Supported by Office of Science

Macroscopic Mode Control Research on NSTX and Related Components of the 5 Year Plan

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US-Japan Workshop on MHD Control, Magnetic Islands and Rotation

November 23-25, 2008

UT-Austin, Austin, Texas

Culham Sci Ctr
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Understanding what profiles and control systems are needed for burning plasmas best occurs before such devices are built

- FESAC US ST mission:
  - *Develop compact, high β, burning plasma capability for fusion energy*

CTF: β_N = 3.8 – 5.9 (W_L = 1-2 MW/m^2) *ST-DEMO: β_N ~ 7.5*
- Both at, or above ideal no-wall β-limit; deleterious effects occur below $\beta_N^{no\text{-}wall}$
- high β_N accelerates neutron fluence goal - takes 20 years at W_L = 1 MW/m^2)

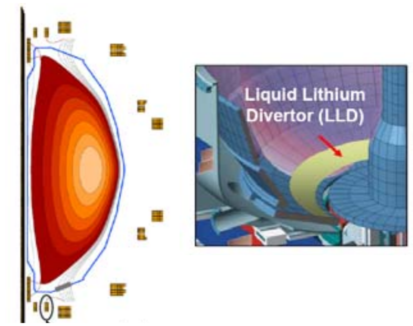
- Stability Goal (in one sentence)
  - Demonstrate reliable maintenance of high β_N with sufficient physics understanding to extrapolate to next-step devices

- Knowledge base needed to bridge to these devices; + physics for ITER
  - Demonstration = Control (of modes and plasma profiles):
    - Need to determine what control is needed *before* CTF (for greatest simplicity)
  - Understanding = Vary parameters (+operate closer to burning plasma levels):
    - Collisionality: influences V_ϕ damping
    - Shaping:
    - Plasma rotation level, profile:
    - *q* level, profile:

All influence β-limiting modes: Kink/ballooning, RWM, NTM

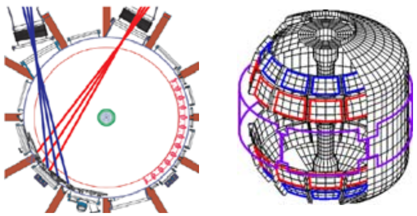
Development of device hardware empowers fundamental stability understanding for robust extrapolation to next-step STs

- Operate at parameters closer to burning plasma (e.g. order of magnitude lower ν_i (PTRANSP))
  - High plasma shaping (κ ~ 3), low l_i operation
    - Vertical stability, kink/ballooning stability, coupling to passive stabilizers
  - Resistive wall mode (RWM) stabilization
    - Understand physics of passive mode stabilization vs. V_ϕ at reduced ν_i
  - Non-axisymmetric field-induced viscosity
    - Non-resonant and resonant, due to 3-D fields and modes at reduced ν_i



- New center stack (B_t = 1T, I_p = 2 MA)
- Liquid Li divertor

- Control modes and profiles, understand key physics
  - Dynamic error field correction (DEFC)
    - Demonstrate sustained V_ϕ with reduced resonant field amplification, under V_ϕ profile control
  - Resistive wall mode control
    - Increase reliability of active control, investigate multi-mode RWM physics under V_ϕ, q control
  - Tearing mode / NTM
    - Stabilization physics at low A, mode locking physics under V_ϕ, q control
  - Plasma rotation control
    - Sources (2^{nd} NBI, magnetic spin-up) and sink (non-resonant magnetic braking)
  - Mode-induced disruption physics and prediction/avoidance



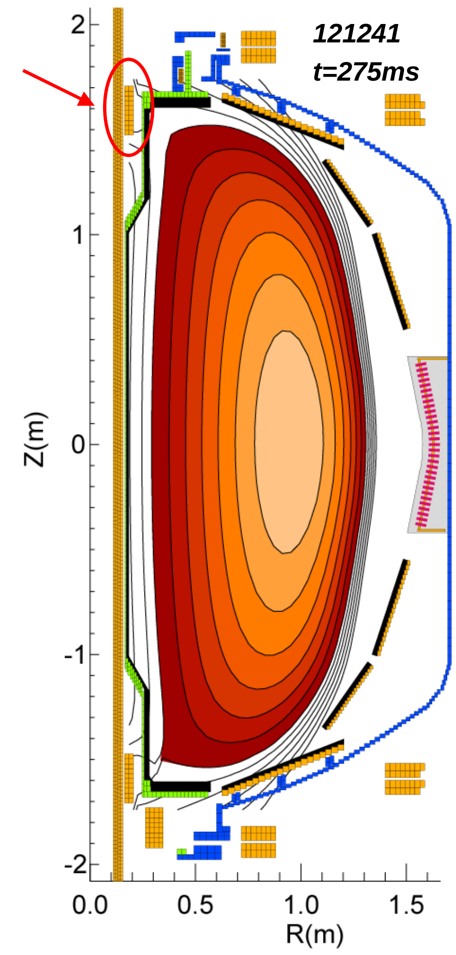
- 2^{nd} NBI (incr.)
- Singly-powered RWM control coils
- RWM coil upgrade (incr.)

Plasma equilibrium goal to access and maintain stable high β_N at high shaping

- **Progress**
  - Central coil PF1A modified (2005) to allow high shaping
  - Sustained $\kappa < 2.7$, $\delta < 0.8$; transient $\kappa = 3$ with record shaping factor, $S_l \equiv q_{95}(I_p/aB_t) = 41$
    - Note: Present CTF design has $\kappa = 3.07$, lower S_l
  - Highest κ and S_l plasmas reached $\beta_N \sim 6$ in 2008

- **Plan summary 2009-2011**
  - Assess/utilize β feedback control using real-time EFIT and NBI power to avoid fast kink/ballooning disruptions
  - Conduct experiments/analysis to maintain high S_l plasmas into wall-stabilized, high $\beta_N > 6$ operating space

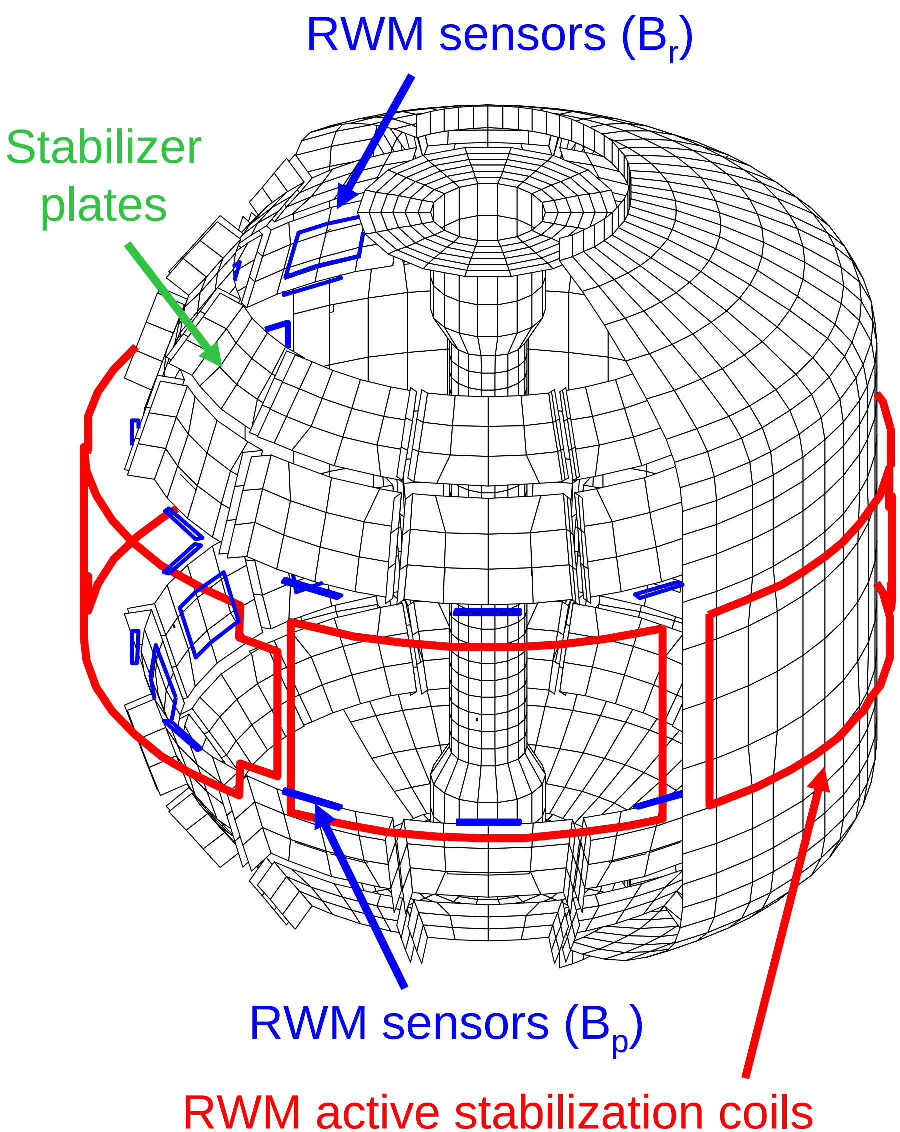
- **Plan summary 2012-2013**
  - Real-time MSE for evaluation of q in real-time EFIT
  - Utilize/analyze β feedback using stability models; q profile control with 2nd NBI (incremental)
  - Study ST-CTF target shapes (increased A) at low ν_i with favorable profiles, determine sensitivity to variations in l_i, δ



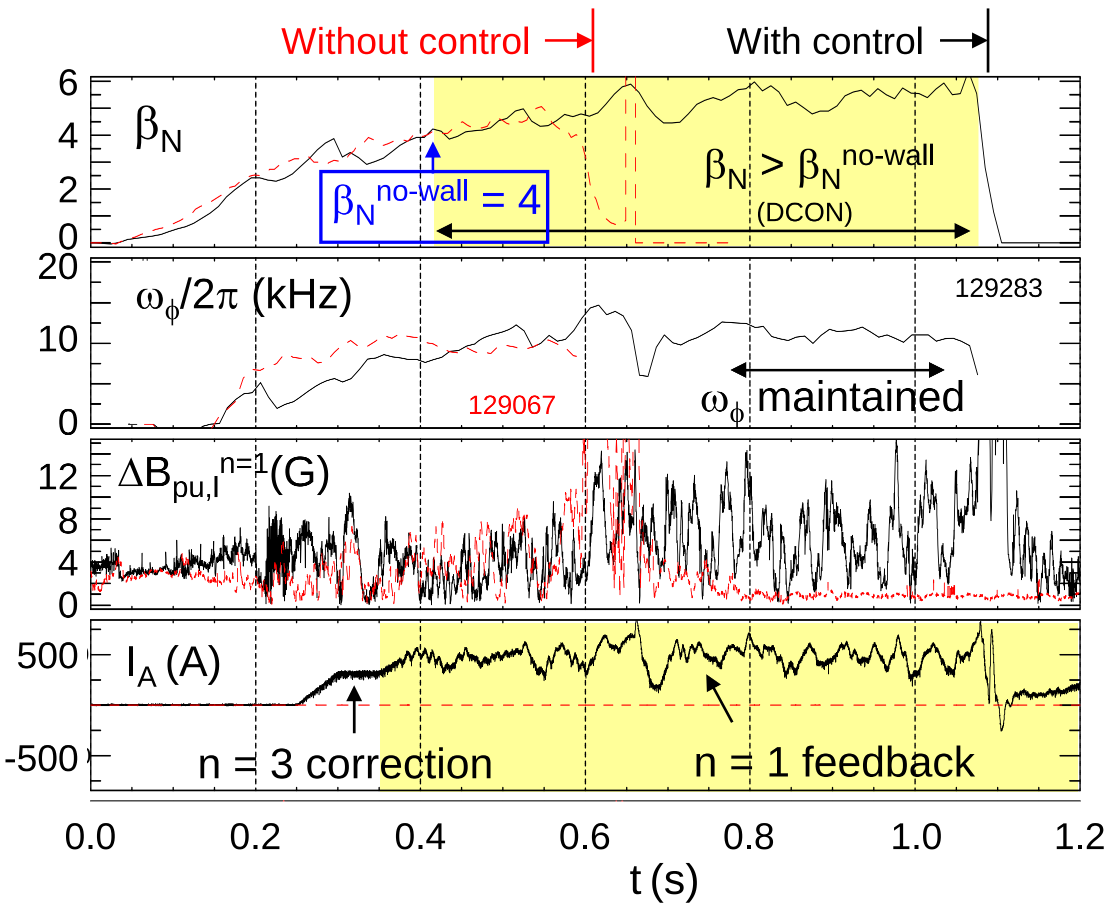
D.A. Gates, et al., *Nucl. Fusion* **47**, 1376 (2007).

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})



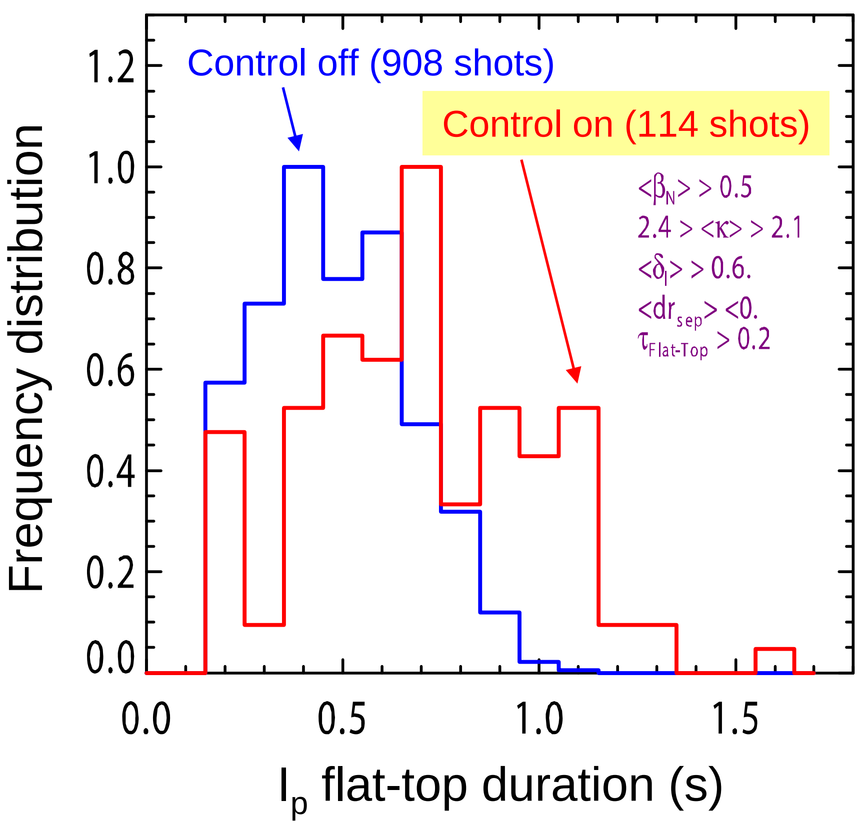
Active RWM control and error field correction maintain high β_N plasma

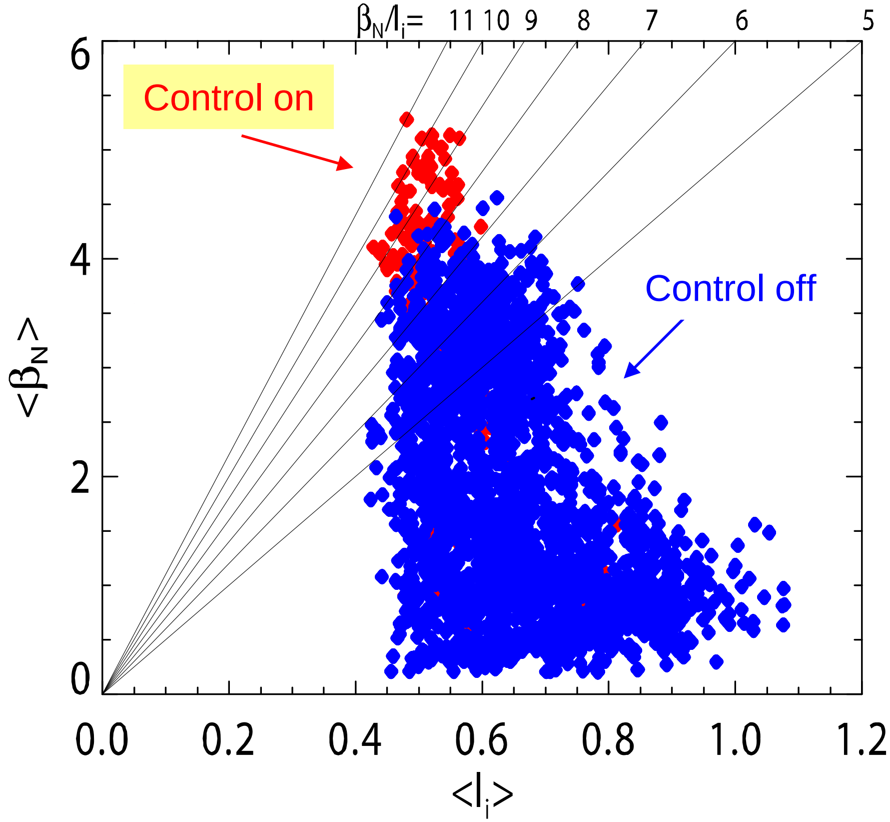


- n = 1 active, n = 3 DC control
  - n = 1 response ~ 1 ms < $1/\gamma_{RWM}$
  - $\beta_N/\beta_N^{no-wall}$ = 1.5 reached
  - best maintains ω_ϕ
- NSTX record pulse lengths
  - limited by magnet systems
  - n > 0 control first used as standard tool in 2008
- Without control, plasma more susceptible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

(Sabbagh, et al., PRL **97** (2006) 045004.)

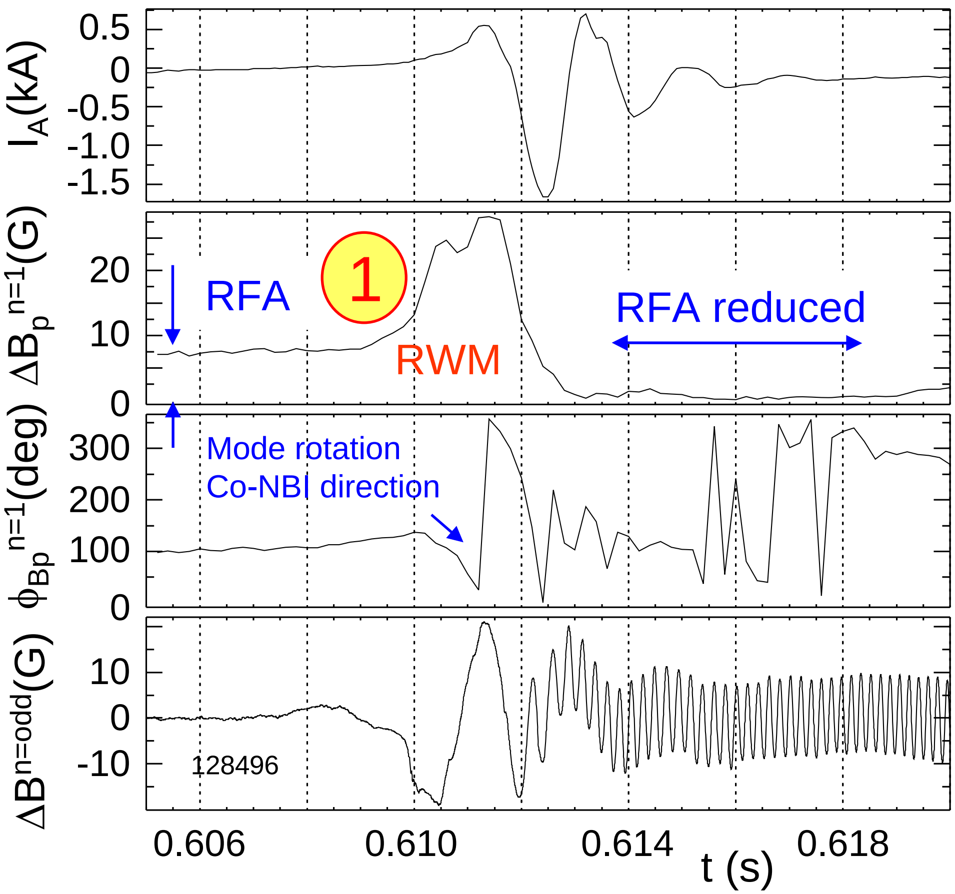
Probability of long pulse and $\langle\beta_N\rangle_{pulse}$ increases significantly with active RWM control and error field correction





- 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



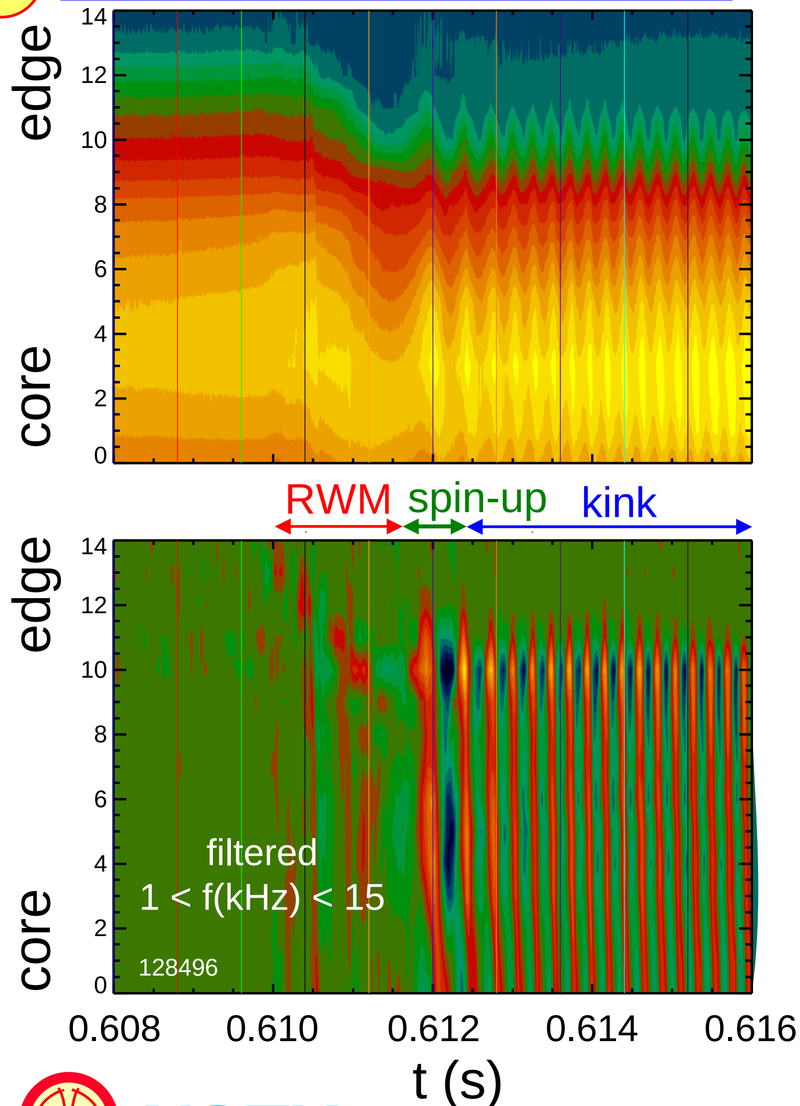
1 RWM grows and begins to rotate

- 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

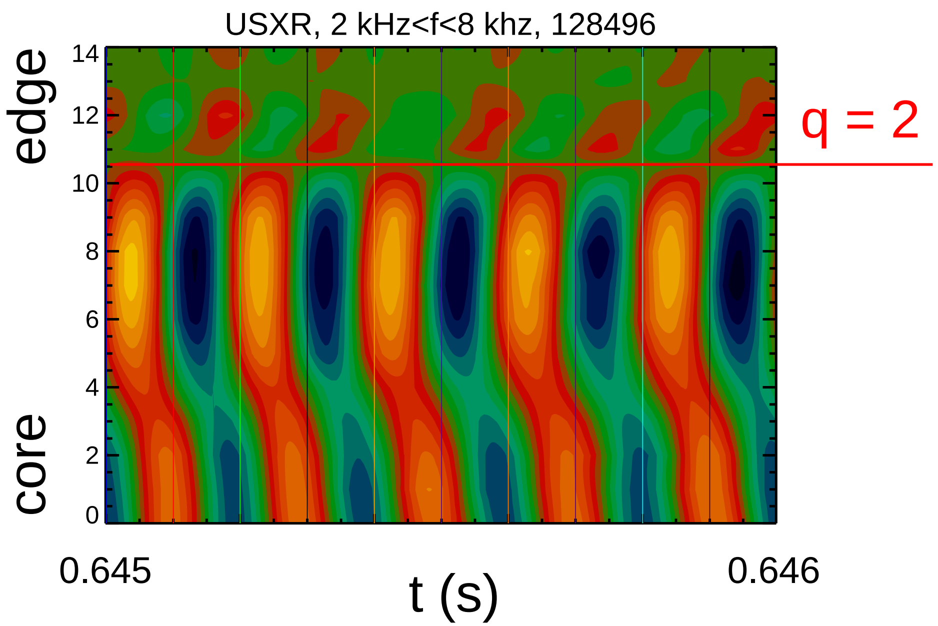
- Conversion from RWM to rotating kink occurs on τ_w timescale
- Kink either damps away, or saturates
  - Tearing mode can appear during saturated kink

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

1 Transition from RWM to kink

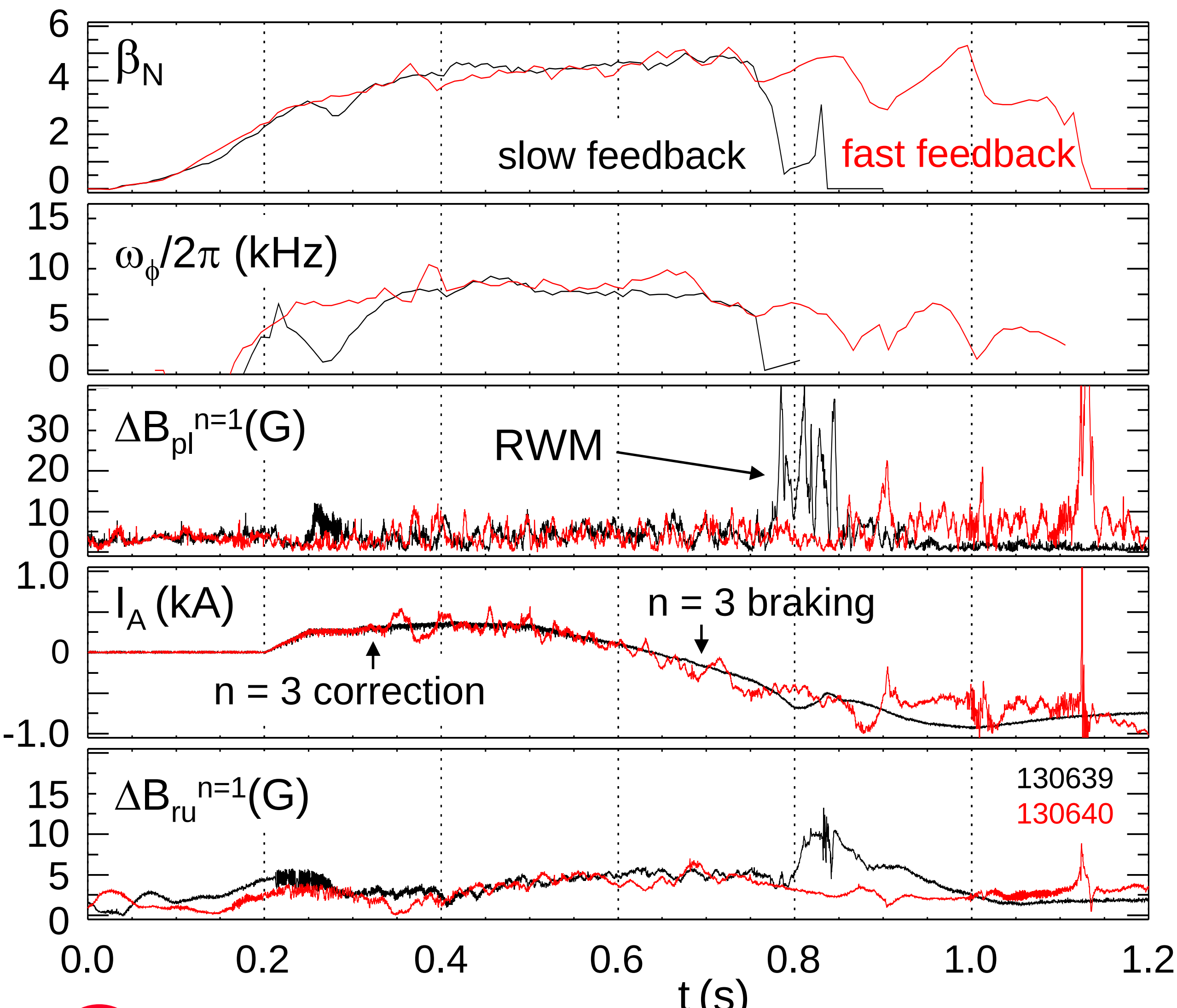


2 Tearing mode appears during kink



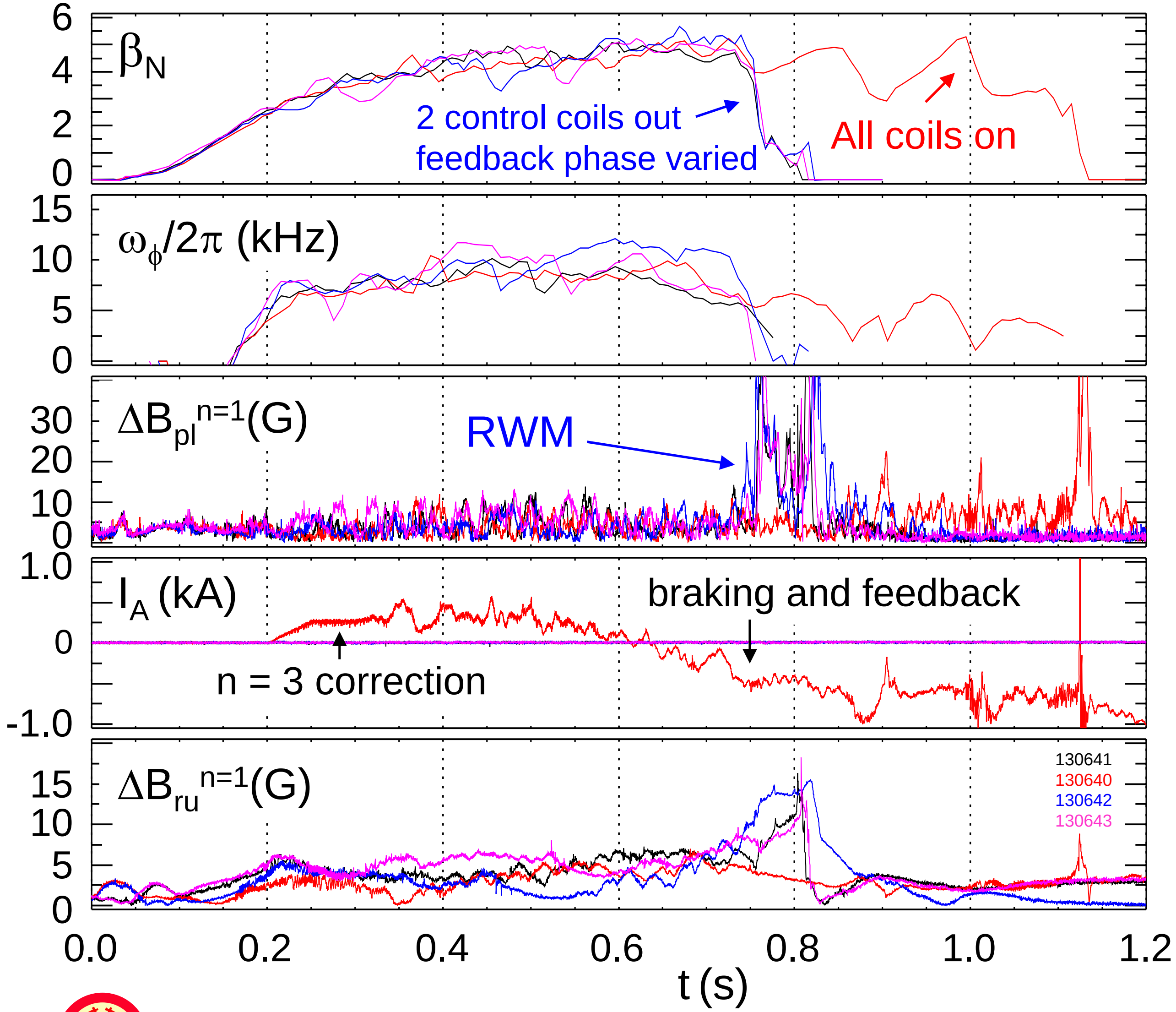
- Initial transition from RWM to saturated kink
- Tearing mode appears after 10 RWM growth times and stabilizes

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



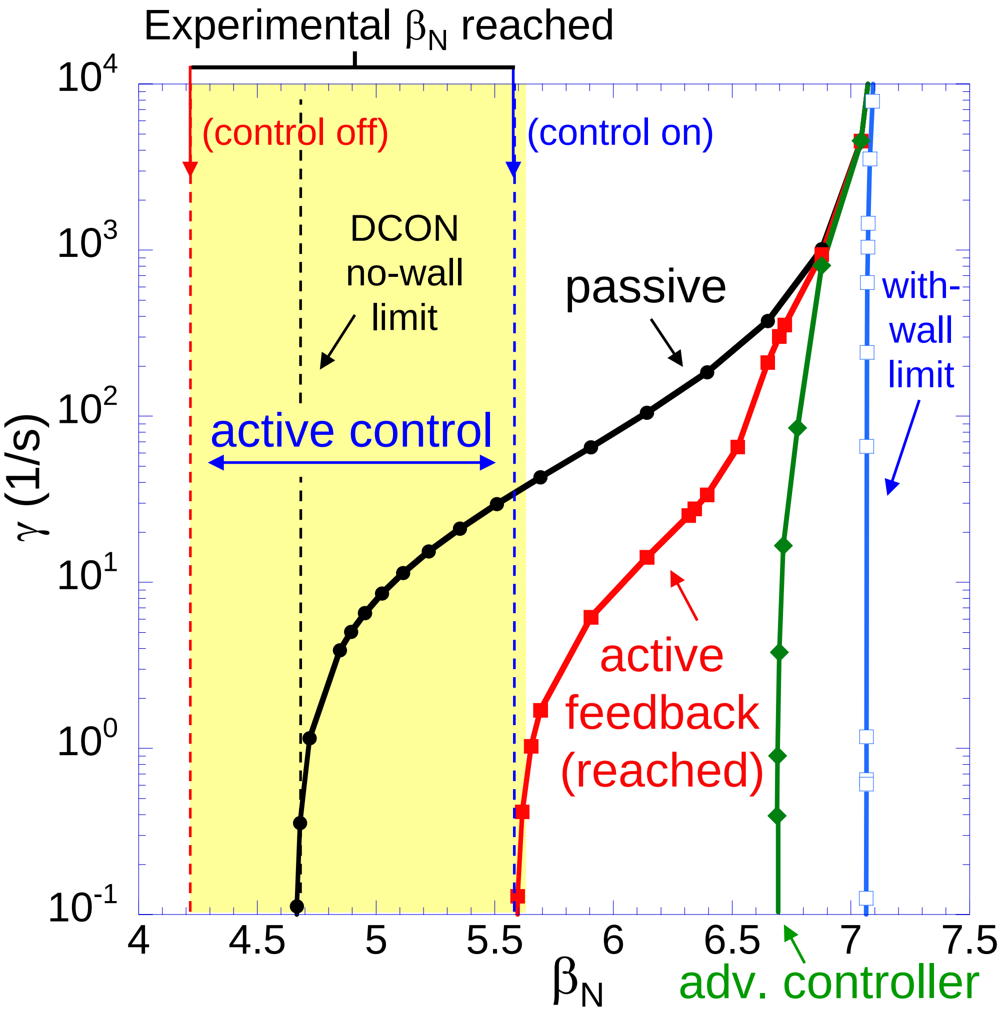
- Low ω_ϕ access for ITER study
  - use n = 3 braking
- n = 1 feedback response speed significant
  - "fast" (unfiltered) n = 1 feedback allows access to low V_ϕ, high β_N
  - "slow" n = 1 "error field correction" (75ms smoothing of control coil current) suffers RWM at ω_ϕ ~ 5kHz near q = 2

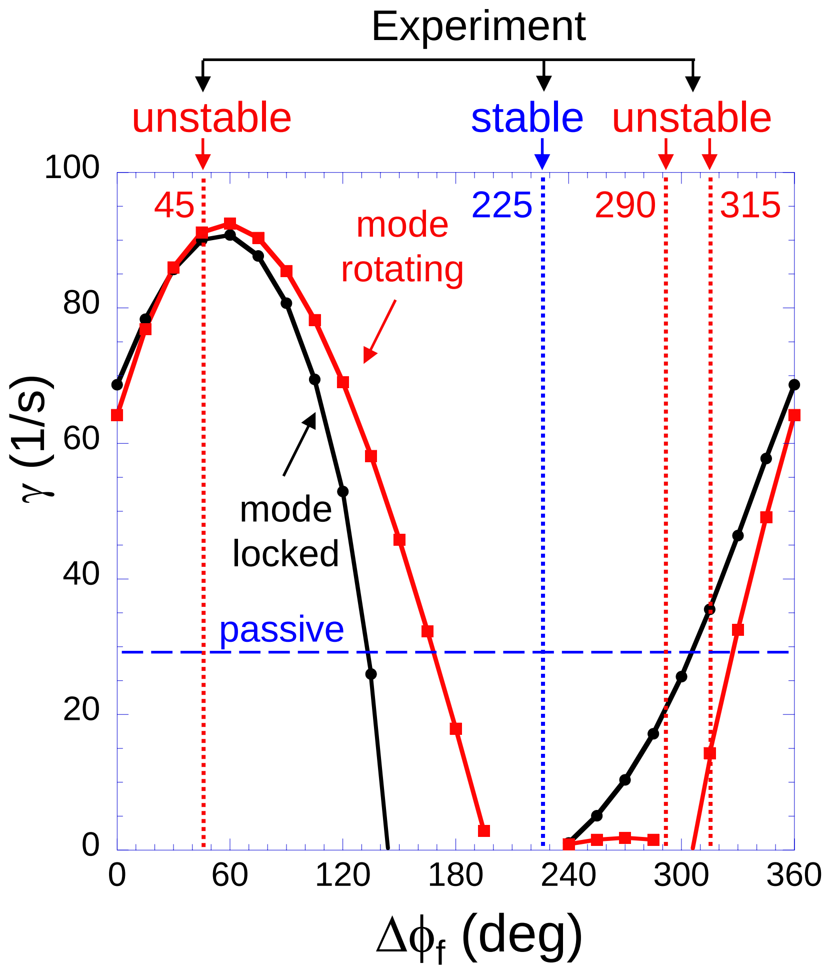
ITER support: Low ω_ϕ, high β_N plasma not accessed when two feedback control coils are disabled



- Low ω_ϕ access for ITER study
  - use n = 3 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

Experimental RWM control performance consistent with theory



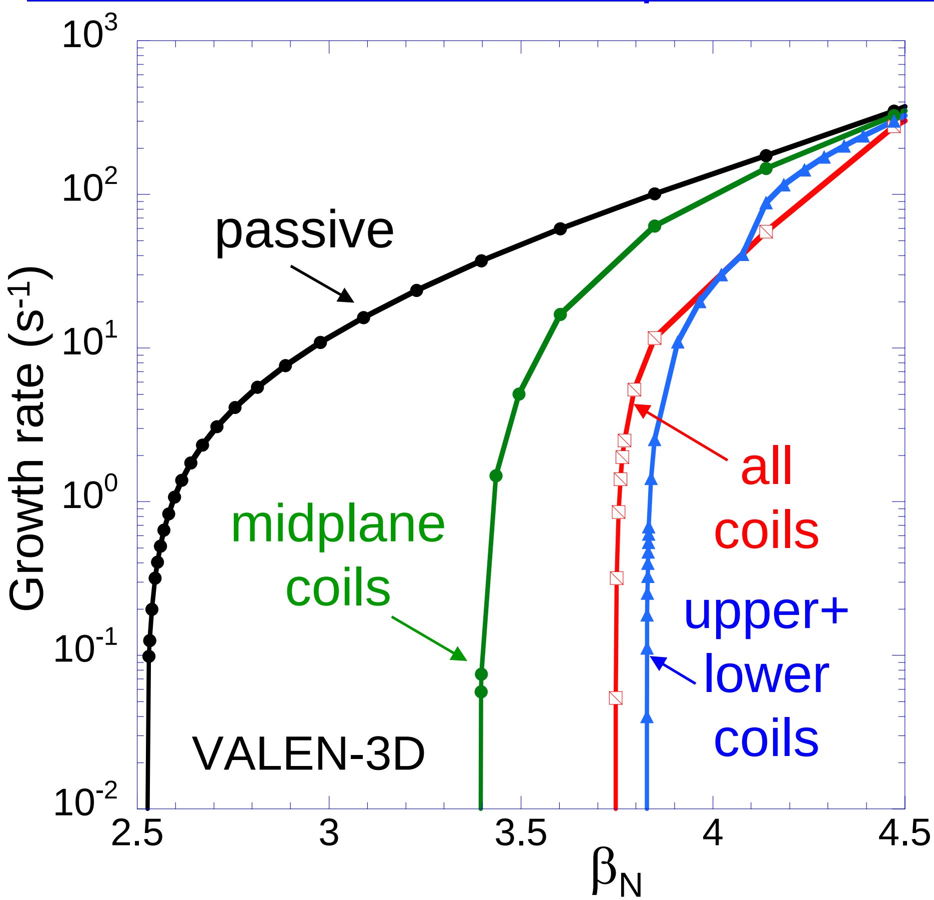


- VALEN code with realistic sensor geometry, plasmas with reduced V_ϕ
- Feedback phase scan shows superior settings

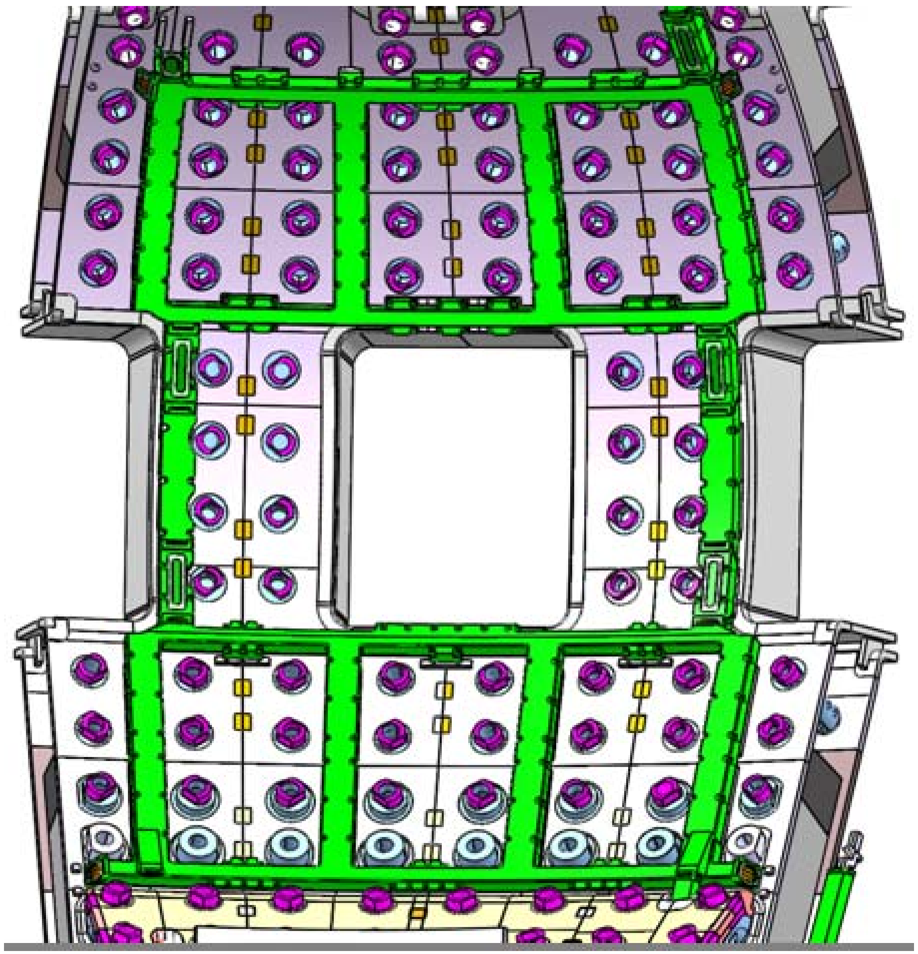
See O. Katsuro-Hopkins talk Mon. PM – adv. controller

Significant β_N increase expected by internal coil proposed for ITER

ITER VAC02 stabilization performance



ITER VAC02 design (40° sector)



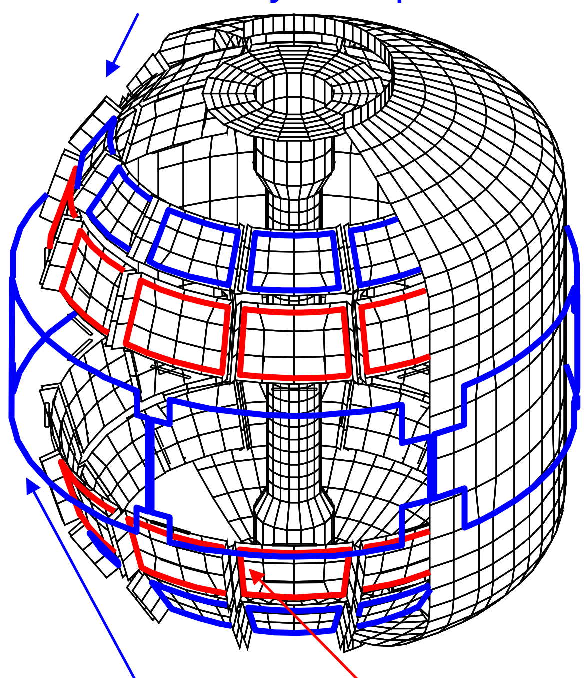
3 toroidal arrays, 9 coils each

- 50% increase in β_N over RWM passive stability

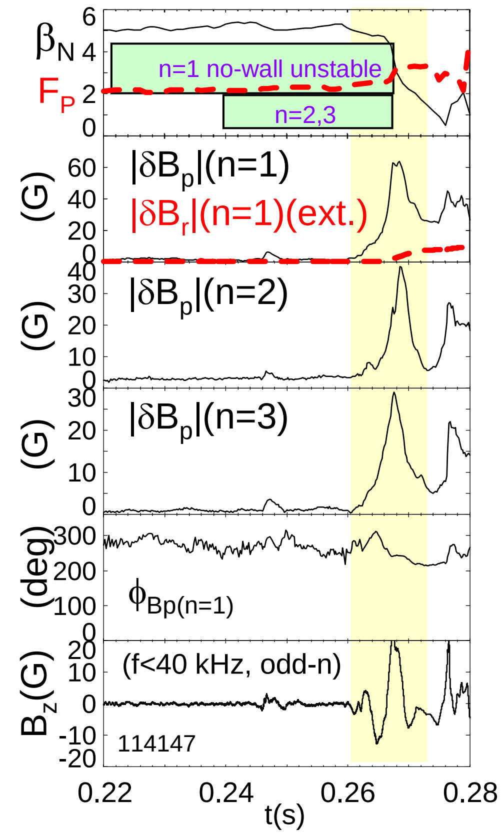
Design work for upgraded non-axisymmetric control capabilities has begun

- **Capabilities**
  - Non-axisymmetric control coil (NCC) – at least four applications
    - RWM stabilization (n > 1, higher β_N)
    - DEFC with greater field correction capability
    - ELM control (n = 6)
    - n > 1 propagation, increased V_ϕ control)
    - Similar to proposed ITER coil design
    - In incremental budget
  - Addition of 2nd SPA power supply unit for simultaneous n > 1 fields
  - Non-magnetic RWM sensors; advanced RWM active feedback control algorithms
  - Alteration of stabilizing plate connections

Proposed Internal Non-axisymmetric Control Coil (NCC) (initial designs - 12 coils toroidally)



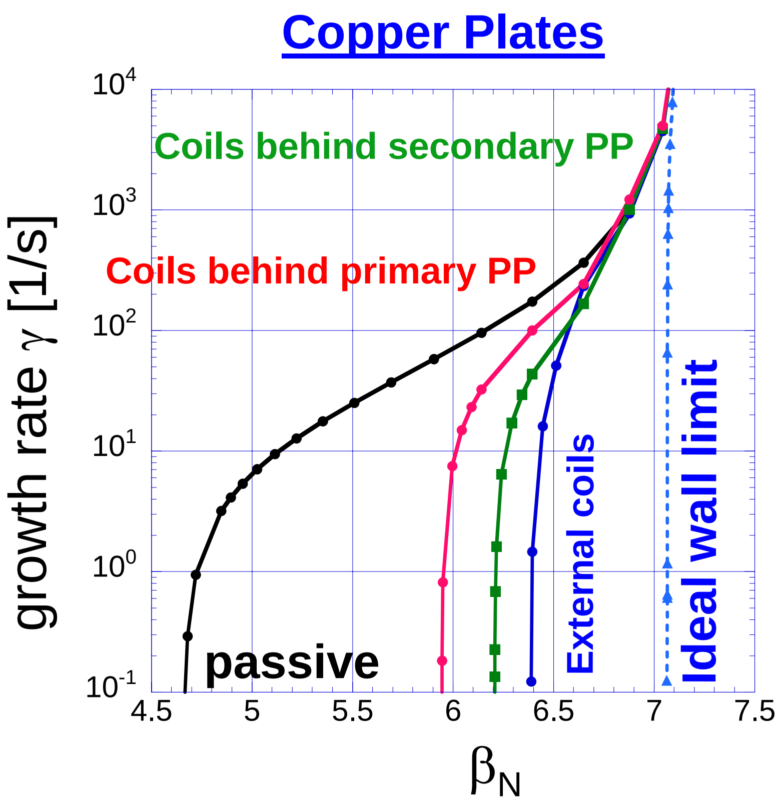
RWM with n > 1 RWM observed

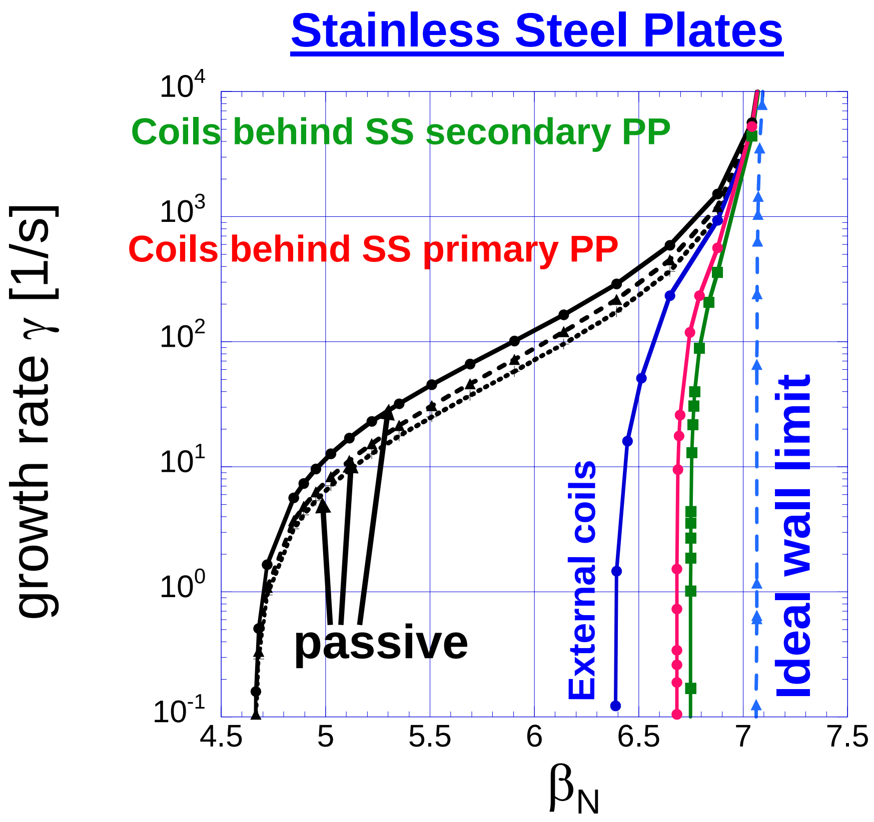


(Sabbagh, et al., Nucl. Fusion **46**, 635 (2006).)

NSTX

VALEN computed RWM stability for proposed RWM control coils upgrade - behind passive plates (PP)

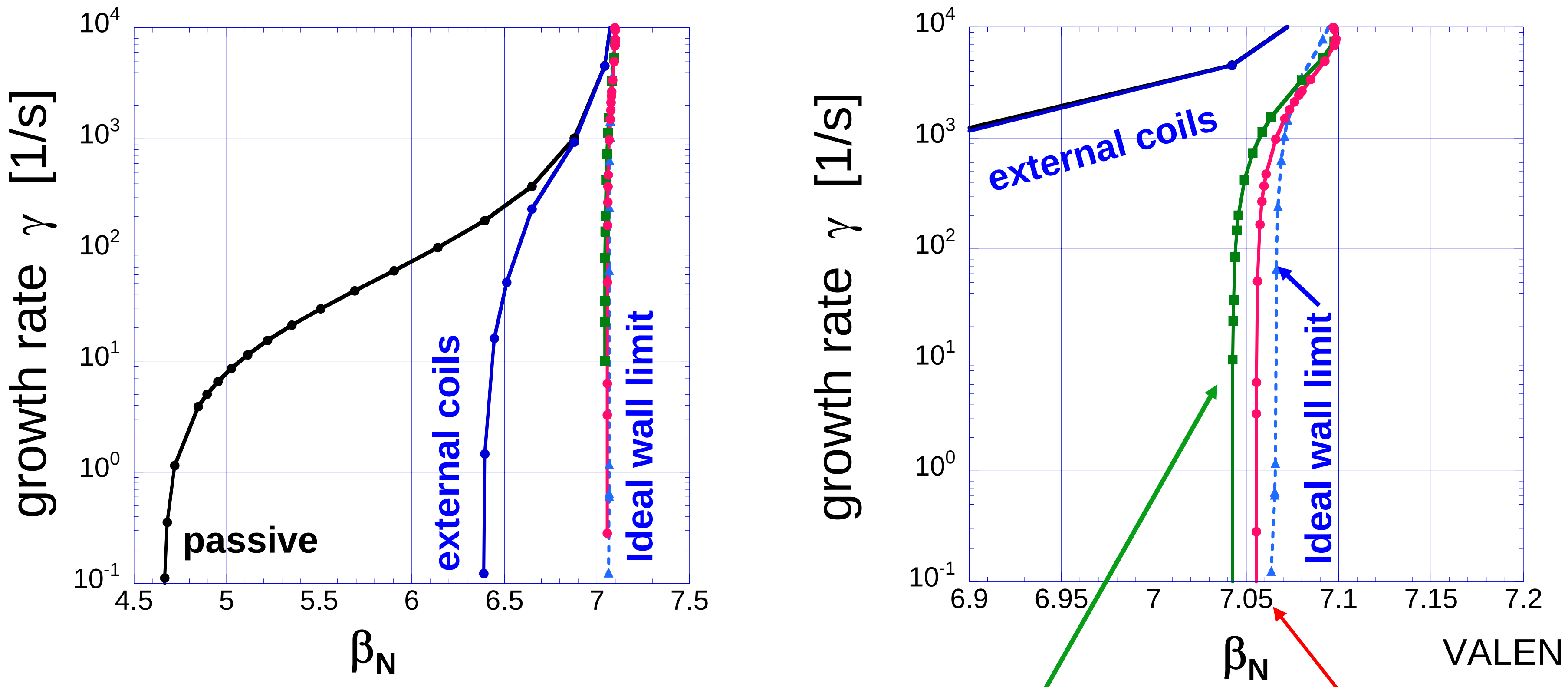




- coils behind copper passive plates perform worse than existing external RWM coil set
- change copper passive plates to SS RWM performs better than existing external coil set

(note: idealized sensors used)

Proposed control coils on plasma side of copper passive plates computed to stabilize to 99% of β_N^{wall}



coils on plasma side Cu secondary PP stabilize to β_N = 7.04

coils on plasma side Cu primary PP stabilize to β_N = 7.05

Ideal wall limit β_N = 7.06

(note: idealized sensors used)

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

- 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)

Trapped ion component of δW_K (plasma integral)

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

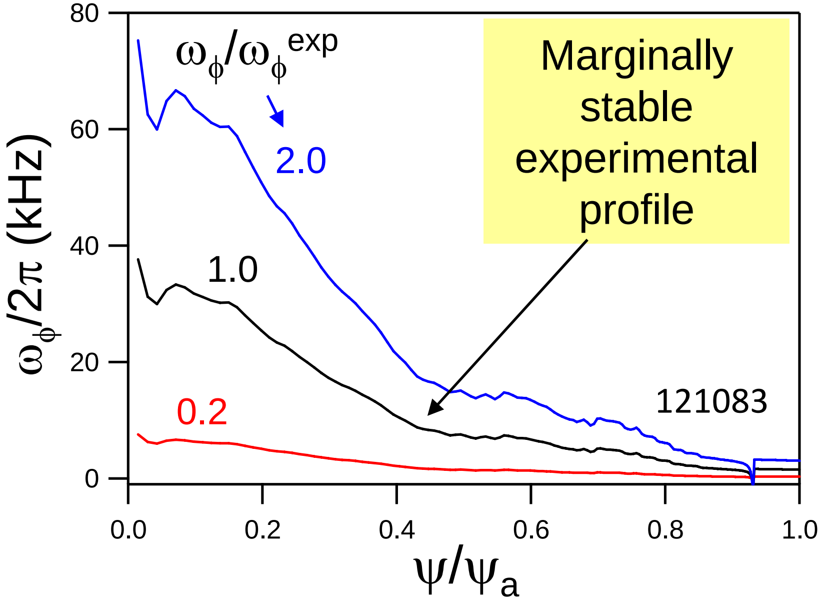
← Energy integral

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

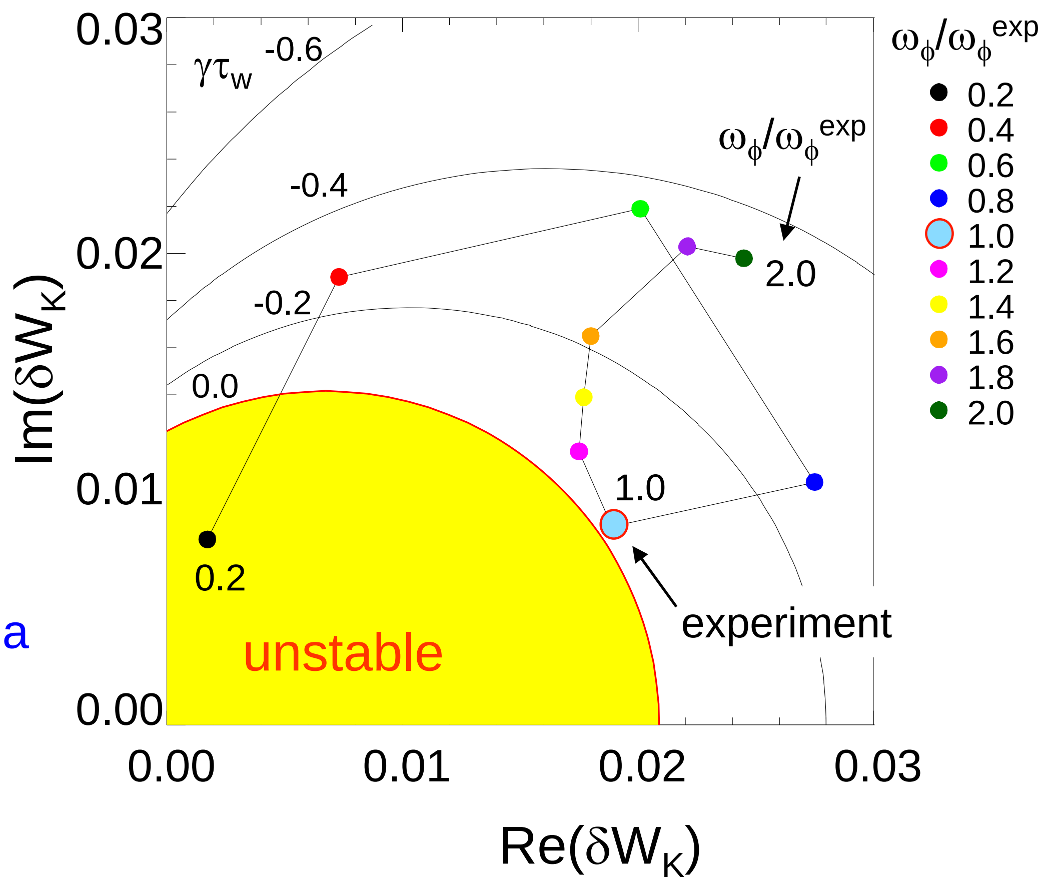
See J.W. Berkery talk, Monday PM

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

Theoretical variation of ω_ϕ



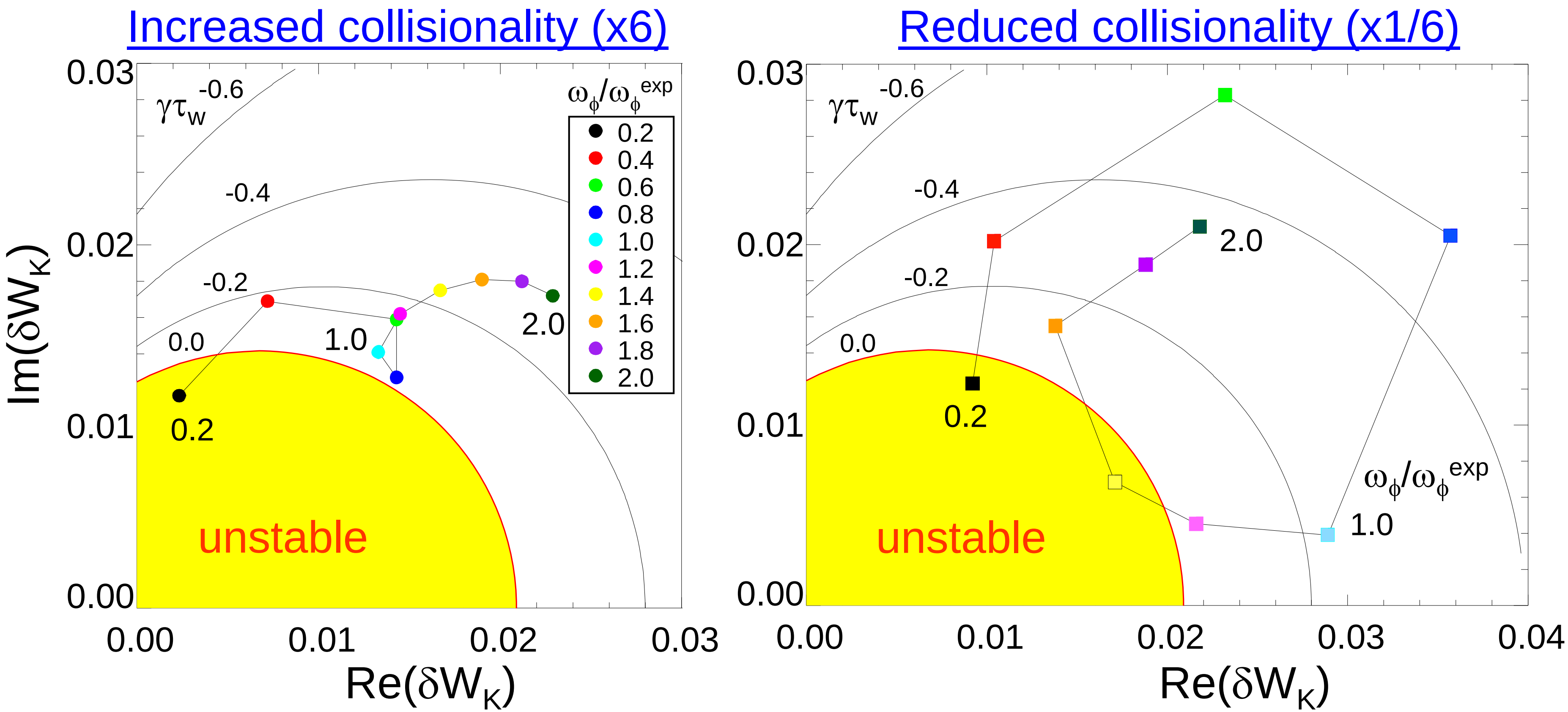
RWM stability vs. V_ϕ (contours of $\gamma\tau_w$)



- 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

See J.W. Berkery talk, Monday PM

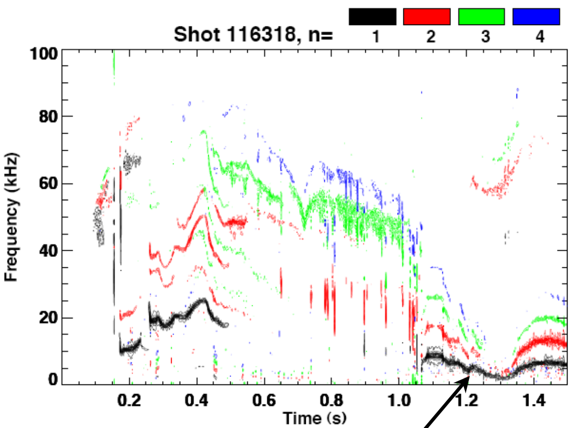
Kinetic model shows overall increase in stability as collisionality decreases



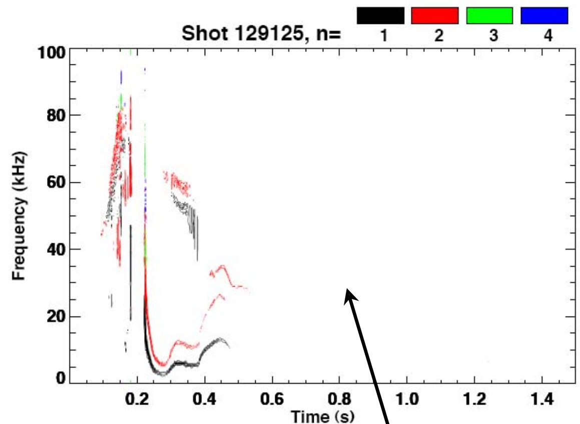
- Vary ν by varying T, n at constant β
- Simpler stability dependence on ω_ϕ at increased ν
- Increased stability at $\omega_\phi/\omega_\phi^{exp} \sim 1$
- Unstable band in ω_ϕ at increased ω_ϕ

Lithium wall conditioning, n=1 RWM control, n=3 error correction also shown to control (eliminate) tearing modes

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

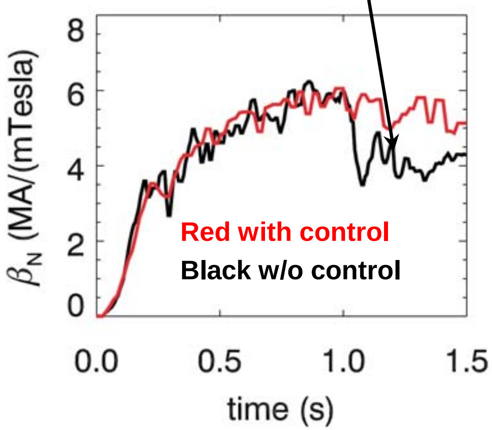


- ***MHD spectrogram with lithium, n=1 feedback and n=3 correction***

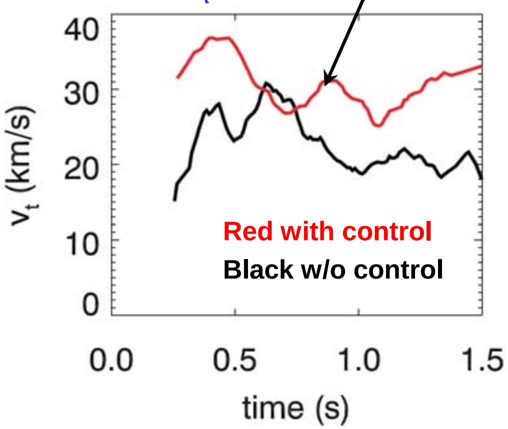


n=1 mode drops β

No MHD, β and rotation maintained



CHERS v_t at R = 139cm

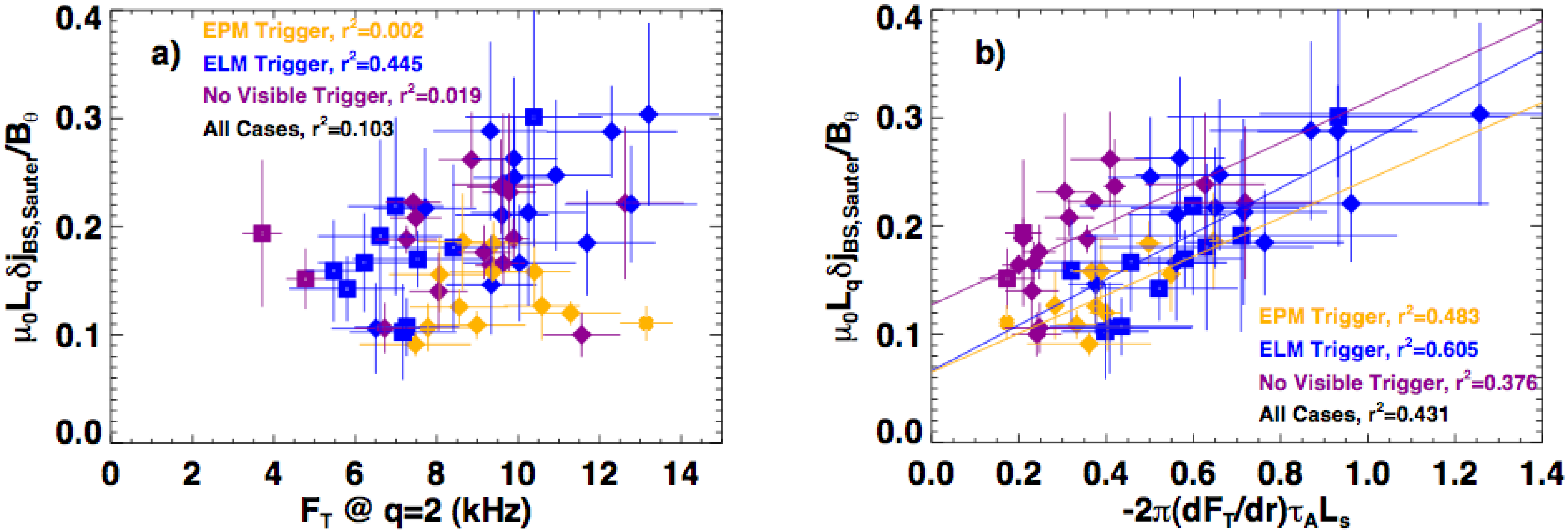


- Physics of tearing mode elimination still under investigation
  - Full suppression of modes not seen on all shots
- If lithium wall conditioning a key element, liquid lithium divertor might be used for NTM control

Required drive for NTM onset better correlated with rotation shear than rotation magnitude

NTM Drive at Onset Only Poorly Correlated with q=2 (Carbon) Rotation

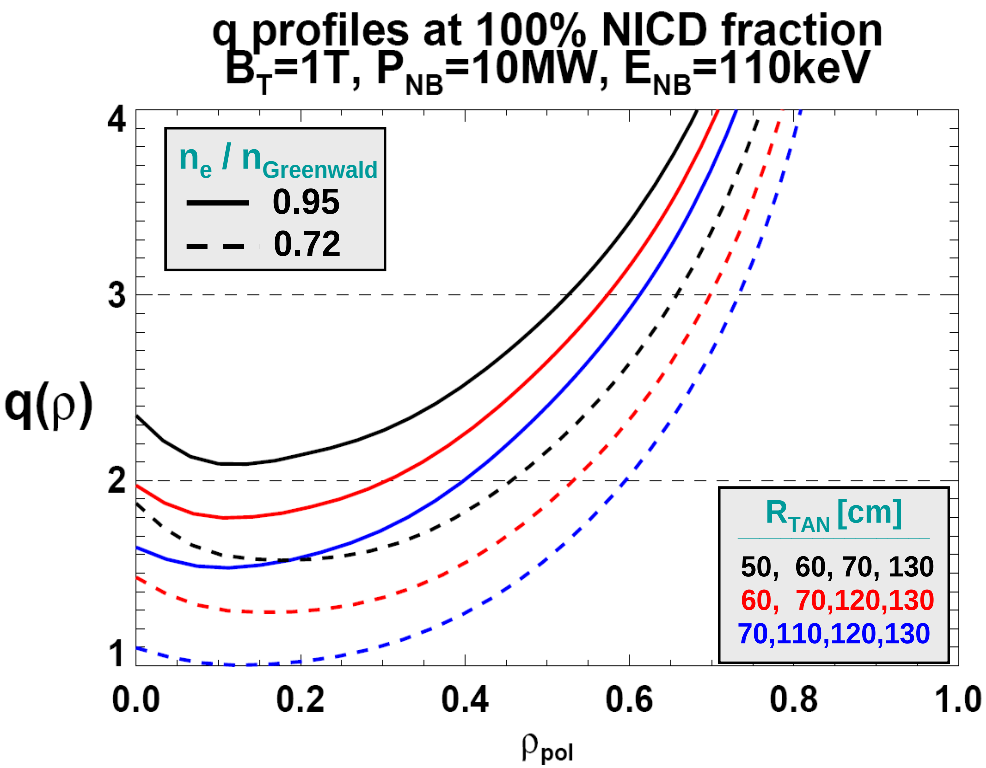
NTM Drive at Onset Better Correlated with Local Flow Shear



- For fixed V_ϕ, order of increasing onset drive: EPM triggers, ELM triggers, and "Triggerless"
- All trigger types have similar dependence on flow shear
  - Dependence likely to related to intrinsic tearing stability, not triggering

S.P. Gerhardt, submitted to Nucl. Fusion

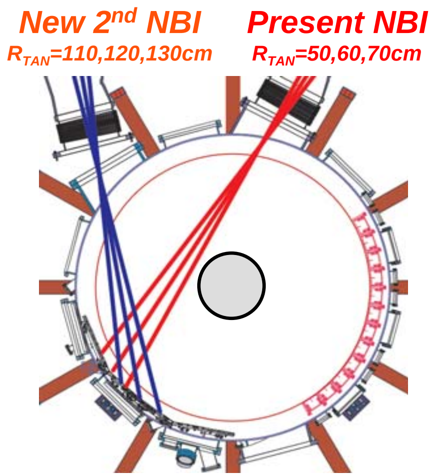
2^{nd} NBI and B_T = 1T with center stack upgrade to be used for study and control of NTMs (and much more…)



- q_{min} > key rationals 1.5, 2 to be used for NTM control

Above: β_N=5, β_T=10%, I_P=0.95MA

β_N=6.1, β_T=16%, q_{min} > 1.3, I_P=1MA at B_T=0.75T possible



- Fully non-inductive scenarios require 2^{nd} NBI (7-10MW of NBI heating) for $H_{98} \leq 1.2$
  - τ_{CR} will increase from 0.35 → 1s if T_e doubles at lower n_e, higher B_T
  - Need 3-4 τ_{CR} times for J(r) relaxation → 5s pulses → need 2^{nd} NBI

Establish predictive physics understanding of NTMs

- 2009-2011: Compete Characterization of NTM Onset, Small Island Physics, Restabilization
  - Characterize the role of V_ϕ and the ideal kink limit on NTM onset thresholds
  - Characterize triggering events, including sawtooth triggered 3/2 modes and "triggerless" NTMs with $q_{min} > 1$
  - Finish characterization of the marginal island width for 2/1 and 3/2 modes, including comparisons to conventional aspect ratio devices
  - Understand details of how Li conditioning and DEFC assist in stabilizing 2/1 modes
- 2009-2011: Establish a program of relevant NTM modeling
  - Implement PEST-III calculations of Δ' for realistic NSTX equilibria, including the effects of nearby rational surfaces
  - Utilize initial value codes like NIMROD for more sophisticated treatment of transport near the island or rotation shear effects on mode coupling and island eigenfunction.
- 2012-2013: Develop scenarios that mitigate/eliminate deleterious NTM activity
  - Quantify the benefits of $q_{min} > 2$ operation, and the role of higher order (3/1, 5/2) modes in this case
  - Utilize increased toroidal field (new center stack) to scale $\rho_{\theta i}$ in single device
  - Utilize 2nd beamline for current profile control, possibly allowing Δ' stabilization of NTMs even with $q_{min} < 2$

Collaborations are an essential element of research plan (GA, AUG, JET, U. of Tulsa,…)

Non-axisymmetric field-induced neoclassical toroidal viscosity (NTV) important for low collisionality ST-CTF, low rotation ITER plasmas

- Significant interest in plasma viscosity by non-axisymmetric fields
  - Physics understanding needed to minimize rotation damping from ELM mitigation fields, modes (ITER, etc.)
  - NTV investigations on DIII-D, JET, C-MOD, MAST, etc.

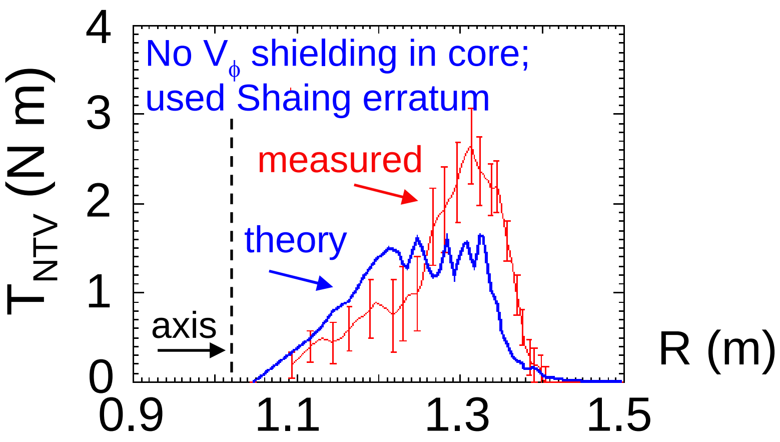
    e.g. A.M. Garofalo, APS 2008 invited (DIII-D)

- Expand studies on NSTX
  - Examine larger field spectrum
  - Improve inclusion of plasma response using IPEC

    J.K. Park, APS 2008 invited
  - Consider developments in NTV theory
    - Reduction, or saturation due to E_r at reduced ion collisionality, multiple trapping states, matching theory through collisionality regimes, etc.
  - Examine NTV from magnetic islands

Measured $d(I\Omega_p)/dt$ profile and theoretical NTV torque (n = 3 field) in NSTX)

W. Zhu, et al., *Phys. Rev. Lett.* **96,** 225002 (2006).



Dominant NTV Force for NSTX collisionality…

$$\left\langle \hat{e}_t \bullet \vec{\nabla} \bullet \overleftrightarrow{\Pi} \right\rangle_{(1/\nu)} = B_t R \left\langle \frac{1}{B_t} \right\rangle \left\langle \frac{1}{R^2} \right\rangle \frac{\lambda_{1i} p_i}{\pi^{3/2} \nu_i} \varepsilon^{3/2} (\Omega_\phi - \Omega_{NC}) I_\lambda$$

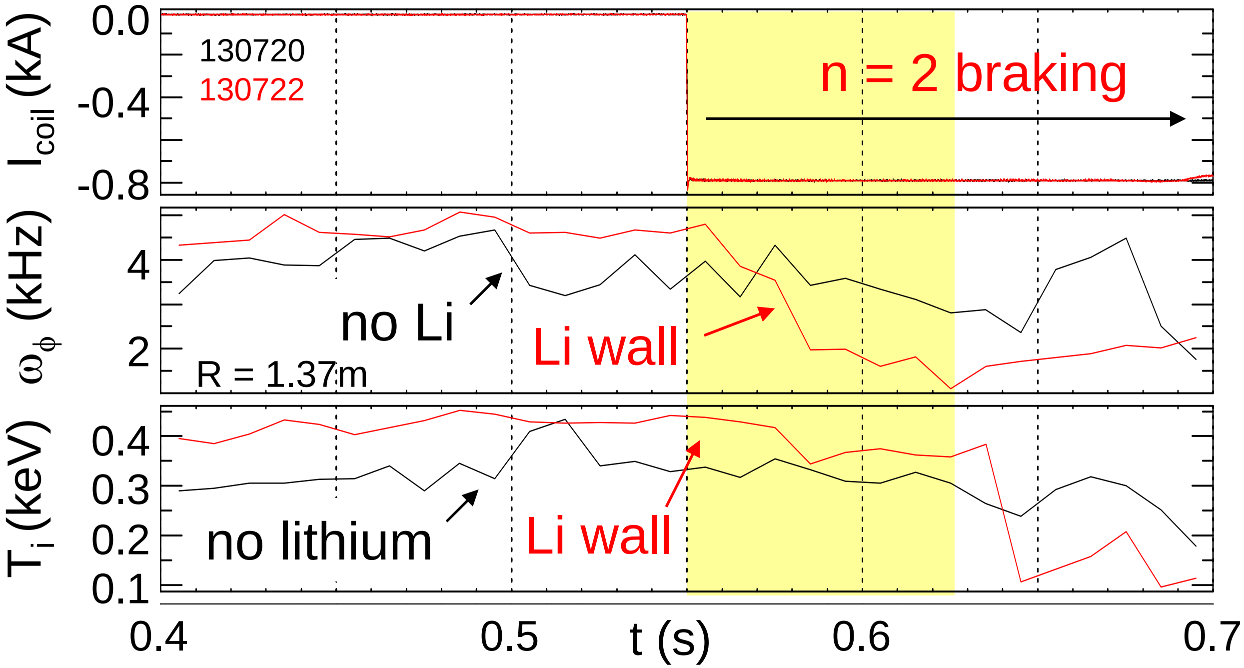
…expected to saturate at lower ν_i

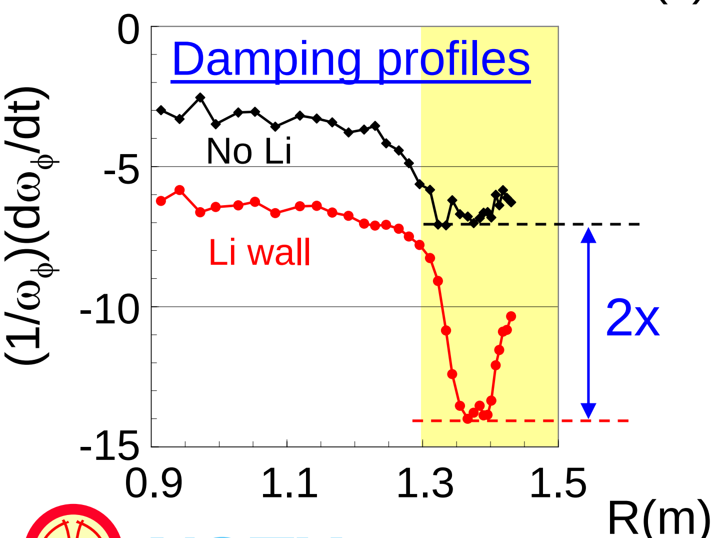
$$\frac{1}{\nu_i} \Rightarrow \frac{\nu_i}{\left(\nu_i^2 + \omega_E^2\right)}$$

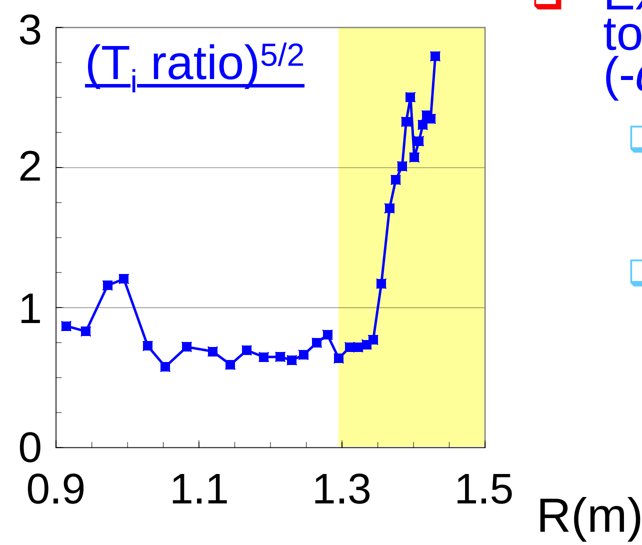
Can examine at order of magnitude lower ν_i with center stack upgrade

NSTX

Stronger non-resonant braking at increased T_i



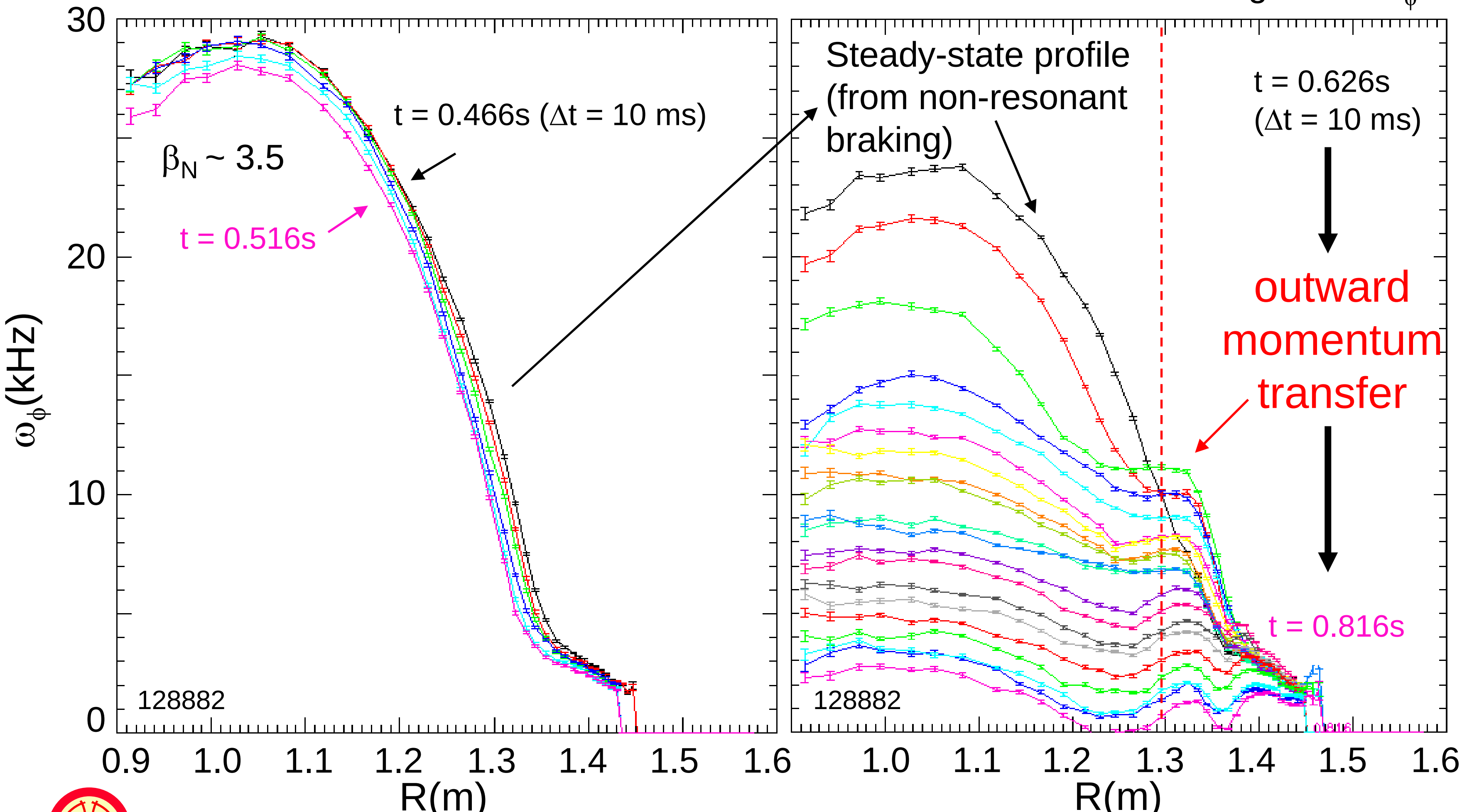




- Observed non-resonant braking using n = 2 field
- Examine T_i dependence of neoclassical toroidal viscosity (NTV)
- Li wall conditioning produces higher T_i in region of high rotation damping
- Expect stronger NTV torque at higher T_i ($-d\omega_\phi/dt \sim T_i^{5/2}\,\omega_\phi$)
  - At braking 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

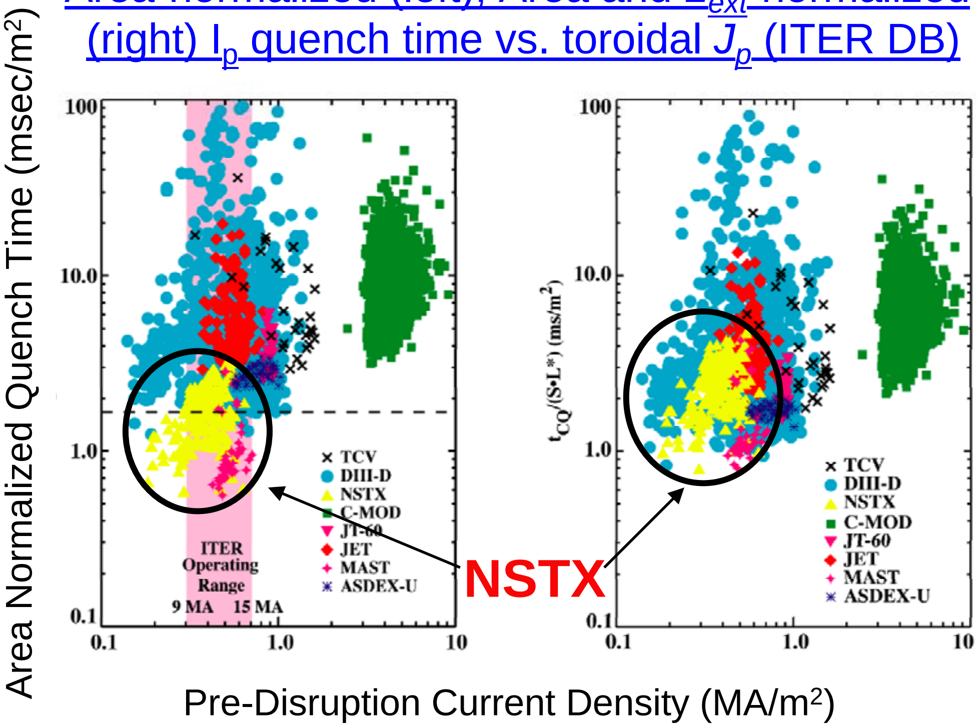
n = 2 non-resonant braking evolution distinct from resonant

- 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

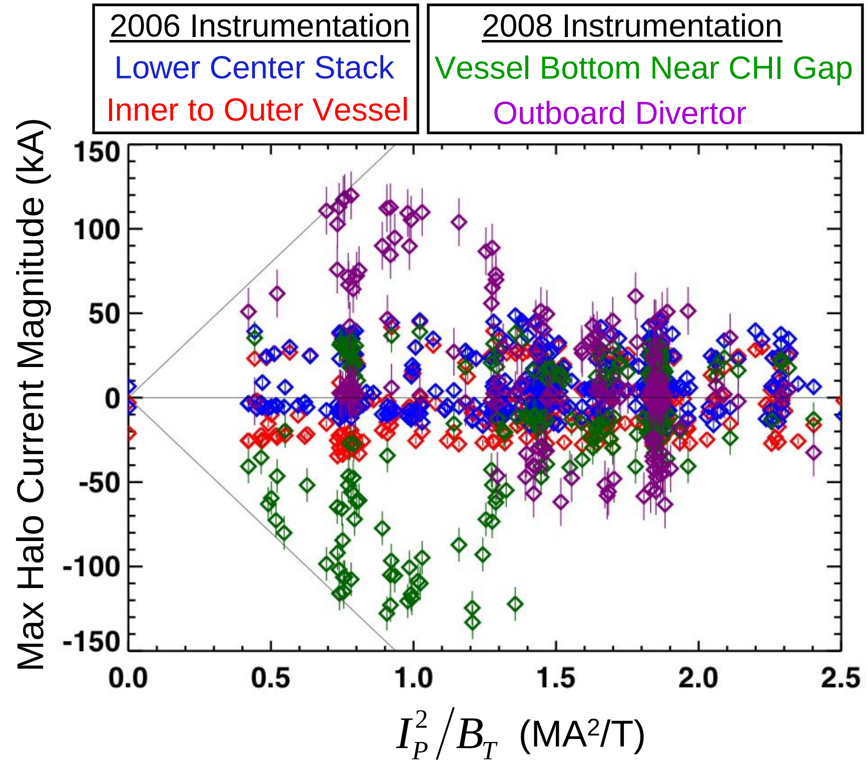


NSTX Disruption Studies Contribute to ITER, Aim to Predict Disruption Characteristics & Onset For Future Large STs

Area-normalized (left), Area and L_{ext}-normalized (right) I_p quench time vs. toroidal J_p (ITER DB)



Halo Current Magnitudes and Scaling



- Fastest NSTX disruption quench times of 0.4 ms/m², compared to ITER recommended minimum of 1.7 msec/m².
- Reduced inductance at high-κ, low-A explains difference

$$\frac{\tau_{L/R}}{S} = \frac{\mu_0}{2\pi\eta}\left[\ln\left(8/\sqrt{\kappa\varepsilon}\right) - 7/4\right]$$

- New instrumentation in 2008 yields significant upward revision of halo current fractions
  - reveals scaling with I_P and B_T.
  - Mitigating effect: Largest currents for deliberate VDEs
- Toroidal peaking reduced at large halo current fraction.

Expand these Results For a Complete Characterization of Disruption Dynamics, Including Prediction Methods

NSTX

Understand the Causes and Consequencs of Disruptions for Next-step STs and ITER

- 2009-2012: Halo current characterization
  - Install arrays of instrumented tiles in outboard divertor, measure currents into LLD trays (2009-10)
  - Utilize CS upgrade to instrument inboard divertor tiles (2011)
  - Understand the halo current paths, toroidal peaking physics, and driving mechanisms, in order to make predicitons for future ST plasmas
- 2009-2011: Thermal quench characterization
  - Determine the fraction of stored energy lost in the thermal quench, compared to that in the pre-disruption phase, over a variety or plasmas and disruptions
  - Utilize fast IR thermography to understand time-scale and spatial distribution of the thermal quench heat flux
  - Predict the impulsive heat loading constraints on future ST PFCs
- 2010-2013: Learn to predict and prevent disruptions
  - Develop real-time diagnostics useful for predicting impending disruptions for relevant ST equilibria and instabilities
  - Test predictive algorithms, to determine the simplest, most robust prediction methods
    - Use in conjunction with stability models and mode control systems developed

High β ST research plan focuses on bridging the knowledge gaps to next-step STs; contributing to ITER

- Macroscopic stability research direction
  - Transition from establishing high beta operation to reliably and predictably sustaining and controlling it – required for next step device
- Research provides critical understanding for tokamaks
  - Stability physics understanding applicable to tokamaks including ITER, leveraged by unique low-*A*, and high β operational regime
  - Specific ITER support tasks
- NSTX provides access to well diagnosed high beta ST plasmas
  - 2009-2011: allows significant advances in scientific understanding of ST physics toward next-steps, supports ITER, and advances fundamental science
  - 2012-2013+: allows demonstration/understanding of reliable stabilization/profile control at lower collisionality – performance basis for next-step STs

Participate in the 2009 NSTX Research Forum! (Dec. 8-10, 2008)
http://nstx-forum-2009.pppl.gov/