Outline & status for: “Progress in understanding error-field physics in NSTX spherical torus plasmas” (red items remain to be done)

0. THEME: low-A and low-B of NSTX provide additional insight into EF physics
1. NSTX locked modes
    1. Discussion of sensor array
        1. Analyze error fields (EFs), sources of n=1 EF
    2. Threshold scaling
        1. linear scaling with plasma density, a weak dependence on BT, and a positive scaling with q shear
        2. Discussion of dependence on choice of q-shear variable, compare to tokamak & Cole PRL
        3. Results extrapolate to a favorable threshold δB21/BT > 1×10-4 for ITER, size scaling implications
        4. IPEC
            1. discussion of code physics
            2. plasma response must be included to explain the empirically determined optimal correction
            3. Importance of poloidal mode coupling – apparent in LM scaling data
            4. best fits to data suggest we are optimizing correction of 3/1 or 4/1 rather than 2/1
        5. Perform MSE reconstructions, include in fits and IPEC analysis
        6. Discussion of pert. Helical flux vs. perturbed Bnorm – how it changes spectrum, consistency w/ IPEC

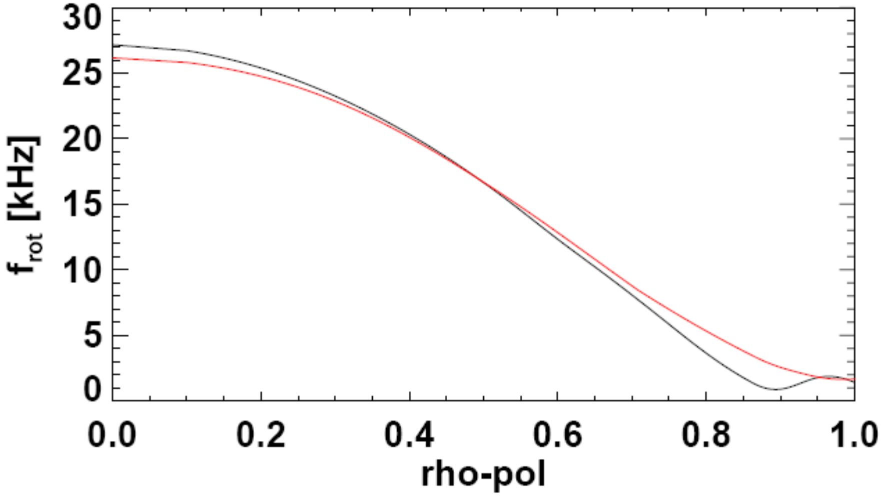
2. $n \geq 1$ EF correction and performance – sensors used to measure EFA, RWM in real-time
    1. Optimized n=1 DEFC using externally applied n=1 pulse + gain & phase optimization
    2. Asymmetry in plasma response to n=3 EF polarity
        1. Determine source of n=3 EF – suspect PF5 – need to analyze coil shape data
    3. Demonstration of pulse-length extension and edge rotation maintenance using n=3 + n=1 DEFC

3. Implications for RWM critical rotation physics
    1. n=3 EF studies show important role of rotation at (rho = 0.6 to 0.95, q=3 to 8)
    2. Study role of toroidicity in kinetic-damping
        1. trapped-particle bounce times strongly modified by low-A – should impact RFA, DEFC, and critical rotation
    3. Implement work of A. Egan into MARS-F calculations – compare theory to data
        1. Summer 2007 - developed parametric fit to bounce/transit times vs local ε and $\mu B_{min}/E$

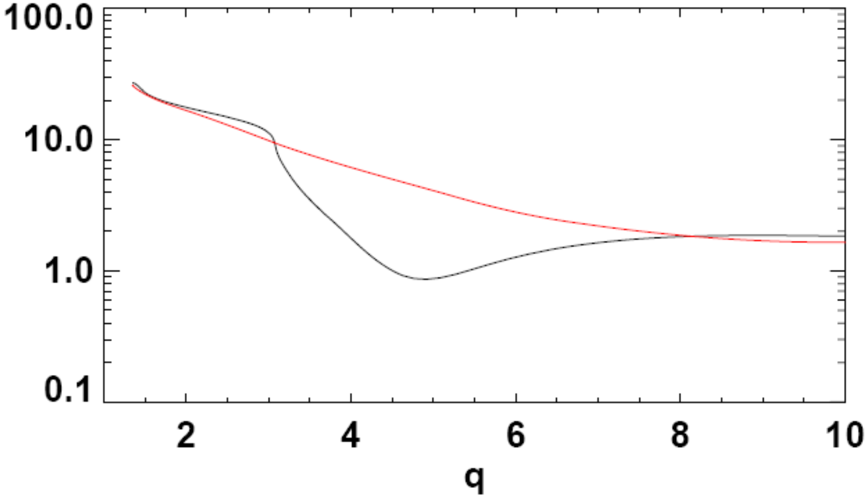
Both shots have n=3 applied – but with opposite polarities

Discharge with lower rotation near rho=0.9 survives

Discharge with higher rotation there suffers RWM collapse



Perhaps rotation shear change/reversal near edge is just as important as magnitude of rotation?



Y. Liu – last IPTA that rotation profile shape is very important in semi-kinetic damping model

- Above no-wall limit, DEFC system responds to amplified error field
- Amplification determined by RWM damping rate
- (semi-kinetic) damping rate predicted to depend on τ_{pass}, τ_{bounce}

τ_{pass} and τ_{bounce} decrease by almost factor of 2 near boundary at low-A

Impacts damping and RFA predictions – will compare to NSTX DEFC data

Line = numerical orbit time

Diamonds = MARS-F analytic

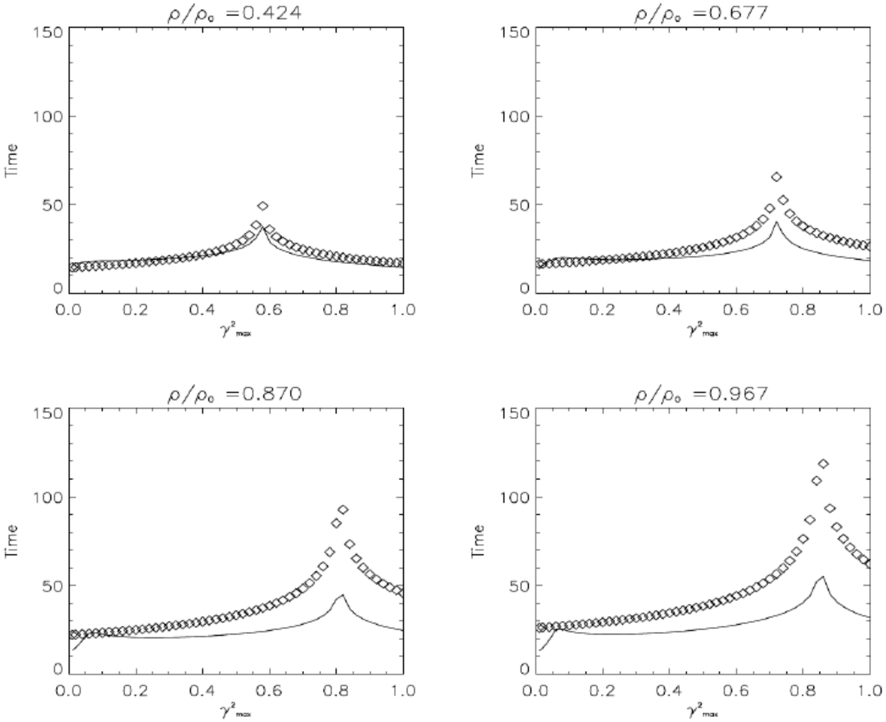


Figure 3: For the low *A*, strongly shaped case, the analytic formulae (8) produces orbit time profiles which deviate significantly from the numerical profiles.

Improved analytic fits to the full numerical orbit times have been developed for implementation in MARS-F

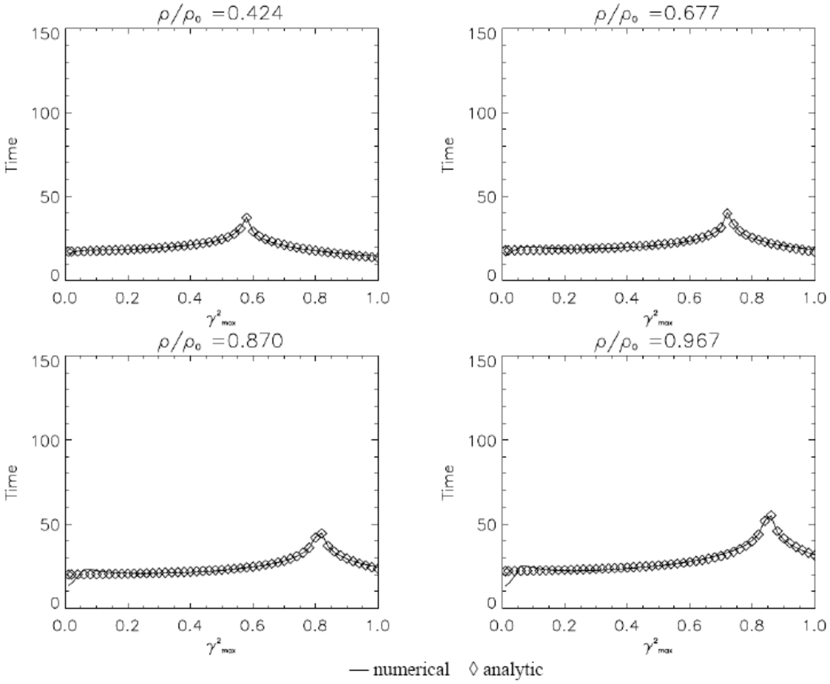
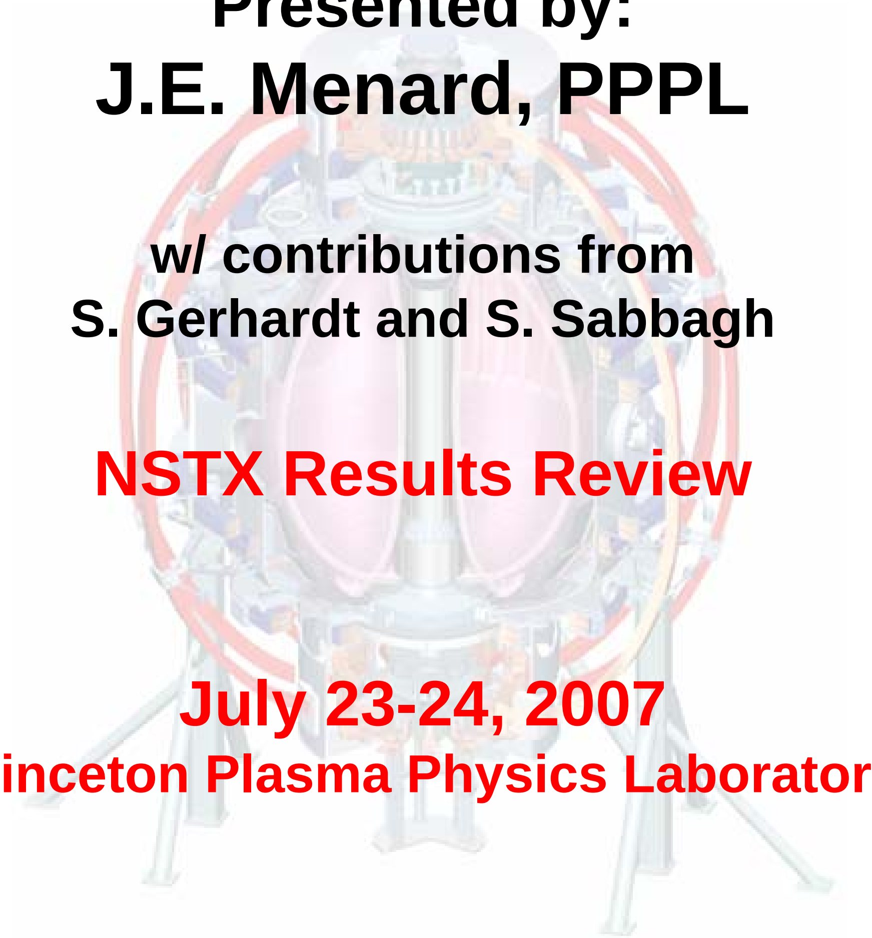


Figure 5: For the low *A*, strongly shaped case, the improved analytic formulae (16) produce orbit time profiles which strongly agree with the numerical profiles. Because (16) reduces to (8) for $c_0 = c_1 = 0$, the large *A*, circular cross section case will show agreement very similar to that seen in Figure 2.

Supported by Office of Science

Results from MHD XP’s 701, 702, 703



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U Rochester
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U Wisconsin

Presented by:

J.E. Menard, PPPL

w/ contributions from
S. Gerhardt and S. Sabbagh

NSTX Results Review

July 23-24, 2007

Princeton Plasma Physics Laboratory

Culham Sci Ctr
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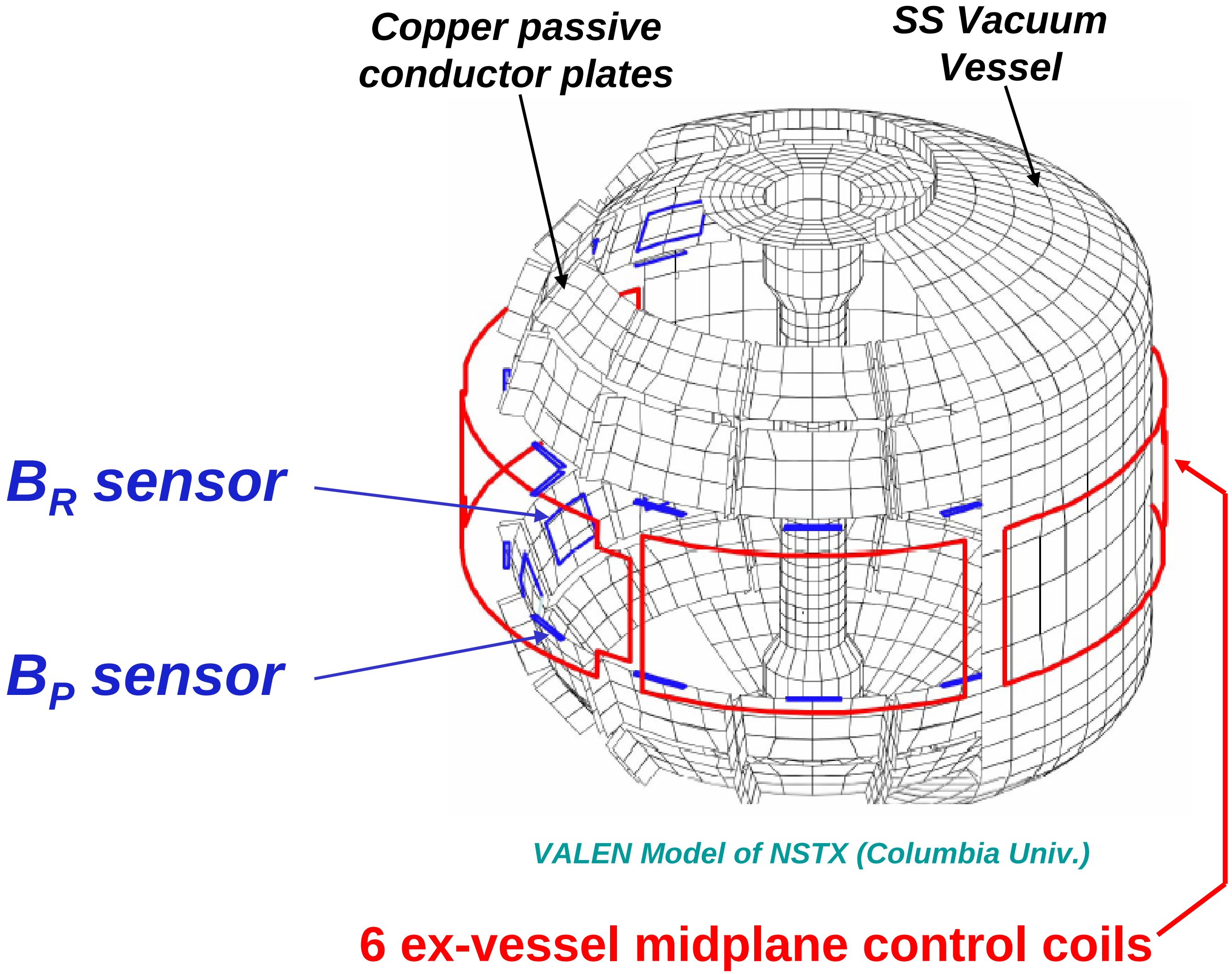
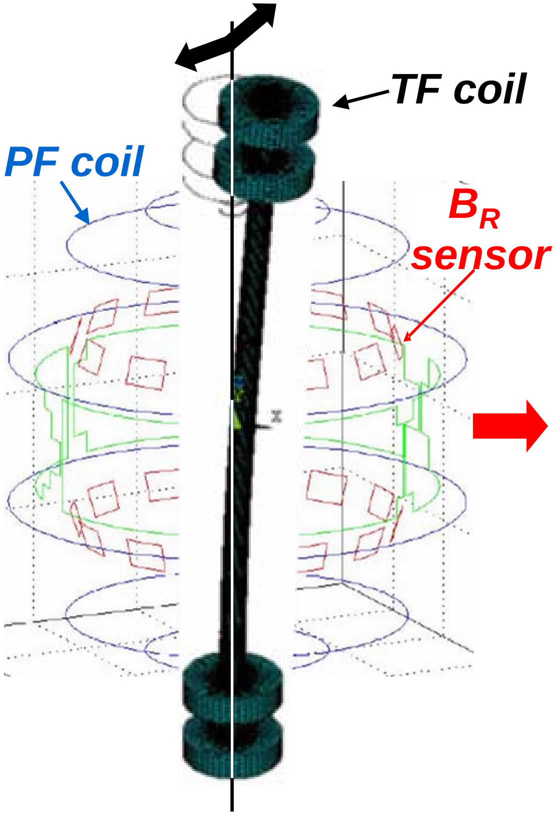
The NSTX RWM/EF coil and sensor system



VALEN Model of NSTX (Columbia Univ.)

Error field source identification and compensation in NSTX

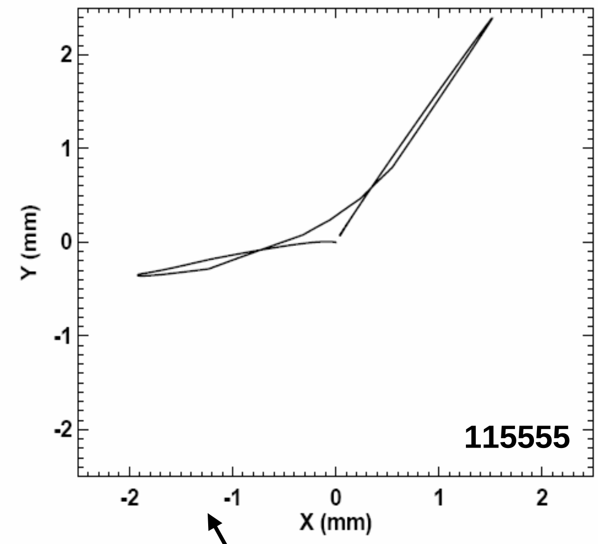
- Some scenarios with lower κ, δ exhibit Ω_{ϕ} and β_N collapse when $\beta_N > \beta_N$ (no-wall)
- Measure 2-3 Gauss $B_{\perp}^{2/1}$ EF in LM experiments… what is EF source?
- **Present picture of EF Source:** EF from/near OH leads at top of machine induces **TF coil motion relative to** B_R sensors (plates, vessel) and thus **the PF coils**



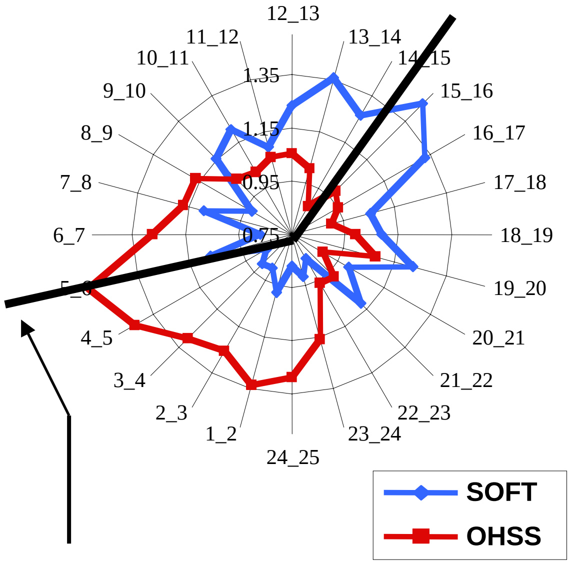
TF coil shift at mid-plane

inferred from B_R sensors

during OH+TF vacuum shot



Normalized TF bottom joint voltage drop from OH+TF test



TF flag-joint voltage variation direction consistent with magnetics

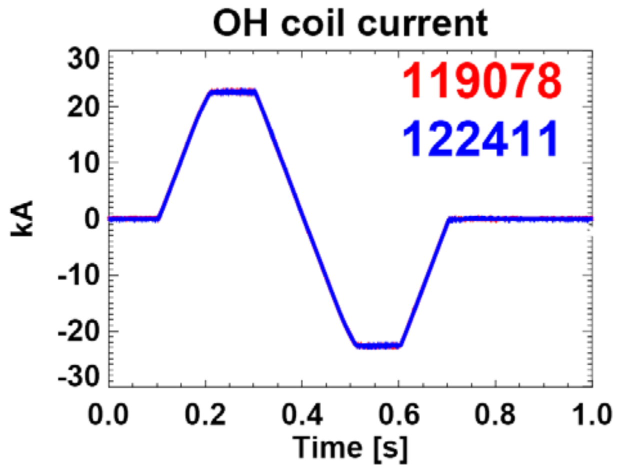
Shim between TF bundle and OH tension tube added before 2007 run to reduce motion

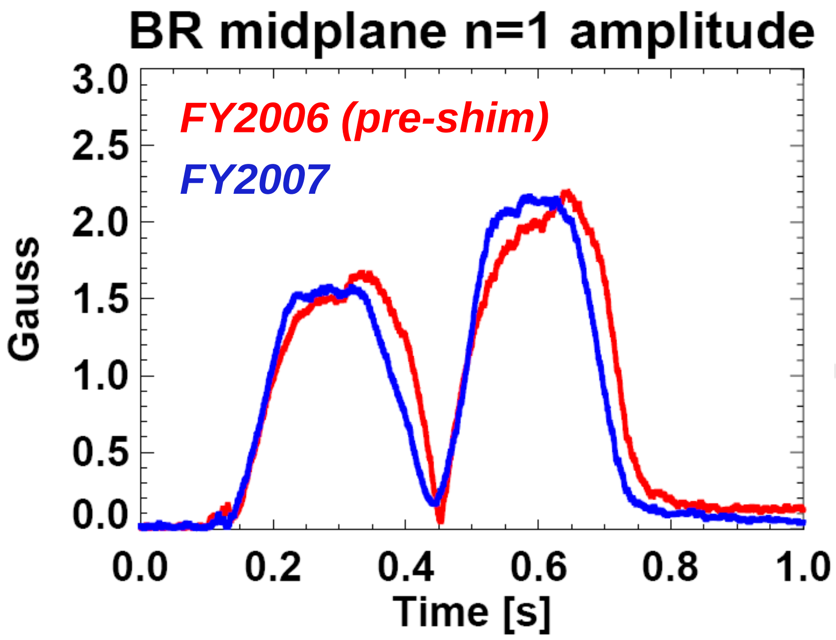
XP701 - Assessment of intrinsic error fields after TF centering

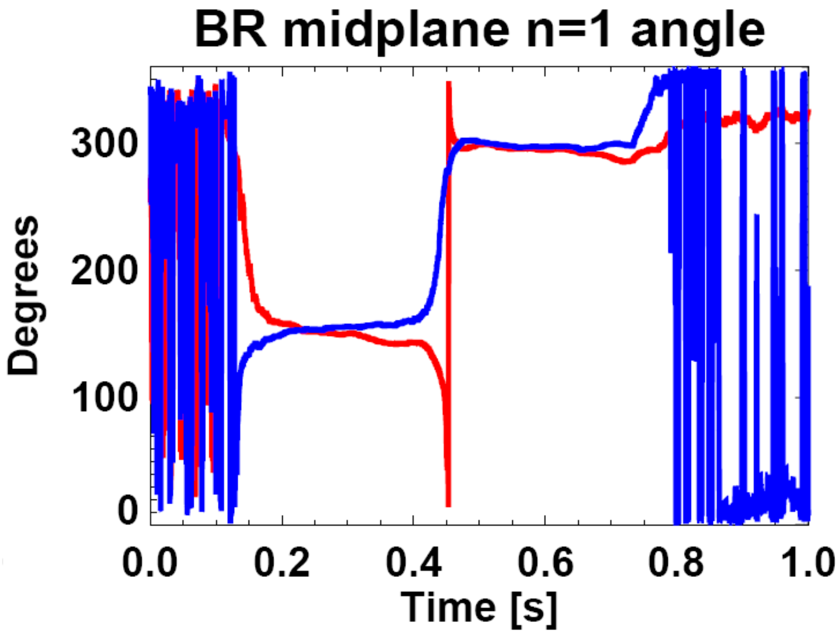
- Assessed modifications to TF coil centering w.r.t. intrinsic EF
  - Intrinsic EF very similar to 2006 for LM ohmic shots
  - Larger difference for long-pulse – lower EF after I_{OH}=0 crossing
- Verified rotation response asymmetry to n=1 applied field
- Could not reproduce 2006 reference discharge for OHxTF EFC algorithm optimization (rotation collapse not observed)
  - Used externally applied n=1 pulses instead in XP702
- NEW: Measured plasma response asymmetry to n=3
  - Pulse-length increases with “corrective” n=3
  - Rotation increases with “corrective” n=3

Error field from fast OH variation largely unchanged

- OH waveform similar to that in ohmic discharges used for locked-mode experiments

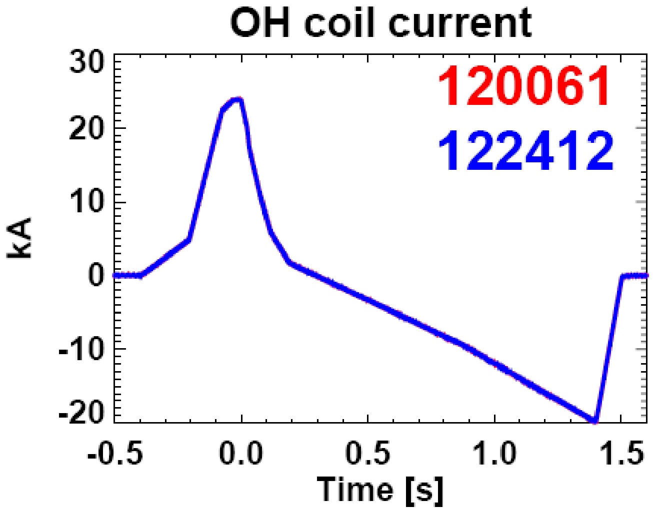


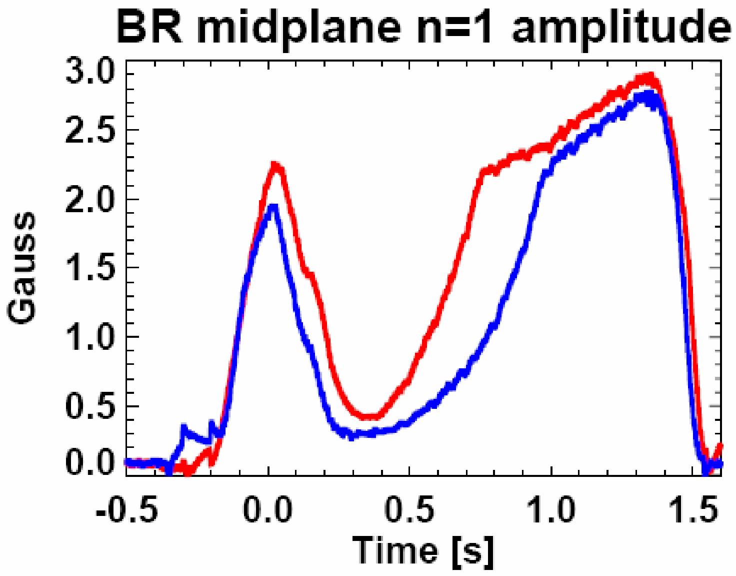


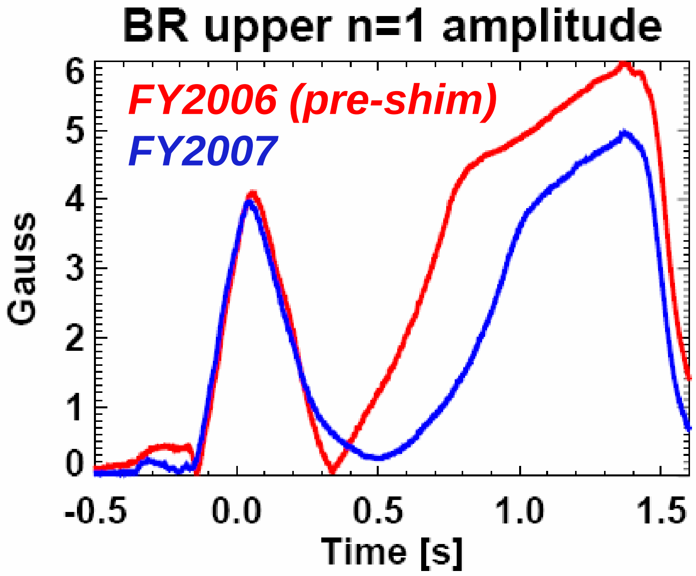


EF from slow OH variation different after I_{OH}=0 crossing

- OH waveform similar to that for NBI H-mode long-pulse
- EF increase is delayed after I_{OH} crossing, but eventually reaches similar amplitude and slope
- Midplane EF amplitude similar, upper EF amplitude reduced late in shot

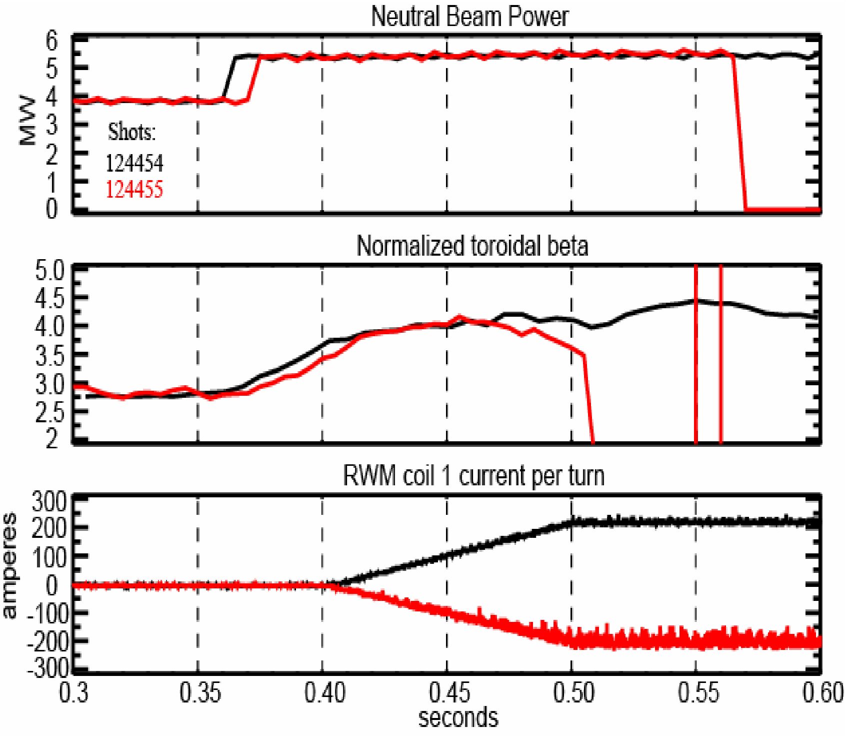

OH coil current

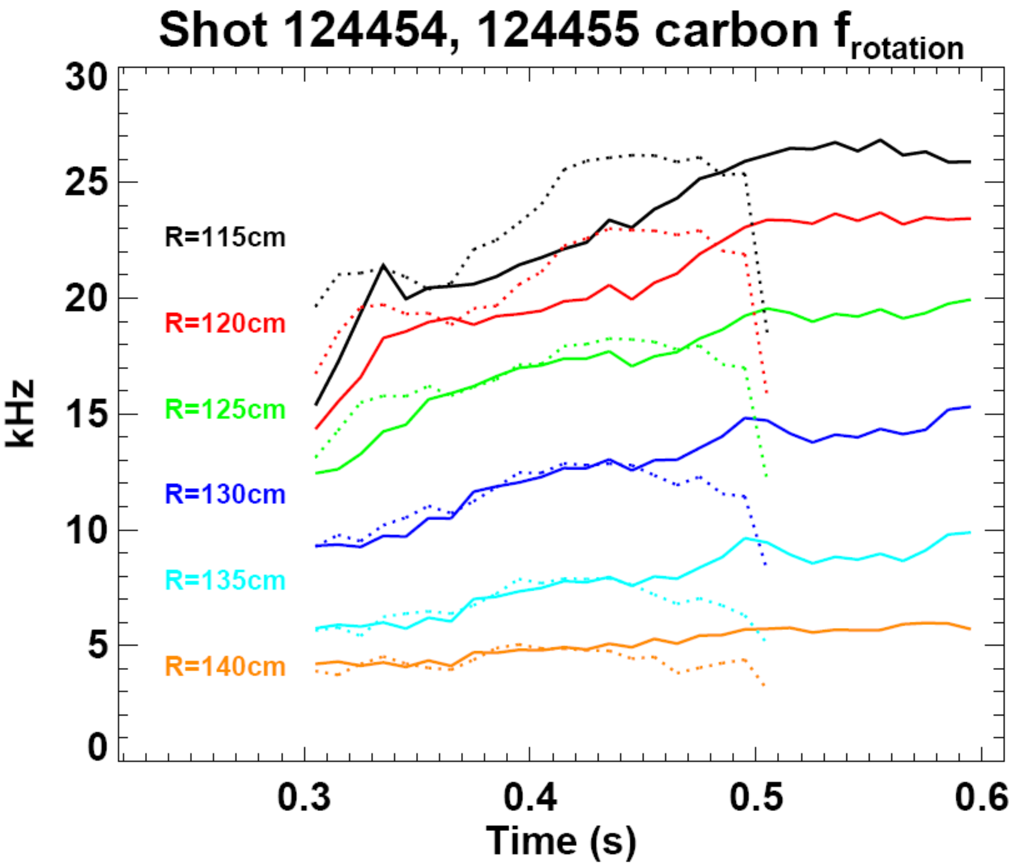

BR midplane n=1 amplitude


BR upper n=1 amplitude

Plasma still exhibits asymmetric response to phase of applied n=1 field

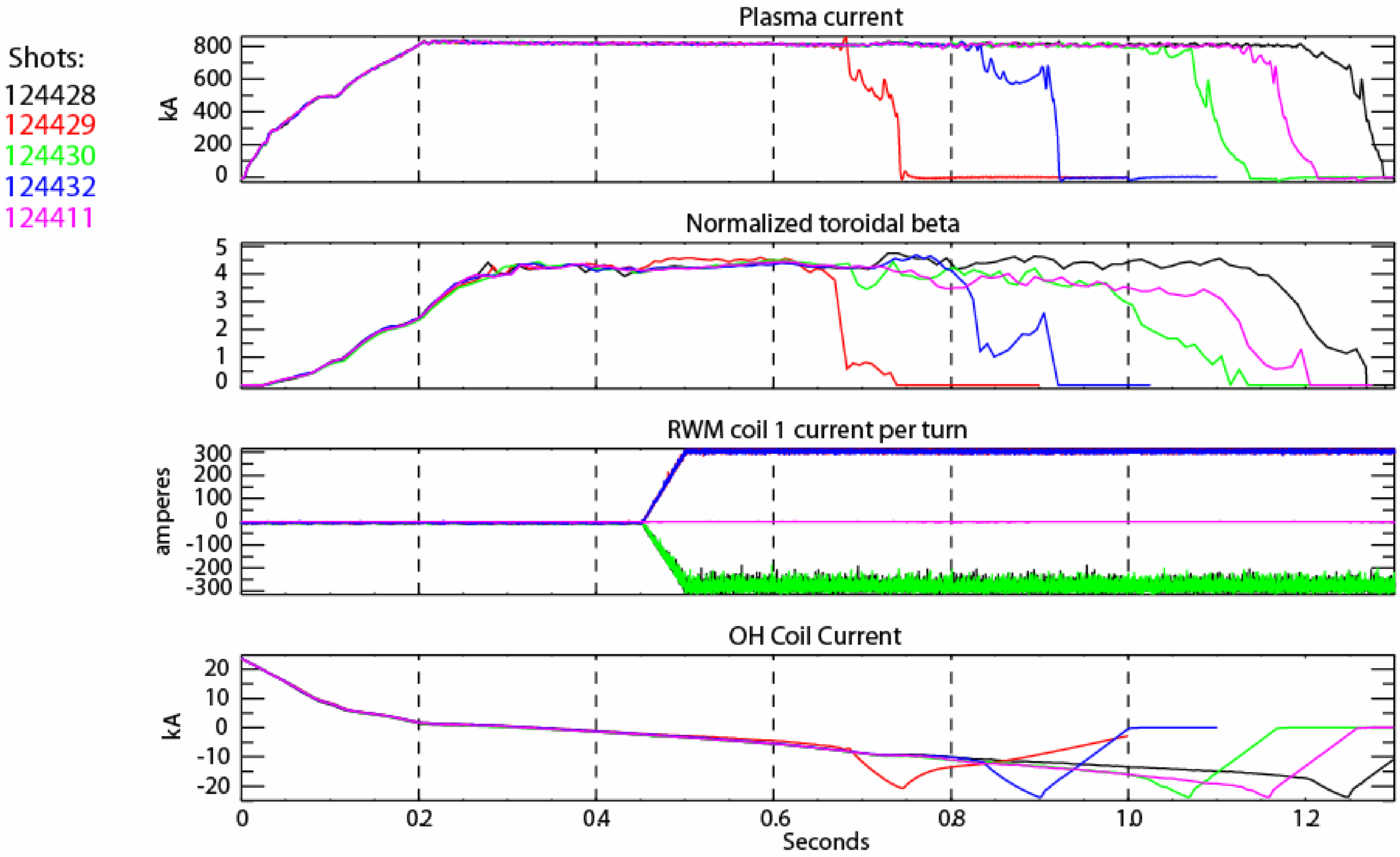
- Rotation collapse begins at t=0.45s, and is most clearly evident for radial positions R > 1.25m





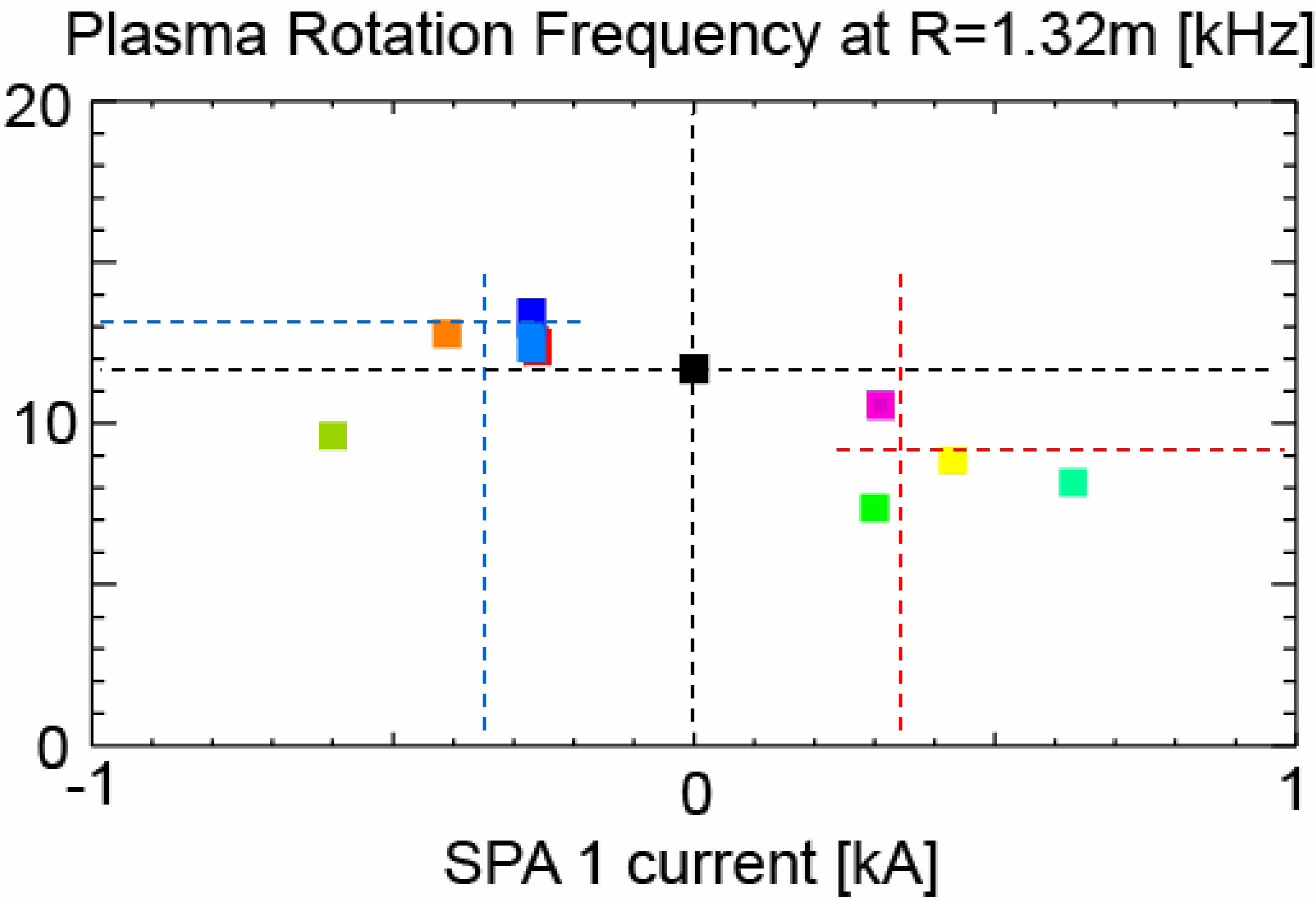
NEW: Plasma exhibits asymmetric response to applied n=3 field

- Pulse-length depends on polarity of applied n=3 field



Outboard Ω_ϕ changes by 30-40% with n=3 polarity flip

- Optimal n=3 current magnitude = 300-400A
- PF5 coil shape data from 2004 → PF5 is source of n=3 EF
  - Need to assess if this is consistent with empirical correction below



XP702 - RFA detection optimization during dynamic error field correction

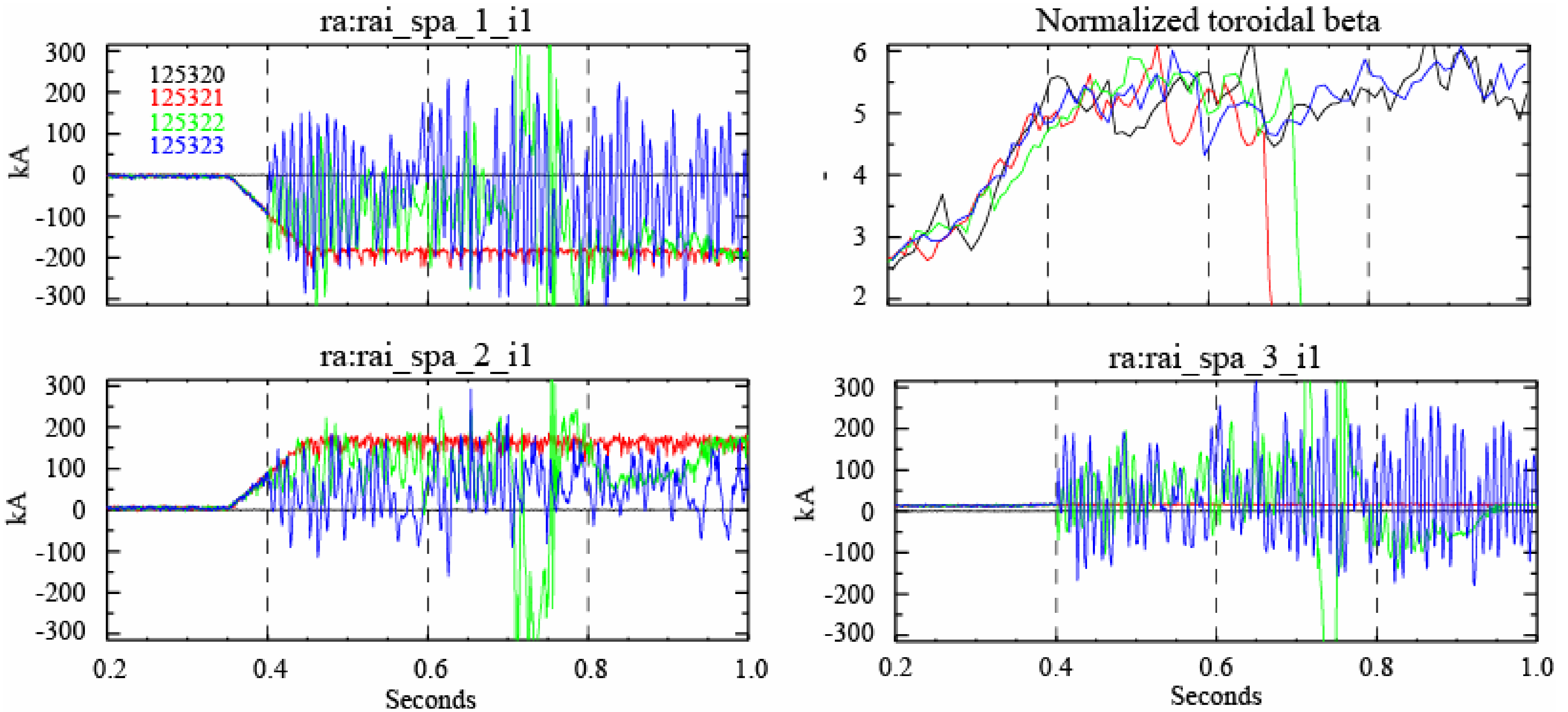
- Implemented real-time mode-ID using U+L B_P and B_R sensors
- Compared DEFC response using upper and lower B_P sensors vs. just using upper B_P sensors (as was used in 2006)
  - More robust mode-ID achieved (higher signal / baseline offset)
  - Higher proportional gain possible (0.7-0.8 vs. 0.5)
- Could not reproduce 2006 reference discharge which previously exhibited intrinsic rotation collapse →
  - Instead, applied n=1 EF pulse to induce collapse when OHxTF small
  - Scanned DEFC phase and gain until applied currents were nulled

  → **feedback system “trained” to eliminate EFA of known source**
- Combination of “trained” n=1 DEFC + n=3 EFC →
  - longest pulse of all shots in XP702
  - sustained plasma rotation

DEFC system trained to null RFA from externally applied/known n=1 error field source

- Optimal phase difference (δ=270°) between measured B_P (U/L avg) and applied B_R required to null n=1 EF pulse
- Sufficient feedback gain also required:

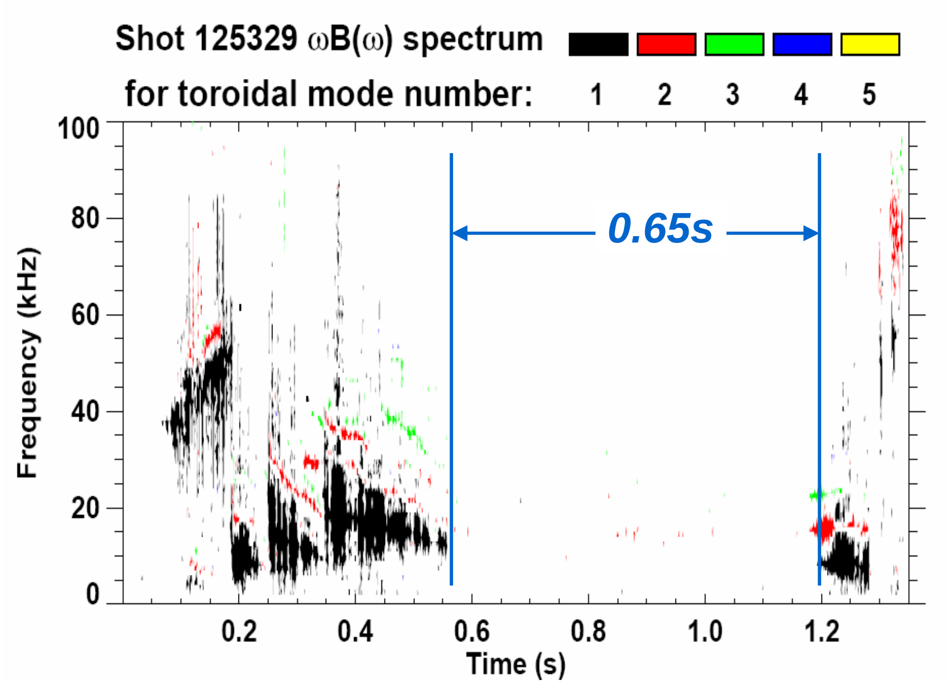
G_P=0.0 ***G_P=0.5*** ***G_P=0.7***

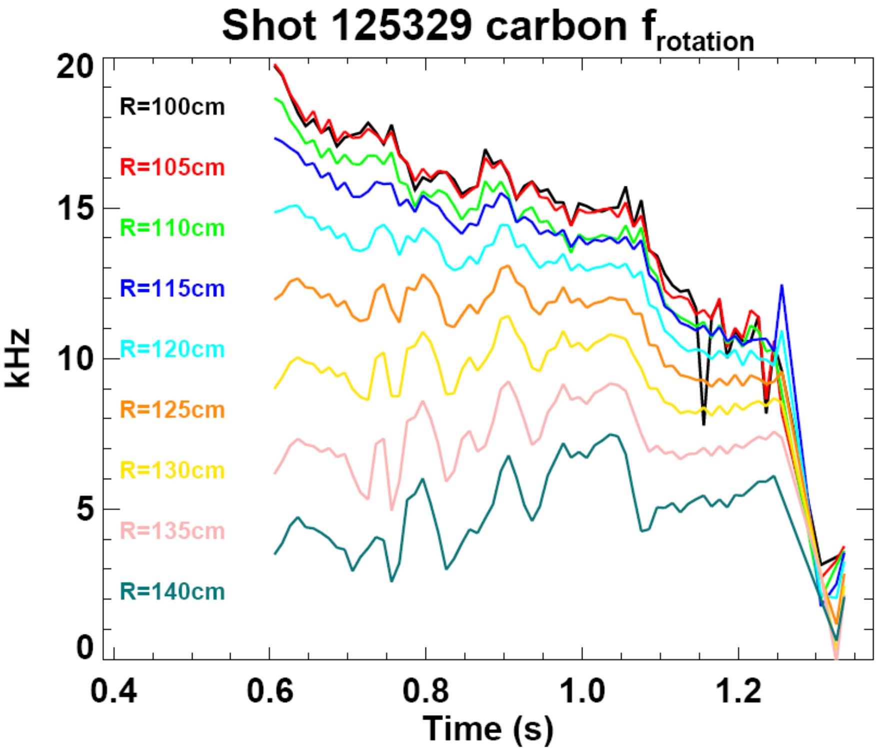


n=1 RFA feedback + n=3 EFC improves performance

- Long period free of core low-f MHD activity
- Plasma rotation sustained over same period
  - Core rotation decreases with increasing f_{GW} → 0.75, P_{RAD} → 3.5MW
  - R > 1.2m rotation slowly increases until t=1.1s (large ELM?)

→ Longest pulse at I_P=900kA





XP703 - B and q scaling of low-density locked-mode threshold at low-A

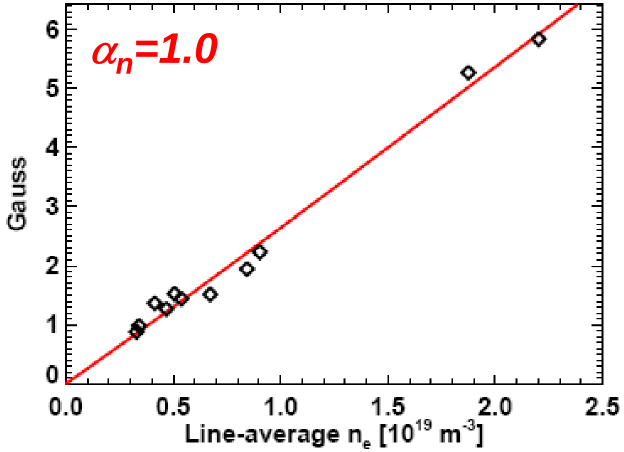
- Extended density range for threshold – now have factor of 4
- Performed B_T scan from 3kG to 5.5kG
- q_{95} scan difficult because high-q does not have q=2 in plasma
  - Found this out after MSE data was obtained
- Threshold increases with increased edge q-shear (w/o MSE)
  - Similarly - also increases with internal inductance
- Obtained MSE data for 4 scenarios of interest
  - q=2 surface is in plasma at time of locking, but NO q=1 surface
  - Core shear is often weakly reversed
  - Measured q profiles not yet included in analysis shown below!
- Locking threshold scaling favorable for ITER

NOTE: Scaling form used below: $B_{21}\,(\text{lock}) \propto n^{\alpha_n}\, B_T^{\alpha_B}\, q^{\alpha_q}\, R^{\alpha_R}$

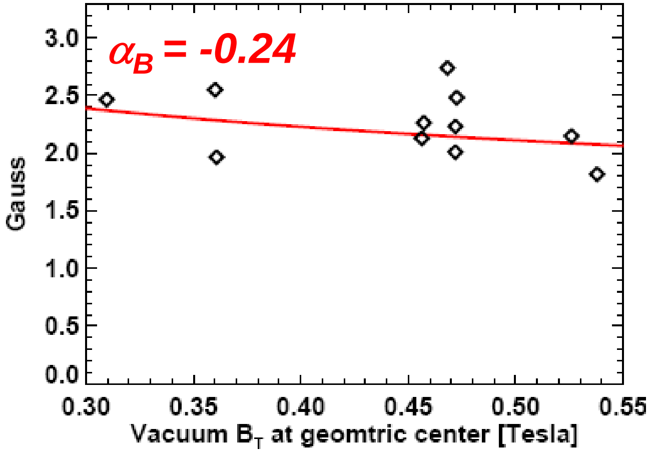
NSTX locking data shows linear density scaling and weak B_T dependence, but unexpected inverse scaling with q_{95}

2/1 B_r

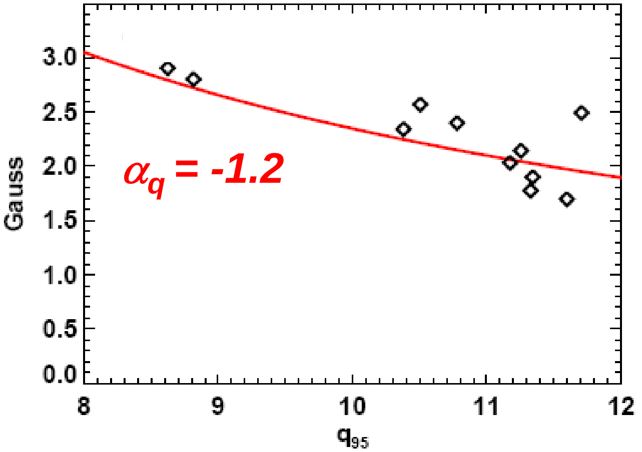
2/1 B_r threshold at q=2 vs. density



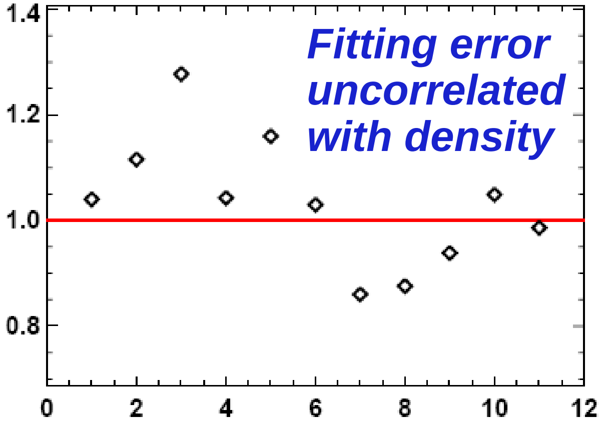
2/1 B_r threshold at q=2 vs. B_T



2/1 B_r threshold at q=2 vs. q_{95}



Measured threshold / best-fit



Fitting error uncorrelated with density

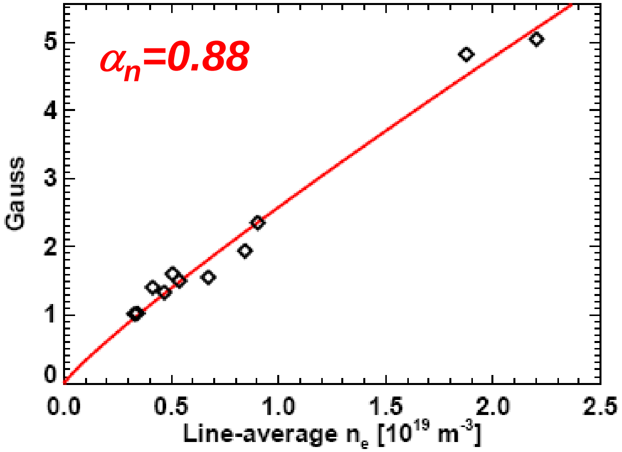
Sample index sorted by density

MSE data (not used for scaling above) shows variation in q_{min} when q_{95} is varied.
q(0) does not = 1 as for other experiments → q_{95} not good proxy for q-shear for NSTX.

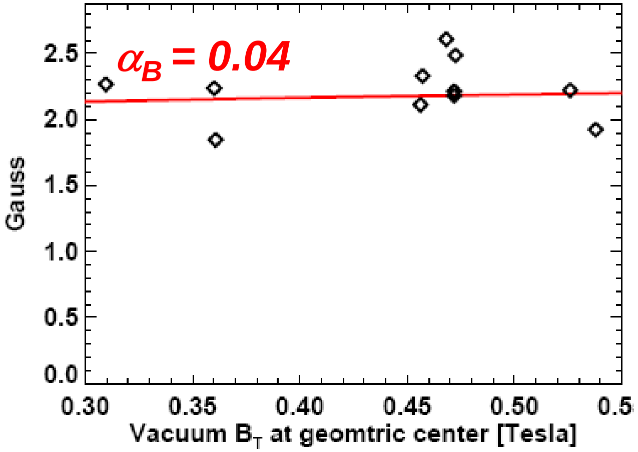
NSTX locking data shows nearly linear density scaling and very weak B_T dependence, and expected positive scaling with edge q-shear

2/1 B_r

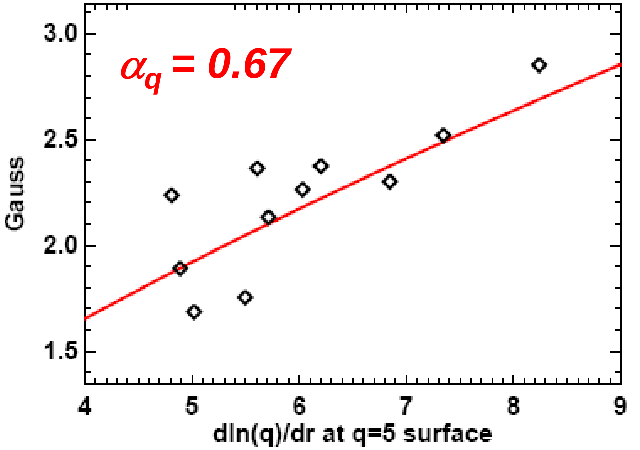
2/1 B_r threshold at q=2 vs. density



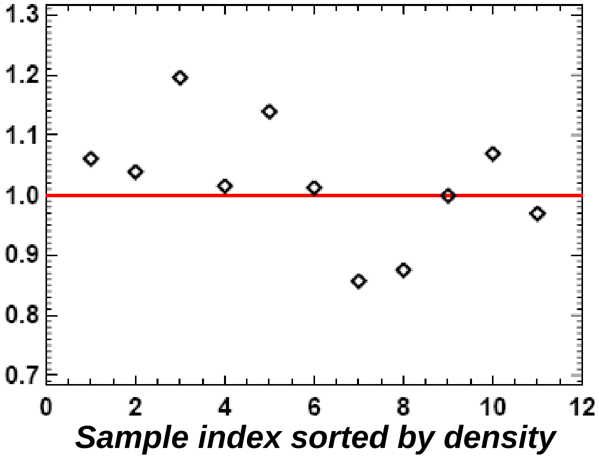
2/1 B_r threshold at q=2 vs. B_T



2/1 B_r threshold at q=2 vs. q-shear



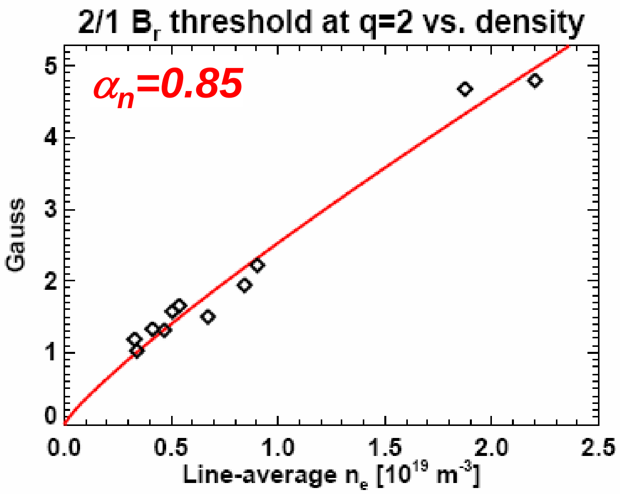
Measured threshold / best-fit

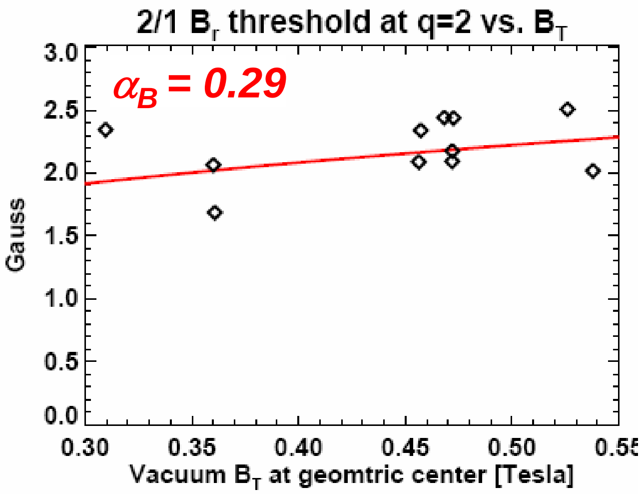


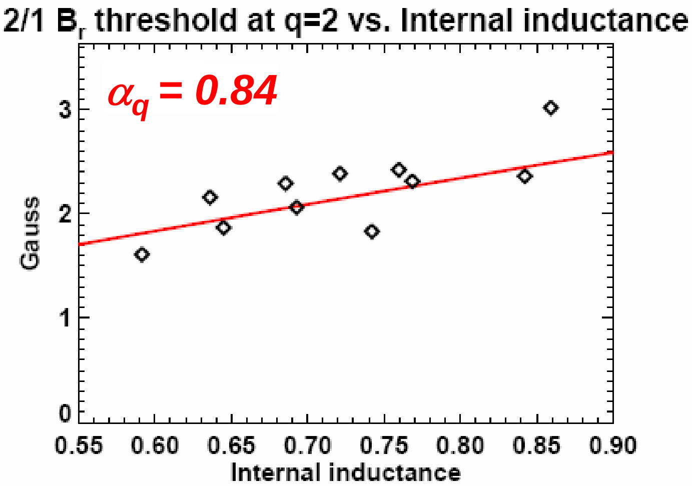
Density and B-field scalings are sensitive to choice of q-scaling variable, but, assuming size scaling coefficient $\alpha_R = 2\alpha_n+1.25(\alpha_B - 1)$ → NSTX α_R = 0.45 to 0.56

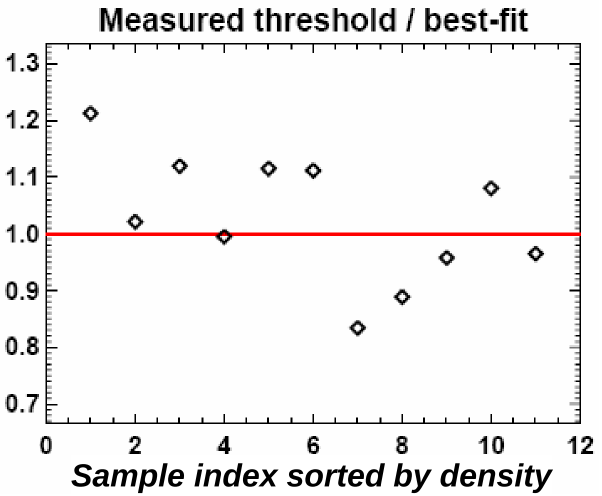
NSTX locking data shows nearly linear density scaling, weak positive B_T dependence, and nearly linear scaling with internal inductance

2/1 B_r


2/1 B_r threshold at q=2 vs. density


2/1 B_r threshold at q=2 vs. B_T


2/1 B_r threshold at q=2 vs. Internal inductance


Measured threshold / best-fit

Density and B-field scalings are sensitive to choice of q-scaling variable:

Range in NSTX: α_R = 0.45 (q_{95}), α_R = 0.56 (q′ at q=5), α_R = 0.8 (l_i)

Large extrapolation from NSTX to ITER, but here it is…

For NSTX q_{95} scaling with:

$n_e = 10^{19} m^{-3}$, $B_T = 5.7T$, $R_0 = 6m$, $\alpha_R = 0.45$, $q_{95} = 3$

ITER B_{21} → 14G, or $B_{21}/B_T = 2.5 \times 10^{-4}$

For NSTX l_i scaling with:

$n_e = 10^{19} m^{-3}$, $B_T = 5.7T$, $R_0 = 6m$, $\alpha_R = 0.8$, $l_i = 1.0$

ITER B_{21} → 30G, or $B_{21}/B_T = 5.2 \times 10^{-4}$

Caution – no q=1 surface in NSTX plasmas which could lower thresholds in ITER (and NSTX)

Also need to propagate uncertainties through analysis properly…

IPEC analysis not yet systematically included in scalings

- IPEC analysis shows that total $B_\perp^{mn}$ (including plasma response) on resonant surfaces differs significantly from vacuum external $B_\perp^{mn}$
  - So how did we account for intrinsic error field in NSTX if plasma response is important, and we didn’t include it?
- Empirically find that different normalization for $B_\perp^{mn}$ can improve accounting for EF using only vacuum fields:
  - Instead use perturbed helical flux:

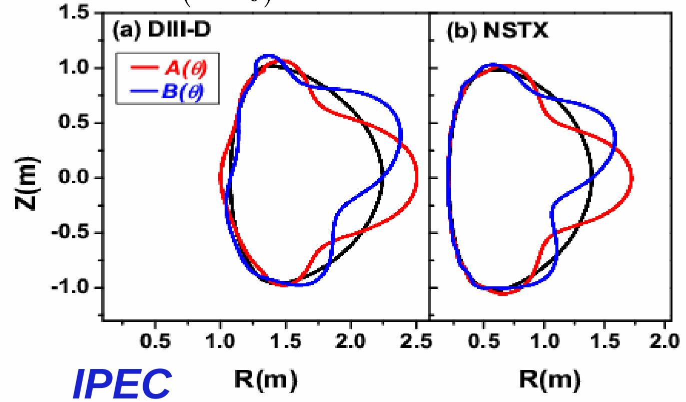
$$\delta\psi_{mn}^{h} = \sigma\left[R^{3}\left|\frac{q}{F}\right|\left(B_Z \delta B_R - B_R \delta B_Z \right)\right]_{mn}$$

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

  - $\delta\psi^h$ scales as $\mathbf{R^2}$ $|\nabla\psi|$ q/F $B_\perp^{mn}$

R^2 scaling of $\delta\psi^h$ apparently provides better geometric representation of fields that generate singular currents, torques, and mode locking

$$\left(\vec{b}^{x} \cdot \hat{n}_b\right) = A(\theta)\cos\varphi + B(\theta)\sin\varphi$$



IPEC

ALL NSTX DATA SHOWN ABOVE USES RENORMALIZED VACUUM $\delta\psi^h$ to compute $\delta B_{2/1}$