Supported by Office of Fusion Energy Sciences Excellent Science Attractive Energy Office of Science

Advances in Global MHD Mode Stabilization Research on NSTX

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22nd IAEA Fusion Energy Conference
October 13 - 18, 2008
Geneva, Switzerland

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Abstract

Stabilizing modes that limit plasma beta and reducing their deleterious effects on plasma rotation are key goals for efficient operation of a fusion reactor. Passive stabilization and active control of global kink/ballooning modes and resistive wall modes (RWM) have been demonstrated on NSTX and research now advances to understanding the stabilization physics and reliably maintaining the high beta plasma for confident extrapolation to ITER and CTF. Active $n = 1$ control experiments with an expanded sensor set, combined with low levels of $n = 3$ field phased to reduce error fields, reduced resonant field amplification and maintained plasma rotation, exceeded normalized beta = 6, and produced record discharge durations limited by magnet system constraints. Details of RWM active control show the mode being converted to a rotating kink that decays, or saturates leading to tearing modes. Discharges with rotation reduced by $n = 3$ magnetic braking suffer beta collapse at normalized beta = 4.2 approaching the no-wall limit, while normalized beta greater than 5.5 has been reached in these plasmas with $n = 1$ active control, in agreement with single-mode RWM theory. Advanced state-space control algorithms proposed for RWM control in ITER theoretically yield significant stabilization improvements. Values of relative phase between the measured $n = 1$ mode and the applied correction field that experimentally produce stability/instability agree with theory. Experimental mode destabilization occurs over a large range of plasma rotation, challenging the notion of a simple scalar critical rotation speed defining marginal stability. Stability calculations including kinetic modifications to ideal theory are applied to marginally stable experimental equilibria. Plasma rotation and collisionality variations are examined in the calculations. Intermediate rotation levels are less stable, consistent with experimental observations. Trapped ion resonances play a key role in this result. Recent experiments have demonstrated magnetic braking by non-resonant n = 2 fields. The observed rotation damping profile is broader than found for n = 3 fields. Increased ion temperature in the region of maximum braking torque increases the observed rate of rotation damping, consistent with theory.

Research advances to understanding mode stabilization physics and reliably maintaining the high beta plasmas

- ☐ Motivation
  - ☐ Maintenance of high β_N with sufficient physics understanding allows confident extrapolation to ITER and CTF

CTF: $\beta_N = 3.8 – 5.9$ (W_L = 1-2 MW/m^2) ST-DEMO: $\beta_N \sim 7.5$

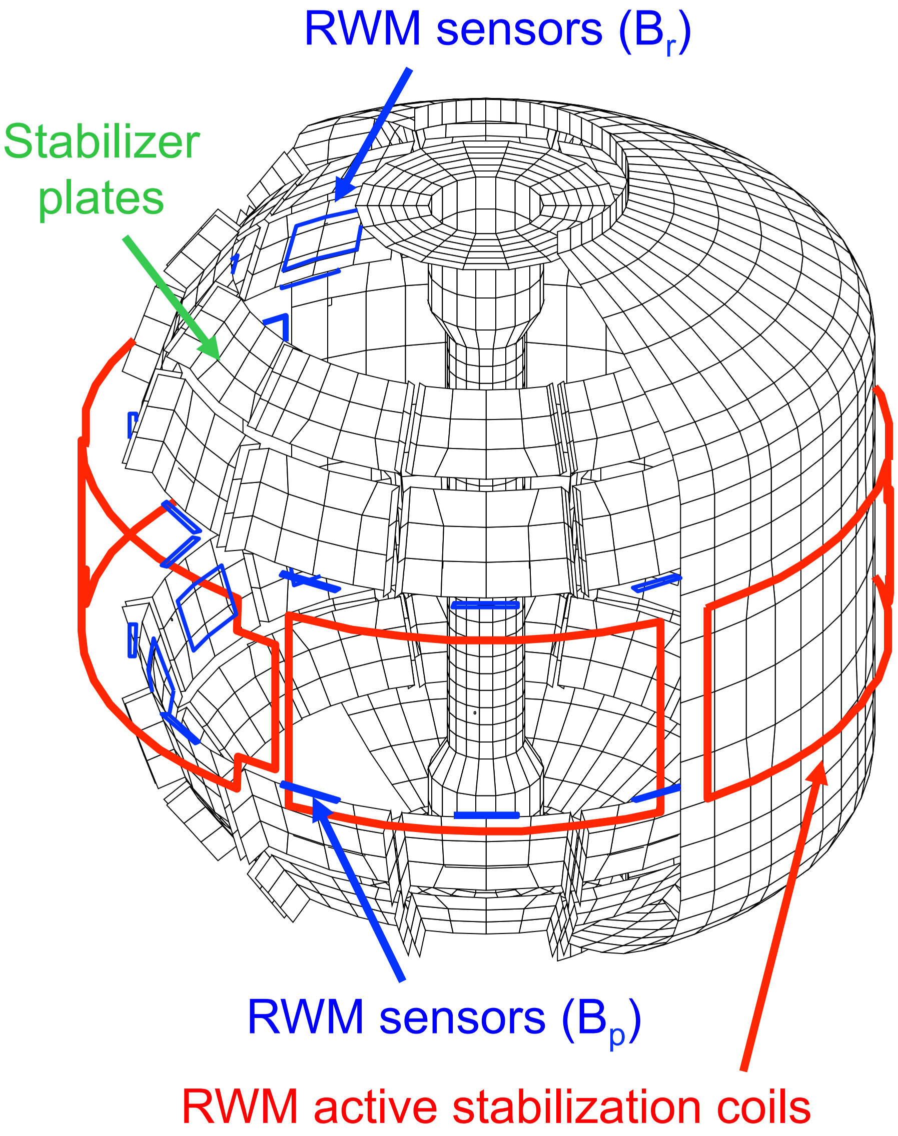
- Both at, or above ideal no-wall β-limit; deleterious effects at ~ ½ $\beta_N^{no\text{-}wall}$

- high β_N accelerates neutron fluence goal - takes 20 years at W_L = 1 MW/m^2)

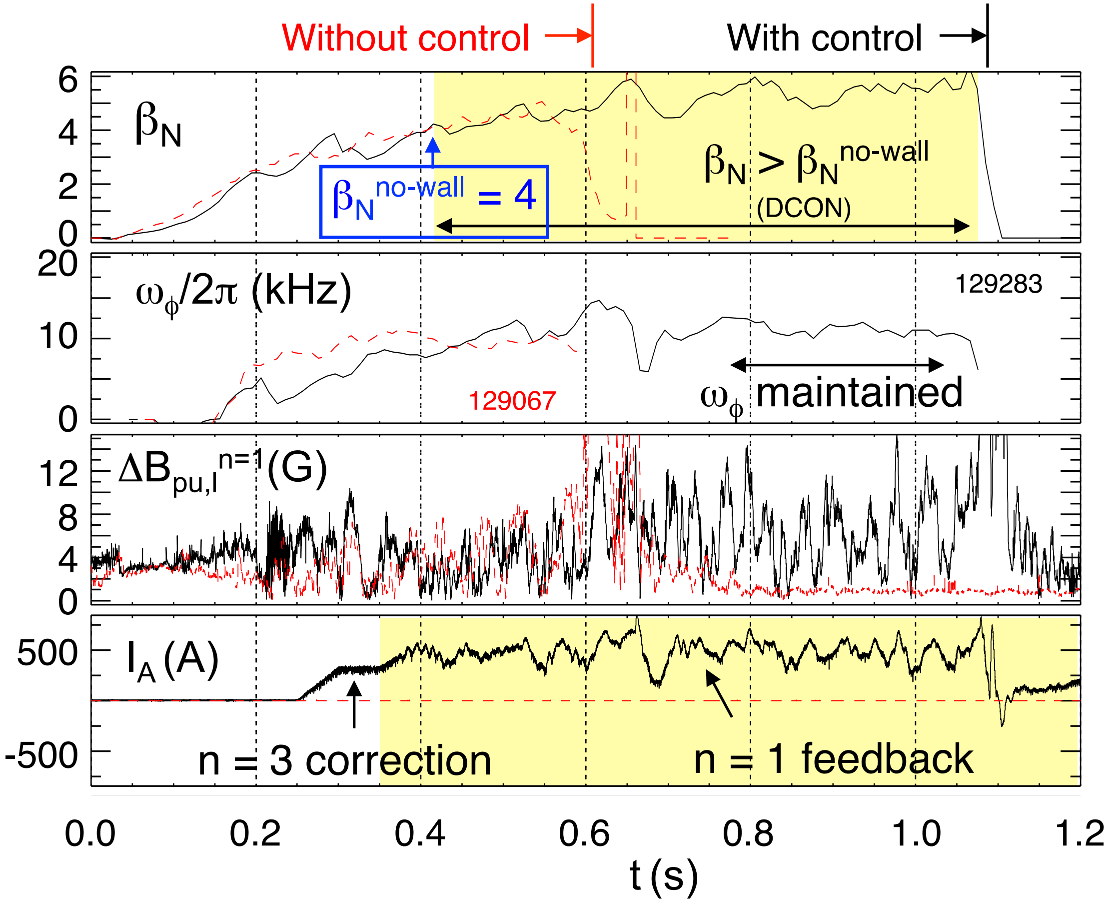
- ☐ Outline
  - ☐ Active control of beta amplified n = 1 fields / global instabilities
  - ☐ Mode dynamics and evolution during active control
  - ☐ Control performance compared to theory, connection to ITER
  - ☐ Kinetic effects on resistive wall mode (RWM) stabilization
  - ☐ Non-axisymmetric field influence on plasma rotation profile

NSTX equipped for passive and active RWM control

- Stabilizer plates for kink mode stabilization
- External midplane control coils closely coupled to vacuum vessel
- Varied sensor combinations used for feedback
  - 24 upper/lower B_p: (B_{pu}, B_{pl})
  - 24 upper/lower B_r: (B_{ru}, B_{rl})

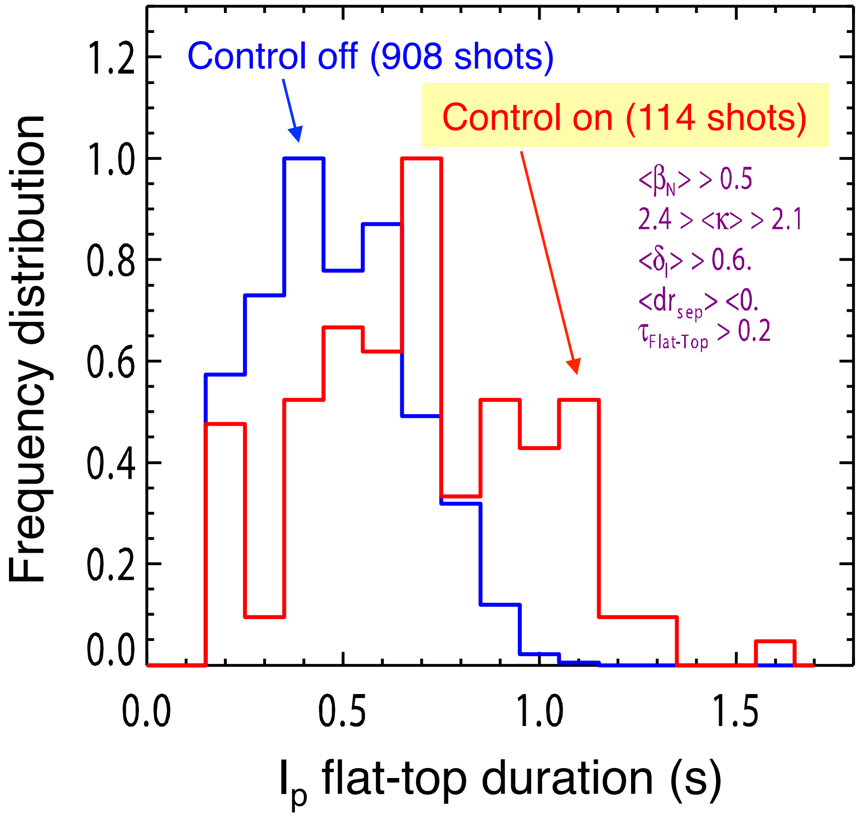


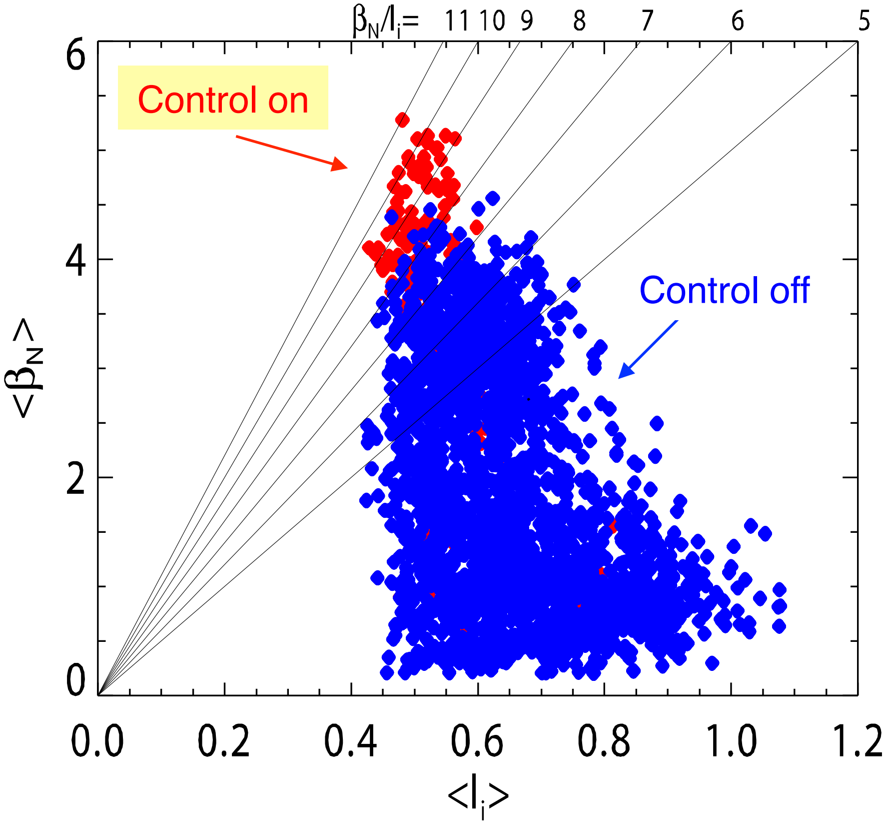
Active RWM control and error field correction maintain high β_N plasma



- n = 1 active, n = 3 DC control
  - n = 1 response ~ 1 ms < 1/γ_{RWM}
  - $\beta_N/\beta_N^{\text{no-wall}} = 1.5$ reached
  - best maintains ω_ϕ
- NSTX record pulse lengths
  - limited by magnet systems
  - n > 0 control first used as standard tool in 2008
- Without control, plasma more susceptible to RWM growth, even at high ω_ϕ
  - Disruption at $\omega_\phi/2\pi$ ~ 8kHz near q = 2
  - More than a factor of 2 higher than marginal ω_ϕ with n = 3 magnetic braking

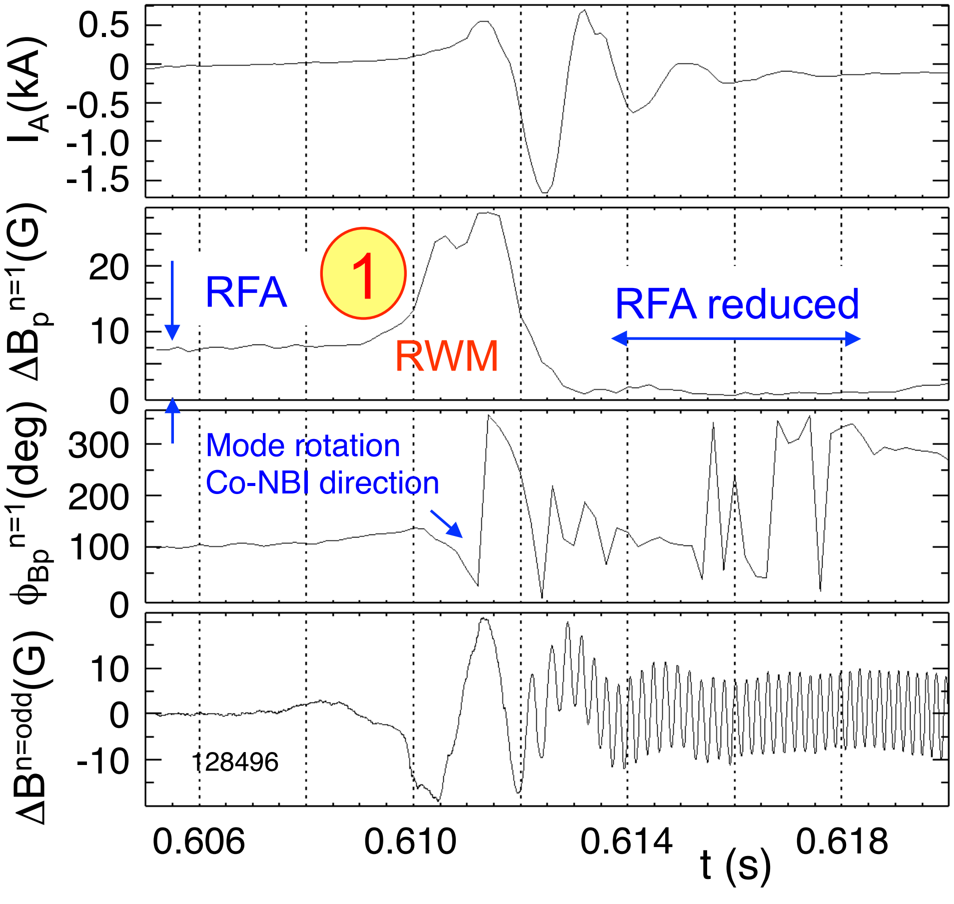
Probability of long pulse and $<\beta_N>_{pulse}$ increases significantly with active RWM control and error field correction





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

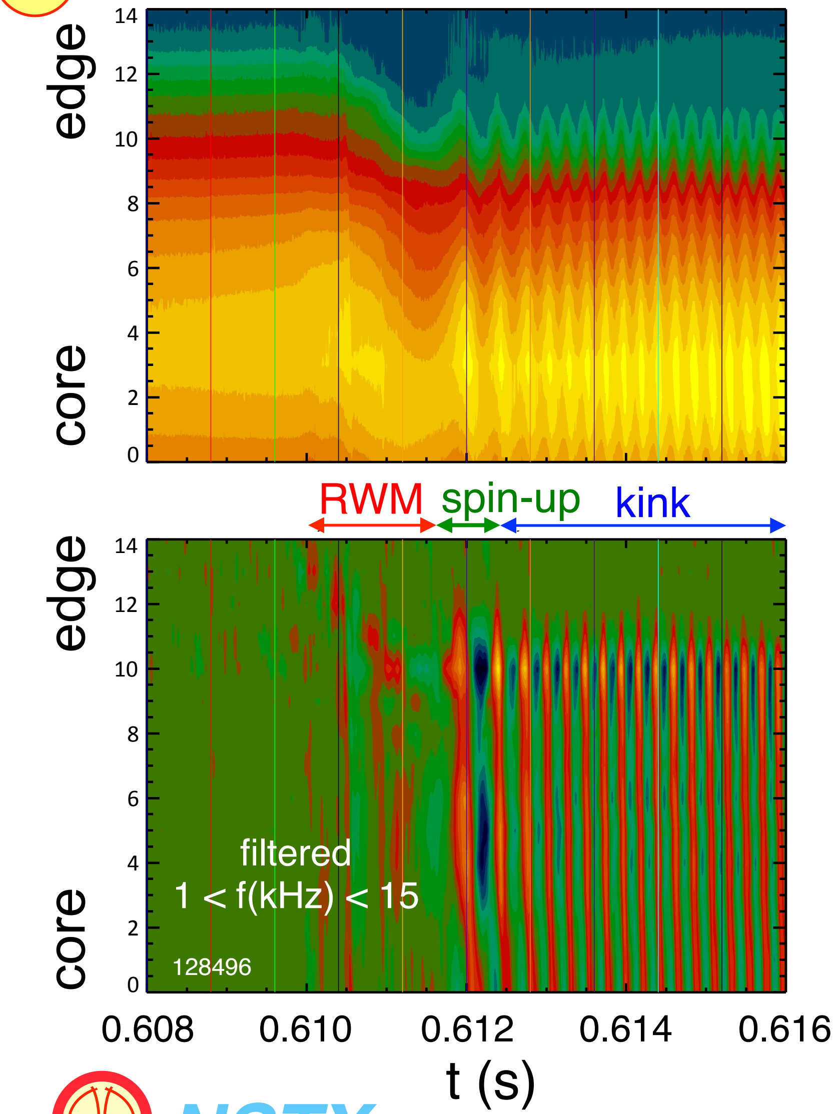
During n=1 feedback control, unstable RWM evolves into rotating global kink



- ① RWM grows and begins to rotate
  - With control off, plasma disrupts at this point
  - With control on, mode converts to global kink, RWM amplitude dies away
  - Resonant field amplification (RFA) reduced
- Conversion from RWM to rotating kink occurs on τ_w timescale
- Kink either damps away, or saturates
  - Tearing mode can appear during saturated kink

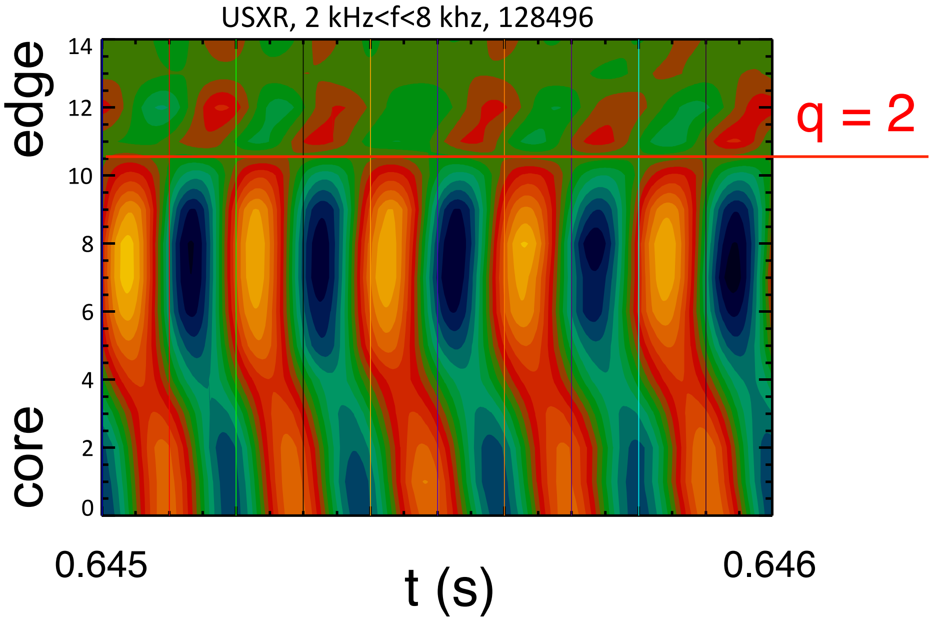
Soft X-ray emission shows transition from RWM to global kink

① Transition from RWM to kink



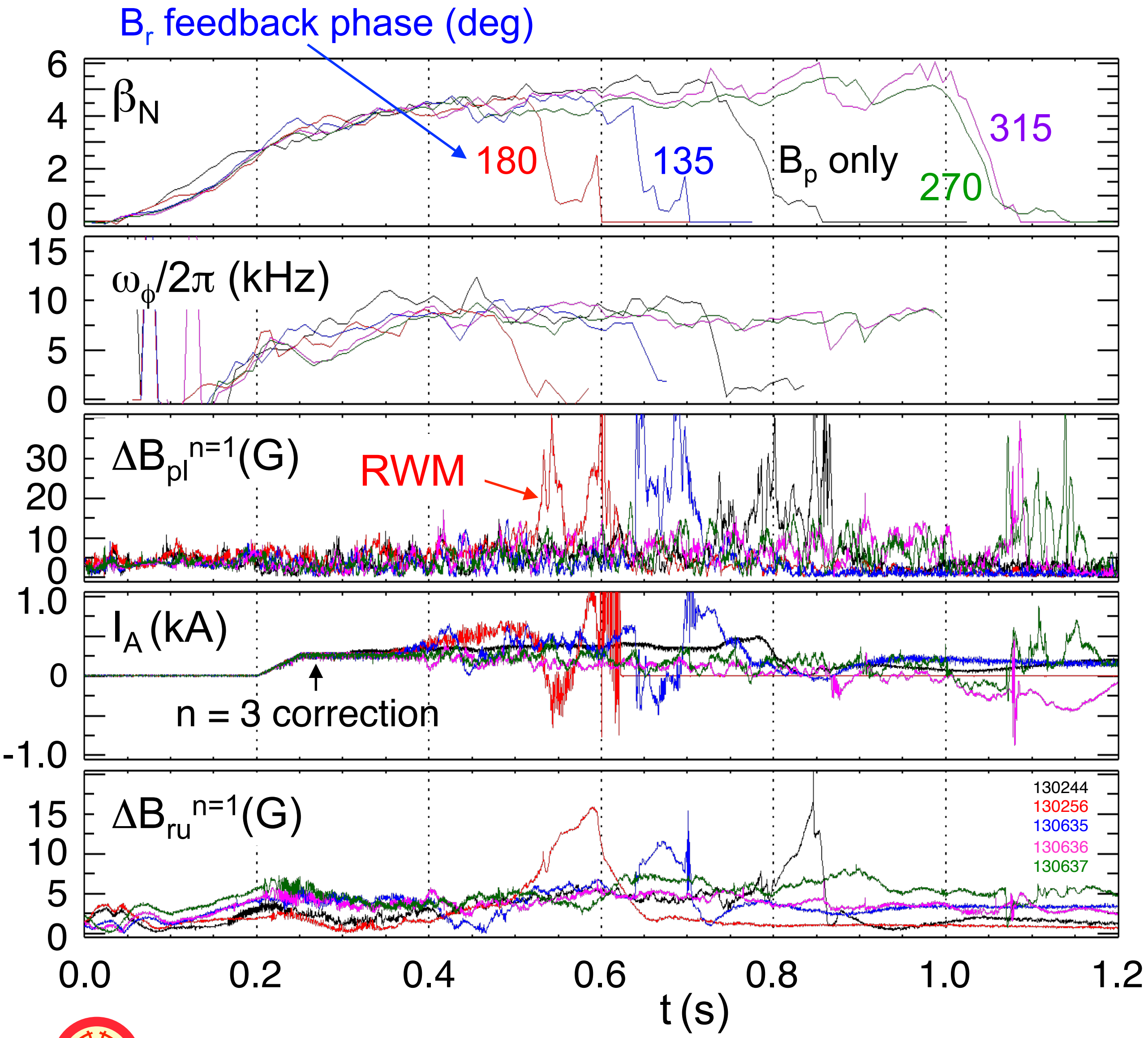
② Tearing mode appears during kink

RWM onset time + 35 ms



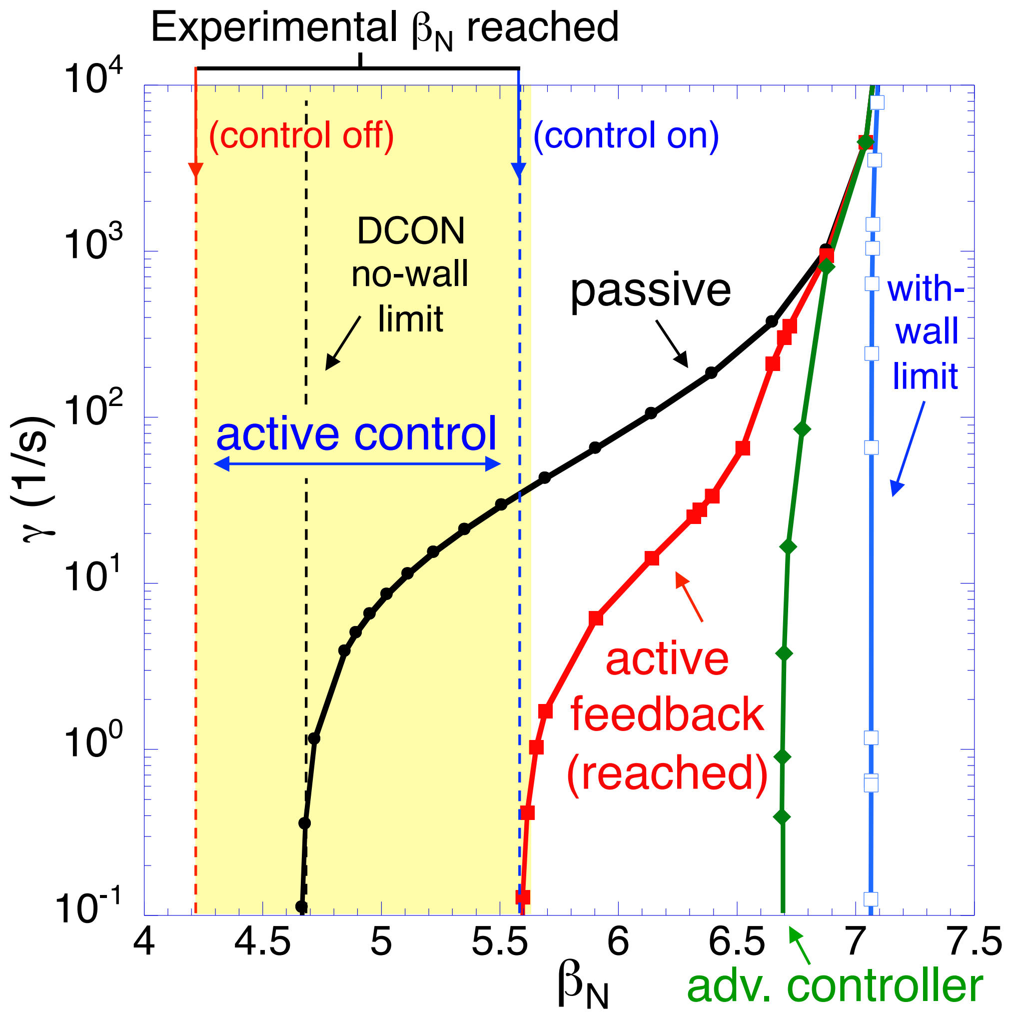
- ☐ Initial transition from RWM to saturated kink
- ☐ Tearing mode appears after 10 RWM growth times and stabilizes

Favorable feedback settings found for B_p + B_r sensors

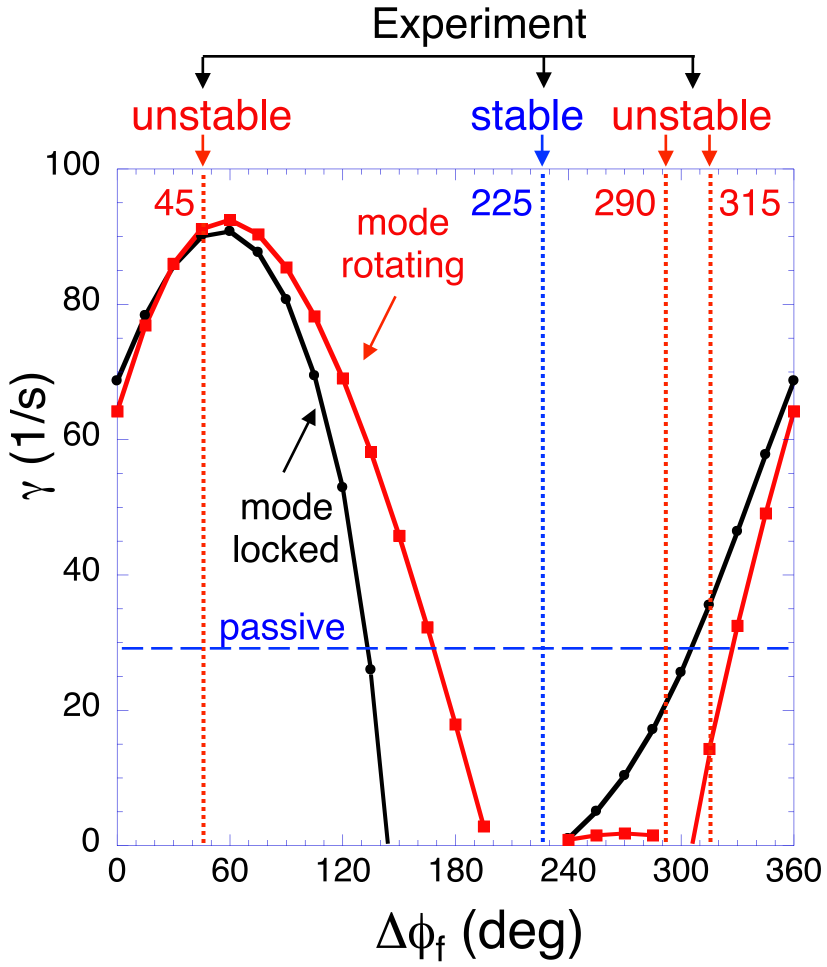


- Steady ω_ϕ
  - n = 1 feedback + n = 3 EFC
- B_r feedback phase scan
  - All RWM sensors used
  - Favorable B_p feedback settings
  - B_r gain, phase varied to find best settings

Experimental RWM control performance consistent with theory



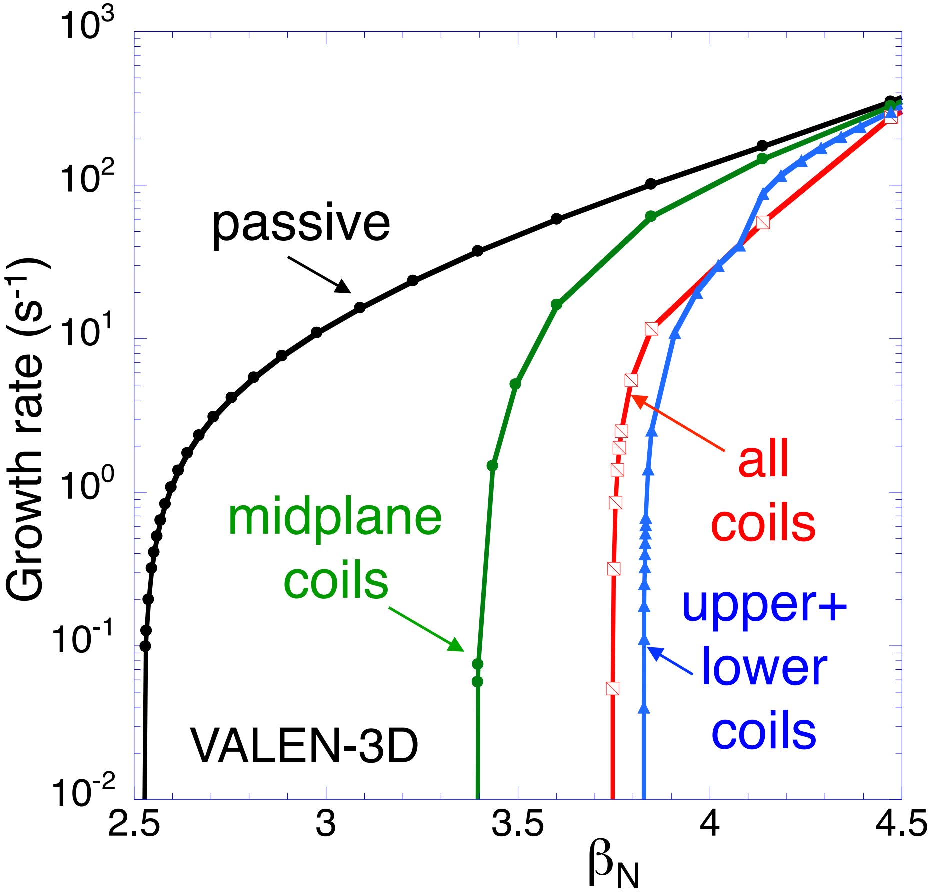
- ❑ VALEN code with realistic sensor geometry, plasmas with reduced V_ϕ



- ❑ Feedback phase scan shows superior settings
  - ❑ Agreement between theoretical and experimental feedback behavior

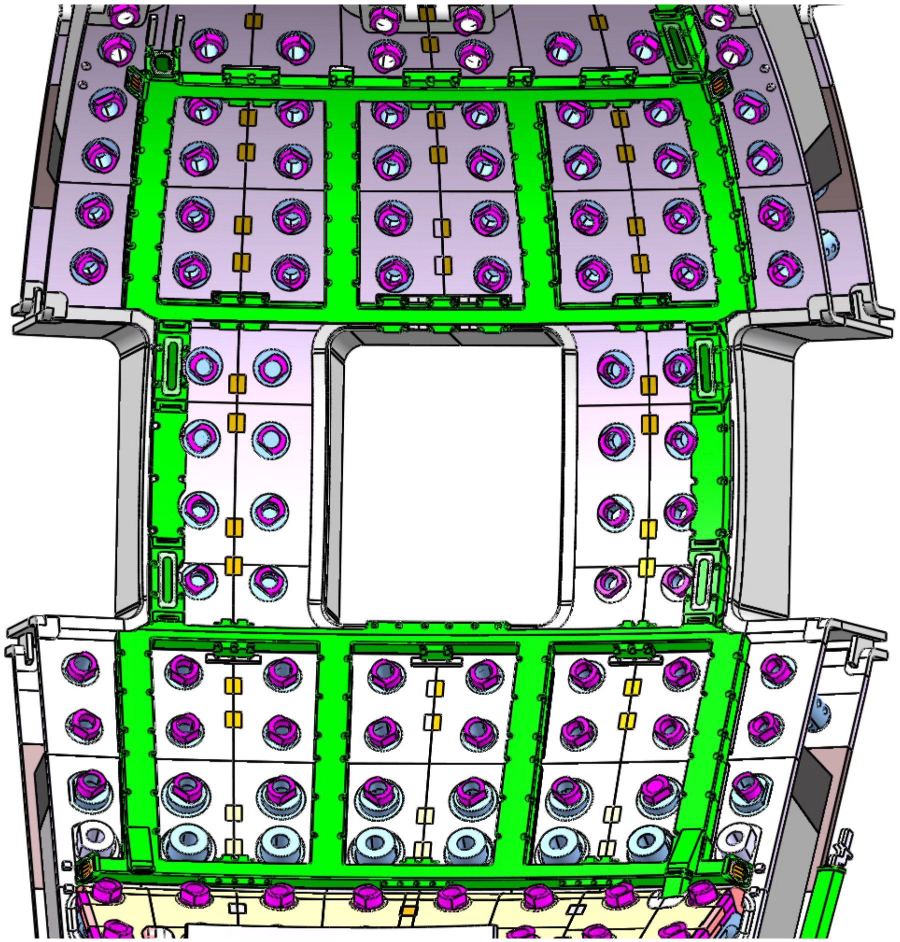
Significant β_N increase expected by internal coil proposed for ITER

ITER VAC02 stabilization performance



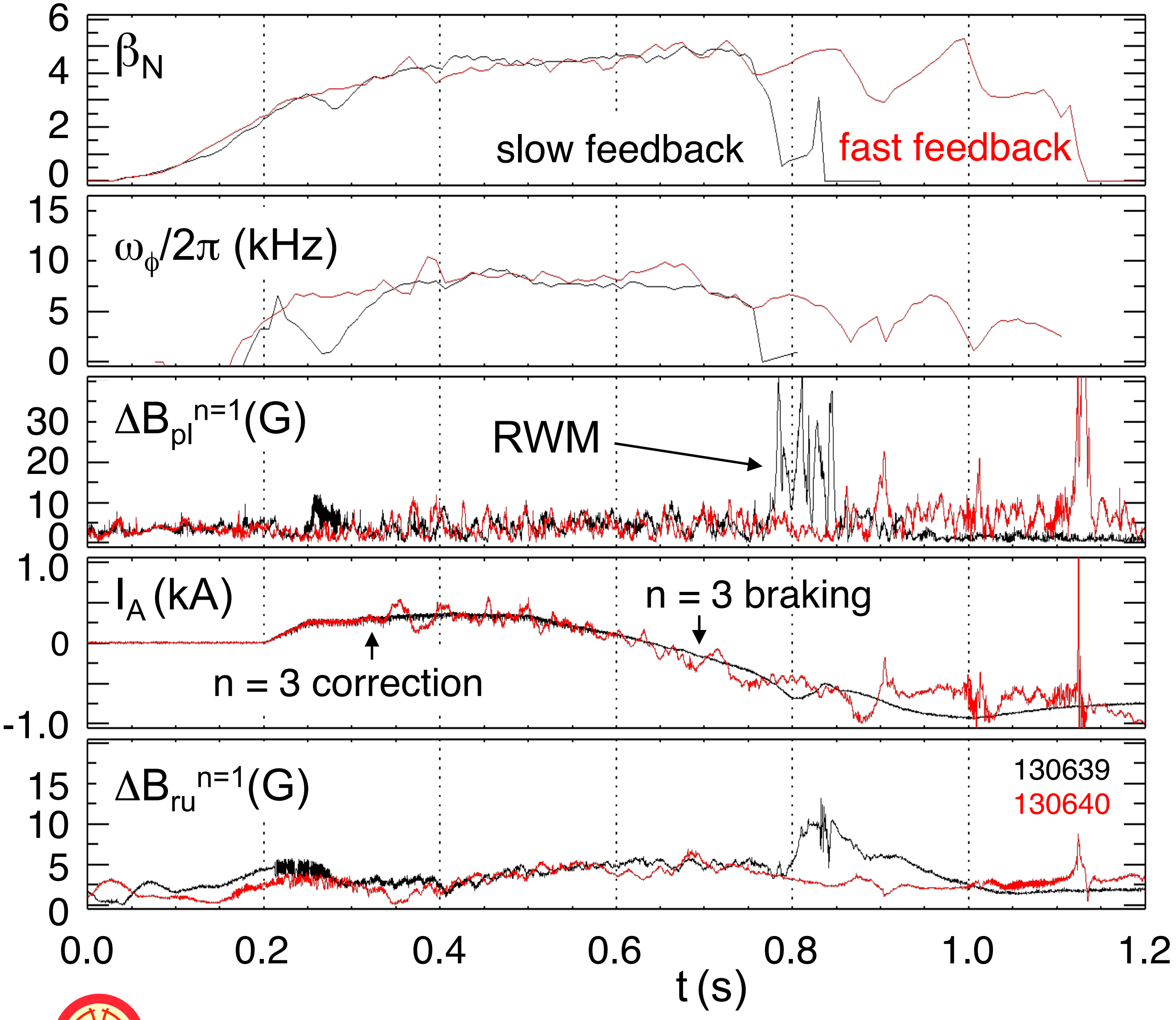
- 50% increase in β_N over RWM passive stability

ITER VAC02 design (40° sector)



3 toroidal arrays, 9 coils each

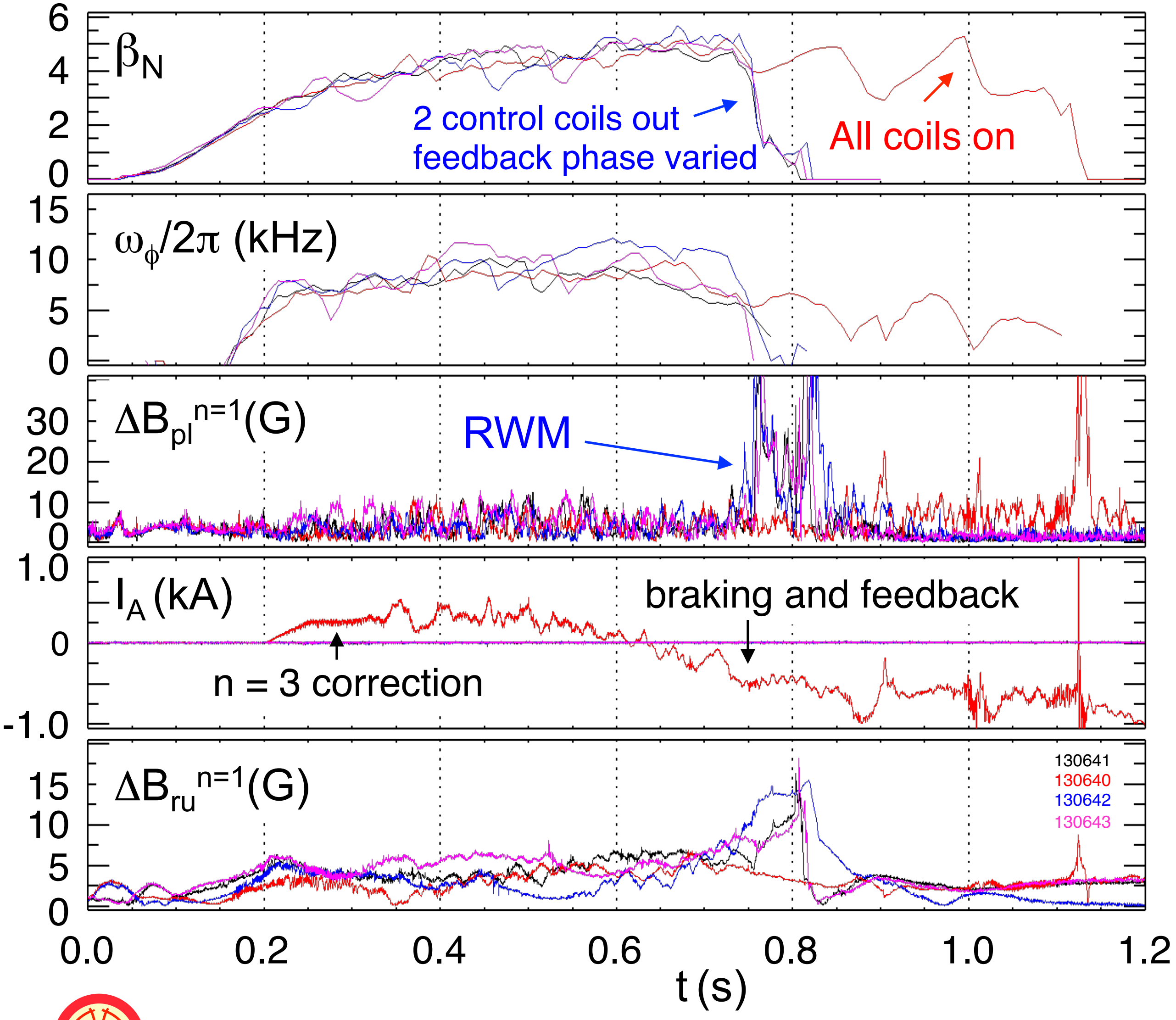
ITER support: Low ω_ϕ, high β_N plasma not accessed when feedback response sufficiently slowed



- Low ω_ϕ access for ITER study
  - use n = 3 braking
- n = 1 feedback response speed significant
  - "fast" (unfiltered) n = 1 feedback allows access to low V_ϕ, high β_N
  - "slow" n = 1 "error field correction" (75ms smoothing of control coil current) suffers RWM at ω_ϕ ~ 5kHz near q = 2

NSTX

ITER support: Low ω_ϕ, high β_N plasma not accessed when two feedback control coils are disabled

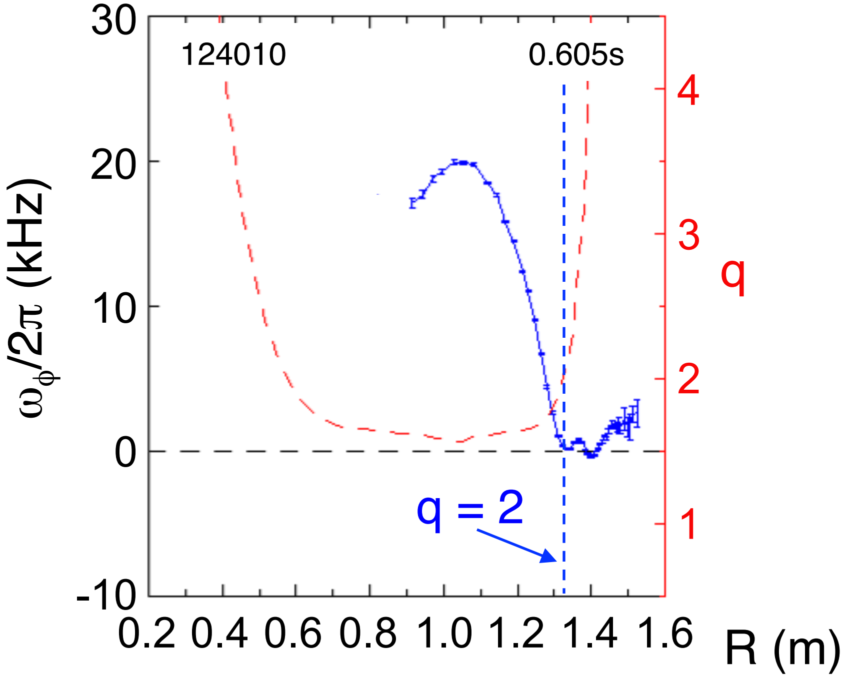


- ❑ Low ω_ϕ access for ITER study
  - ❑ use braking
- ❑ n = 1 feedback doesn't stabilize plasma with 2 of 6 control coils disabled
  - ❑ scenario to simulate failed coil set in ITER
  - ❑ Feedback phase varied, but no settings worked
  - ❑ RWM onset at identical time, plasma rotation

NSTX

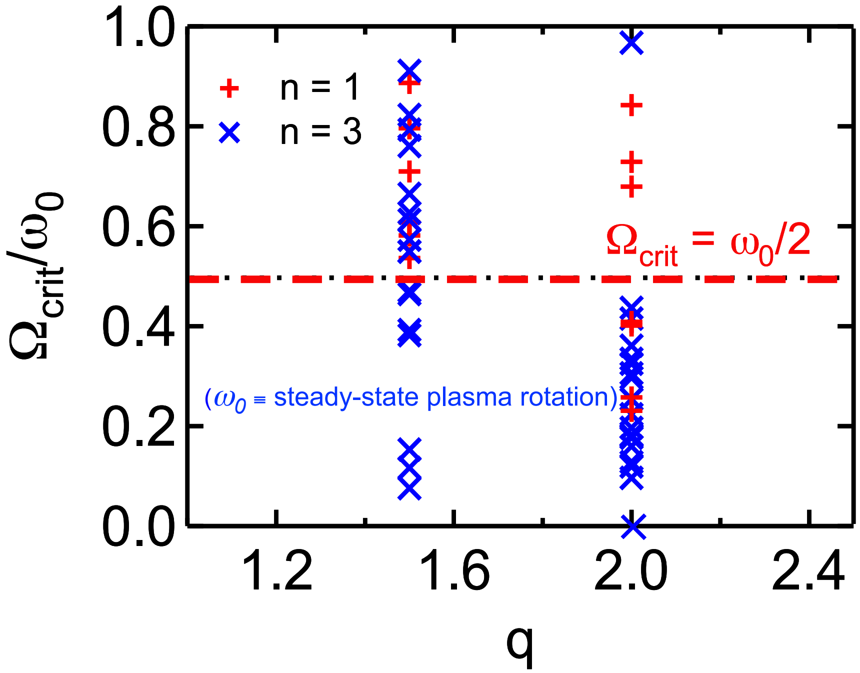
Non-resonant magnetic braking allows V_ϕ modification to probe RWM critical rotation and stabilization physics

- ❑ Scalar plasma rotation at q = 2 inadequate to describe stability
  - ❑ Marginal stability $\beta_N > \beta_N^{\text{no-wall}}$, $\omega_\phi^{q=2} = 0$



- ❑ Ω_{crit} doesn't follow simple $\omega_0/2$ rotation bifurcation relation

A.C. Sontag, et al., NF **47** (2007) 1005.



- ❑ Slowest rotation profiles produced in NSTX are at DIII-D balanced-NBI levels
- ❑ Ion collisionality profile variation appears to alter experimental Ω_{crit} profile

Modification of Ideal Stability by Kinetic theory (MISK code) investigated to explain experimental stability

- Simple critical ω_ϕ threshold stability models or loss of torque balance do not describe experimental marginal stability

Sontag, et al., Nucl. Fusion **47** (2007) 1005.

- Kinetic modification to ideal MHD growth rate
  - Trapped and circulating ions, trapped electrons
  - Alfven dissipation at rational surfaces

$$\gamma\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$$

Hu and Betti, Phys. Rev. Lett **93** (2004) 105002.

- Stability depends on
  - Integrated ω_ϕ profile: resonances in δW_K (e.g. ion precession drift)
  - Particle collisionality

ω_ϕ profile (enters through ExB frequency)

$$\omega_E = \omega_\phi^D - \omega_{*i}^D - \frac{v_\theta^D}{2\pi R}\frac{B_\phi}{B_\theta}$$

Trapped ion component of δW_K (plasma integral)

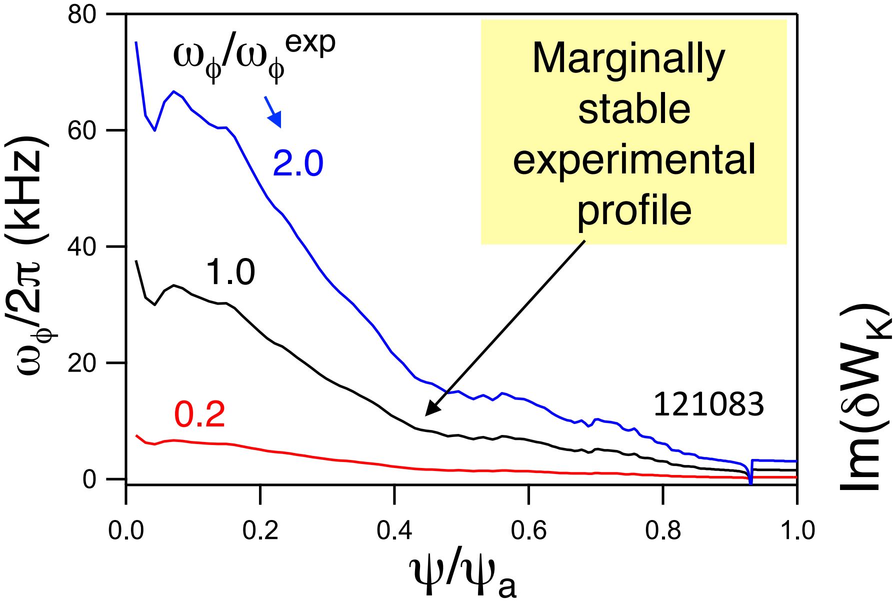
$$\delta W_K \propto \int \left[\frac{\omega_{*N} + \left(\hat{\varepsilon} - {}^{3}\!/_{2}\right)\omega_{*T} + \omega_E - \omega - i\gamma}{\langle\omega_D\rangle + l\omega_b - i\nu_{eff} + \omega_E - \omega - i\gamma}\right]\hat{\varepsilon}^{\frac{5}{2}} e^{-\hat{\varepsilon}}\, d\hat{\varepsilon}$$

← Energy integral

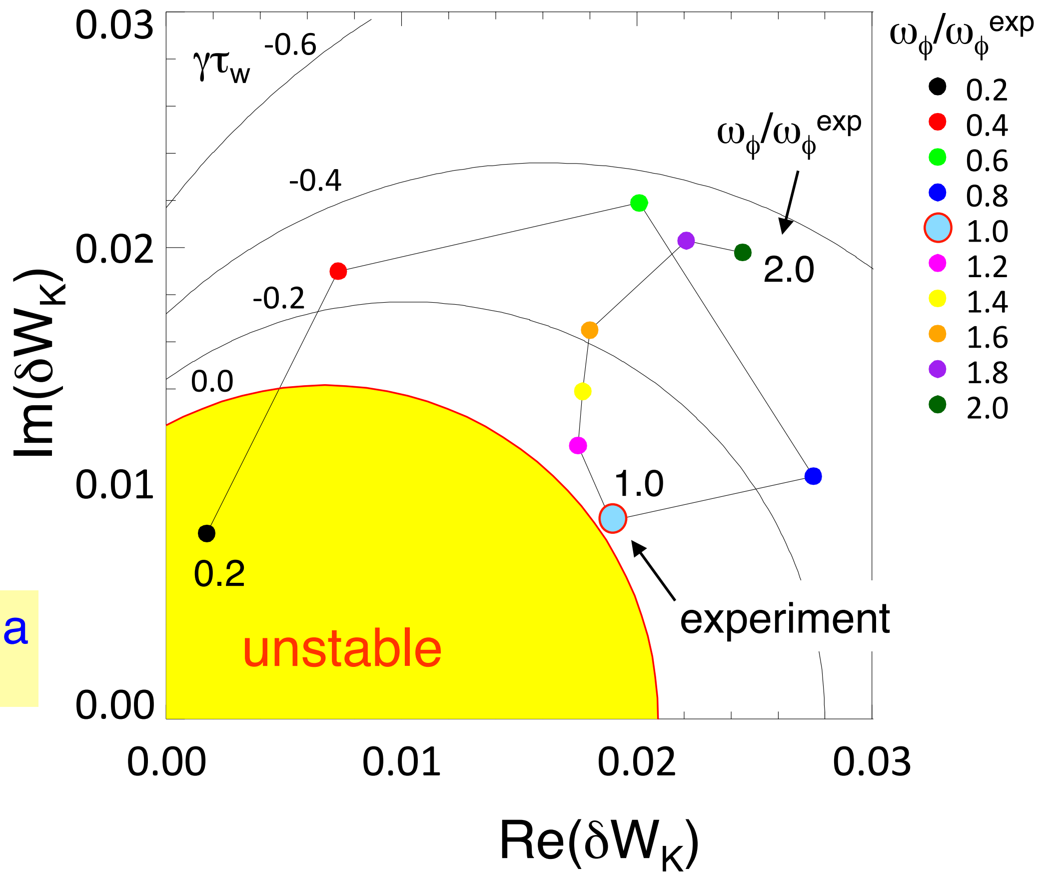
precession drift bounce collisionality

Kinetic modifications show decrease in RWM stability at relatively high V_ϕ – consistent with experiment

Theoretical variation of ω_ϕ

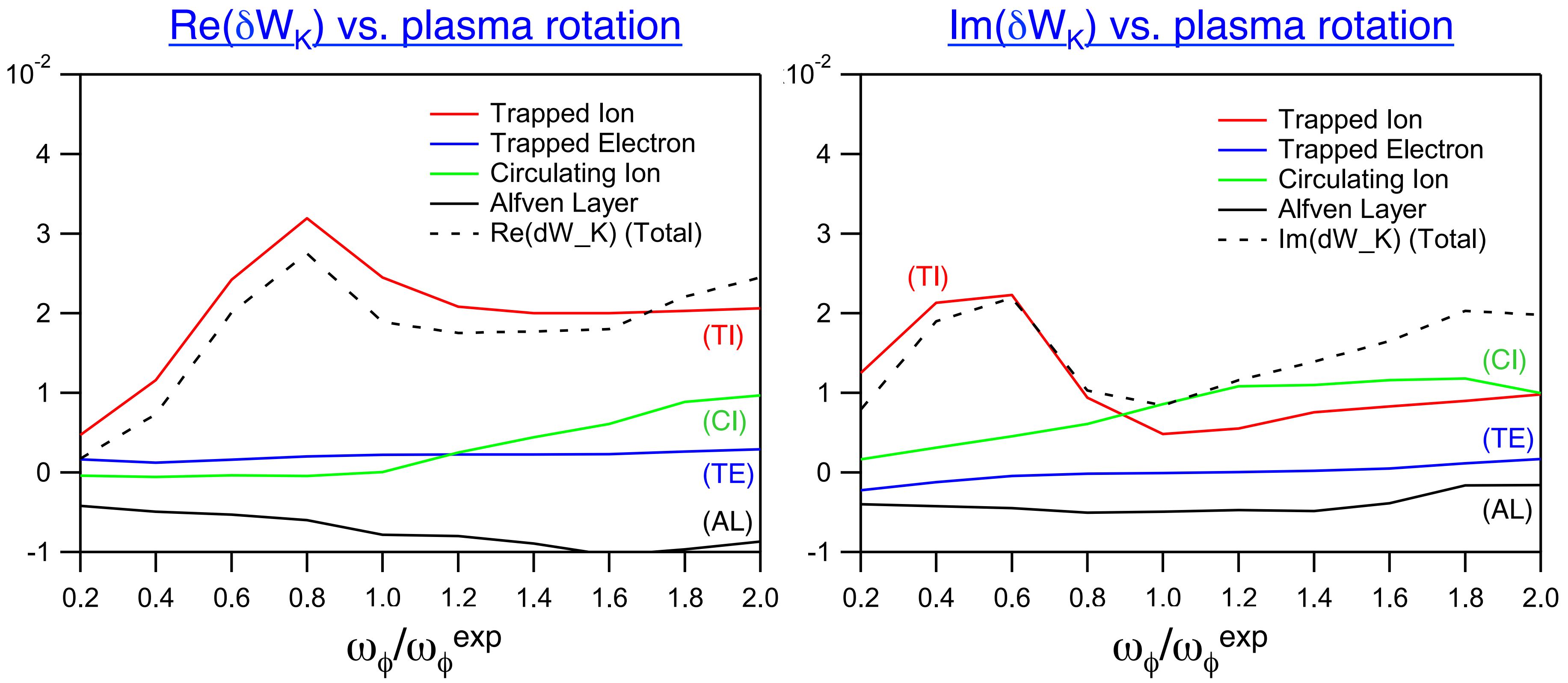


RWM stability vs. V_ϕ (contours of $\gamma\tau_w$)



- Marginal stable experimental plasma reconstruction, rotation profile ω_ϕ^{exp}
- Variation of ω_ϕ away from marginal profile increases stability
- Unstable region at low ω_ϕ

Stabilizing influence of kinetic effects changes as plasma rotation varies

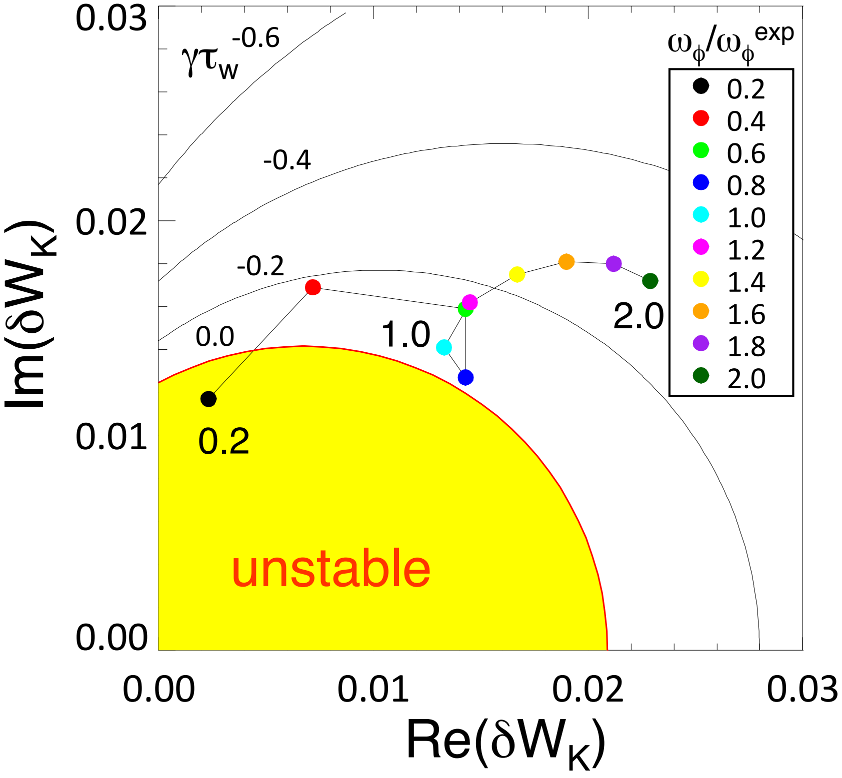

Re(δW_K) vs. plasma rotation

Im(δW_K) vs. plasma rotation

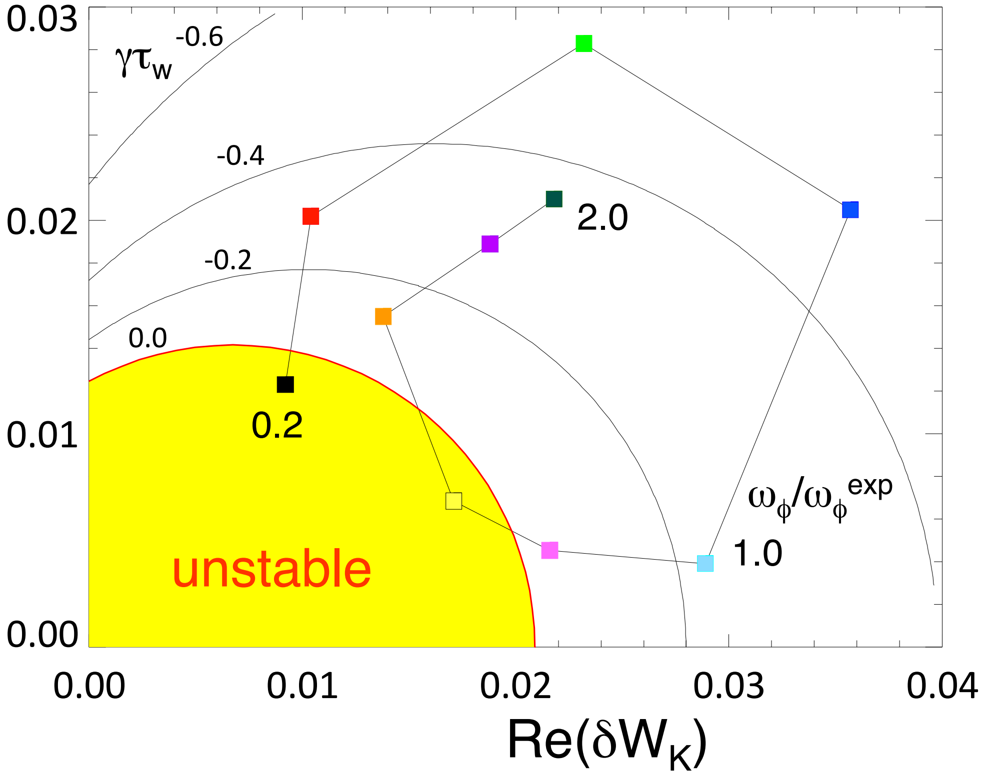
- ❑ Low ω_ϕ : kinetic effects relatively small => plasma unstable
- ❑ Intermediate ω_ϕ : trapped ion strengthens/weakens => stable/marginal
- ❑ High ω_ϕ : circulating ion stabilization increases => plasma stable

Kinetic model shows overall increase in stability as collisionality decreases

Increased collisionality (x6)

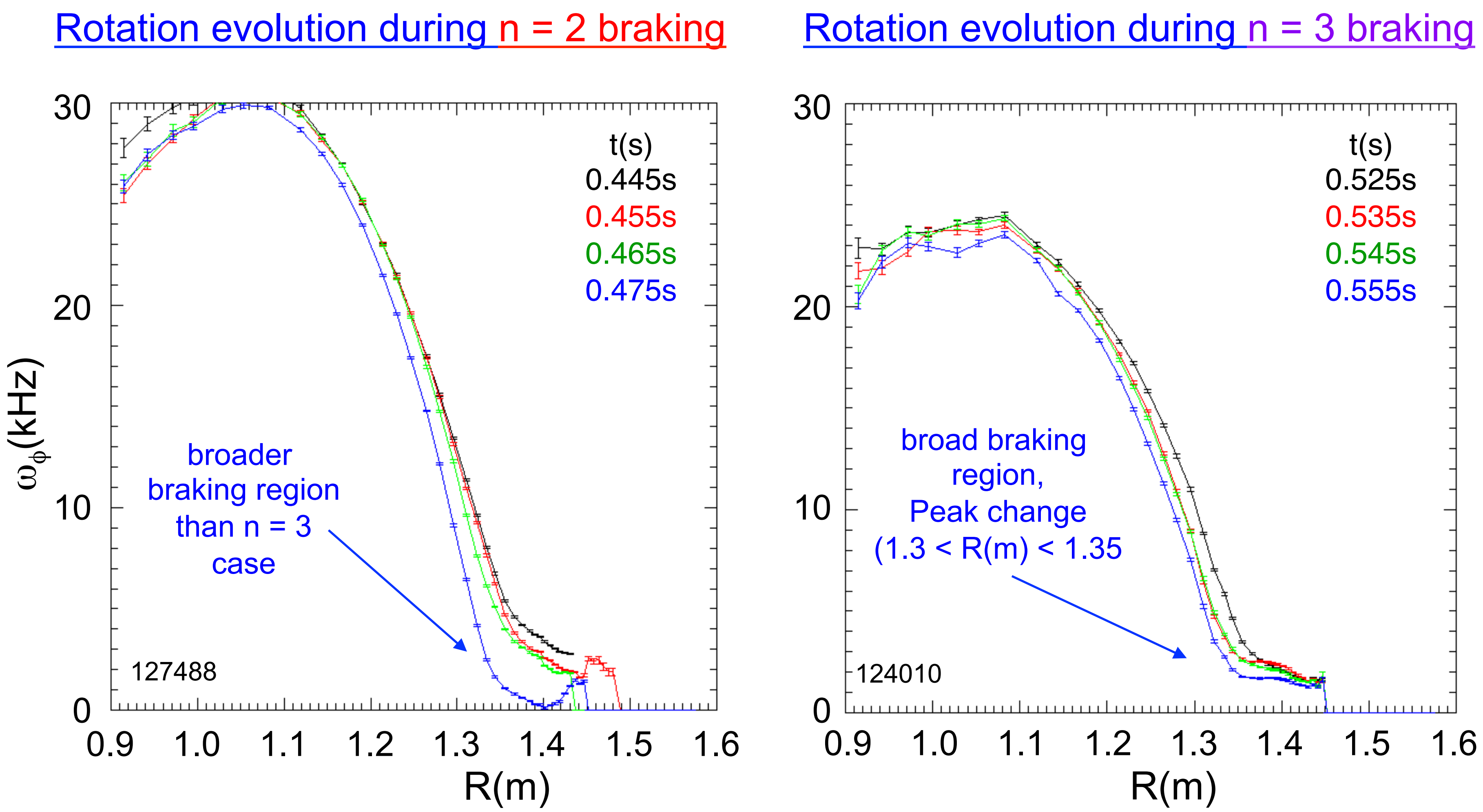


Reduced collisionality (x1/6)



- Vary ν by varying T, n at constant β
- Simpler stability dependence on ω_ϕ at increased ν
- Increased stability at $\omega_\phi/\omega_\phi^{exp} \sim 1$
- Unstable band in ω_ϕ at increased ω_ϕ

Non-resonant rotation braking produced using n = 2 field



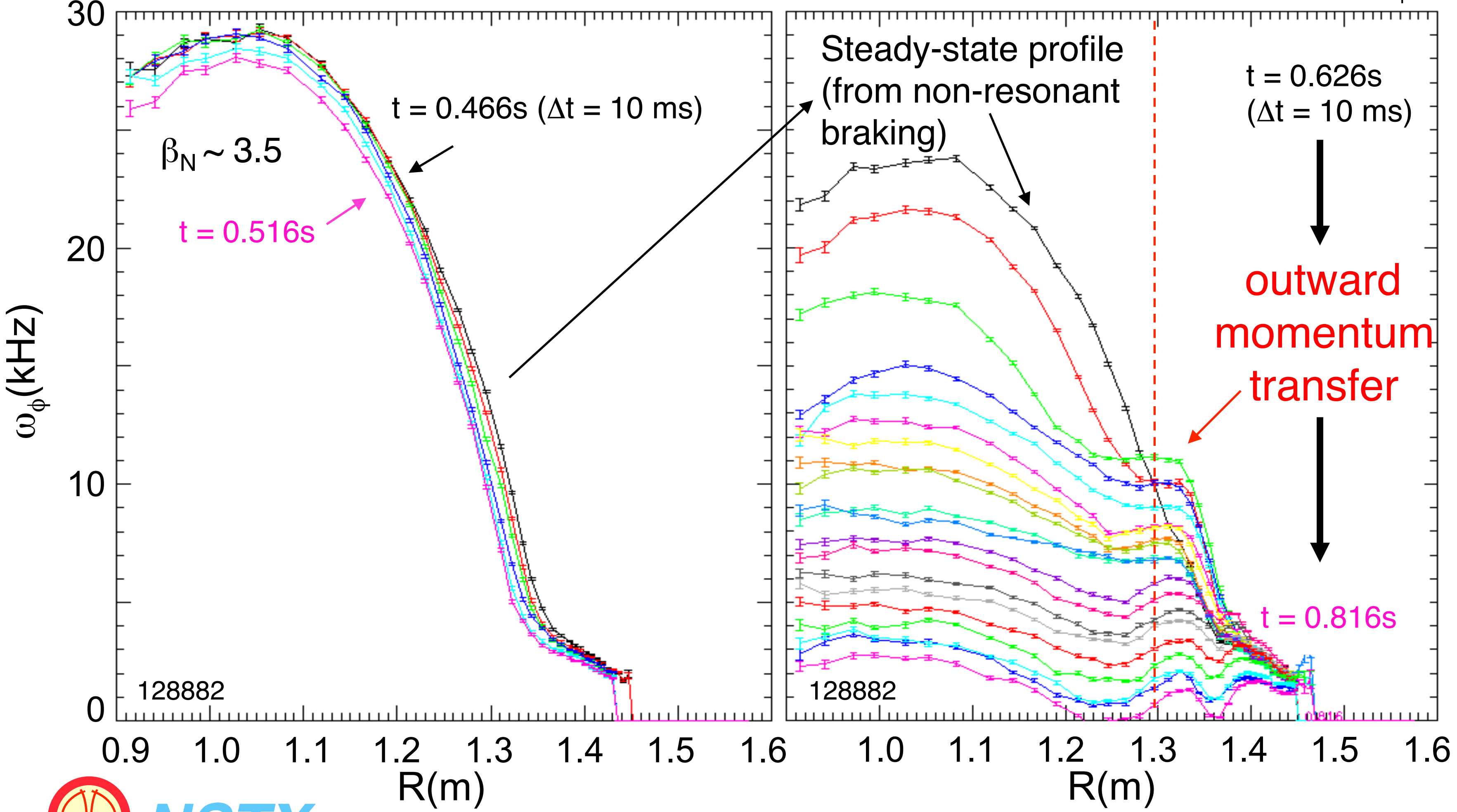
broader braking region than n = 3 case

broad braking region, Peak change (1.3 < R(m) < 1.35

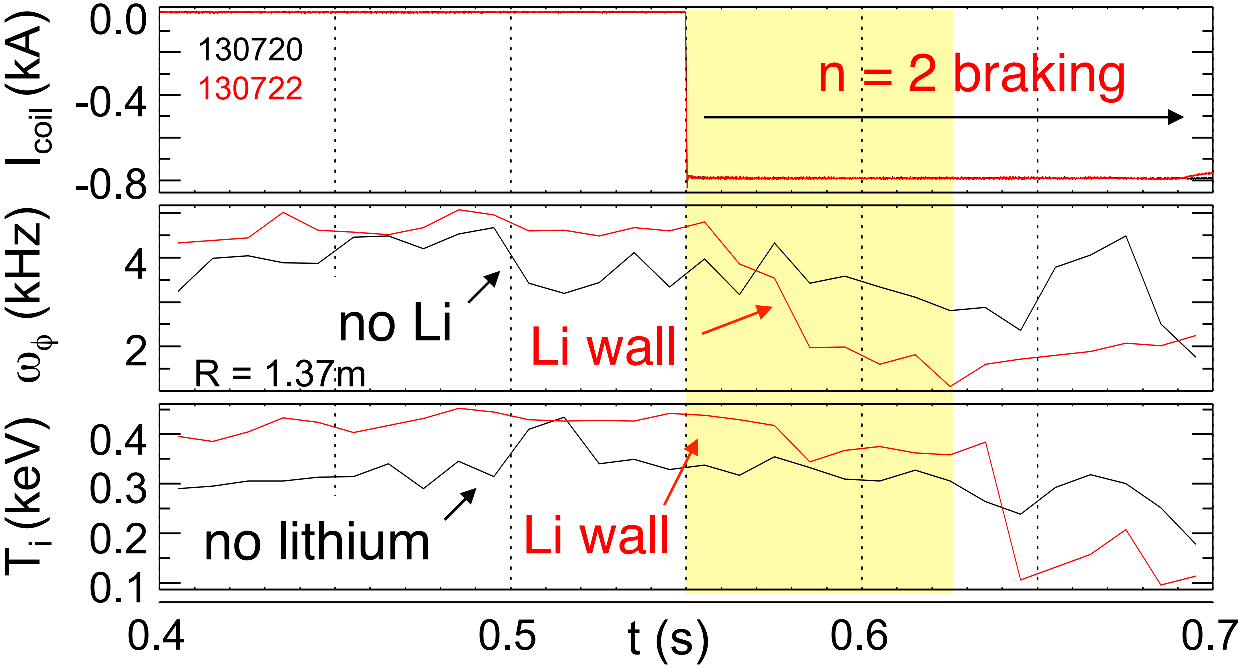
- ❑ n = 2 has broader braking profile than n = 3 field (from field spectrum)

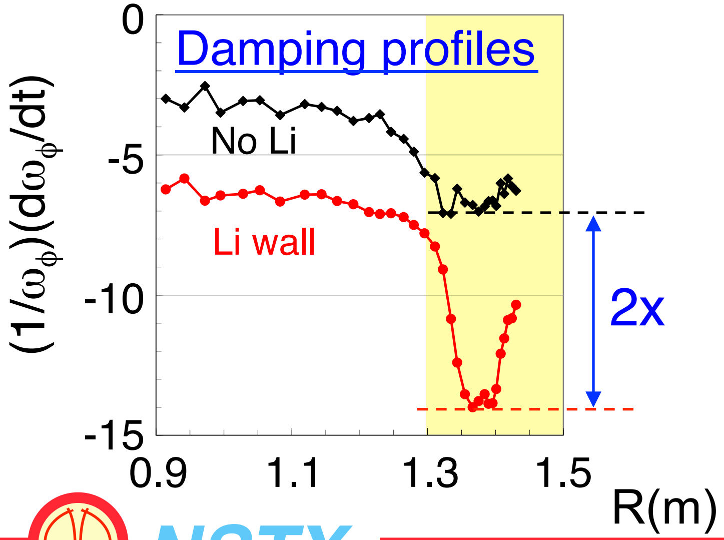
n = 2 non-resonant braking evolution distinct from resonant

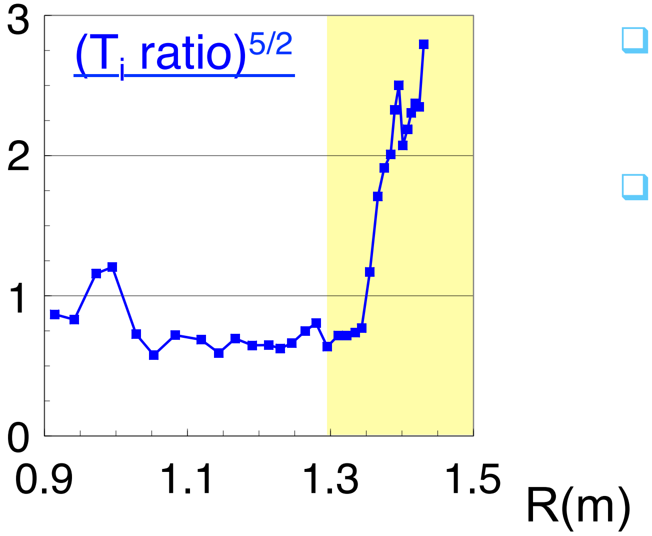
- Non-resonant:
  - broad, self-similar reduction of profile
  - Reaches steady-state (t = 0.626s)
- Resonant:
  - Clear momentum transfer across rational surface
  - evolution toward rigid rotor core
  - Local surface locking at low ω_ϕ



Stronger non-resonant braking at increased T_i

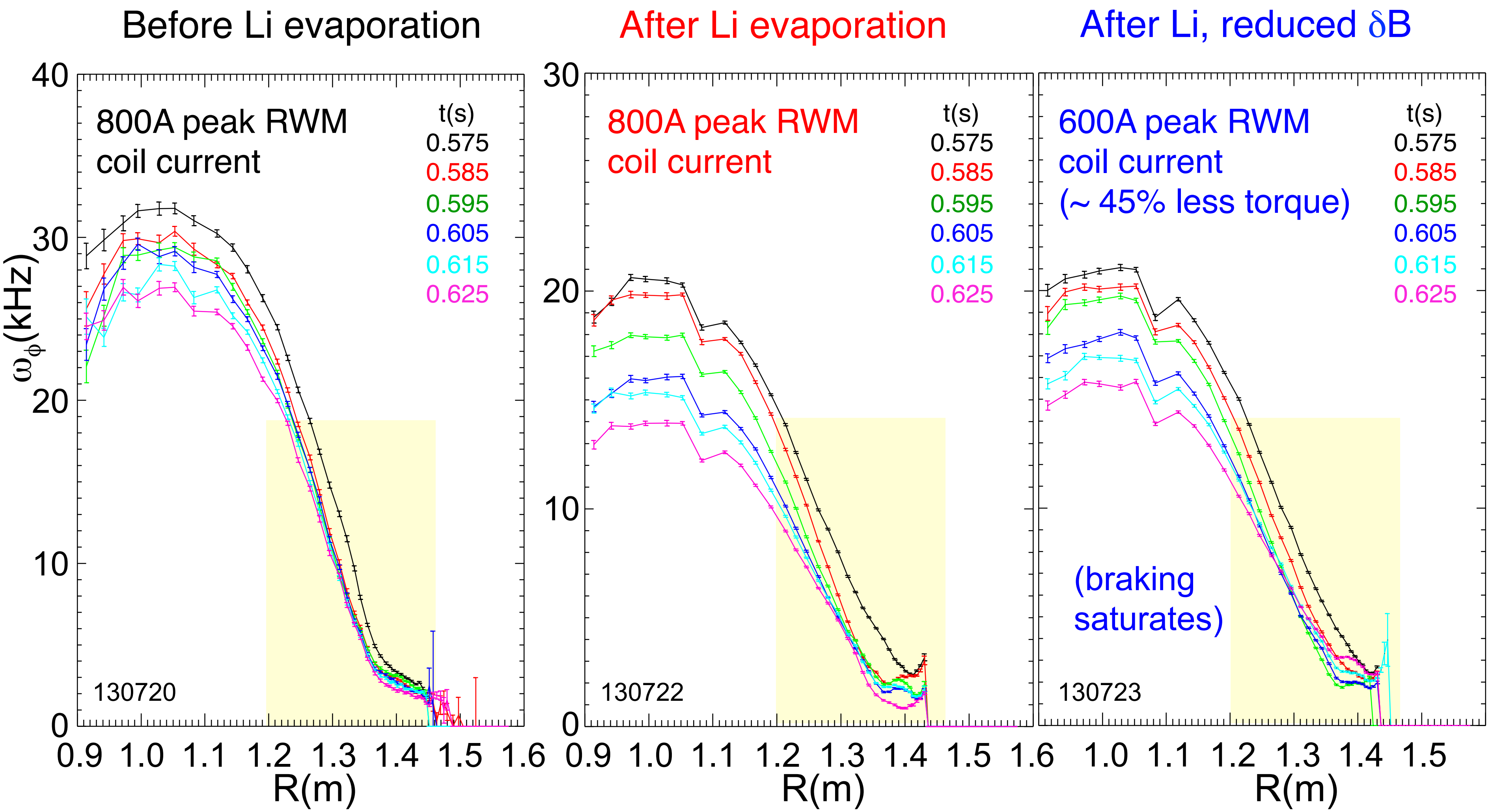






- ❑ Examine T_i dependence of neoclassical toroidal viscosity (NTV)
- ❑ Li wall conditioning produces higher T_i in region of high rotation damping
- ❑ Expect stronger NTV torque at higher T_i ($-d\omega_\phi/dt \sim T_i^{5/2}\,\omega_\phi$)
  - ❑ At braking onset, T_i ratio$^{5/2}$ = $(0.45/0.34)^{5/2} \sim 2$
  - ❑ Consistent with measured $d\omega_\phi/dt$ in region of strongest damping

Non-resonant n = 2 braking evolution altered by Li evaporation



Before Li evaporation

After Li evaporation

After Li, reduced δB

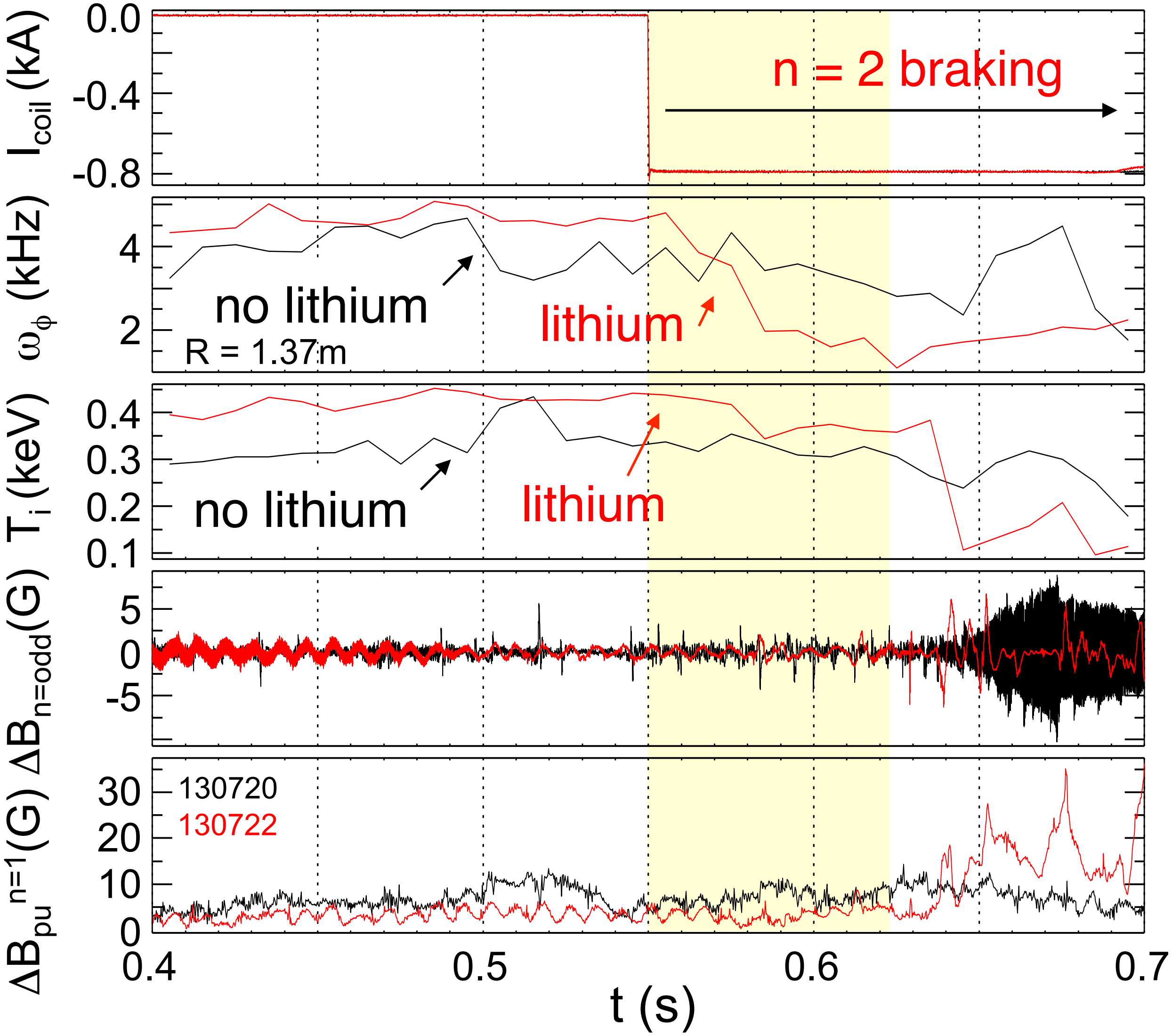
- Stronger ω_ϕ damping by NTV at higher T_i ($\tau_{NTV} \sim T_i^{5/2}$)
- The ω_ϕ saturates in case with lithium at reduced applied δB

Advances in global mode feedback control, kinetic stabilization physics and magnetic braking research

- Active n = 1 control, DC n = 3 error field correction maintain high β_N plasma over ideal $\beta_N^{\text{no-wall}}$ limit for long pulse
  - Growing RWM converts to kink that stabilizes; can yield tearing mode
- Control performance compares well to theory
  - Significant β_N increase expected for ITER with proposed internal coil
- Kinetic modifications to ideal stability can reproduce behavior of observed RWM marginal stability vs. V_ϕ
  - Simple critical rotation threshold models for RWM stability inadequate
- Non-resonant V_ϕ braking observed due to n = 2 applied field
  - Braking magnitude increases with increased T_i

Reprints

Stronger non-resonant braking at increased T_i



- ☐ Examine T_i dependence of neoclassical toroidal viscosity (NTV)
- ☐ Li wall conditioning produces higher T_i in region of high rotation damping
- ☐ Expect stronger NTV torque at higher T_i ($\sim T_i^{5/2}$)
  - ☐ At braking onset, Ti ratio$^{2.5}$ = $(0.45/0.34)^{2.5} \sim 2$
  - ☐ Consistent with measured $d\omega_\phi/dt$ in region of strongest damping