NSTX

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

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52nd APS DPP Meeting

November 9th, 2010

Chicago, Illinois

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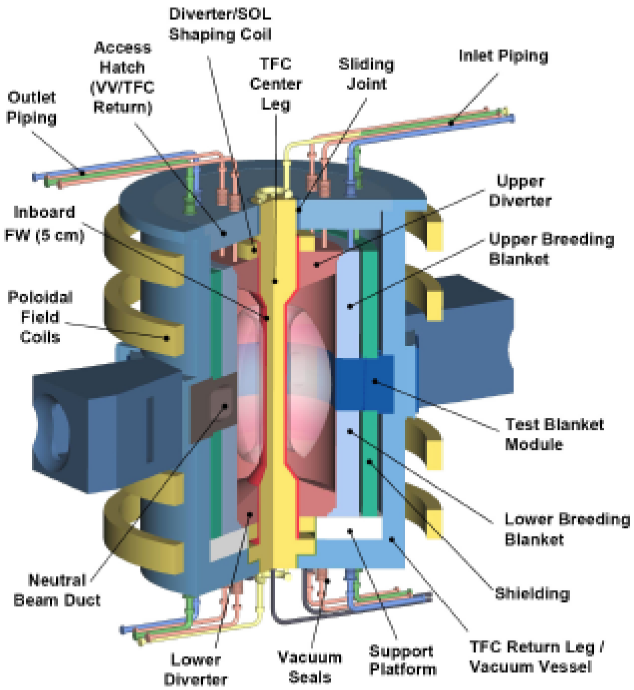
V1.6

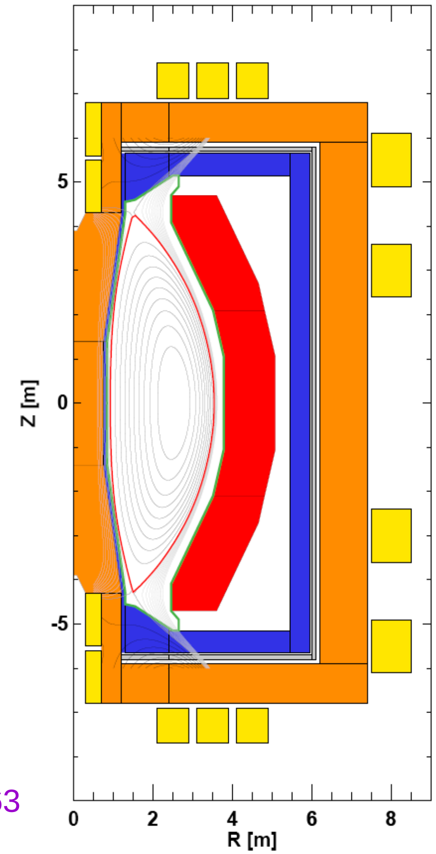
Future ST fusion applications will have high elongation, broad current profiles, high normalized beta

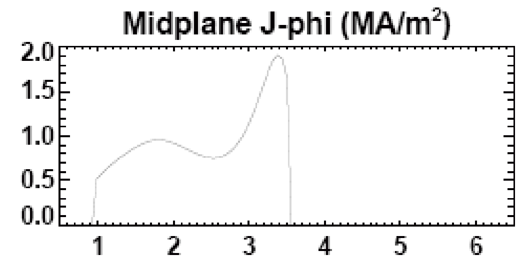
FSNF / ST-CTF



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

ST-Pilot (Q_{eng} = 1)





- R = 2.23 m, A = 1.7
- I_p = 16 MA, B_t = 2.4T
- l_i = 0.47, κ = 3.2
- β_N = 5.2, β_t = 30% (Q_{eng} = 1)

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

- Broad current profiles (low l_i) consistent with high bootstrap current fraction; important to maintain high elongation
- Demonstrating / understanding kink / RWM stability at low l_i is important

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

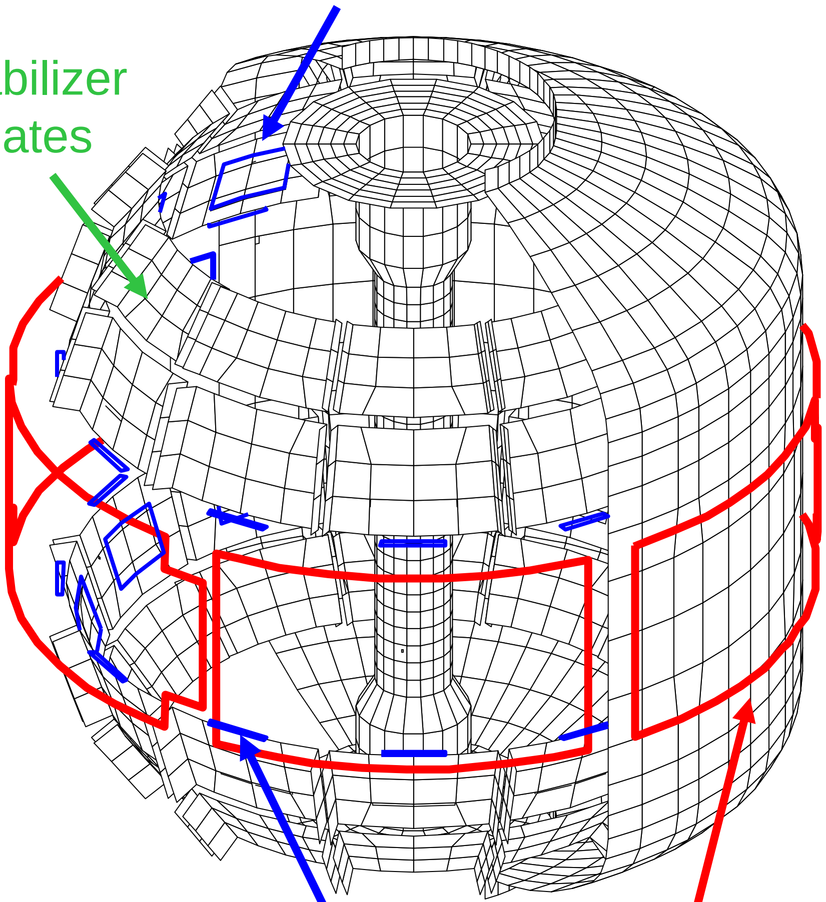
- Motivation
  - Achieve high β_N with sufficient physics understanding to allow confident extrapolation to spherical torus applications (e.g. ST Component Test Facility, ST-Pilot plant, ST-DEMO)

    NP9.00011 Peng
    UP9.00006 Hawryluk
  - Sustain target β_N of ST applications with margin to reduce risk
  - Leverage unique ST operating regime to test physics models, apply to ITER

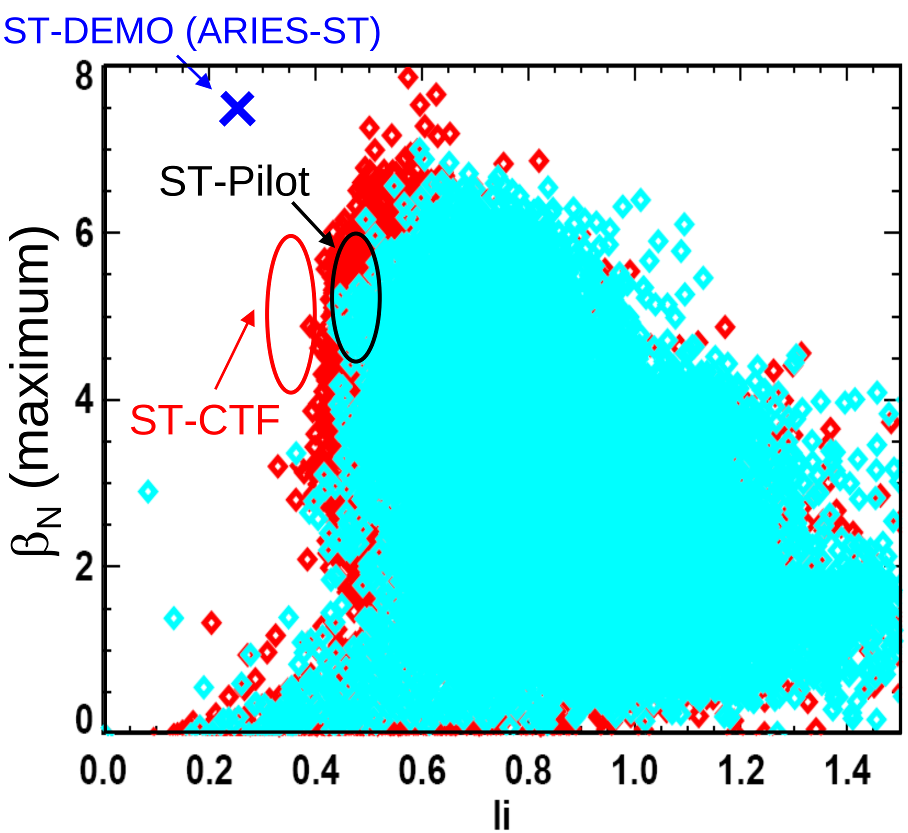
- Physics Research Addressed
  - Plasma operation at low plasma internal inductance (l_i)
  - Resistive wall mode (RWM) destabilization at high plasma rotation
  - RWM active control enhancements / advances at low l_i
  - Combined control systems to maintain $\langle\beta_N\rangle_{pulse}$ at varied ω_ϕ
  - Multi-mode RWM spectrum in high β_N plasmas

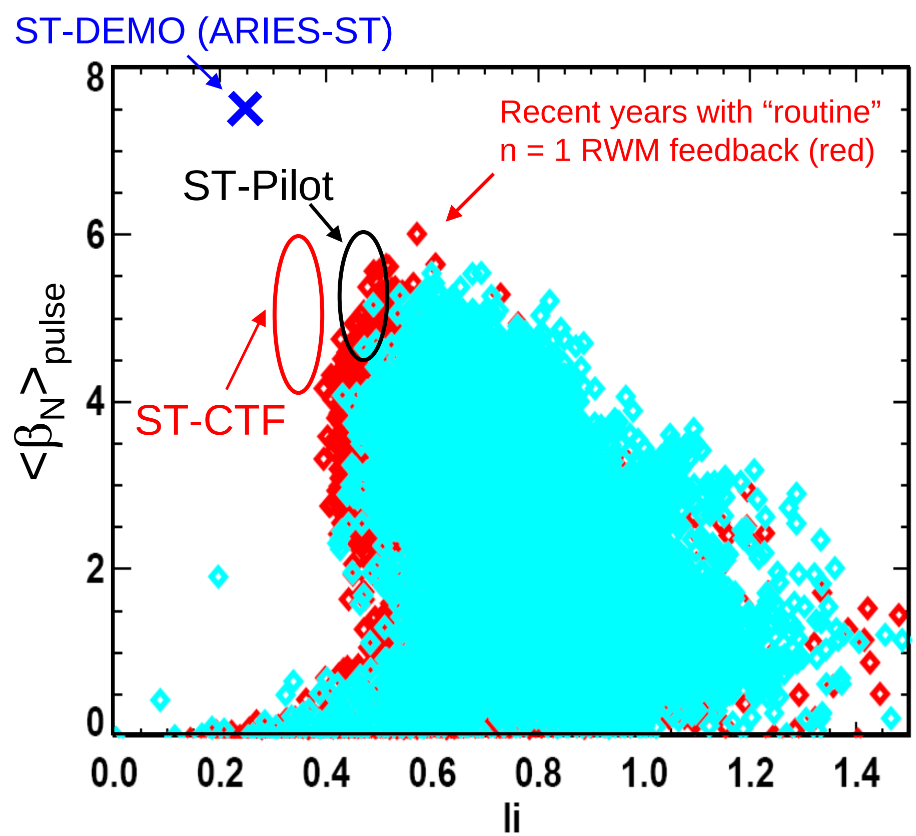
NSTX is a spherical torus equipped for passive and active global MHD control, application of 3D fields

- 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 ω_ϕ by NTV
  - n = 1 RWM control
- Varied sensor combinations used for RWM feedback
  - 48 upper/lower B_p, B_r



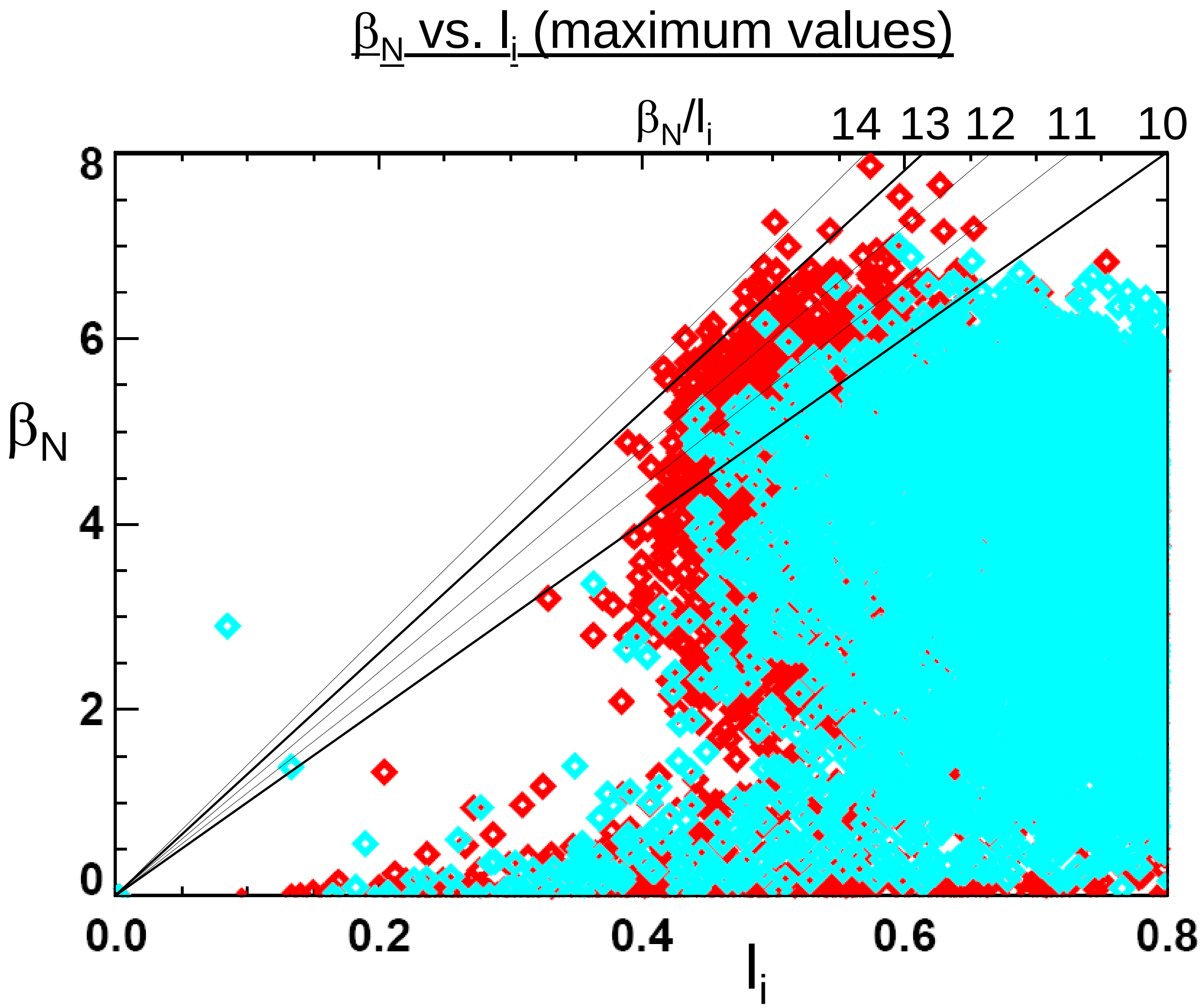
Operation aims to produce sustained low l_i and high pulse-averaged β_N





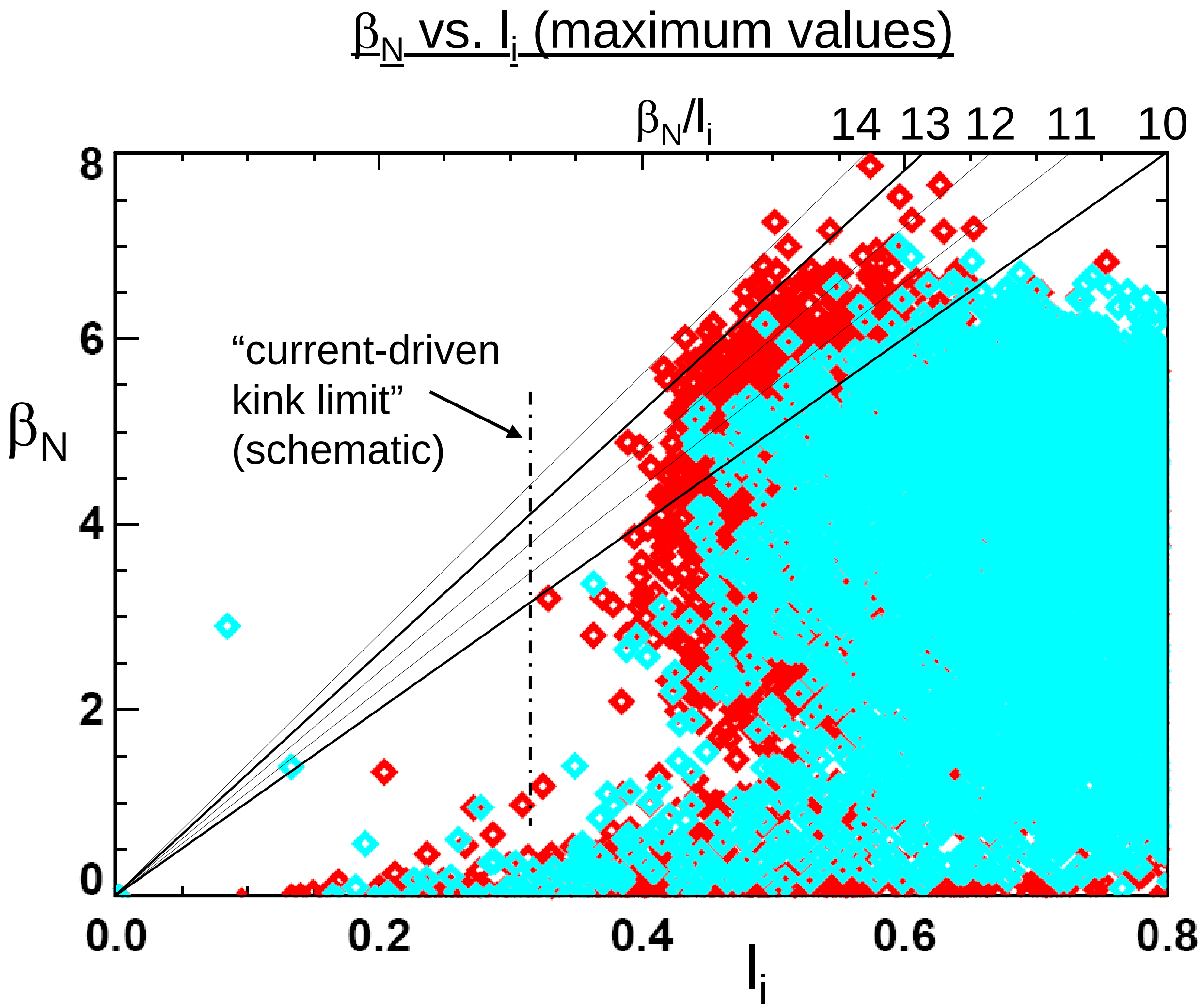
- Next-step ST fusion devices aim to operate at low l_i (high bootstrap current fraction > 50%) and high β_N
- Focus on sustained low l_i and high $<\beta_N>_{pulse}$

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



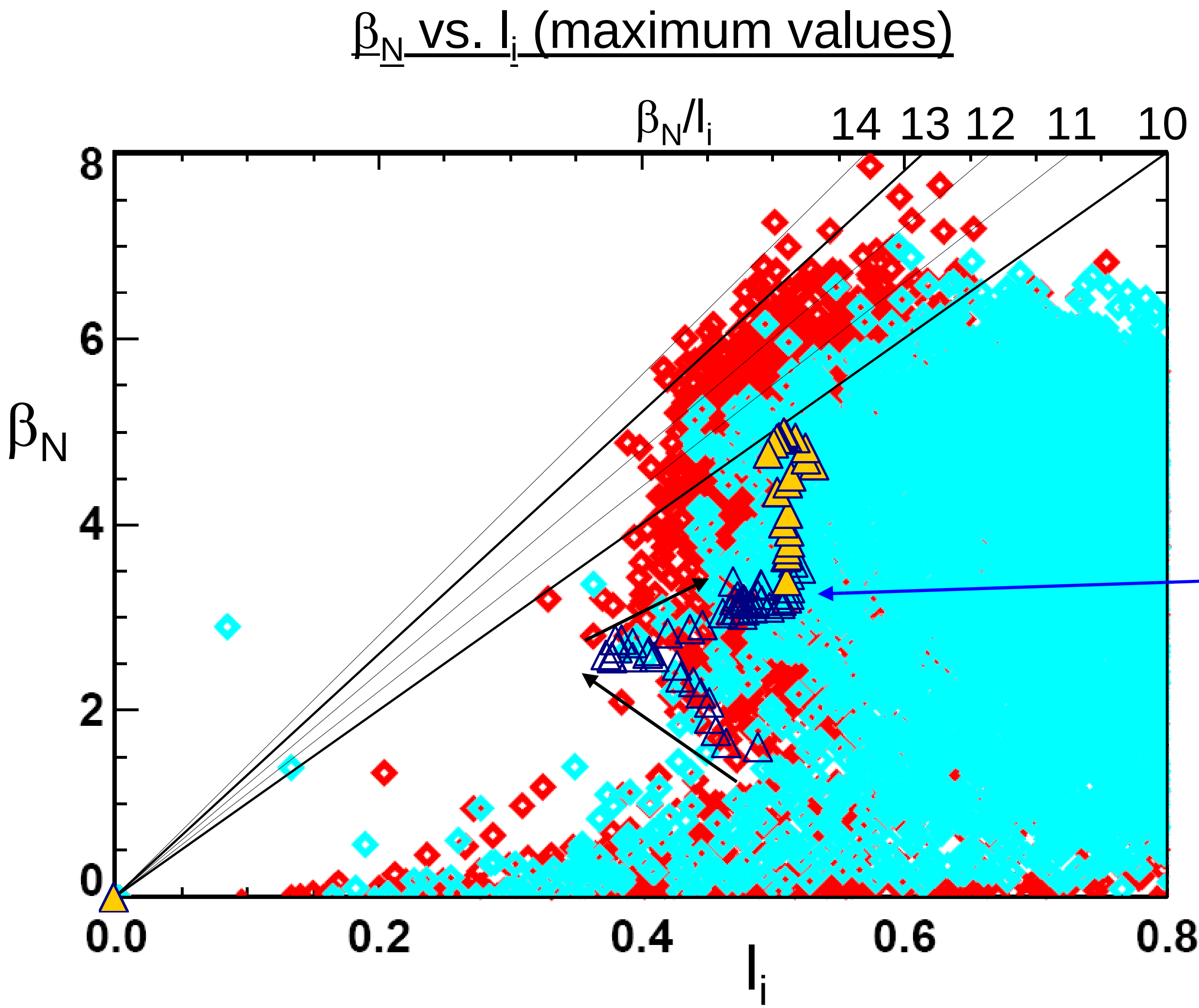
- β_N/l_i is a common parameter to evaluate global stability
  - Kink/ballooning and RWM stability
- Significant increase in maximum β_N/l_i
  - Upper limit now between 13 - 14

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



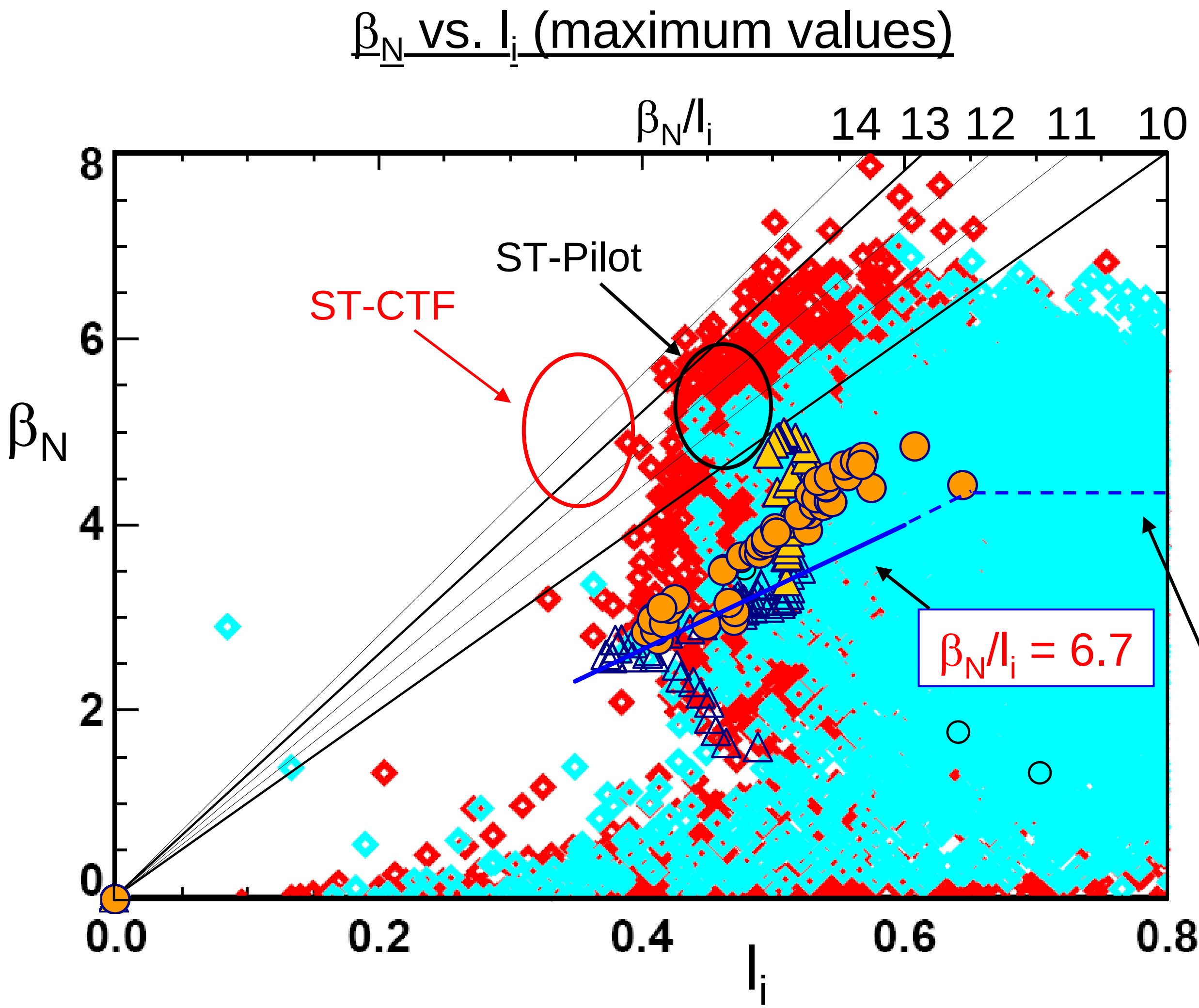
- β_N/l_i is a common parameter to evaluate global stability
  - Kink/ballooning and RWM stability
- Significant increase in maximum β_N/l_i
  - Upper limit now between 13 - 14
- At sufficiently low l_i, "current driven kink" limit exists
  - Plasma unstable without conducting wall, or FB control, at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

Ideal no-wall stability limit decreases for low l_i plasmas



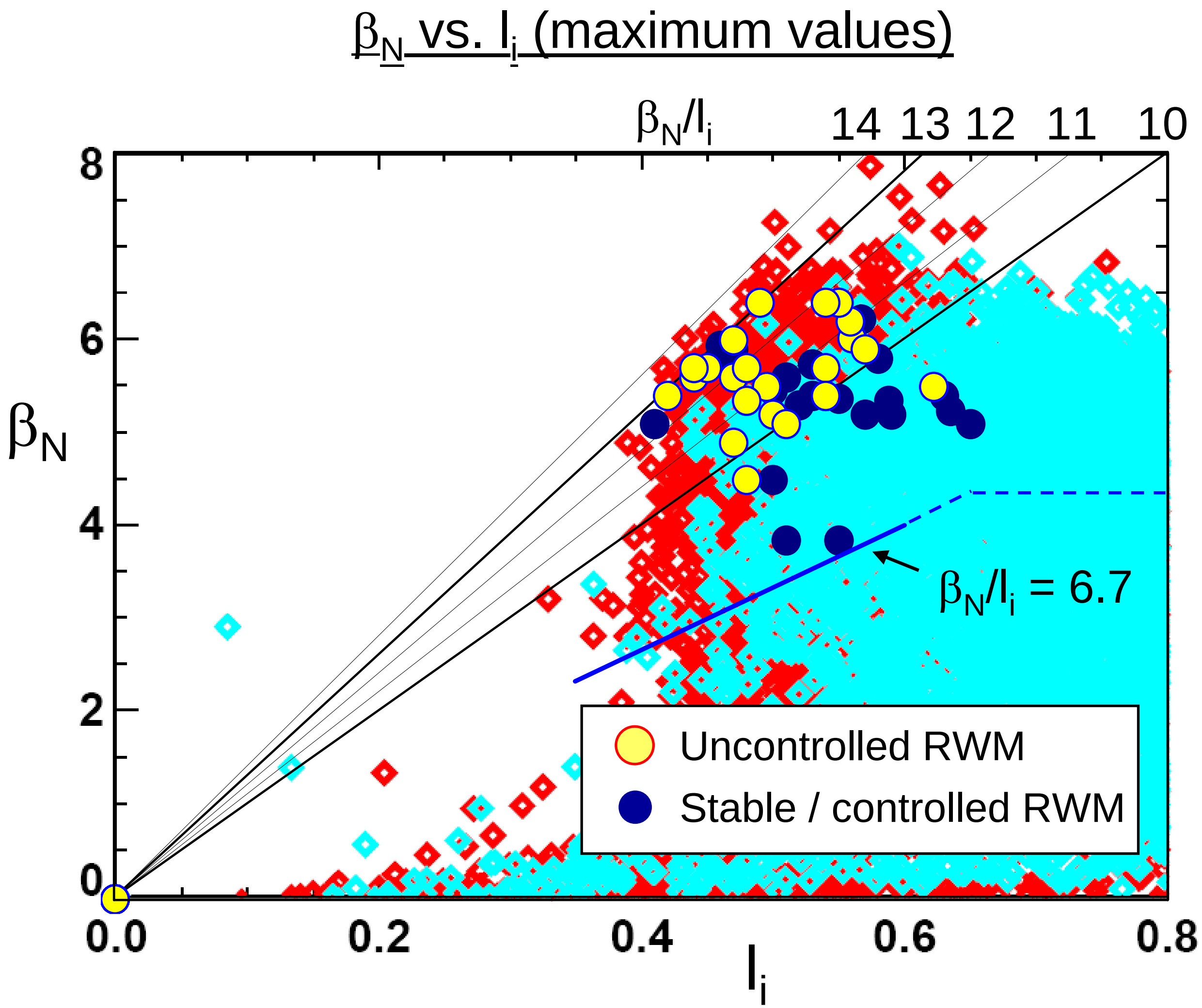
- Examine high plasma current, I_p >= 1.0MA, high non-inductive fraction ~ 50%
- Ideal n = 1 no-wall stability computed for discharge trajectory
  - Plasma exceeds no-wall limit at β_N = 3.4, l_i = 0.51

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



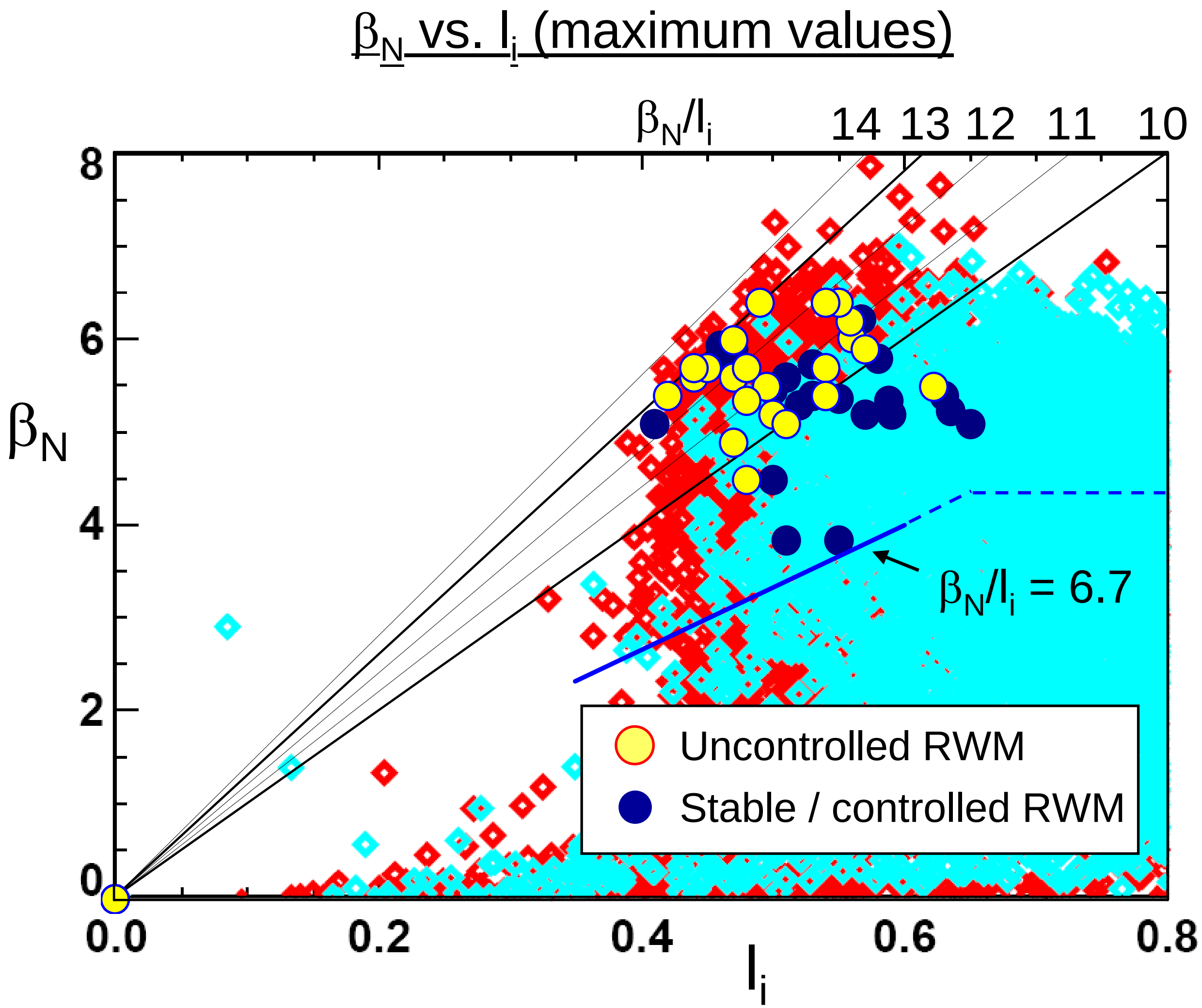
- Examine high plasma current, I_p >= 1.0MA, high non-inductive fraction ~ 50%
- Ideal n = 1 no-wall stability computed for discharge trajectory
  - Plasma exceeds no-wall limit at β_N = 3.4, l_i = 0.51
  - Adding trajectories yields β_N/l_i = 6.7 for l_i = 0.38 – 0.5
  - Significantly lower than usual no-wall limit at higher l_i (β_N = 4.3)

Experiments aimed to produce sustained low l_i and high β_N



- High I_p >= 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
    - Half of cases run
  - Locked tearing modes

(NEW SLIDE HERE – show improved long-pulse shots – segway to rest of talk) sustained low l_i and high β_N

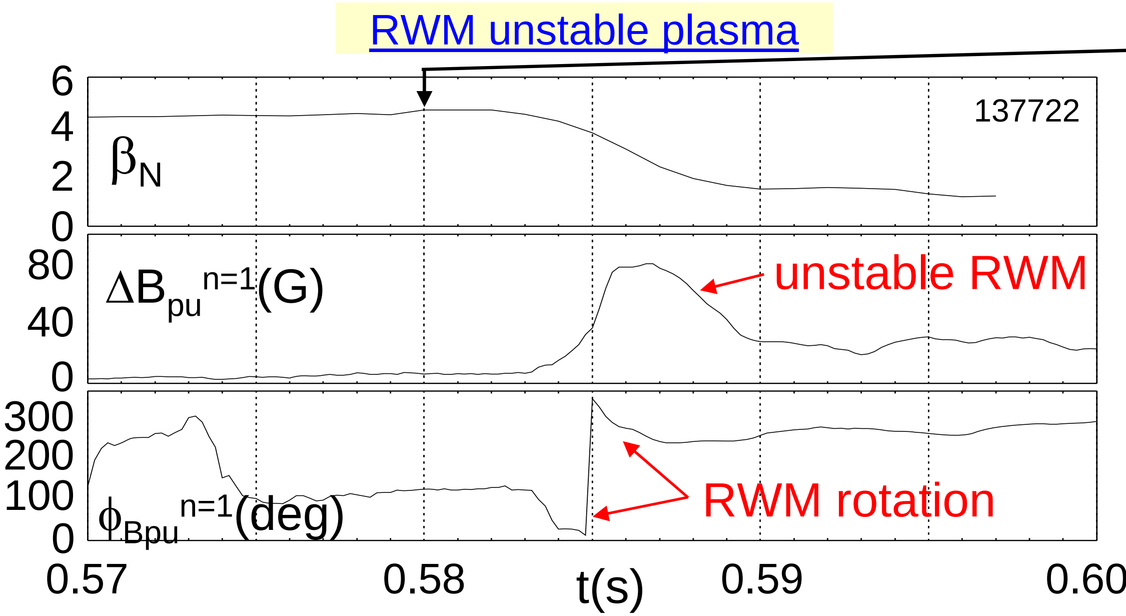


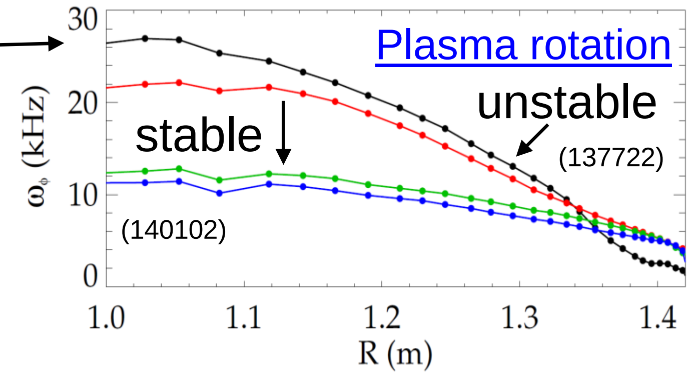
- High I_p >= 1.0MA, high non-inductive fraction ~ 50%
- Latest experiments
  - Yielded low l_i
  - Access high β_N/l_i
  - Reduced disruption probability (EXPLAIN THIS)

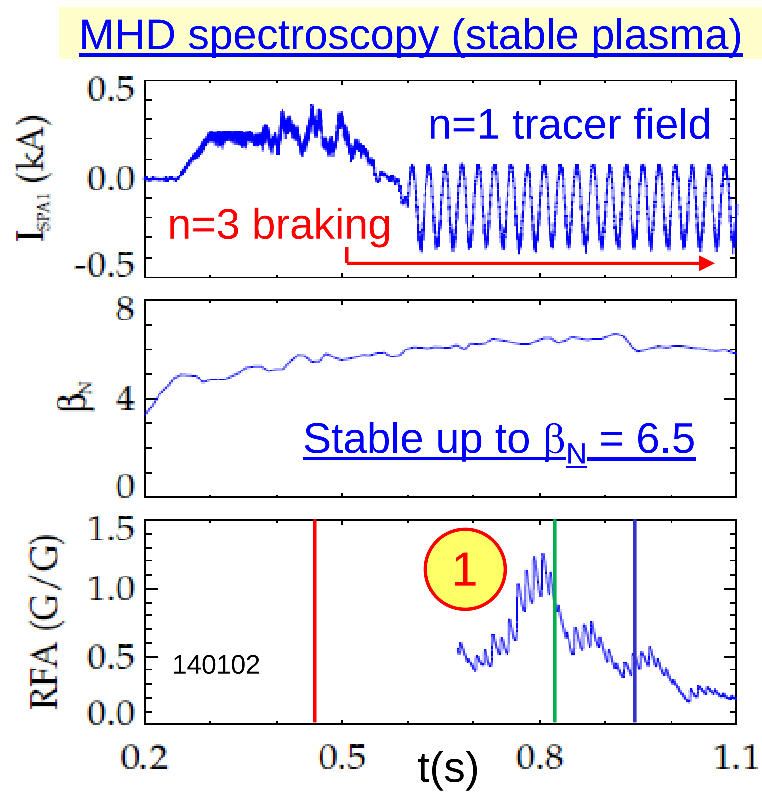
Characterization of Disruption Stats and Wtot variation here

- Show improved disruption statistics and Wtot variation
- Disruption Statistics
- Wtot variation

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)

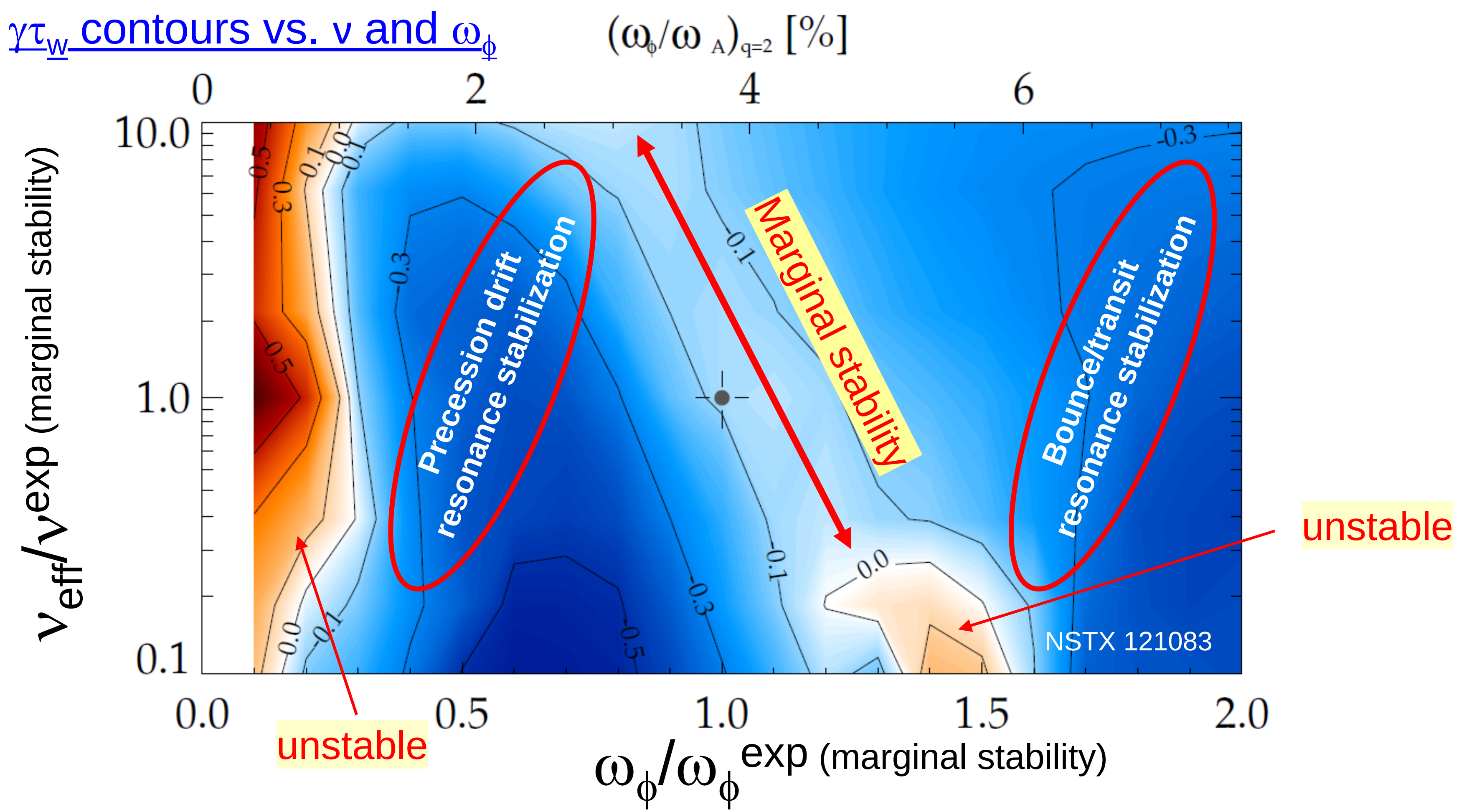
$$\delta W_K \propto \int \left[\frac{\omega_{*N} + \left(\hat{\varepsilon} - \frac{3}{2}\right)\omega_{*T} + \omega_E - \omega - i\gamma}{\langle \omega_D \rangle + l\omega_b - i\nu_{eff} + \omega_E - \omega - i\gamma} \right] \hat{\varepsilon}^{\frac{5}{2}} e^{-\hat{\varepsilon}} d\hat{\varepsilon}$$

← Energy integral

precession drift ($\langle \omega_D \rangle$), bounce ($l\omega_b$), collisionality (ν_{eff})

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

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

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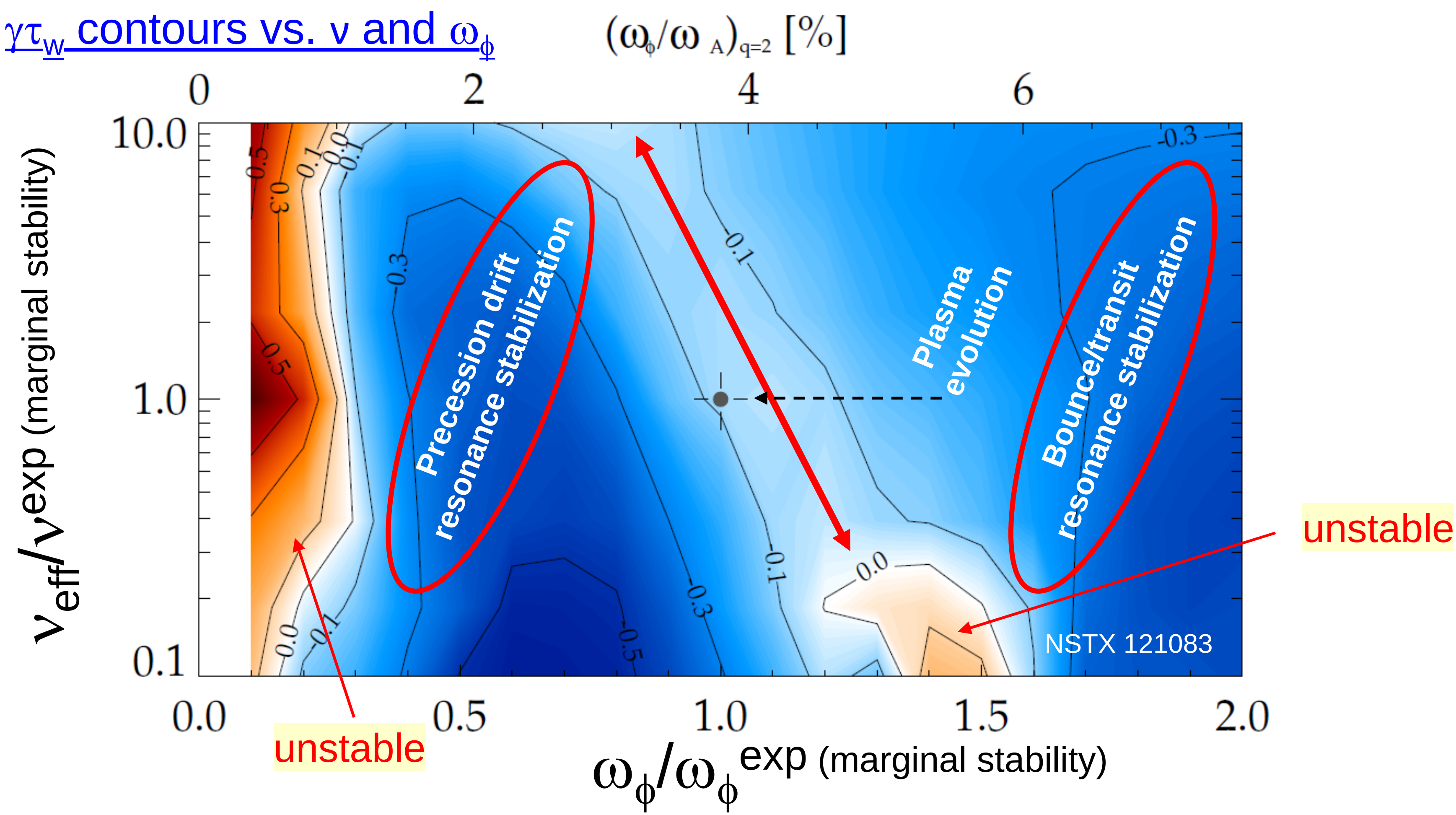

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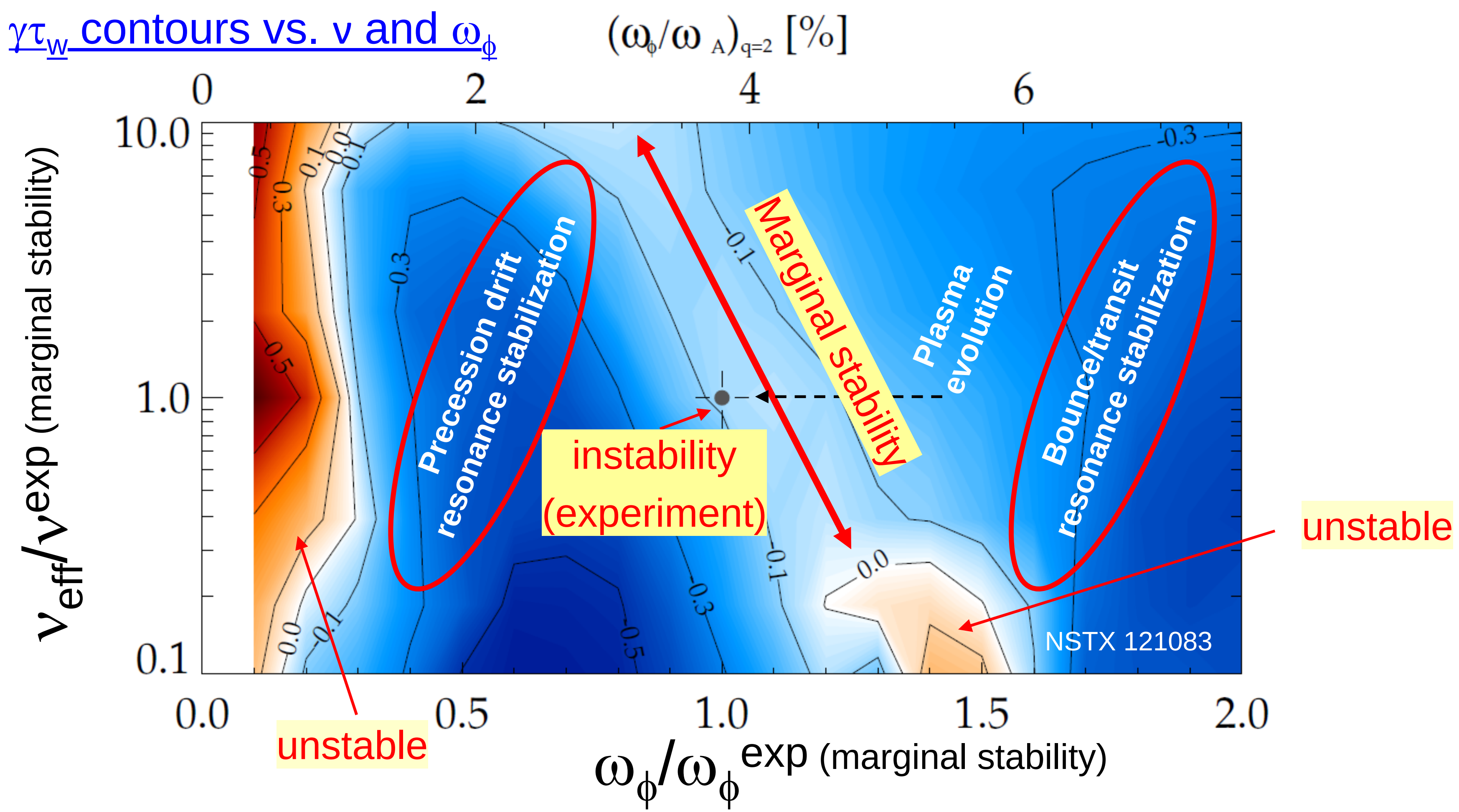


- Destabilization appears between precession drift resonance at low ω_ϕ, bounce/transit resonance at high ω_ϕ
- Destabilization moves to increased ω_ϕ as ν decreases

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

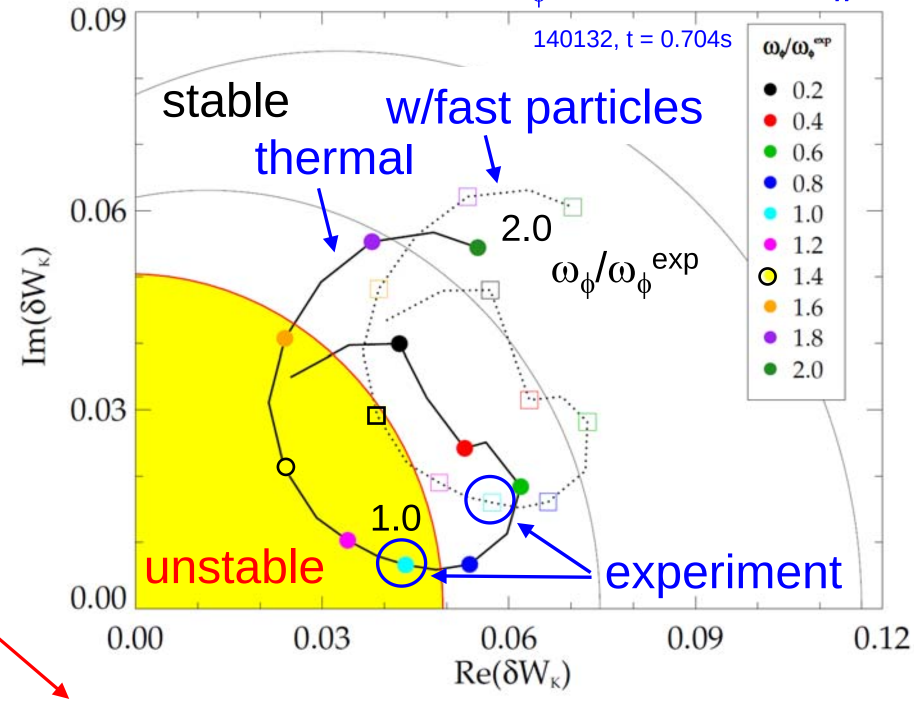
MISK calculations show reduced stability in low l_i target plasma as ω_ϕ is reduced, RWM instability is approached

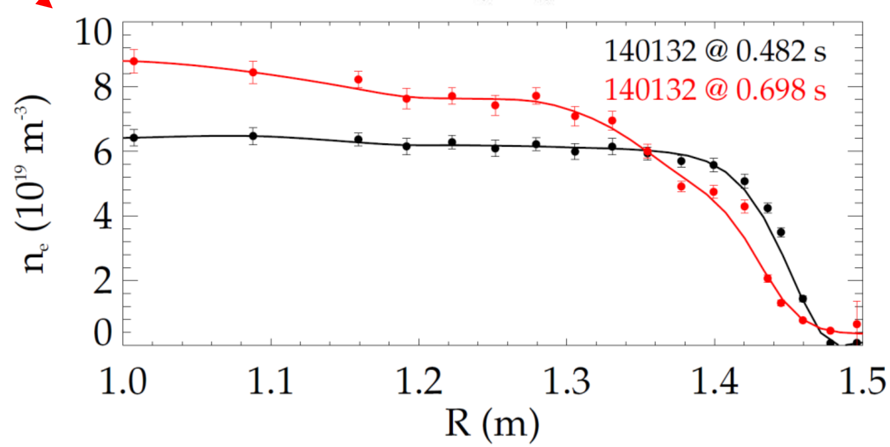
- Stability evolves
  - l_i increases in time as RWM instability is approached, but remains low (l_i = 0.42)
  - MISK computation shows plasma to be stable at time of minimum l_i
  - Region of reduced stability vs. ω_ϕ found before RWM becomes unstable (l_i = 0.49)
    - Co-incident with a drop in edge density gradient – reduces kinetic stabilization

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

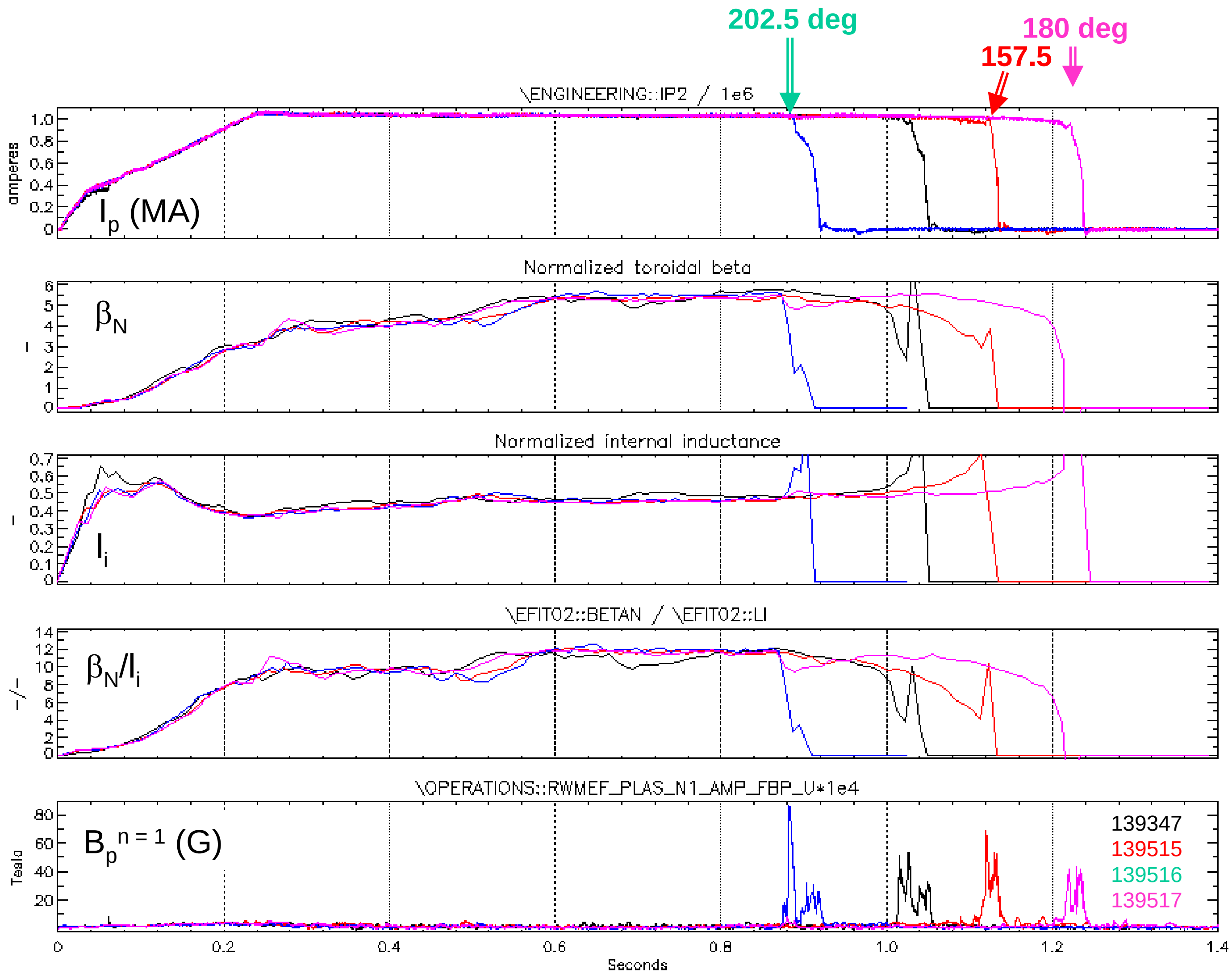
- BP9.00057 J. Berkery, et al.
- Also, see poster for detail

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



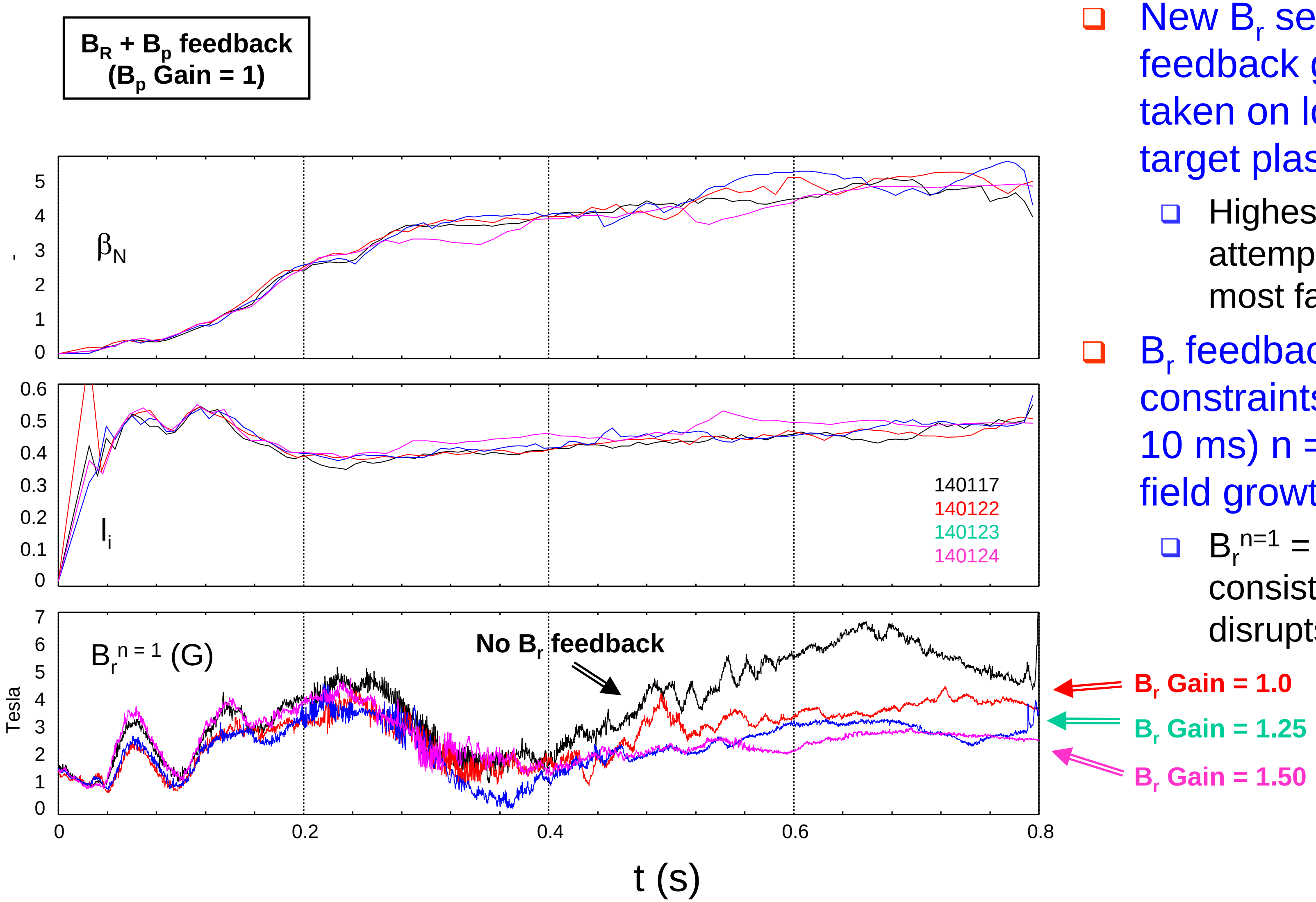


(Bp Feedback Phase Slide): Adjusting B_p sensor feedback phase around 180 degrees led to long-pulse, low l_i, high β_N/l_i



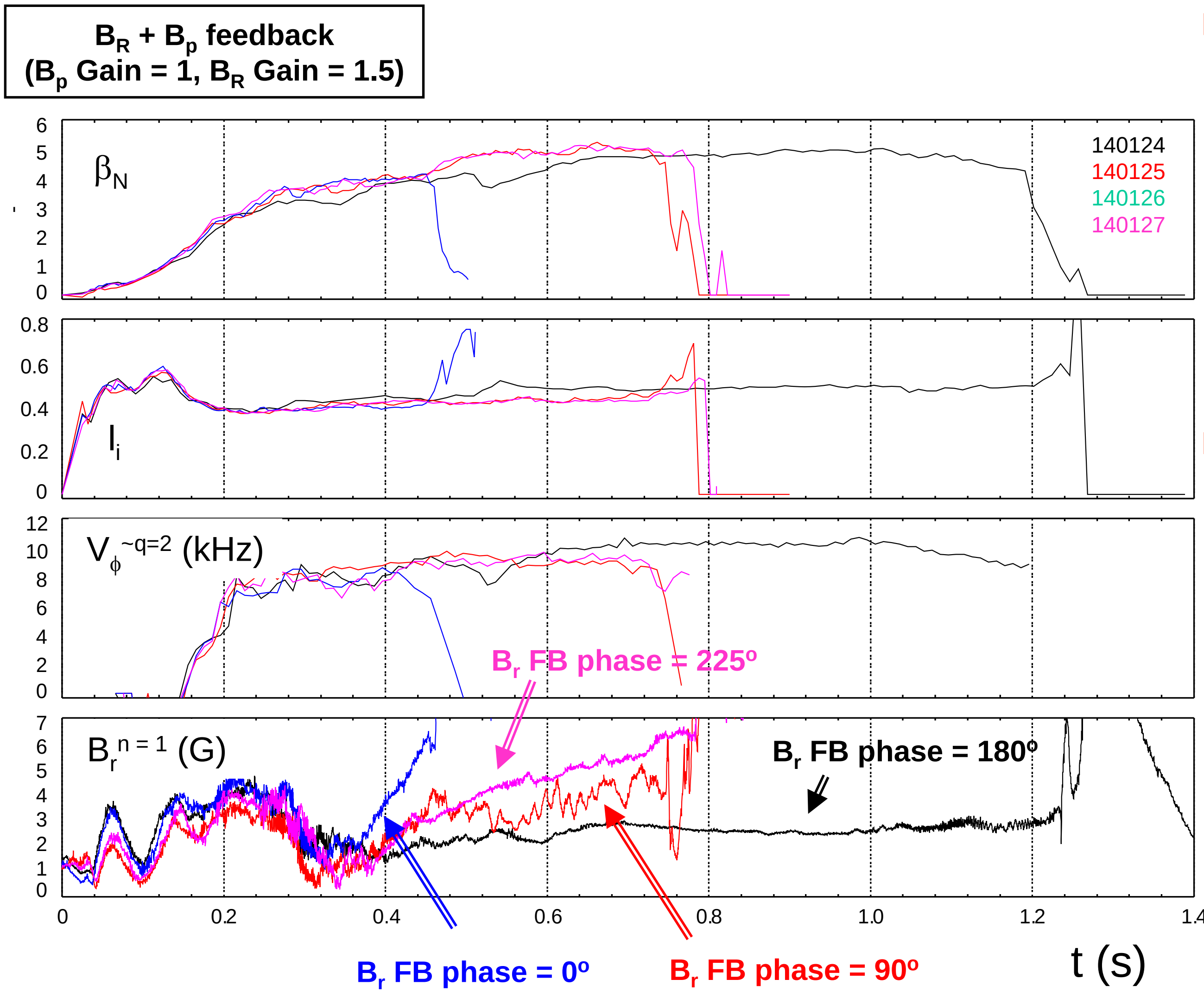
- Steady, high β_N/l_i
  - Between 12 – 13
- Low l_i state retained

(Br sensor slide – combine gain and phase scan?): RWM B_R sensor feedback reduces n= 1 radial error field significantly



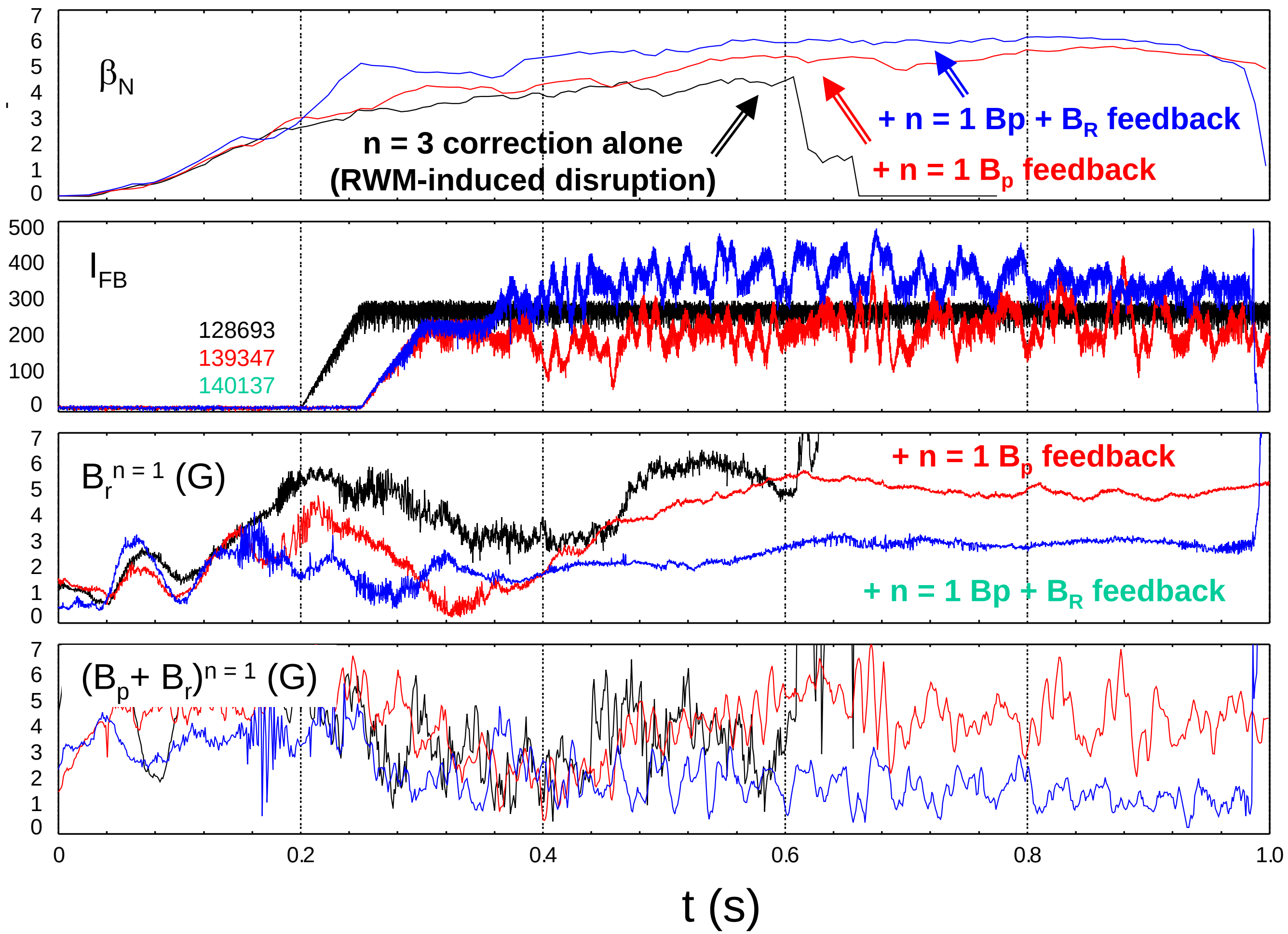
- New B_r sensor feedback gain scan taken on low l_i target plasmas
  - Highest gain attempted (1.5) most favorable
- B_r feedback constraints slow (~ 10 ms) n = 1 radial field growth
  - $B_r^{n=1}$ = 9G consistently disrupts plasma

RWM B_r sensor n= 1 feedback phase variation shows clear settings for positive/negative feedback



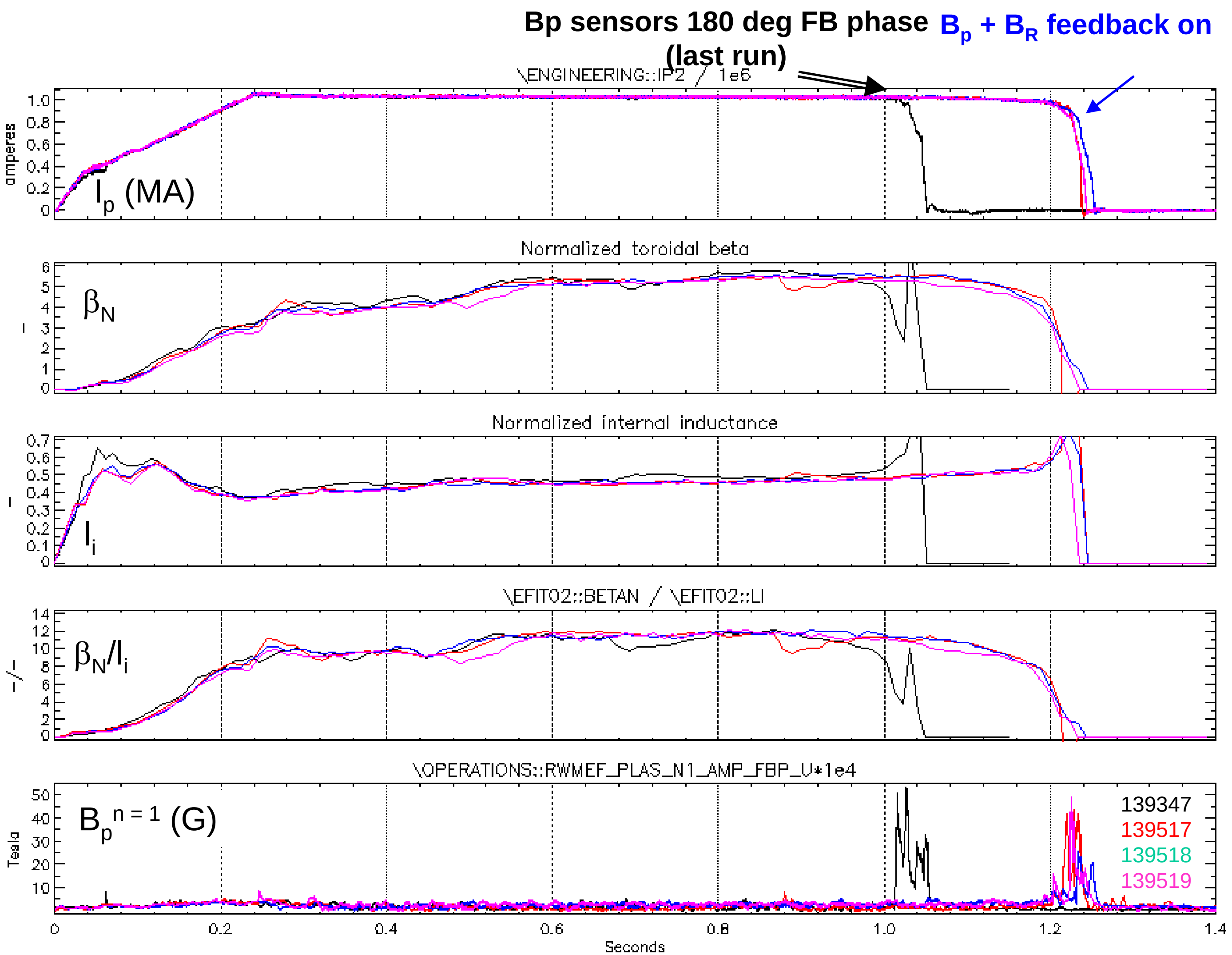
- B_r sensor feedback phase scan shows superior settings
  - Result clarified significantly by new MIU algorithm OHxTF compensation
- Positive/negative feedback produced at expected phase values
  - 180° negative FB
  - 90° positive FB
  - n=1 growth/decay of other settings bracketed by these settings

(ADD Mode dynamics / physics here): Use of combined RWM sensor n= 1 feedback yields best reduction of n = 1 fields / improved stability



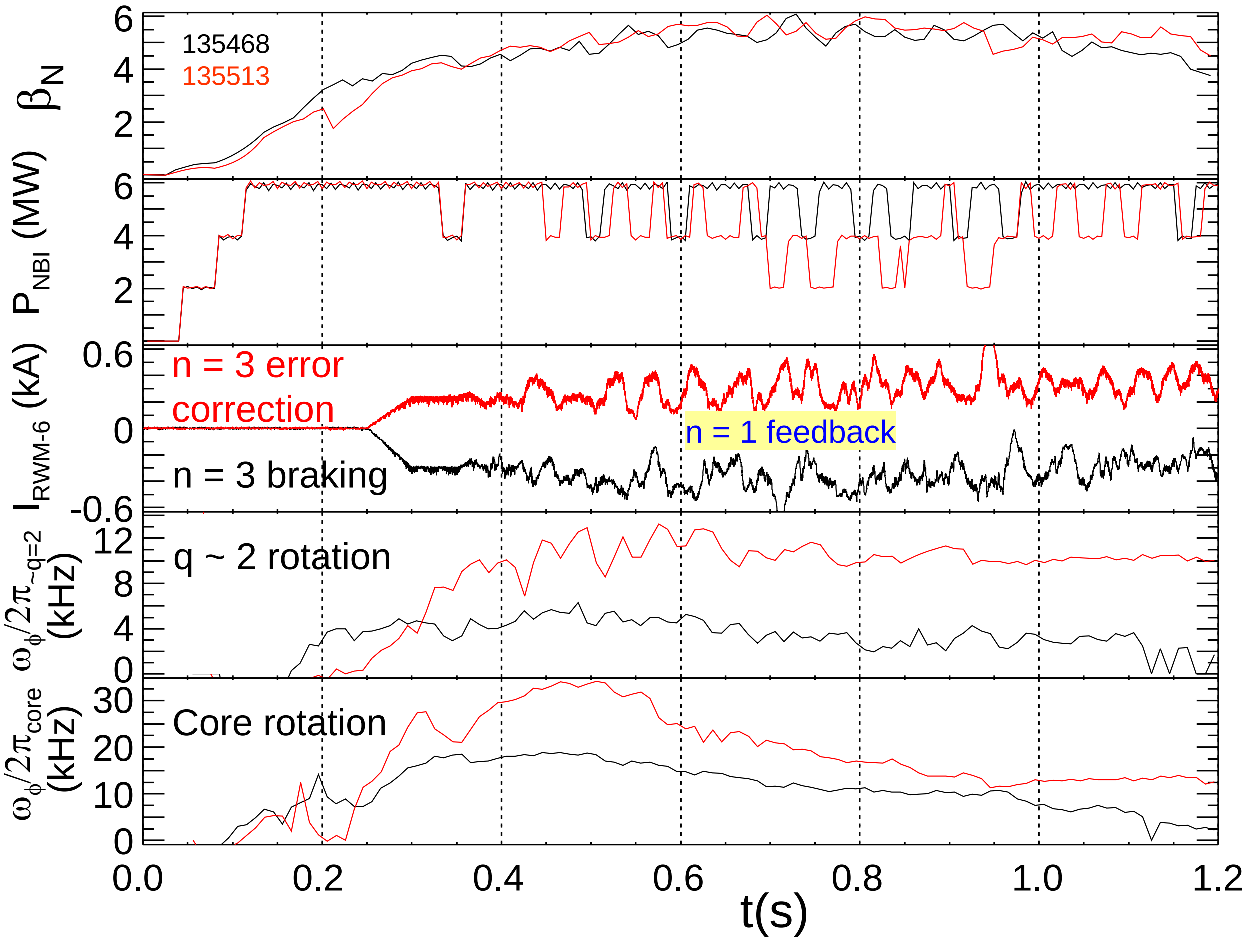
- Varied levels of n > 1 field correction
  - n = 3 DC error field correction alone more subject to RWM instability
  - n = 1 B_p sensor fast feedback sustains plasma
  - Addition of n = 1 B_R sensor FB prevents disruptions when amplitude reaches ~ 9G, better sustains rotation

B_R sensors added: longest pulse plasmas, high performance



- Combined use of Bp and Br sensor feedback is best
  - Cases ran with MIU compens. on, or off
  - Continued use of feedback has MIU compens. on with good result

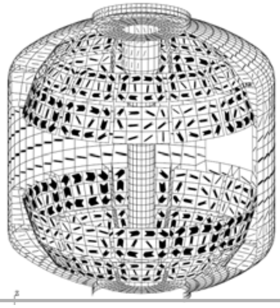
β_N feedback combined with n = 1 RWM control to reduce β_N fluctuations at varied plasma rotation levels



- 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 added to n = 1 feedback (2010)
  - Full sensor set further reduces n = 1 amplitude, improves control

New RWM state space controller (RWMSC) implemented to sustain high β_N

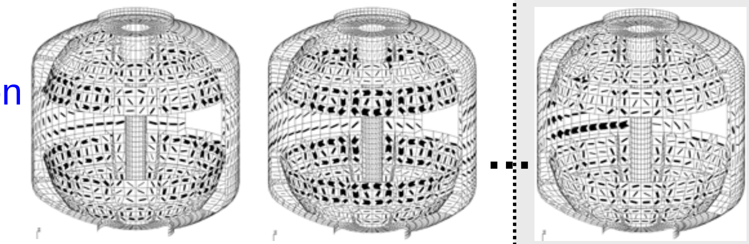
Full 3-D model ~3000+ states



Balancing transformation

State reduction (< 20 states)

RWM eigenfunction (2 phases, 2 states)



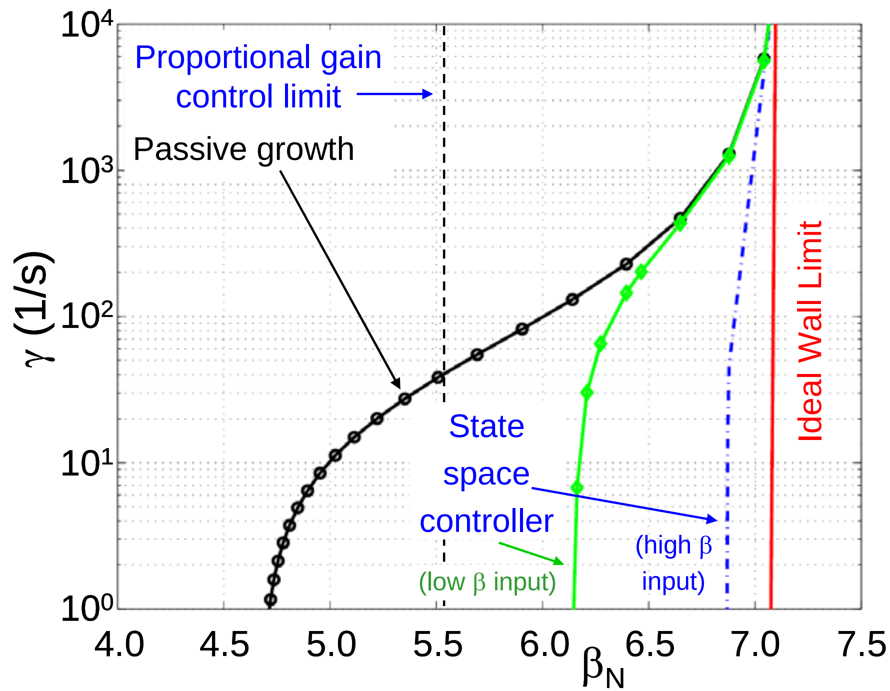
$(\hat{x}_1, \hat{x}_2)$ $\hat{x}_3$ $\hat{x}_4$ ... $\hat{x}_N$ truncate

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

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

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

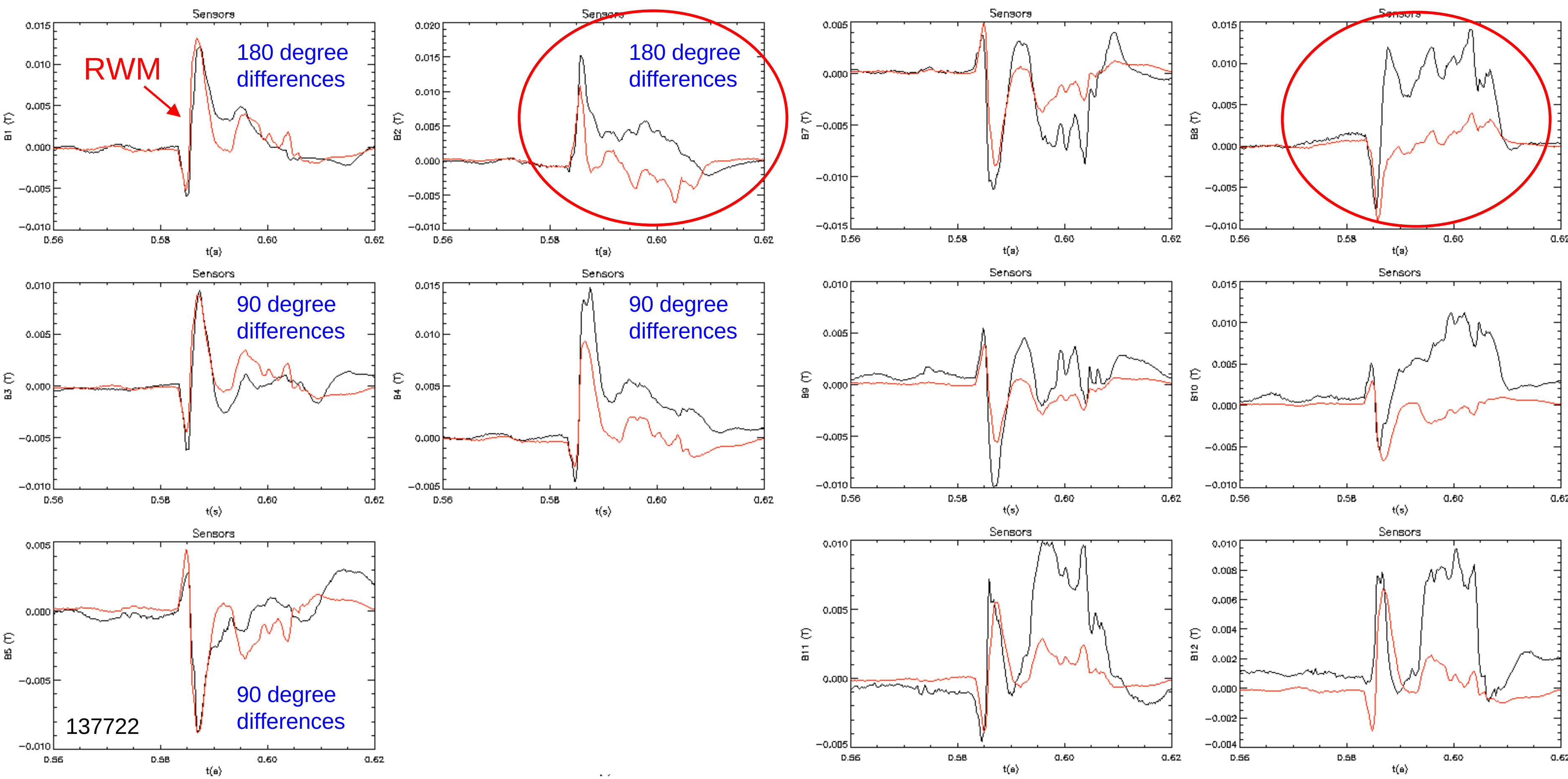
Theoretical feedback performance (ω_ϕ = 0, 12 states)



RWM state space controller with 2 states reproduces initial sensor response to mode

Bp UPPER Sensor differences

Bp LOWER Sensor differences



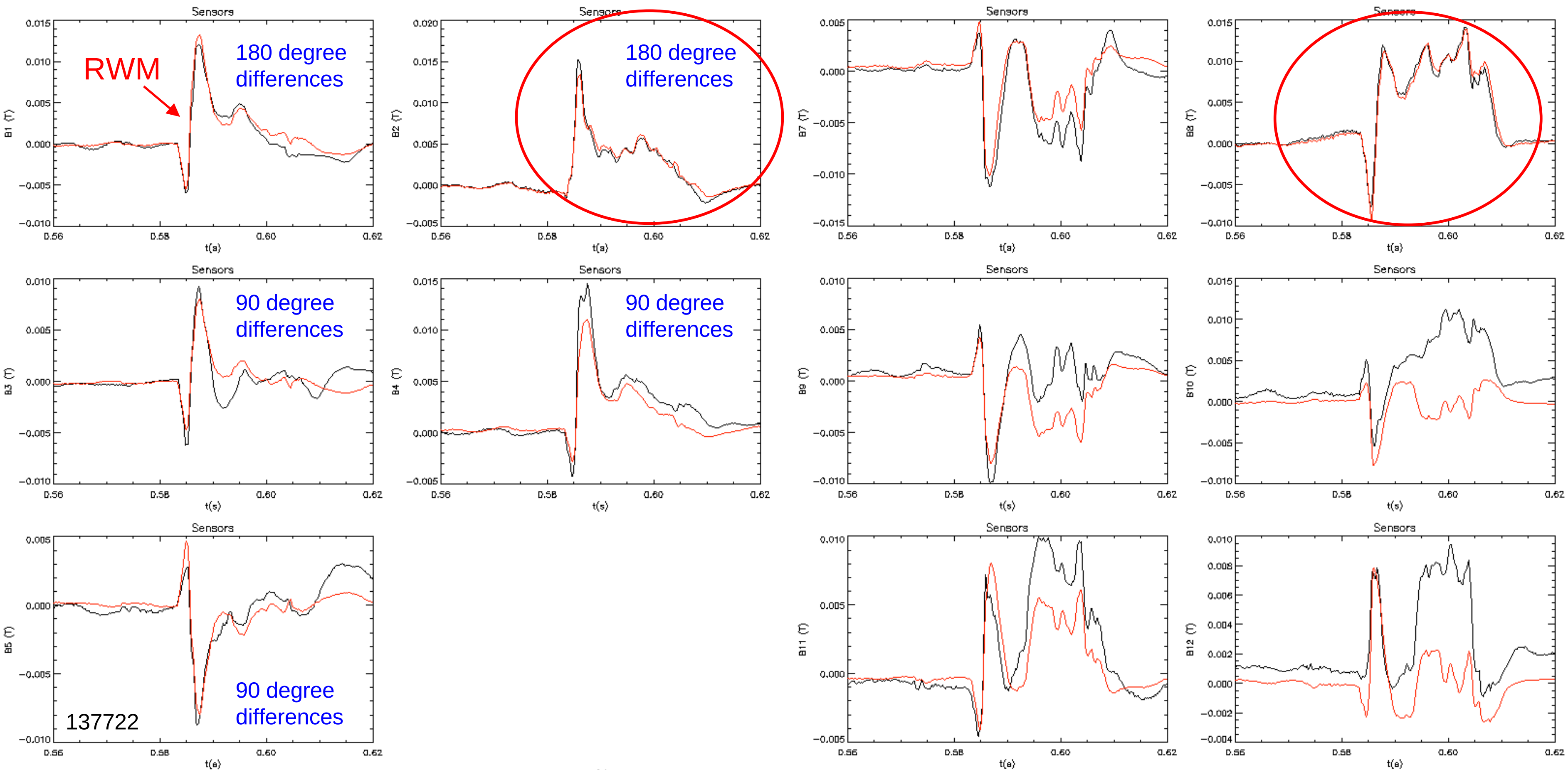
- Reasonable match to all B_p sensors during RWM onset, large differences later in evolution

Black: experiment
Red: offline RWMSC

RWM state space controller with 7 states improves match to sensors over entire evolution

Bp UPPER Sensor differences

Bp LOWER Sensor differences

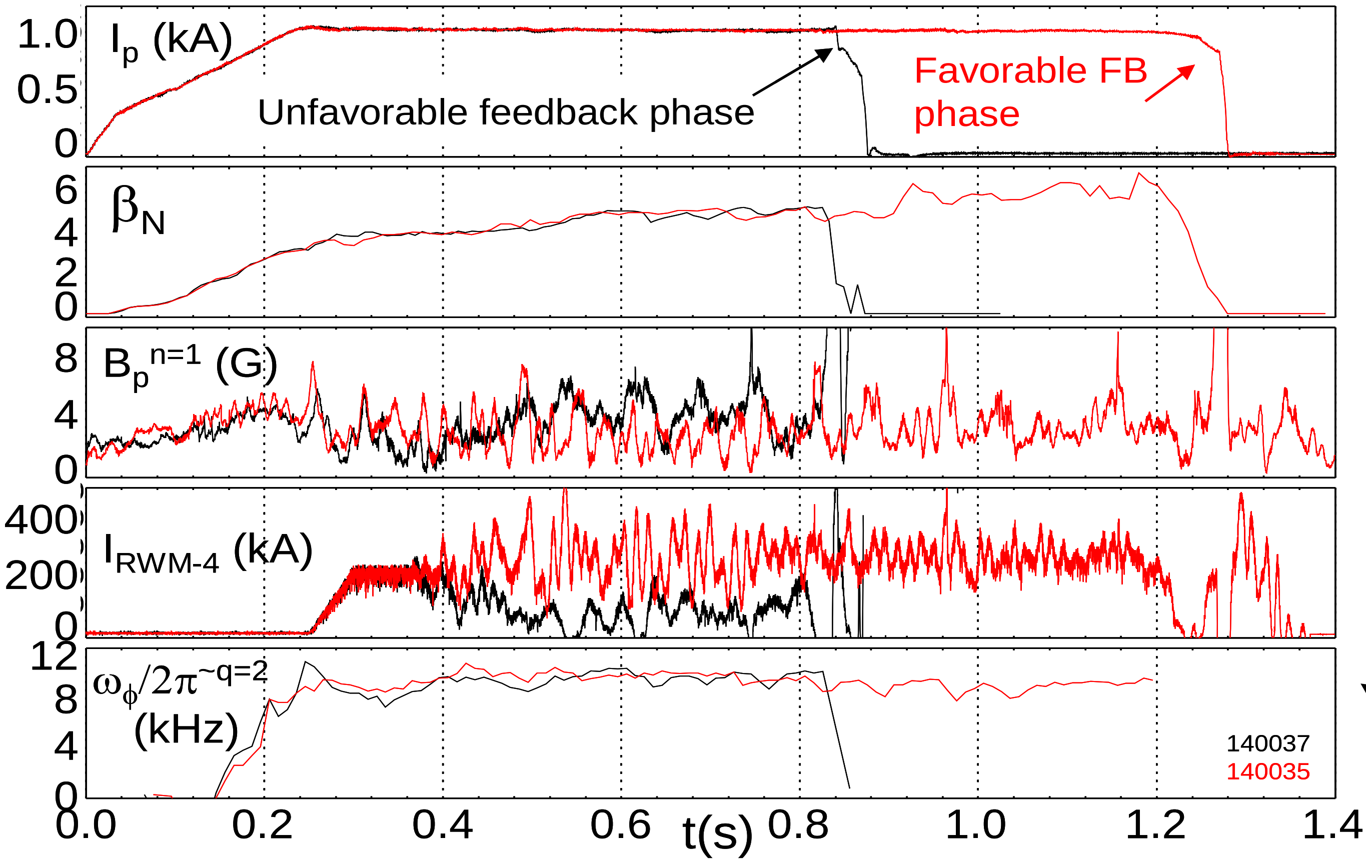


- Some 90 degree sensor differences not as well matched
  - May indicate need for n = 2 eigenfunction state

Black: experiment
Red: offline RWMSC

New RWM state space controller sustains high β_N plasma

RWM state space feedback (12 states)

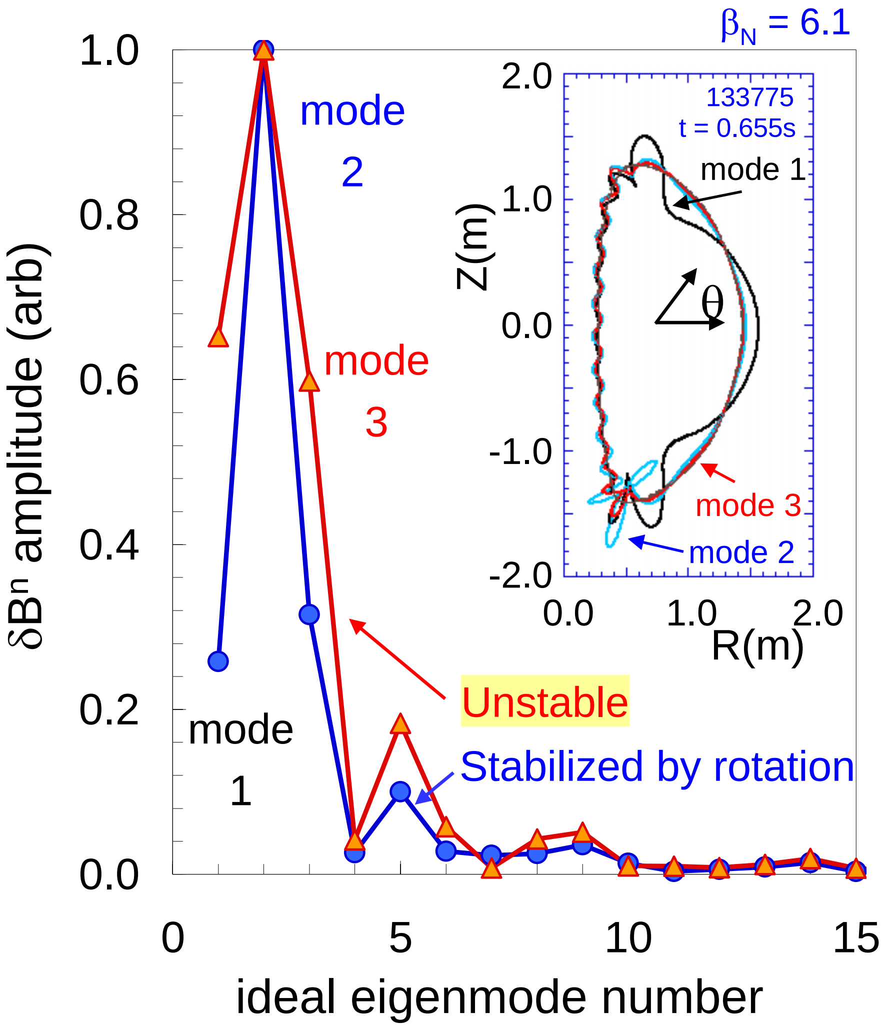


Successful First Experiments

- 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

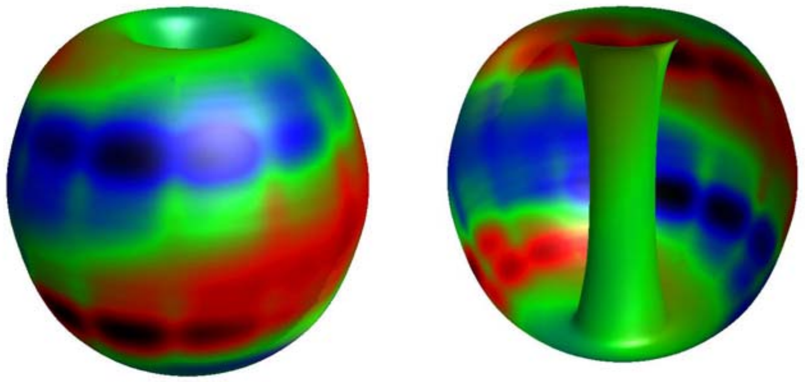
Multi-mode RWM computation shows 2nd eigenmode component has dominant amplitude at high β_N in NSTX stabilizing structure

δB^n RWM multi-mode composition



mmVALEN code

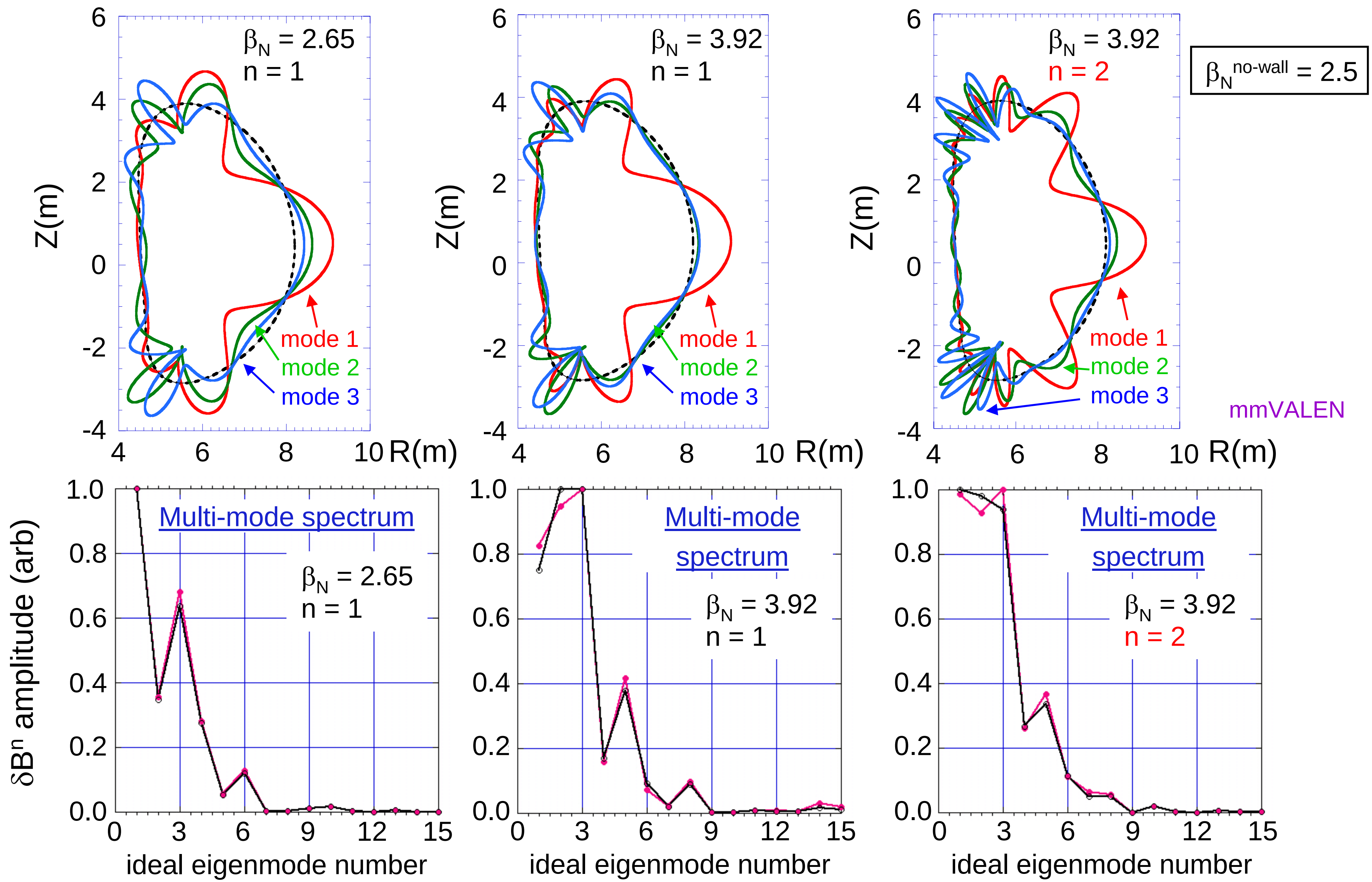
δB^n from wall, multi-mode response



- 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 kHz
- ITER scenario IV multi-mode spectrum
  - Significant spectrum for n = 1 and 2

BP9.00059 J. Bialek, et al.

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 Plasmas

Physics addressed	Implications for Future STs (NBI-driven, high ω_ϕ)	Implications for ITER advanced scenarios (low ω_ϕ)
❑ RWM instability observed at intermediate ω_ϕ correlates with kinetic stability theory	❑ ω_ϕ profile control ❑ Sufficient EP stabilization	❑ Sufficient EP stabilization needed at low ω_ϕ
❑ n = 1 RWM, β_N feedback control maintains high β_N at varied ω_ϕ using n = 3 NTV ω_ϕ profile modification	❑ Potential control compatibility	❑ Potential control at low ω_ϕ if EP stabilization insufficient
❑ (text)	❑ (text)	❑ (text)
❑ Initial success of RWM state space controller at high β_N	❑ More flexibility of control coil placement	❑ More flexibility of control coil placement
❑ Multi-mode RWM physics spectrum	❑ Determine RWM control impact	❑ Determine RWM control impact