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Error field physics studies in NSTX for high-beta plasmas

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for the NSTX Research Team

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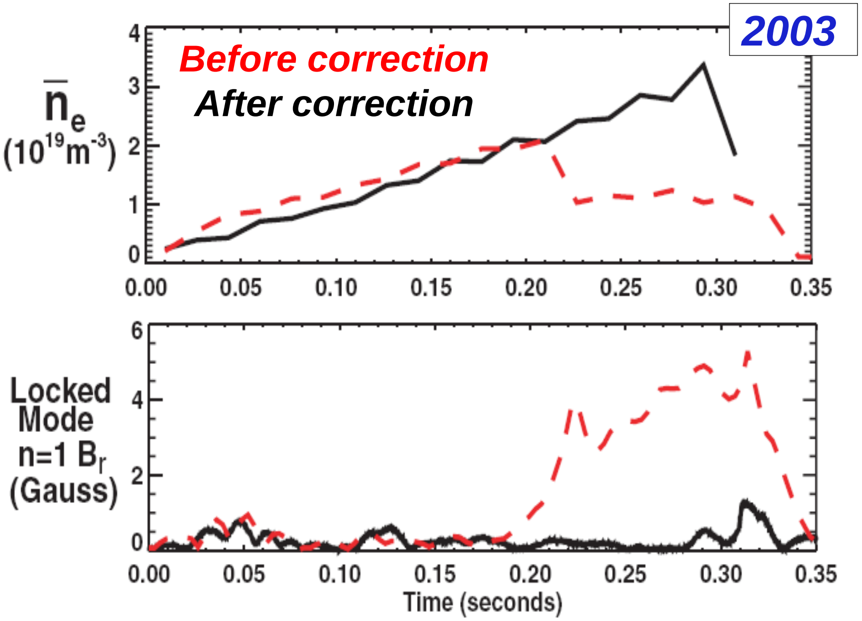
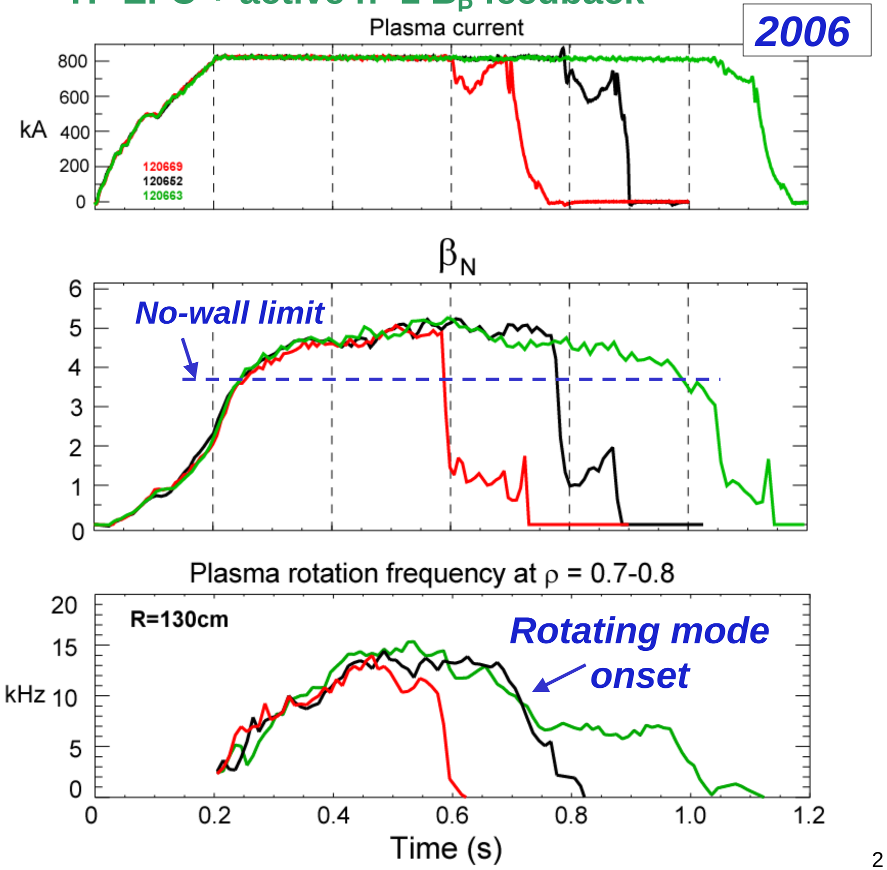
Detection and correction of small (<0.1%) low-n deviations from axisymmetry can significantly improve plasma performance

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

- **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

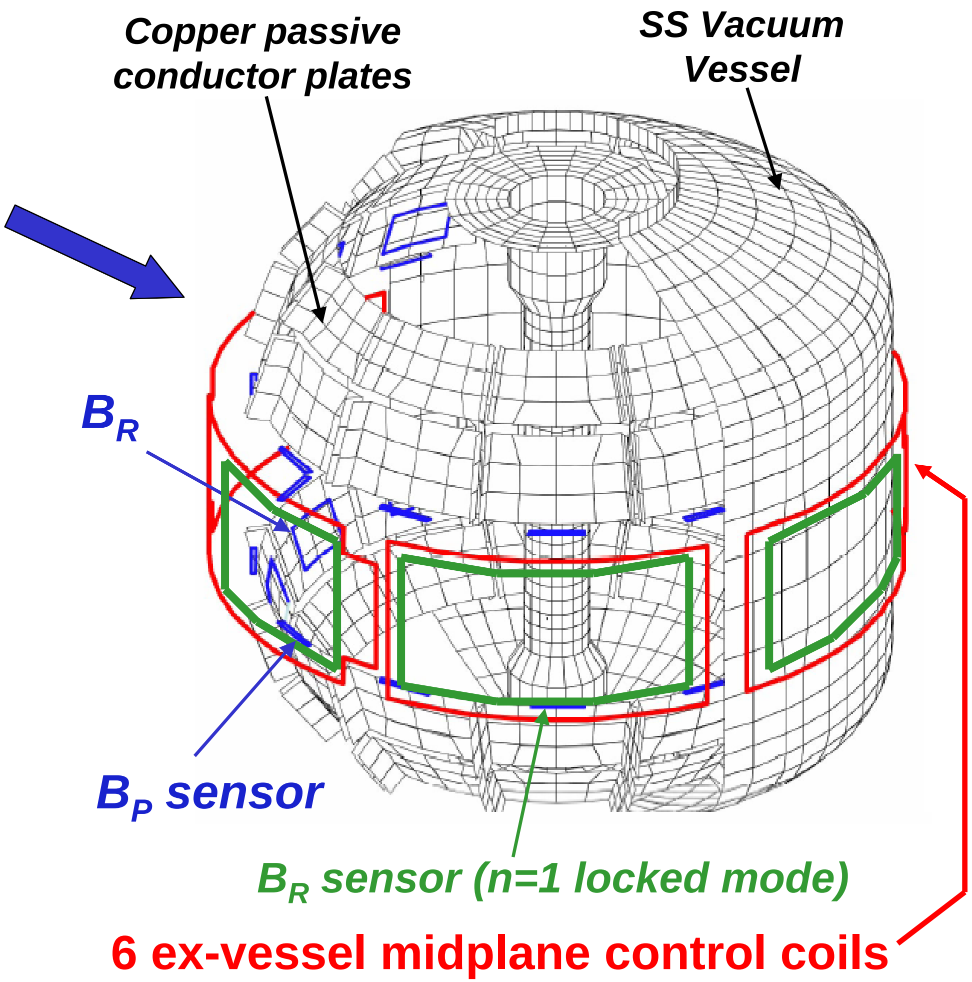
Effective EF and RWM control relies heavily on robust detection of small (~1G) non-axisymmetric magnetic fields

- 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



Copper passive conductor plates

SS Vacuum Vessel

B_R

B_P sensor

B_R sensor (n=1 locked mode)

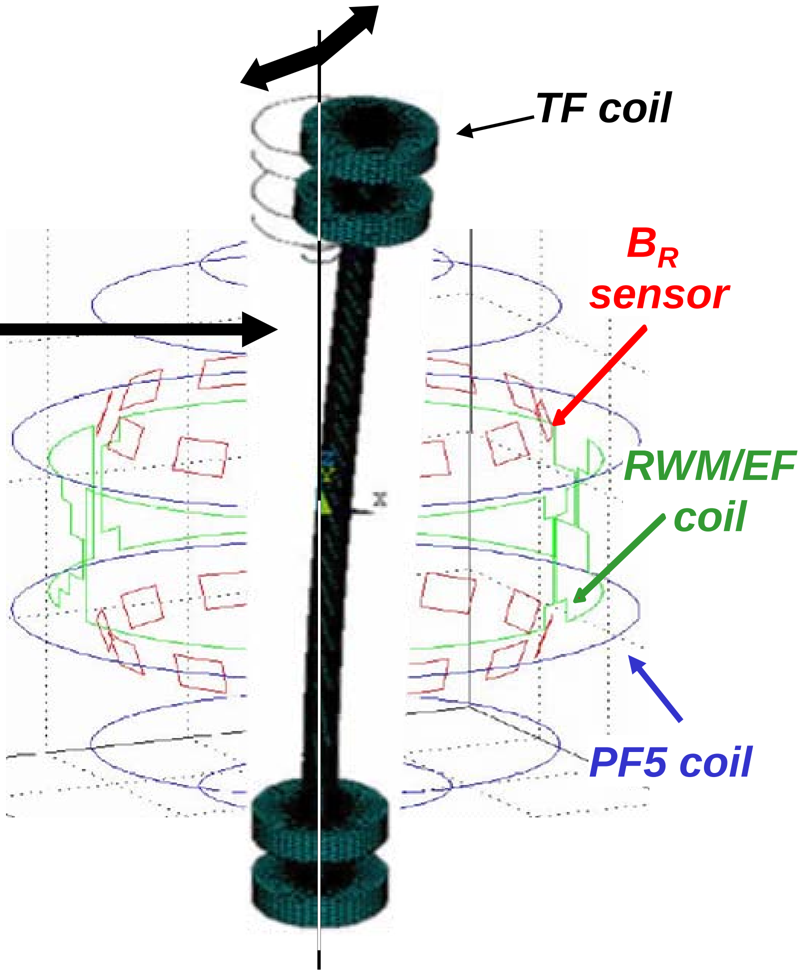
6 ex-vessel midplane control coils

VALEN Model of NSTX (Columbia Univ.)

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

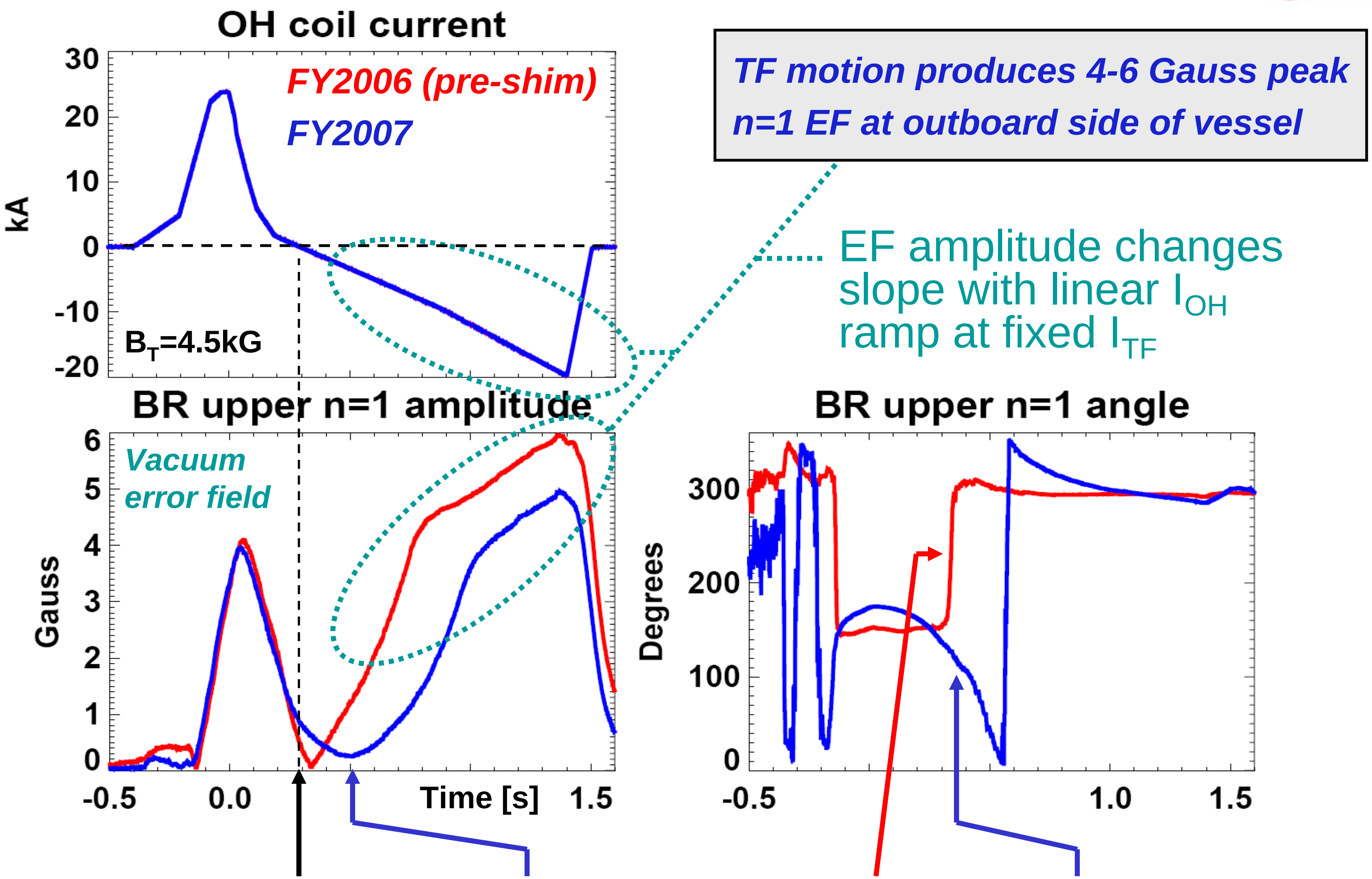
Error field detection & correction timeline:

- **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 $\propto I_{OH}$ x I_{TF}, but has additional time lags and non-linearities which complicate correction



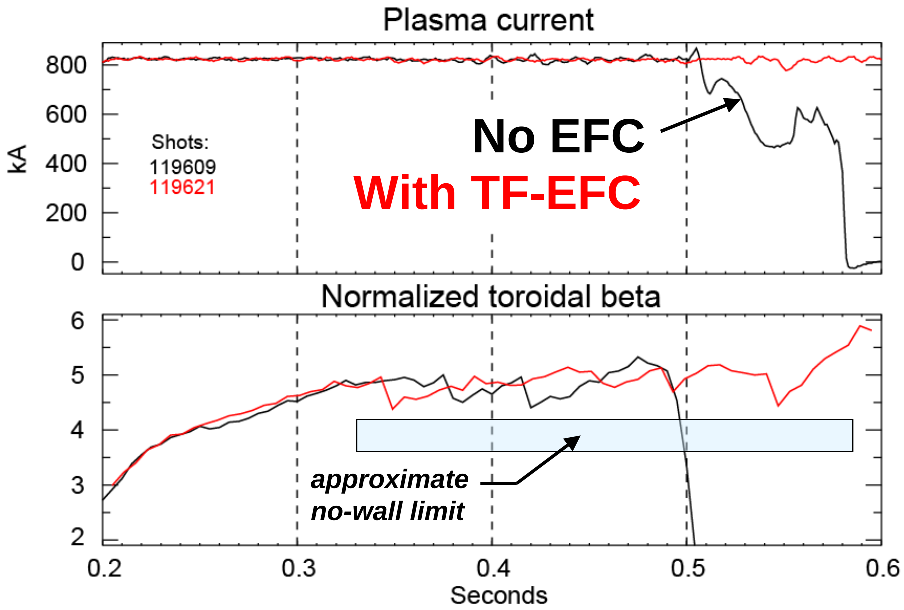
TF motion produces 4-6 Gauss peak n=1 EF at outboard side of vessel

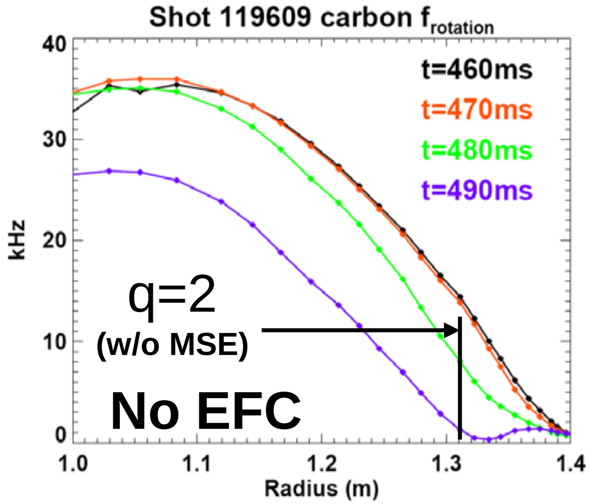
EF amplitude changes slope with linear I_{OH} ramp at fixed I_{TF}

OH zero crossing precedes minimum EF by 0.2s

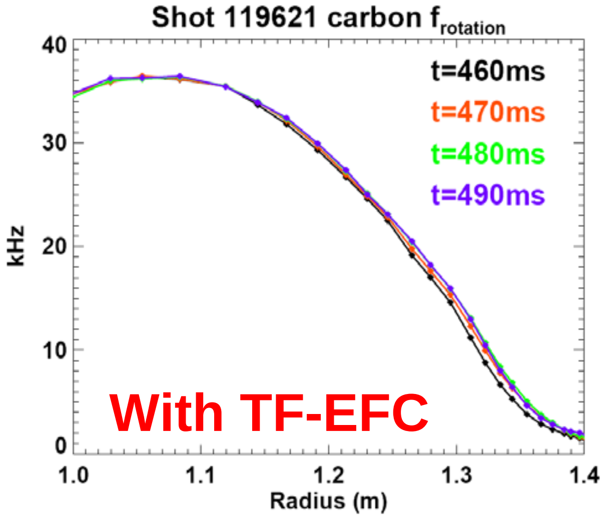
EF phase flips more slowly and in opposite direction following shimming

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

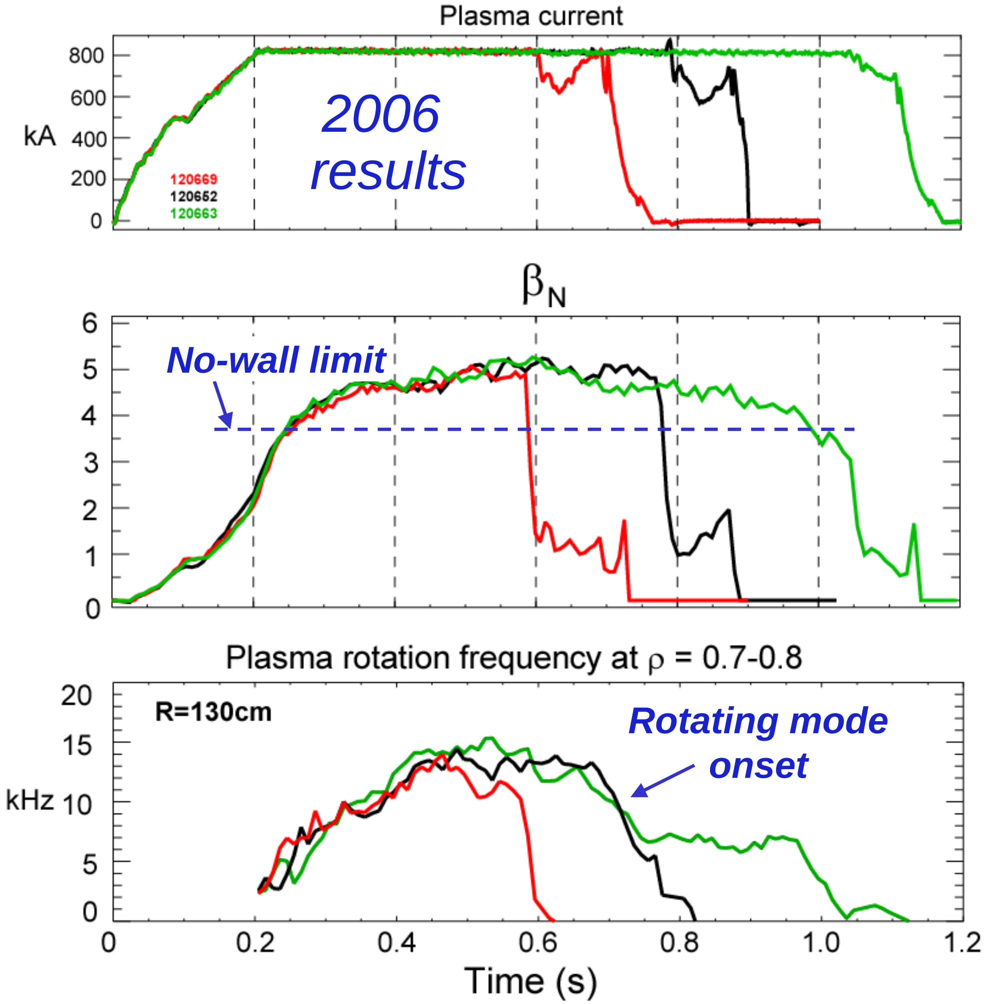
2006 - *combination* of pre-programmed TF-EFC + n=1 feedback ($B_{P\text{-}U}$ sensors) was required to maximize rotation and pulse-length

- 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)

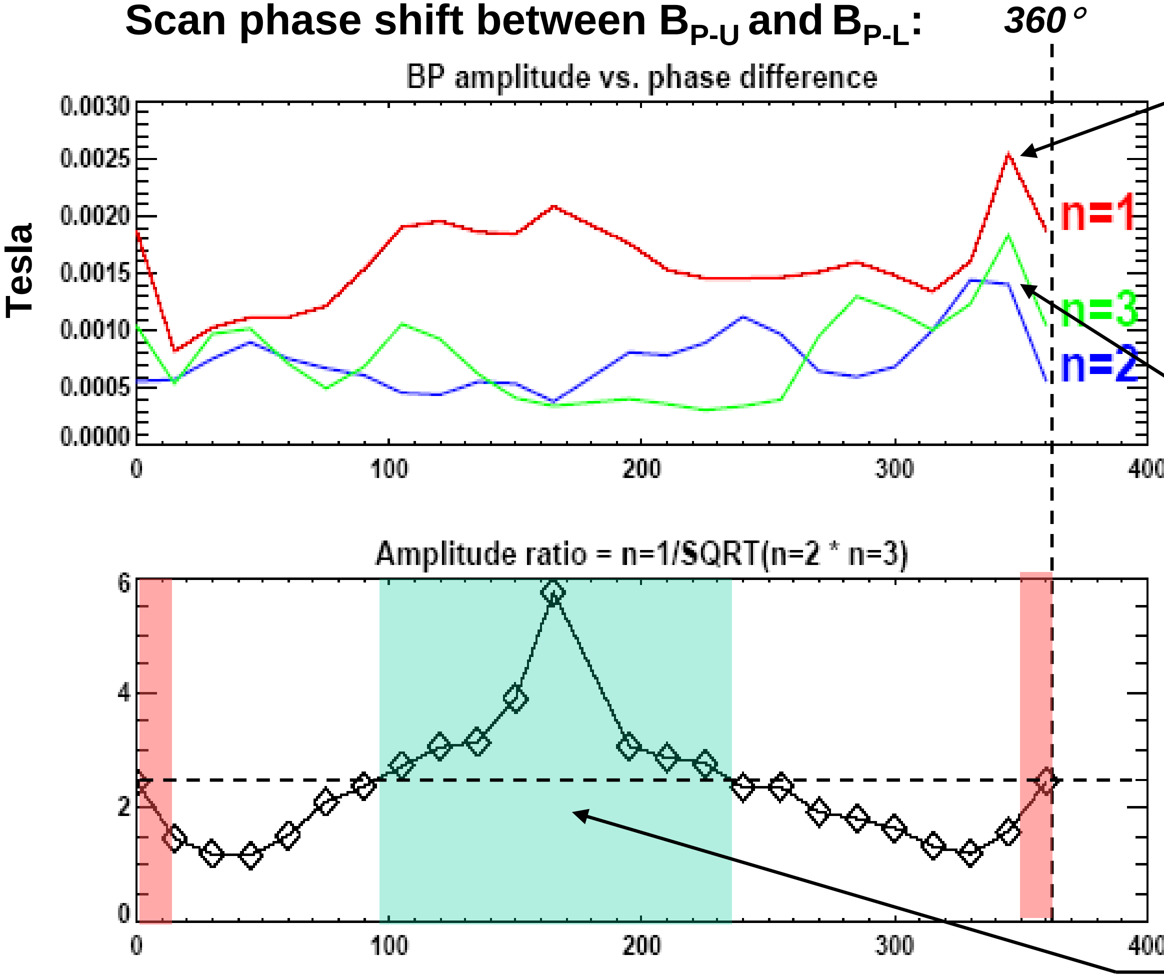
- “noise” and “deformation” motivate improved mode detection in 2007:
  - Use optimal combination of U & L
    - Maximize sensitivity to RFA/RWM
    - Decrease sensitivity to deformation
  - Also try B_R for EF detection, control
  - Also try mixture of B_R and B_P

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



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 $B_{P\text{-}L}$:



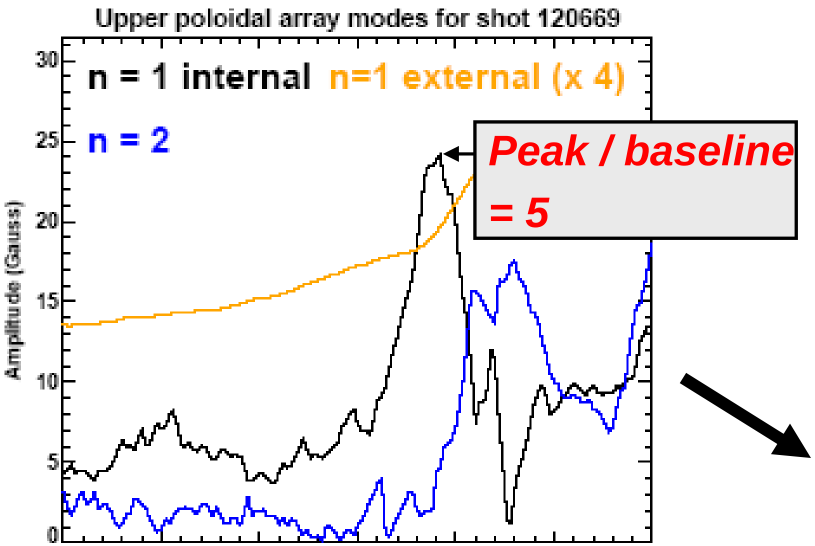
Relative phase shift between upper and lower B_P sensors [Degrees]

- 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

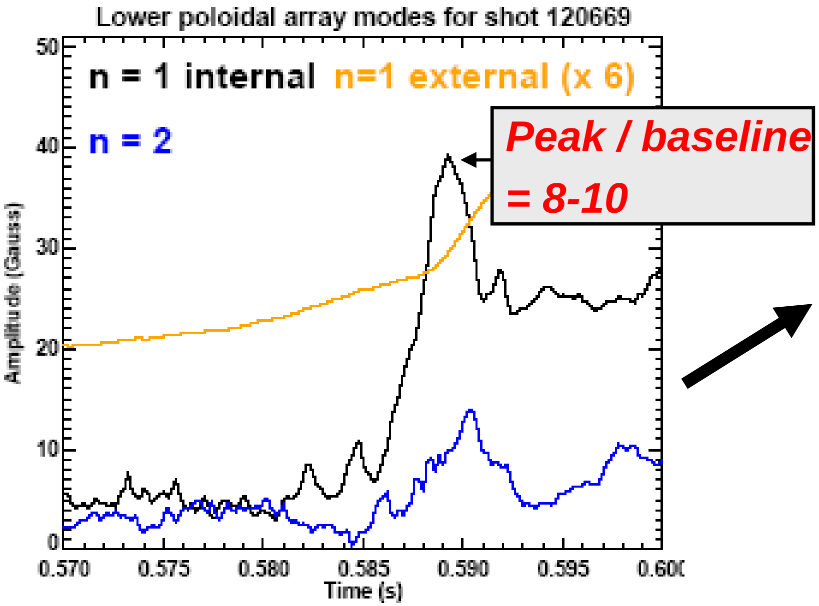
Optimal shift increases n=1 signal / baseline by 2-3 × → higher stable feedback gain

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

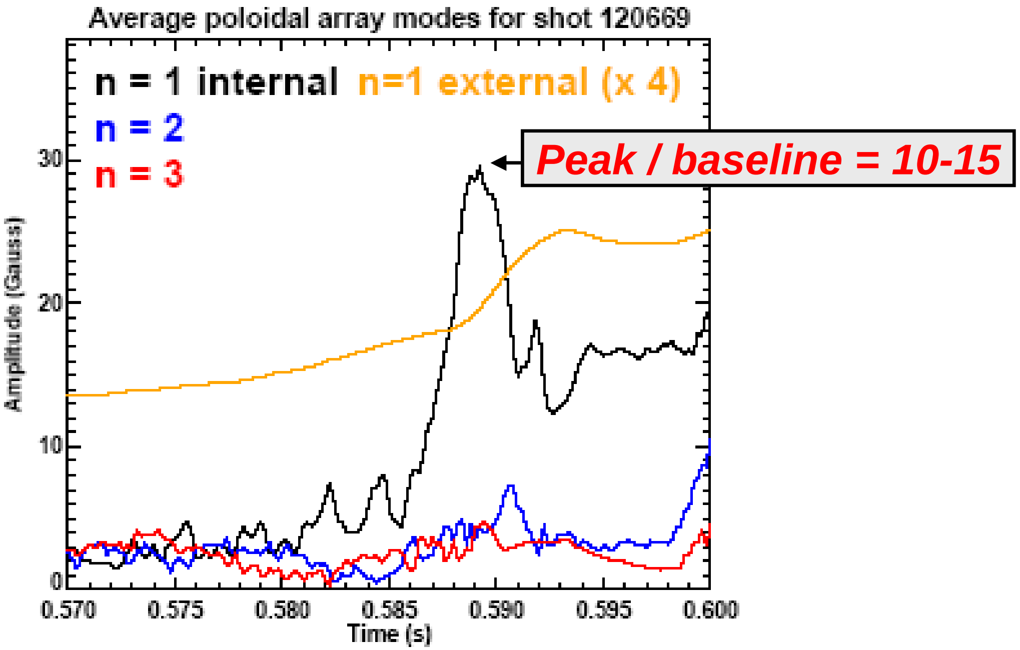
Optimal upper-lower average increases amplitude / baseline factor of 2-3 → higher feedback gain possible


Upper poloidal array modes for shot 120669

Peak / baseline = 5


Lower poloidal array modes for shot 120669

Peak / baseline = 8-10


Average poloidal array modes for shot 120669

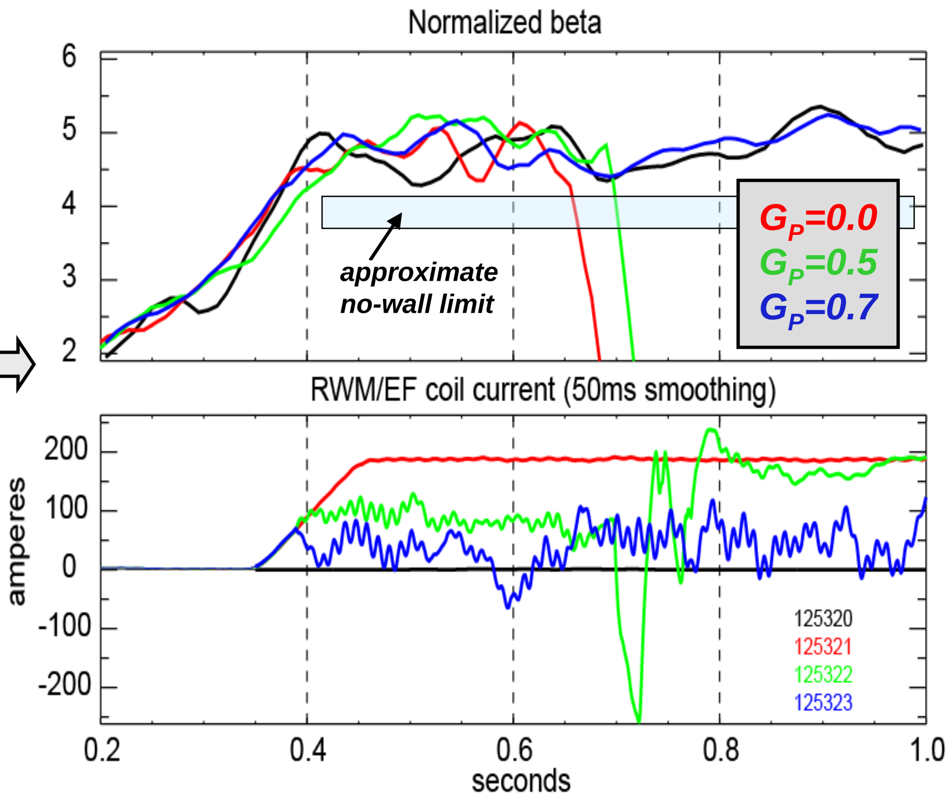
Peak / baseline = 10-15

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 *only feedback on RFA***

EFC algorithm developed in FY07:

- Use time *with minimal intrinsic EF* 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 (!)**

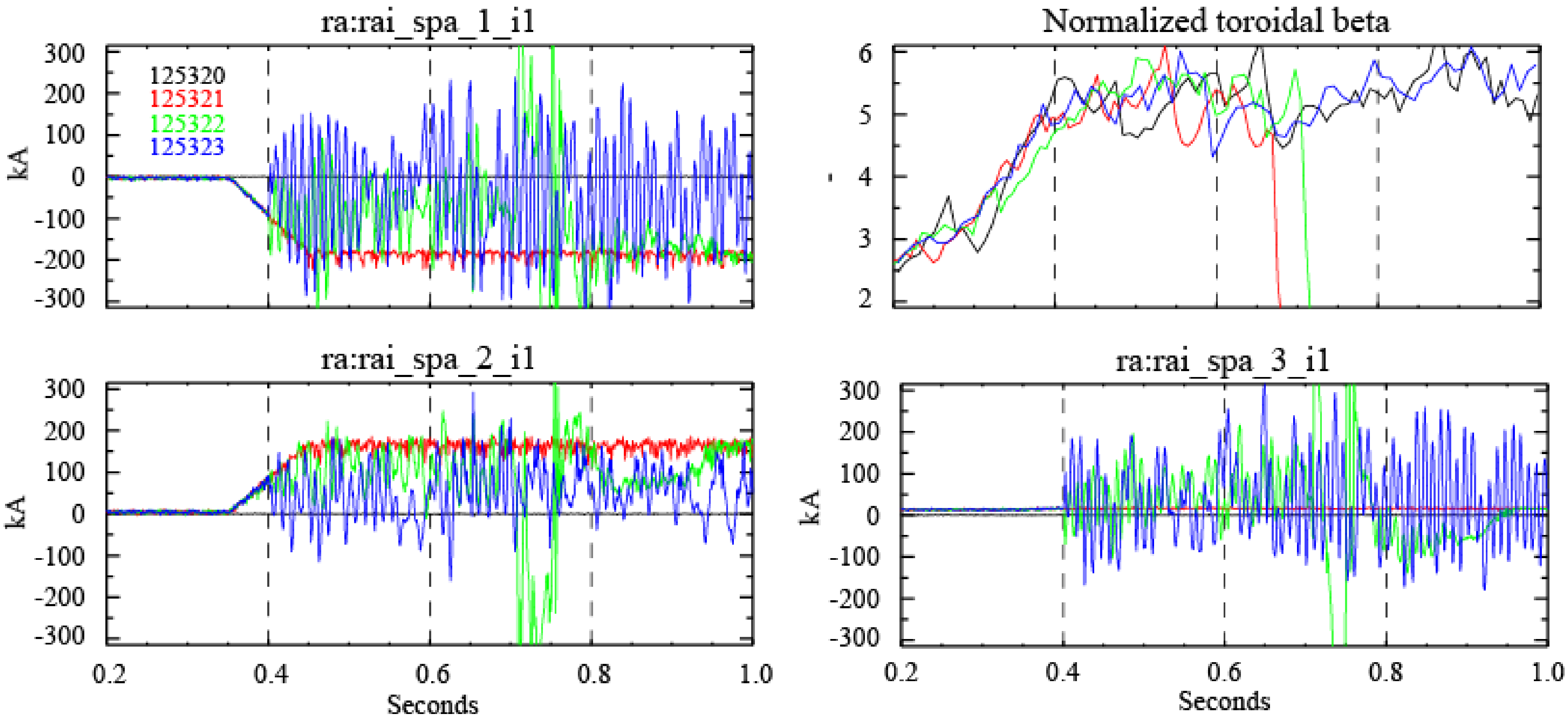


→ *Use same gain/phase settings to suppress RFA from intrinsic EF **and** any unstable RWMs*

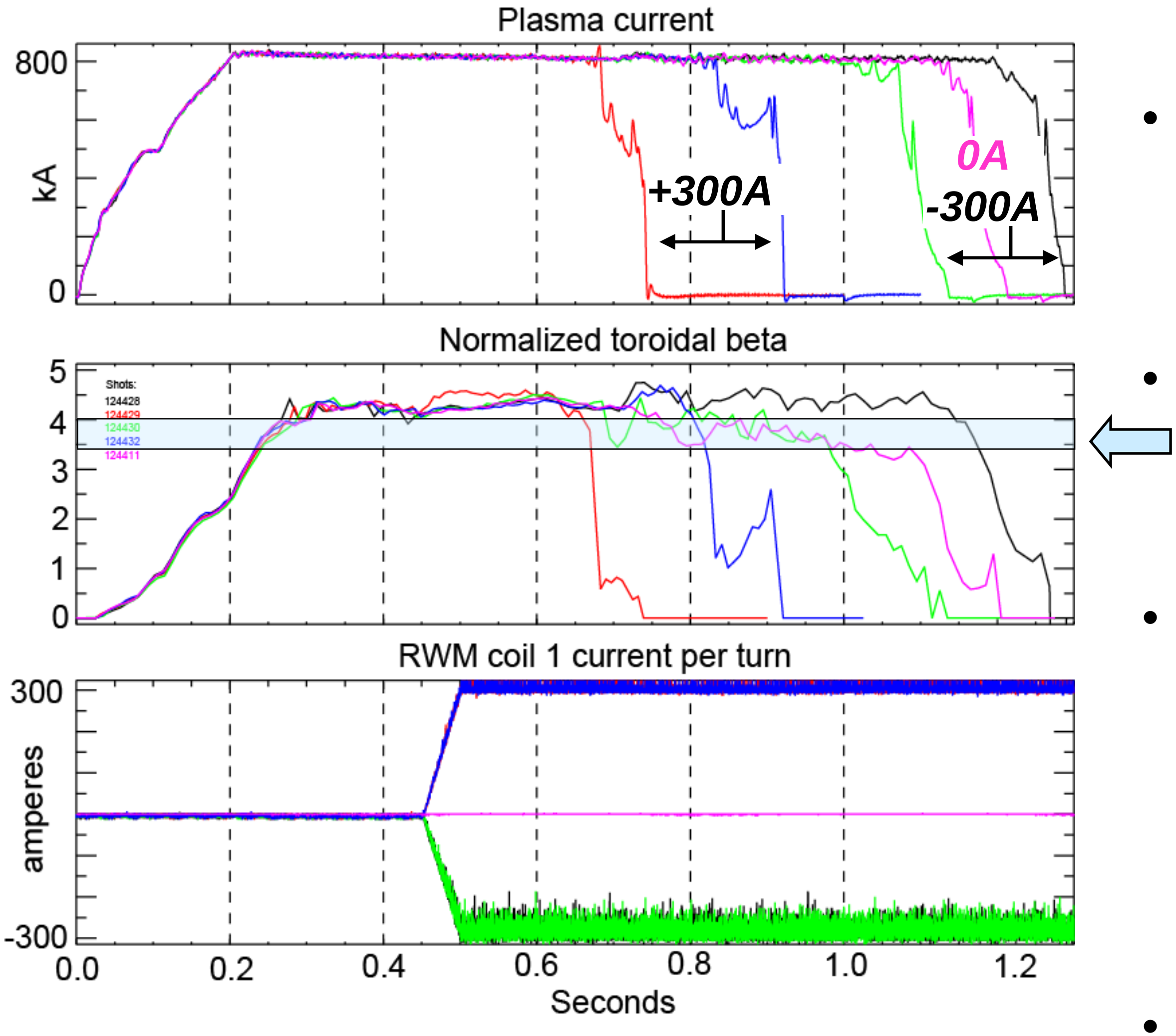
Optimal phase difference δ=270° between measured U/L avg B_P & applied B_R minimizes mean of each SPA current simultaneously

- 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 β_N

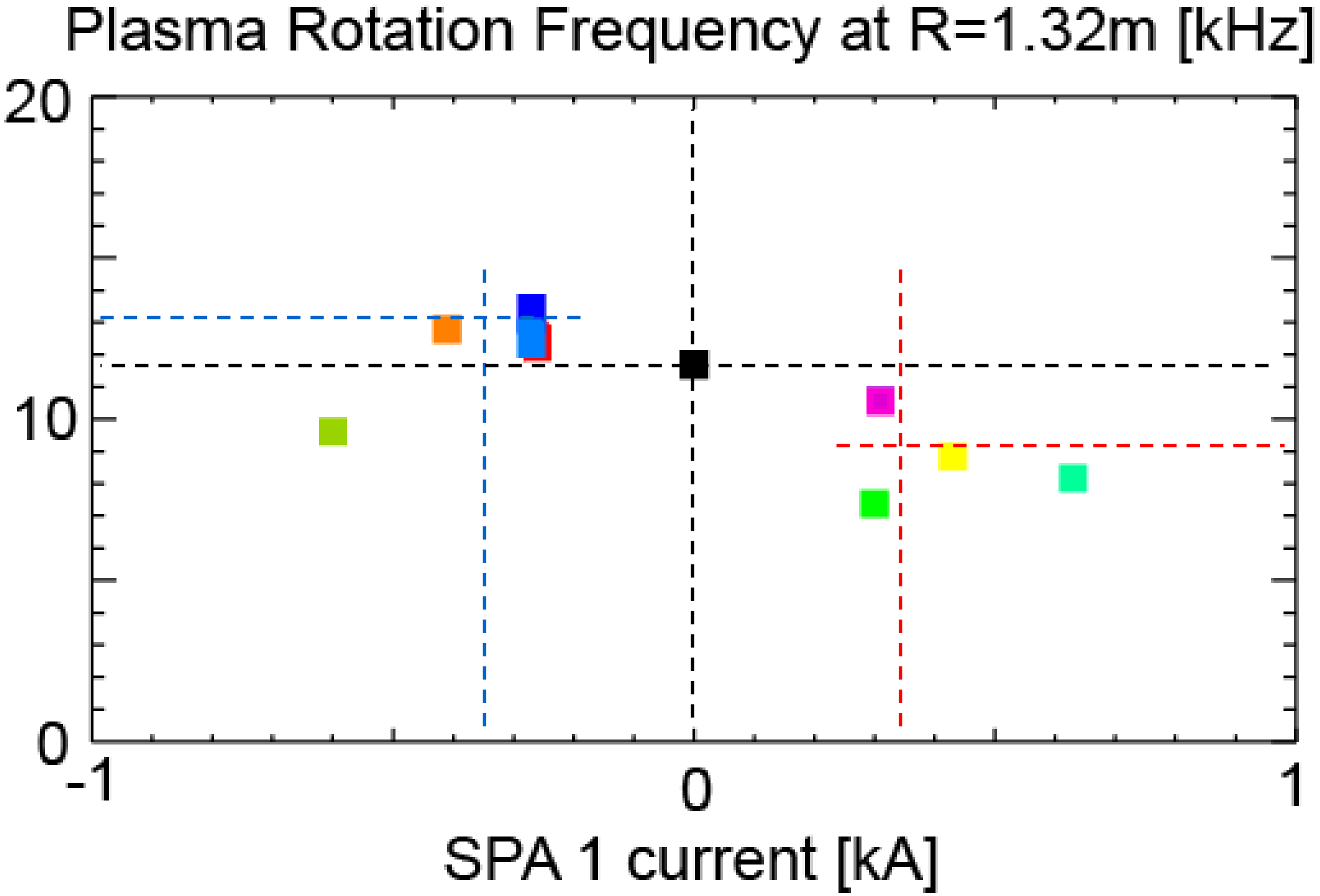


- Pulse-length depends on polarity of applied n=3
  - Anti-corrective polarity disrupts I_P and β
- Plasmas operate above n=1 no-wall limit → RFA
  - slows rotation →
  - destabilizes n=1 RWM
- Correction current magnitude for n=3 similar to that for n=1 correction
  - Applied n=3 $|B_R|$ is ≈ 6G at 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**

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

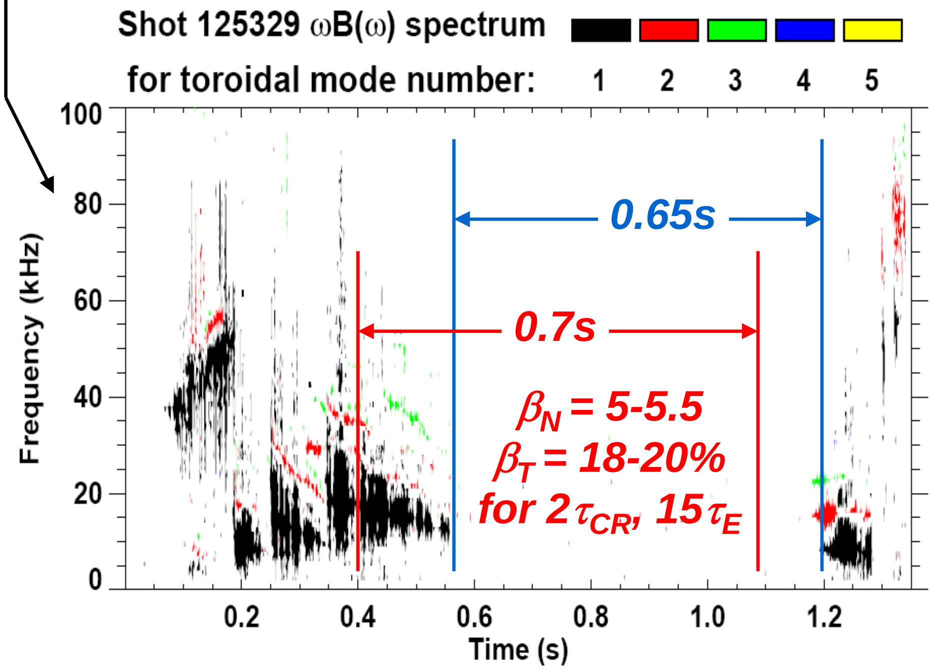
- Optimal n=3 current magnitude = 300-400A
- Coil shape data indicates VF coil (PF5) produces some n=3 EF
  - Need to assess if PF5 EF is consistent with empirical correction below



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-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



0.65s

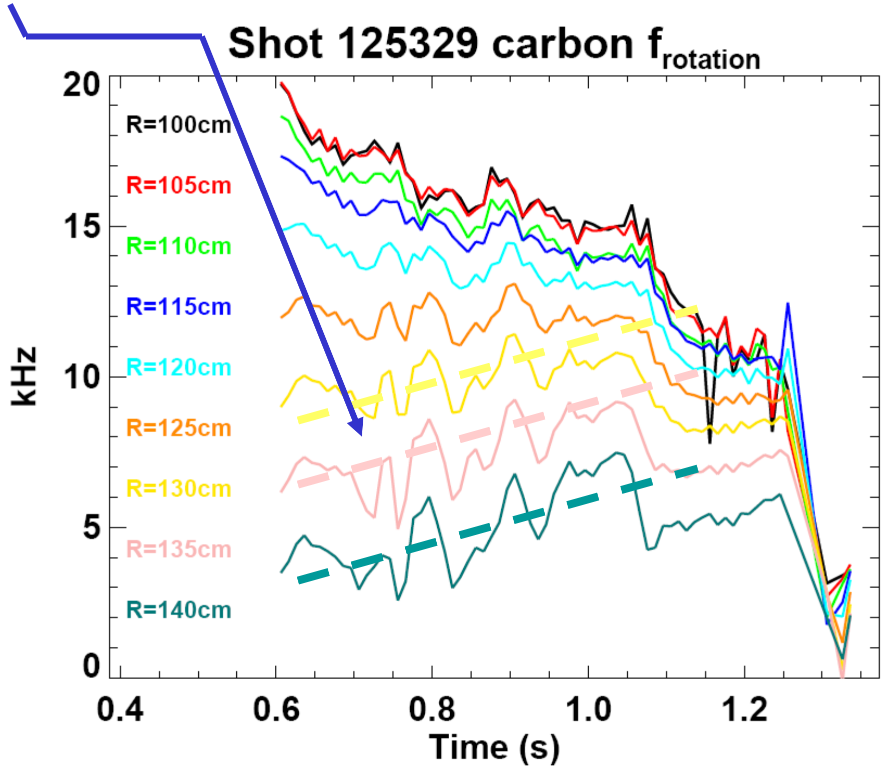
0.7s

β_N = 5-5.5

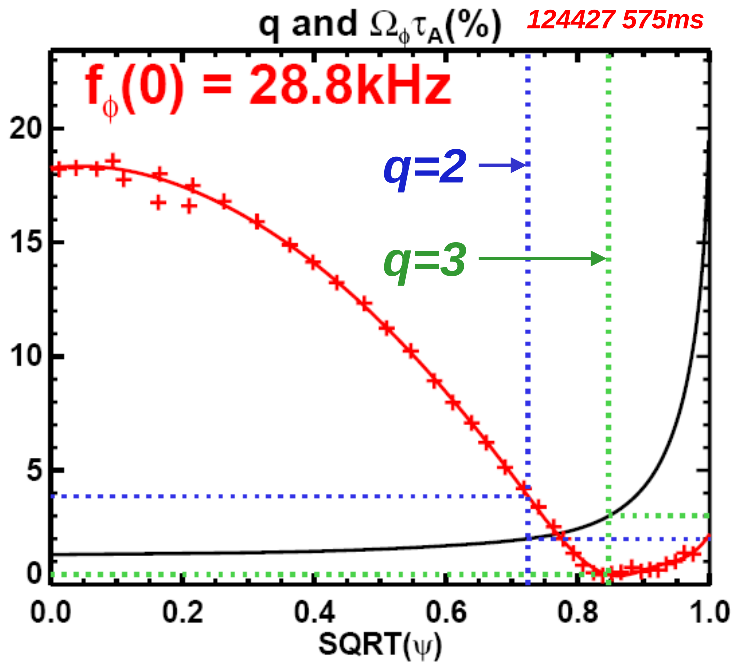
β_T = 18-20%

for 2τ_{CR}, 15τ_E

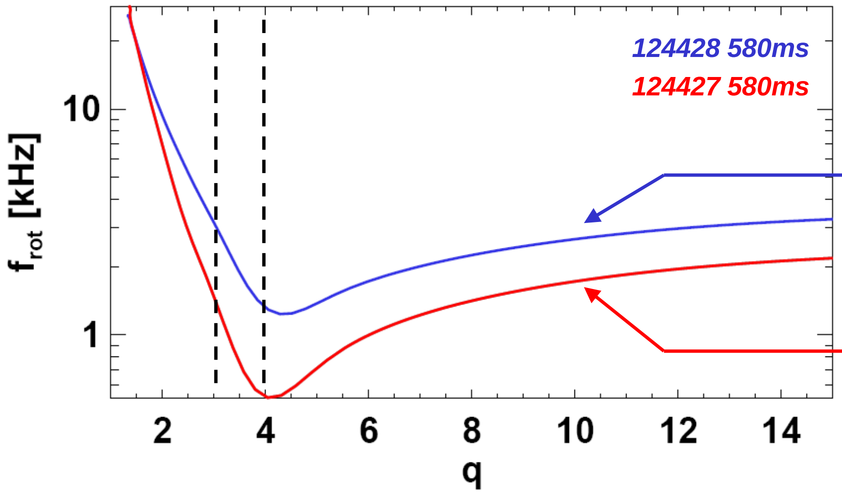
For reference: $\tau_{CR} \approx$ 0.3s, τ_E=40-50ms



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



- 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)



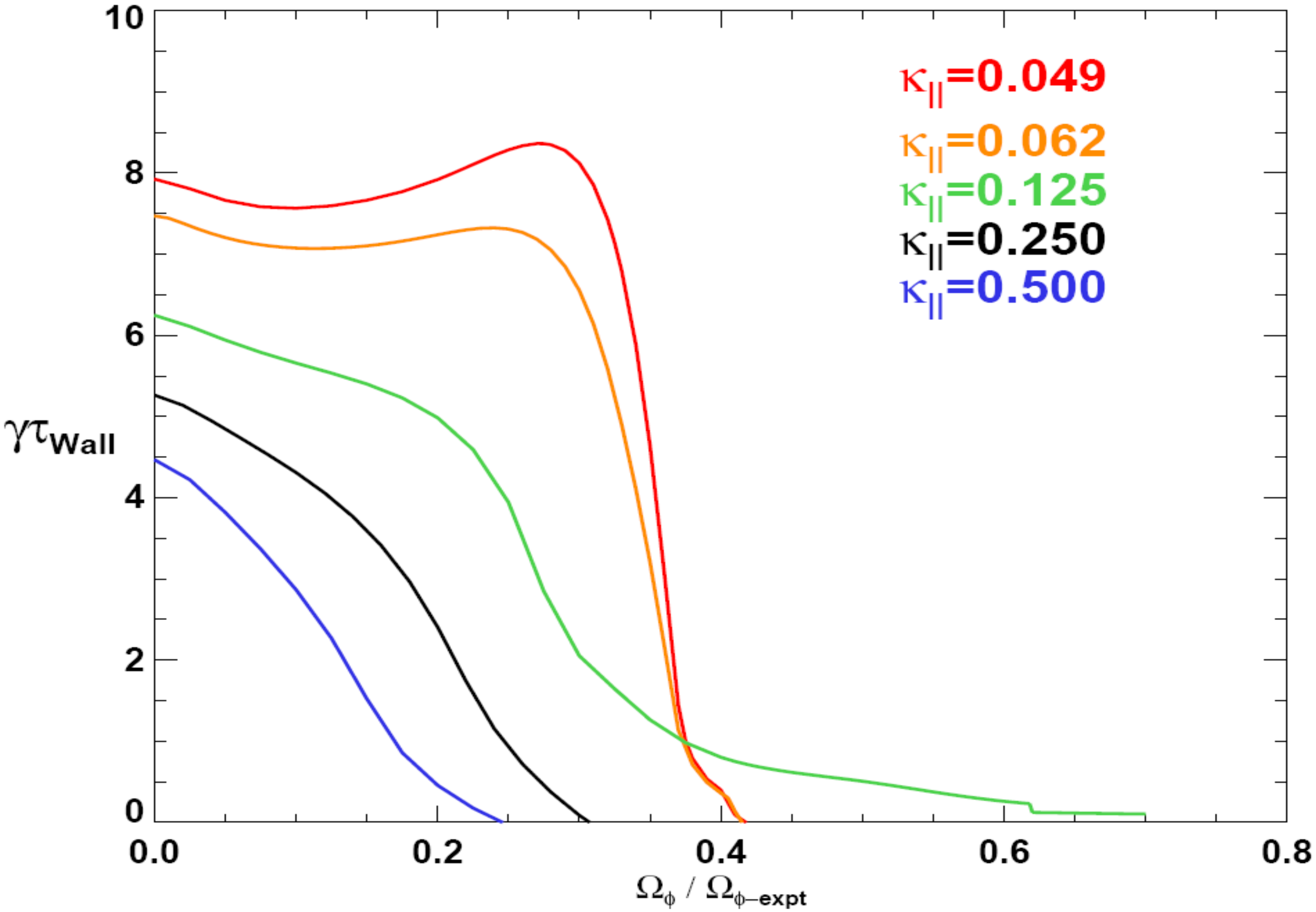
- n=3 EFC increases the rotation primarily on surfaces with q ≥ 3

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

MARS-F sound-wave damping model under-predicts critical rotation from n=3 experiments by factor of 2-5



Next – test semi-kinetic damping model in MARS-F at low-A

- 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:

Inverse aspect ratio

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

Normalized rotation frequency

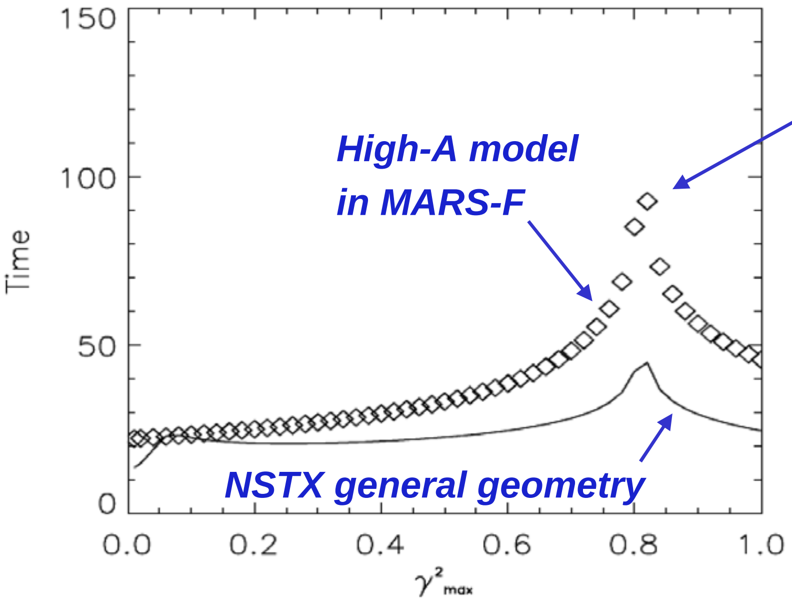
Normalized orbit time

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

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

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

$\sqrt{\psi_n} = 0.870$



High-A model in MARS-F

NSTX general geometry

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, $\varepsilon_r \equiv a/R_0 \sqrt{\psi_n} \neq \varepsilon_B \equiv (B_{max}-B_{min})/(B_{max}+B_{min})$

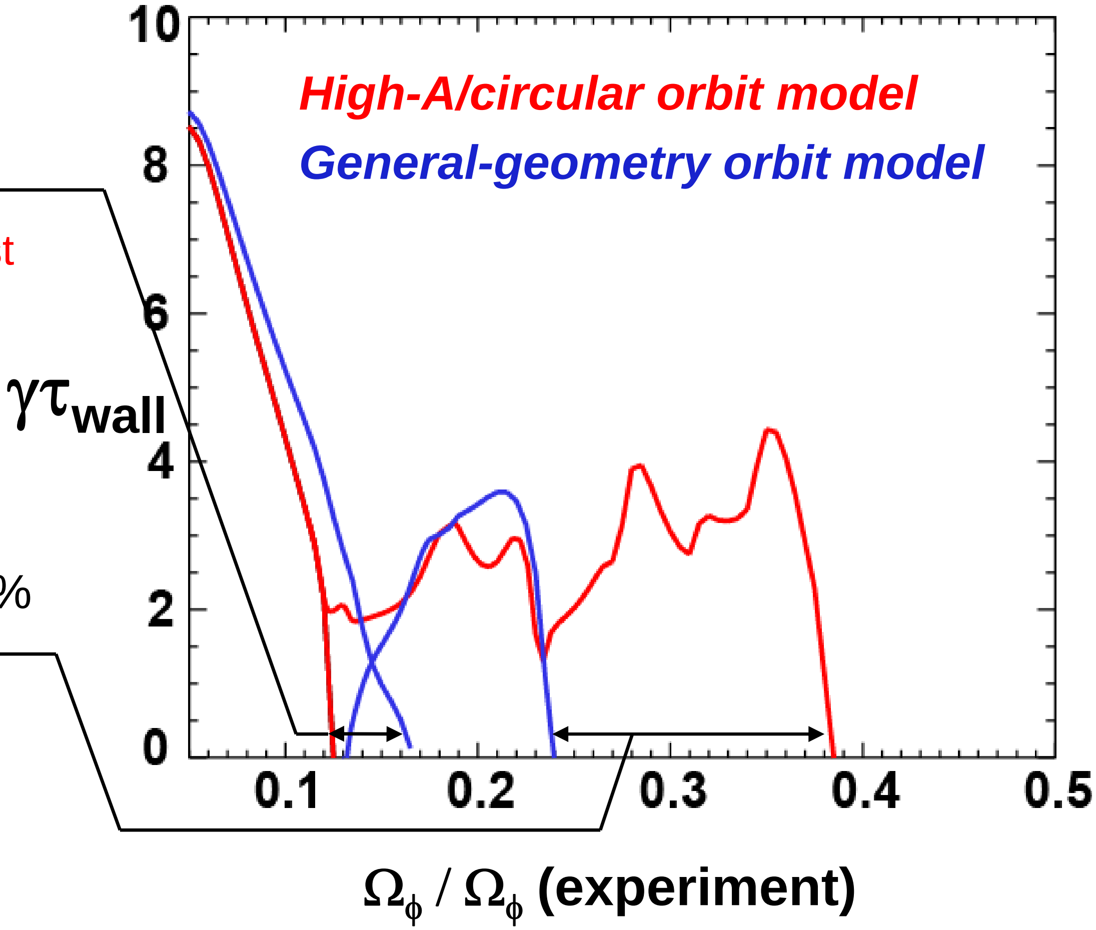
$\varepsilon_B \approx 0.6 \times \varepsilon_R$ in NSTX core, and ε_B should be used

→ increased dissipation

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

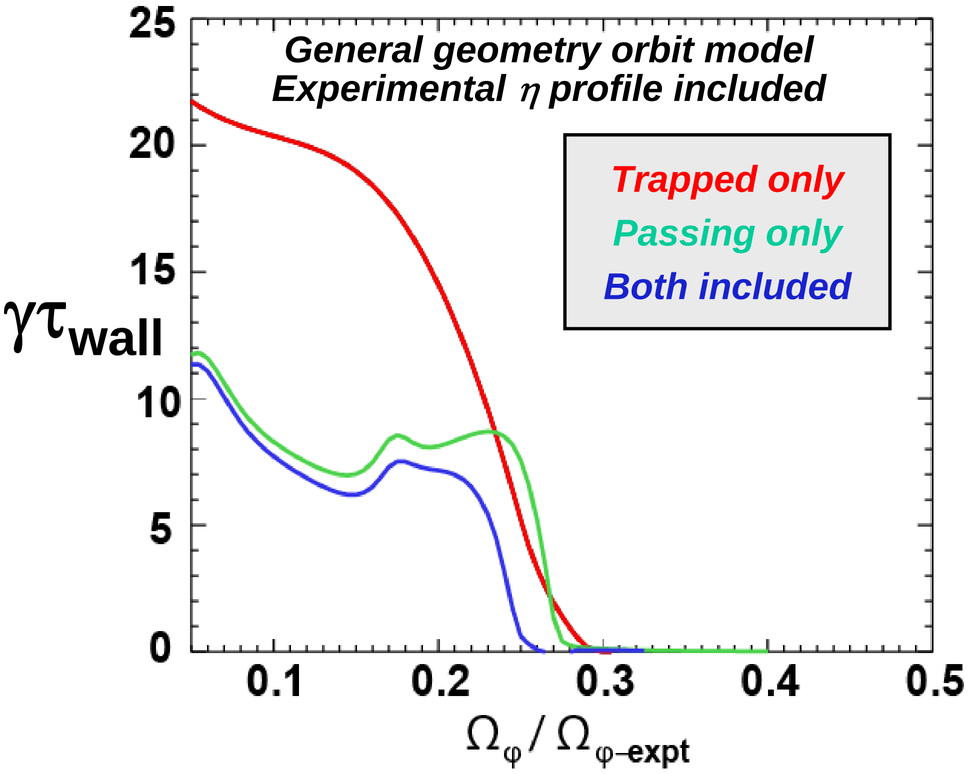
General geometry corrections significantly modify the critical rotation frequency, and MARS-F **under-predicts** the experimental values

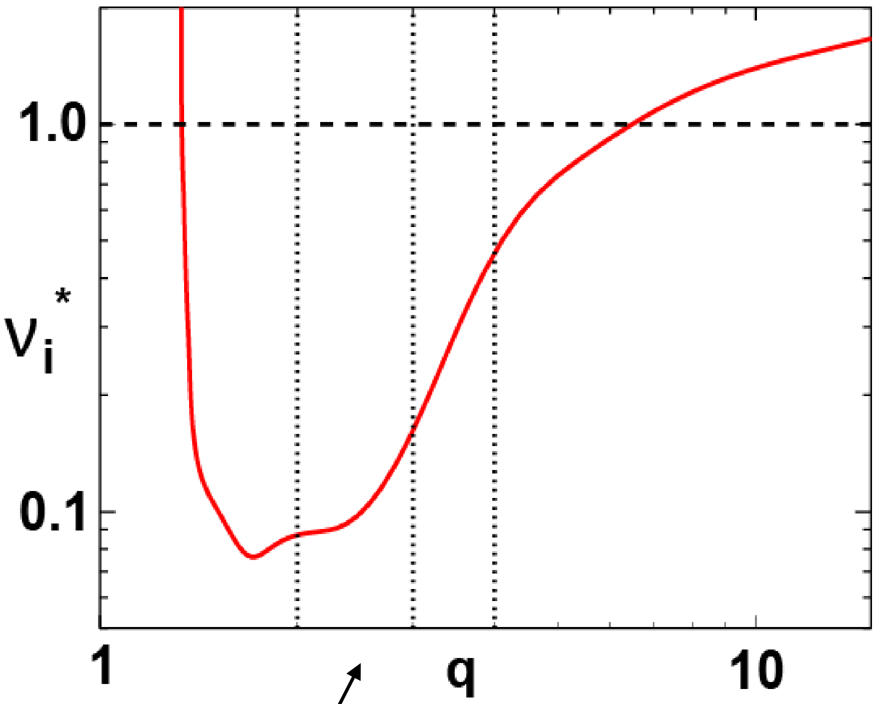
- General geometry corrections increase predicted RWM Ω_{crit} (low Ω_ϕ root) by 35%
  - However, critical rotation of lowest rotation root is **only 16%** of experimental value
- However, other similar roots w/ more internal eigenfunctions dominate at higher rotation and increase critical rotation to 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 ν_i^* → 1 for q ≥ 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

- 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