XP1023: Optimized RWM control for high $\langle\beta_N\rangle_{pulse}$ at low collisionality and l_i - Update

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NSTX Results / Theory Review

December 1st, 2010

PPPL

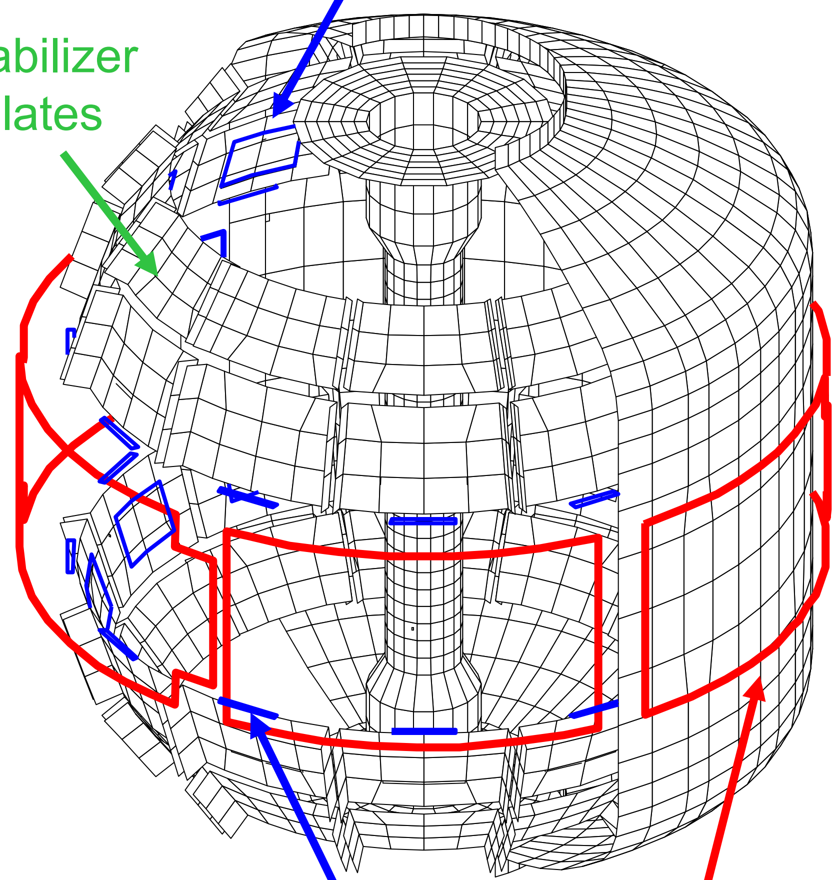
V1.0

XP1023: Optimized RWM feedback control for high $<\beta_N>_{pulse}$ at low collisionality and l_i

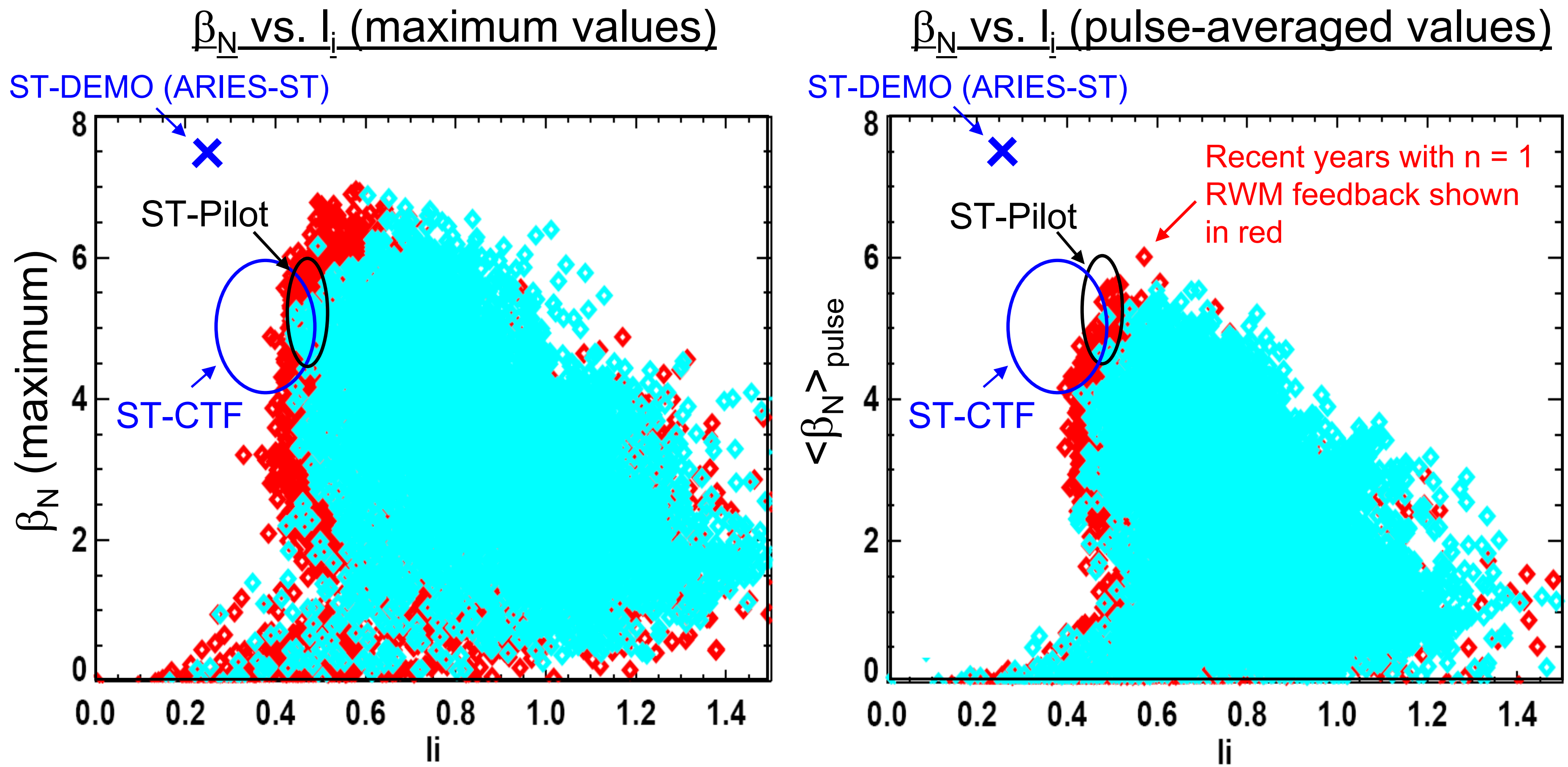
- **Motivation**
  - Next-step ST devices (including the planned upgrade of NSTX) aim to operate at plasma collisionality and broad current (low l_i) below usual NSTX levels
  - 2009 XP948 showed significantly higher RWM activity, lower β_N limit, in reduced l_i plasmas (l_i ~ 0.45 and below)
- **Progress**
  - Controlled collisionality scans mostly dropped, otherwise XP completed
  - Significant improvement in stabilizing low l_i target for maximum pulse length
    - Plasma had unstable RWMs without FB control at relatively high V_ϕ
  - Optimal settings for n = 1 RWM control with B_p feedback changed significantly
    - Analysis commencing with single and multi-mode VALEN to understand this
  - Feedback on B_R sensors optimized and works well; feedback phase setting very different than found in XP802
    - Due to OHxTF compensation of B_R in the miu algorithm, key for reproducibility
    - Best settings successfully used for fiducial, shots in general since 8/26/10; n = 1 B_p + B_R feedback used on different plasmas for comparison/analysis to low l_i plasmas
  - Plasma rotation reduced in low l_i target plasmas once B_p + B_R FB established
    - Plasmas at reduced plasma rotation just starting to be analyzed

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

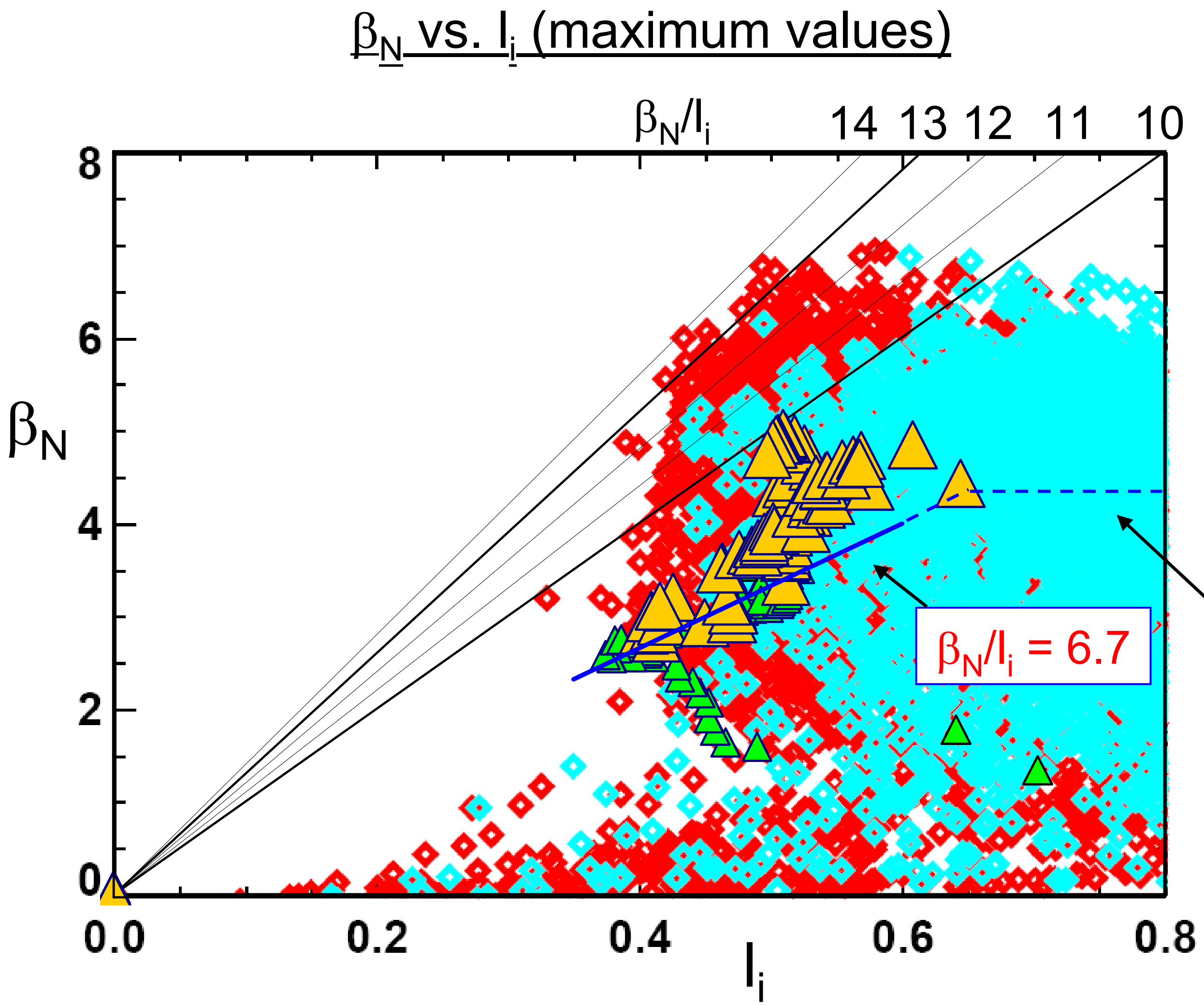


Operation has aimed to produce sustained low l_i and high pulse-averaged β_N



- 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

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
- Significant increase in maximum β_N/l_i
  - Upper limit now between 13 - 14
- Ideal n = 1 no-wall stability computed for discharge trajectory
  - Adding trajectories yields $\beta_N/l_i = 6.7$ for $l_i = 0.38 – 0.6$
  - Significantly lower than no-wall limit at higher l_i ($\beta_N = 4.3$)

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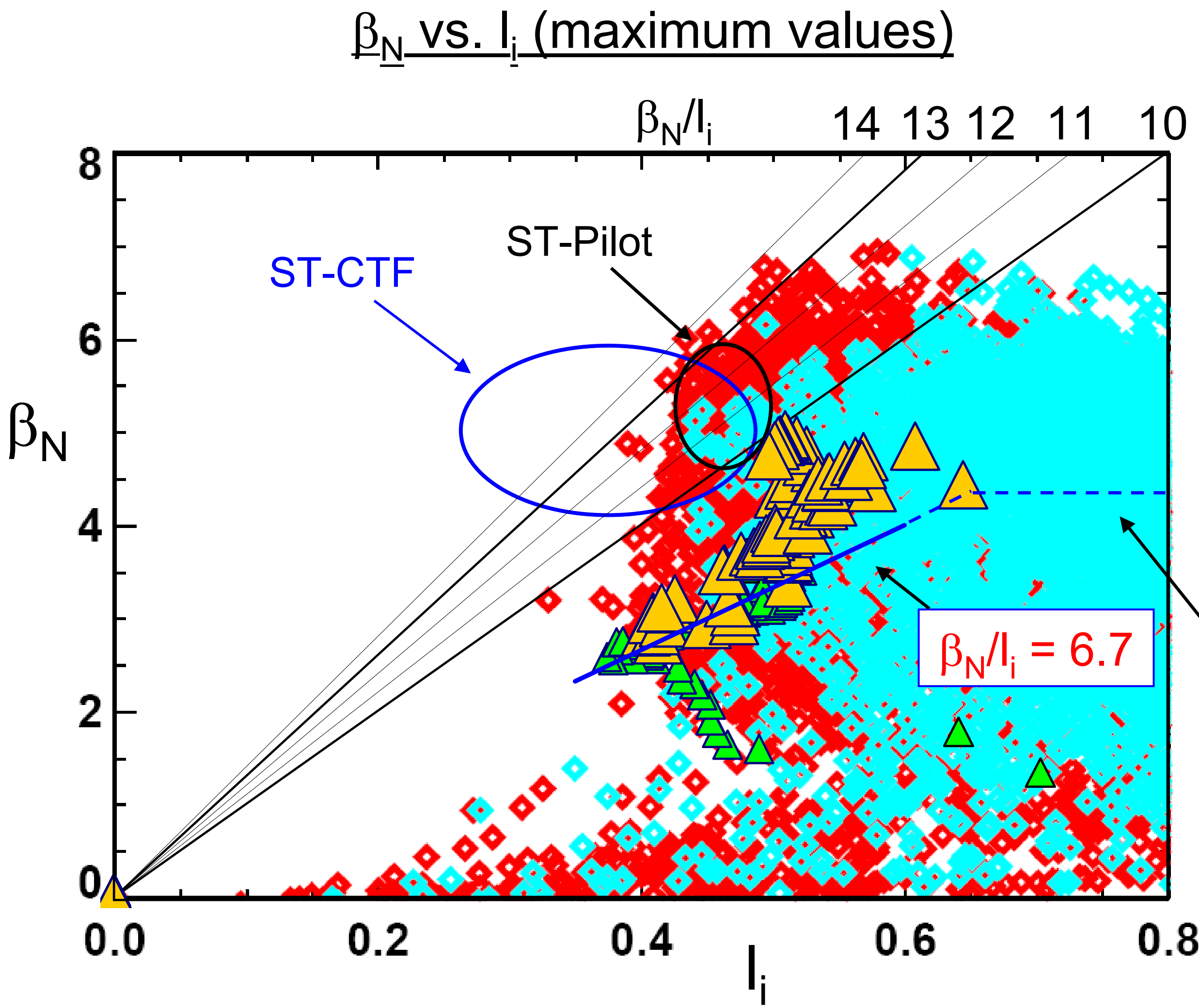

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  - RWM control will be important for future ST fusion devices

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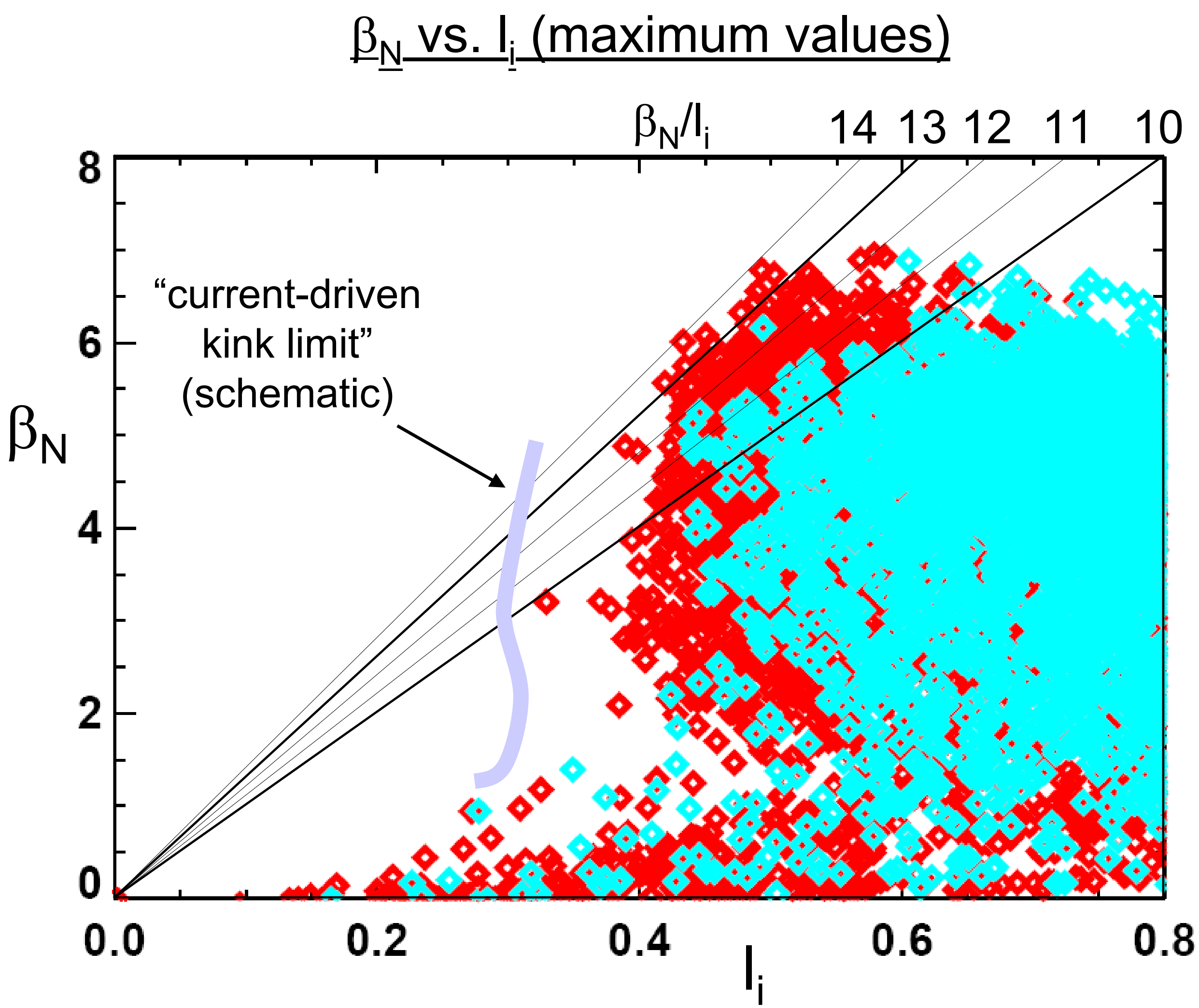
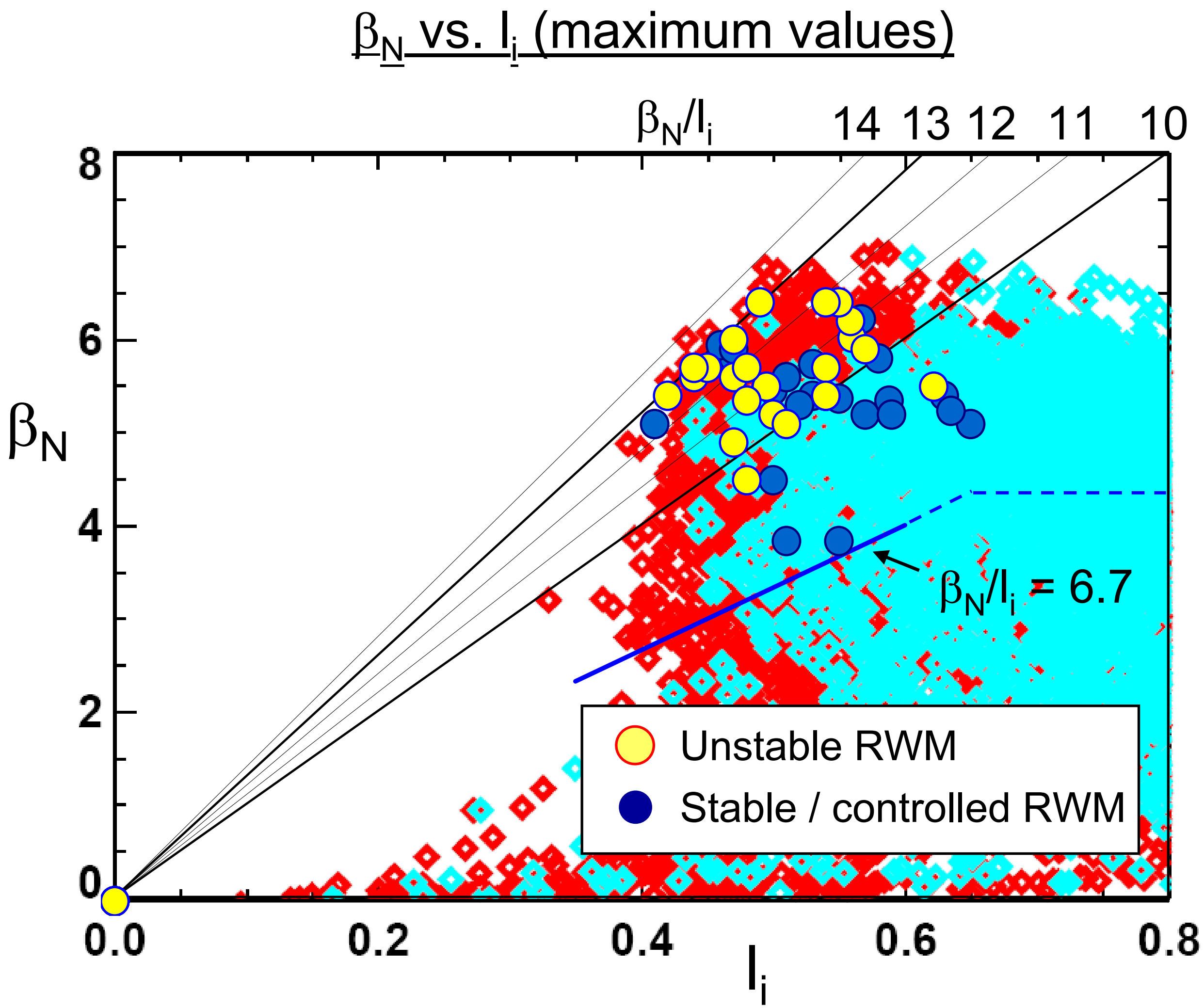


- Examine high plasma current, $I_p \geq 1.0$MA, high non-inductive fraction ~ 50%, $l_i \sim 0.4 – 0.5$
- Significant increase in maximum β_N/l_i
  - Upper limit now between 13 - 14
- At sufficiently low l_i, "current driven kink" limit exists
  - Further analysis will examine where this boundary exists in (l_i,β_N) space

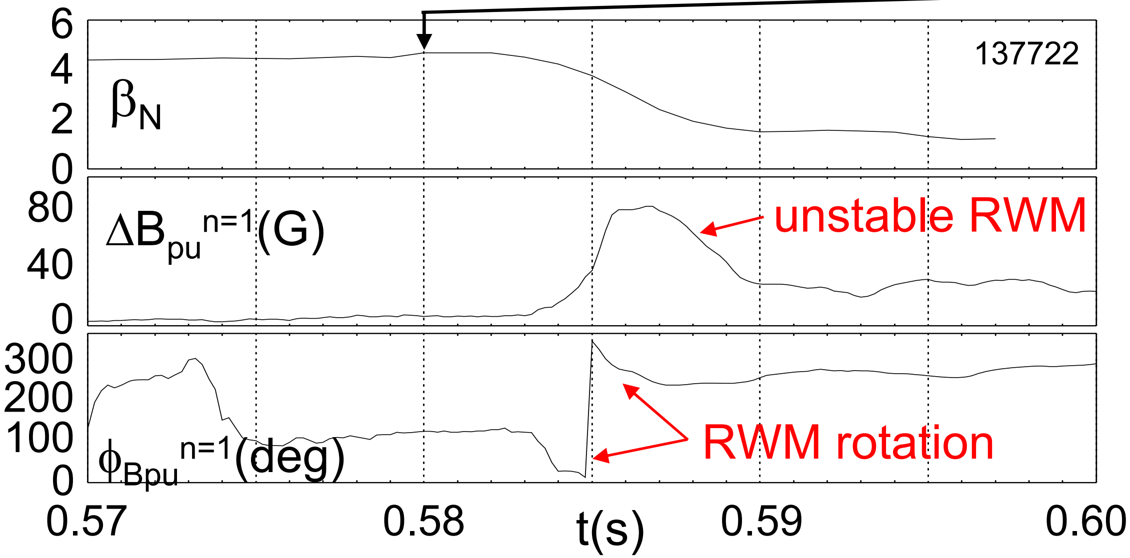
Global stability examined for experiments aimed to produce sustained low l_i and high β_N at high plasma current

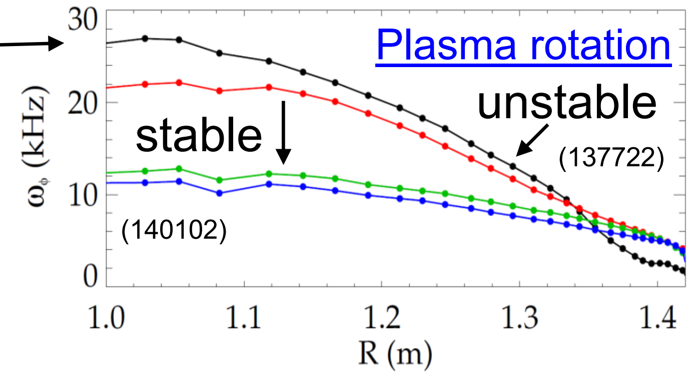


- High $I_p \geq$ 1.0MA, high non-inductive fraction ~ 50%
- Initial experiments
  - Yielded low l_i
  - Access high β_N/l_i
  - High disruption probability
- Instabilities leading to disruption
  - Unstable RWM
    - 48% of cases run
  - Locked tearing modes

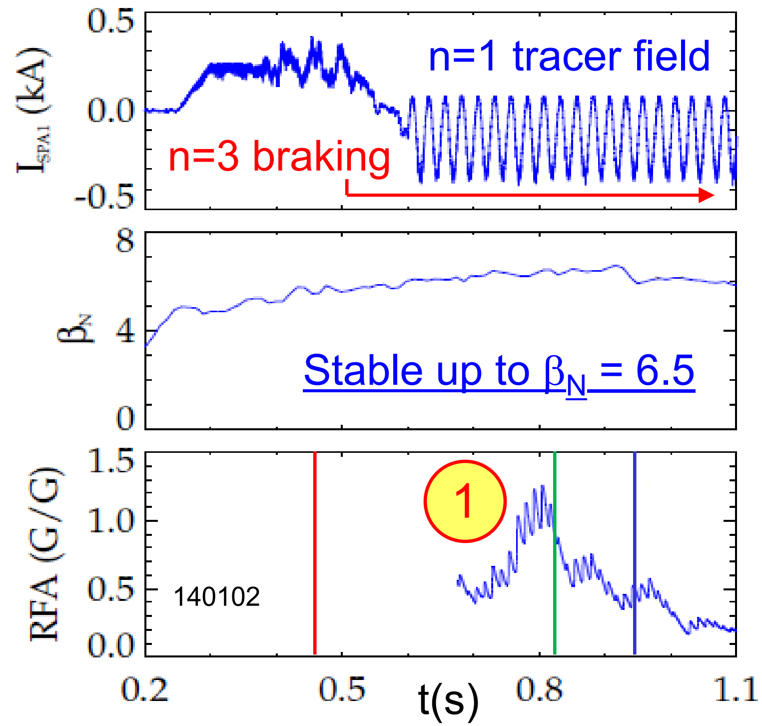
Low plasma rotation level (~ 1% ω_{Alfven}) is insufficient to ensure RWM stability, which depends on ω_ϕ profile

RWM unstable plasma





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 (1)
  - Plasma moves to more stable regime (lower RFA) at lower rotation (β_N up to 6.5)

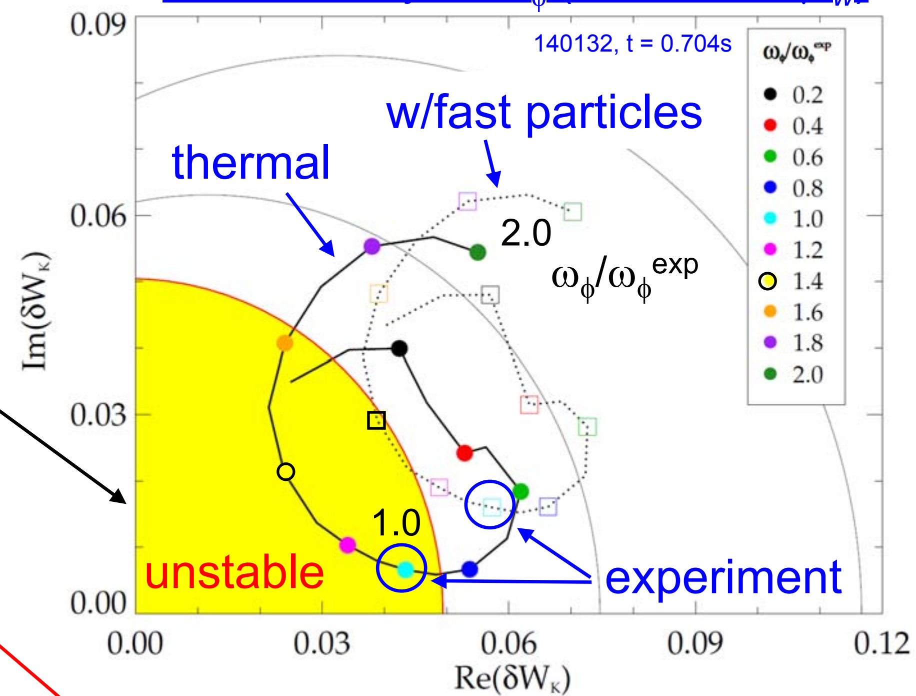
S.A. Sabbagh, et al., IAEA FEC 2010, Paper EXS/5-5

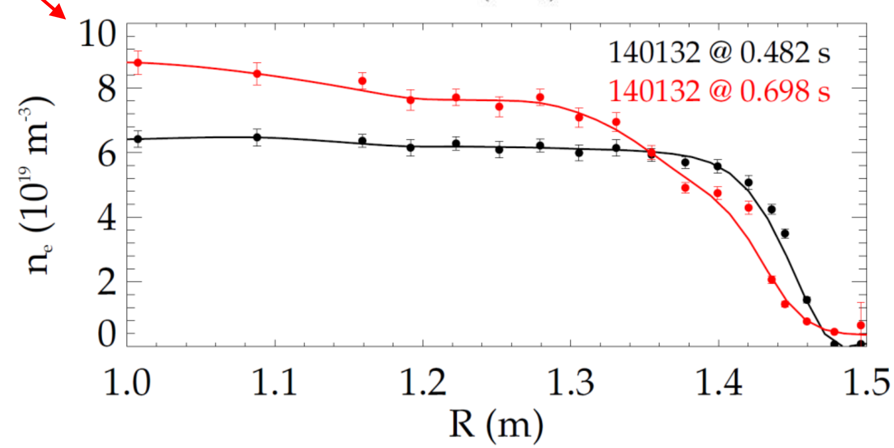
MISK code calculations show reduced stability in low l_i target plasma as ω_ϕ is reduced, RWM instability is approached

- **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

- See Xp1020 talk by J. Berkery this meeting for further MISK detail / analysis plans

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



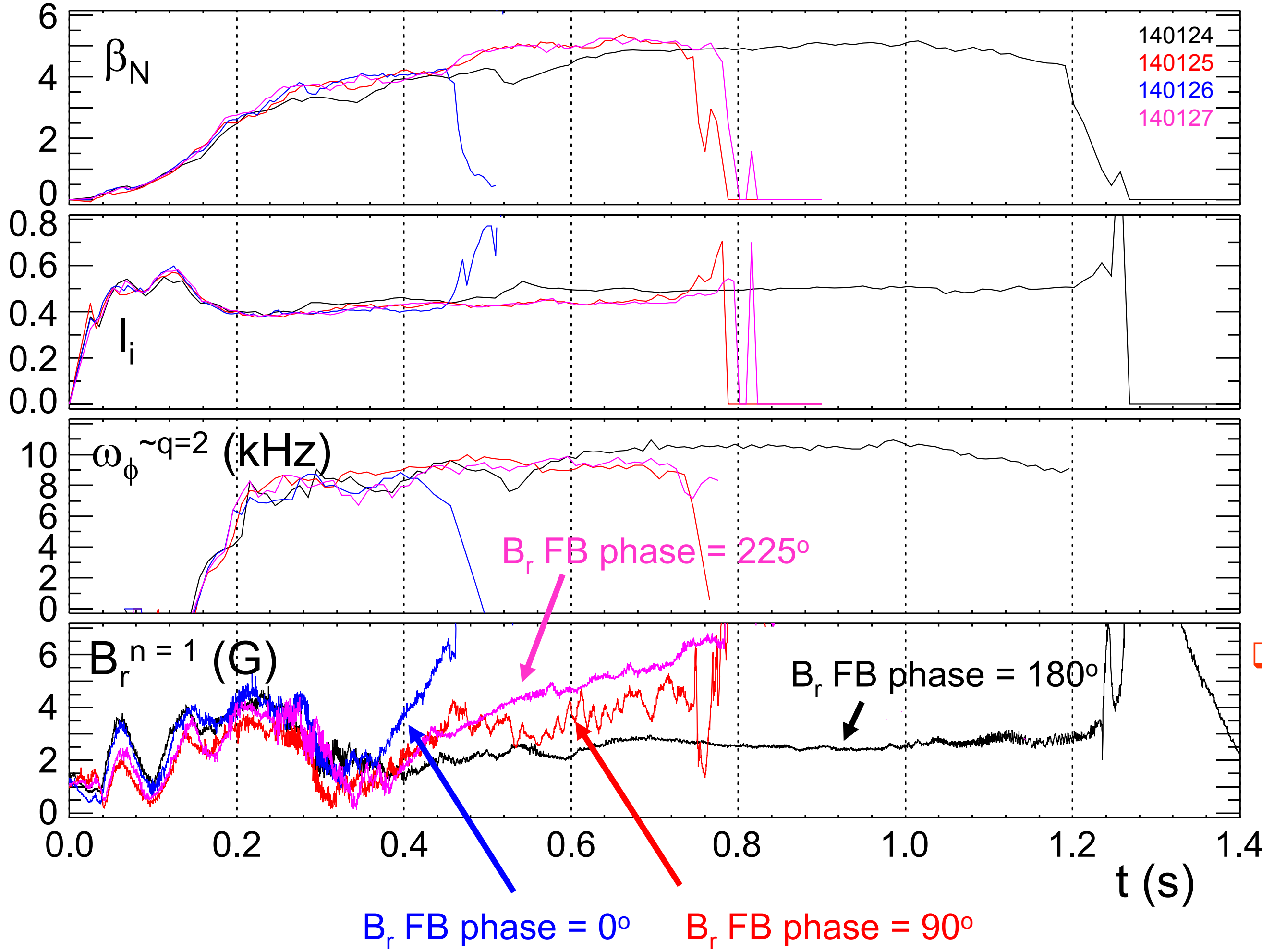


References for MISK analysis of NSTX:

- 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

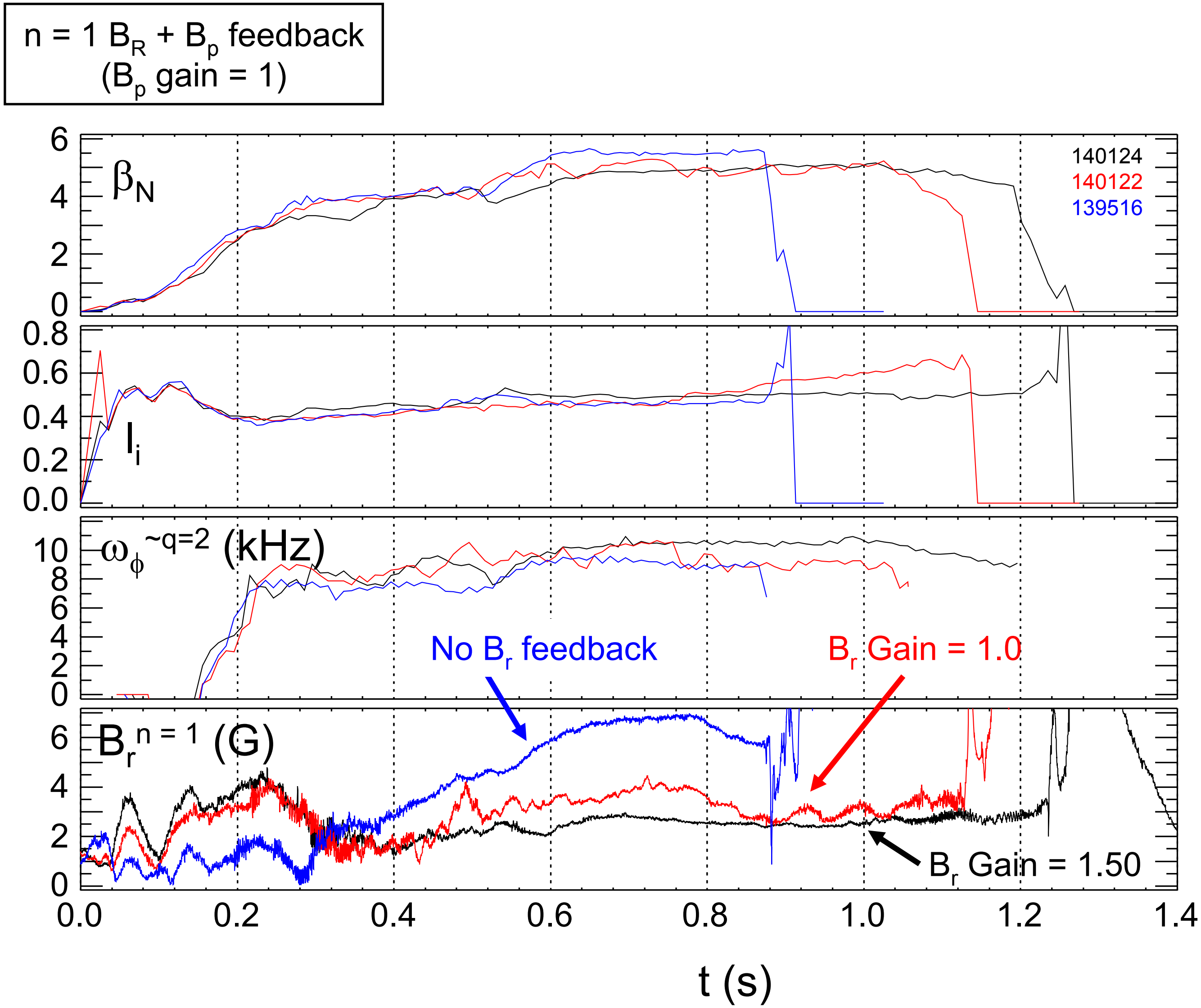
RWM B_r sensor n = 1 feedback phase variation shows clear settings for improved feedback when combined with B_p sensors

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



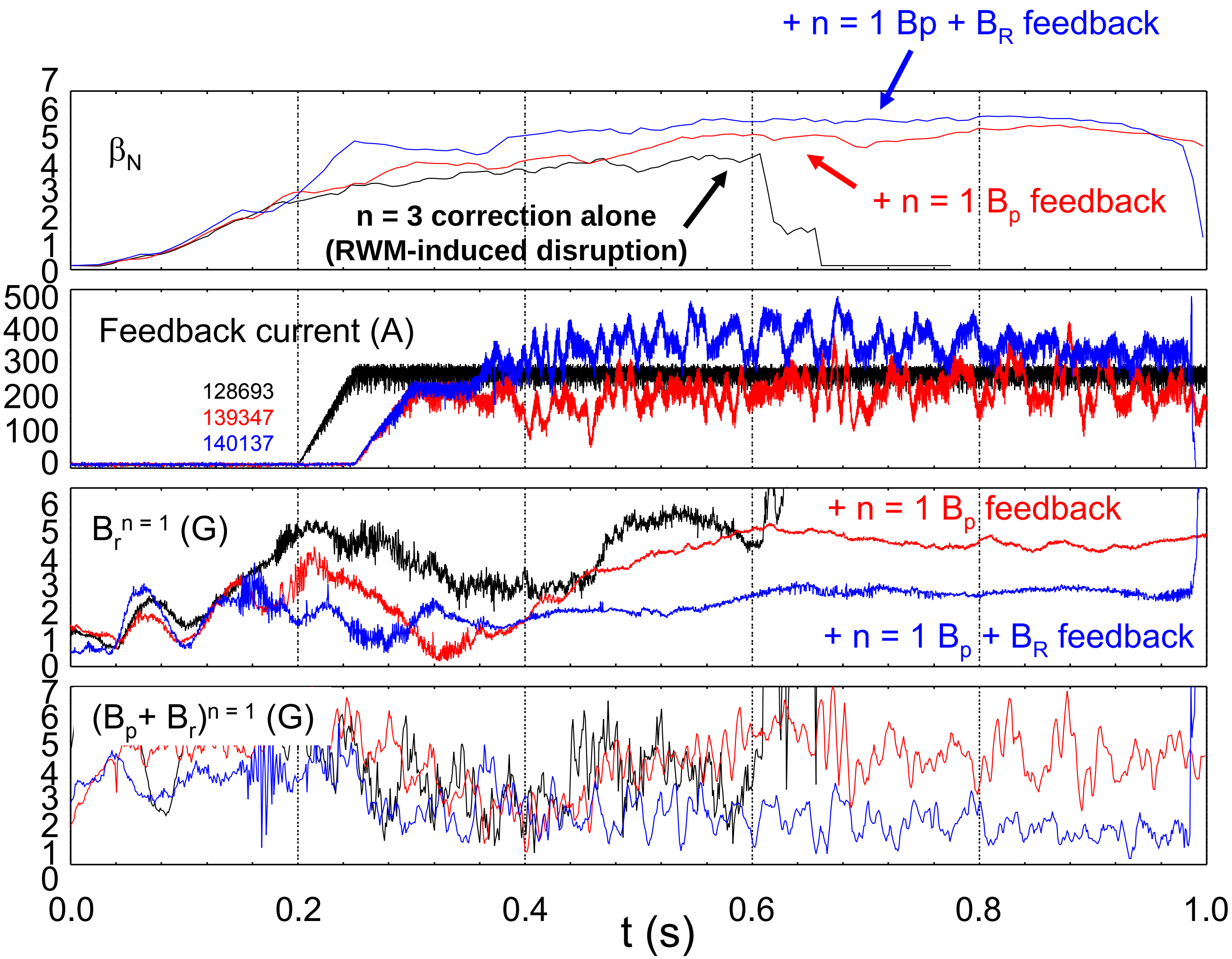
- Recent corrections to B_r sensors improve measurement of plasma response
  - Removed significant direct pickup of time-dependent TF intrinsic error field
  - Positive/negative feedback produced at theoretically expected phase values
- Adjustment of B_p sensor feedback phase from past value further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

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



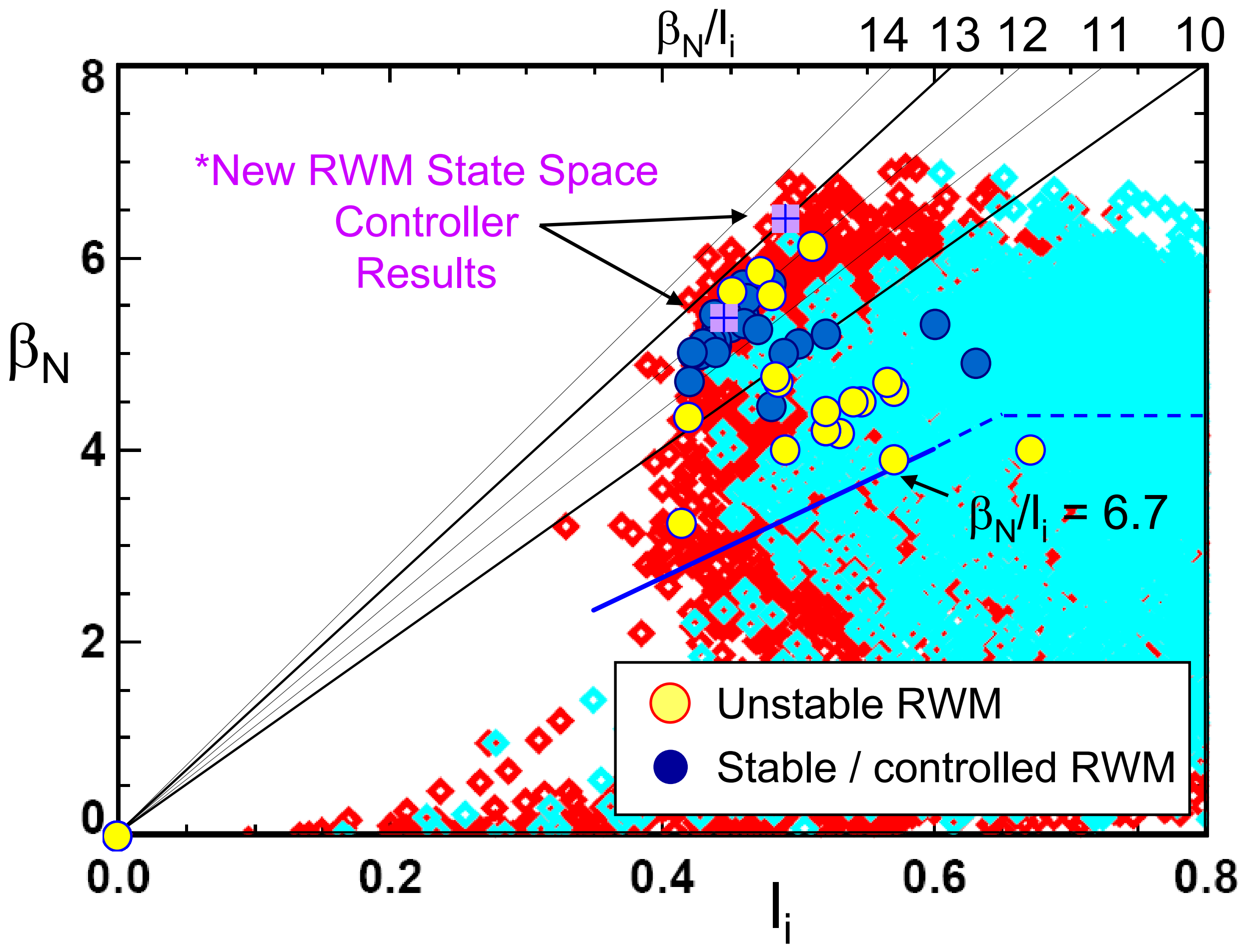
- New B_r sensor feedback gain scan on low l_i plasmas
  - Highest gain attempted (1.5) most favorable
- B_r feedback constrains slow (10's of ms) n = 1 radial field growth
  - Addition of n = 1 B_R sensors in feedback prevents disruptions when $|\delta B_r^{n=1}| \sim 9$G; better sustains plasma rotation

Use of combined $B_r + B_p$ 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 Br, Bp 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)

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

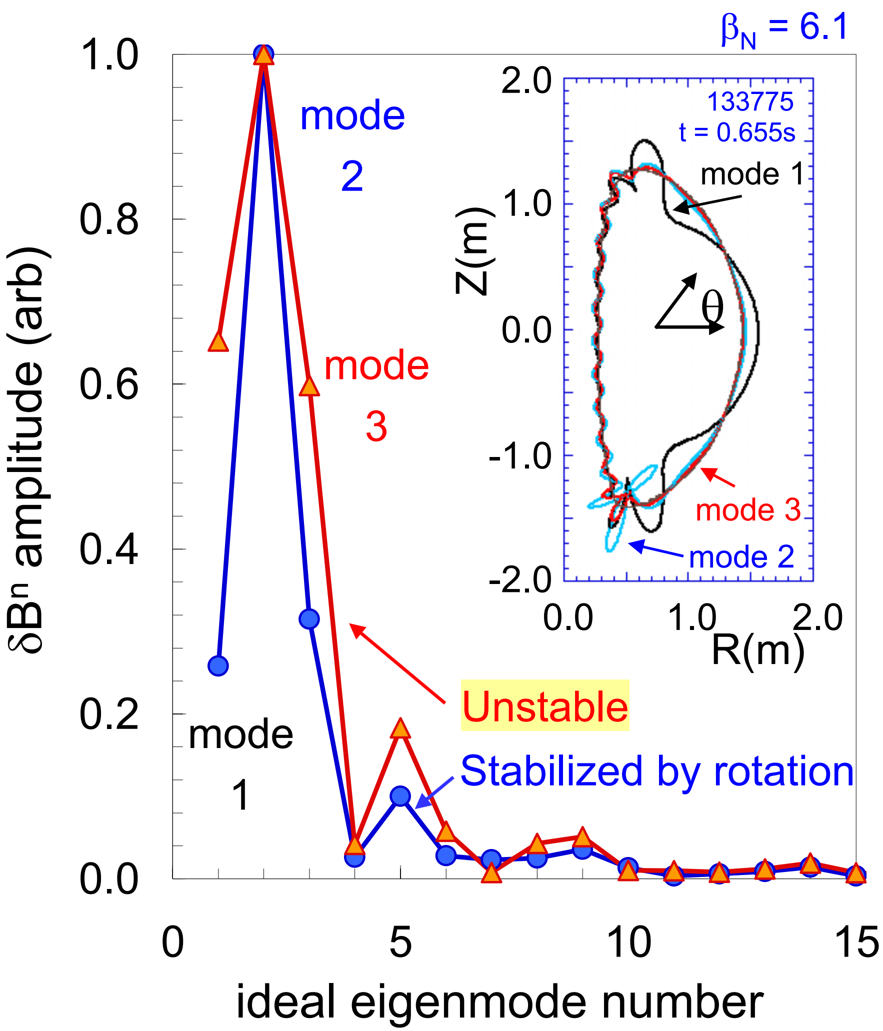


*More detail on RWM state space controller results shown in XP1022 talk by Y.-S. Park, et al., this meeting

- 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

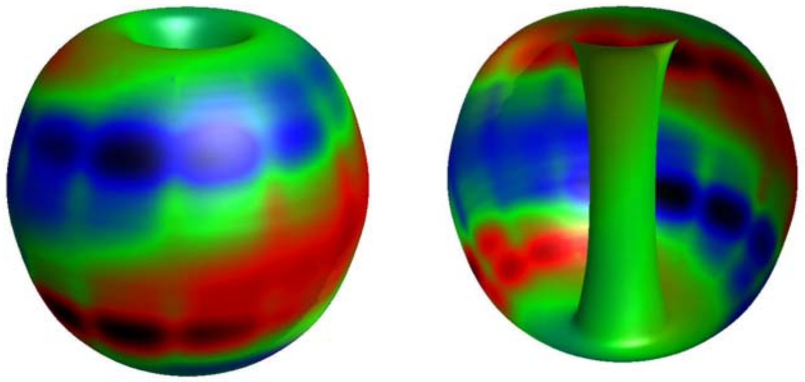
Multi-mode RWM computation shows 2nd eigenmode component has dominant amplitude at high β_N in NSTX stabilizing structure

δB^n RWM multi-mode composition



mmVALEN code – see talk by J. Bialek, et al. for code detail

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

Greater success in controlling global instabilities in low l_i target plasmas via improvements to n = 1 RWM control – analysis continues...

- Success in stabilizing high β_N plasmas at $I_p \geq 1$ MA with reduced l_i
  - Incidence of RWM-induced disruption greatly reduced by
    - n = 1 RWM B_p sensor settings "optimized"
    - n = 1 RWM B_R sensors added to B_p sensors in feedback
    - Best settings successfully used for fiducial and shots in general since 8/26/10; greater unstable global mode statistics
    - Further analysis will compare stability of low l_i targets to other target plasmas
- Considerable physics detail of RWM control dynamics
  - A few shots show RWM mode rotation, spinup, and stabilization
    - Higher probability / differences now compared to results in SAS, et al, NF 50 (2010) 025020?
    - Shots with high suppression of n = 1 B_R field (e.g. 139359 B_r feedback) show RWM rotation (favorable); correlation of mode rotation and n = 1 feedback amplitude?
- Future Analysis
  - Complete evaluation of disruption statistics
  - Compare single and multi-mode VALEN analysis to n = 1 feedback performance
    - Including effect of different conducting structure model, $B_p + B_R$ feedback, etc.
  - Ideal and MISK analysis of RWM stability of target plasmas – dependence on l_i
  - Plasmas rotation variation in these plasma just starting to be investigated
    - Comparison of MISK analysis of these plasmas to past MISK results to be done
  - Compare to RWM state-space controller – offline and real-time results