Avoidance of Neoclassical Tearing Mode Locking and Disruption by Feedback-driven Mode Rotation Control

M. Okabayashi[1], E.J. Strait[2], A.M. Garofalo[2], J.M. Hanson[4], Y. In[3], R.J. La Haye[2], D. Shiraki[4], and F. Volpe[4]

[1]Princeton Plasma Physics Laboratory, Princeton, New Jersey 08543-0451, USA.
[2]General Atomics, PO Box 85608, San Diego, California 9186-5608, USA.
[3]FAR-TECH, Inc., 10350 Science Center Dr., San Diego, California 92121-1136, USA
[4]Columbia University, New York, New York 10027, USA

Theory and Simulation of Disruptions
M. B. Gottlieb Auditorium
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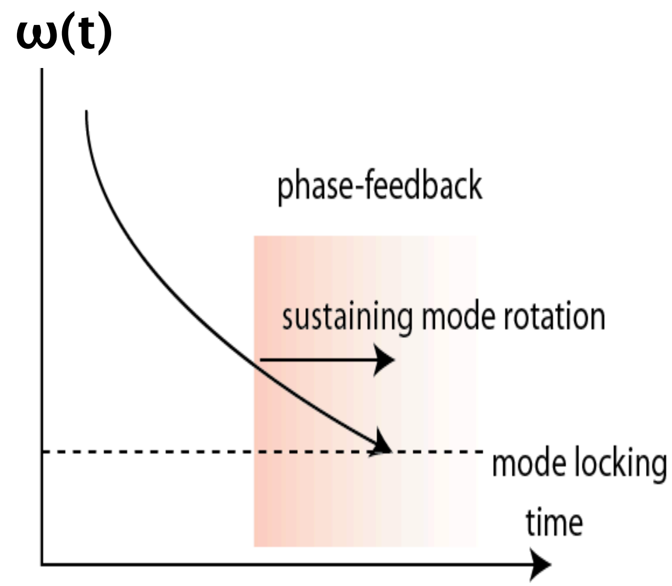
Motivation

Tokamak reactor requires:

- Assurance of NTM/TM locking avoidance is prerequisite for orderly shutdown such as the termination of hundreds Mega Joules of magnetic stored energy.



An Approach:

- Injection of the electro-magnetic (EM) torque using 3D coils by forcing finite toroidal phase shift between the mode and applied feedback field

Outline

(1) Introduction

- Two scenarios were investigated in DIII-D: preliminary results (q95 ~ 4)

(2) Sustaining high β_N NTM - Avoidance of locking and disruption

(3) Orderly shut down process by reducing NBI power
-working as Dynamic Error Field Correction as well as NTM locking avoidance

(4) A Simple Model

- Comments

(5) RFX-mod/tokamak explores independently TM-disruption avoidance with similar feedback approach ➔ Feedback scheme seems robust

(6) ELM-like MHD bursting clouds are synchronized with NTM (possible impact on disruption process)

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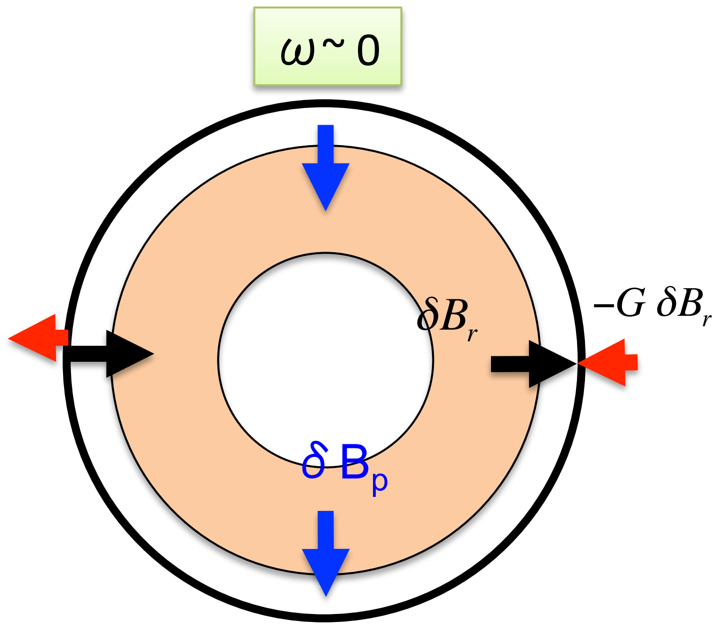
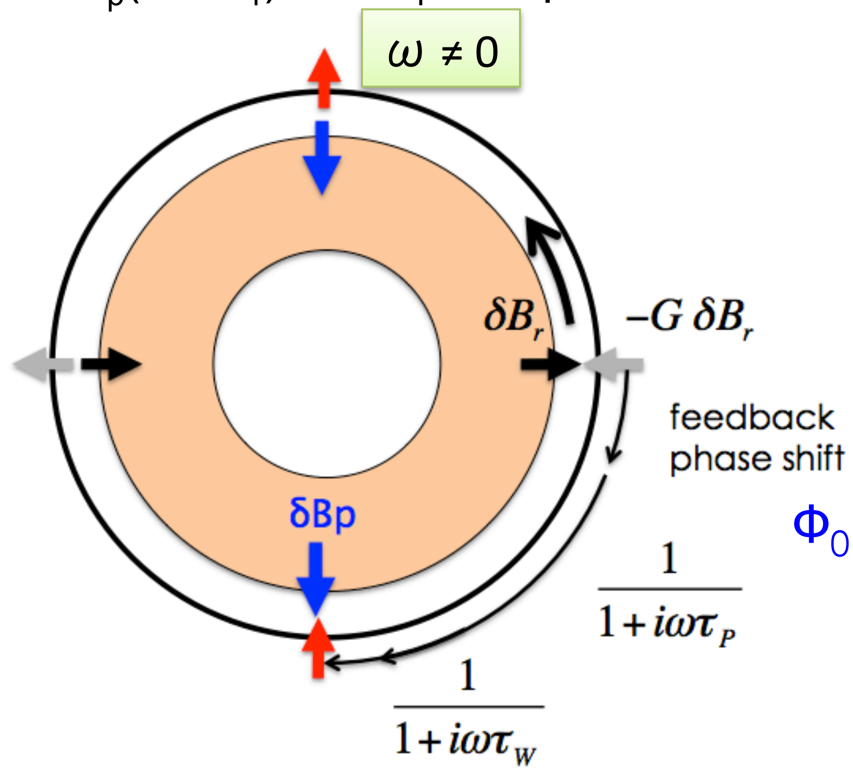
Feedback-driven torque control maximizes the electro-magnetic $\delta B_{p.mode}$ X $B_{r.ext}$ torque

RWM control

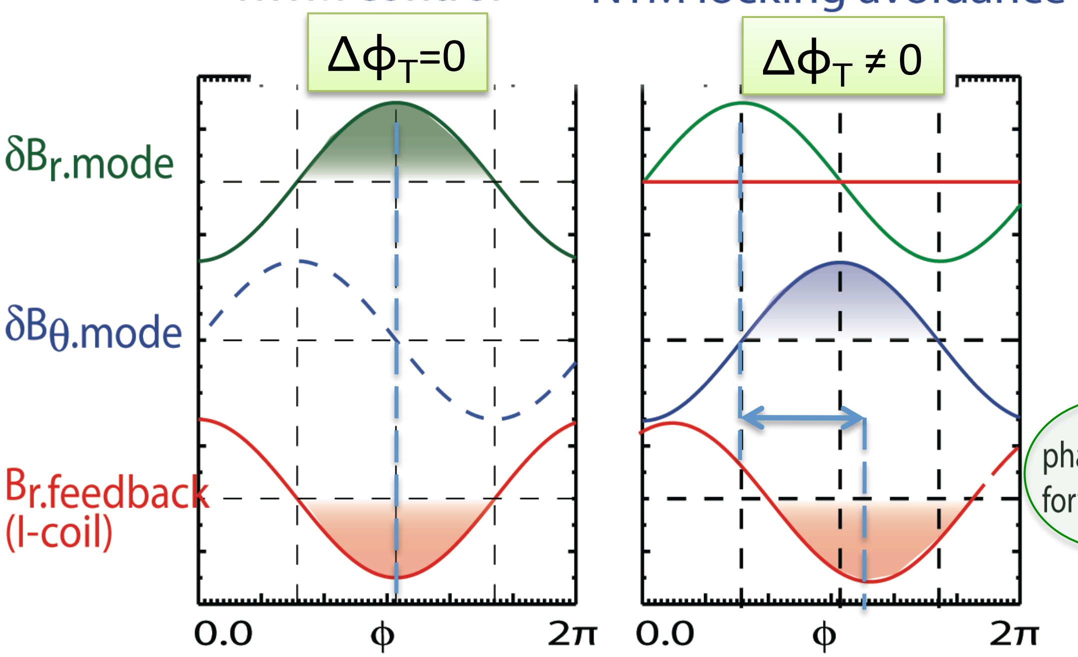


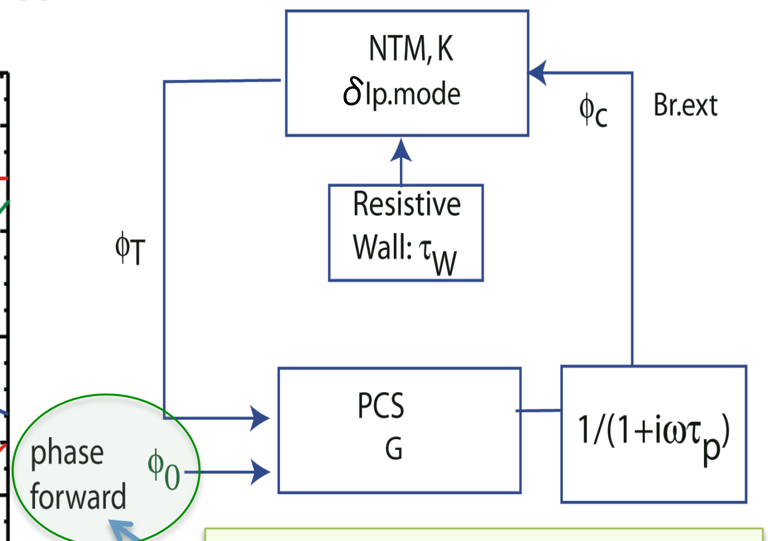
$T \propto \delta B_p(-G\delta B_r)\sin\Delta\Phi_T$: torque control



Feedback radial field phase can be synchronized with the poloidal field component of NTM by adjusting feedback parameters, such as gain G and filtering time τ_p and presetting of initial phase shift, ϕ_0

RWM control feedback functions for torque control and locking avoidance

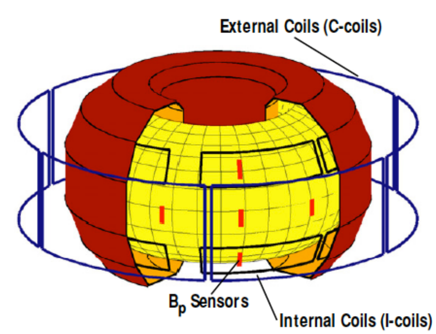




Forcing to guarantee finite torque

- Steady state Torque

$$\frac{\omega}{\tau_{\text{loss}}} = (Q_{NBI}/I) - (T/I) B_{\text{r.ext}} \delta B_{p.mode} \sin \Delta\phi_T$$



$$\Delta\phi_T = \angle(B_{\text{r.ext}}, \delta B_{r.\text{modes}}) = \angle(B_{\text{r.ext}}, \delta I_{\text{p.modes}}) - \pi/2$$

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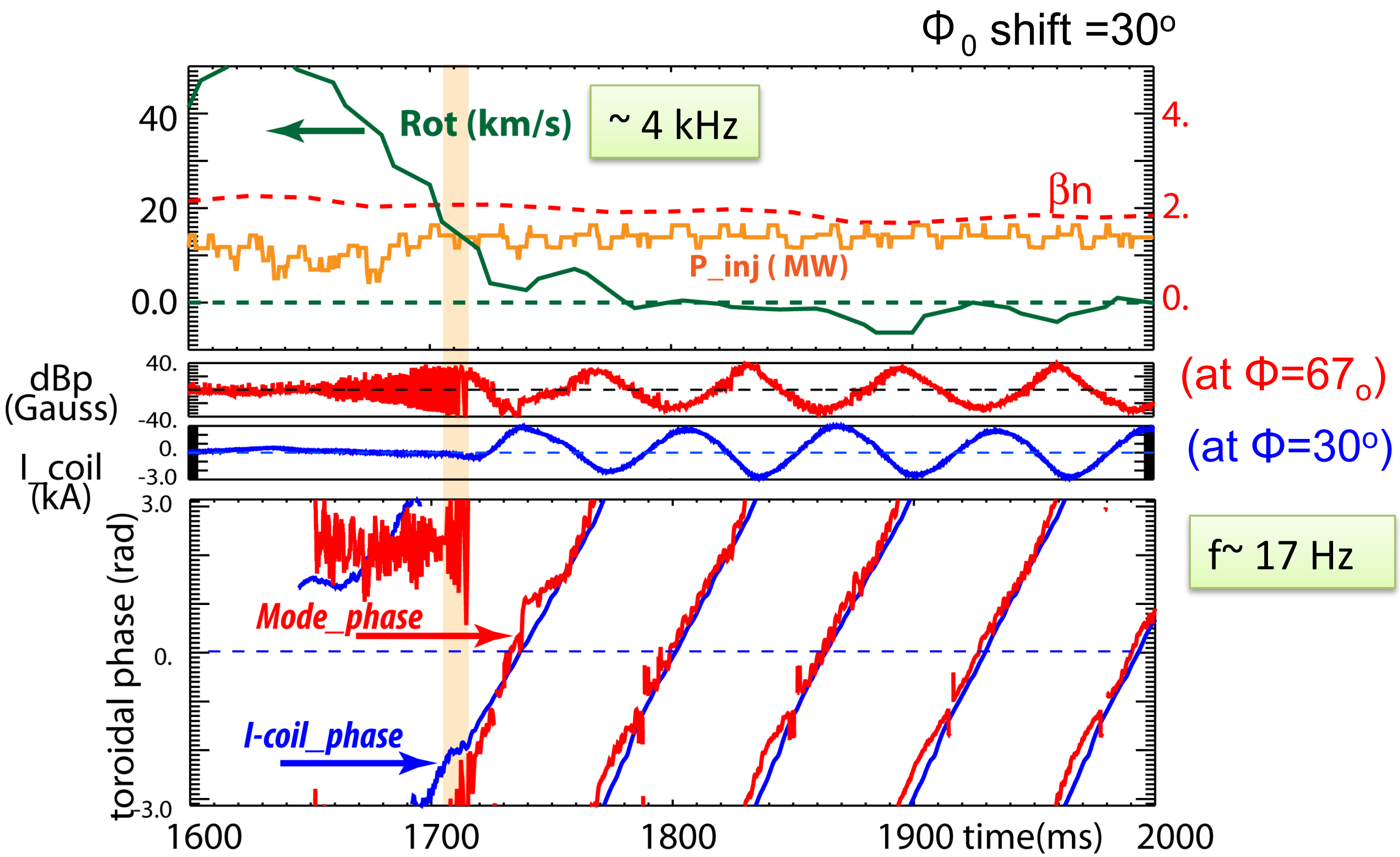
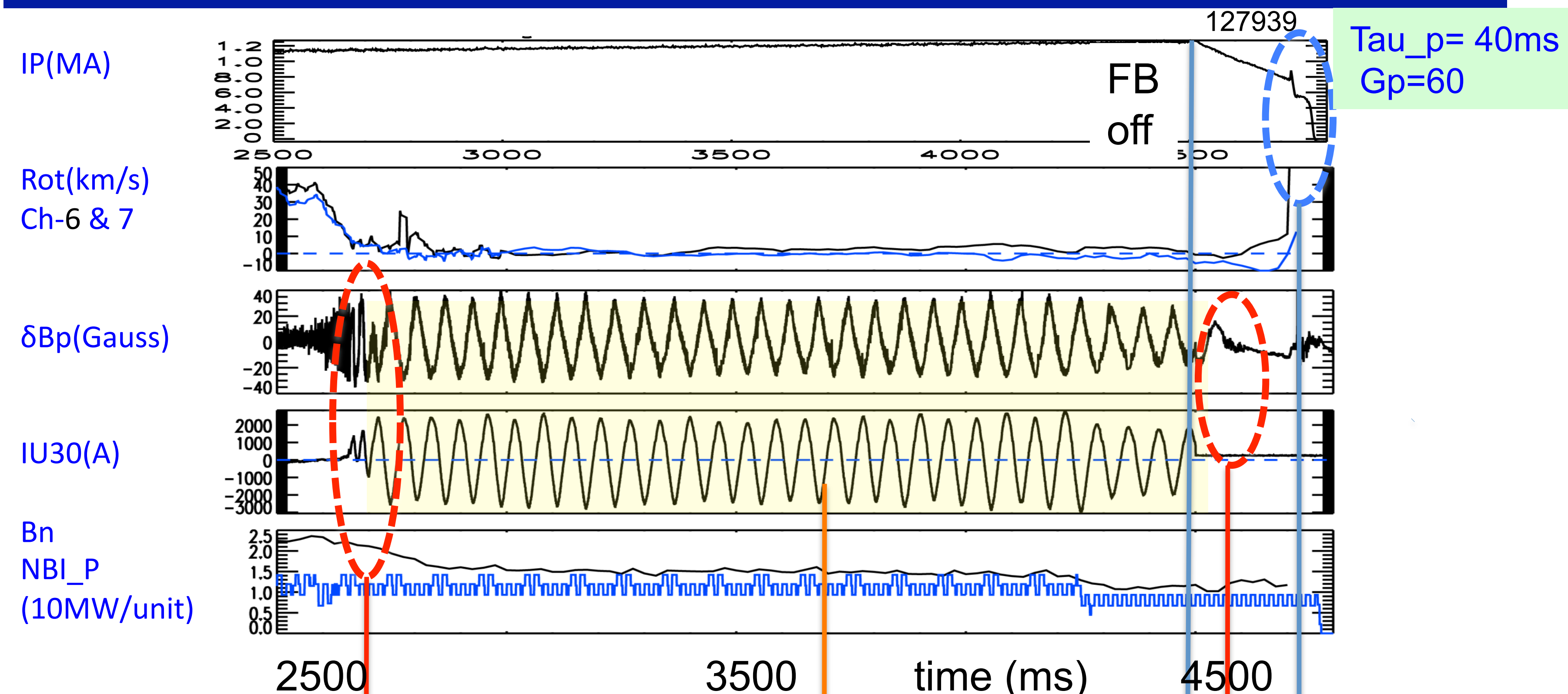
The phases of feedback current and mode δBp became "nearly in phase", producing max. torque, when the mode frequency was reduced to the order of ≈ $1/\tau_p$.



• τ_p=40 ms, gain=60: typical DEFC feedback parameters (τ_w=2.5 ms)

NTM mode-locking can be avoided



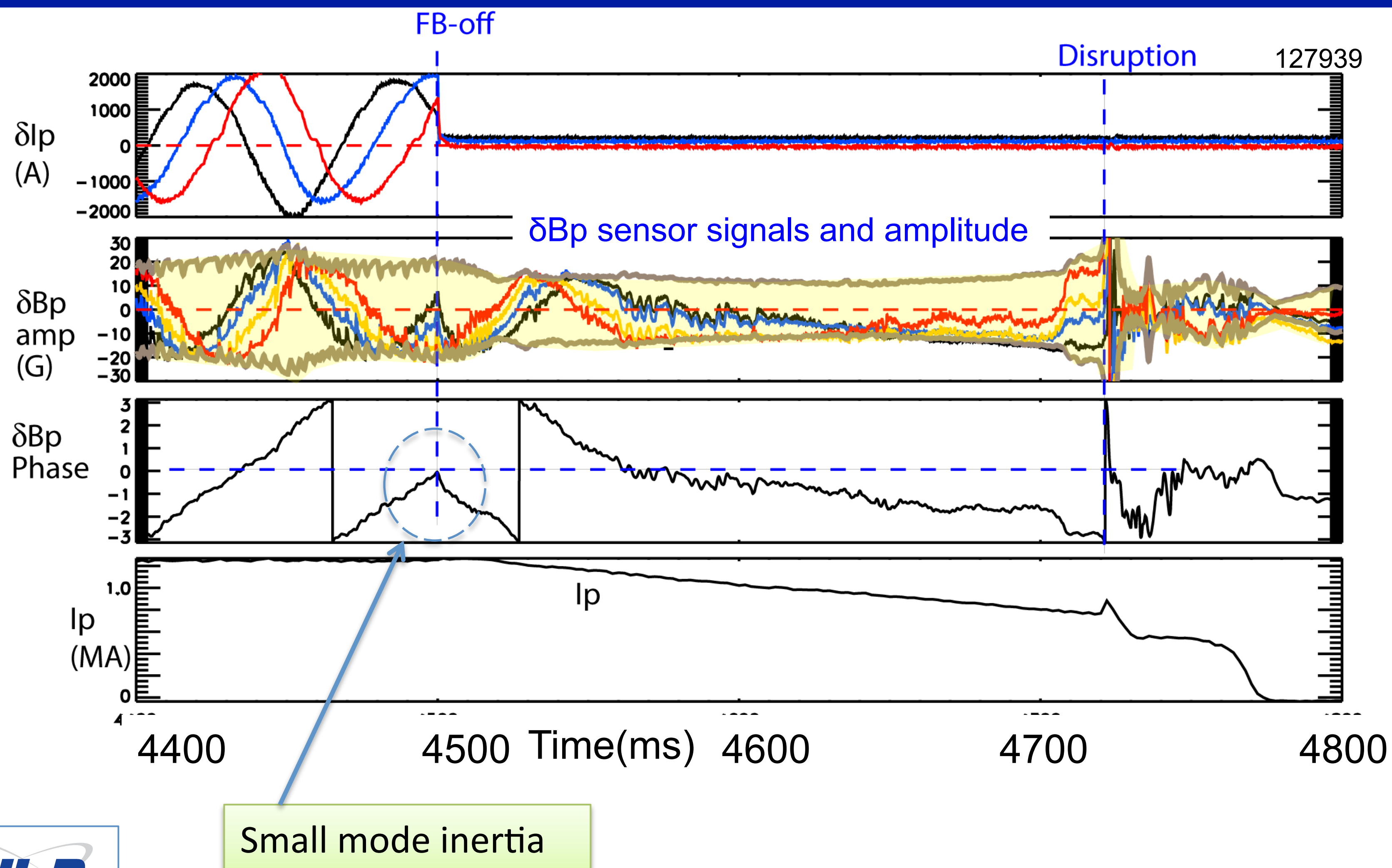
- mode (plasma) rotation became low activating feedback (FB filter time constant =40ms)

- FB self-adjusted ~15 Hz rotation.

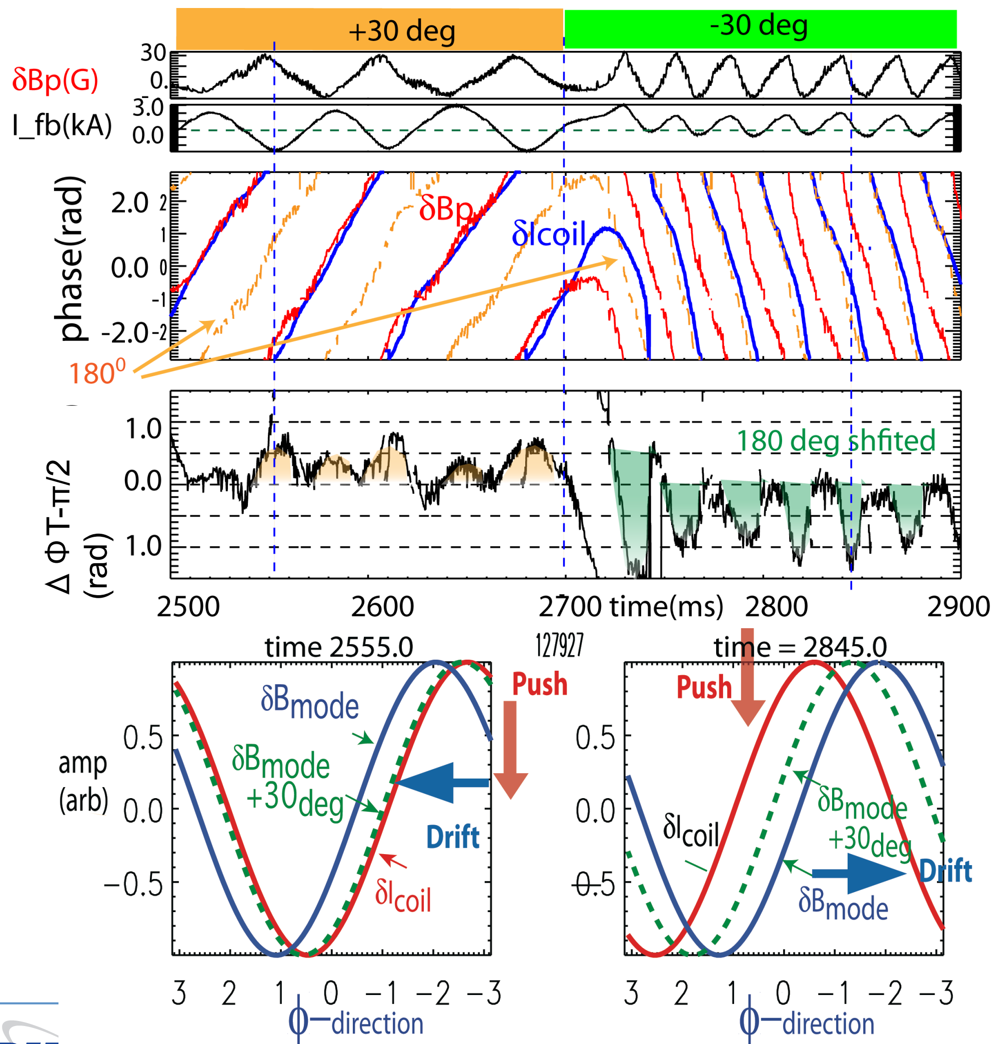
- Locking with ~ 10-15 G after FB turned off,

- Disruption

FB turning-off leads to a locked NTM and disruption



The toroidal phase offset determines the direction of mode rotation (phase shift from +30 deg → -30 deg)



- Rotation direction changes with the 180° shift of $\delta B_{p.mode}$

- Frequency difference is due to Doppler shift by other torque

Due to forward δΦ shift

Troque by NBI

$f_{obs(\pm)} = \pm \delta f_{shift} + f_{doppler}$

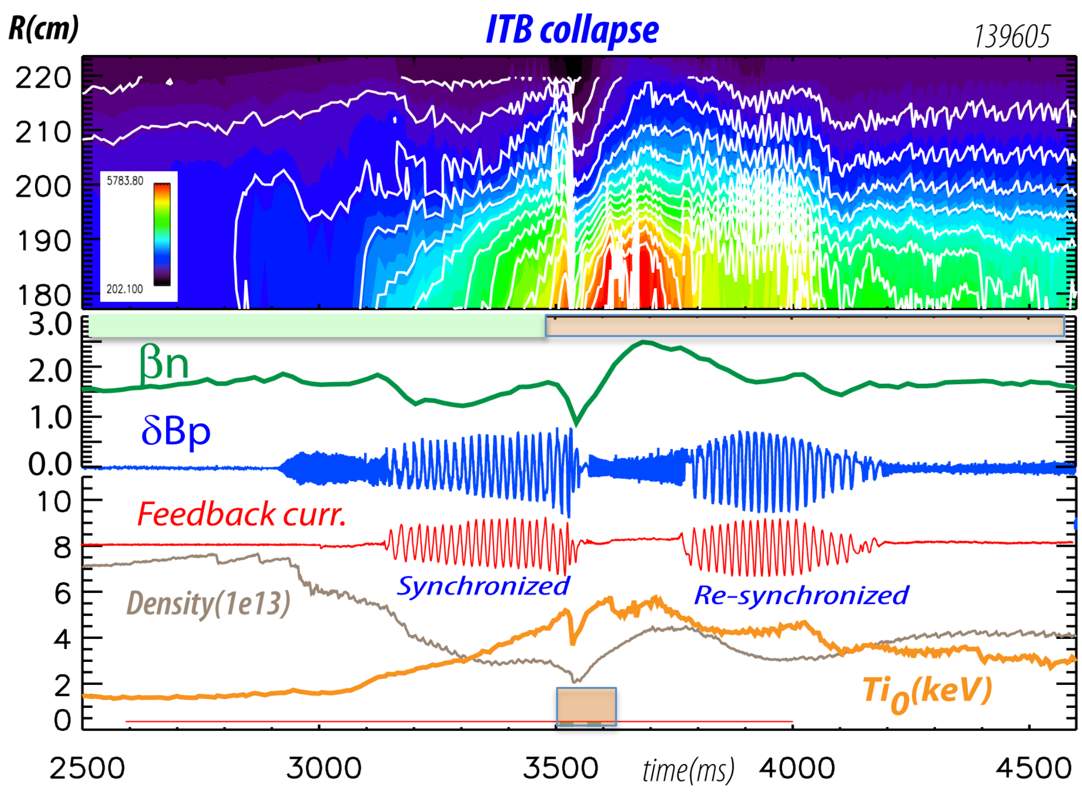
$f_{obs(-)}$= -14 Hz

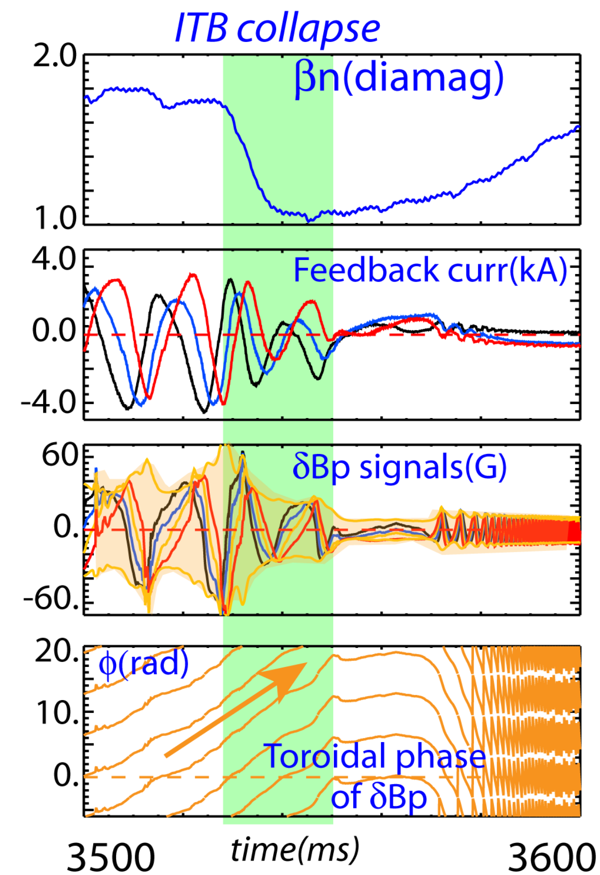
$f_{obs(+)}$= +33 Hz

$f_{doppler}$ = + 10 Hz

δf_{shift} = + 24 Hz

EM torque input is sufficient enough to avoid ITB collapse disruption even when the density is pumped out by NTM





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TauP=10 ms and Gain 60

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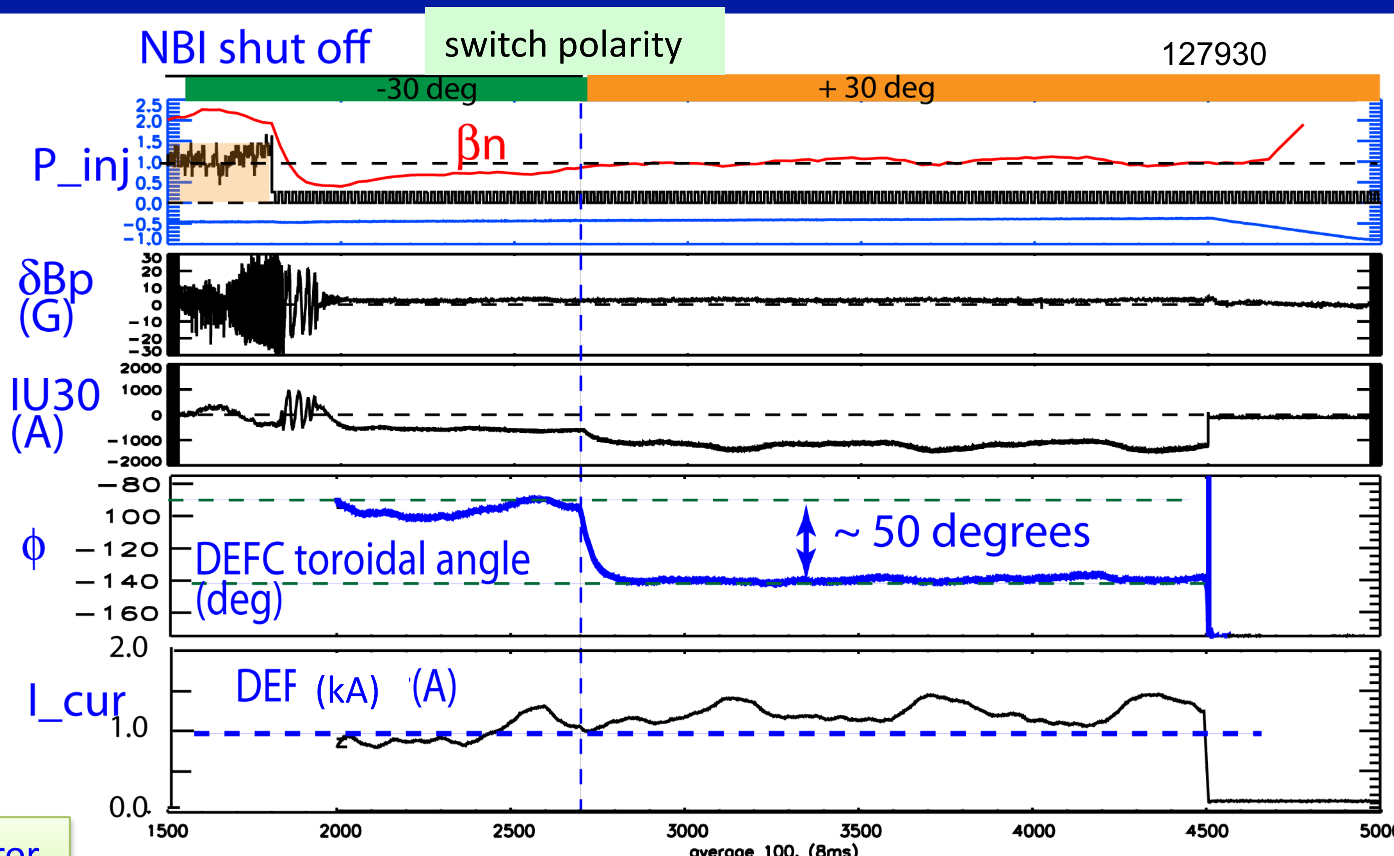
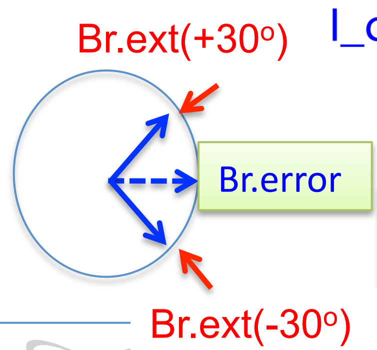
When the NTM is suppressed, the system functions as DEFC.
-current max. location shifts with sensor shift from +30° to -30° deg





Appeared as the consequence of EFC change due to lower betan (NBI turned off)

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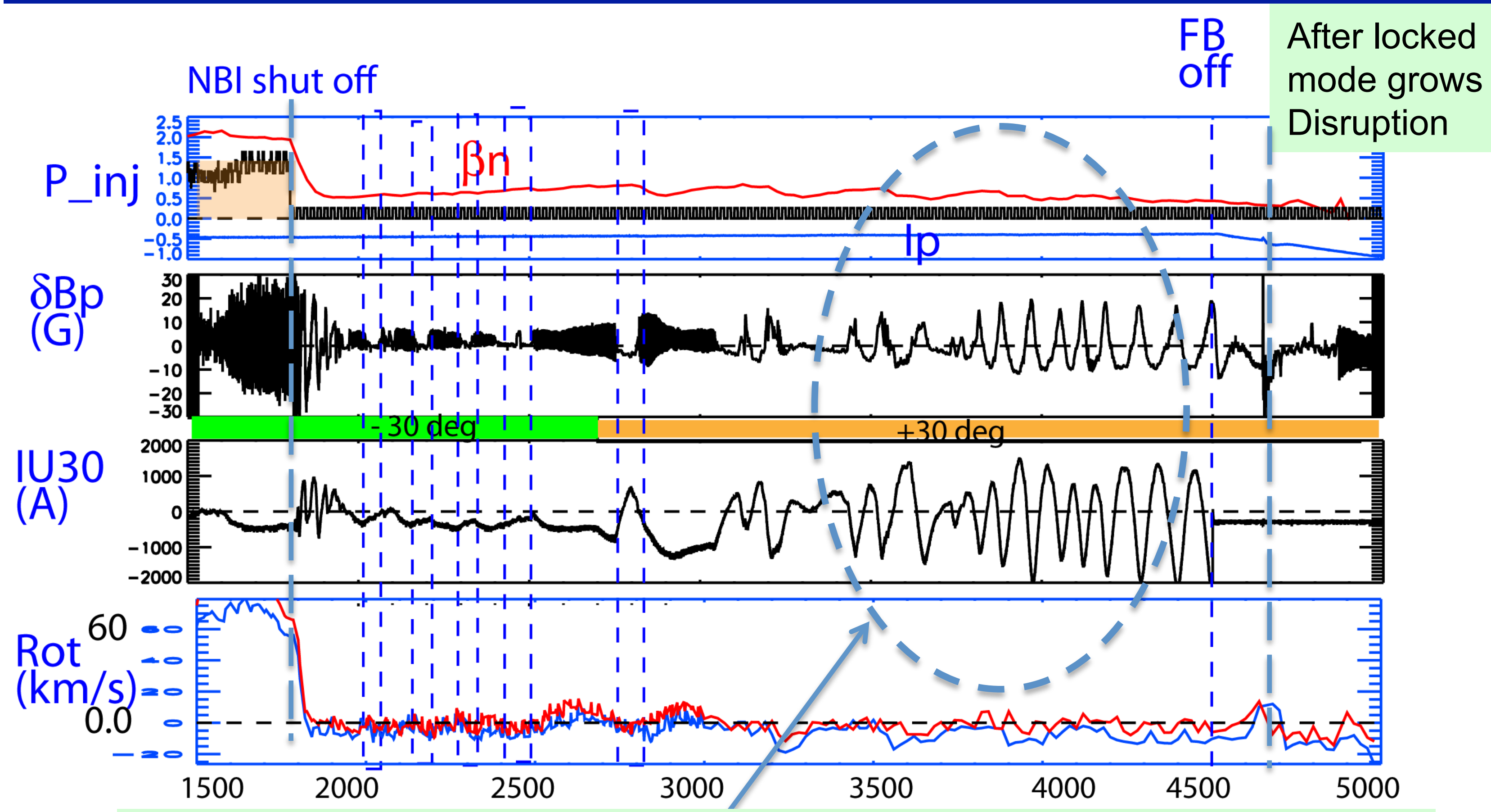
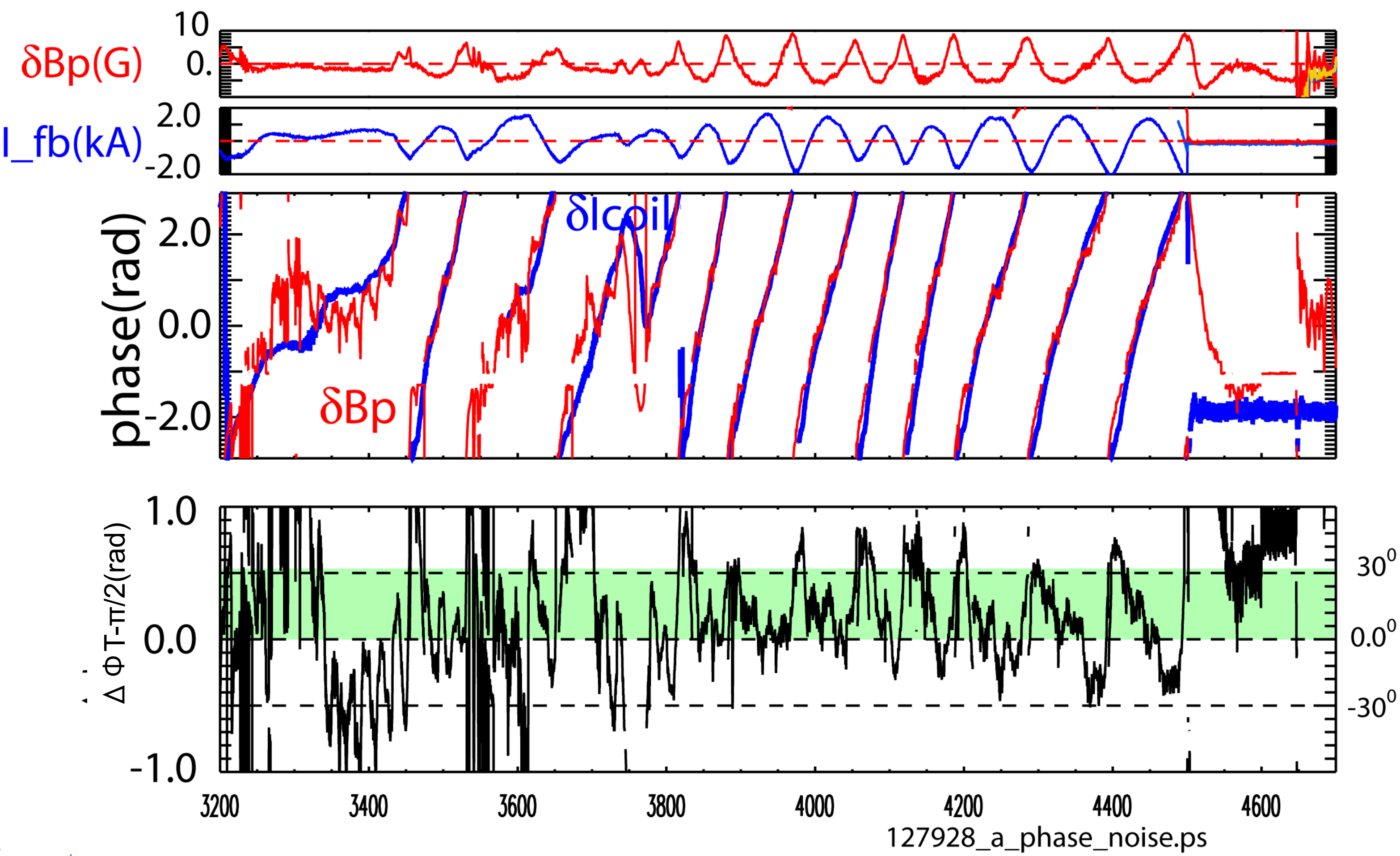
Feedback controls the NTM/TM in an orderly shut down process



• EM torque controls the mode by self-adjusting frequency 5- 10 Hz

Maximum torque "near 90°" was provided by feedback even during lock/unlocked period



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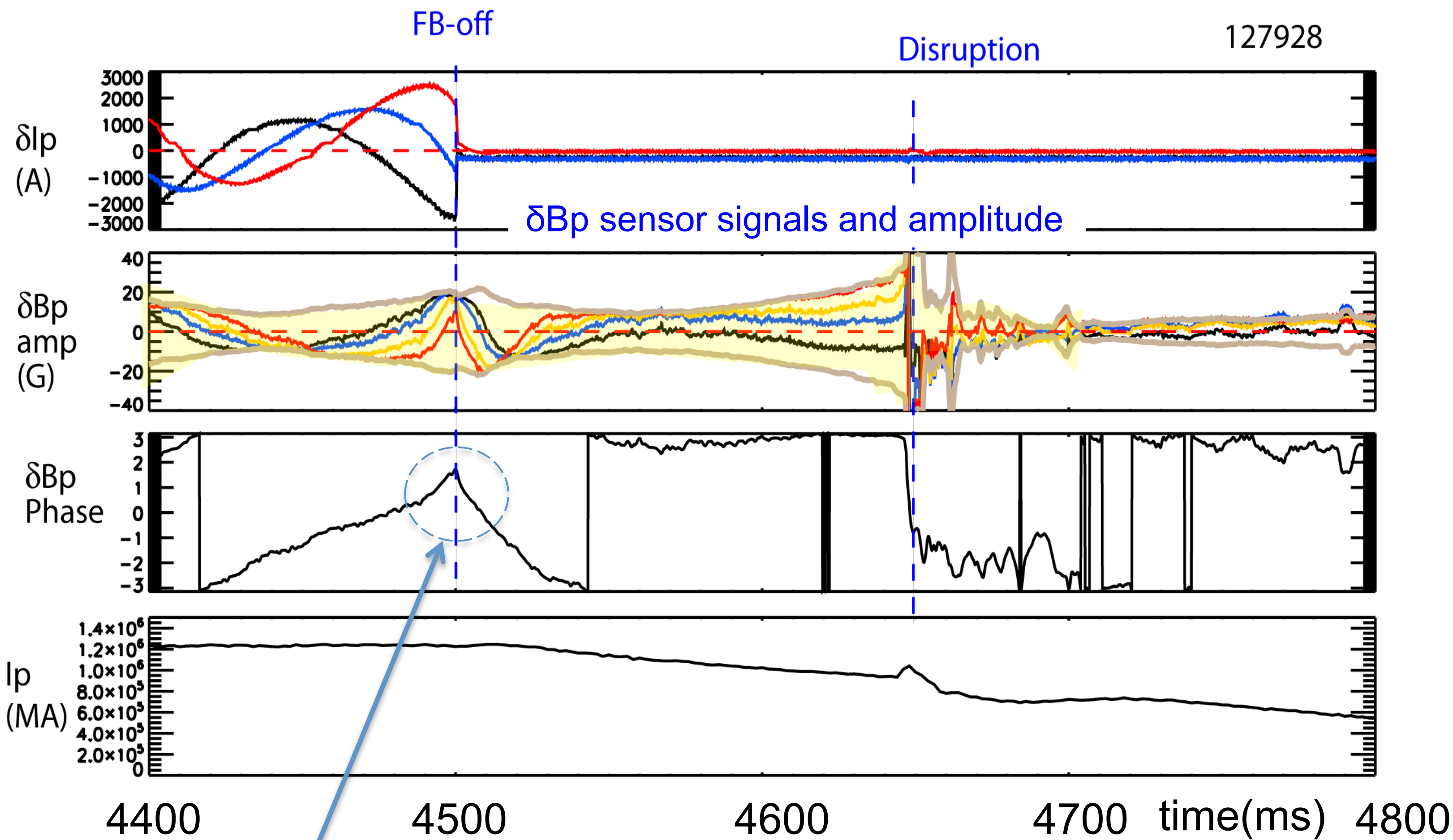

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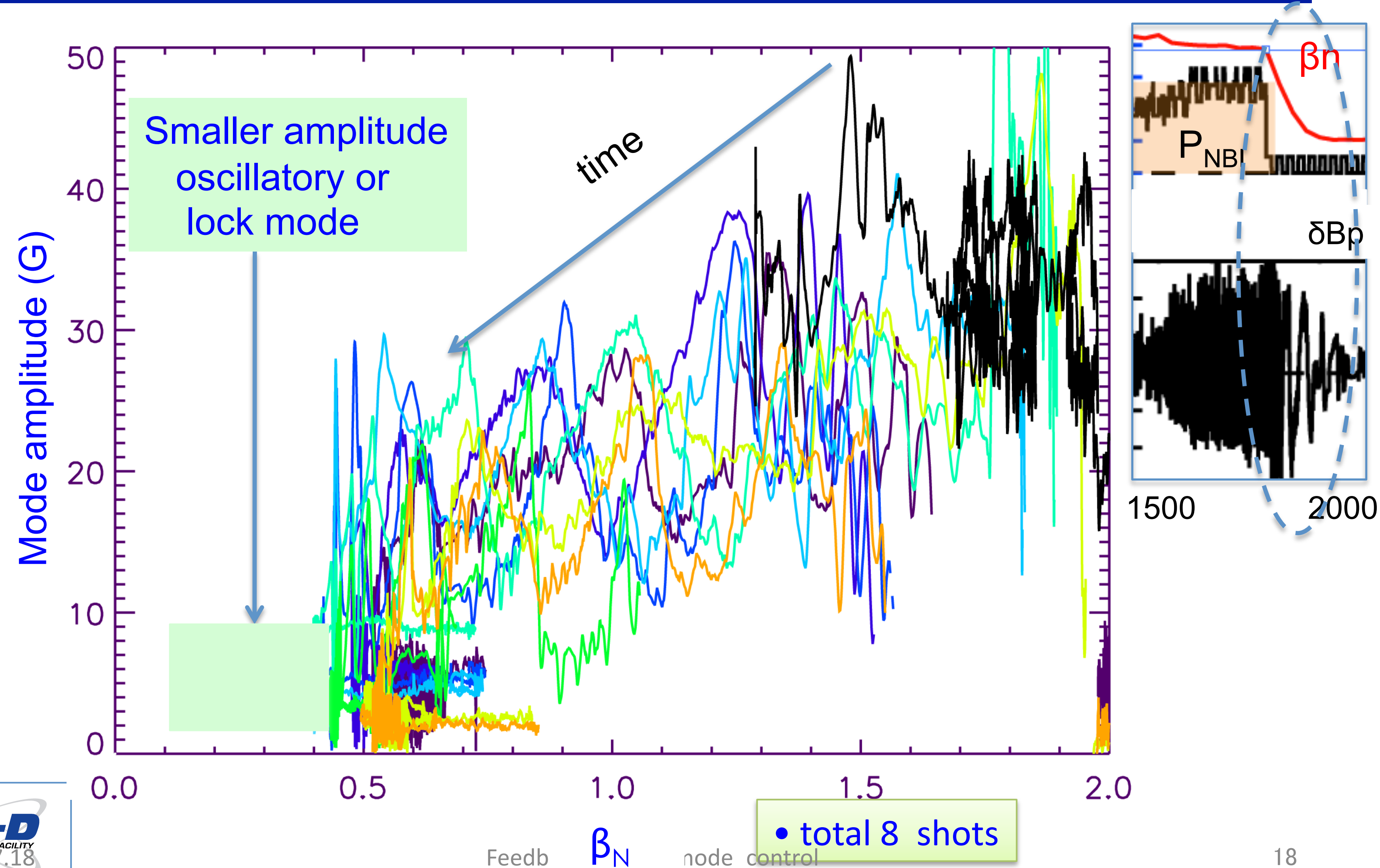
- Rapid change of direction Implies small inertia term

Feedback assisted reproducible smooth landing to lower β_N stage when NBI is terminated.



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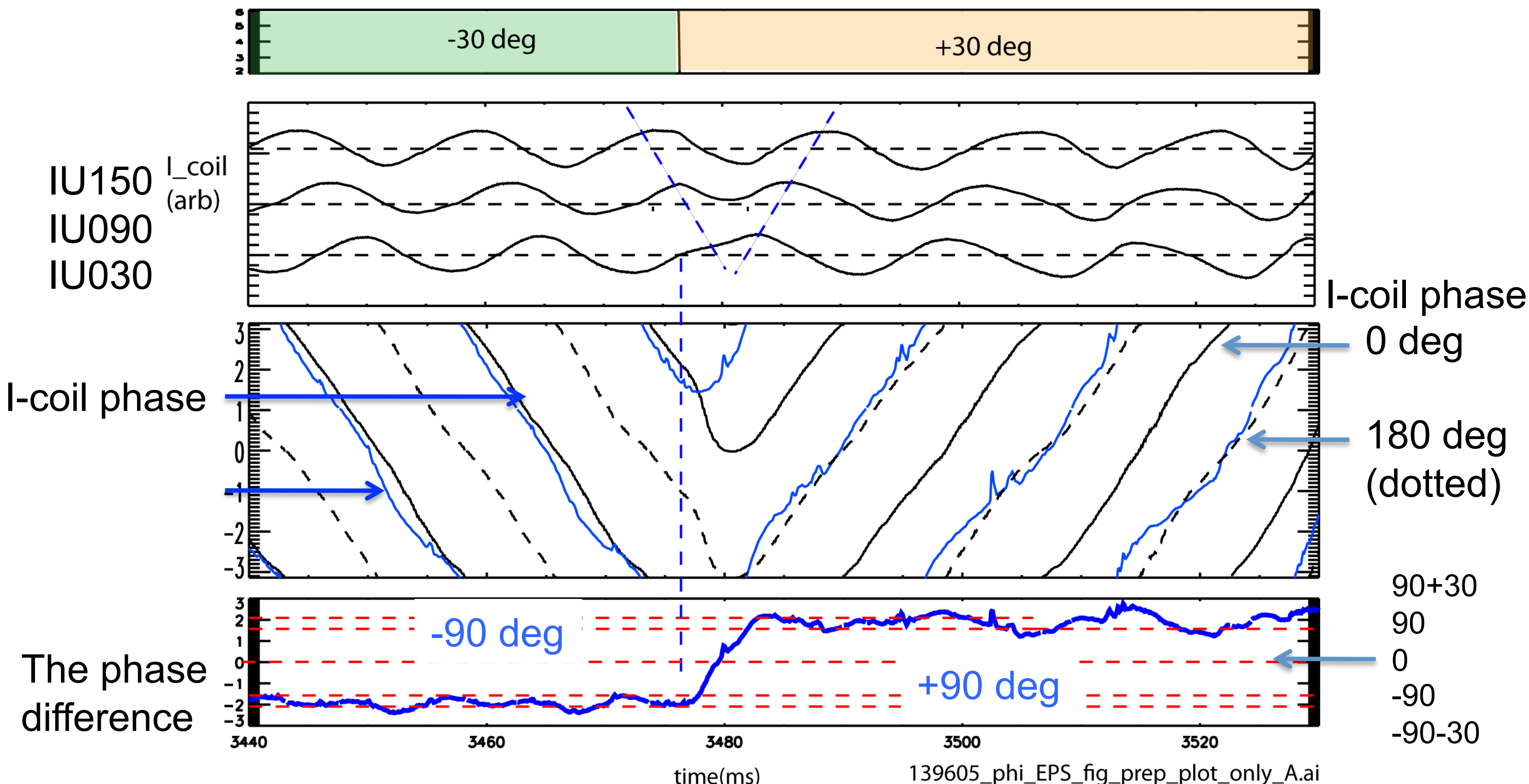
A unique feature of this approach: Presetting the phase offset leads to max. torque in the given direction



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- The polarity shift causes only ~10ms delay in the plasma response -> small mode inertia

A simple model

- Torque balance equation:

$$I\frac{d}{dt}\omega = Q_{NBI} - I\frac{\omega}{\tau_{\text{loss}}} - \int \overrightarrow{\delta I}_{\text{mod}\,e} X \vec{B}_{ext}\, dS$$

Moment of mode inertia

Momentum input

Total angular momentum confinement time constant

EM torque

- Torque balance condition in steady state

$$\frac{\omega}{\tau_{\text{loss}}} = (Q_{NBI}/I) - (T/I) B_{\text{r.ext}} \delta B_{p.\text{mode}} \sin\Delta\phi_T$$

Here, we assume the weak loss case, (Q_{NBI}-ω/τ_{loss}) ~ zero limit

- EM torque input to NTM is dissipated by the resistive wall

A cylindrical model

Assuming the geometrical factors: the wall, sensors and coil are located close to the plasma surface

Resistive wall dissipation

Feedback field phase shift

$$\text{Torque Input: } A(\omega) = \text{Im}aginary\left\{\left(\frac{-i\omega\tau_w}{(i\omega\tau_w+1)} + \frac{G\exp(i\phi_0)}{(1+i\omega\tau_w)(1+i\omega\tau_p)}\right)\left|\delta B_p\right|^2\right\}$$

→ $$A(\omega) \propto \frac{f}{g}$$

$$f = -(\omega\tau_p)^3(\tau_w/\tau_p) - (\omega\tau_p)(\tau_w/\tau_p) + G\sin(\phi_0)(1-(\omega\tau_p)^2(\tau_w/\tau_p)) - G\cos(\phi_0)(\omega\tau_p)(1+(\tau_w/\tau_p))$$

$$g = (1+(\omega\tau_p)^2)(1+(\omega\tau_p)^2(\tau_w/\tau_p)^2)$$

The toroidal shift ϕ_0 preset determines the direction of mode rotation

$$A(\omega) \propto \frac{f}{g}$$

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$$g = (1+(\omega\tau_p)^2)(1+(\omega\tau_p)^2(\tau_w/\tau_p)^2)$$

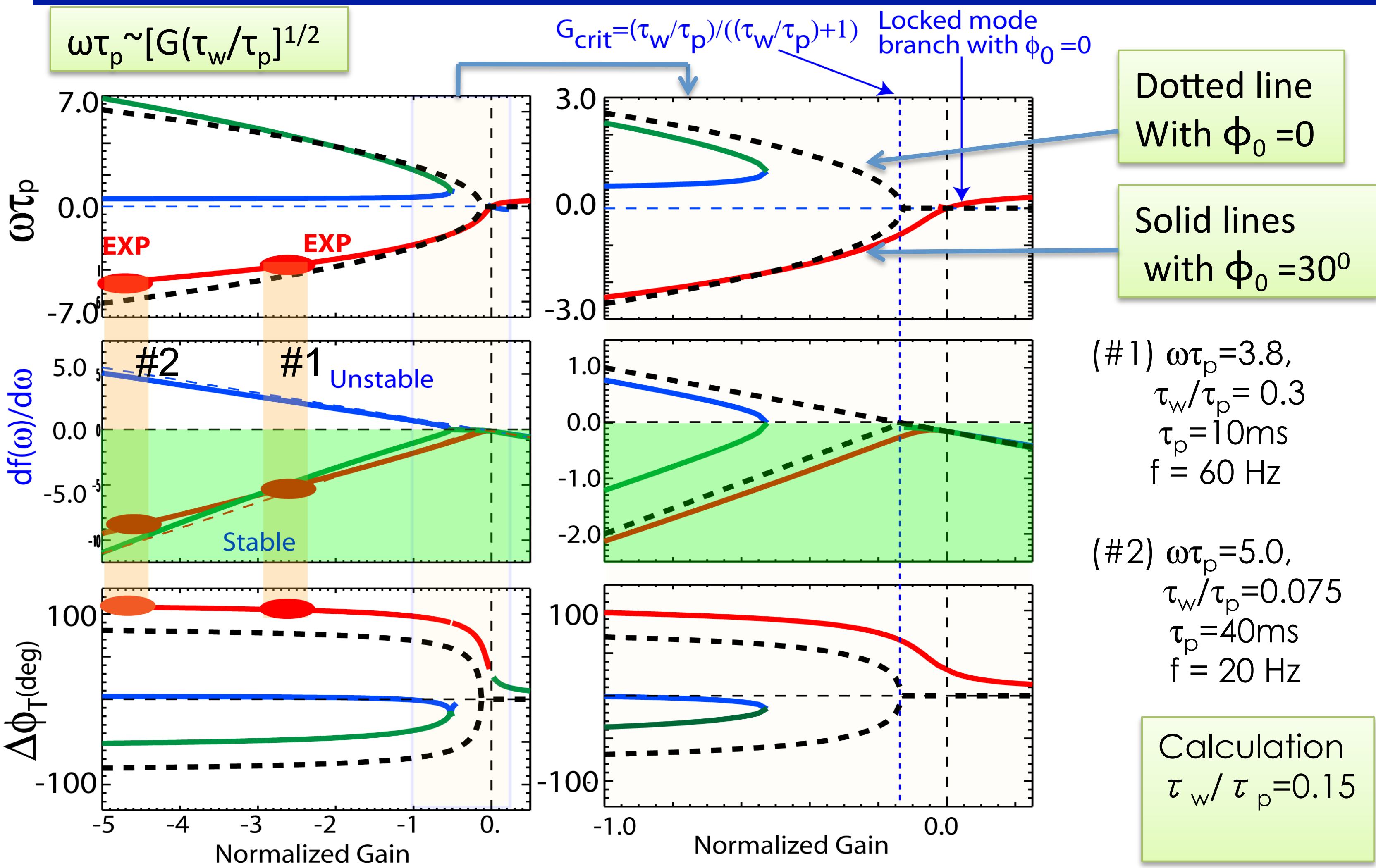
with **ω → $-\omega$ together with ϕ_0 → $-\phi_0$**

- Torque balance: $f(\omega) = 0$
- Stability of the torque balance: $\partial A/\partial\omega < 0$ → $\partial f/\partial\omega < 0$

Both remain intact

→ toroidal shift ϕ_0 preset determines the mode direction.

The model predictions are consistent with key experimental observations



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➔ Feedback approach seems robust for EM torque injection

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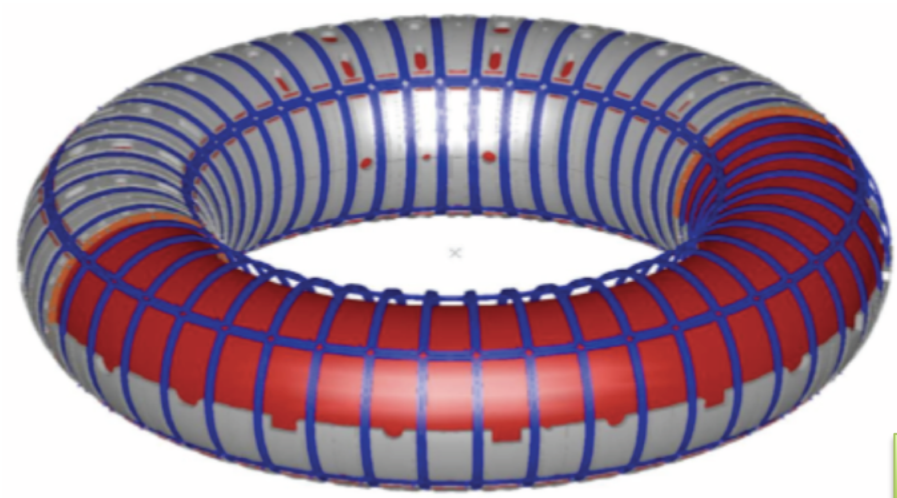
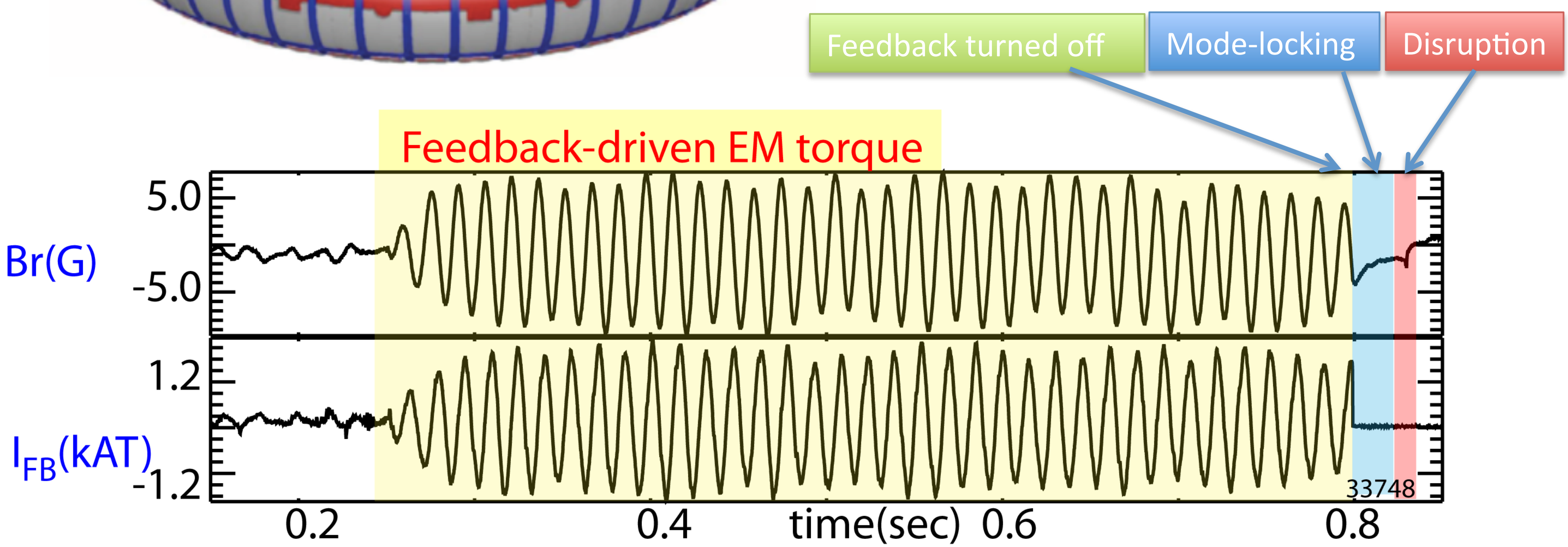
RFX-Mod-tokamak also successfully avoided TM-locking and disruption by feedback-driven EM torque control
- The feedback approach seems robust--



RFX-mod/Tokamak
- circular plasma
- Feedback coils outside shell:192
- shell time constant ~ 50 ms
- q95 ~ 2.2
- ne ~ 0.5xGW density limit



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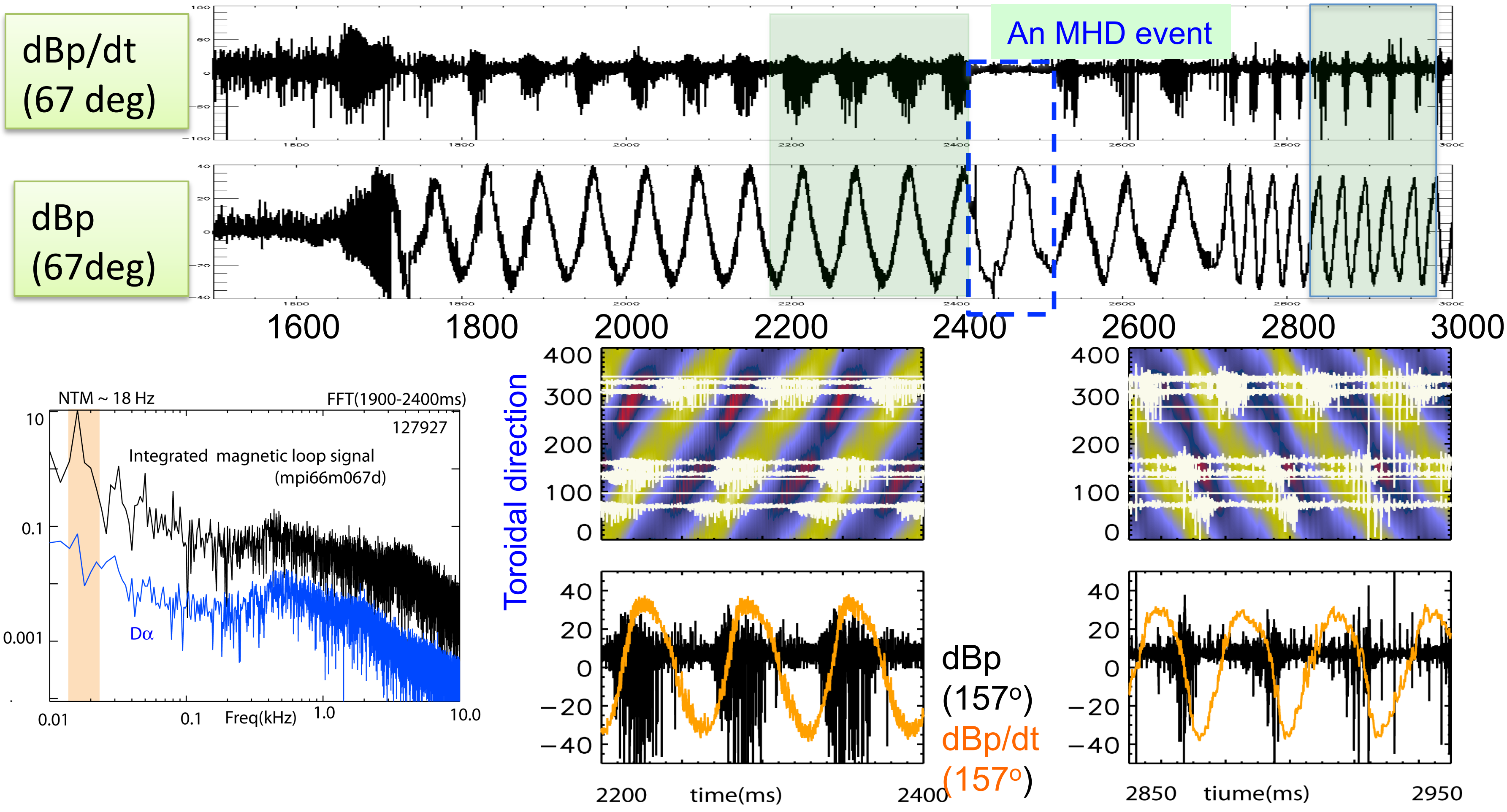
Fast MHD bursts are located on one side of propagating slope of 18 Hz NTM



The bursting MHD behavior is similar to the ideal mode excited by the increased pressure gradient as observed in TFTR

PRL 1995,Vol 75, p1765 by W. Park, E. Fredrickson et al.,: ballooning mode excited by internal kink

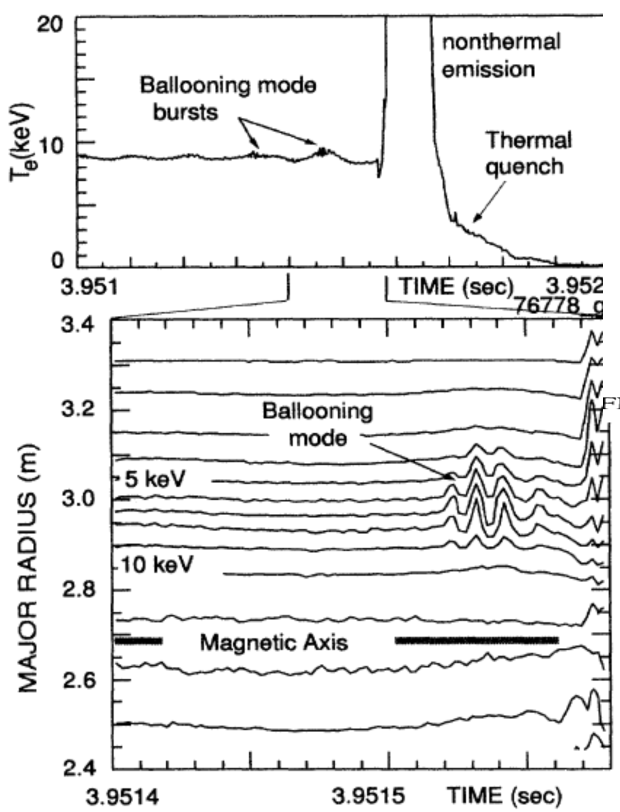
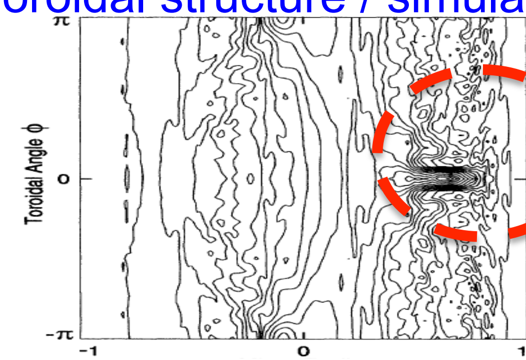


FIG. 7. The experimental ECE signals.

Toroidal structure / simulation



Extremely localized

Poloidal structure /simulation

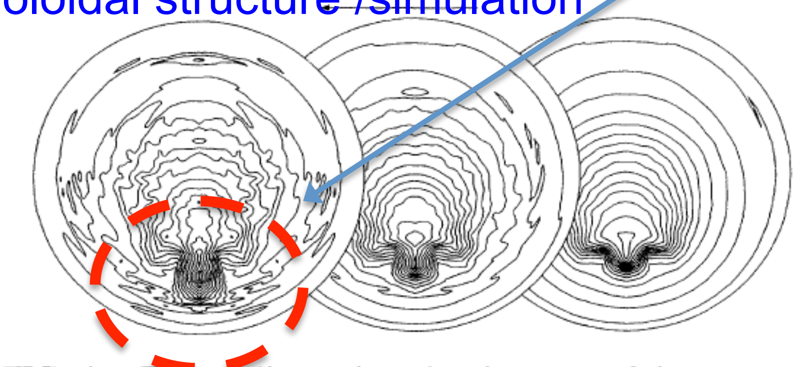


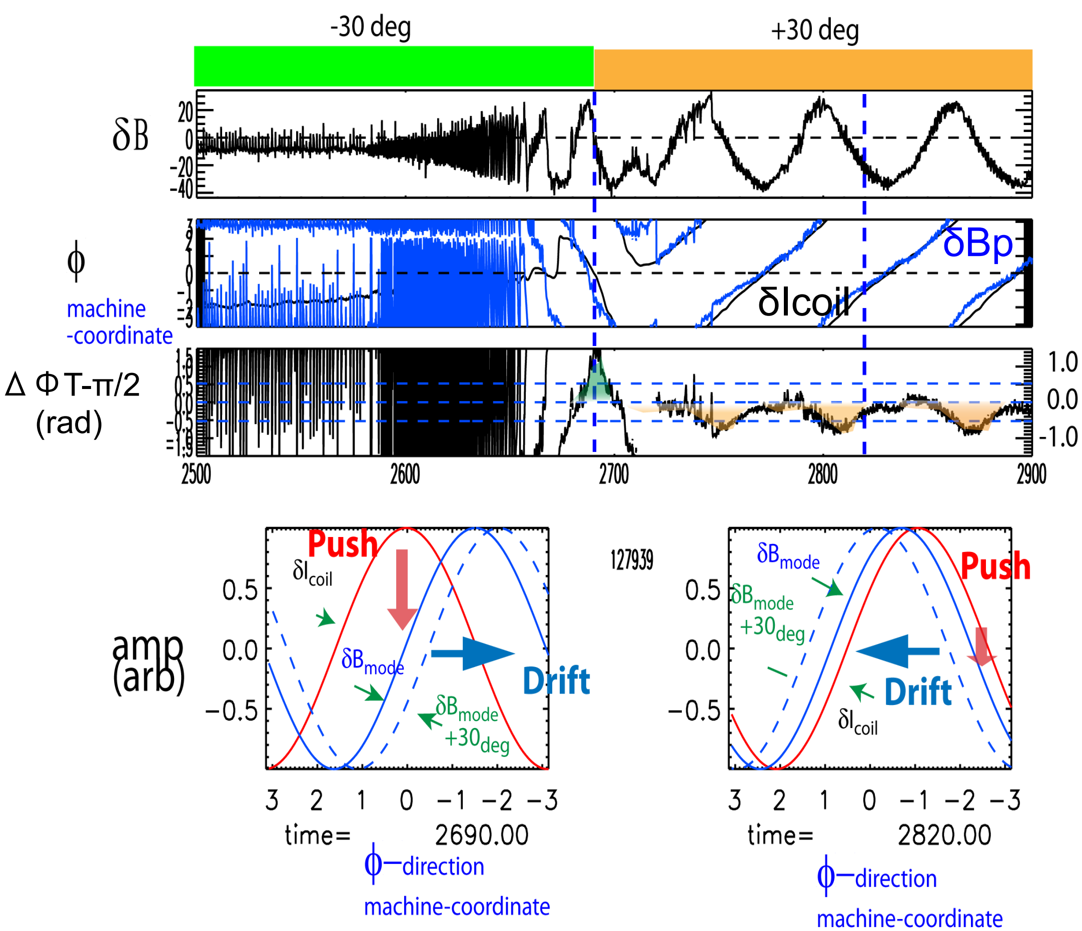
FIG. 4. The nonlinear time development of the pressure.

Summary

- NTM-locking disruption avoidance by feedback-driven mode control has been developed in DIII-D.
  - proof of principle: demonstration with two β_N levels (so far with q_95 ≥ 4)
  - key elements: forced toroidal shift, built-in DEFC
- Independent achievement by RFX-mod / Tokamak implies the feedback-based EM control is robust.
- This feedback-based EM control scheme is useful, for example,
  - to provide orderly shutdown of magnetic energy
  - to avoid the frequency range of mechanical resonances
- Theoretical analysis of ELM-like MHD synchronized with NTM is important to understand NTM-locking and its disruptions

supplement

The reversed order of preset Φ^0 shows similar intrinsic rotation (preset toroidal shift from -30 deg → +30 deg)



- A possibility of frequency change is due to Doppler shift

$f_{obs(\pm)} = \pm\, \delta f_{shift} + f_{doppler}$

$f_{obs(-)}$= -16Hz

$f_{obs(+)}$= +30 Hz

$f_{doppler}$=+ 7 Hz

f_{shift} = 23 Hz

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Comparison of model and experiments

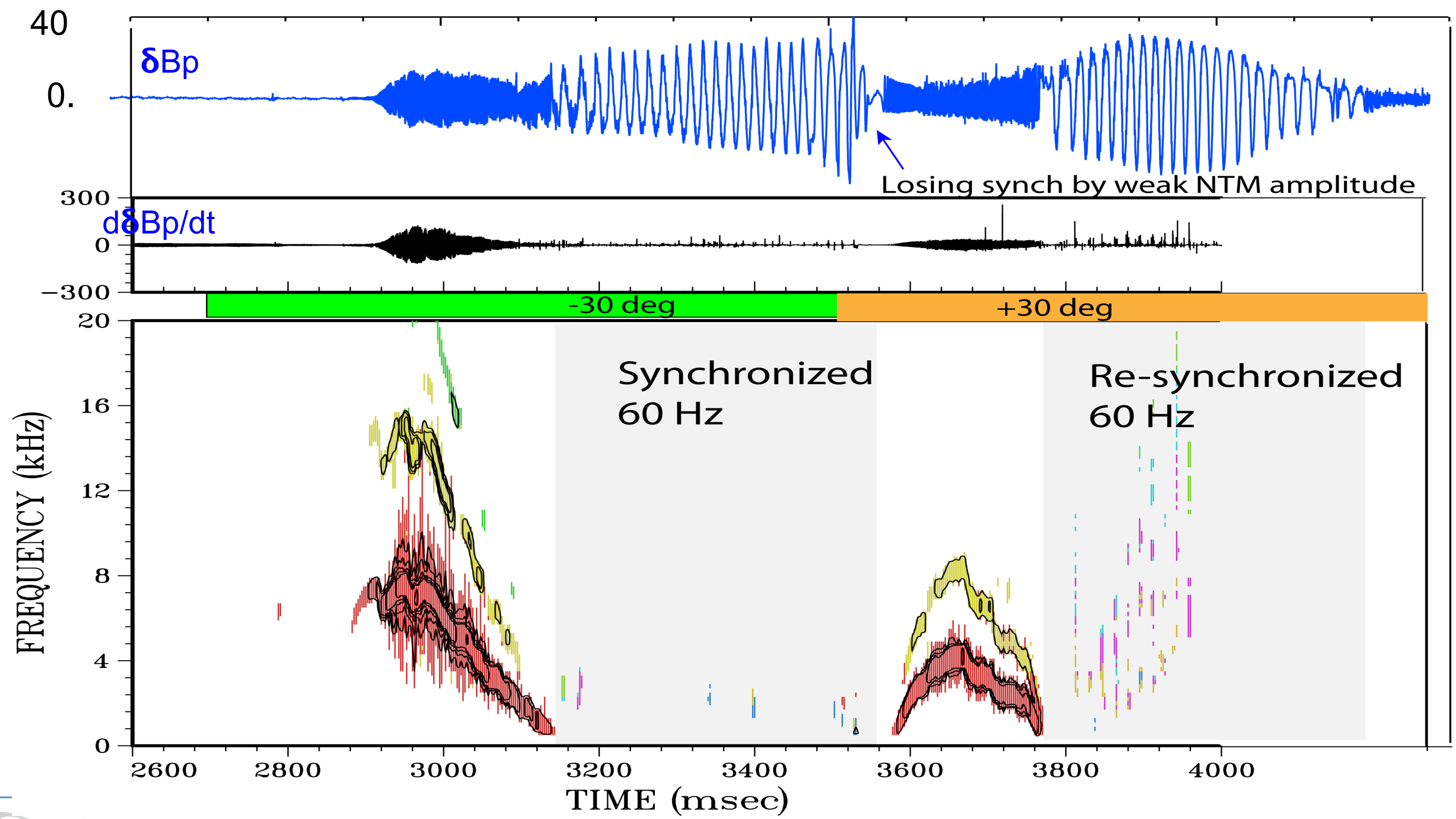
- Predictions with a simple model are consistent with various observations

  - asymptotic rotation :$\omega\tau_p \sim [G(\tau_w/\tau_p)]^{1/2}$
    , less sensitive to details feedback settings)

- Presetting phase shift, Φ_0 improves:

  - separate degenerated branches near ω zero and
    decoupling from other modes, enhancing the stability
    of branches,

After the NTM is desynchronized, it can be re-synchronized when the amplitude grows



Accelerating torque sustains high β_N discharge even with a large global MHD event