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Recent RWM control, stabilization physics, and non-resonant magnetic braking results in NSTX

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For the

NSTX Macroscopic Stability Topical Science Group

12th Meeting of the ITPA MHD Stability Topical Group

October 20-22, 2008

CRPP, Lausanne, Switzerland

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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/m²)   *ST-DEMO*: $\beta_N \sim 7.5$

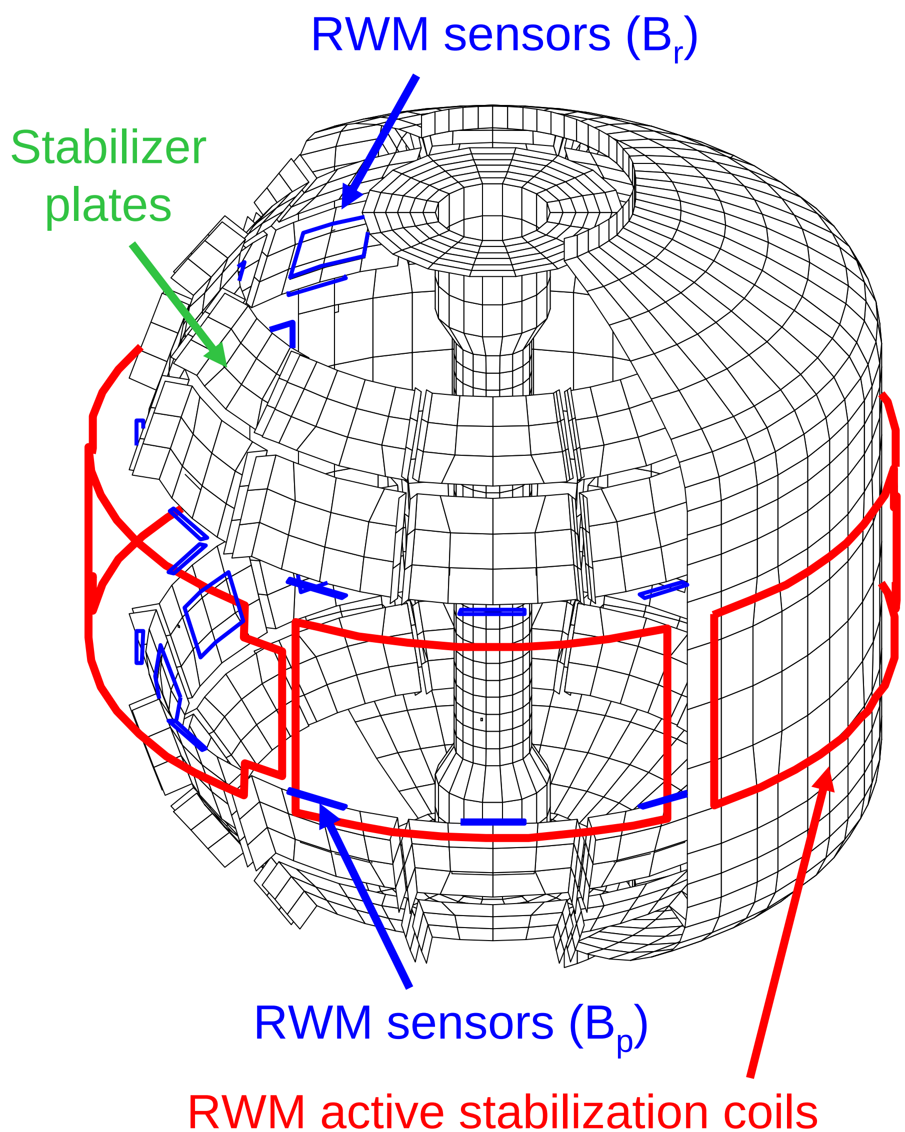
- Both at, or above ideal no-wall β-limit; deleterious effects at ~ ½ $\beta_N^{no\text{-}wall}$

- high β_N accelerates neutron fluence goal - takes 20 years at W_L = 1 MW/m²)

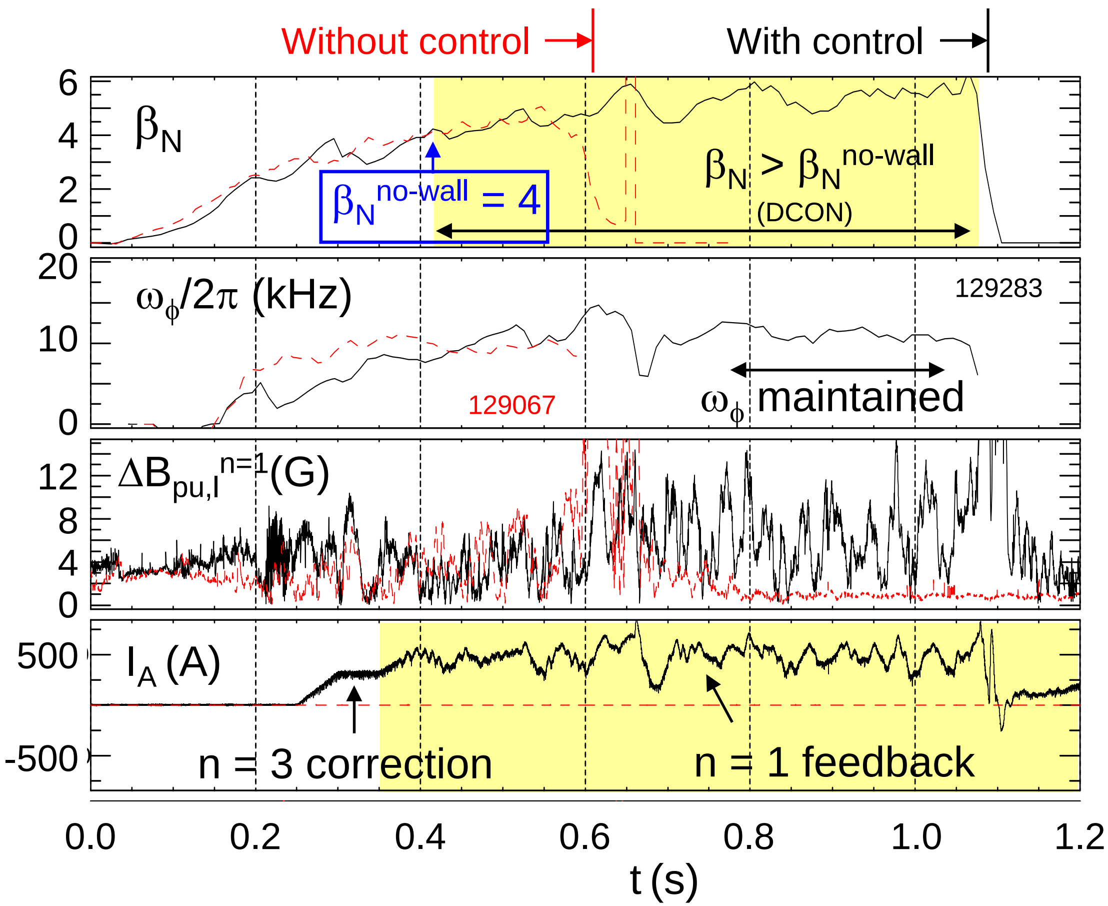
- Outline
  - Active control of beta amplified n = 1 fields / global instabilities
  - Mode dynamics and evolution during active control
  - Control performance compared to theory, connection to ITER
  - Kinetic effects on resistive wall mode (RWM) stabilization
  - Non-axisymmetric field influence on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

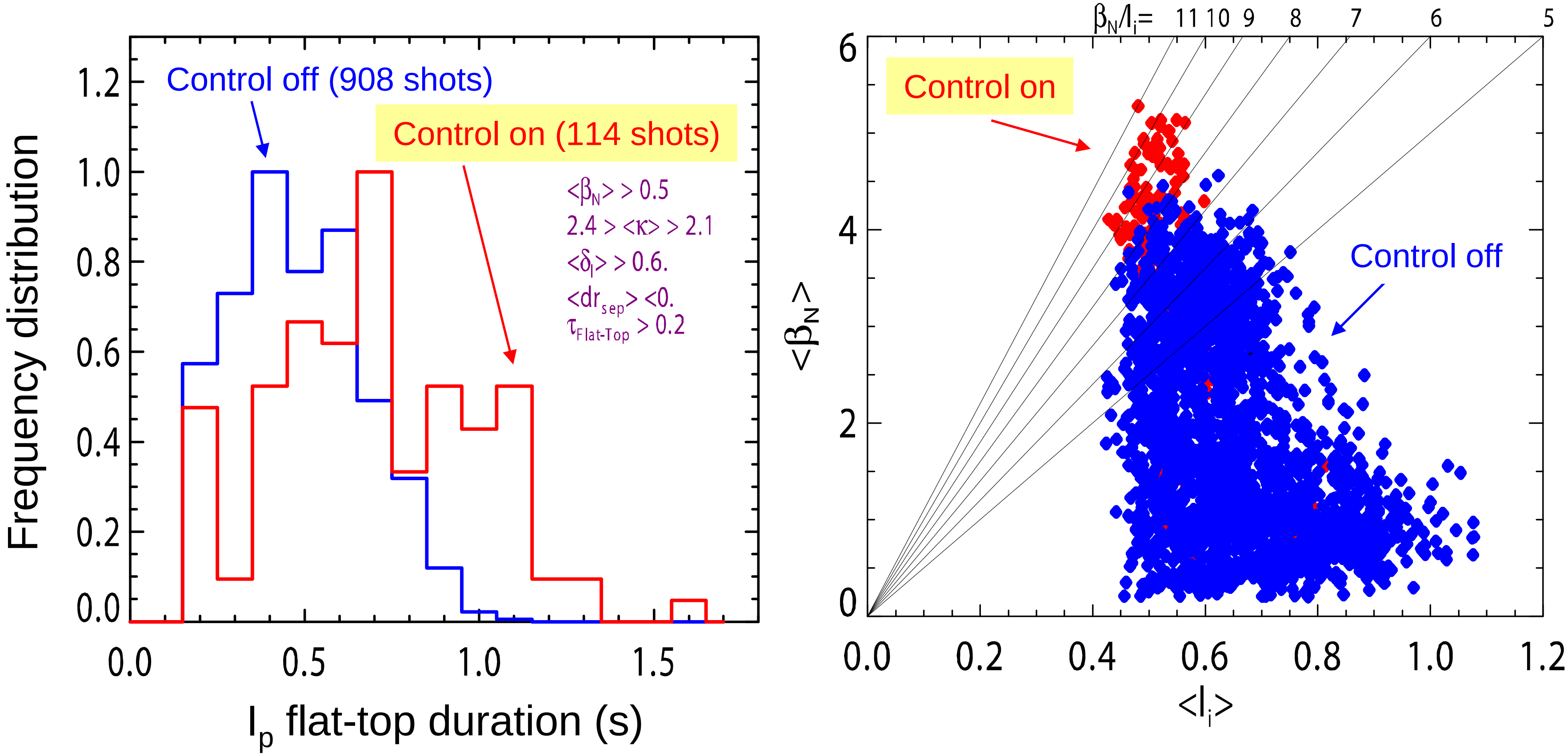


Active RWM control and error field correction maintain high β_N plasma



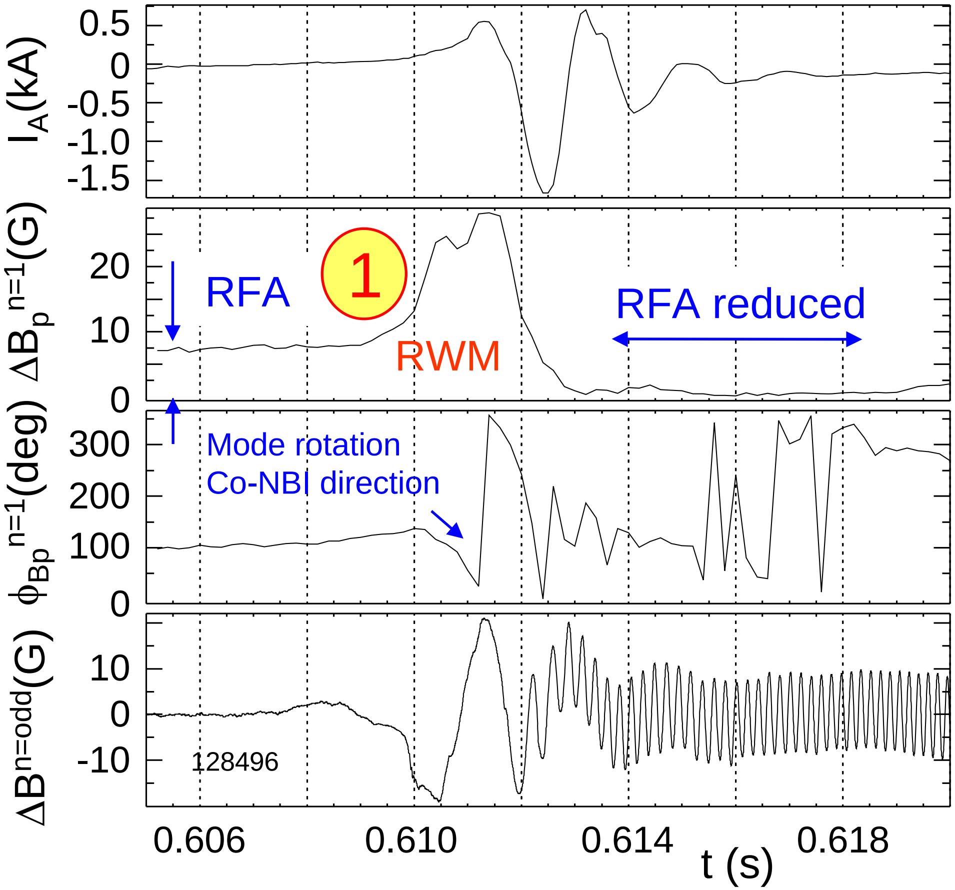
- n = 1 active, n = 3 DC control
  - n = 1 response ~ 1 ms < $1/\gamma_{RWM}$
  - $\beta_N/\beta_N^{no-wall}$ = 1.5 reached
  - best maintains ω_ϕ
- NSTX record pulse lengths
  - limited by magnet systems
  - n > 0 control first used as standard tool in 2008
- Without control, plasma more susceptible 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 $\langle\beta_N\rangle_{pulse}$ 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

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



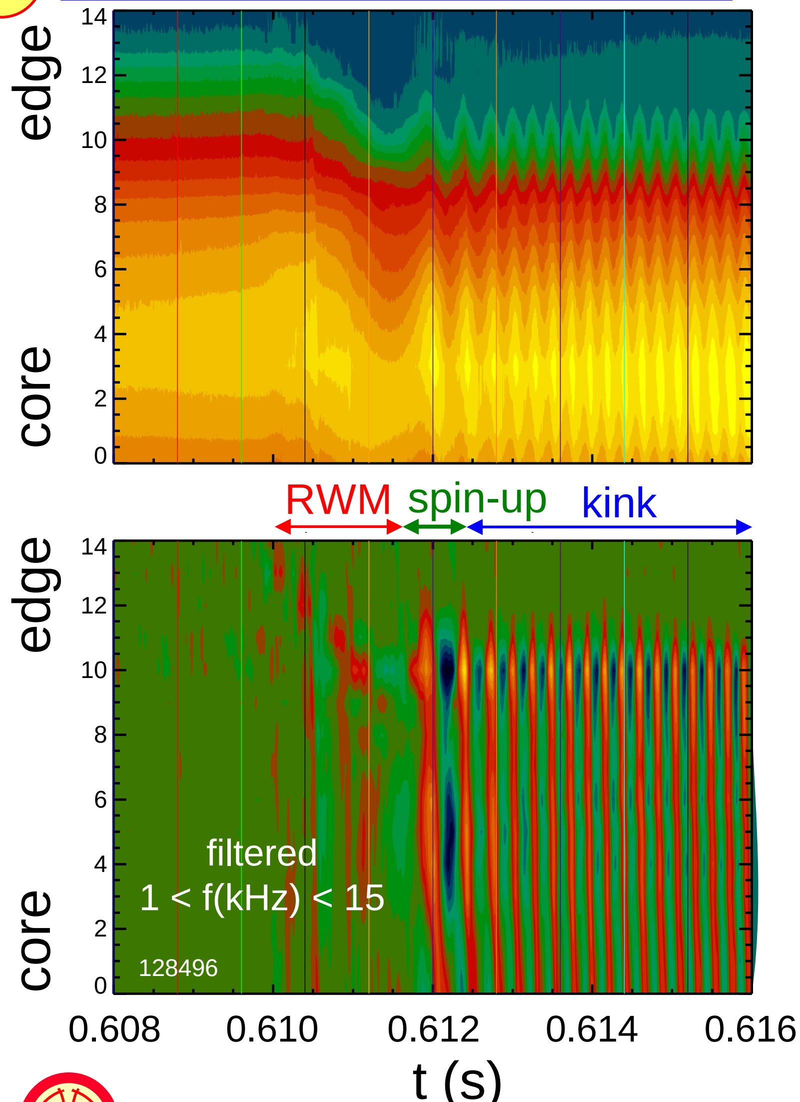
1 RWM grows and begins to rotate

- 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

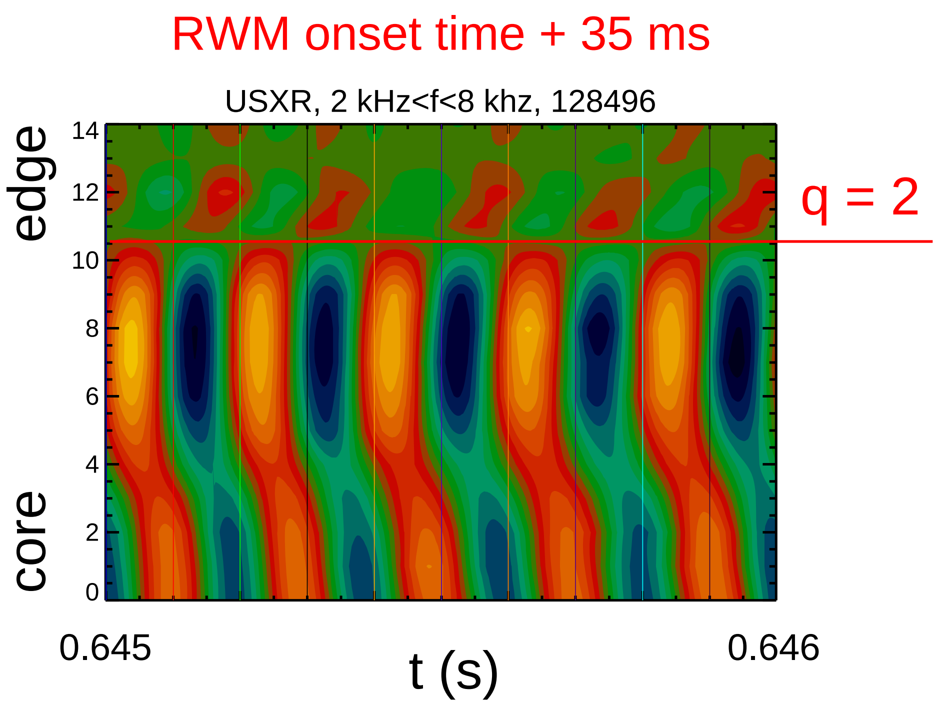
- Conversion from RWM to rotating kink occurs on τ_w timescale
- Kink either damps away, or saturates
  - Tearing mode can appear during saturated kink

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

1 Transition from RWM to kink

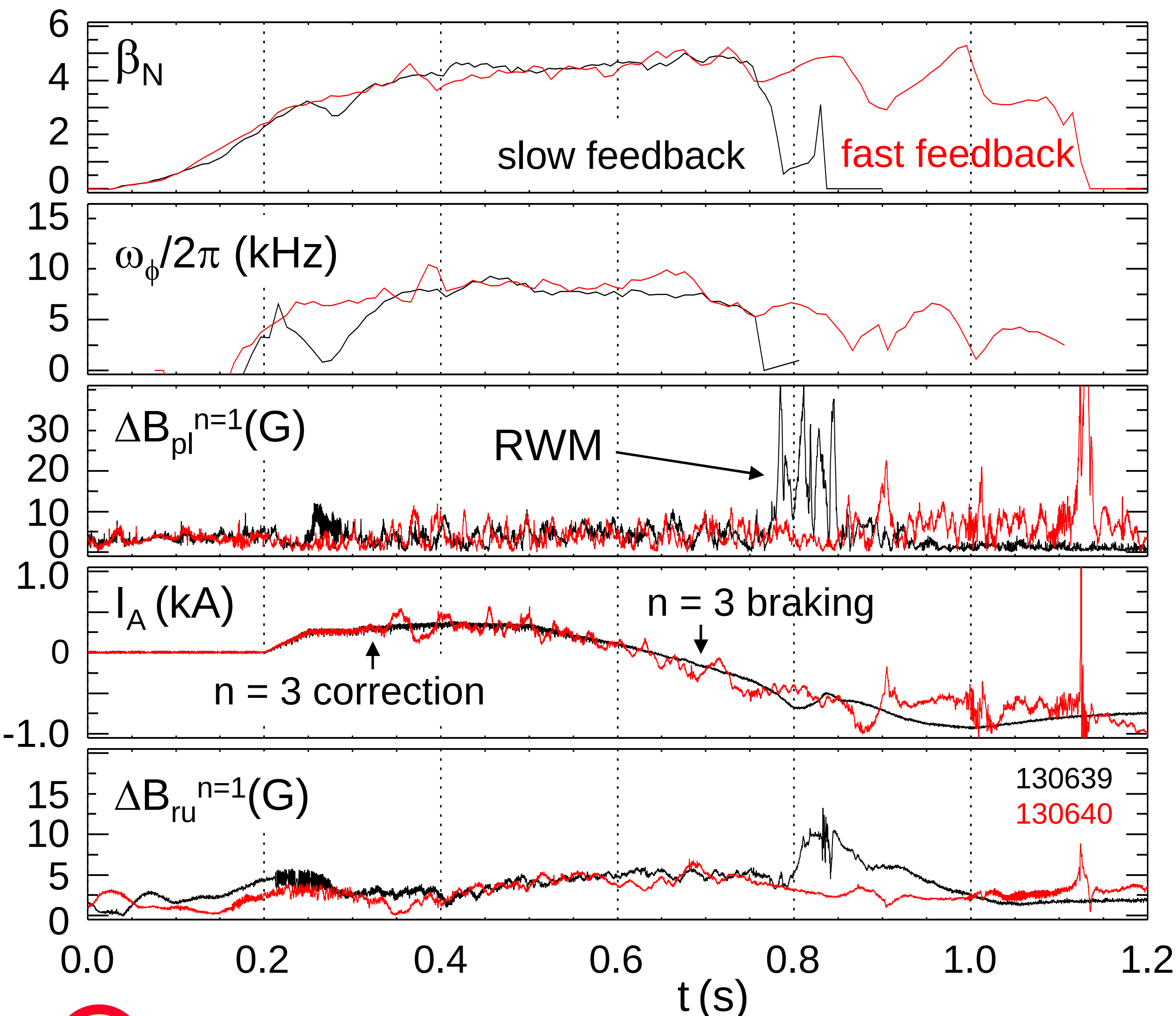


2 Tearing mode appears during kink



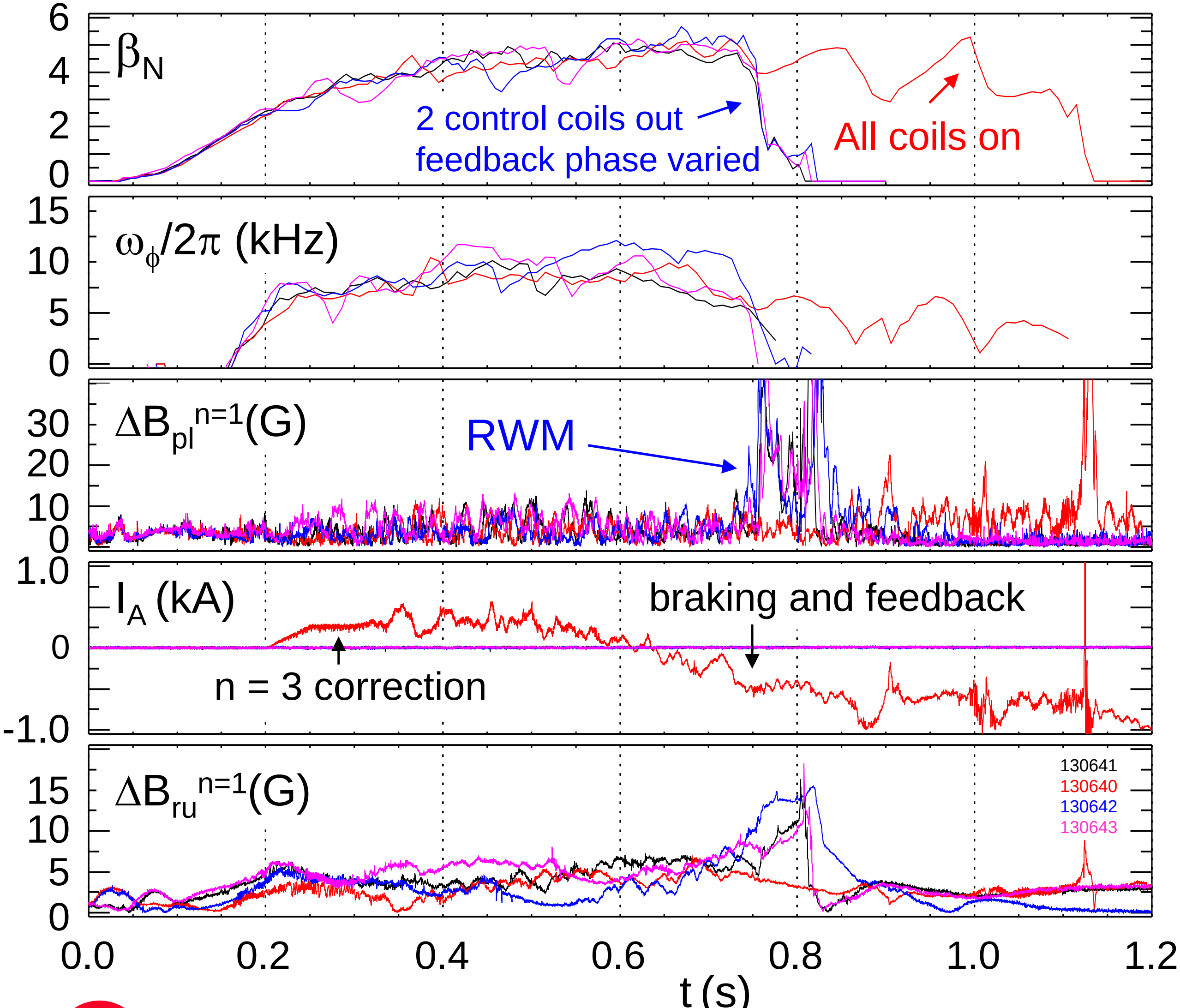
- Initial transition from RWM to saturated kink
- Tearing mode appears after 10 RWM growth times and stabilizes

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 $\omega_\phi \sim$ 5kHz near q = 2

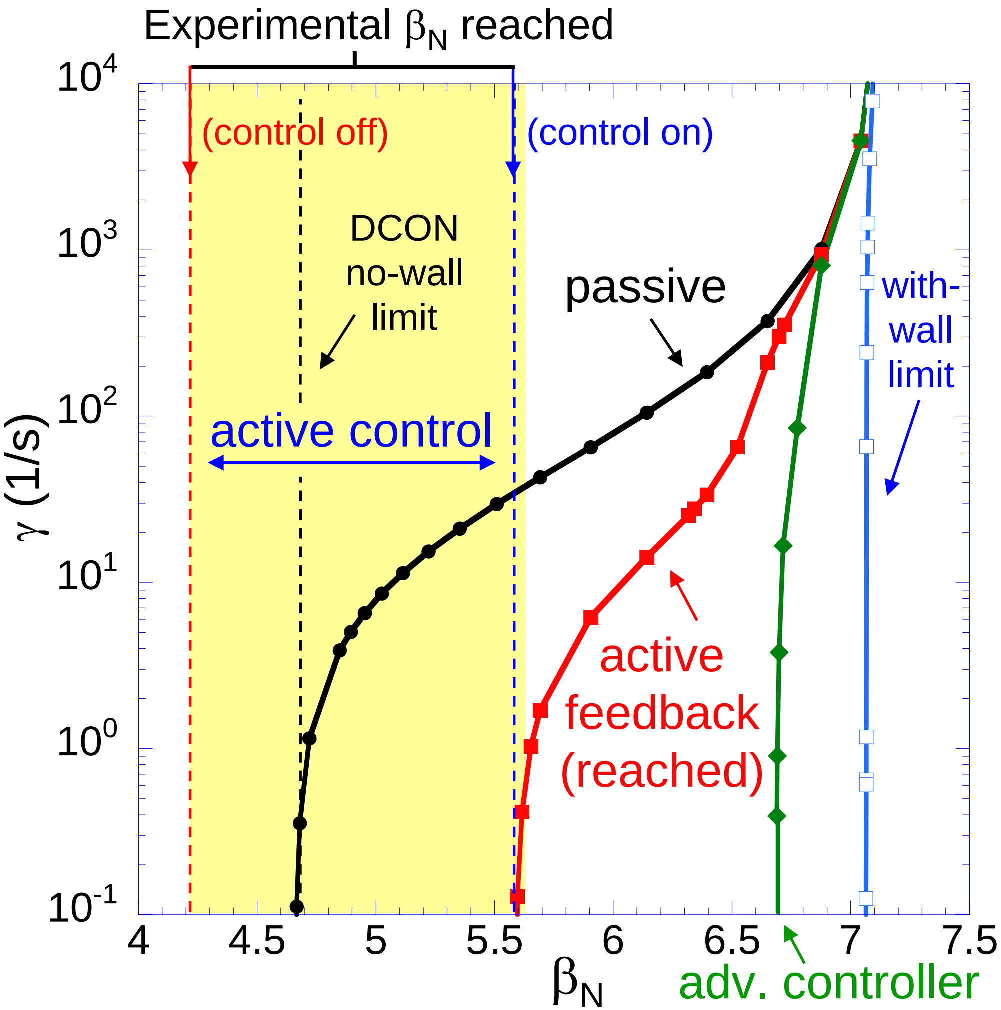
ITER support: Low ω_ϕ, high β_N plasma not accessed when two feedback control coils are disabled

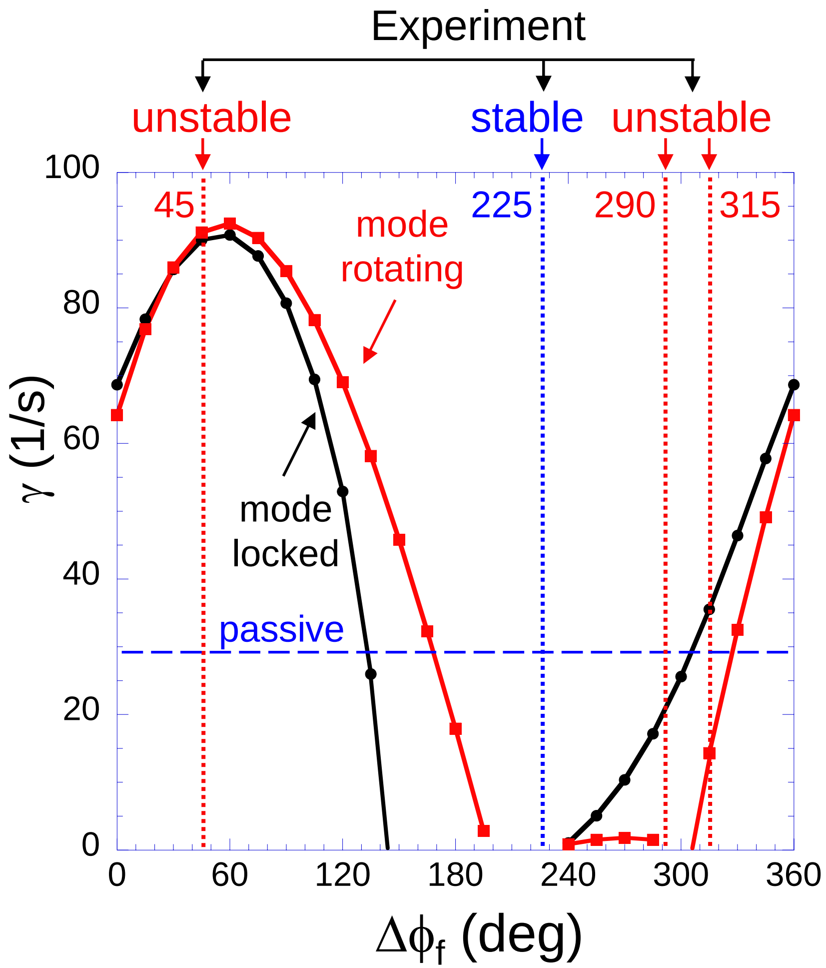


- Low ω_ϕ access for ITER study
  - use braking
- n = 1 feedback doesn't stabilize plasma with 2 of 6 control coils disabled
  - scenario to simulate failed coil set in ITER
  - Feedback phase varied, but no settings worked
  - RWM onset at identical time, plasma rotation

NSTX

Experimental RWM control performance consistent with theory



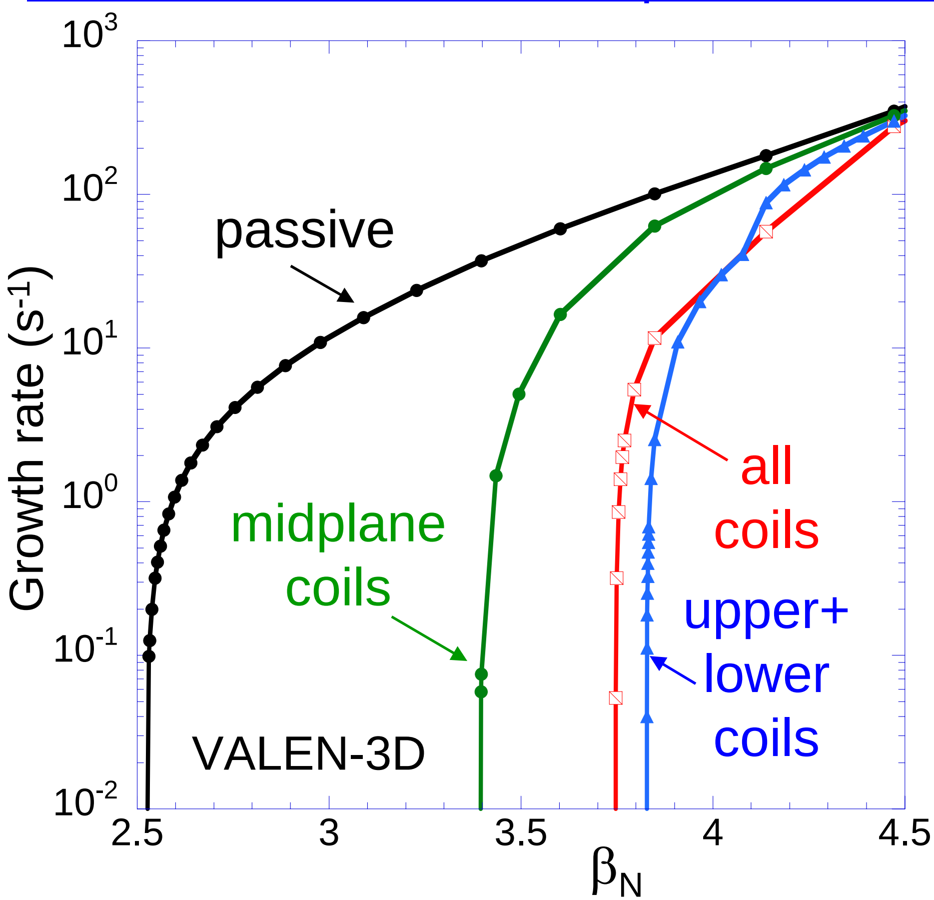


- VALEN code with realistic sensor geometry, plasmas with reduced V_ϕ

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

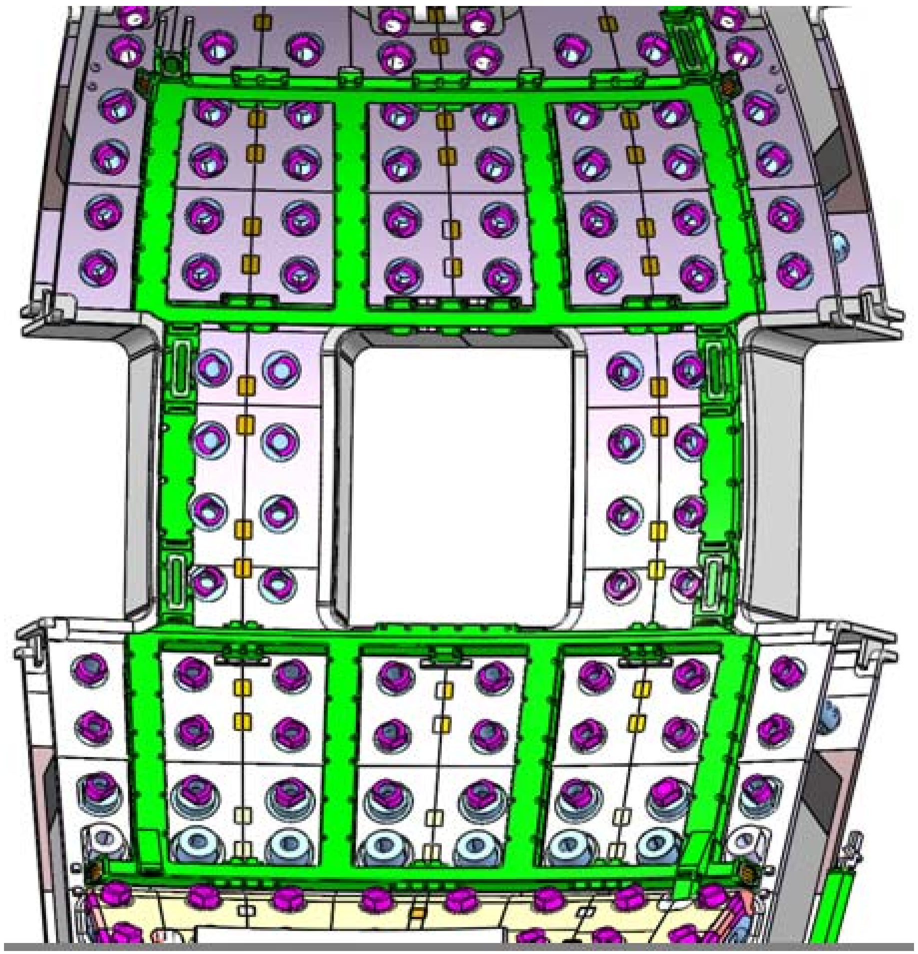
Significant β_N increase expected by internal coil proposed for ITER

ITER VAC02 stabilization performance



- 50% increase in β_N over RWM passive stability

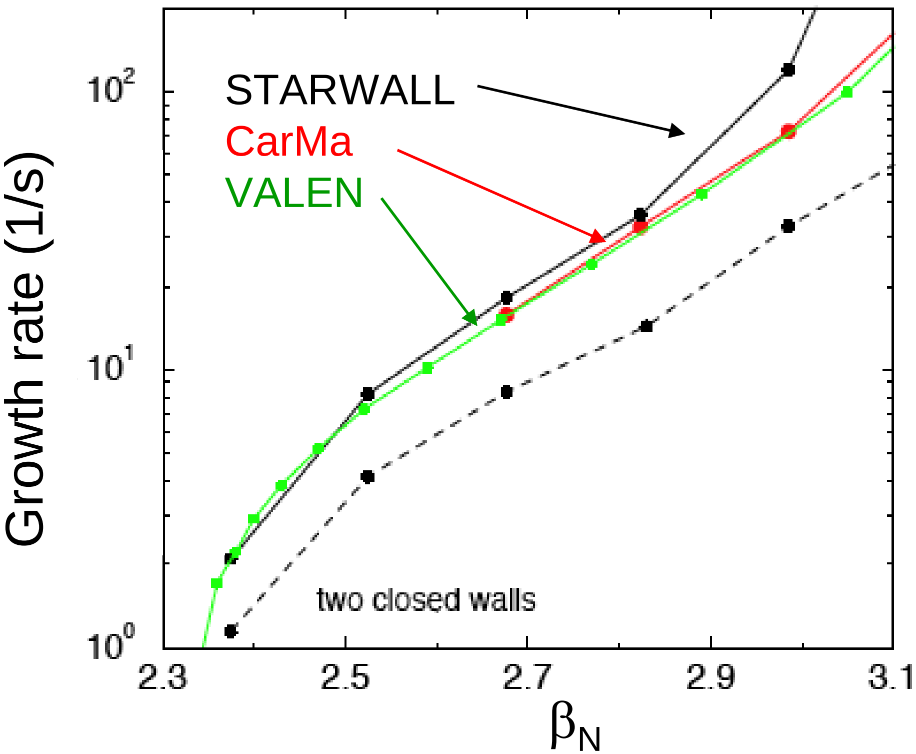
ITER VAC02 design (40° sector)



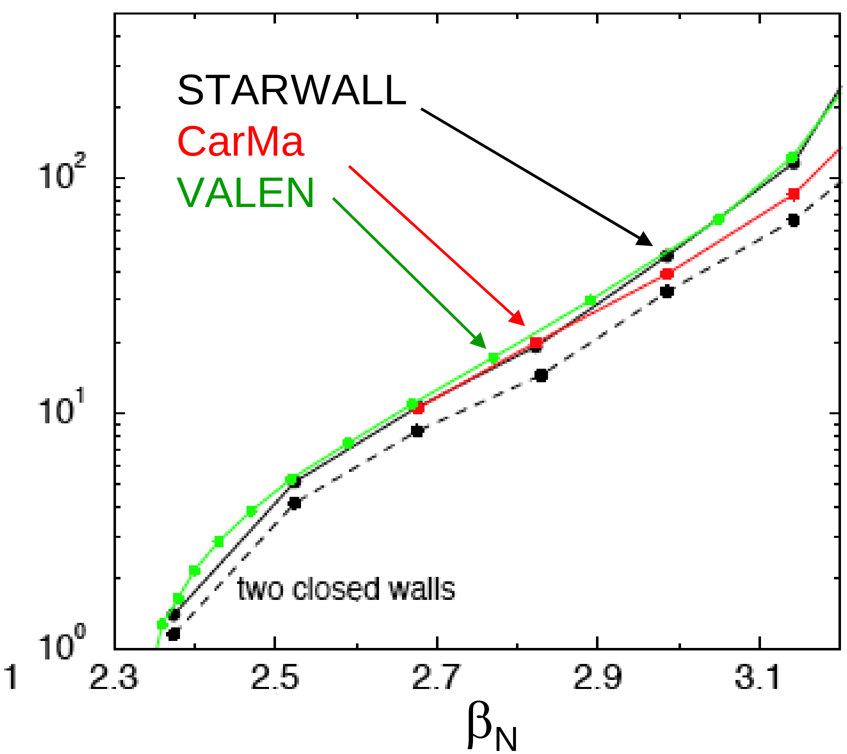
3 toroidal arrays, 9 coils each

VALEN, STARWALL, & CarMa in good agreement on passive RWM growth with 3D ITER Vacuum Vessel

With ports



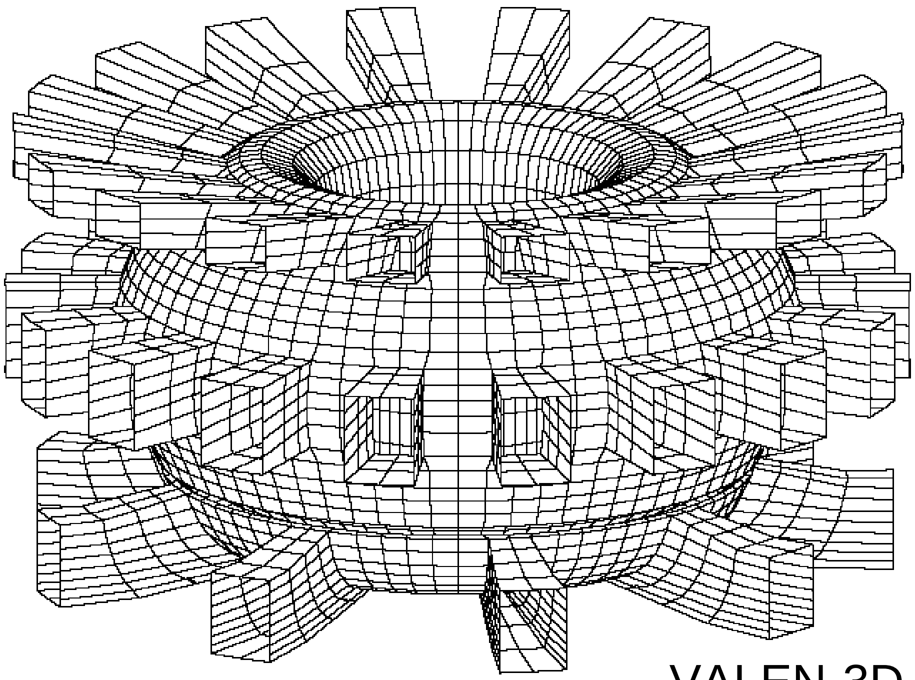
With ports and extensions

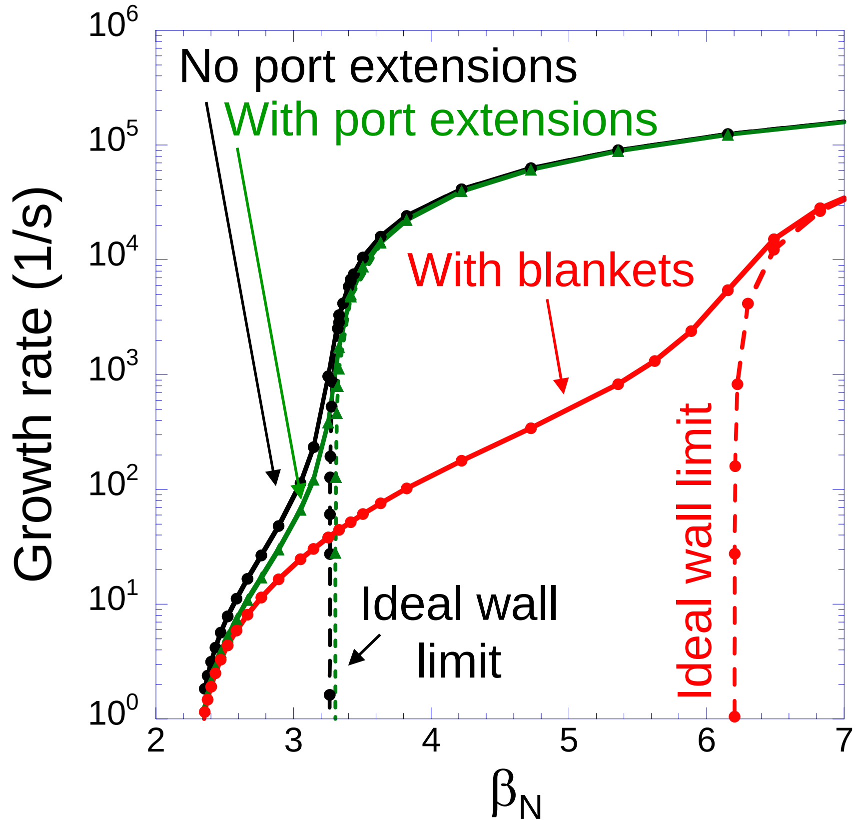


- Single-Mode model in all codes
  - Complex 3D ITER VV models for passive RWM growth rates in Scenario 4 plasma

ITER blanket modules affect RWM passive stability significantly more than port extensions

Inner wall w/port extensions

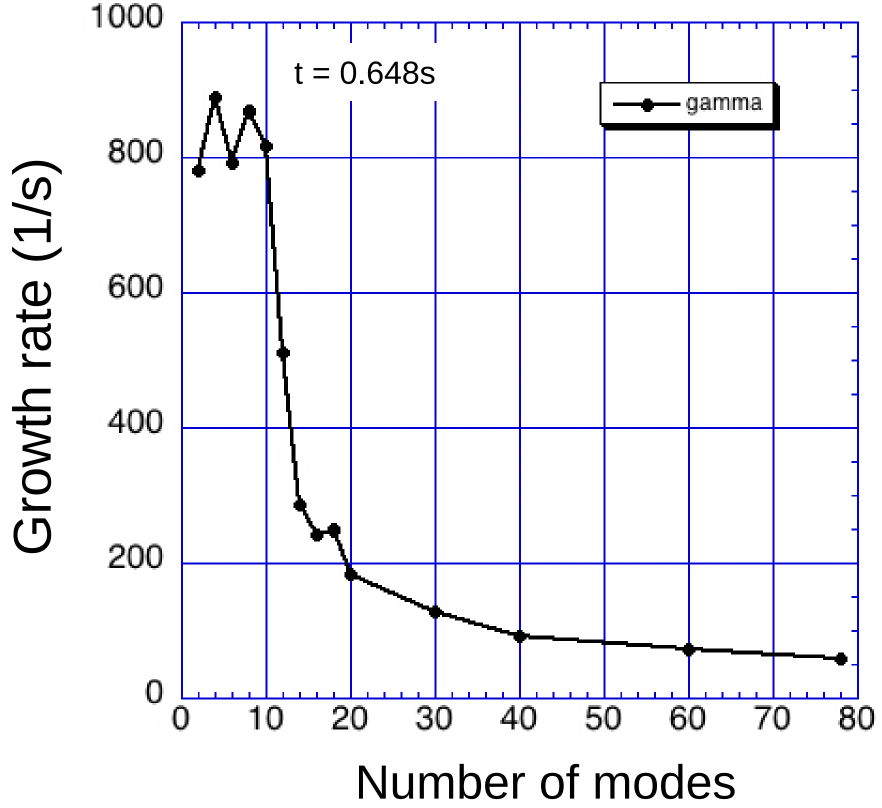


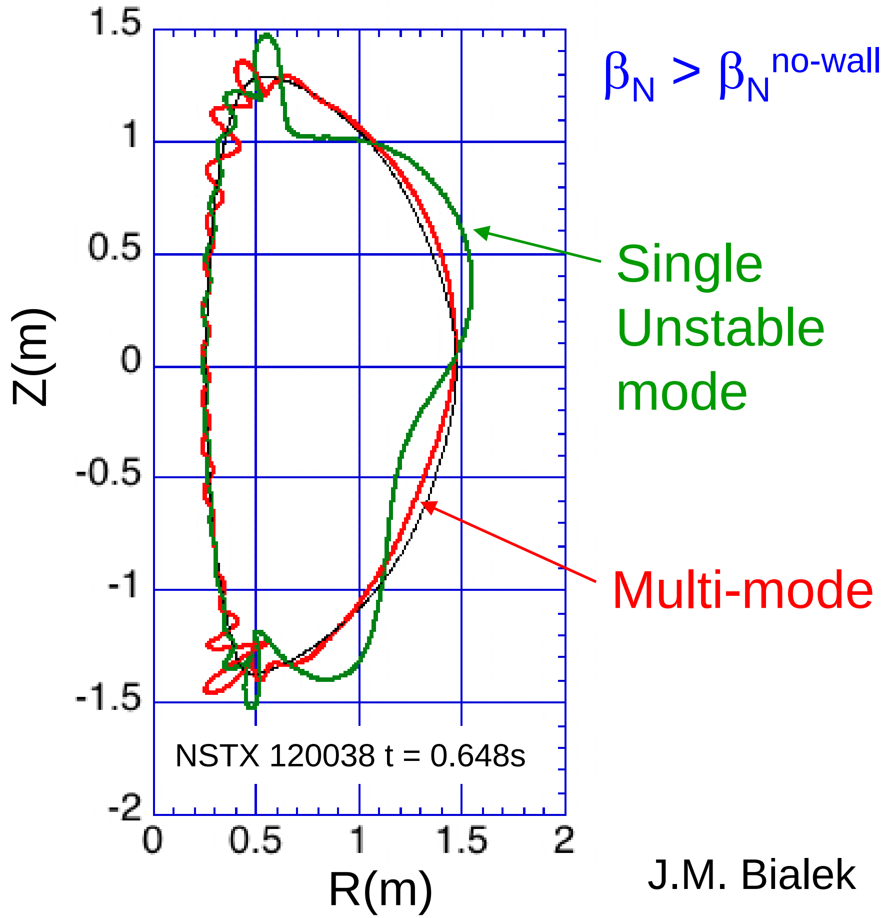


- Double-walled vacuum vessel with port extensions (STARWALL model)
- 50% change to growth rate with port extensions alone
- Far greater change w/blankets

Multi-mode version of VALEN now being tested and compared to experiment

NSTX shot 120038





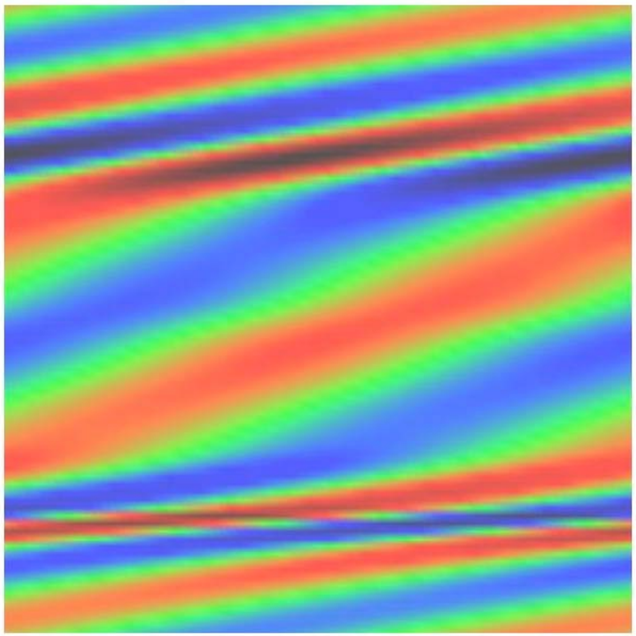
J.M. Bialek

- RWM growth rate decreases rapidly with increased number of modes up to ~ 40 modes
- Larger mode spectrum decreases poloidal variation of mode amplitude

mmVALEN shows modest qualitative changes to n = 1 RWM structure in DIII-D

Single mode

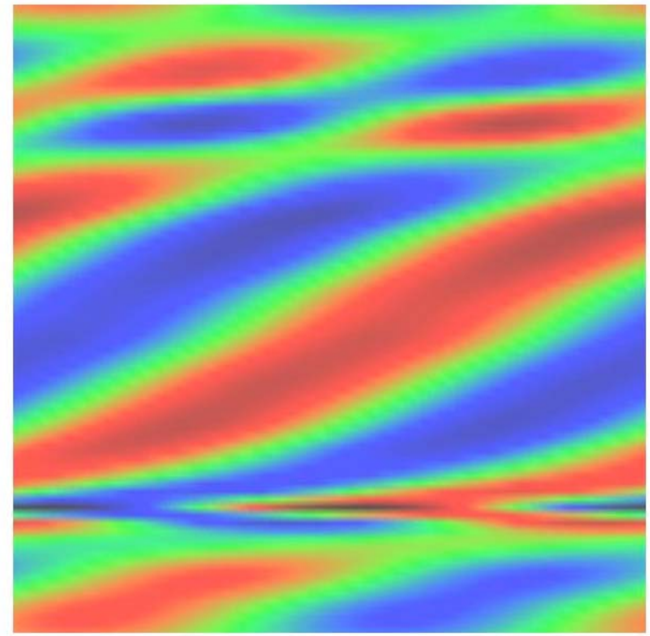
Poloidal angle



Toroidal angle

Multi-mode

Poloidal angle



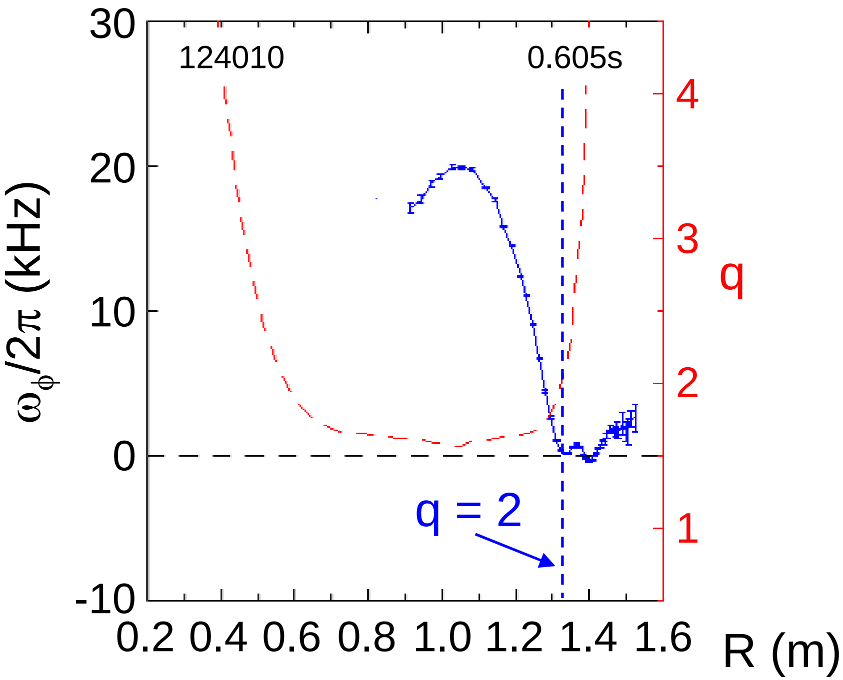
Toroidal angle

DIII-D 125701, t = 2.5s

- Multi-mode pattern shows influence of resistive wall
  - Eigenfunctions with n = 1 used
  - Code capable of including higher n modes - to be tested and compared to experiment

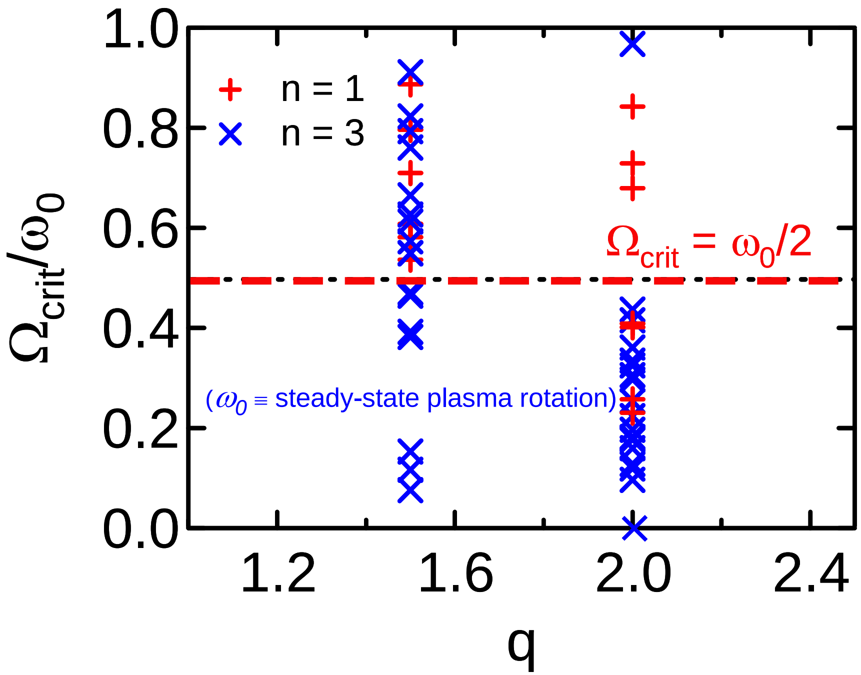
Non-resonant magnetic braking allows V_ϕ modification to probe RWM critical rotation and stabilization physics

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



- 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)

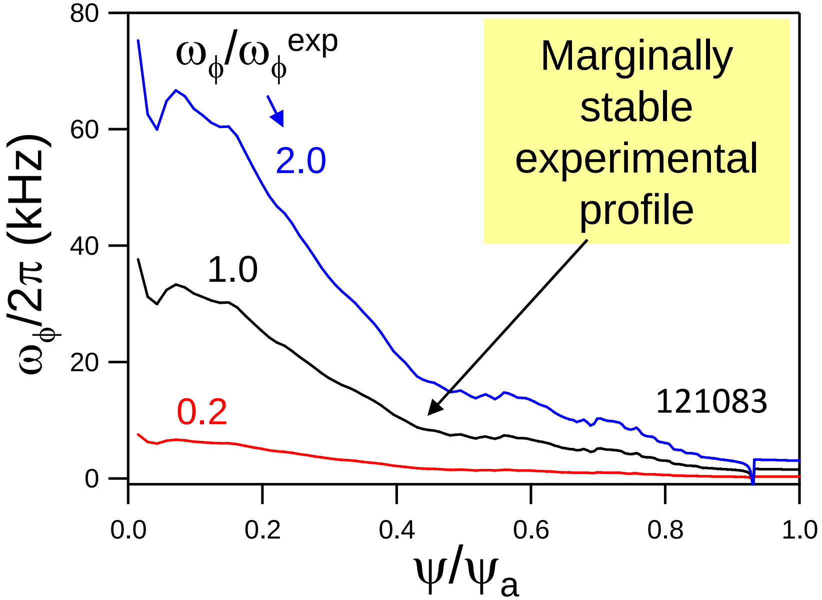
$$\delta W_K \propto \int \left[\frac{\omega_{*N} + \left(\hat{\varepsilon} - 3/2\right)\omega_{*T} + \omega_E - \omega - i\gamma}{\langle\omega_D\rangle + l\omega_b - i\nu_{eff} + \omega_E - \omega - i\gamma} \right] \hat{\varepsilon}^{\frac{5}{2}} e^{-\hat{\varepsilon}} d\hat{\varepsilon}$$

← Energy integral

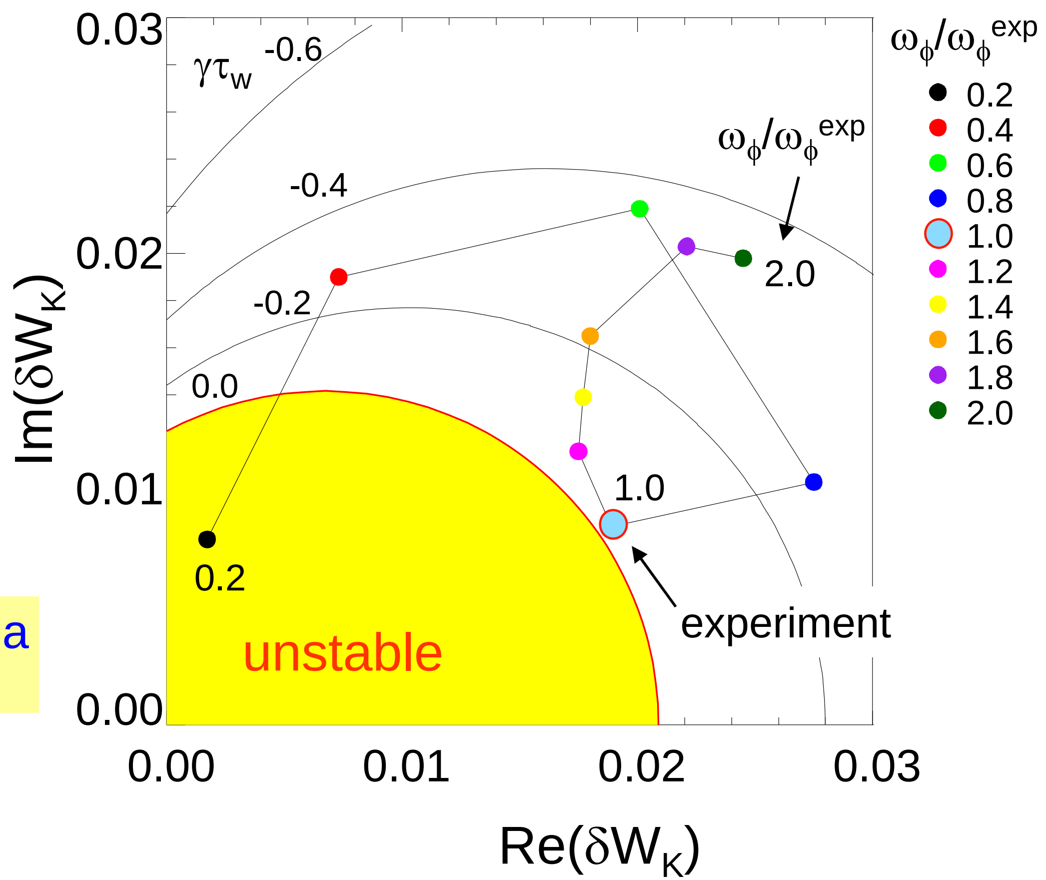
precession drift (→ $\langle\omega_D\rangle$) bounce (→ $l\omega_b$) collisionality (→ ν_{eff})

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

Theoretical variation of ω_ϕ

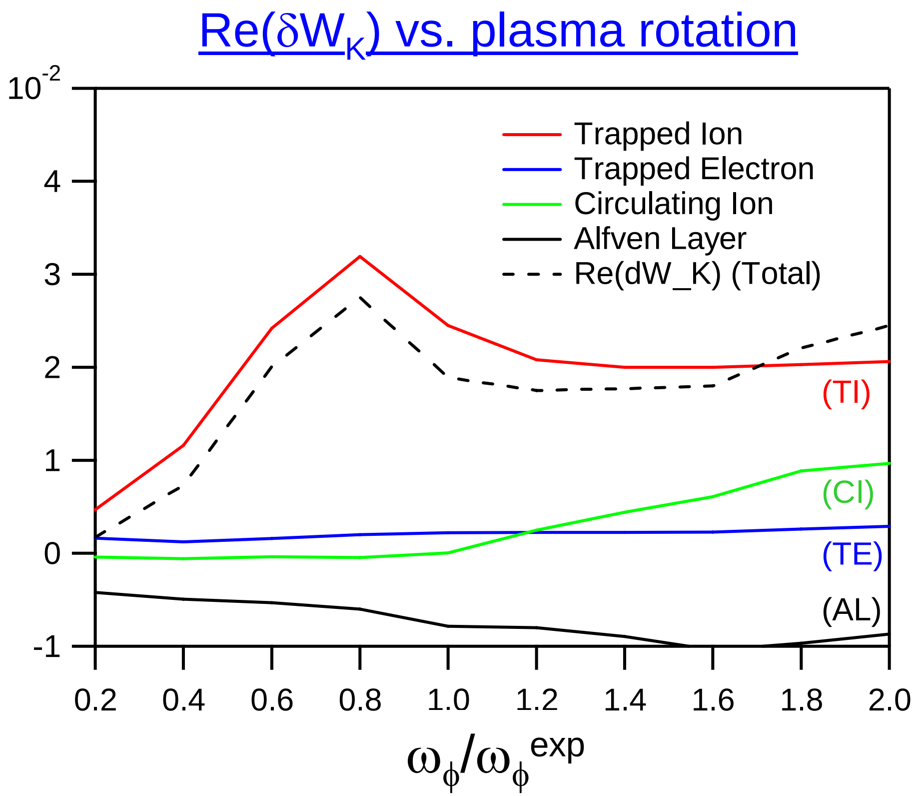


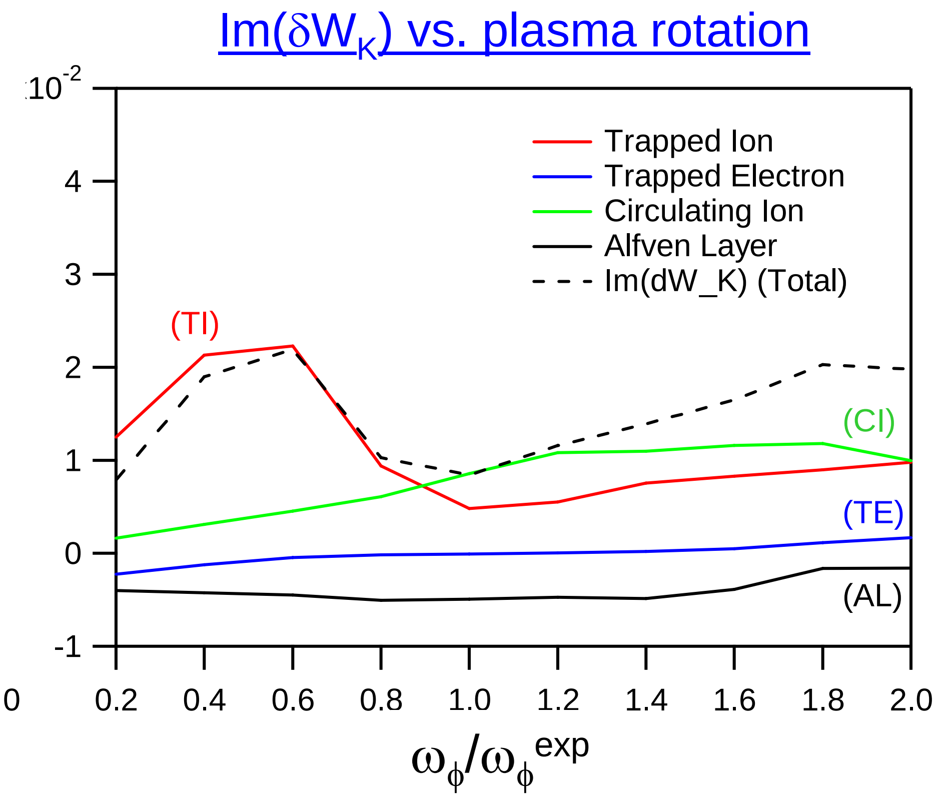
RWM stability vs. V_ϕ (contours of $\gamma\tau_w$)



- 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

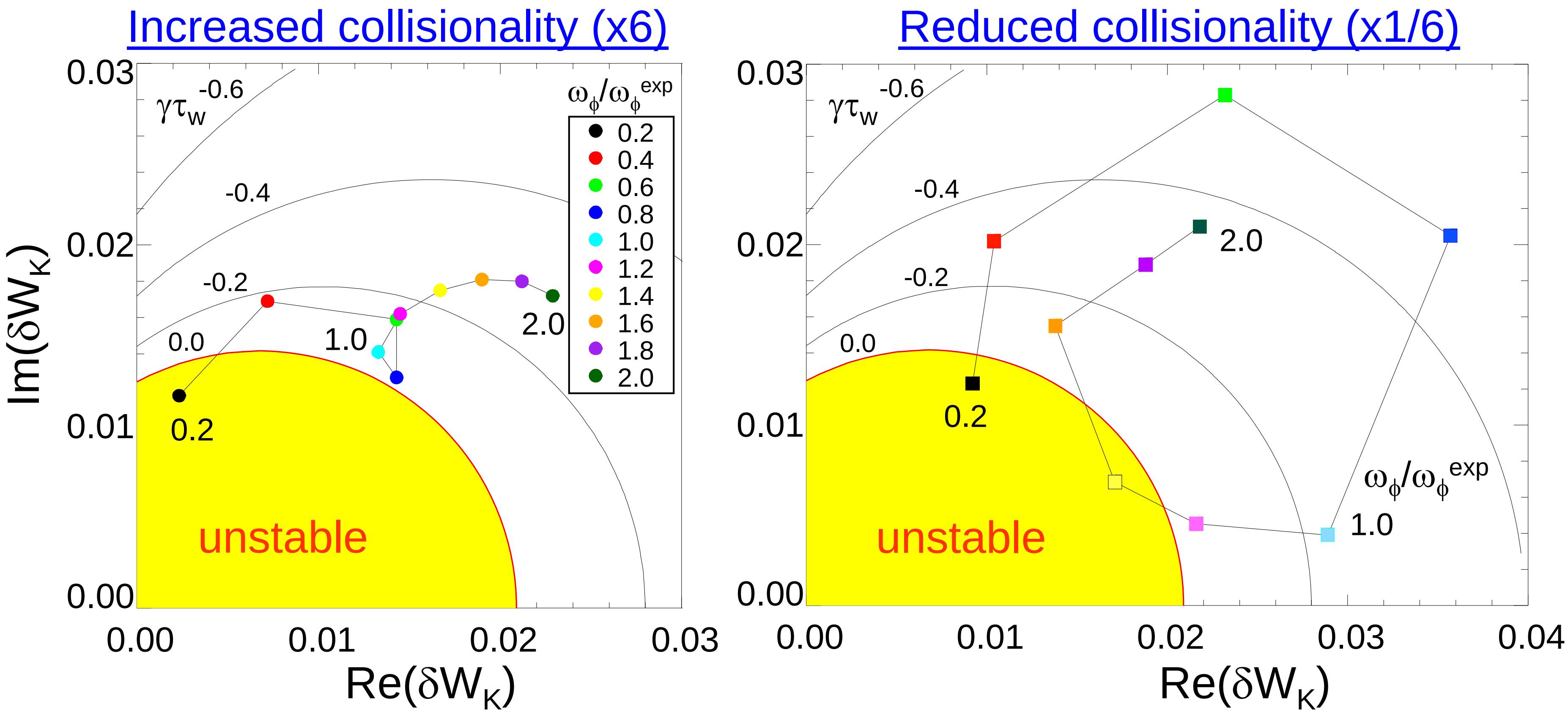
Stabilizing influence of kinetic effects changes as plasma rotation varies





- 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

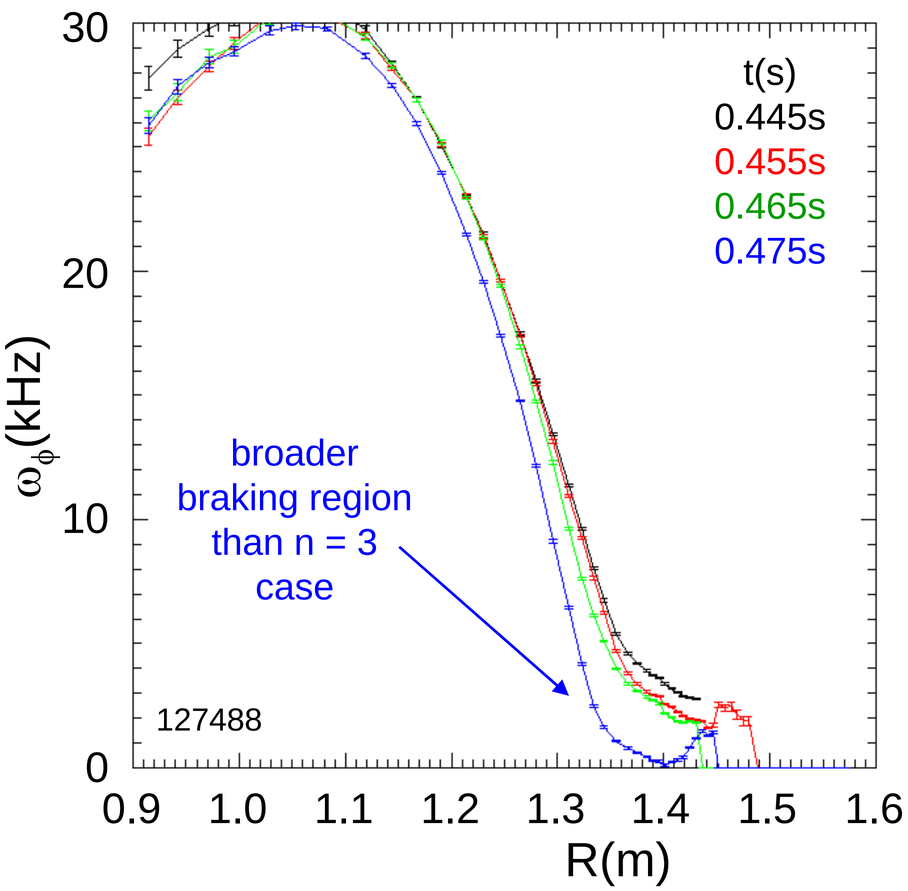
Kinetic model shows overall increase in stability as collisionality decreases



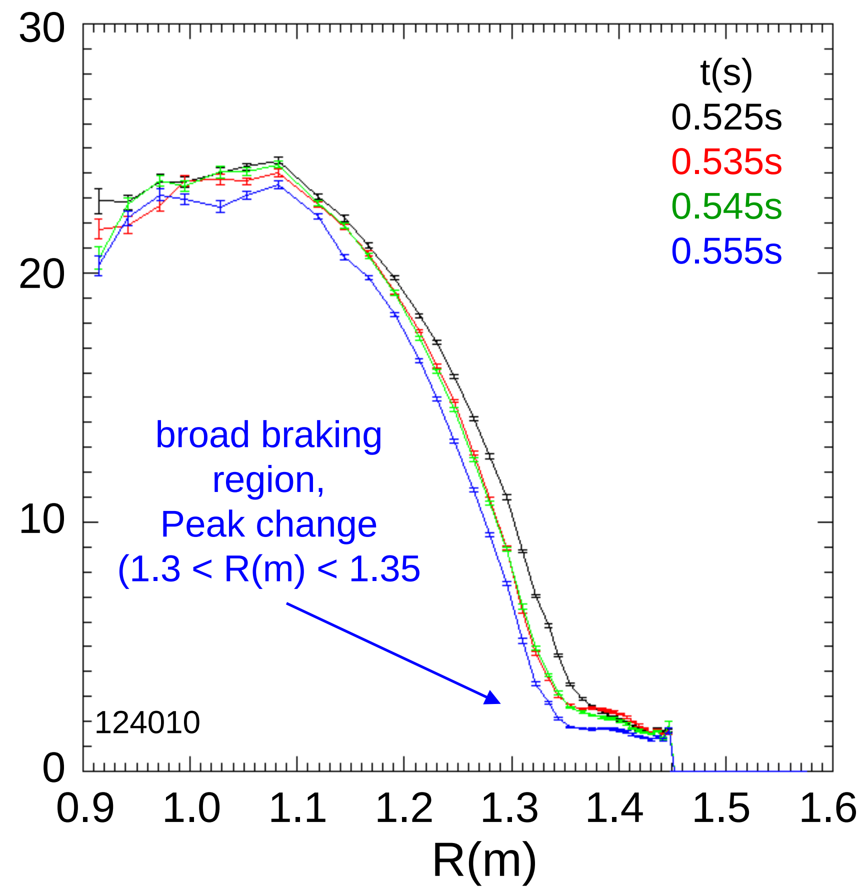
- Vary ν by varying T, n at constant β
- Simpler stability dependence on ω_ϕ at increased ν
- Increased stability at $\omega_\phi/\omega_\phi^{exp} \sim 1$
- Unstable band in ω_ϕ at increased ω_ϕ

Non-resonant rotation braking produced using n = 2 field

Rotation evolution during n = 2 braking

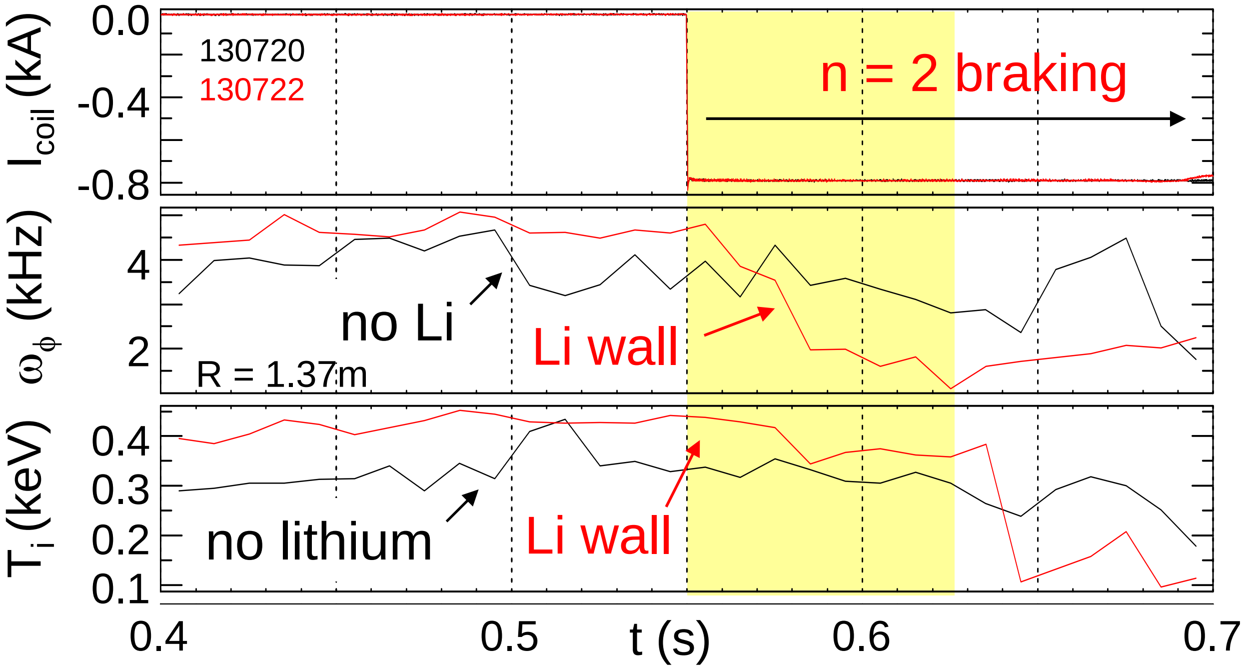


Rotation evolution during n = 3 braking

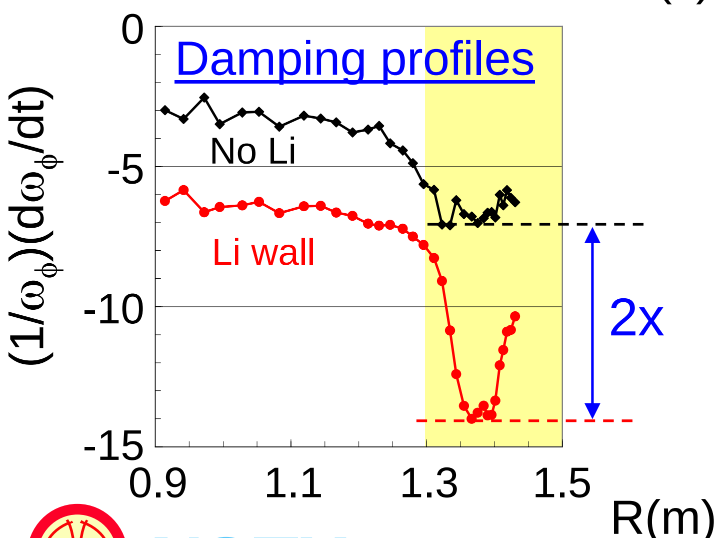


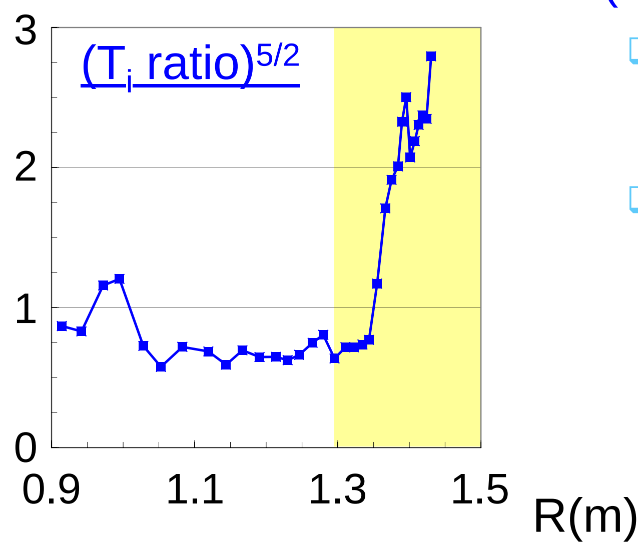
- n = 2 has broader braking profile than n = 3 field (from field spectrum)

Stronger non-resonant braking at increased T_i



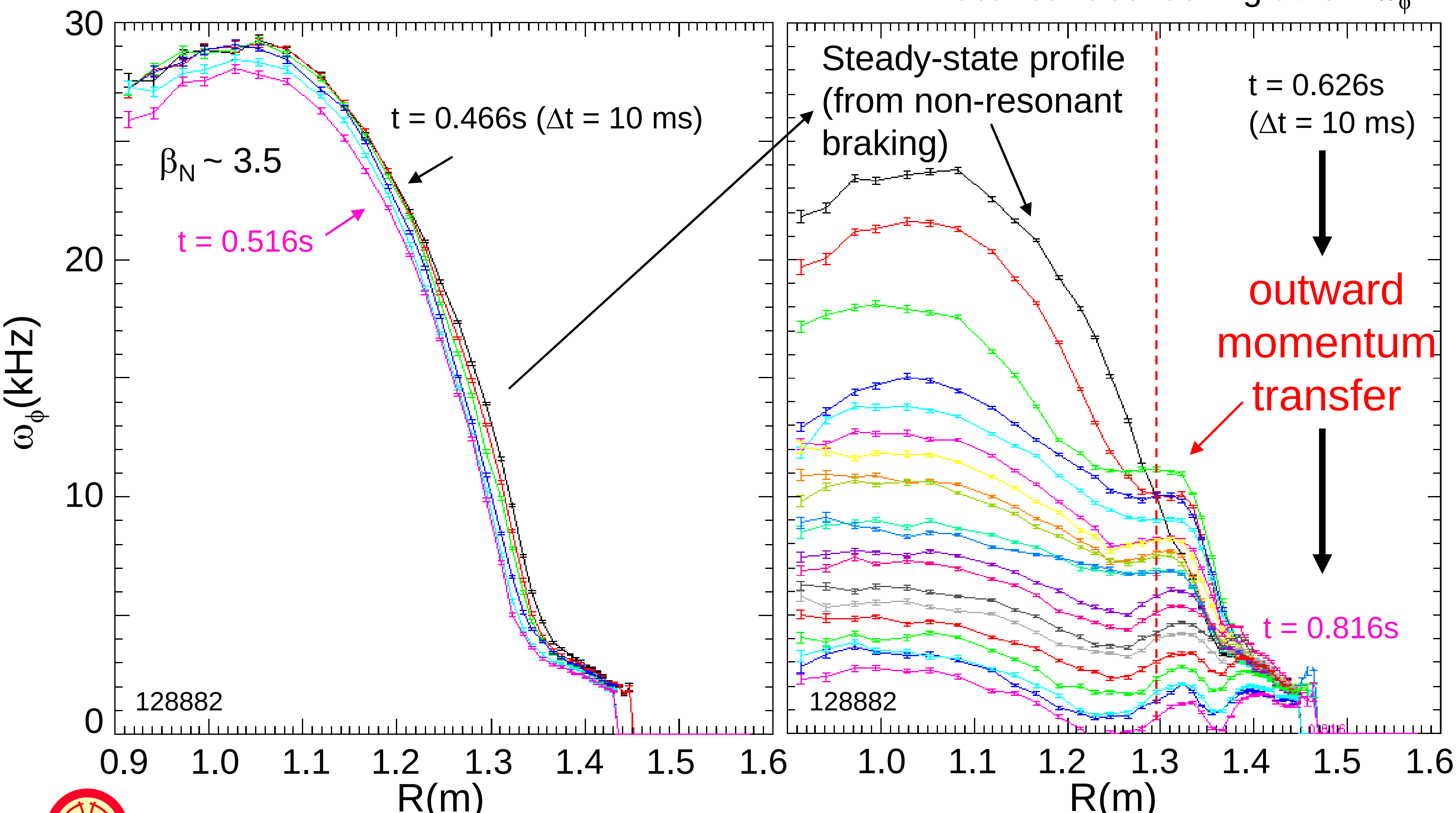
- Examine T_i dependence of neoclassical toroidal viscosity (NTV)
- Li wall conditioning produces higher T_i in region of high rotation damping
- Expect stronger NTV torque at higher T_i ($-d\omega_\phi/dt \sim T_i^{5/2}\,\omega_\phi$)
  - At braking onset, T_i ratio$^{5/2}$ = $(0.45/0.34)^{5/2} \sim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





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



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 $\beta_N^{no\text{-}wall}$ 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