Progress Toward Stabilization of Low Internal Inductance Spherical Torus Plasmas in NSTX

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V2.2

ABSTRACT

Steady-state spherical torus plasmas for fusion applications, such as a component test facility or demonstration power plant, target operation with high non-inductive current fraction. These broad current profile targets have low values of plasma internal inductance, l_i, less than 0.4, near to the lower end of present NSTX operation. A key significance of this operation is that it approaches the purely current-driven ideal kink limit, which by definition exceeds the no-wall stability limit for all values of plasma normalized pressure (beta). In this regime, passive or active kink and resistive wall mode (RWM) stabilization is critical. Experiments on NSTX have recently approached this condition, evidenced by a significant reduction of the n = 1 no-wall stability limit computed by DCON. This limit drops from normalized beta of 4.2 – 4.6 at $l_i \sim 0.6$, to 3.4 at $l_i \sim 0.5$, to below 2.8 for $l_i \sim 0.4$. Nevertheless, passive and active RWM control has produced high toroidal beta up to 28 percent, and normalized beta up to 6.5 (nearly double the no-wall limit), closely following a record normalized beta to l_i ratio of 13 between $l_i = 0.4$ - 0.5. Non-inductive current fraction reaches 0.5 in these high normalized current plasmas. However, the disruption probability of these plasmas increases significantly, with about half of the discharges suffering terminating instabilities. Alteration of n = 1 RWM control system parameters, plasma rotation profile, and the role of beta feedback is examined to potentially improve mode stability. Ion precession drift and bounce frequency resonance stabilization is examined for these plasmas and compared to the identified stabilization reduction at intermediate plasma rotation and higher l_i [1,2].

[1] J.W. Berkery, et al., Phys. Rev. Lett. **104**, 035003 (2010); J.W. Berkery, et al., PoP **17**, 082504 (2010)

[2] S.A. Sabbagh, et al., Nucl. Fusion **50** , 025020 (2010)

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NSTX is Addressing Global Stability Needs for Maintaining Low l_i, High Beta Plasmas for Fusion Applications

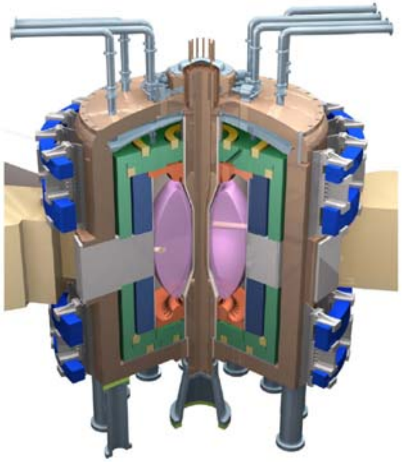
- Motivation
  - Sustain high β_N with sufficient physics understanding to allow confident extrapolation to spherical torus applications (e.g. ST Component Test Facility, ST-Pilot plant, ST-DEMO)

    NP9.00011 Peng
    UP9.00006 Hawryluk
  - Operate at low internal inductance (l_i), consistent with desired high elongation and non-inductive (bootstrap, etc.) current fraction
  - Demonstrating / understanding global mode stability at low l_i is key

- Physics Research Addressed in this Talk
  - Global mode stability at low internal inductance
  - Resistive wall mode (RWM) destabilization at high plasma rotation, ω_ϕ
  - RWM active control advances to maintain high β_N at low l_i,varied ω_ϕ
  - Multi-mode RWM spectrum in high β_N plasmas

Future ST fusion applications will have high elongation, broad current profiles, high normalized beta

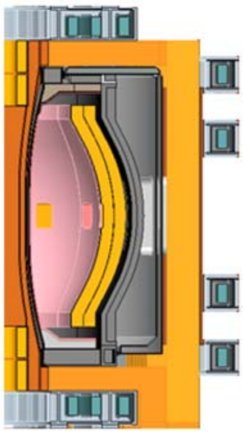
FNSF / ST-CTF

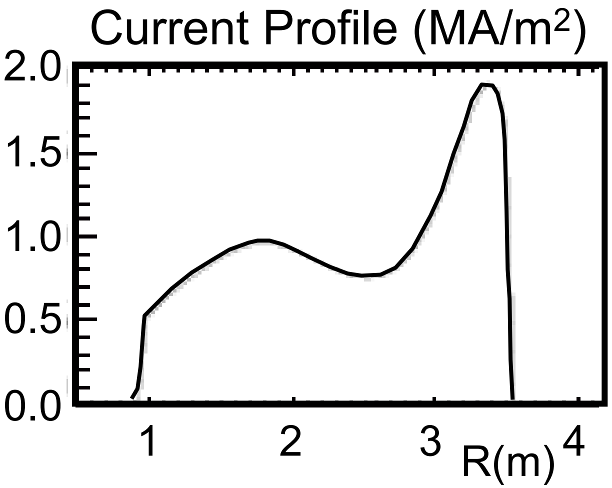


Y.K.M. Peng, et al., PPCF **47** (2005) B263

ST-Pilot (Q_{eng} = 1)

J. Menard, et al., IAEA FEC 2010 Paper FTP/2-2





l_i = 0.47, κ = 3.2
R = 2.23 m, A = 1.7
I_p = 16 MA, B_t = 2.4T
β_N = 5.2, β_t = 30%

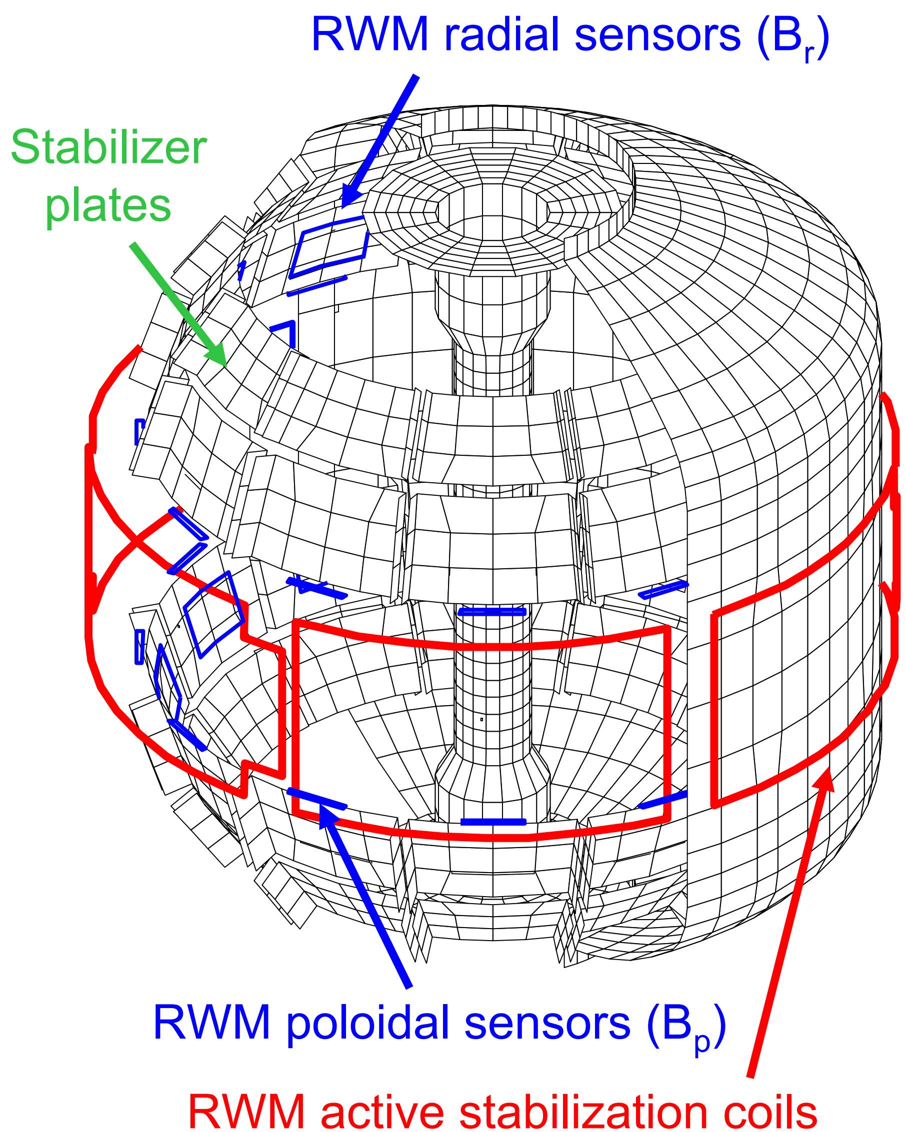
- Broad current profile → low $l_i = \langle B_p^2 \rangle / \langle B_p \rangle_\psi^2$, has global mode stability implications
  - Improved vertical (n = 0) and wall-stabilized, rotating kink (n =1) stability
  - Decreased RWM stability, influenced by ω_ϕ
  - "Troyon limit" (ideal, static n = 1 no-wall stability limit)

$\beta_N = 10^8 \beta_t a B_t / I_p$ = constant ~ 3;   variants: $\beta_N \propto l_i$, $\beta_N \propto$ 1/(pressure peaking)

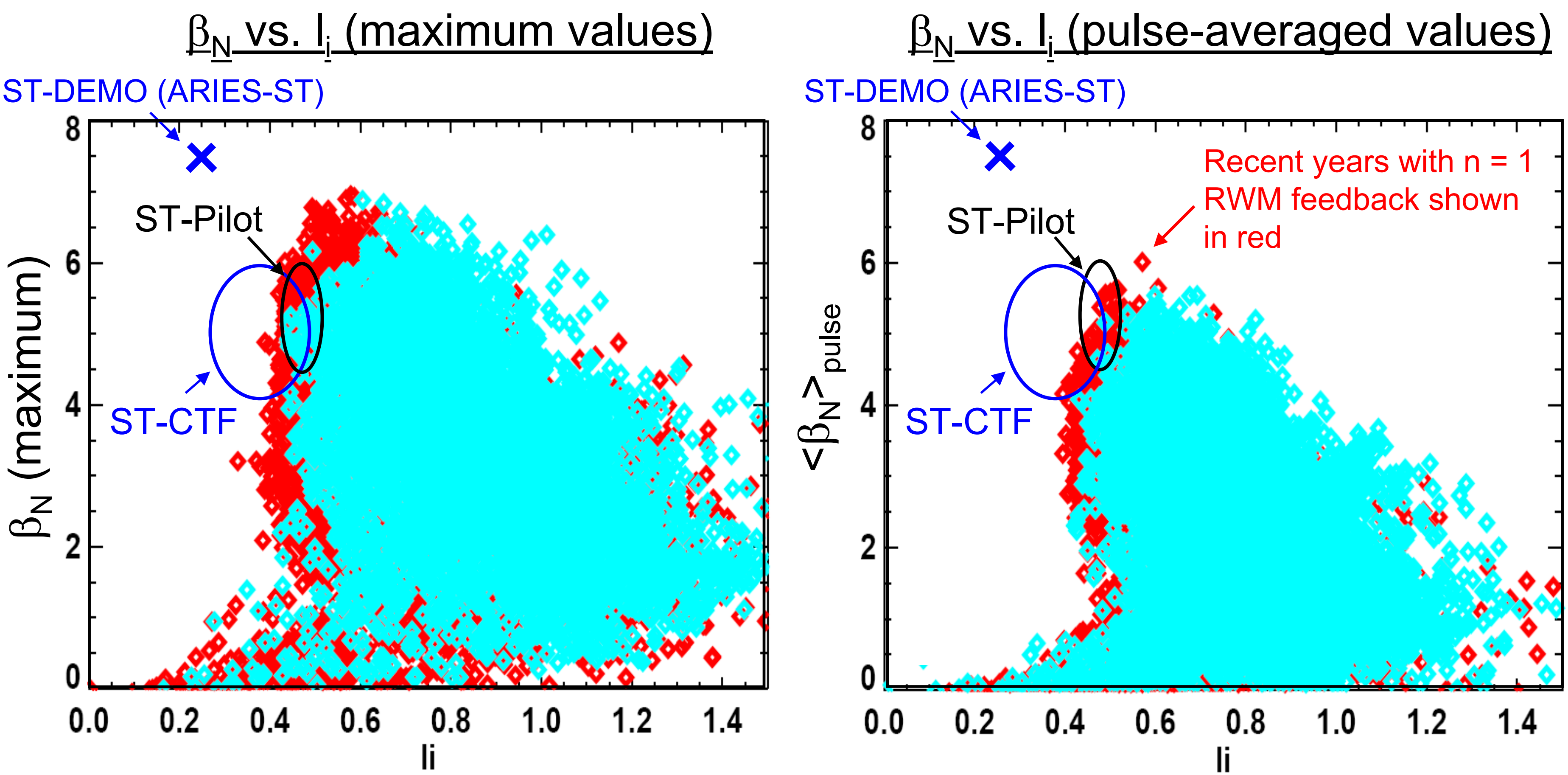
Operation at higher β_N possible by passive or active RWM stabilization   ($\beta_t = 2\mu_0 \langle p \rangle / B_t^2$)

NSTX is a spherical torus equipped to study passive and active global MHD control, rotation variation by 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
- Copper stabilizer plates for kink mode stabilization
- Midplane control coils
  - n = 1 – 3 field correction, magnetic braking of ω_ϕ by NTV
  - n = 1 RWM control
- Combined sensor sets now used for RWM feedback
  - 48 upper/lower B_p, B_r

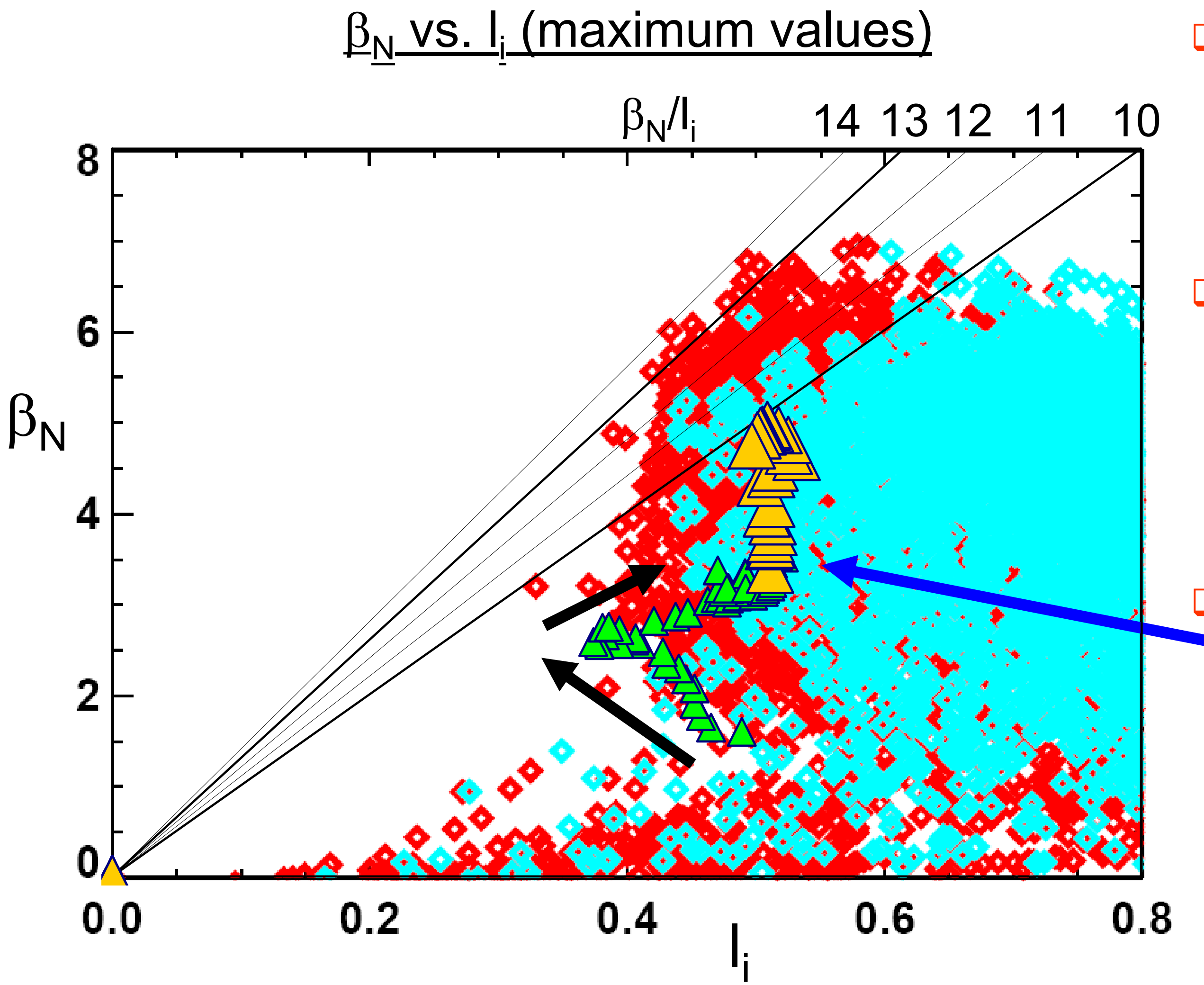


Operation has aimed to produce sustained low l_i and high pulse-averaged β_N



- Plasmas have begun to reach low l_i and high $\langle\beta_N\rangle_{pulse}$ suitable for next-step ST fusion devices
  - Some parameters (e.g. elongation > 3) still need to be reached self-consistently

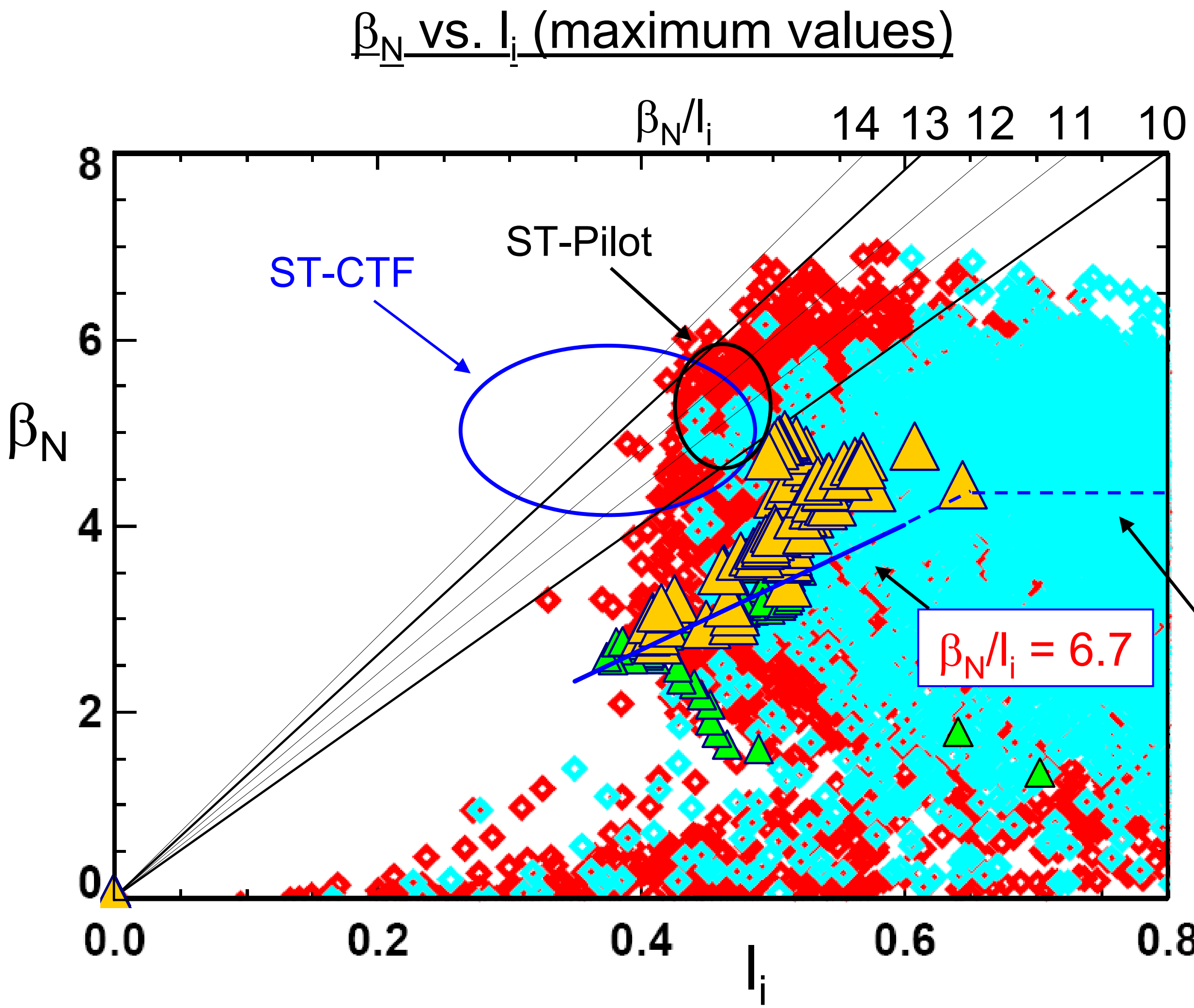
Operational space expanded to low l_i and high β_N ; Ideal n = 1 no-wall stability examined for low l_i plasmas



- Significant increase in maximum β_N/l_i
  - Upper limit now between 13 - 14
- Examine high plasma current, $I_p \geq 1.0$MA, high non-inductive fraction ~ 50%, l_i ~ 0.4 – 0.5
- Ideal n = 1 no-wall stability computed for discharge trajectory
  - Green: below limit
  - Gold: above limit
  - Exceeds no-wall limit at β_N = 3.4, l_i = 0.51

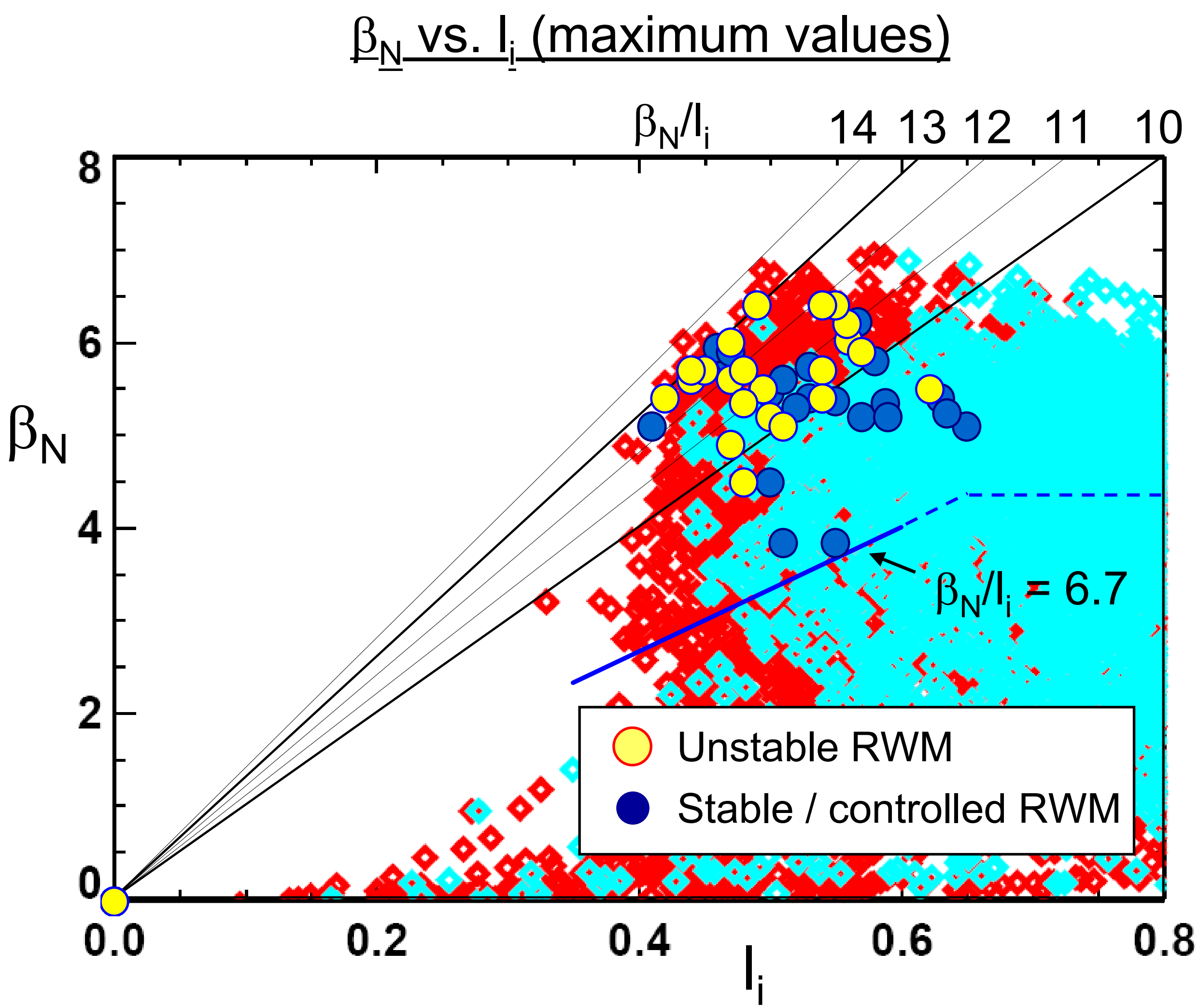
DCON (A. H. Glasser)

Ideal n = 1 no-wall stability limit decreases for low l_i plasmas



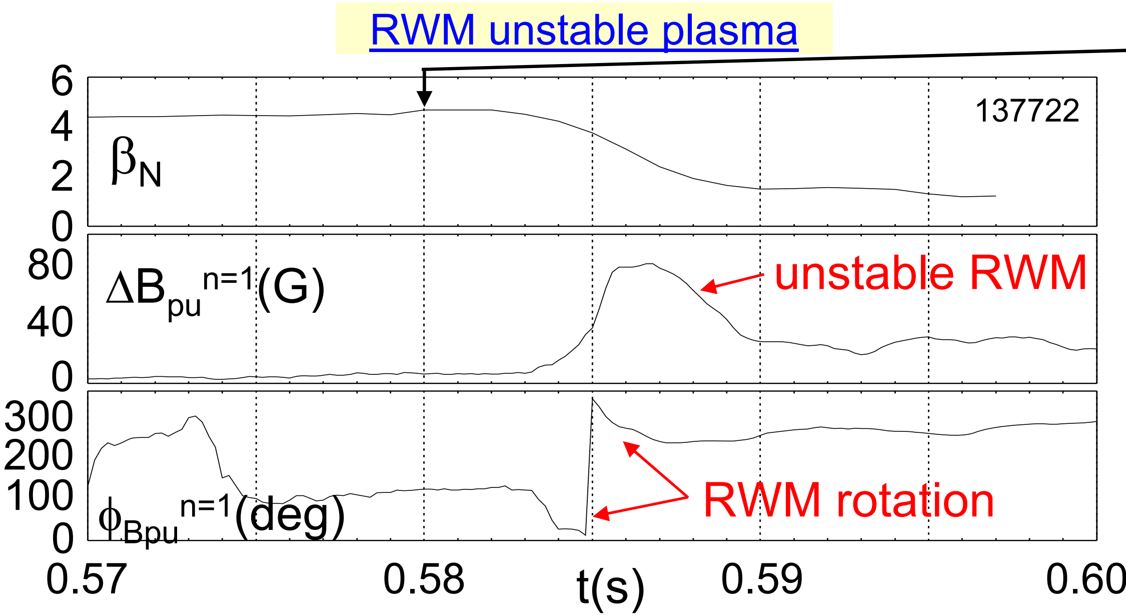
- Examine high plasma current, $I_p \geq 1.0$MA, high non-inductive fraction ~ 50%, l_i ~ 0.4 – 0.5
- Ideal n = 1 no-wall stability computed for discharge trajectory
  - Adding trajectories yields β_N/l_i = 6.7 for l_i = 0.38 – 0.6
  - Significantly lower than no-wall limit at higher l_i (β_N = 4.3)
  - RWM control will be important for future ST fusion devices

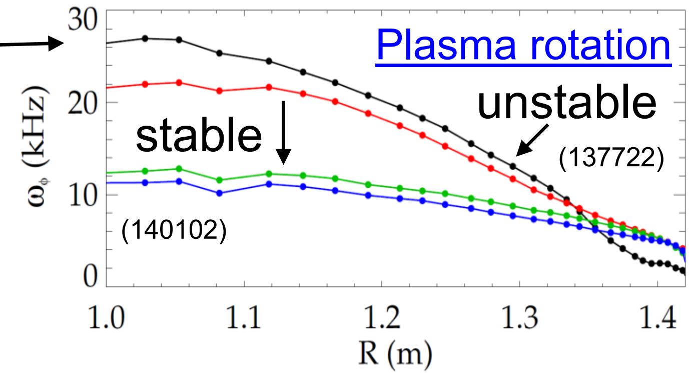
Global stability examined for experiments aimed to produce sustained low l_i and high β_N at high plasma current

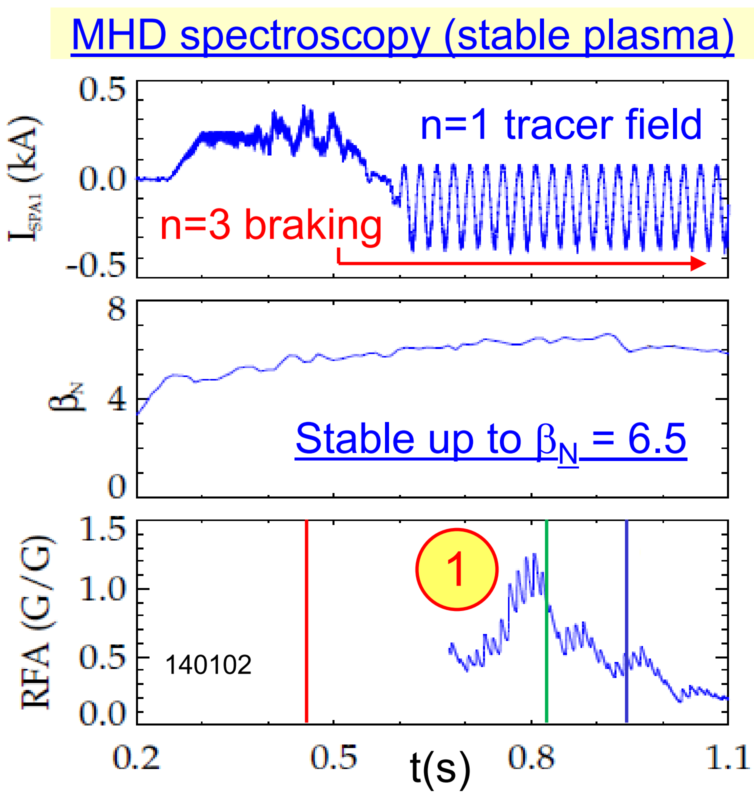


- High $I_p \geq$ 1.0MA, high non-inductive fraction ~ 50%
- Initial experiments
  - Yielded low l_i
  - Access high β_N/l_i
  - High disruption probability
- Instabilities leading to disruption
  - Unstable RWM
    - 48% of cases run
  - Locked tearing modes

Low plasma rotation level (~ 1% ω_{Alfven}) is insufficient to ensure RWM stability, which depends on ω_ϕ profile







- **RWM unstable plasma**
  - Instability occurs at relatively high rotation level, and not at highest β_N (4.7)
- **RWM stable plasma**
  - MHD spectroscopy: increased resonant field amplification (RFA) indicates reduced stability (1)
  - Plasma moves to more stable regime (lower RFA) at lower rotation (β_N up to 6.5)

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

- Reason: simple critical ω_ϕ threshold stability models do not fully describe RWM marginal stability in NSTX Sontag, et al., Nucl. Fusion **47** (2007) 1005.
- 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)

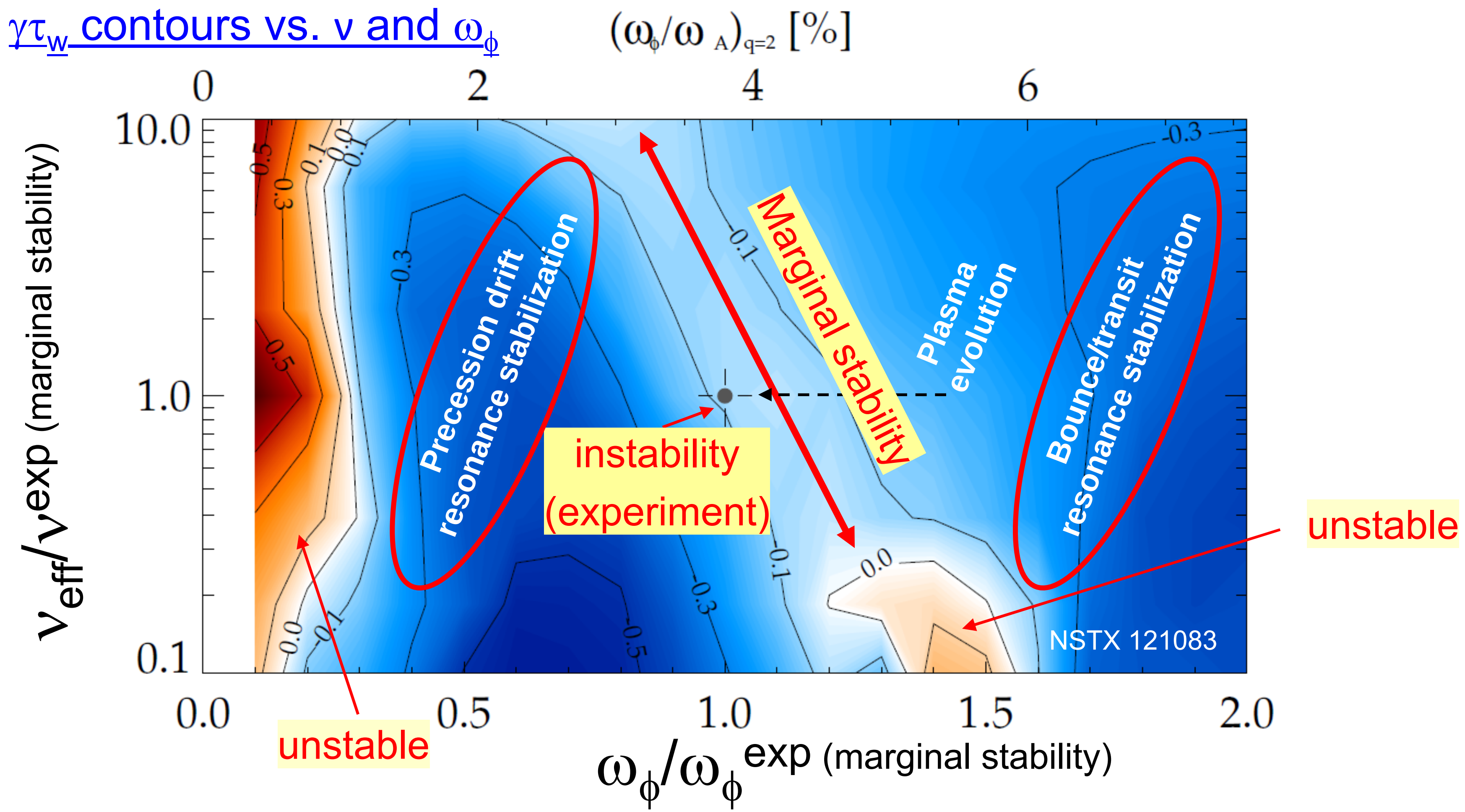
$$\delta W_K \propto \int \left[\frac{\omega_{*N} + \left(\hat{\varepsilon} - \frac{3}{2}\right)\omega_{*T} + \omega_E - \omega - i\gamma}{\langle\omega_D\rangle + l\omega_b - i\nu_{eff} + \omega_E - \omega - i\gamma} \right] \hat{\varepsilon}^{\frac{5}{2}} e^{-\hat{\varepsilon}} d\hat{\varepsilon}$$

← Energy integral

precession drift — bounce — collisionality

BP9.00057 J. Berkery, et al.

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



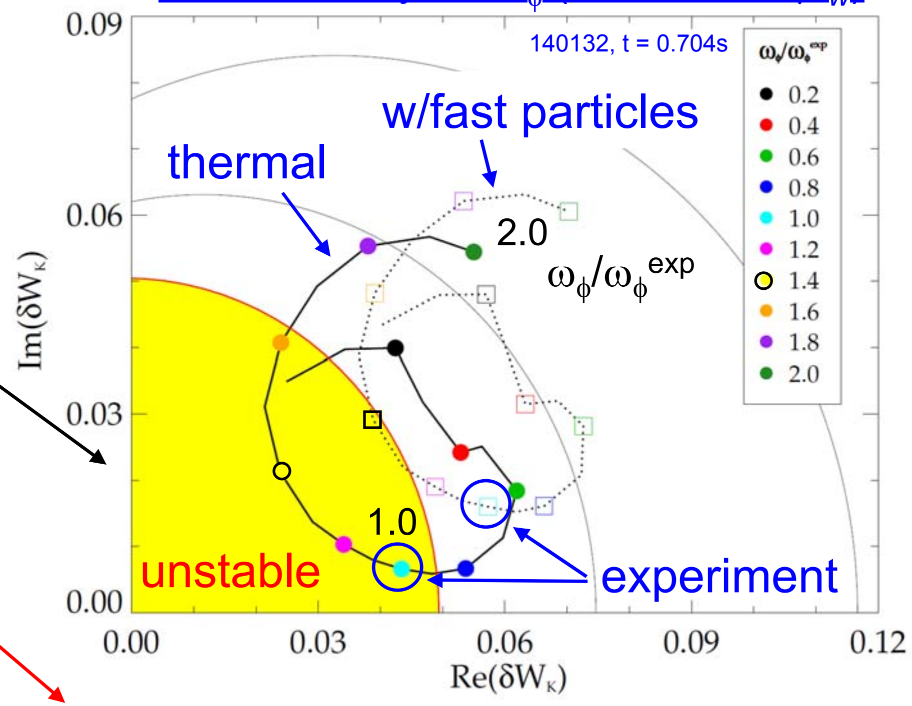
- Destabilization appears between precession drift resonance at low ω_ϕ, bounce/transit resonance at high ω_ϕ
- Destabilization moves to increased ω_ϕ as ν decreases

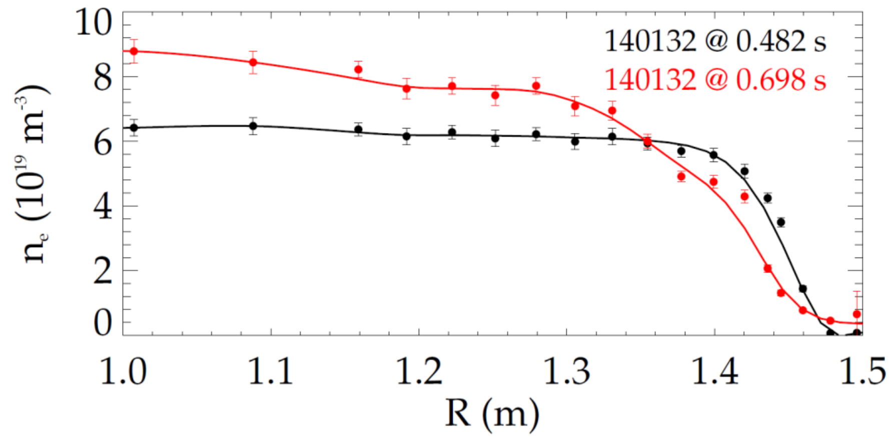
J.W. Berkery, et al., PRL **104** (2010) 035003
S.A. Sabbagh, et al., NF **50** (2010) 025020

MISK calculations show reduced stability in low l_i target plasma as ω_ϕ is reduced, RWM instability is approached

- Stability evolves
  - MISK computation shows plasma to be stable at time of minimum l_i
  - Region of reduced stability vs. ω_ϕ found before RWM becomes unstable (l_i = 0.49)
    - Co-incident with a drop in edge density gradient – reduces kinetic stabilization

RWM stability vs. ω_ϕ (contours of $\gamma\tau_w$)



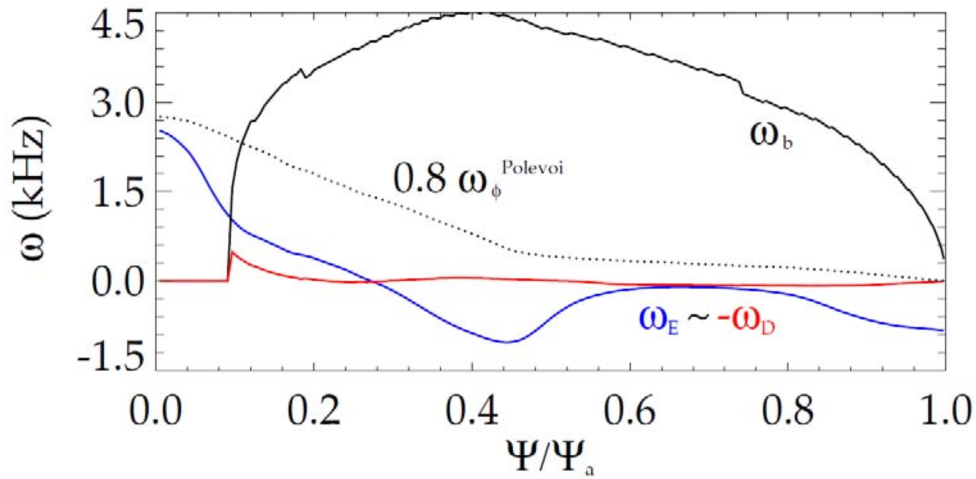


- MISK application to ITER (advanced scenario IV)
  - RWM unstable at expected rotation
  - Only marginally stabilized by alphas at β_N = 3

- BP9.00057 J. Berkery, et al.
- Also, see poster for detail

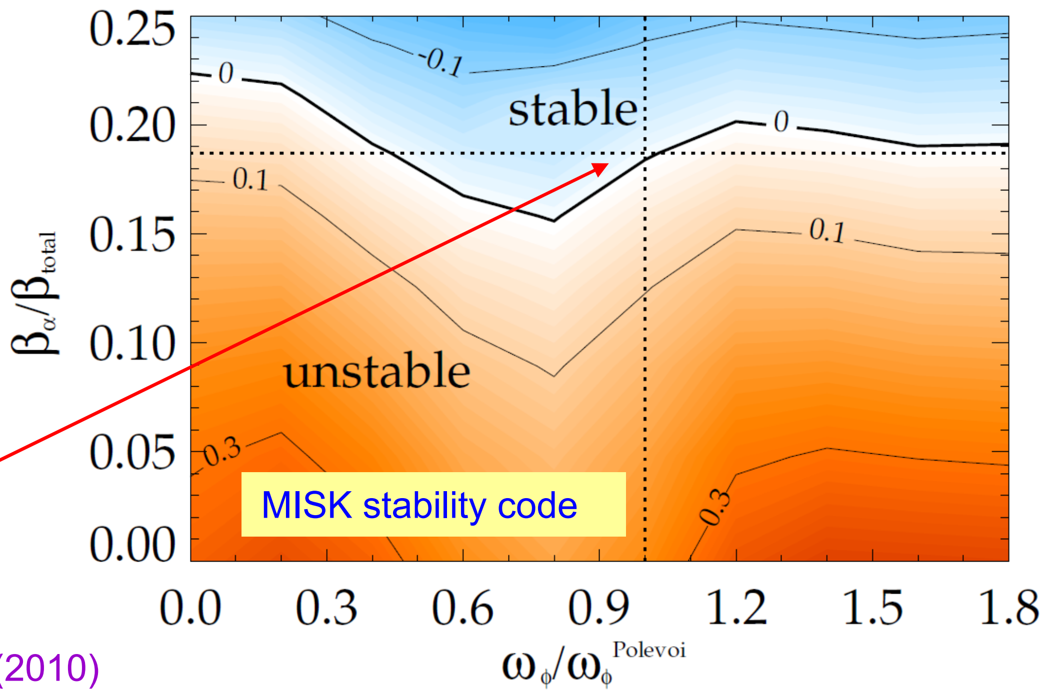
ITER Advanced Scenario IV: RWM just reaches marginal stability by energetic particles with $\beta_N = 3$

- **Equilibrium**
  - With $\beta_N = 3$ (20% above n = 1 no-wall limit)
  - Plasma rotation profile linear in normalized poloidal flux



- **Plasma rotation effect**
  - Stabilizing precession drift resonance weakly enhances stability near $\omega_\phi = 0.8\ \omega_\phi^{Polevoi}$

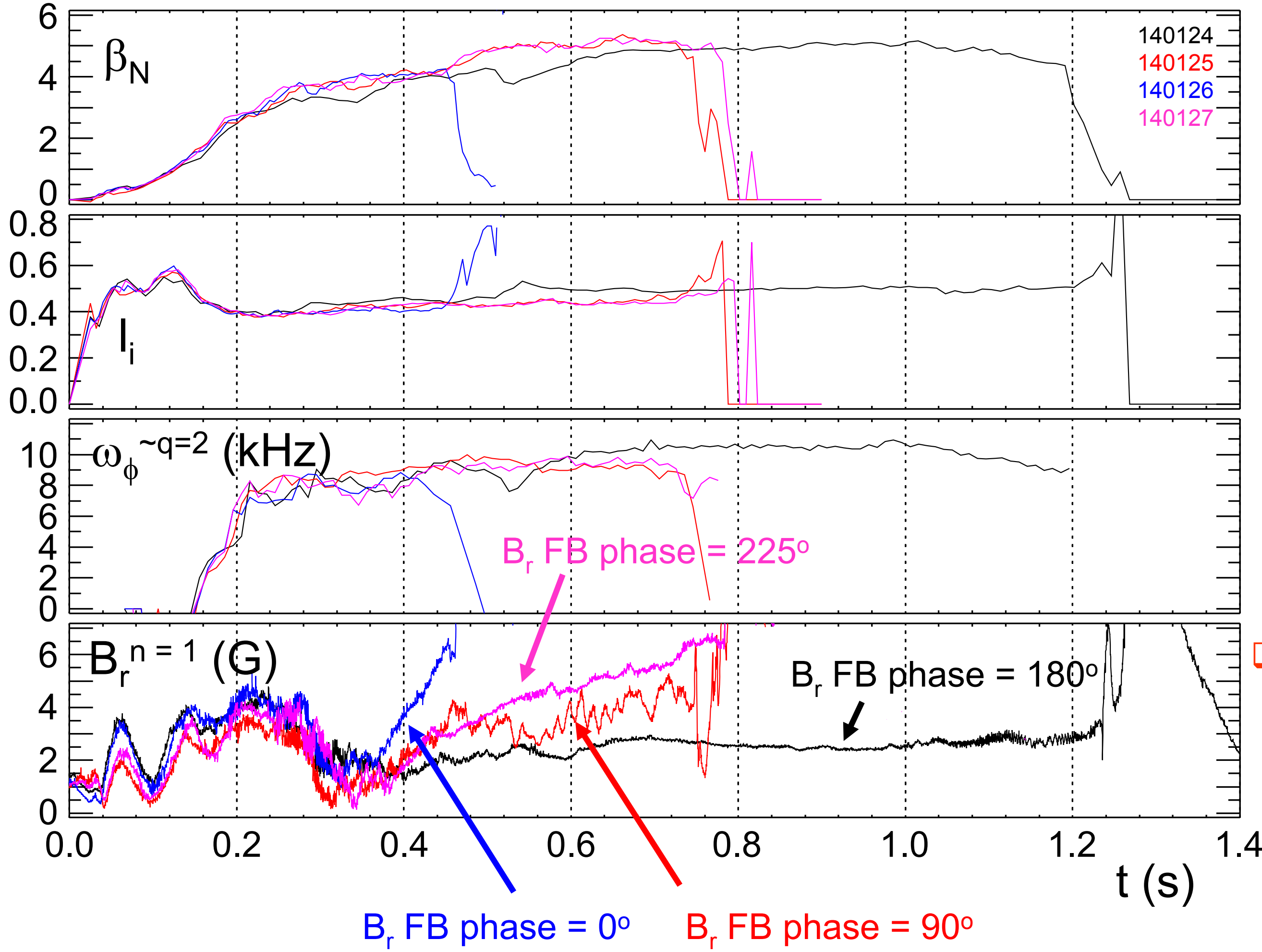
- **Energetic particle (EP) effect**
  - Alpha particles are required for RWM stabilization at <u>all</u> ω_ϕ
  - Near RWM marginal stability at ITER expected $\beta_\alpha/\beta_{total}$ = 0.19 at $\omega_\phi = \omega_\phi^{Polevoi}$



J.W. Berkery, et al., Phys. Plasmas **17**, 082504 (2010)

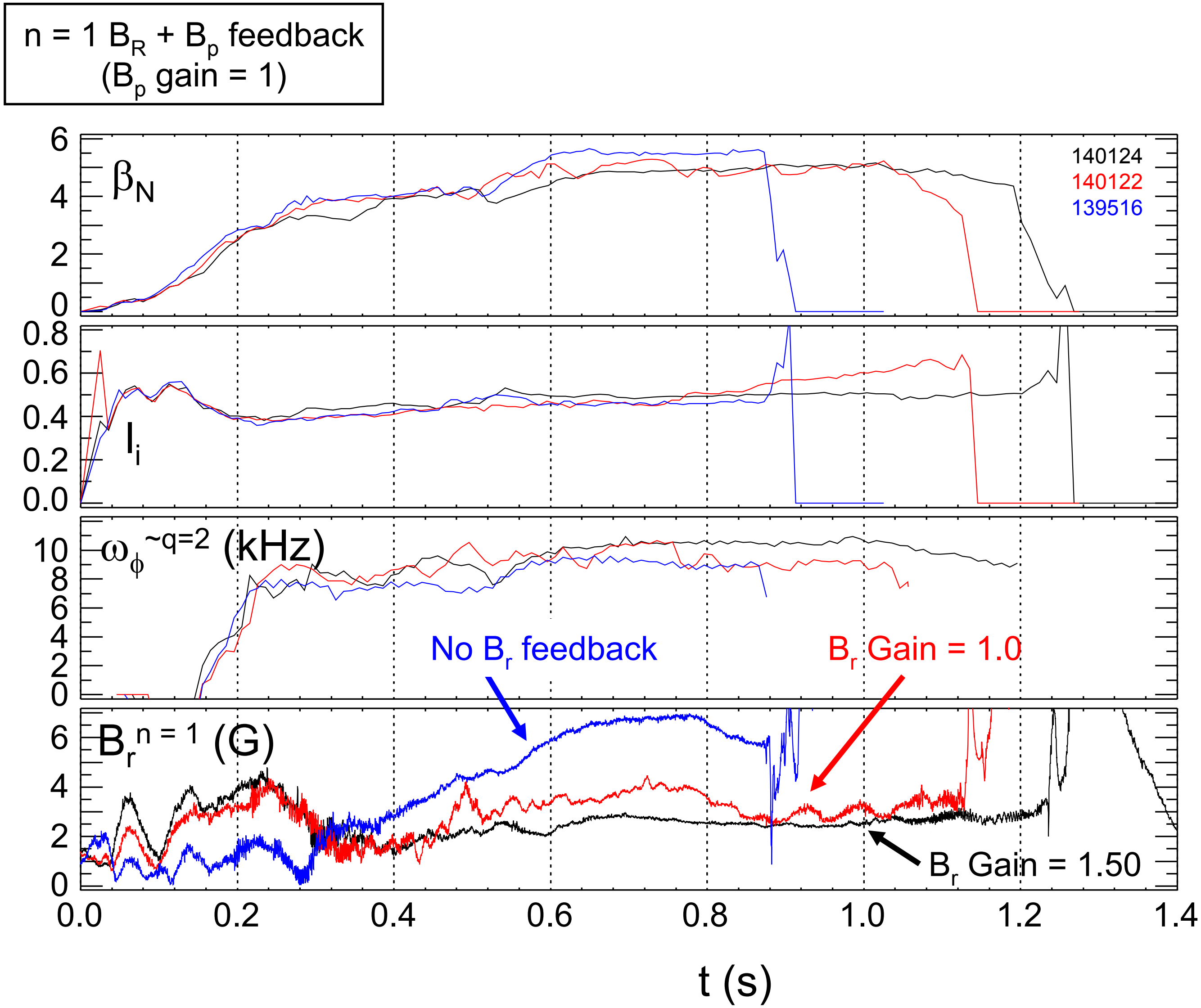
RWM B_r sensor n = 1 feedback phase variation shows clear settings for improved feedback when combined with B_p sensors

n = 1 B_R + B_p feedback
(B_p gain = 1, B_R gain = 1.5)



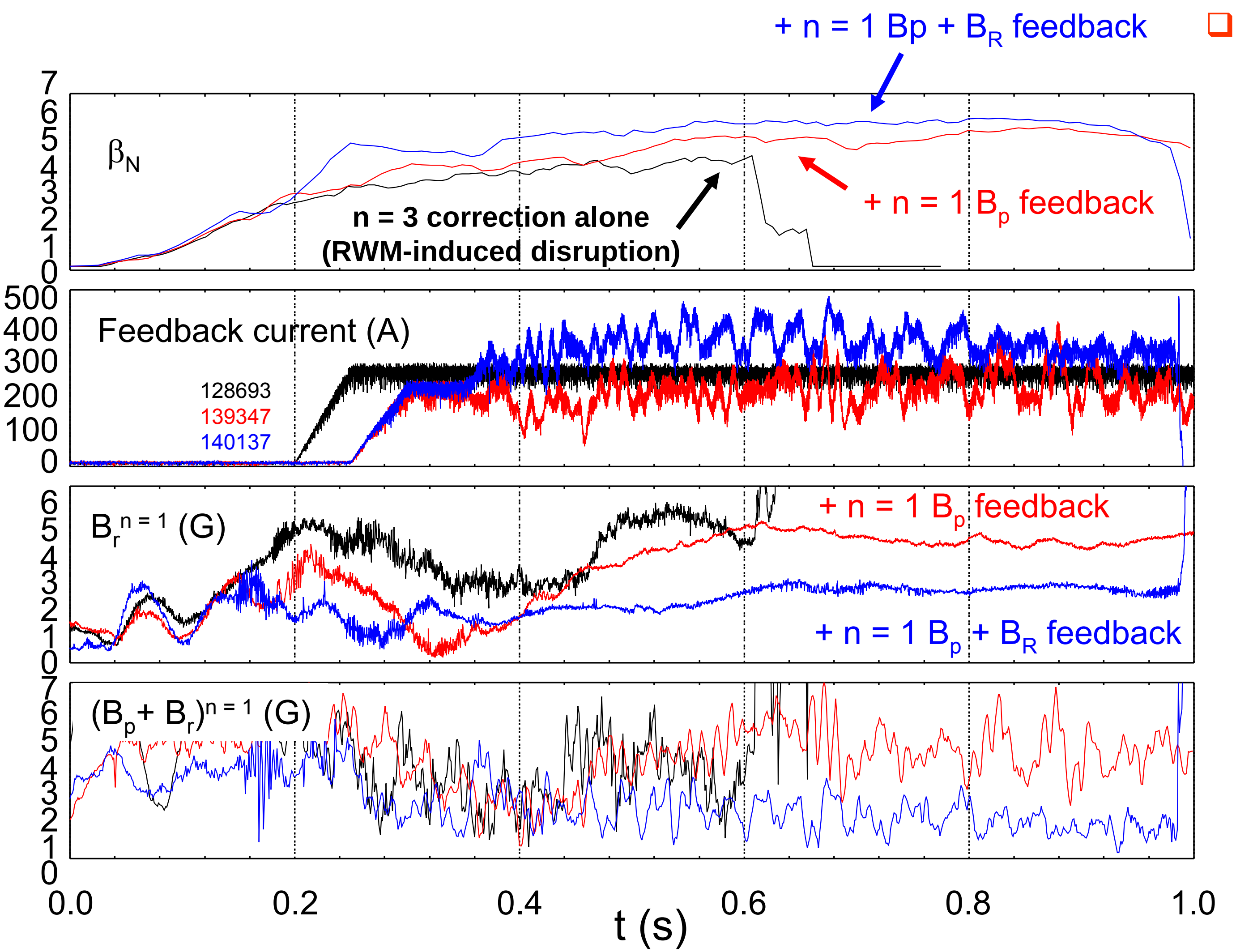
- Recent corrections to B_r sensors improve measurement of plasma response
  - Removed significant direct pickup of time-dependent TF intrinsic error field
  - Positive/negative feedback produced at theoretically expected phase values
- Adjustment of B_p sensor feedback phase from past value further improved control performance

RWM B_R sensor feedback gain scan shows significantly reduced n= 1 radial error field



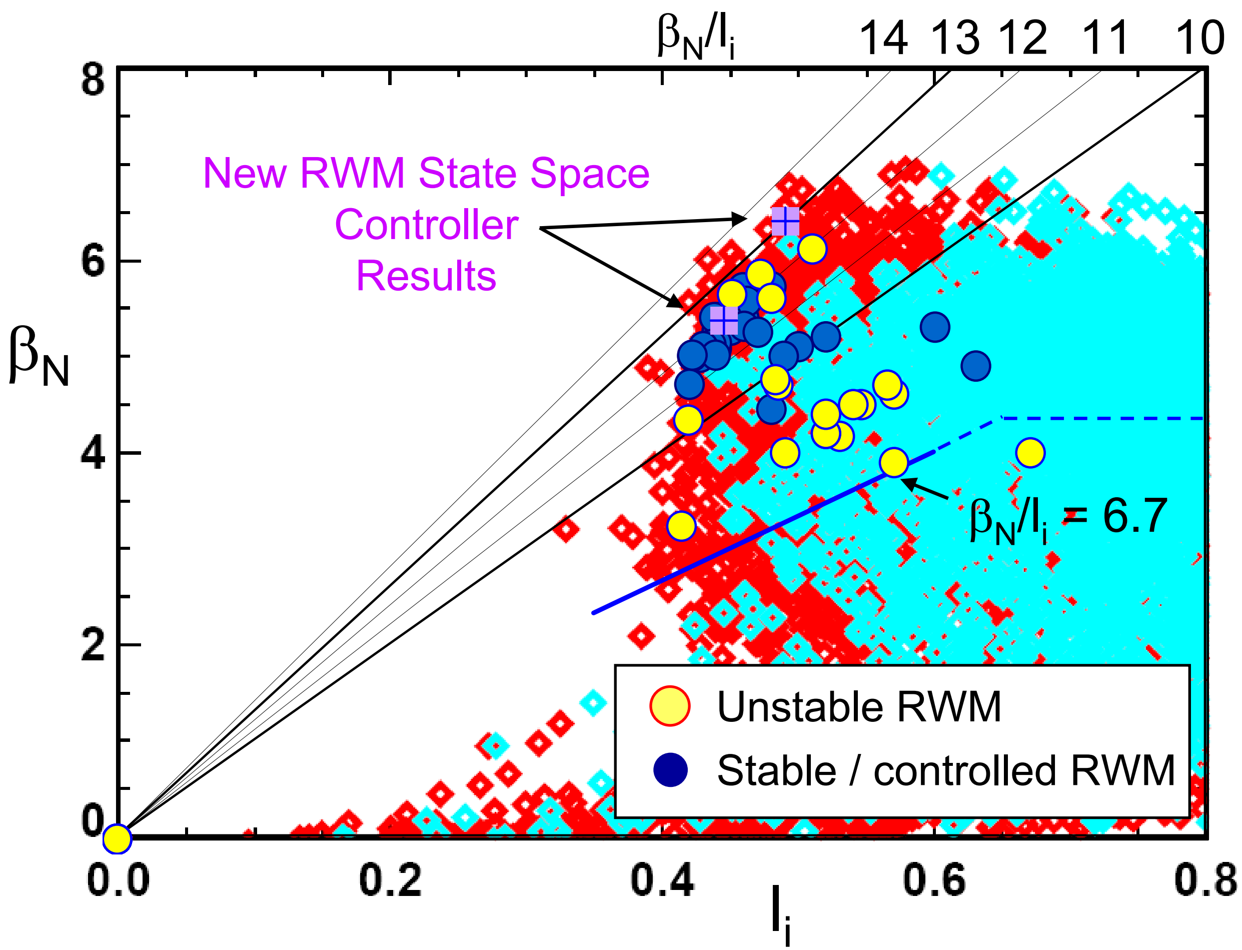
- New B_r sensor feedback gain scan on low l_i plasmas
  - Highest gain attempted (1.5) most favorable
- B_r feedback constrains slow (10's of ms) n = 1 radial field growth
  - Addition of n = 1 B_R sensors in feedback prevents disruptions when $|\delta B_r^{n=1}| \sim 9$G; better sustains plasma rotation

Use of combined RWM sensor n= 1 feedback yields best reduction of n = 1 field amplitude / improved stability



- Combination of DC error field correction, n = 1 feedback
  - n = 3 DC error field correction alone more subject to RWM instability
  - n = 1 B_p sensor fast RWM feedback sustains plasma
  - Addition of n = 1 B_R sensors in feedback reduce the combined B_p + B_r n = 1 field to low level (1–2 G)

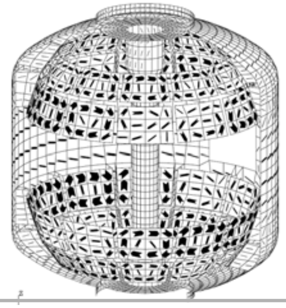
Improvements in stability control techniques significantly reduce unstable RWMs at low l_i and high β_N



- Subset of discharges
  - High $I_p \geq 1.0$MA
  - n = 1 control enhancements
  - Mild ω_ϕ alteration
- Latest results
  - Yielded low l_i
  - Access high β_N/l_i
  - Significantly reduced disruption probability due to unstable RWM
    - 14% of cases with $\beta_N/l_i > 11$
    - Much higher probability of unstable RWMs at lower β_N, β_N/l_i

New RWM state space controller implemented to sustain high β_N

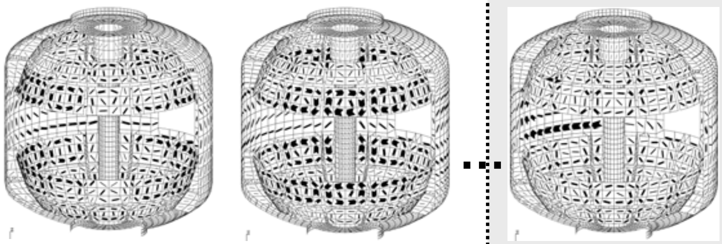
Full 3-D model ~3000+ states



Balancing transformation

State reduction (< 20 states)

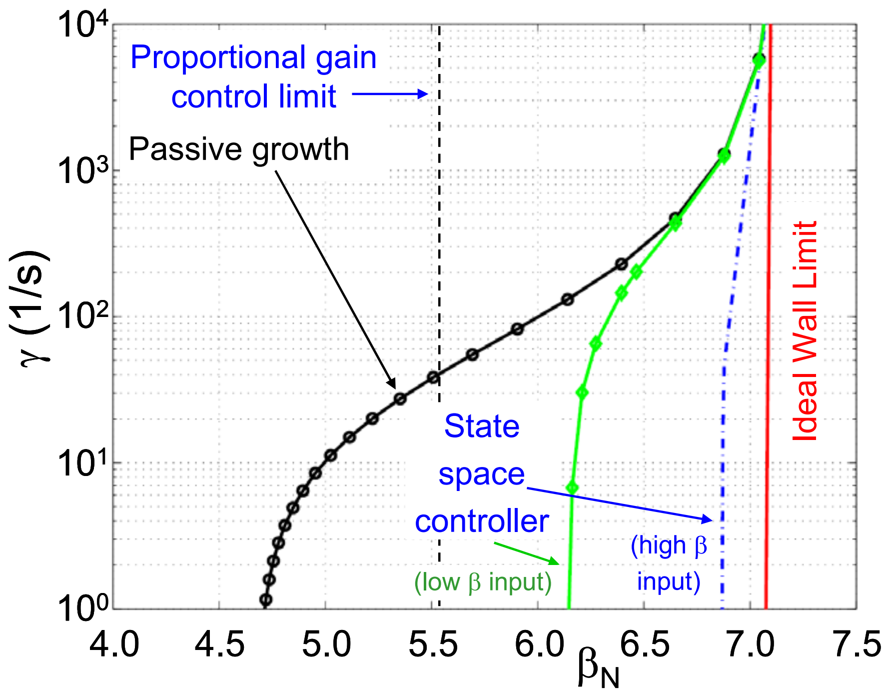
RWM eigenfunction (2 phases, 2 states)



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

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

Theoretical feedback performance (ω_ϕ = 0, 12 states)

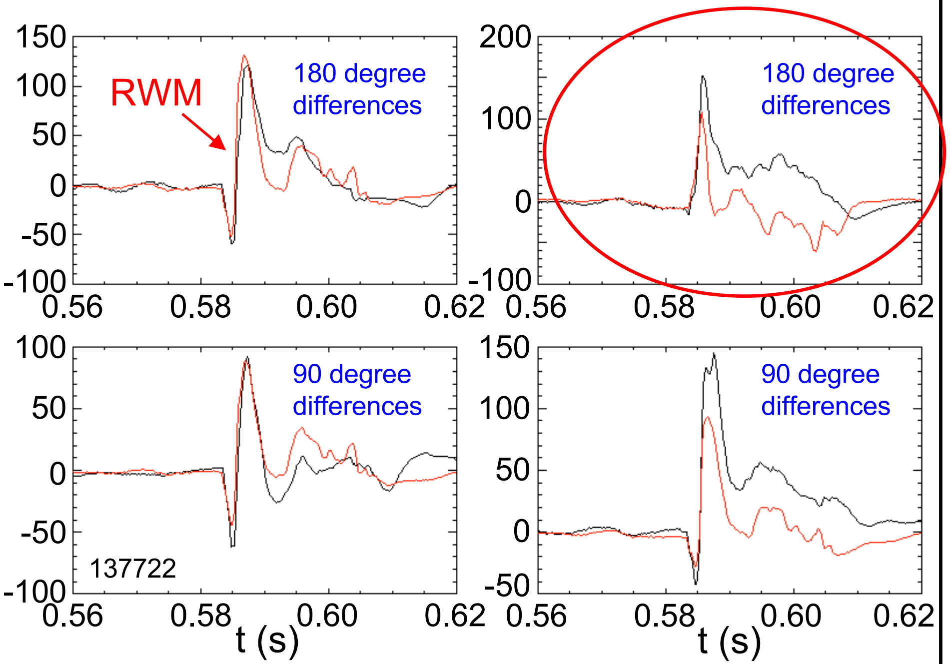


- Controller can compensate for wall currents
  - Including mode-induced current
- Potential to allow more flexible control coil positioning
  - May allow control coils to be moved further from plasma, shielded
  - Examined for ITER

Katsuro-Hopkins, et al., NF **47** (2007) 1157

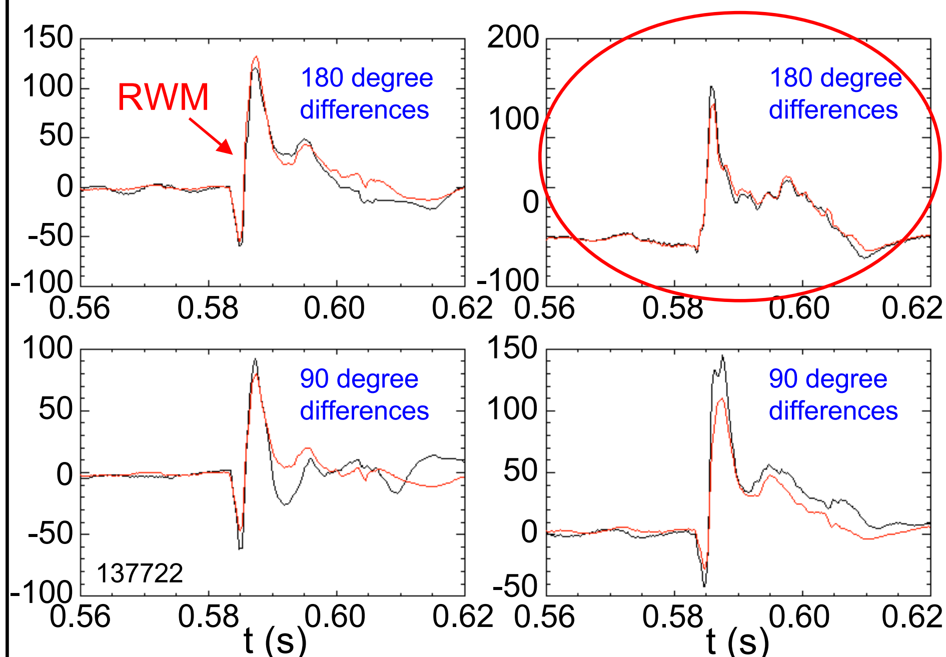
Increased number of states in RWM state space controller improves match to sensors over entire mode evolution

RWM Upper B_p Sensor Differences (G) – 2 States



- Reasonable match to all B_p sensors during RWM onset, large differences later in evolution

RWM Upper B_p Sensor Differences (G) – 7 States

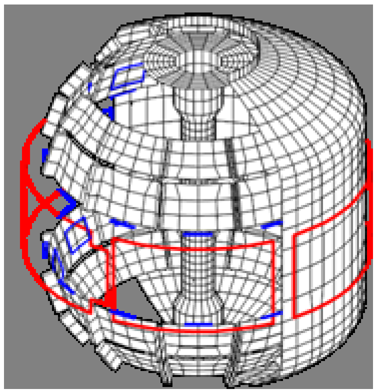


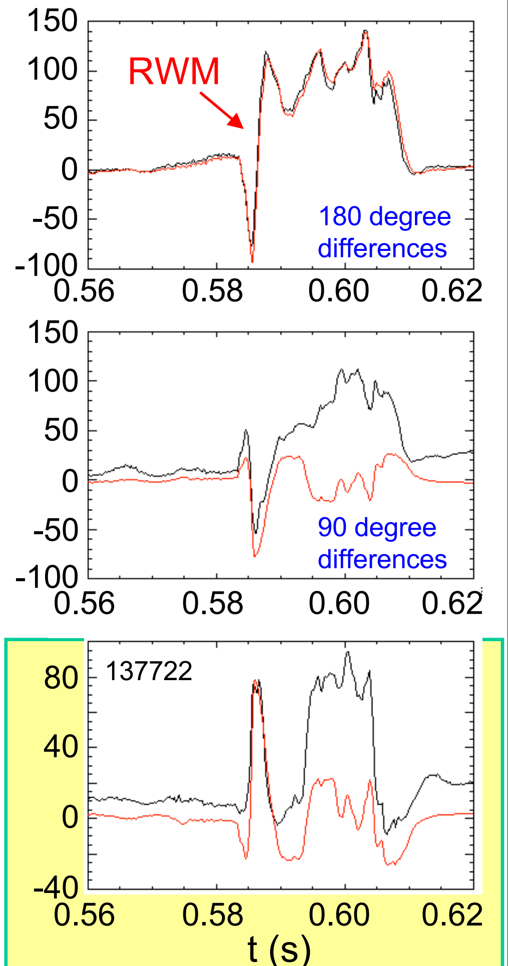
- Some 90 degree differences not as well matched
  - May indicate the need for an n = 2 eigenfunction state

Black: experiment   Red: offline RWM state space controller

3-D conducting structure detail can improve RWM state space controller match to sensors

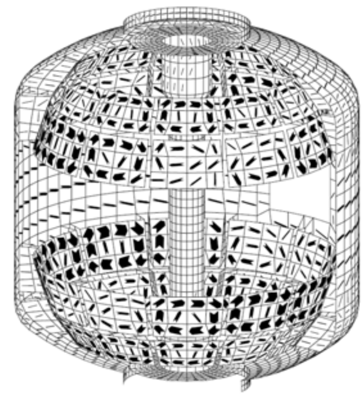
RWM Lower B_p Sensor Differences (G) – NO PORT

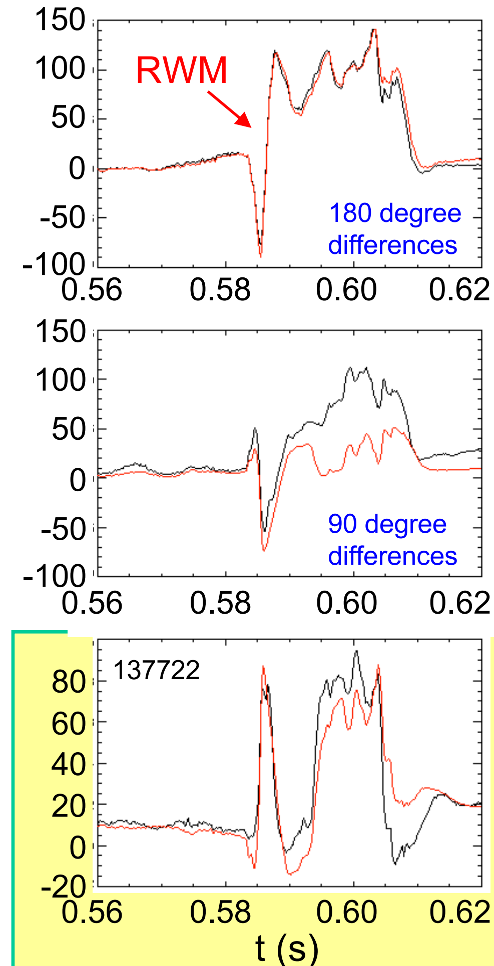




- Some 90 degree differences not well matched

RWM Lower B_p Sensor Differences (G) – NBI PORT



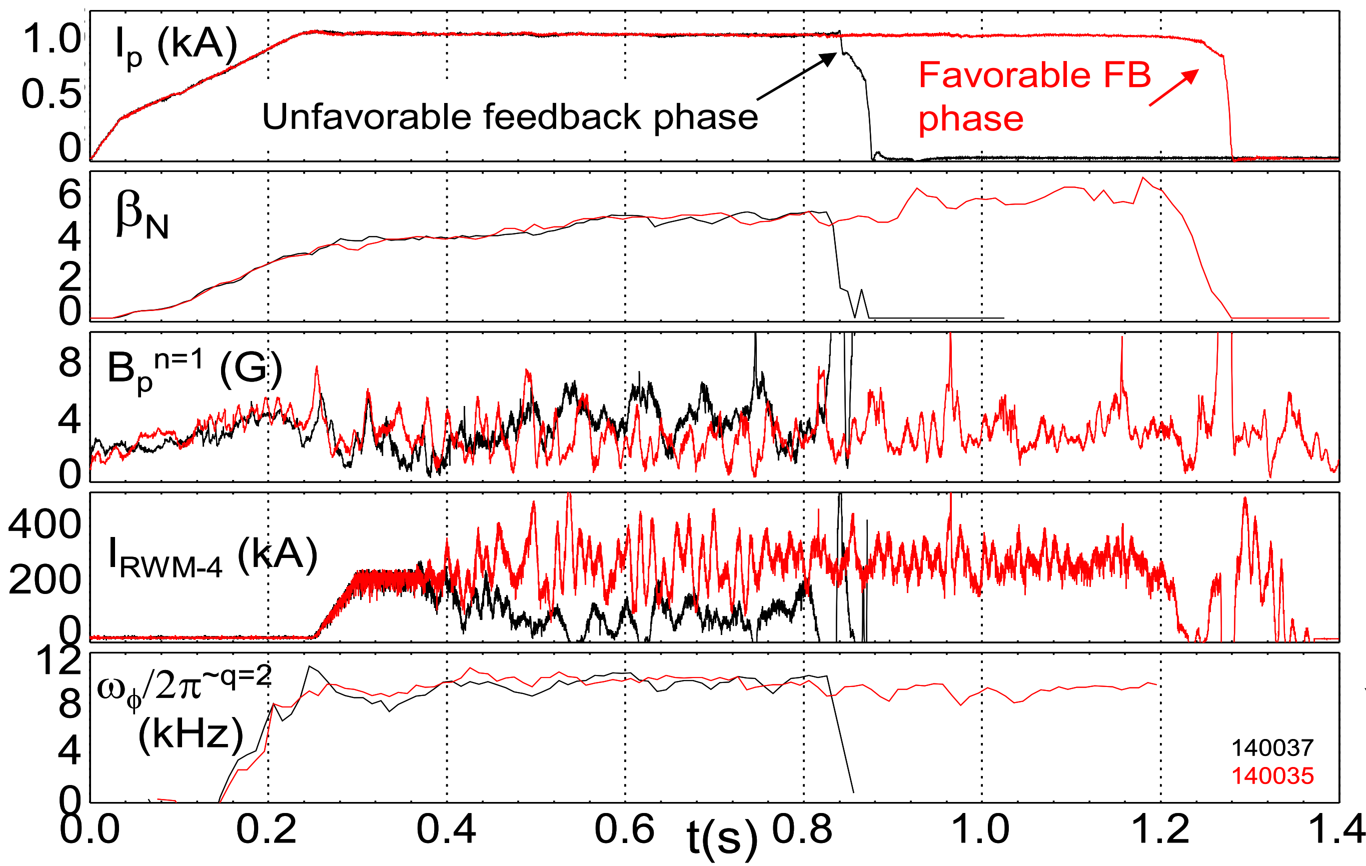


- Adding NBI port leads to greater match on some sensors

Black: experiment Red: offline RWM state space controller

New RWM state space controller sustains high β_N, low l_i plasma

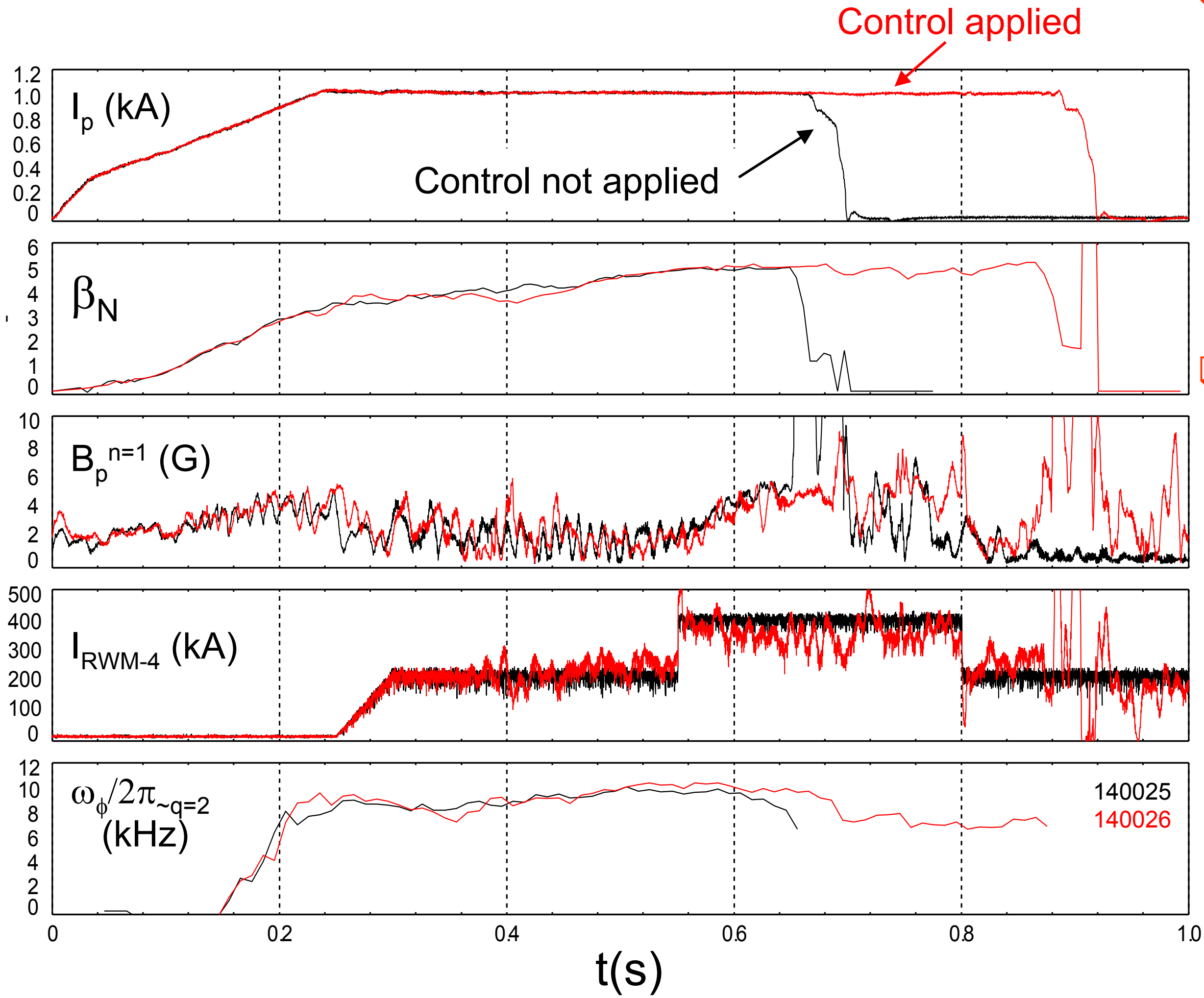
RWM state space feedback (12 states)



Successful First Experiments

- n = 1 applied field suppression
  - Suppressed disruption due to n = 1 field
  - (See poster for detail)
- Feedback phase scan
  - Best feedback phase produced long pulse, β_N = 6.4, β_N/l_i = 13

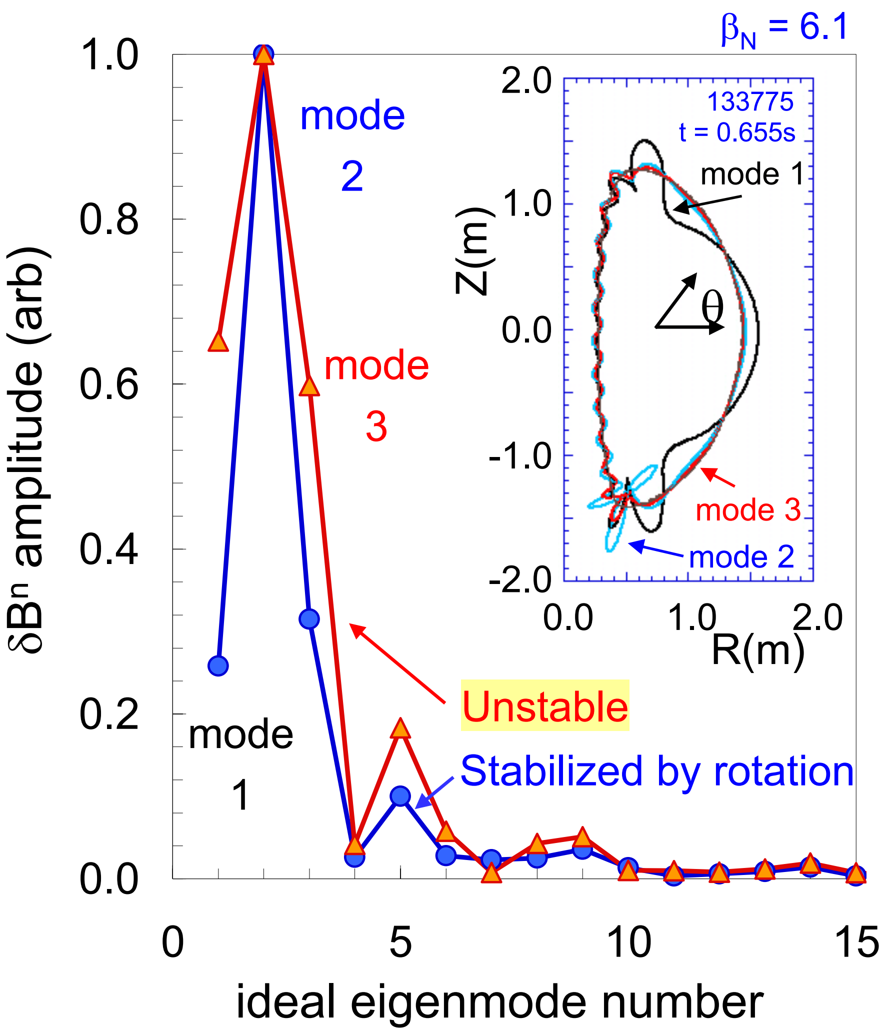
RWM state space controller sustains otherwise disrupted plasma caused by DC n = 1 applied field



- n = 1 DC applied field
  - Simple method to generate resonant field amplication
  - Can lead to mode onset, disruption
- RWM state space controller sustains discharge
  - With control, plasma survives n = 1 pulse
  - n = 1 DC field reduced
  - Transients controlled and do not lead to disruption
  - NOTE: initial run – gains NOT optimized

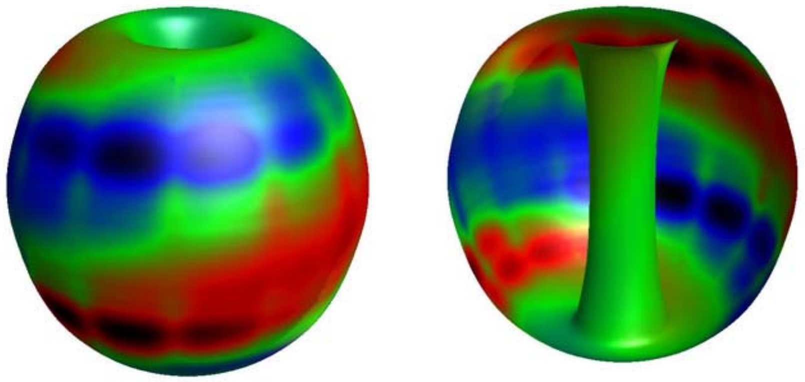
Multi-mode RWM computation shows 2nd eigenmode component has dominant amplitude at high β_N in NSTX stabilizing structure

δB^n RWM multi-mode composition



mmVALEN code

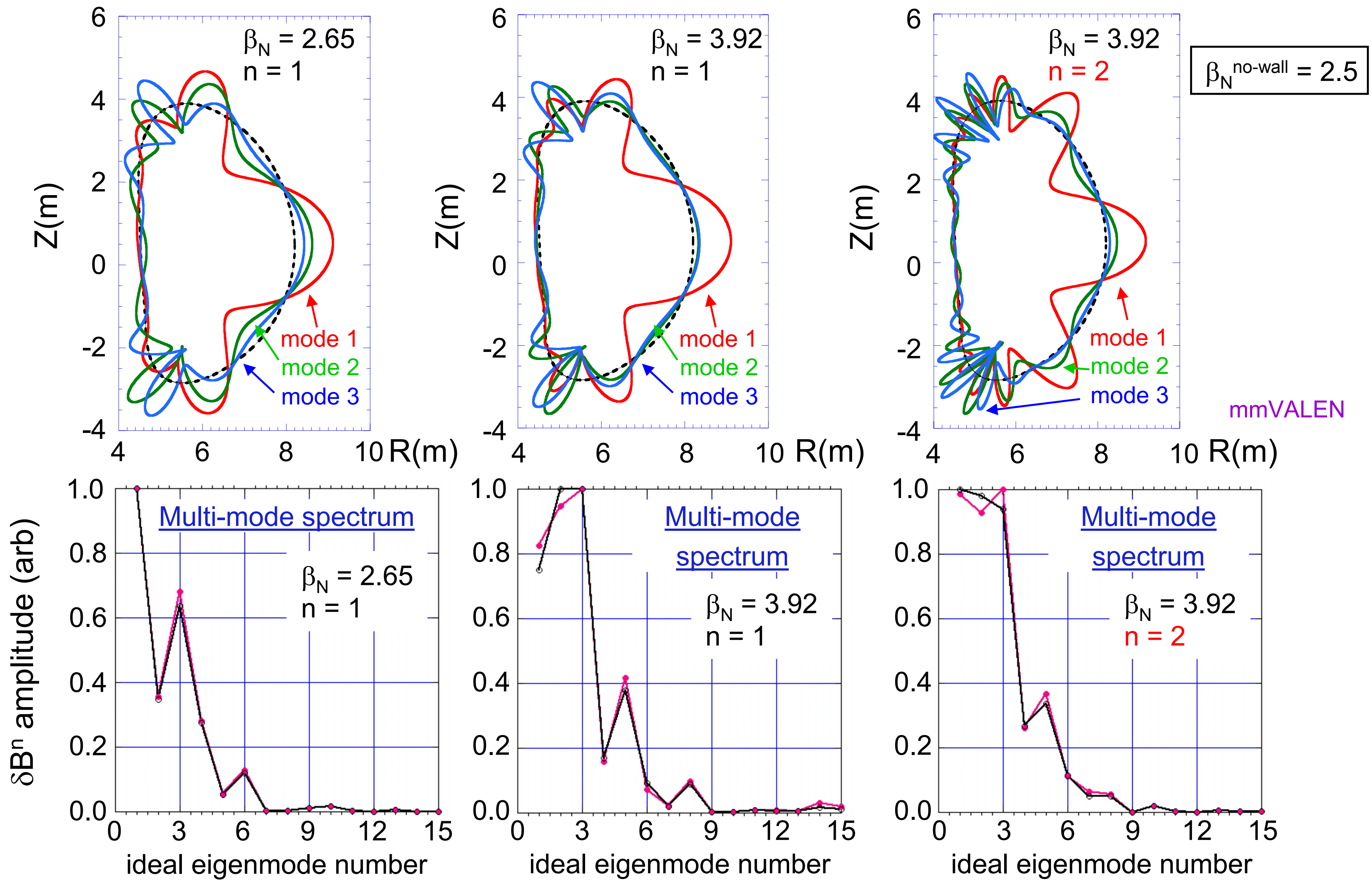
δB^n from wall, multi-mode response



- NSTX RWM not stabilized by ω_ϕ
  - Computed growth time consistent with experiment
  - 2nd eigenmode ("divertor") has larger amplitude than ballooning eigenmode
- NSTX RWM stabilized by ω_ϕ
  - Ballooning eigenmode amplitude decreases relative to "divertor" mode
  - Computed RWM rotation ~ 41 Hz, close to experimental value ~ 30 Hz
- ITER scenario IV multi-mode spectrum
  - Significant spectrum for n = 1 and 2

BP9.00059 J. Bialek, et al.; see poster for detail

ITER Advanced Scenario IV: multi-mode RWM spectra computation shows significant ideal eigenfunction amplitude for several components



NSTX is Addressing Global Stability Needs Furthering Steady Operation of High Performance ST Plasmas

- Success in producing and stabilizing high β_N plasmas with reduced l_i
  - Approaching conditions needed for ST fusion applications
  - Incidence of RWM-induced disruption greatly reduced using control upgrades
- RWM instability observed at intermediate plasma rotation correlates with kinetic stability theory
  - Potential need for rotation control in future ST devices; evaluation of energetic particle (EP) stabilization
  - Initial analysis of low l_i plasmas indicates similar stability dependence on ω_ϕ
- New RWM state space controller sustains low l_i, high β_N plasma
  - Potential for greater flexibility of RWM control coil placement in future burning plasma devices
- Computed multi-mode RWM spectrum at high β_N with 3D conducting structure shows significant amplitude of higher order ideal eigenmodes

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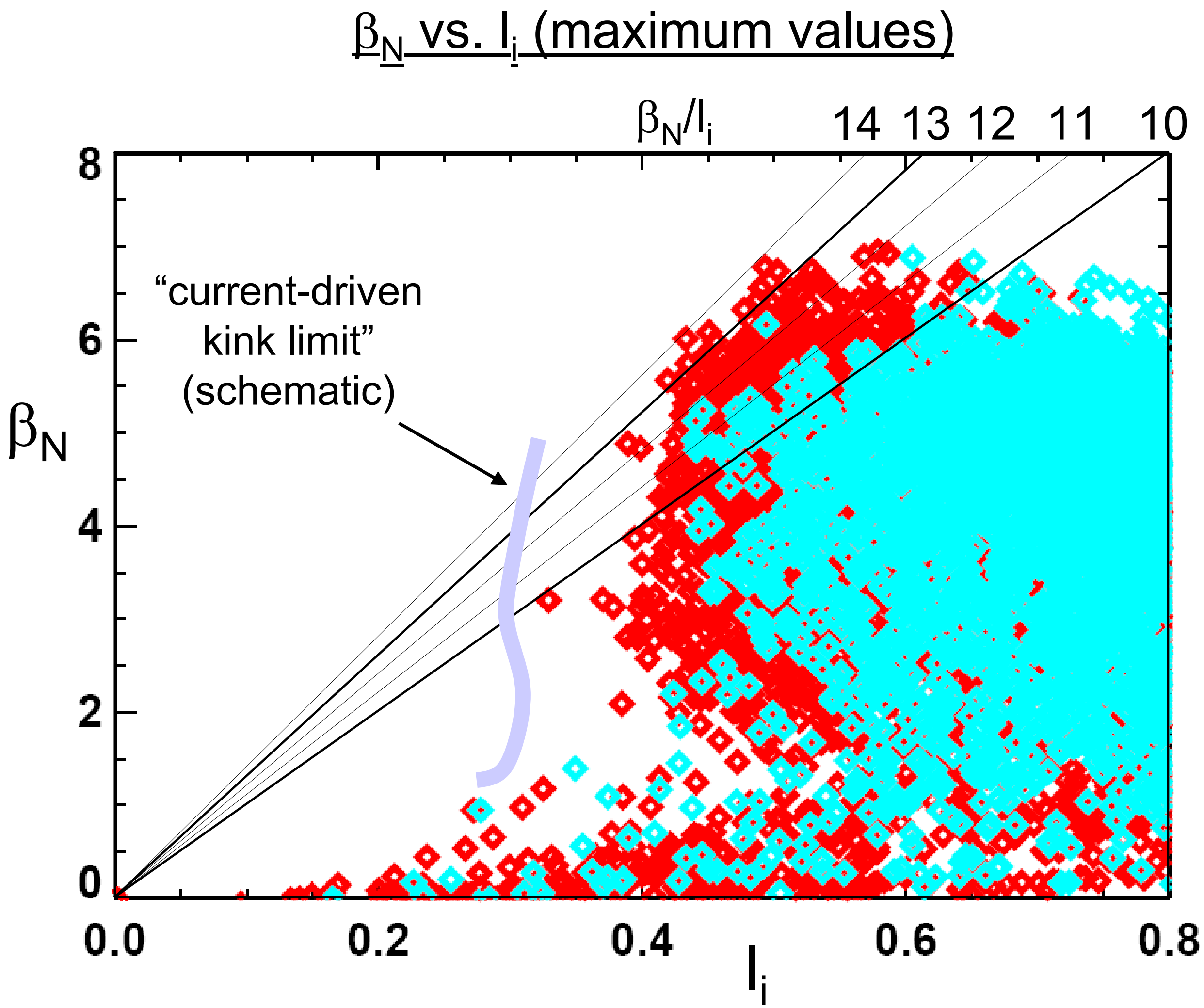
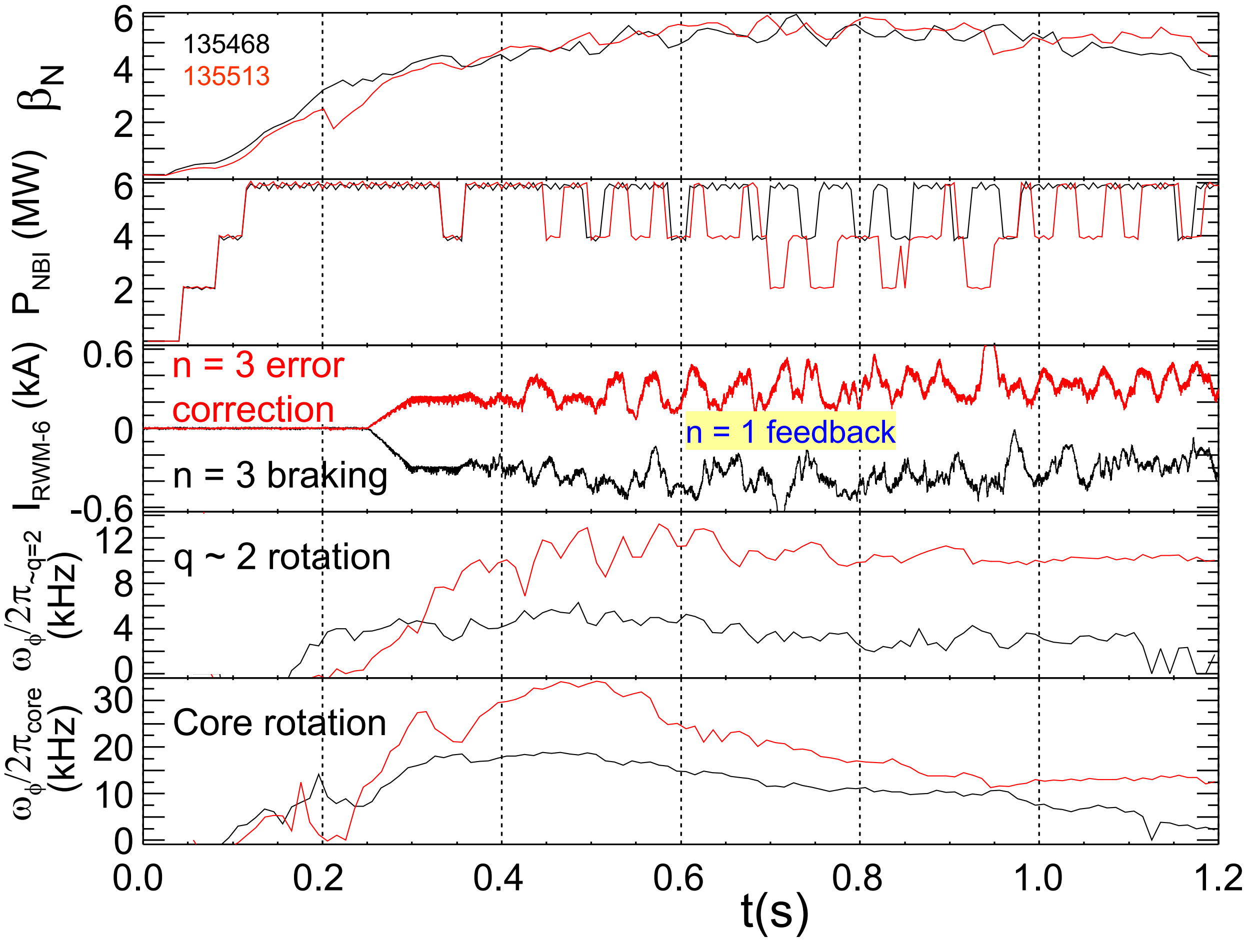
Operational space is expanding to low l_i and high β_N



- β_N/l_i is a common parameter to evaluate global stability
  - Kink/ballooning and RWM stability
- Significant increase in maximum β_N/l_i
  - Upper limit now between 13 - 14
- At sufficiently low l_i, "current driven kink" limit exists
  - Plasma unstable at any β_N value without conducting wall, or feedback control

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 is compatible with β_N FB control
- Steady β_N established over long pulse
  - independent of ω_ϕ over a large range
- Radial field sensors recently added to n = 1 feedback