NSTX

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Search for Multiple Resistive Wall Modes at High Normalized Beta in NSTX*

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14th Workshop on Active Control of MHD Stability: Active MHD Control in ITER
November 11, 2009
Princeton Plasma Physics Laboratory

v1.1

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NSTX Macrostability Research is Targeting Maintenance of Plasma at High β_N with Minimal Fluctuation

- Talk Topics
  - Search for multiple resistive wall modes at high β_N (main topic)
  - Potential importance of multi-mode RWM physics at increased q_{min}
  - Experiments with combined β_N and magnetic feedback control
  - Non-resonant rotation damping at low ω_E

Appearance of low frequency oscillations in magnetic and kinetic diagnostics at high β_N investigated as multiple RWMs

Motivation

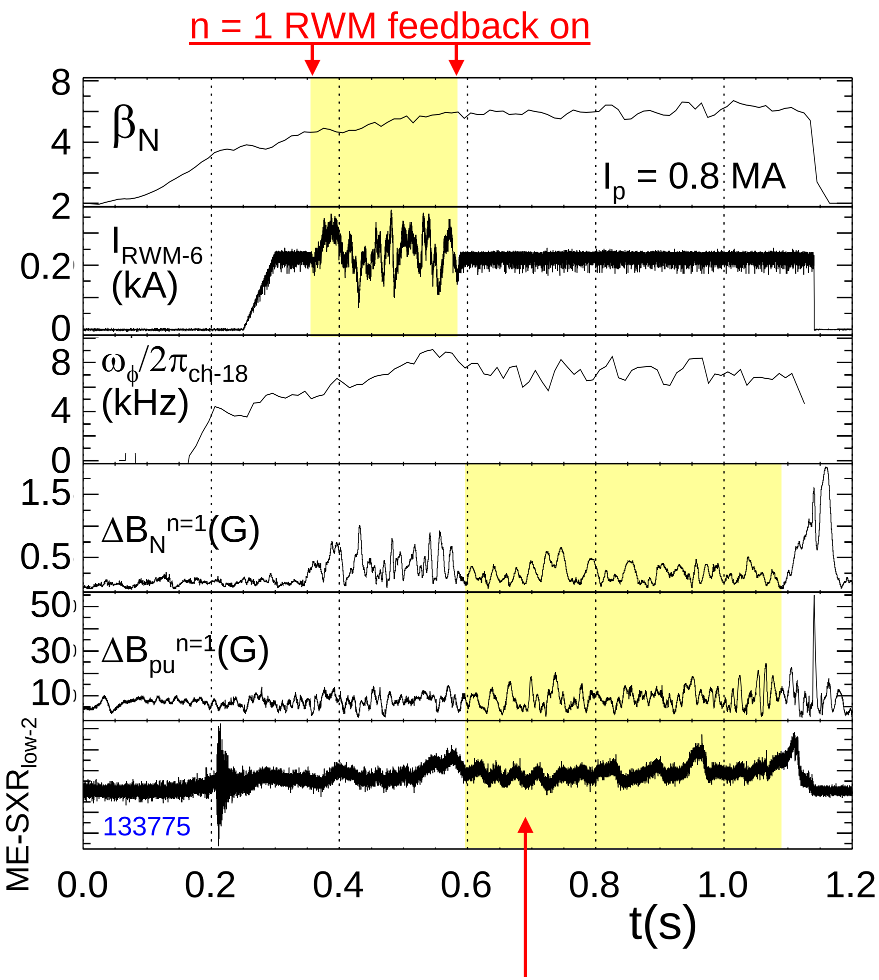
- Maintenance of plasma at high β_N with minimal time variation is needed for future fusion devices
- Physics understanding of significant measured resistive wall mode (RWM) sensor activity is important to sustain steady high β_N
  - required to optimize RWM control

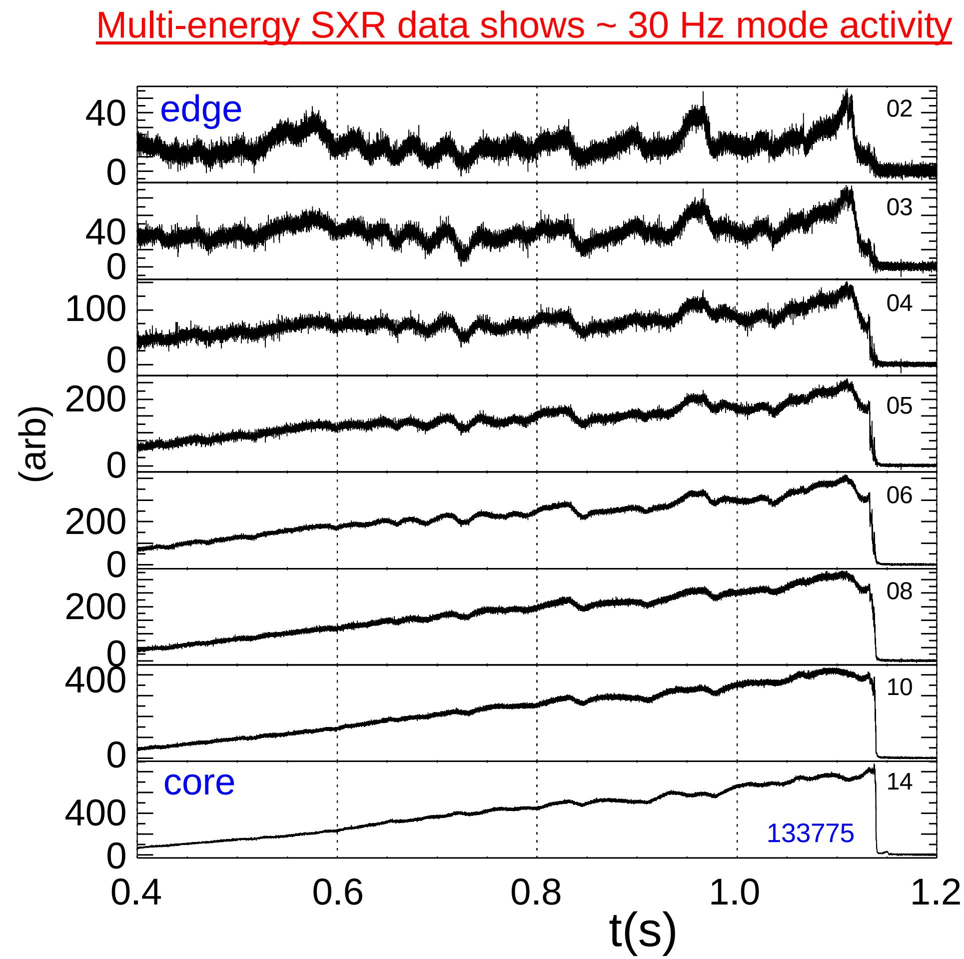
Observations / Goals

- Mode activity observed in RWM frequency range in magnetic and kinetic diagnostics at high β_N (β_N up to 7.4 reached in 2009)
- Is the observed mode activity related to, or independent of unstable RWM activity?
  - If same mode, supports single mode physics model
  - If another mode, supports multi-mode theory

Either conclusion is important to optimize β_N and RWM feedback control

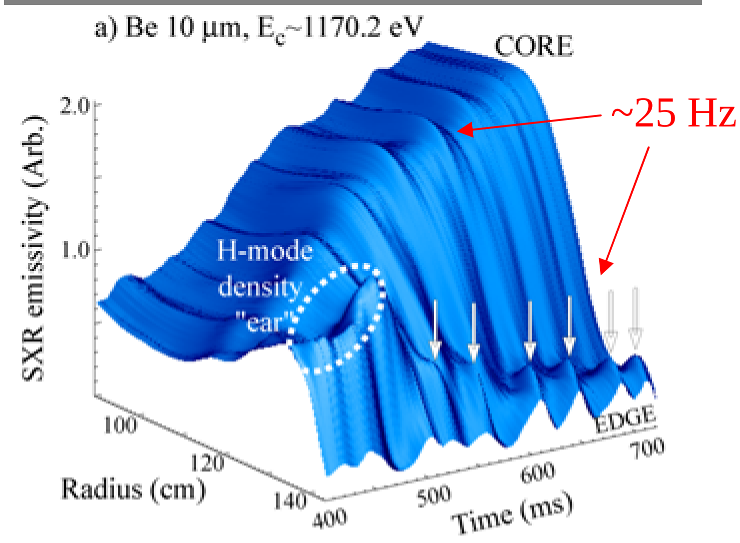
High β_N shots exhibit low frequency mode activity in magnetic and kinetic diagnostics

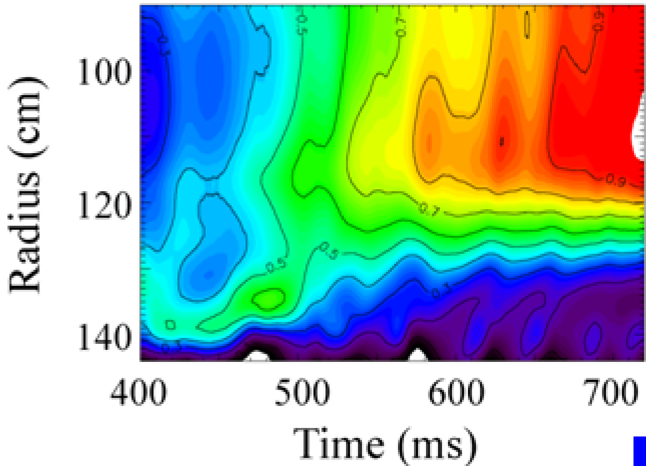




- Mode activity in RWM frequency range coincident in magnetics, SXR
- Soft X-ray measurements show low frequency mode activity is global

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





L. Delgado-Aparicio – this meeting

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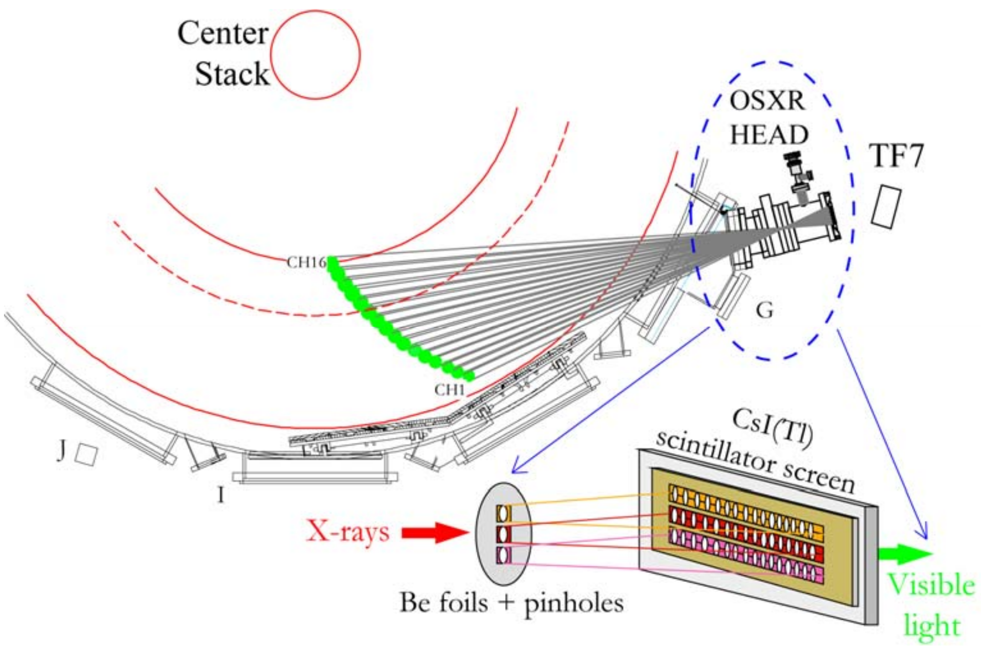
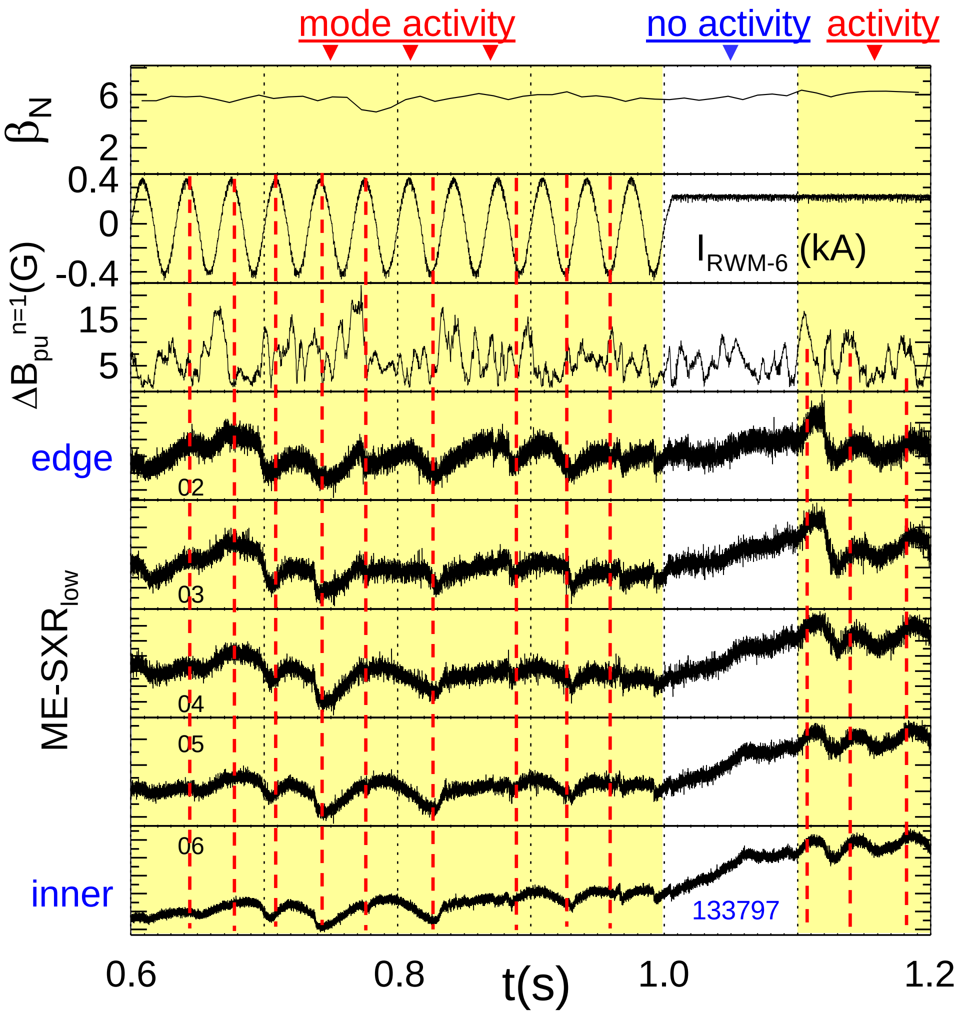
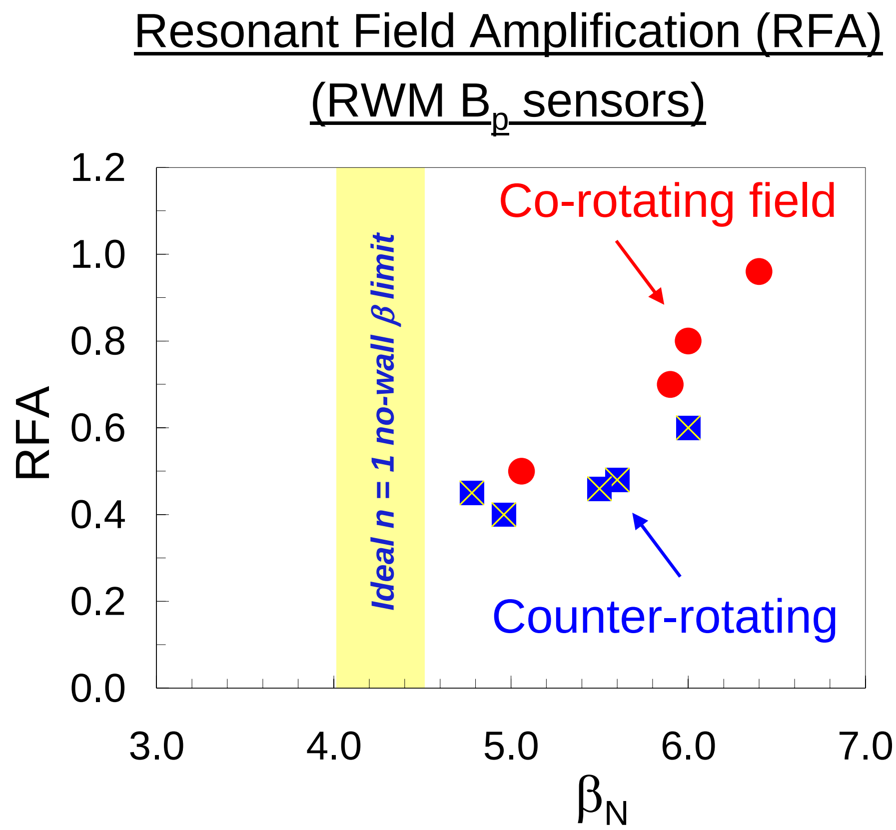
Multi-energy soft X-ray (ME-SXR) viewing geometry



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

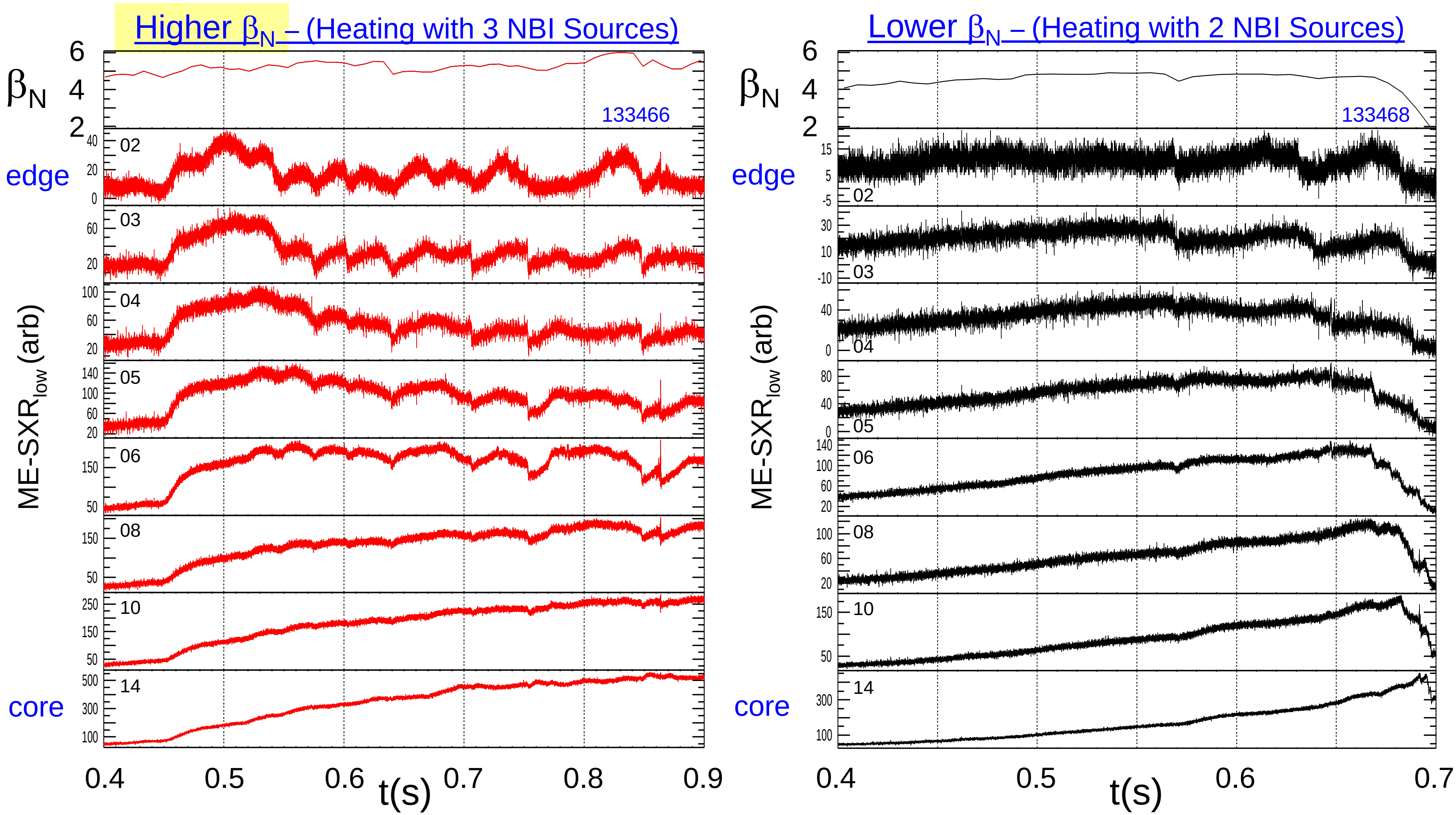
Resonant field amplification of rotating applied field observed in magnetics, along with oscillations in ME-SXR signals





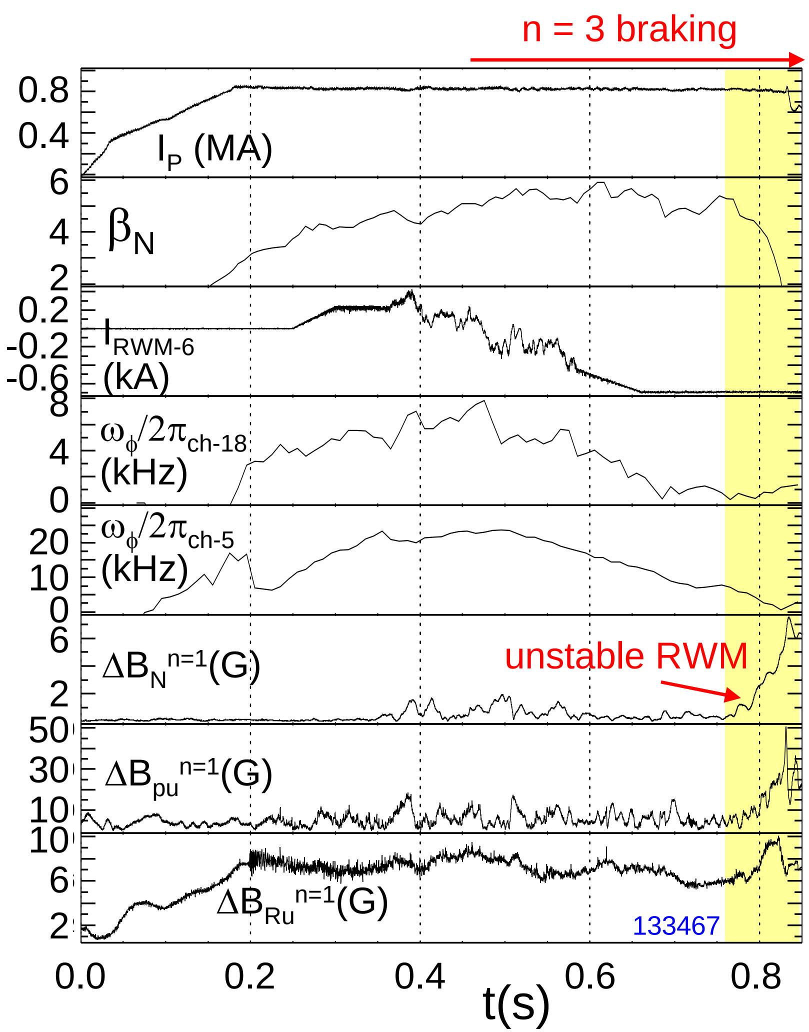
- Mode activity in ME-SXR observed during applied co-rotating AC field
- Activity stops when applied AC field stops; returns when magnetic activity returns

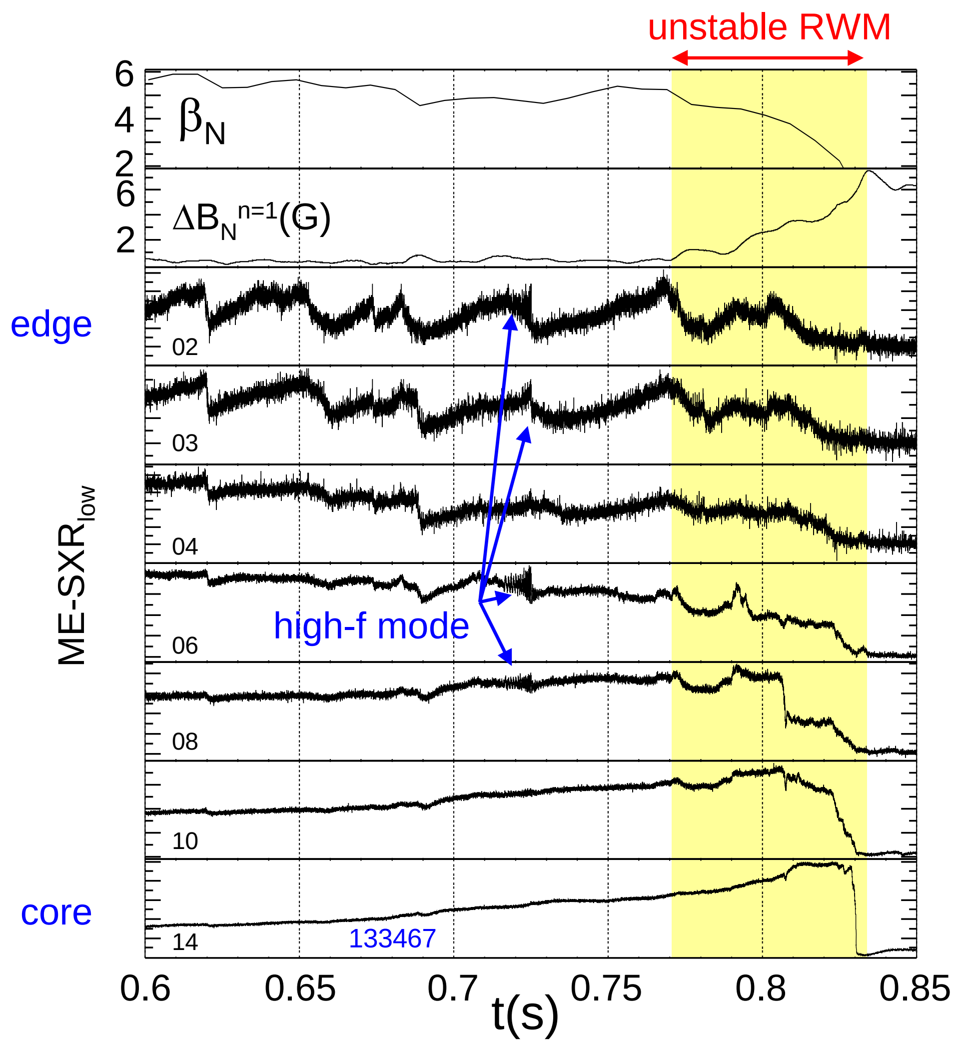
Low frequency mode observed in ME-SXR covers greater radial extent as β_N increased



- Proximity to marginal stability (e.g β_N plus ω_ϕ level) may be key
  - The ideal $\beta_N^{no\text{-}wall}$ ~ 4 - 4.4 for n = 1 modes in these plasmas

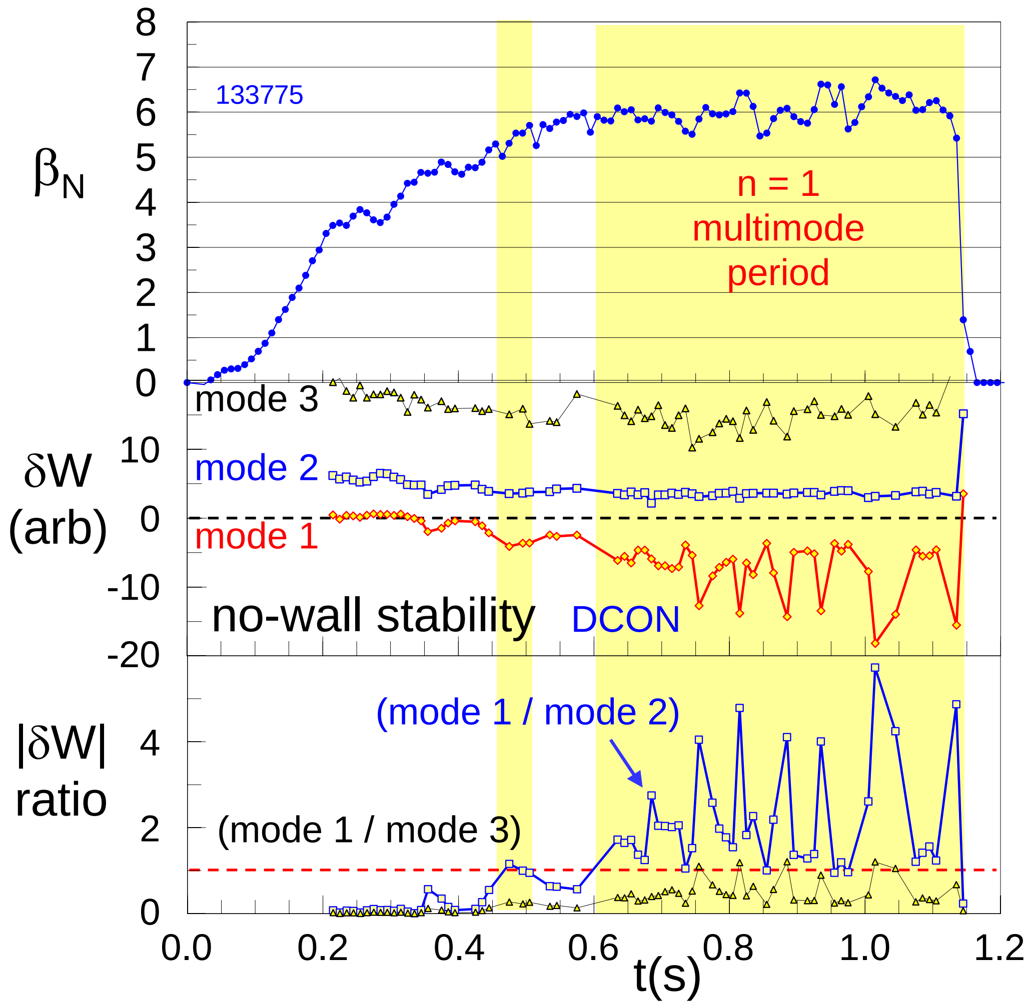
When unstable, observed growing n = 1 RWM appears to be independent of the driven, ~30 Hz activity

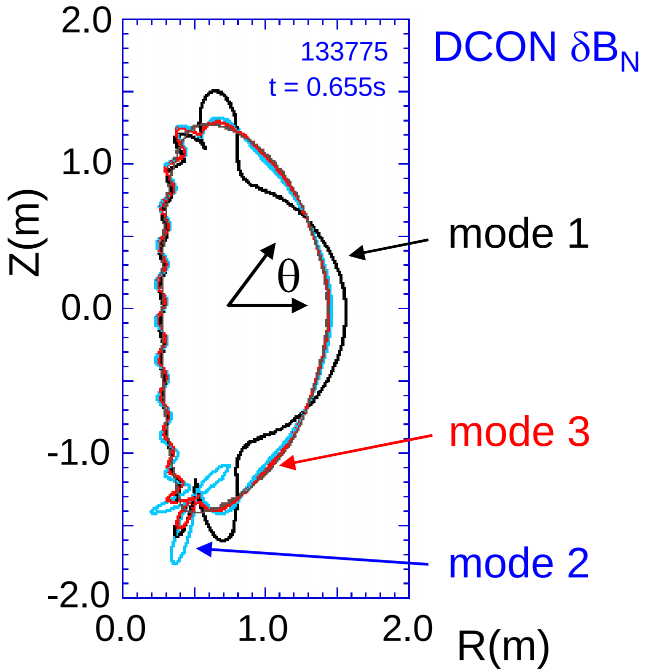


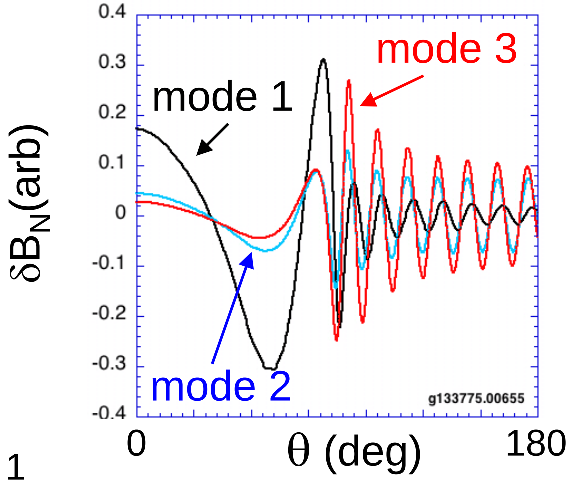


- Unstable RWM is locked; driven mode co-rotating at low frequency
- Unstable RWM grows (magnetics); low frequency mode appears steady in SXR

Multimode response theoretically is expected to be significant at high β_N



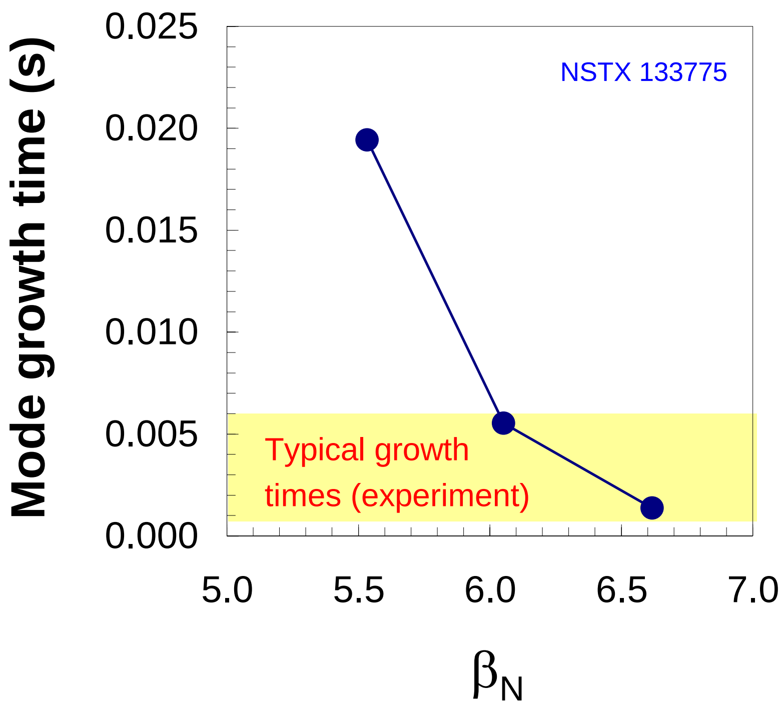




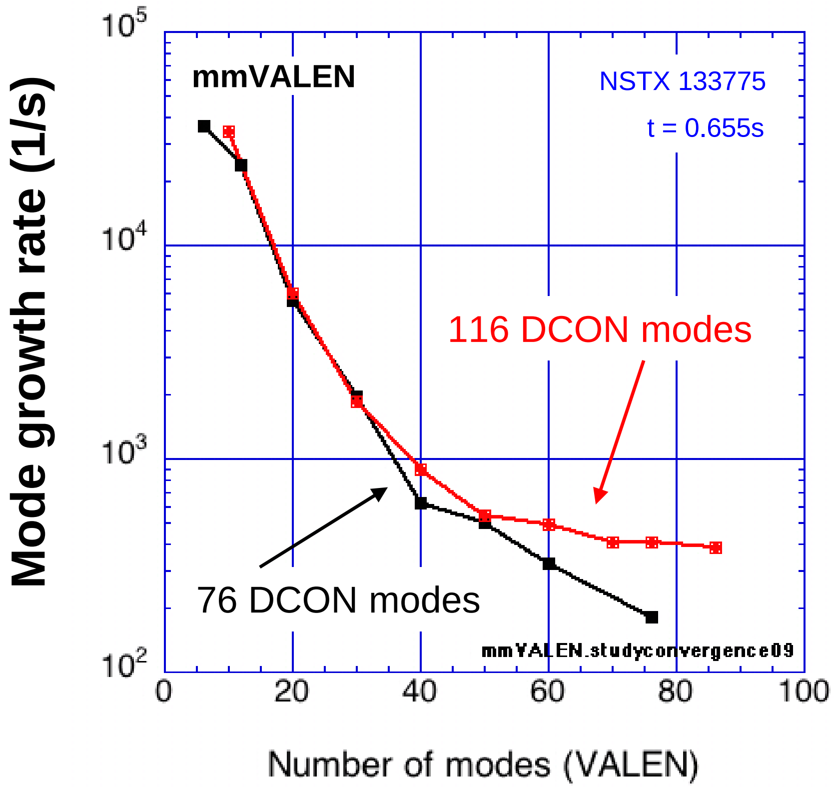
- Boozer multimode criterion for n = 1 met at high β_N (PoP **10** (2003) 1458.)
  - $|\delta W|$ smallest for 2nd n = 1 eigenfunction
  - Ratio of $|\delta W|$ for 3rd vs. 1st least stable mode sometimes also > 1

New multi-mode VALEN code reproduces typical observed RWM growth times in high β_N NSTX plasmas

RWM growth time vs. β_N



Growth rate vs. # of modes

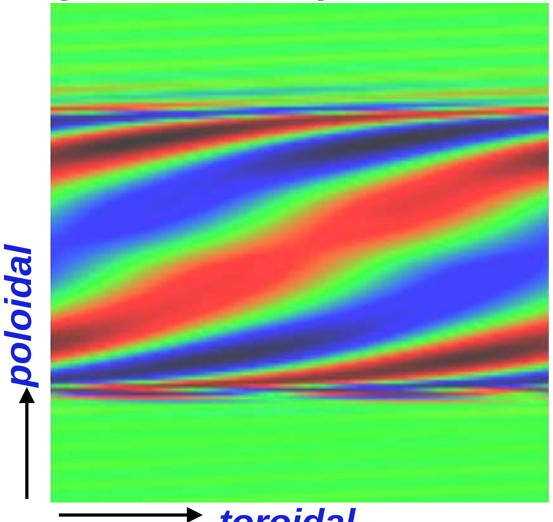


- Typical experimental growth times are reproduced with no free parameters
- Significant number of modes needed for convergence

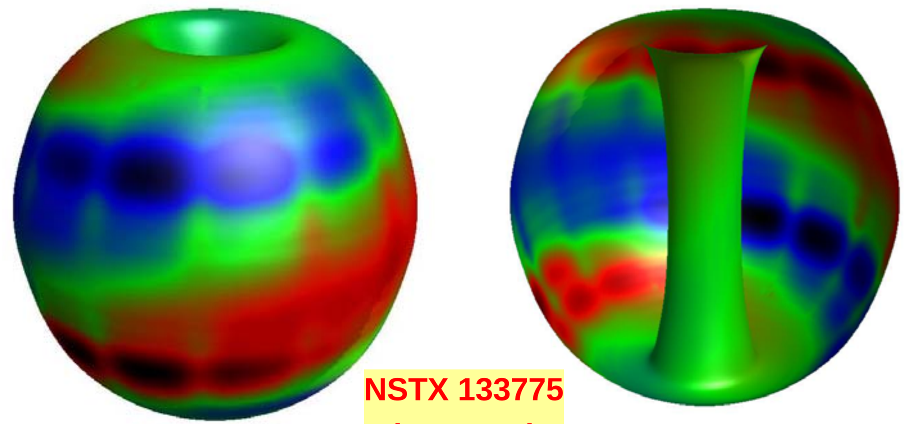
J. Bialek

Multi-mode perturbed field response in mmVALEN shows influence of 3-D structures

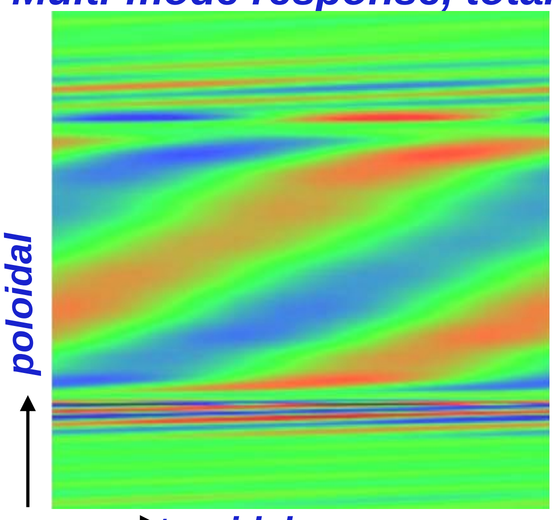
Single mode response, total δB^n



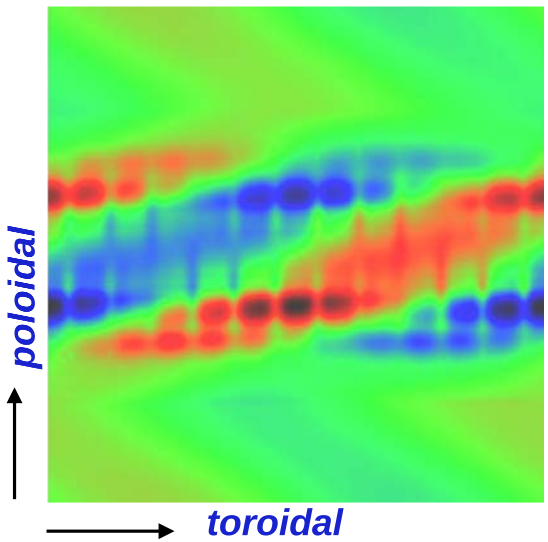
δB^n from wall, multi-mode response



Multi-mode response, total δB^n



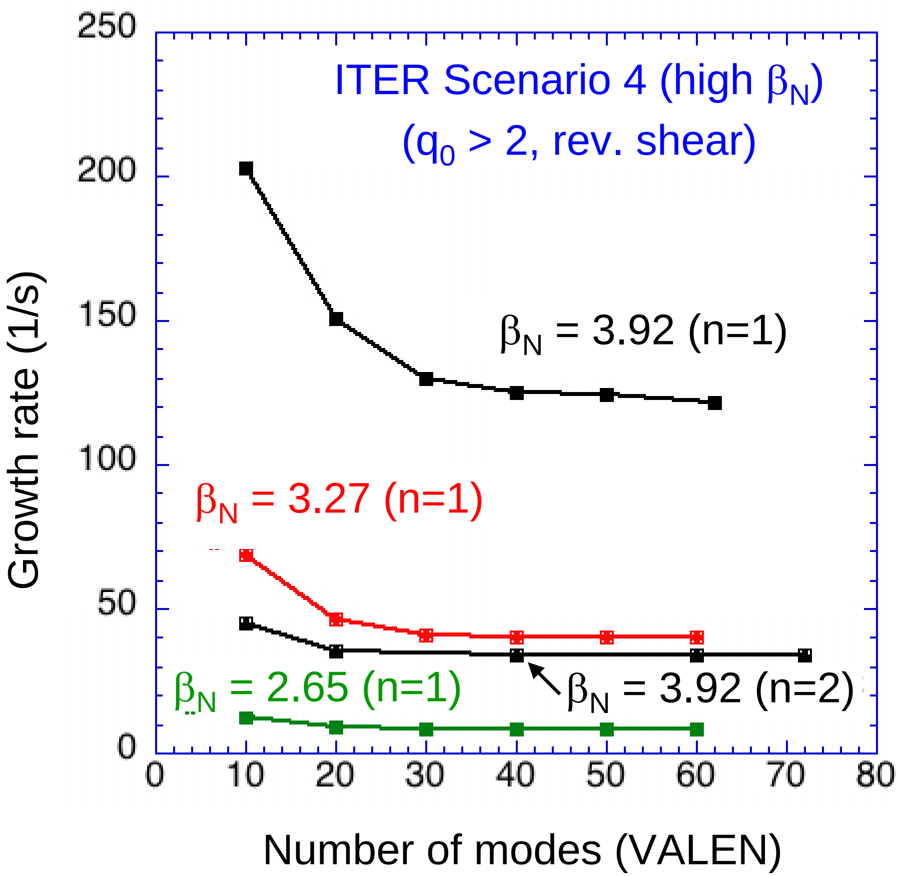
B^n from wall, multi mode response



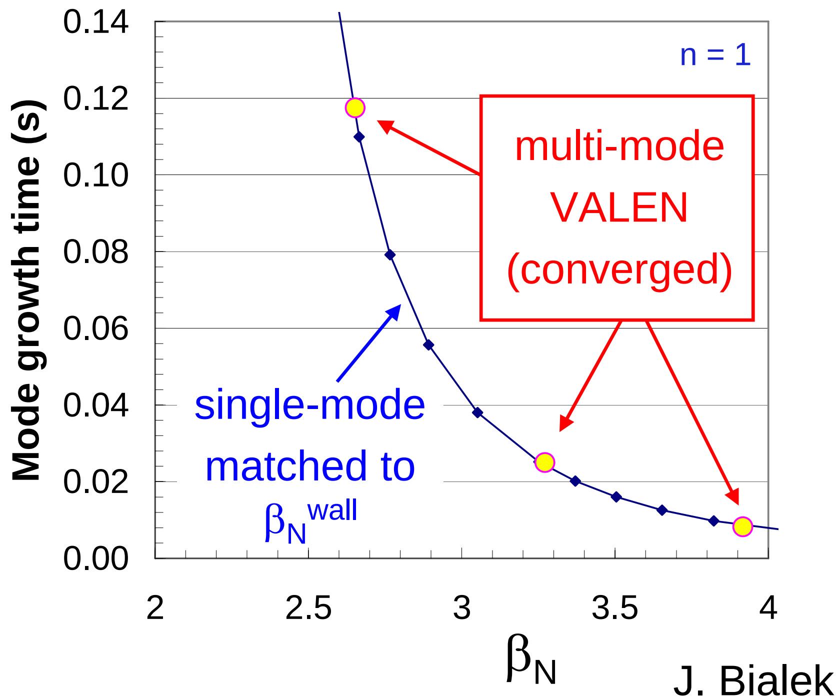
J. Bialek

Importance of multi-mode RWM at moderate β_N and increased q_{min} illustrated by ITER Scenario 4

RWM growth rate (VALEN) vs. # of modes



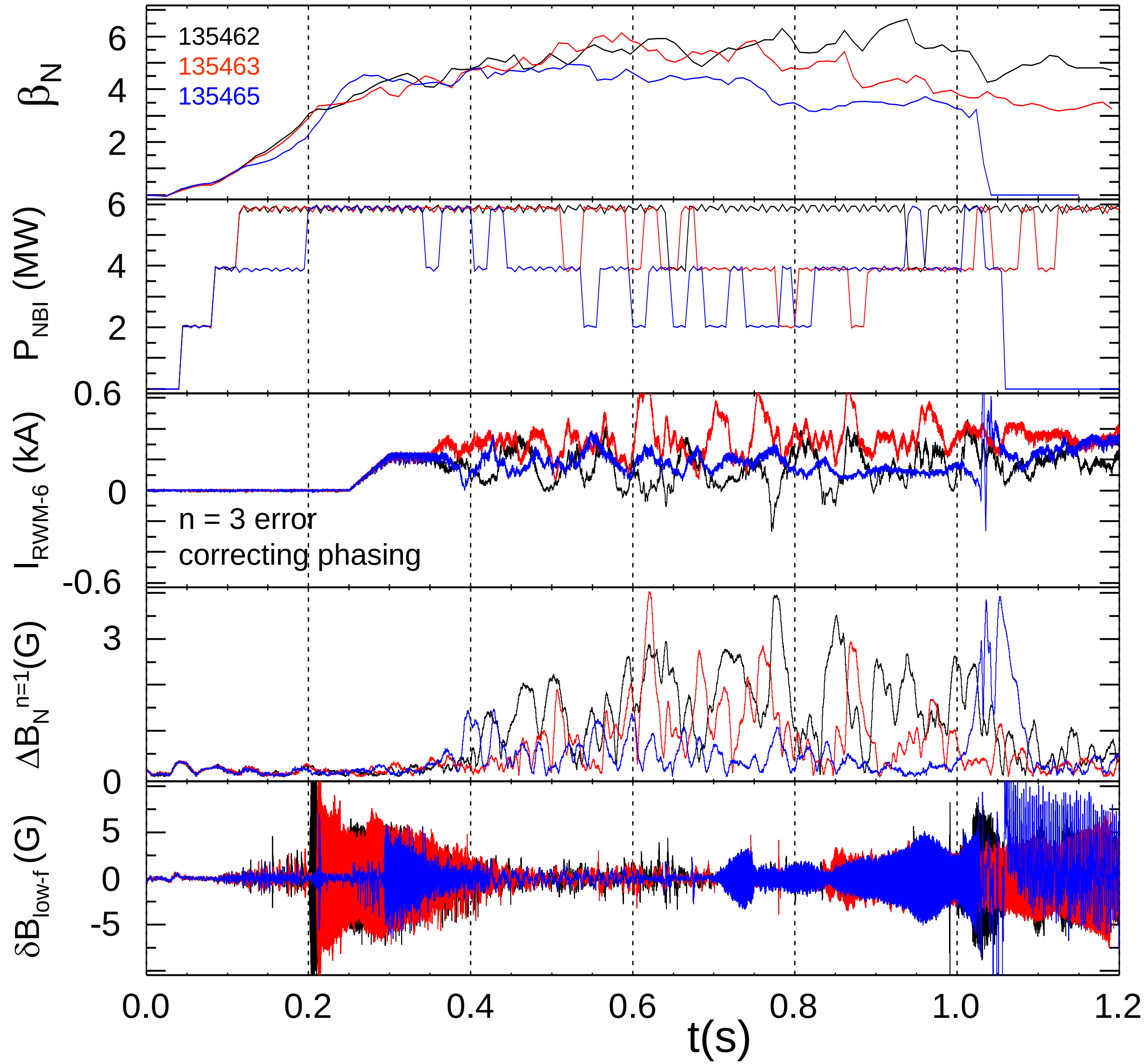
Growth time vs. betaN - ITER Scen 4



J. Bialek

- DCON δW shows several modes with high response
  - Three n = 1 modes at high β_N
  - Two n = 2 modes at high β_N
- At highest β_N, n =1 and 2 are unstable
- Future STs planned to operate with q > 2: key to verify multi-mode model

Successful NBI power limitation via β_N feedback in 2009 run

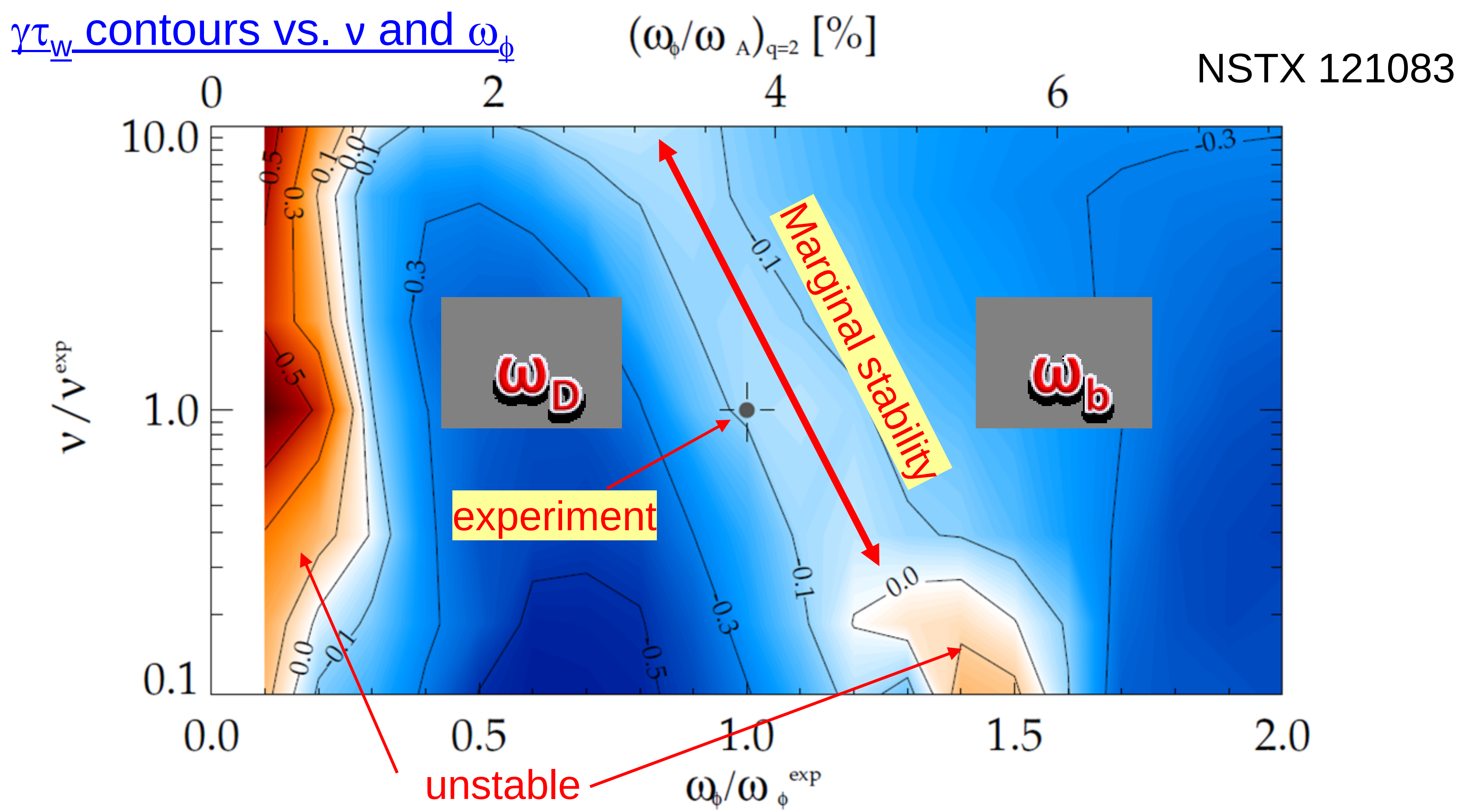


- Cases with n = 3 correcting field (highest ω_ϕ)
  - Nominal targets β_N = 4,5,6
  - NBI blocking shows FB
    - NBI power turned back on when n = 1 rotating mode appears
  - n = 1 rotating mode activity significant due to NBI variation

S. Gerhardt, D. Mastrovito, D. Gates

XP934: S.A. Sabbagh

Channel of "Weak Rotation" for RWM passive stabilization observed in MISK calculations for NSTX, consistent with instability in experiment

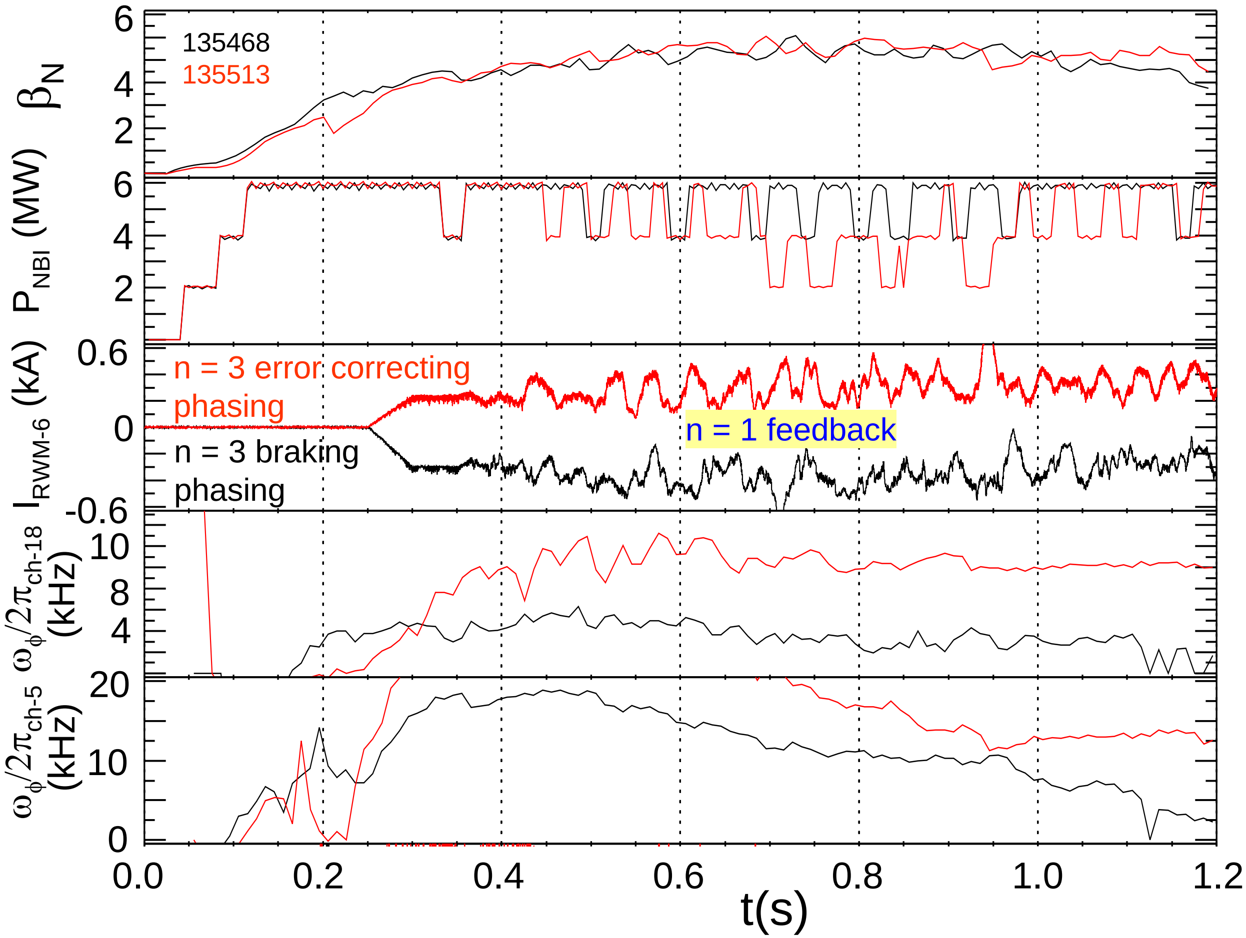


- Stabilization from precession drift resonance at low rotation and bounce resonance at high rotation

J.W. Berkery (APS DPP 2009 invited talk; present meeting)

- Stability dependence on collisionality key for ST fusion burn devices

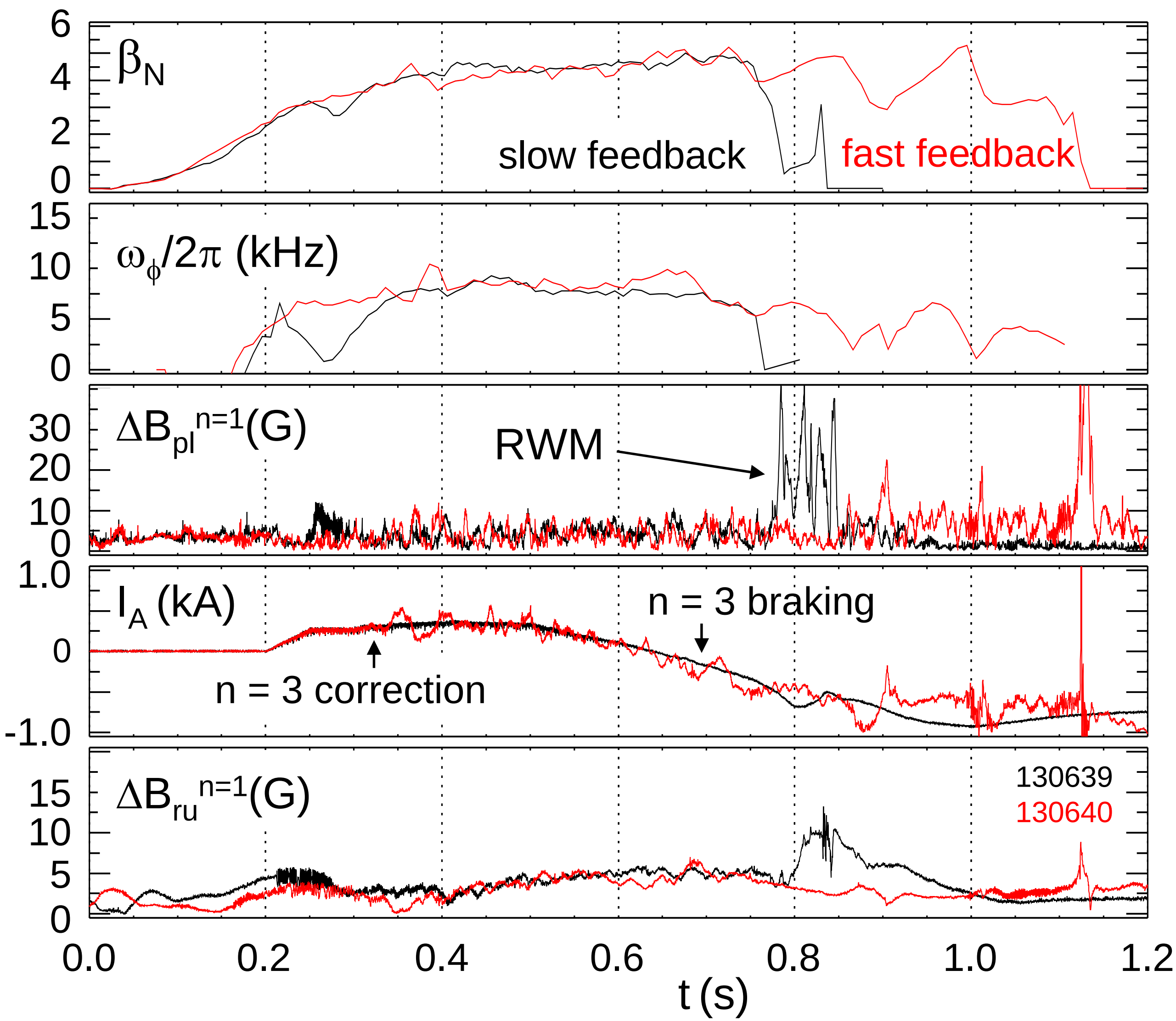
Successful β_N feedback at varied plasma rotation levels



- Prelude to ω_ϕ control in NSTX
  - 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

XP934: S.A. Sabbagh

REMINDER from 2008 mode control meeting: Low ω_ϕ, high β_N plasma not accessed when feedback response sufficiently slowed

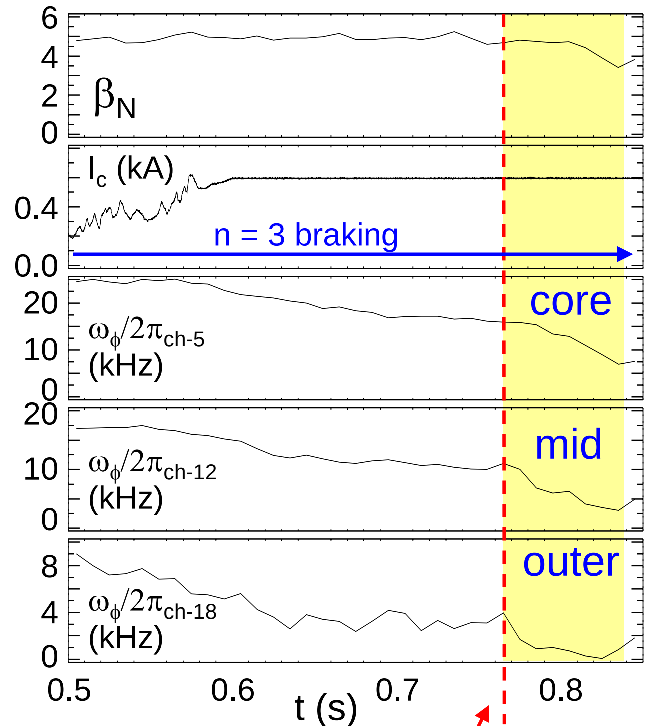


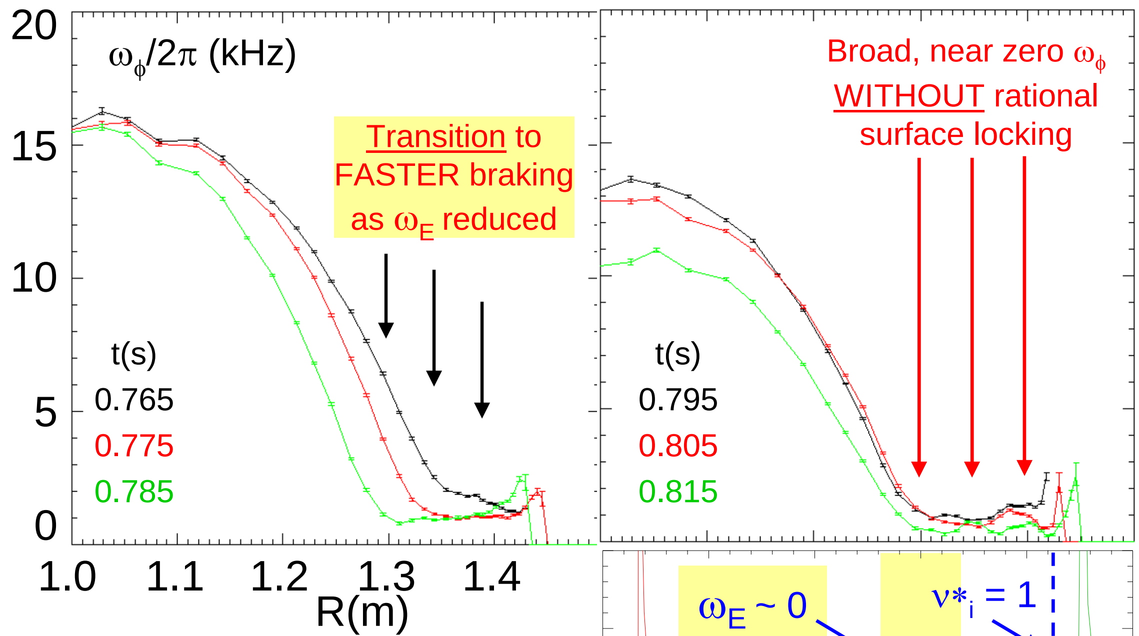
- Low ω_ϕ access for ITER study
  - use n = 3 braking
- n = 1 feedback response speed significant
  - "fast" (unfiltered) feedback allows access to low V_ϕ, high β_N
  - "slow" n = 1 "error field correction" (75ms smoothing of control coil current) suffers RWM
- Large β_N excursion at low ω_ϕ
  - Motivated work to reduce β_N variation

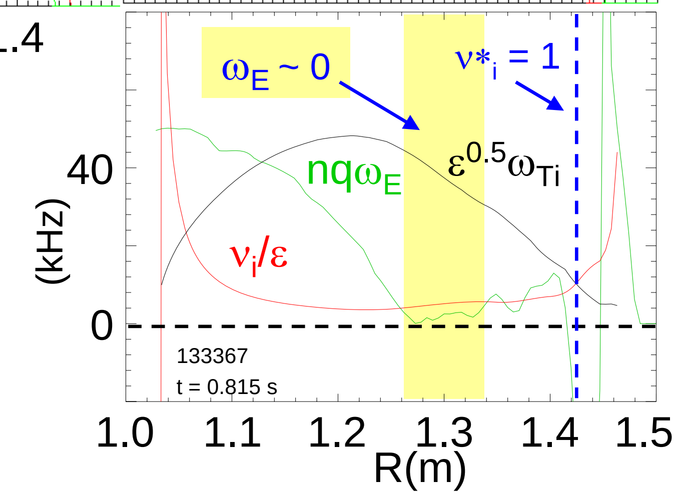
NSTX experiments examining Neoclassical Toroidal Viscosity (NTV) collisionless regime formulae, scaling

- Past NSTX work
  - V_ϕ damping consistent with "$1/\nu$ regime" magnitude & scaling ($T_i^{5/2}$)
    e.g., Zhu, et al., PRL 2006; Sabbagh, et al. IAEA FEC 2008 EX/5-1 (sub. Nucl. Fusion)
- Present goal
  - Investigate damping over range of $\nu_i/nq\omega_E$ to determine if expected theoretical changes occur to NTV-induced magnetic braking
- Results
  - NTV braking observed over all $\nu_i/nq\omega_E(R)$ variations made in experiment
    - Strong braking observed at increased T_i with lithium, even if $(\nu_i/\varepsilon)/nq\omega_E < 1$
  - Magnetic braking at low ω_ϕ, but without locking
    - Occurs most likely with Li wall preparation
  - Apparent lack of $1/\omega_\phi$ scaling of drag torque on resonant surfaces at low ω_ϕ
    - Provocative result – is current layer / island width decreasing at low ω_ϕ
    - …or perhaps drag due to "island NTV" ~ ω_ϕ (K.C. Shaing et al., PRL **87** (2001))
    - …or perhaps due to superbanana plateau physics (K.C. Shaing et al., PPFC **51** (2009))

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







- Faster braking with
  - Constant β_N, applied n = 3 field
  - No mode activity

- Torque not $\propto 1/\omega_\phi$ (non-resonant)
  - NTV in "1/ν regime" ($|nq\omega_E| < \nu_i/\varepsilon$ and $\nu^*_i < 1$)
  - Stronger braking expected when $\omega_E \sim 0$ (superbanana plateau)

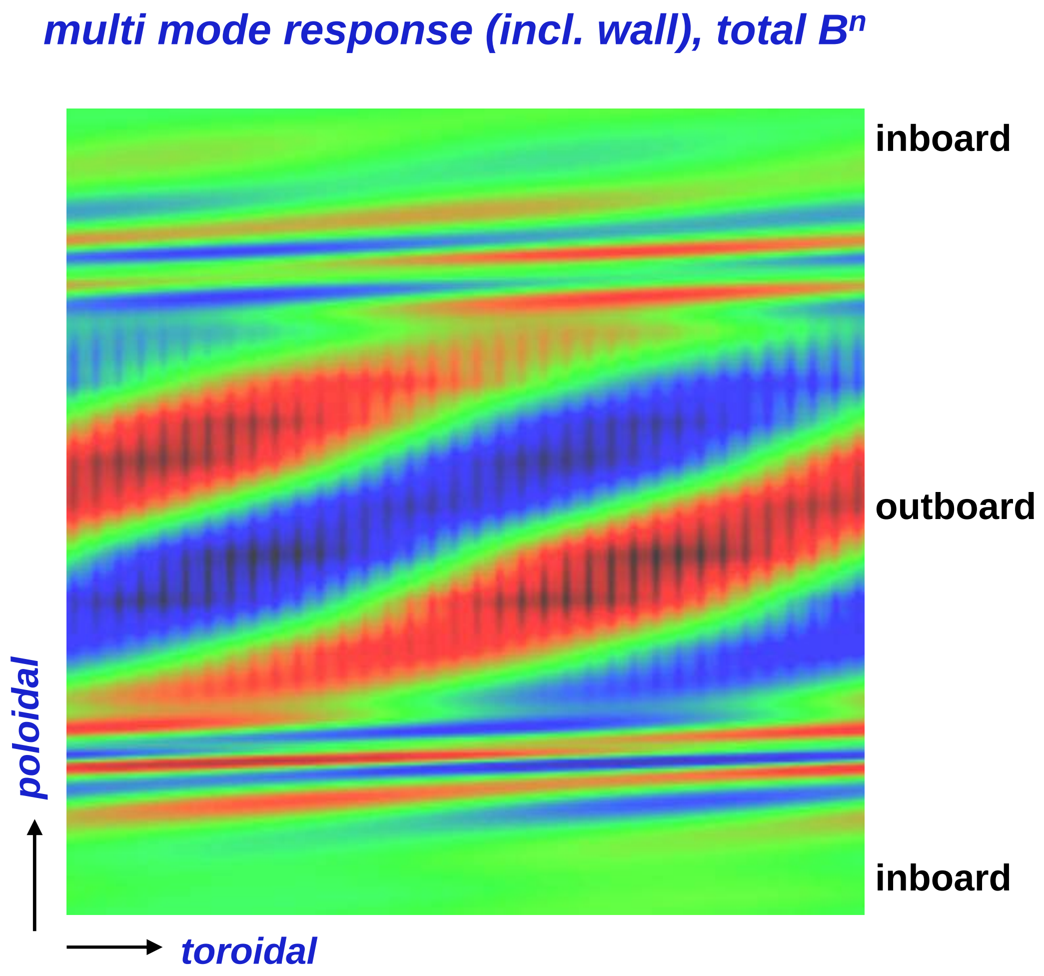
XP933: S.A. Sabbagh

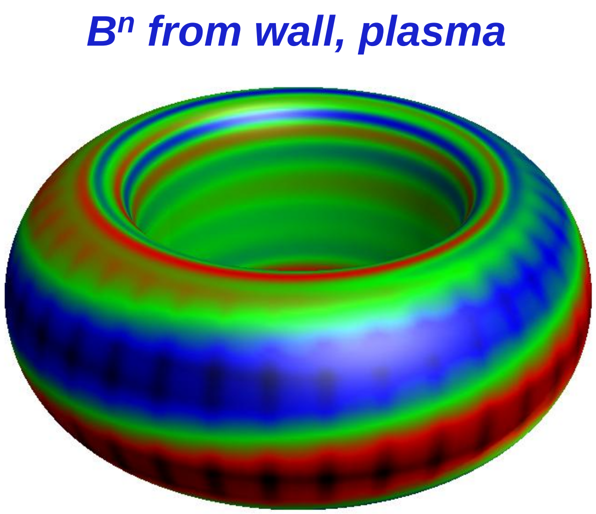
NSTX Macrostability Research in 2009 is Addressing Topics Furthering Steady Operation of High Performance Plasmas

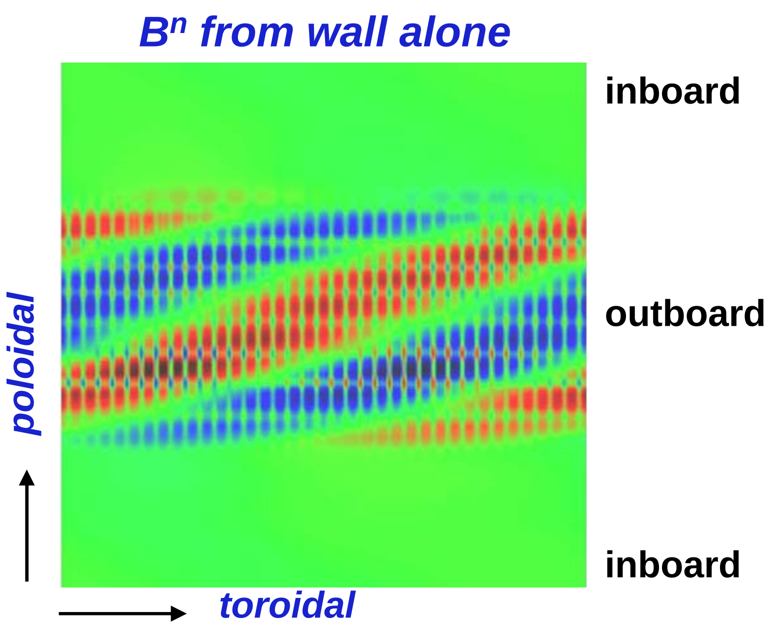
- Low frequency ~ $O(1/\tau_{wall})$ activity at high β_N has characteristics of a driven RWM
  - Mode co-rotating at frequency near natural n = 1 RWM resonance
  - Mode observed in SXR covers greater radial extent as β_N increased
  - Resonant field amplification of co-rotating applied field observed in magnetics, along with oscillations in ME-SXR
- Theory: multi-mode RWM response important at high β_N
  - 2nd mode is stable, so experimental mode is driven (not saturated)
  - multi-mode VALEN code reproducing typically observed growth rates
- Observed growing n = 1 RWM appears to be independent of the driven, ~ 30 Hz mode activity
  - Supports multi-mode RWM theory
- Successful control of NBI power via new β_N feedback system; initial success in regulation of β_N at varied plasma rotation levels
- Strong non-resonant braking (NTV) observed for all $\nu_i/nq\omega_E(R)$ variations made; apparent increase in braking strength at low ω_E (key ω_ϕ for control)

Additional slides

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



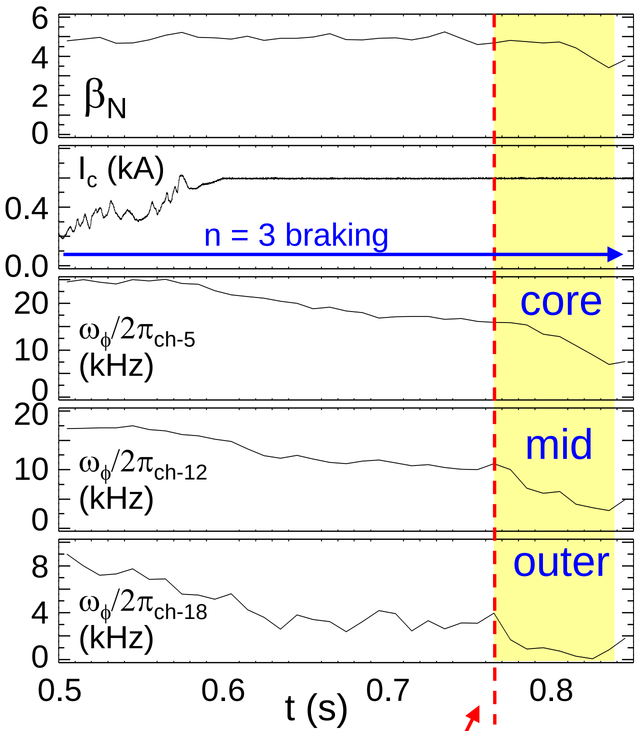


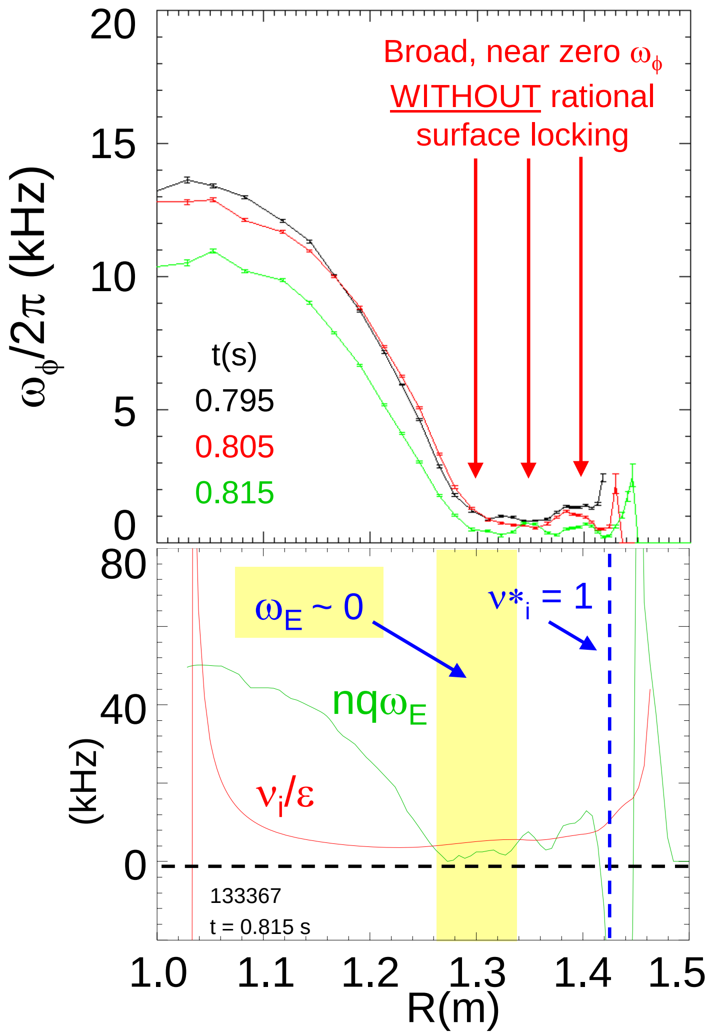


- n = 1 eigenfunctions shown

J. Bialek

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





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