MHD Stability Research on NSTX and 3D Effects

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Joint US-Japan MHD Workshop / ITPA MHD Meeting

March 8 - 12, 2010

National Institute for Fusion Science, Toki, Japan

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v1.5

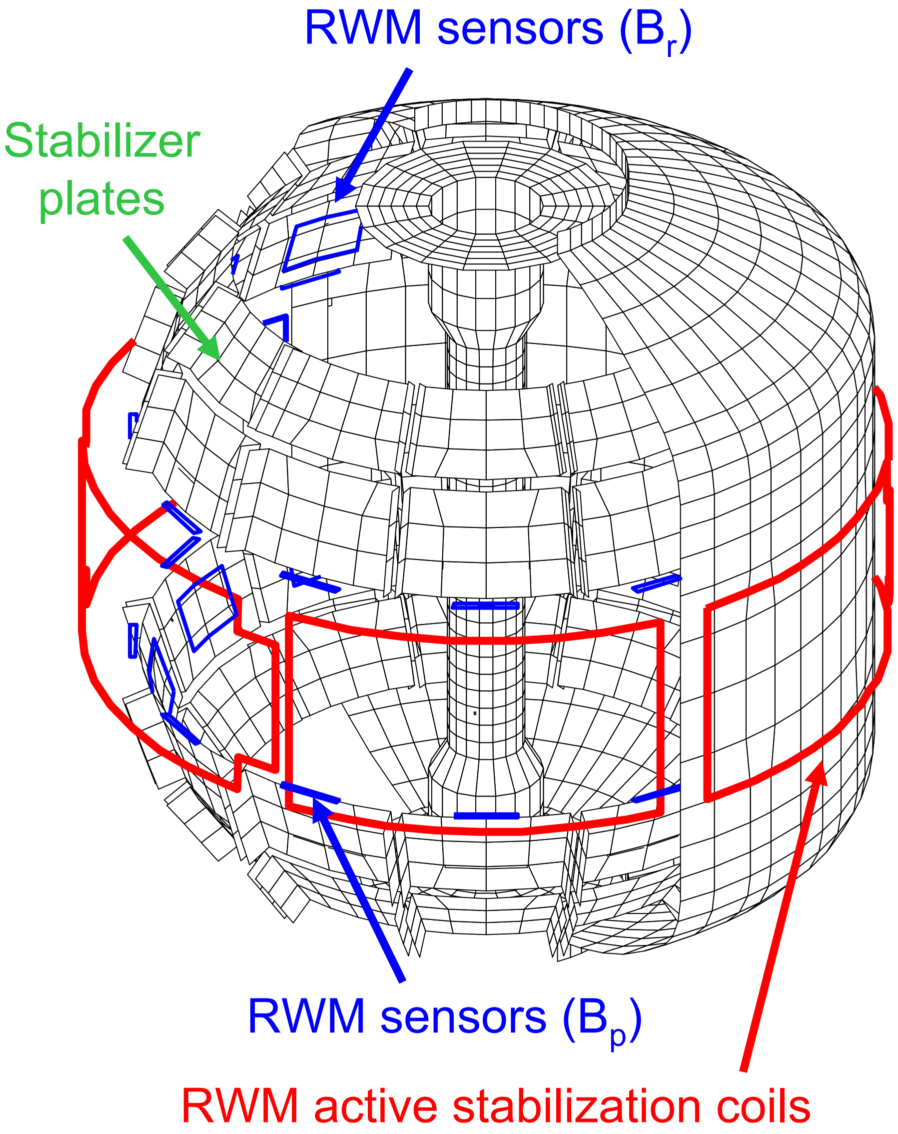
NSTX MHD Research is Addressing Needs for Maintaining Long-Pulse, High Performance Spherical Torus Plasmas

- Motivation
  - Maintenance of high β_N with sufficient physics understanding allows confident extrapolation to ST applications (e.g. ST-CTF, 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

- 3-D field / mode physics knowledge needed to ensure steady-state ST
  - n = 1 locked mode behavior at low to moderate $\beta_N < \beta_N^{no\text{-}wall}$
  - Ability of plasma rotational stabilization to maintain high β_N
  - Physics of 3D fields to control plasma rotation profile (for greater stability, confinement)
  - NTM onset and marginal island width for stabilization
  - 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, general 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%, B_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
  - ELM modification
- Varied sensor combinations used for RWM feedback
  - 48 upper/lower B_p, B_r

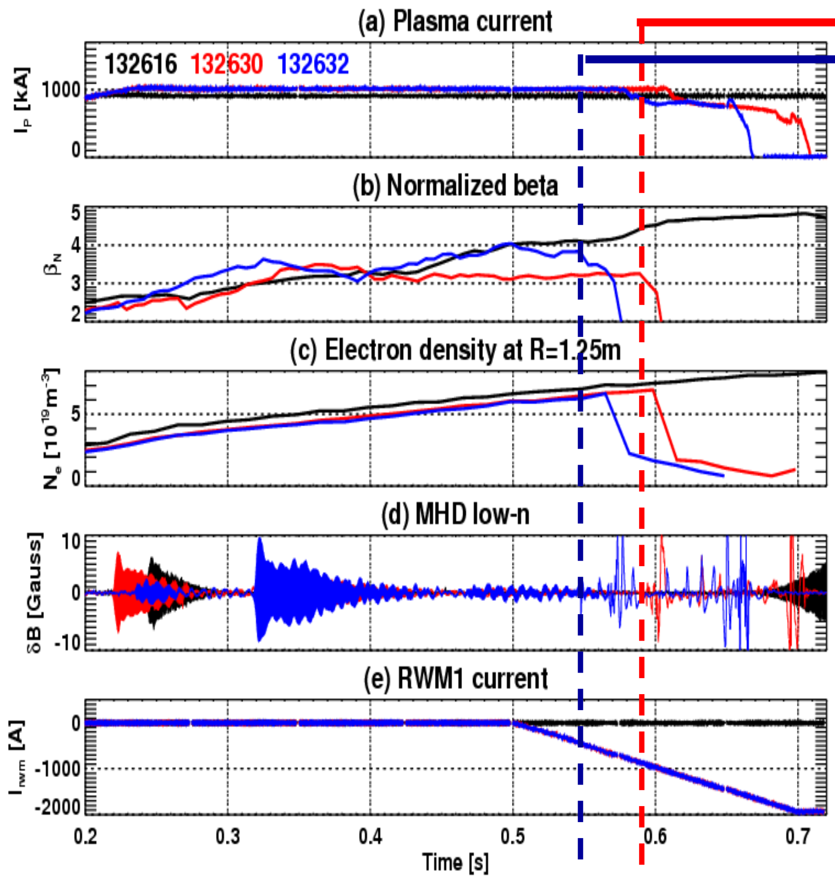


NSTX MHD Research – 3D effects: Topics Covered in Talk

- ❑ 3D fields and mode locking
- ❑ Resistive wall mode stability physics
- ❑ Non-resonant magnetic braking by 3D fields
- ❑ NTM threshold physics
- ❑ Improving $\langle\beta_N\rangle_{pulse}$ with active n = 1 control, β_N feedback control

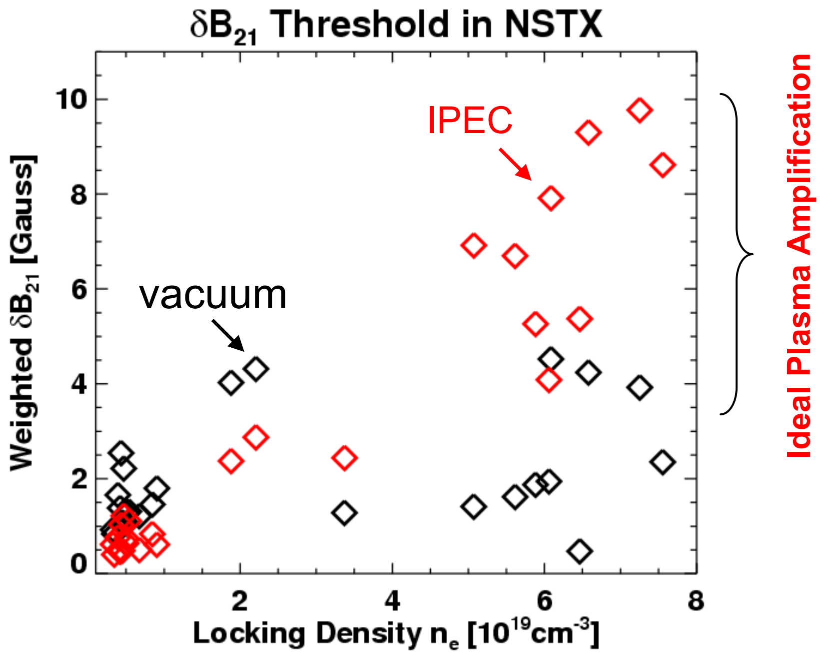
Ideal plasma amplification of applied resonant field restores linear correlation of mode locking threshold with density

ITPA MDC-2,14



Higher-β locked earlier (w/ smaller n = 1 currents)

Lower-β locked later (w/ larger n = 1 currents)



- n = 1 error field threshold for mode locking decreased as β_N increased
- n = 1 rotating modes sometimes observed, study limited to static modes
- IPEC resonant field joins linear n_e correlation from low-β to increased-β

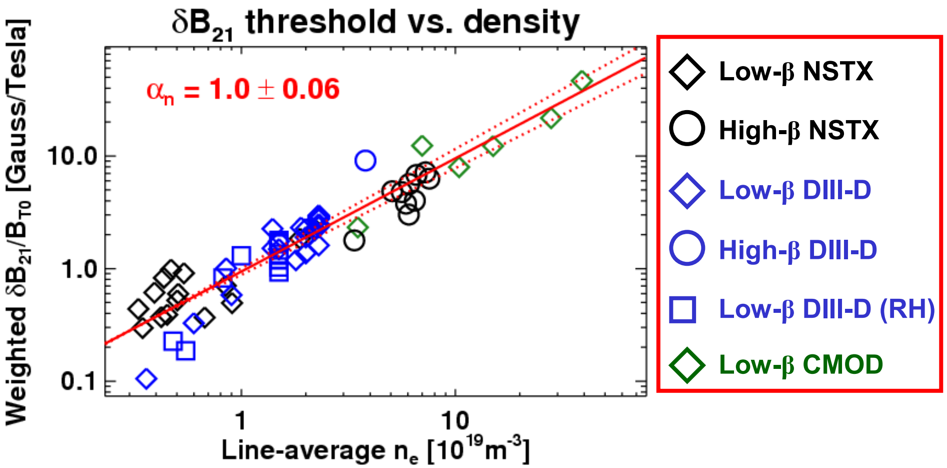
XP903: J.-K. Park (see talk, Monday afternoon)

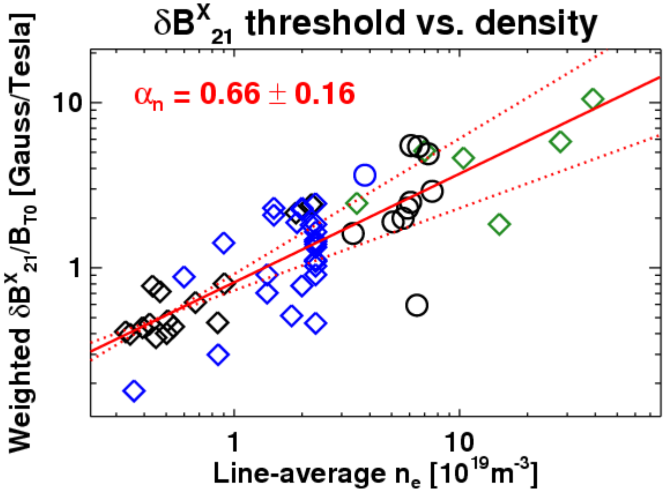
IPEC computed total resonant field unifies linear dependence of mode locking threshold on density among devices

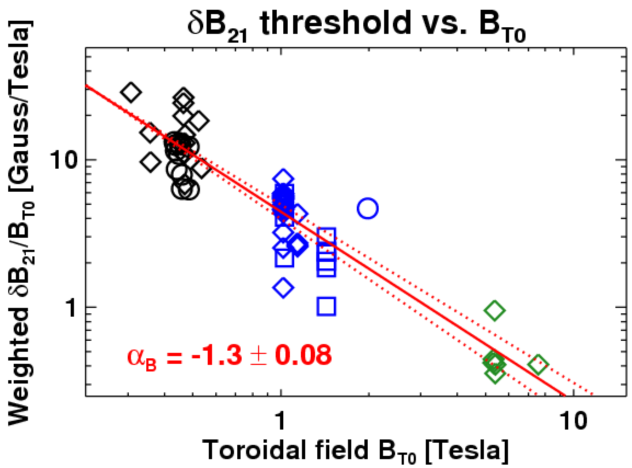
ITPA MDC-2,14

Total resonant field w/ plasma response (IPEC)

External resonant field only





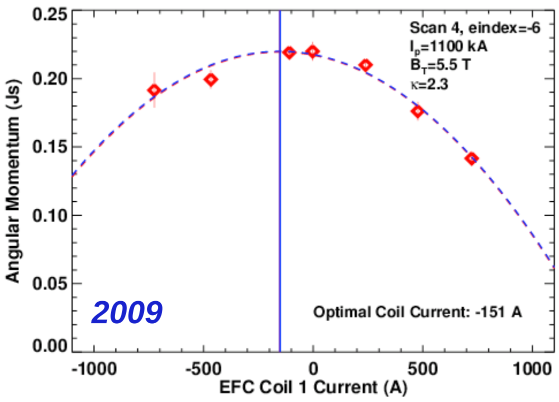


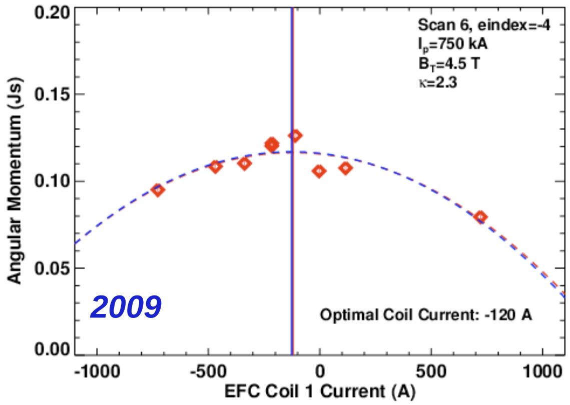
- Inter-machine mode onset, locking study
  - n = 1 applied field threshold for mode locking decreases as β_N increases (Park)
  - n = 1 and 3 field effect on rotating/locked mode onset is through impact on V_ϕ shear, torque (not direct mode interaction) (Buttery)

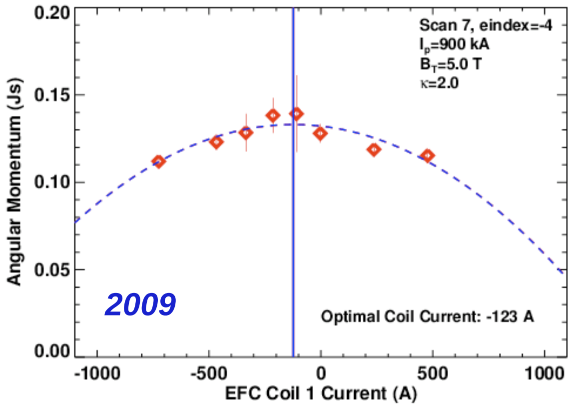
$$\frac{\delta B_{21}}{B_{T0}} \le 1.0\times 10^{-4}\left(n[10^{19}m^{-3}]\right)^{1.0}\left(B_{T0}[T]\right)^{-1.3}\left(R_0[m]\right)^{0.78}$$

XP903: J.-K. Park XP915: R. Buttery (GA)
(see talks by Park, Buttery on Monday afternoon)

Optimal n = 3 Error Field Correction Determined vs. I_P, B_T







- “optimal” n = 3 error field correction attained by maximizing angular momentum, scanning I_p, B_t, elongation
- n = 3 error field consistent with known equilibrium field coil distortion
  - scales with equilibrium field coil current
  - field phase and amplitude of correction is consistent with that expected from coil distortion
- n = 3 error field correction routinely used to maximize plasma performance in conjunction with n = 1 RWM feedback control

XP902: S. Gerhardt

NSTX MHD Research – 3D effects: Topics Covered in Talk

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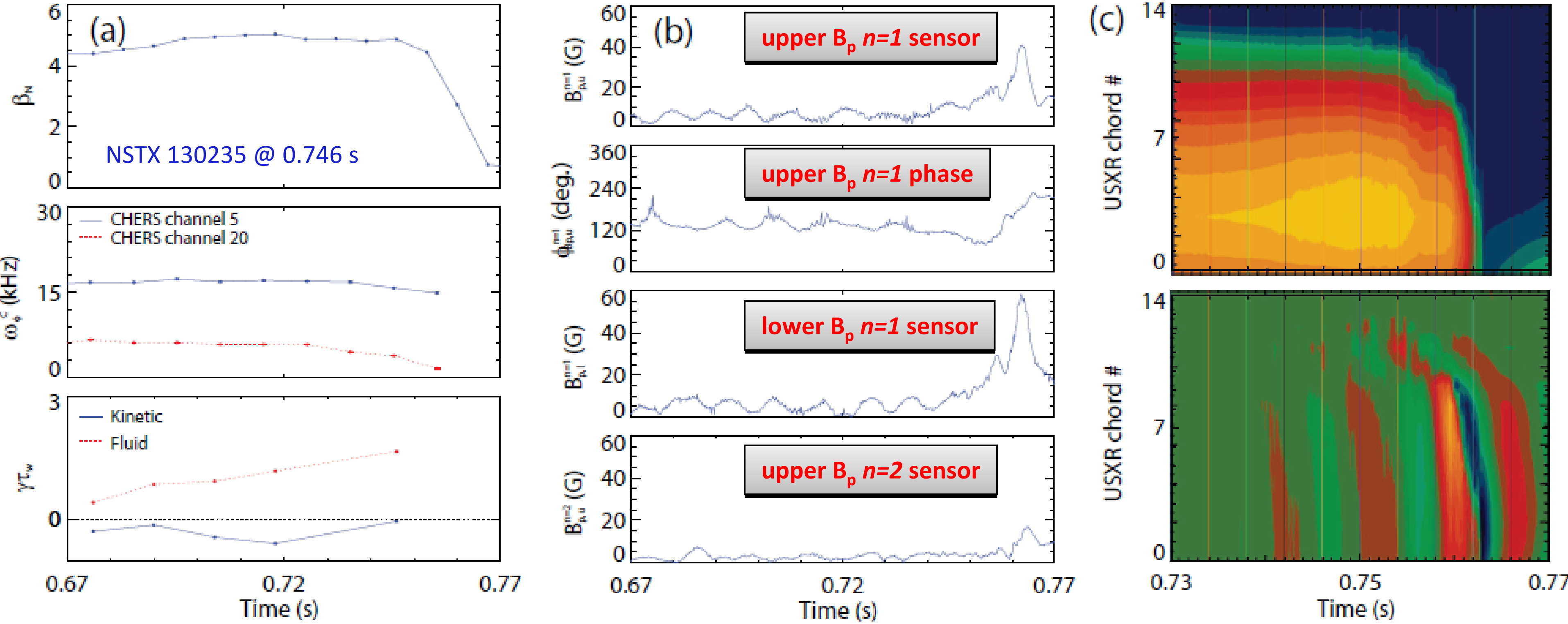
Resistive wall modes can terminate NSTX plasmas at intermediate plasma rotation levels without active control



- 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!

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)

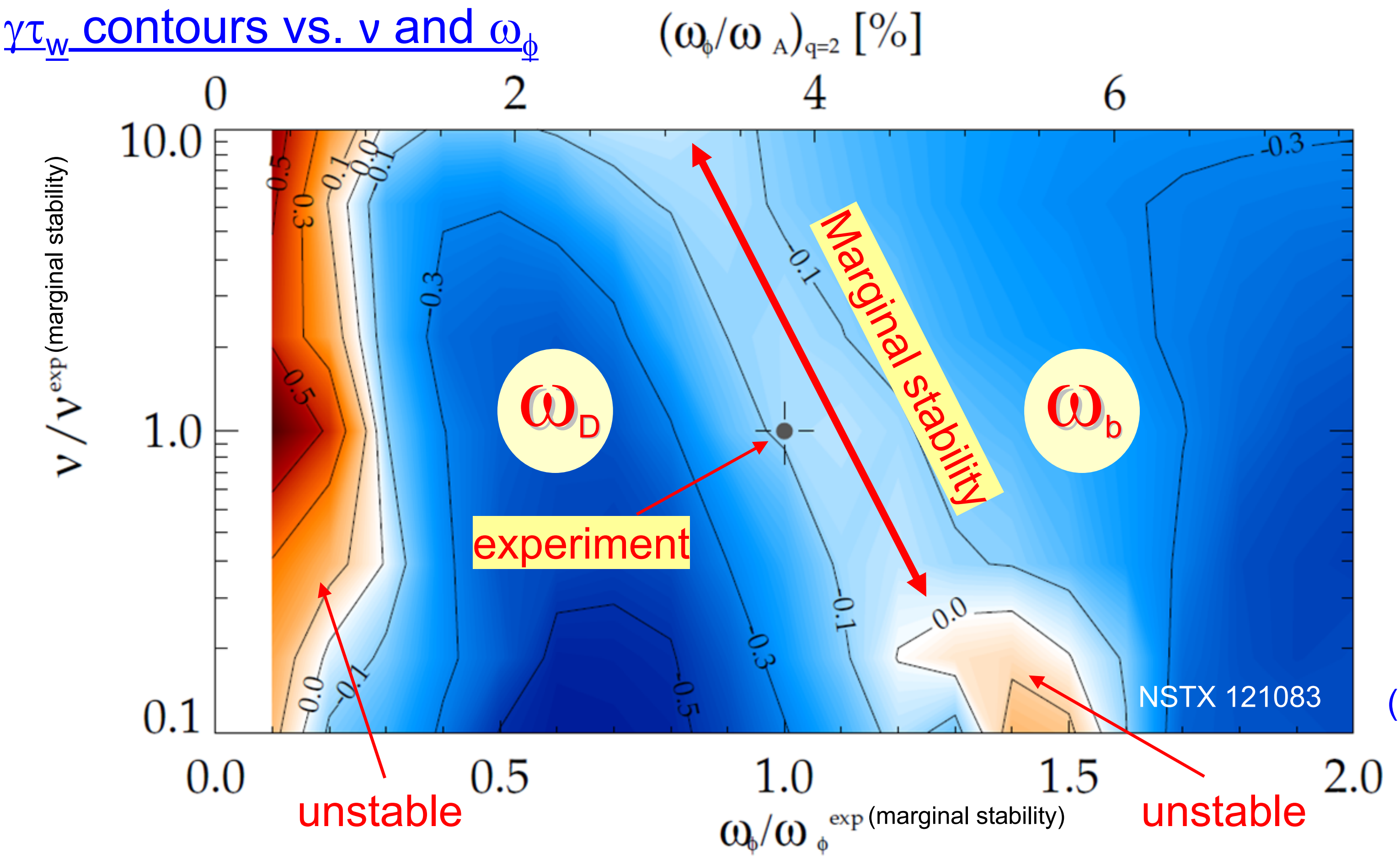
$$\delta W_K \propto \int \left[\frac{\omega_{*N} + \left(\hat{\varepsilon} - 3/2\right)\omega_{*T} + \omega_E - \omega - i\gamma}{\langle\omega_D\rangle + l\omega_b - i\nu_{eff} + \omega_E - \omega - i\gamma} \right] \hat{\varepsilon}^{\frac{5}{2}} e^{-\hat{\varepsilon}} d\hat{\varepsilon}$$

← Energy integral

precession drift   bounce   collisionality

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

ITPA MDC-2


$\gamma\tau_w$ contours vs. ν and ω_ϕ

Marginal stability

experiment

unstable

unstable

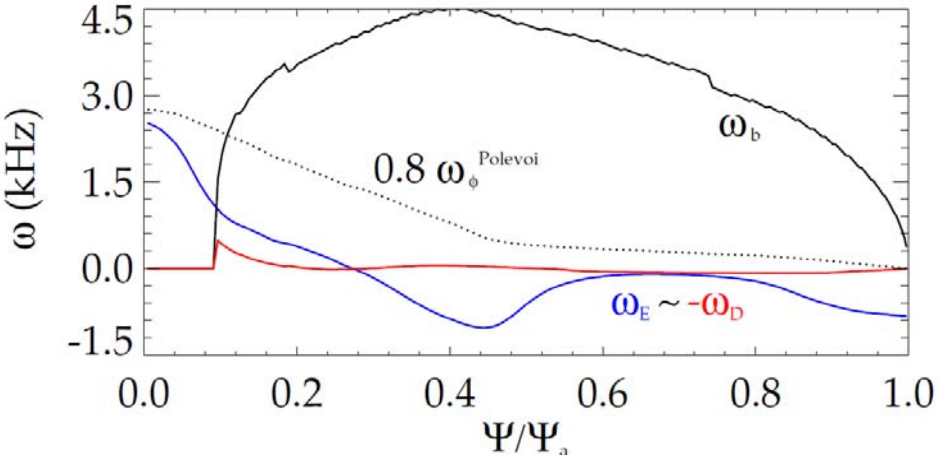
J. Berkery
(Columbia U.)

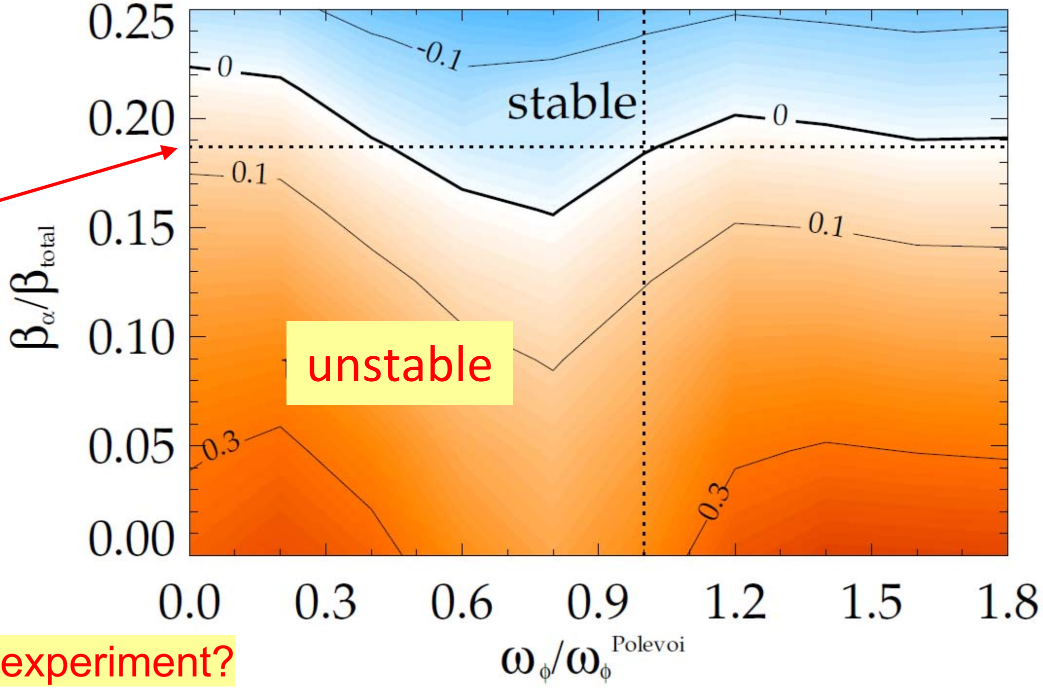
- Destabilization appears between precession drift resonance at low V_ϕ, bounce resonance at high V_ϕ

(J.W. Berkery, et al., PRL (2010) 035003; APS 2009 inv. talk)

MISK computed RWM stability of ITER advanced scenario 4 including energetic particles near marginal at $\beta_N = 3$

- ITER advanced scenario 4
  - With β_N = 3 (20% above n = 1 no-wall limit)
  - Polevoi plasma rotation profile (IAEA FEC 2002)
- Energetic particle (EP) effect
  - Isotropic slowing down distribution of alphas
  - Present model yields significant stabilization
  - At expected $\beta_\alpha/\beta_{total}$ = 0.19, near RWM marginal stability
- Plasma rotation effect
  - Stabilizing precession drift resonance $\omega_\phi = 0.8\ \omega_\phi^{Polevoi}$

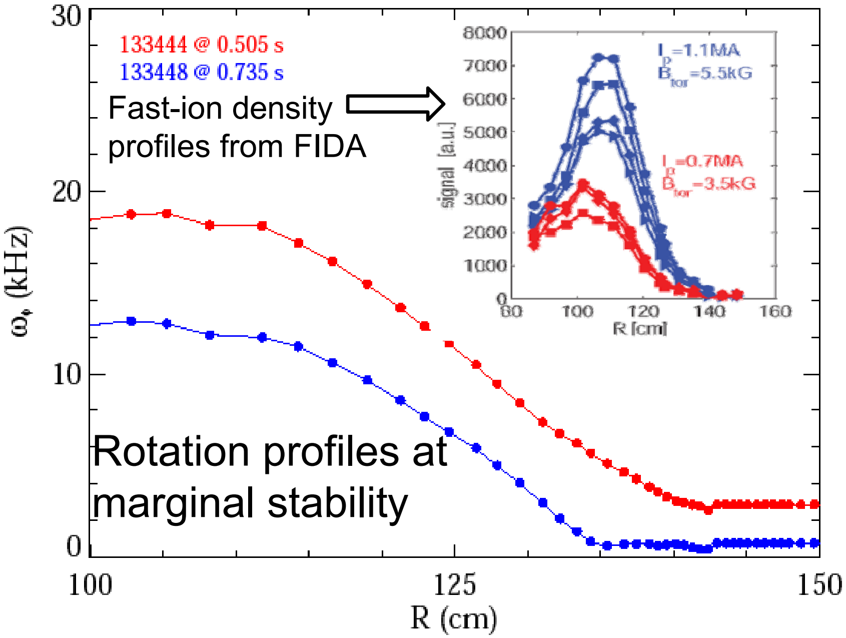




How does MISK result with EP compare to experiment?

Experimental RWM stability is changed by EP population, present MISK mode overestimates stability somewhat

- Fast particle fraction altered by scaling I_p, B_t at fixed q
  - Fast-ion D_α measurements (FIDA) confirm successful scan of energetic particle fraction
  - TRANSP confirms change in β_{fast}
- At RWM marginal stability, ω_ϕ profiles are altered at different EP fraction
  - Plasmas always reach instability
- MISK calculations indicate stability
  - But - change in $\gamma\tau_{wall}$ due to EP effects (0.35) is same magnitude as change due to ω_ϕ variation
- Presently implementing new terms in MISK computed δW
  - Adding destabilizing electrostatic term important at high ω_E
  - Adding non-isotropic distribution of NBI fast particles

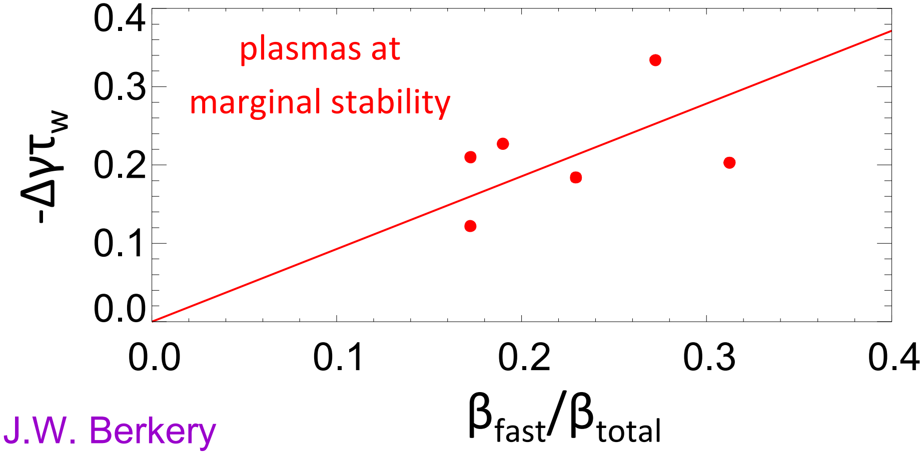


133444 @ 0.505 s
133448 @ 0.735 s

Fast-ion density profiles from FIDA

Rotation profiles at marginal stability

Increase in stability from energetic particles



plasmas at marginal stability

XP921: J.W. Berkery

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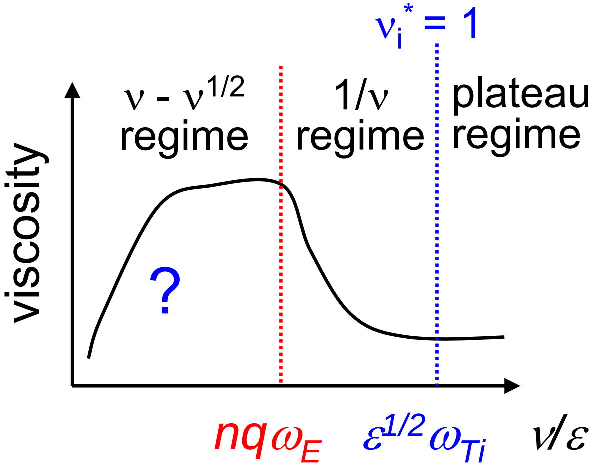
NSTX experiments examining 3-D field-induced neoclassical viscosity theory (NTV) in collisionless plasma regime



❑ Present goal

- ❑ Investigate NTV-induced magnetic braking over range of collisionality, ω_E (i.e. $\nu_i/|\varepsilon nq\omega_E|$)
  - Key for ITER, ST Component Test Facility
  - If $\nu_i/|\varepsilon nq\omega_E|$ << 1: NTV saturated (indep. of ν)
  - If $\nu_i/|\varepsilon nq\omega_E|$ > 1 : NTV ~ $1/\nu$
  - If low ω_E ($< \omega_{\nabla B}$): NTV maximized (indep. of ν) (superbanana plateau: K.C. Shaing, et al, PPCF **51** (2009) 035009)

K.C. Shaing, et al, PPCF **51** (2009) 035004

❑ Past NTV work

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

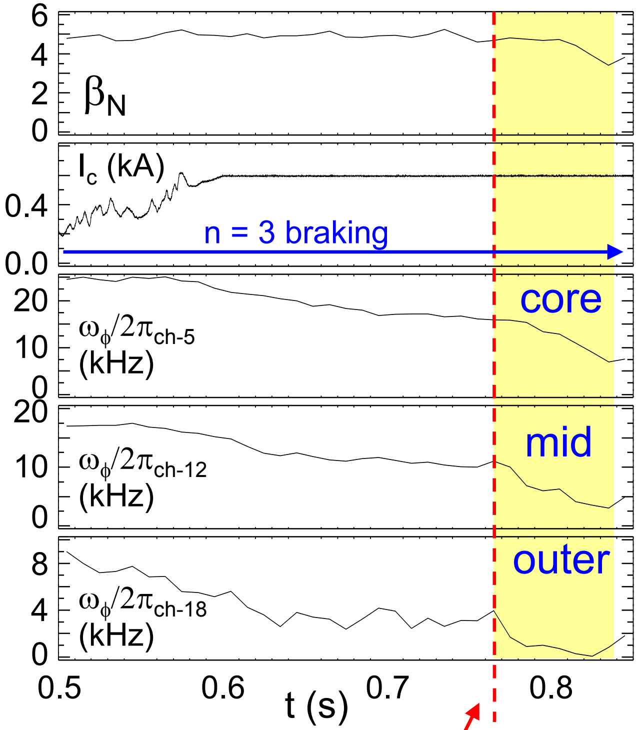
e.g. Zhu, et al., PRL **96** (2006) 225002; S.A. Sabbagh, et al, NF **50** (2010) 025020

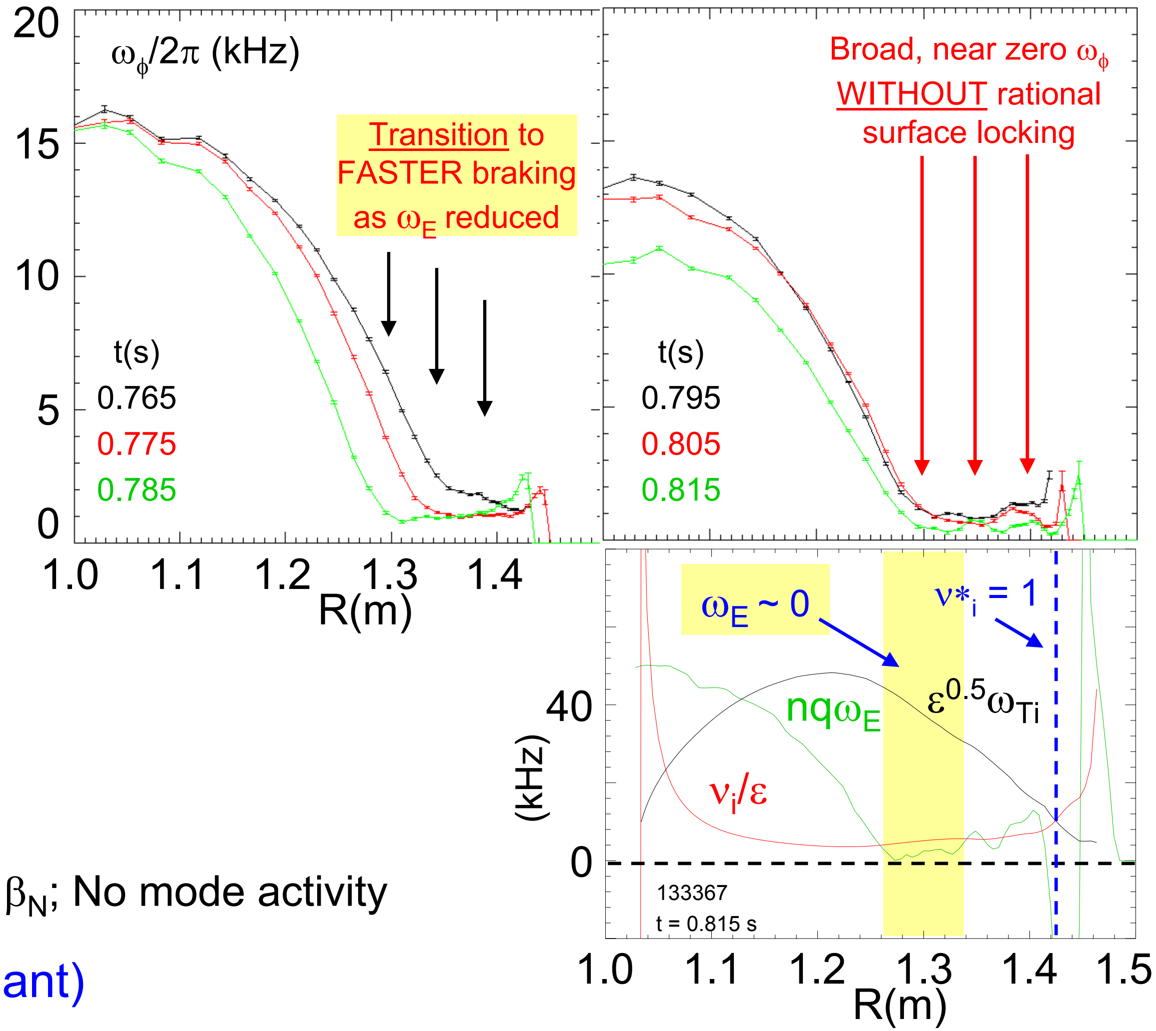
$$\left\langle \hat{e}_t \bullet \vec{\nabla} \bullet \overleftrightarrow{\Pi} \right\rangle_{(1/\nu)} = B_t R \left\langle \frac{1}{B_t} \right\rangle \left\langle \frac{1}{R^2} \right\rangle \frac{\lambda_{1i} p_i}{\pi^{3/2} \nu_i} \varepsilon^{3/2} (\omega_\phi - \omega_{NC}) I_\lambda$$

❑ Recent experimental results

- ❑ NTV braking observed over all $\nu_i/|\varepsilon nq\omega_E|$ variations made in experiment
  - Strong NTV braking observed at increased T_i even if $\nu_i/|\varepsilon nq\omega_E|$ < 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.C. Shaing et al., PRL **87** (2001) 245003)
  - Perhaps due to superbanana plateau physics

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 $1/\nu$ 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) – analysis continues

XP933: S.A. Sabbagh

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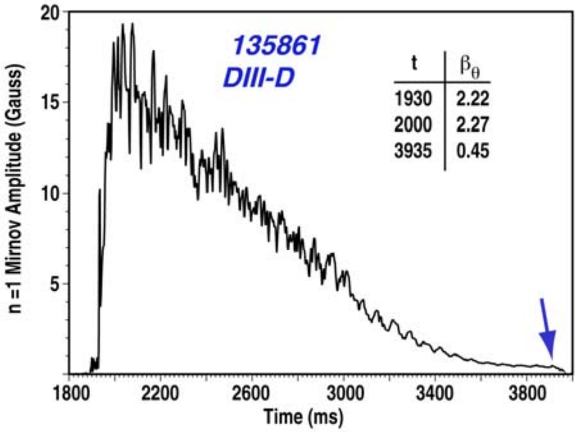
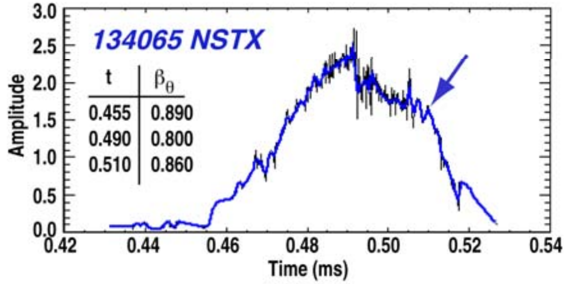
m/n = 2/1 NTM marginal island width for stability compared in analogous NSTX and DIII-D experiments

NTM restabilized by NBI power reduction



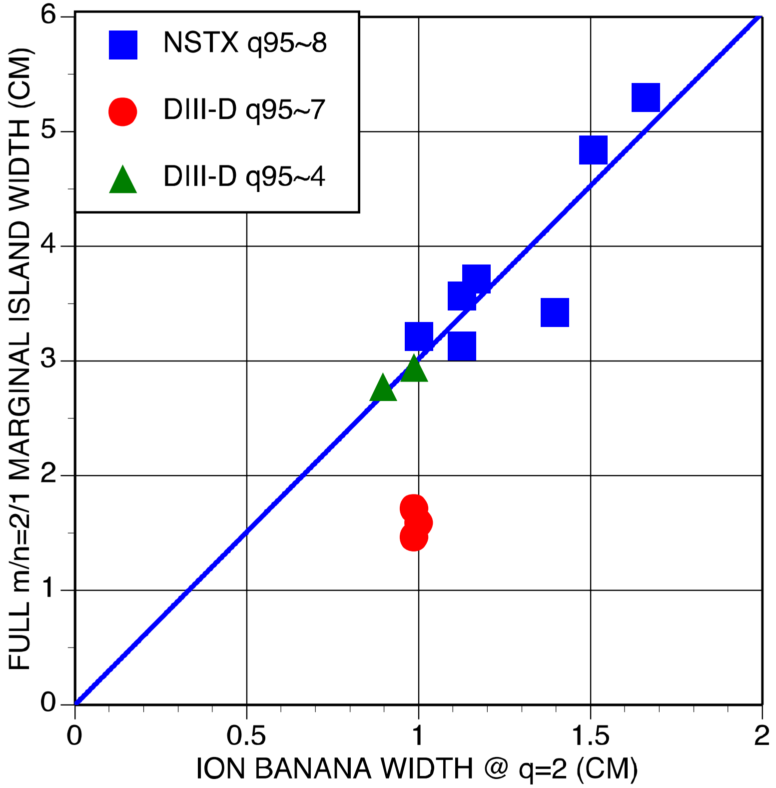
t	β_θ
1930	2.22
2000	2.27
3935	0.45



t	β_θ
0.455	0.890
0.490	0.800
0.510	0.860

- DIII-D
  - Used gas puff to stay in H-mode
- NSTX
  - Achieved a reproducible onset condition using modest Li evaporation

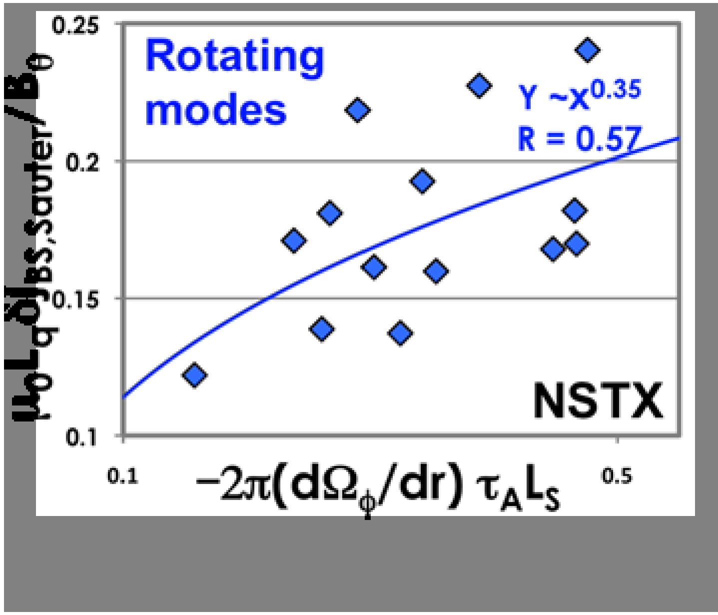
NSTX XP914: R. LaHaye

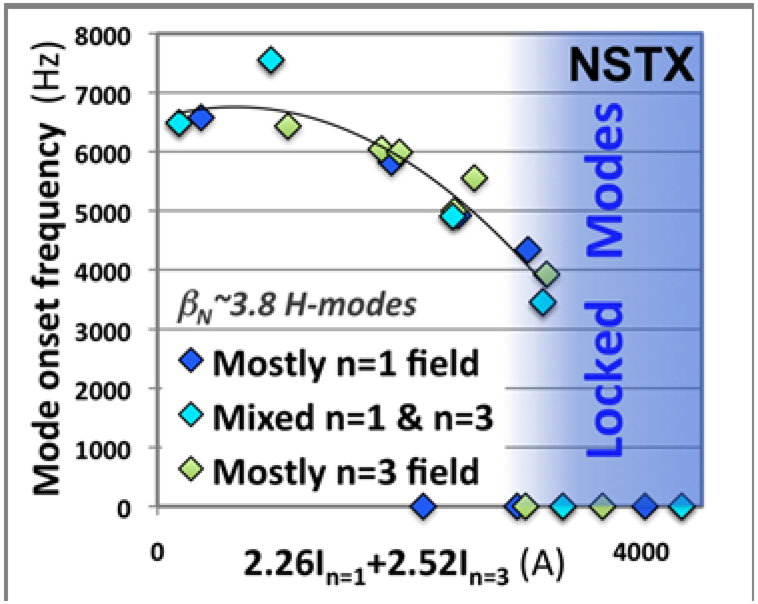


- $W_{marg}/\varepsilon^{0.5}\rho_{\theta i}$ ratio ~ 2 in tokamaks
  - AUG, DIII-D, JET data for 3/2 mode
- Initial analysis: $W_{marg}/\varepsilon^{0.5}\rho_{\theta i}$ ratio ~ 3
  - For NSTX at q_{95} = 8, DIII-D at q_{95} = 4
  - Ratio ~ 1.6 for DIII-D q_{95} ~ 7

NSTX studies show how 3-D fields change tearing stability

- Braking plasma changes bootstrap drive needed to trigger NTM
    - Variation of ω_ϕ by applied n = 1, 3 fields
    - Action correlates better with rotation shear, rather than rotation
    - Consistent with previous NTM onset scans
    - 3D fields act on NTM through rotation profile change, rather than direct interaction





- Continuity between rotating & locked mode onset
    - Field and β ramped with varying rates
    - More field early → mode sooner + locked
    - **Significant braking → leads to mode**
    - ***Criteria for instability is about what is required to perturb torque balance***

XP915: R. Buttery (see talk, Monday afternoon)

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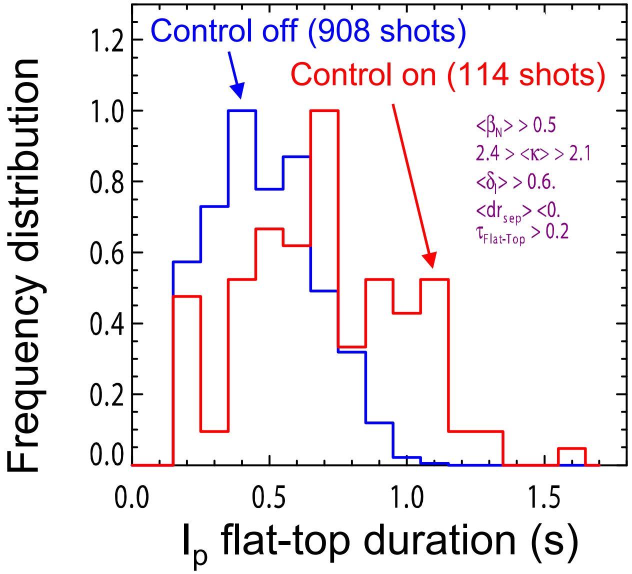
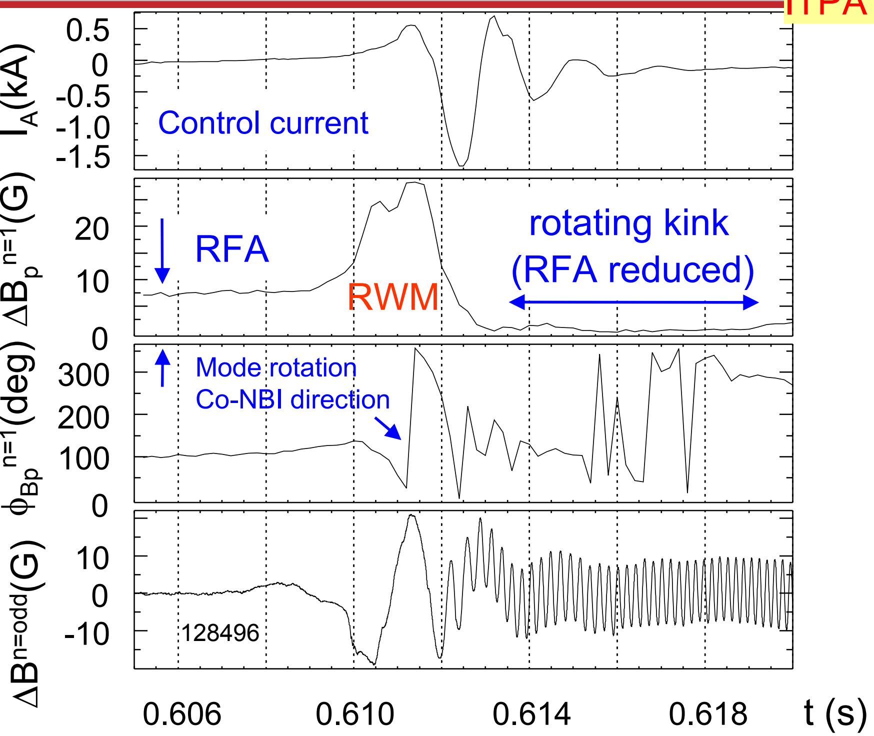
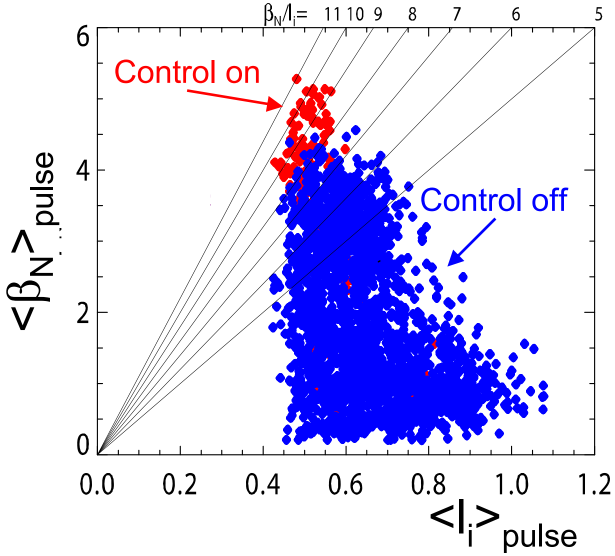
RWM control physics examined, disruptivity initially assessed

ITPA MDC-2







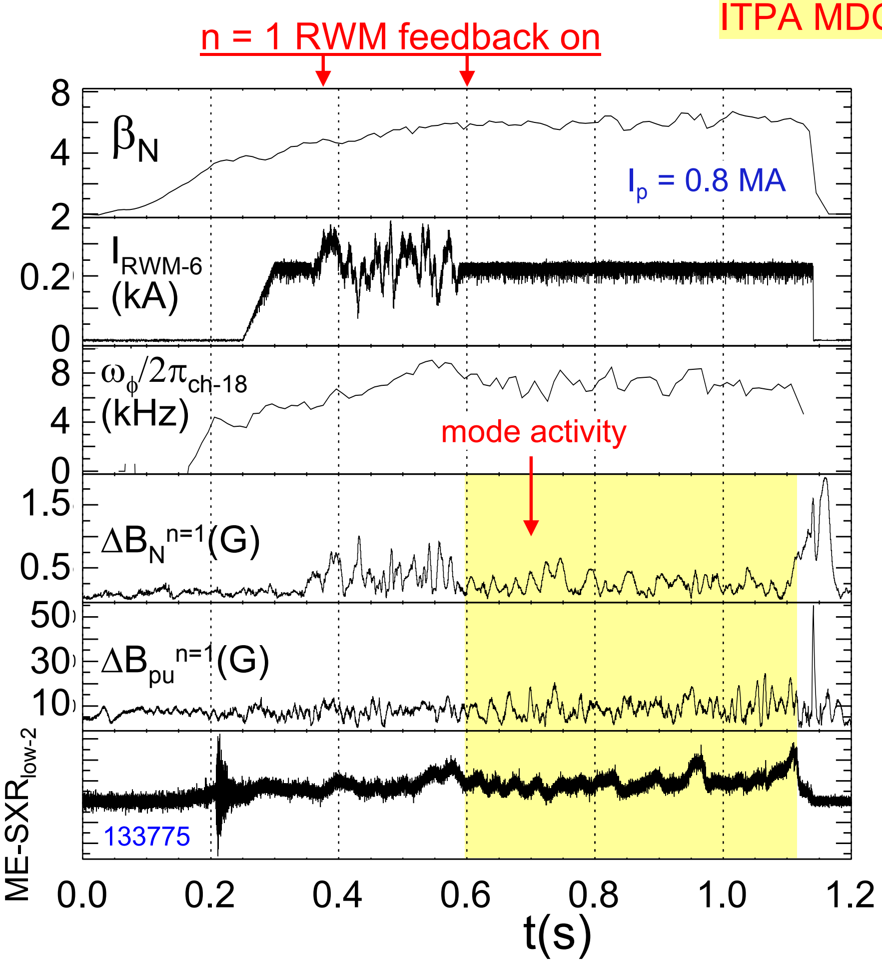
S.A. Sabbagh, et al, NF **50** (2010) 025020

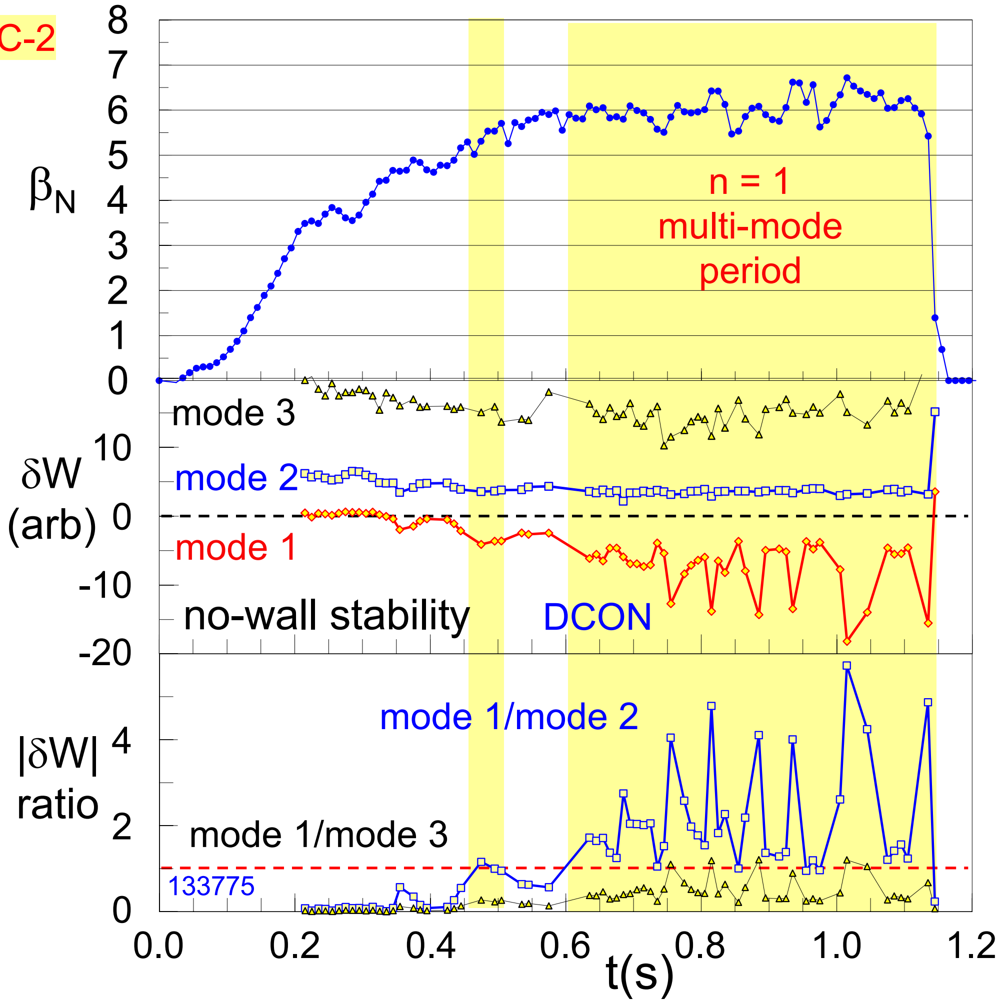
- Important physics affecting future research
  - Plasma rotation important for control
    - RWM conversion to rotating, damped kink needs V_ϕ
    - Larger β_N fluctuation at low V_ϕ
  - RWM control effective at low l_i (key for future STs)
  - n = 1 feedback response speed significant
    - unstable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

(XP902: S. Gerhardt)

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

ITPA MDC-2





- 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 (Boozer, PoP 10 (2003) 1458.)

XP931: Delgado-Aparicio; XP935: Sabbagh (Columbia)

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

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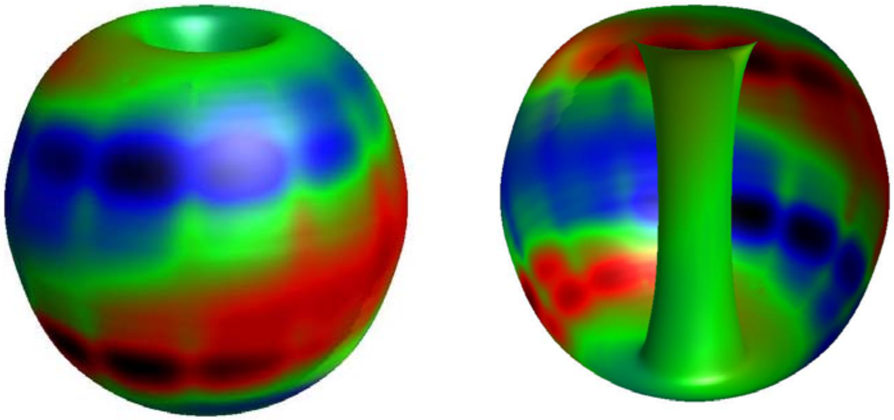
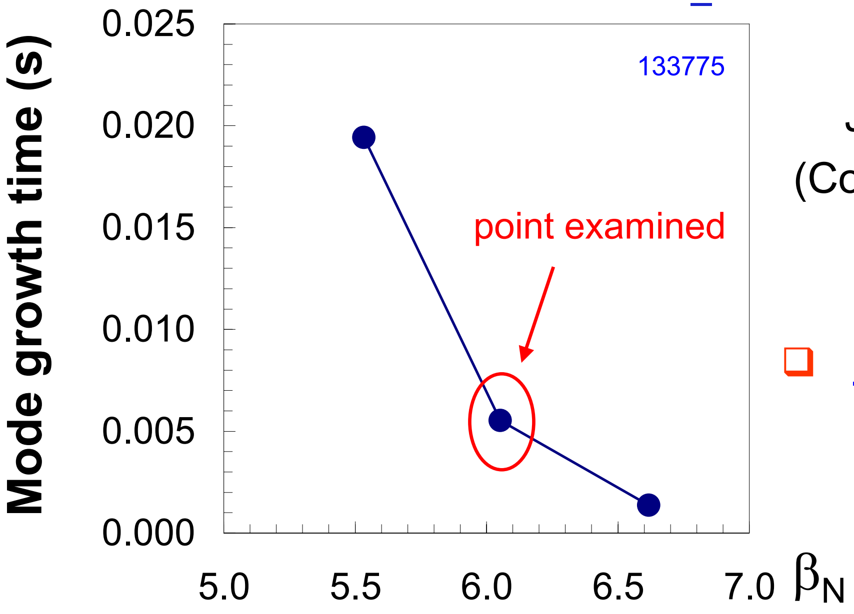
δB^n from wall, multi-mode response



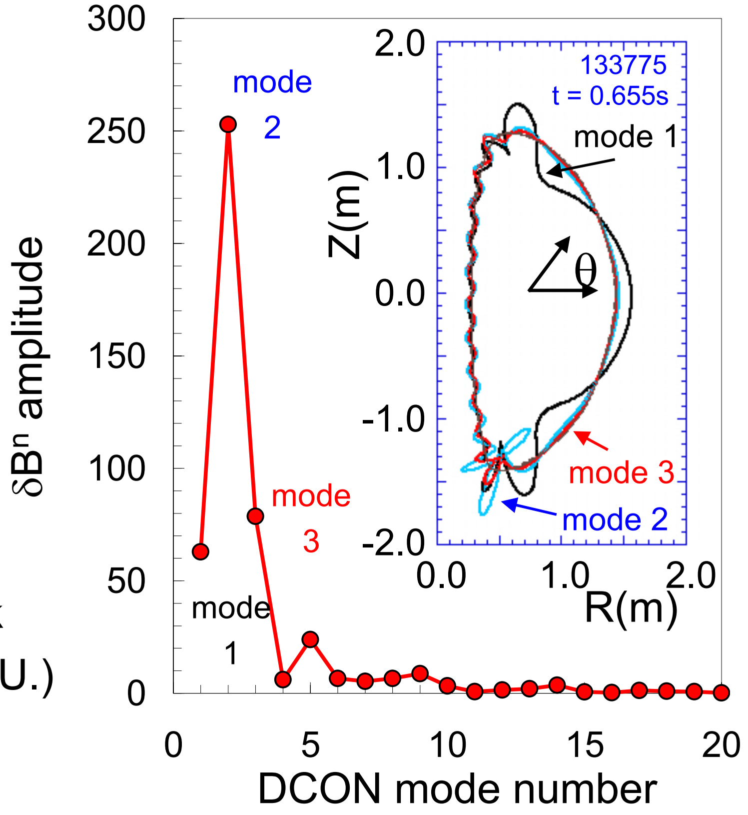
RWM growth time vs β_N



J. Bialek

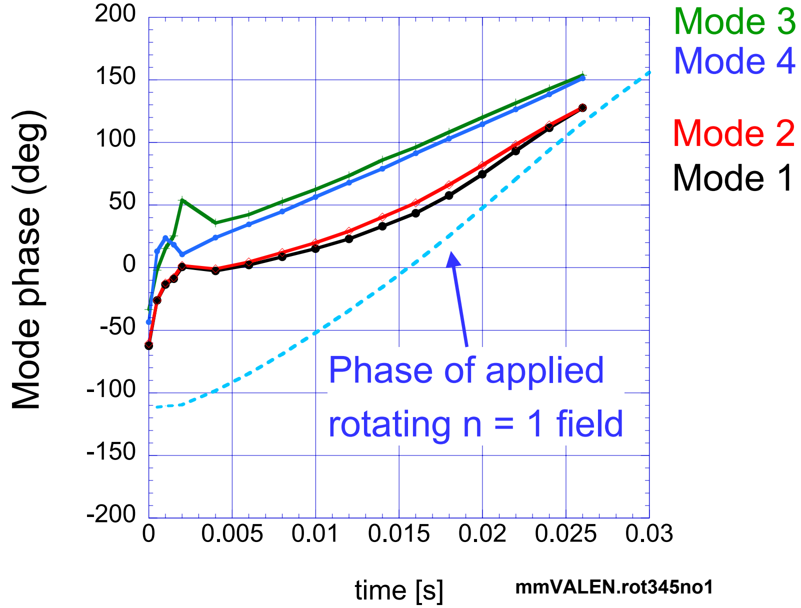
(Columbia U.)

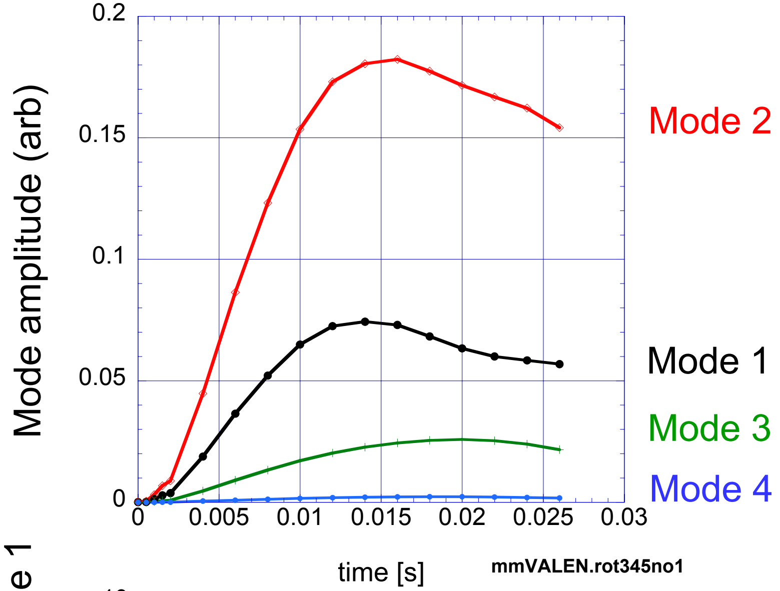
δB^n multi-mode composition

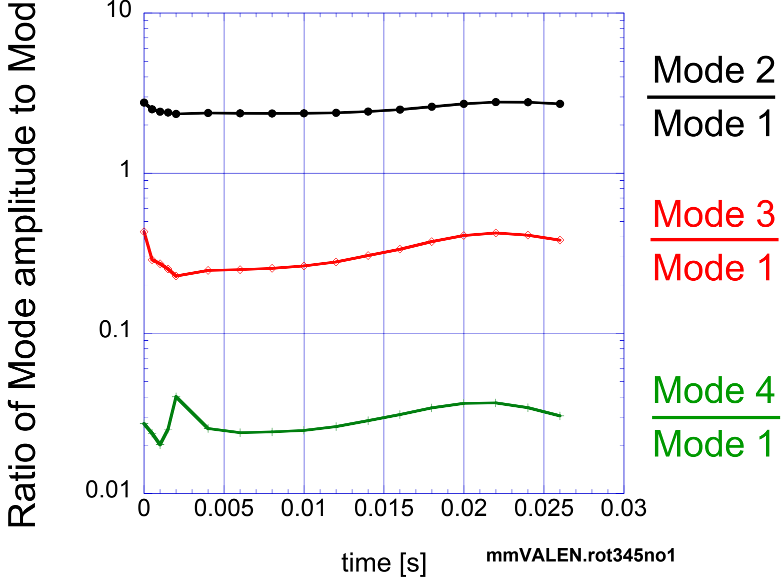


- 2010+ plans
  - Improved RWM sensor compensation
  - Analyze role of multi-mode RWM in control
  - State-space RWM control algorithm

Initial VALEN tests of multi-mode time evolution show n = 1 eigenmodes tracking phase of an applied n = 1 field





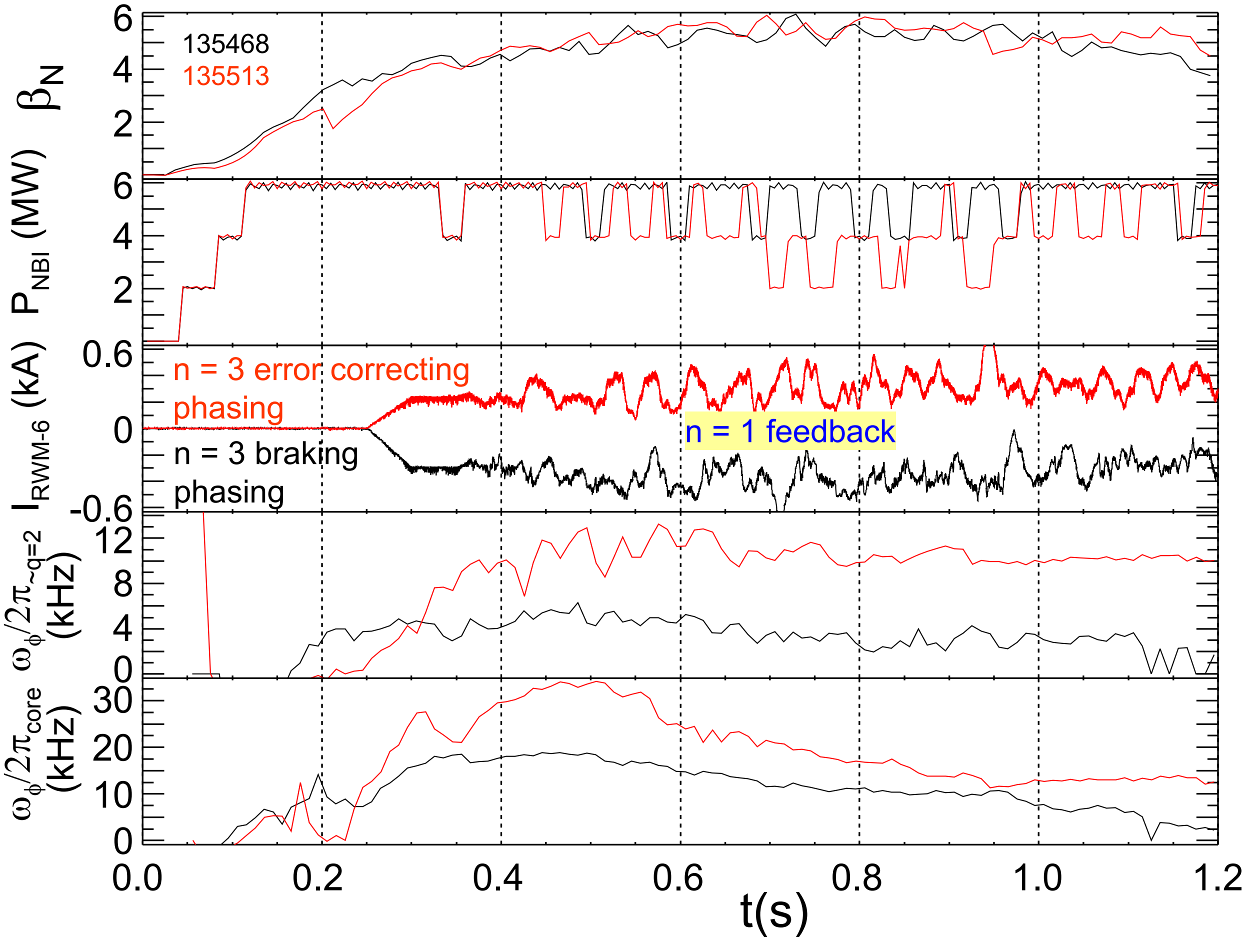


- Simulated n = 1 toroidally rotating field from RWM control coils
- Eigenmodes
  - track n = 1 applied field phase
  - Vary in relatively amplitude by a small amount

J. Bialek (Columbia U.)

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

Addresses PAC25-17-(1)



- 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

- 2010+ plans
  - XP to investigate lower plasma rotation, l_i, collisionality

XP934: Sabbagh (Columbia U.)

S.A. Sabbagh, S. Gerhardt, D. Mastrovito, D. Gates

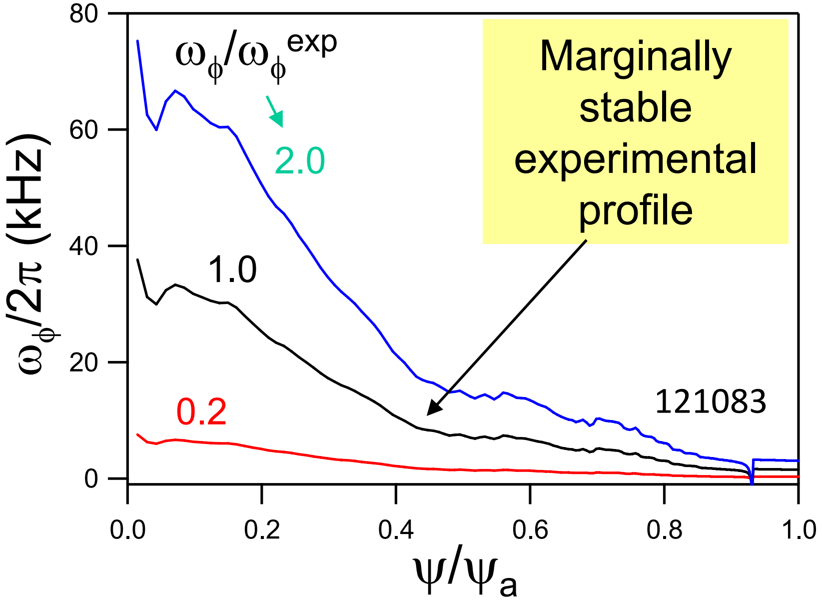
NSTX MHD Research is Addressing Topics Furthering Steady Operation of High Performance Plasmas

- Ideal plasma amplification of applied $n = 1$ resonant field (IPEC) joins linear density scaling of mode locking threshold from low to moderate-β
  - Optimal $n=3$ error field correction determined vs. I_P, B_T
- RWM instability, observed at intermediate plasma rotation, correlates with kinetic stability theory; role of energetic particles under study
- Strong non-resonant braking observed NTV braking observed from all $\nu_i/\varepsilon nq\omega_E(R)$ variations made; apparent transitions in NTV at low ω_ϕ
- Expanded NTM onset experiments continue to find best correlation between NTM onset drive and flow shear
- Low frequency ~ $O(1/\tau_{wall})$ mode activity at high β_N being investigated as potential driven RWM
- Theory shows multi-mode RWM response may be important at high β_N; multi-mode VALEN code now passing initial tests
- Successful NBI power limitation via new β_N feedback control system; initial success in regulation of β_N at varied plasma rotation levels

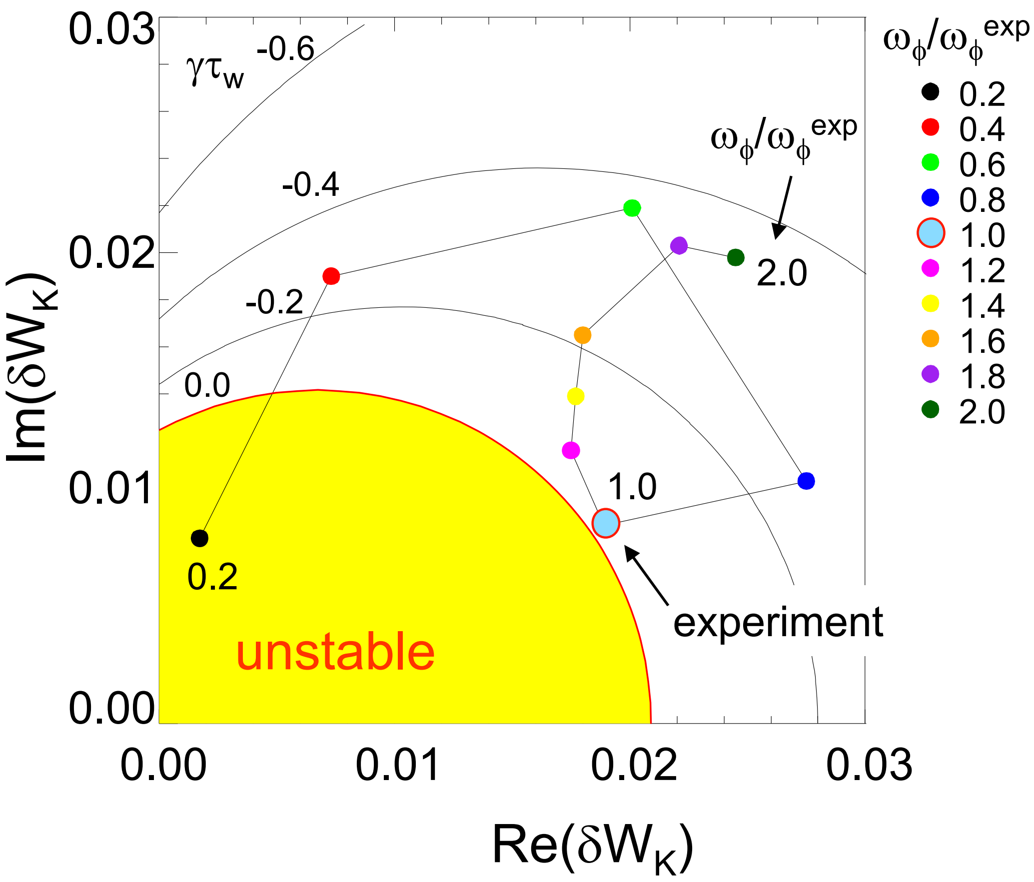
Backup Slides

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 $\gamma\tau_w$)



- Marginally 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

Inclusion of energetic particles in MISK: isotropic slowing down distribution (ex. alphas in ITER)

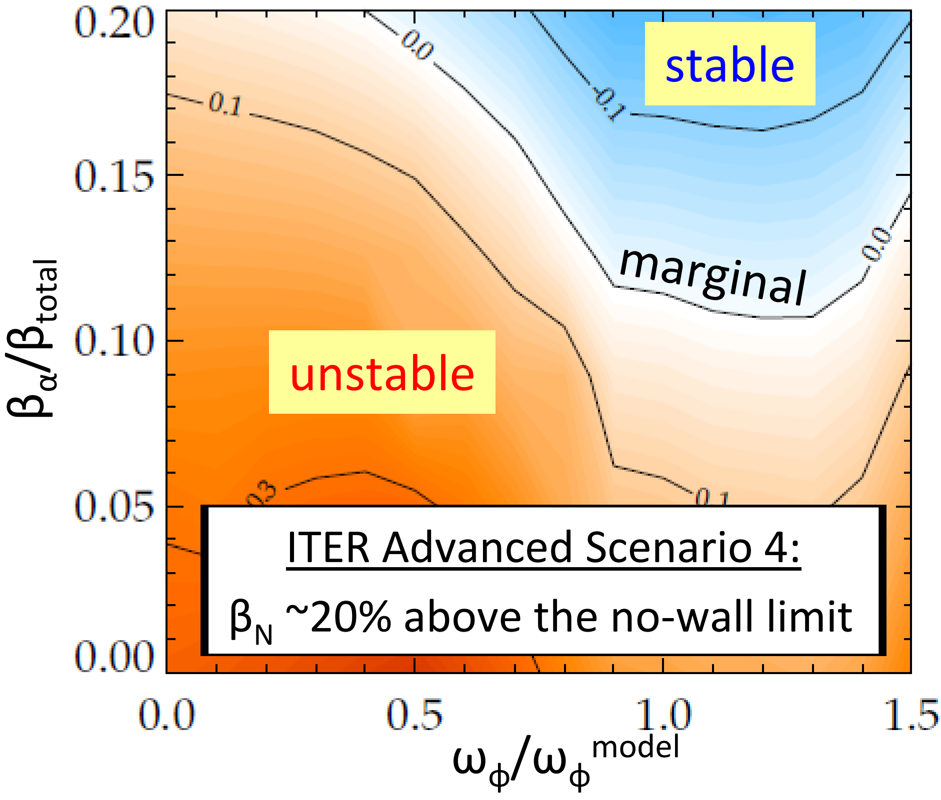
Thermal Particles: Maxwellian

$$\delta W_K \sim \left[\frac{(\omega_r + i\gamma)\frac{\partial f}{\partial \varepsilon} + \frac{\partial f}{\partial \Psi}}{\langle \omega_D \rangle + l\omega_b - i\nu_{\mathrm{eff}} + \omega_E - \omega_r - i\gamma} \right]$$

E.P.s: Slowing-down

$$f(\varepsilon, \Psi) = \frac{C(\Psi)}{\varepsilon^{\frac{3}{2}} + \varepsilon_c^{\frac{3}{2}}}$$

- Energetic particles add to δW_K, lead to greater stability
- Example: α particles in ITER
  - Higher β_α leads to greater stability
  - Isotropic f is a good approx.
- Model ω_ϕ profile linear in ψ

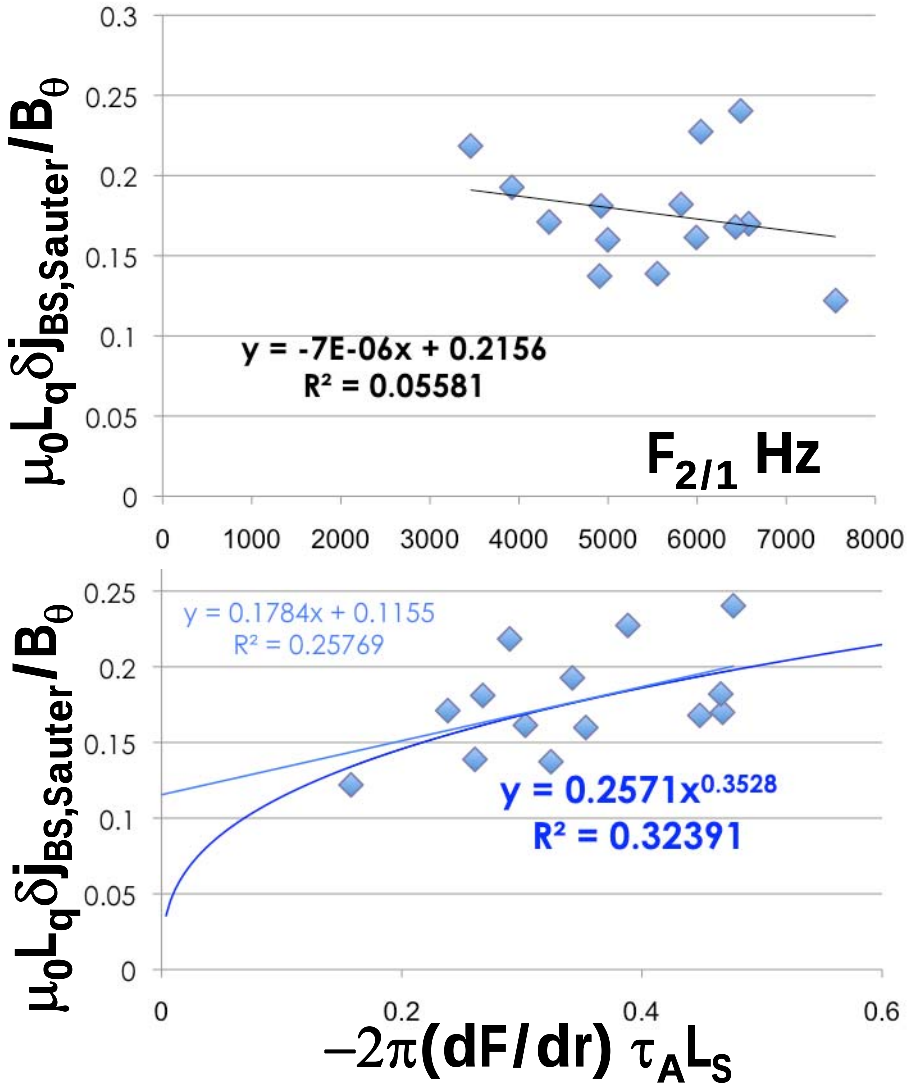


ITER Advanced Scenario 4:

β_N ~20% above the no-wall limit

Required (missing) bootstrap drive for NTM onset better correlated with rotation shear than rotation magnitude

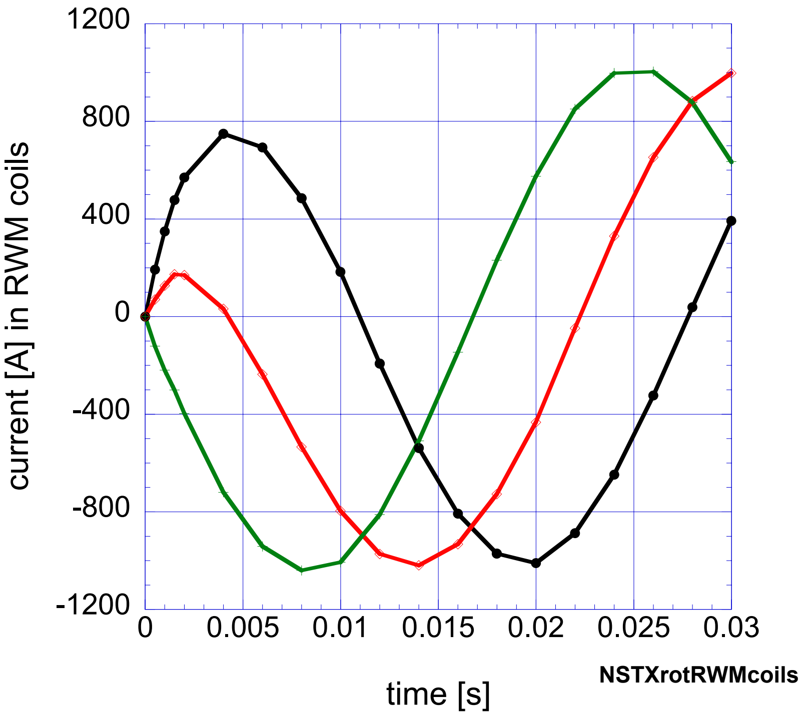
- ❑ Rotation variation via n = 1 or 3 applied field
  - ❑ Operational space fully spanned up to locked mode limits
- ❑ No measureable trend vs. rotation
- ❑ Weak positive correlation with normalized rotation shear
  - ❑ Lowest/highest thresholds at low/high rotation shear
  - ❑ 2d fit vs rotation & rotation shear offers little improvement
  - ❑ Consistent with prior results (S.P. Gerhardt, et al., 2008)



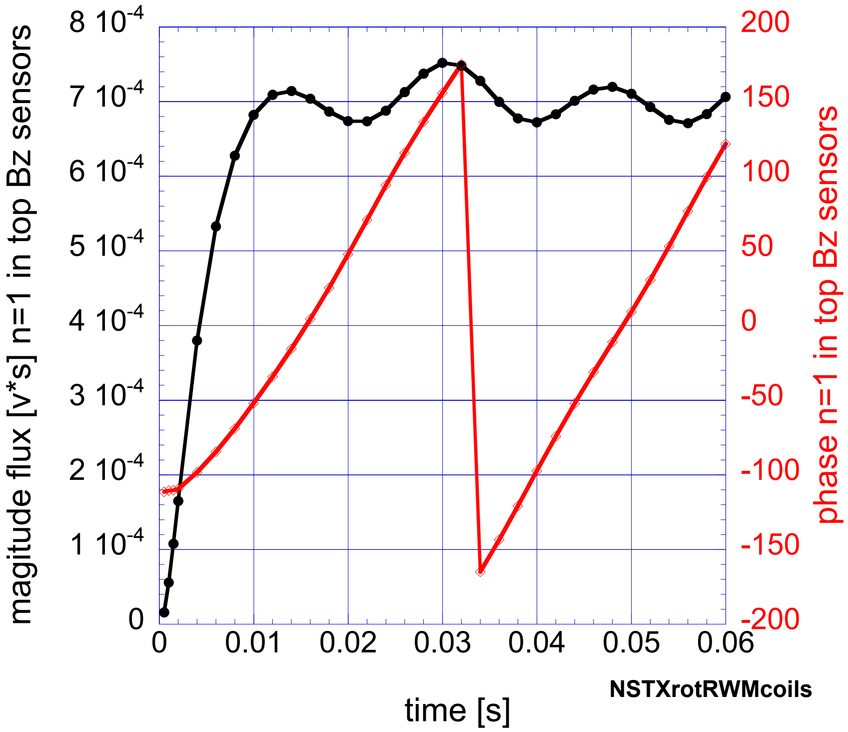
XP915: R. Buttery

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

Modeled currents in RWM control coils

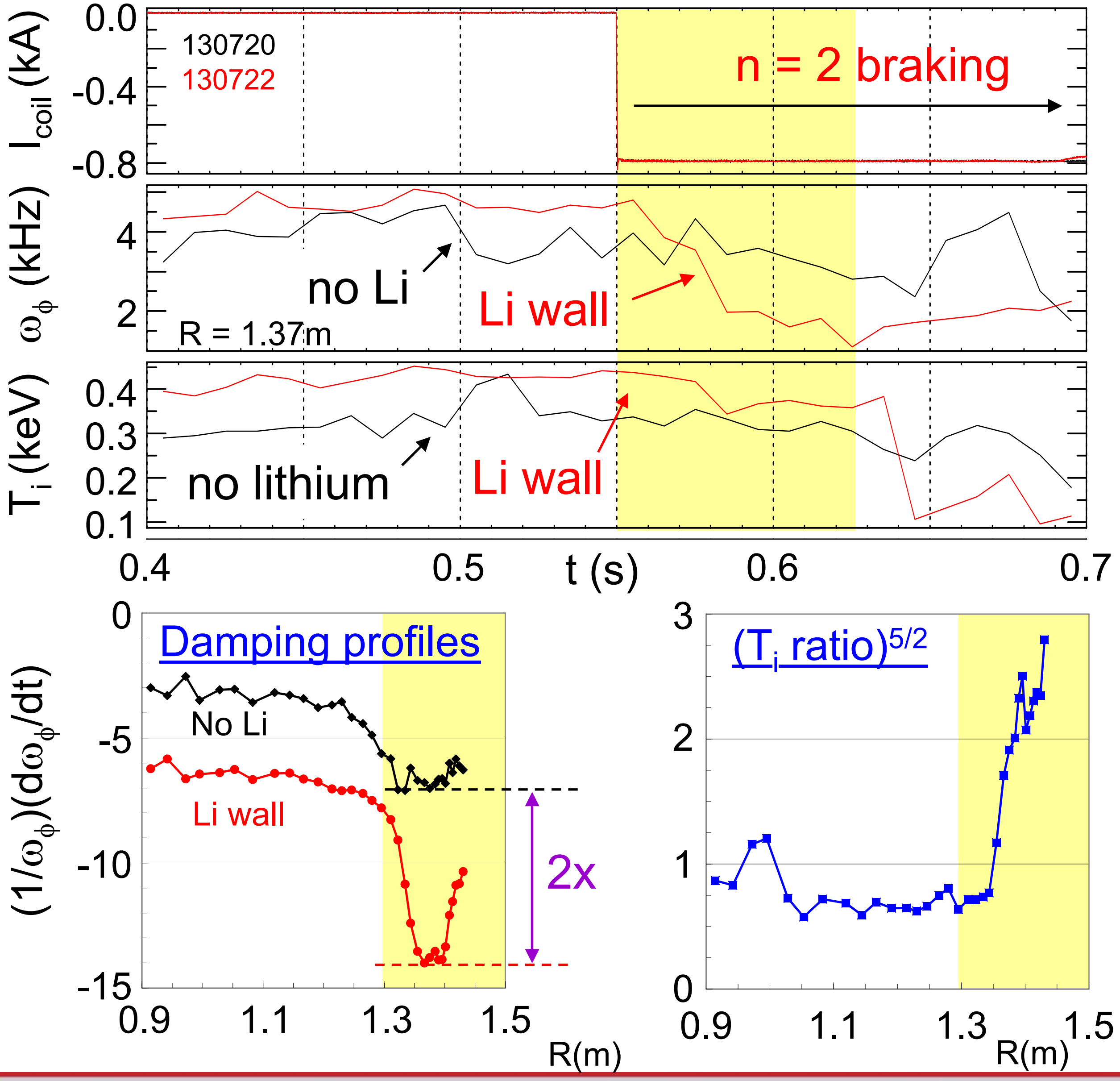


Modeled n = 1 RWM sensor amplitude and phase



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

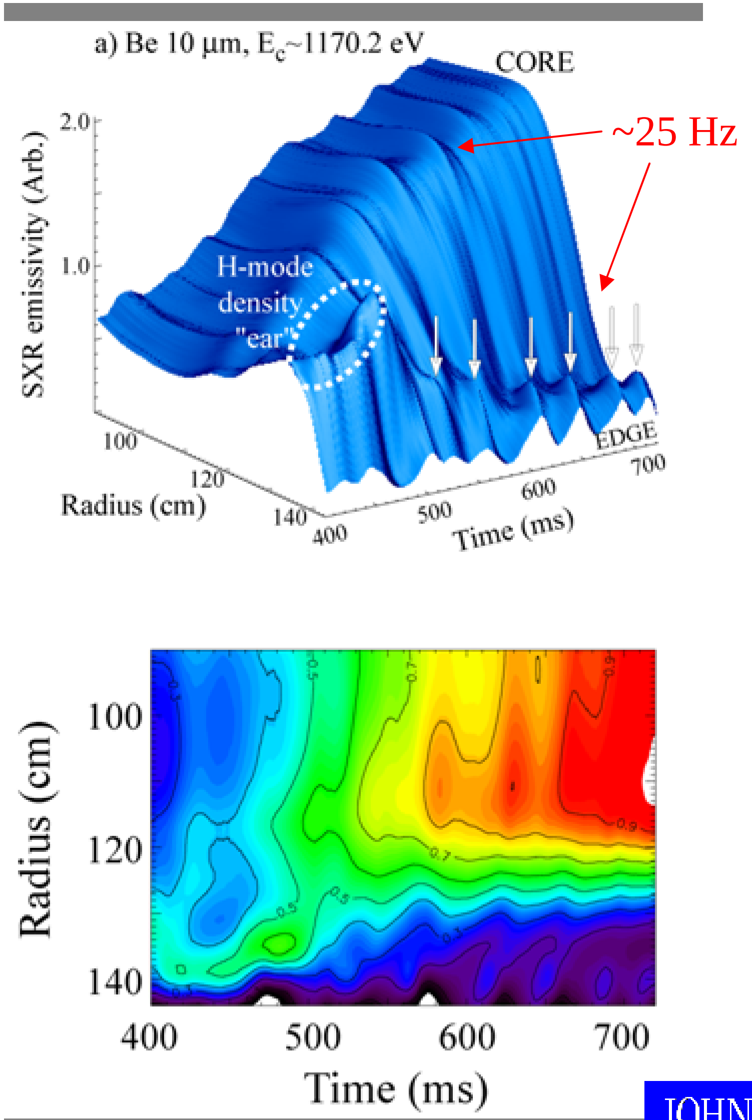
Stronger non-resonant braking at increased T_i



- ❑ 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 $d\omega_\phi/dt$

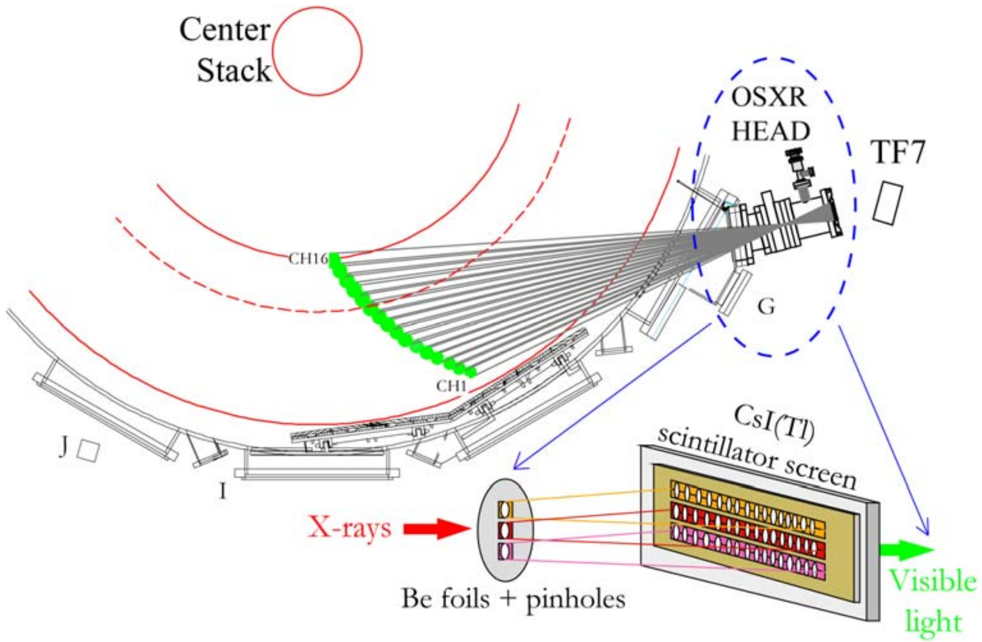
S.A. Sabbagh, et al, NF **50** (2010) 025020

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



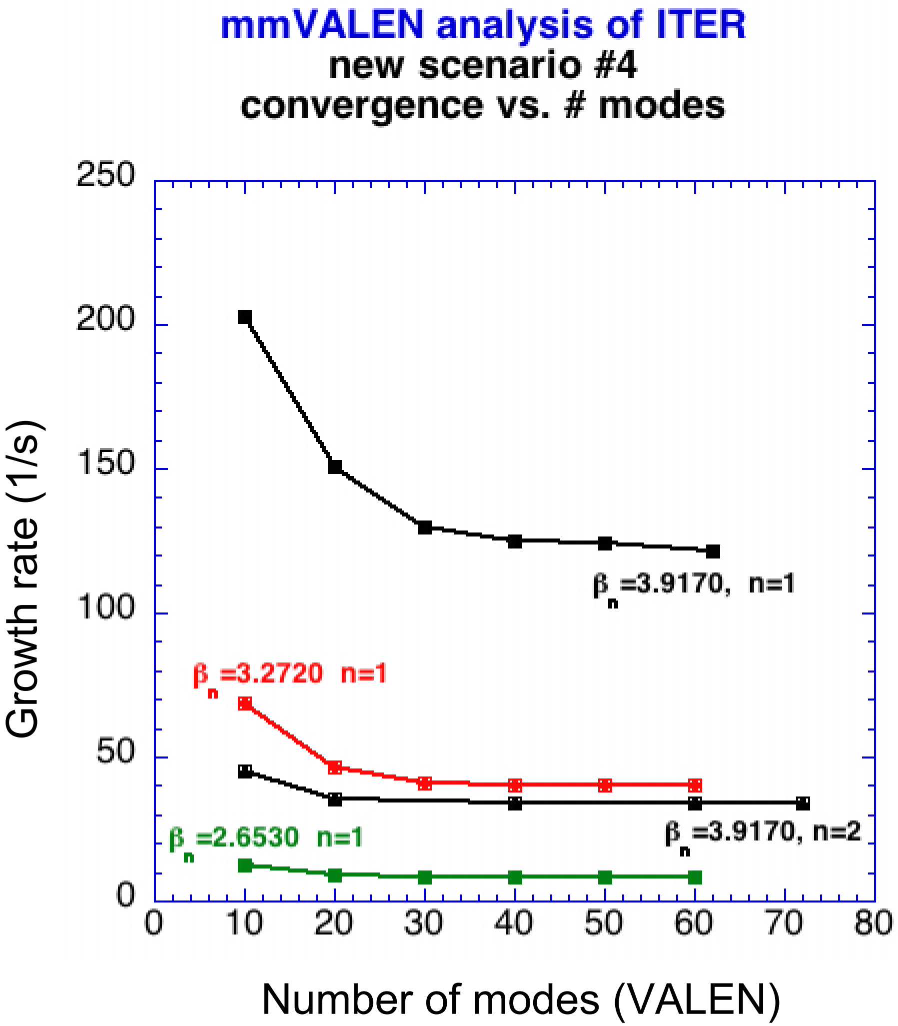
L. Delgado-Aparicio (JHU)

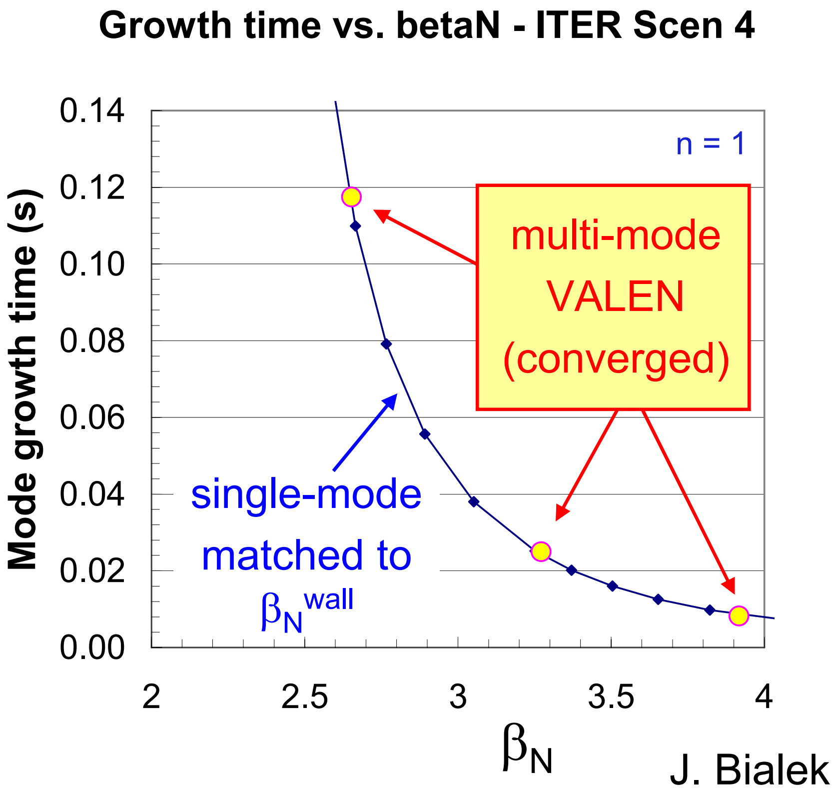
Multi-energy soft X-ray (ME-SXR) viewing geometry



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

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





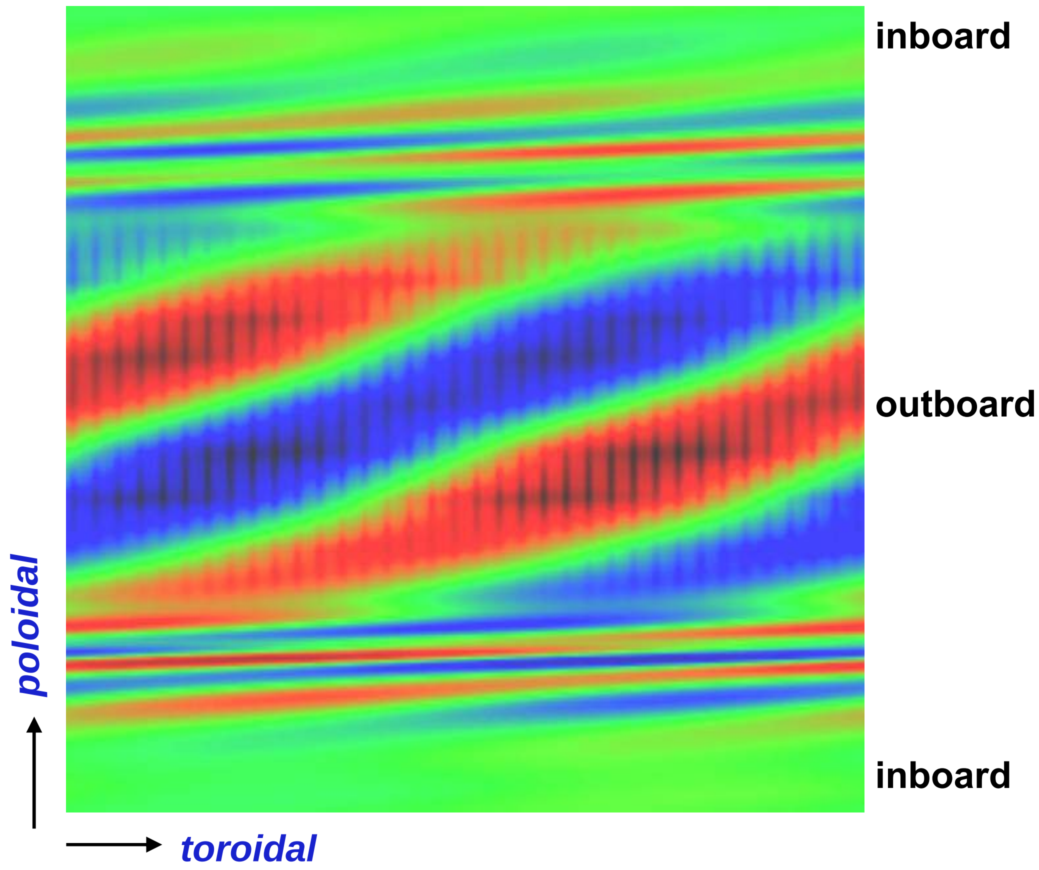
J. Bialek

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

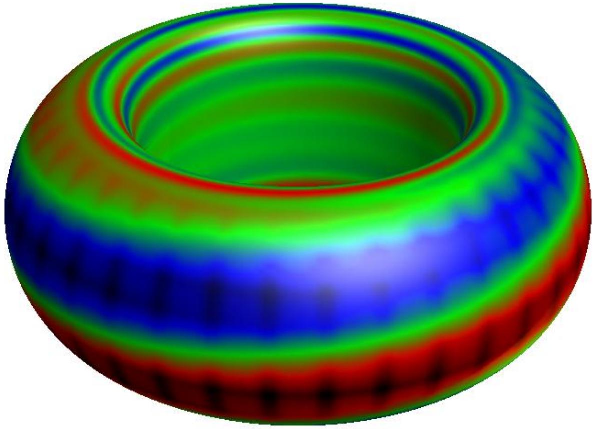
- DCON δW shows several modes with high response
  - Three n = 1 modes at high β_N
  - Two n = 2 modes at high β_N

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

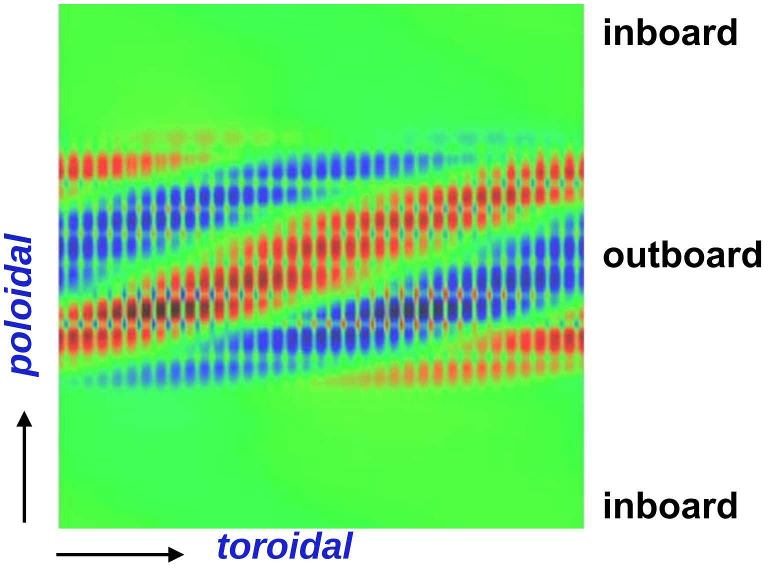
multi mode response (incl. wall), total B^n



B^n from wall, plasma



B^n from wall alone



- n = 1 eigenfunctions shown

J. Bialek