NSTX Supported by U.S. DEPARTMENT OF ENERGY Office of Science

RWM Stabilization with State Space Control and Multi-component Sensors in NSTX

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16th Workshop on MHD Stability Control

November 21st, 2011

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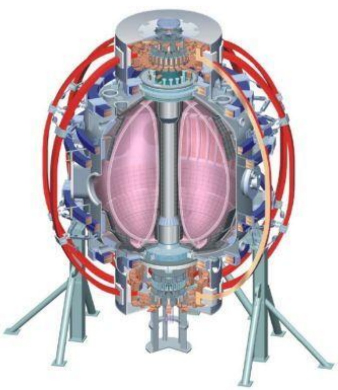

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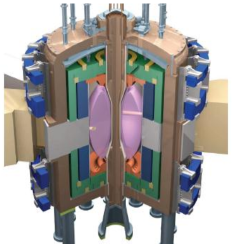
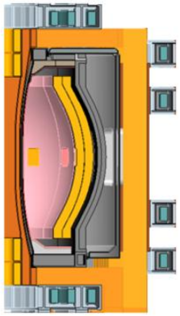
V1.1

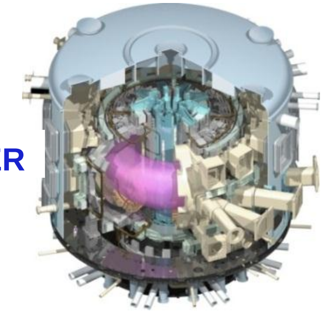
NSTX is Addressing Global Stability Needs for Maintaining Low l_i, High Beta Plasmas for Fusion Applications



Fusion Nuclear Science Facility (FNSF)



ST Pilot Plant



ITER

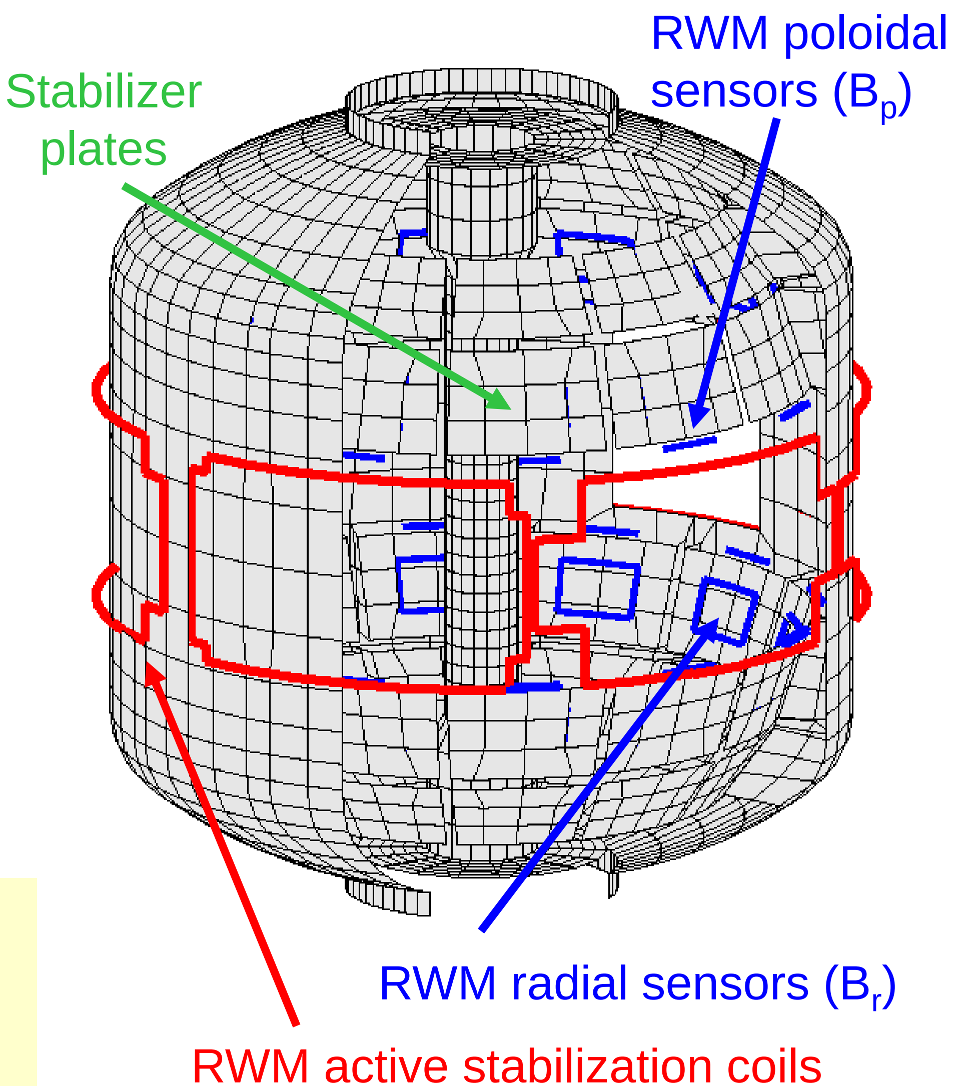
- Motivation
  - Maintain high β_N stability, validate predictive and control capability to allow confident extrapolation to ST fusion applications and ITER

- Outline
  - Resistive wall mode stabilization at low internal inductance, l_i
  - RWM active control advances to improve stabilization
  - Model-based RWM state space controller (RWMSC)
  - Multi-mode RWM / DEFC spectrum for RWMSC use

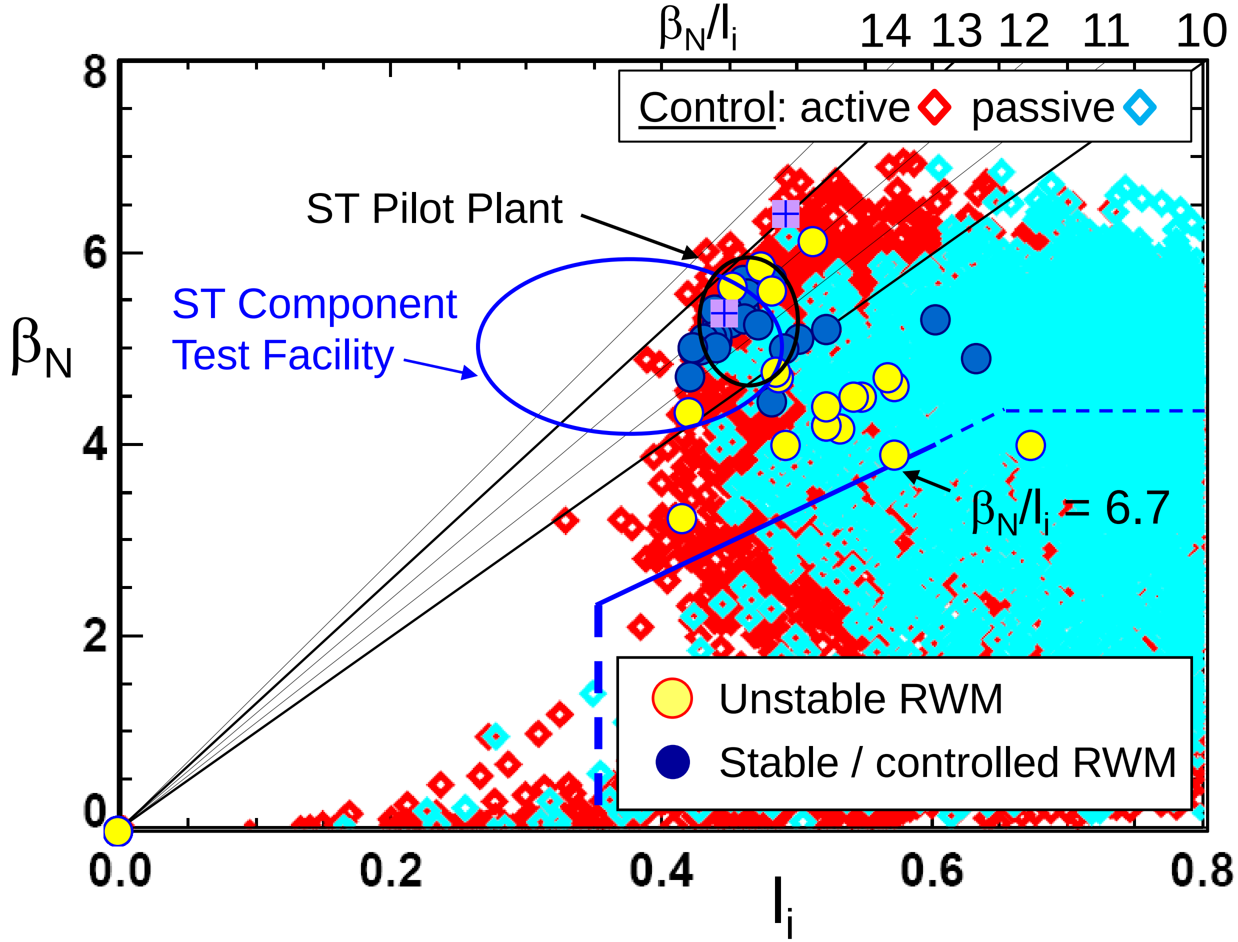
NSTX is a spherical torus equipped to study passive and active global MHD control

- 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

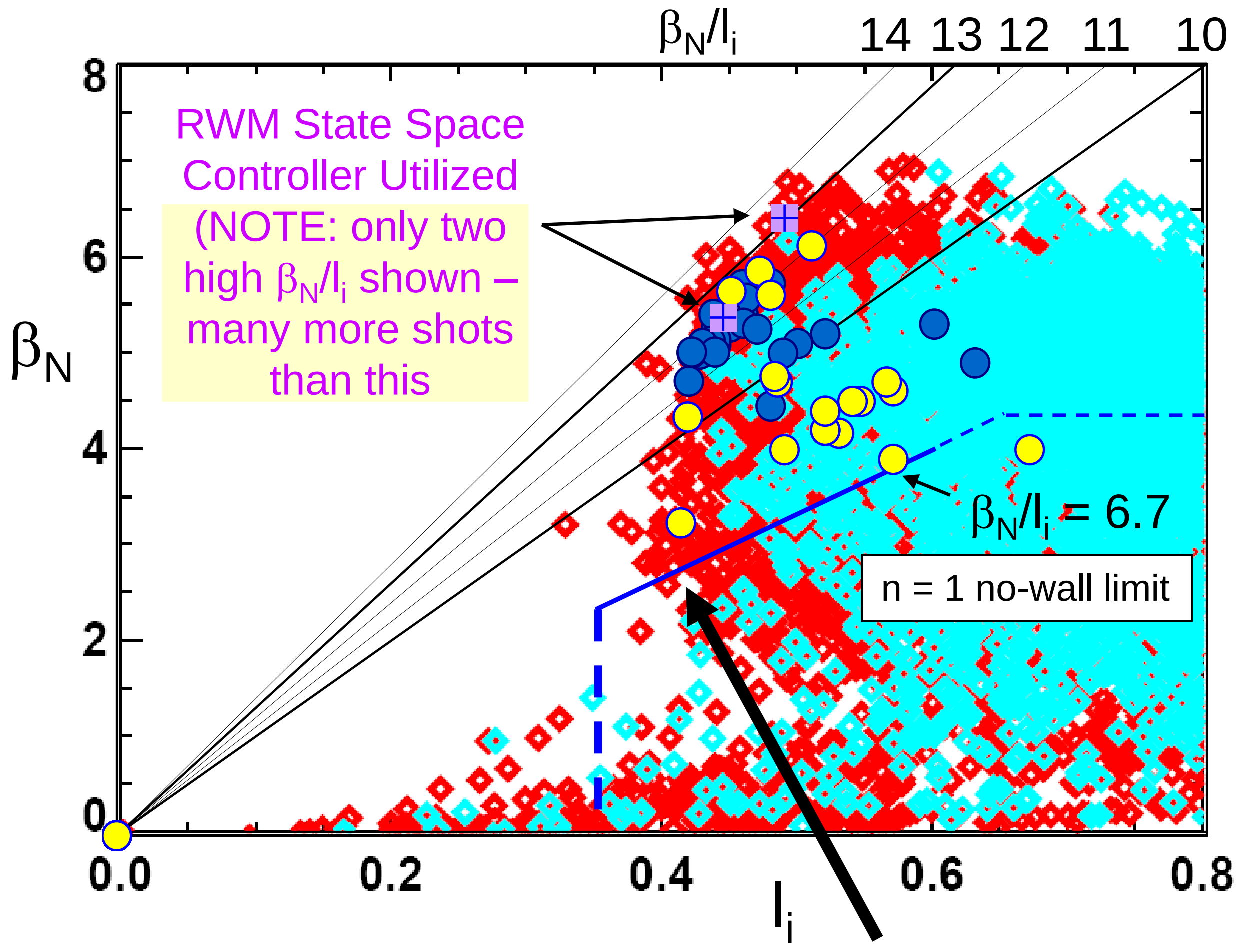


- Initial experiments
  - 48% disruption probability by RWM
- Experiments with control enhancements
  - Significantly reduced disruption probability with control enhancements
    - 14% of cases with $\beta_N/l_i > 11$

Plasma internal inductance (l_i):

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

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



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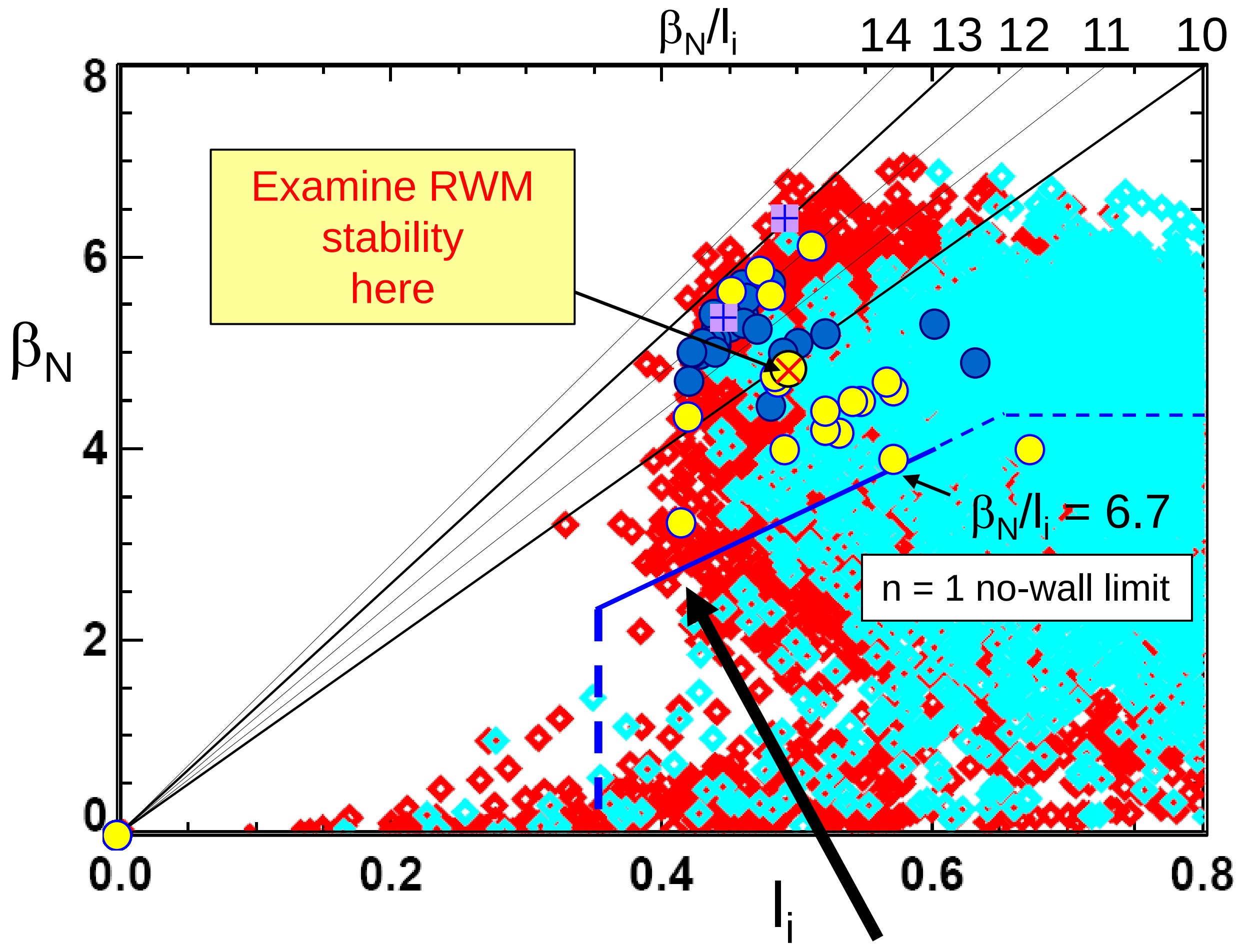
    - 14% of cases with $\beta_N/l_i > 11$
    - Much higher probability of unstable RWMs at lower β_N, why??

- 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

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



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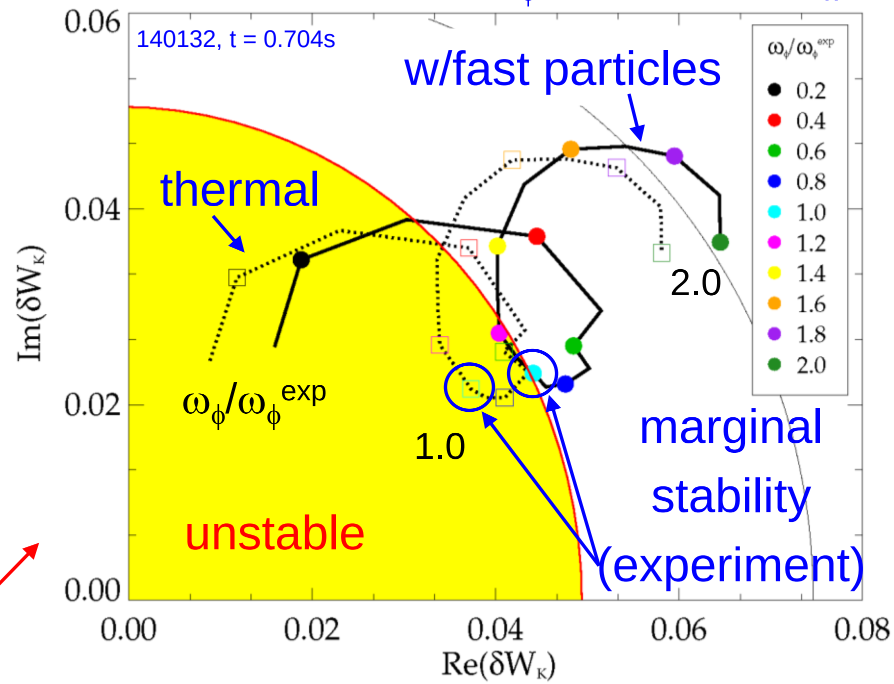
Kinetic stability calculations show reduced stability in low l_i target plasma as ω_φ is reduced, RWM becomes unstable

- Stability evolves
  - Computation shows stability at time of minimum l_i
  - Region of reduced stability vs. ω_φ found when RWM becomes unstable (l_i = 0.49)
- Quantitative agreement between theory/experiment
  - MISK, MARS-K, HAGIS code benchmarking (ITPA MDC-2)
  - MISK ω_D calc. improved
    - (already good) agreement between theory/experiment improved (no free params.)
    - Best agreement with fast particle effects included

(Key for NSTX/DIII-D unified result (IAEA 2010))

MISK code

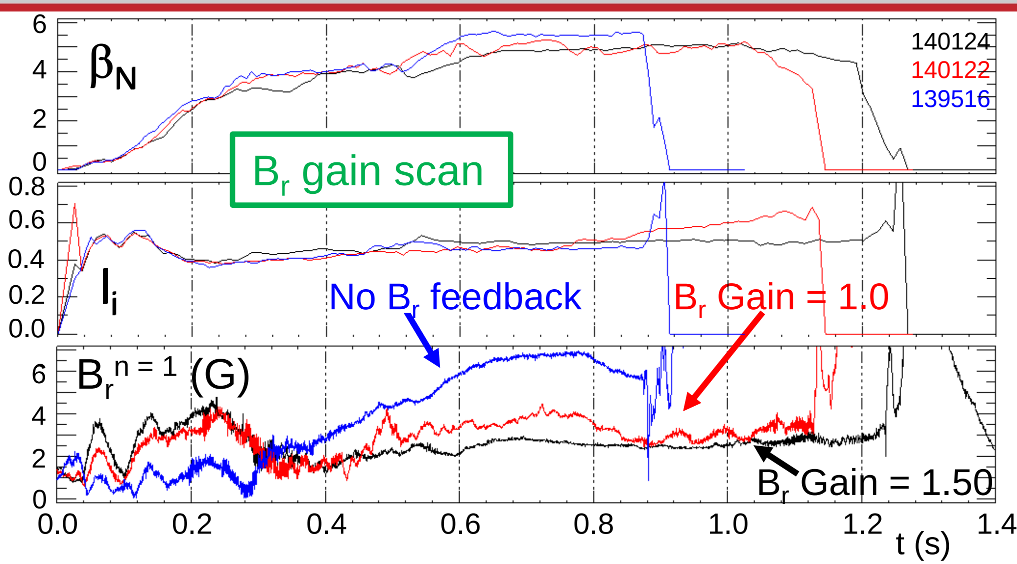
RWM stability vs. ω_ϕ (contours of $\gamma\tau_w$)

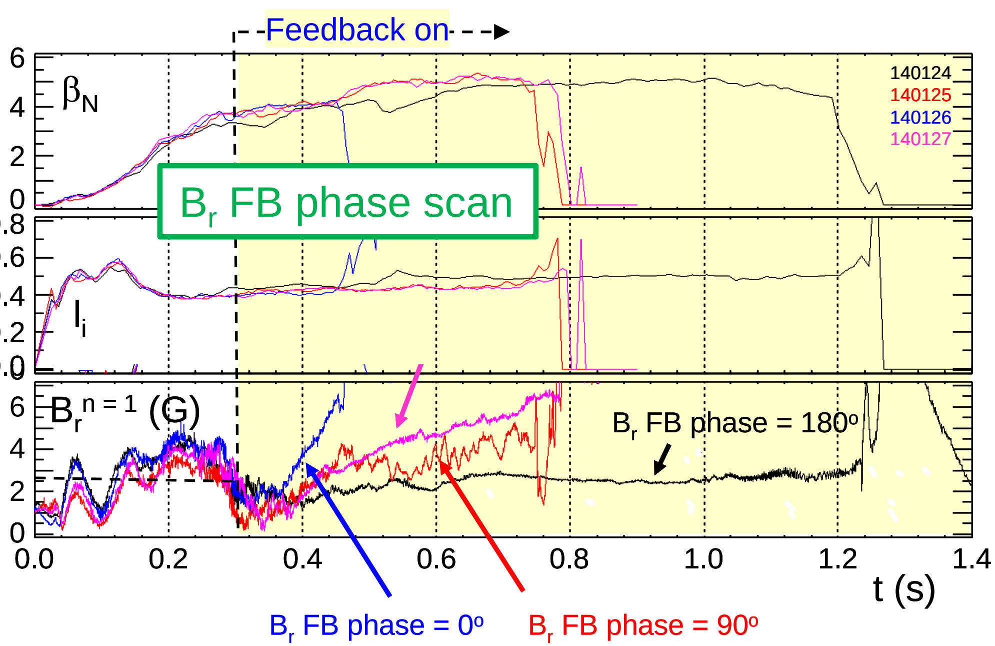


(more quantitative comparison to theory)

- S.A. Sabbagh, et al., IAEA FEC 2008, Paper EX/5-1
- 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

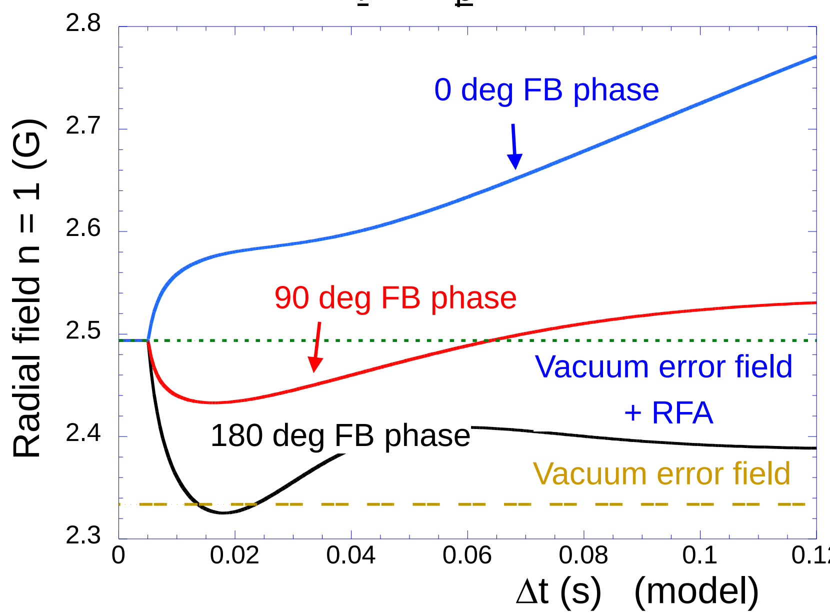
Combined RWM B_r + B_p sensor feedback gain and phase scans produce significantly reduced n = 1 field





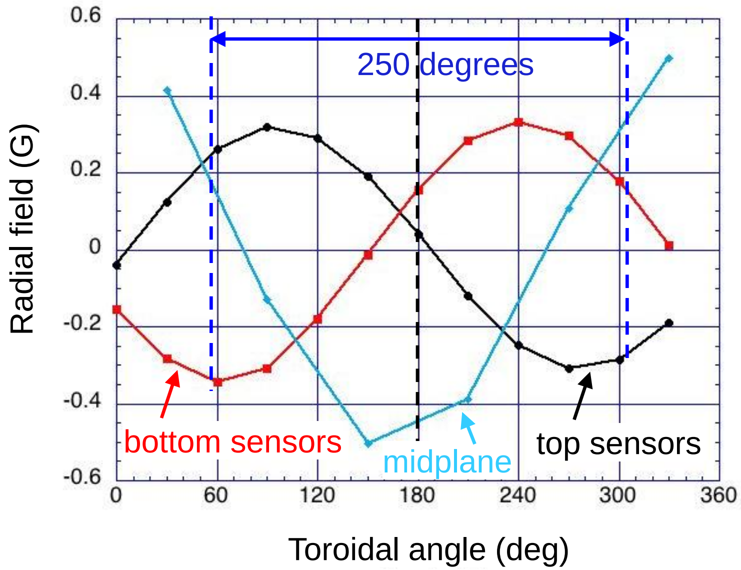
- Favorable B_p + B_r feedback (FB) settings found (low l_i plasmas)
  - Fast RWM growth ~ 2 - 3 ms control by B_p
  - B_r FB controls (~10 ms ~ $\tau_{w\text{-radial}}$) n=1 field amplification, modes
- Time-evolved theory simulation of B_r+B_p feedback follows experiment

Simulation of B_r + B_p control (VALEN)

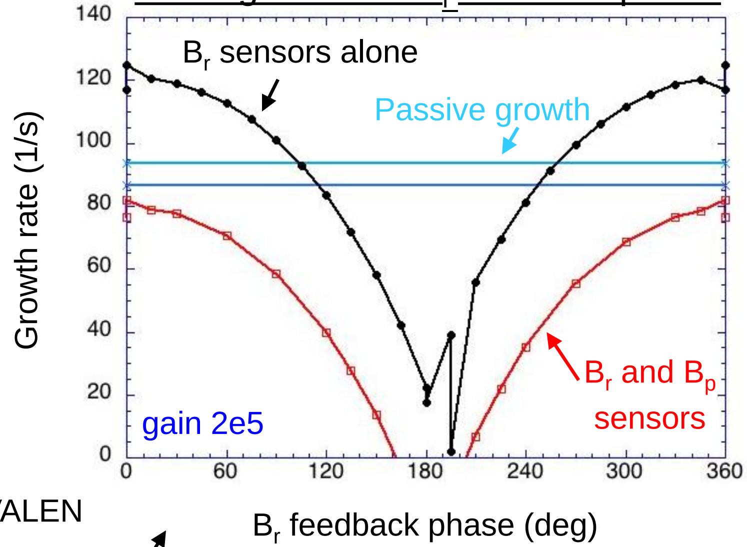


RWM feedback using upper/lower B_p and B_r sensors modeled and compared to experiment

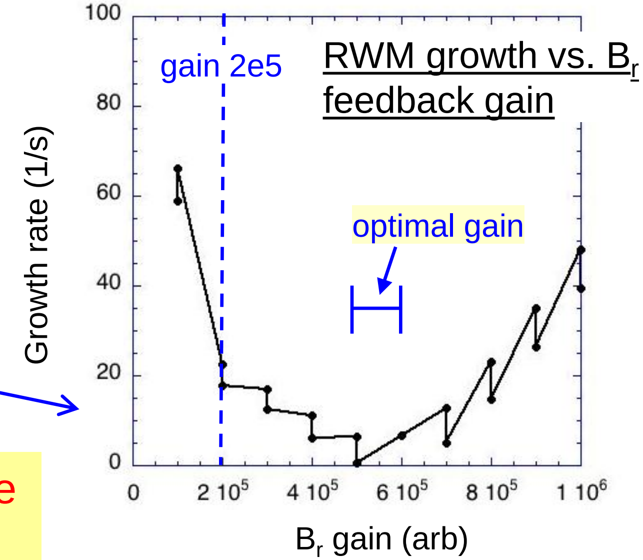
Modeled B_r field at sensors and midplane



RWM growth vs. B_r feedback phase



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 ~ $\tau_{w\text{-}radial}$ with optimal gain
- Theory shows optimal feedback phase used in experiments; gain used is near optimal

MISK results, sensor measurements: use marginal ideal mode eigenfunction in RWM state space controller

Model-based RWM state space controller in NSTX advances present PID controller

- PID (our present, successful workhorse)
  - Feedback logic operates to reduce n = 1 amplitude (n = 1 phase/ampl. input)
  - No a priori knowledge of mode physics, controller stability
  - Only knowledge of mode structure: spatial phase offset of upper/lower sensors

- State space control
  - States reproduce characteristics of full 3-D model: conducting structure, plasma response, mode shape, feedback control currents via matrix operations
    - Boozer permeability model used for plasma response
    - A key quantity to compare to measurements is mode pitch at large R
  - Observer (computes sensor estimates)
    - RWM sensor estimates provided by established methods (Kalman filter)
    - useful as an analysis tool to compare plant output to measurements
  - Controller (computes control currents)
    - Controller gain computed by established methods: gains for each coil and state

- Many shots taken in NSTX with RWM state space control
  - Two dedicated run days, near-record β_N/l_i in sustained plasmas, gain/phase scans, hundreds of shots run with low gain (e.g. observer scoping studies)

New State Derivative Feedback Algorithm needed for Current Control

- State equations to advance

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

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

Control vector, *u*; controller gain, K_c

Observer est., *y*; observer gain, K_o

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

- Previously published approach found to be formally “uncontrollable” when applied to current control
- State derivative feedback control approach

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

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

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

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

Advance discrete state vector

$$\hat{\vec{x}}_t = A\vec{x}_{t-1} + B\vec{u}_{t-1}; \hat{\vec{y}}_t = C\hat{\vec{x}}_t \qquad \text{(time update)}$$

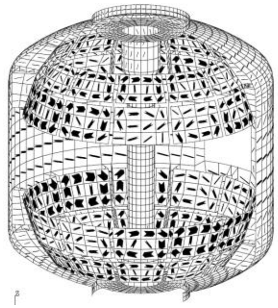
$$\vec{x}_{t+1} = \hat{\vec{x}}_t + A^{-1}K_o(\vec{y}_{sensors(t)} - \hat{\vec{y}}_t) \qquad \text{(measurement update)}$$

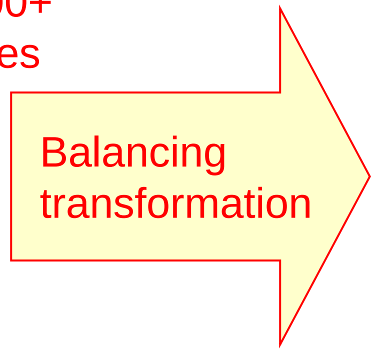
Written into the PCS (GA)

- General (portable) matrix output file for operator
- PCS code recently generalized by K. Erickson

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

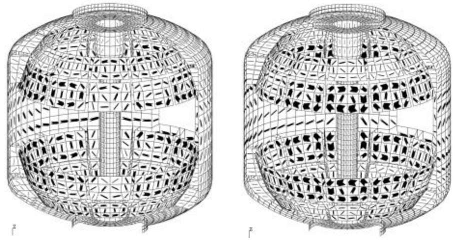
Full 3-D model ~3000+ states





State reduction (< 20 states)

RWM eigenfunction (2 phases, 2 states)

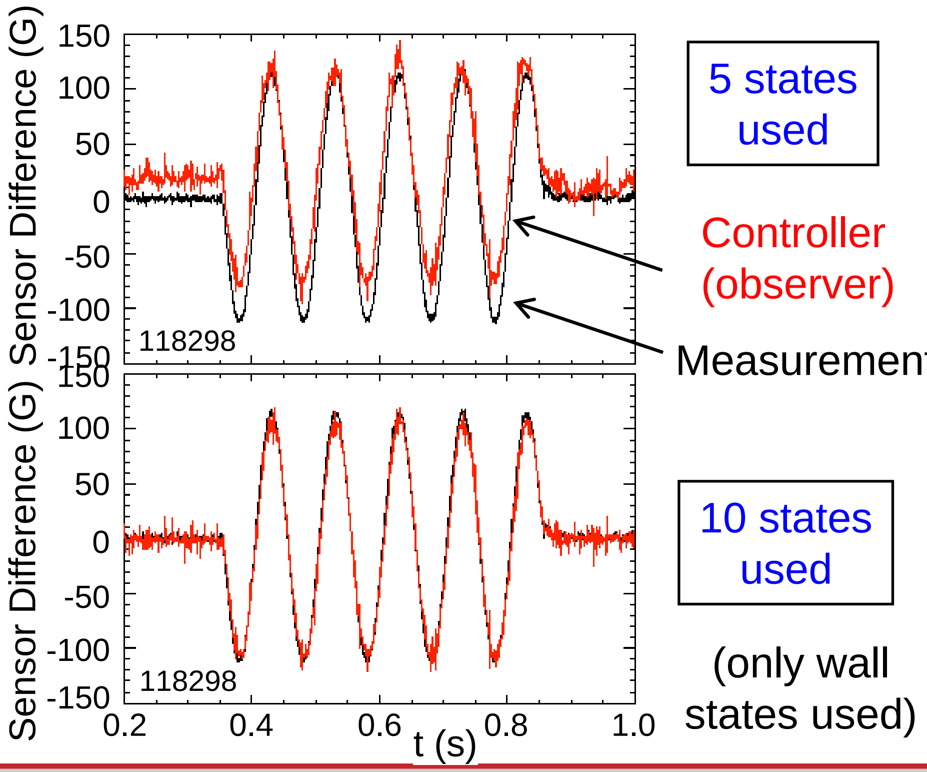


$(\hat{x}_1, \hat{x}_2)$ $\hat{x}_3$ $\hat{x}_4$ ...

- Controller model can compensate for wall currents
  - Includes plasma 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 (with n = 1, or n > 1) in feedback

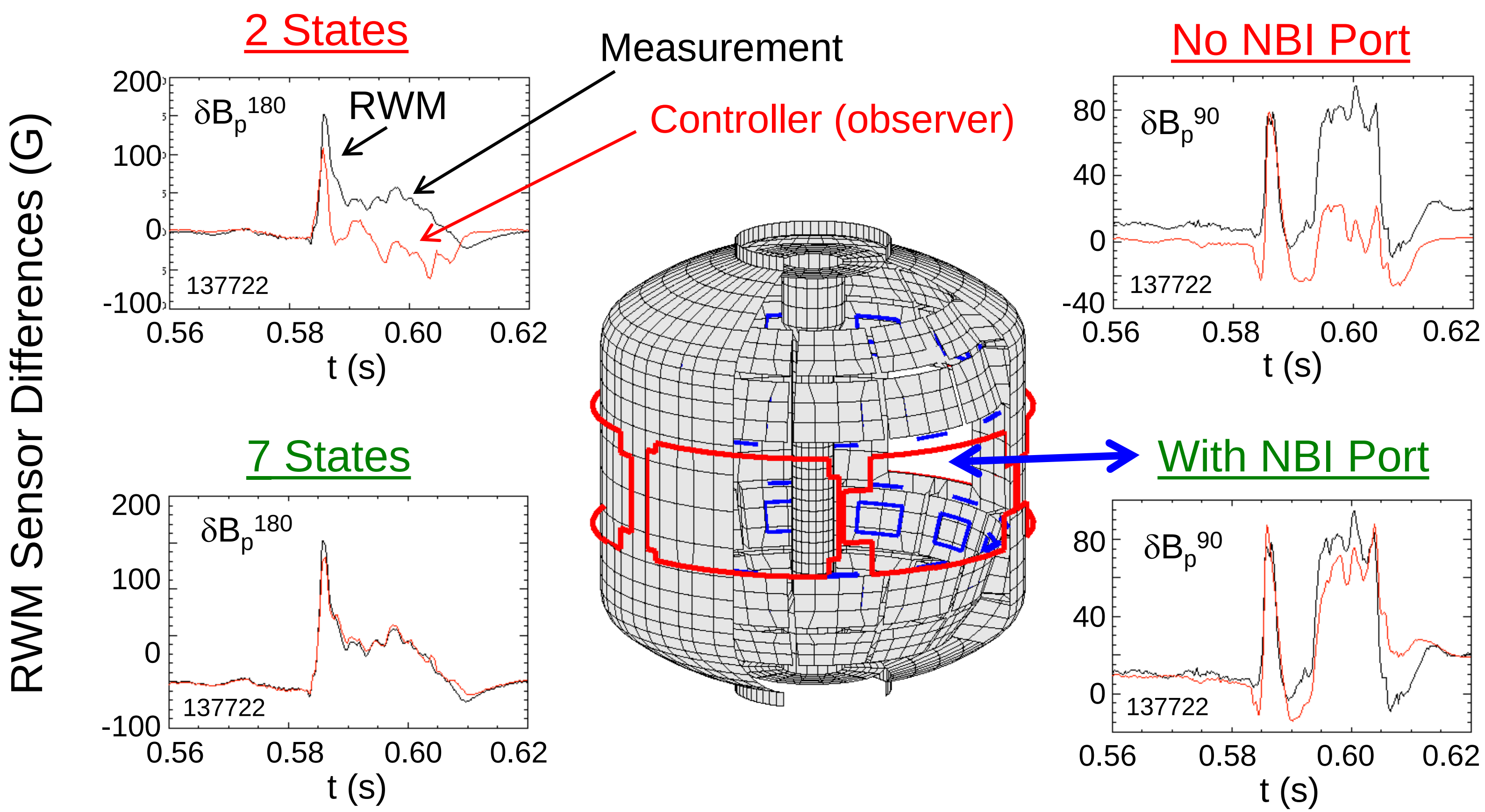
Controller reproduction of n = 1 field in NSTX



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

A) Effect of Number of States Used

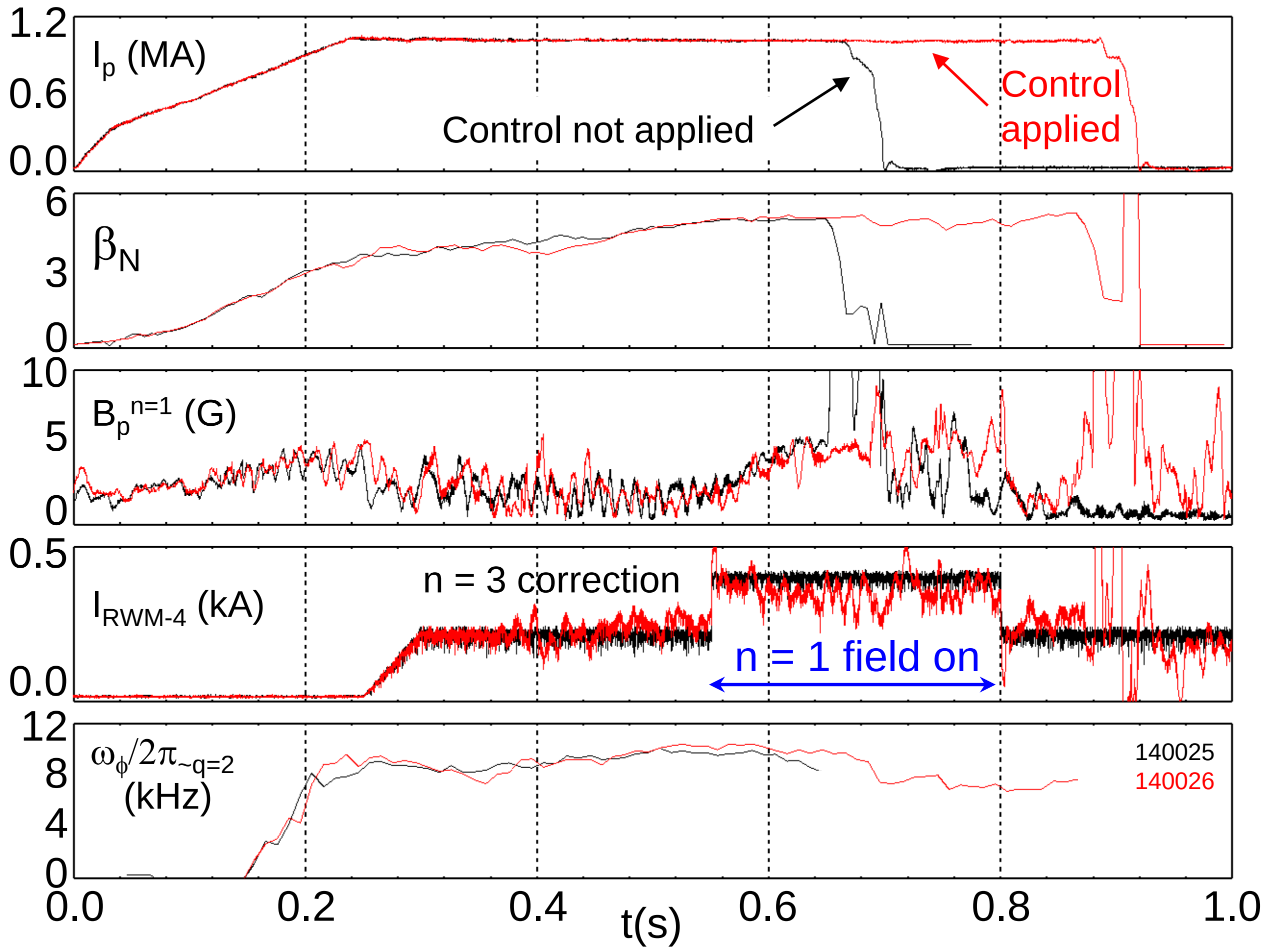
B) Effect of 3D Model Used



- 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

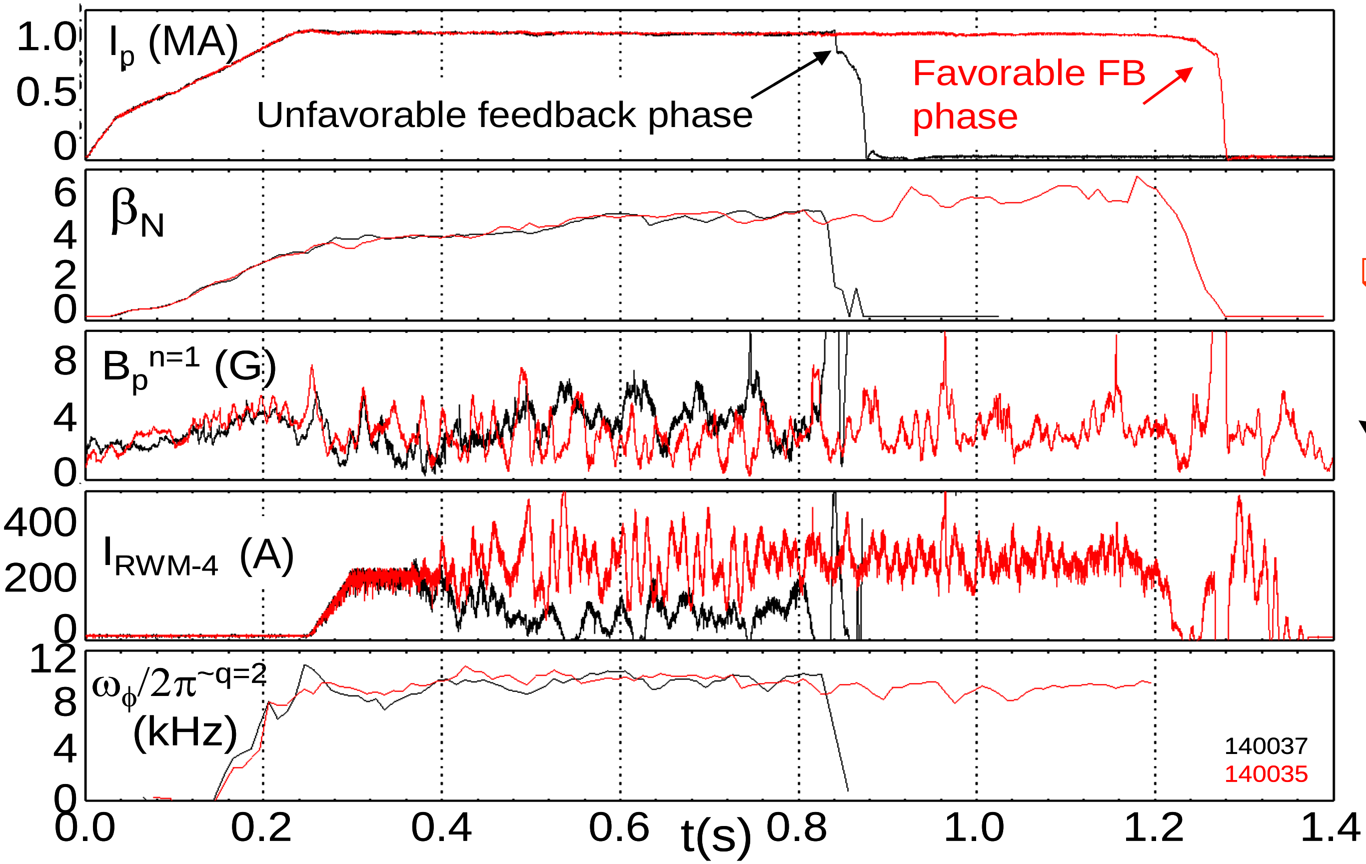
RWM state space feedback (12 states)



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

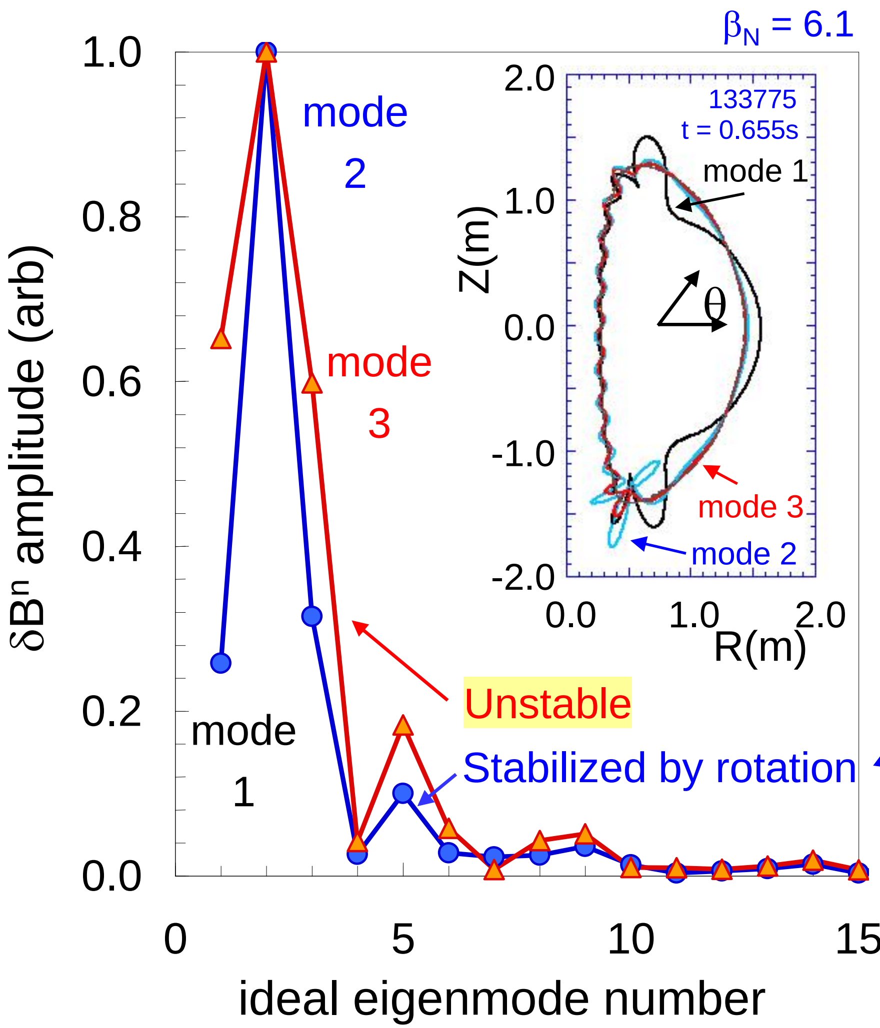
RWM state space feedback (12 states)



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

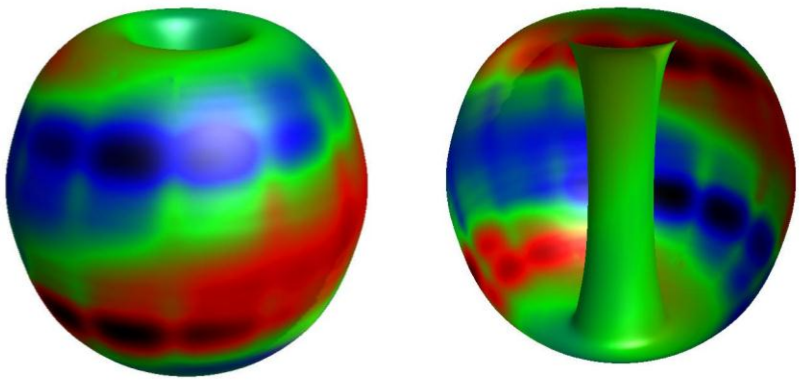
Multi-mode computation for RWM & DEFC: 2nd eigenmode component has dominant amplitude at high β_N in NSTX 3D stabilizing structure

δB^n RWM multi-mode composition



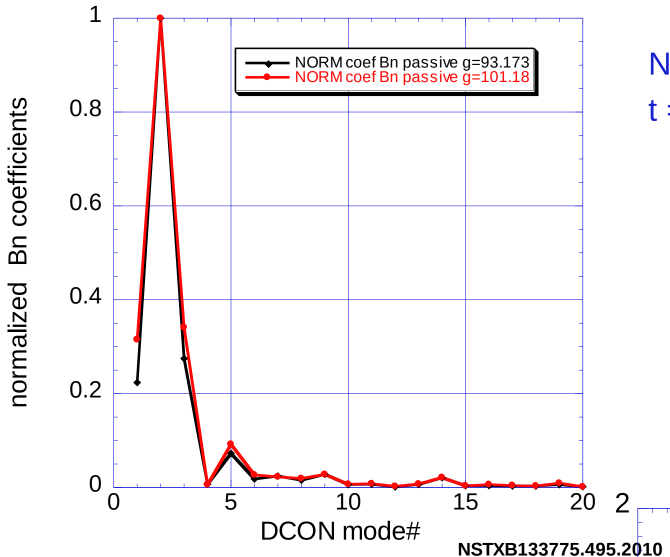
mmVALEN code

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 (or "α")
  - 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

Multi-mode RWM spectrum in NSTX @ β_N=5.54 has significant 2nd eigenfunction contribution, B_R perturbation not greatly changed at large R



NSTX shot #133775

t = 0.495 [s]

DCON mode weighted sums shown below

Illustration of B_normal signature for RWM mode

normal distance from plasma surface corresponds to B_normal

γ = 93.17 [1/s]

β_N = 5.54

γ = 101.18 [1/s]

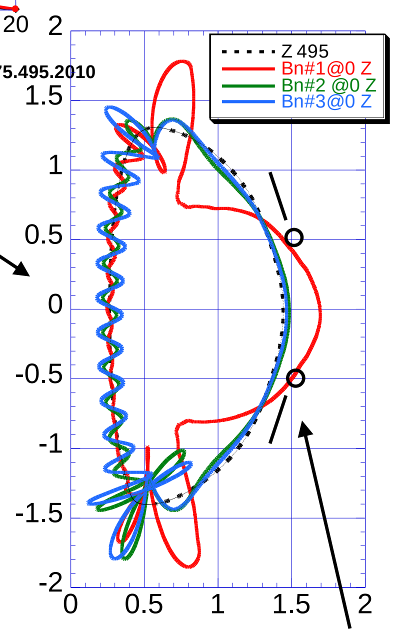
β_N = 5.54

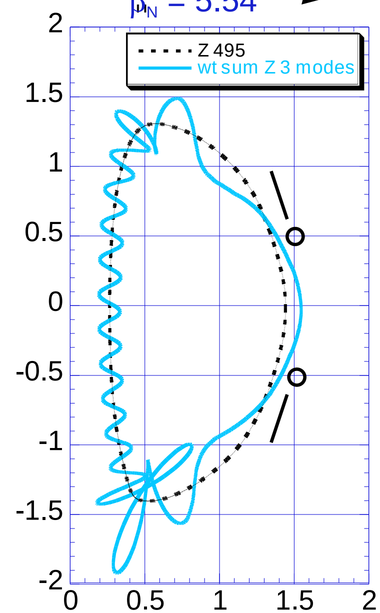
Illustration of DCON modes equal weights

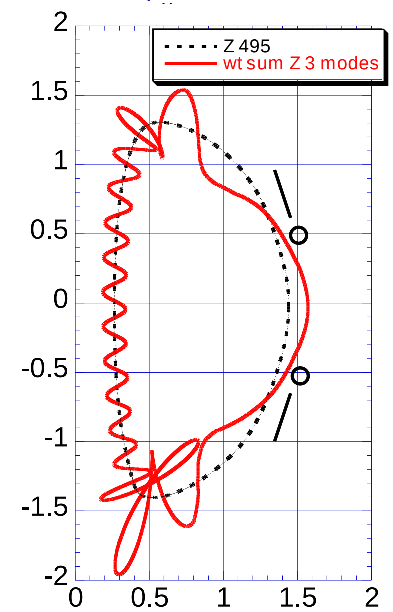
#1 thru #3,

each DCON mode shown with max B_n = 0.5[m]

normal distance from plasma surface (black dashed line) corresponds to B_normal



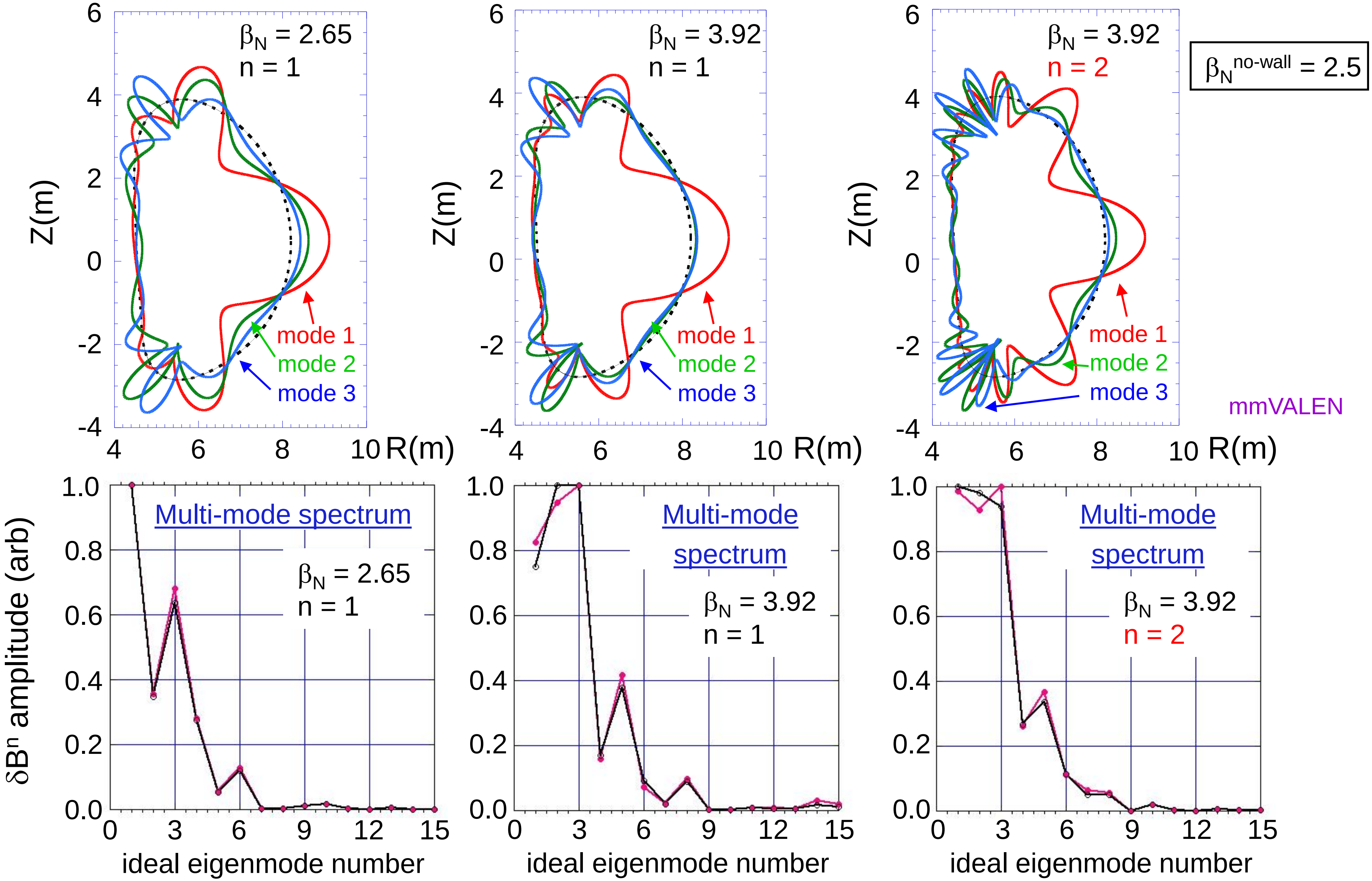




RWM B_R and B_p sensor locations

mmVALEN code

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

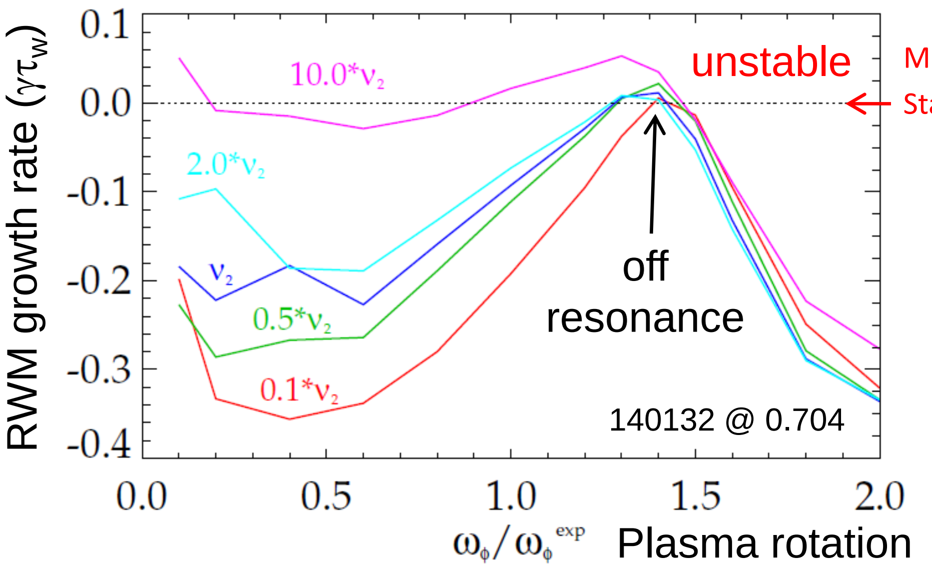


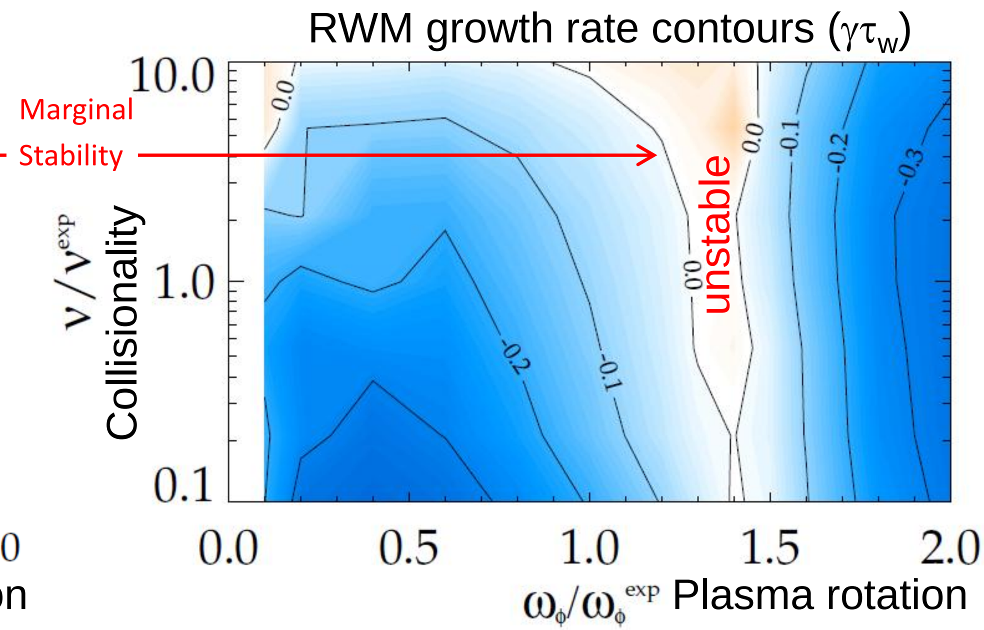
NSTX is Addressing Global Stability Needs Furthering Steady Operation of High Performance ST / Tokamak Plasmas

- 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)
  - Multi-mode spectrum computed for NSTX and ITER scenario IV for direct use in state space controller (RWM control & DEFC)

Supporting Slides

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



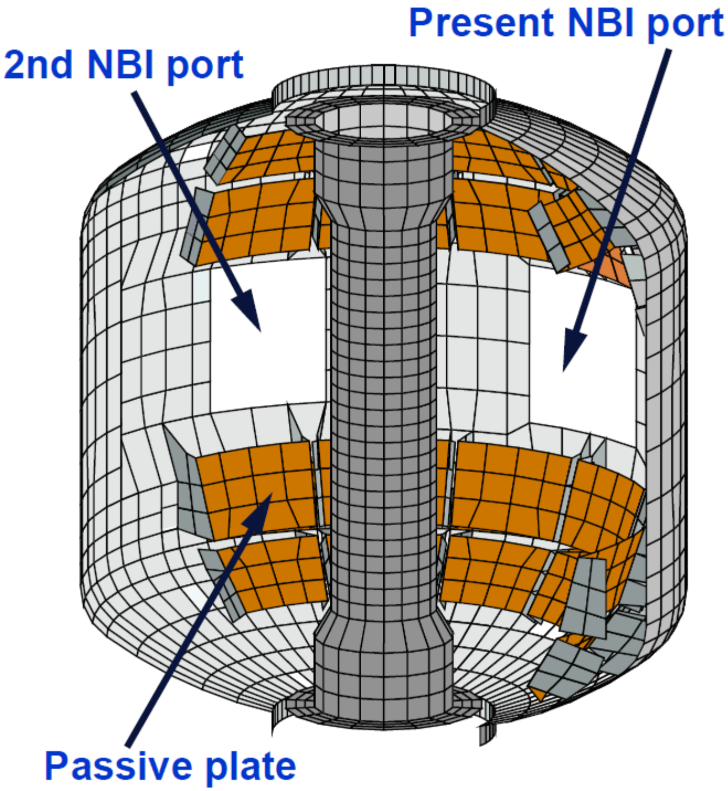


- NSTX-tested kinetic RWM stability theory: 2 competing effects at lower ν
  - Stabilizing collisional dissipation reduced (expected from early theory)
  - Stabilizing resonant kinetic effects enhanced (contrasts early RWM theory)
- Expectations in NSTX-U, tokamaks at lower ν (e.g. ITER)
  - Stronger 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

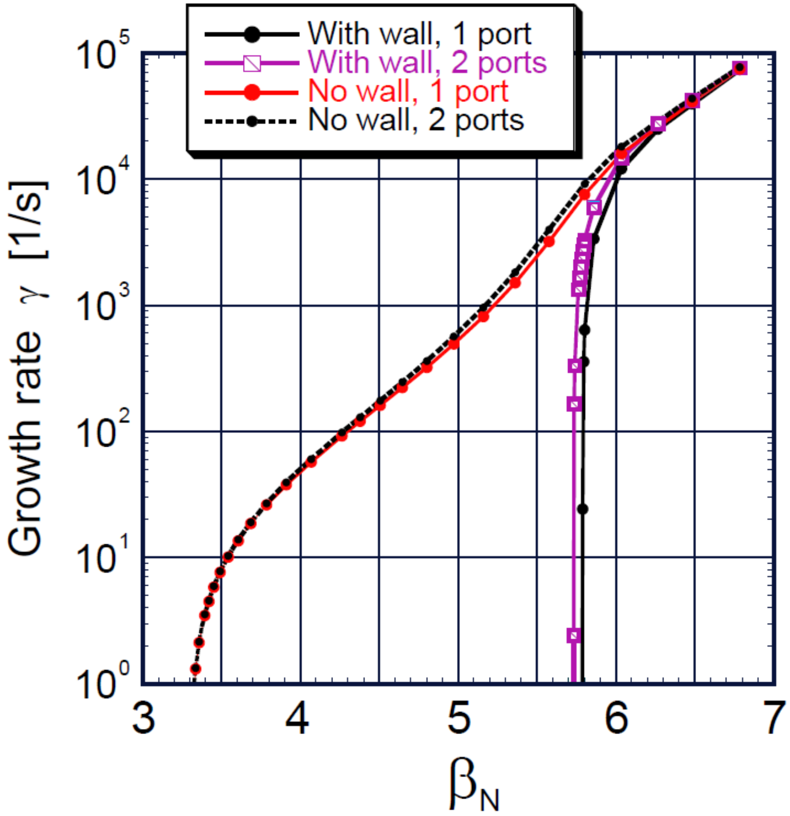
J.W. Berkery et al., PRL **106**, 075004 (2011)

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



Long-Wavelength MHD Stability at High Pressure Required for ITER and Other Next-Step Devices

- Motivation
  - The resistive wall mode (RWM) is a primary cause plasma disruption at high β
  - Understanding passive stabilization physics determining RWM stability is critical to extrapolate stability requirements for future devices

- Very brief history
  - Early theory: RWM can be stabilized by sufficient plasma rotation
  - Critical ω_ϕ for passive stability assessed (Ω_{crit})
  - Low levels of Ω_{crit} (< 0.5% Alfven at q =2) suggested
  - RWMs found to be unstable at relatively high ω_ϕ, and stability depends on profile, not simple scalar value – no simple, low Ω_{crit}!
  - Stability model including kinetic effects evaluated (NSTX) - can explain greater complexity of RWM marginal stability
  - <u>Present effort</u>: comparison of stability model in codes and experiments