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NSTX

# Progress in understanding error-field physics in NSTX spherical torus plasmas


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**J.E. Menard, PPPL**
for the NSTX Research Team


**Error Field Workshop**
Friday, November 16, 2007
Rosen Centre Hotel - Orlando, Florida


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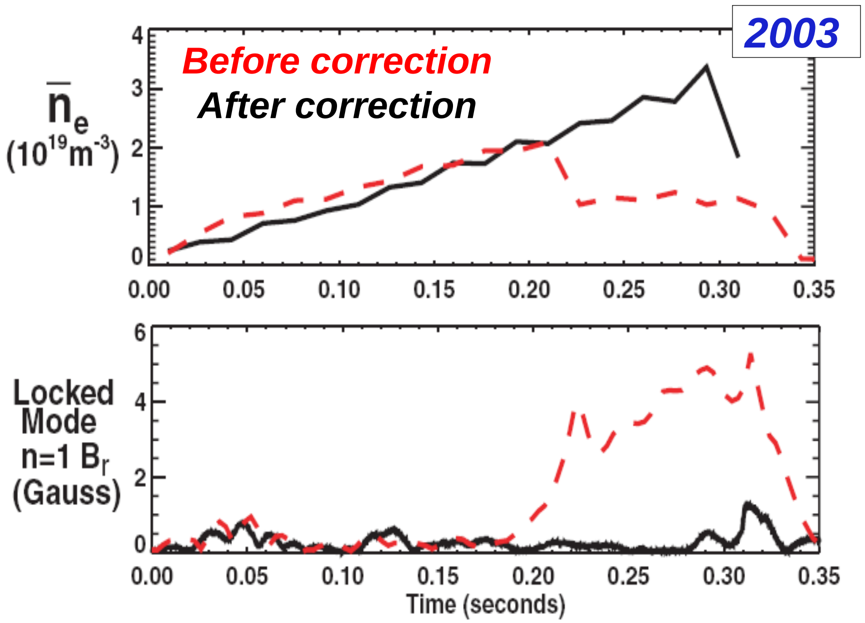
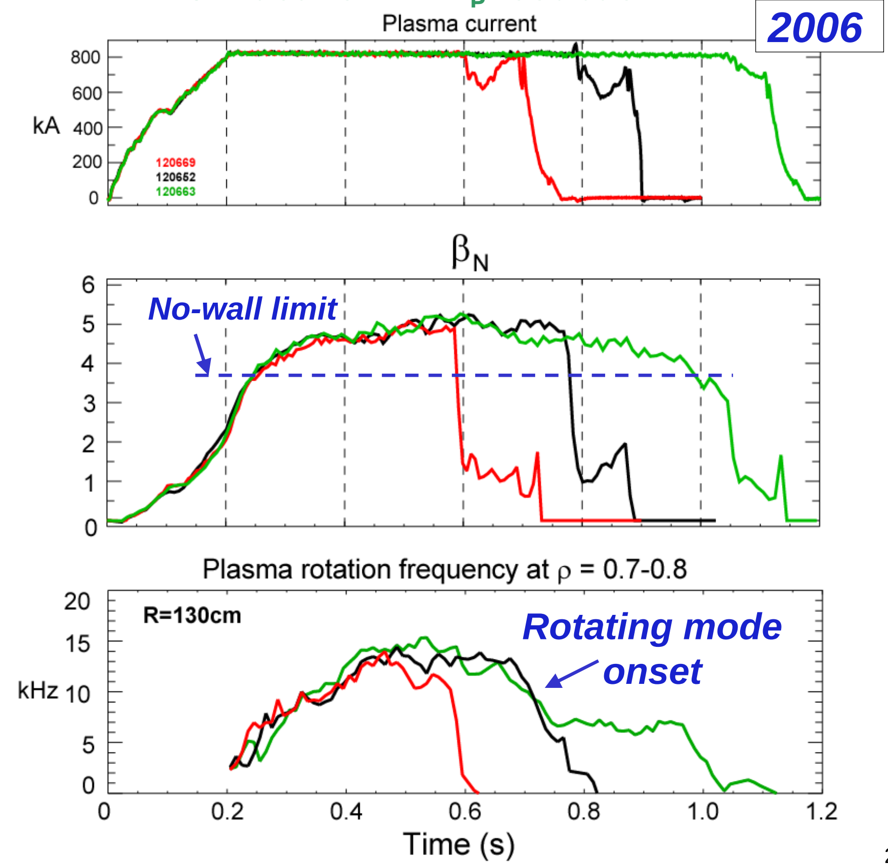
# Detection and correction of small (<0.1%) low-n deviations from axisymmetry can significantly improve plasma performance

- Correction of n=1 PF coil error fields allowed stable operation at low density w/o mode locking




- Correction of n=1 TF coil error field → extended stable operation with $\beta > \beta_{no\text{-}wall}$

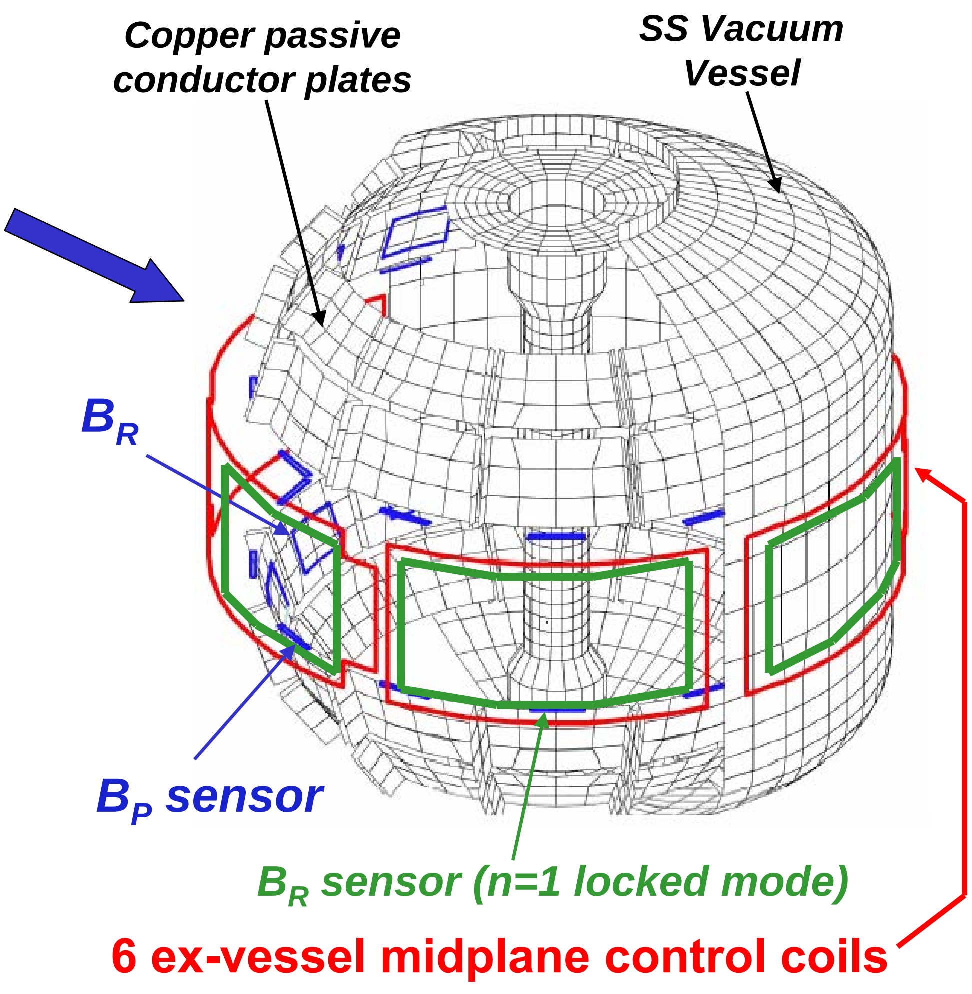
- No error field control during high $\beta_N$ phase
- TF-EFC
- TF-EFC + active n=1 $B_P$ feedback




- Subsequently, sustained high-β operation was routinely achieved, however rotation decay during discharge still observed

# Effective EF and RWM control relies heavily on robust detection of small (~1G) non-axisymmetric magnetic fields

- NSTX has powerful low-f mode detection capabilities:
  - 54 sensors, 2 components of B:
    - 30 radial ($B_R$) and 24 poloidal ($B_P$)
    - 6 $B_R$'s are ex-vessel saddle coils
  - Toroidal mode-numbers n=1, 2, 3
    - Only n=1 used in real-time thus far
- In FY06 only $B_{P\text{-}U}$ used for control
  - Limited by available run time
- In FY07 several new RWM/EF sensor combinations tested :
  - $B_{P\text{-}U}$ + $B_{P\text{-}L}$
  - $B_{R\text{-}U}$ + $B_{R\text{-}L}$
  - $B_{P\text{-}U}$ + $B_{P\text{-}L}$ with spatial offset
  - All sensors in combination
- $B_{P\text{-}U}$ + $B_{P\text{-}L}$ discussed in this talk



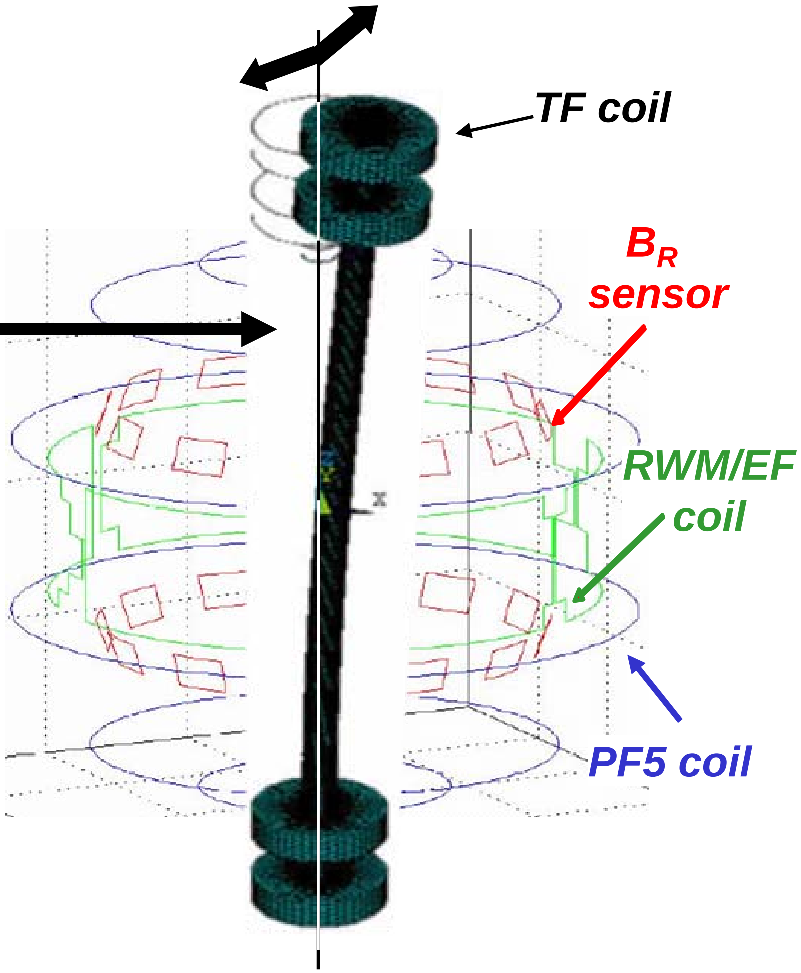

*VALEN Model of NSTX (Columbia Univ.)*

# The NSTX low-frequency mode detection system has been instrumental in identifying vacuum error fields

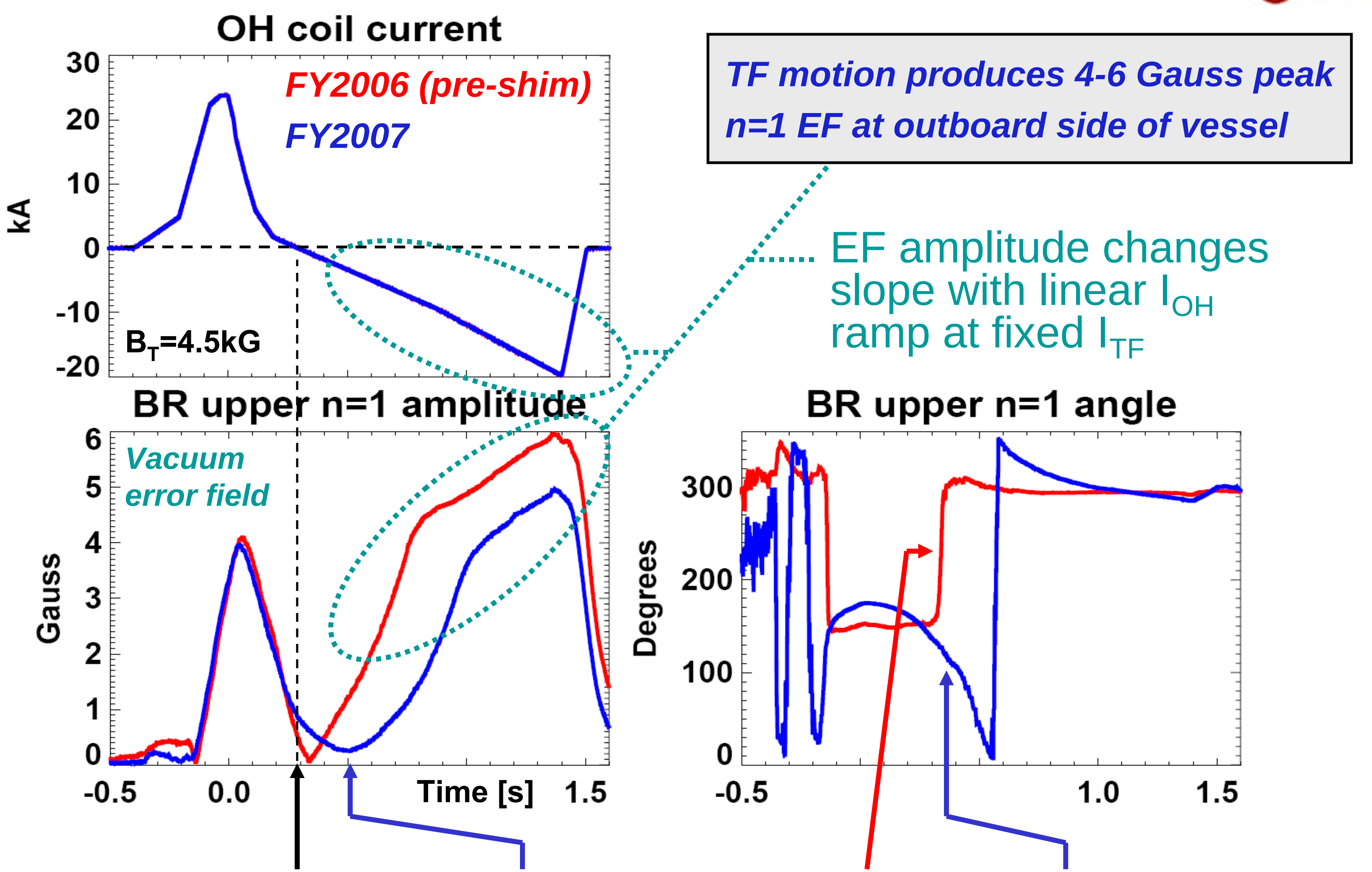
## Error field detection & correction timeline:

- **2001** – Primary vertical field coil (PF5) identified as n=1 EF source, and was corrected in 2002 → sustained high $\beta$
- **2006** – Determined force (from OH leads) at top of machine induces **TF coil motion 1-2 mm at midplane relative to PF coils**
  - → **n=1 $B_R$ EF at outboard midplane**
- **2007** – shimmed TF w.r.t. OH to minimize relative motion of OH and TF
  - – **n=1 EF reduced, but not eliminated**
- **2008-2009 –** will improve connections at OH lead area to reduce forces and EF

*(Displacement exaggerated to show tilting motion)*



# n=1 EF from TF coil motion is $\propto I_{OH} \times I_{TF}$, but has additional time lags and non-linearities which complicate correction




**TF motion produces 4-6 Gauss peak n=1 EF at outboard side of vessel**

EF amplitude changes slope with linear $I_{OH}$ ramp at fixed $I_{TF}$

OH zero crossing precedes minimum EF by 0.2s

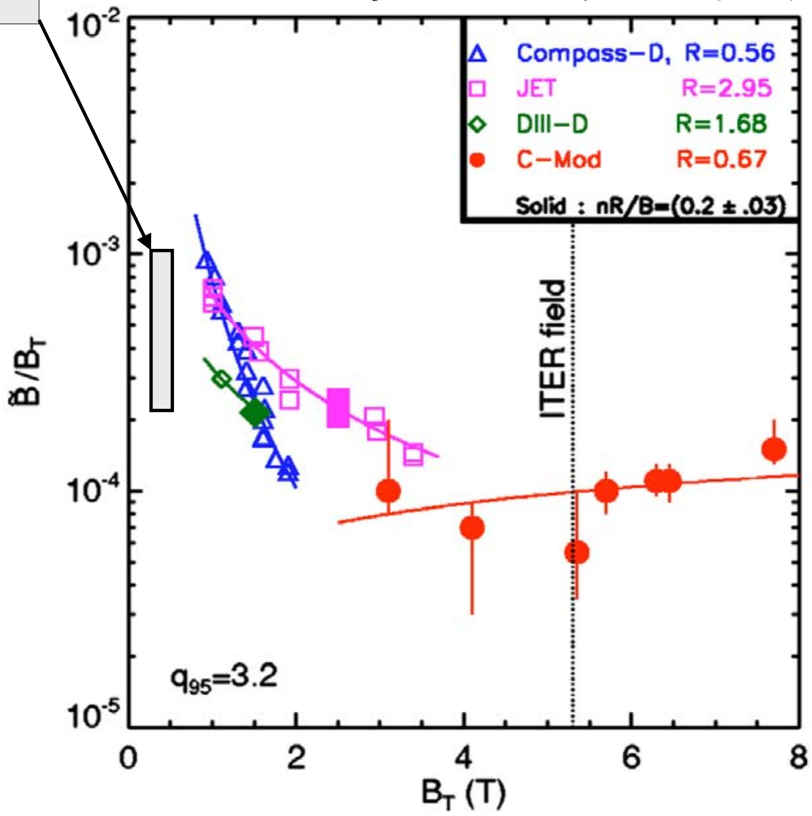
EF phase flips more slowly and in opposite direction following shimming

# NSTX locked mode (LM) studies test locking theories in an extended parameter regime, and establish scalings for the ST

***NSTX LM data extends database to low $B_T$***

- **OHxTF EF model used to estimate the intrinsic EF in calculation of total**
- Linear n=1 EF ramp applied by EF coils to induce LM – detect w/ magnetics
- Span factor of 4 in $n_e = 0.5 – 2{\times}10^{19} m^{-3}$
- Span nearly factor of 2 in $B_T$ = 3 – 5.5kG
- Best fit to data obtained using core shear variable $dq/d\rho|_{q=2}$
  - Commonly used $q_{95}$ not well correlated with shear due to $q_0 > 1$ (no sawteeth)

Wolfe *et al.* Phys. Plasmas **12**, 056110 (2005)




***NOTE: Scaling form used here:*** $\boldsymbol{B_{21}(lock) / B_T \propto n^{\alpha_n} B_T^{\alpha_B} q^{\alpha_q} R^{\alpha_R}}$

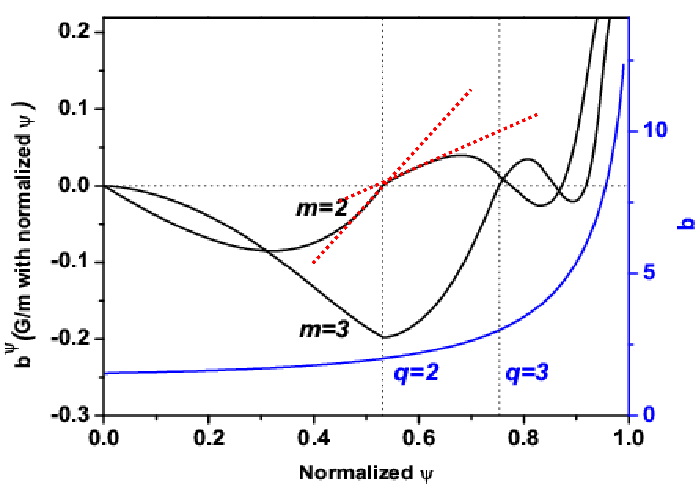
# Analysis of error fields has improved significantly with recent Ideal Perturbed Equilibrium Code - IPEC (from DCON+VACUUM)

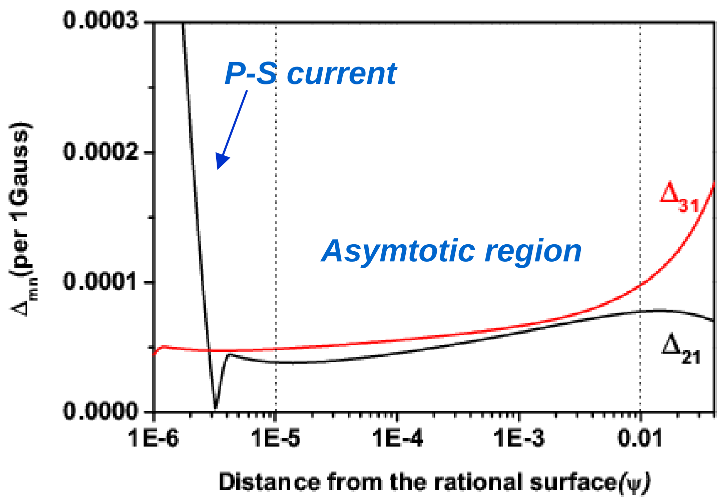
- IPEC finds perturbed equilibrium $\vec{f}_{ideal}(\vec{\xi})=\vec{0}=\vec{\nabla}\delta p+\delta\vec{J}\times\vec{B}+\vec{J}\times\delta\vec{B}$ from an axisymmetric equilibrium $\vec{\nabla}P=\vec{J}\times\vec{B}$ given an external perturbation $\delta\vec{B}^x$

- Ideal MHD constraint does not allow islands, so 3D equilibrium has singular currents to preserve magnetic topology - $\left(\delta\vec{B}\cdot\vec{\nabla}\psi\right)_{mn}=0$ at $q=m/n$

$$\Delta_{mn}=\left[\frac{\partial}{\partial\psi}\left(\frac{\delta\vec{B}\cdot\vec{\nabla}\psi}{\vec{B}\cdot\vec{\nabla}\varphi}\right)\right]_{mn} \Rightarrow \vec{j}_s=\frac{\Delta_{mn} i m e^{i(m\theta-n\varphi)}}{\mu_0 n^2\left(\oint dS B^2/|\vec{\nabla}\psi|^3\right)}\delta(\psi-\psi_{mn})\vec{B} \Rightarrow \left(\delta\vec{B}\cdot\hat{n}\right)_{mn}$$

*Jump of derivative of radial field* — *Parallel singular current preventing magnetic islands from opening* — *Total resonant $B_\perp$ driving magnetic islands (w/o rotation)*



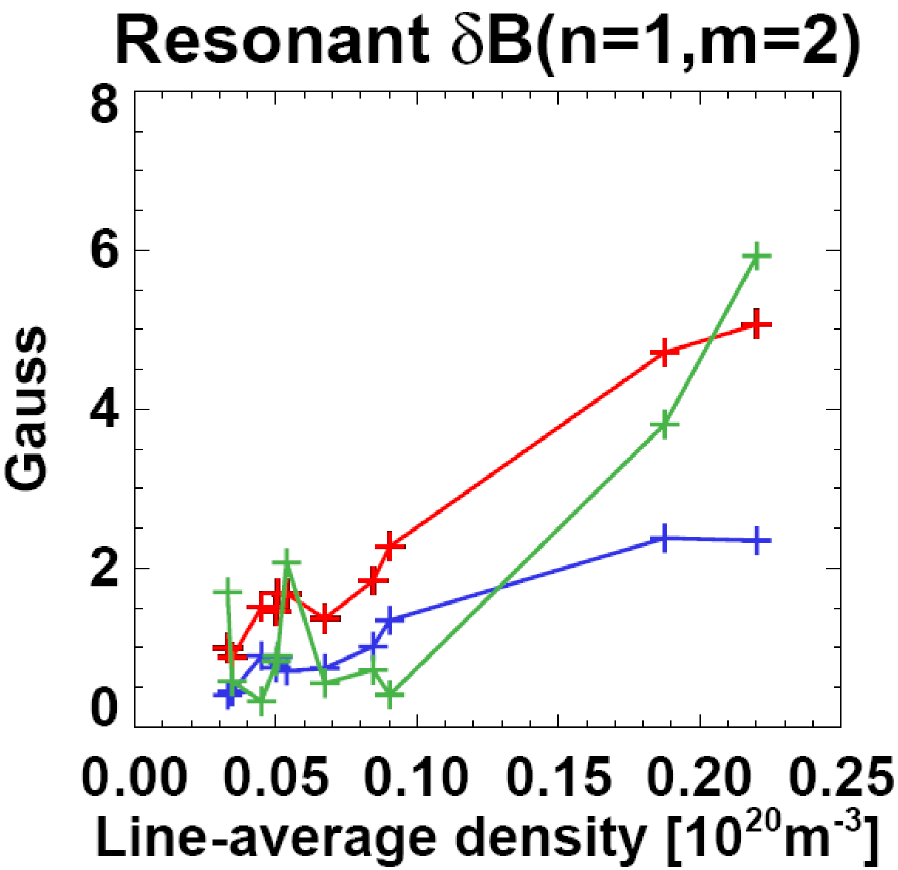



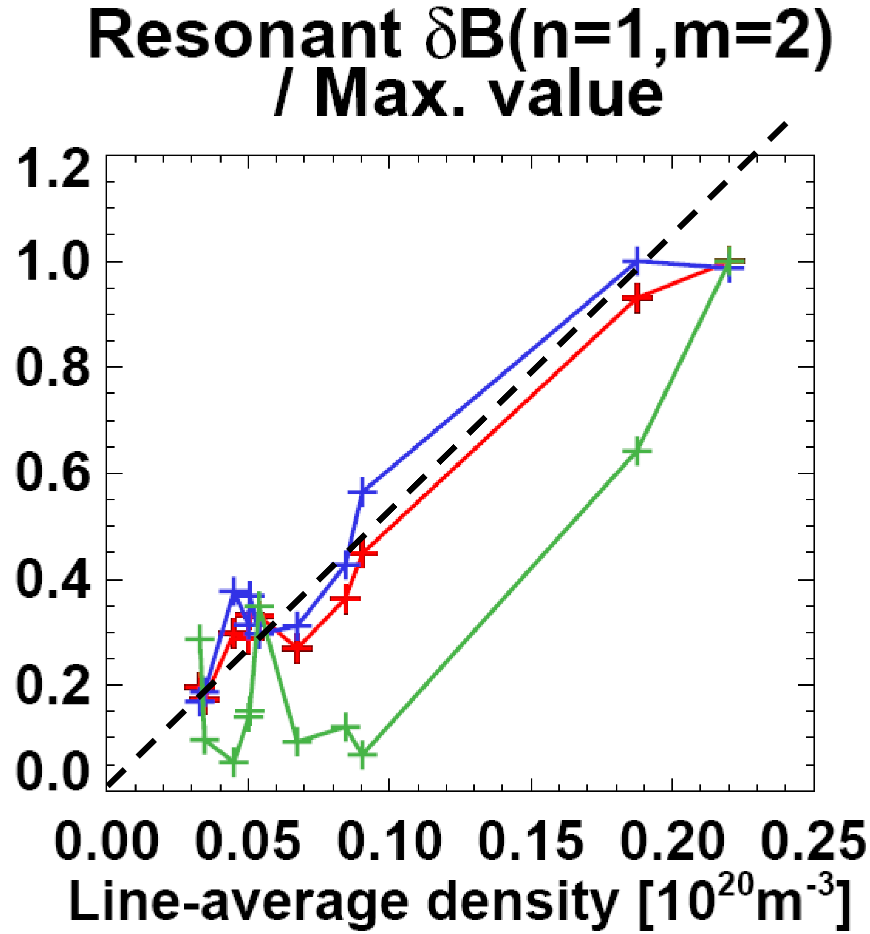



• *IPEC: J.-K. Park, PoP 052110 (2007), Locked mode: J.-K. Park, PRL 195003 (2007)*

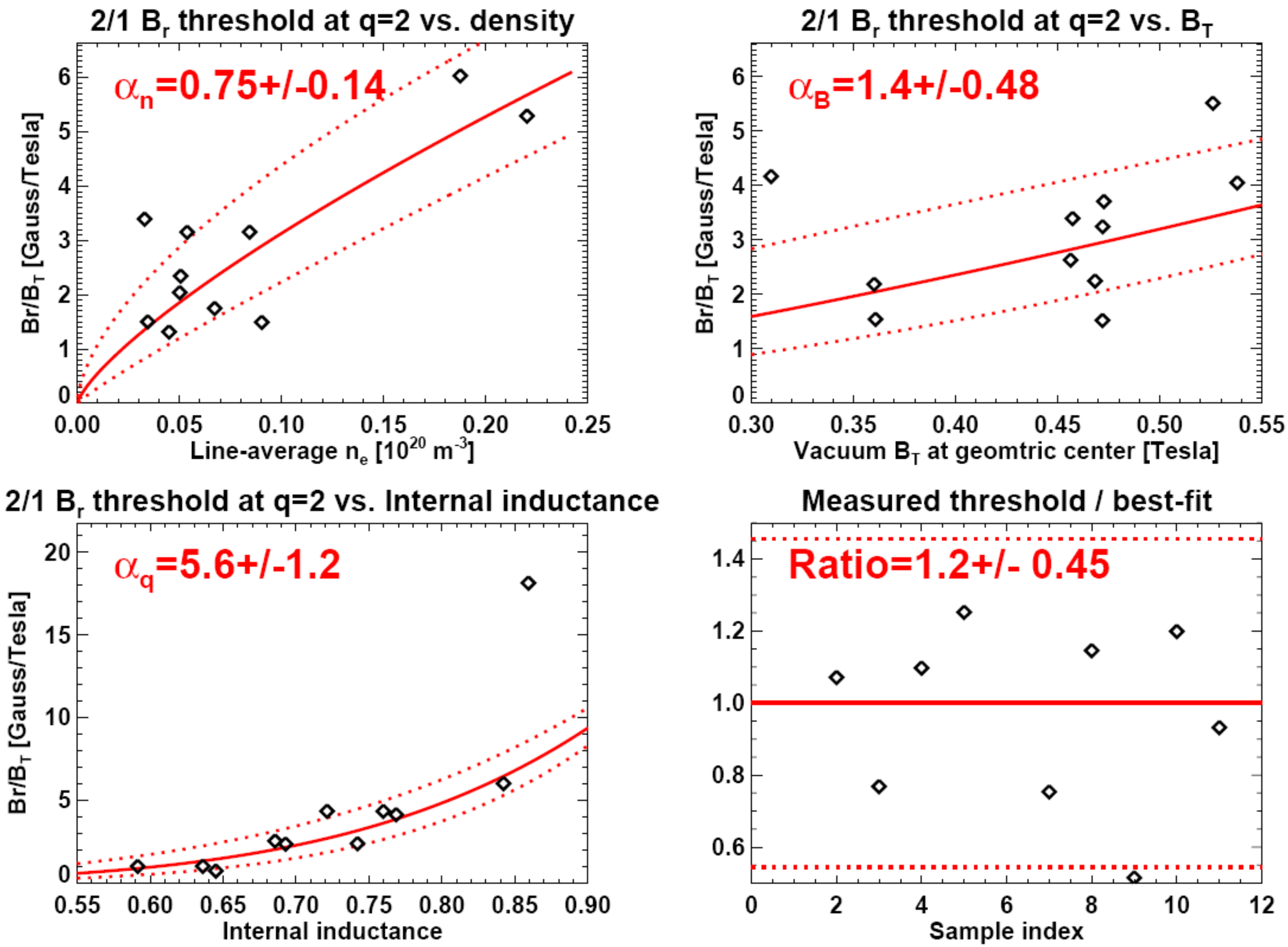
# Locking field from IPEC ($\delta B_{\perp}^{2,1}$ at q=2) exhibits more deviation from density linearity than vacuum field calculations

**Vacuum $\delta B_{\perp}$ (most commonly used)**
**Vacuum perturbed helical flux $\delta\psi_h$**
**Include plasma response (IPEC)**



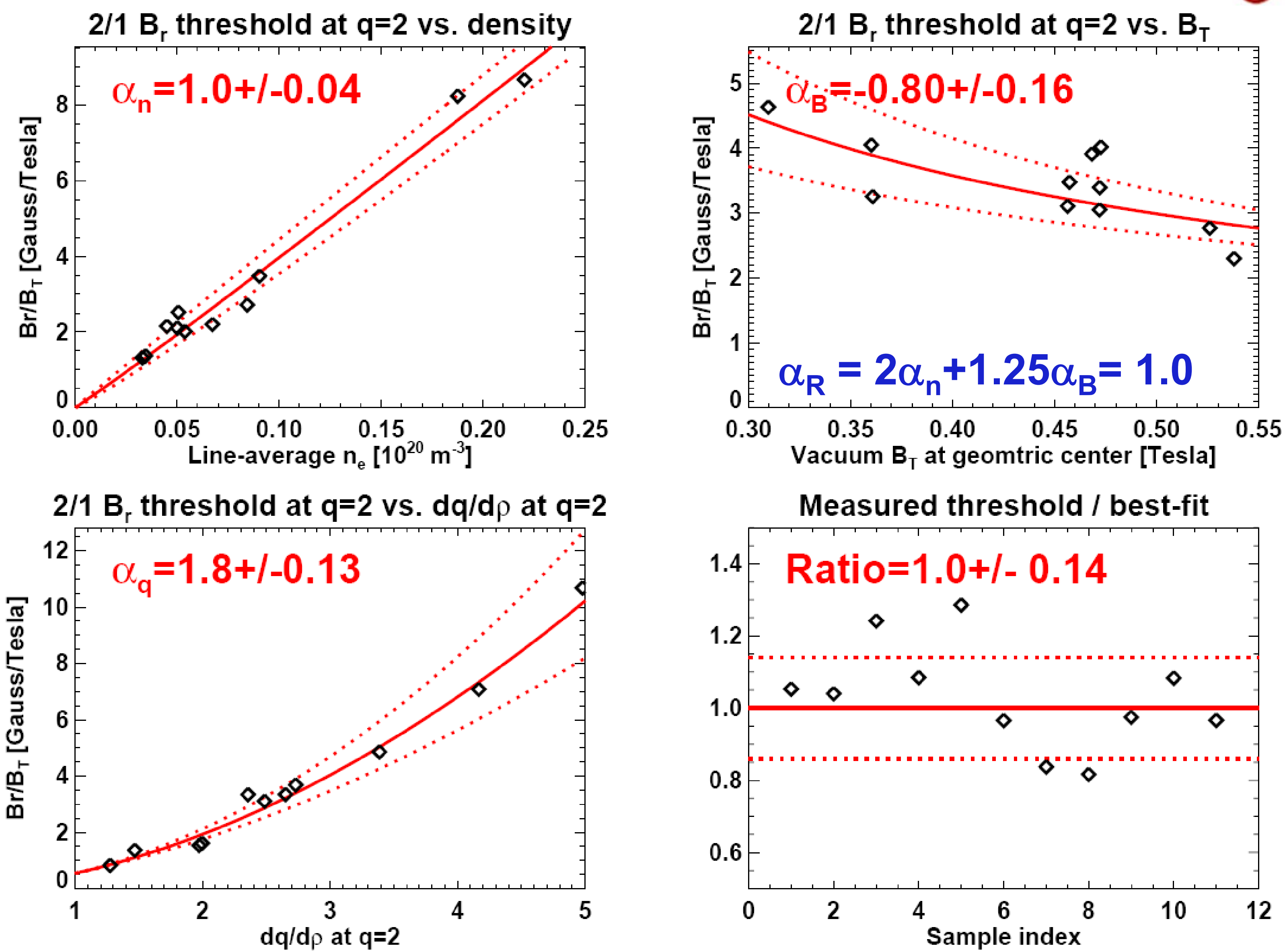



# Locking threshold fit using IPEC $\delta B_{\perp}^{2,1}$ at q=2 cannot be well fit using internal inductance for q-shear variable

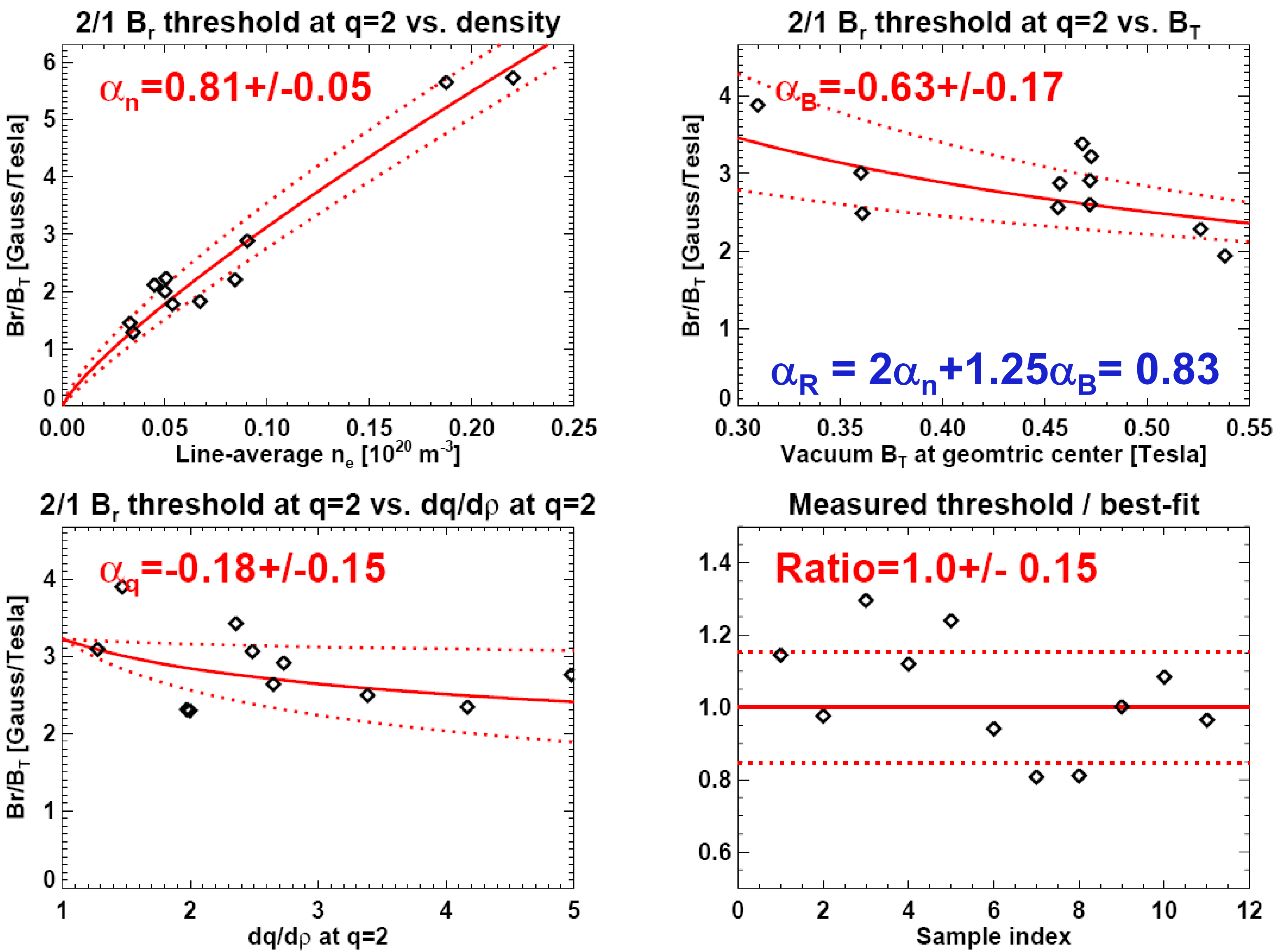



- *Similar poor fit obtained using $q_{95}$*

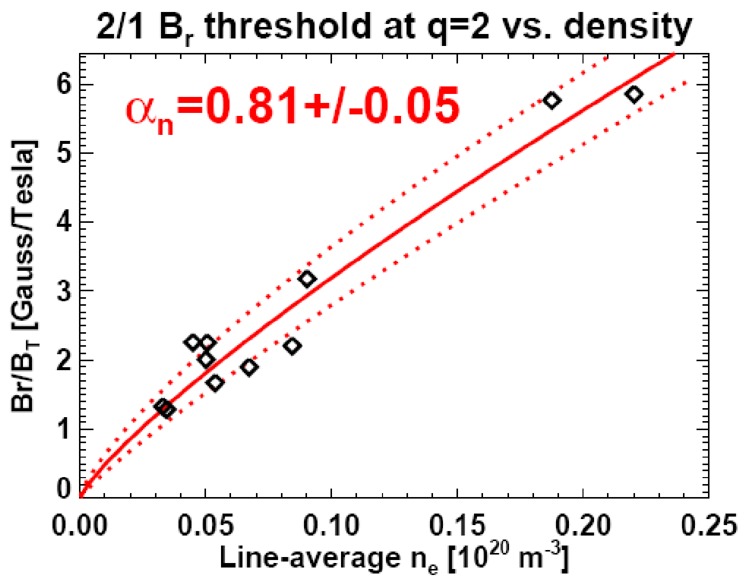
# Locking threshold fit using IPEC $\delta B_{\perp}^{2,1}$ at q=2 has lowest fitting error if local shear at q=2 is used for q-shear variable

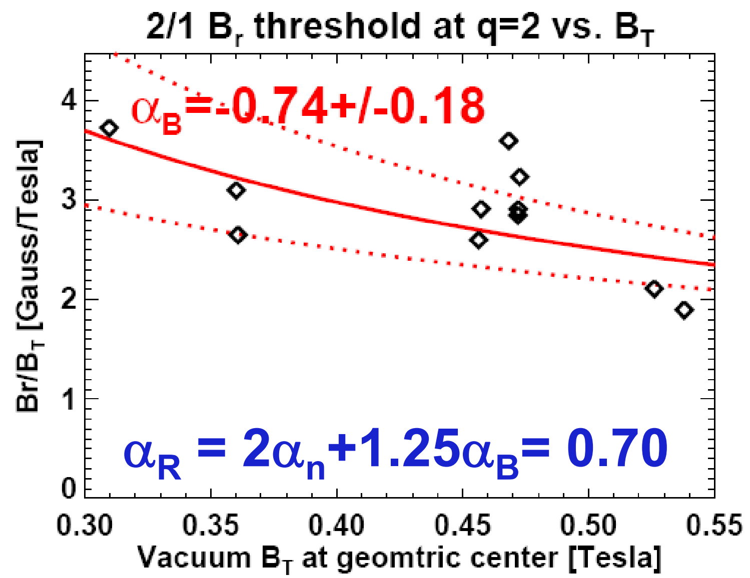


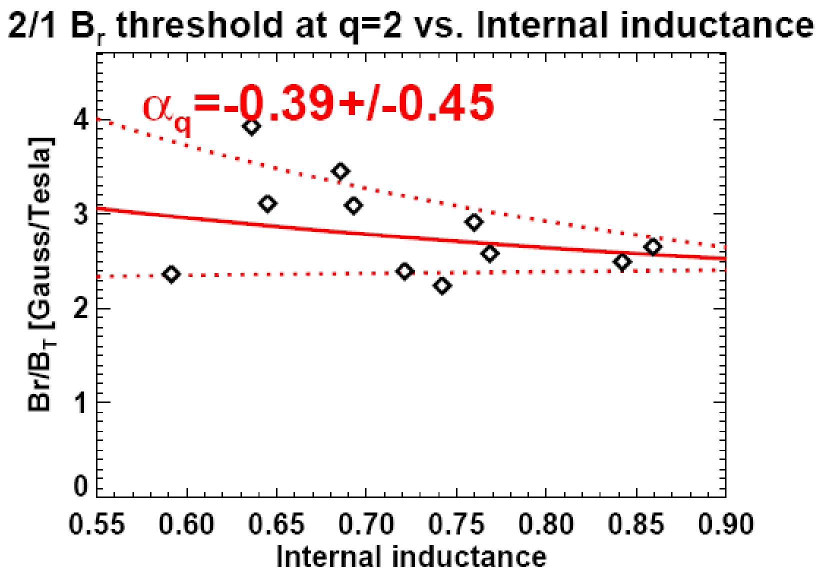
# Locking threshold fit using vacuum $\delta B_\perp^{2,1}$ at q=2 has reduced $\alpha_n$, $|\alpha_B|$, $\alpha_R$ and much weaker dependence on $dq/d\rho|_{q=2}$

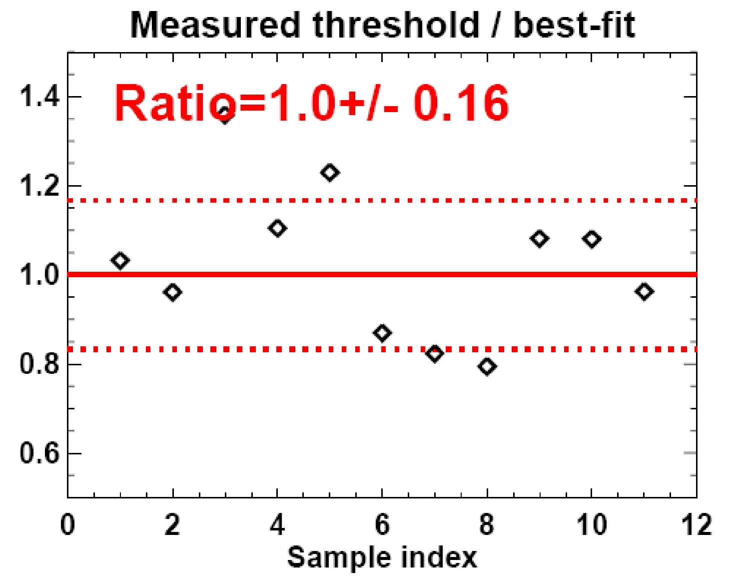


# Unlike IPEC case, locking threshold fit using vacuum $\delta B_{\perp}^{2,1}$ at q=2 can be fit using internal inductance for q-shear, but $\alpha_R$ << 1



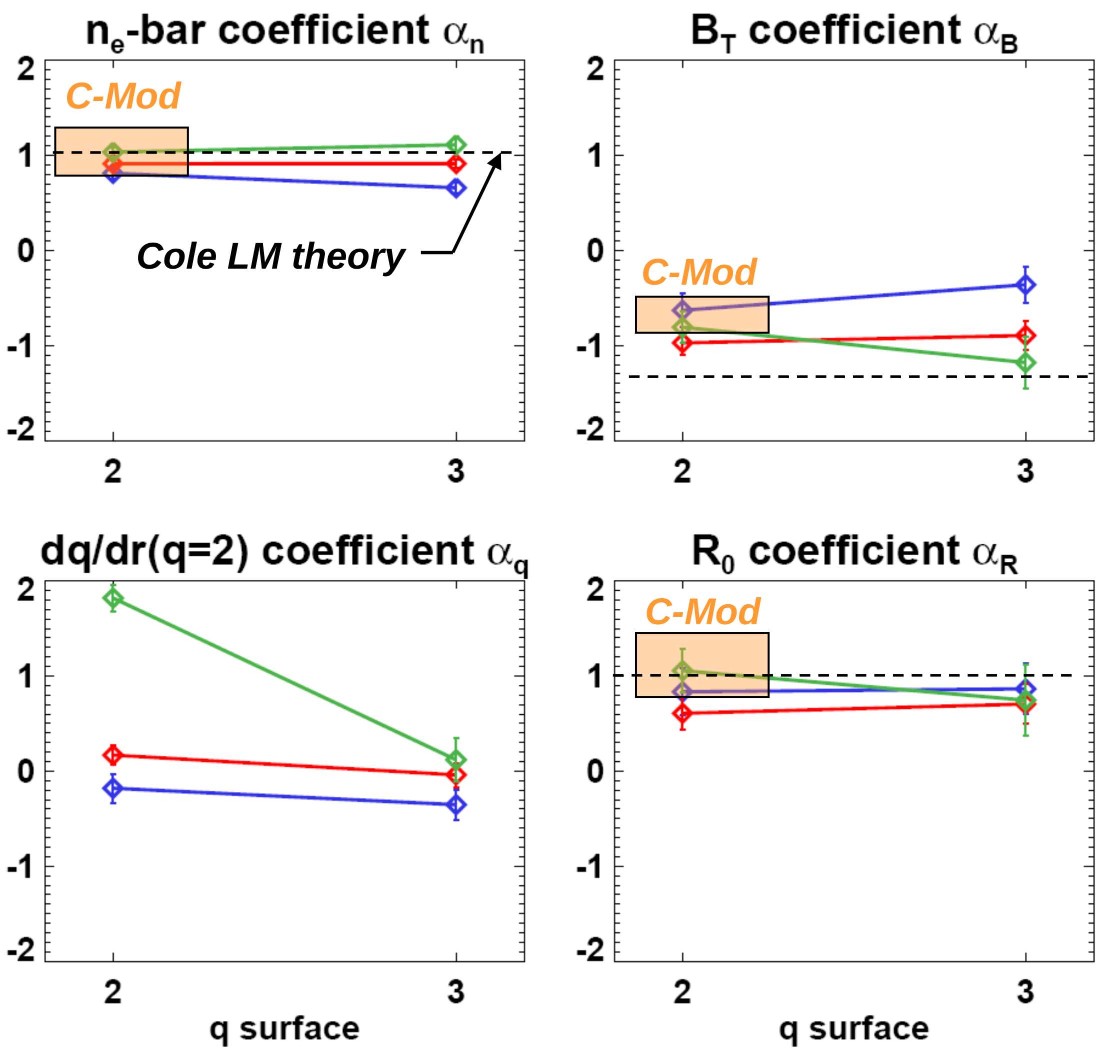



# NSTX data shows linear density scaling and inverse $B_T$ dependence consistent with higher-A, $B_T$ tokamaks and recently improved LM theory

Data also allows assessment of impact of different calculations of perturbed B-field:




**Vacuum $\delta B_\perp$ (most commonly used)**
**Vacuum perturbed helical flux $\delta\psi_h$**
**Include plasma response (IPEC)**

**Assume size scaling coefficient:**

$$\alpha_R = 2\alpha_n + 1.25\alpha_B$$

**(Connor-Taylor invariance)**

**Mean coefficients using q=2 and 3:**

$\alpha_n = 0.73$ $\alpha_B = -0.50$ $\alpha_R = 0.85$
$\alpha_n = 0.91$ $\alpha_B = -0.93$ $\alpha_R = 0.66$
$\alpha_n = 1.07$ $\alpha_B = -0.99$ $\alpha_R = 0.90$

***IPEC-derived coefficients are the most consistent with recent theory by A. Cole:***

$$\left|\frac{b^{\mathrm{vac}}_{r,nm}}{B_\phi}\right|_{\mathrm{crit}} \propto n_e B_\phi^{-1.3} R_0 \tau_V^{-1/2} \sigma.$$

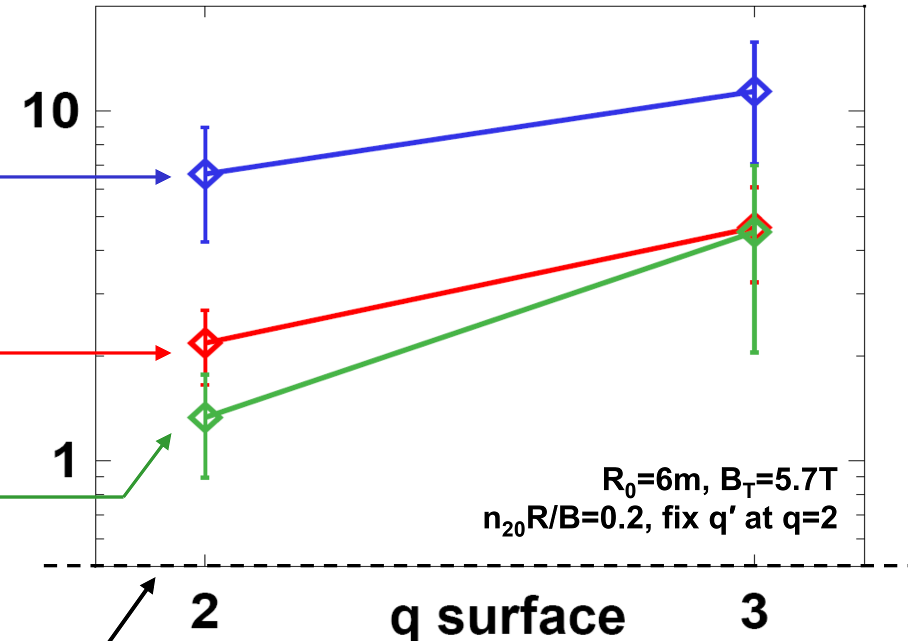
PRL **99,** 065001 (2007)

# Extrapolation to ITER from NSTX data illustrates the importance of the plasma response, and has favorable projection for ITER

Vacuum $\delta B_\perp^{mn}$ (most commonly used) threshold **2-5** × **higher** than IPEC
→Vacuum $\delta B_\perp^{mn}$ ***not valid*** for NSTX

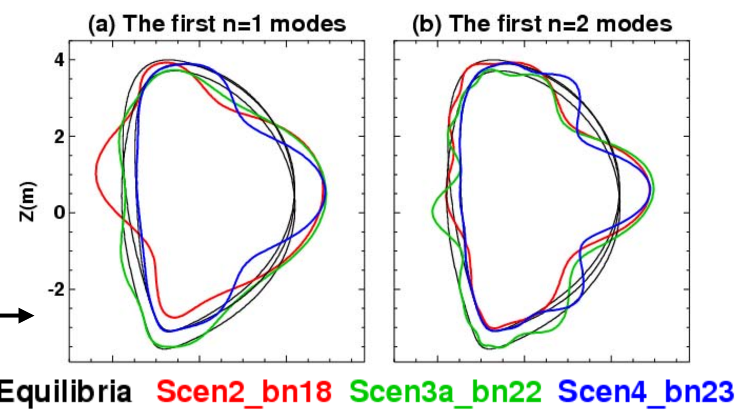
Vacuum $\delta\psi_h^{mn} \propto (|\nabla\psi|R^2B_\perp)^{mn}$ threshold **1-2** × **higher** than IPEC

**Include plasma response (IPEC)**

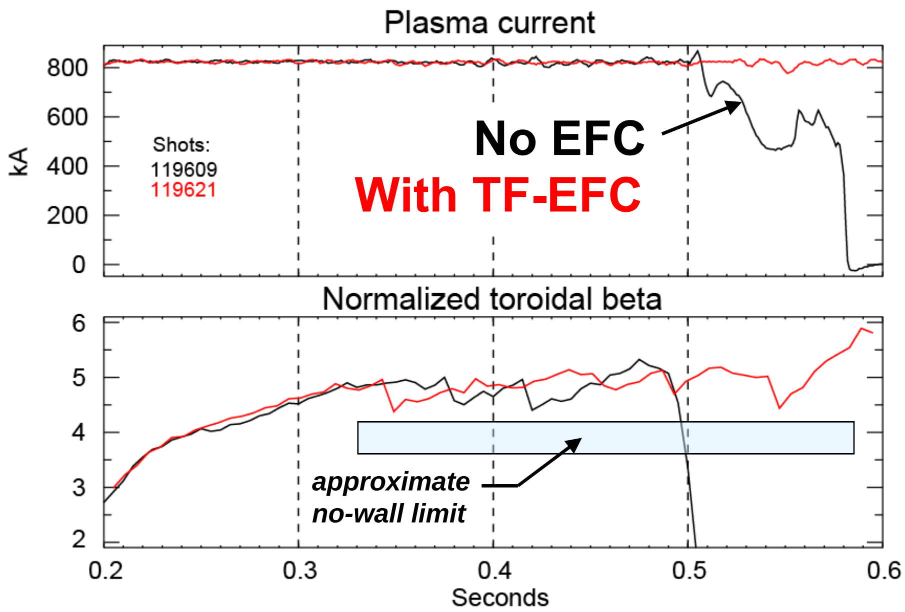


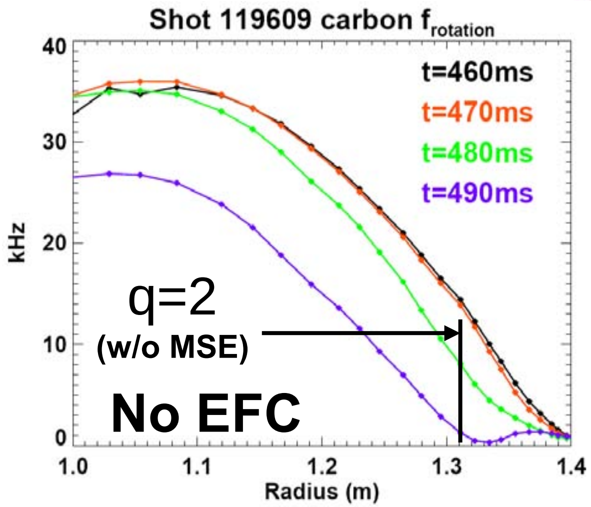

**Minimum threshold $B_r$ / $B_T$ = 1- 4 G/T is 2-3× higher than minimum EF correction capability of ITER (favorable result)**

**Beginning to use IPEC to model optimal multi-scenario EF mitigation for ITER**

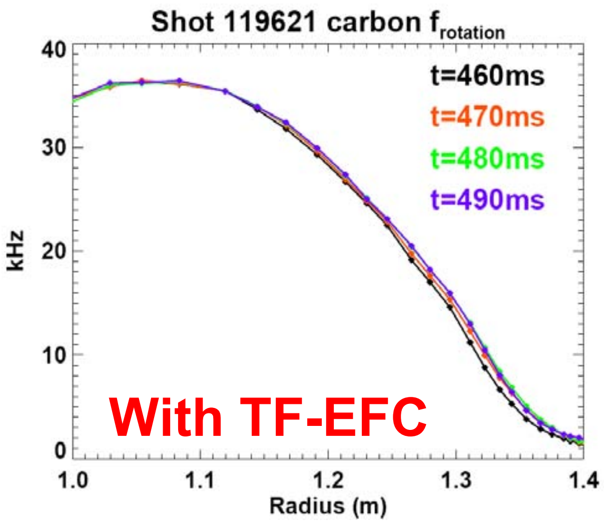


# At high β, EF correction can aid sustainment of high toroidal rotation needed for passive (rotational) stabilization of the RWM




- Use real-time $I_{OH} \times I_{TF}$, incorporate observed time-lag and non-linearity of EF
- Empirically minimize rotation damping near q=2-3 for 100-200ms of reference shot
  - Extrapolate in time, balance m=2 against m=0 ***(non-resonant!)*** of EF from moving TF
  - Correction coefficients must be altered for different q(ρ,t), startup, shape, etc.



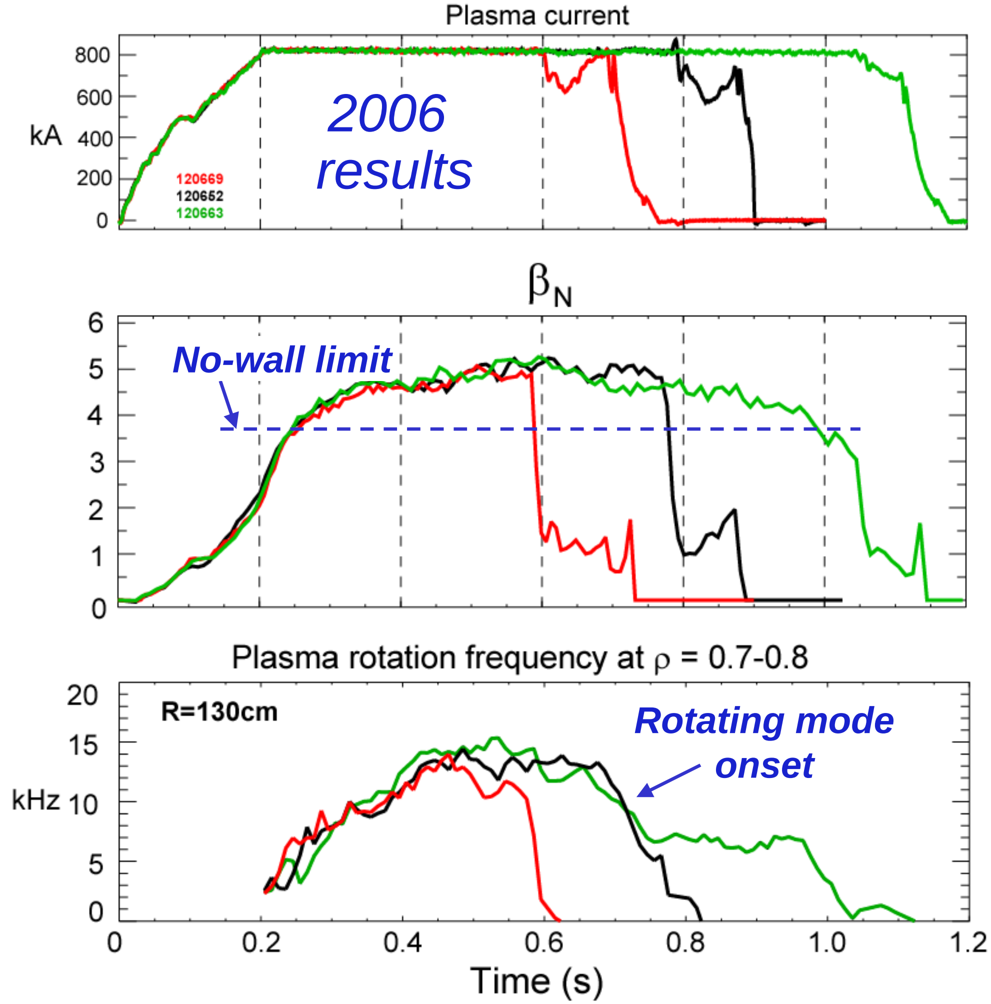

***Algorithm did not work well in 2007 – in part due to more complicated time dependence of TF-EF***

# 2006 - *combination* of pre-programmed TF-EFC + n=1 feedback ($B_{P-U}$ sensors) was required to maximize rotation and pulse-length

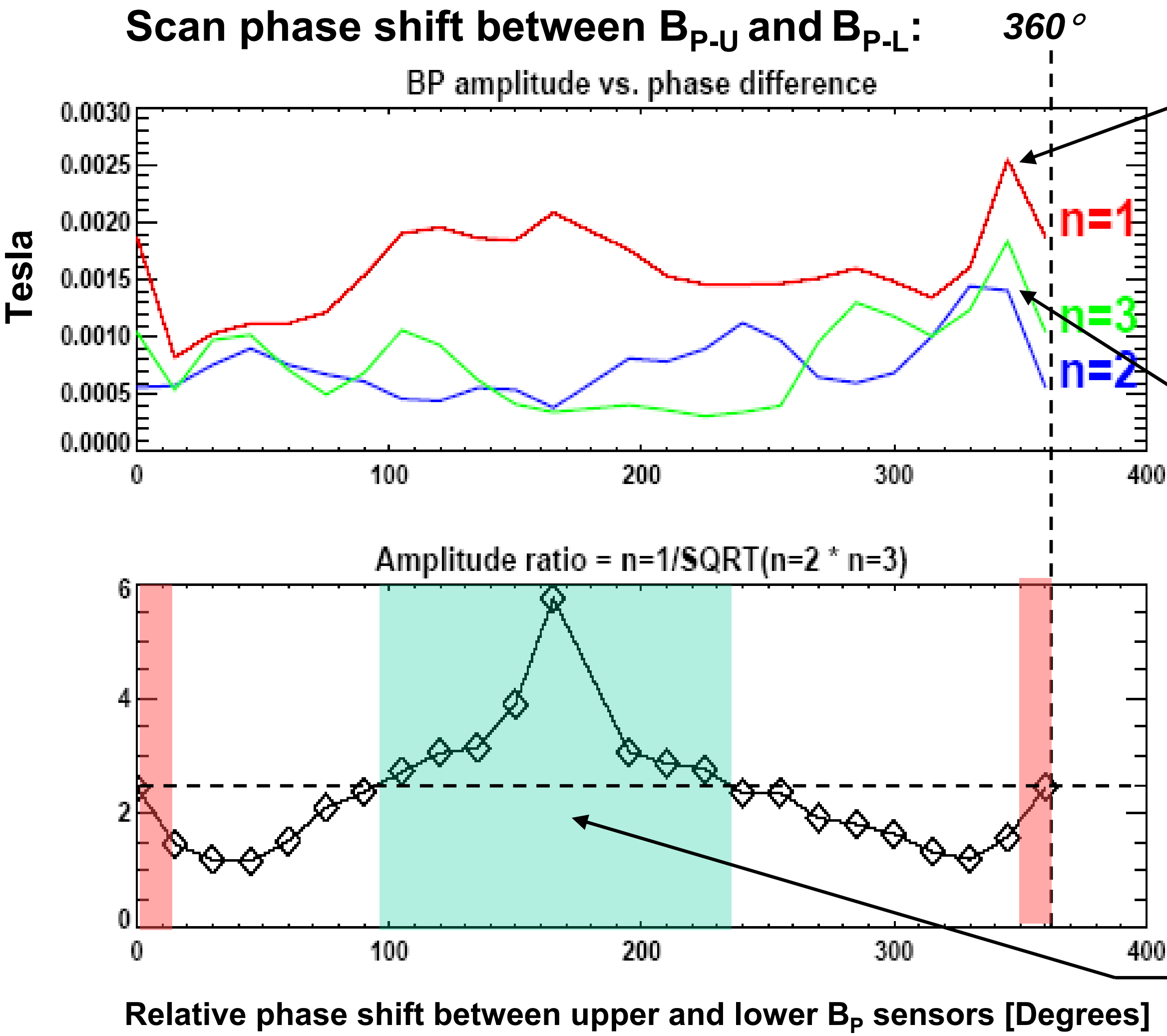
- Feedback alone (not shown) extended pulse amount similar to that achieved with TF-EFC alone
  - Combination was best
- Gain limited by noise and offsets
- Mode "deformation" also observed
  - RFA/RWM would appear in lower array but not upper (or vice-versa)

- "noise" and "deformation" motivate improved mode detection in 2007:
  - Use optimal combination of U & L
    - Maximize sensitivity to RFA/RWM
    - Decrease sensitivity to deformation
  - Also try $B_R$ for EF detection, control
  - Also try mixture of $B_R$ and $B_P$

- **No error field control during high $\beta_N$ phase**
- **TF-EFC**
- **TF-EFC + active n=1 $B_{P-U}$ feedback**



# Optimized $B_P$ sensor usage improves detection of low-f n=1 mode, enabling improved feedback suppression of RFA and RWMs

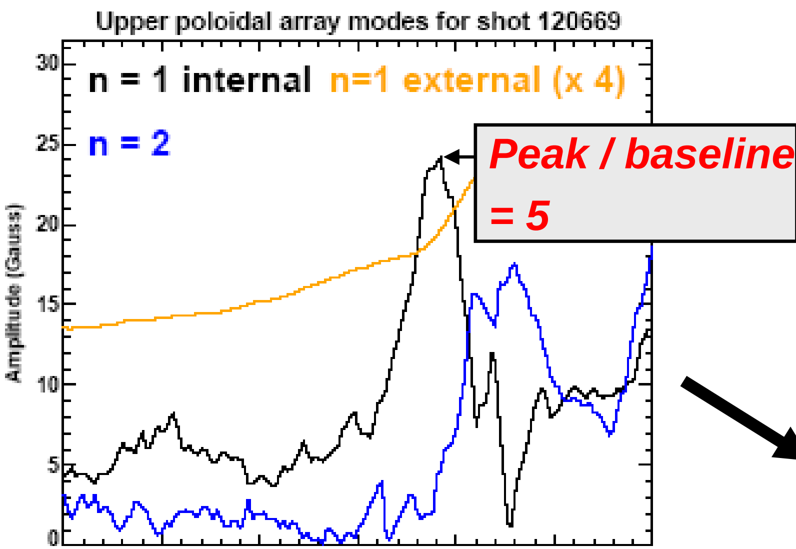


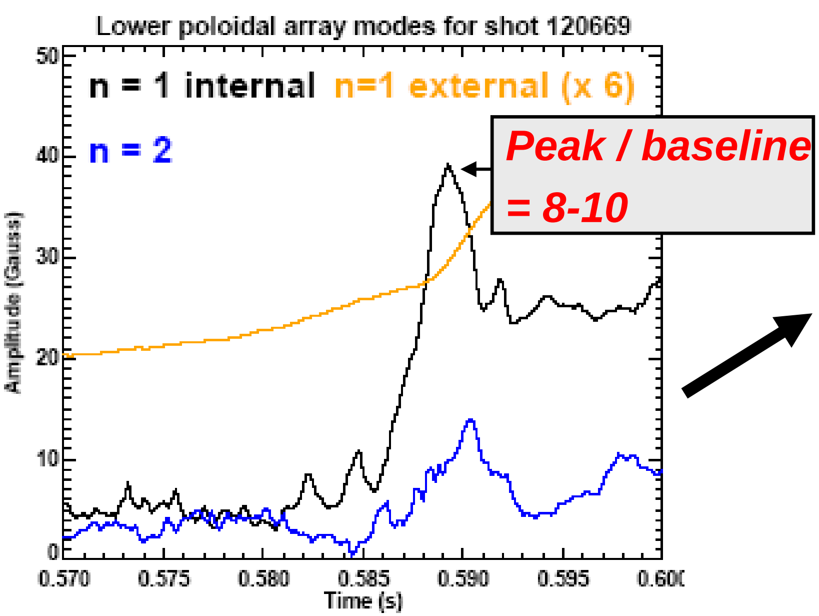

- Detected n=1 amplitude is highest near 0° phase shift
  - Consistent with simple up-down average with small offset due to mode helicity + sensor separation
- But, n > 1 components are also detected for "pure" n=1 mode
  - mode finite amplitude effects
  - eddy currents
  - conducting wall non-axisymmetry
  - sensor/detection imperfections
- Improved discrimination between n=1 and n > 1 obtained with different U-L phase shift range
  - 150-160° is found to be optimal
  - Wider range of n=1 discrimination

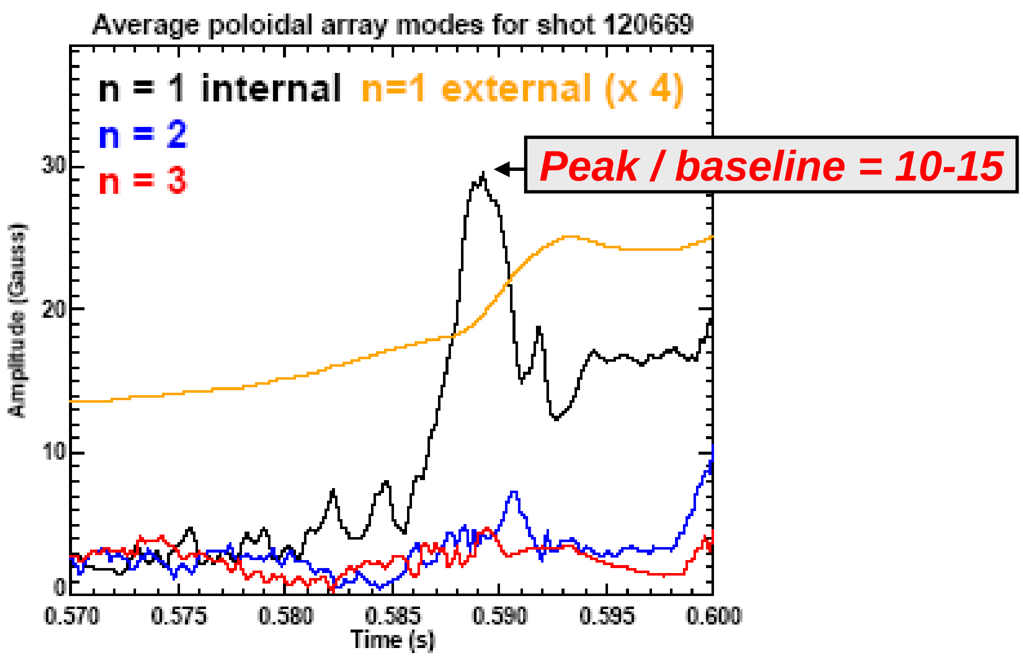
**Optimal shift increases n=1 signal / baseline by 2-3 × → higher stable feedback gain**

# Optimal U/L average of $B_P$ signals improves mode-ID sensitivity

Optimal upper-lower average increases amplitude / baseline factor of 2-3 → higher feedback gain possible



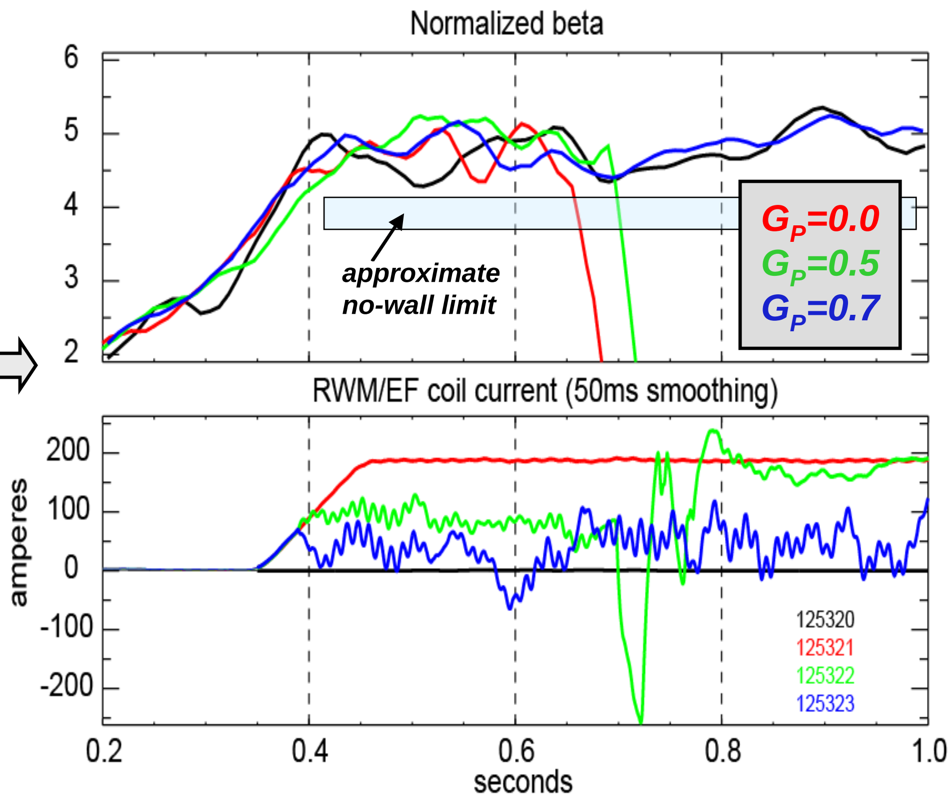



# In 2007, using optimized $B_P$ sensors in control system allowed feedback to provide most/all n=1 error field correction at high $\beta$

- **Previous n=1 EF correction required a priori estimate of intrinsic EF**
- Additional sensors → detect modes with RWM helicity → increased signal to noise
- Improved detection → higher gain → **EF correction using *only feedback on RFA***

**EFC algorithm developed in FY07:**

- Use time *with minimal intrinsic EF* and RWM stabilized by rotation
- Intrinsic $\Omega_\phi$ collapse absent in 2007 → **purposely apply n=1 EF to reduce rotation, destabilize RWM**
- Find corrective feedback phase that reduces applied EF currents
- Increase gain until applied EF currents are nearly completely nulled and plasma stability restored




- **Then turn off applied error field (!)**

→ *Use same gain/phase settings to suppress RFA from intrinsic EF **and** any unstable RWMs*

# Optimal phase difference δ=270° between measured U/L avg $B_P$ & applied $B_R$ minimizes all time-averaged currents simultaneously

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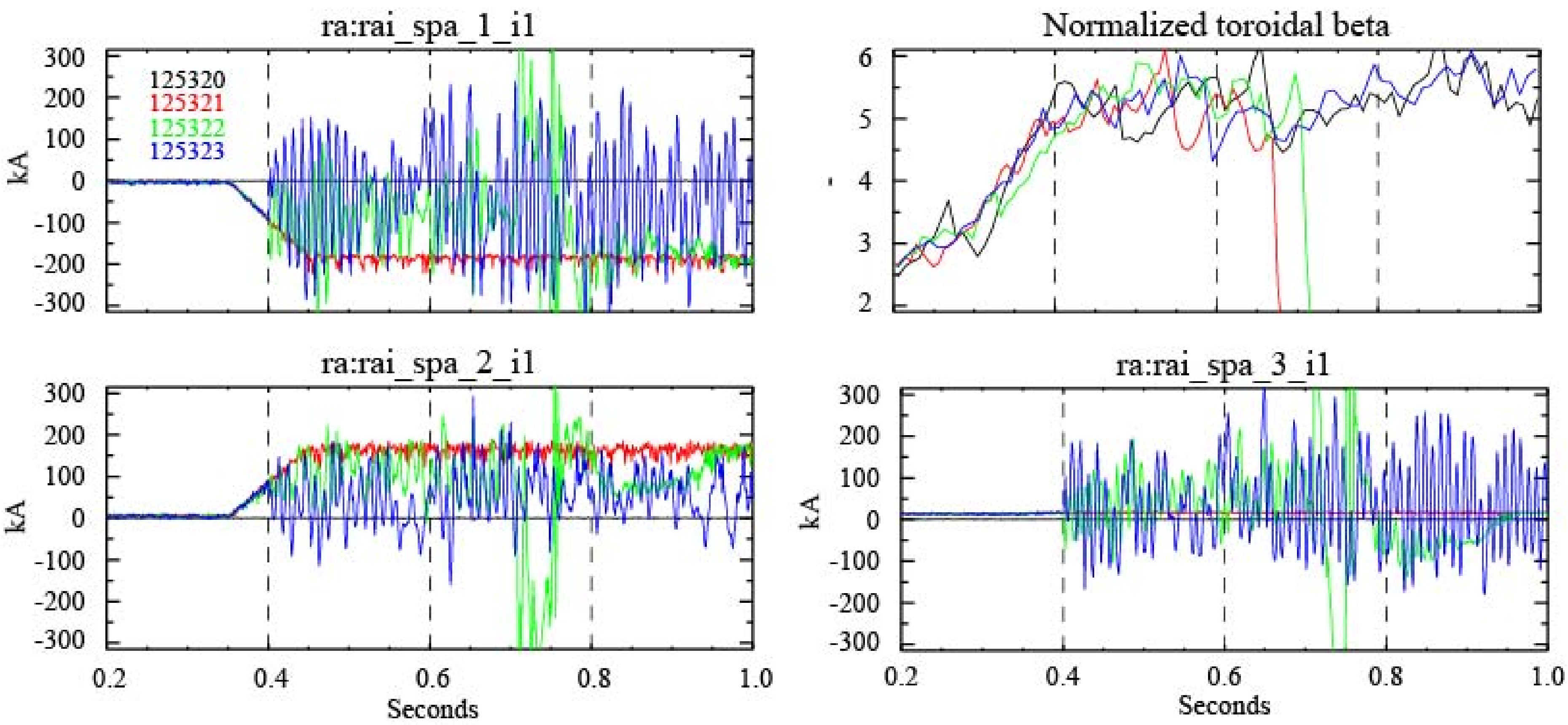
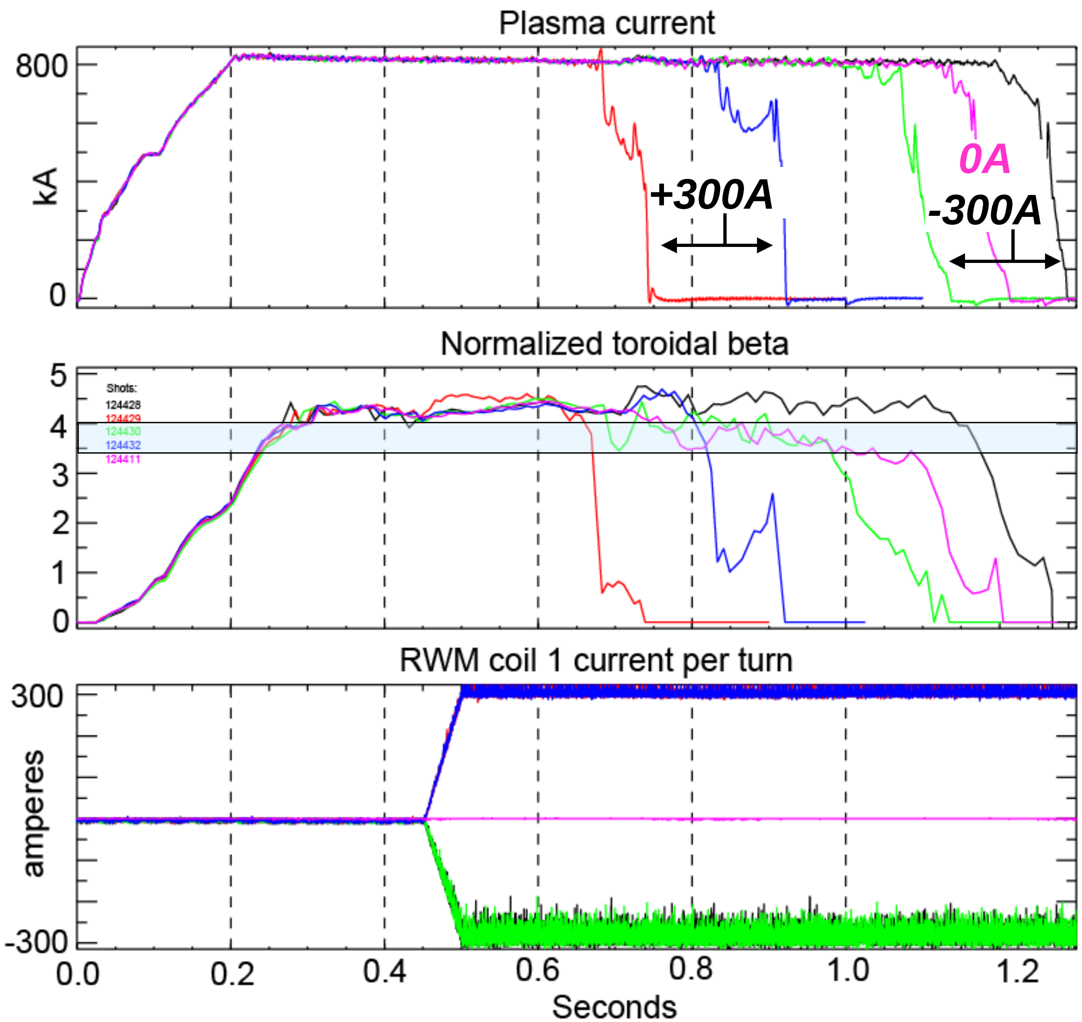
- Again, sufficient gain is required:

*$G_P$=0.0* *$G_P$=0.5* *$G_P$=0.7*



# NEW: Discovered high-*n* error fields (*n*=3) important at high $\beta_N$

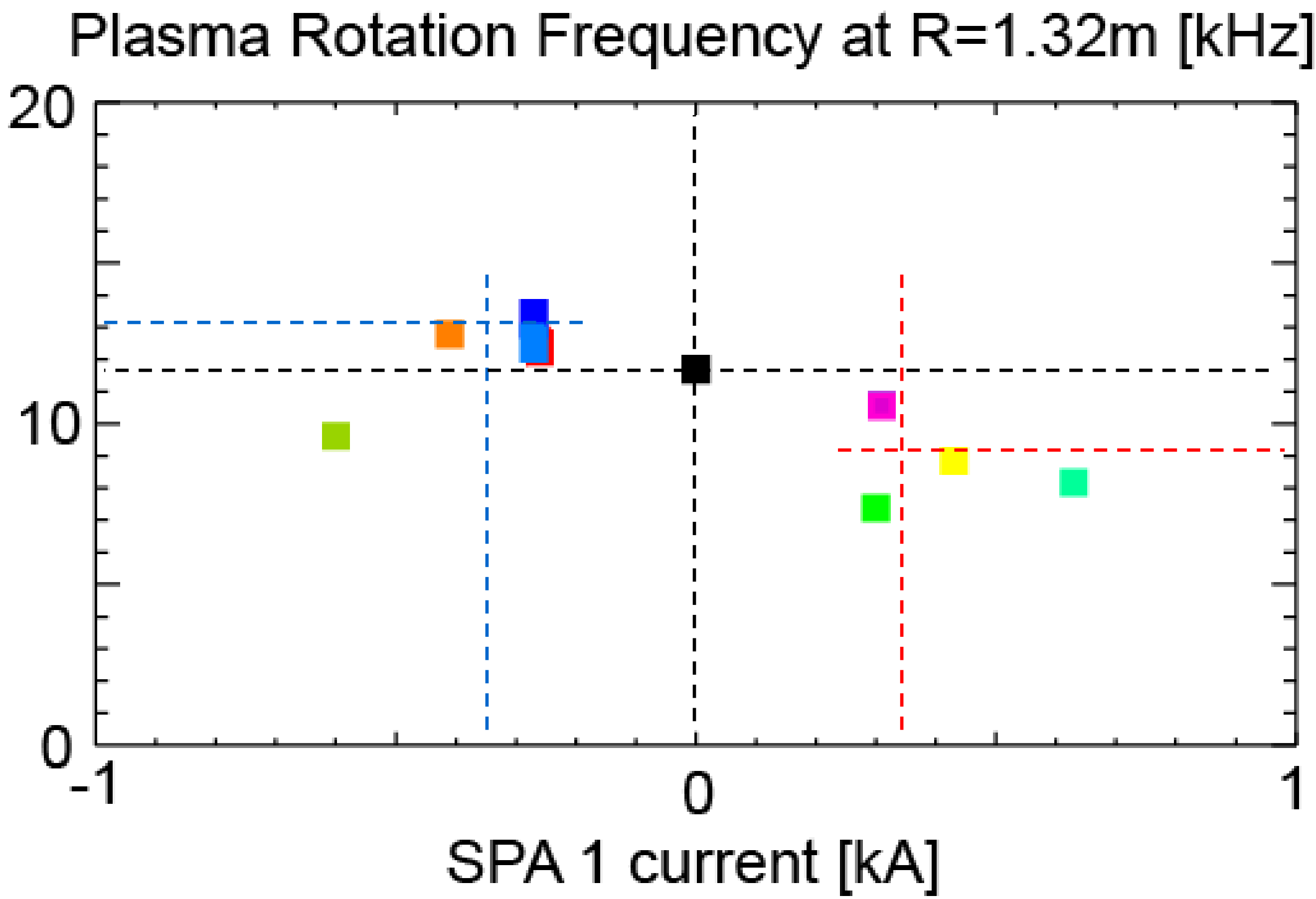



- Pulse-length depends on polarity of applied n=3
  - Anti-corrective polarity disrupts $I_P$ and $\beta$
- Plasmas operate above n=1 no-wall limit → RFA
  - slows rotation →
  - destabilizes n=1 RWM
- Correction current magnitude for n=3 similar to that for n=1 correction
  - Applied n=3 $|B_R|$ is ≈ 6G at outboard midplane
  - Fortuitous phase match between intrinsic n=3 EF and field coils can apply
- Assessing n=3 EF sources...

***• n > 1 error fields not commonly addressed in present devices, or in ITER***

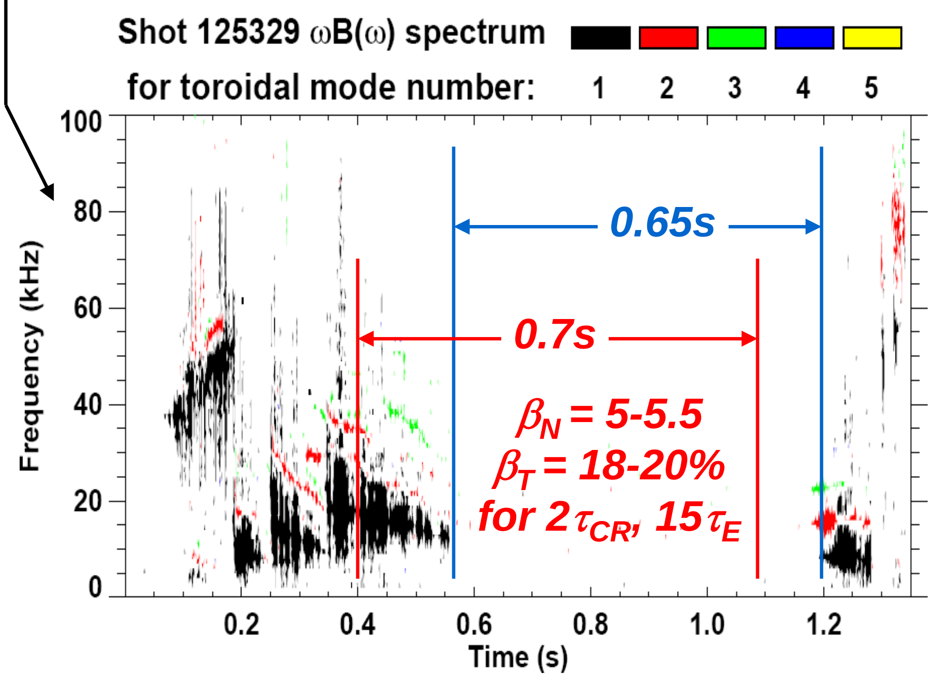
# Outboard $\Omega_\phi$ changes by 30-40% with n=3 polarity flip

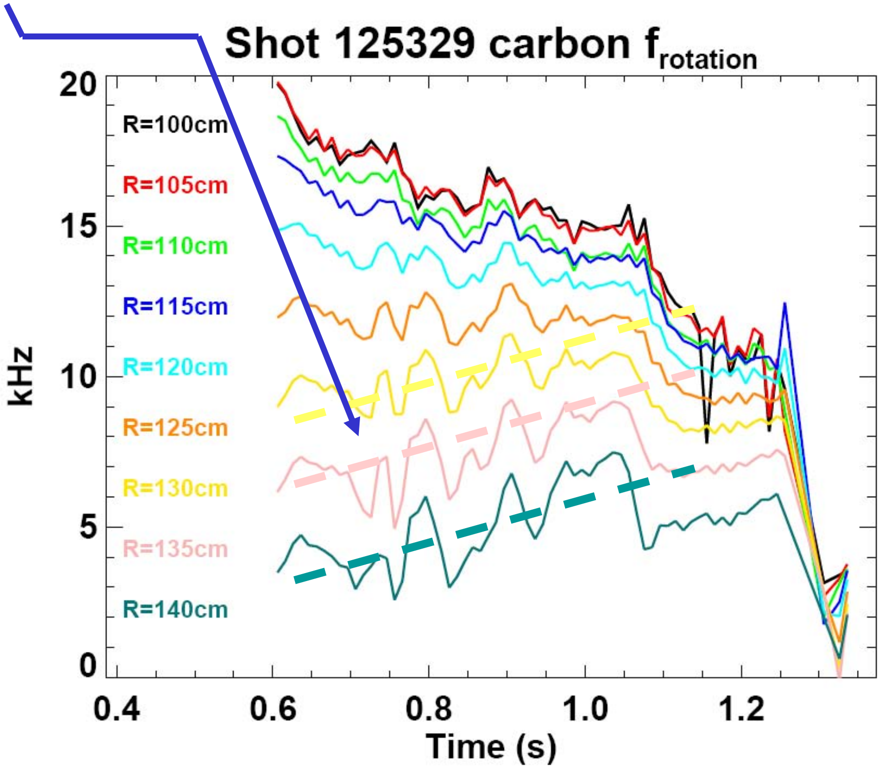
- Optimal n=3 current magnitude = 300-400A
- Coil shape data indicates VF coil (PF5) produces some n=3 EF
  - Need to assess if PF5 EF is consistent with empirical correction below



# Simultaneous multiple-n correction improves performance
## (Optimized feedback control of n=1 $B_P$ RFA + pre-programmed n=3 correction)

- Record pulse-length at $I_P$=900kA, with sustained high-$\beta$
- Long period free of core low-f MHD activity
- Plasma rotation sustained over same period
  - Core rotation decreases with increasing density ($f_{GW}$ → 0.75), but…
  - R > 1.2m rotation slowly ***increases*** until large ELM at t=1.1s




*For reference: $\tau_{CR} \approx$ 0.3s, $\tau_E$=40-50ms*

# NSTX experiments have improved the understanding of magnetic error fields and their correction at low and high $\beta$

- Low density, low-$\beta$ locked mode studies highlight the importance of plasma response and toroidicity, and predict favorable locking thresholds for ITER
- Multiple-n (n = 1, 3) EF correction improves sustained high-$\beta_N$ operation
- General geometry corrections to particle orbit times can significantly modify the RWM critical rotation calculated by MARS-F – up to 50% variation in NSTX
- Present semi-kinetic damping theory generally under-predicts critical rotation → explore mechanisms that might decrease dissipation

***We invite you to participate in and submit experimental ideas to the NSTX Research Forum, Nov. 27-29, 2007, http://nstx-forum-2008.pppl.gov***