NSTX

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Macroscopic Stability Progress and Plans

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PPPL

for the NSTX Research Team

NSTX PAC Meeting

February 4th, 2010

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Princeton, NJ

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NSTX Macrostability Research is Addressing Needs for Maintaining Long-Pulse, High Performance STs

- Motivation (from ReNeW theme 5 chapter, ReNeW Thrust 16)
  - Maintenance of high β_N with sufficient physics understanding allows confident extrapolation to ST applications (e.g. FNSF, DEMO)
  - Sustain target β_N of ST applications with margin to reduce risk
  - Evolve research to study plasmas with lower l_i and collisionality (closer to levels of future ST applications); varied, low V_ϕ (ITER)

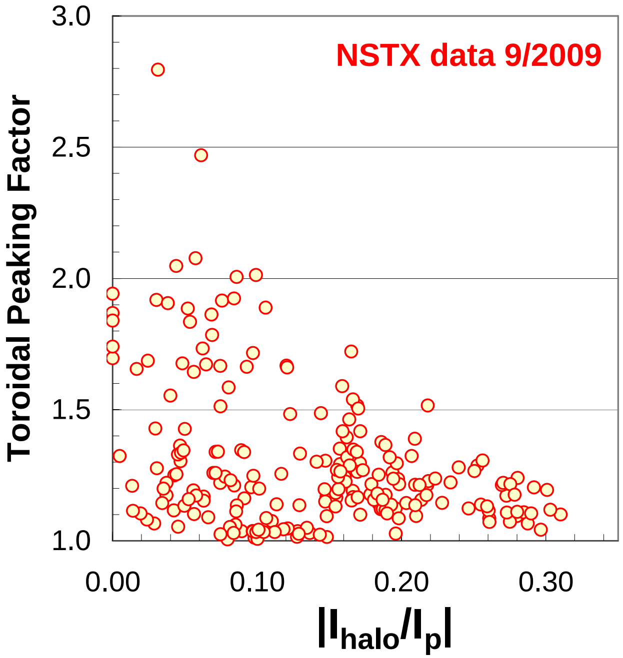
- Outline
  - Macrostability milestones and priorities
  - ITER/ITPA MHD stability group participation
  - Results supporting FY09 milestone and PAC-25 recommendations
  - 2010 research plans / experiments
  - 2011-2012 research plans

Results/plans supporting PAC-25 recommendations, ITPA MHD stability groups tasks (MDCs) are labeled throughout

Macrostability priorities guided by future ST and ITPA physics needs

- Macrostability Priorities
  - *Understand active and passive RWM stabilization physics to improve mode control and assess disruptivity and sustainable beta near and above the ideal no-wall limit (Milestone R10-1)*
  - *Evaluate MHD and 3-D field sources of plasma viscosity and assess the impact of V_ϕ on stability, including the NTM*
  - *Develop an understanding of the deleterious effects of disruptions in an ST, including halo current generation and properties of the thermal quench*

- Active ITPA contributions/participation
  - 7 ITPA MHD stability group tasks addressed (http://nstx-forum-2010.pppl.gov/macroscopic_stability.html)
    - Nearly all experiments contribute
  - NSTX delivered 2 - 3 presentations at each of the last 3 ITPA MHD meetings (Sabbagh)
  - NSTX was first contributor to 2009 expanded ITPA disruption database (Gerhardt)
    - Data being used for NSTX-U design
  - Supporting MHD working groups (e.g. sawtooth)



First step to producing / extrapolating steady, high β_N: Understand physics of disruptive modes

- NSTX R09-1 Milestone
  - *Understand the physics of RWM stabilization and control as a function of plasma rotation*
  - Approach:
    - Experiments probed marginal RWM stability, examined RWM passive and active control vs. plasma rotation, V_ϕ
    - RWM can terminate NSTX plasmas at both low and intermediate plasma rotation levels without active control (no simple, scalar Ω_{crit})
    - Modification of Ideal Stability by Kinetic theory (MISK code) used to explain experimental RWM stabilization (Hu and Betti, Phys. Rev. Lett **93** (2004) 105002)
    - Stability depends on resonances in δW_K (e.g. ion precession drift), collisionality

Trapped ion component of δW_K (plasma integral)

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

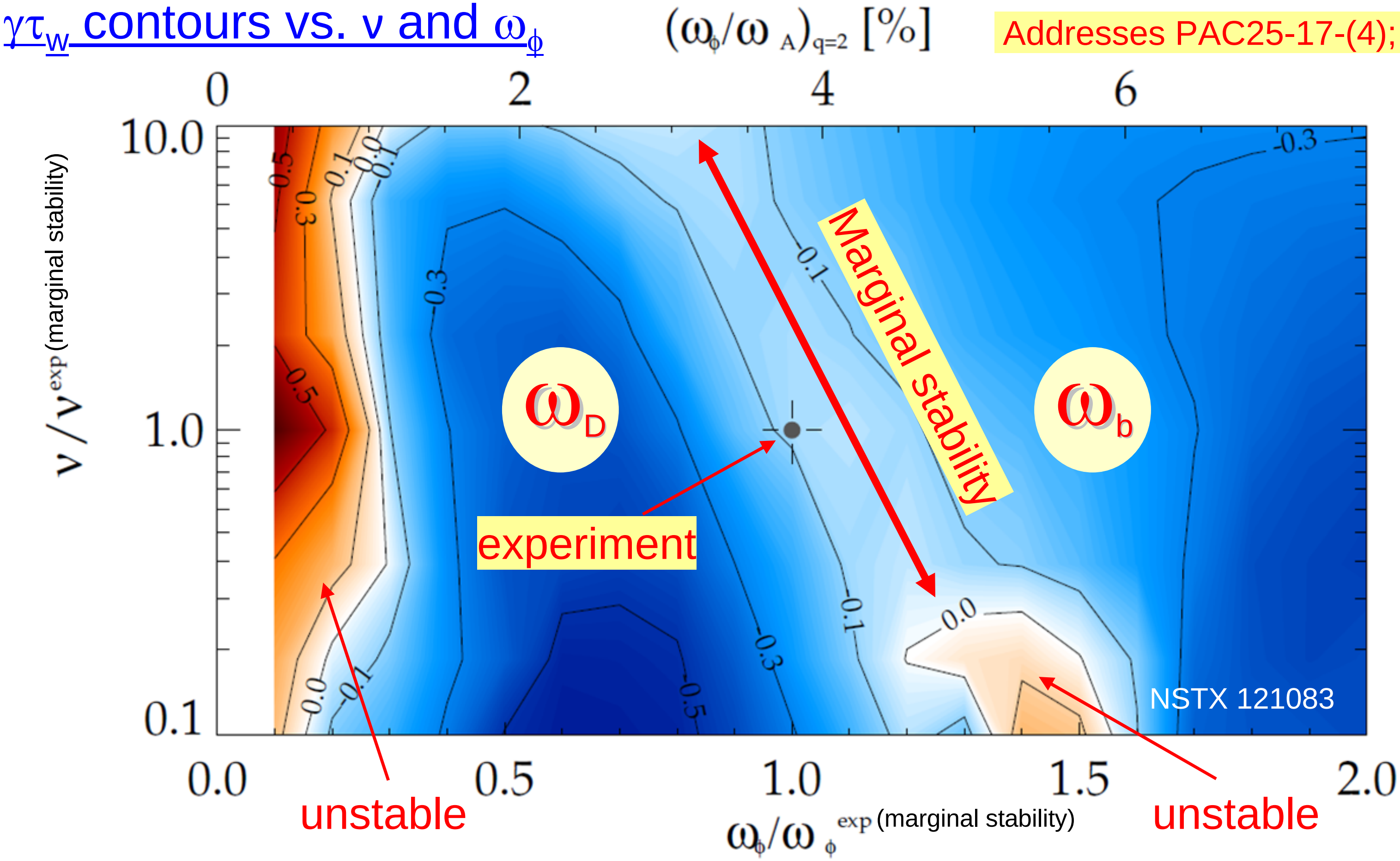
← Energy integral

precession drift 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

Addresses PAC25-17-(4); ITPA MDC-2

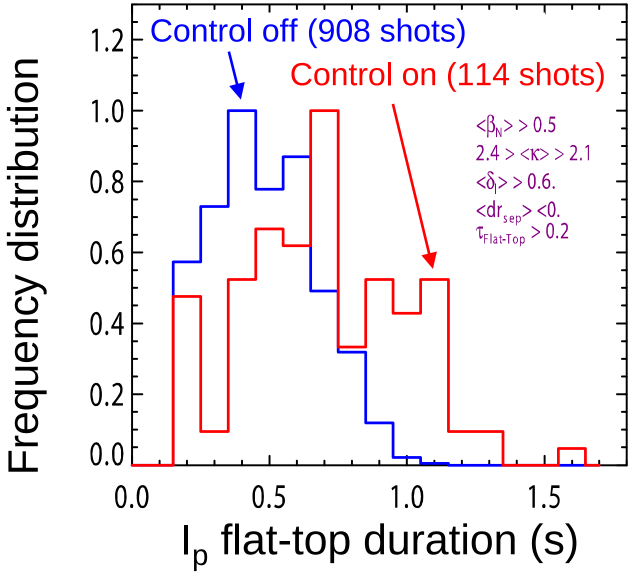


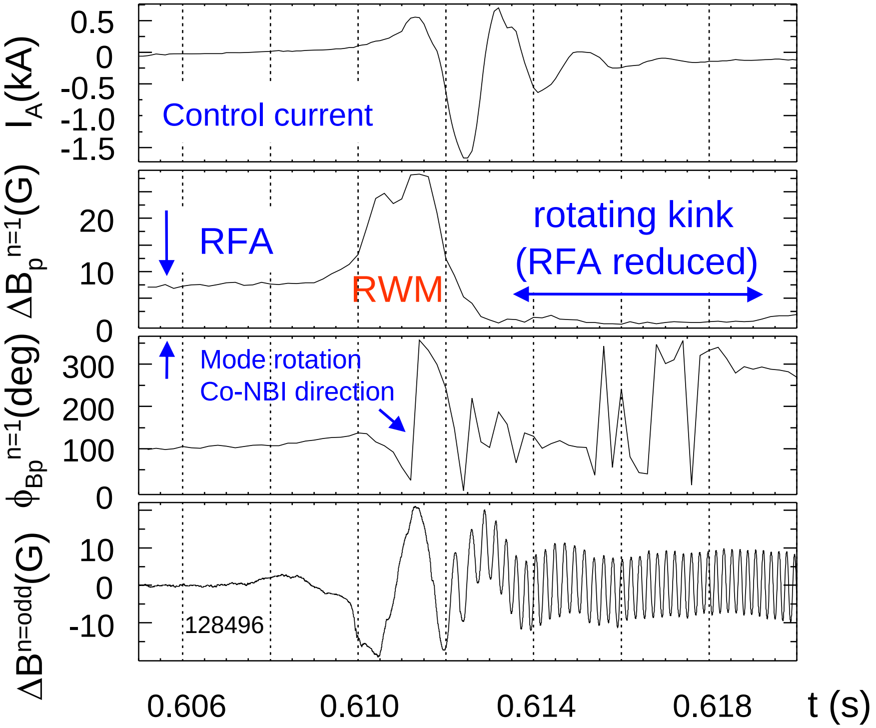
J. Berkery
(Columbia U.)

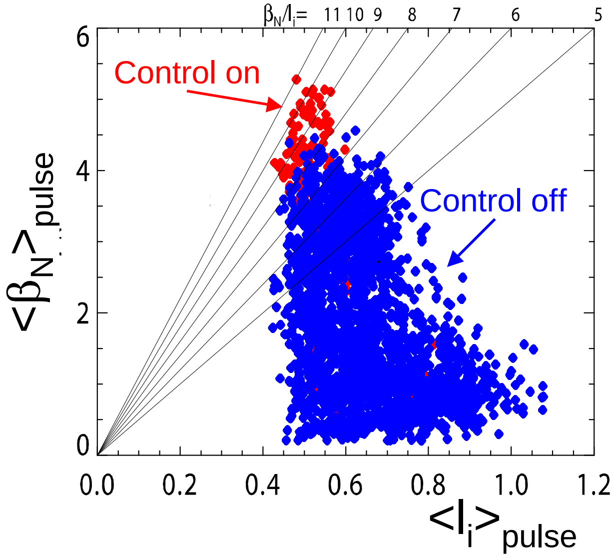
- Destabilization appears between precession drift resonance at low V_ϕ, bounce resonance at high V_ϕ (J.W. Berkery, et al., PRL (2010) 035003; APS 2009 inv. talk)
- 2010+ plan: stability dependence on ν to be studied using LLD, NSTX-U

RWM control physics examined, disruptivity initially assessed

Addresses PAC25-17-(1); 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

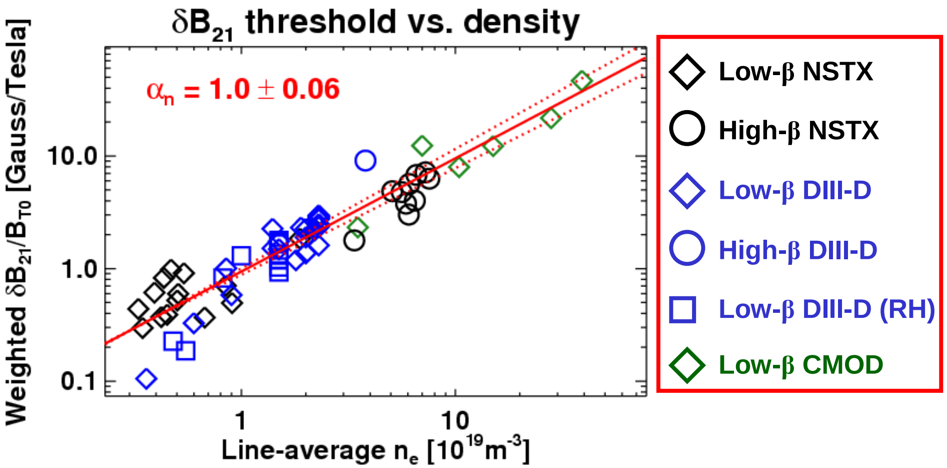
(XP902: S. Gerhardt)

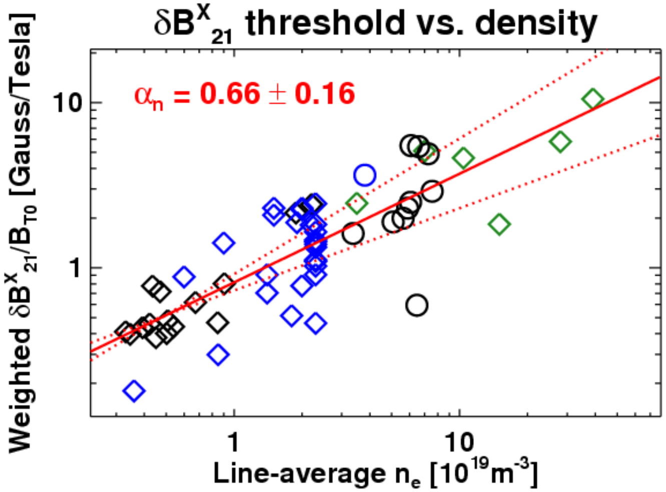
IPEC computed total resonant field unifies linear dependence of mode locking threshold on density among devices

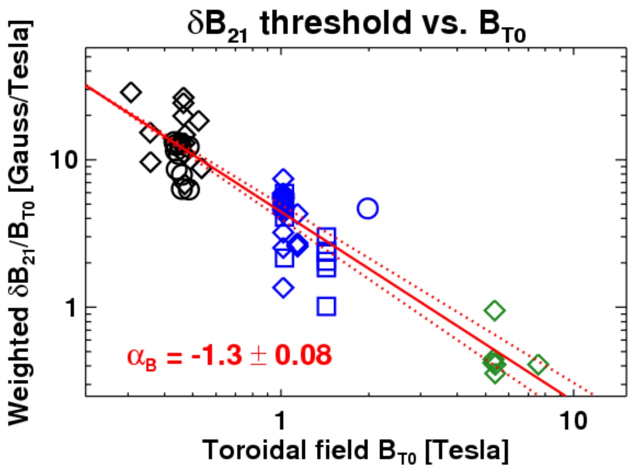
ITPA MDC-2,14

Total resonant field w/ plasma response (IPEC)

External resonant field only







$$\frac{\delta B_{21}}{B_{T0}} \leq 1.0\times10^{-4}\left(n[10^{19}m^{-3}]\right)^{1.0}\left(B_{T0}[T]\right)^{-1.3}\left(R_0[m]\right)^{0.78}$$

- 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)
- 2010 Plans
  - Extend error field amplification and mode locking study to low torque plasma

XP903: J.-K. Park XP915: R. Buttery (GA)

Second step to producing / extrapolating steady, high β_N : Extend instability understanding toward future target plasmas

- NSTX R10-1 Milestone
  - *Assess sustainable beta, disruptivity near/above the ideal no-wall limit*

tools/ diagnostics

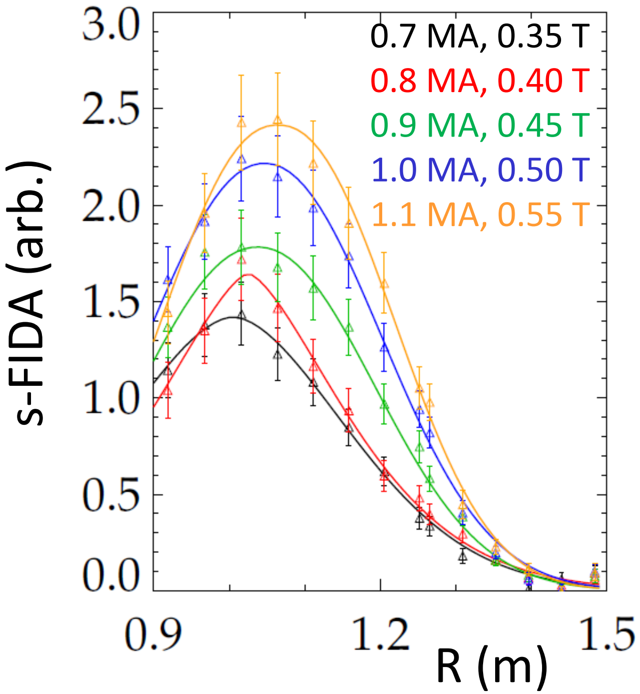
- Experiments leverage LLD to access targeted operational regimes
- Halo current diagnostics in LLD; new multi-energy SXR system; BES

- Planned experiments / approaches / analysis: (ITPA MDC-2,4,14,15,17)
  - Extend mode stabilization results of long-pulse duration, high β_N plasmas to lower l_i, ν, V_ϕ, input torque (two XPs, 2 days) (PAC25-18)
  - Determine decreased RWM stability vs. V_ϕ and EP content with MHD spectroscopy (one XP, 1 day) (PAC25-17-(4))
  - Extend error field amplification (RFA) and mode locking density threshold study to low torque plasma (one XP, 1 day) (PAC25-18)
  - Improve β_N feedback, RWM control to reduce disruptivity (3 XPs, 2.5 days)
  - Halo current study with extended diagnostics (1 XP, 1 day)
  - Determine NTM stability vs. q_{min} evolution (1 XP, 0.5 day)
  - Analyze potential multi-mode RWM behavior at high β_N (analysis/piggyback)
  - Global/ELM stability vs. edge J, q, ν; peeling/ballooning (ITER) (2 XP, 1 day)

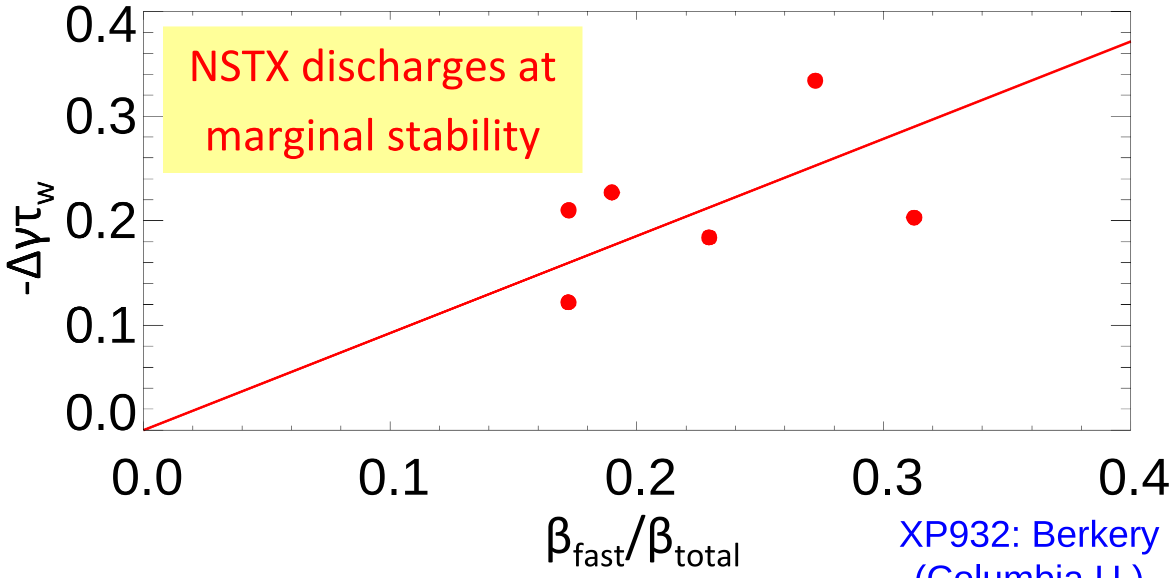
MISK calculations of 2009 experiment show that RWM stability increases linearly with energetic particle content

Addresses PAC25-23(i); ITPA MDC-2

Energetic particle content varied



Increase in stability from energetic particles



XP932: Berkery (Columbia U.)

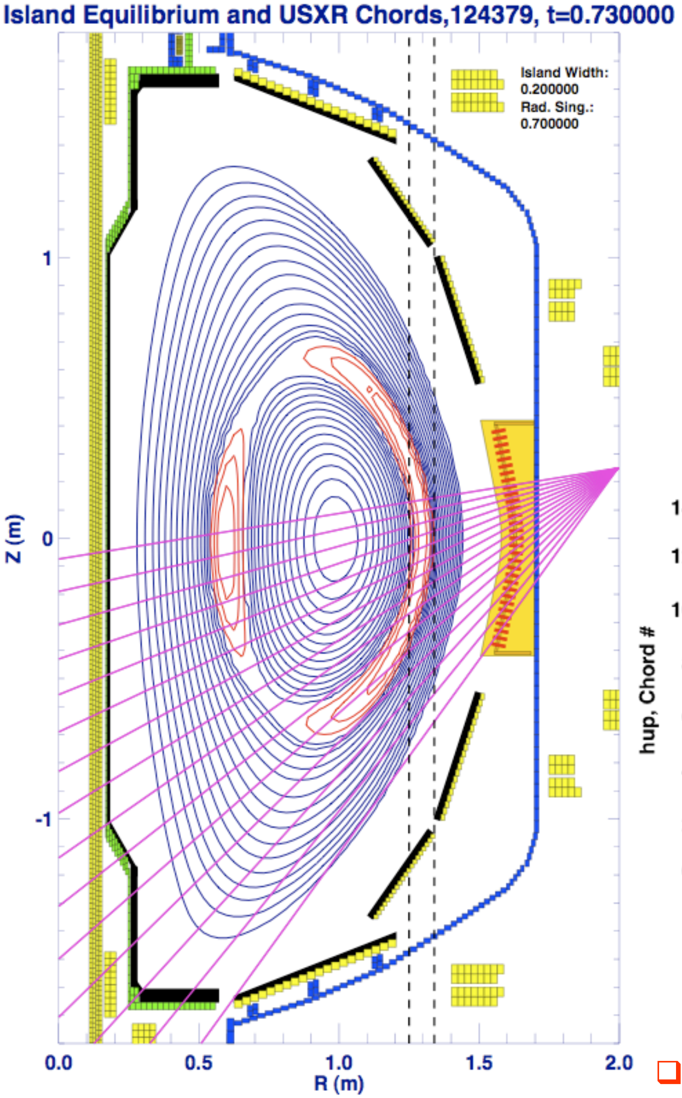
- Model quantitatively overpredicts stability with EPs included
  - improving fast particle distribution; thermal/energetic particle importance
- MISK calculations indicate importance of energetic ions for RWM stability in DIII-D low rotation plasmas

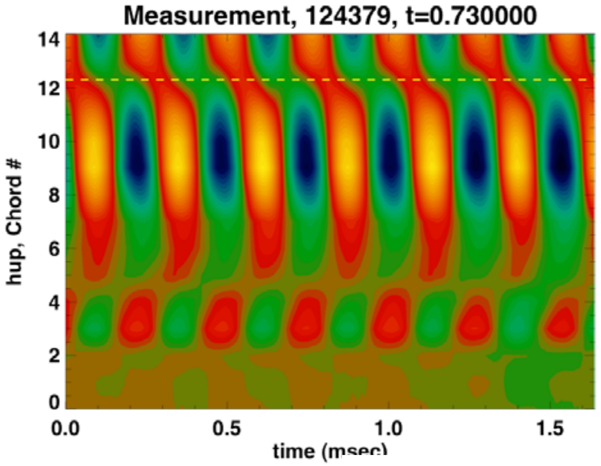
Addresses PAC25-17-(2,4); ITPA MDC-2

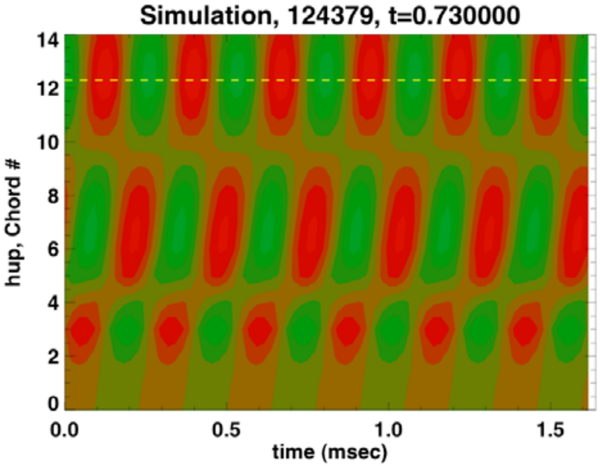
  - Motivation for DIII-D experiment MP 2009-99-07 (H. Reimerdes, et al.)
- 2010+ plans: Unify RWM stabilization physics: NSTX, DIII-D, JT-60U

2/1 NTM is an important beta-limiting mode in NSTX

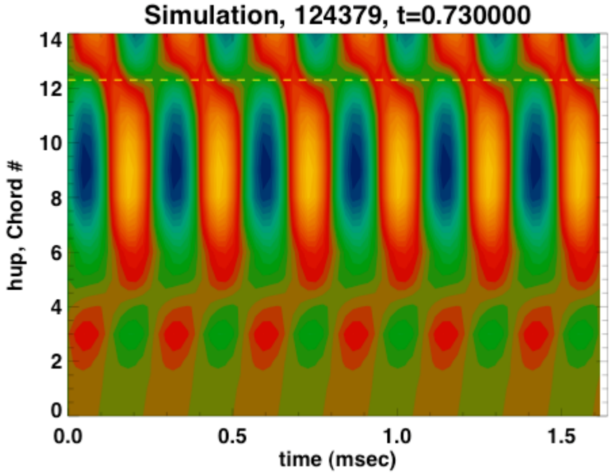
ITPA MDC-4,14







2,1 only



2,1 + 1,1 pert

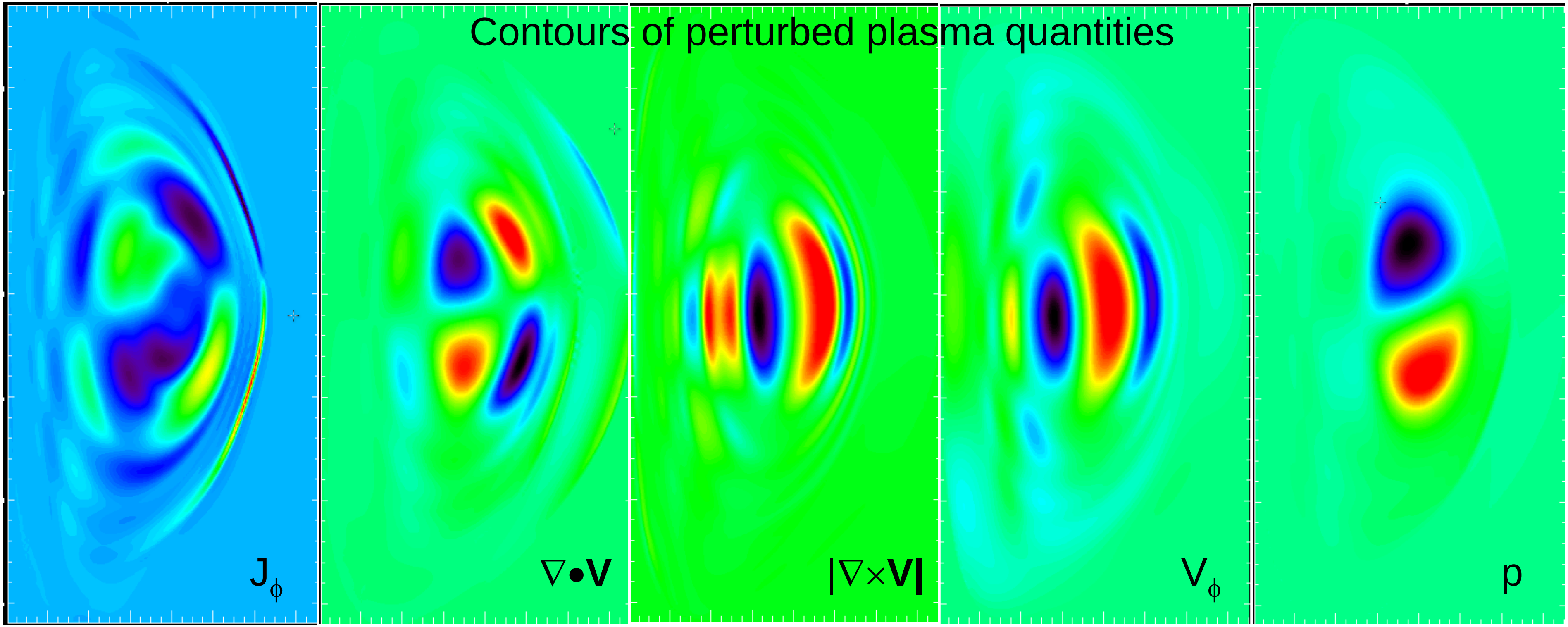
- Eigenfunction analysis of multichord USXR data shows coupling of 2/1 mode NTM to 1/1 ideal kink (ubiquitous)

S.P. Gerhardt

M3D-C^1 code now being used to simulate coupled 2/1 + 1/1 mode observed in experiment

ITPA MDC-4,14

Contours of perturbed plasma quantities

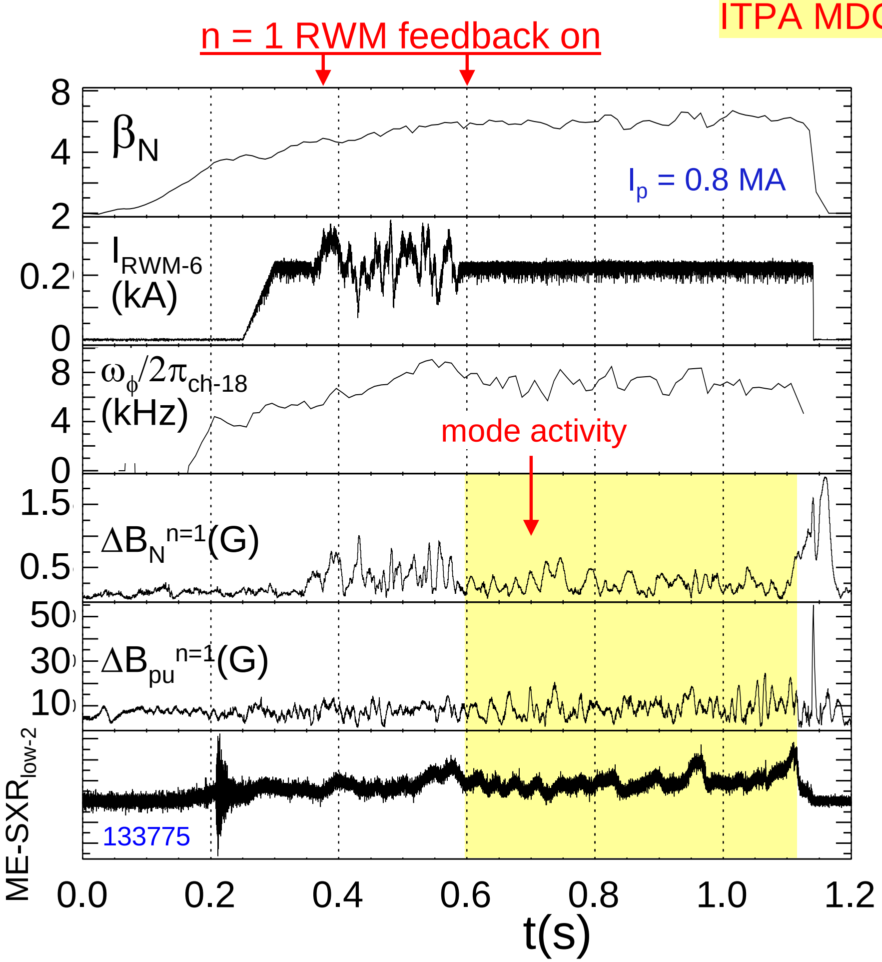


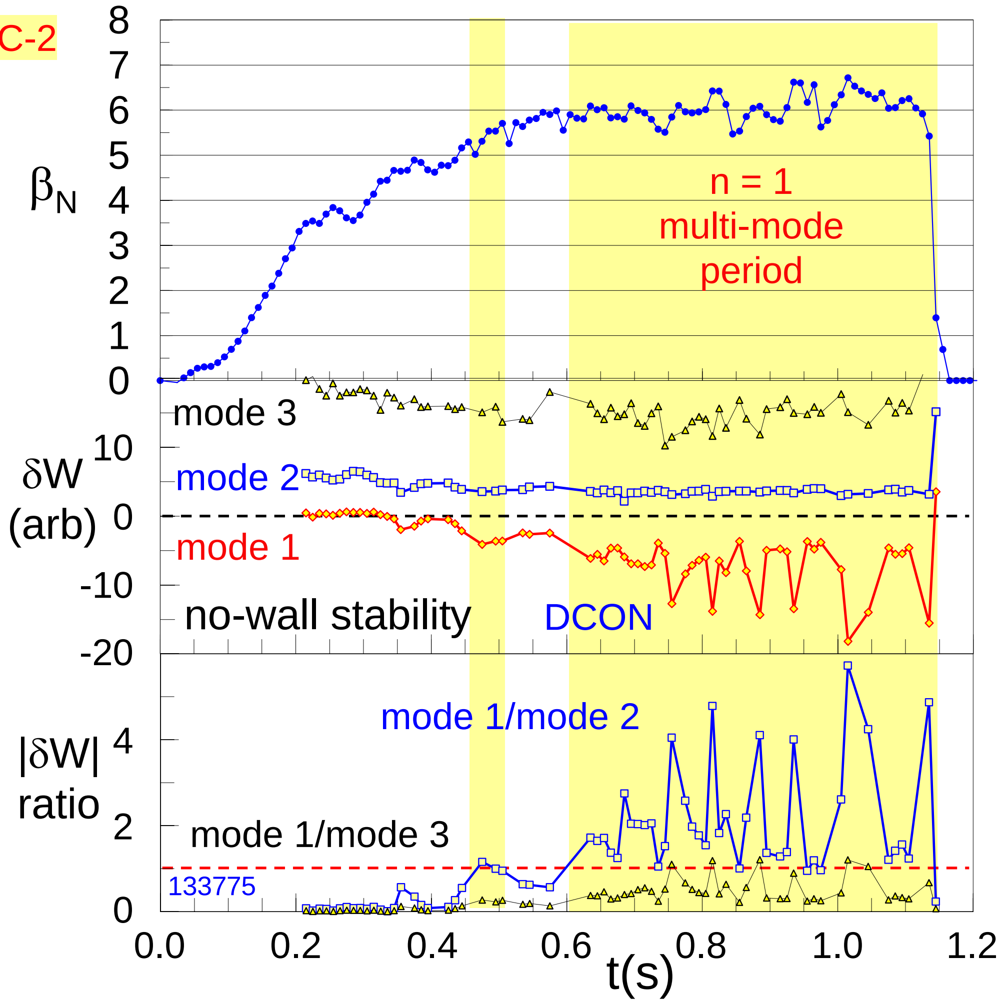
J. Breslau / S. Jardin

- Study conducted using experimental equilibrium
  - define η and thermal conductivity; impose random perturbation
  - solve time-dependent resistive MHD equations as initial-value problem
- An *n* = 1 mode found with some characteristics of the experimental mode
  - Shows m=1 and m=2 components of plasma quantities
  - 1/1 perturbation appears ideal (no q=1 surface); 2/1 shows current sheet, tearing
  - q scaling study suggests experiment is close to marginal stability for this mode

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

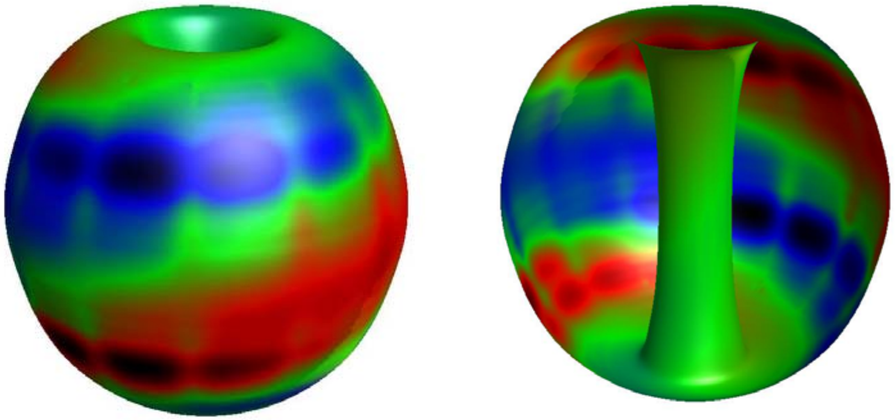
- ❑ RWM multi-mode response expected to be significant at high β_N (Boozer, PoP 10 (2003) 1458.)

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

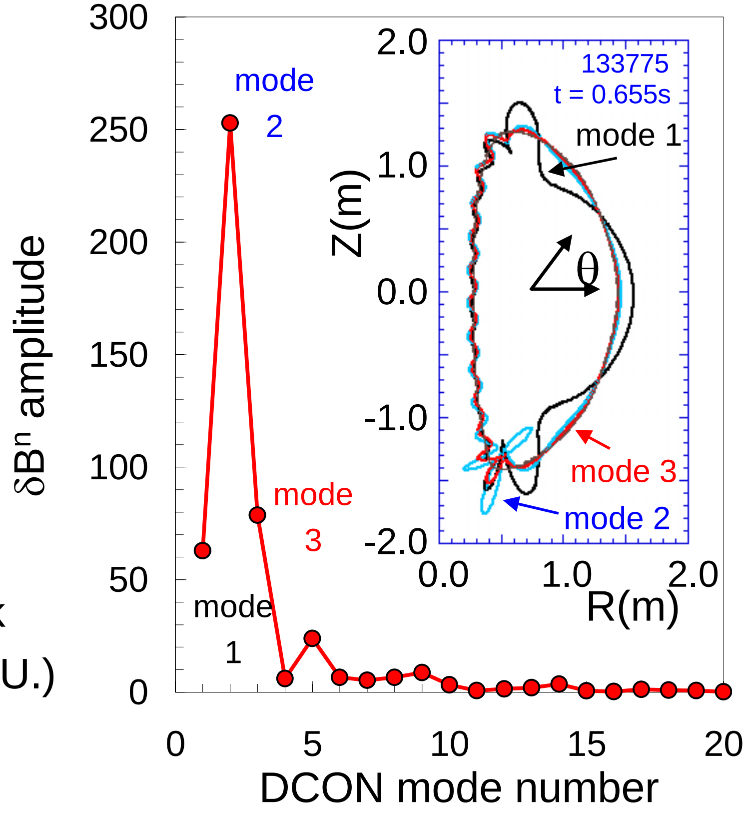
Multi-mode RWM VALEN computation shows 2nd mode has dominant amplitude at high β_N in NSTX stabilizing structure

ITPA MDC-2

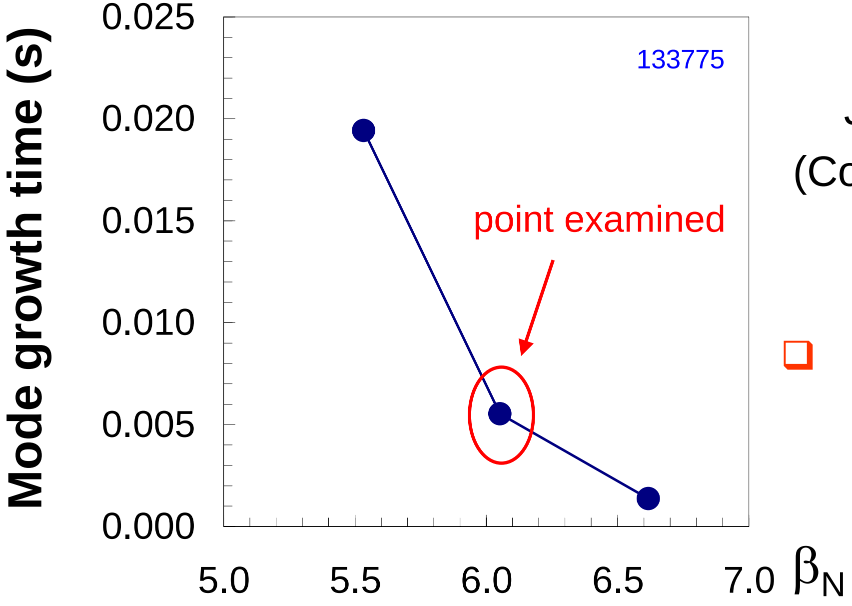
δB^n from wall, multi-mode response



δB^n multi-mode composition



RWM growth time vs β_N



J. Bialek
(Columbia U.)

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

Third step to extrapolating steady, high β_N: Observed sensitivity of RWM stability on plasma rotation motivates planned V_ϕ control

- Macrostability FY11 Milestone (incremental)
  - *Assess RWM and rotation damping physics at reduced collisionality*

    tools/ diagnostics

    - *Addition of 2nd SPA for independent RWM coil currents (more flexible V_ϕ control)*
    - *Initial real-time V_ϕ measurement (up to 4 radial positions)*
  - Plans/Approach: (ITPA MDC-2,12,17)
    - Comparison of RWM stability to theory at reduced ν with EP effects
    - Further verification of neoclassical toroidal viscosity (NTV) over full range of ν_i and ω_E, NTV offset at low torque (one XP 2010 – 0.5 days) (PAC25-18)
    - Further investigation of increased non-resonant magnetic braking at low ω_E
    - Provide data and understanding for optimized NTV rotation control

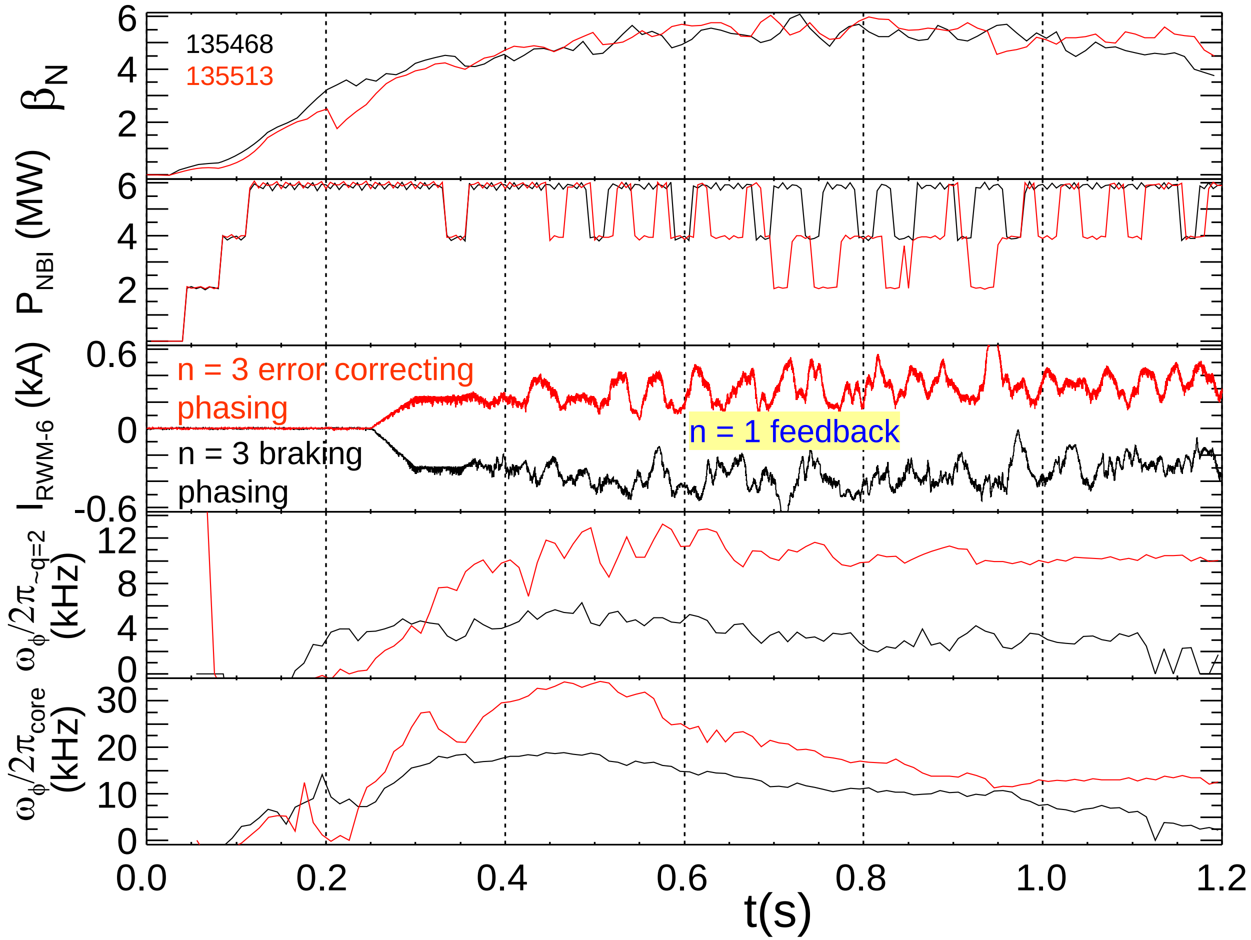
- Macrostability FY12 Milestone
  - *Investigate physics and control of rotation & rotation damping at low collisionality (joint with ASC group)*

    tools

    - *Real-time V_ϕ control (initial implementation)*
  - Plans/Approach:
    - Bring together key scalings of resonant and non-resonant (NTV) damping physics to support real-time model of V_ϕ control
    - Explore avoidance of decreased RWM stability with planned V_ϕ control

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

Addresses PAC25-17-(1)



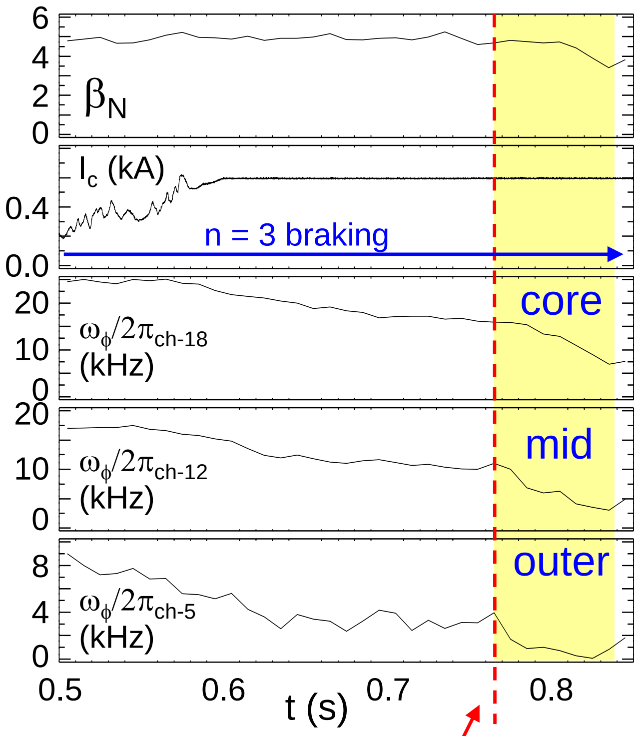
- Prelude to ω_ϕ control
  - Reduced ω_ϕ by n = 3 braking does not defeat FB control
  - Increased P_{NBI} needed at lower ω_ϕ
- Steady β_N established over long pulse
  - independent of ω_ϕ over a large range

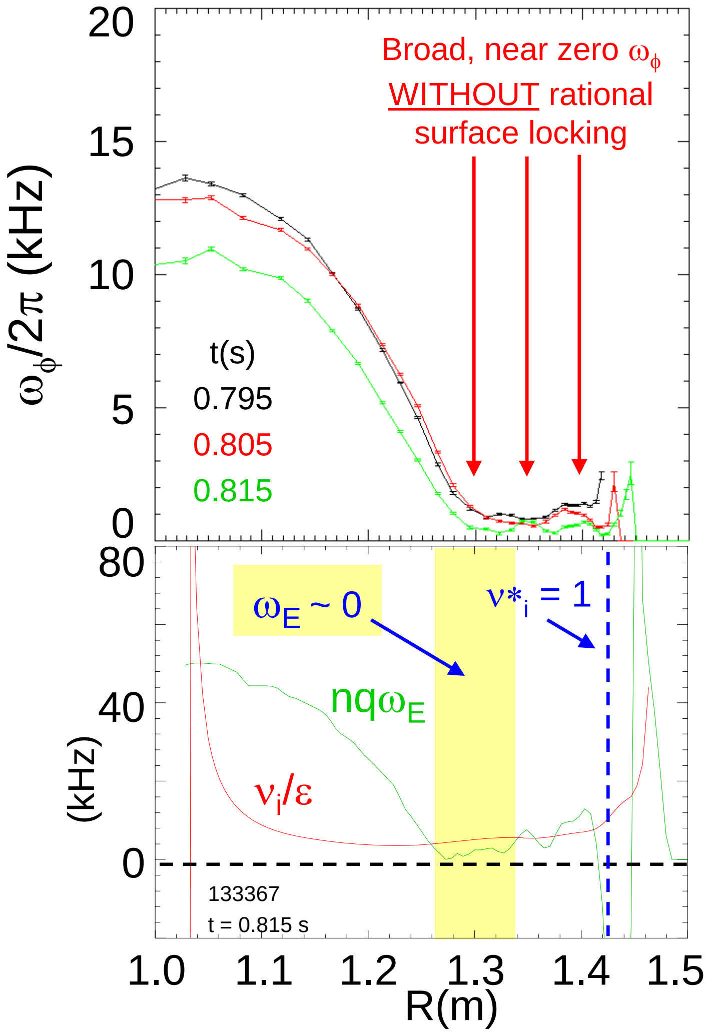
- 2010+ plans
  - XP to investigate lower plasma rotation, l_i, collisionality

XP934: Sabbagh (Columbia U.)

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

Rotation control needs to model certain complexities of NTV rotation damping physics, such as behavior at low ω_E





XP933: Sabbagh
(Columbia U.)

- 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) (K.C. Shaing et al., PPFC **51** (2009)) – analysis continues

Macrostability Research in 2009 – 2012 Addresses Physics Understanding Needed to Bridge To Future Long-Pulse, High Performance STs

- 2009: Better stability physics understanding to maintain steady β_N
  - RWM instability, observed at intermediate plasma rotation, correlates with kinetic stability theory; role of energetic particles under study
  - Ideal plasma amplification of applied n = 1 resonant field (IPEC) unifies linear dependence of mode locking threshold on density among devices
  - Expanded NTM onset experiments find best correlation between NTM onset drive and flow shear; island width for restabilization ($\propto \varepsilon^{0.5}\rho_{\theta i}$) fits tokamaks, NSTX
- 2010: Improve stability physics understanding / control for next devices
  - Improve successful β_N and n = 1 RWM control to sustain high β_N with varied V_ϕ levels at reduced l_i, ν, V_ϕ, input torque; compare RWM stabilization physics - NSTX/tokamaks
  - Extend error field amplification/mode locking density study to low torque plasma
  - Use multi-mode RWM theory to investigate low frequency ~ $O(1/\tau_{wall})$ mode activity at high β_N as potential driven RWM
- 2011-12: Improve understanding of V_ϕ damping by 3-D fields for V_ϕ control
  - Rotation control needs to model certain observed complexities of NTV rotation damping physics, such as behavior at low ω_E; apply V_ϕ control for passive RWM control
  - Unify RWM stabilization physics between NSTX and tokamaks

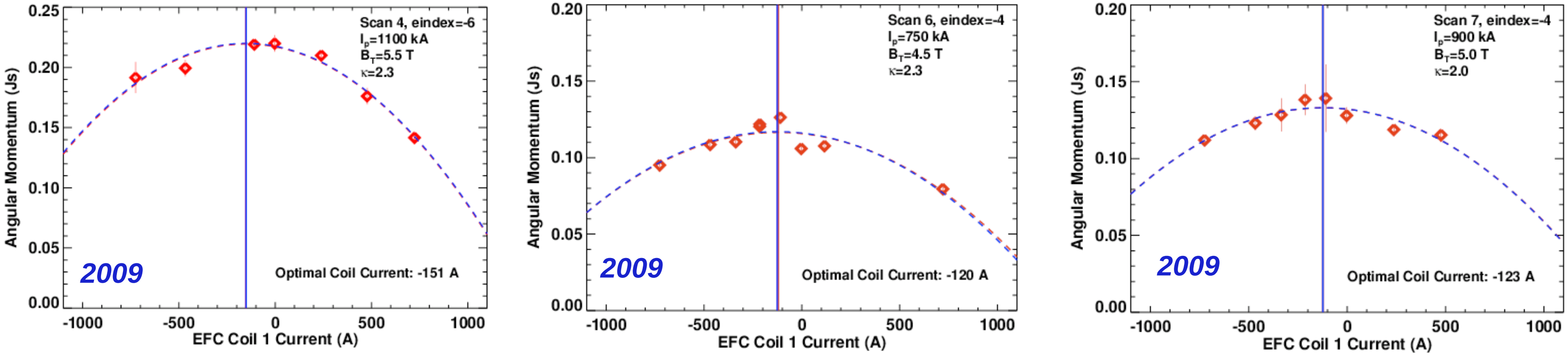
Working closely with other experiments to understand MHD physics for NSTX-U and future ST development, ITPA/ITER

Macroscopic Stability TSG - Backup Slides

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

ITPA MDC-2, MDC-12

Plasma angular momentum vs. correction current



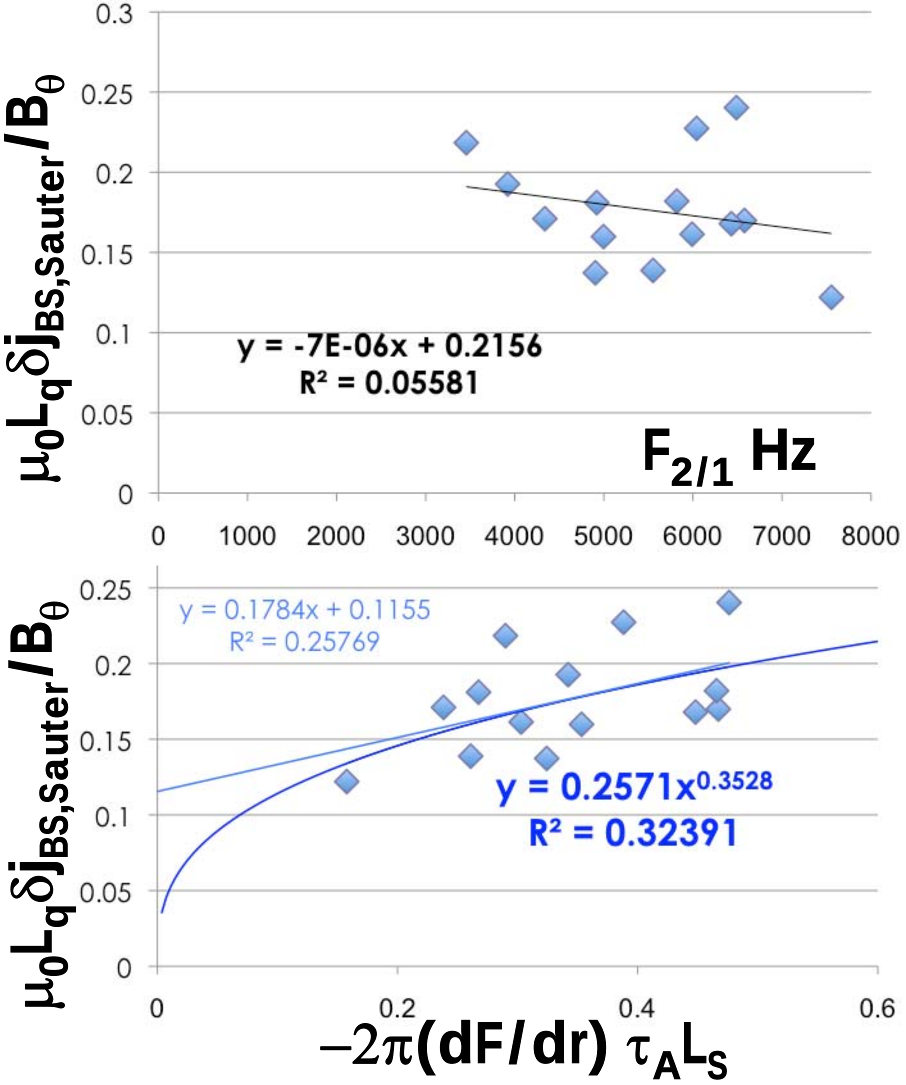
- "optimal" n = 3 error field correction attained by maximizing angular momentum, scanning I_p, B_t, elongation
- n = 3 error field consistent with known equilibrium field coil distortion
  - scales with equilibrium field coil current
  - field phase and amplitude of correction is consistent with that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

XP902: S. Gerhardt

3D field effect leading to NTM onset is through V_ϕ shear, not resonant interaction

ITPA MDC-4,14

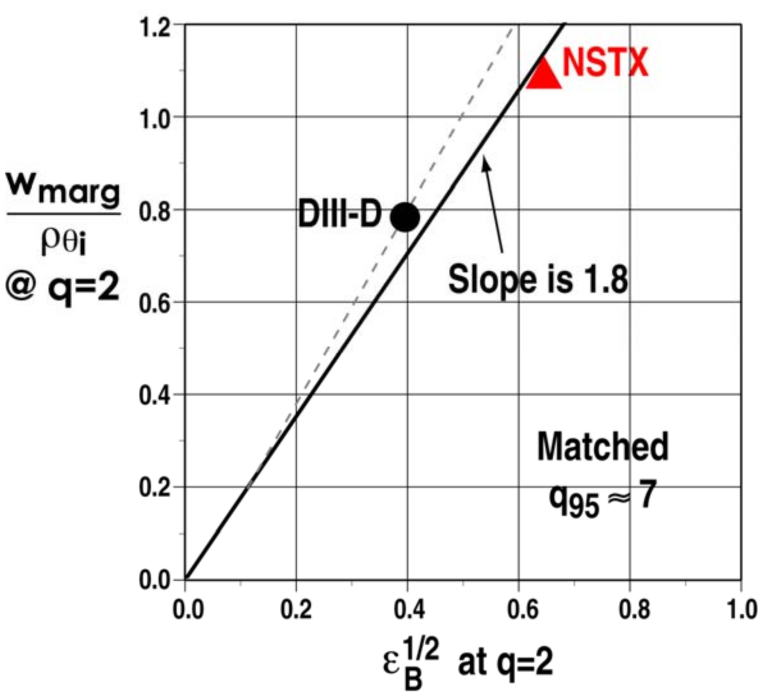
- Rotation variation via n = 1 or 3 applied field
  - Operational space fully spanned
  - Required bootstrap drive for NTM onset better correlated with V_ϕ shear than V_ϕ magnitude
  - Consistent with prior results (S.Gerhardt, et al., Nucl. Fus. 49 (2009) 032003)
- Physics implication
  - Criterion for mode onset set by perturbing torque balance (for both rotating/locked modes)
- Using data to assess if there is a unified scaling of error field threshold (for locked and rotating modes) in D3D H-modes



XP915: R. Buttery (GA)

Consistent pre-2009 DIII–D/NSTX results on m/n = 2/1 NTM marginal island width for stability; good restabilization data sets in 2009

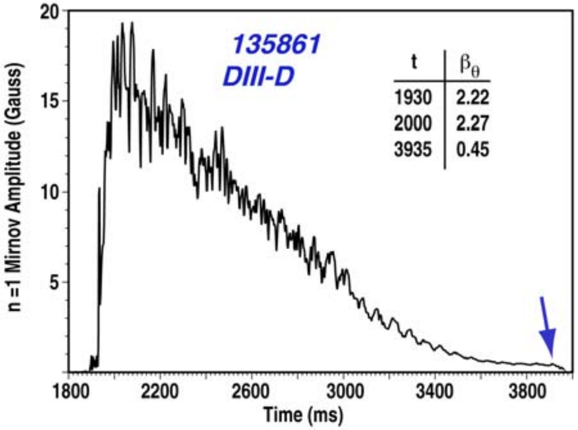
Pre-2009

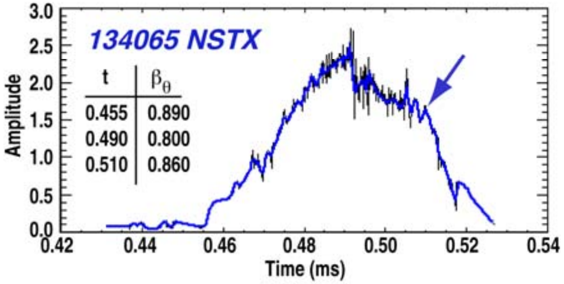


- $W_{marg}/\varepsilon^{0.5}\rho_{\theta i}$ ratio ~ 2 in tokamaks
  - AUG, DIII-D, JET data for 3/2 mode
- First results show $W_{marg}/\varepsilon^{0.5}\rho_{\theta i}$ also ~ 2 for NSTX (2/1 mode) (!)

2009 data

ITPA MDC-4,14



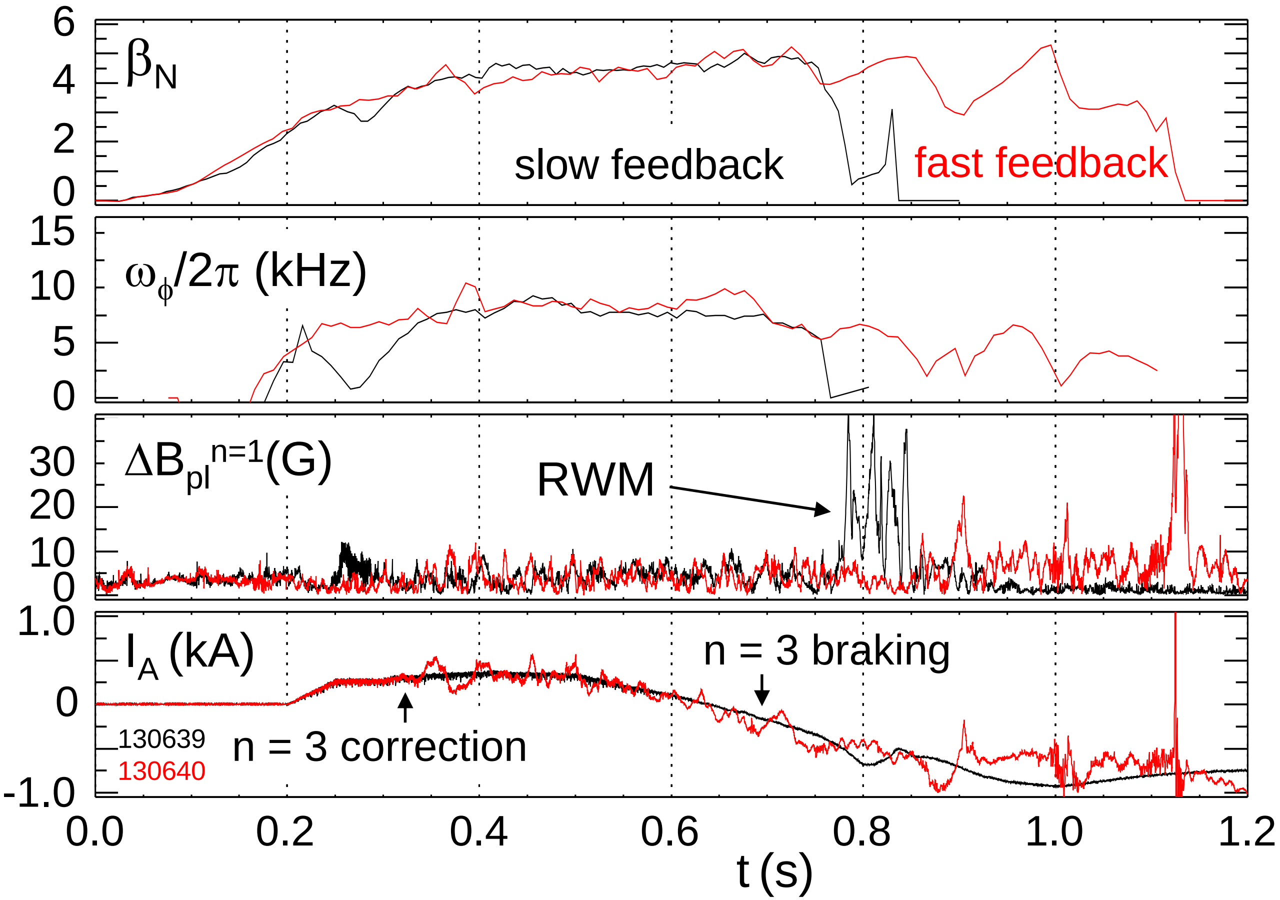


- Status: DIII-D
  - Used gas puff to stay in H-mode
  - 5 good 2/1 (and 2 good 3/1) cases
- Status: NSTX
  - Achieved a reproducible onset condition using modest Li evaporation
  - 8 good cases (2009)

NSTX XP914: R. LaHaye (GA)

High β_N difficult to access at low plasma rotation when RWM feedback response sufficiently slowed

Addresses PAC25-17-(1); ITPA MDC-2

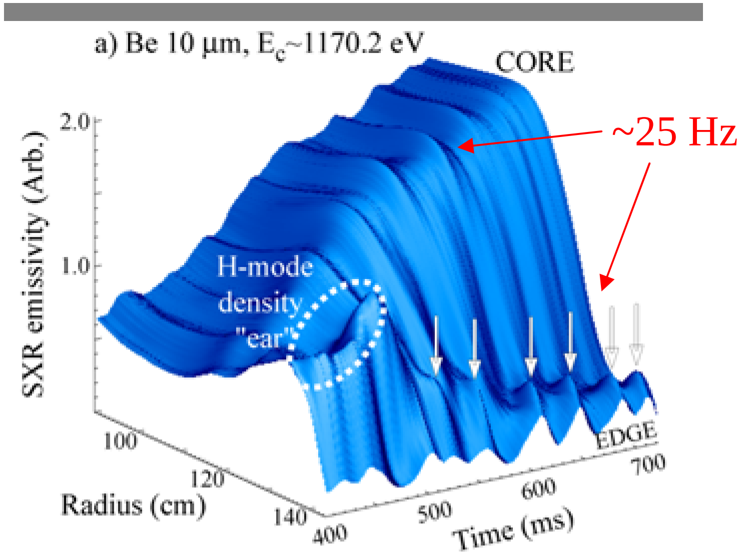


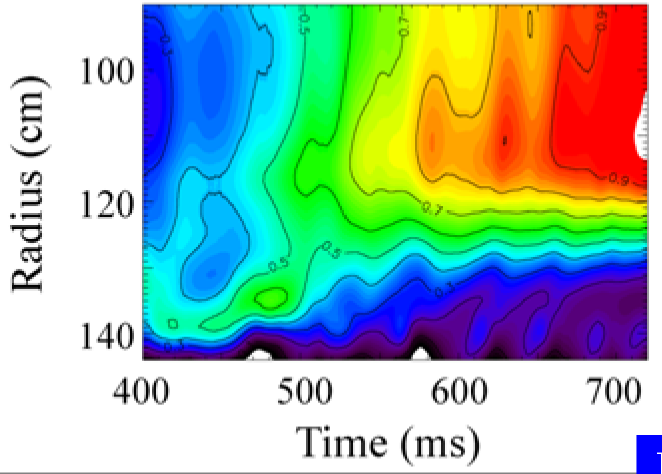
S.A. Sabbagh, et al, NF **50** (2010) 025020

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

- Reference also contains physics of RWM control during n = 1 feedback

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





L. Delgado-Aparicio (JHU)

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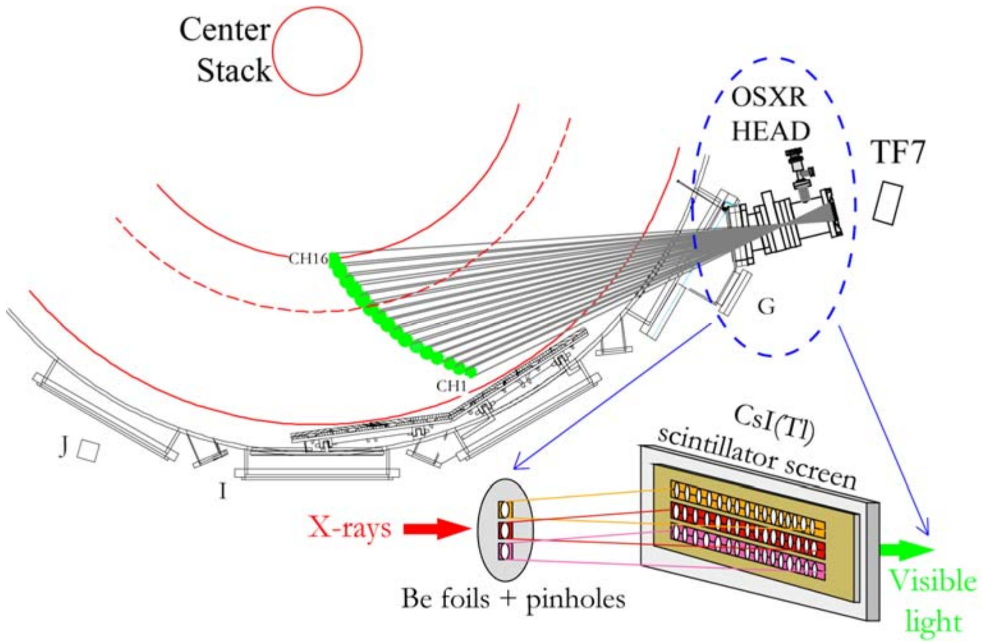
Multi-energy soft X-ray (ME-SXR) viewing geometry



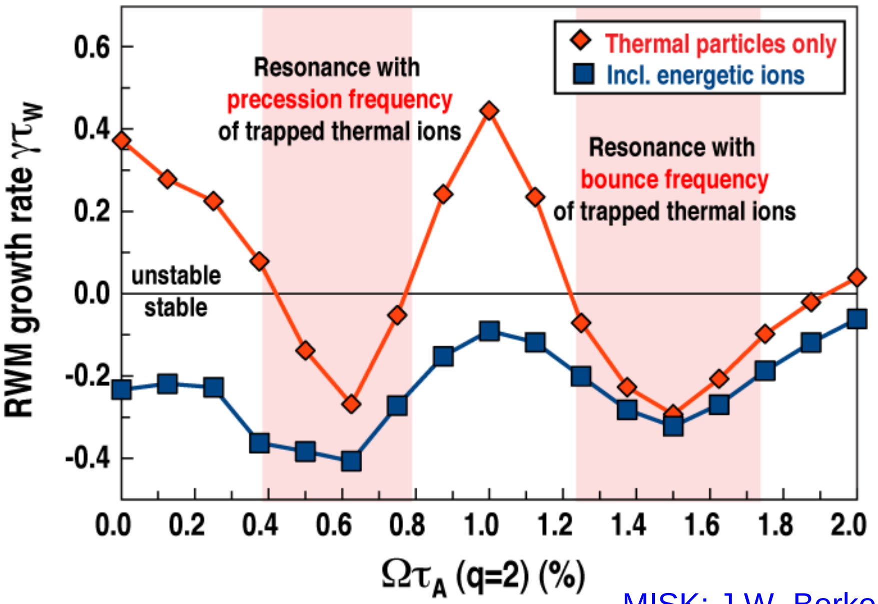
- RWM characteristics
  - Propagation in the co-NBI direction
  - Observed frequency near measured RWM resonance (Sontag, et al., NF **47** (2007) 1005.)

MISK calculations indicate importance of energetic ions for RWM stability in low rotation DIII-D plasmas

- **Motivation for DIII-D experiment MP 2009-99-07 (H. Reimerdes, et al.)**
  - **Control room result from 1/14/10 run qualitatively supports theory**
- **Kinetic calculations using thermal particles only predict RWM to be most unstable at finite rotation**
  - Resonance with **precession frequency** of trapped particles at lower rotation
  - Resonance with **bounce frequency** of trapped particles at higher rotation

Addresses PAC25-17-(2,4); PAC25-23(i); ITPA MDC-2

MISK: DIII-D 135773 t=2.8s (modified)

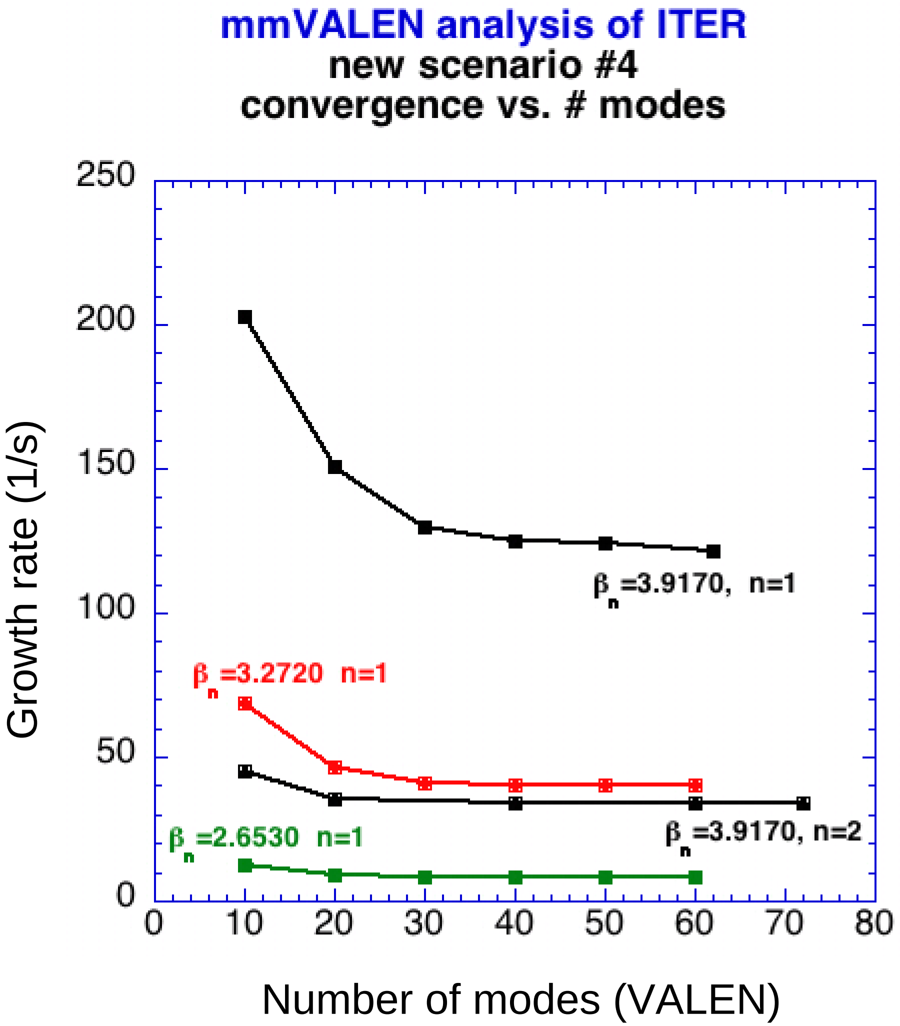


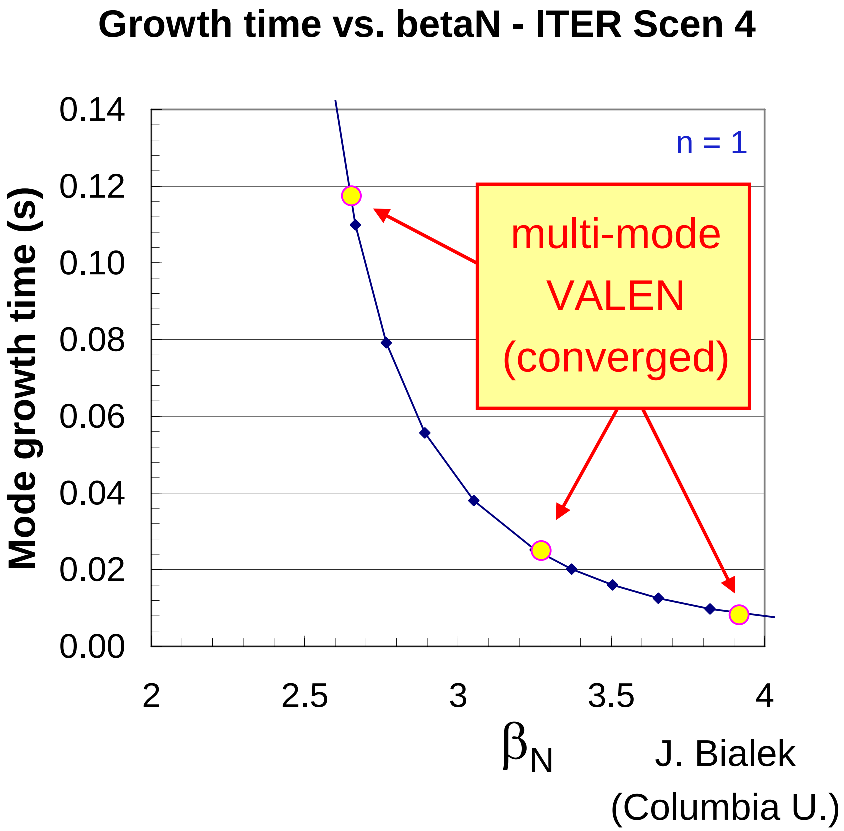
MISK: J.W. Berkery (Columbia U.)

- **Trapped energetic ions (W_{fast}/W_{tot} ~23%) predicted to stabilize the equilibrium across the entire (low) rotation range**
  - Rotation dependence smeared out by resonance with precession frequency of trapped energetic ions
  - Low rotation wall stabilized plasmas typically have W_{fast}/W_{tot}>30%

H. Reimerdes (Columbia U.)

Multi-mode VALEN code applied to ITER Scenario 4 cases (reversed shear)





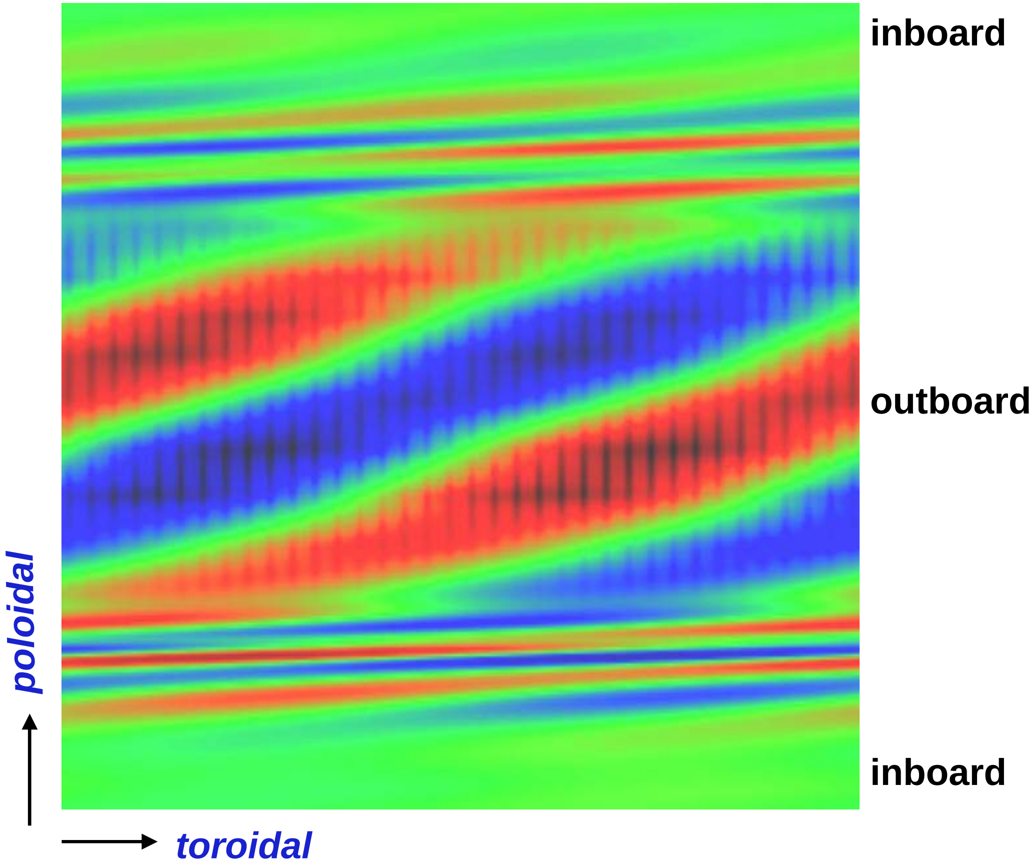
J. Bialek (Columbia U.)

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

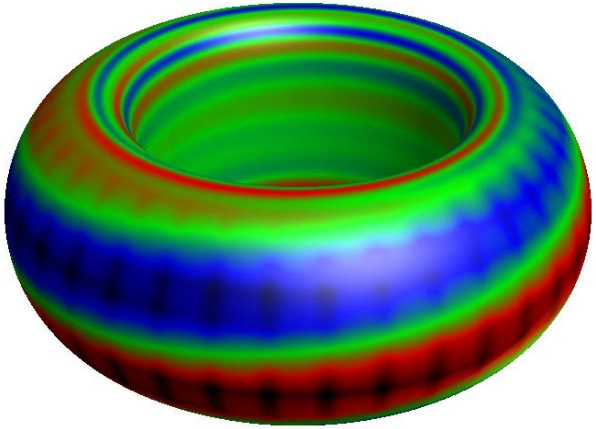
- At highest β_N, n =1 and 2 are unstable

Illustration of $B^n(\theta,\phi)$ on plasma surface from multi-mode VALEN code for ITER Scenario 4, $\beta_N = 3.92$

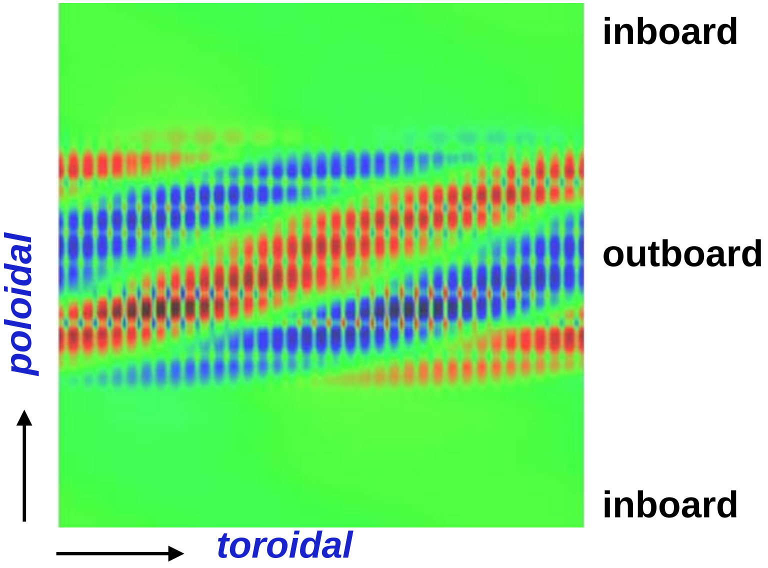
multi mode response (incl. wall), total B^n



B^n from wall, plasma



B^n from wall alone

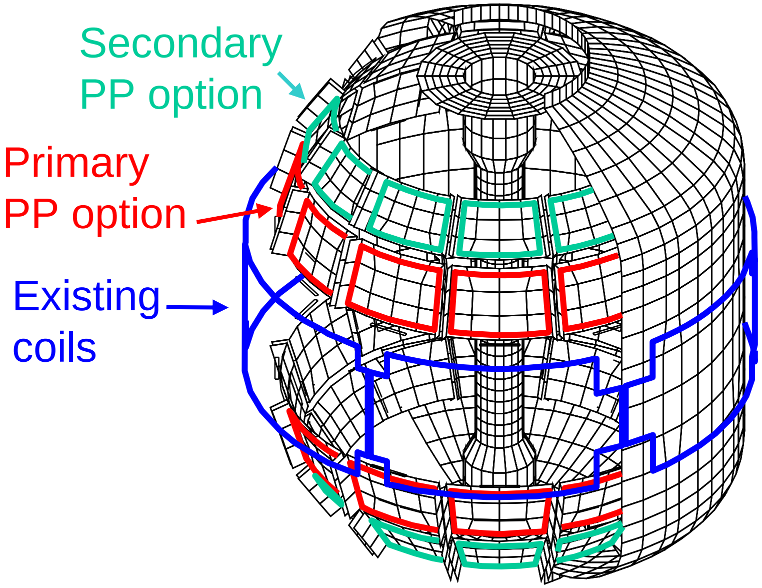


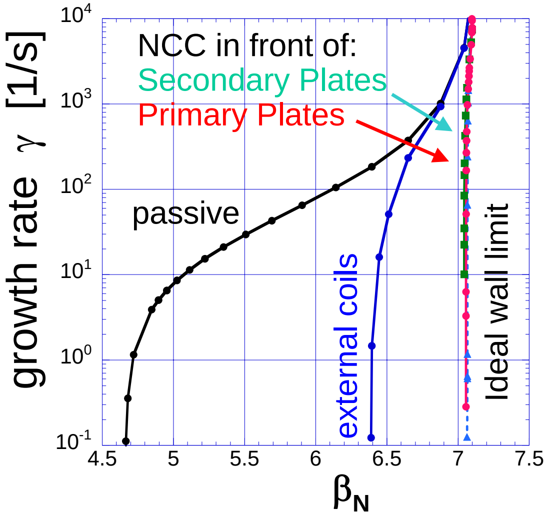
- n = 1 eigenfunctions shown

J. Bialek (Columbia U.)

Proposed Nonaxisymmetric Control Coil (NCC) Will Expand Control Capabilities, Understanding of 3D Effects

- Non-axisymmetric control coil (NCC) – at least four applications:
  - RWM stabilization (n>1, up to 99% of n=1 with-wall β_N)
  - DEFC with greater poloidal spectrum capability
  - ELM control via RMP (n = 6).
  - n > 1 propagation, increased V_ϕ control).
  - Similar to proposed ITER coil design.
- Addition of 2nd SPA power supply unit:
  - Feedback on n > 1 RWMs
  - Independent upper/lower n=1 feedback, for non-rigid modes.
- Design activities continue:
  - GA collaboration (T. Evans) computed favorable coil combinations/variations for RMP ELM suppression of NSTX plasmas (2009)
  - CU group assessing design for RWM stabilization capabilities compatible with ELM control





Addresses PAC25-18

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