

Stabilization of Low Internal Inductance Plasmas and First RWM State Space Control Experiments in NSTX

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Japan Workshop**

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

□ Motivation

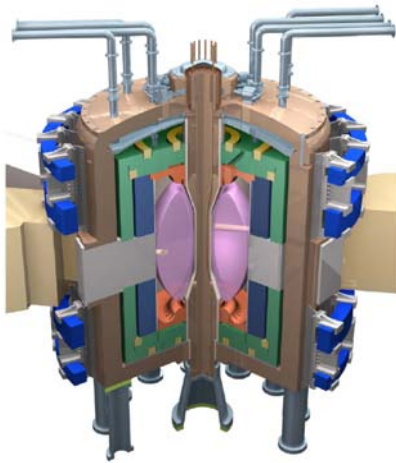
- Sustain high β_N with sufficient physics understanding to allow confident extrapolation to spherical torus applications (e.g. ST Component Test Facility, ST-Pilot plant, ST-DEMO)
- Operate at low internal inductance (I_i), consistent with desired high elongation and non-inductive (bootstrap, etc.) current fraction
- Demonstrating / understanding global mode stability at low I_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 I_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

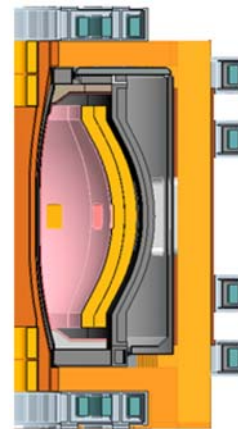
FNSF / ST-CTF



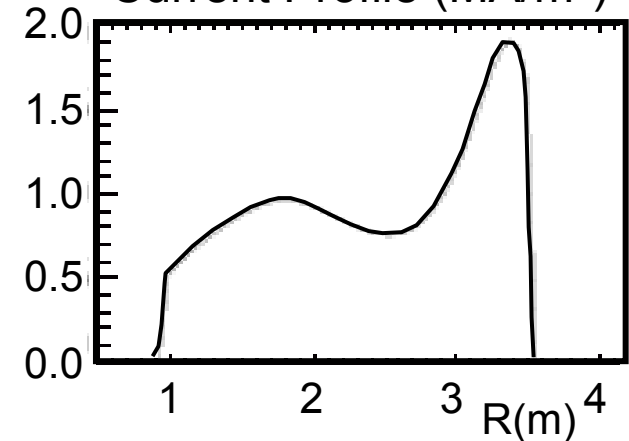
Y.K.M. Peng, et al., PPCF **47** (2005) B263

ST-Pilot ($Q_{\text{eng}} = 1$)

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



Current Profile (MA/m²)



$$I_i = 0.47, \kappa = 3.2$$

$$R = 2.23 \text{ m}, A = 1.7$$

$$I_p = 16 \text{ MA}, B_t = 2.4 \text{ T}$$

$$\beta_N = 5.2, \beta_t = 30\%$$

❑ Broad current profile \rightarrow low $I_i = \langle B_p^2 \rangle / \langle B_p \rangle_\psi^2$, has global mode stability implications

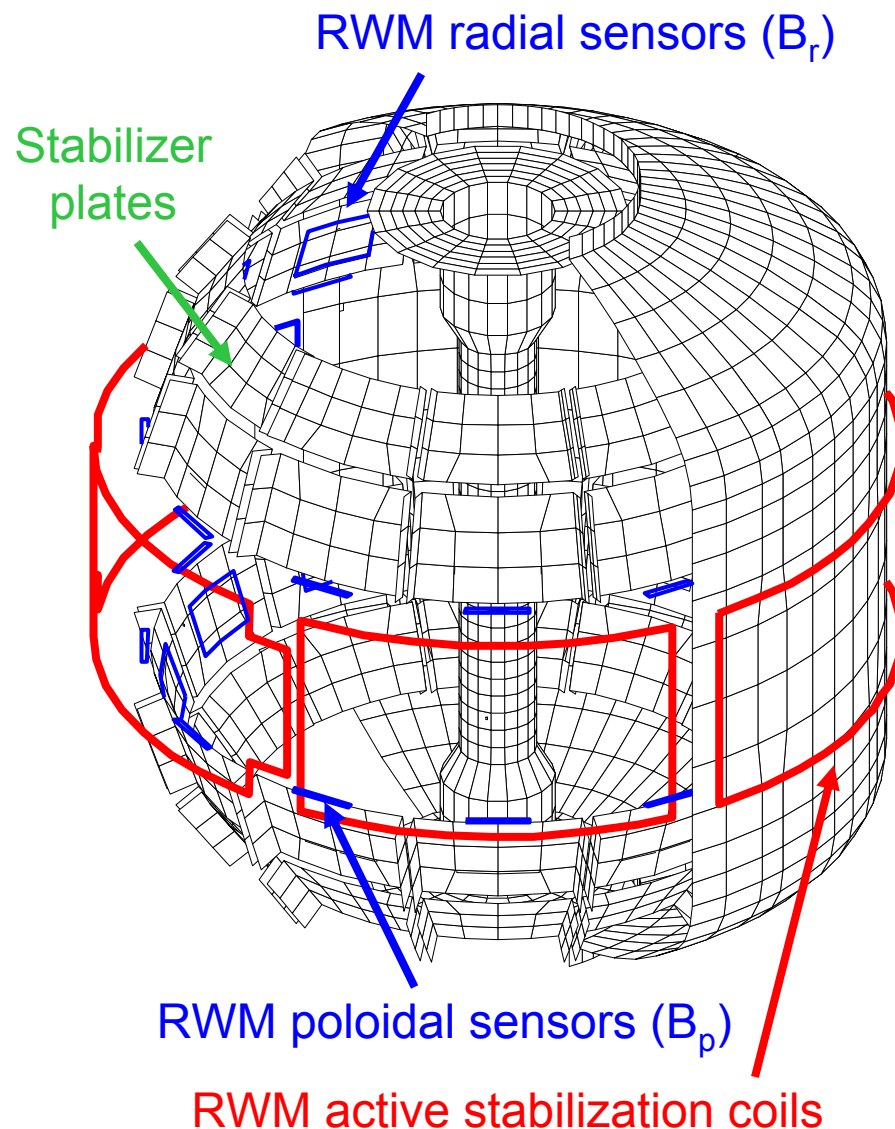
- ❑ Improved vertical ($n = 0$) and wall-stabilized, rotating kink ($n = 1$) stability
- ❑ Decreased RWM stability, influenced by ω_ϕ
- ❑ “Troyon limit” (ideal, static $n = 1$ no-wall stability limit)

$$\beta_N = 10^8 \beta_t a B_t / I_p = \text{constant} \sim 3; \text{ variants: } \beta_N \propto I_i, \beta_N \propto 1/(\text{pressure peaking})$$

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

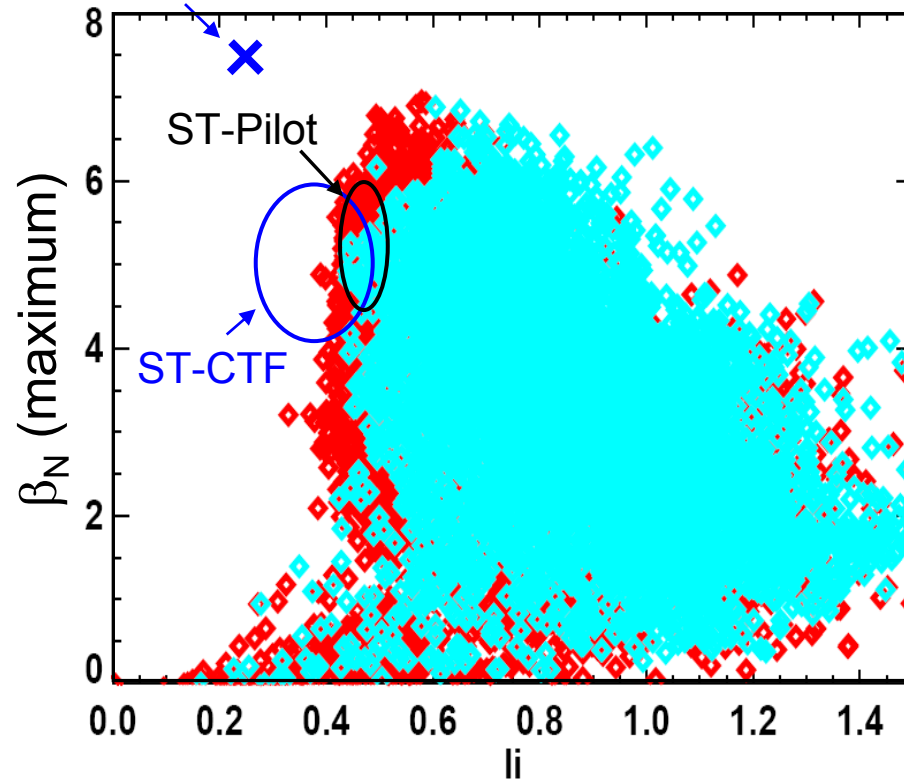
- ❑ High beta, low aspect ratio
 - ❑ $R = 0.86 \text{ m}$, $A > 1.27$
 - ❑ $I_p < 1.5 \text{ MA}$, $B_t = 5.5 \text{ kG}$
 - ❑ $\beta_t < 40\%$, $\beta_N > 7$
- ❑ Copper stabilizer plates for kink mode stabilization
- ❑ Midplane control coils
 - ❑ $n = 1 - 3$ field correction, magnetic braking of ω_ϕ 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 I_i and high pulse-averaged β_N

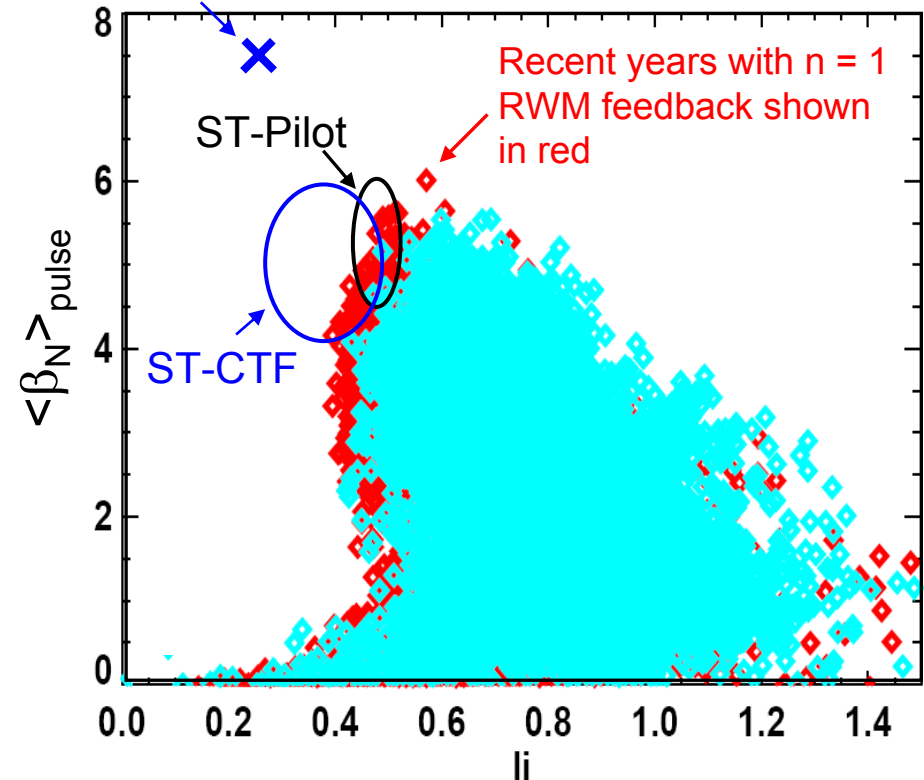
β_N vs. I_i (maximum values)

ST-DEMO (ARIES-ST)



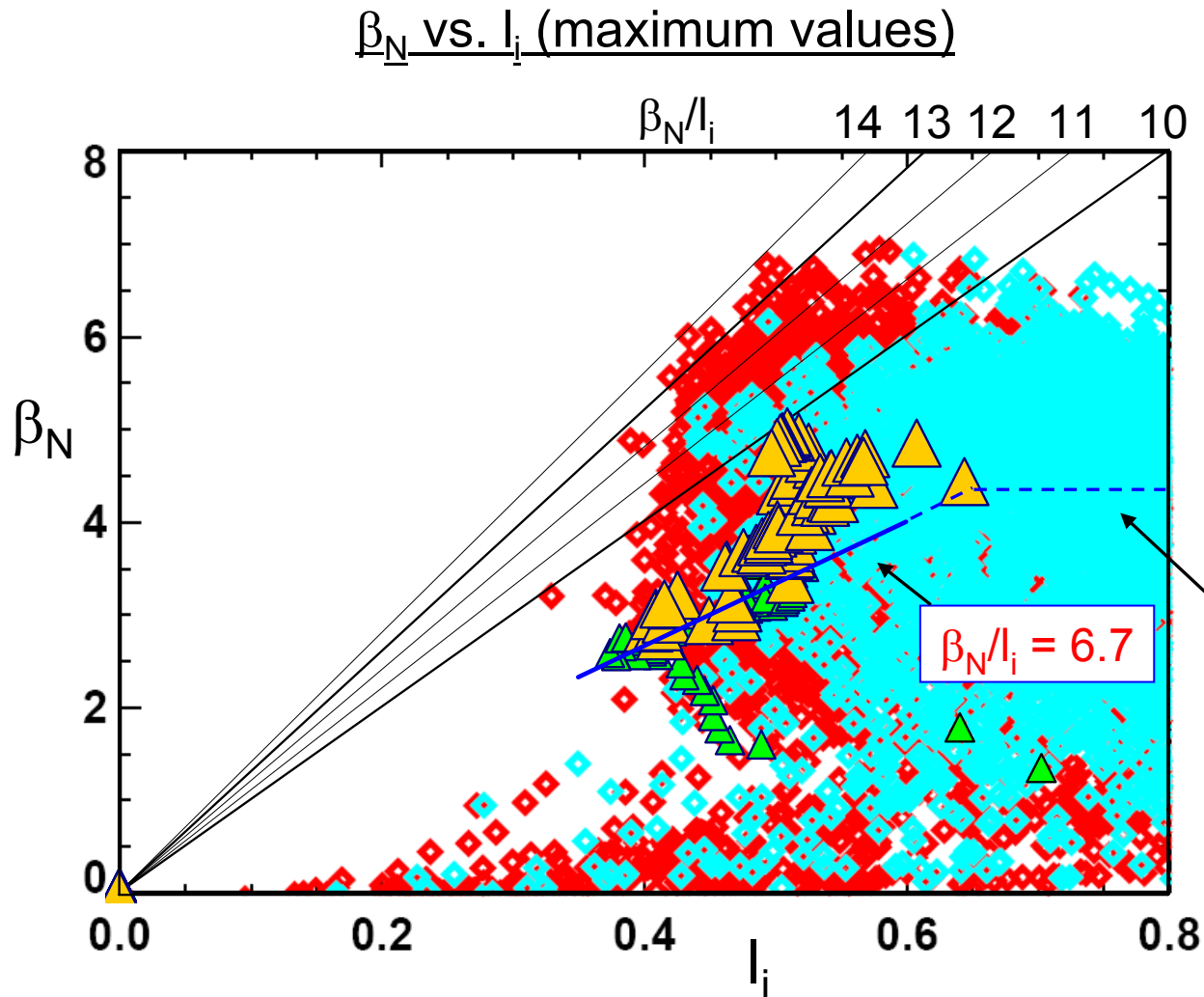
β_N vs. I_i (pulse-averaged values)

ST-DEMO (ARIES-ST)



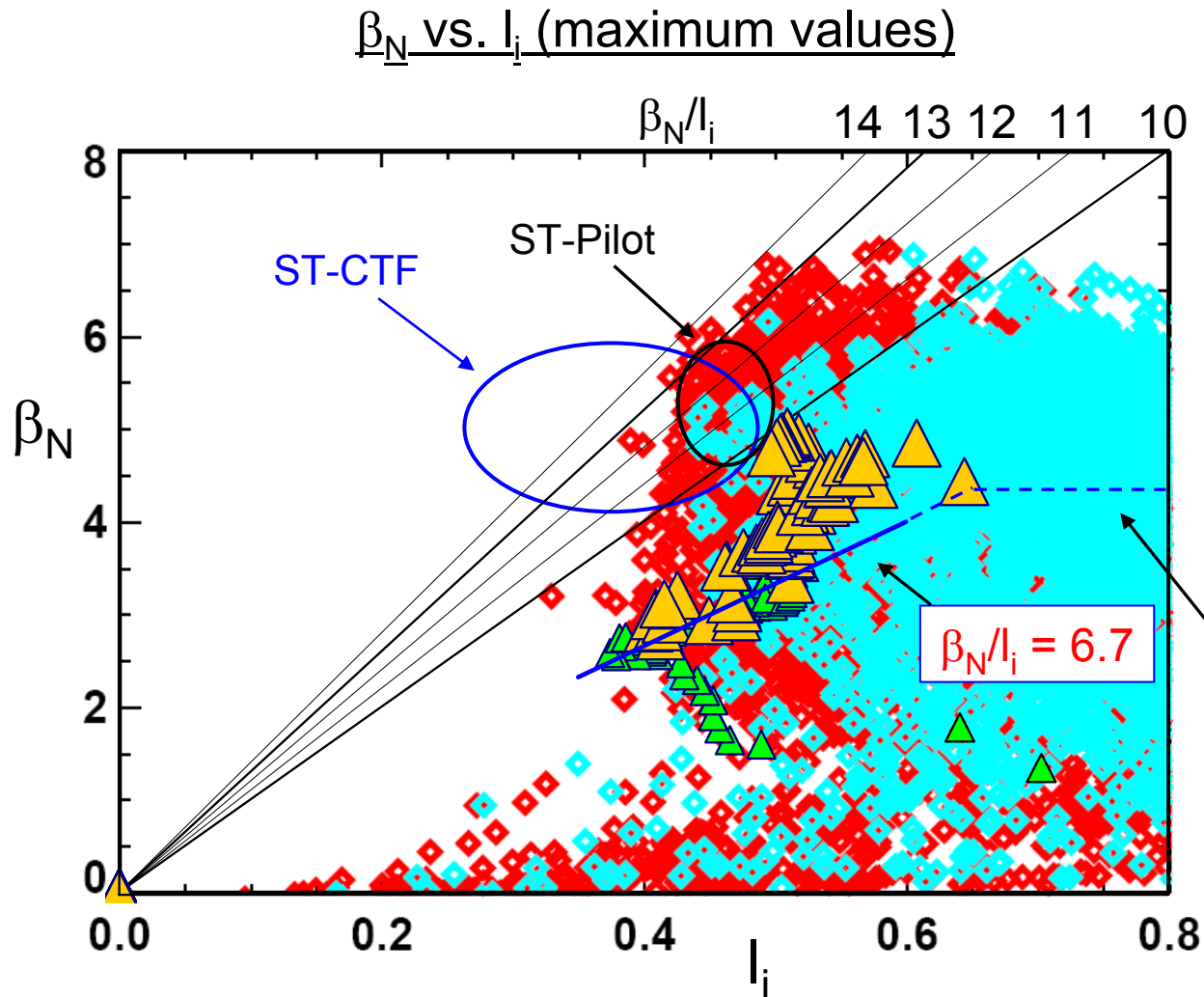
- Plasmas have begun to reach low I_i and high $\langle \beta_N \rangle_{\text{pulse}}$ suitable for next-step ST fusion devices
 - Some parameters (e.g. elongation > 3) still need to be reached self-consistently

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



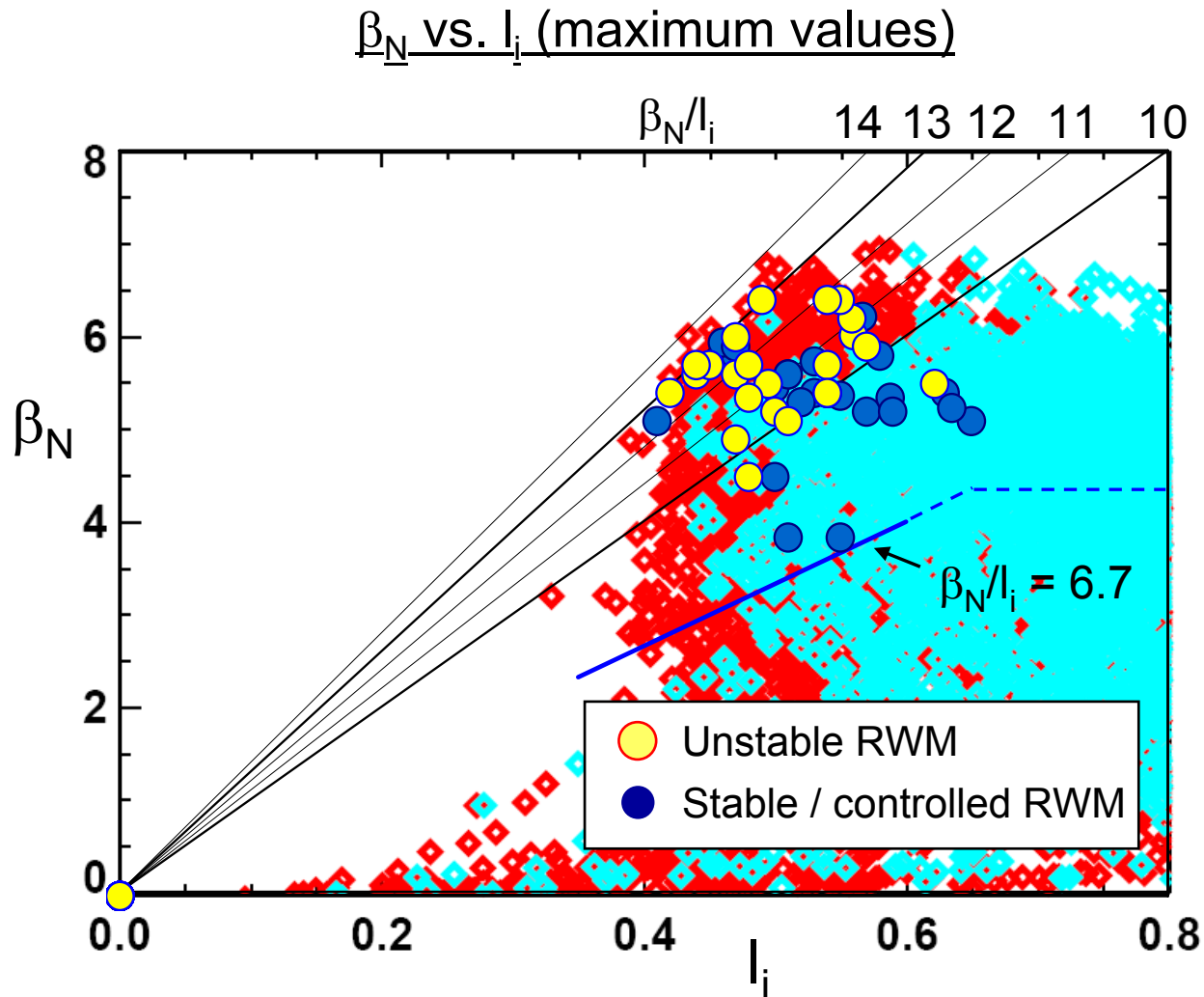
- Examine high plasma current, $I_p \geq 1.0\text{MA}$, high non-inductive fraction $\sim 50\%$, $I_i \sim 0.4 - 0.5$
- Significant increase in maximum β_N/I_i
 - Upper limit now between 13 - 14
- Ideal $n = 1$ no-wall stability computed for discharge trajectory
 - Adding trajectories yields $\beta_N/I_i = 6.7$ for $I_i = 0.38 - 0.6$
 - Significantly lower than no-wall limit at higher I_i ($\beta_N = 4.3$)

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 - Adding trajectories yields $\beta_N/I_i = 6.7$ for $I_i = 0.38 - 0.6$
 - Significantly lower than no-wall limit at higher I_i ($\beta_N = 4.3$)
 - RWM control will be important for future ST fusion devices

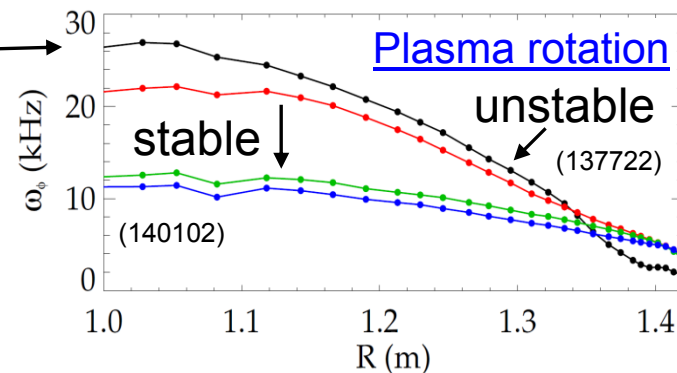
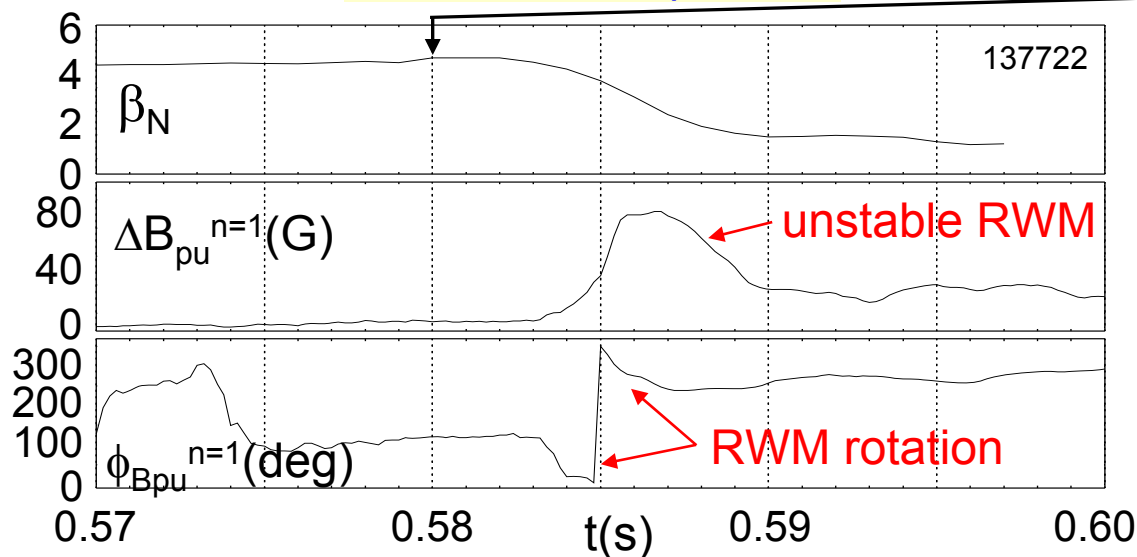
Global stability examined for experiments aimed to produce sustained low I_i and high β_N at high plasma current



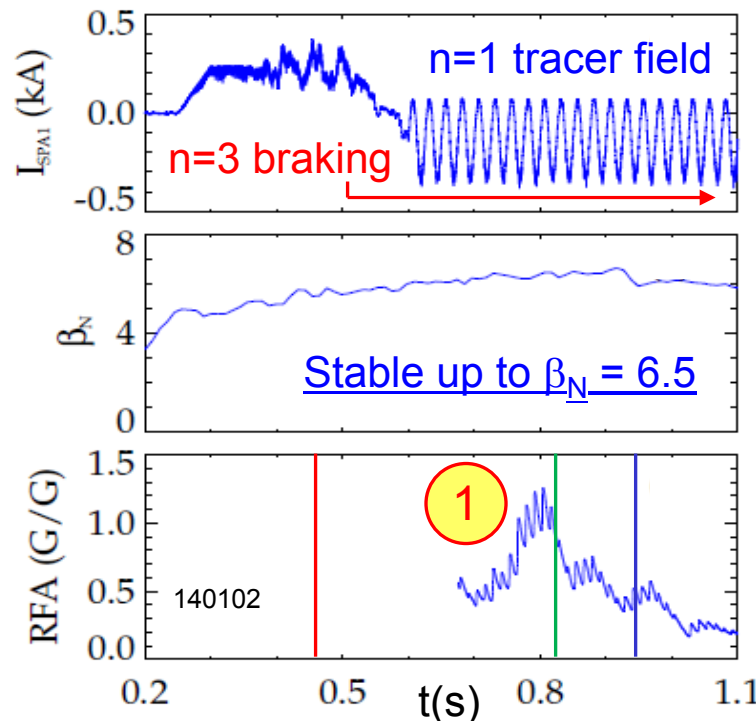
- High $I_p \geq 1.0\text{MA}$, high non-inductive fraction $\sim 50\%$
- Initial experiments
 - Yielded low I_i
 - Access high β_N/I_i
 - High disruption probability
- Instabilities leading to disruption
 - Unstable RWM
 - 48% of cases run
 - Locked tearing modes

Low plasma rotation level ($\sim 1\% \omega_{\text{Alfvén}}$) is insufficient to ensure RWM stability, which depends on ω_ϕ profile

RWM unstable plasma



MHD spectroscopy (stable plasma)



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
- Plasma moves to more stable regime (lower RFA) at lower rotation (β_N up to 6.5)

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

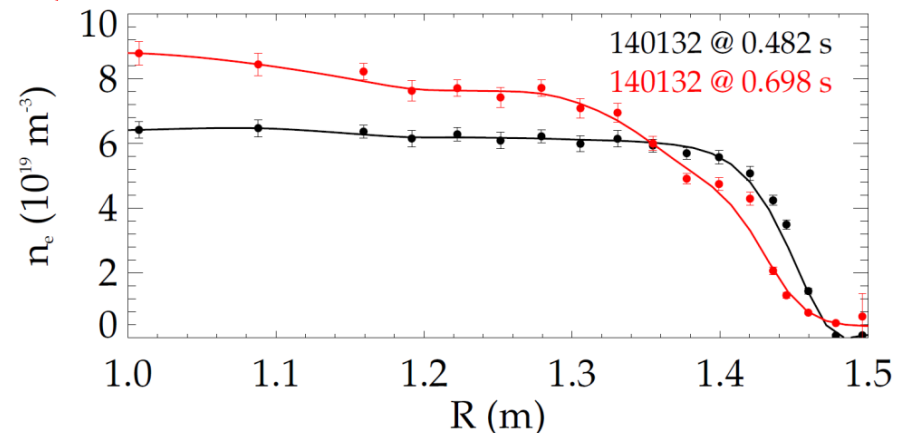
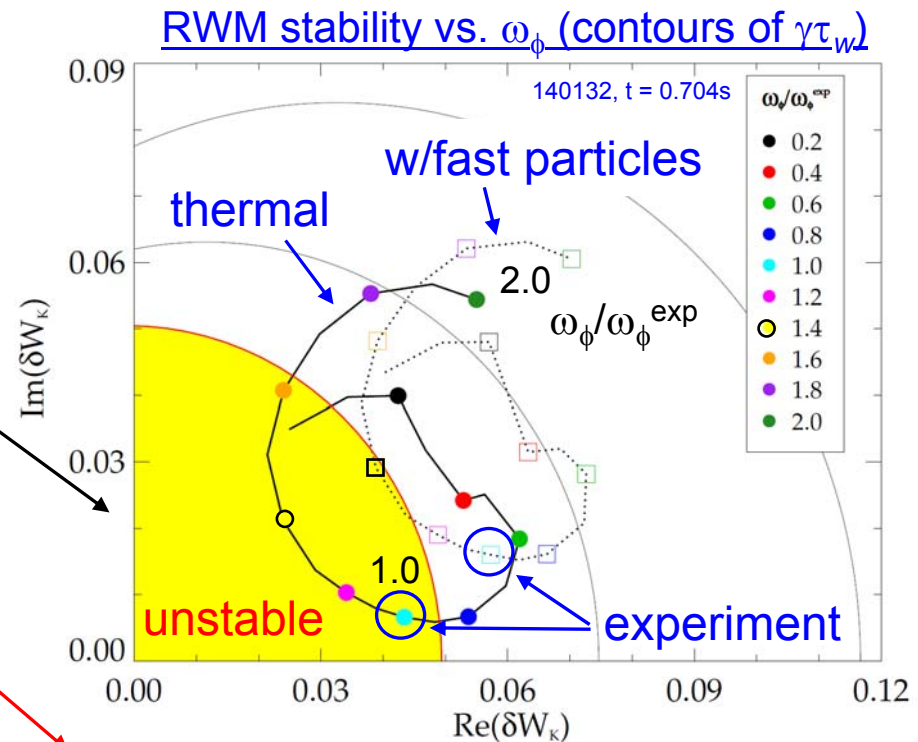
Stability evolves

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

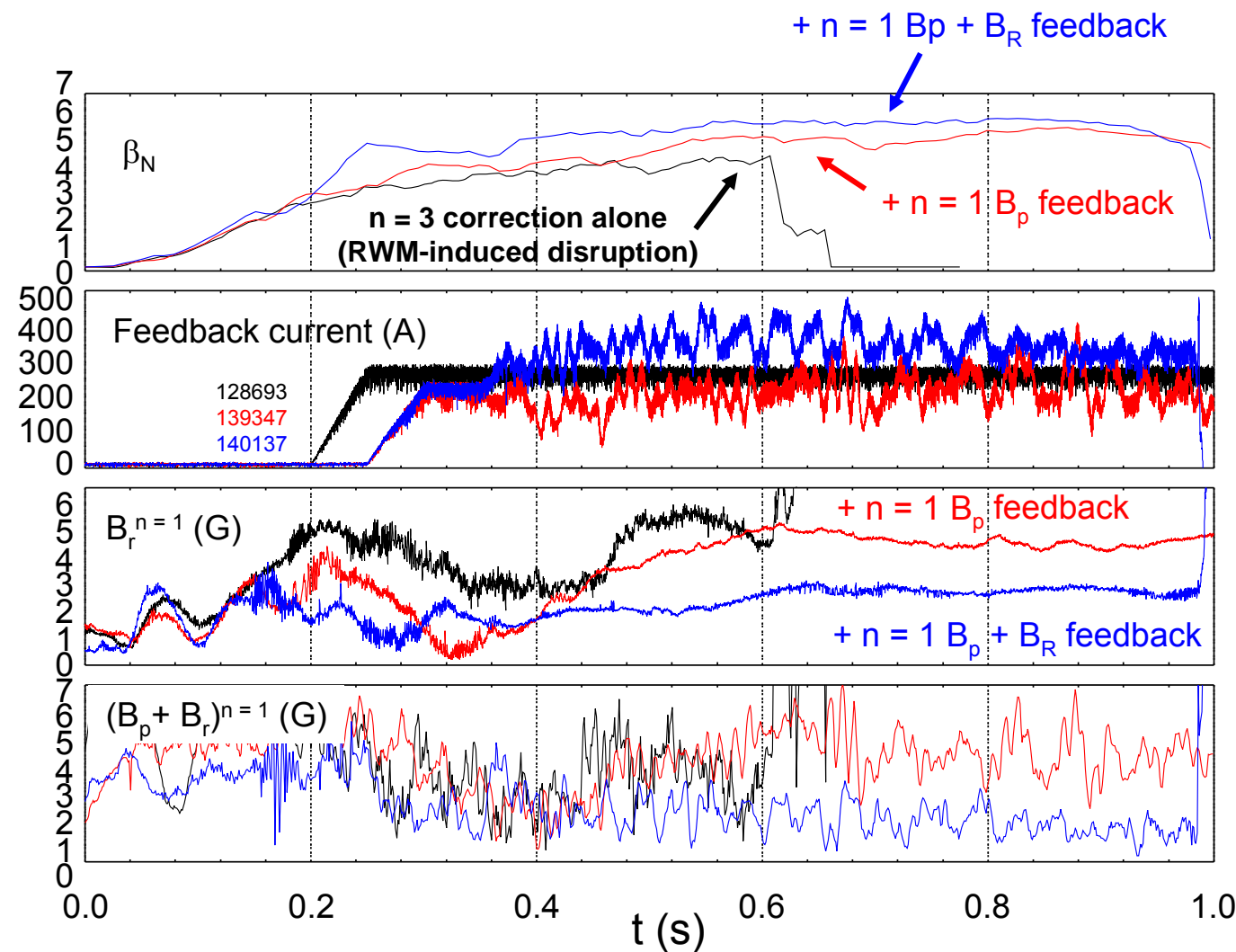
MISK application to ITER (advanced scenario IV)

- ❑ RWM unstable at expected rotation
- ❑ Only marginally stabilized by alphas at $\beta_N = 3$

- J.W. Berkery, et al., PRL **104** (2010) 035003
- S.A. Sabbagh, et al., NF **50** (2010) 025020
- J.W. Berkery, et al., Phys. Plasmas **17**, 082504 (2010)
- S.A. Sabbagh, et al., IAEA FEC 2010, Paper EXS/5-5



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



□ Combination of DC error field correction, $n=1$ feedback

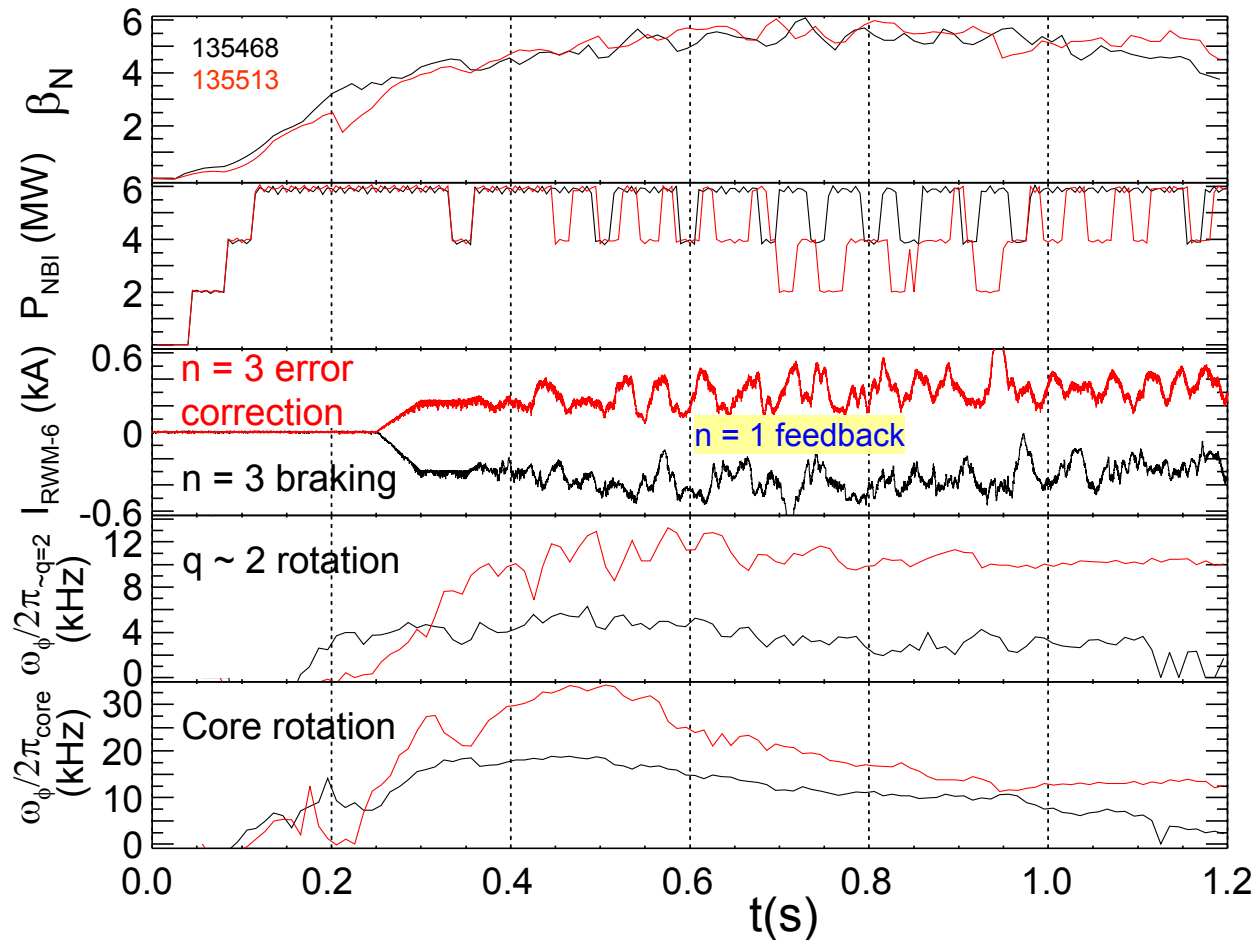
□ Dedicated scans to optimize B_r , B_p sensor feedback phase and gain

□ $n=3$ DC error field correction alone 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)

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



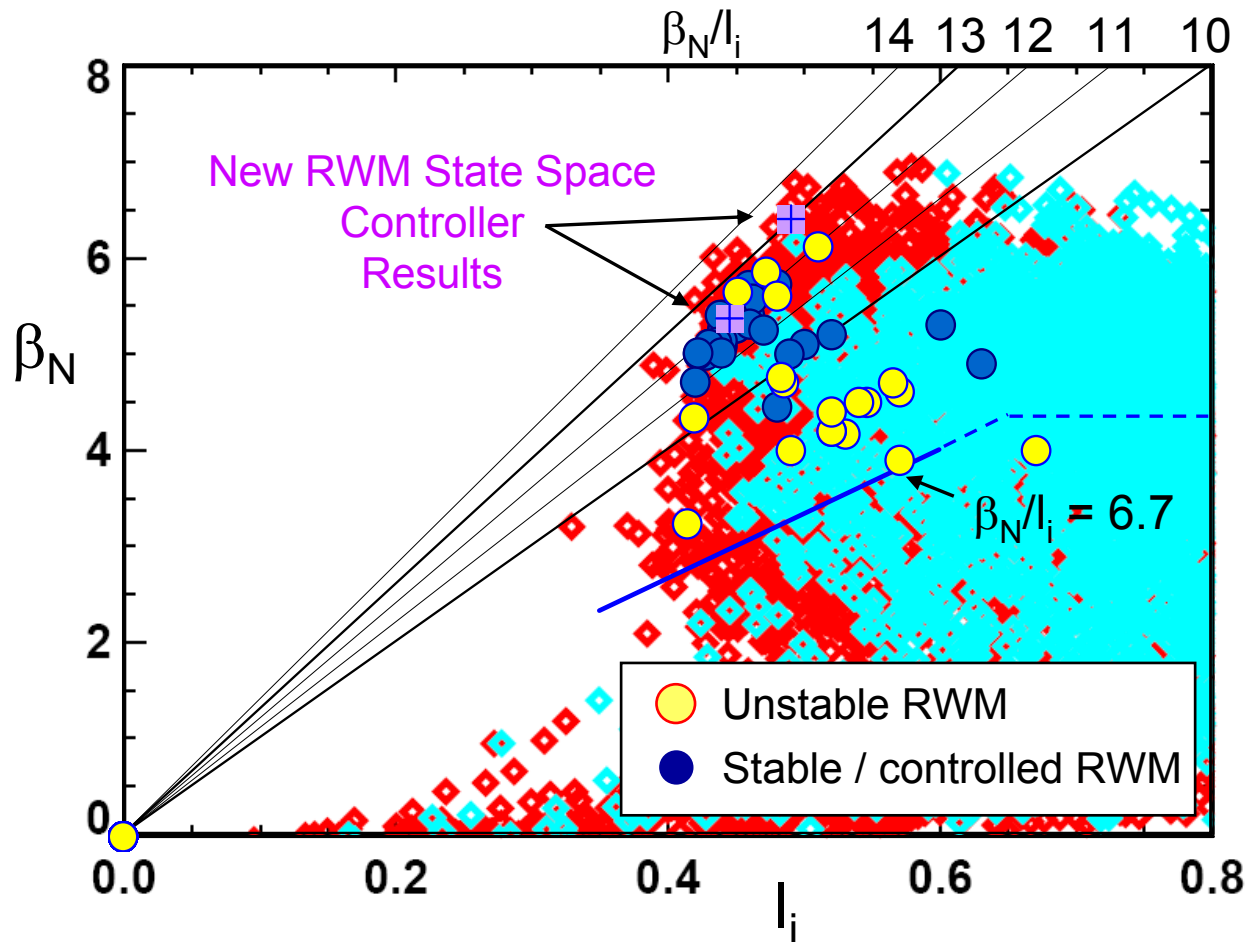
□ Prelude to ω_ϕ control

- 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

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



Subset of discharges

- High $I_p \geq 1.0\text{MA}$
- $n = 1$ control enhancements
- Mild ω_ϕ alteration

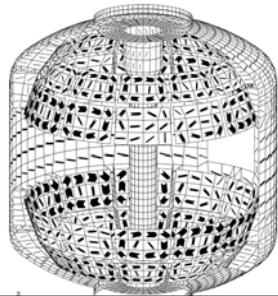
Latest results

- Yielded low I_i
- Access high β_N/I_i
- Significantly reduced disruption probability due to unstable RWM

- 14% of cases with $\beta_N/I_i > 11$
- Much higher probability of unstable RWMs at lower β_N , β_N/I_i

New RWM state space controller implemented to sustain high β_N

Full 3-D model ~3000+ states

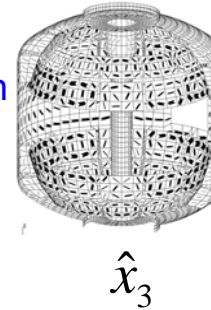


Balancing transformation

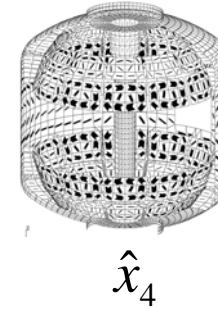
State reduction (< 20 states)

RWM eigenfunction (2 phases, 2 states)

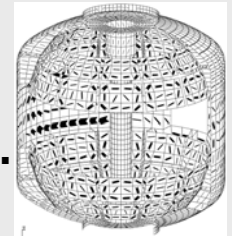
(\hat{x}_1, \hat{x}_2)



\hat{x}_3



\hat{x}_4



\hat{x}_N
truncate

$$\vec{x} = \begin{pmatrix} \vec{I}_w & \vec{I}_{cc} & I_p \end{pmatrix}^T; \quad \vec{u} = \dot{\vec{I}}_{cc}$$

$$\vec{A} = -\vec{L}_1^{-1} \vec{R}; \quad \vec{B} = \vec{L}_1^{-1} \vec{L}_2$$

$$\vec{y} = \vec{\Phi}_{sensors}; \quad \vec{C} = \vec{M}$$

- Controller can compensate for wall currents

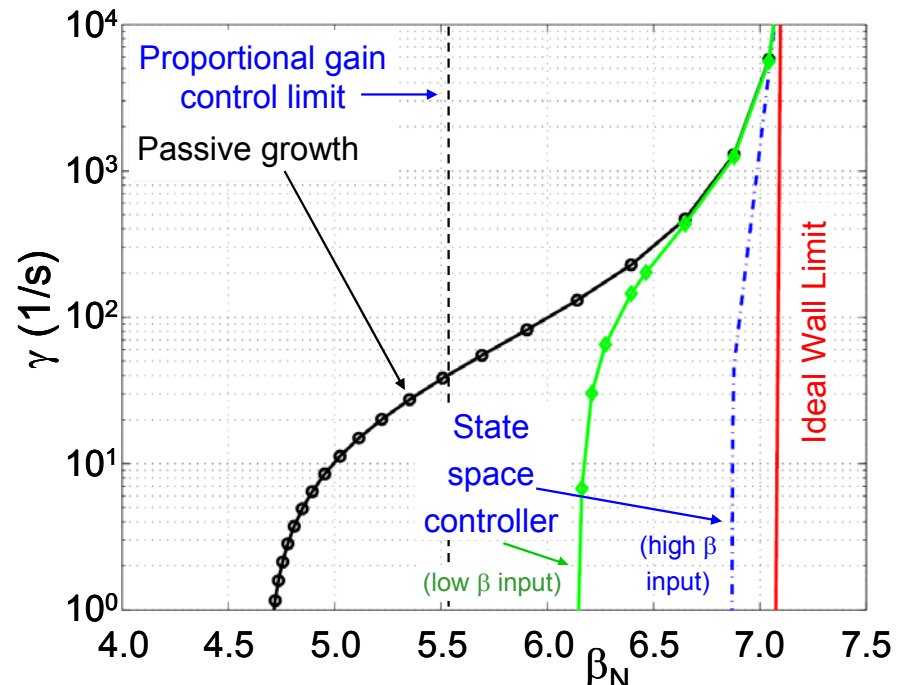
- Including mode-induced current

- 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

Theoretical feedback performance ($\omega_\phi = 0$, 12 states)



NSTX RWM state space controller advances present PID controller

❑ PID (our present, successful workhorse)

- ❑ $n = 1$ phase/amplitude of RWM sensors provides input to controller
- ❑ feedback logic operates to reduce $n = 1$ amplitude
- ❑ No a priori knowledge of mode structure, physics, controller stability

❑ State space control

- ❑ States reproduce characteristics of full 3-D model: conducting structure, plasma response, and feedback control currents via matrix operations
- ❑ Observer (computes sensor estimates)
 - RWM sensor estimates provided by established methods (Kalman filter)
 - ❑ Allows error specification on measurements and model – full covariance matrix
 - Difference between sensor measurements and state space estimates are used to correct the model at each time point; useful as an analysis tool
- ❑ Controller (computes control currents)
 - Controller gain computed by established methods: gains for each coil and state
- ❑ State space method amenable to expansion

State Derivative Feedback Algorithm used for Current Control

State equations to advance

$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \quad \vec{u} = -K_c \vec{x} = \vec{i}_{cc}$$

$$\vec{y} = C\vec{x} + D\vec{u}$$

Advance discrete state vector

$$\hat{\vec{x}}_t = A\vec{x}_{t-1} + B\vec{u}_{t-1}; \hat{\vec{y}}_t = C\hat{\vec{x}}_t$$

$$\vec{x}_{t+1} = \hat{\vec{x}}_t + A^{-1}K_o(\vec{y}_{sensors(t)} - \hat{\vec{y}}_t)$$

Control vector, u ; controller gain, K_c

Observer est., y ; observer gain, K_o ; $D = 0$

K_c , K_o computed by standard methods
(e.g. Kalman filter used for observer)

“time update”

“measurement update”

State derivative feedback: superior control approach

$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \quad \vec{u} = -\hat{K}_c \dot{\vec{x}} \longrightarrow \vec{I}_{cc} = -\hat{K}_c \vec{x}$$

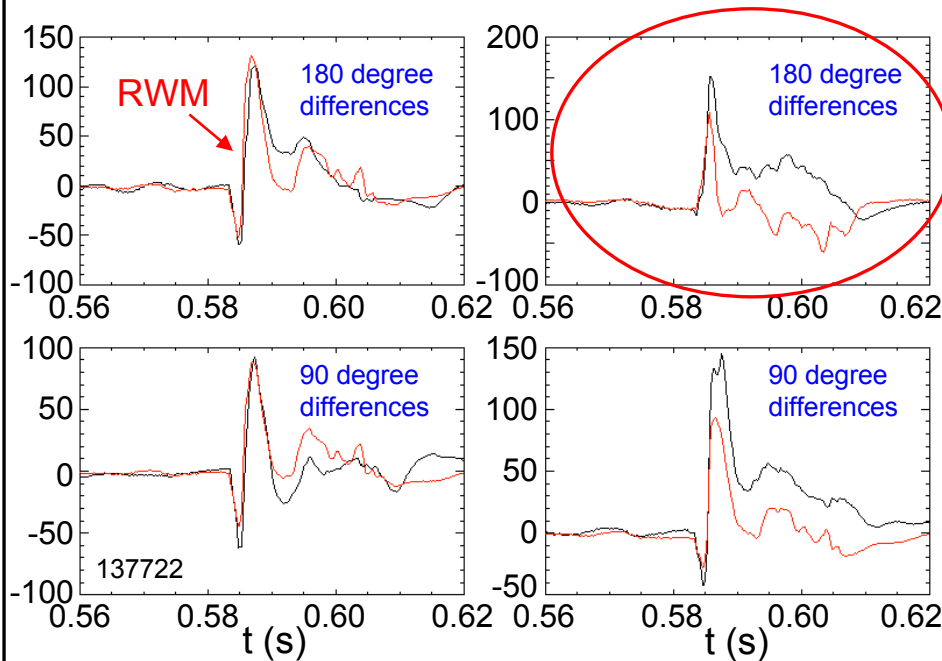
$$\dot{\vec{x}} = ((I + B\hat{K}_c)^{-1} A)\vec{x}$$

- new Ricatti equations to solve to derive control matrices
 - still “standard” solutions in control theory literature

e.g. T.H.S. Abdelaziz, M. Valasek., Proc. of 16th IFAC World Congress, 2005

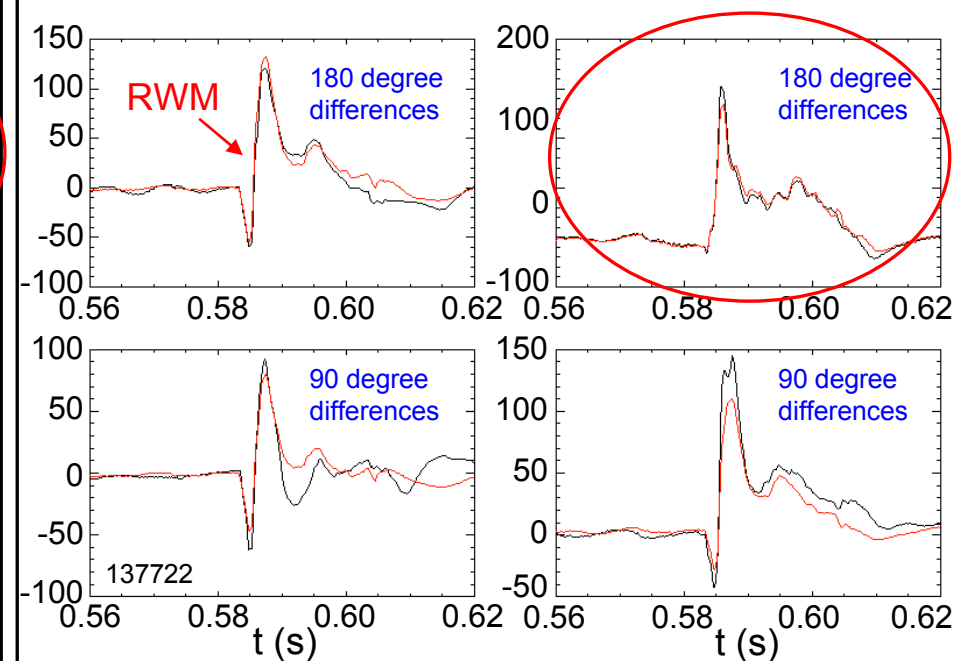
Increased number of states in RWM state space controller improves match to sensors over entire mode evolution

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

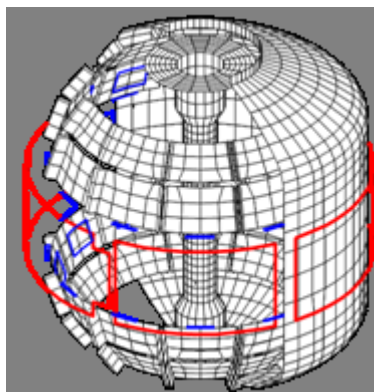


- Some 90 degree differences not as well matched
 - May indicate the need for an $n = 2$ eigenfunction state

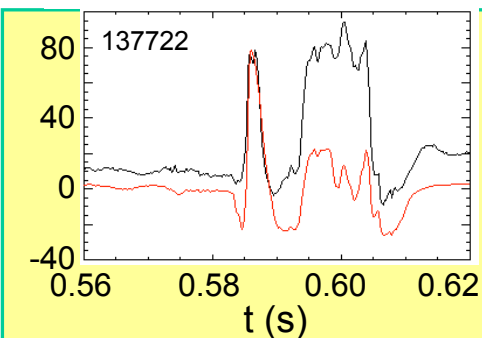
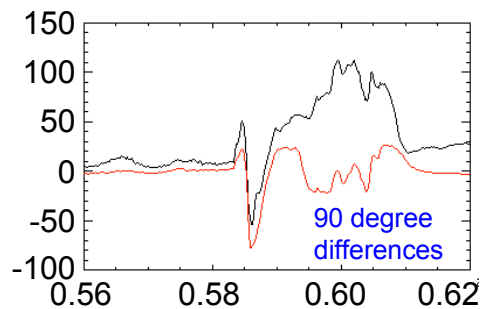
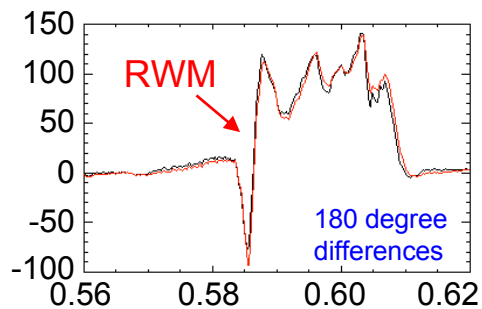
Black: experiment Red: offline RWM state space controller

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

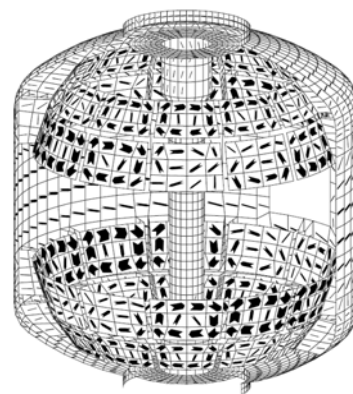
RWM Lower B_p Sensor Differences (G) – NO PORT



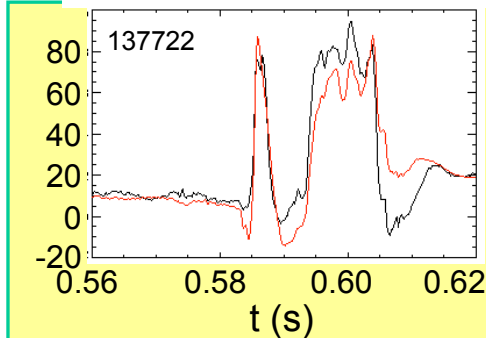
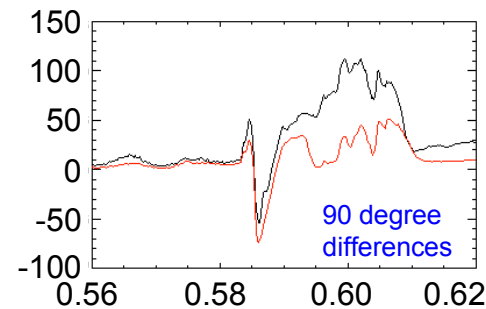
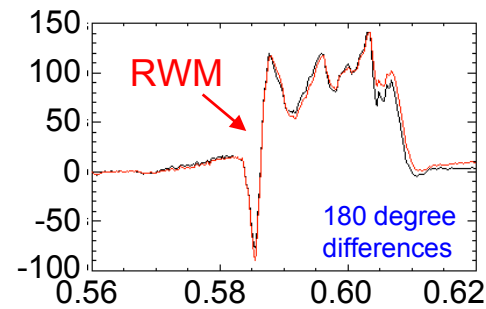
Some 90 degree differences not well matched



RWM Lower B_p Sensor Differences (G) – NBI PORT



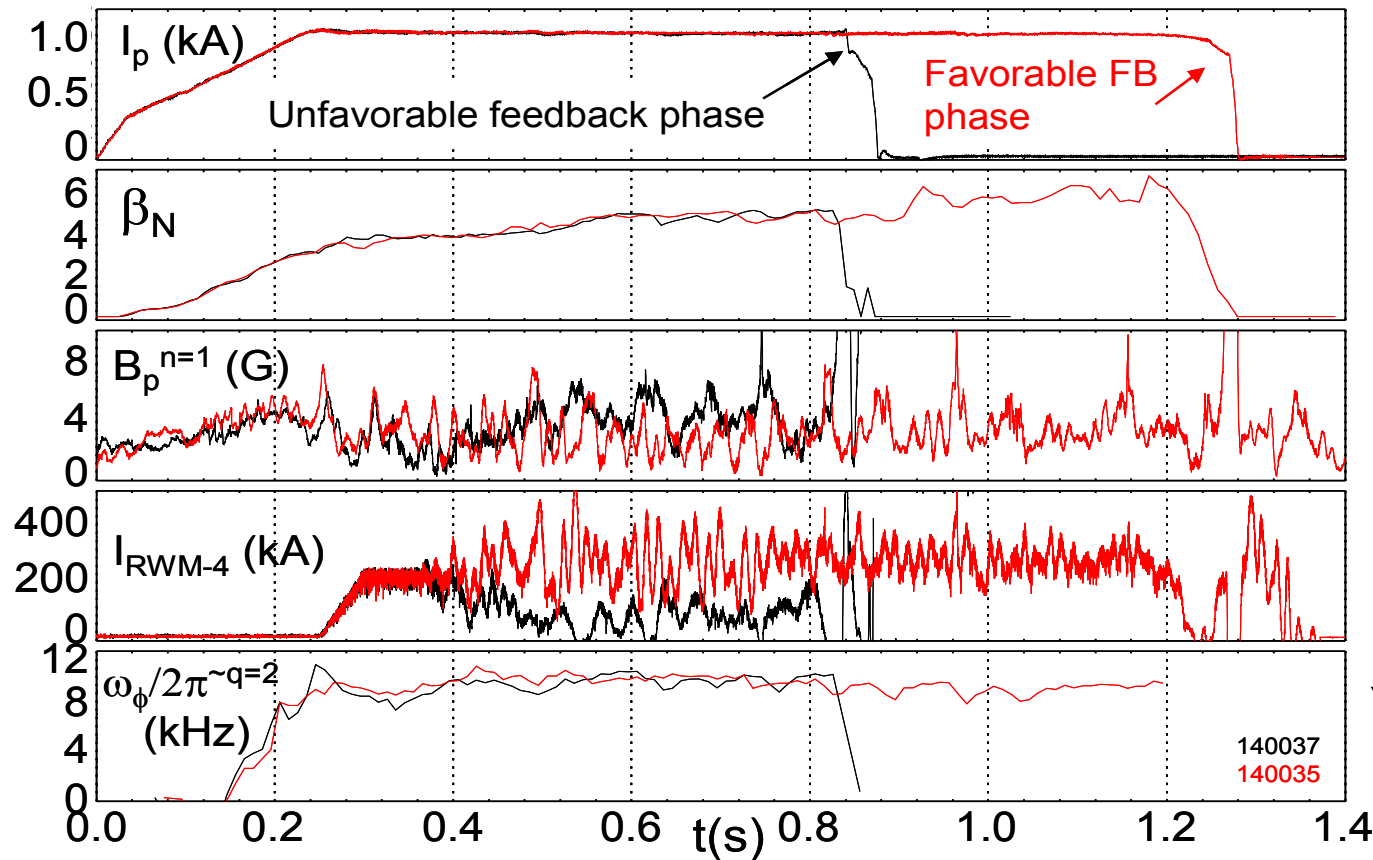
Adding NBI port leads to greater match on some sensors



Black: experiment Red: offline RWM state space controller

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

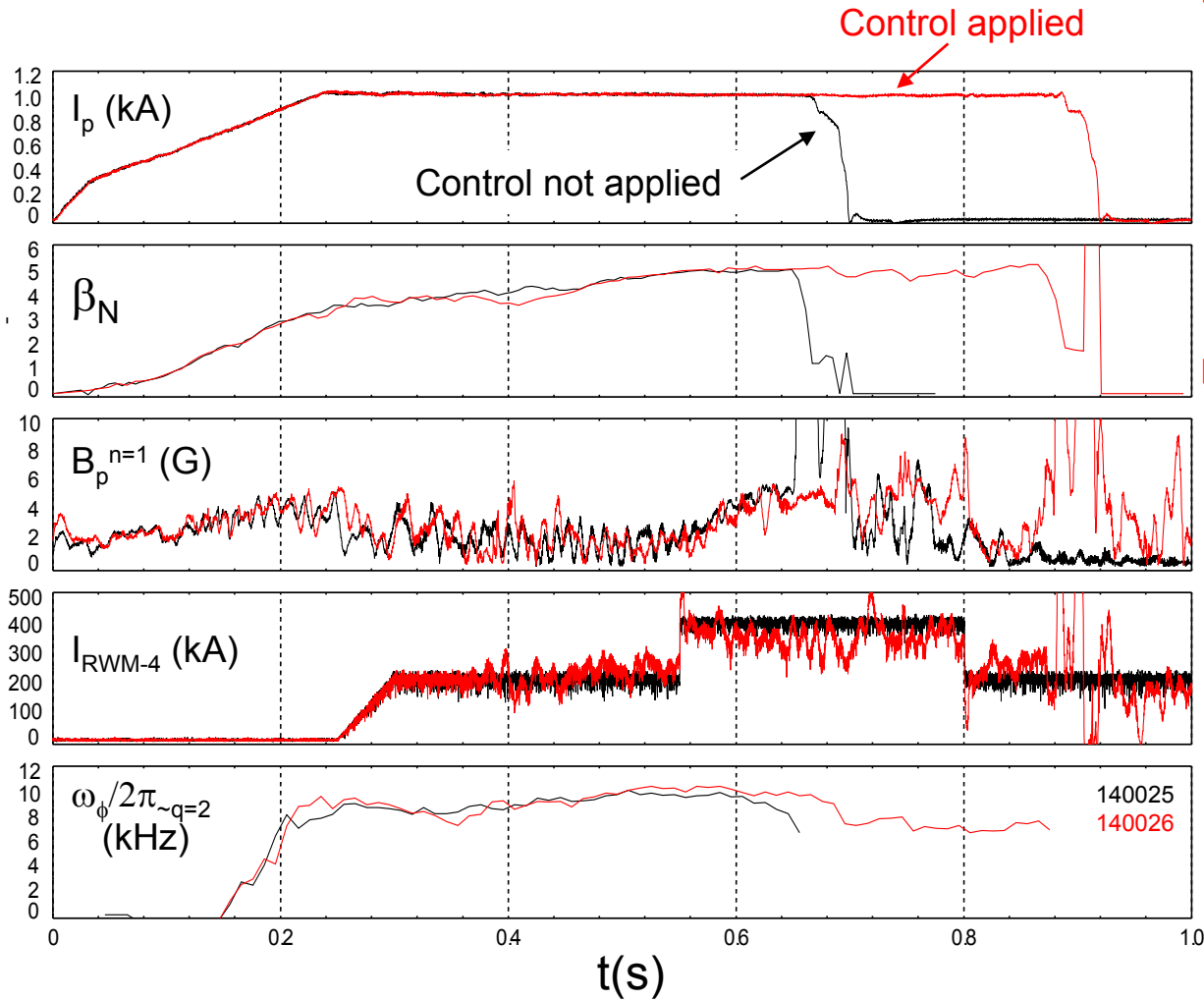
RWM state space feedback (12 states)



Successful First Experiments

- $n = 1$ applied field suppression
 - Suppressed disruption due to $n = 1$ field
- Feedback phase scan
 - Best feedback phase produced long pulse, $\beta_N = 6.4$, $\beta_N/I_i = 13$

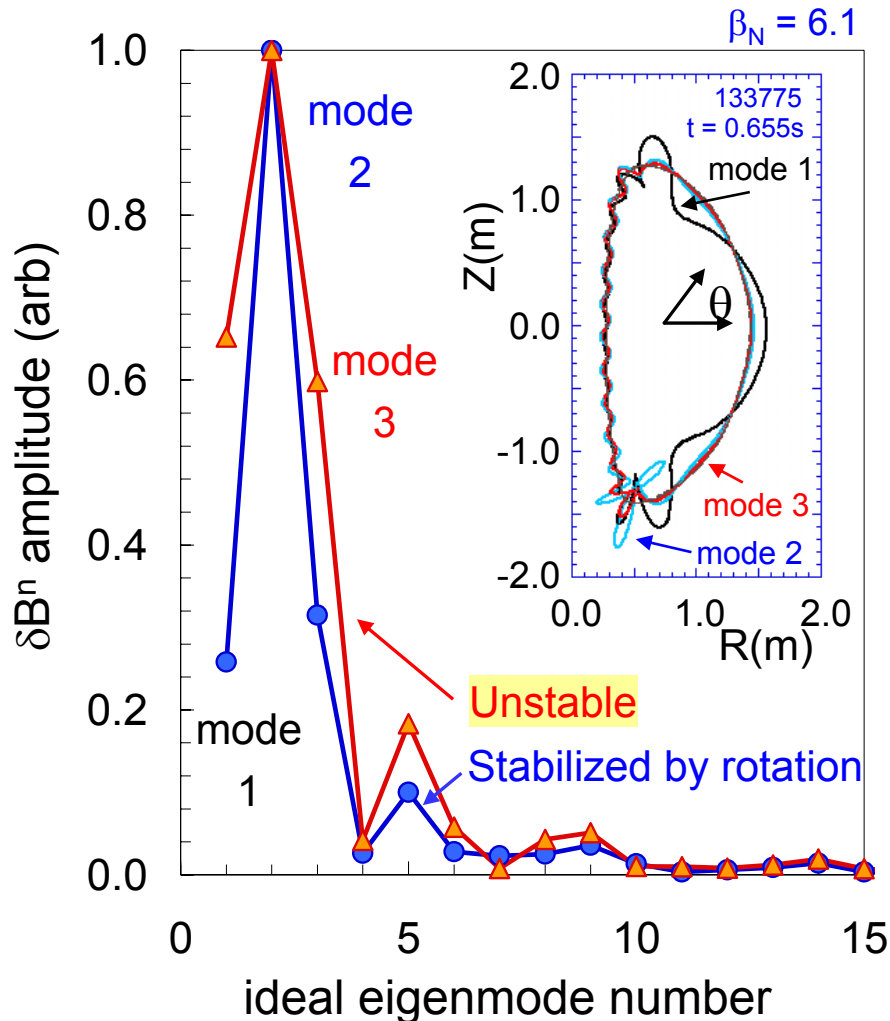
RWM state space controller sustains otherwise disrupted plasma caused by DC $n = 1$ applied field



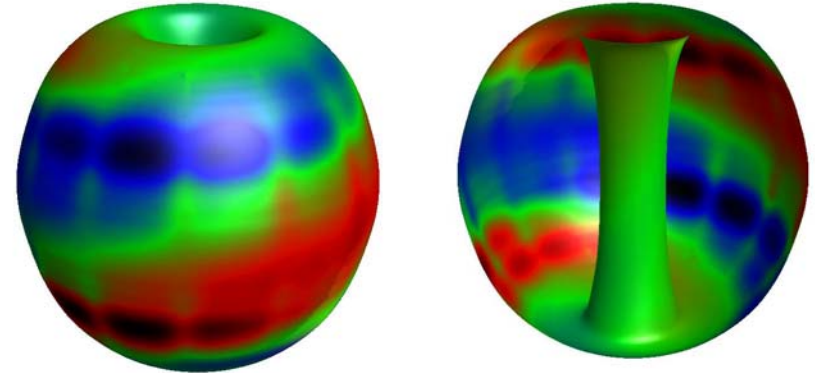
- ❑ $n = 1$ DC applied field
 - ❑ Simple method to generate resonant field amplification
 - ❑ Can lead to mode onset, disruption
- ❑ RWM state space controller sustains discharge
 - ❑ With control, plasma survives $n = 1$ pulse
 - ❑ $n = 1$ DC field reduced
 - ❑ Transients controlled and do not lead 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



δB^n from wall, multi-mode response



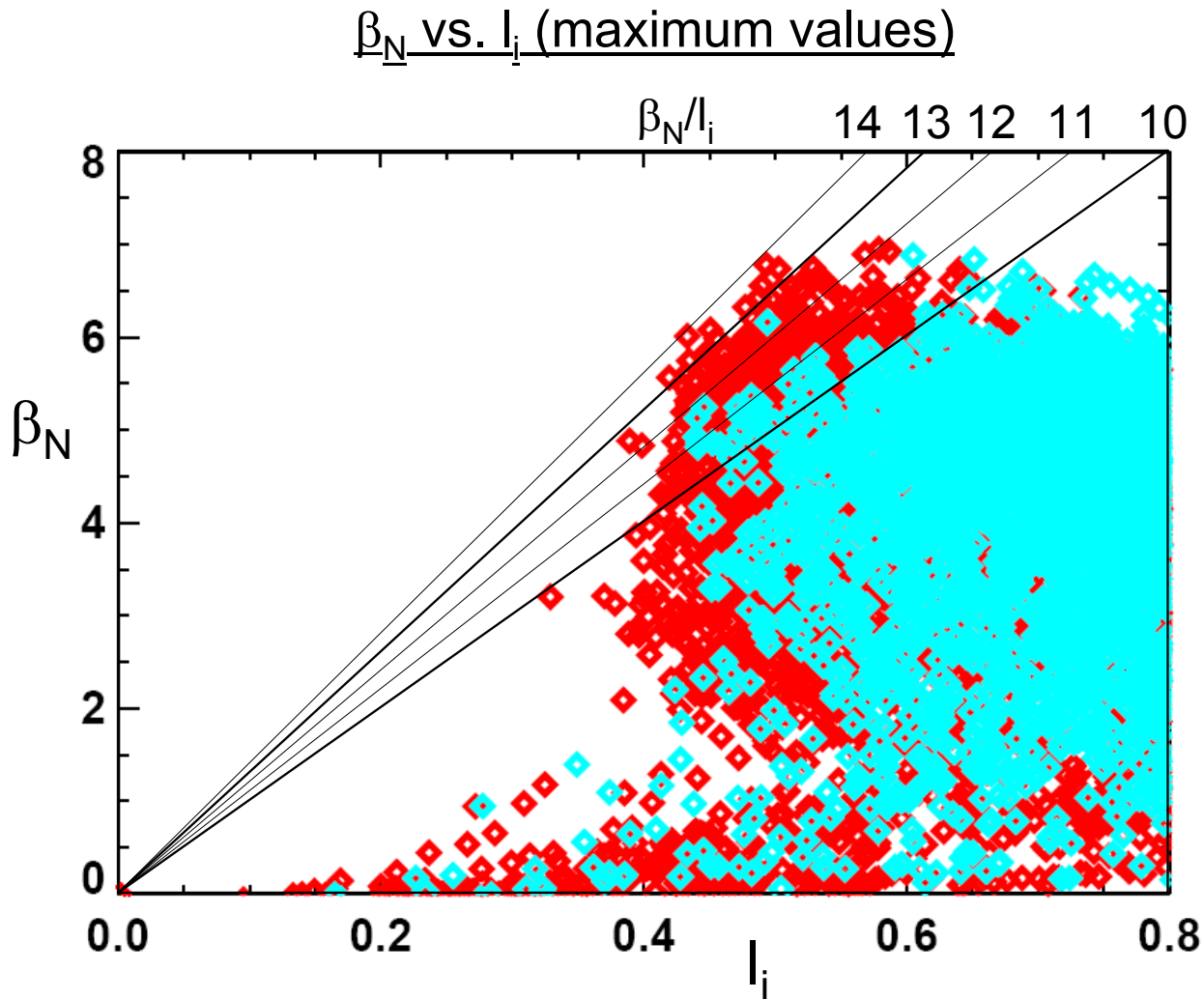
- NSTX RWM not stabilized by ω_ϕ
 - Computed growth time consistent with experiment
 - 2nd eigenmode (“divertor”) has larger amplitude than ballooning eigenmode
- NSTX RWM stabilized by ω_ϕ
 - Ballooning eigenmode amplitude decreases relative to “divertor” mode
 - Computed RWM rotation ~ 41 Hz, close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

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 I_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 I_i plasmas indicates similar stability dependence on ω_ϕ
- ❑ New RWM state space controller sustains low I_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

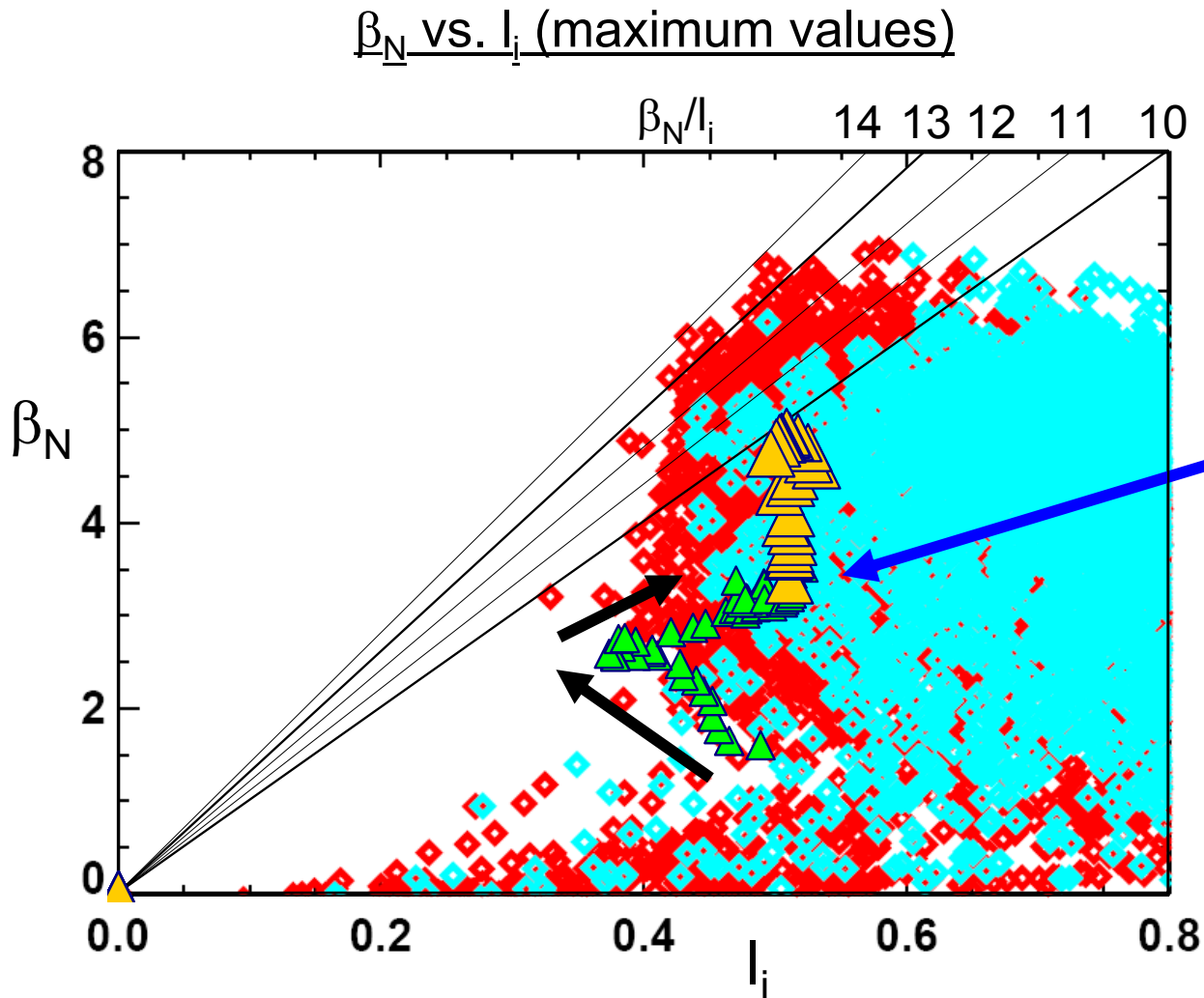
Backup Slides

Operational space is expanding to low I_i and high β_N



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

Ideal $n = 1$ no-wall stability examined for low I_i plasmas



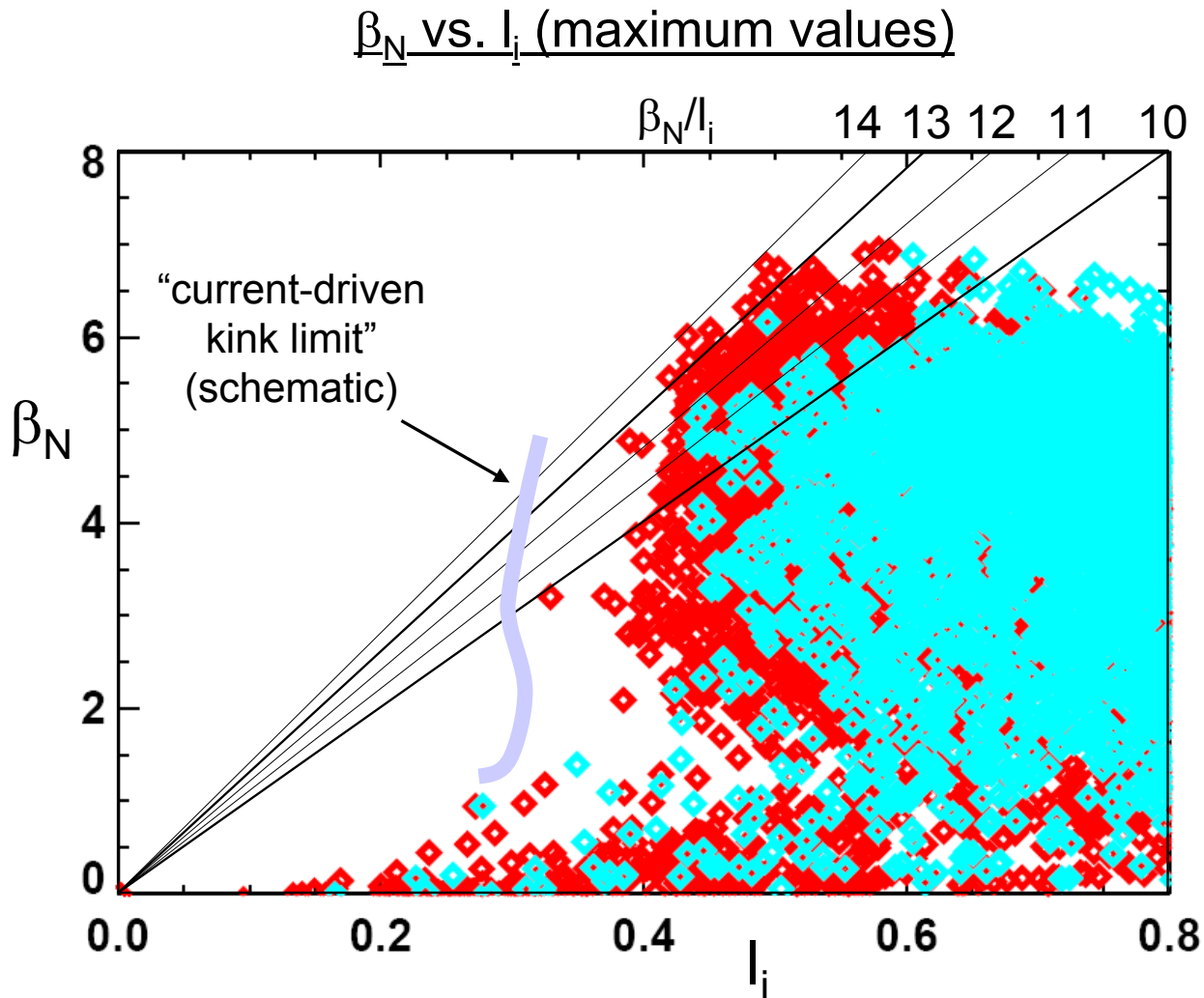
Examine high plasma current, $I_p \geq 1.0\text{MA}$, high non-inductive fraction $\sim 50\%$, $I_i \sim 0.4 - 0.5$

Ideal $n = 1$ no-wall stability computed for discharge trajectory

- Green: below limit
- Gold: above limit
- Exceeds no-wall limit at $\beta_N = 3.4$, $I_i = 0.51$

DCON (A. H. Glasser)

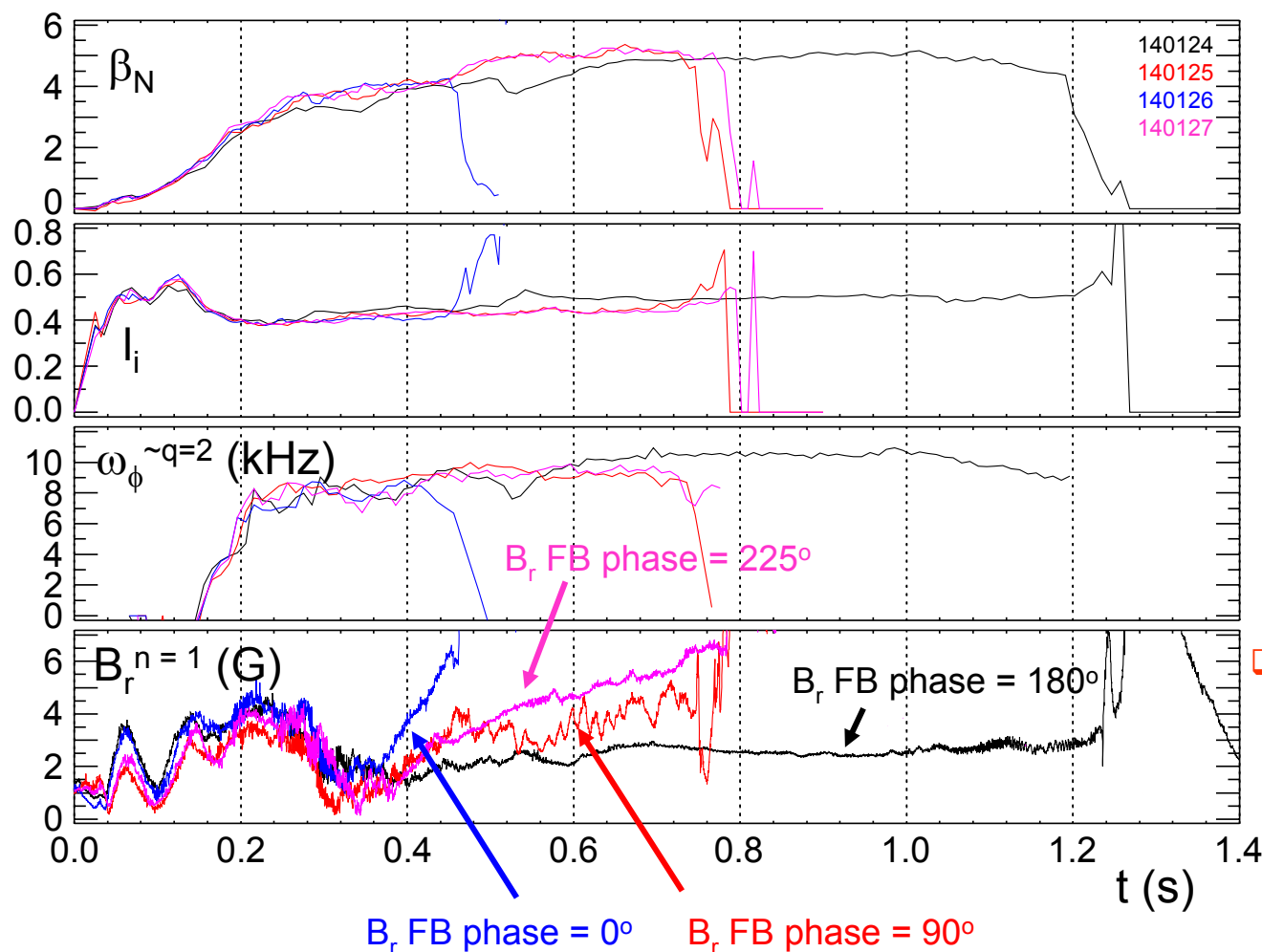
Operational space is expanding to low I_i and high β_N



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

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)



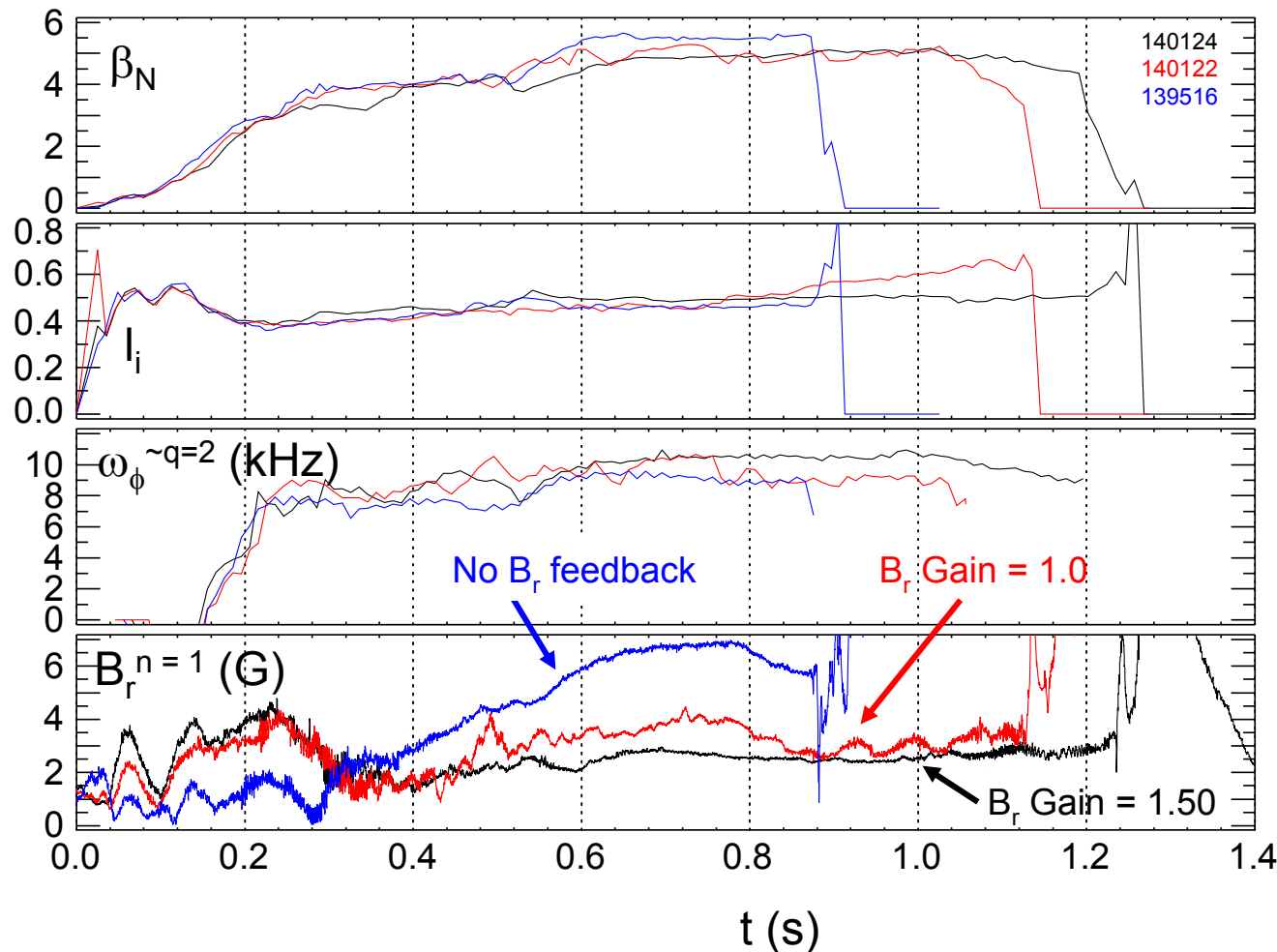
Recent corrections to B_r sensors improve measurement of plasma response

- 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

$n=1 B_R + B_p$ feedback
(B_p gain = 1)



□ New B_r sensor feedback gain scan on low I_i plasmas

□ Highest gain attempted (1.5) most favorable

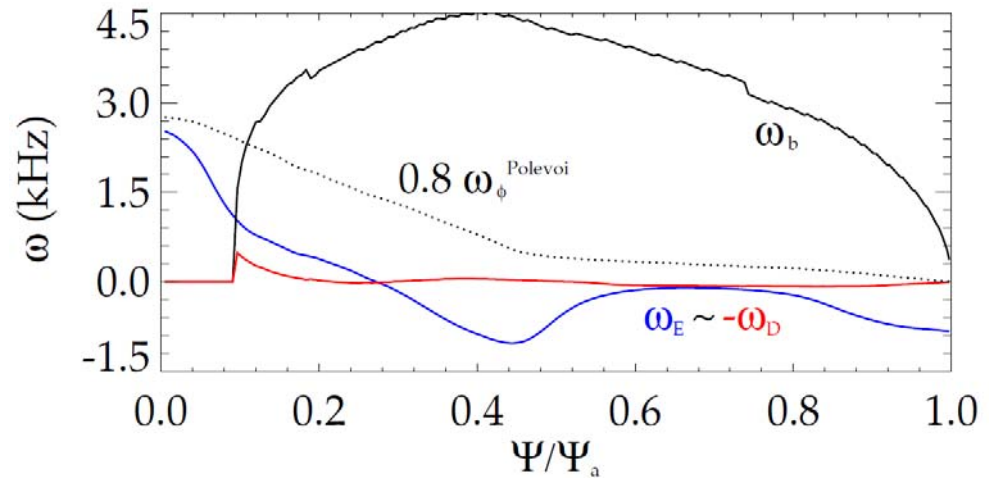
□ B_r feedback constrains slow (10's of ms) $n=1$ radial field growth

□ Addition of $n=1$ B_R sensors in feedback prevents disruptions when $|\delta B_r^{n=1}| \sim 9$ G; better sustains plasma rotation

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

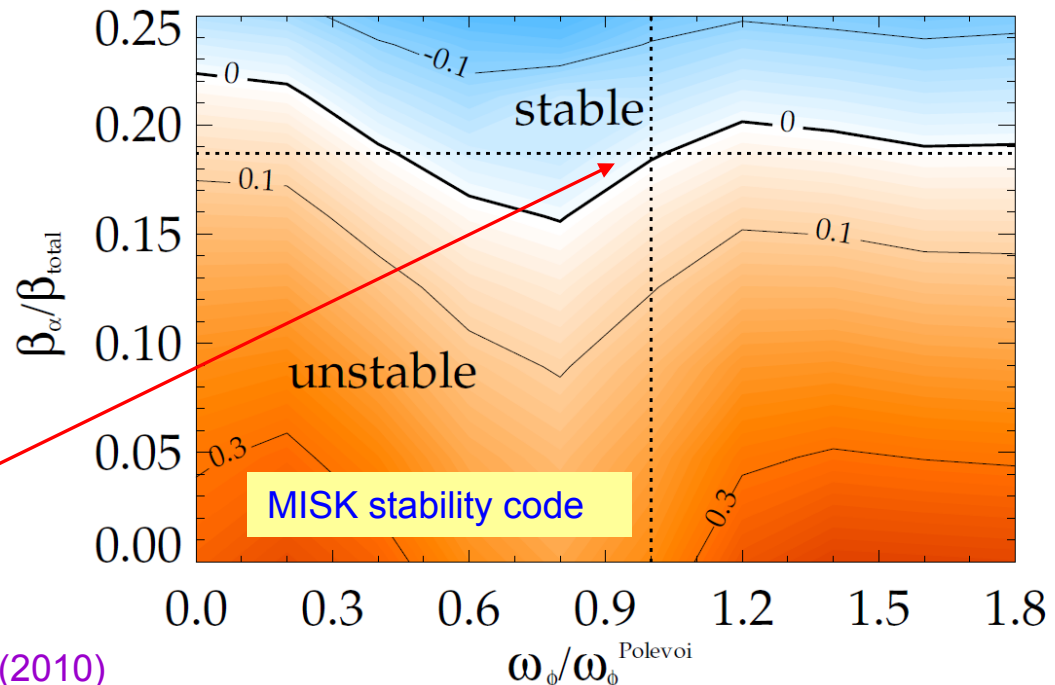


Plasma rotation effect

- Stabilizing precession drift resonance weakly enhances stability near $\omega_\phi = 0.8 \omega_\phi^{\text{Polevoi}}$

Energetic particle (EP) effect

- Alpha particles are required for RWM stabilization at all ω_ϕ
- Near RWM marginal stability at ITER expected $\beta_\alpha/\beta_{\text{total}} = 0.19$ at $\omega_\phi = \omega_\phi^{\text{Polevoi}}$



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

