RWM Stabilization and Maintenance of High Beta Plasmas in NSTX

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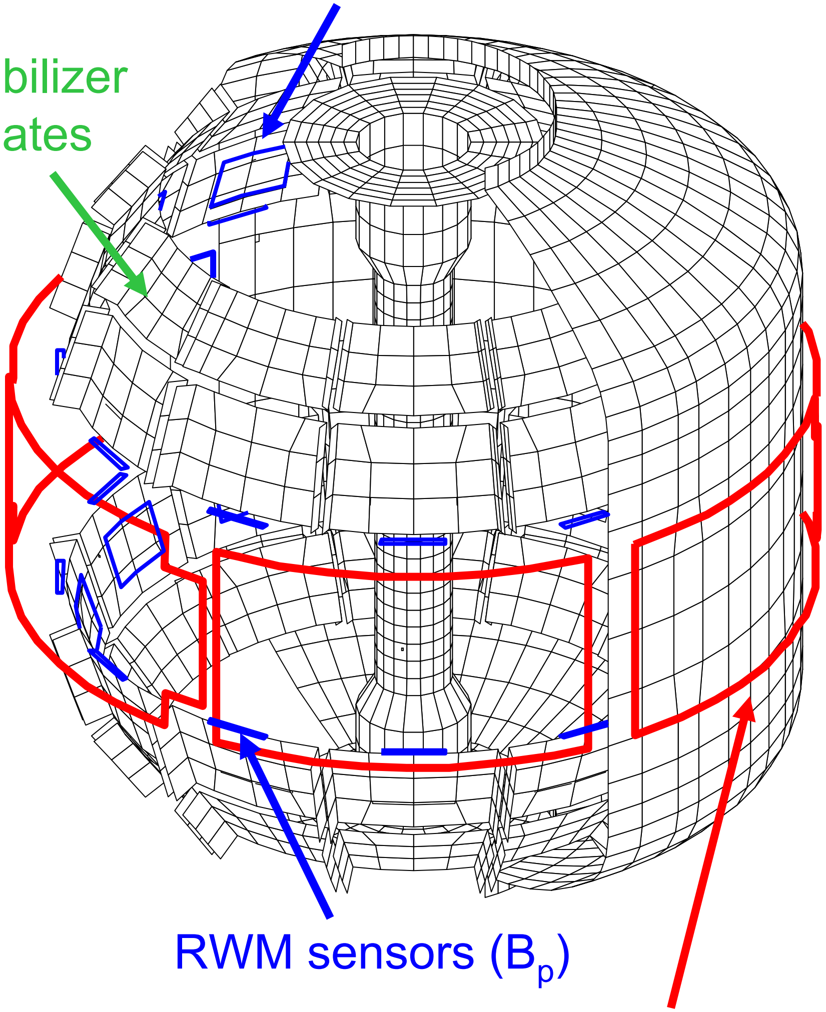
NSTX MHD Research is Addressing Needs for Maintaining Long-Pulse, High Performance Spherical Torus Plasmas

- Motivation
  - Maintenance of high β_N with sufficient physics understanding allows confident extrapolation to ST applications (e.g. ST Component Test Facility, ST-DEMO)
  - Sustain target β_N of ST applications with margin to reduce risk
  - Leverage unique ST operating regime to test physics models, apply to ITER

- Related Research Addressed
  - Physics of plasma rotational stabilization to maintain high β_N
  - Physics of resistive wall mode (RWM) active control
  - Physics of 3D fields to control plasma rotation profile (for greater stability, confinement)
  - Multiple scalable control systems to maintain $\langle\beta_N\rangle_{\text{pulse}}$
  - Possibility of multiple RWMs that can affect active mode control

NSTX is a spherical torus equipped for passive and active global MHD control, application of 3D fields

- High beta, low aspect ratio
  - R = 0.86 m, A > 1.27
  - I_p < 1.5 MA, B_t = 5.5 kG
  - β_t < 40%, β_N < 7.4
- Copper stabilizer plates for kink mode stabilization
- Midplane control coils
  - n = 1 – 3 field correction, magnetic braking of V_ϕ
  - n = 1 resistive wall mode (RWM) control
- Varied sensor combinations used for RWM feedback
  - 48 upper/lower B_p, B_r



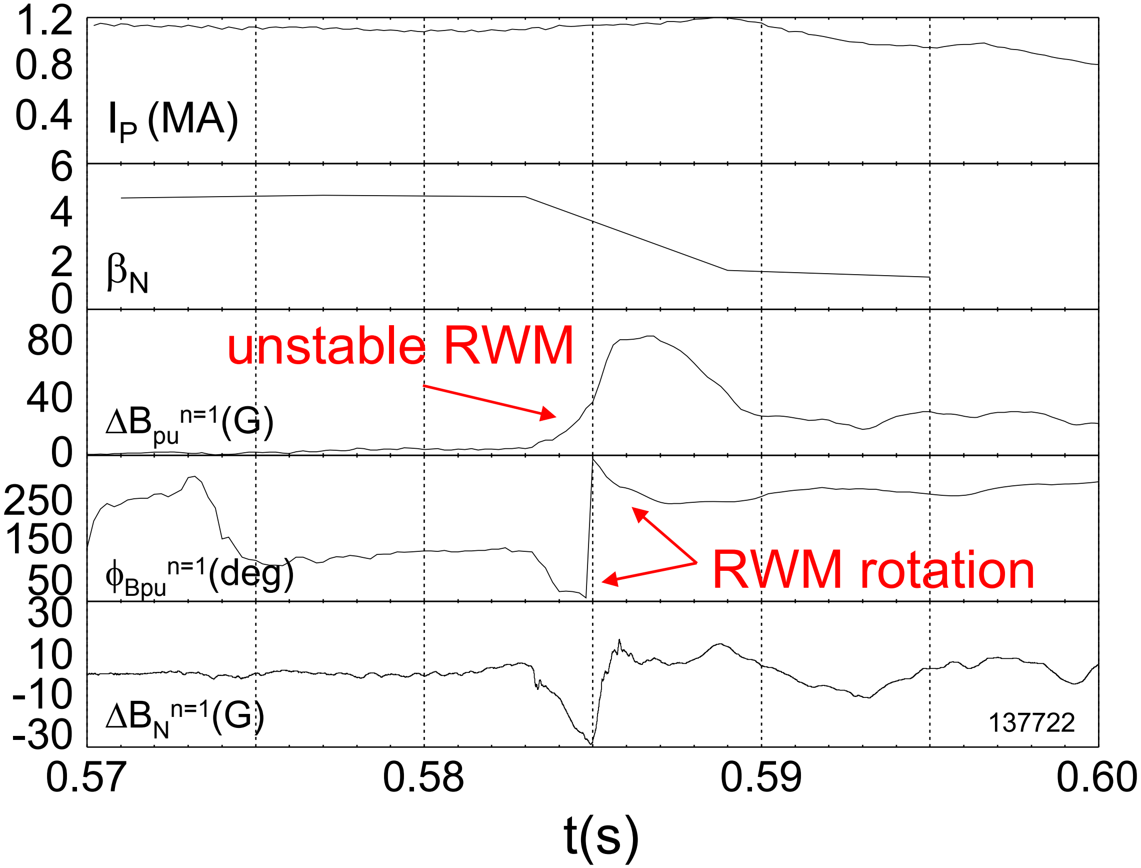
RWM sensors (B_r)

Stabilizer plates

RWM sensors (B_p)

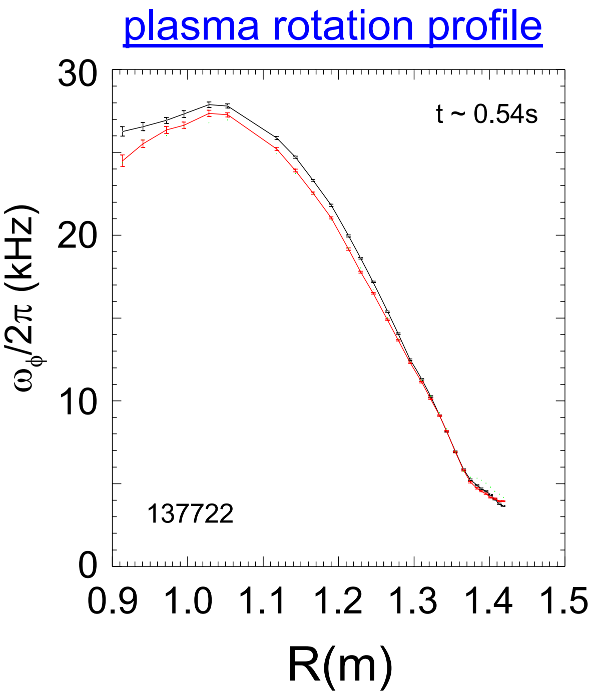
RWM active stabilization coils

Resistive wall modes can terminate discharges at significant plasma rotation levels



unstable RWM

RWM rotation



high ω_φ alone is not sufficient for stability!

- Instability occurs at relatively high rotation level, and not at highest β_N
- Understanding this physics is crucial to ensure sustained plasmas, and to extrapolate to future devices

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)

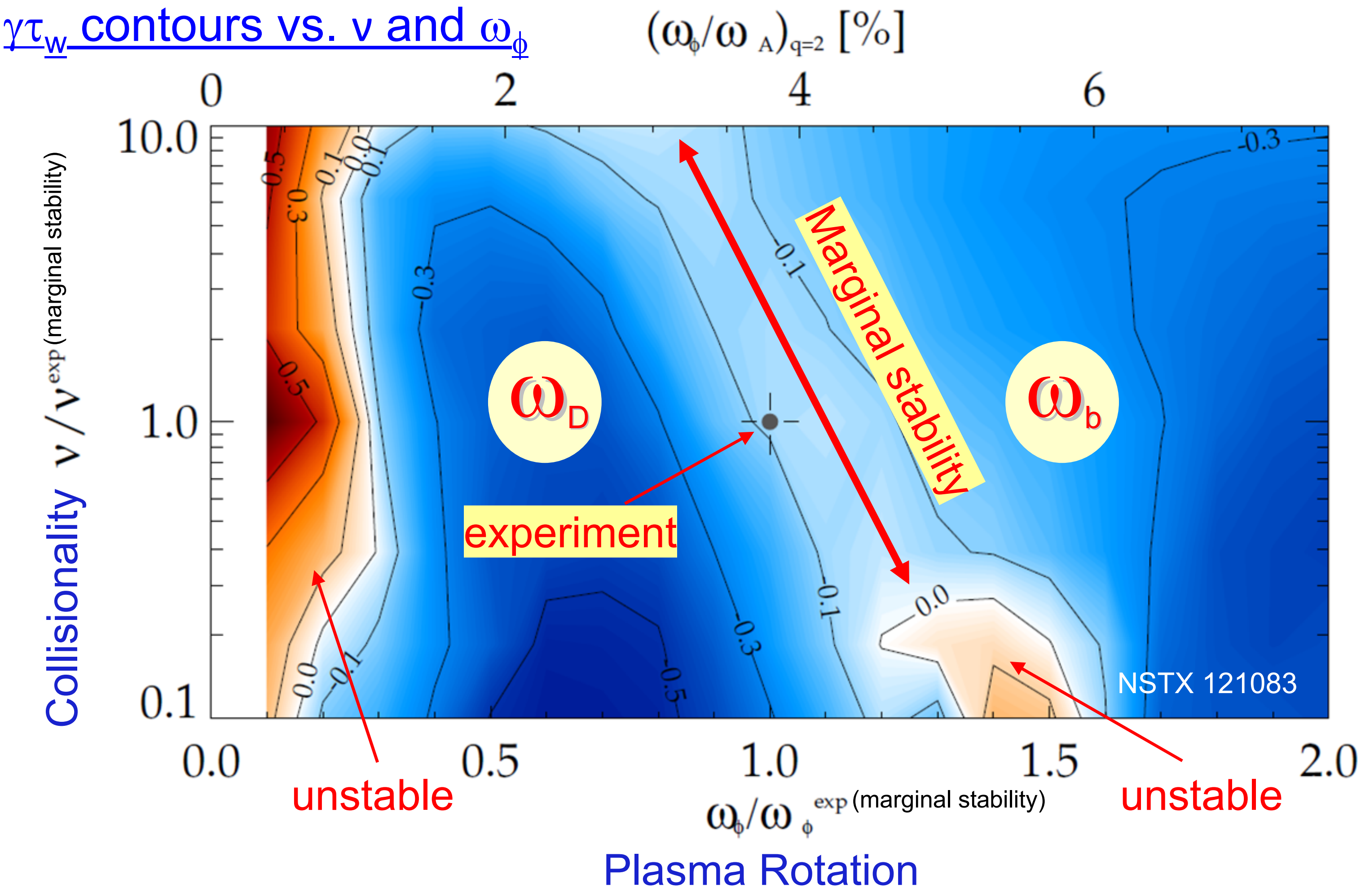
$$\delta W_K \propto \int \left[\frac{\omega_{*N} + \left(\hat{\varepsilon} - 3/2\right)\omega_{*T} + \omega_E - \omega - i\gamma}{\langle \omega_D \rangle + l\omega_b - i\nu_{eff} + \omega_E - \omega - i\gamma} \right] \hat{\varepsilon}^{\frac{5}{2}} e^{-\hat{\varepsilon}} d\hat{\varepsilon}$$

← Energy integral

precession drift bounce collisionality

MISK calculations consistent with RWM destabilization at intermediate plasma rotation; stability altered by collisionality

$\gamma\tau_w$ contours vs. ν and ω_ϕ



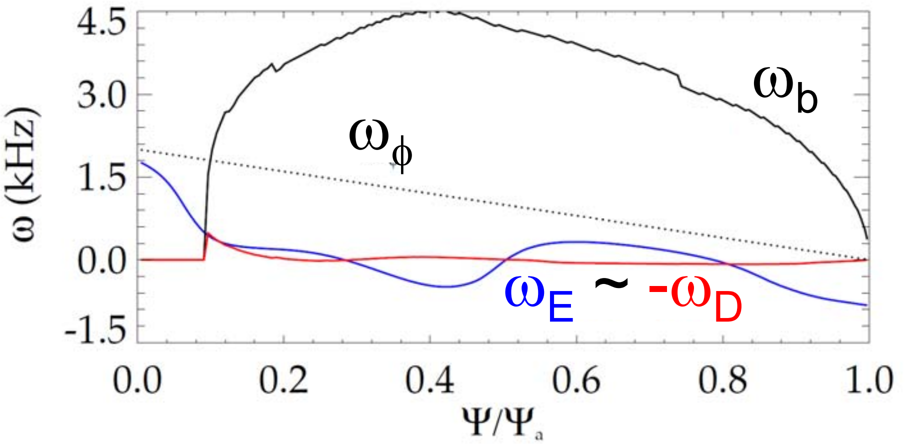
- Destabilization appears between precession drift resonance at low V_ϕ, bounce resonance at high V_ϕ

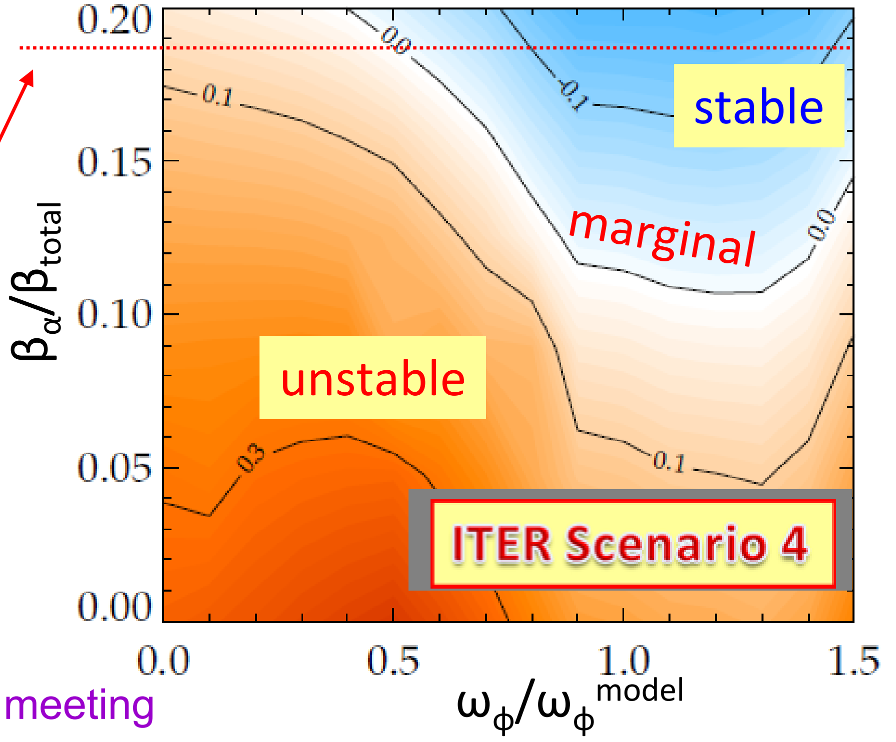
J.W. Berkery, et al., PRL **104** (2010) 035003

Column 2

ITER advanced scenario 4 has RWM stabilized by energetic particles near marginal at β_N = 3 (MISK computation)

- Equilibrium
  - With β_N = 3 (20% above n = 1 no-wall limit)
  - Plasma rotation profile linear in normalized poloidal flux
- Plasma rotation effect
  - Stabilizing precession drift resonance enhances stability near $\omega_\phi = 1.2\,\omega_\phi^{model}$
- Energetic particle (EP) effect
  - Isotropic slowing down distribution of alphas
  - Alpha particles are required for RWM stabilization at <u>all</u> ω_ϕ
  - At ITER expected $\beta_\alpha/\beta_{total}$ = 0.19, RWM stable at $\omega_\phi = \omega_\phi^{model}$
  - With Polevoi rotation profile (IAEA FEC 2002), plasma is only marginally stable
    - See J.W. Berkery, poster P4.106, this meeting

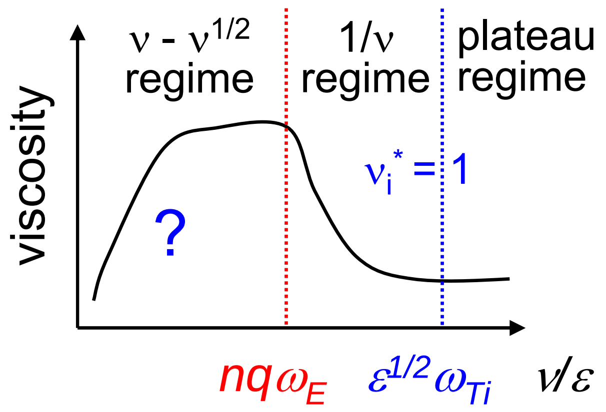




NSTX (co-NBI) utilizes 3-D field-induced neoclassical viscosity (NTV) in collisionless plasma regime to alter plasma rotation

❑ Present goal

- ❑ Investigate NTV-induced magnetic braking over range of collisionality, ω_E (i.e. $\nu_i/|\varepsilon n q \omega_E|$)
  - Key for ITER, ST Component Test Facility
  - If $\nu_i/|\varepsilon n q \omega_E| << 1$: NTV saturated (indep. of ν)
  - If $\nu_i/|\varepsilon n q \omega_E| > 1$: NTV ~ $1/\nu$
  - If low ω_E ($< \omega_{\nabla B}$): NTV maximized (indep. of ν) (superbanana plateau)



❑ NSTX experience

- ❑ ω_ϕ damping consistent with "$1/\nu$ regime" magnitude & scaling ($T_i^{5/2}$)

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

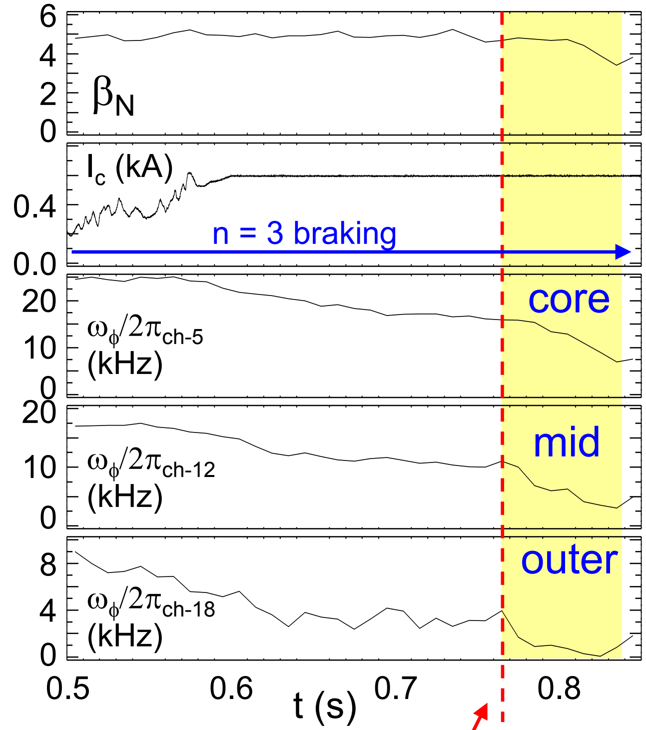
W. Zhu, et al., PRL **96** (2006) 225002

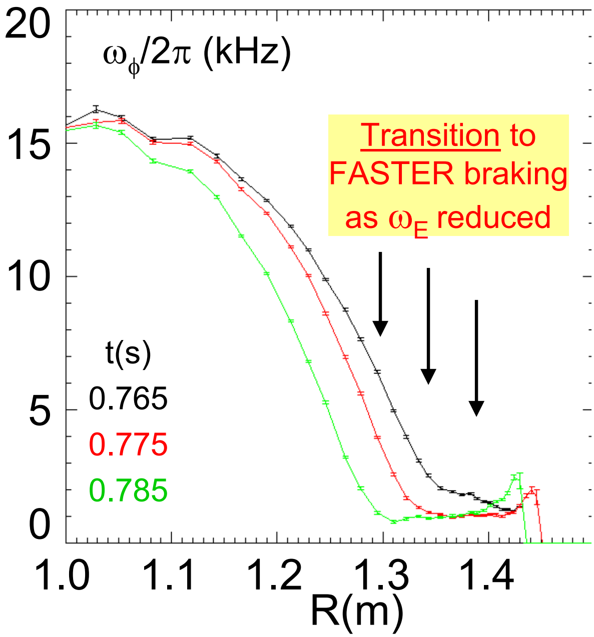
S.A. Sabbagh, et al, NF **50** (2010) 025020

❑ Recent results

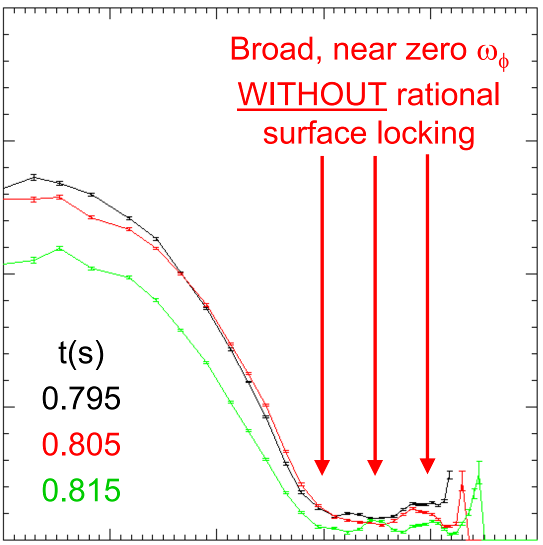
- ❑ NTV braking observed over all $\nu_i/|\varepsilon n q \omega_E|$ variations made in experiment
  - Strong NTV braking observed at increased T_i even if $\nu_i/|\varepsilon n q \omega_E| < 1$
- ❑ Stronger braking at constant 3-D applied field as ω_E, ω_ϕ reduced
  - Not due to resonant drag at rational q (no locking, no $1/\omega_\phi$ scaling of torque)
  - Perhaps due to "island NTV" ~ ω_ϕ (K. Shaing et al., PRL **87** (2001) 245003)
  - Perhaps due to superbanana plateau physics (K. Shaing et al., PPCF **51** (2009) 035009)

Stronger braking with constant n = 3 applied field and β_N as ω_E reduced – accessing superbanana plateau NTV regime

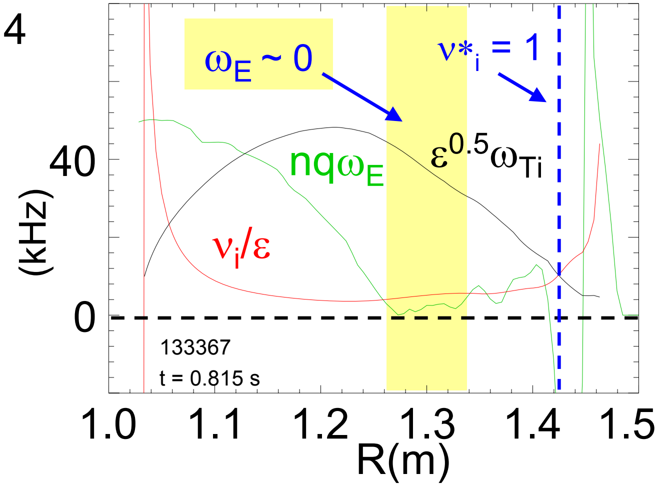




Transition to FASTER braking as ω_E reduced



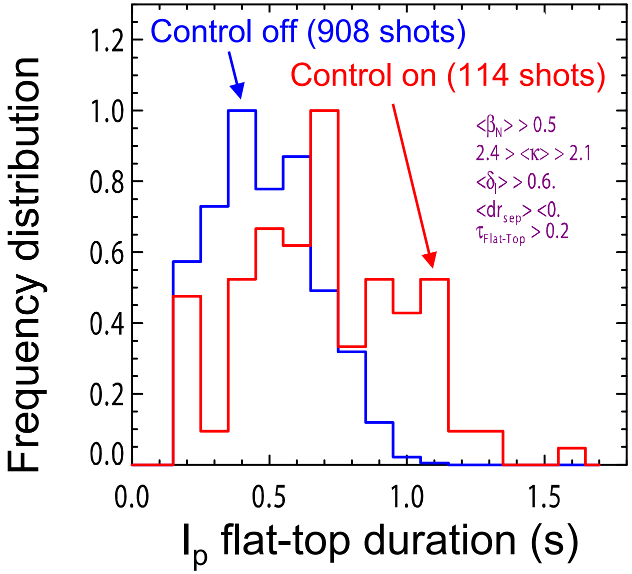
Broad, near zero ω_ϕ WITHOUT rational surface locking

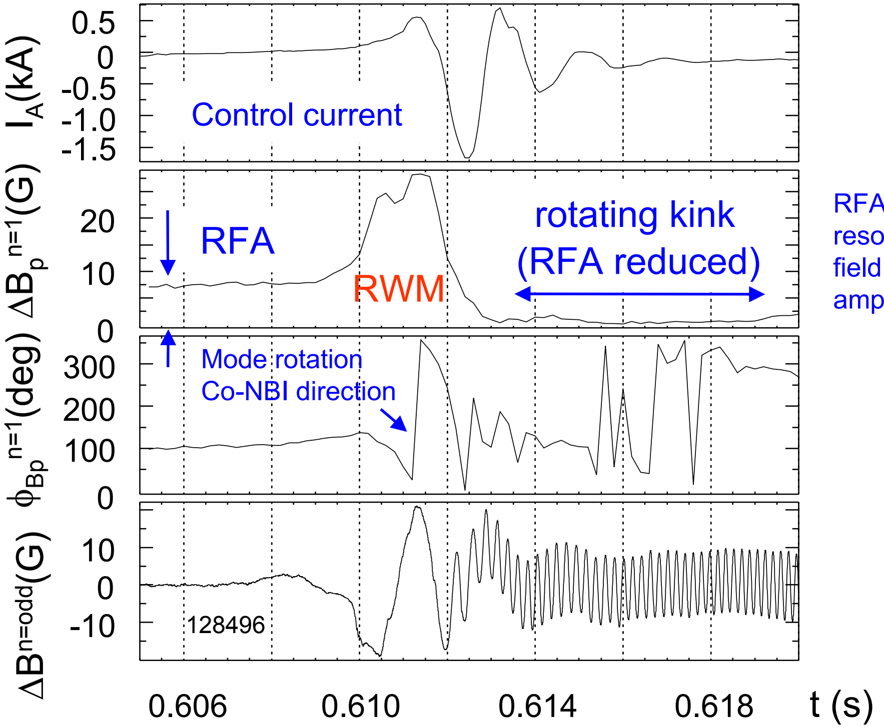


- Faster braking with
  - Constant applied n = 3 field, β_N; No mode activity
- Torque not $\propto 1/\omega_\phi$ (non-resonant)
  - NTV satisfies 1/ν regime criterion ($|nq\omega_E| < \nu_i/\varepsilon$ and $\nu^*_i < 1$)
  - Stronger braking expected at low ω_E (superbanana plateau regime)

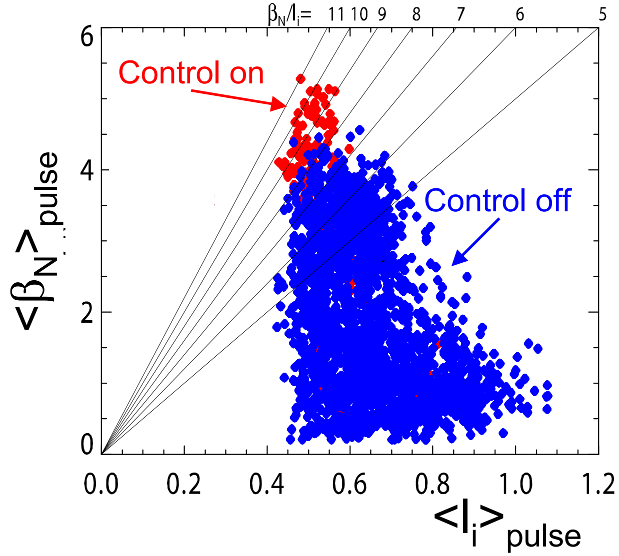
    (K.C. Shaing et al., PPFC **51** (2009) 035009)

RWM control physics examined, disruptivity initially assessed





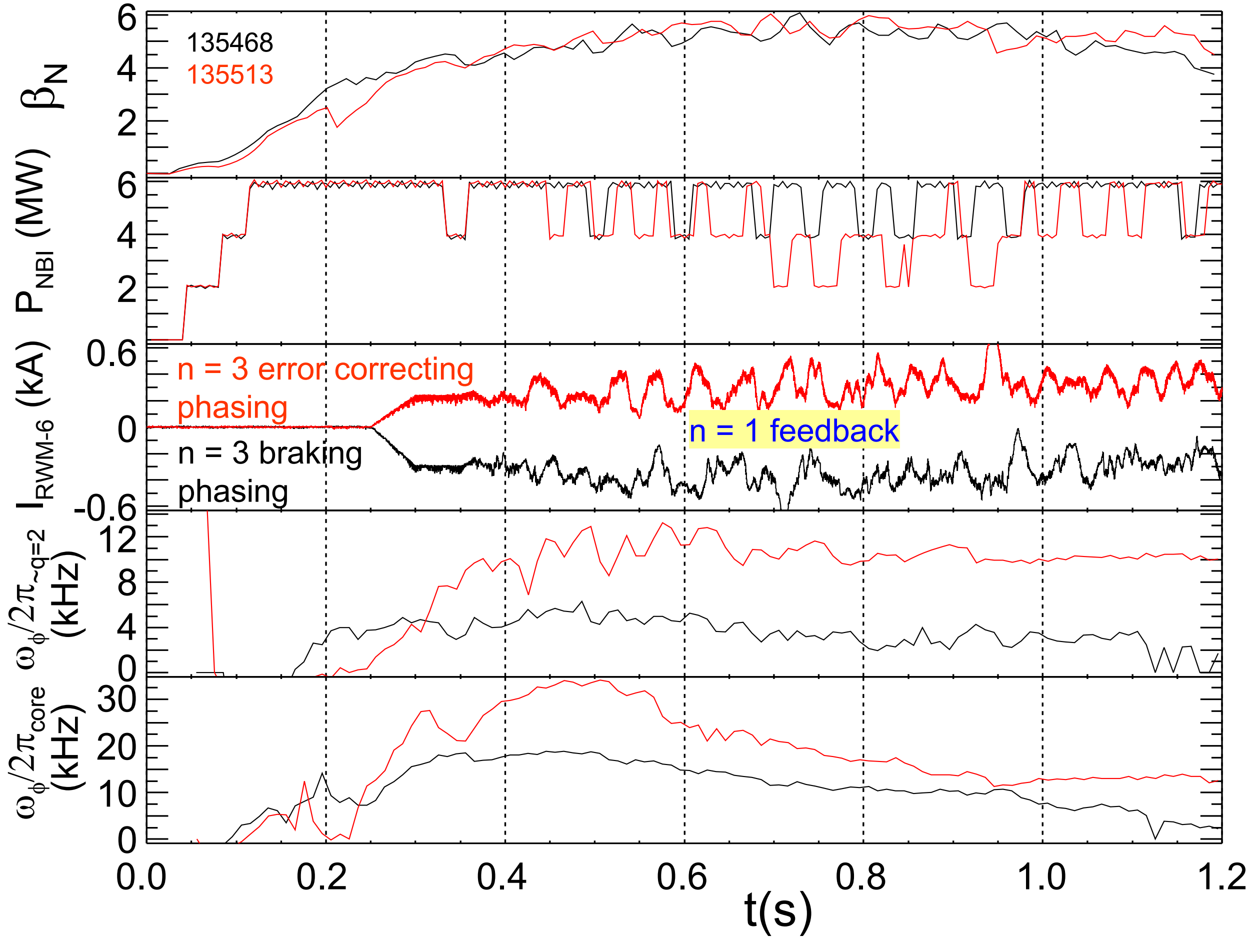
RFA = resonant field amplification



- Important physics affecting future research
  - Plasma rotation important for control
    - RWM conversion to rotating, damped kink needs V_ϕ
    - Larger β_N fluctuation at low V_ϕ
  - RWM control effective at low l_i (key for future STs)
  - n = 1 feedback response speed significant
    - RWM more likely unstable if feedback response is slowed (e.g. slow error field correction)
  - Optimal n=3 error field correction found vs. I_P, B_T

S.A. Sabbagh, et al, NF **50** (2010) 025020

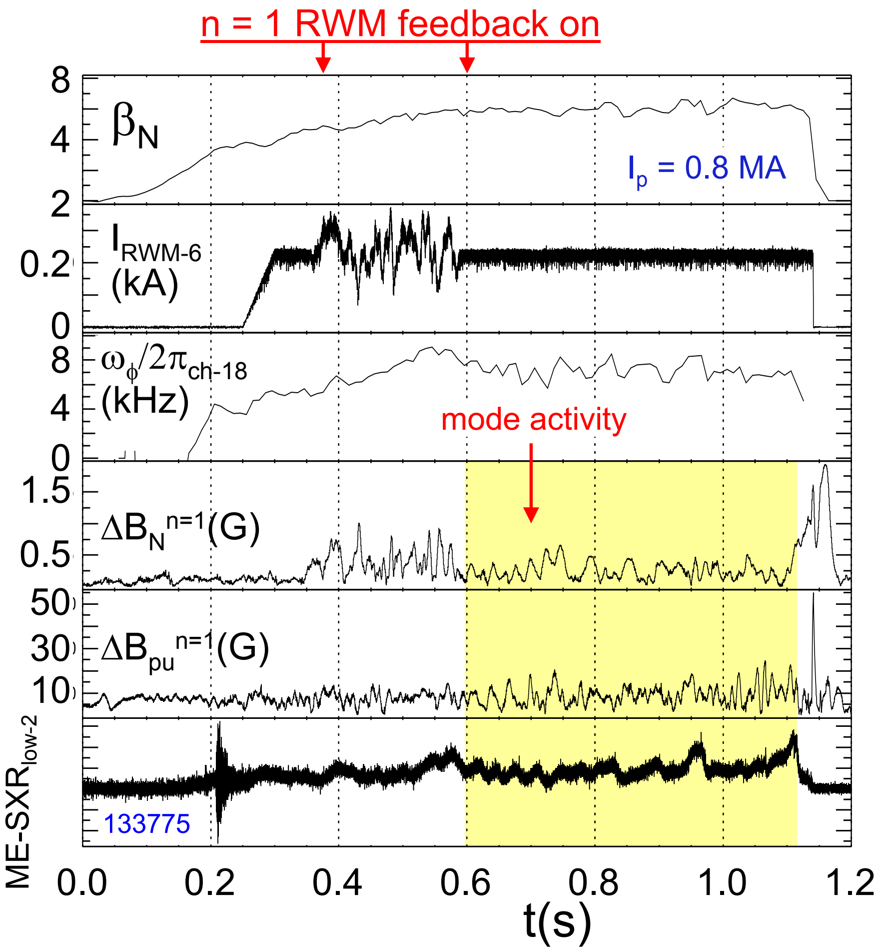
β_N feedback combined with n = 1 RWM control to reduce β_N fluctuations at varied plasma rotation levels

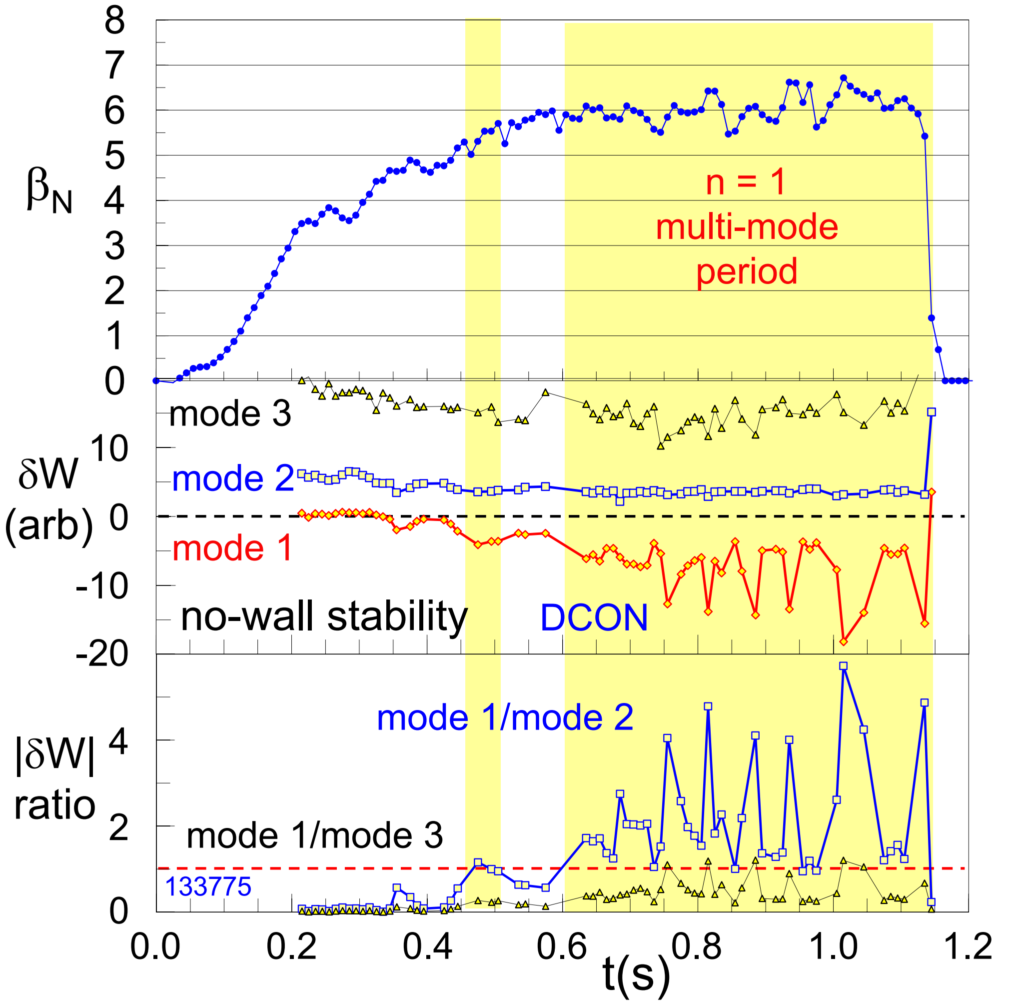


- Prelude to ω_ϕ control
  - Reduced ω_ϕ by n = 3 braking does not defeat FB control
  - Increased P_{NBI} needed at lower ω_ϕ
- Steady β_N established over long pulse
  - independent of ω_ϕ over a large range

Column 3

Activity in RWM frequency range coincident in magnetic and kinetic diagnostics investigated as multi-mode RWM

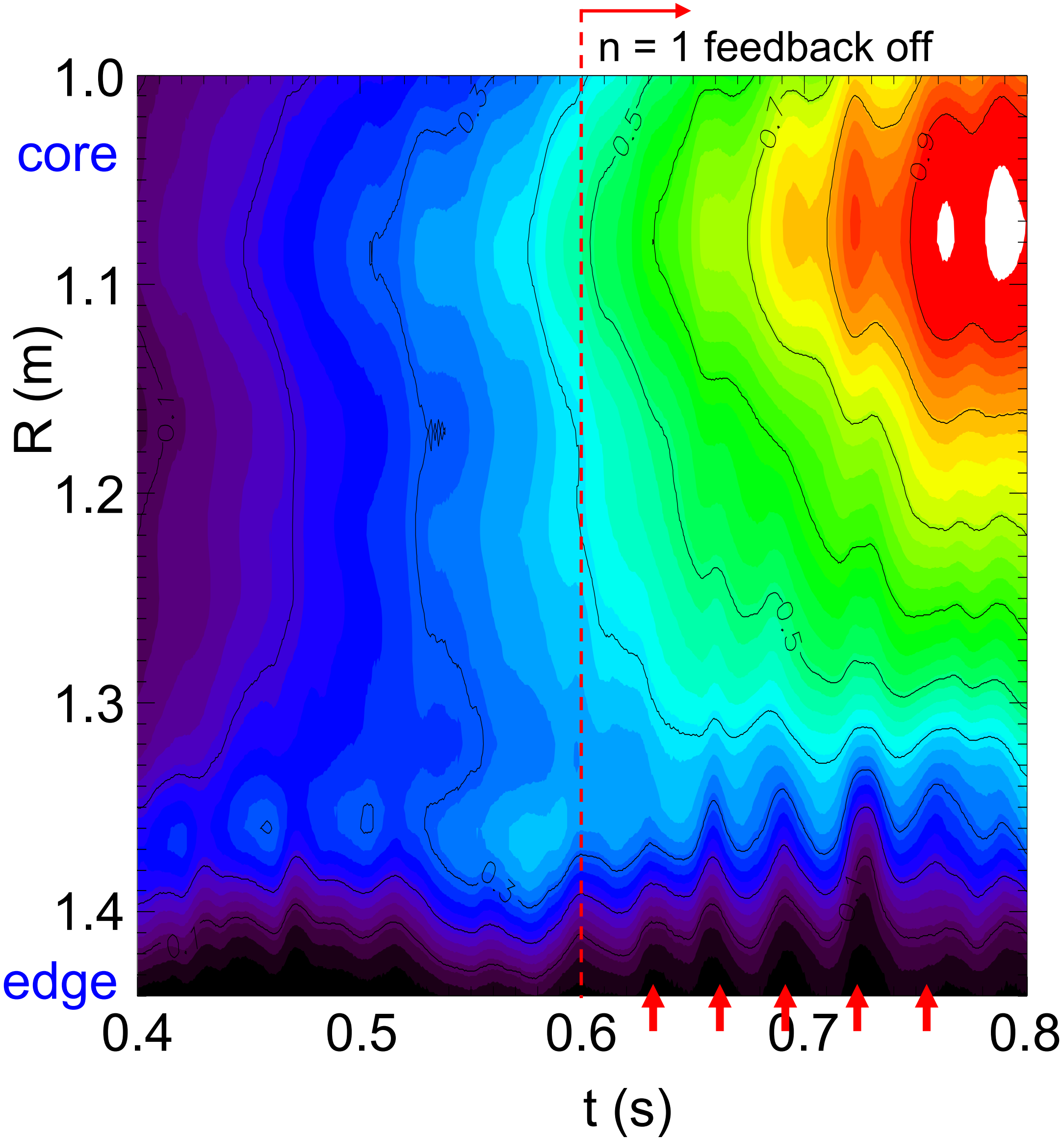


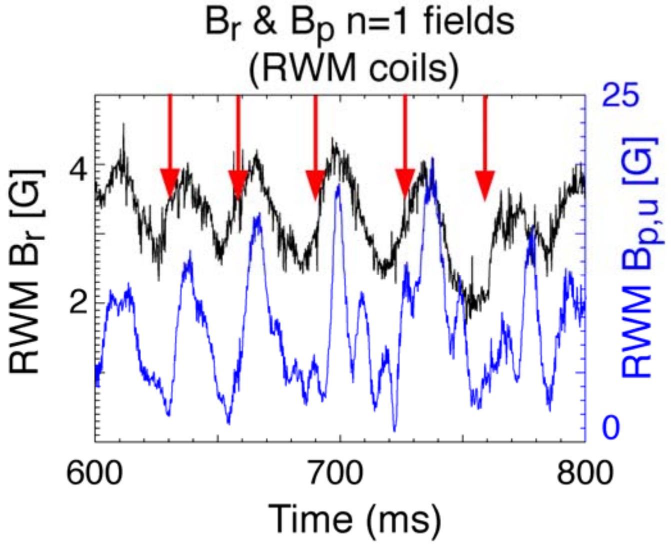


- ❑ Activity has characteristics of driven RWM
  - ❑ Magnitude, radial extent increases in SXR as β_N increases; low frequency (~ 30Hz)
  - ❑ Activity appears separate from unstable RWM

- ❑ RWM multi-mode response expected to be significant at high β_N (A.H. Boozer, Phys. Plasmas **10** (2003) 1458.)

Multi-energy soft X-ray reconstructed emission shows mode activity correlated to n = 1 activity seen in RWM magnetic sensors



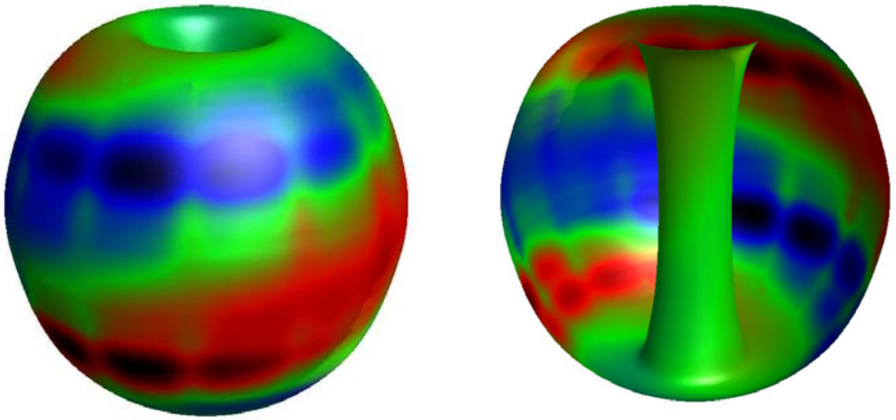

B_r & B_p n=1 fields (RWM coils)

- ❑ Mode activity in RWM frequency range (~30 Hz) seen in both magnetic and kinetic diagnostics
- ❑ ME-SXR reconstructions show that mode activity is global
- ❑ When active feedback is turned off, mode amplitude grows in time (kinetic and magnetic diagnostics)

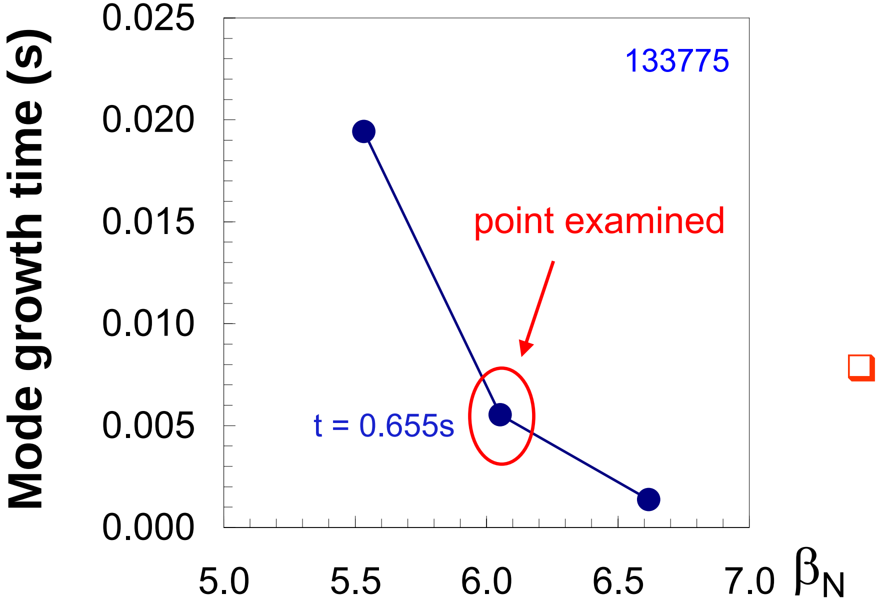
For diagnostic detail, see L. Delgado-Aparicio, poster P4.119, this meeting

Multi-mode RWM VALEN computation shows 2nd mode has dominant amplitude at high β_N in NSTX stabilizing structure

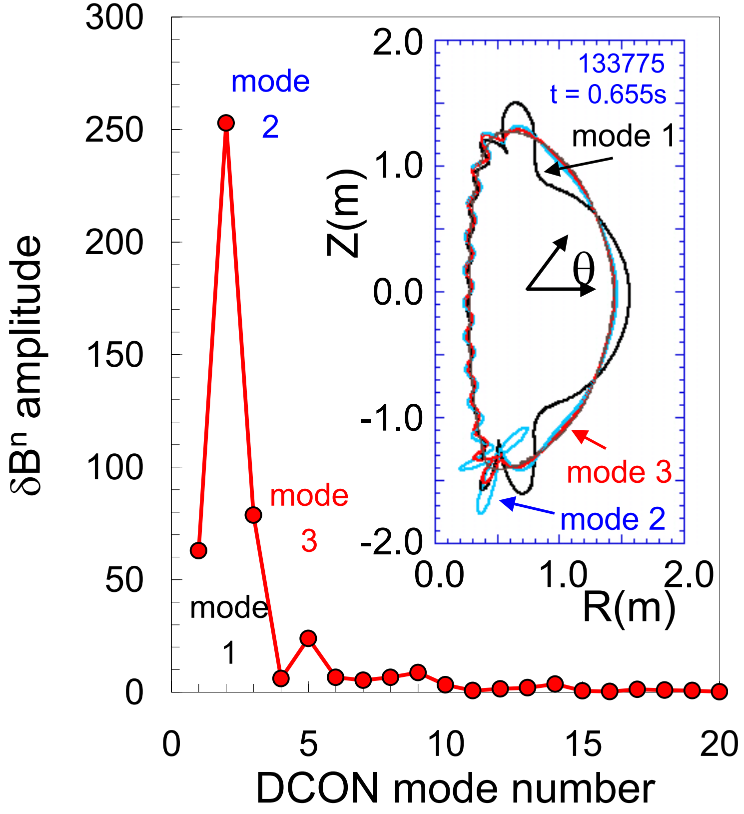
δB^n from wall, multi-mode response



RWM growth time vs β_N

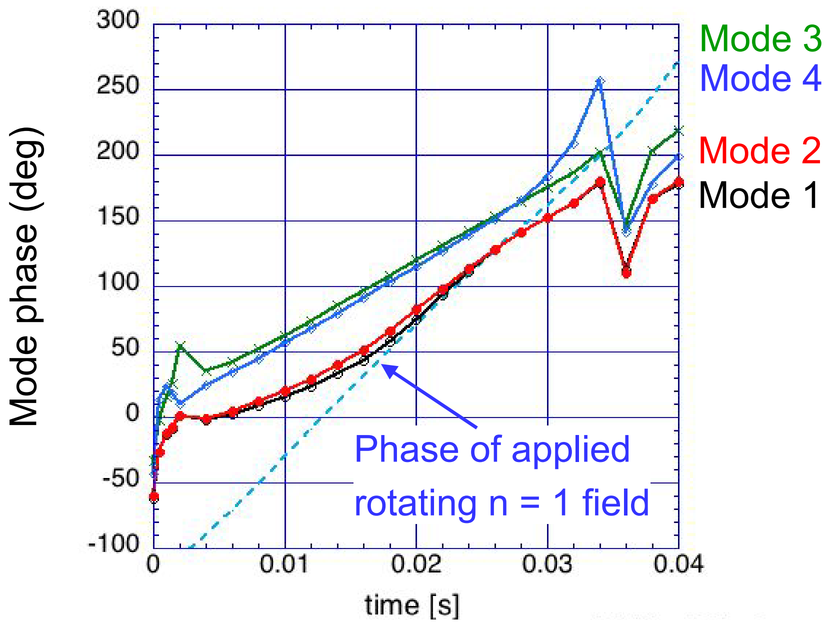


δB^n multi-mode composition

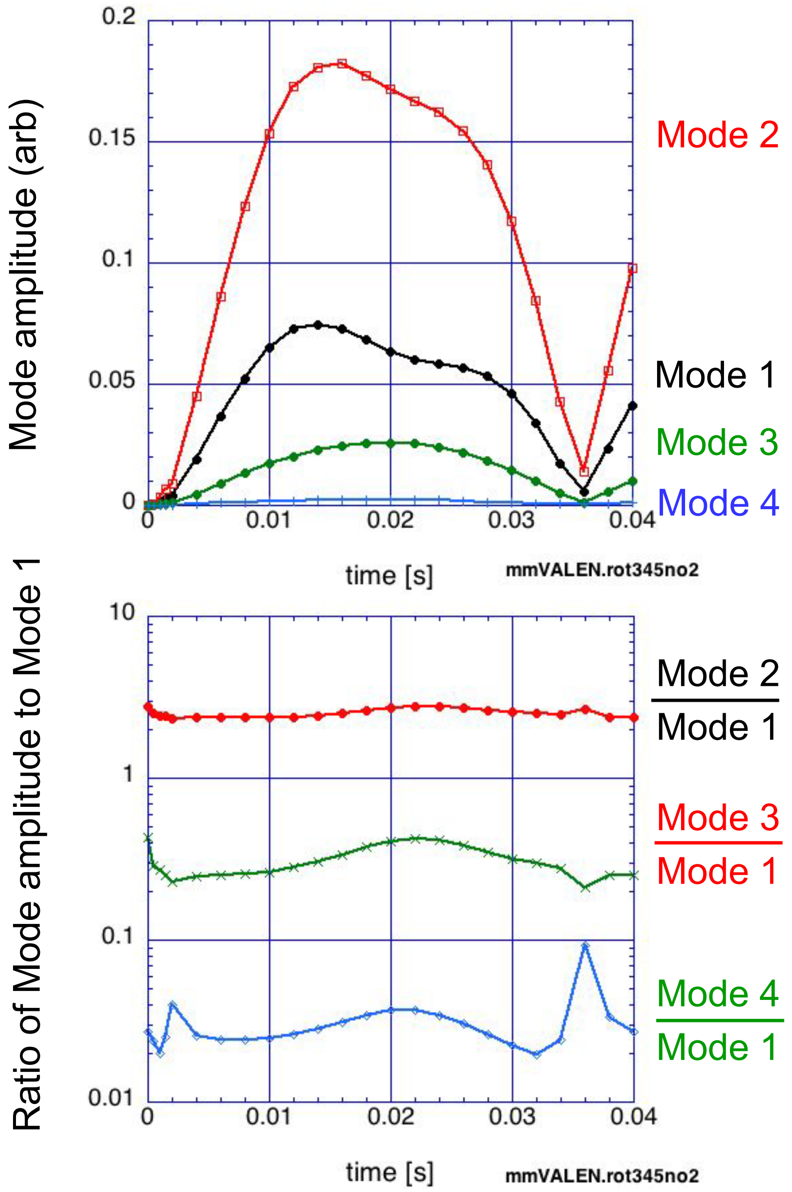


- Multi-mode calculations
  - Ideal mode growth time consistent with experiment
  - Significant spectrum out to ~ 10 modes; 2nd mode has dominant amplitude

Initial VALEN tests of multi-mode time evolution show n = 1 stable eigenmode amplitude dominates least stable mode



- Simulated n = 1 toroidally rotating field from RWM control coils
  - 180° toroidal rotation of field shown
- Eigenmodes
  - track n = 1 applied field phase
  - mode 2 amplitude largest, with ratio to mode 1 amplitude of 2-3
  - vary in relative amplitude a modest amount



NSTX MHD Research is Addressing Topics Furthering Steady Operation of High Performance ST Plasmas

- n = 1 RWM feedback control combined with new β_N feedback control shows regulation of high β_N at varied plasma rotation levels
- RWM instability, observed at intermediate plasma rotation, correlates with kinetic stability theory (J.W. Berkery, et al., PRL **104** (2010) 035003)
  - role of energetic particles (EP) under study: see J.W. Berkery poster P4.106
  - ITER advanced scenario 4 requires EP stabilization at expected ω_ϕ
- Strong non-resonant NTV braking observed from all $\nu_i/\varepsilon nq\omega_E(R)$ variations made
  - apparent transitions in NTV (stronger magnetic braking) at low ω_E
- Low frequency ~ $O(1/\tau_{wall})$ mode activity at high β_N being investigated as potential driven (stable) RWM
- Theory shows multi-mode RWM response may be important at high β_N; multi-mode VALEN code illustrates multi-mode spectrum, evolution

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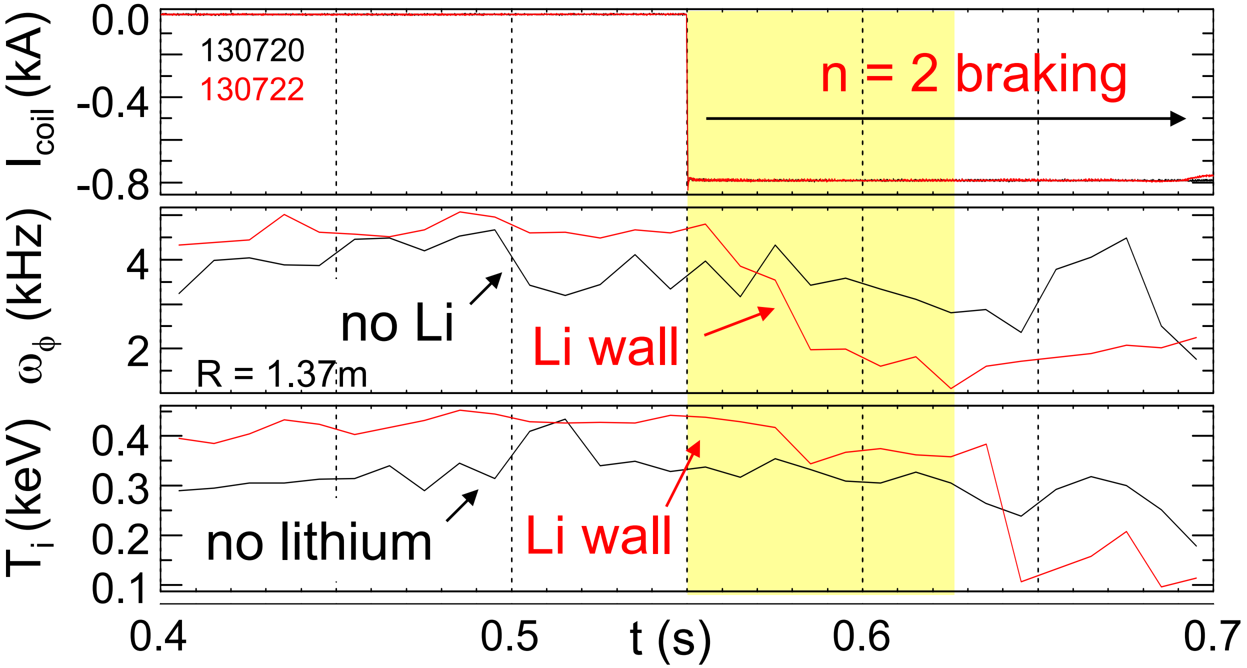
- See J.W. Berkery at this meeting for immediate questions related to the poster
- Print email address below for poster reprints, or email sabbagh@pppl.gov

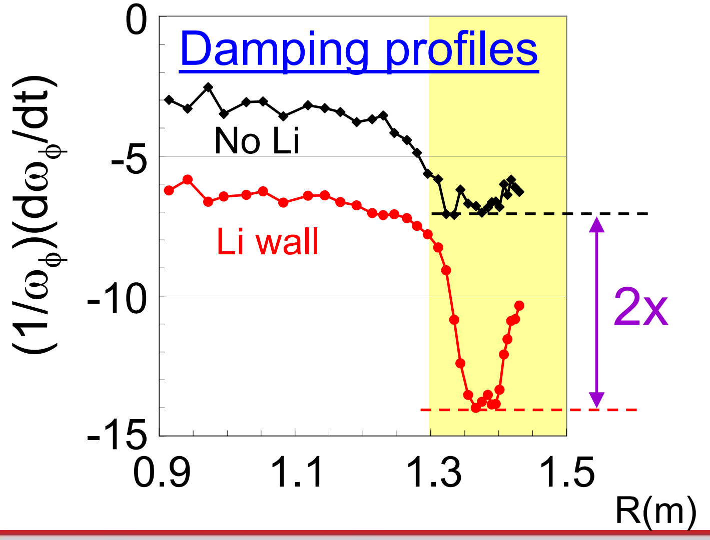
Backup Slides

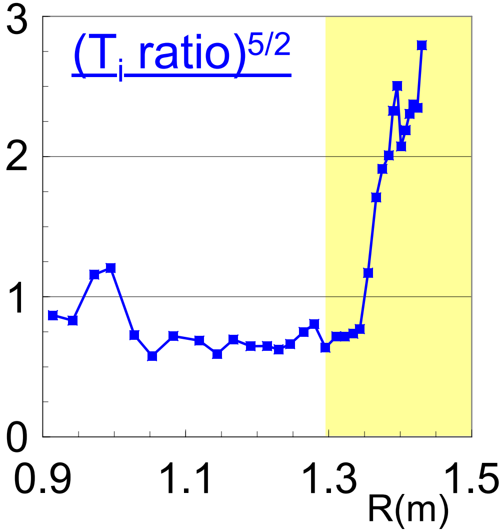
Subjects and Slides

- ❑ Subjects
  - ❑ Motivation: need high performance sustained indefinitely in future devices
    - Success with rotation and active n = 1 control
  - ❑ Issues remain for sustained stability, addressed by present research
    - RWM at high rotation (RWM stabilization physics), NTV to adjust rotation/control rotation, combined feedback control, multi-mode
- ❑ Col 1
  - ❑ Outline
  - ❑ NSTX overview, RWM coils, sensors
  - ❑ RWM at high rotation 137722
  - ❑ MISK overview
  - ❑ Weakened RWM stability due to rotation profile mismatch with resonances
- ❑ Col 2
  - ❑ MISK EP result for ITER (point to JWB poster for detail and NSTX XP results)
  - ❑ NTV overview
  - ❑ NTV superbanana plateau
  - ❑ Active control overview
  - ❑ Combined feedback and varied rotation
- ❑ Col 3
  - ❑ NSTX and driven (stable) RWM
  - ❑ ME-SXR reconstructions
  - ❑ VALEN multi-mode 1
  - ❑ VALEN multi-mode 2
  - ❑ Summary slide

Stronger non-resonant braking at increased T_i





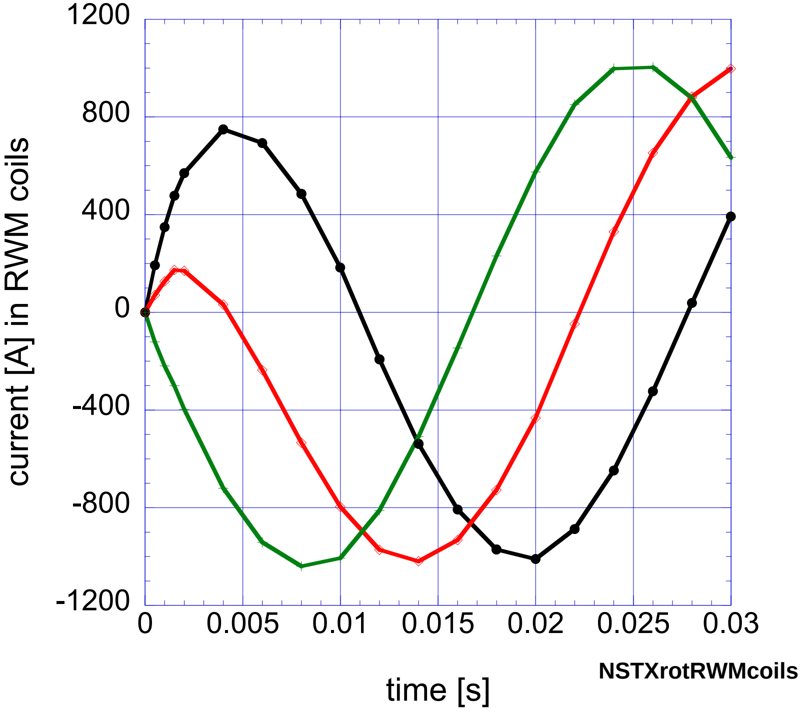


- Observed NTV braking using n = 2 field configuration
- Expect stronger NTV torque at higher T_i $(-d\omega_\phi/dt \sim T_i^{5/2}\,\omega_\phi)$
  - At braking onset, T_i ratio$^{5/2}$ = $(0.45/0.34)^{5/2} \sim 2$
  - Consistent with measured $d\omega_\phi/dt$

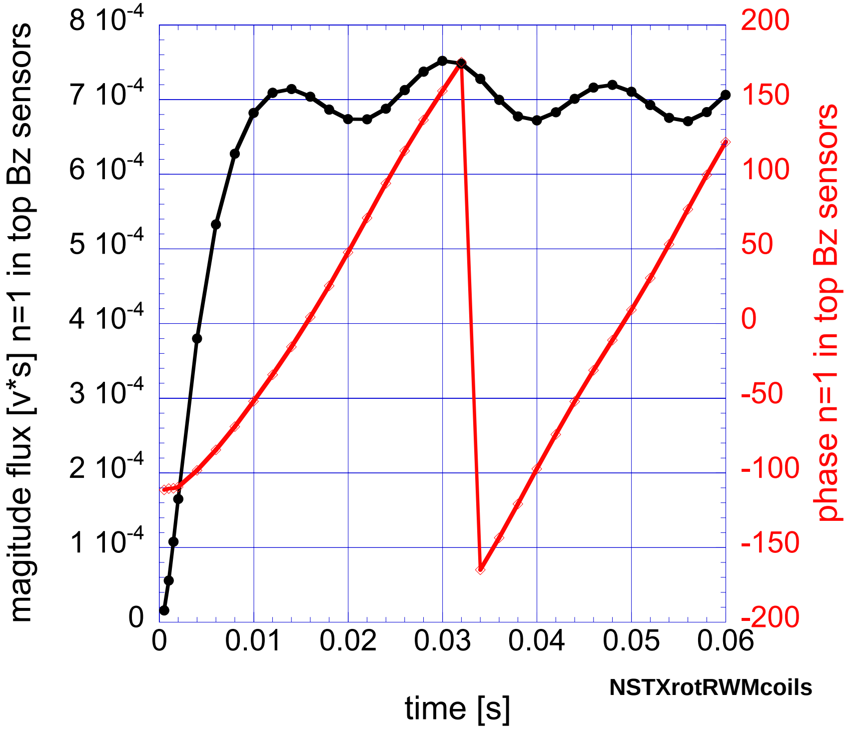
S.A. Sabbagh, et al, NF **50** (2010) 025020

VALEN test of multi-mode time evolution - toroidally rotating n = 1 applied field

Modeled currents in RWM control coils

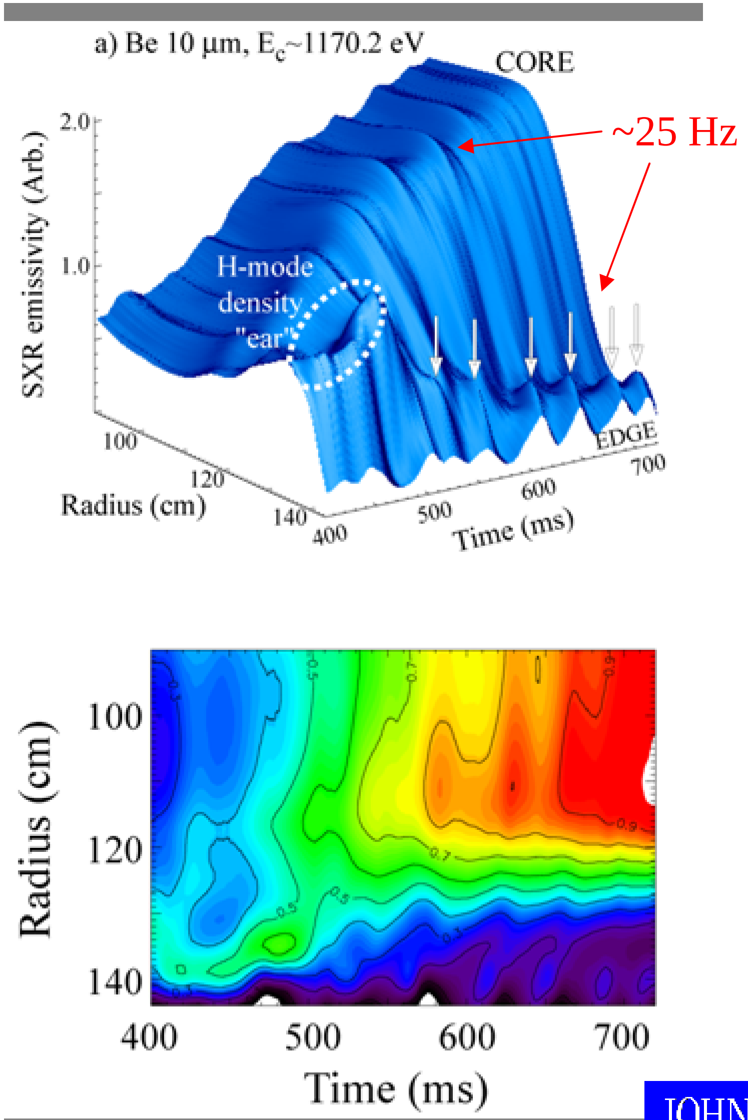


Modeled n = 1 RWM sensor amplitude and phase

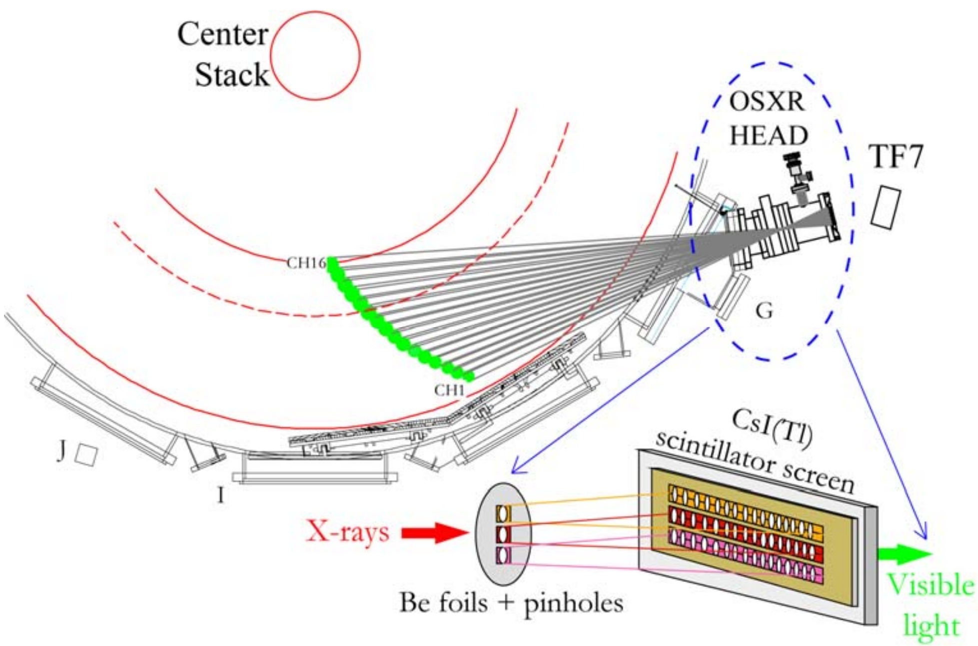


- Used to determine if eigenmodes will track phase of n = 1 applied field, lock to the plates/vessel, change in relative amplitude

Multi-energy soft X-ray measurements consistent with mode being a driven RWM



Multi-energy soft X-ray (ME-SXR) viewing geometry

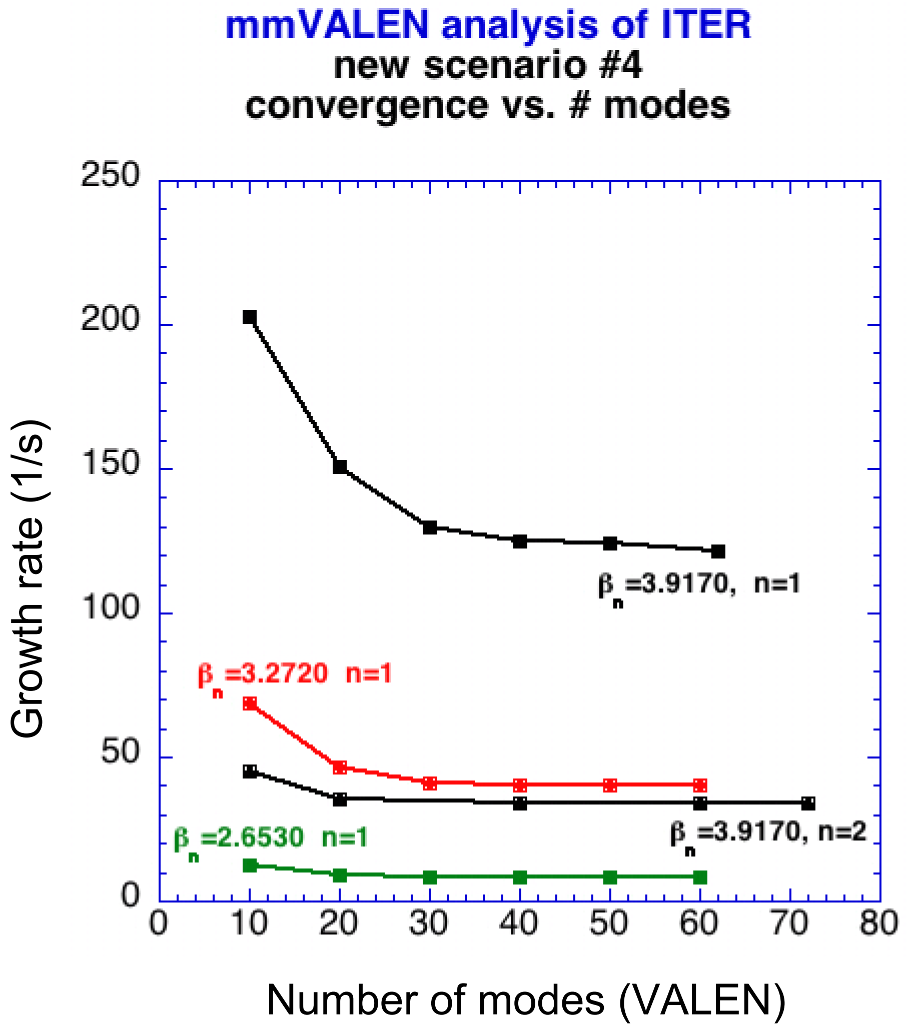


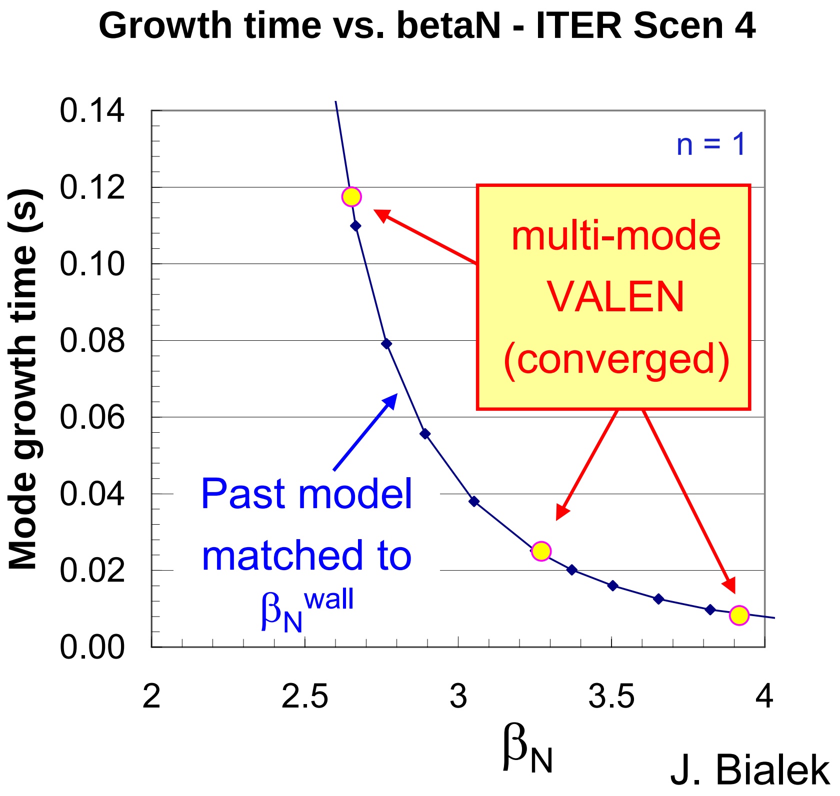
- RWM characteristics
  - Propagation in the co-NBI direction
  - Observed frequency near measured RWM resonance (Sontag, et al., NF **47** (2007) 1005.)

L. Delgado-Aparicio (JHU)

JOHNS HOPKINS UNIVERSITY

Multi-mode VALEN code (RWM control) testing successfully on ITER Scenario 4 cases (reversed shear)



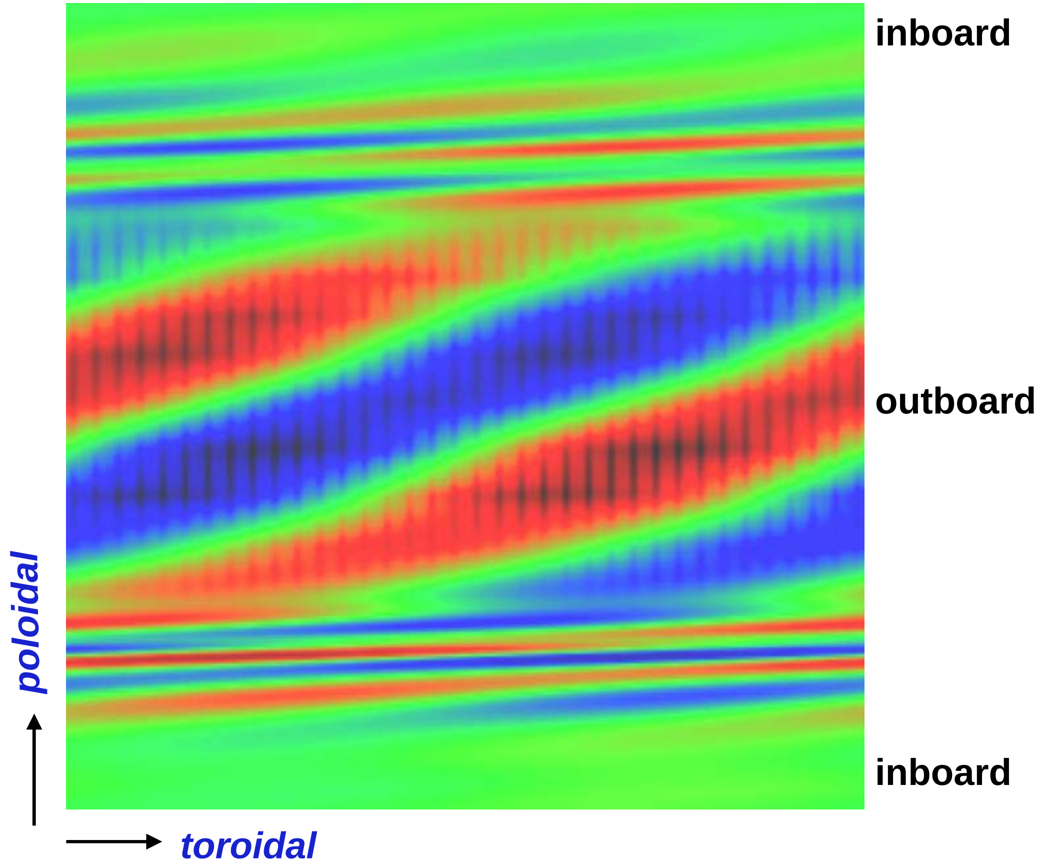


- At highest β_N, n =1 and 2 are unstable

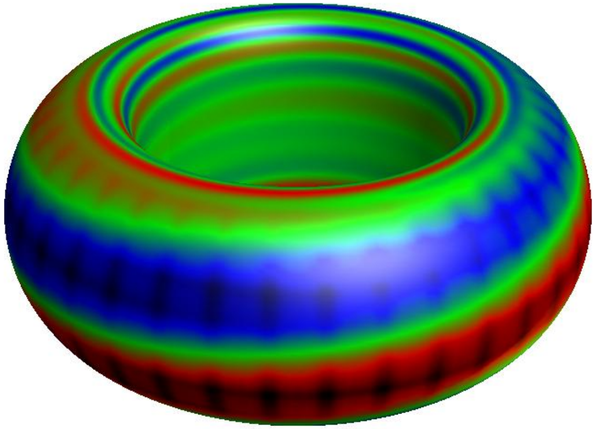
- DCON δW shows several modes with high response
  - Three n = 1 modes at high β_N
  - Two n = 2 modes at high β_N

Illustration of $B^n(\theta,\phi)$ on plasma surface from mmVALEN for ITER Scenario 4, β_N = 3.92

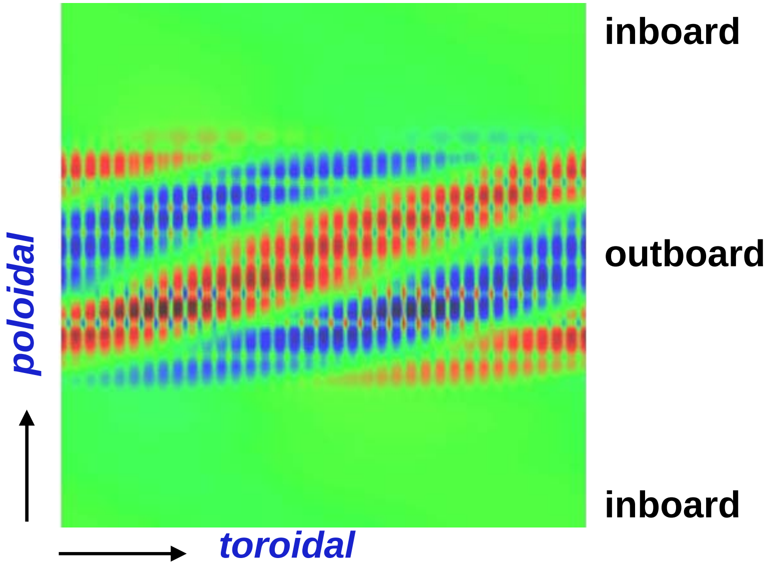
multi mode response (incl. wall), total B^n



B^n from wall, plasma



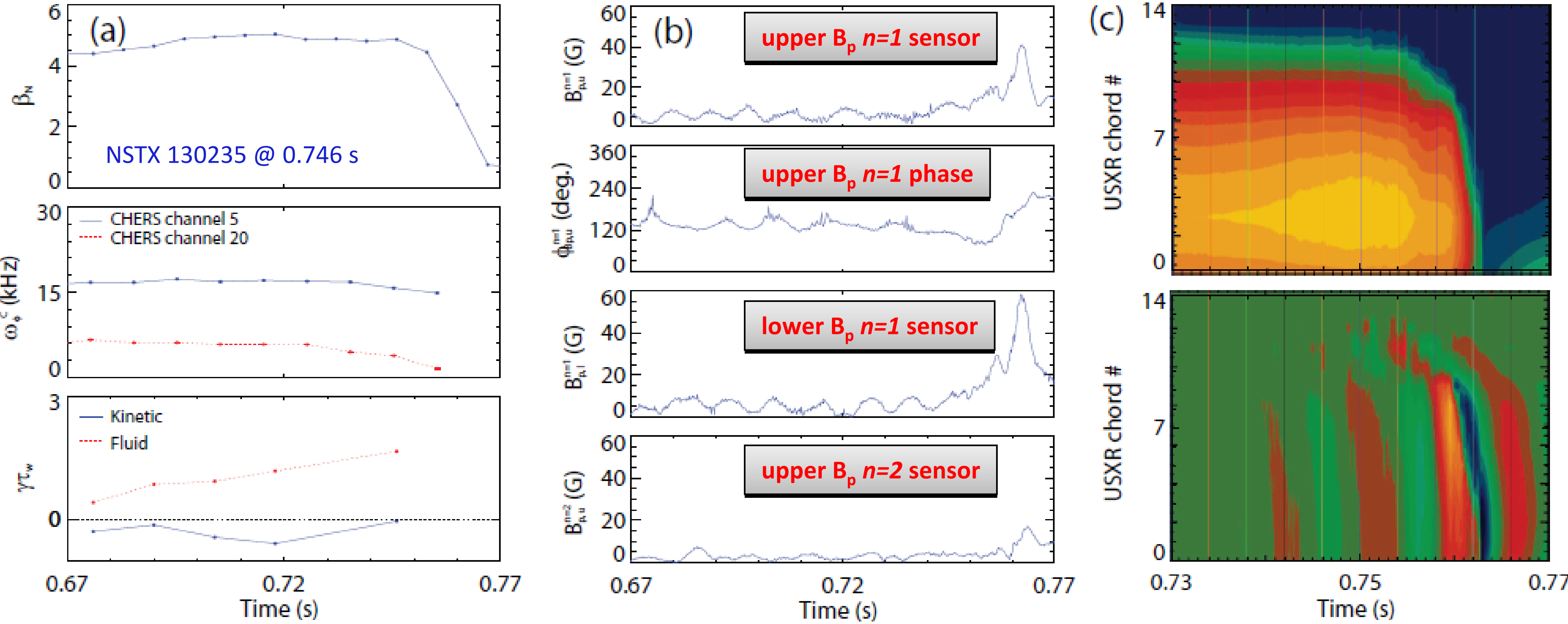
B^n from wall alone



- n = 1 eigenfunctions shown

J. Bialek

Resistive wall modes can terminate NSTX plasmas at intermediate plasma rotation levels without active control



- Change in plasma rotation frequency, ω_φ
- Growing signal on low frequency poloidal magnetic sensors
- Global collapse in USXR signals
- Leads to β collapse and plasma disruption ⇒ high ω_φ alone is not enough!