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NSTX

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

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for the NSTX Research Team

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Rosen Centre Hotel - Orlando, Florida

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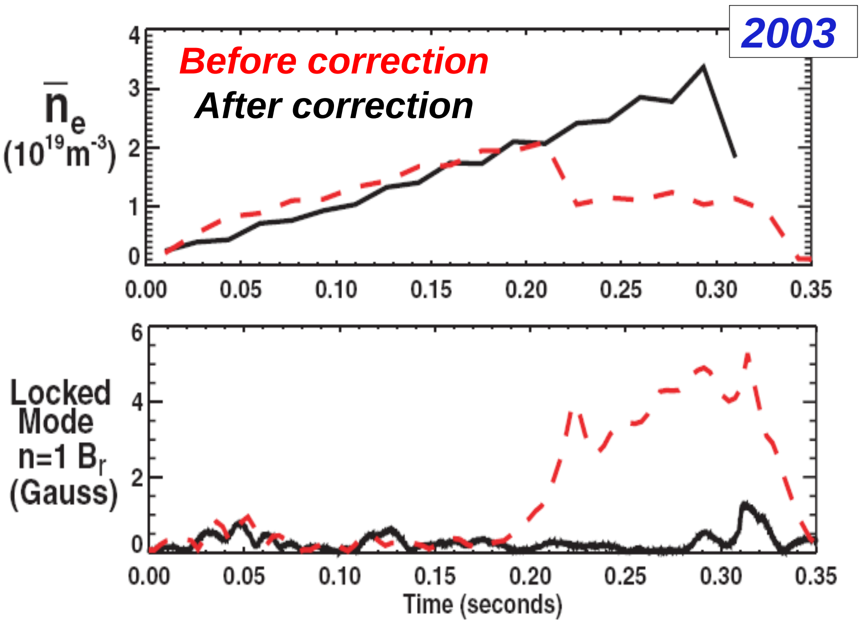
The low A, low B_T, and wide range of plasma β of NSTX plasmas provide new insight into the physics of magnetic error fields and their correction

- Detection & correction of static error fields and low-frequency instabilities
- Low density, low-β locked mode threshold scalings + theory advances
- Sustained high β_N and rotation from error field correction, including n > 1
- Comparison of RWM critical rotation data to theory (MARS-F code)

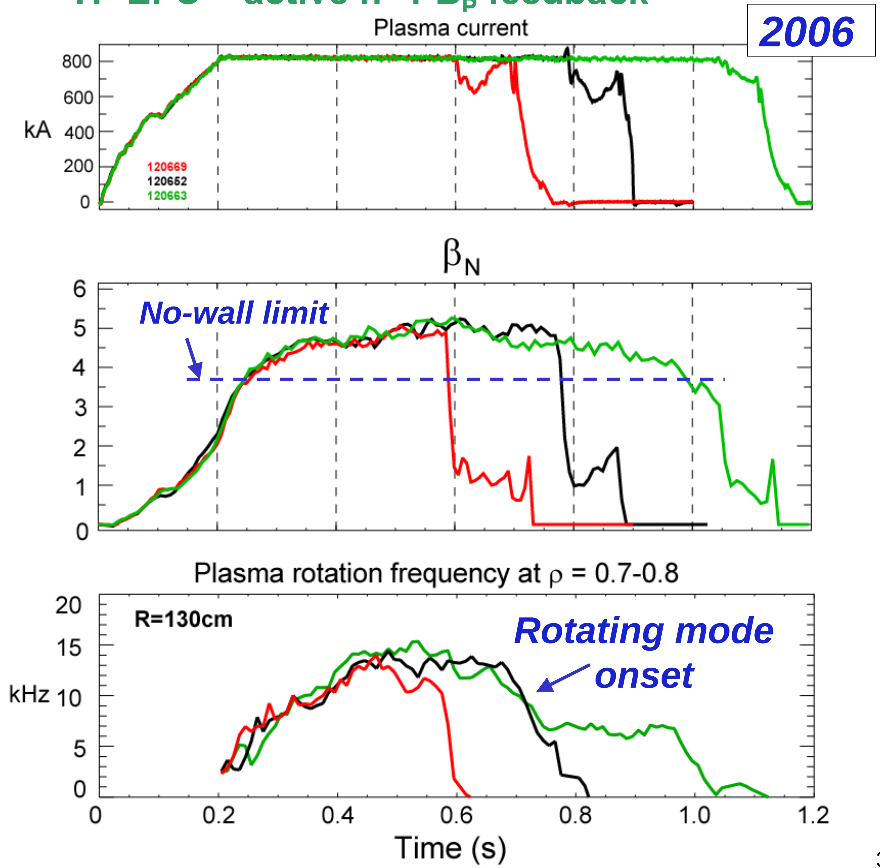
Detection and correction of small (<0.1%) low-n deviations from axisymmetry can significantly improve plasma performance

- 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 $\beta > \beta_{no\text{-}wall}$

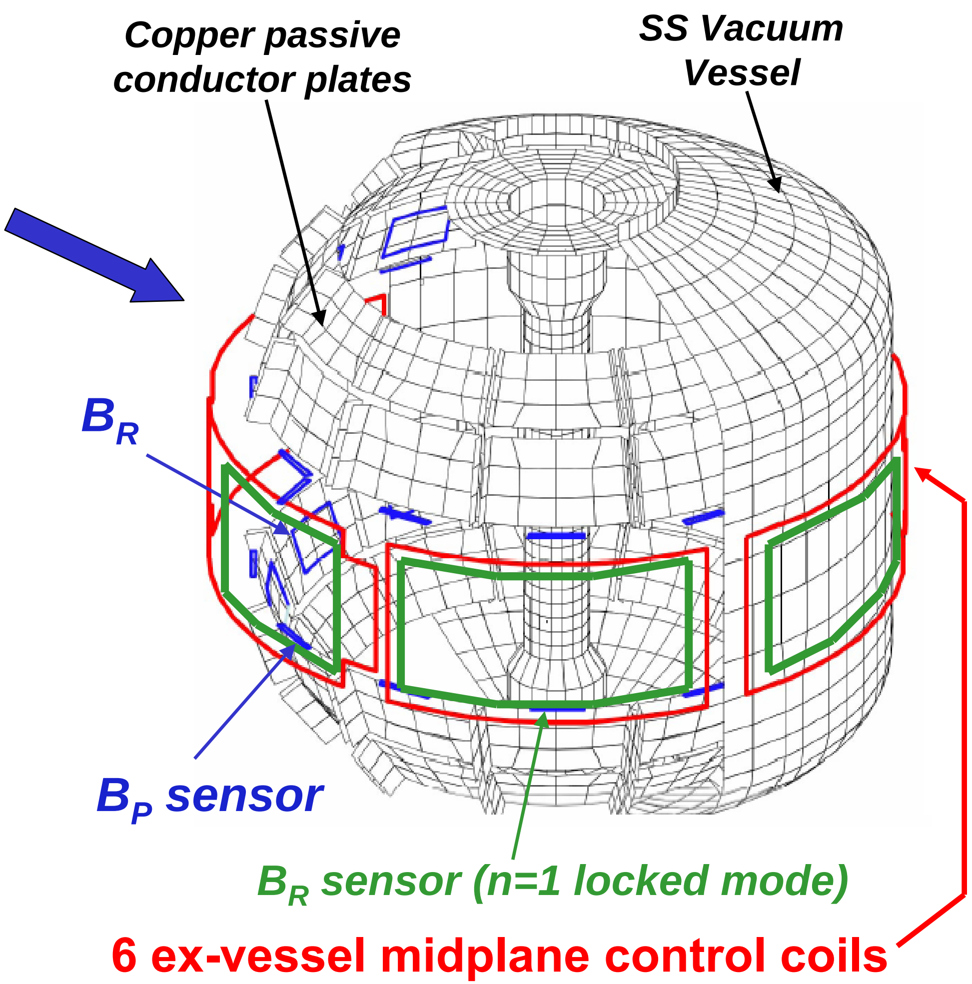
- **No error field control during high β_N phase**
- **TF-EFC**
- **TF-EFC + active n=1 B_p feedback**



- 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



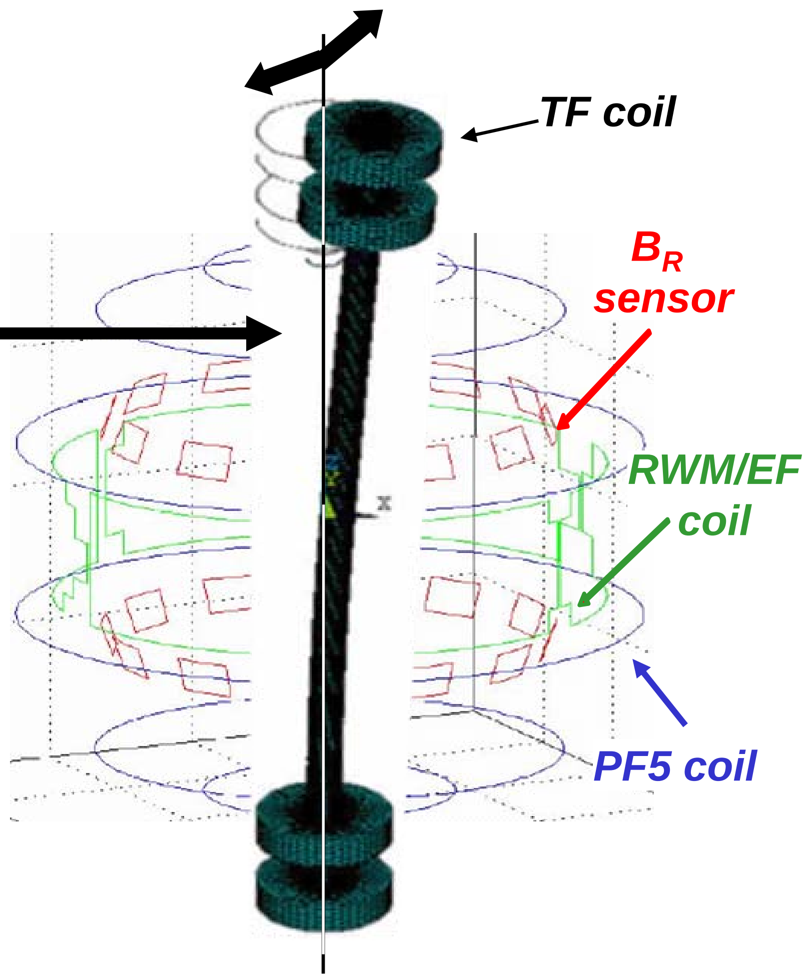
VALEN Model of NSTX (Columbia Univ.)

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

Error field detection & correction timeline:

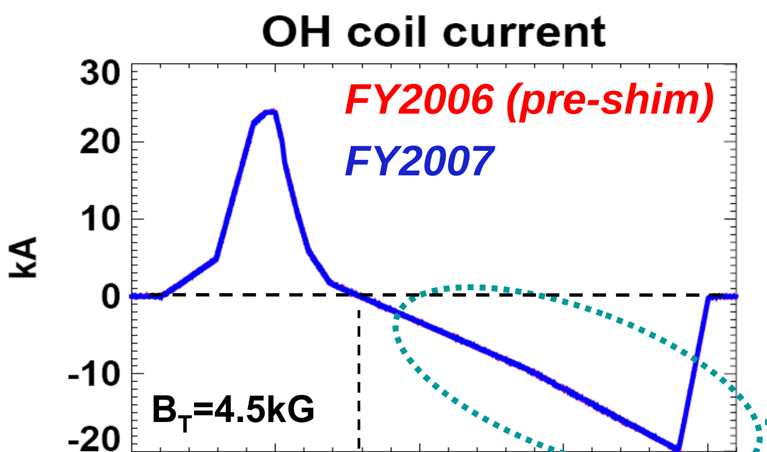
- **2001** – Primary vertical field coil (PF5) identified as n=1 EF source, and was corrected in 2002 → sustained high β
- **2006** – Determined force (from OH leads) at top of machine induces **TF coil motion 1-2 mm at midplane relative to PF coils**
  - → **n=1 B_R EF at outboard midplane**
- **2007** – 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)

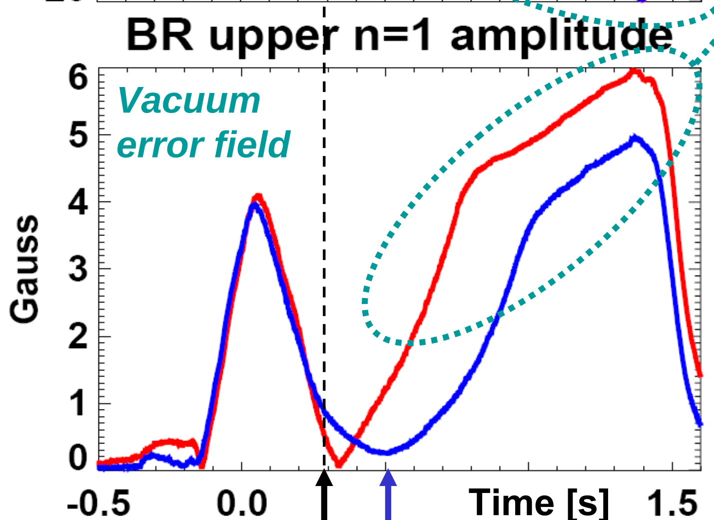


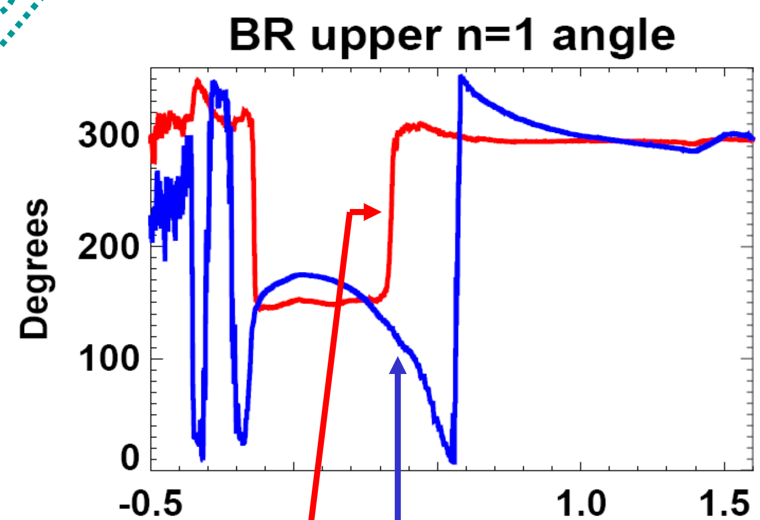
n=1 EF from TF coil motion is $\propto I_{OH} \times I_{TF}$, but has additional time lags and non-linearities which complicate correction

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

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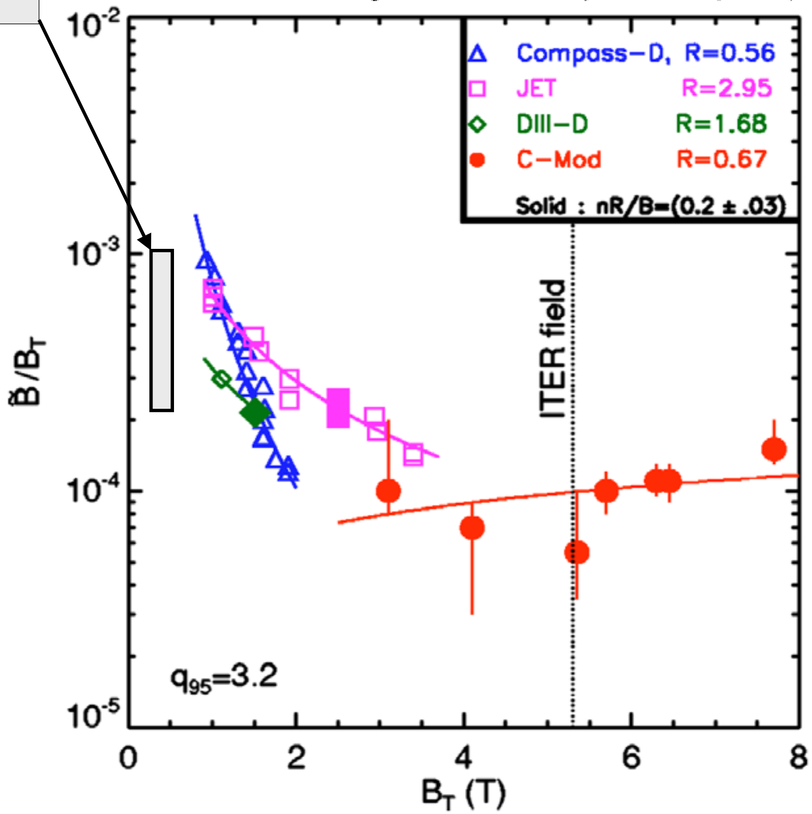
NSTX locked mode (LM) studies test locking theories in an extended parameter regime, and establish scalings for the ST

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 $n_e = 0.5 - 2\times10^{19} m^{-3}$
- 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: $B_{21}(\text{lock}) / B_T \propto n^{\alpha_n} B_T^{\alpha_B} q^{\alpha_q} R^{\alpha_R}$

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 $\delta\vec{B}^x$

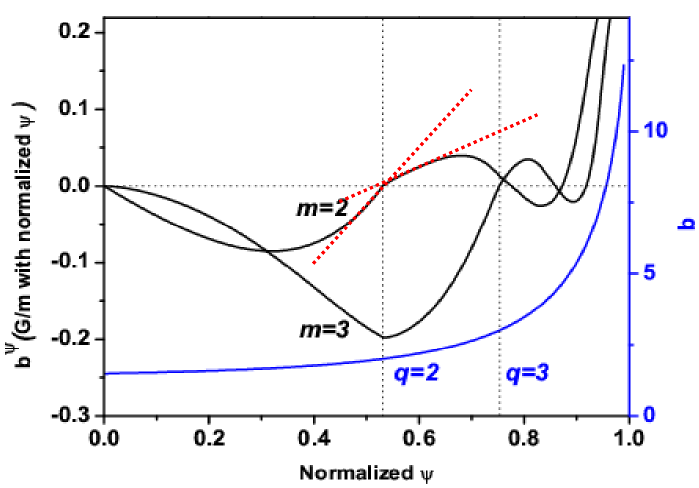
- Ideal MHD constraint does not allow islands, so 3D equilibrium has singular currents to preserve magnetic topology - $\left(\delta\vec{B} \cdot \vec{\nabla}\psi\right)_{mn} = 0 \;\; at \;\; q = m/n$

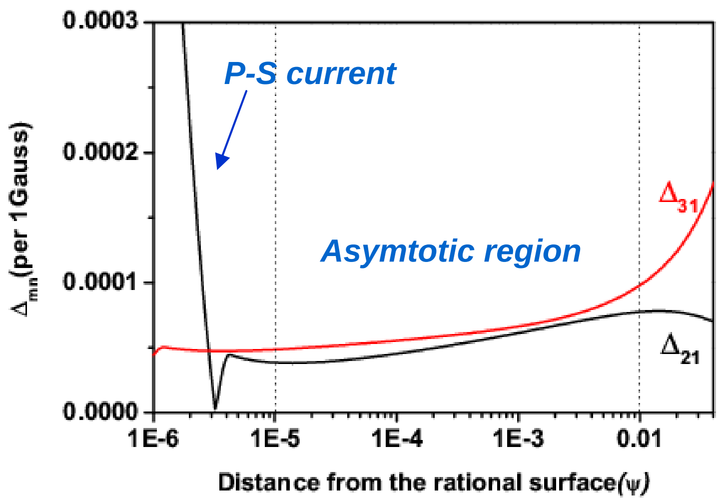
$$\Delta_{mn} = \left[\frac{\partial}{\partial\psi}\left(\frac{\delta\vec{B}\cdot\vec{\nabla}\psi}{\vec{B}\cdot\vec{\nabla}\varphi}\right)\right]_{mn} \rightarrow \vec{j}_s = \frac{\Delta_{mn} i m e^{i(m\theta - n\varphi)}}{\mu_0 n^2 \left(\oint dS B^2 / \left|\vec{\nabla}\psi\right|^3\right)}\delta(\psi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

Jump of derivative of radial field

Parallel singular current preventing magnetic islands from opening

Total resonant $B_\perp$ driving magnetic islands (w/o rotation)

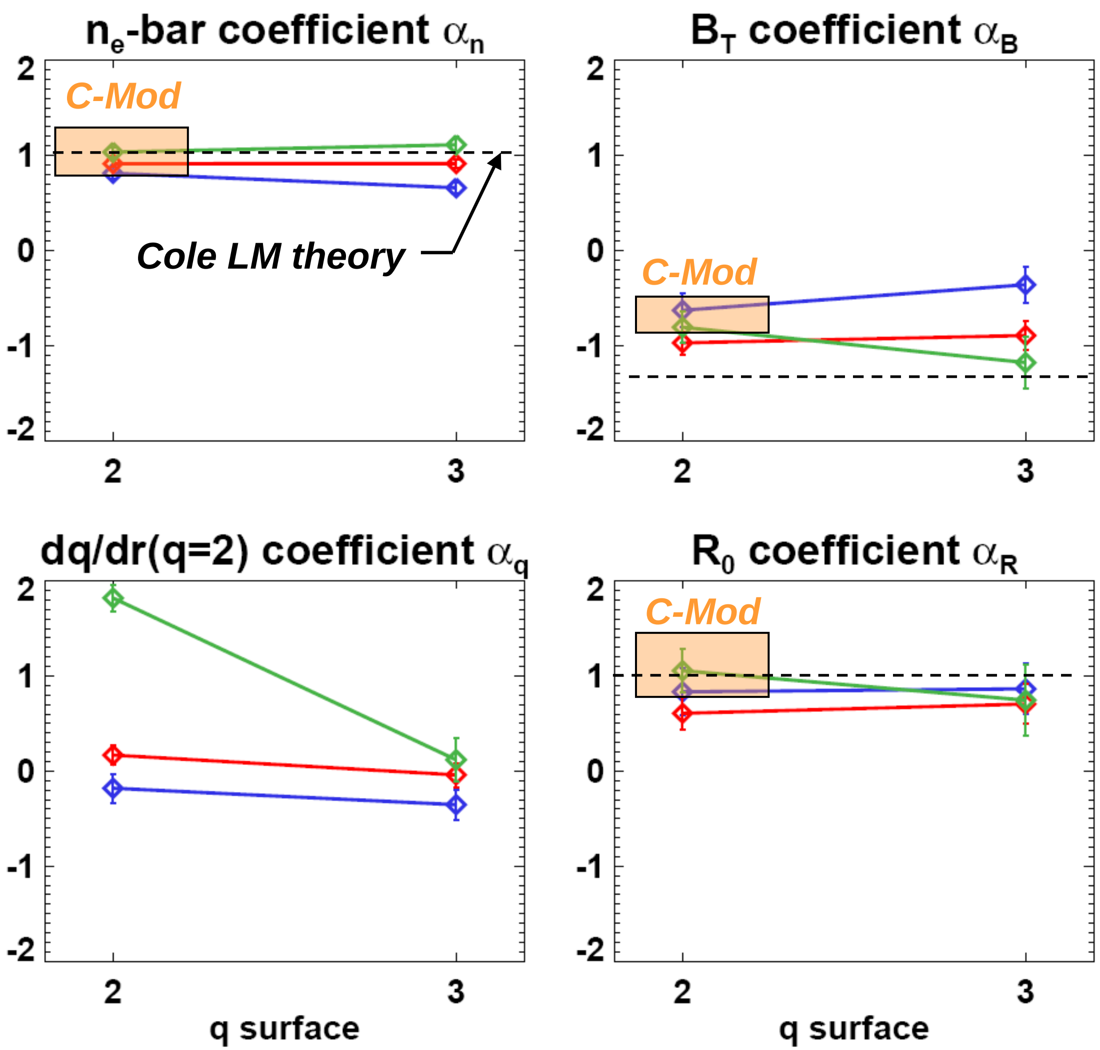




• *IPEC: J.-K. Park, PoP 052110 (2007), Locked mode: J.-K. Park, PRL 195003 (2007)*

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:

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

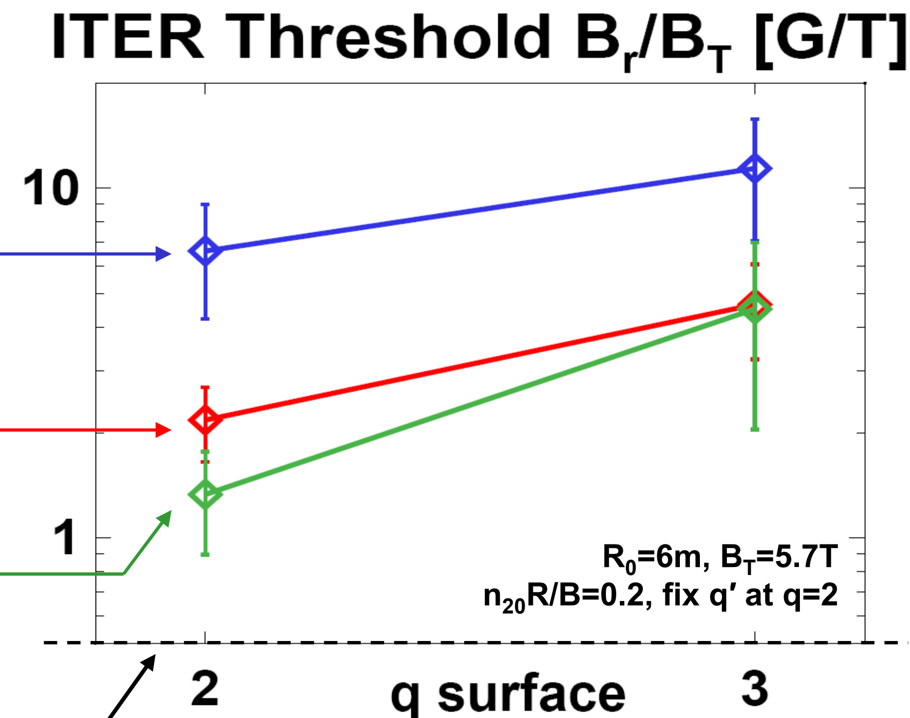
PRL **99**, 065001 (2007)

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

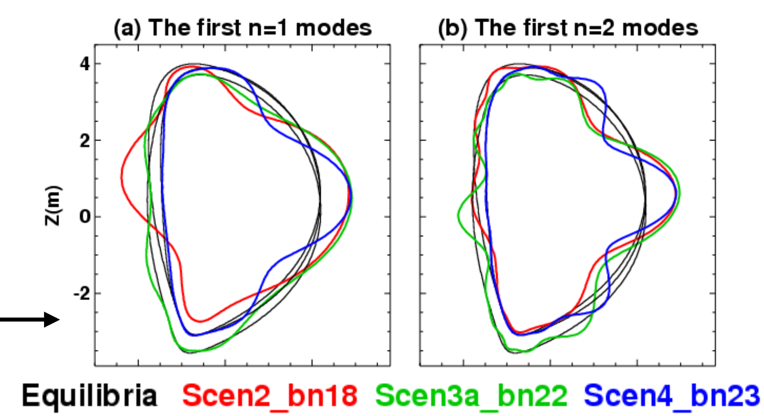
Vacuum $\delta\psi_h^{mn} \propto (|\nabla\psi|R^2B_\perp)^{mn}$
threshold **1-2** × **higher** than IPEC

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



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- Sustained high β_N and rotation from error field correction, including n > 1
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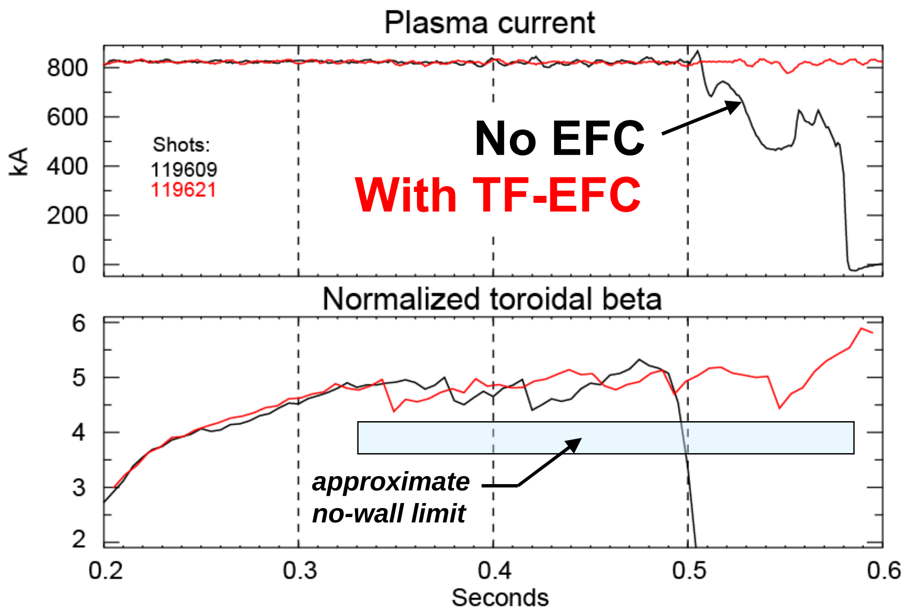
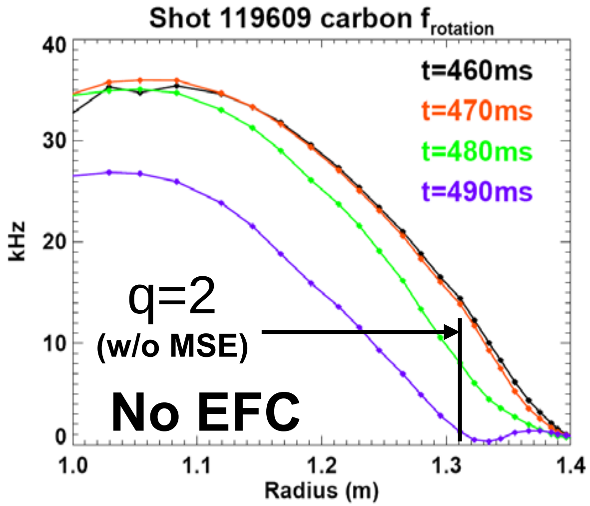
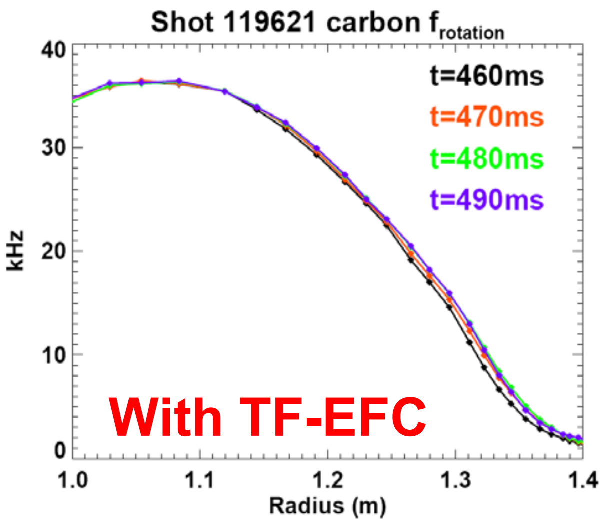
At high β, EF correction can aid sustainment of high toroidal rotation needed for passive (rotational) stabilization of the RWM





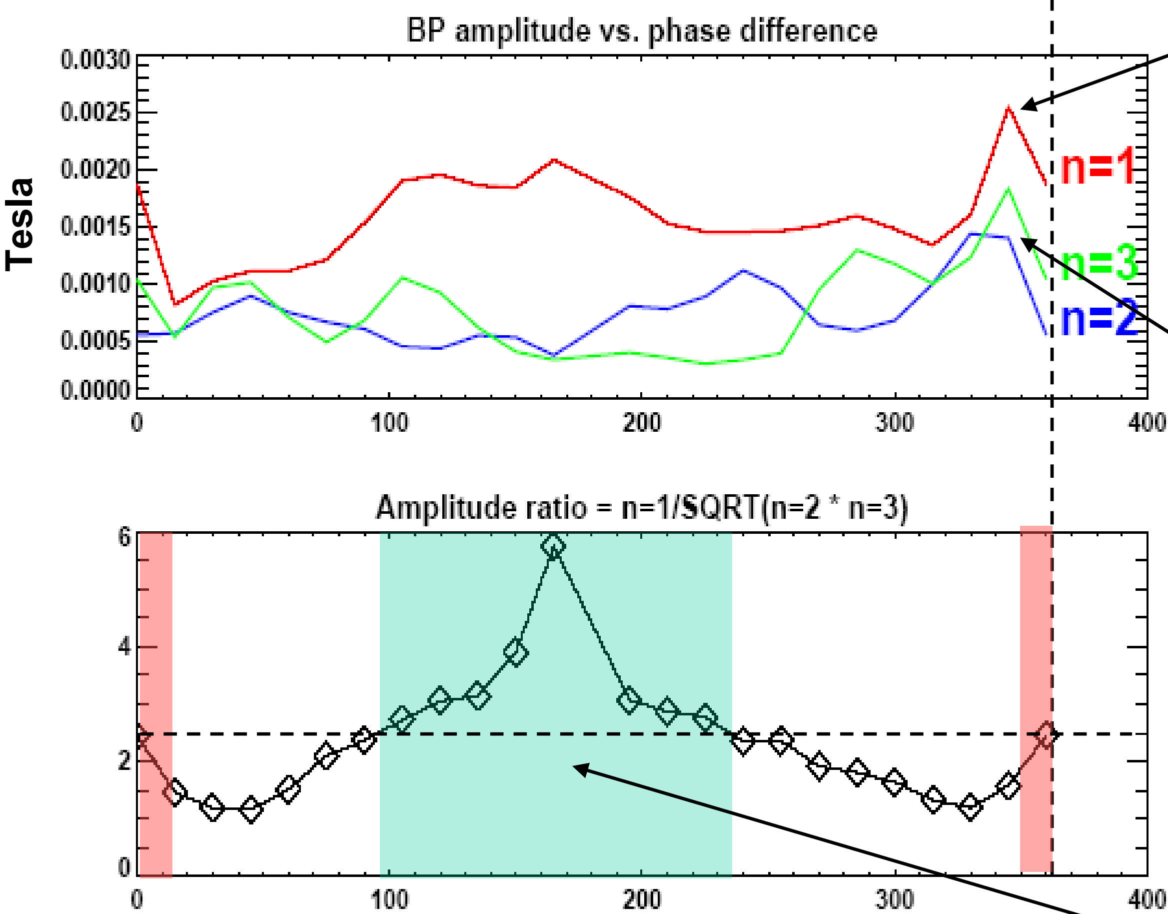
- Use real-time $I_{OH} \times I_{TF}$, incorporate observed time-lag and non-linearity of EF
- Empirically minimize rotation damping near q=2-3 for 100-200ms of reference shot
  - Extrapolate in time, balance m=2 against m=0 ***(non-resonant!)*** of EF from moving TF
  - Correction coefficients must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

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

Scan phase shift between $B_{P\text{-}U}$ and $B_{P\text{-}L}$: ***360°***



Relative phase shift between upper and lower B_P sensors [Degrees]

- 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

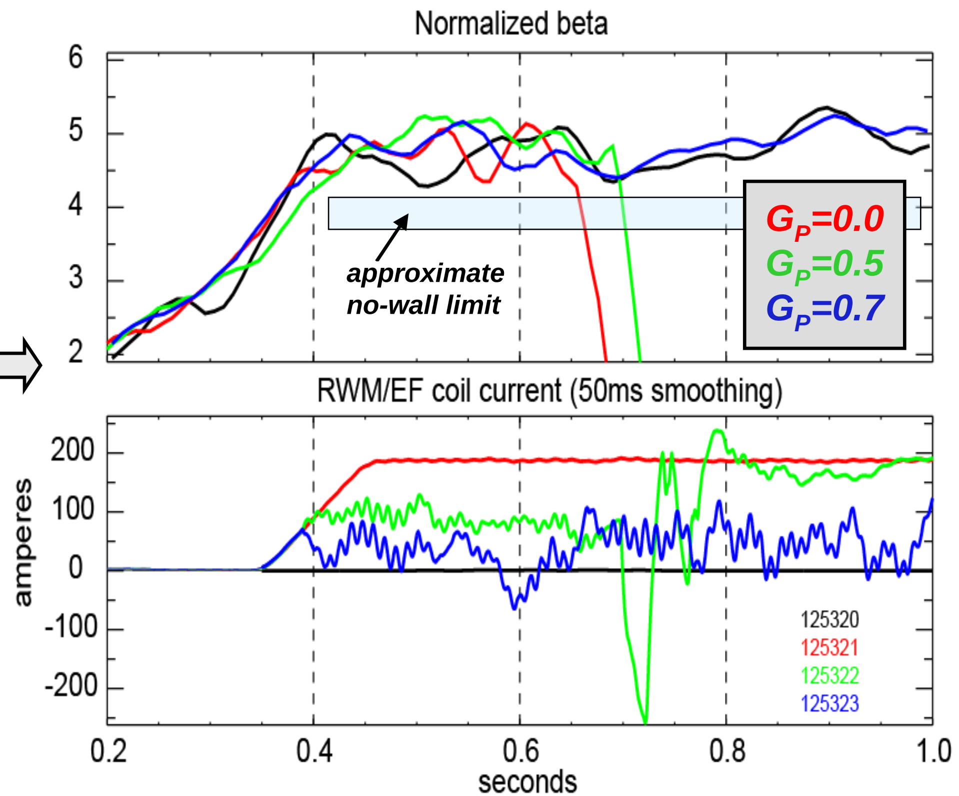
Optimal shift increases n=1 signal / baseline by 2-3 × → higher stable feedback gain

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

- **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 *<u>only feedback on RFA</u>***

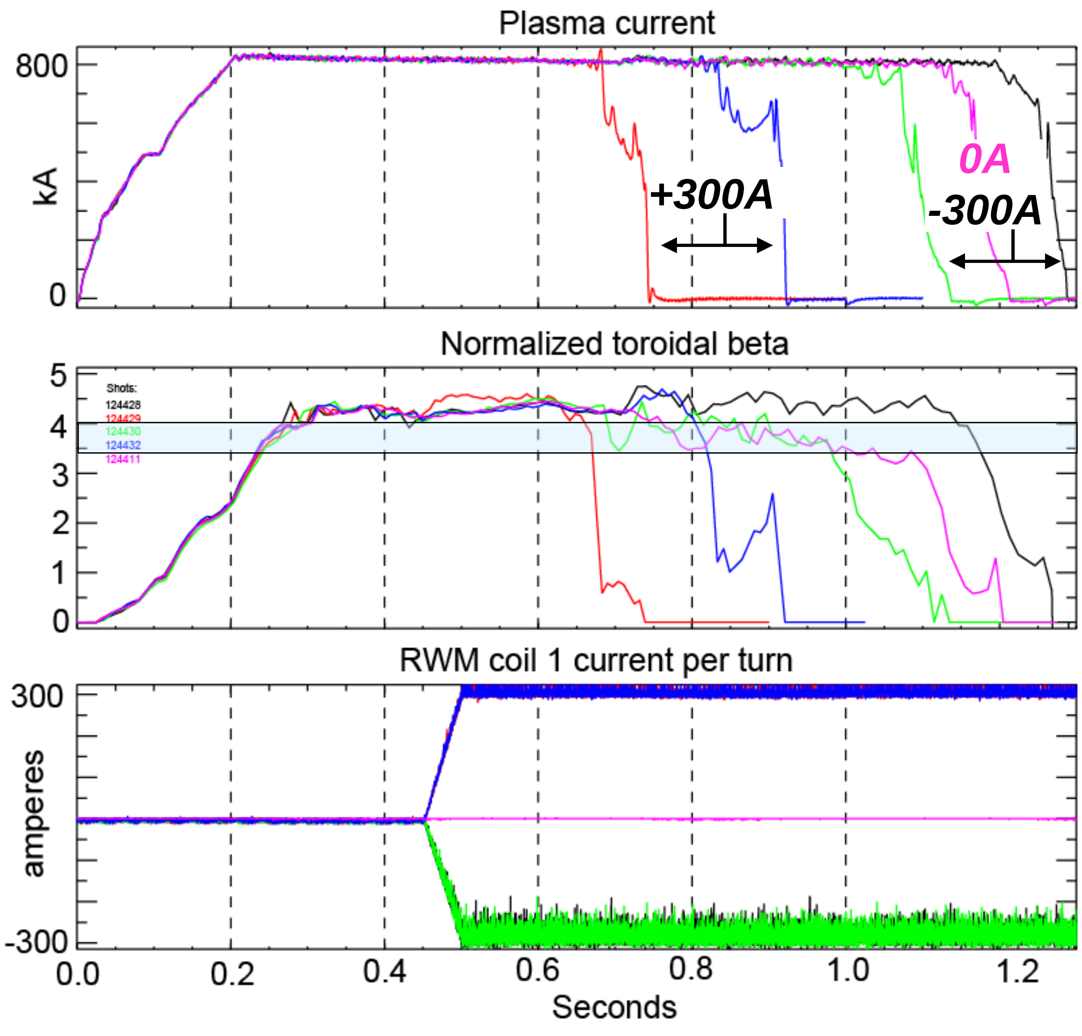
<u>EFC algorithm developed in FY07:</u>

- Use time *<u>with minimal intrinsic EF</u>* and RWM stabilized by rotation
- Intrinsic Ω_ϕ 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*

NEW: Discovered high-*n* error fields (*n*=3) important at high β_N



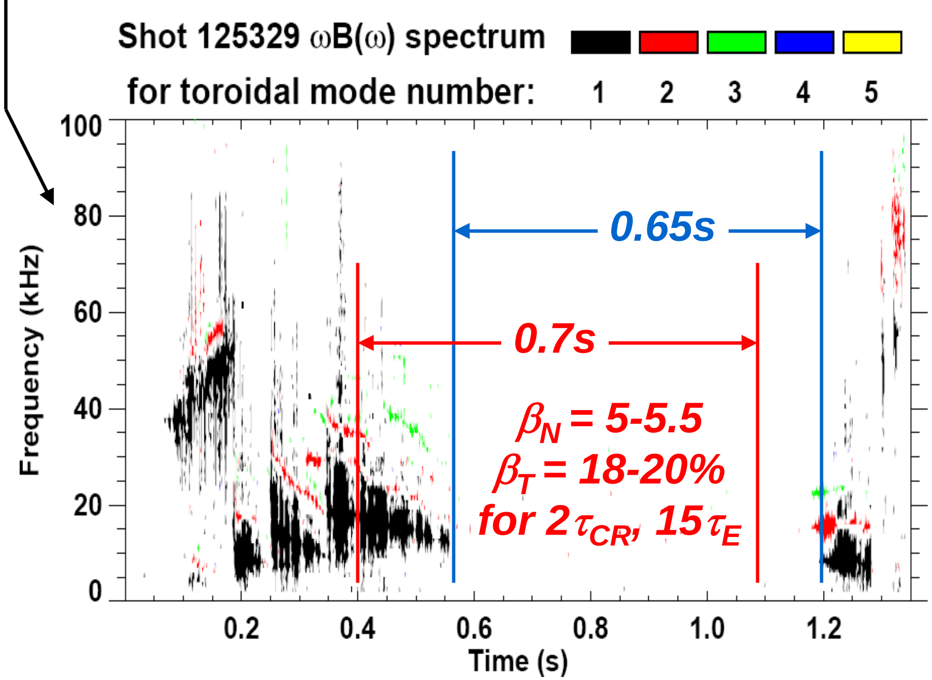
- Pulse-length depends on polarity of applied n=3
  - Anti-corrective polarity disrupts I_P and β
- Plasmas operate above n=1 no-wall limit → RFA
  - slows rotation →
  - destabilizes n=1 RWM
- Correction current magnitude for n=3 similar to that for n=1 correction
  - Applied n=3 $|B_R|$ is ≈ 6G at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

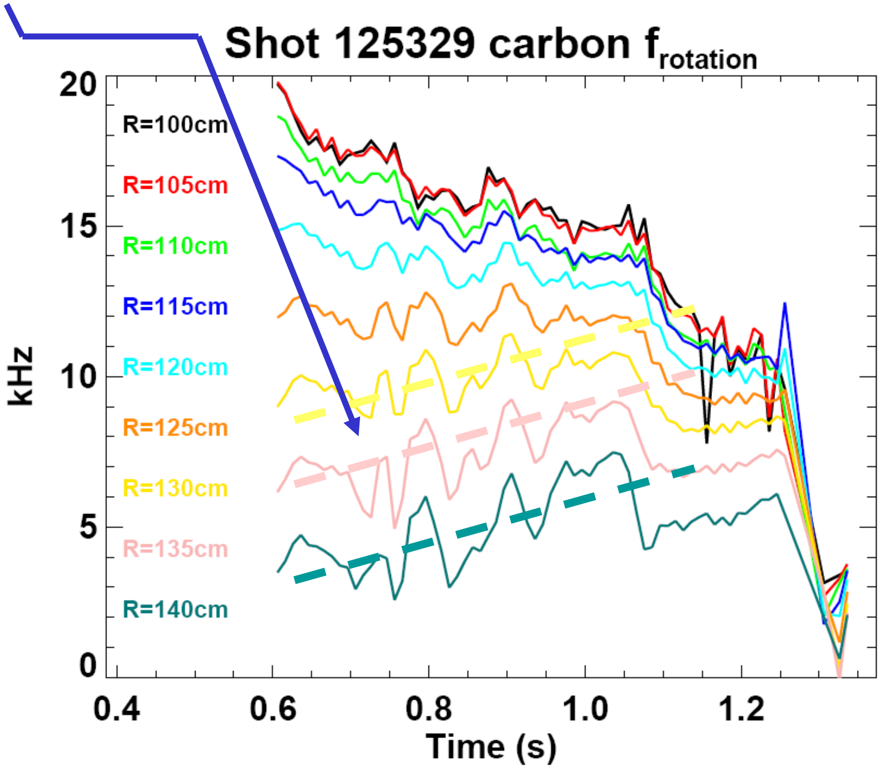
• n > 1 error fields not commonly addressed in present devices, or in ITER

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-β
- 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: $\tau_{CR} \approx 0.3$s, τ_E=40-50ms

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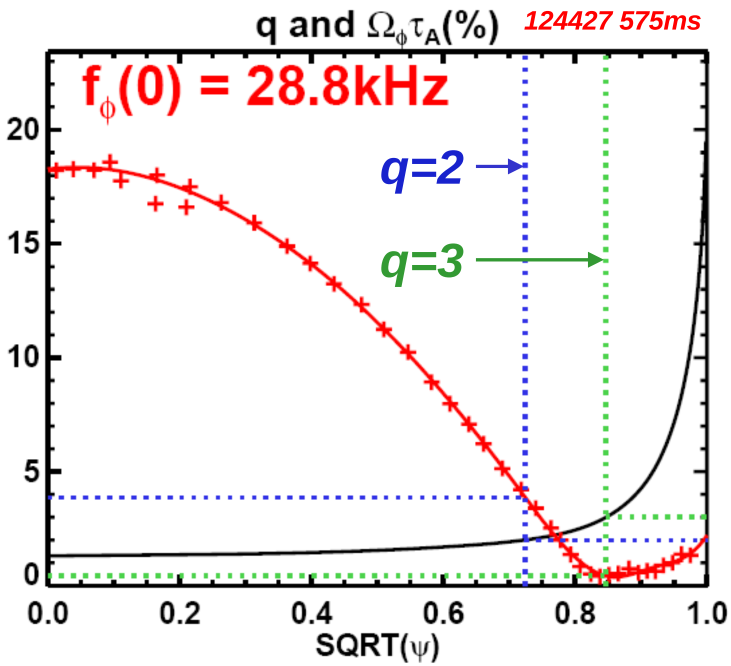
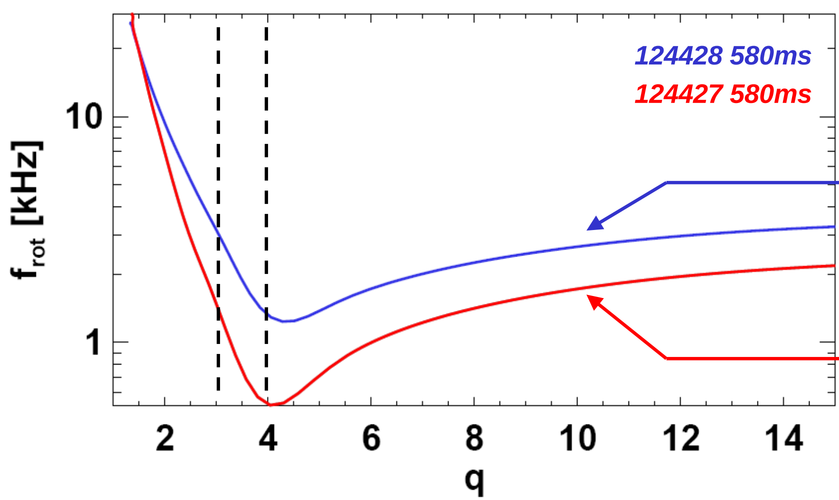
In the n=3 EFC experiments, edge rotation for ρ > 0.75 determines stability of discharges and resultant pulse-length

NSTX



- Discharges in n=3 EFC studies have low rotation at low-order rationals relative to the core rotation
  - $\Omega_\phi\tau_A$ (ρ=0) = 18%
  - $\Omega_\phi\tau_A$ (q=2) = 4% (4.5 × lower)
  - $\Omega_\phi\tau_A$ (q=3) = 0.4-1% (18-45 × lower)



- n=3 EFC increases the rotation primarily on surfaces with q ≥ 3

With n=3 EFC, rotation is sufficient to stabilize n=1 RWM

Without n=3 EFC, rotation is lower and discharge has RWM disruption

n=3 EFC discharges bracket critical rotation profile for n=1 RWM, motivating comparison to MARS-F stability code

- **However**, low-A and strong shaping of NSTX violate high-A/circular formulation of particle trapped and passing orbit times implemented in MARS-F semi-kinetic damping model:

$$\text{Dissipation} \propto -\mathrm{Im}(\hat{\Delta}_C) \equiv D_C(\Omega_C, \epsilon_r) = \frac{\sqrt{\pi}}{2}\,\Omega_C^7 \int_0^{1/(1+\epsilon_r)} \tau^8 \exp(-\tau^2\Omega_C^2)(2-\lambda)^2 \, d\lambda$$

Inverse aspect ratio (→ ϵ_r)

Normalized rotation frequency (→ Ω_C)

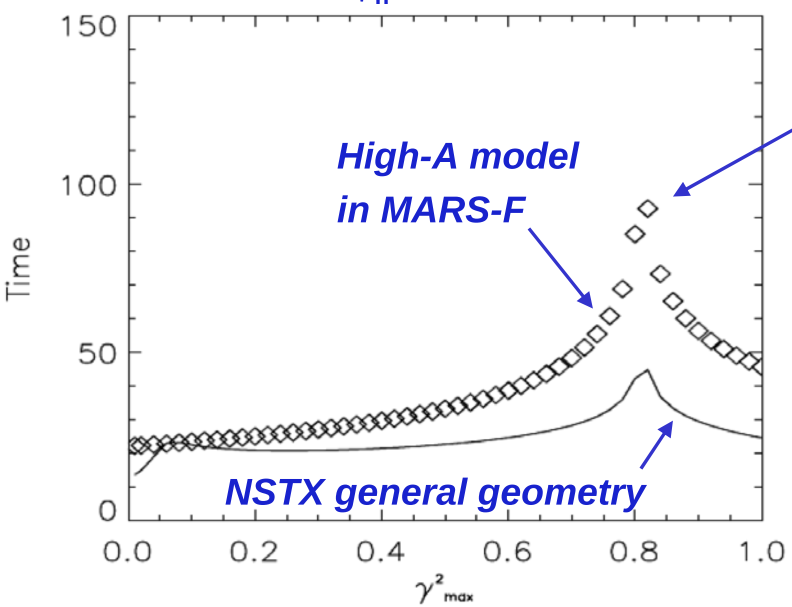
Normalized orbit time (→ τ)

$$\Omega_C = \frac{\Omega_\phi}{|nq - m'|\,\omega_s} \quad \longrightarrow \quad \omega_s \equiv \frac{(2T/M)^{1/2}}{qR}$$

$$\tau = \hat{K}(k)(\kappa_C / 2\epsilon_r)^{1/2}$$

$$\kappa_C \equiv k^2(1-\epsilon_r) + 2\epsilon_r = k^2/\lambda$$

$\sqrt{\psi_n} = 0.870$



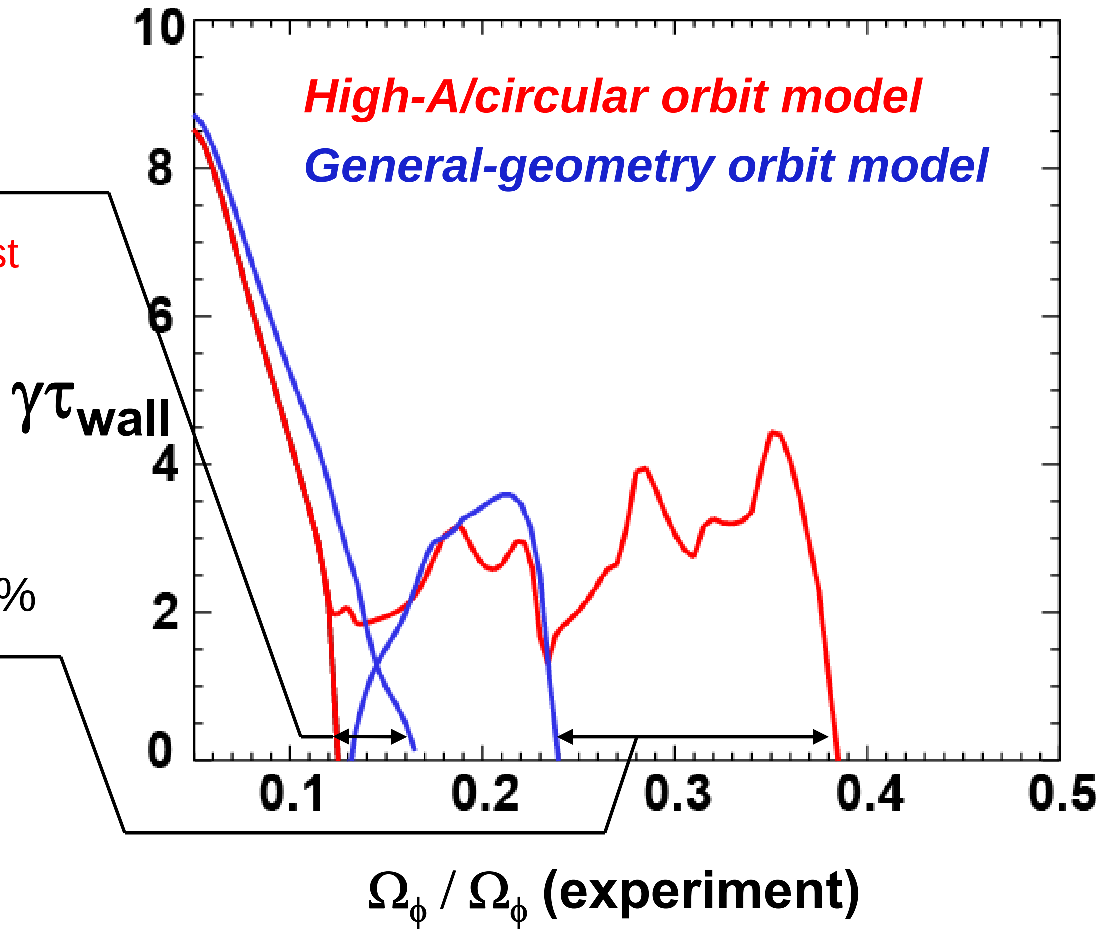
The high-A model over-predicts the orbit time τ by up to a factor of 2 at large r/a in NSTX
→ decreased dissipation

But, $\varepsilon_r \equiv a/R_0 \sqrt{\psi_n} \neq \varepsilon_B \equiv (B_{max}-B_{min})/(B_{max}+B_{min})$
$\varepsilon_B \approx 0.6 \times \varepsilon_R$ in NSTX core, and ε_B should be used
→ increased dissipation

General geometry corrections have been implemented in MARS-F and tested (preliminary)

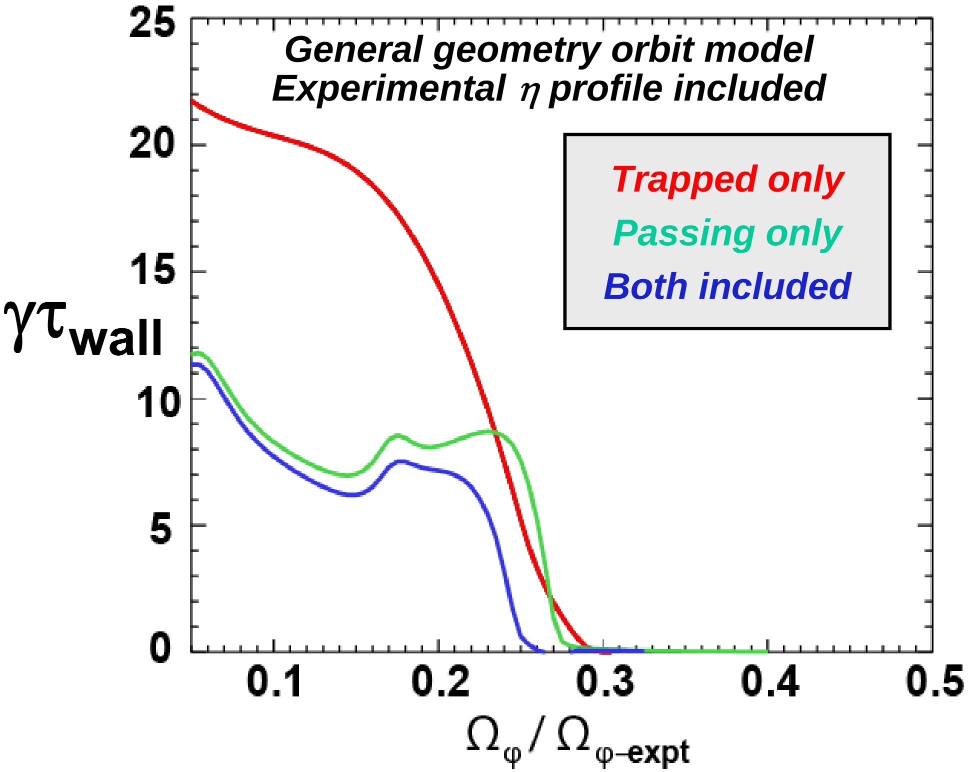
General geometry corrections significantly modify the critical rotation frequency, and MARS-F **under-predicts** the experimental values

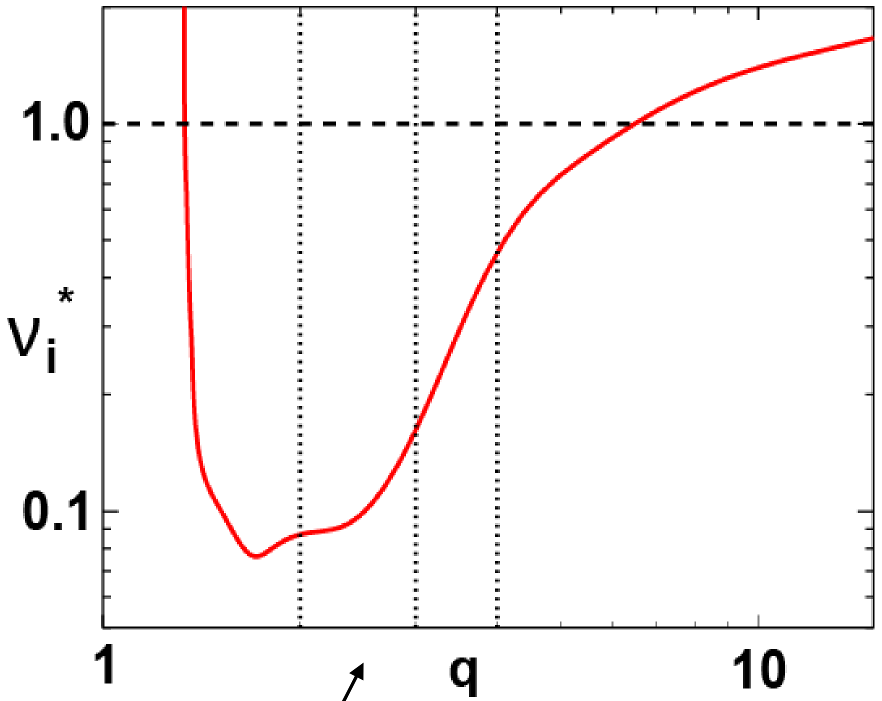
- General geometry corrections increase predicted RWM Ω_{crit} (low Ω_ϕ root) by 35%
  - However, critical rotation of lowest rotation root is **only 16%** of experimental value
- However, other similar roots w/ more internal eigenfunctions dominate at higher rotation and increase critical rotation to 25-40% of experimental value
  - Roots have low ω_r like RWM
  - Stabilized by high rotation → complicated spectrum



- Overall, MARS-F (high-A) semi-kinetic damping under-predicts critical rotation
  - NSTX by 40-75%, DIII-D by 20-40%, JET by 0-20%
  - General geometry effects important, but **reduced dissipation needed to explain data**

Passing particles dominate dissipation and give rise to local minima in growth rate vs. rotation frequency





- Ion collisionality $\nu_i^* \rightarrow 1$ for $q \geq 4$ at large r/a in NSTX
  → Collisional decorrelation of wave-particle interaction between RWM and barely-passing low-energy orbits could be strong effect
- Future work: How does decorrelation modify predicted dissipation & Ω_{crit} ?

NSTX experiments have improved the understanding of magnetic error fields and their correction at low and high β

- Low density, low-β 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-β_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