NSTX

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Resistive Wall Mode Stabilization and Plasma Rotation Damping Considerations for Maintaining High Beta Plasma Discharges in NSTX

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

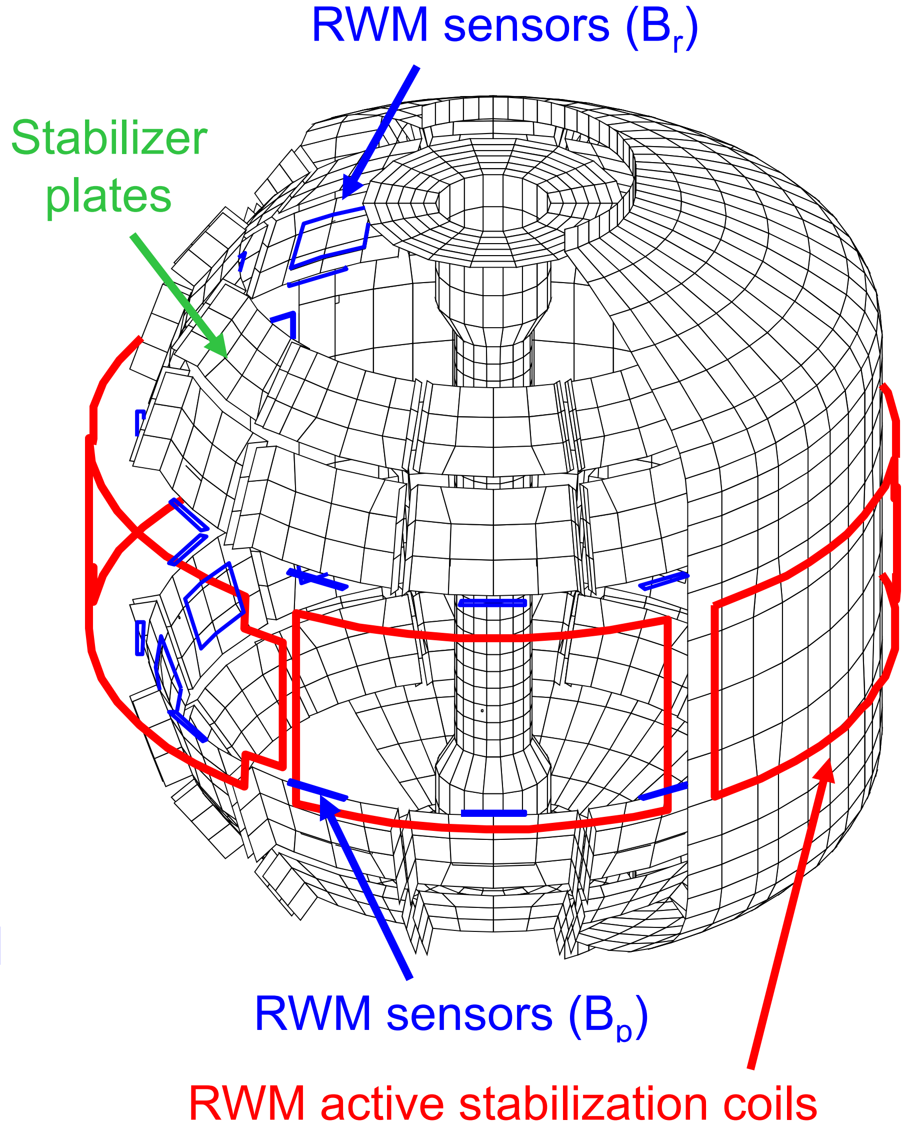
More detail / closer connection to ST-CTF and ST Pilot here

- Motivation
  - Achieve high β_N with sufficient physics understanding to allow confident extrapolation to ST applications (e.g. ST Component Test Facility, ST-Pilot plant, 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

- Physics Research Addressed
  - Physics of plasma rotational stabilization to maintain high β_N
  - Resistive wall mode (RWM) active control
  - Multiple scalable control systems to maintain $\langle\beta_N\rangle_{pulse}$
  - Physics of 3D fields to control plasma rotation profile (for greater stability, confinement)
  - Multi-mode RWM spectrum in high β_N plasmas

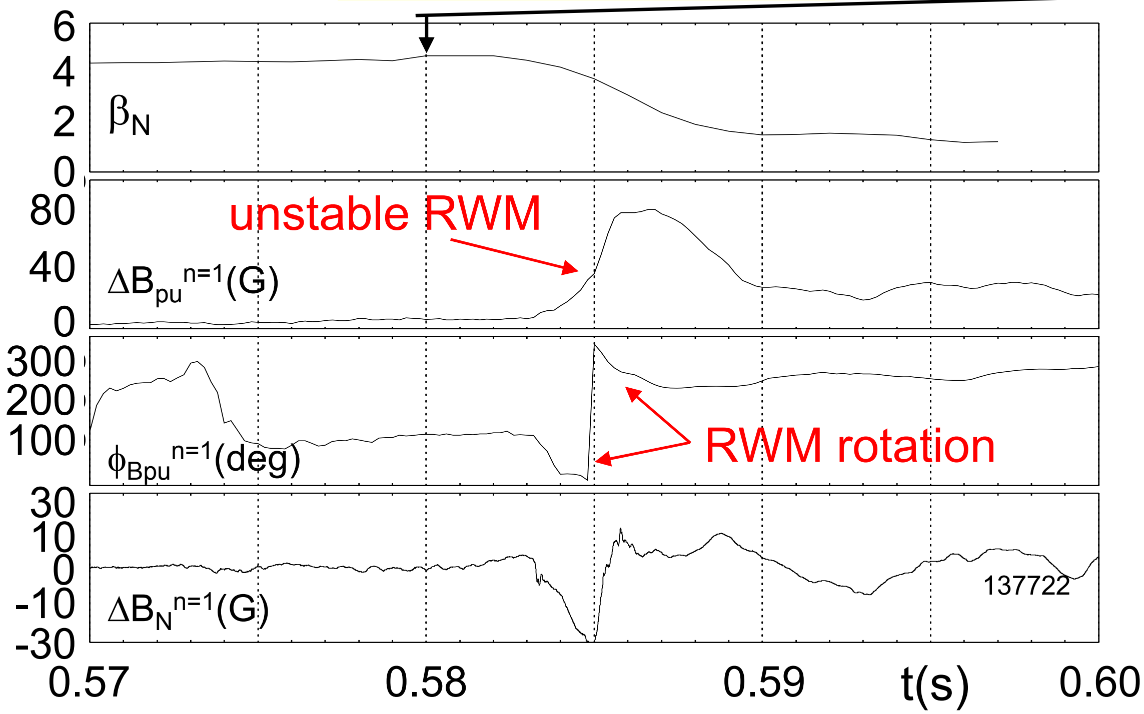
NSTX is a spherical torus equipped for passive and active global MHD control, application of 3D fields

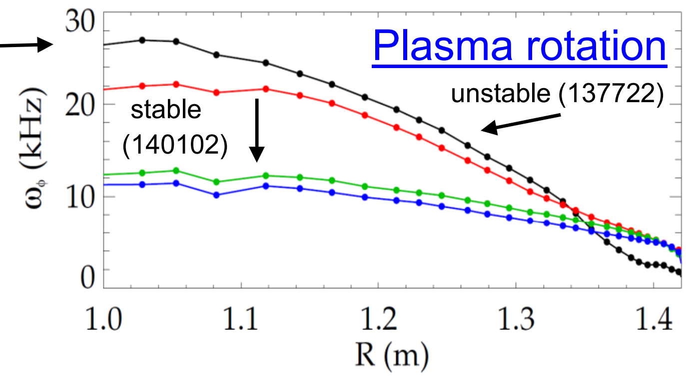
- High beta, low aspect ratio
  - R = 0.86 m, A > 1.27
  - I_p < 1.5 MA, B_t = 5.5 kG
  - β_t < 40%, β_N < 7.4
- Copper stabilizer plates for kink mode stabilization
- Midplane control coils
  - n = 1 – 3 field correction, magnetic braking of V_ϕ
  - n = 1 resistive wall mode (RWM) control
- Varied sensor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



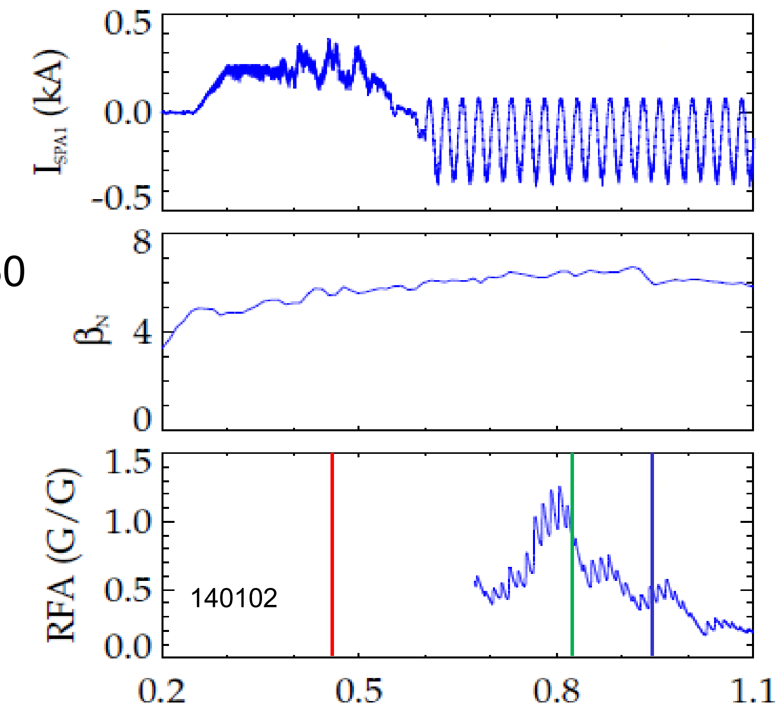
Resistive wall modes can terminate discharges at significant plasma rotation levels

RWM unstable plasma





MHD spectroscopy (stable plasma)



- Instability occurs at relatively high rotation level, and not at highest β_N
- MHD spectroscopy shows increased resonant field amplification (RFA) in stable plasmas
- Understanding this physics is crucial to ensure sustained plasmas in present/future devices

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

- Simple critical ω_ϕ threshold stability models, loss of torque balance do not describe experimental RWM marginal stability Sontag, et al., Nucl. Fusion **47** (2007) 1005.
  - Small ω_ϕ not sufficient condition for stability
- Kinetic modification to ideal MHD growth rate
  - Trapped / circulating ions, trapped electrons, etc.
  - Energetic particle (EP) stabilization

$$\gamma\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$$

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, EP fraction

ω_ϕ profile (enters through ExB frequency)

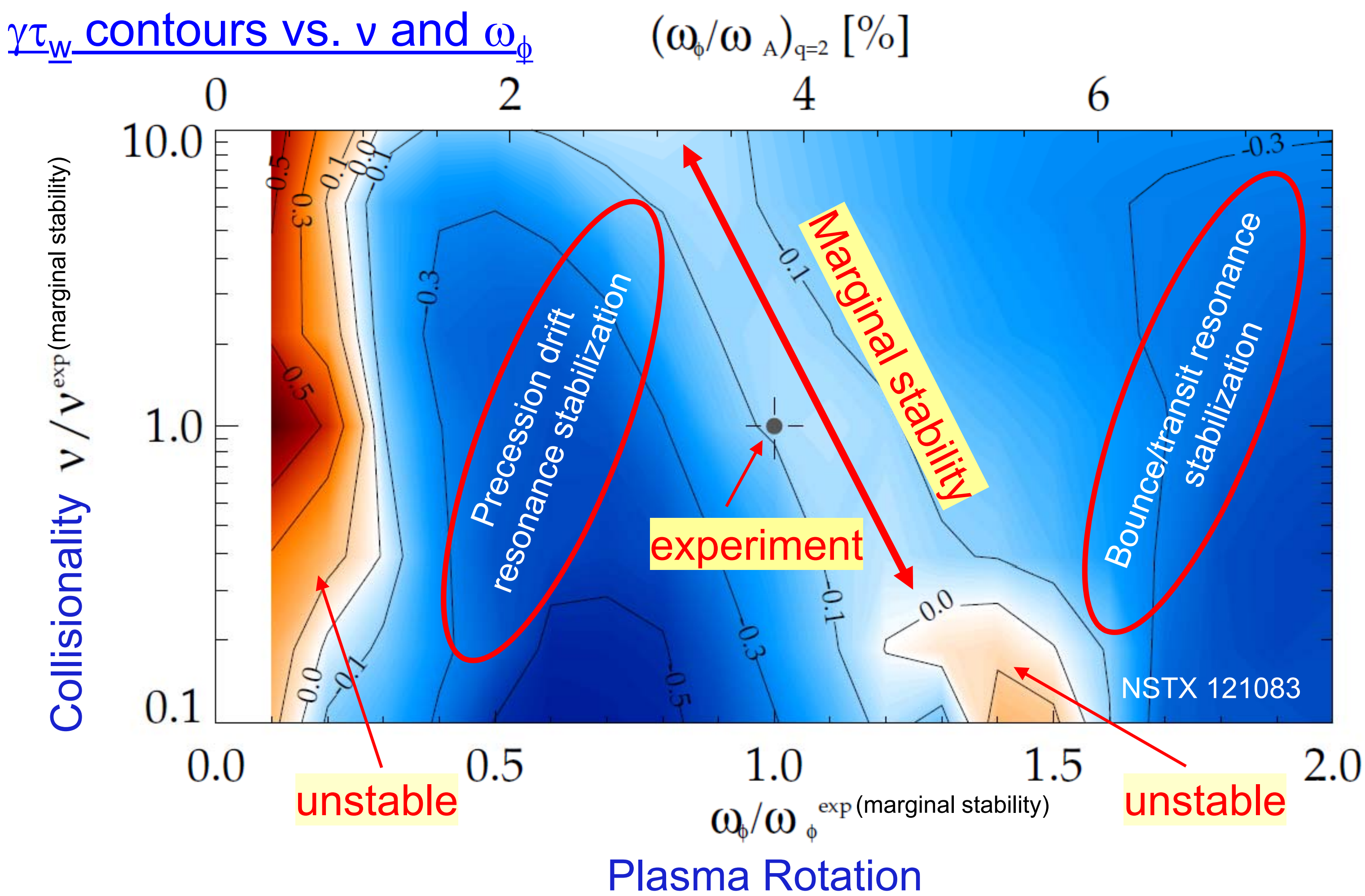
Trapped ion component of δW_K (plasma integral)

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

← Energy integral

precession drift — bounce — collisionality

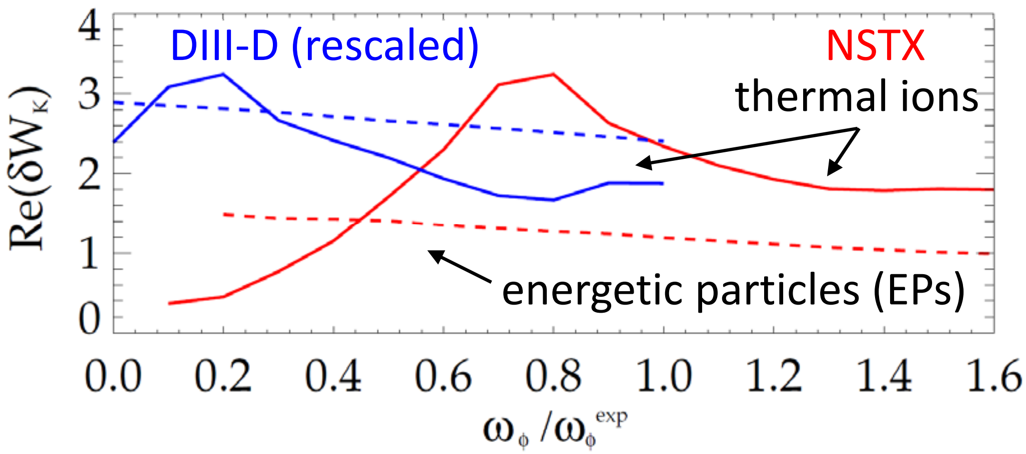
MISK calculations consistent with RWM destabilization at intermediate plasma rotation; stability altered by collisionality

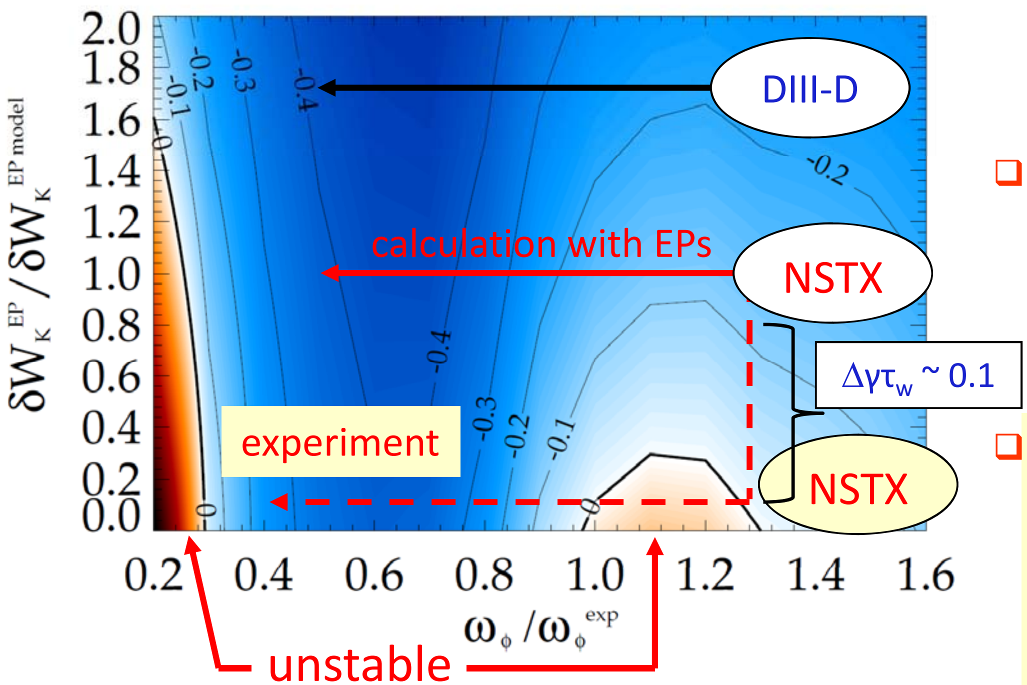


- Destabilization appears between precession drift resonance at low ω_ϕ, bounce/transit resonance at high ω_ϕ

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

Model of kinetic modifications to ideal stability can unify RWM stability results between devices





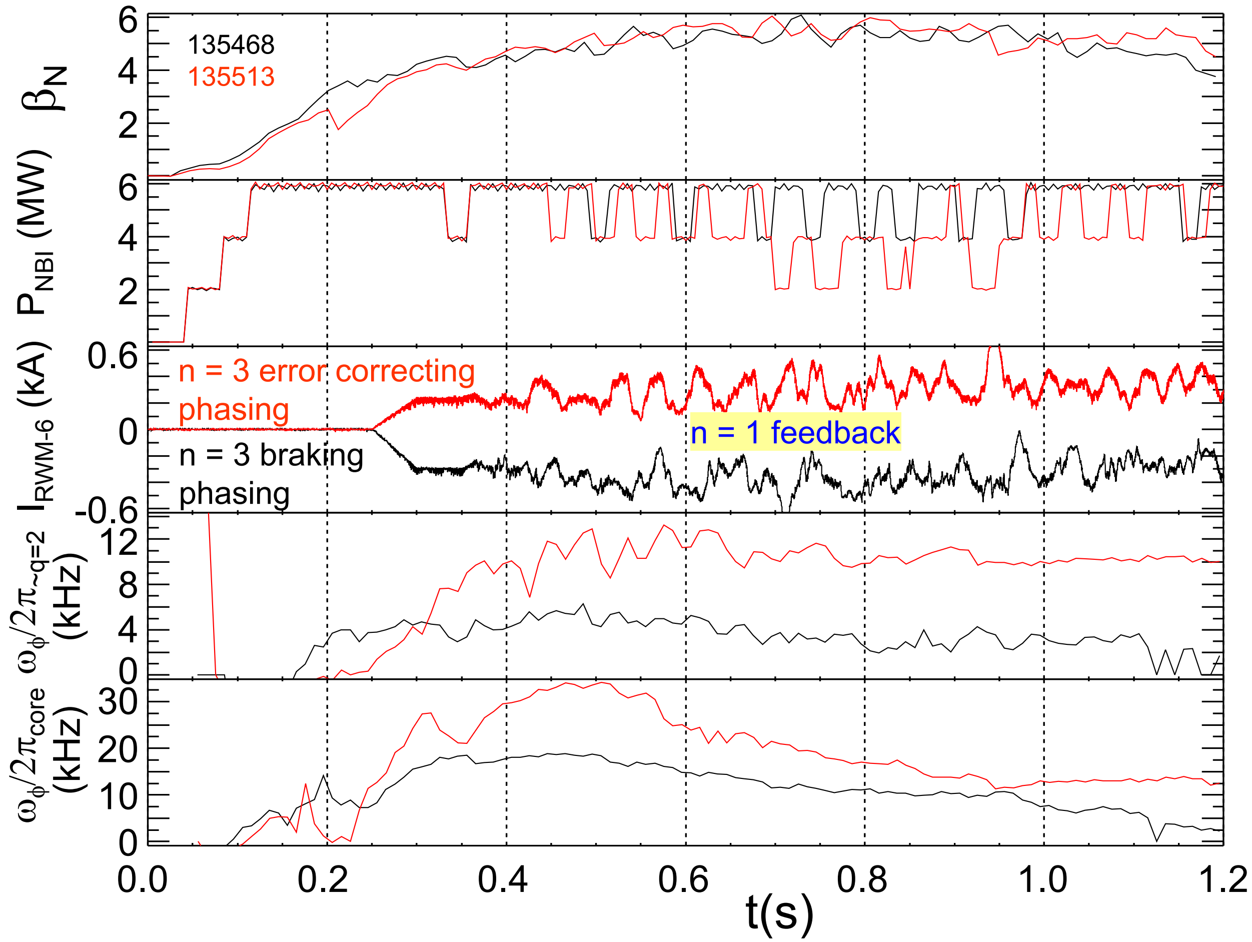
- **NSTX**
  - Less EP stability (p_a/p_{tot} = 4% at Ψ/Ψ_a= 0.75) – RWM can cross marginal point as ω_φ is varied
  - MISK currently overpredicts stability
- **DIII-D**
  - More EP stability (p_a/p_{tot} = 9.5% at Ψ/Ψ_a= 0.75) – RWM stability for all ω_φ
  - RWM destabilized by events that reduce EP population

    H. Reimerdes, et al., paper EXS/5-4
- **JT-60U**
  - EWM unstable plasmas near computed ideal stability
  - MISK stability analysis underway

    G. Matsunaga, et al., paper EXS/5-3
- **ITER (advanced scenario 4)**
  - RWM unstable at expected rotation
  - Only marginally stabilized by alphas at β_N = 3

    See poster (EXS/5-5) for more detail

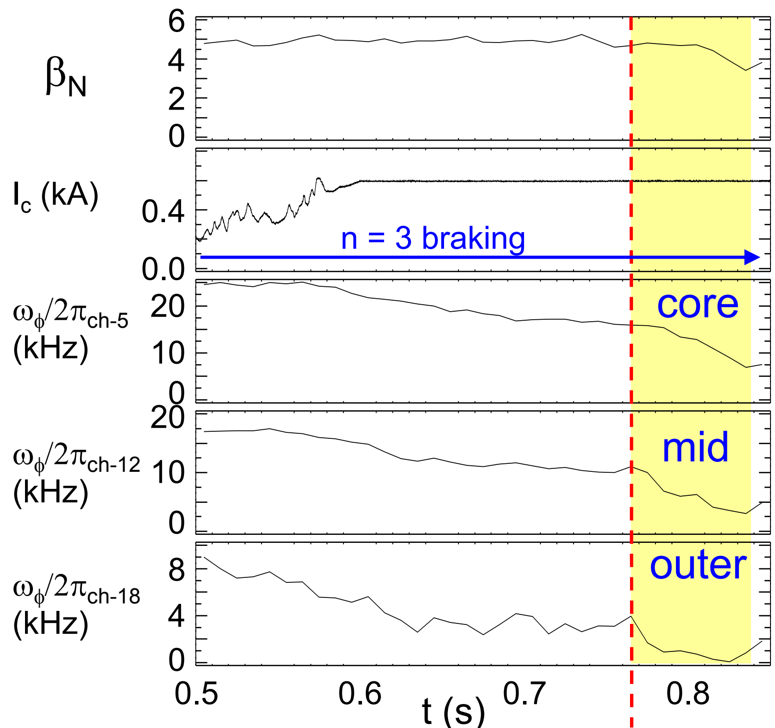
β_N feedback combined with n = 1 RWM control to reduce β_N fluctuations at varied plasma rotation levels

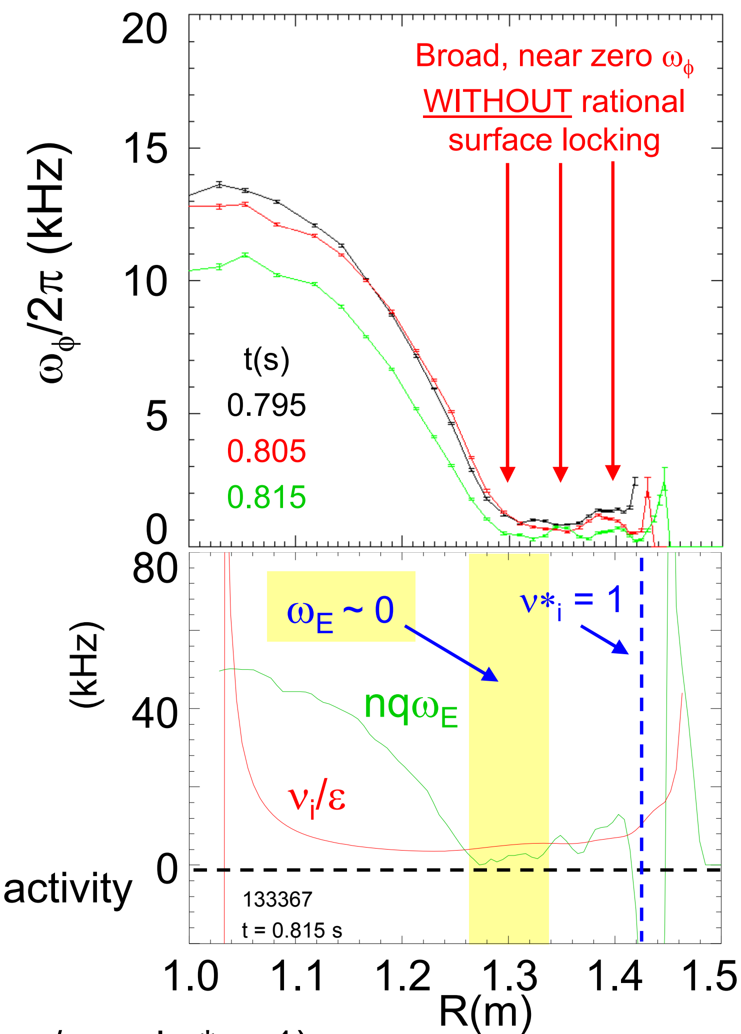


- Prelude to ω_ϕ control
  - Reduced ω_ϕ by n = 3 braking does not defeat FB control
  - Increased P_{NBI} needed at lower ω_ϕ
- Steady β_N established over long pulse
  - independent of ω_ϕ over a large range

Add latest results from XP1023
Re: Bp, Br n = 1 feedback

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

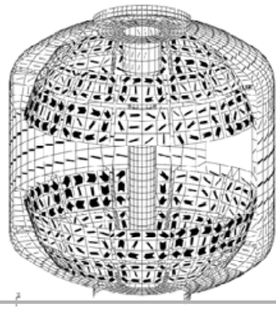




- Faster braking with
  - Constant applied n = 3 field, β_N; No mode activity
- Torque not $\propto 1/\omega_\phi$ (non-resonant)
  - NTV satisfies $1/\nu$ regime criterion ($|nq\omega_E| < \nu_i/\varepsilon$ and $\nu^*_i < 1$)
  - Stronger braking expected at low ω_E (superbanana plateau regime)
    (K.C. Shaing et al., PPFC **51** (2009) 035009)

New RWM state space controller sustains high β_N plasma

Full 3-D model ~3000+ states

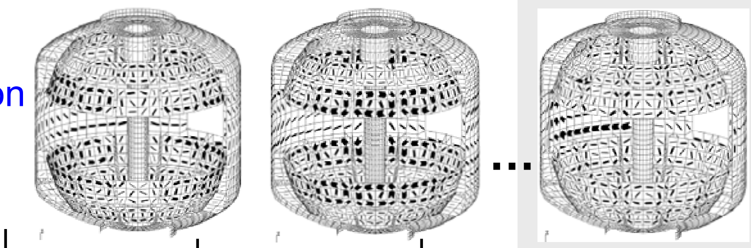


- device R, L, mutual inductances
- instability B field / plasma response
- modeled sensor response

Balancing transformation

State reduction

RWM eigenfunction (2 phases, 2 states)

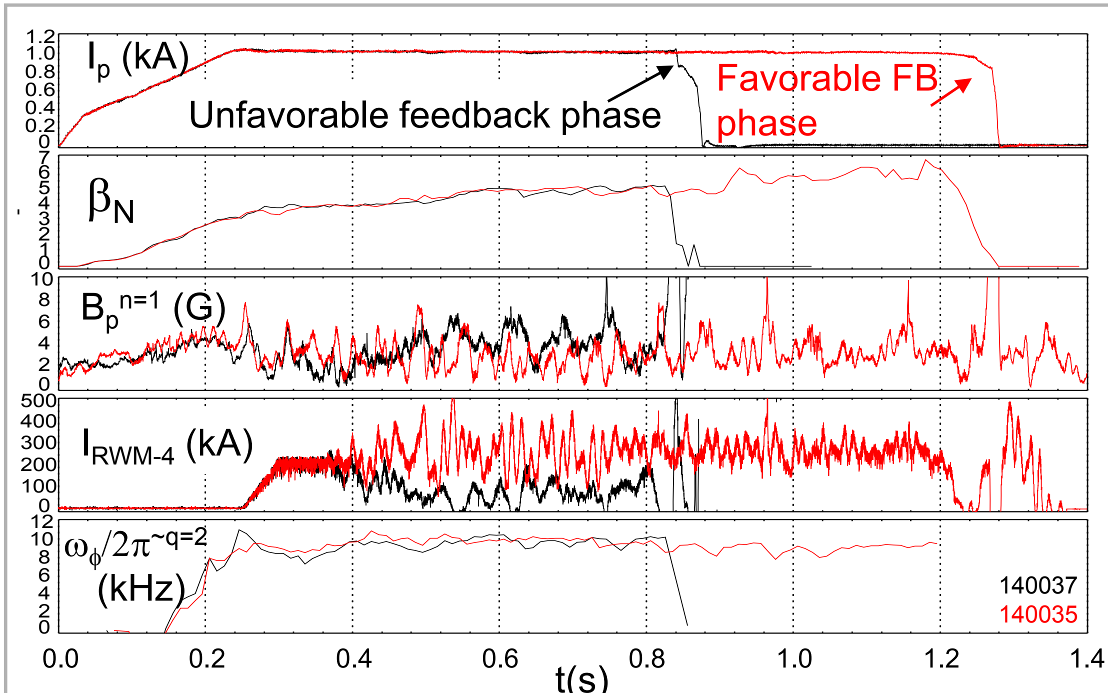


$(\hat{x}_1, \hat{x}_2)\downarrow$ $\hat{x}_3 \downarrow$ $\hat{x}_4 \downarrow$ $\hat{x}_N$

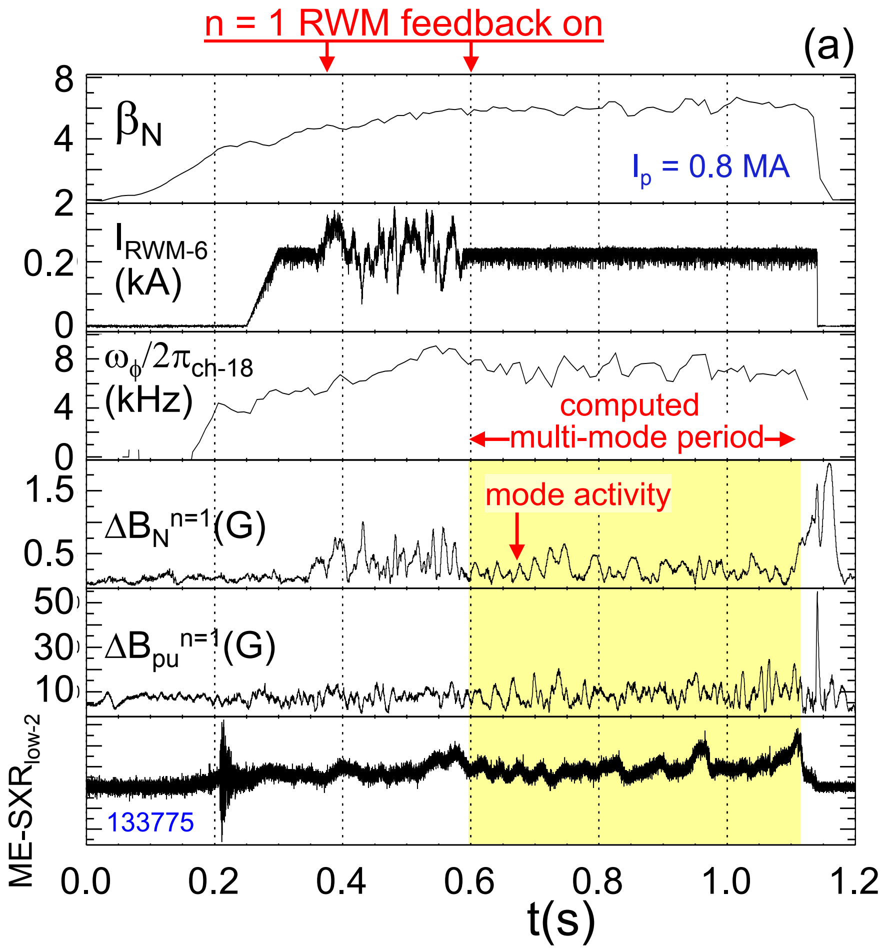
N_r ~ 2 - 20 states $(\hat{x}_1, \hat{x}_2, \hat{x}_3, \ldots, \hat{x}_{N_r})$ truncate

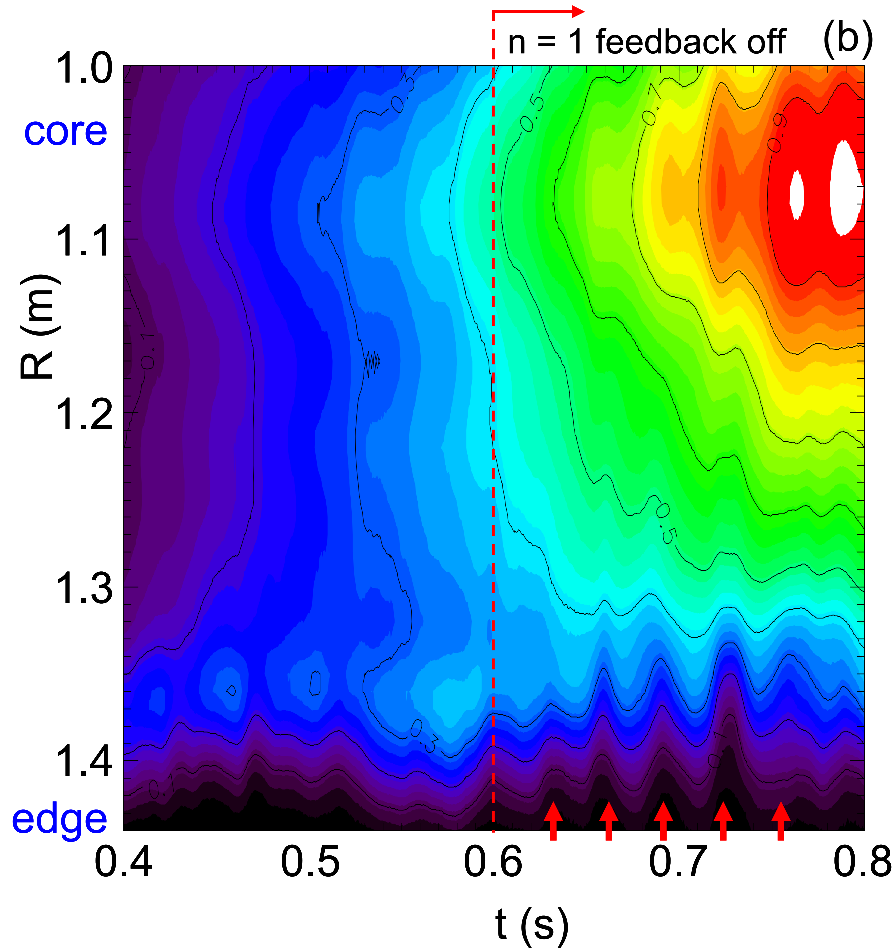
+ sensor measurements

- Study RWM control physics with coils behind conducting material
  - NSTX especially well-suited for this research
  - Examined for ITER
    Katsuro-Hopkins, et al., NF (2007) 1157
- High beta plasma experiments
  - Suppressed disruption due to n = 1 applied error field
  - Best feedback phase produced long pulse, β_N > 6.4, β_N/l_i > 13



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

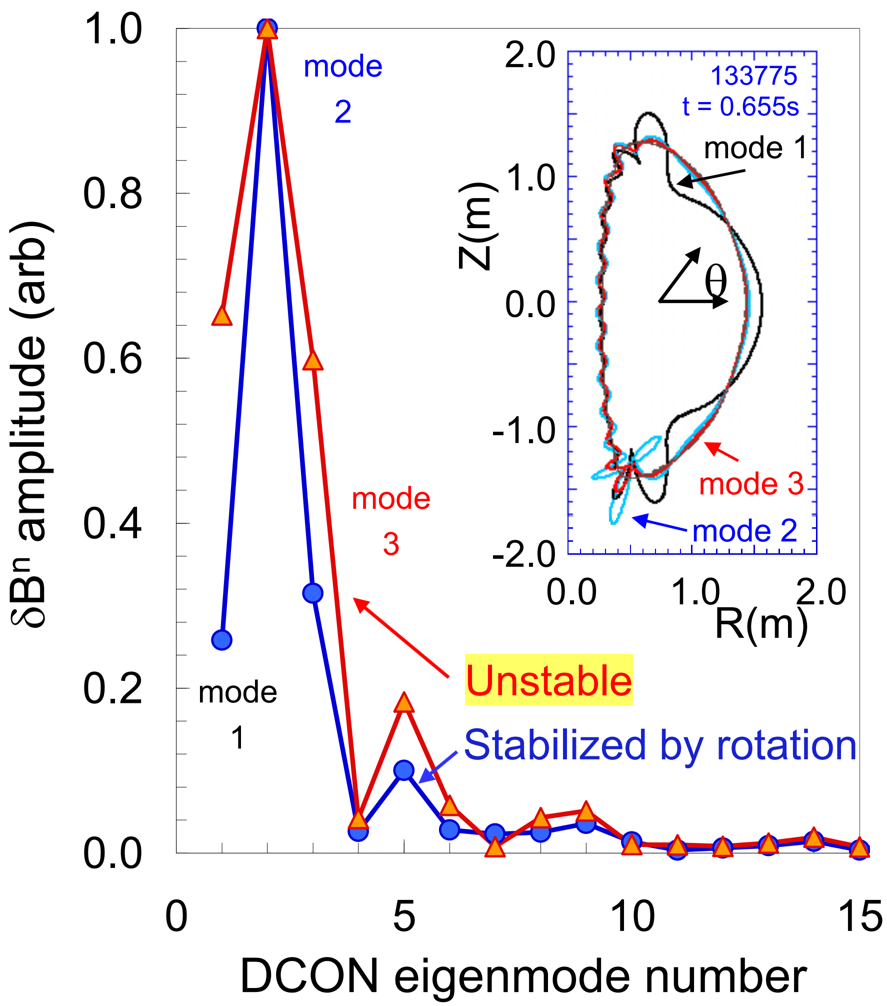




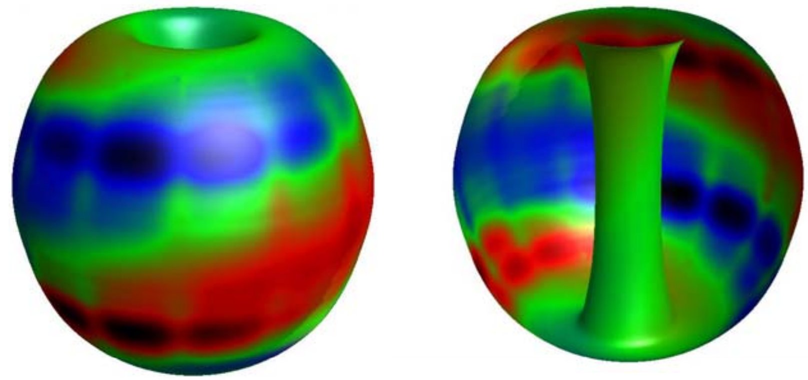
- Activity has characteristics of RWM
  - Mode activity in RWM frequency range (~30 Hz) seen in both magnetic, kinetic diagnostics
  - Stability calculations indicate multi-mode RWM response expected to be significant at β_N > 5.5
- Multi-energy soft X-ray emission
  - Indicates global mode, magnitude, radial extent increases as β_N increases
  - Activity correlated with magnetic fluctuations

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

δB^n RWM multi-mode composition



δB^n from wall, multi-mode response



- NSTX unstable multi-mode RWM
  - Computed mode growth time consistent with experiment (β_N = 6.1)
  - Significant spectrum out to ~ 10 modes
- NSTX stabilized multi-mode RWM
  - Amplitude of 1st eigenmode decreases when stabilized, 2nd remains large
  - Computed RWM rotation ~ 41 Hz, close to experimental value ~ 30 kHz
- ITER scenario IV multi-mode spectrum
  - Significant spectrum to 6th eigenmode

See poster (EXS/5-5) for more detail

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

- RWM instability, observed at intermediate plasma rotation, correlates with kinetic stability theory (J.W. Berkery, et al., PRL **104** (2010) 035003)
  - Theory of kinetic modifications to ideal stability general enough to unify RWM stability results between devices
  - ITER advanced scenario 4 requires EP stabilization at expected ω_ϕ
- n = 1 RWM feedback control combined with new β_N feedback control shows regulation of high β_N at varied plasma rotation levels
  - Compatible with plasma rotation control by non-resonant 3D fields
- Strong non-resonant NTV braking observed from all $\nu_i/\varepsilon nq\omega_E(R)$ variations made

  Add NTV offset rotation result
  - Transitions in NTV (stronger magnetic braking) at low ω_E
- New RWM state space controller sustains high β_N plasma
  - Important for burning plasma devices with conducting structure shielding control coils
- Theory shows multi-mode RWM response important at high β_N; multi-mode RWM spectrum shows significant amplitude in higher order modes