Plasma performance improvements from optimized error field correction in NSTX

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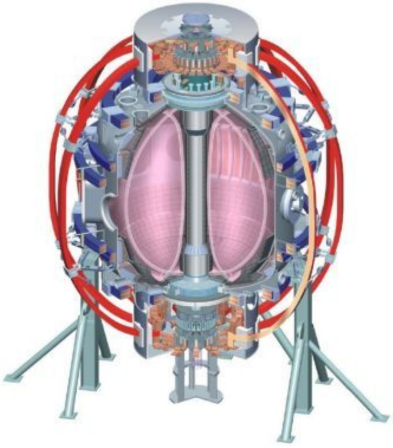

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Abstract

The active suppression of n=1 resonant field amplification (RFA) of intrinsic error fields was previously shown to lead to pulse length extension at high beta in NSTX. The correction of intrinsic n=3 error fields was also found to maintain/increase plasma rotation near the plasma boundary resulting in further pulse length extension for operation above the no-wall limit. More recently, the optimal n=3 error field correction (EFC) was determined as a function of plasma current indicating that n=3 intrinsic EF is most likely related to the PF or TF coil system rather than the OH coil as is the case for the n=1 intrinsic EF. Importantly, n=2 error fields were also investigated and measured to be small, indicating odd-n (n=1 and 3) EFs are most prominent in NSTX. Finally, the time response of the n=1 RFA suppression has been optimized by optimizing the low-pass filtering and proportional gain to more robustly control n=1 RFA and unstable n=1 RWMs. Overall, the combined n=3 EFC and n=1 RFA and RWM control has been instrumental in reliably increasing the duration of operation above the no-wall limit. This improved control was used in achieving record pulse-lengths on NSTX and is being applied to a wide range of operating scenarios in NSTX.

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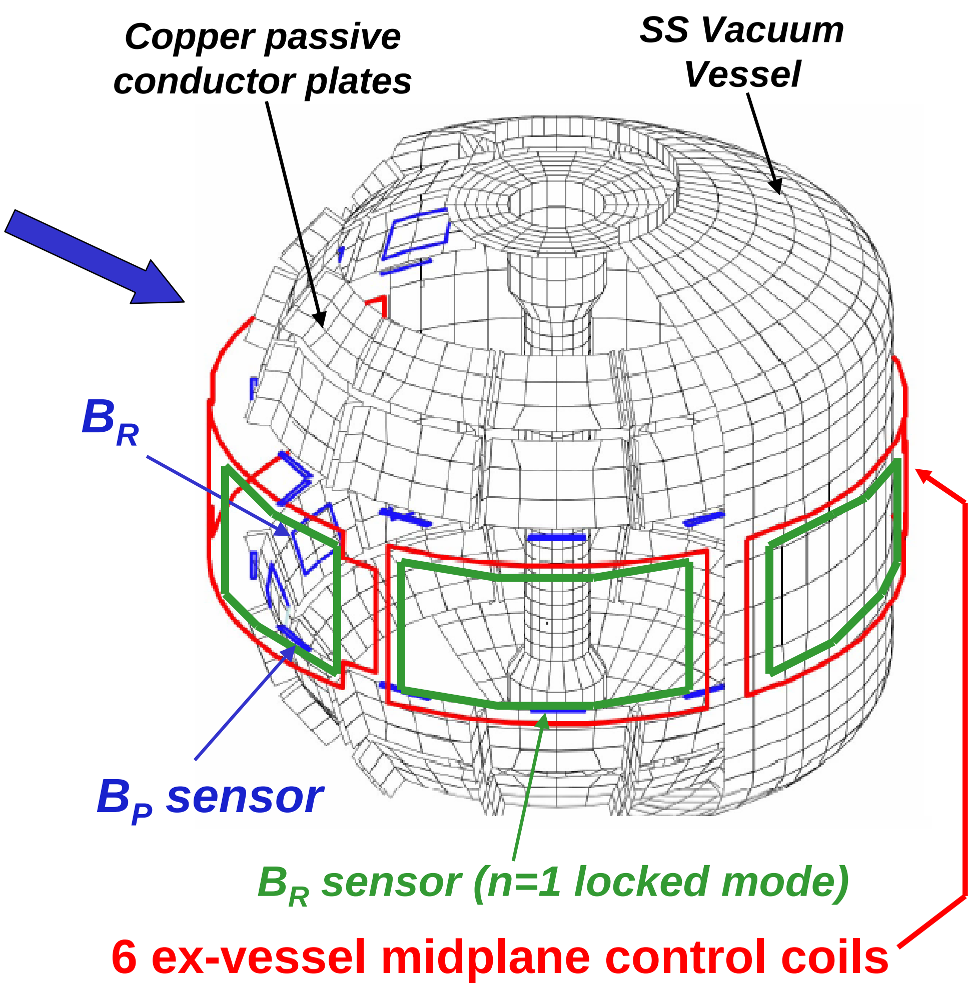
Effective EF and RWM control relies heavily on robust detection of small (~1G) non-axisymmetric magnetic fields

- 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

- Several RWM/EF sensor combinations used:
  - $B_{P\text{-}U} + B_{P\text{-}L}$
  - $B_{R\text{-}U} + B_{R\text{-}L}$
  - $B_{P\text{-}U} + B_{P\text{-}L}$ with spatial offset
  - All sensors in combination

- $B_{P\text{-}U} + B_{P\text{-}L}$ described here



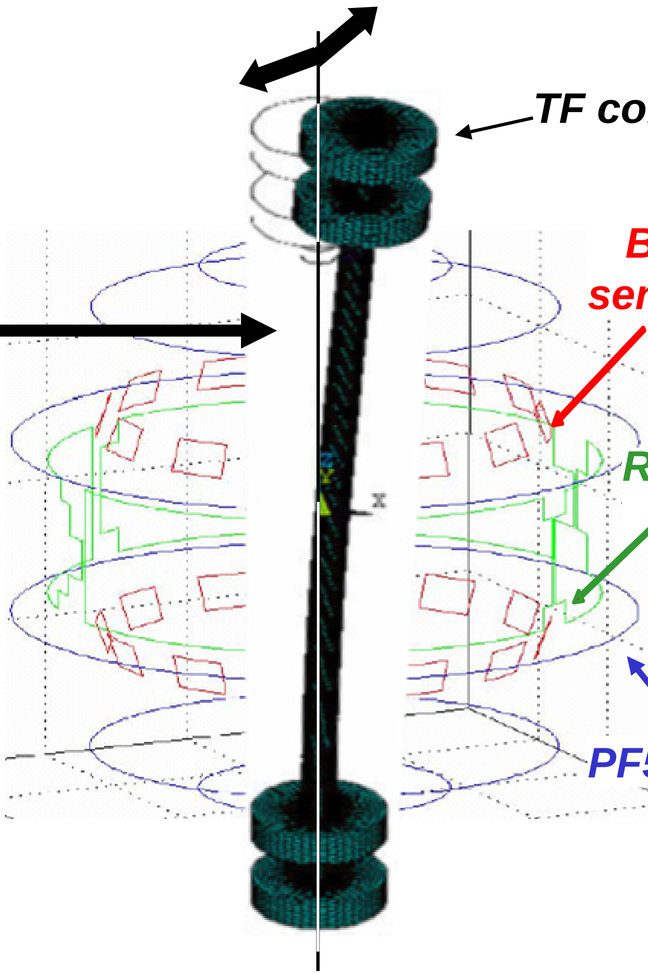
VALEN Model of NSTX (Columbia Univ.)

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

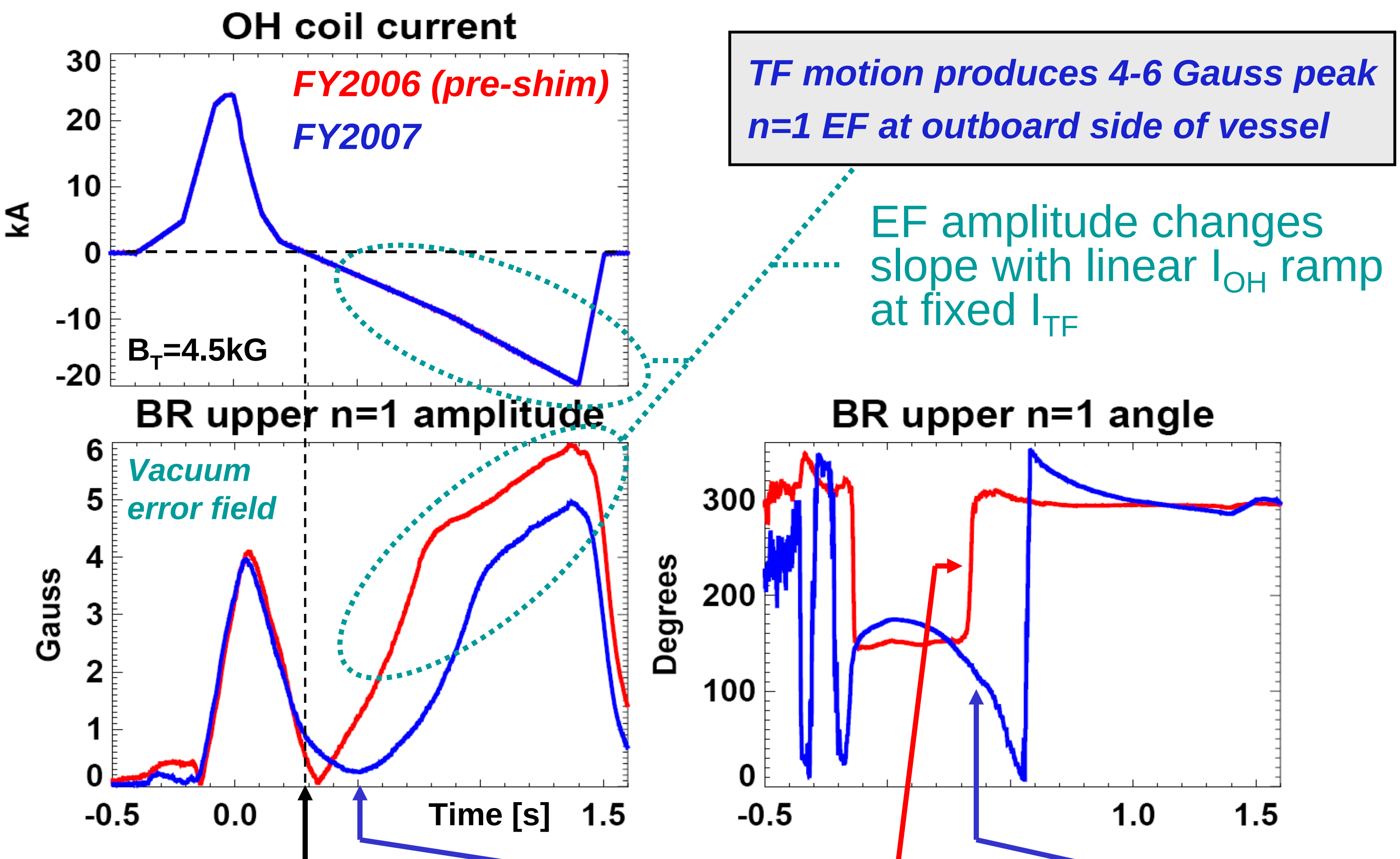
<u>**Error field detection & correction timeline:**</u>

- **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
  – <u>**n=1 EF reduced, but not eliminated**</u>
- **2007-2008** – identified n=3 intrinsic EF, find no evidence of significant n=2 EF

(Displacement exaggerated to show tilting motion)



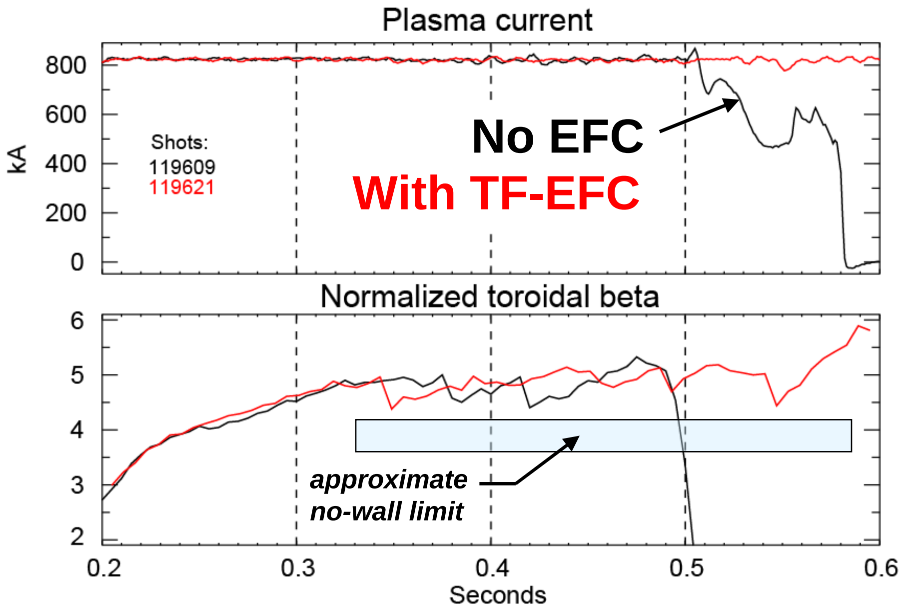
n=1 EF from TF coil motion is $\propto I_{OH} \times I_{TF}$, but has additional time lags and non-linearities which complicate correction



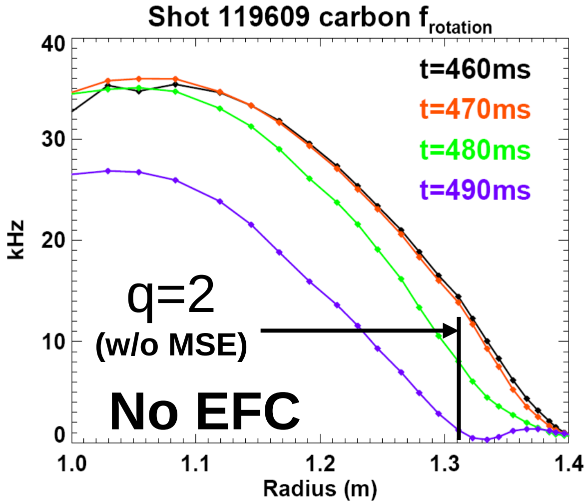
OH zero crossing precedes minimum EF by 0.2s

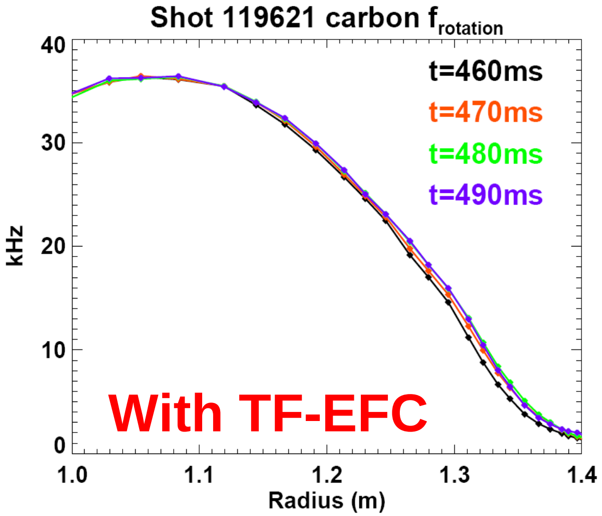
EF phase flips more slowly and in opposite direction following shimming

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



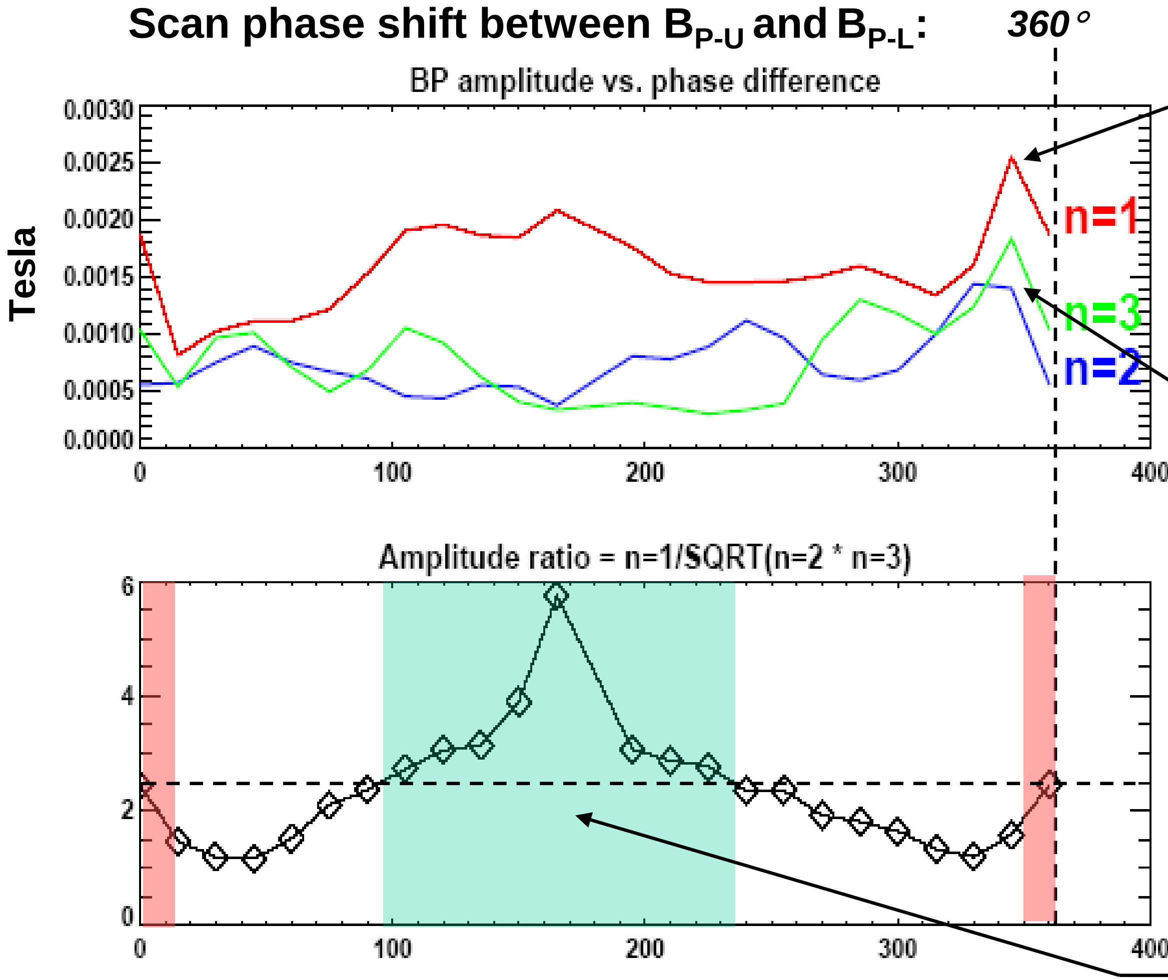
- Use real-time $I_{OH} \times I_{TF}$, incorporate observed time-lag and non-linearity of EF
- Empirically minimize rotation damping near q=2-3 for 100-200ms of reference shot
  - Extrapolate in time, balance m=2 against m=0 ***(non-resonant!)*** of EF from moving TF
  - Correction coefficients must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





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

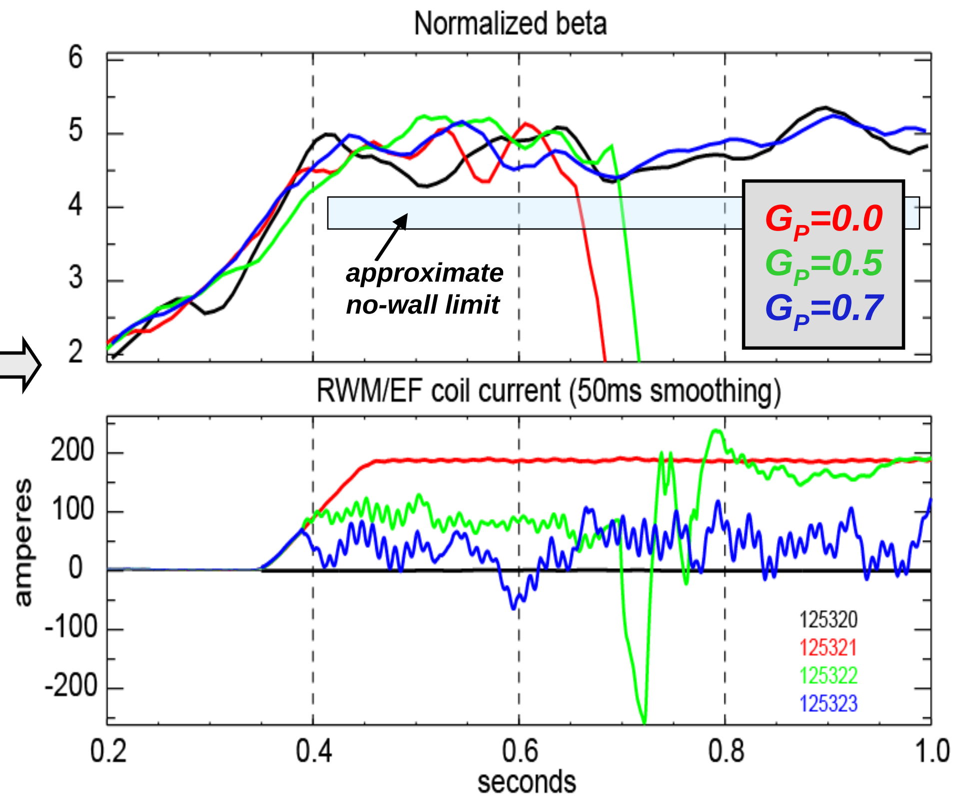
Optimal shift increases n=1 signal / baseline by 2-3 × → higher stable feedback gain

Using optimized B_P sensors in control system allows 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*

2008: n=1 feedback gain and low-pass filter time-constant optimized at high current I_P= 1.1MA

- Instead of applying known n=1 EF, used OHxTF EF
  - 1.1MA uses full OH swing

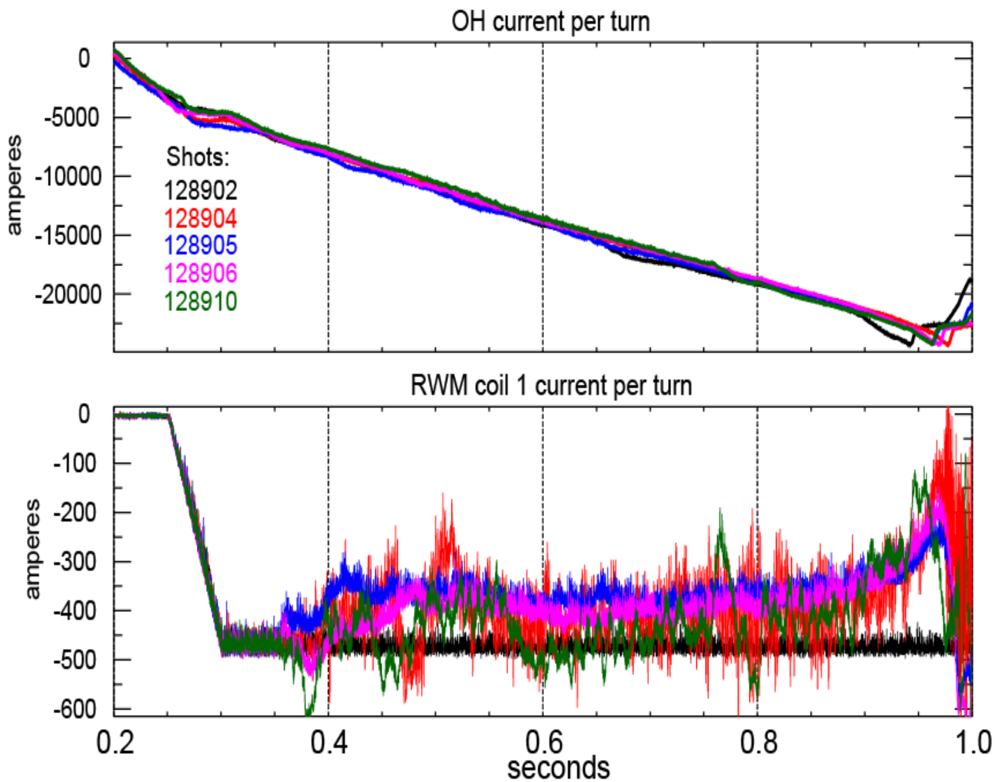
- Use B_P U/L averaging and include n=3 EFC

- Increased gain scan by factor of 3: from 0.7 → 2
  - Response to n=1 RFA from OH×TF error field changes very little for G_P > 1
  - System marginally stable at G_P = 2 for τ_{LPF} as low as 1-2ms

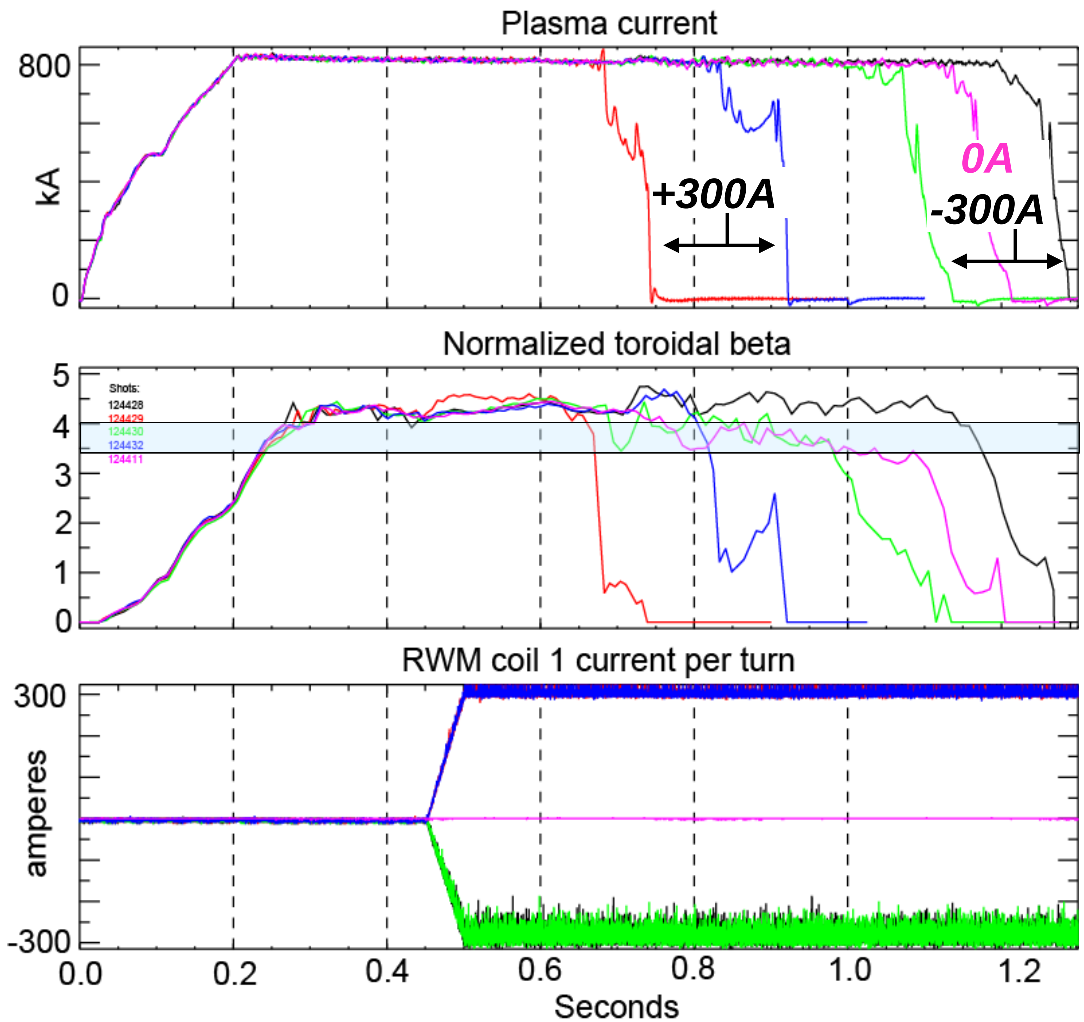
Optimal control parameters:

G_P = 1-1.5, τ_{LPF} = 2-5ms

G_P = 0
G_P =1.0, τ_{LPF} = 0
G_P =1.0, τ_{LPF} = 50ms
G_P =1.5, τ_{LPF} = 50ms
G_P =2.0, τ_{LPF} = 5ms



Correction of intrinsic n=3 error fields important at high β_N



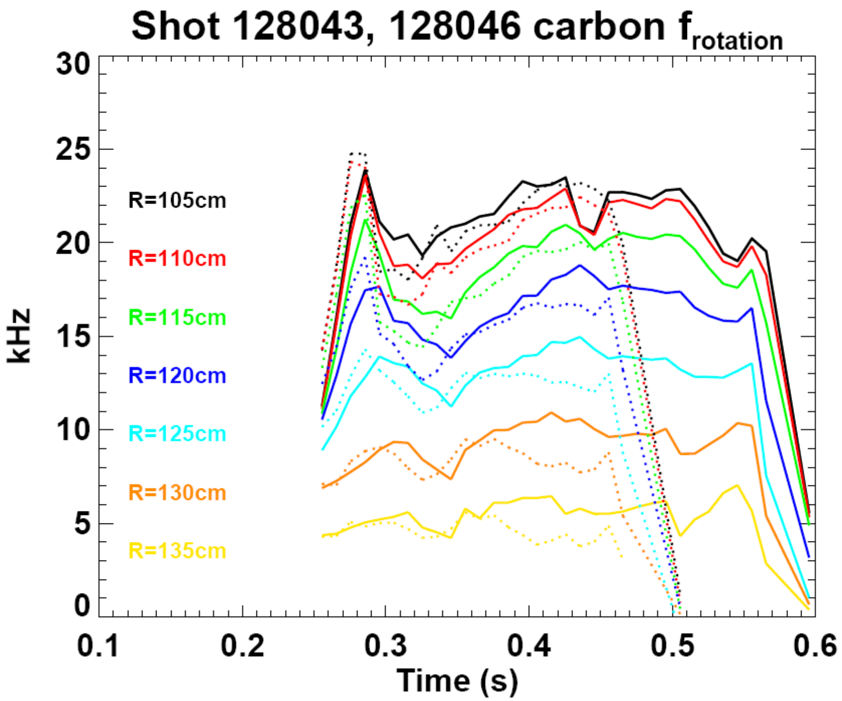
- Pulse-length depends on polarity of applied n=3
  - Anti-corrective polarity disrupts I_P and β
- Plasmas operate above n=1 no-wall limit → RFA
  - slows rotation →
  - destabilizes n=1 RWM
- Correction current magnitude for n=3 similar to that for n=1 correction
  - Applied n=3 $|B_R|$ is ≈ 6G at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

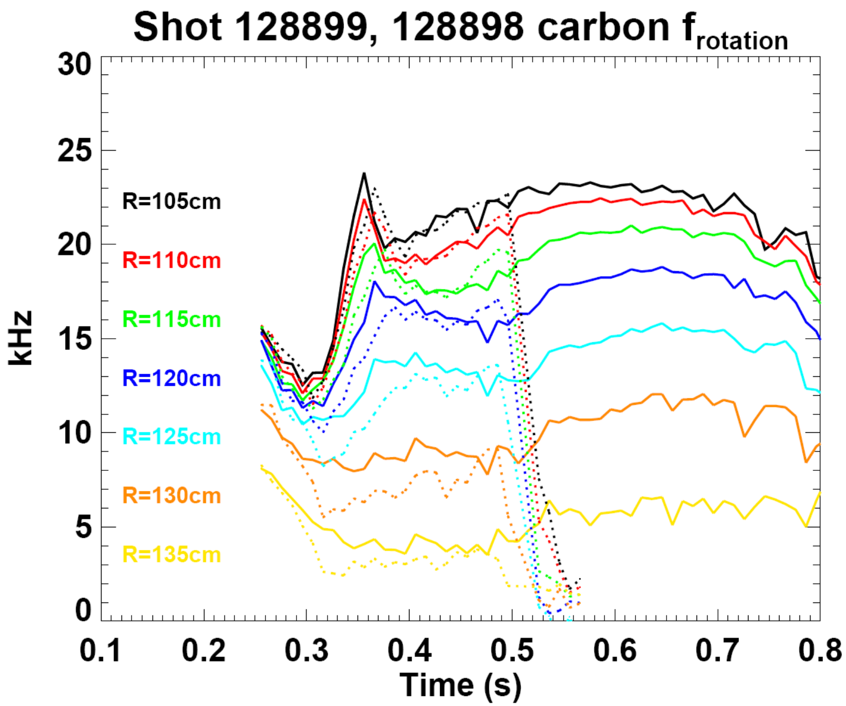
• ***n > 1 error fields not commonly addressed in present devices, or in ITER***

Method: Assess n=3 error field vs. vertical field (PF5 coil), toroidal field

n=3 field applied at t=0.25s

Corrective = solid
Anti-corrective = dashed



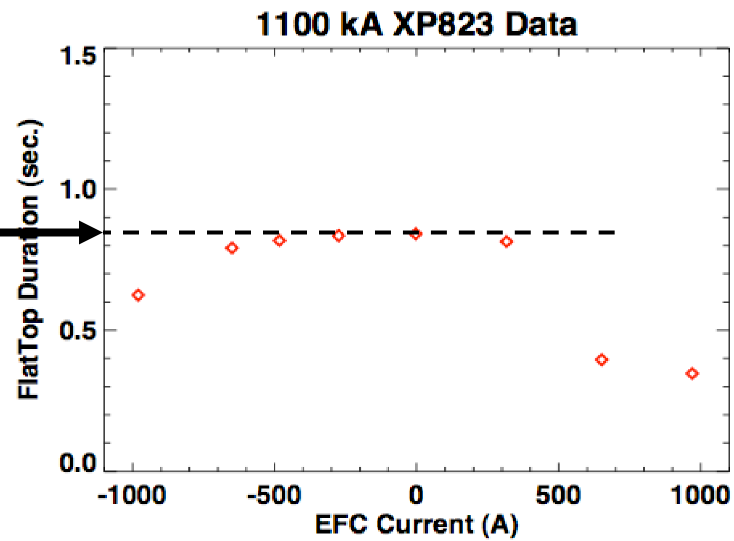


- I_P = 750kA → lower VF
- Lower TF, same q

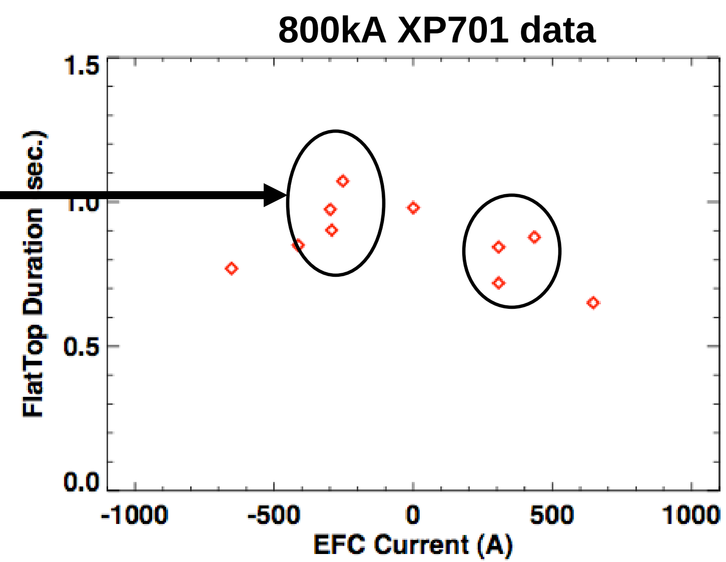
- I_P = 1.1MA → higher VF
- Same TF → lower q

Pulse length is unreliable guide for optimal EF correction

• The pulse durations of many shots at the highest current tested = 1.1MA are limited by available OH flux, rather than n=3 applied field



• Pulse duration at fixed n=3 field can also exhibit significant variation



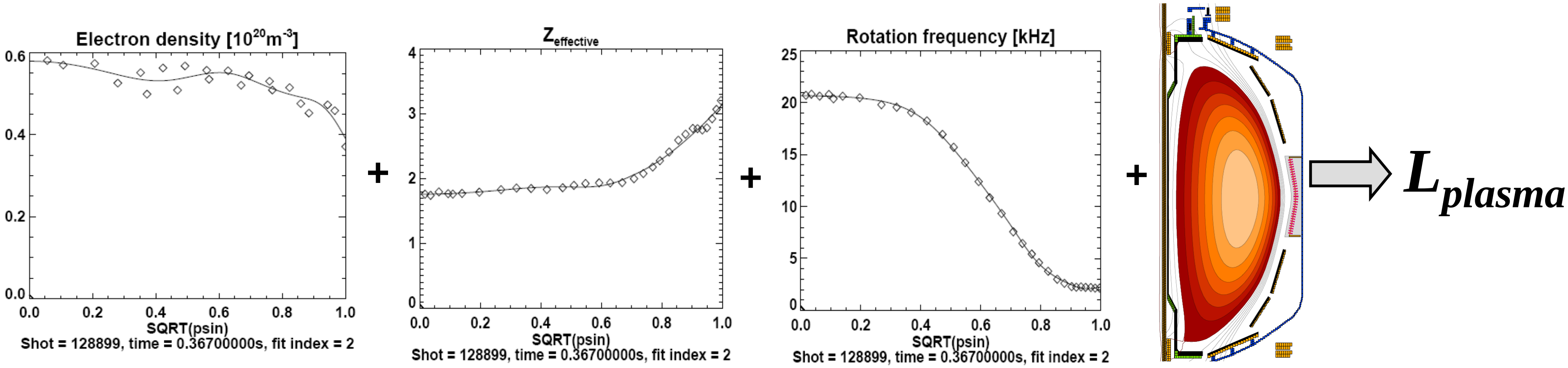
→ Use plasma angular momentum as the metric for optimization

Method utilized to determine optimal n=3 correction

- Compute total plasma angular momentum
  - Use up to 5 kinetic profile time-slices before collapse

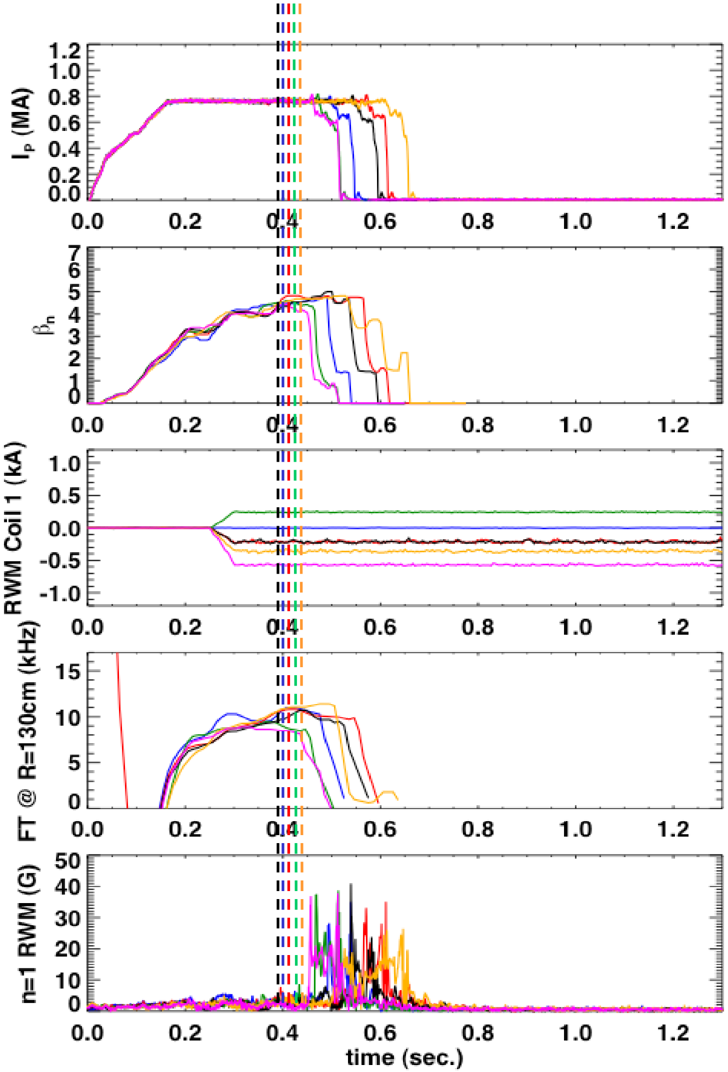
- Fit angular momentum data vs. correction coil current
  - Fit to quadratic and cubic function of correction coil current

Total plasma angular momentum: $$L_{plasma} \equiv \int \rho_{mass}(\psi)\,\Omega_{\phi}(\psi)\,R^2\,dV$$



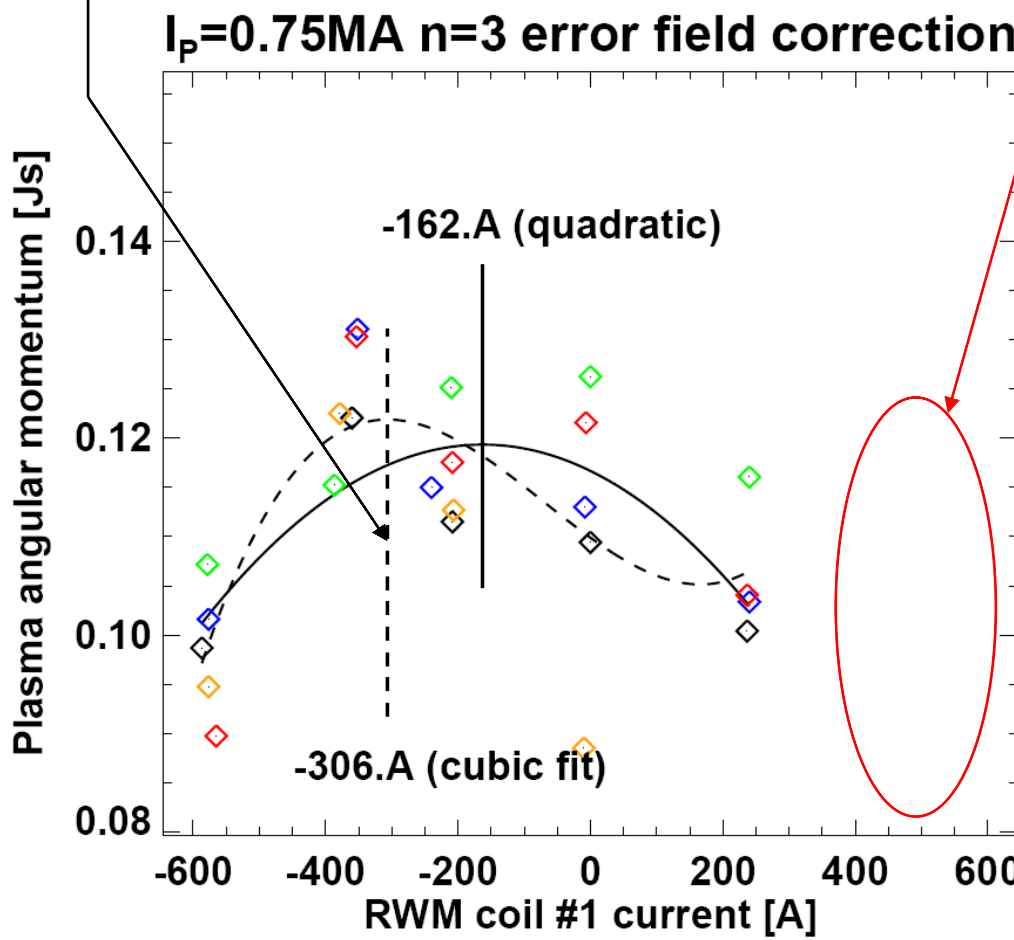
Optimal n=3 error field correction fit for lower I_P, lower B_T

Angular momentum computed at times shown



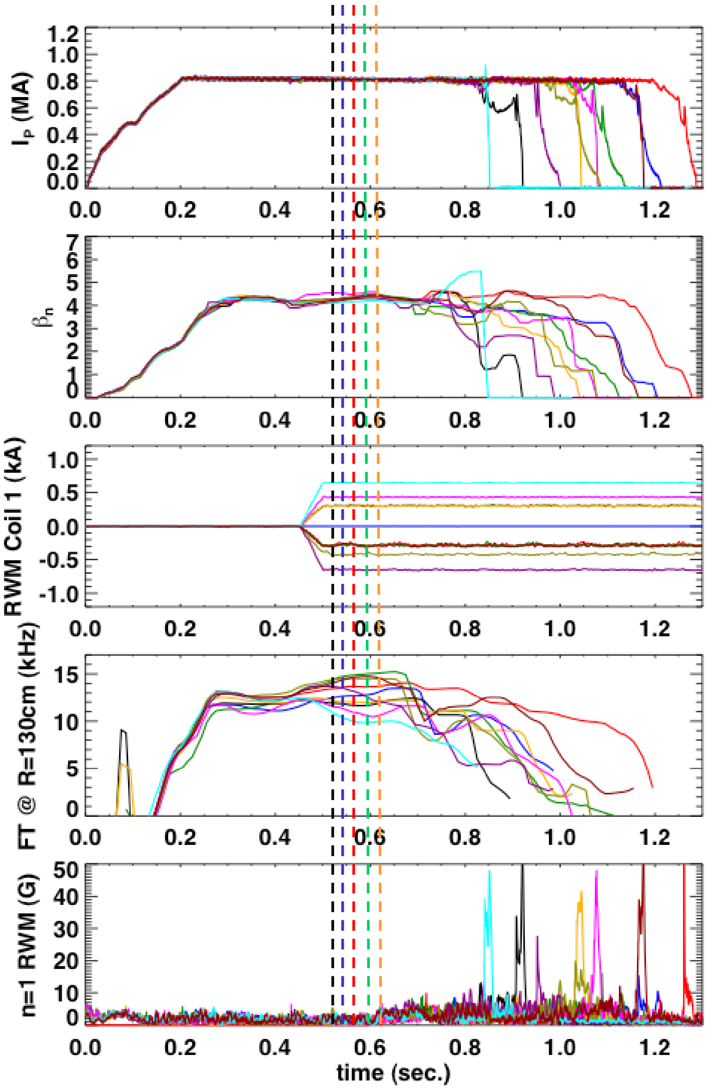
Cubic fit likely influenced by lack of data at +600A

Does cubic over-estimate optimal correction current?

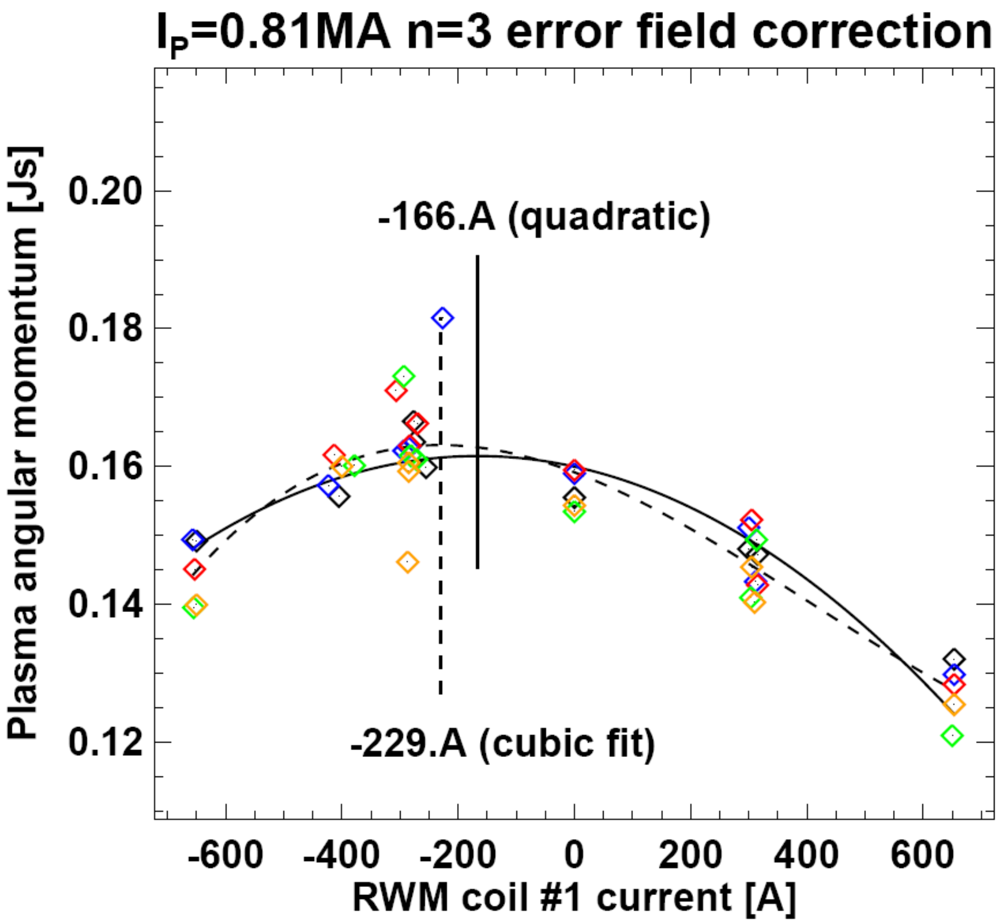


Optimal n=3 error field correction fit for lower I_P, higher B_T

Angular momentum computed at times shown

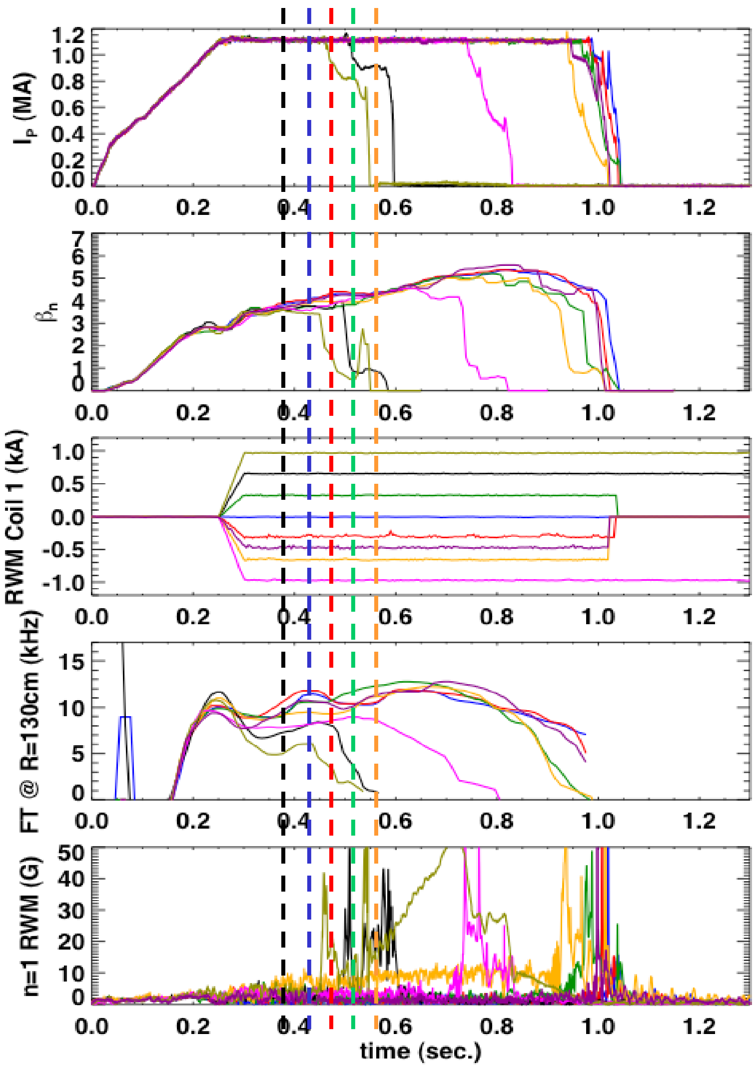


Cubic fit results in 38% higher correction current than quadratic fit

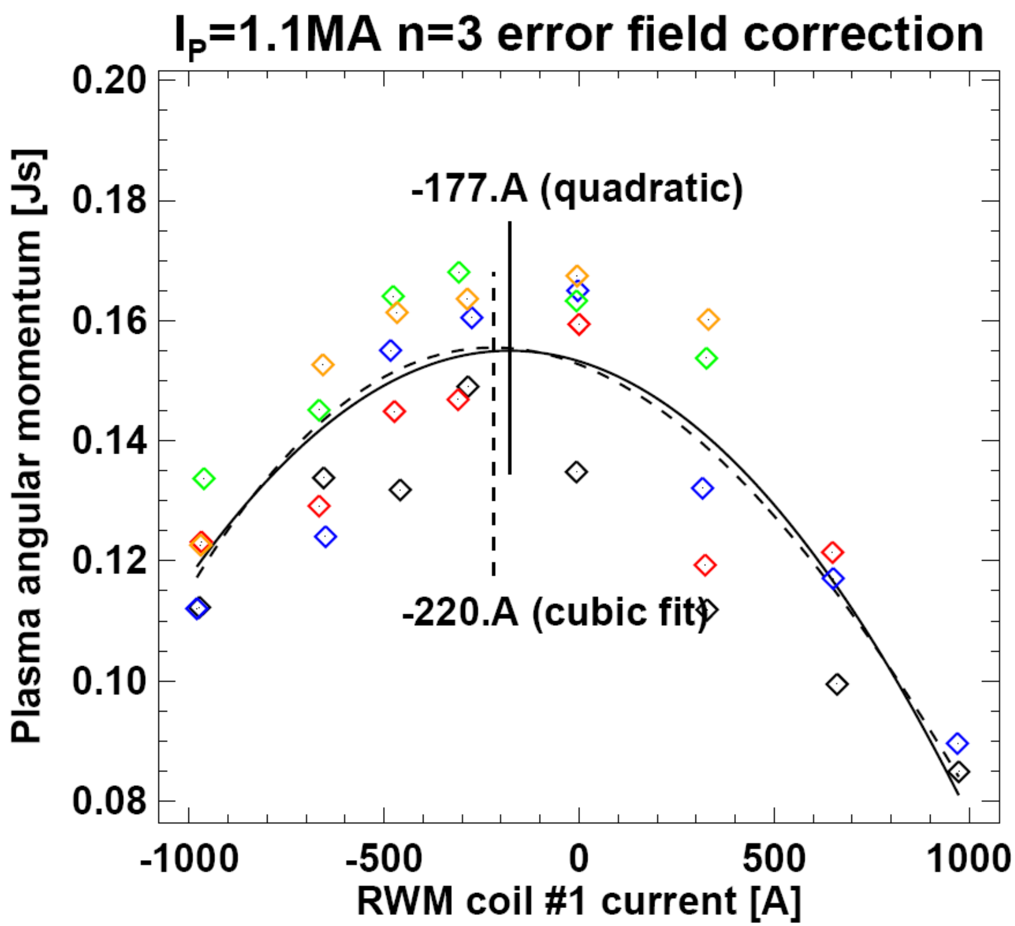


Optimal n=3 error field correction fit for higher I_P, higher B_T

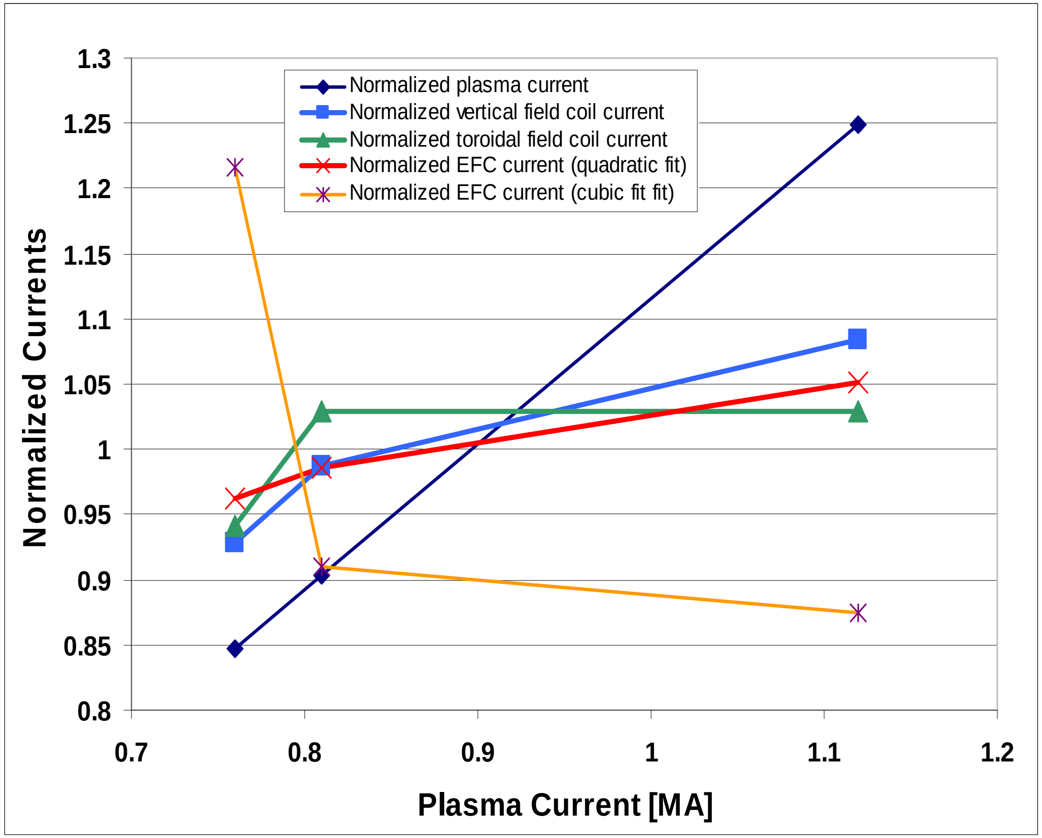
Angular momentum computed at times shown



Cubic fit results in 24% higher correction current than quadratic fit



Assessment of most probable n=3 error field source

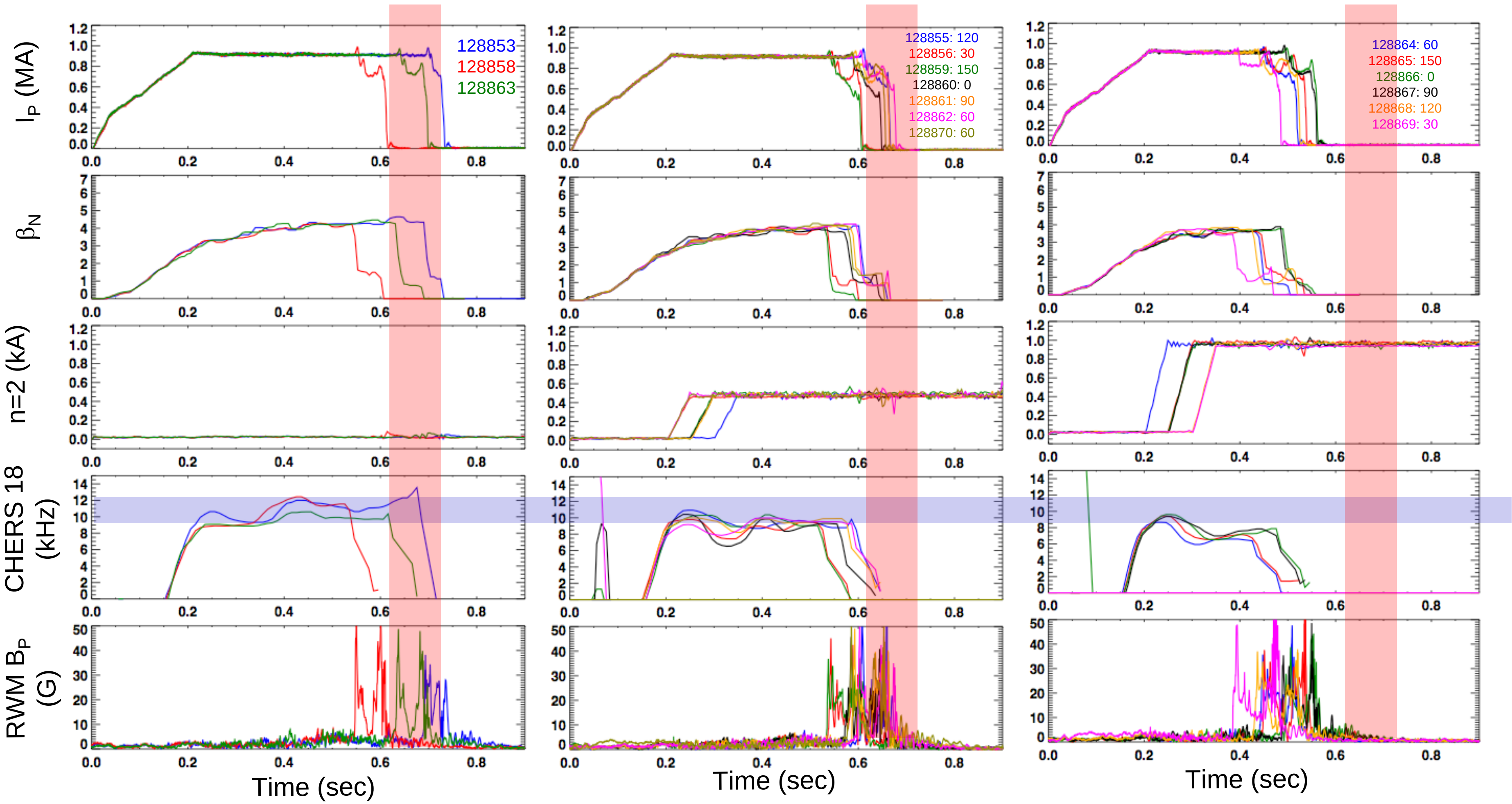


1. **Cubic-fit EFC *anti-correlated* with possible EF sources:**
   - **Vertical field (VF)**
   - **Toroidal field (TF)**
2. **Quadratic-fit EFC correlated with plasma, VF, and TF currents**
3. **Quadratic-fit EFC slope most closely matches VF, TF slopes**
4. **Correlation coefficients between Quadratic-fit EFC and VF and TF:**
   - **R^2 = 0.99 for VF**
   - **R^2 = 0.71 for TF**

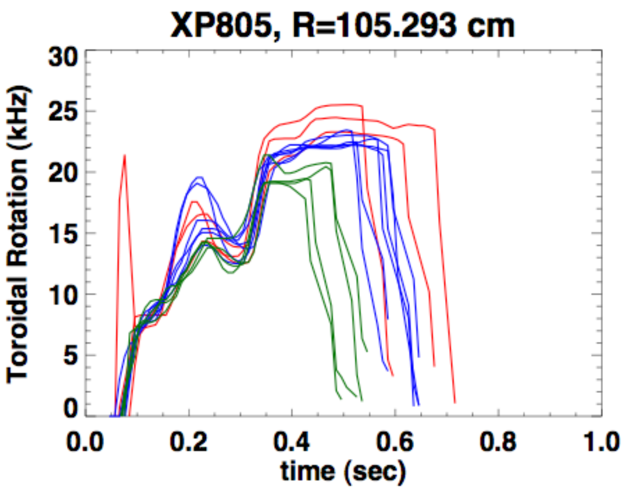
- **Conclusions:**
  - **Most probable source of n=3 EF is vertical field (PF5), but TF is also possible source**
  - **Phase of intrinsic n=3 EF cannot be determined – further EFC optimization possible**
  - **Torque variation with I_{RWM} consistent with δB^2 dependence → consistent with NTV**

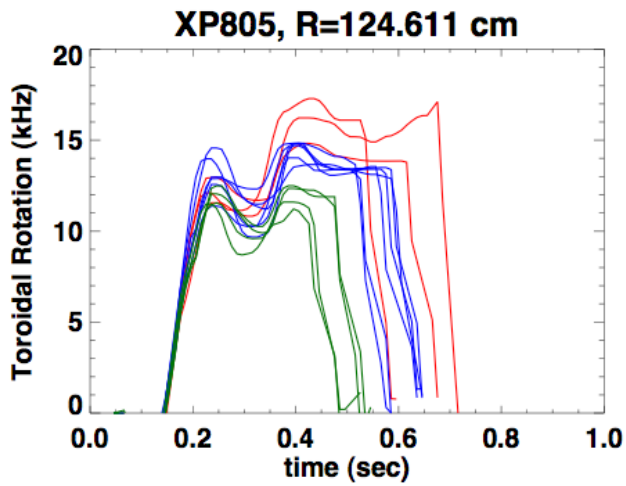
No significant n=2 intrinsic error field identified

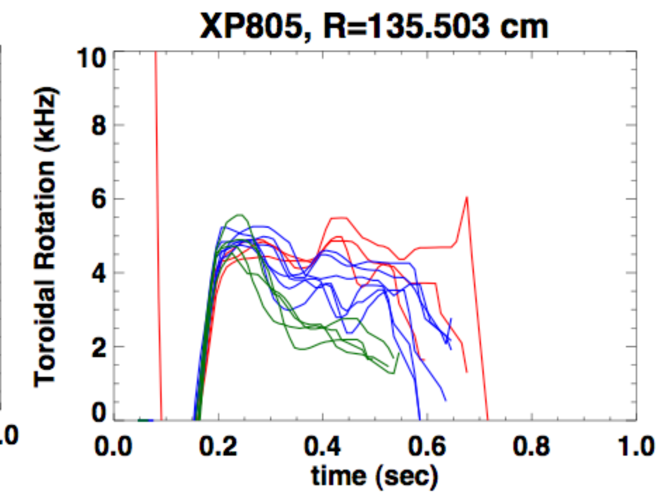
- Shot duration and duration of high β_N and rotation reduced with applied n=2
- Results independent of phase & amplitude for 0.5kA, 1kA → n=2 intrinsic EF < 500A



Applied n=2 field results in systematic decrease in rotation

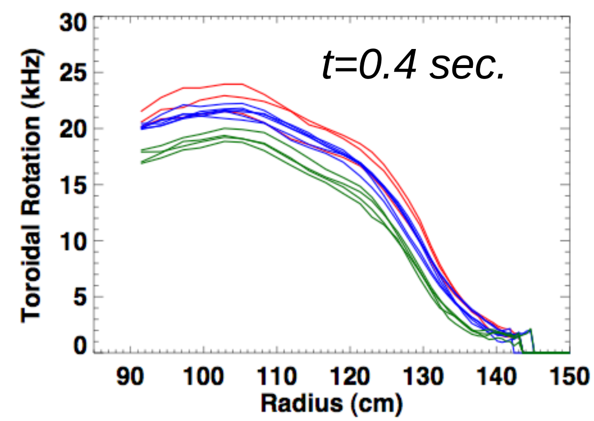






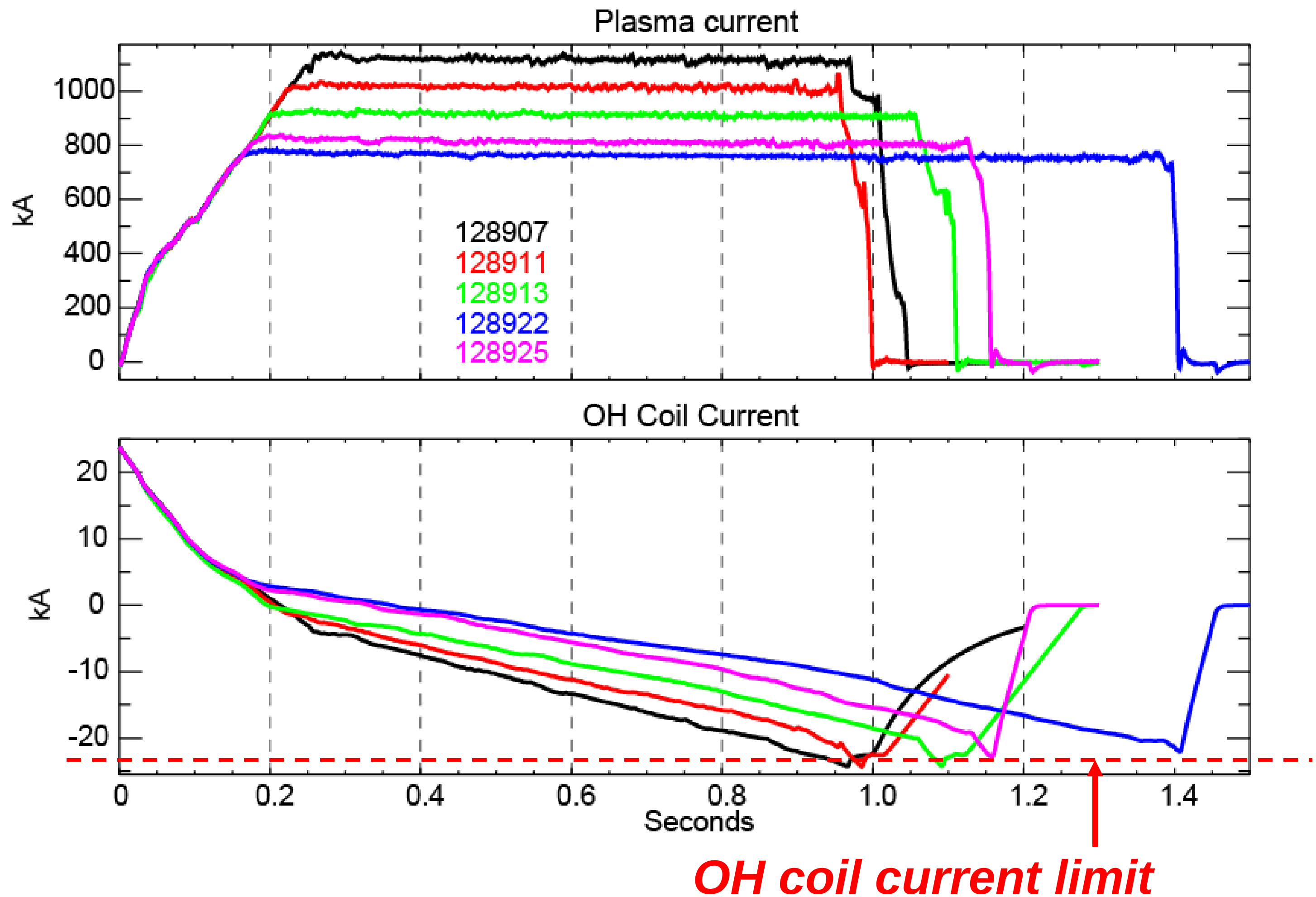
Color Code
3 Reference Shots
7 Shots with 500 A n=2
4 Shots with 1000A n=2

Decrease Occurs Across the Entire Profile



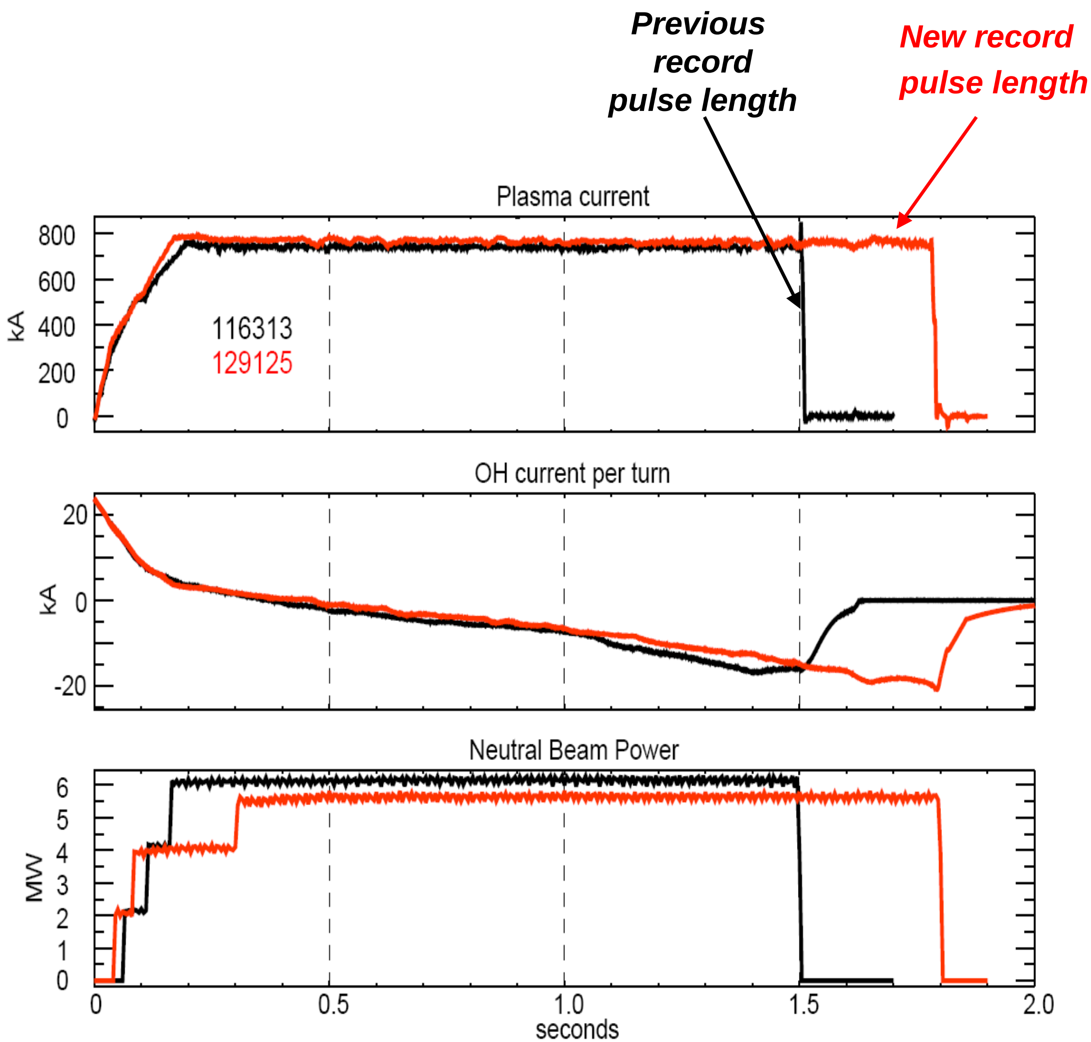
n=3 EFC + n=1 feedback was successfully applied to wide range of plasma current = 0.75-1.1MA

- Pulses run reliably until nearly all OH flux is consumed



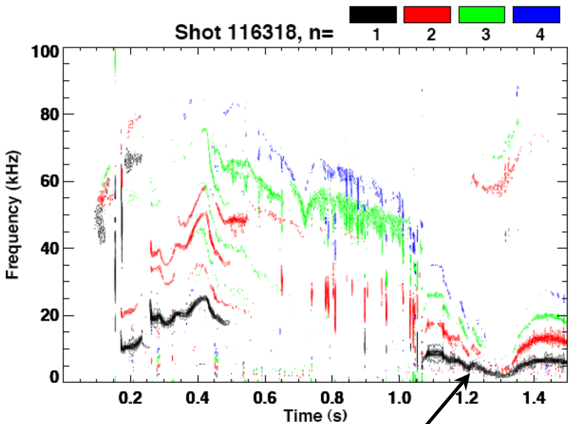
Optimized n=3 EFC + n=1 feedback + Lithium → record NSTX pulse-lengths

- Flux consumption reduced following LITER experiments
  - Lower V_{LOOP} at lower P_{NBI}
- Li + optimized EFC →
  - Avoid late n=1 rotating mode
  - Rotation sustained
  - $\beta_N \geq 5$ sustained 3-4 τ_{CR}
  - record pulse-length = 1.8s

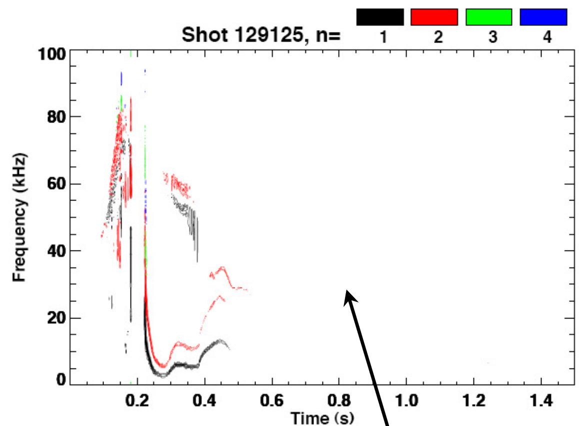


n=3 error correction combined with n=1 RFA/RWM feedback control increases β and rotation, and extends pulse

- ***MHD spectrogram w/o n=1 feedback and n=3 correction***

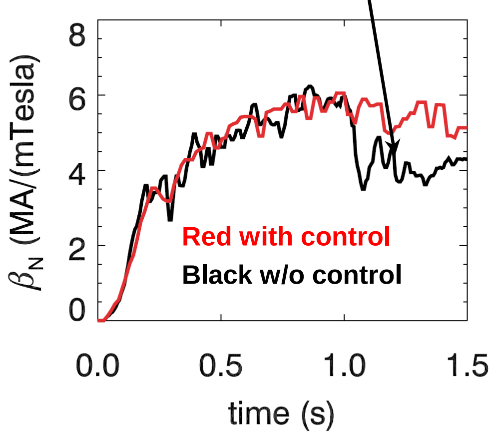


- ***MHD spectrogram with n=1 feedback and n=3 correction***

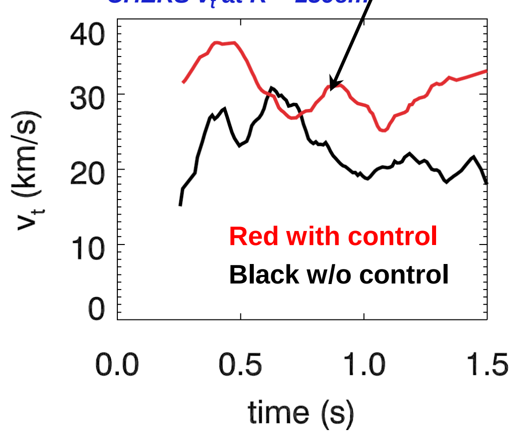


n=1 mode drops β

No MHD, β and rotation maintained

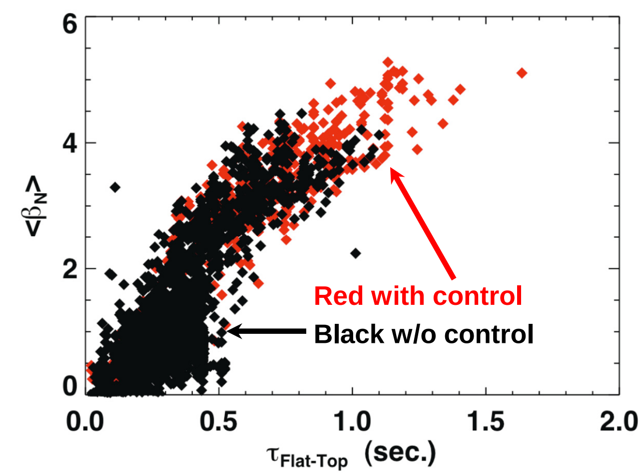


CHERS v_t at R = 139cm

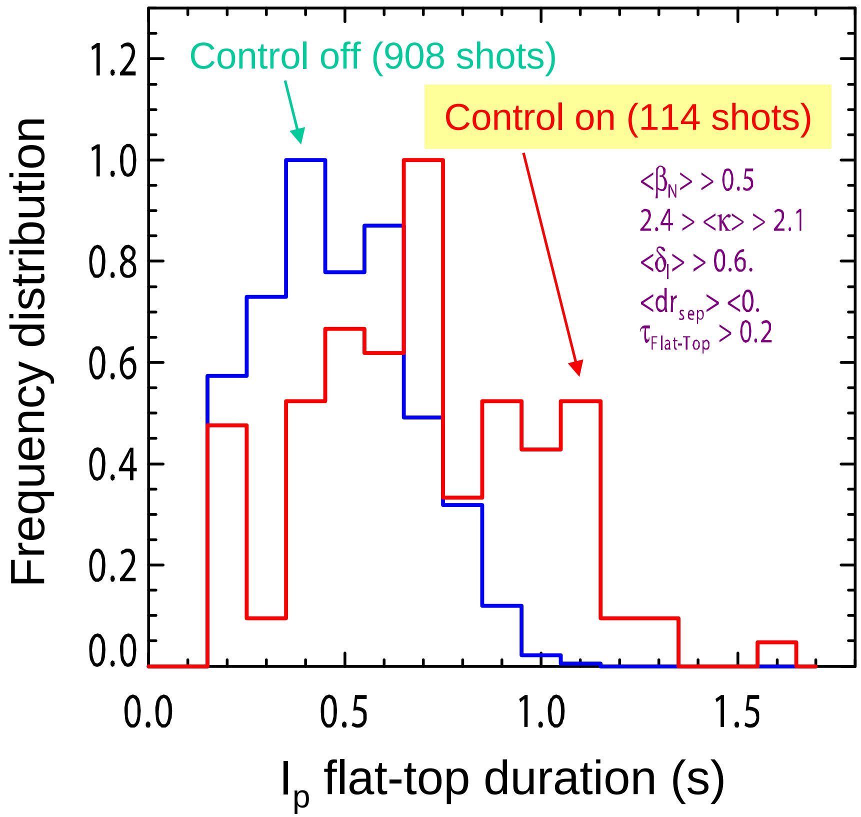


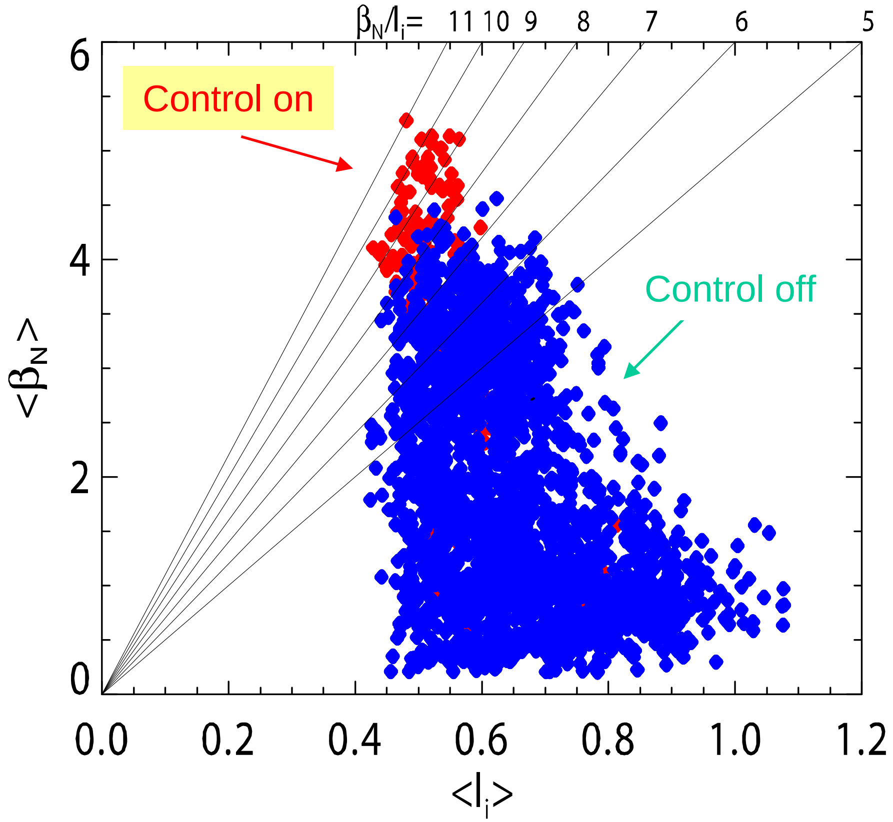
- Non-axisymmetric feedback algorithm has been developed using unique feedback training scheme
  - Prevents onset of MHD modes
  - Plasma rotation is maintained throughout discharge
- Control statistically raises β and increase pulse length

Pulse averaged β_N vs. current flat-top



Probability of long pulse and $\langle\beta_N\rangle_{pulse}$ increases significantly with active RWM control and error field correction





- Standard H-mode operation shown
  - I_p flat-top duration > 0.2s (> 60 RWM growth times)
- Control allows $\langle\beta_N\rangle_{pulse} > 4$
  - β_N averaged over I_p flat-top

Conclusions

- Extensive non-axisymmetric magnetic sensor array useful for detecting and correcting intrinsic n=1 error fields
- Dominant n=1 error field results from TF bundle motion from electromagnetic interaction between OH and TF coils
- Gain and low-pass filter optimization of n=1 active feedback control successfully suppresses resonant field amplification (RFA) of n=1 EF and unstable RWMs
- n=3 intrinsic error field adversely impacts high-beta operation, and is most likely associated with vertical field coil
- No evidence (yet) of significant n=2 intrinsic error field
- Combination of n=3 EF correction + n=1 active feedback control improves plasma performance for a wide range of conditions: sustained high rotation, β → record pulse duration

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