Magnetic Feedback Strategy Near No-wall Stability Limit

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In collaboration with

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FAR-TECH

Magnetic feedback control would be the indispensable tool to bridge physics and engineering in high-β plasmas

- **The RWM stabilization is essential to sustain high performance plasmas in ITER or reactor-grade devices**

- **Although passive RWM stabilization is ideal, both the uncertainty of pressure-driven RWM stability boundary and pending experimental evidence challenge the robustness of the concept**

- **Even if RWM is passively stabilized, a coupling of marginally stable RWM with other MHD activities readily destabilizes the plasmas, requiring another safeguard (e.g. magnetic feedback control)[1,2]**

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[1]M. Okabayashi *et al*, NF(2009); [2]Y. In *et al*, PPCF (2010);

Several challenges need to be addressed for successful magnetic feedback control near no-wall stability limit

Physics-oriented

- Resonant Field Amplification
- Uncertainty of RWM stability boundary
- Preciseness of feedback
- Multimode identification

Potential Problems

Engineering-oriented

- Error Field Correction
- Robustness of RWM stabilization
- Effectiveness of feedback
- Multimode control

Enabling Solutions

The requirements of direct feedback (DF) stabilization on RWM have been specified*

Physics-oriented

- Resonant Field Amplification
- Uncertainty of RWM stability boundary
- Preciseness of feedback
- Multimode identification

Potential Problems

Engineering-oriented

- Error Field Correction
- Robustness of RWM stabilization *
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- Multimode control

Enabling Solutions

* Y. In *et al.*, MHD workshop (2009); Y. In *et al*, PPCF (2010)

The EFC strategy also needs to be developed in consideration of RWM stability*

Physics-oriented

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Enabling Solutions

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* Y. In *et al.*, IAEA FEC, Daejon, Korea (2010);

Outline

- **Introduction**
  - **Distinction between EFC and DF stabilization on RWM**
  - **Magnetic feedback control system in DIII-D**

- **Magnetic feedback in low-β plasmas**
  - Subtlety of EFC in stable, marginal, and unstable RWM regimes

- **Magnetic feedback in high-β plasmas**
  - **Broadband magnetic feedback**

- **Conclusions**

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The EFC is to minimize the lack of axisymmetry of external fields that vary slower than wall characteristic time τ_w

- **The roles of error-field-correction (EFC) and direct feedback (DF) stabilization on RWM are distinctive in magnetic feedback control**

  "The EFC is to minimize the lack of axisymmetry of external fields, while the DF stabilization on RWM is to nullify the magnetic perturbation originating from unstable RWM" [1]

- **Unstable RWM is extremely sensitive to any small but uncorrected resonant EF**

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[1] **Y. In *et al*, NF (2010)**

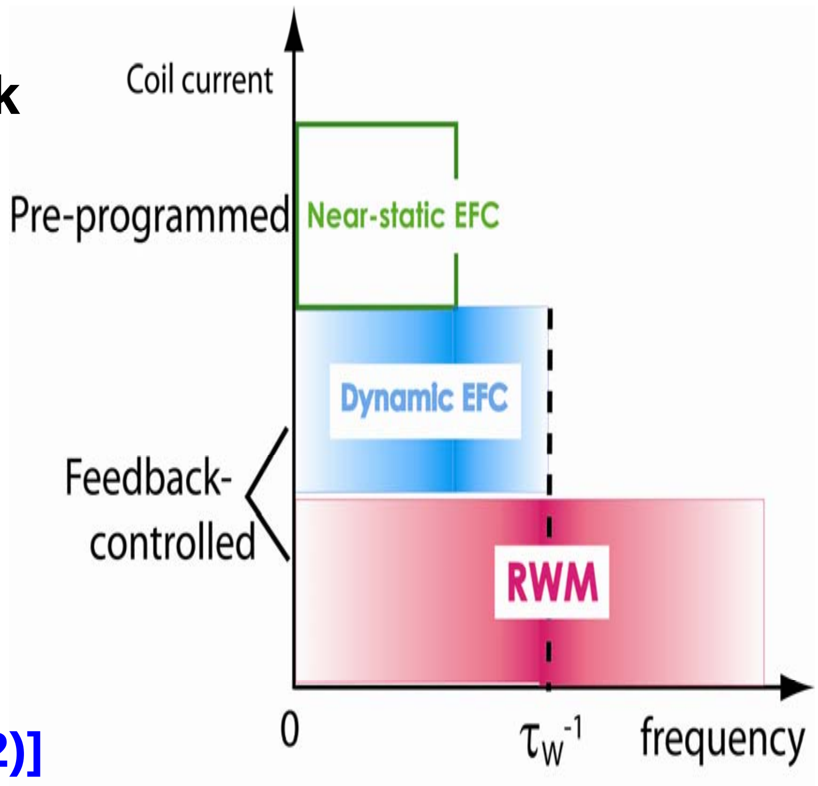
Magnetic feedback control system is primarily required to reduce the resonant component in plasmas

Strategy against the resonant $\delta B^{n=1}$ ($=\delta B_{EF}+\delta B_{RWM}+$?)

- **Pre-programmed EFC**

  [bandwidth << τ_w^{-1}]

  - **Duplicate the "optimized" feedback coil currents *(usually requires a few iterations of DEFC)***
  - **Empirical formula of error fields with respect to I_p and B_t *(popular but insufficient in high-β)***



- **Dynamic EFC (DEFC)**

  [bandwidth < τ_w^{-1}]

  - Feedback-controlled EFC

[See also Garofalo, La Haye, Scoville, NF (2002)]

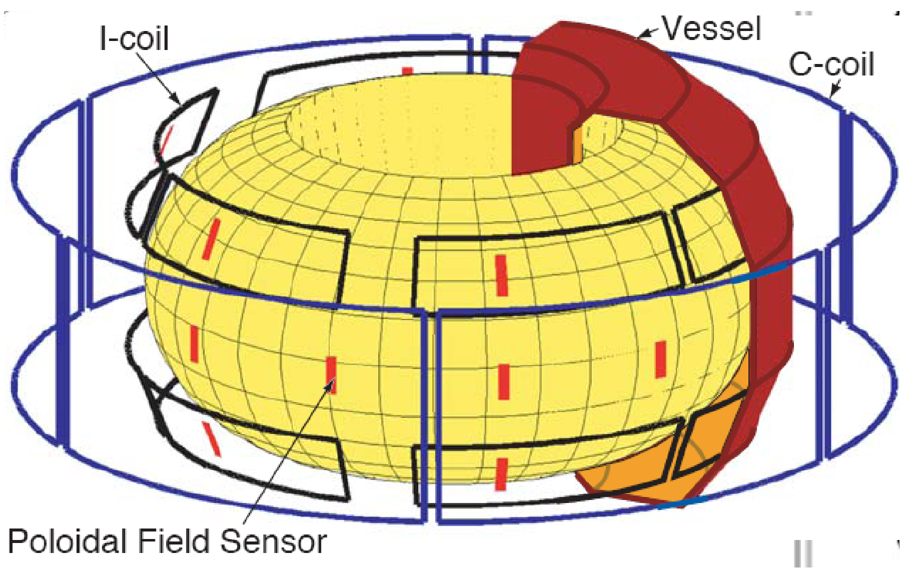
- **Direct Feedback**

  [bandwidth > γ_0 (~ τ_w^{-1})]

where τ_w^{-1} : resistive wall characteristic frequency

DIII-D is uniquely equipped with internal coils for fast time response and external feedback coils for slower time response

- **Tools**
  - **Internal coils ("I-coils"):** **Direct Feedback** + **Dynamic**/**Pre-programmed** **EFC**
  - **External coils ("C-coils"):** **Dynamic**/**Pre-programmed** **EFC**



- **Magnetic feedback control**

$V_{FB}^{n=1}$ → **Power Supply** → **Plant (DIII-D/RWM)** $(\tau_w, \tau_{L/R}, \delta I_{FB}^{n=1})$ → $\delta B^{n=1}$ + **?** → **Controller** → Power Supply

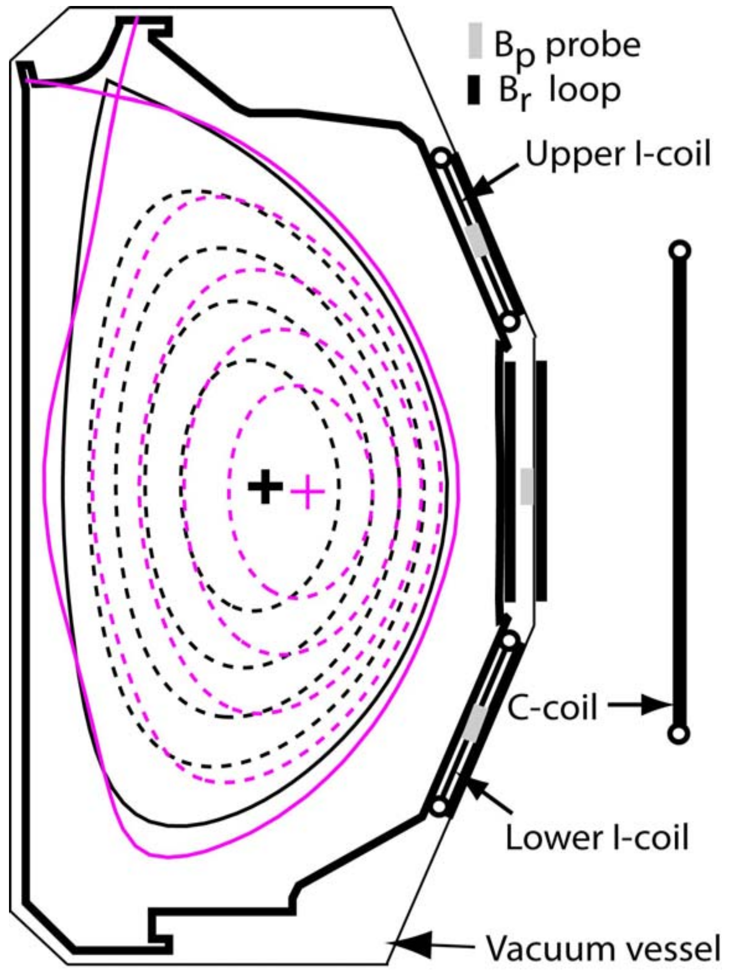
Controller

$$K(s) = \frac{1}{1+s\tau_p}\left[G_p + \frac{G_d s\tau_d}{1+s\tau_d}\right]$$

$G_{p,d}$: Gain $\tau_{p,d}$: time constant
where p - proportional, and
d - derivative

? : *Unknown n=1 error field*

Reproducible current-driven RWMs during low-β ohmic discharges provide a simple system for feedback tests [1, 2]



- **Error field (EF) closely tied with RWM stability**
- **A part of EF topology, similar to that of RWM**

➔ **So, RWM control system can also be used for EFC**

- **Current-driven RWM (in low-β) *vs* pressure-driven RWM (high-β)**
  - **Similar external mode structure, as well as $\tau_g = \gamma_0^{-1} \sim \tau_w$**
  - **BUT, little or no passive sources of stabilization (e.g. rotational stabilization[3], kinetic effects[4])**

[1] Y. In *et al*, PPCF (2010) [2] Y.Q. Liu *et al*, PoP (2010);
[3] Bondeson and Ward, PRL (1994) [4] Hu and Betti, PRL (2004)

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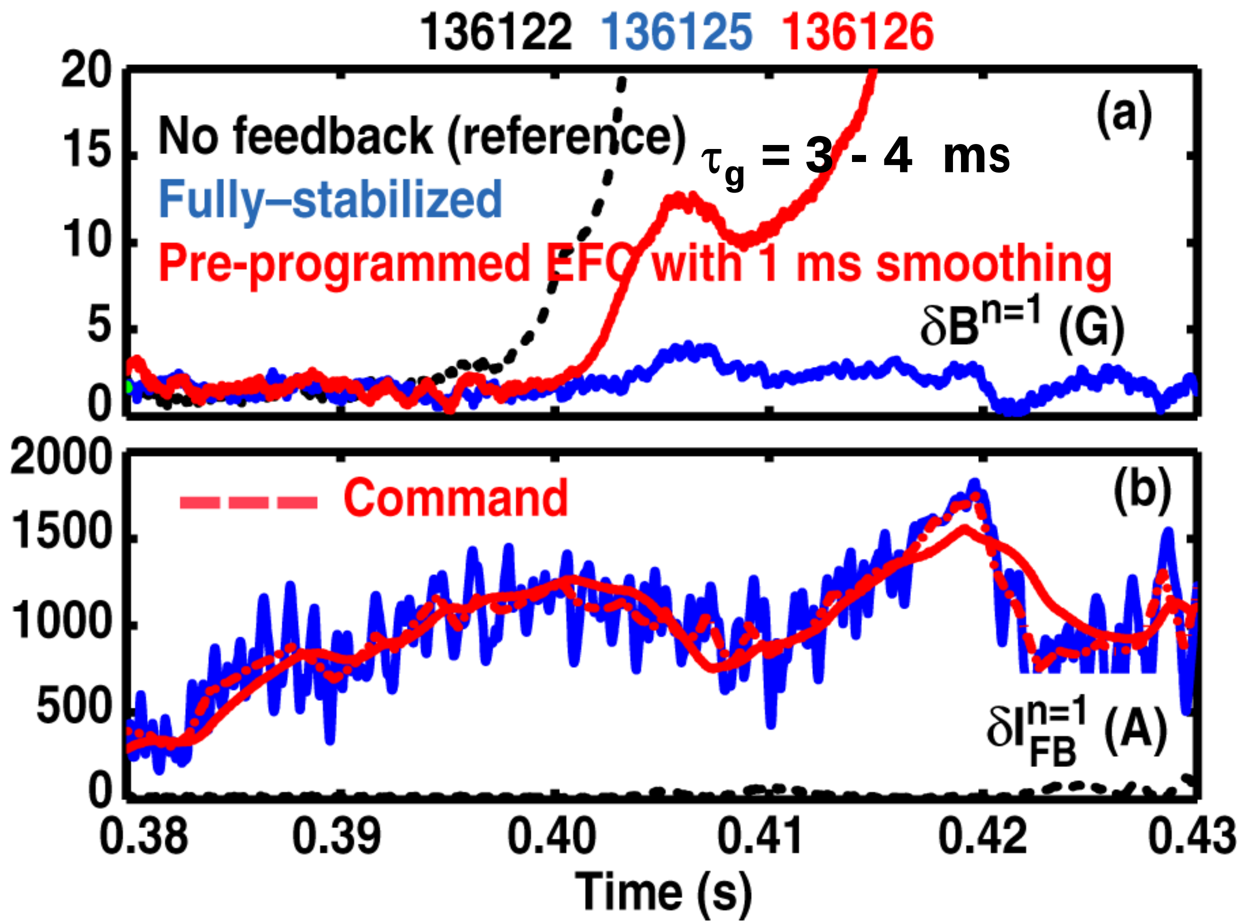
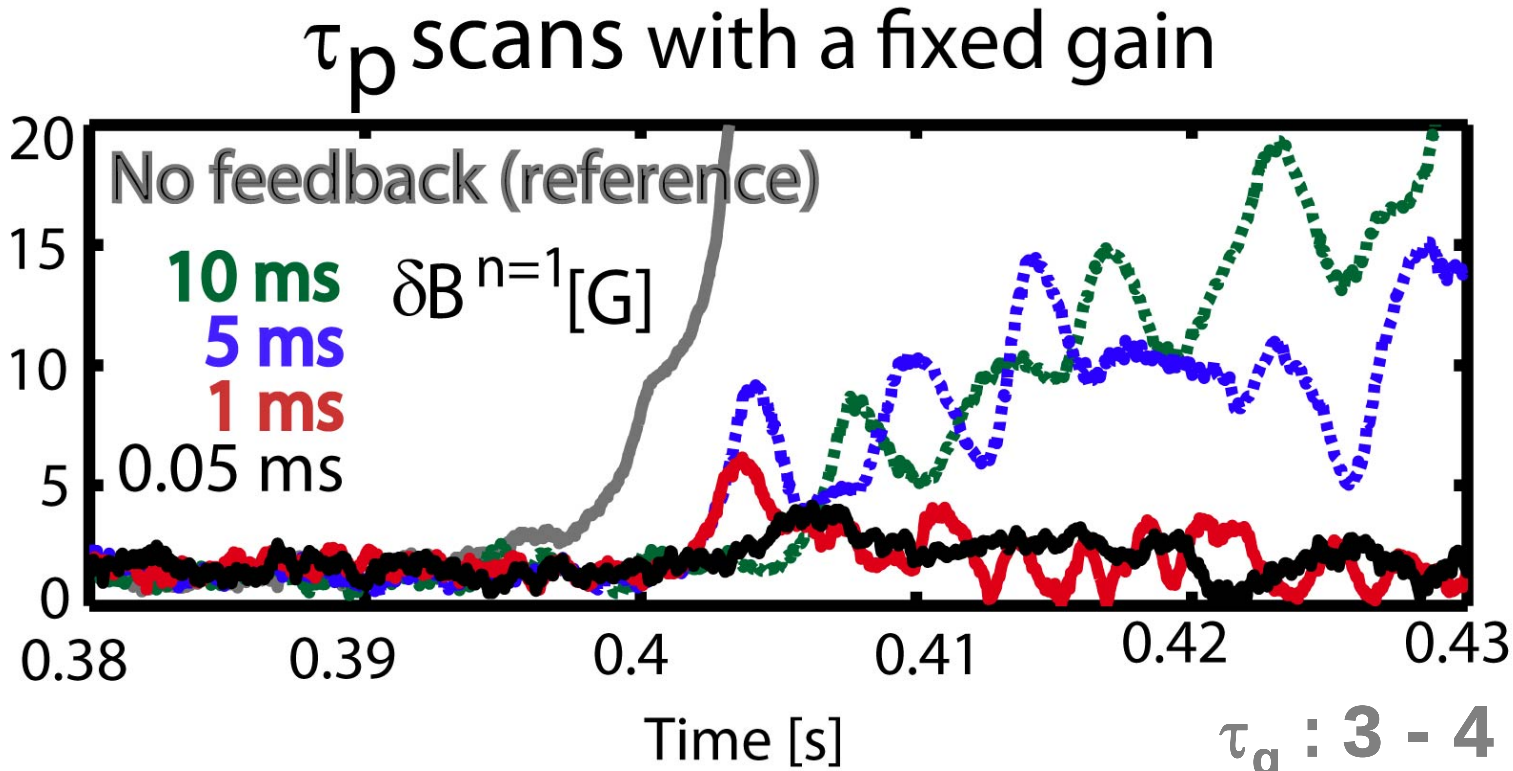
Active feedback control is required to stabilize RWM



- ***Pre-programmed currents that duplicate the feedback output do not provide stabilization*** [1]

[1] **Y. In *et al*, NF (2010)**

The RWM feedback action should be taken faster than the mode growth time, as predicted[1, 2]



τ_g : 3 - 4 ms

- When $\tau_p < \tau_g$: effective , while $\tau_p > \tau_g$:ineffective

  where τ_p : feedback response time

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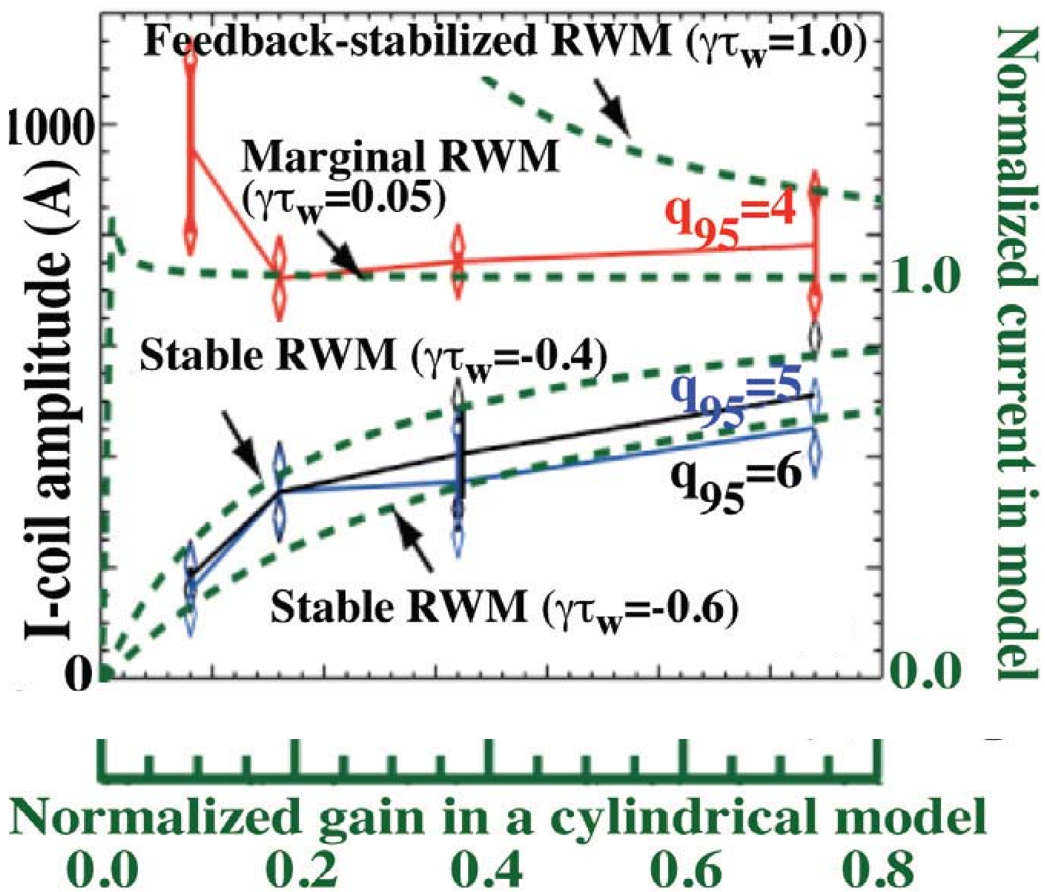
[1]E.J. Strait *et al*, NF (2003) [2]Y. In *et al*, PPCF (2010)

The EFC strategy needs to be developed in consideration of the RWM stability conditions



- **Experimental results (*stable* *and* *marginal* RWMs) are consistent with an analytic cylindrical model[1]**
- **Feedback-controlled EFC always underestimates the EF in stable RWM regime, while being predicted to overestimate it in unstable RWM regime**
- ***In both stable and unstable RWM regimes,* high gain helps the feedback coil current converge to the desired EF correction level**

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[1] M. Okabayashi *et al*, NF (1998)

Broadband magnetic feedback aiming at active RWM stabilization adds more benefits to high-β plasmas

Unlike low-β plasmas, high-β plasmas requires further understanding about

- **Stronger plasma response: *non-ideal MHD effect***

  resonant field amplification (RFA)

- **Passive sources of RWM stabilization**

  - **Rotational stabilization (shielding or braking)**

  - **Kinetic effects**

  e.g. resonance (mode-particle) with trapped energetic particles (n_{EP}) moving in the relevant frequencies of precession-drift and/or bounce

- **Resilience against other MHD events (e.g. edge-localized modes (ELMs), Fishbones etc): coupling or destabilization**

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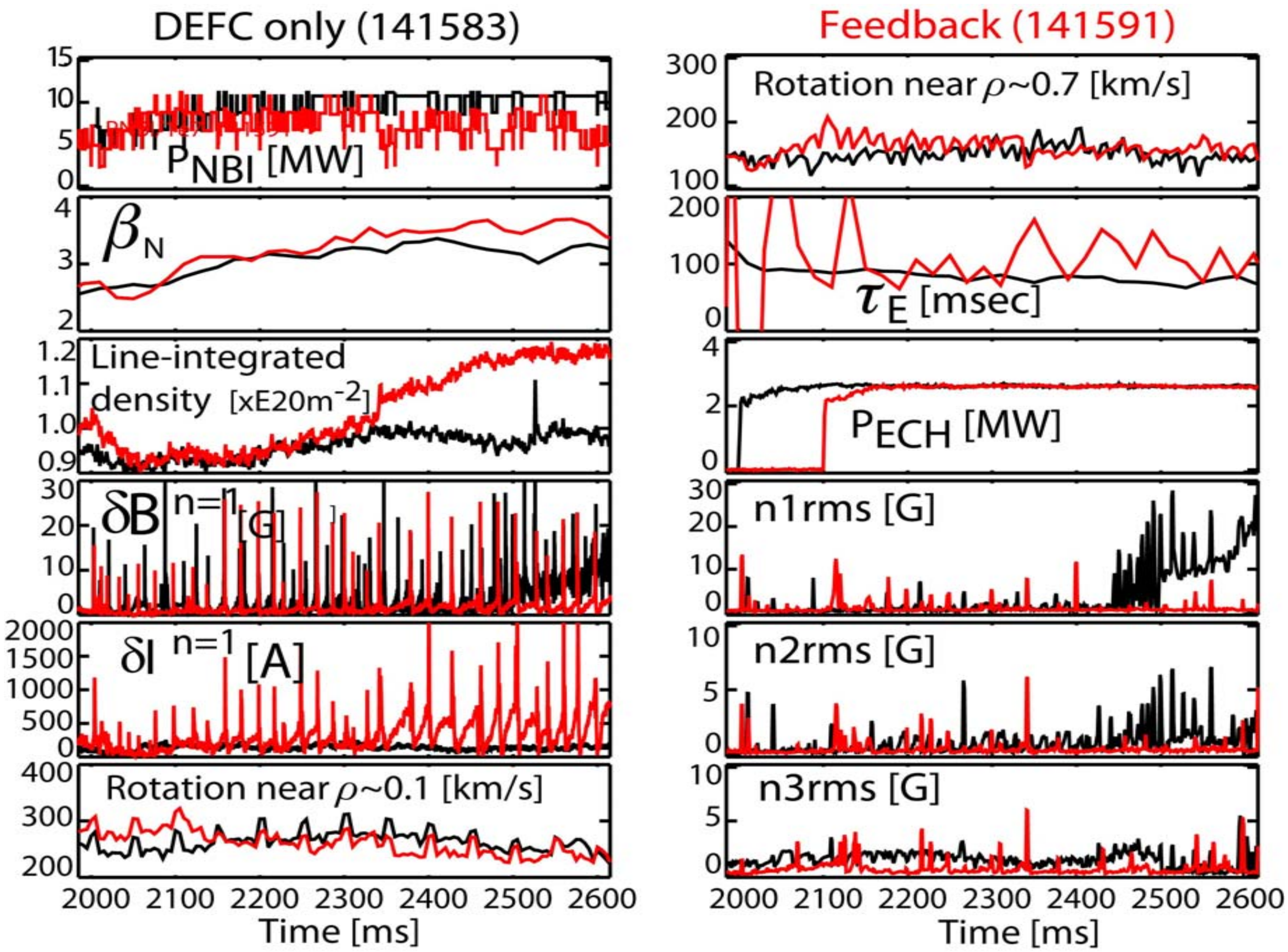
Broadband magnetic feedback appears contributing to improved τ_E, density and β_N



Similar ECCD deposition

- ***The broadband feedback may remove resonant δB (from various bursty MHD events or uncorrected residual error field) quickly, before RFA or coupling with RWM is involved***

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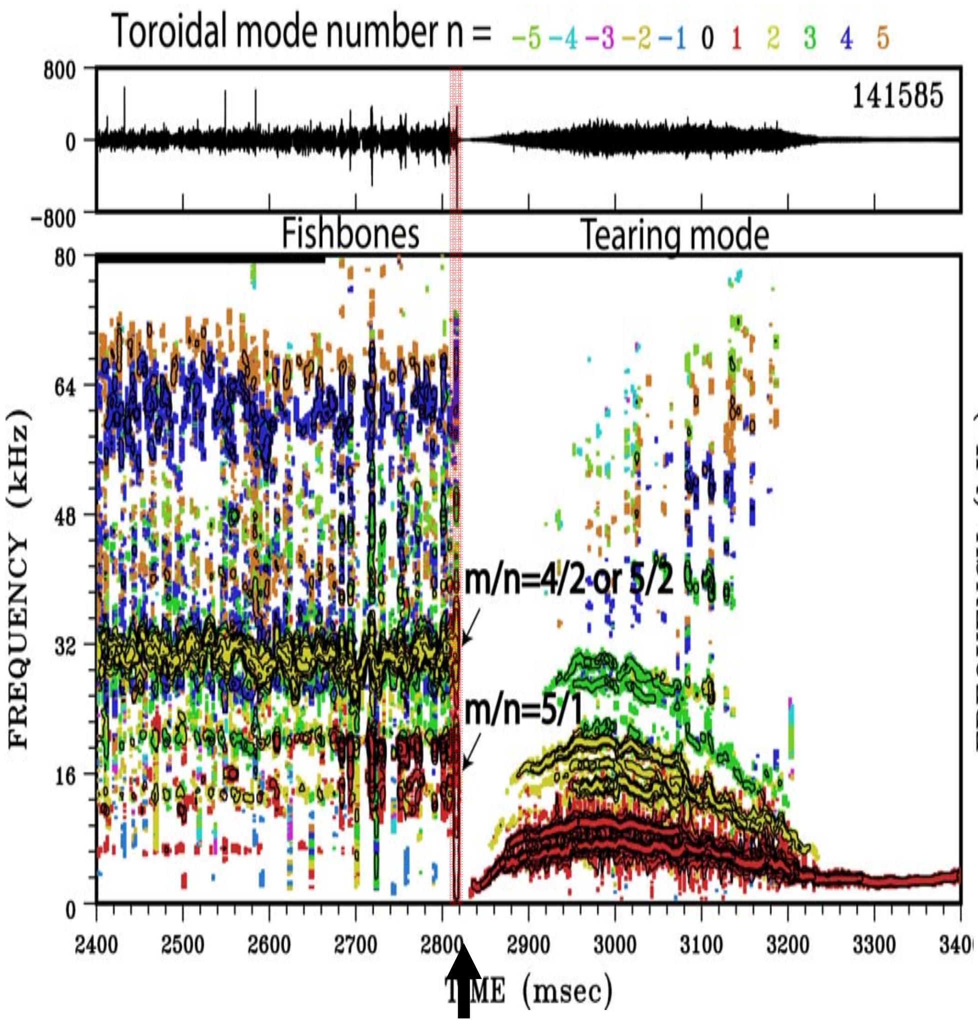
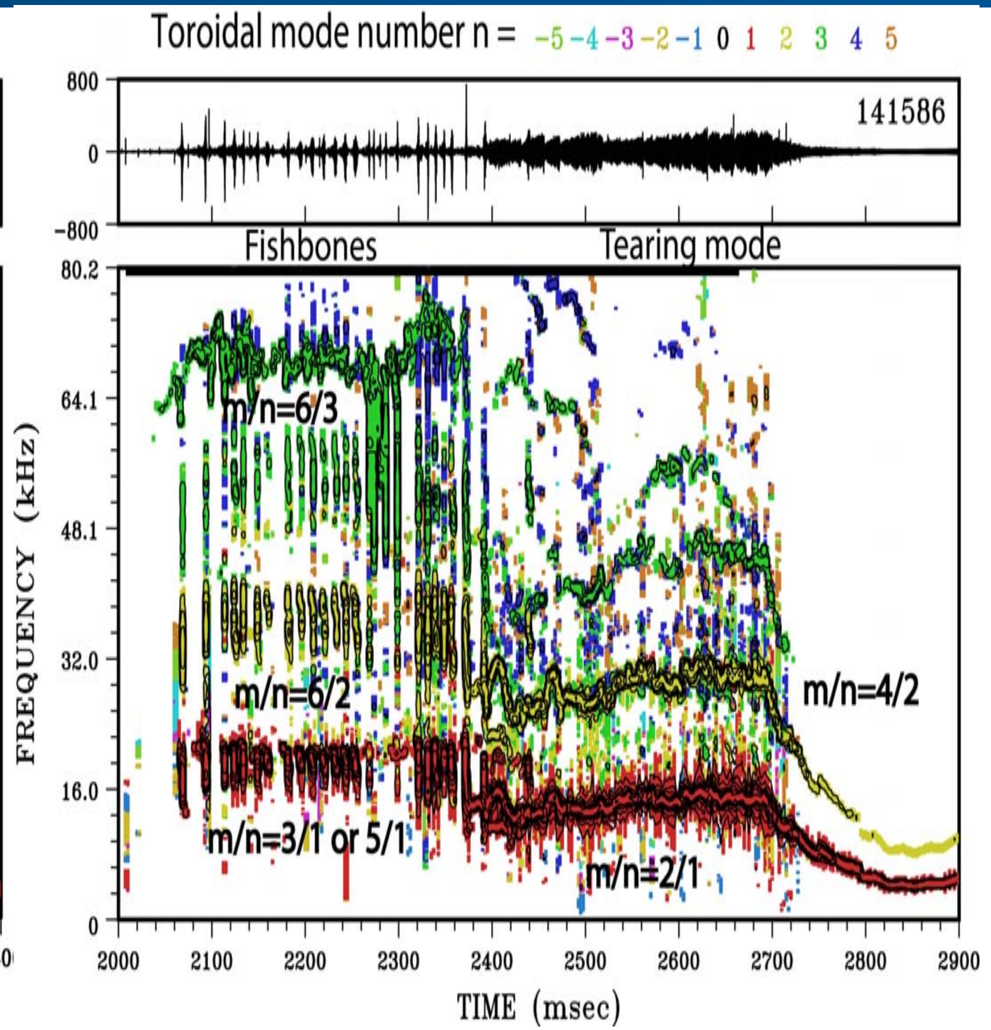
BUT magnetic feedback does not remove fishbone-driven kink-like mode nor fishbone-driven tearing mode directly





Before and after a fishbone-driven kink-like mode, followed by tearing

Fishbone-driven tearing mode

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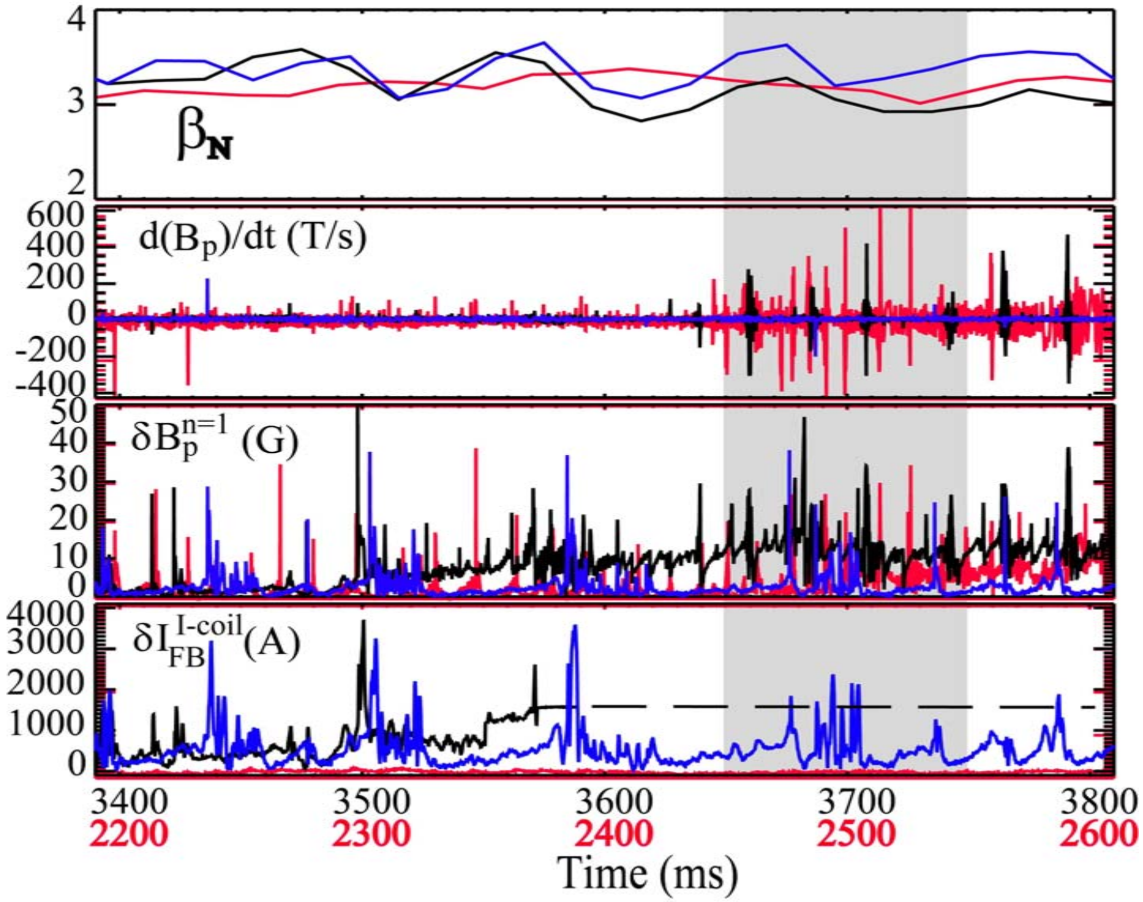
(Feedback: G_p = 40, τ_p = 0.5 msec)

A systematic comparison in high-β plasmas shows the importance of EFC and broadband feedback



Loss of EFC (no EFC)

DEFC

Broadband feedback

Elevated baseline of ~10G error field

Required EFC coil current of ~1.5kA

- Given the plasma conditions (with $\beta_N > 3$), a comparison of no feedback (black) vs DEFC (red) allow for |RFA|~ 7 G/kA

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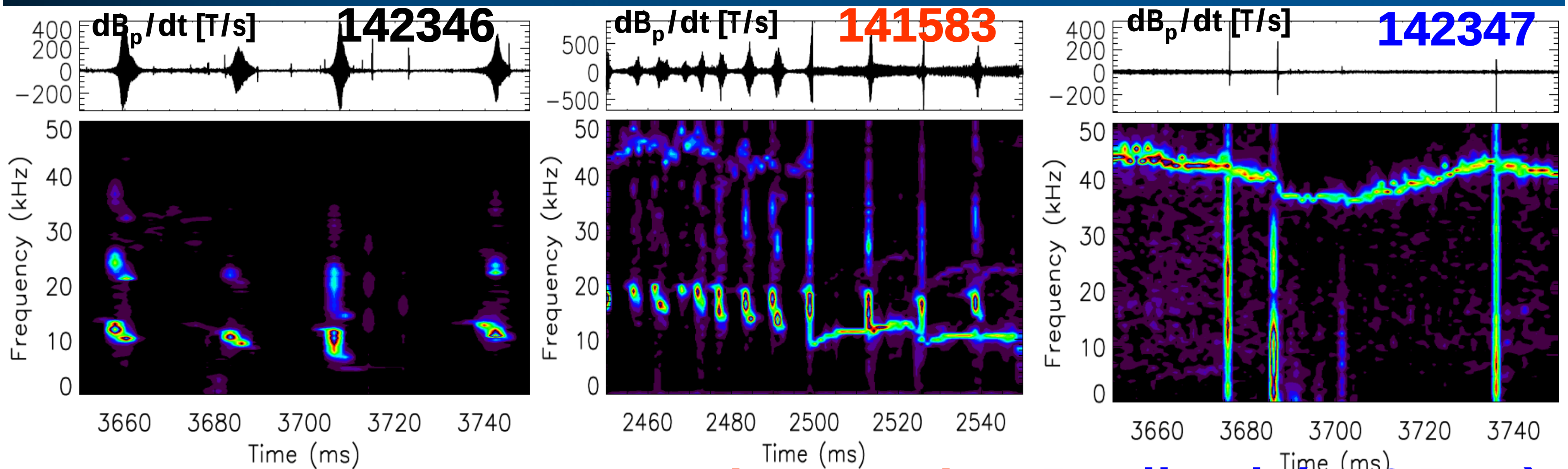
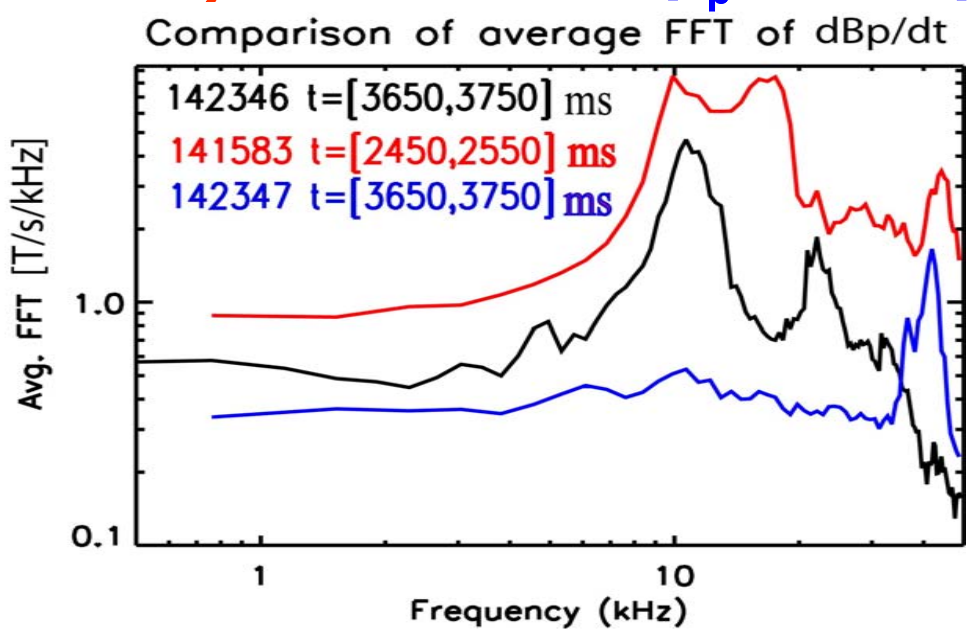
The feedback did not remove the fishbones, though there were some changes in terms of mode spectra



No feedback

DEFC (τ_p=50 ms)

Feedback (τ_p=0.5 ms)



Based on a B-dot probe

- The penetration and life times of resonant δB could be important

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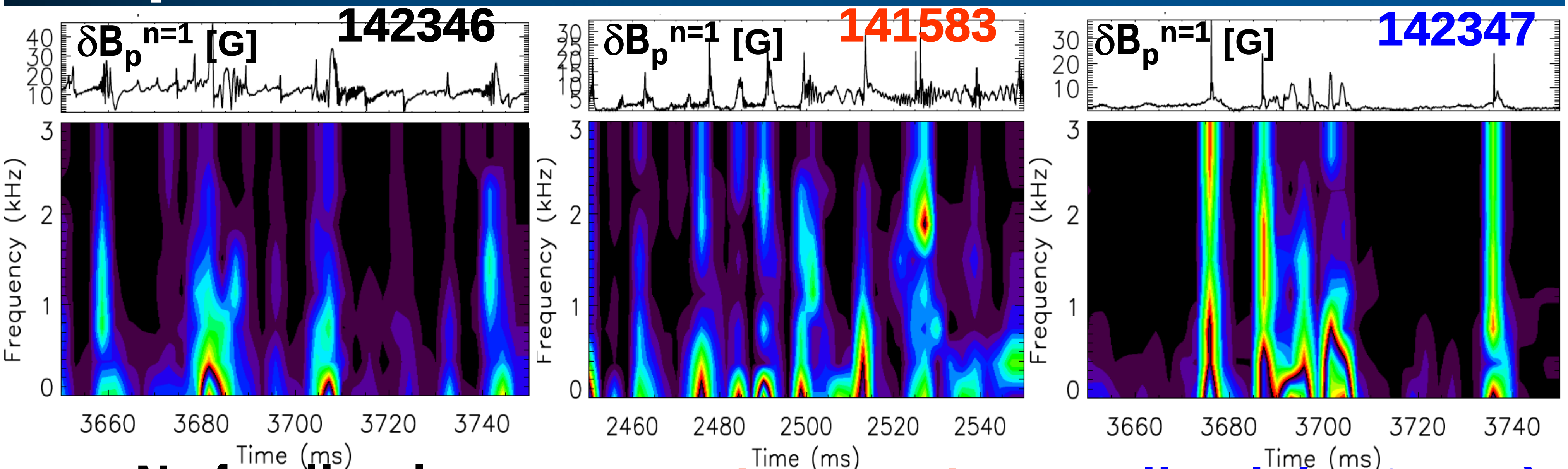
The resonant δB is substantially reduced as expected, as the bandwidth is broadened



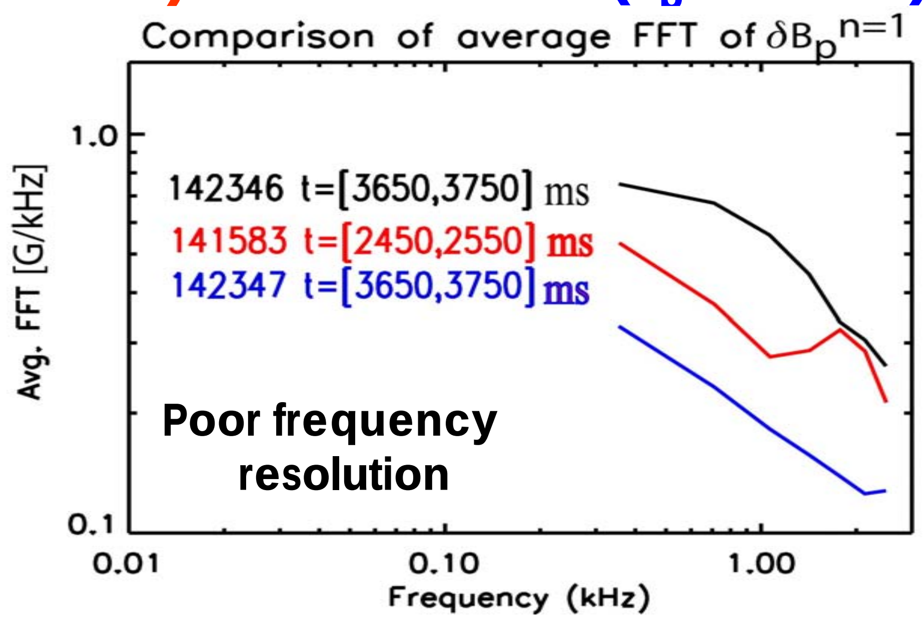
No feedback

DEFC (τ_p=50 ms)

Feedback (τ_p=0.5 ms)

Based on RWM sensor (i.e. integrated signal of B-dot probe)

- Unlike conventional DEFC ($\omega < \tau_W^{-1}$), broadband feedback has reduced resonant δB



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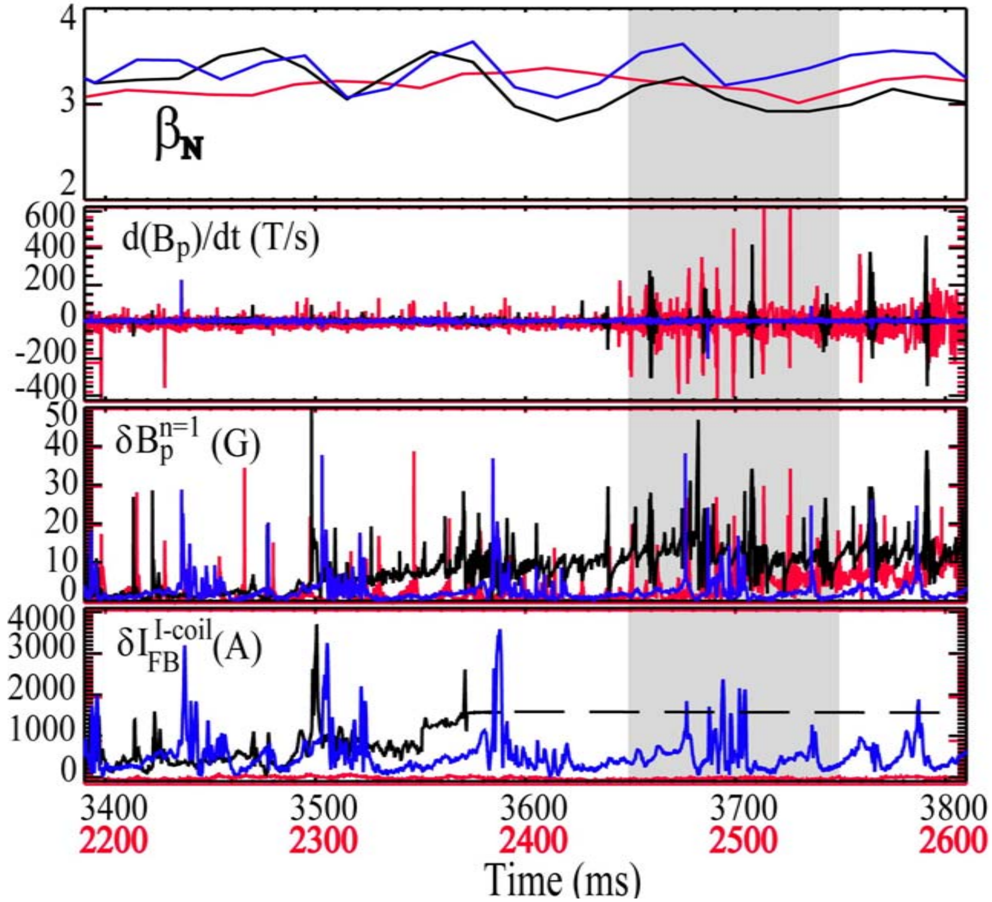
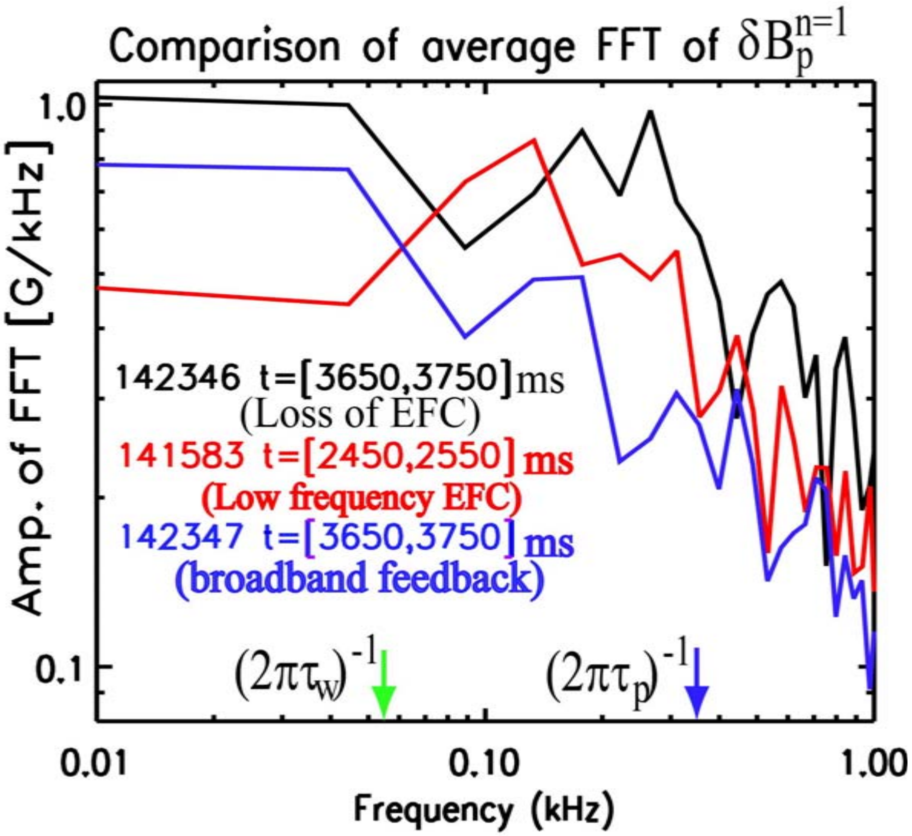
Broadband magnetic feedback in high-β plasmas enhances the decay rates of bursty MHD events





- **Broadband magnetic feedback would be an effective tool in enhancing the decay rates of the resonant δB driven by bursty MHD events, as well as in providing the necessary EFC and DF on RWM.** [See also Reimerdes *et al*, PPCF (2007)]

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Magnetic feedback-controlled EFC and active RWM stabilization is essential in high-β plasmas

- The **EFC strategy should be developed in consideration of the RWM stability** status (*stable, marginal and unstable*)

- **Broadband magnetic feedback *(beyond τ_w^{-1})*** appears contributing to improved τ_E, density and β_N
  - *Removes resonant δB (from various bursty MHD events or uncorrected residual error field) quickly, before RFA or coupling with RWM is involved*

→ *helps to create and sustain high-performance plasmas*

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