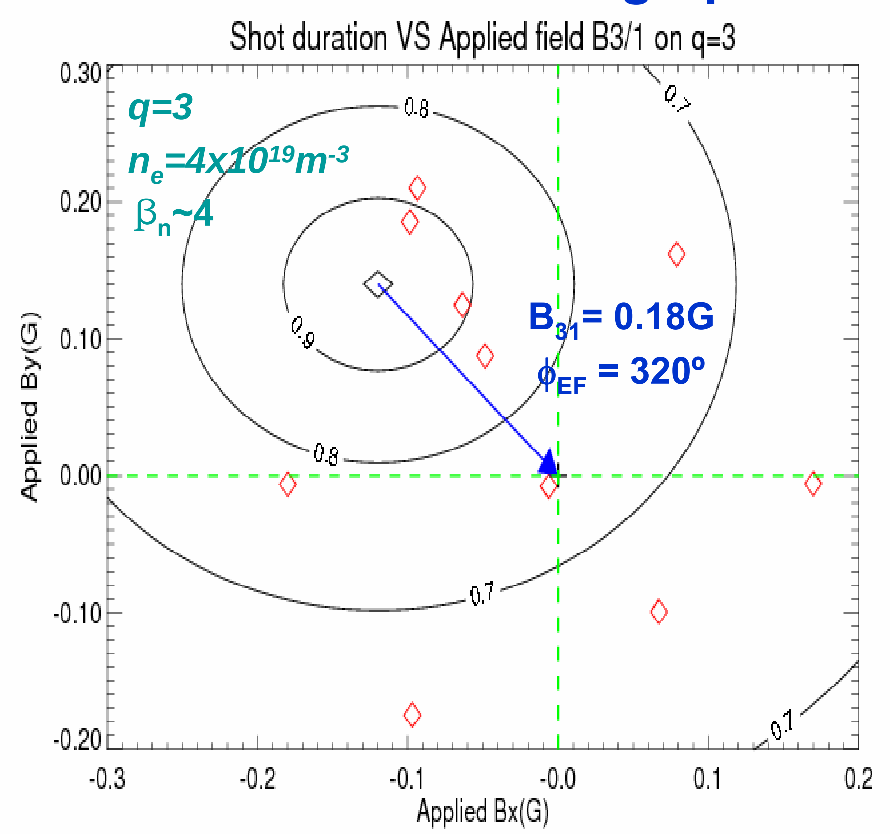
Locking threshold experiments indicate clear asymmetry in response to varied EF direction

- **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



Error Fields (EF) identifications I

- Non ideal formation of coils produces Error Fields (EF)
  - External EF by intrinsic deformation and dynamic changes of coils
  - Internal EF by surface currents on other surfaces
- The respective EF harmonics matter on rational surfaces
  - 2/1 on q=2 surface is the primary source of locked mode
  - Higher modes can have influences on 2/1 modes by coupling activities
- n=1 component EF is produced by the lowest order deformation
  - Shifts and tilts of each coils are the most important sources
- Each EF sources can be analyzed by linearization
  - Each EF vectors can be add up linearly because of small deformations
  - Different magnitudes and phases on different q surface shapes

$$B_{nm}^{EF} = \sum_{i}^{each\ coils} I_i(t)\left(S_i(t)\overline{\xi_{nm}^{EF}(profile)} + T_i(t)\overline{\eta_{nm}^{EF}(profile)} \right) + Internal\ EF$$

$Where\ I_i\ is\ current,\ S_i\ is\ shift\ and\ T_i\ is\ tilt\ of\ each\ coils$

Error Fields (EF) identifications II

- The meaningful EF can be defined by helical flux

  : Surface integration of perturbed B perpendicular to helical surface

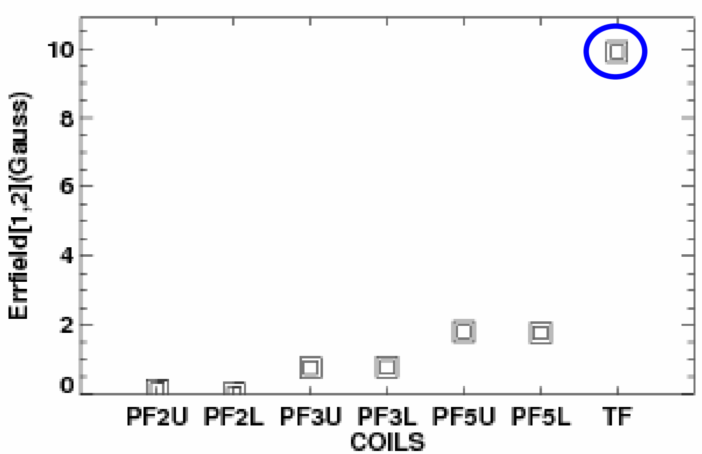
  - For convenience in this article, EF is defined by

$$B_{mn}^{EF}\,(or\,\xi_{mn}^{EF}\,,\zeta_{mn}^{EF}\,)\equiv\psi_{mn}^{h}=\sigma\left[\,R^{3}\left|\frac{q}{F}\right|(\,B_{Z}\delta B_{R}-B_{R}\delta B_{Z}\,)\right]_{mn}$$

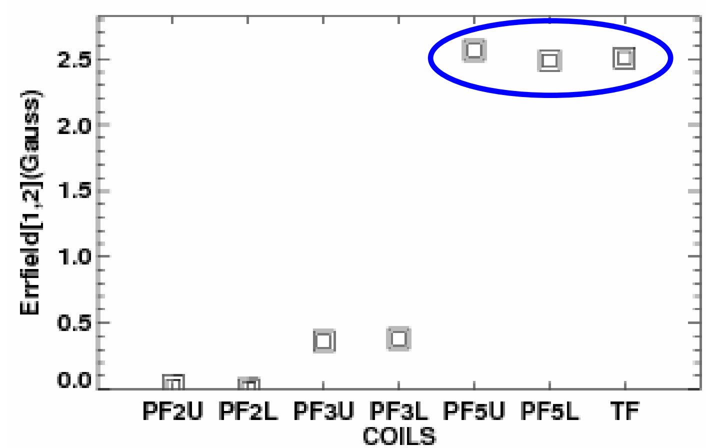
Where σ *is a polarity and phase factor and* $F=B_{\phi}R$

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

By same shift with current weights



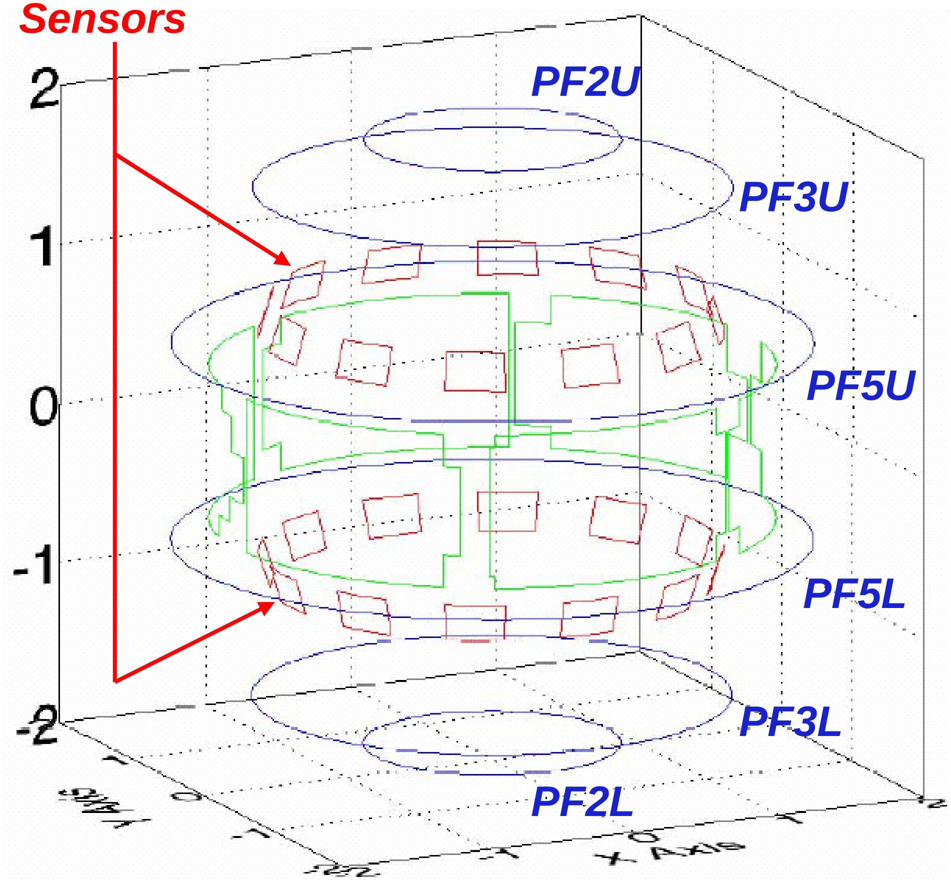
By same tilt with current weights



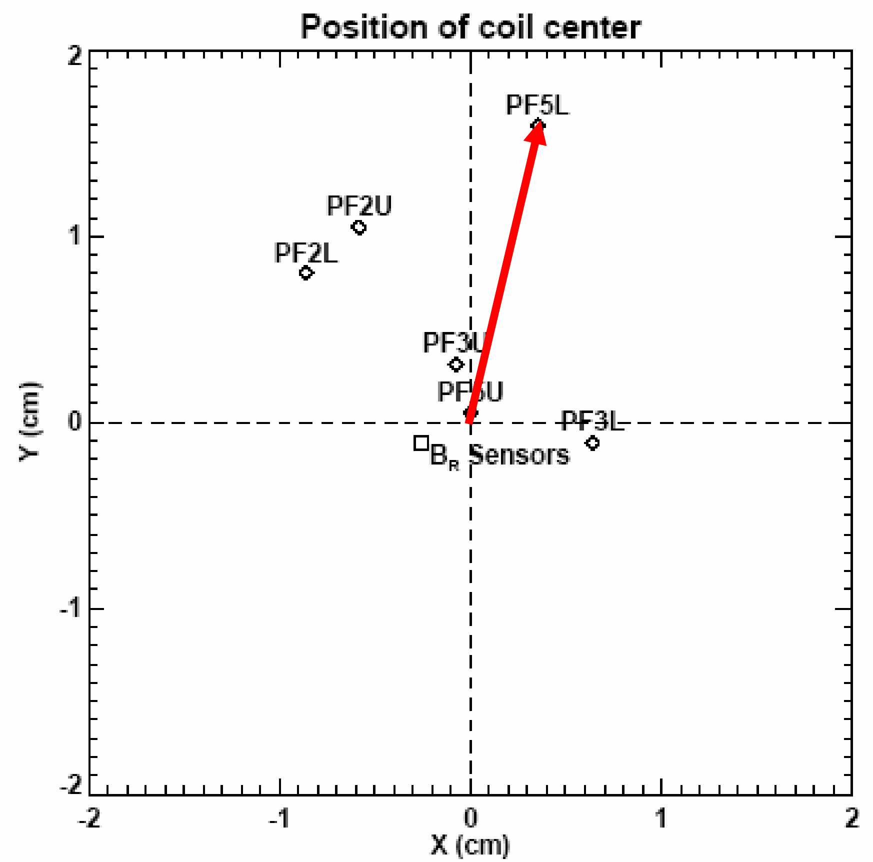
EF Sources I : PF coil up/down asymmetry inferred from internal B_R sensors

NSTX

Filament model of coil/sensor system

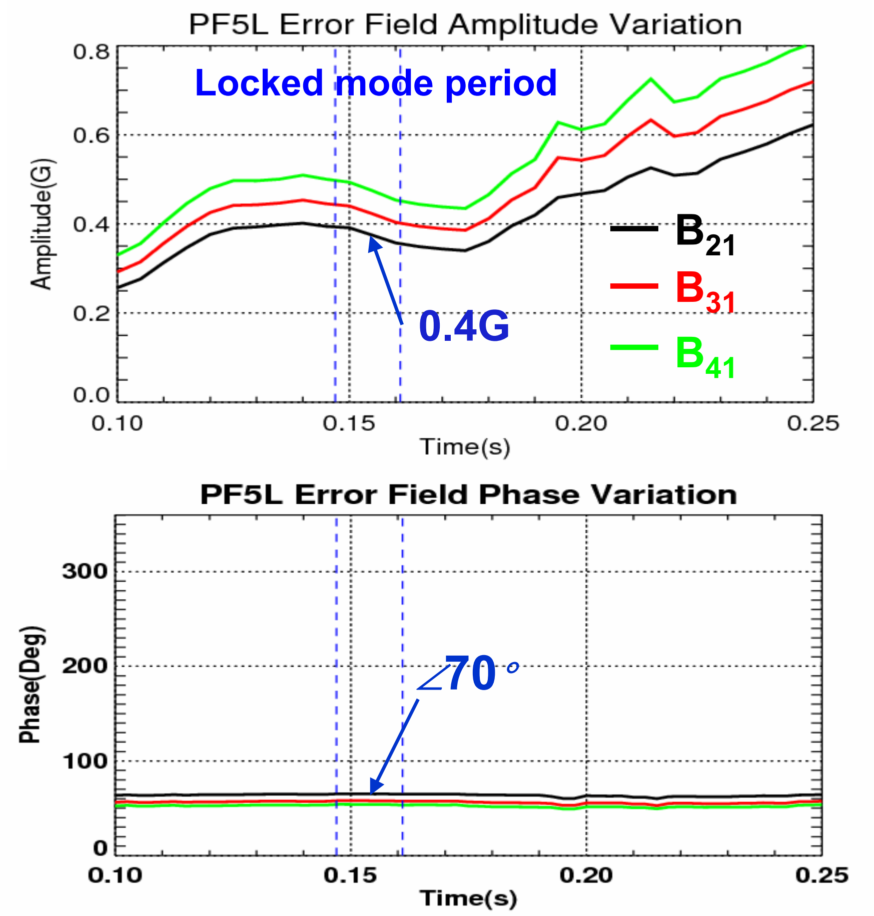


Largest apparent shift occurs in primary vertical field coils (PF5)

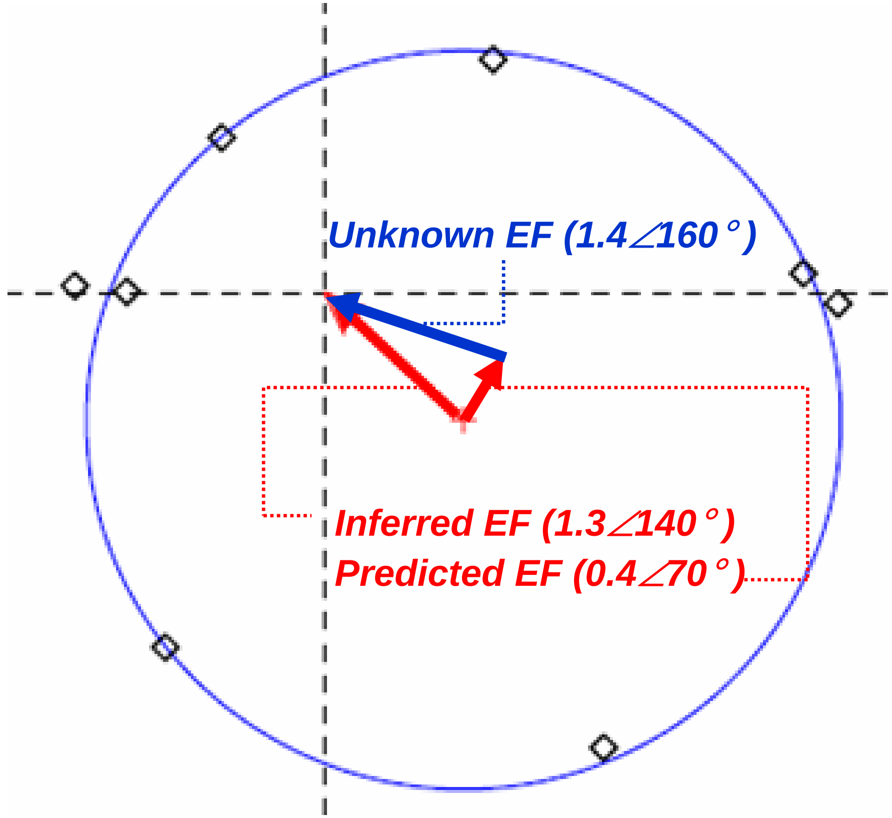


Static PF5L shift model based on measurement show disagreement with low-β experiments

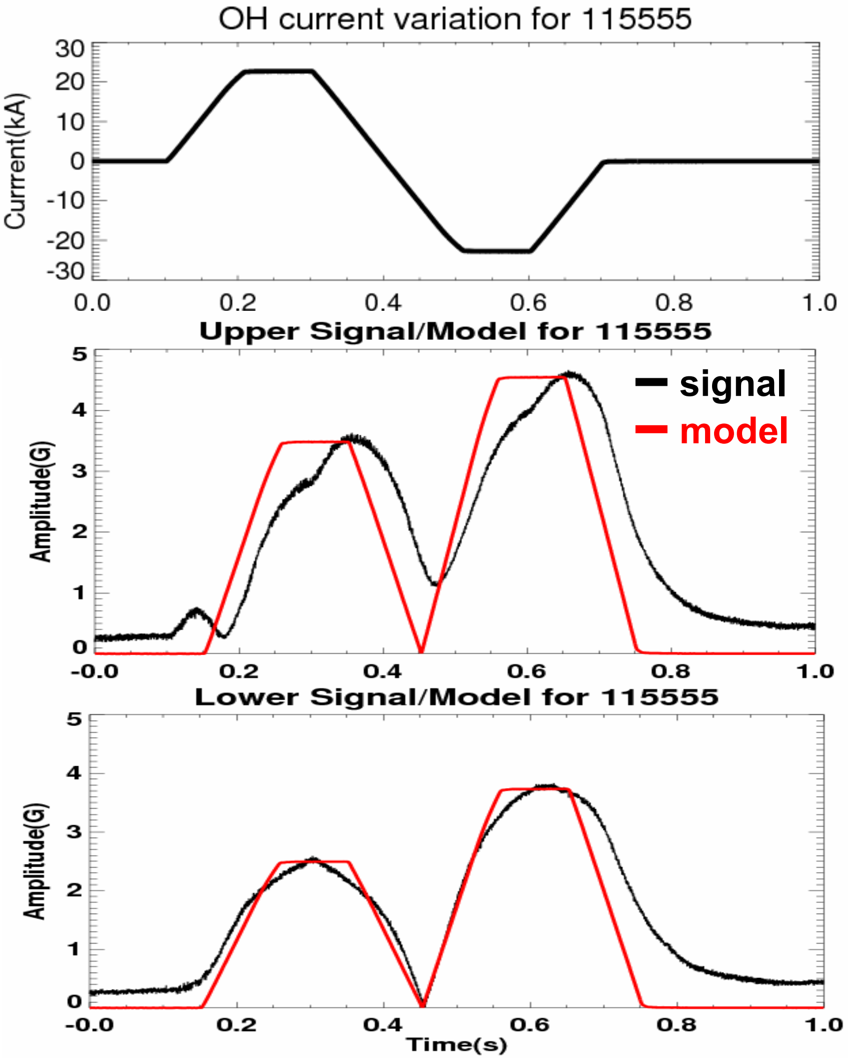
- EF by PF5L shift is nearly constant during locked mode



Small correction to unknown EF
: Need TF EF information



EF Sources II: Linear OH×TF model can explain time dependence of unknown EF

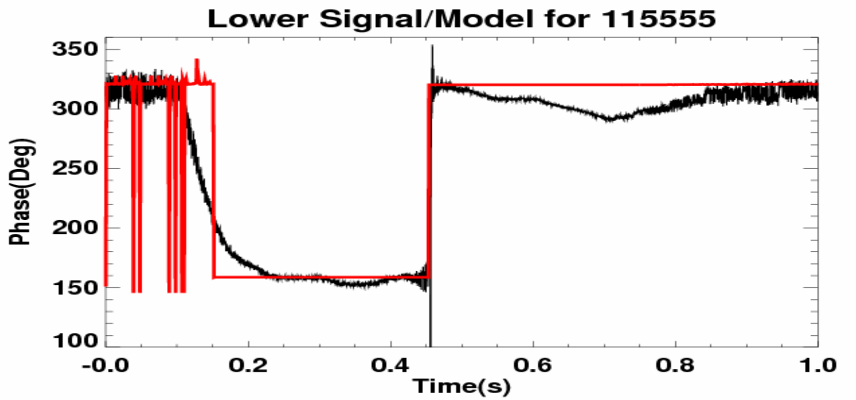


- **OH and TF coils are expected to make time-dependent EF by interaction in joints and clearly by vacuum shots**
- **To explain two types of asymmetries, apply linear model of two polarities with TF tilt and shift**
- **Time lag of 50ms is necessary**

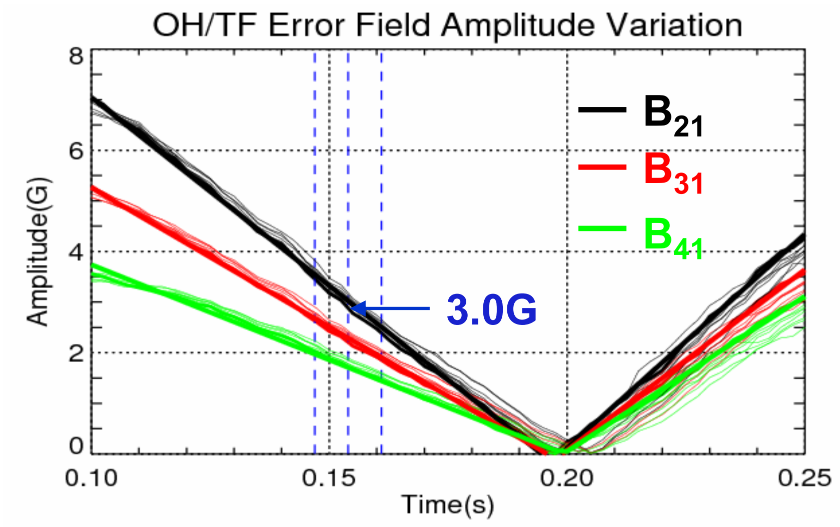
$$X = (I_{OH}(t-0.05)/24kA)(I_{TF}(t-0.05)/40kA)$$

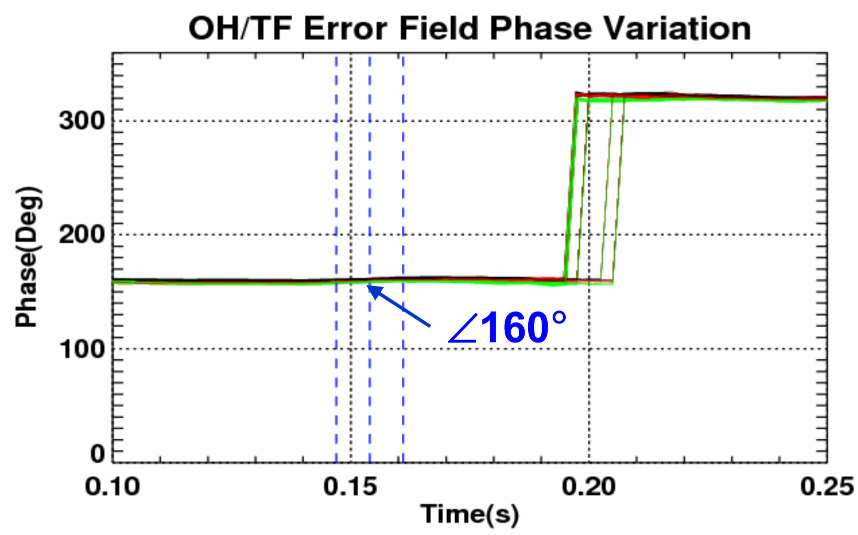
$$Shift(m) = 0.0052X\angle 238^\circ + 0.0012|X|\angle 194^\circ$$

$$Tilt(^\circ) = 0.048X\angle 241^\circ + 0.009|X|\angle 118^\circ$$



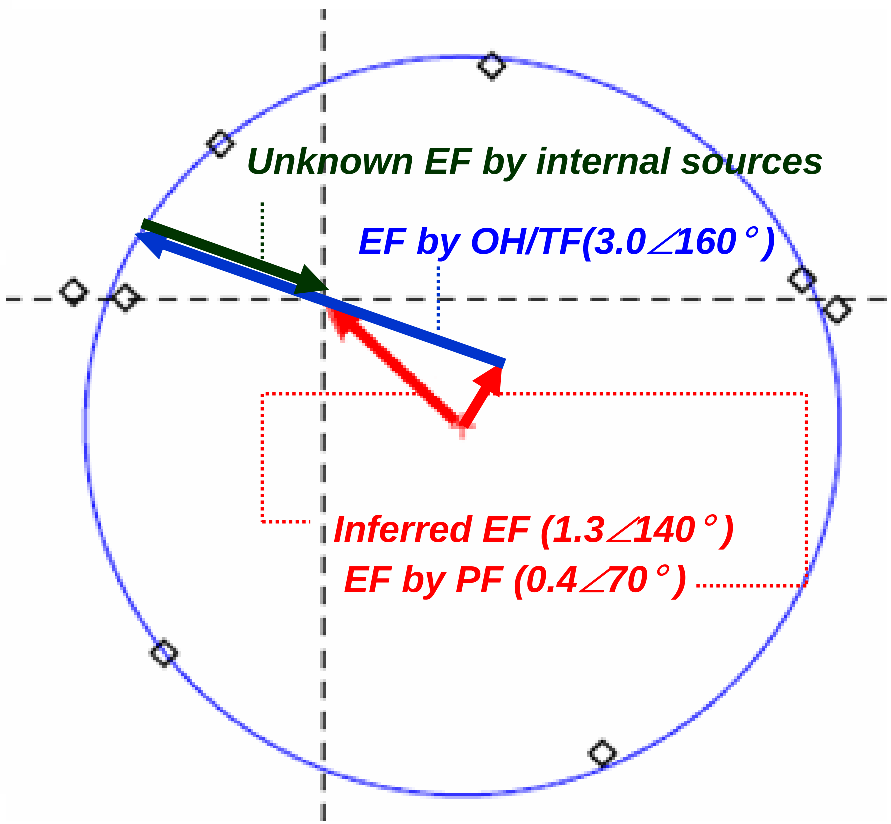
Static analysis of external sources shows good agreement only in phase





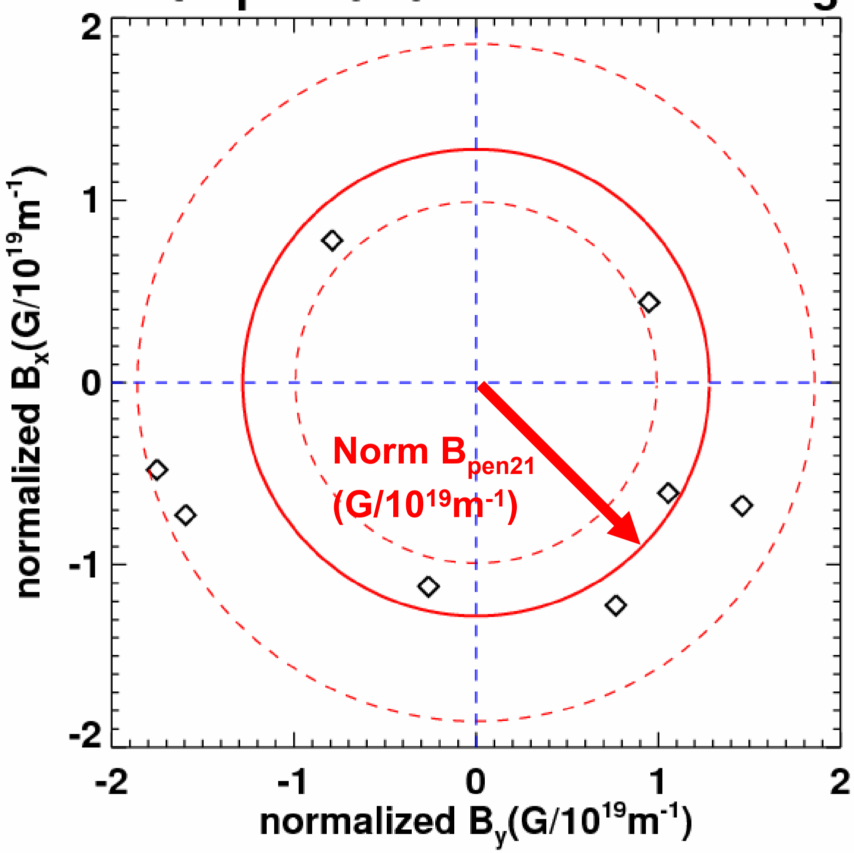
- **Average external EF at relevant time is in same phase with inferred EF, but still need more to explain apparent different magnitude**

: Need Internal modification



EF Sources III: Internal EF from mode coupling with sidebands can explain unknown EF with proper scaling

Total penetration EF and Scaling



- Normalize penetration EF by Locked mode scaling form to consider sideband coupling effect

Regression Analysis with

$$B_{pen21} = C B_T^{\alpha} n_e^{\beta} q_{95}^{\gamma} \;\; (\, Assume \; \alpha \sim 0, \beta \sim 1\,)$$

$$T \propto B_{pen21}^{\;2} = \left[B^{EF}_{\perp 21}(t) + U \bullet B^{EF}_{\perp 31}(t) \right]^2 + w(t) B^{EF}_{\perp 31}(t)^2$$

$$B^{EF}_{\perp nm} = B^{OHTF}_{\perp nm}(t) + B^{SPA}_{\perp nm}(t) + B^{PF}_{\perp nm}$$

$$\left\langle B_{pen21} Rr \right\rangle = 1.3 \left(\frac{B_T}{T} \right) \left(\frac{n_e}{10^{19}\, m^{-3}} \right) \left(\frac{q_{95}}{10} \right)^{0.79}$$

$$with \; U = (-1.5, -1.3), \; w \sim 0$$

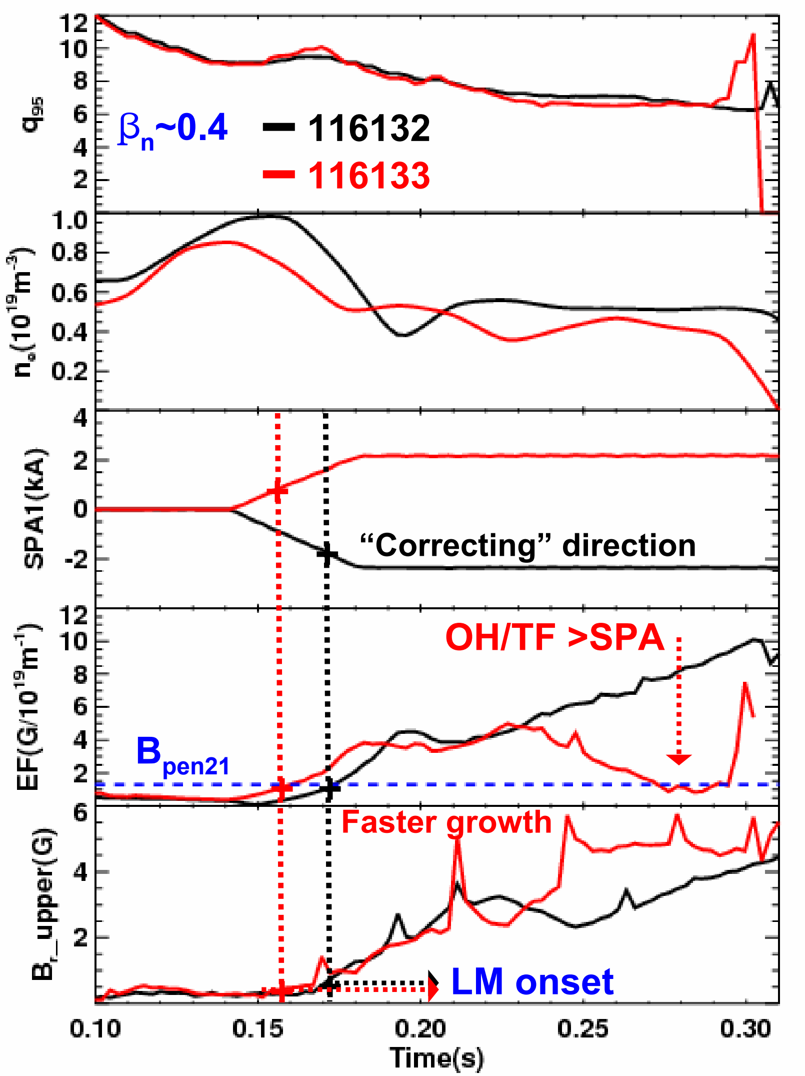
With assumption of $\langle Rr \rangle \sim 2$,

$$B_{pen} = 0.65 \left(\frac{n_e}{10^{19}\, m^{-3}} \right) \left(\frac{q_{95}}{10} \right)^{0.79} \quad in \; NSTX$$

$$compare \;\; B_{pen} = 0.7 \left(\frac{n_e}{10^{19}\, m^{-3}} \right) \left(\frac{q_{95}}{10} \right)^{0.79} \quad in \; DIII-D$$

Rf) Nuclear Fusion 43 (2003) p253, converted

Total EF time evolutions are consistent with locked mode behavior in low-β plasmas

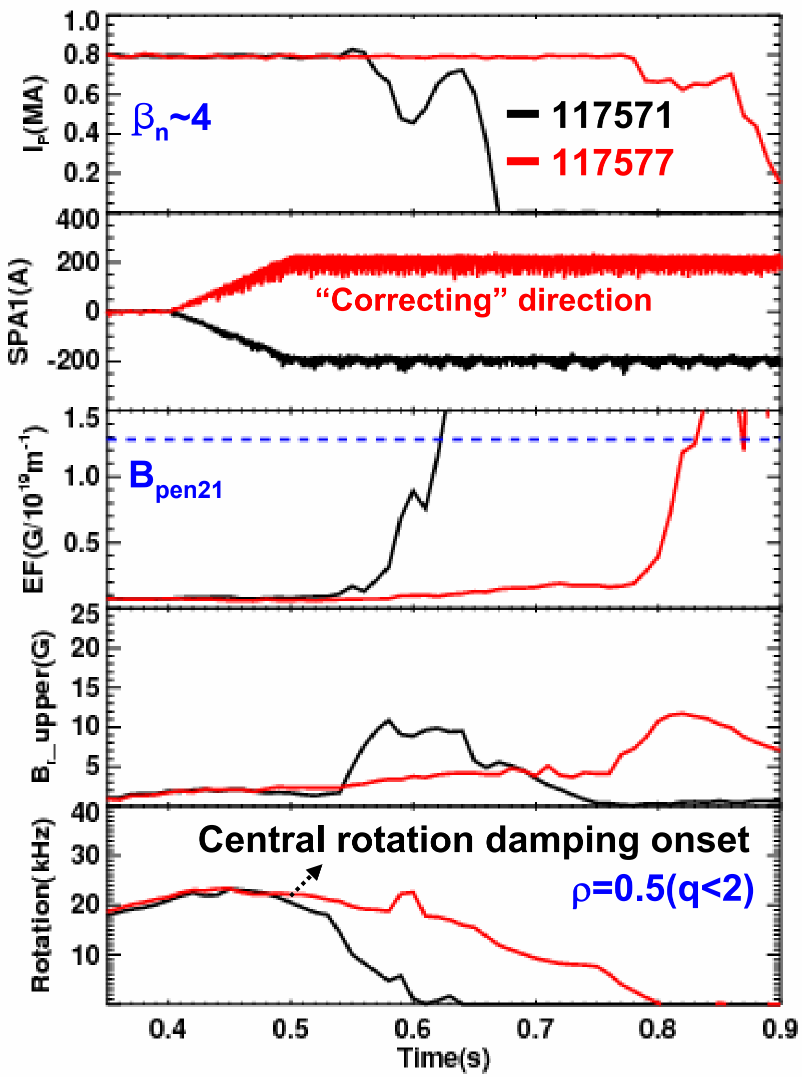


- Locked mode scaling from assumptions of **external PF, dynamic OH/TF EF** and **internal sideband EF** matches reasonably to low-β plasma experiments

- Applied external currents can control locked mode by maintaining total EF below B_{pen21}, but **should follow EF dynamically**

- Applied external coils cannot control EF amplifications after locked mode onset

The higher modes of EF should be considered for prediction of high-β plasma responses



As expected,

- **The reduced EF by RWM coils prevents earlier locking and disruption of high-β plasmas**
- **The "correcting" direction of EF in high-β is opposite to one in low-β because of OH polarity changes during long operation**

However,

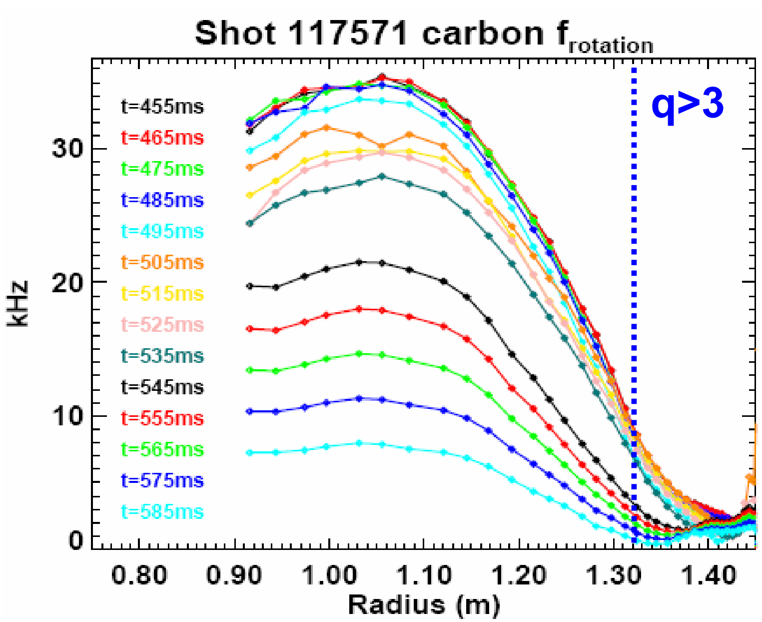
- **Plasmas are locked although B_{21}^{EF} is maintained in very low level comparing to B_{pen21}**
- **Rotation damping is observed internally before locking**

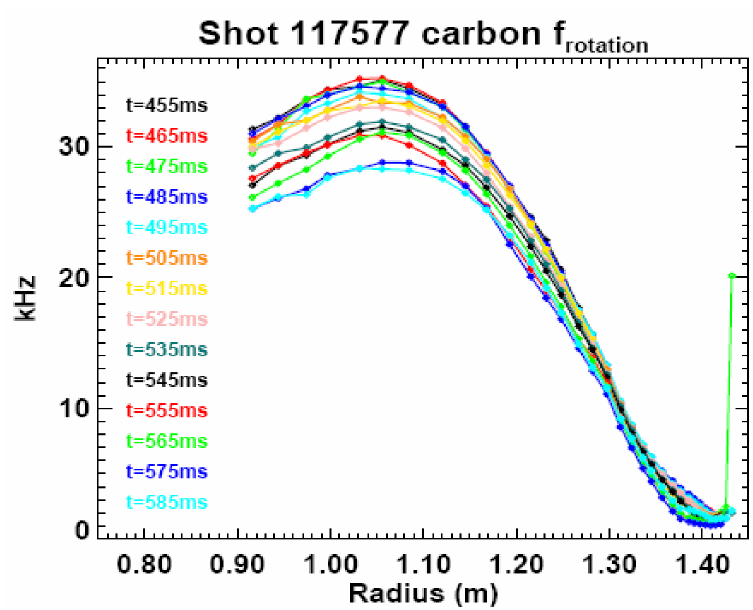
Possibly,

- **The higher modes and/or RWM should be considered**

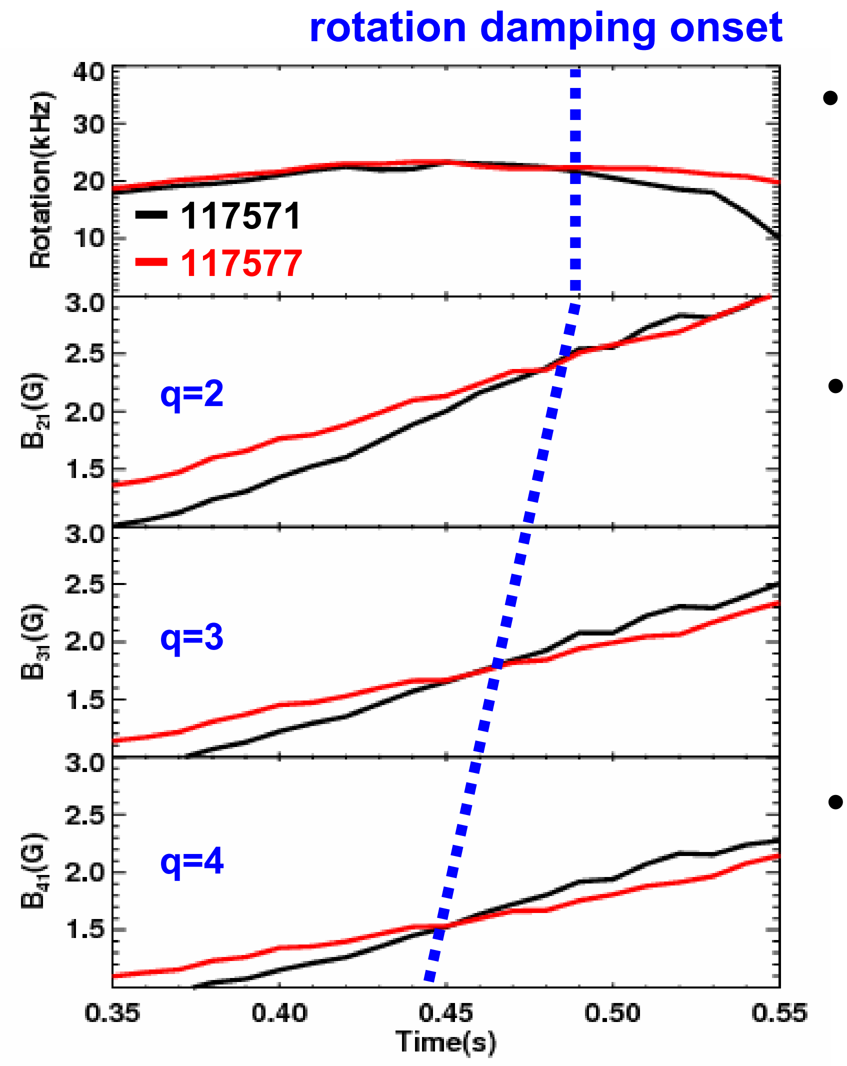
Plasma rotation indicates error fields affect various surfaces globally

- Rotation around q=2 surface is damped after locking of rotations on higher mode rational surfaces: importance of EF on higher q surfaces
  - Rotation is damped in “non-correcting” directions and leads to earlier island locking and/or RWM formation
  - Central rotation is sustained in “correcting” direction and extending pulse length



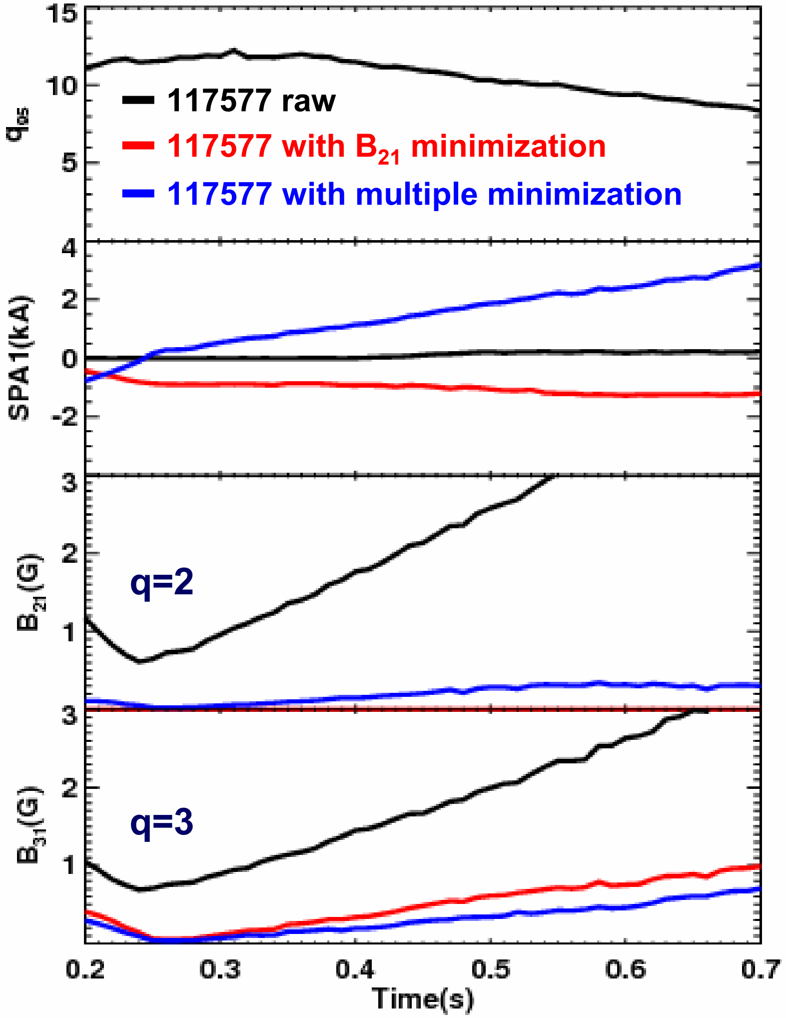


The consideration of higher resonant EF is necessary for plasma behavior in long time scale

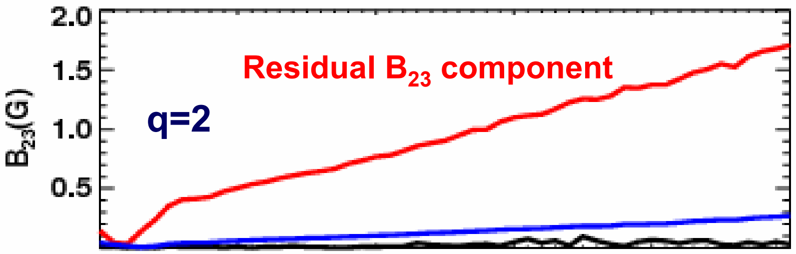


- The "non-correcting" and "correcting" EF are **different more clearly in higher modes** in higher resonant q surfaces
- Time evolutions of EF indicate that higher resonant error fields respond **more sensitively to perturbed error fields, affect to lower and inner surfaces, and finally change global plasma behavior**
- The penetration and coupling of higher resonant modes of EF are unknown but important in long time scale

The applied EF by RWM coils should be preprogrammed for minimization of multiple modes



- The most dangerous B_{21}^{EF} on q=2 surface can be completely removed by proper RWM coil currents, but with various residual EF, especially large n=3 components
- As expected in high-β plasmas, multiple minimization and/or reduction below penetration EF of various resonant error fields is necessary for suppression of locked mode and/or RWM in long time scale



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