NSTX

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Resistive Wall Mode Stabilization to Sustain High Normalized Beta at Low Internal Inductance in NSTX

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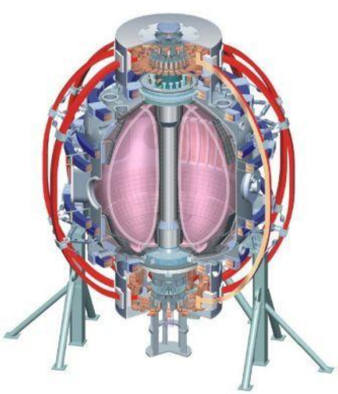

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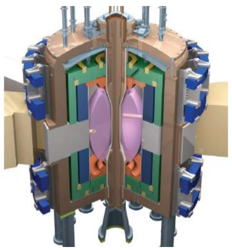
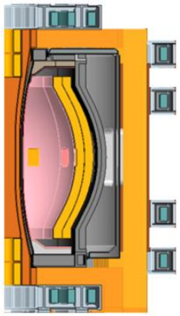
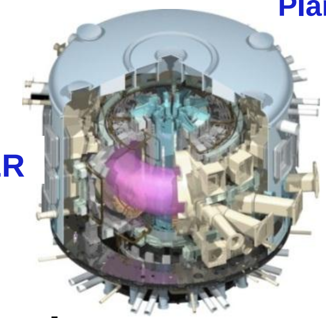
V2.1

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

- Motivation
  - Maintain high β_N stability, validate predictive and control capability to allow confident extrapolation to ST fusion applications and ITER





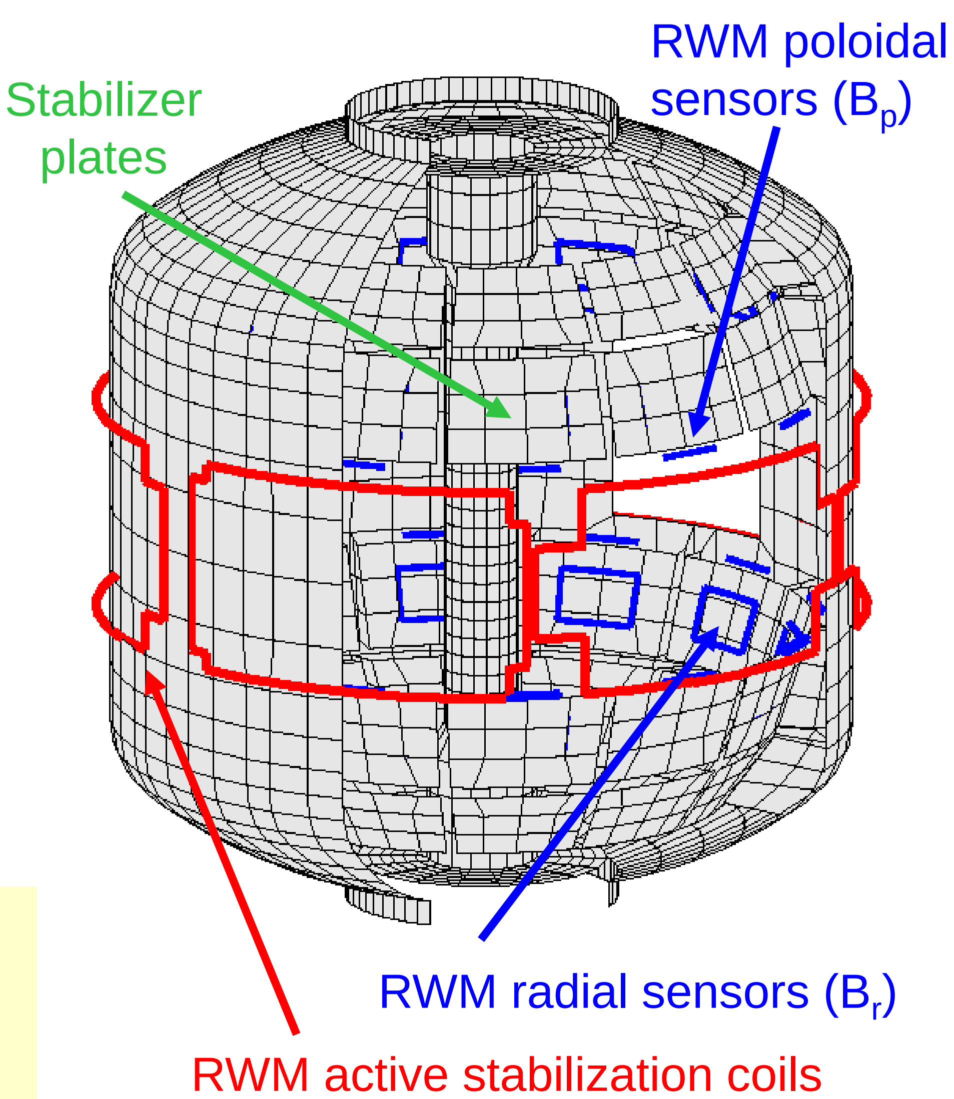


- Outline
  - Resistive wall mode stabilization at low internal inductance, l_i
  - Analysis of RWM passive stability at low l_i
  - RWM active control advances to improve stabilization
  - Model-based RWM state space controller use

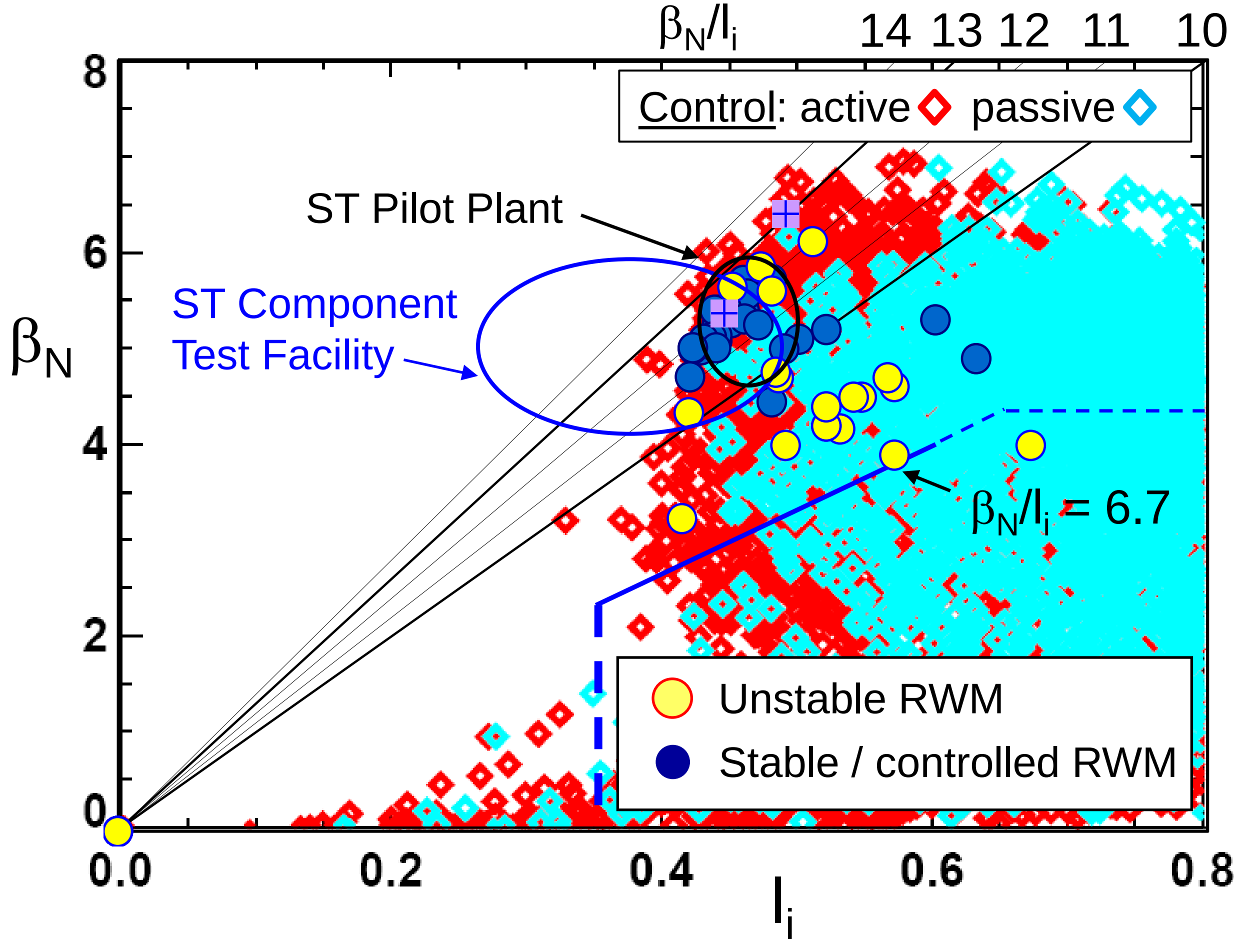
NSTX is a spherical torus equipped to study passive and active global MHD control

- 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

3D Structure Model



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



- Initial experiments
  - 48% disruption probability by RWM
- Experiments with control enhancements
  - Significantly reduced disruption probability with control enhancements
    - 14% of cases with $\beta_N/l_i > 11$

<u>Plasma internal inductance (l_i):</u>

- Integral measure of the peakedness of the current profile
- Low l_i typical of non-inductive operation, and at high κ (for vertical stability)

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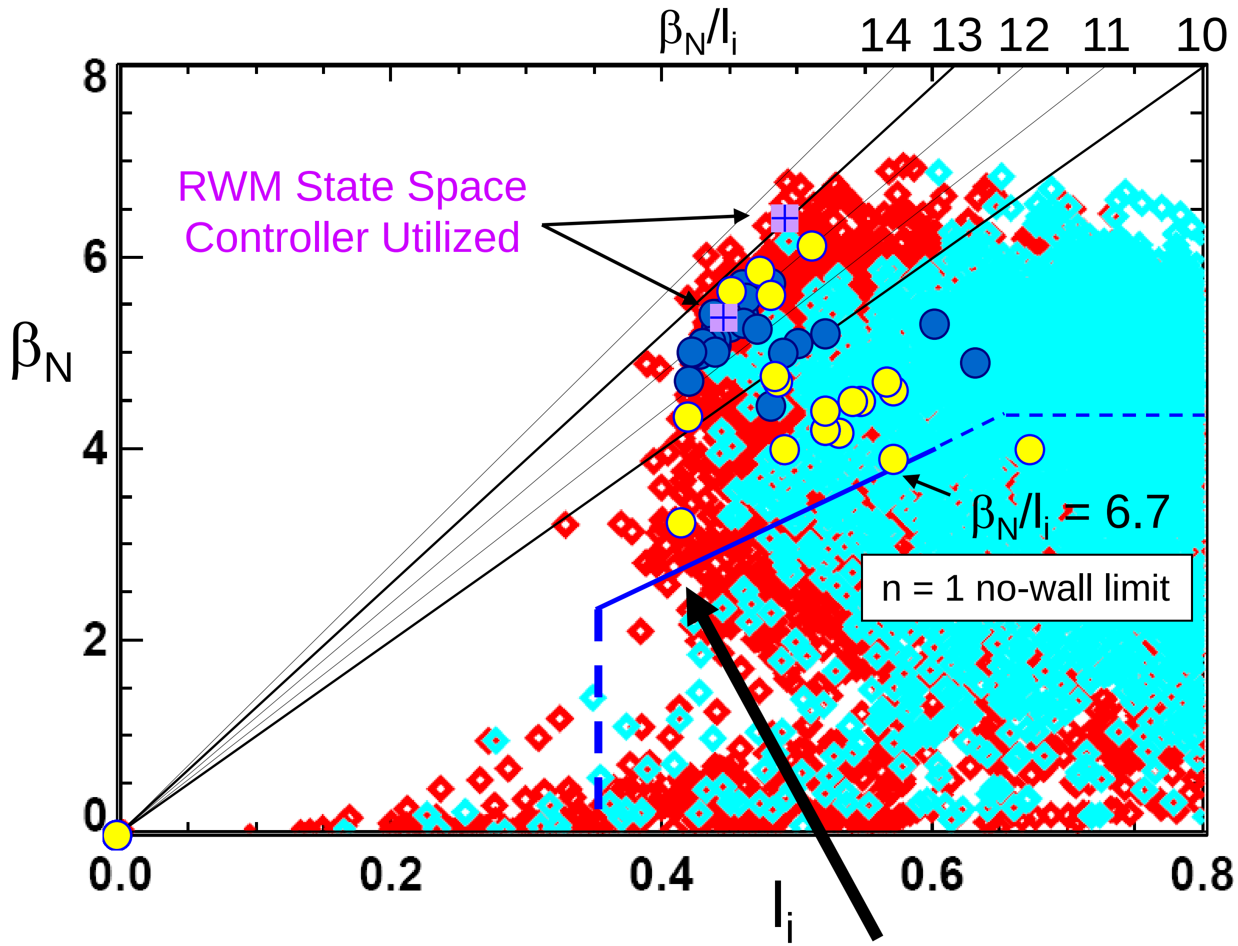

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    - Much higher probability of unstable RWMs at lower β_N, why??

- Computed n = 1 no-wall limit β_N/l_i,~ 6.7 (low l_i range 0.4 – 0.6)
- Synthetic equilibria variation: n = 1 no-wall unstable at all β_N at $l_i \lesssim 0.38$ (current-driven kink limit)
  - significant for NSTX-U, next-step ST operation

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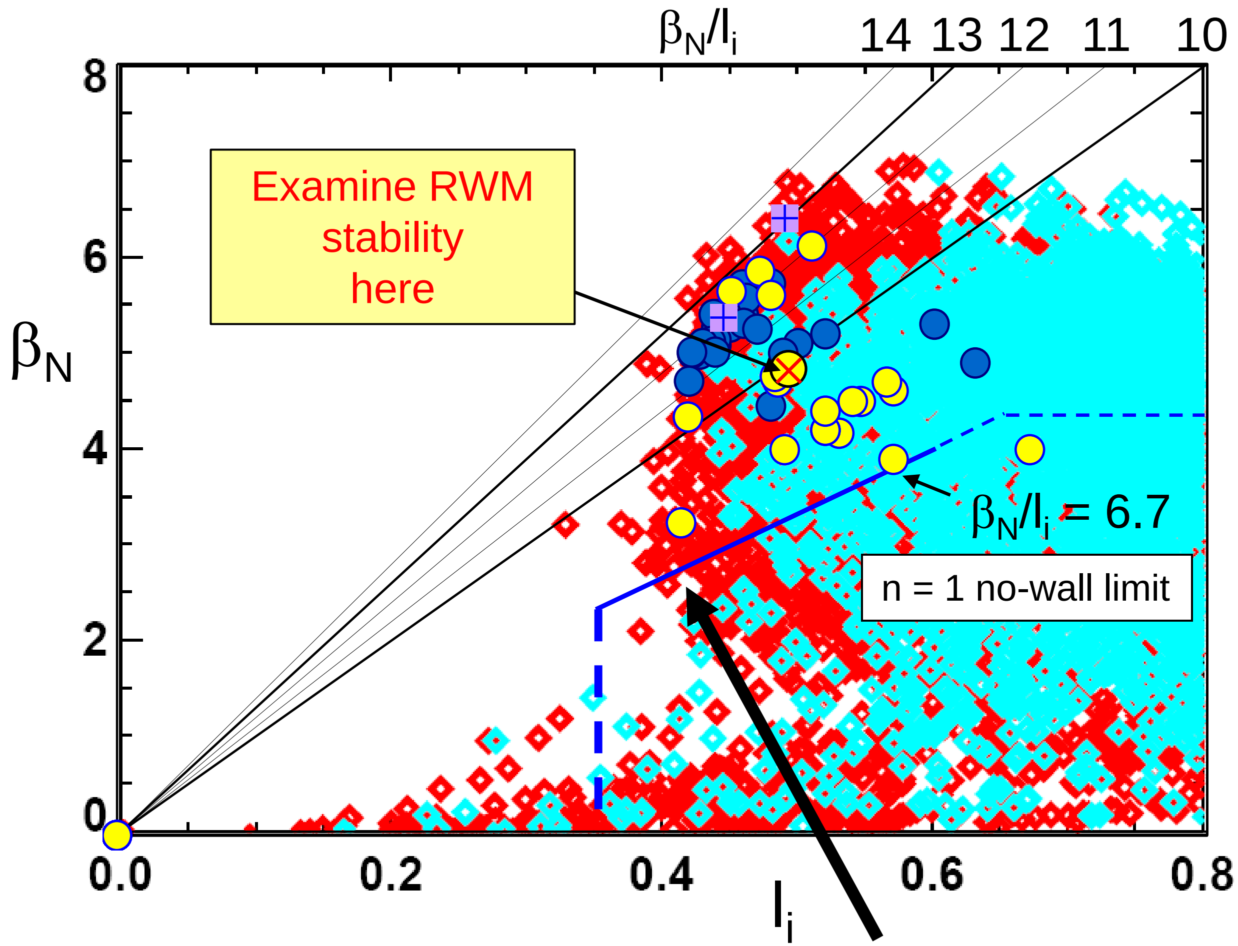

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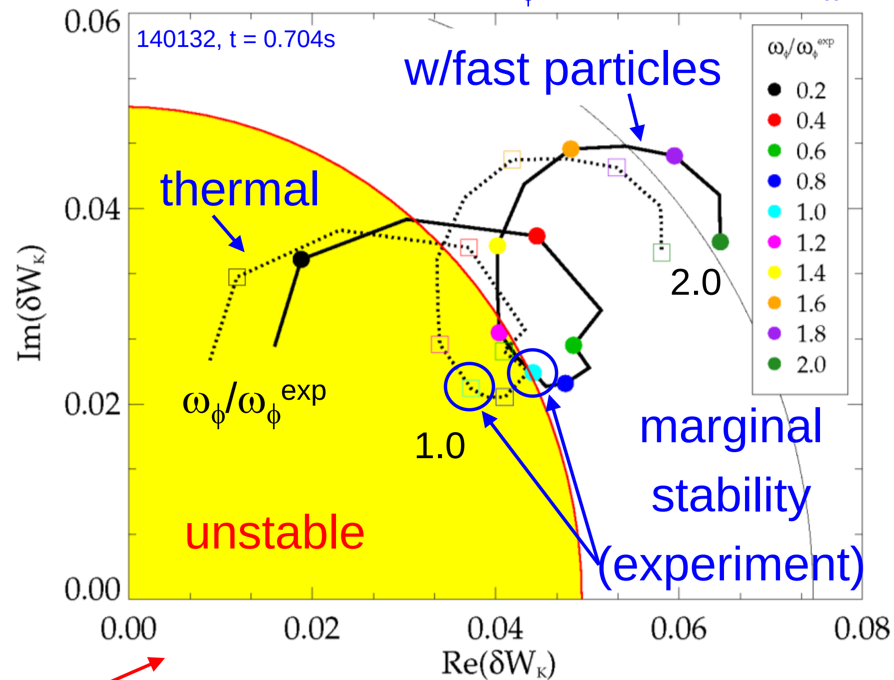
Kinetic stability calculations show reduced stability in low l_i target plasma as ω_φ is reduced, RWM becomes unstable

- Stability evolves
  - Computation shows stability at time of minimum l_i
  - Region of reduced stability vs. ω_φ found before RWM becomes unstable (l_i = 0.49)
- Quantitative agreement between theory/experiment
  - MISK, MARS-K, HAGIS codes being benchmarked (ITPA)
  - MISK calculation of ω_D improved
    - Agreement between theory/experiment improved
    - Best agreement with fast particle effects included

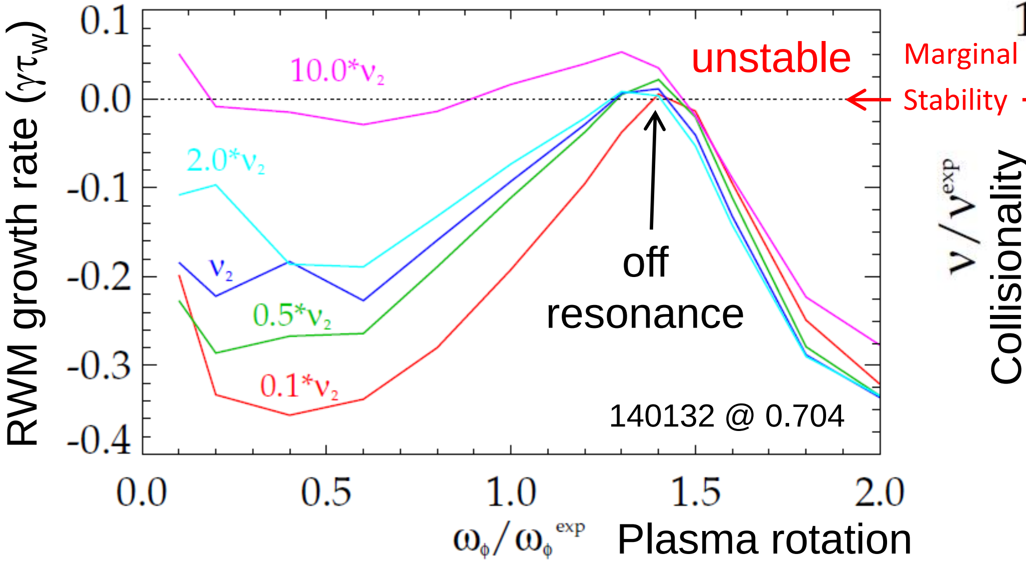
MISK code RWM stability vs. ω_ϕ (contours of $\gamma\tau_w$)

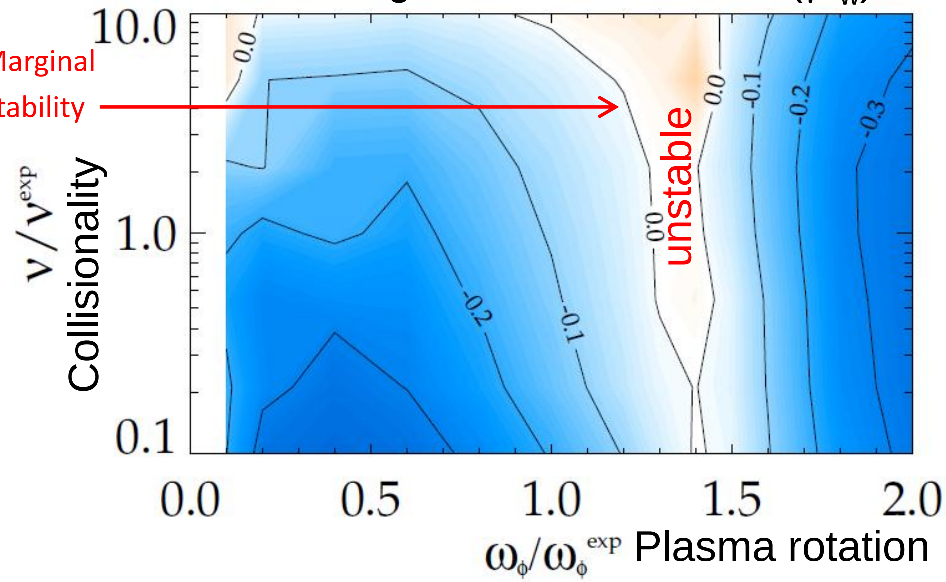


(more quantitative comparison to theory)

- 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

Reduced collisionality (ν) is stabilizing for resistive wall modes, but only near kinetic resonances



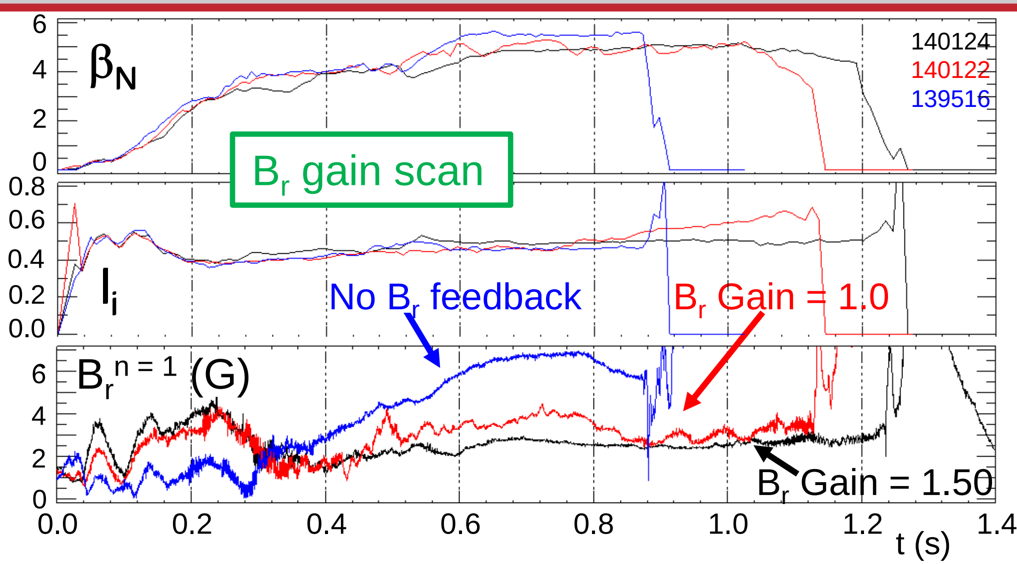


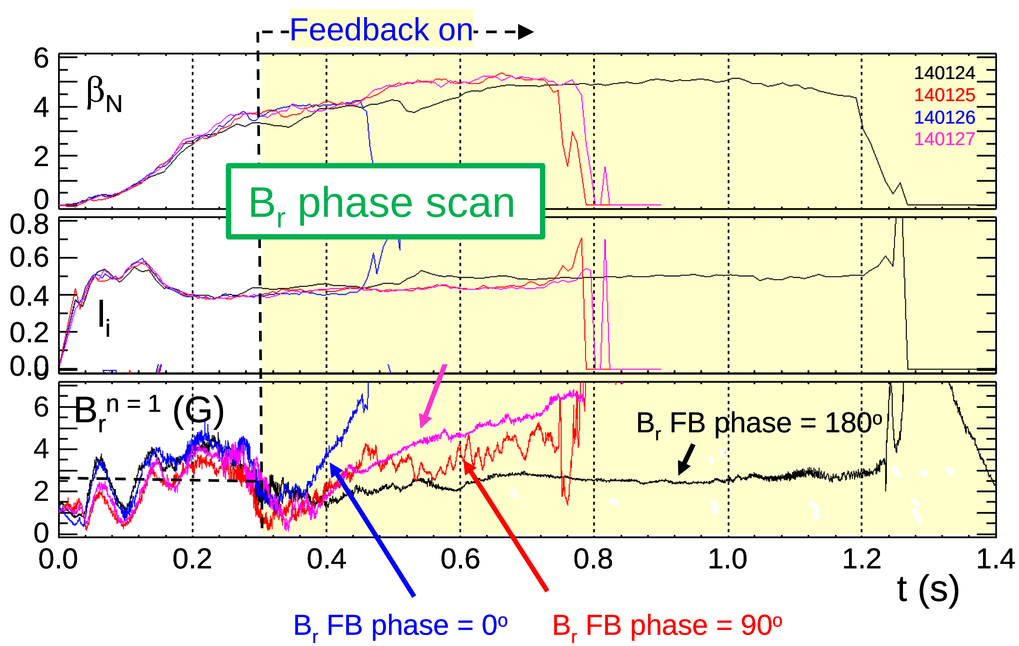
- NSTX-tested kinetic RWM stability theory: 2 competing effects at lower ν
  - Stabilizing collisional dissipation reduced (expected from early theory)
  - Stabilizing resonant kinetic effects enhanced (contrasts early RWM theory)
- Expectations in NSTX-U, tokamaks at lower ν (e.g. ITER)
  - Stronger stabilization near ω_ϕ resonances; almost no effect off-resonance
  - Plasma stability gradient vs. rotation increases
    - important to avoid unfavorable rotation, suppress transient RWM with active control

J.W. Berkery et al., PRL **106**, 075004 (2011)

See J.M. Bialek et al., poster PP9.47 (Wednesday, PM)

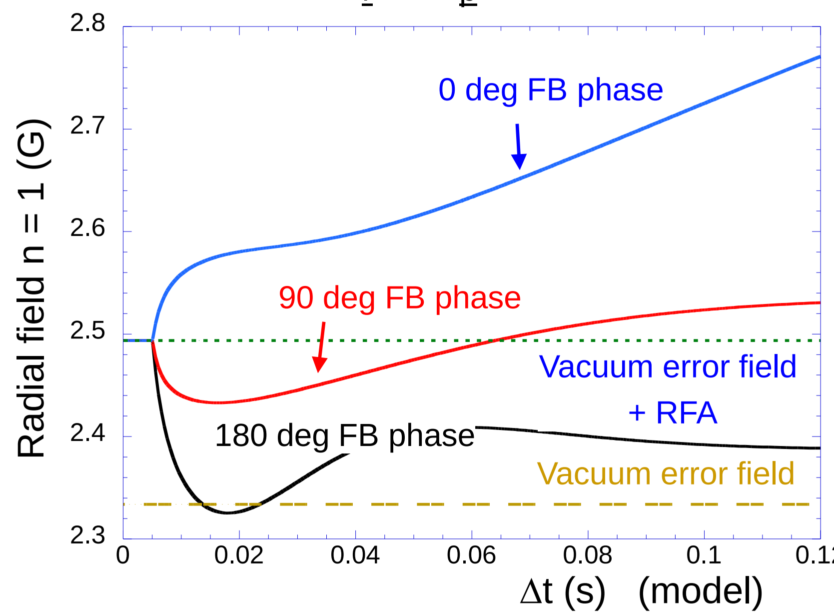
Active Control: combined RWM B_r + B_p sensor feedback gain and phase scans produce significantly reduced n = 1 field



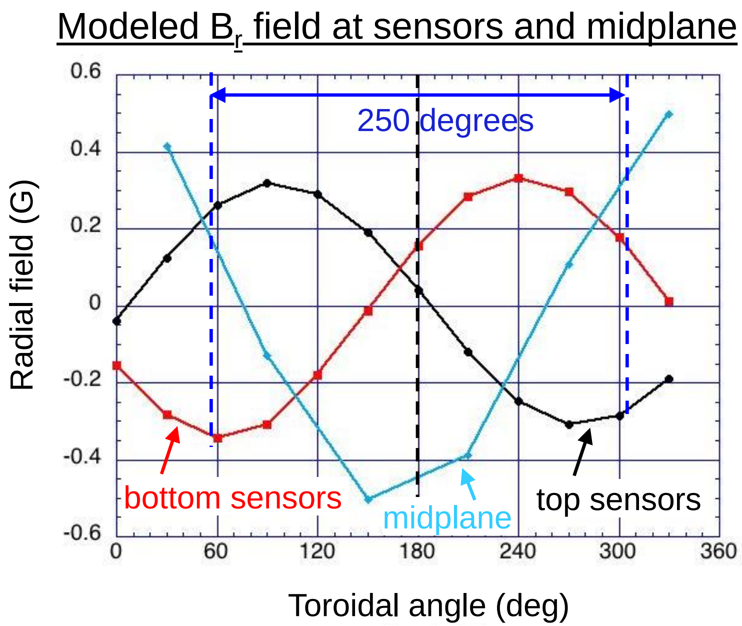


- Favorable B_p + B_r feedback (FB) settings found (low l_i plasmas)
  - Fast RWM growth ~ 2 - 3 ms control by B_p
  - B_r feedback controls slower (~10 ms) n=1 field amplification, modes
- Time-evolved theory simulation of B_r+B_p feedback follows experiment

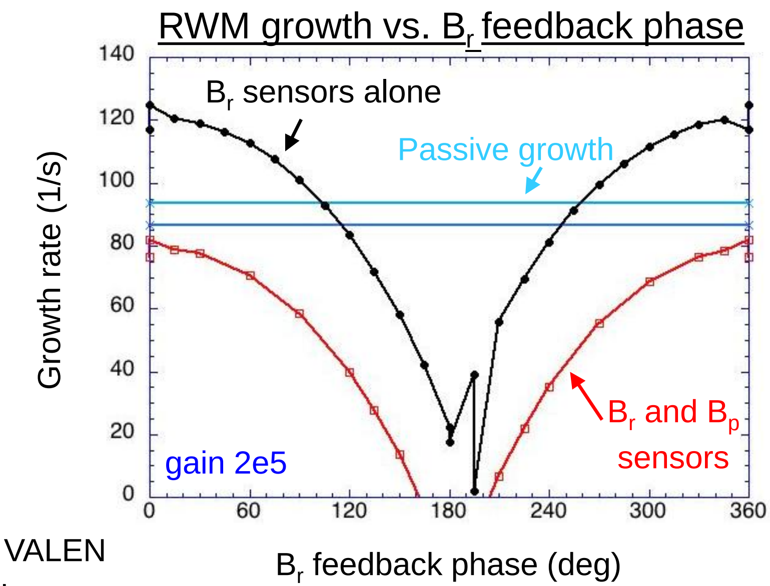
Simulation of B_r + B_p control (VALEN)



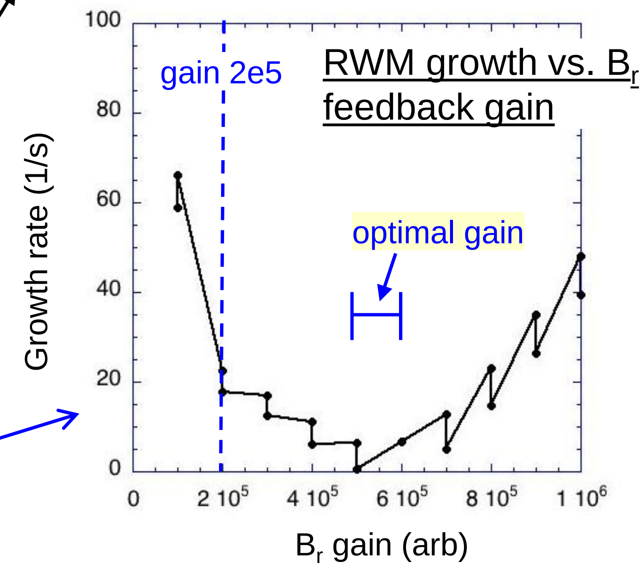
RWM feedback using upper/lower B_p and B_r sensors modeled and compared to experiment



DCON, VALEN codes

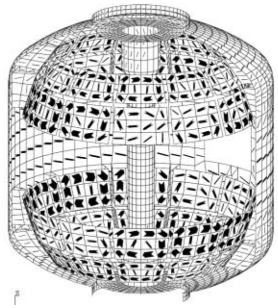


- Both B_r, B_p feedback contribute to active control
  - B_r mode structure and optimal feedback phase agrees with parameters used in experiment
  - B_r feedback alone provides stabilization for growth times down to ~ 10 ms with optimal gain
- Theory shows optimal feedback phase used in experiments; gain used is near optimal



Model-based RWM state space controller including 3D model of plasma and wall currents used at high β_N

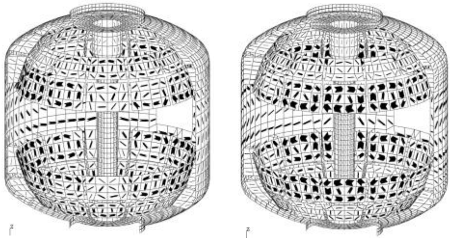
Full 3-D model ~3000+ states



Balancing transformation

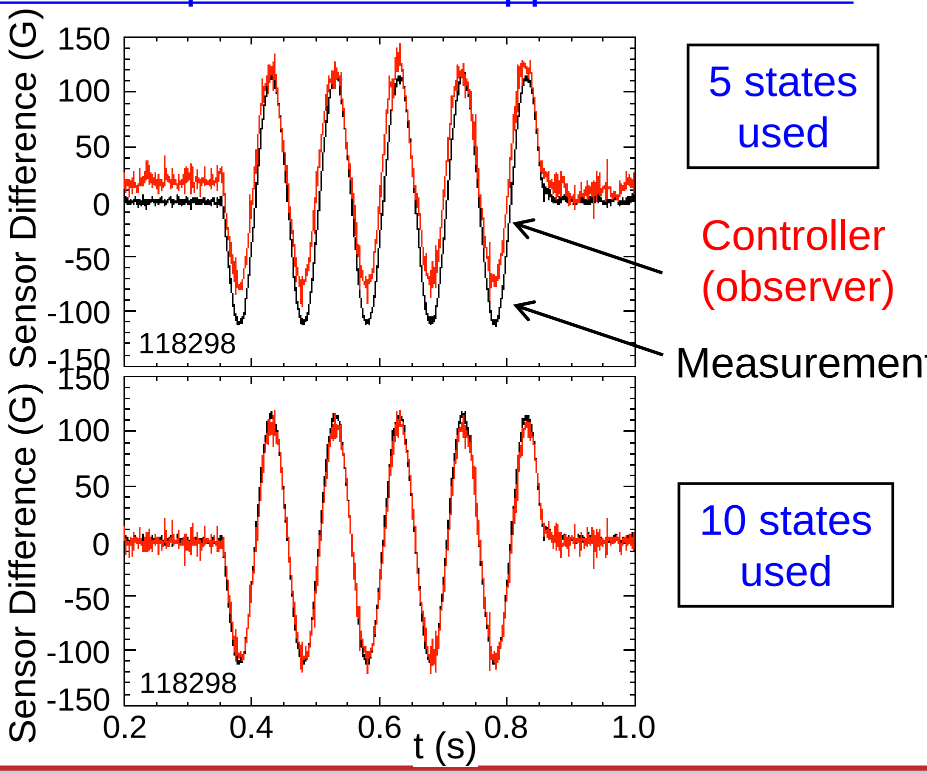
State reduction (< 20 states)

RWM eigenfunction (2 phases, 2 states)



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

Controller reproduction of applied n = 1 field



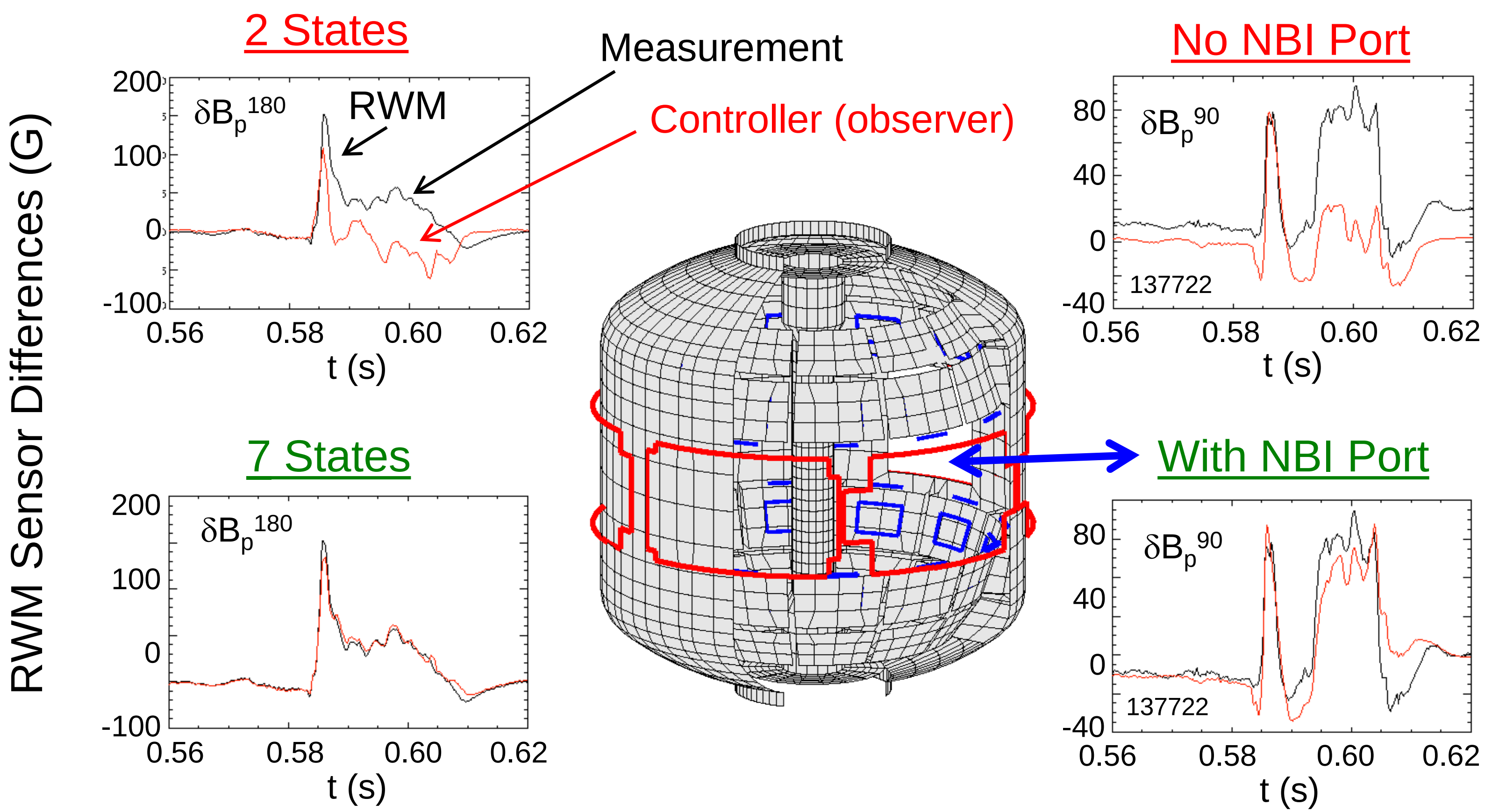
- Controller models, can compensate for wall currents
  - Including mode-induced current
- Potential to allow more flexible control coil positioning
  - May allow control coils to be moved further from plasma, and be shielded (e.g. for ITER)

    Katsuro-Hopkins, et al., NF **47** (2007) 1157
- Straightforward inclusion of multiple modes (n > 1) in feedback

Open-loop comparisons between sensor measurements and state space controller show importance of states and model

A) Effect of Number of States Used

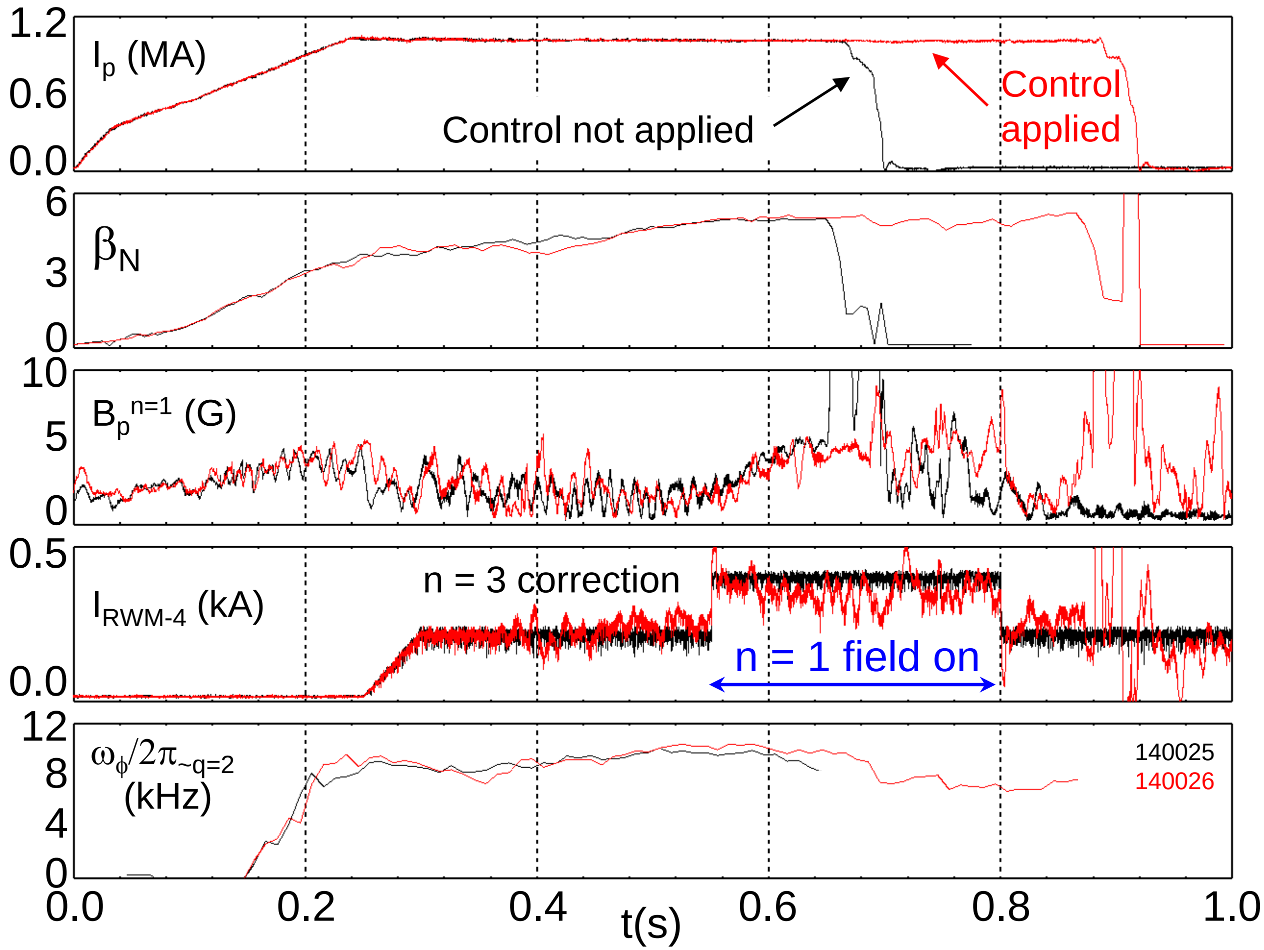
B) Effect of 3D Model Used



- Improved agreement with sufficient number of states (wall detail)
- 3D detail of model important to improve agreement

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

RWM state space feedback (12 states)



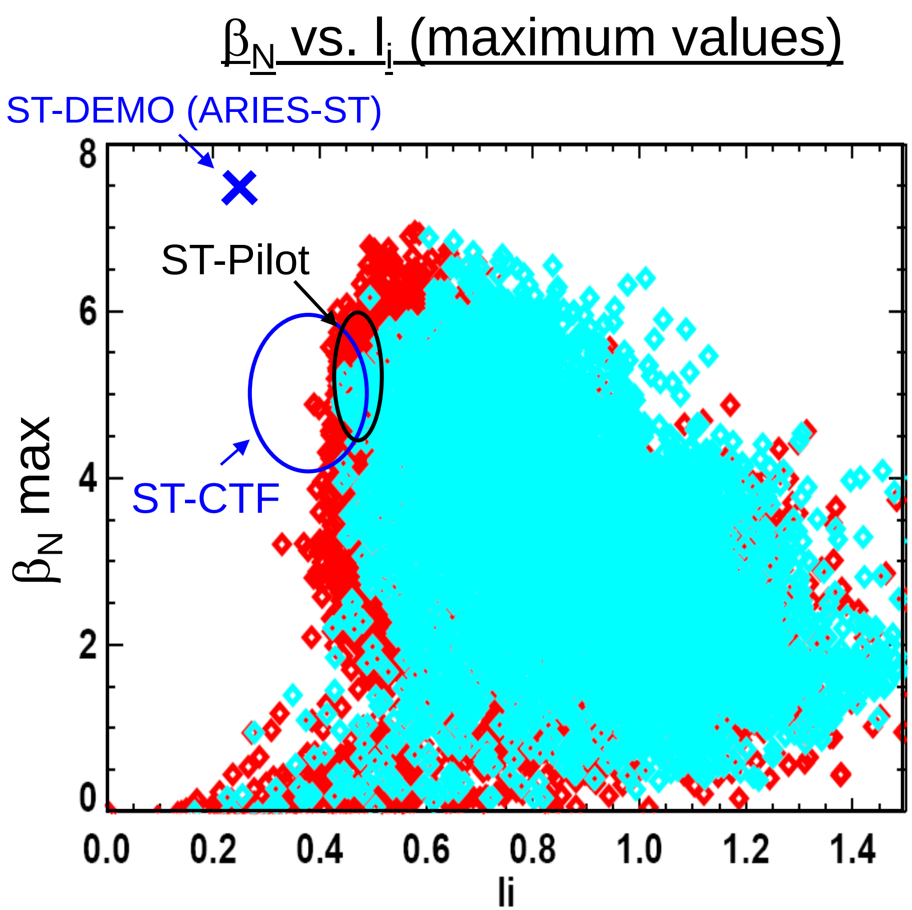
- n = 1 DC applied field test
  - Generate resonant field amplication, disruption
  - Use of RWM state space controller sustains discharge
- RWM state space controller sustains discharge at high β_N
  - Best feedback phase produced long pulse, β_N = 6.4, β_N/l_i = 13

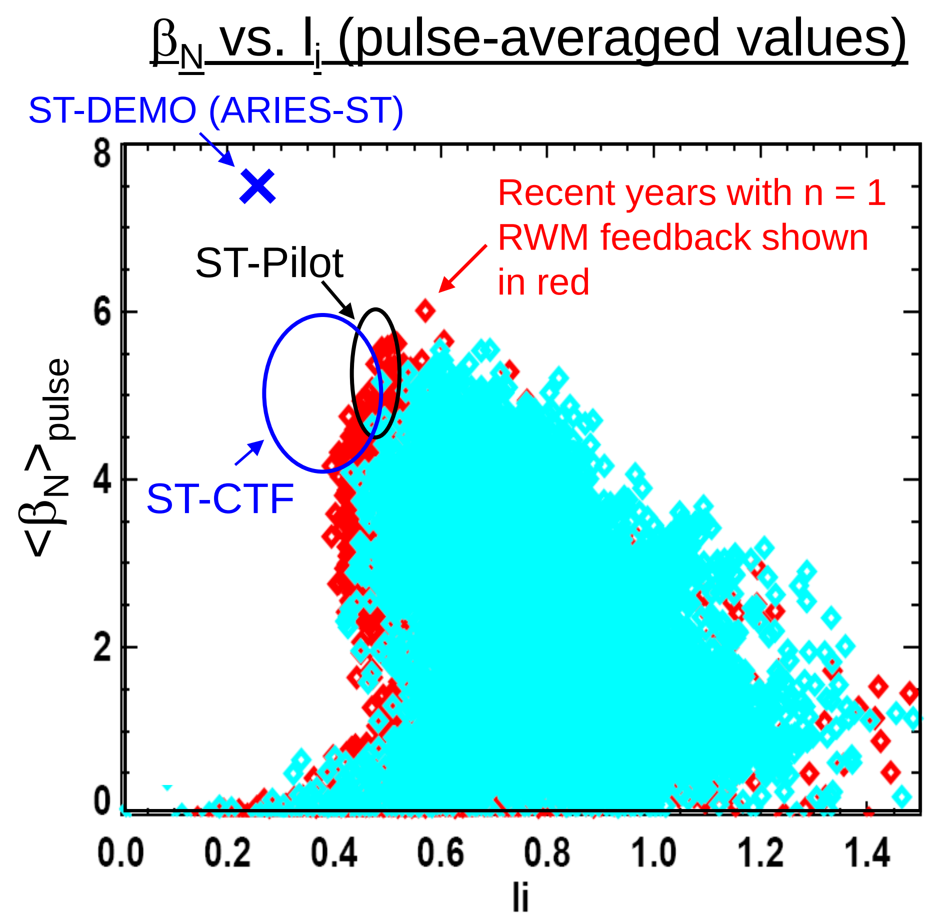
NSTX is Addressing Global Stability Needs Furthering Steady Operation of High Performance ST / Tokamak Plasmas

- Significant reduction in disruption probability in high β_N plasmas with reduced l_i
- Quantitative agreement between RWM marginal stability and kinetic stabilization theory for low l_i, high β_N plasmas
- Use of combined B_r + B_p RWM sensor n= 1 feedback improves reduction of n = 1 field amplitude, improved stability
- RWM state space controller sustains low l_i, high β_N plasma
  - Potential for greater flexibility of RWM control coil placement and shielding in future burning plasma devices (e.g. FNSF, ITER)

Supporting Slides

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

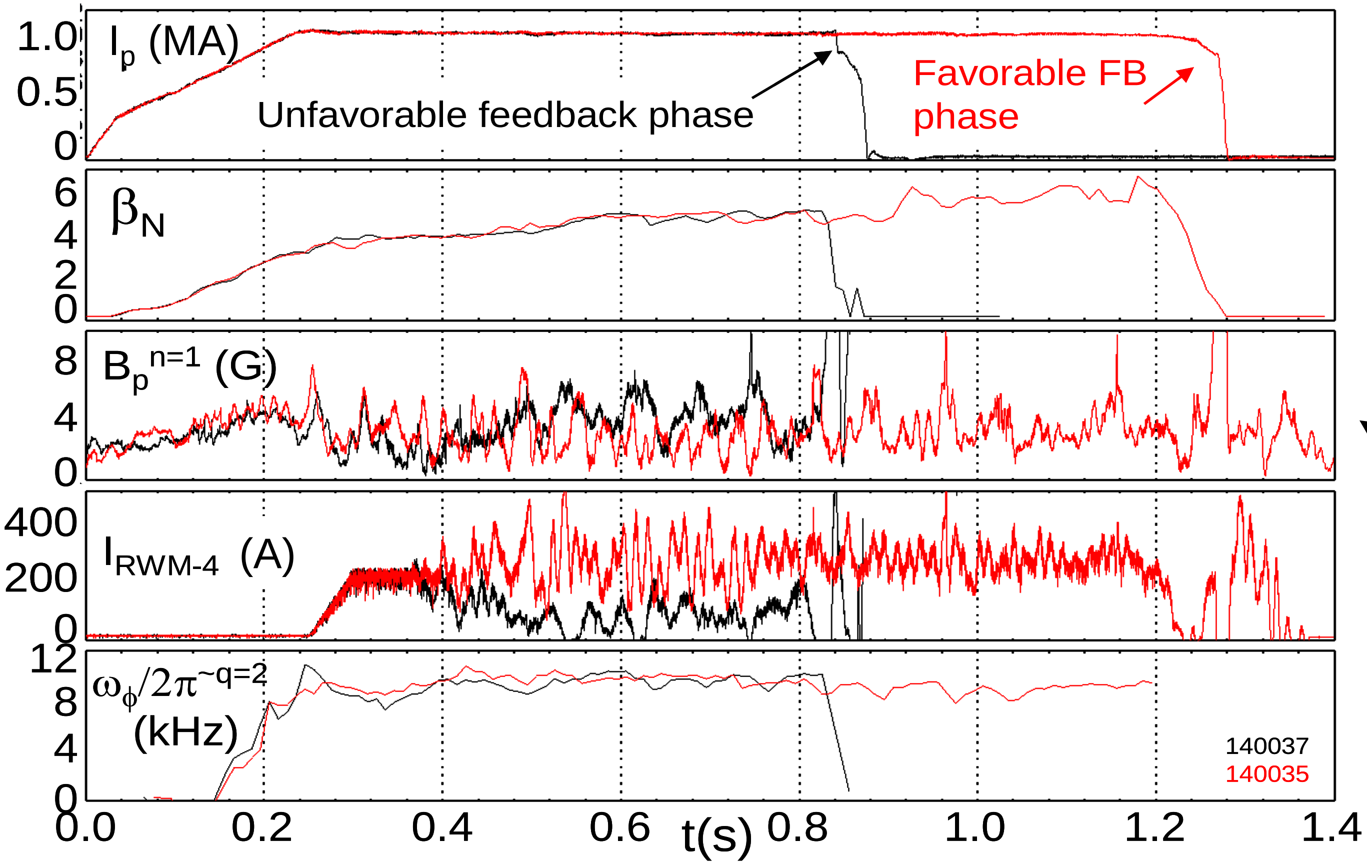




- Plasmas have begun to reach low l_i and high $<\beta_N>_{pulse}$ suitable for next-step ST fusion devices
  - Some parameters (e.g. elongation > 3) still need to be reached self-consistently

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

RWM state space feedback (12 states)

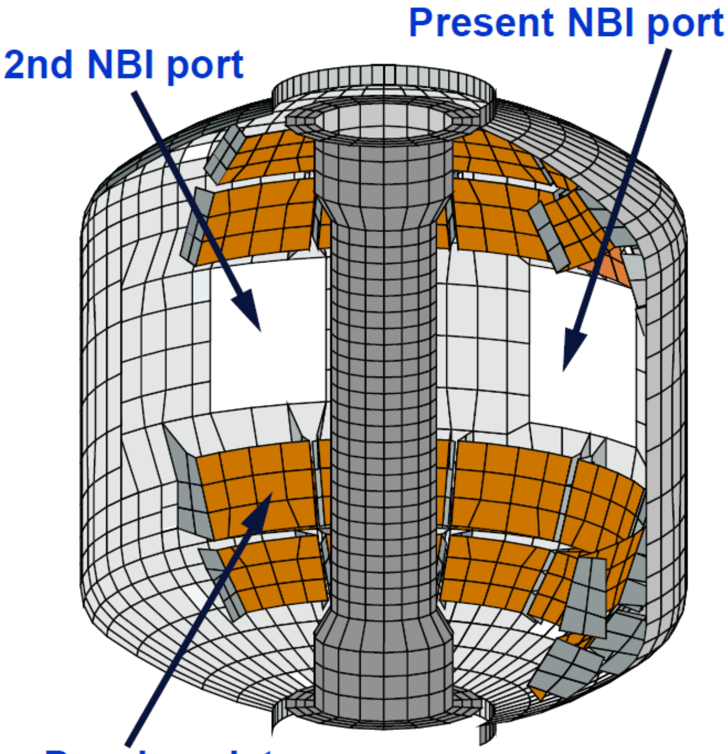


Successful First Experiments

- Feedback phase scan
  - Best feedback phase produced long pulse, β_N = 6.4, β_N/l_i = 13

Second NBI beam port in NSTX-U makes a small difference in with-wall limit

VALEN model of NSTX Upgrade passive conducting structure



VALEN computed RWM growth rate vs. β_N