Active resistive wall mode and plasma rotation control for disruption avoidance in NSTX-U

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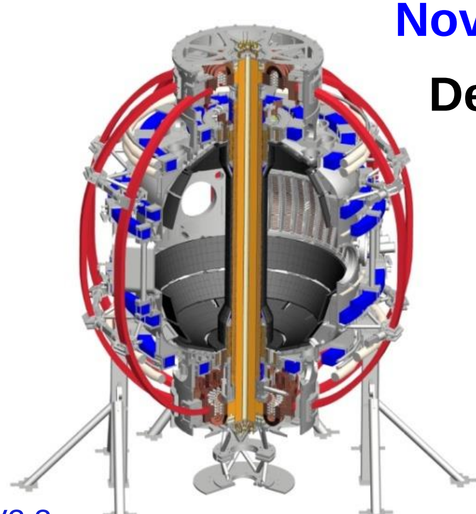


V2.3

Near-complete disruption avoidance in long-pulse tokamak devices is a new "grand challenge" for stability research

- Disruption avoidance is an urgent need for the spherical torus (ST), ITER, and tokamaks in general
  - Preparing several physics-based control approaches for disruption prediction / avoidance (P&A) in NSTX-U

- Outline (approaches discussed here)
  - MHD spectroscopy at high beta
  - Kinetic RWM stabilization physics criteria
  - Plasma rotation feedback control using NTV
  - Model-based active RWM control and 3D coil upgrade

Disruption categorization (NSTX database)

- % Having strong low frequency n = 1 magnetic precursors
  → 55%
- % Associated with large core rotation evolution
  → 46%

S. Gerhardt et al., NF **53** (2013) 063021

MHD spectroscopy, to be used for disruption P&A, reveals non-intuitive stability dependencies at high β_N

- MHD spectroscopy experiments
  - measured resonant field amplification (RFA) of applied n = 1 tracer field in high β_N plasmas at varied ω_ϕ
  - Higher RFA shows reduced mode stability

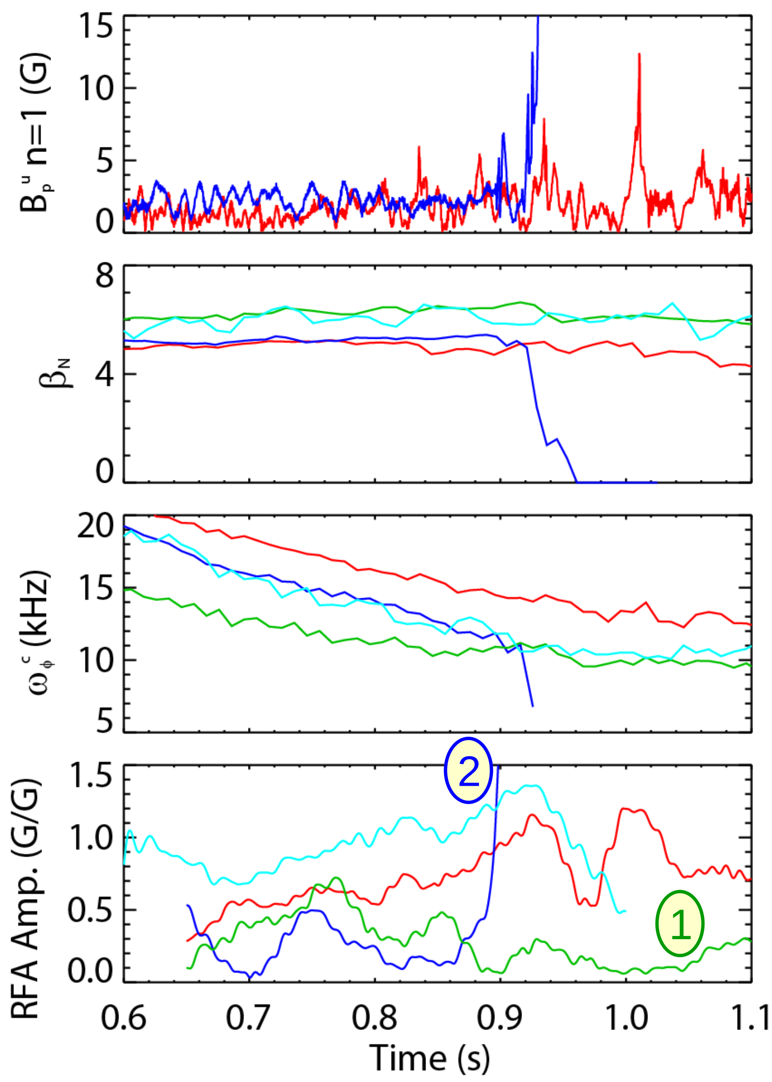
RFA = $B_{plasma}/B_{applied}$

- Counter-intuitive results:
  1. Highest β_N, lowest ω_ϕ (green): most stable
  2. Lowest β_N, medium ω_ϕ (blue): unstable

- Physics understanding given by kinetic RWM theory (simplified here):

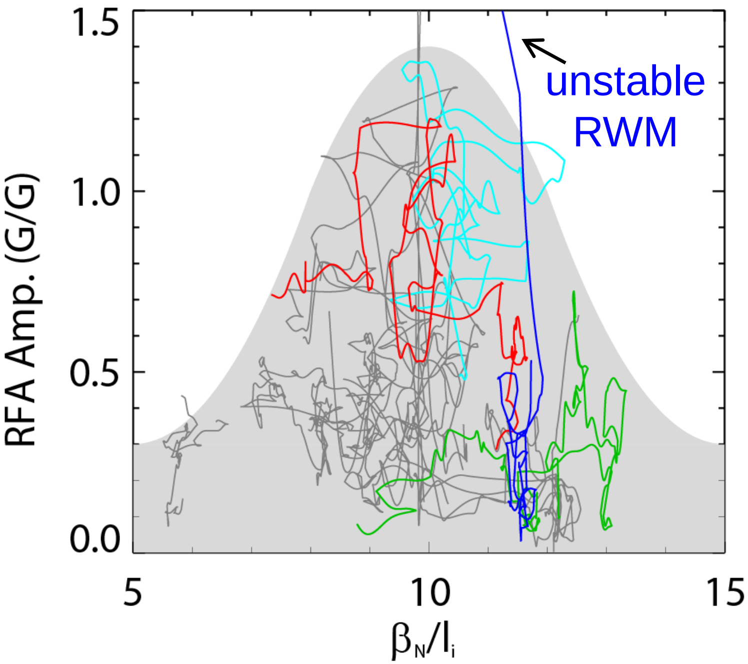
Precession Drift | ~ Plasma Rotation | Collisionality

$$\delta W_k \sim \frac{1}{\langle \omega_D \rangle + \omega_E - i\nu_{eff}}$$

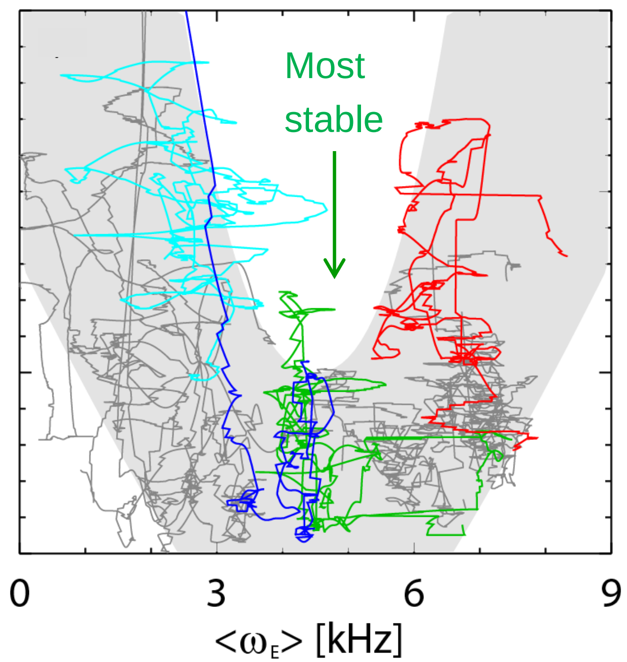


Experiments directly measuring global stability using MHD spectroscopy (RFA) support kinetic RWM stability theory

Resonant Field Amplification vs. β_N/l_i



RFA vs. rotation (ω_E)



(trajectories of 20 experimental plasmas)

- **Stability vs. β_N/l_i**
  - decreases up to $\beta_N/l_i = 10$, ***increases*** at higher β_N/l_i
  - Consistent with kinetic resonance stabilization

- **Stability vs. rotation**
  - Largest stabilizing effect from ion precession drift resonance with ω_ϕ

Minimize $|\langle\omega_D\rangle + \omega_E|$

$$\delta W_k \sim \frac{1}{\langle \omega_D \rangle + \omega_E - i\nu_{eff}}$$

- **Stability at lower ν**
  - Collisional dissipation is reduced
  - Stabilizing resonant kinetic effects are enhanced
  - Stabilization when near broad ω_φ resonances; almost no effect off-resonance

S. Sabbagh et al., NF **53** (2013) 104007

Berkery TI2.002 (Th)

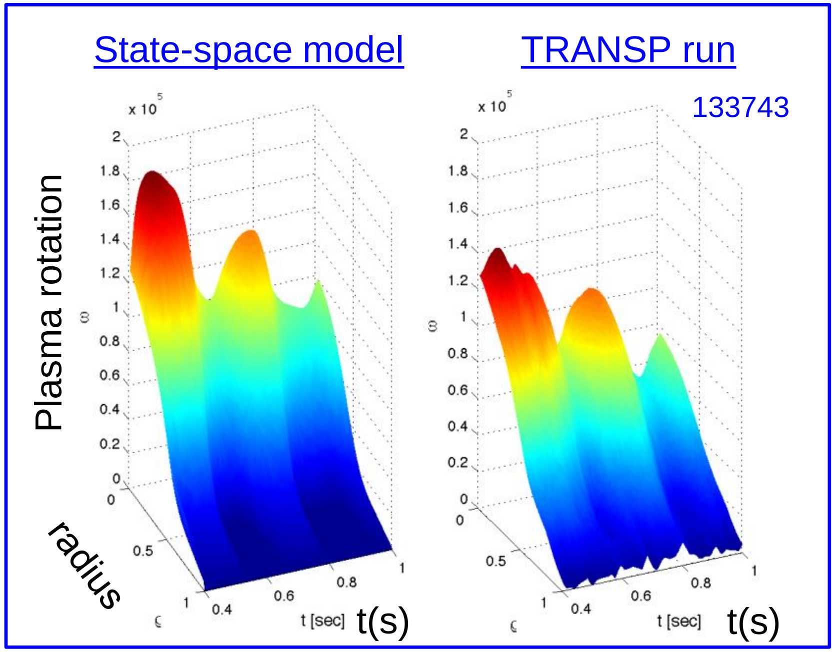
Model-based, state-space rotation controller designed to use Neoclassical Toroidal Viscosity (NTV) profile as an actuator

- Momentum force balance – ω_ϕ decomposed into Bessel function states

$$\sum_i n_i m_i \left\langle R^2 \right\rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho}\right)^{-1} \frac{\partial}{\partial \rho}\left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \chi_\phi \left\langle (R \nabla \rho)^2 \right\rangle \frac{\partial \omega}{\partial \rho}\right] + T_{NBI} + T_{NTV}$$

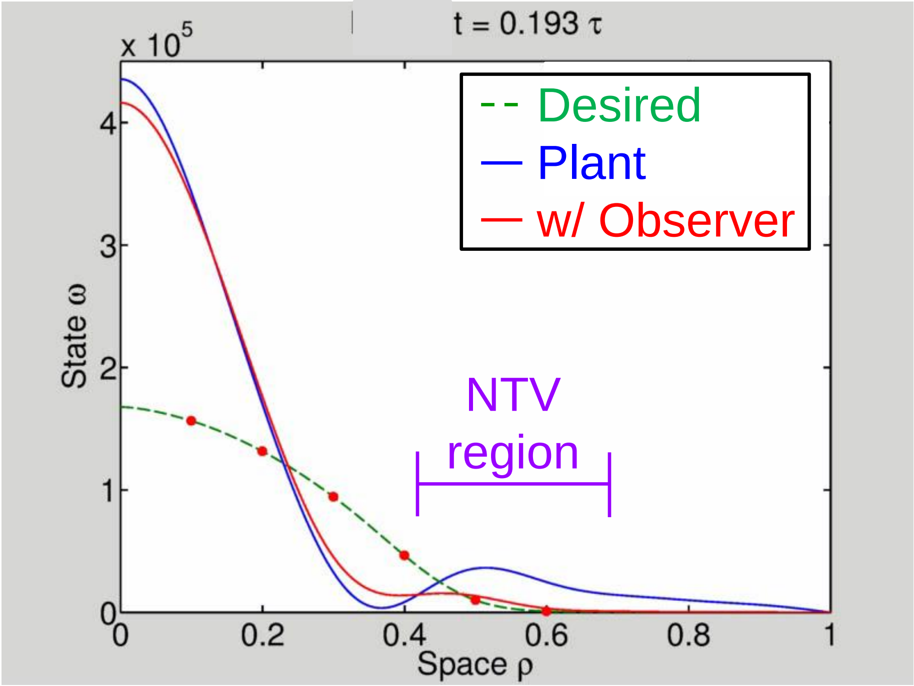
- NTV torque:

$$T_{NTV} \propto K \times f\left(n_{e,i}{}^{K1} T_{e,i}{}^{K2}\right) g\left(\delta B(\rho)\right)\left[I_{coil}{}^{2} \omega\right] \quad \text{(non-linear)}$$



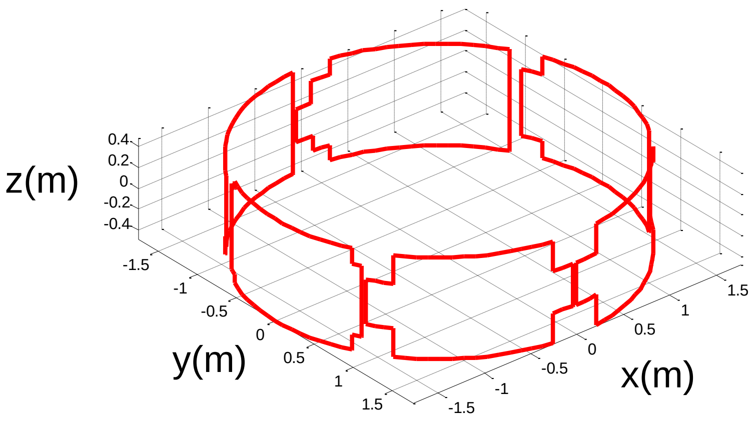
Goumiri NP8.040 (We)

Feedback using NTV: "n=3" $\delta B(\rho)$ spectrum



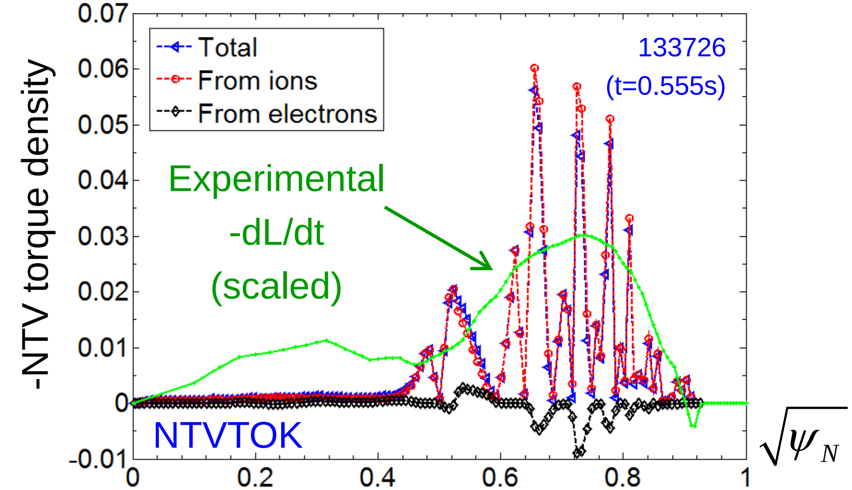
Expanded NTV torque profile model for control being developed from theory/comparison to experimental data

NSTX 3D coils used for rotation control

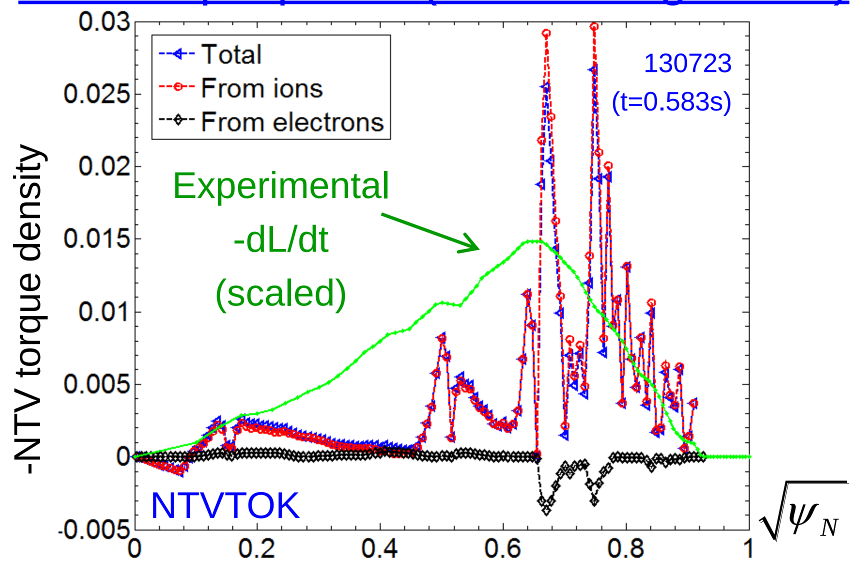


- **New analysis: NTVTOK code**
  (Sun, Liang, Shaing, et al., NF **51** (2011) 053015)
  - Shaing's connected NTV model, covers all ν, and superbanana plateau regimes
    (Shaing, Sabbagh, Chu, NF **50** (2010) 025022)
  - Past quantitative agreement with theory found in NSTX for plateau, "1/ν " regimes
    (Zhu, Sabbagh, Bell, et al., PRL **96** (2006) 225002)
  - Full 3D coil specification, ion and electron components considered, no A assumptions

NTV torque profile (n = 3 configuration)

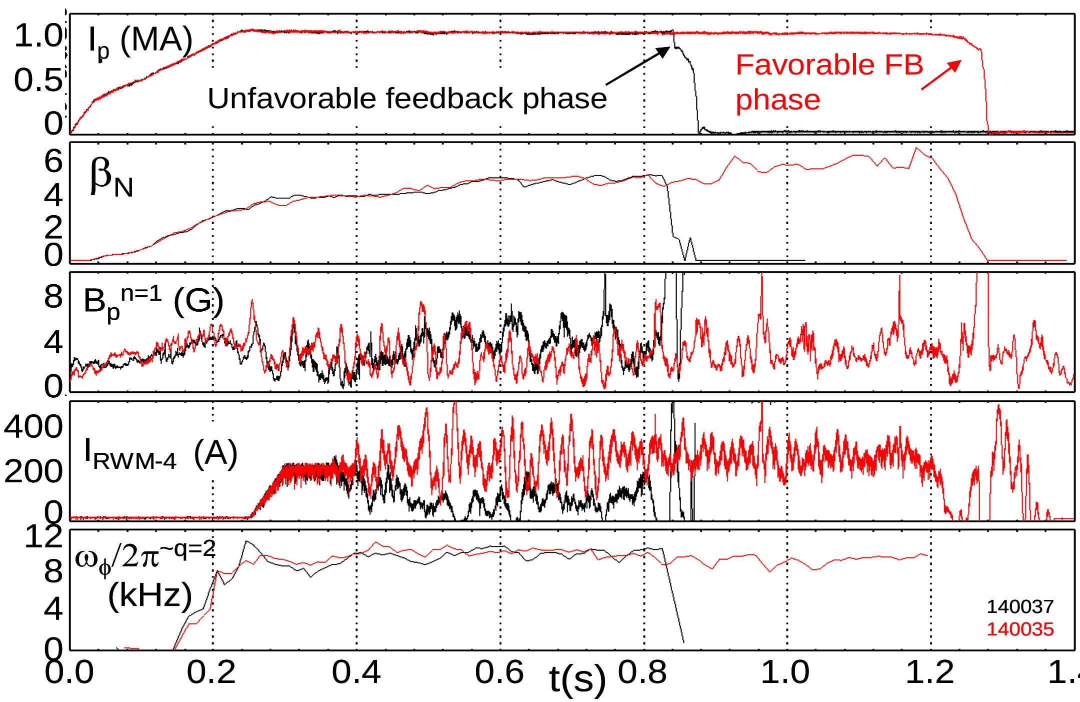


NTV torque profile (n = 2 configuration)



Model-based RWM state space controller including 3D plasma response and wall currents used at high β_N in NSTX

RWM state space controller in NSTX at high β_N



- 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

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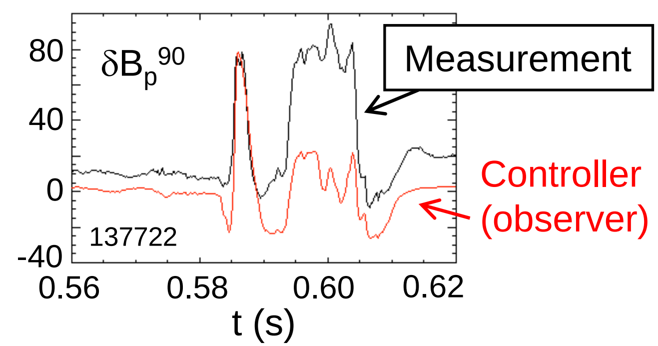
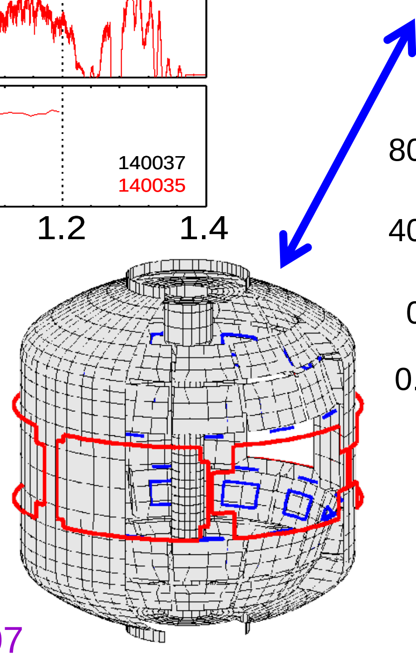
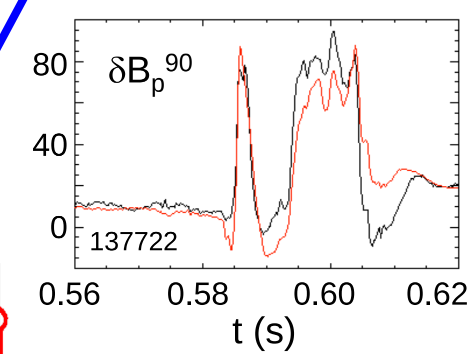
Effect of 3D Model Used

No NBI Port





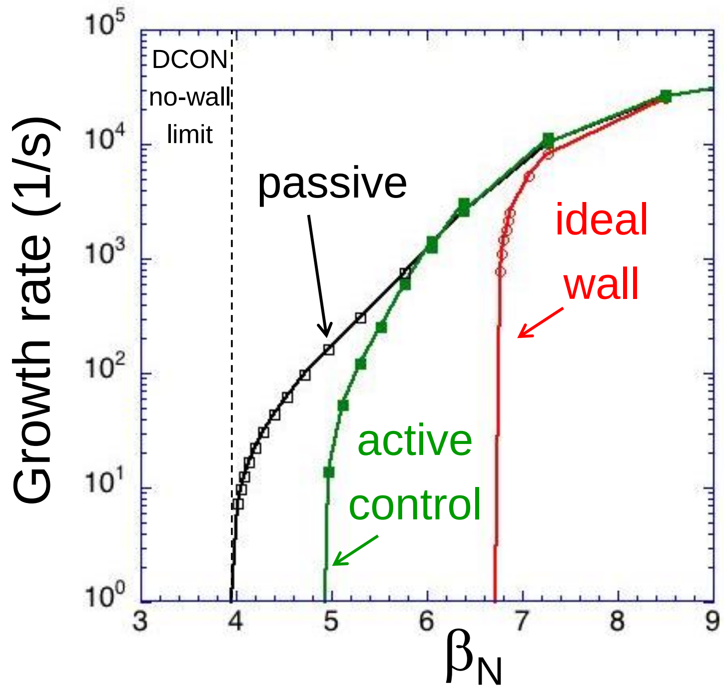
With NBI Port



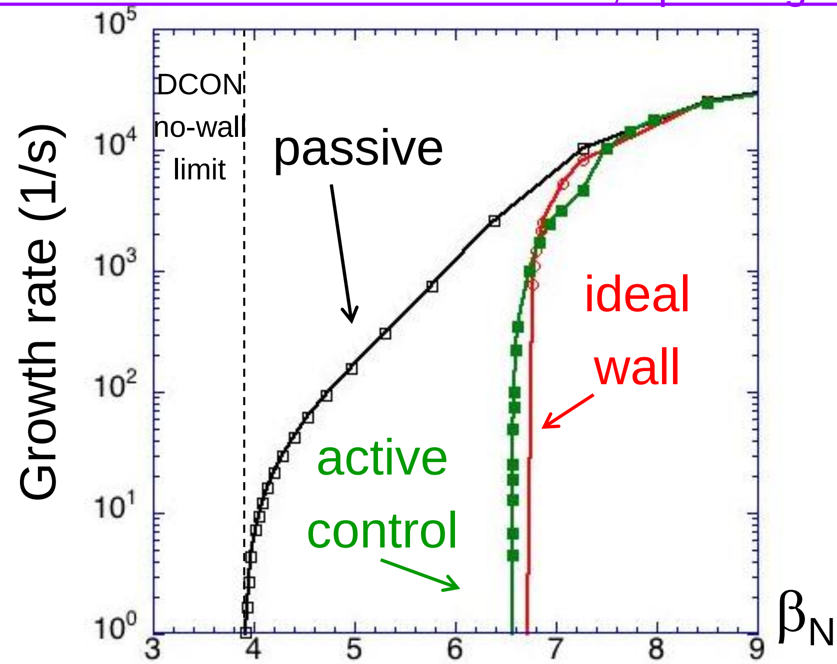
- 3D detail of model is important to improve sensor agreement

RWM active control capability will increase significantly when Non-axisymmetric Control Coils (NCC) are added to NSTX-U

Using present midplane RWM coils

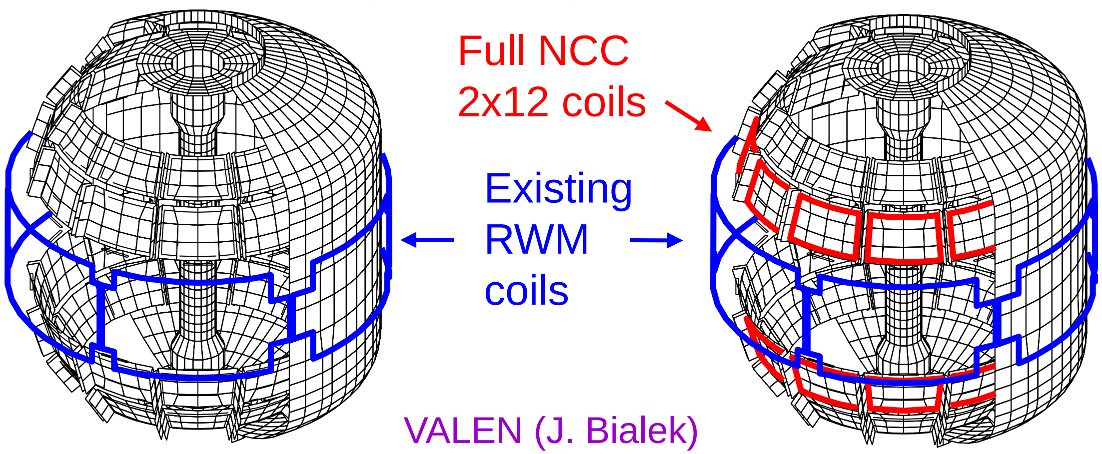


NCC 2x12 with favorable sensors, optimal gain



- Performance enhancement
  - Present RWM coils: active control to $\beta_N/\beta_N^{no\text{-}wall} = 1.25$
  - Add NCC 2x12 coils, optimal sensors: active control to $\beta_N/\beta_N^{no\text{-}wall} = 1.67$
  - Partial NCC options also viable

J.-K. Park NP8.003 (We)

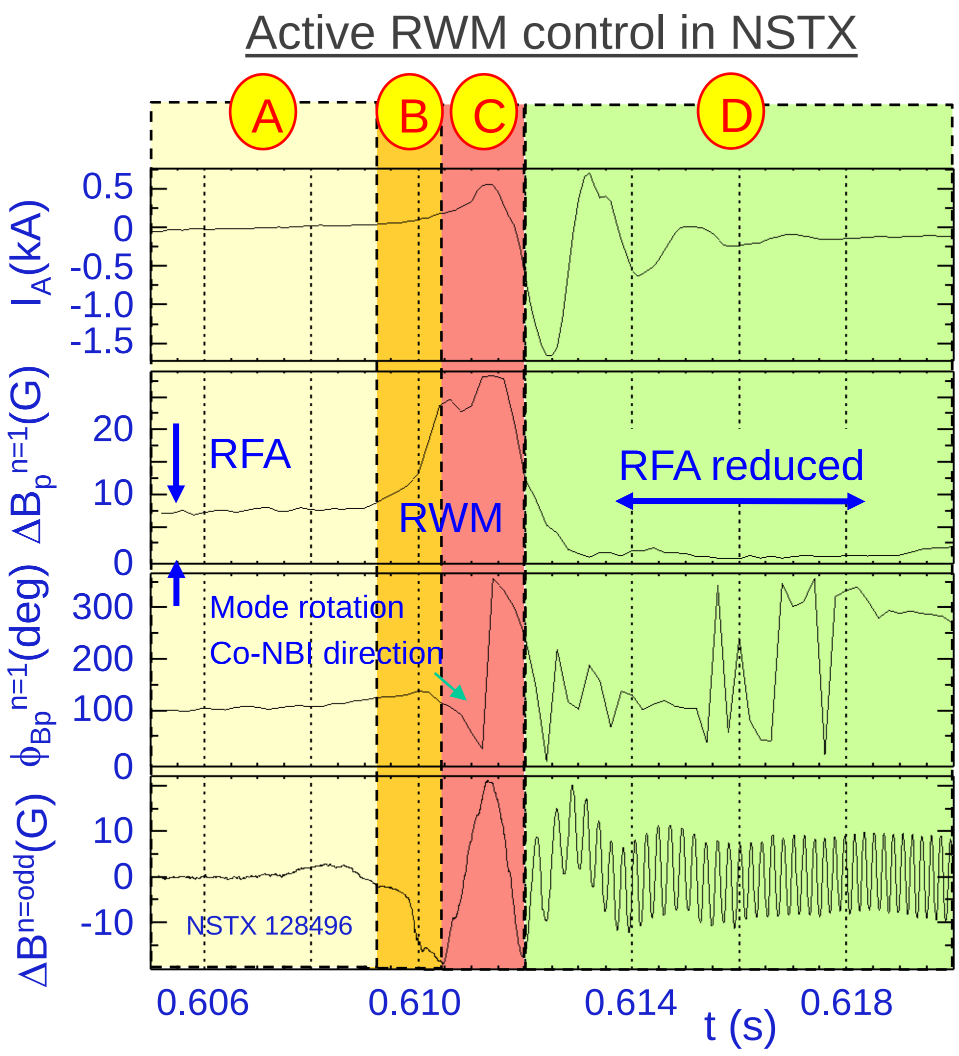


NSTX-U is addressing disruption prediction and avoidance of global modes with a multi-faceted physics and control plan

- **MHD spectroscopy at high beta**
  - Resonant field amplification shows an *increase* in stability at very high $\beta_N/l_i > 10$ in NSTX
  - Stability dependence on collisionality supports kinetic stabilization theory: lower ν can *improve* stability (contrasts early theory)
- **Kinetic RWM stability physics models**
  - Broad precession drift resonance condition to minimize $|\omega_E + \omega_D|$ yields increased stability
- **Plasma rotation control**
  - First closed-loop feedback of model-based state-space controller successful using NTV as sole actuator
  - Expanded NTV profile quantitative modeling underway
- **Active RWM control**
  - Demonstrated model-based RWM state space control at high $\beta_N > 6$
  - Planned expansion of 3D coil set on NSTX-U computed to significantly enhance control performance

Supporting Slides Follow

Highly successful disruption P&A needs to exploit several phases to avoid mode-induced disruption



S.A. Sabbagh, et al., Nucl. Fusion **50** (2010) 025020

(A) Pre-instability

- RFA to measure stable γ
- Profile control to reduce RFA
- Real-time stability modeling for disruption prediction

(B) Instability growth

- Profile control to reduce RFA
- Active instability control

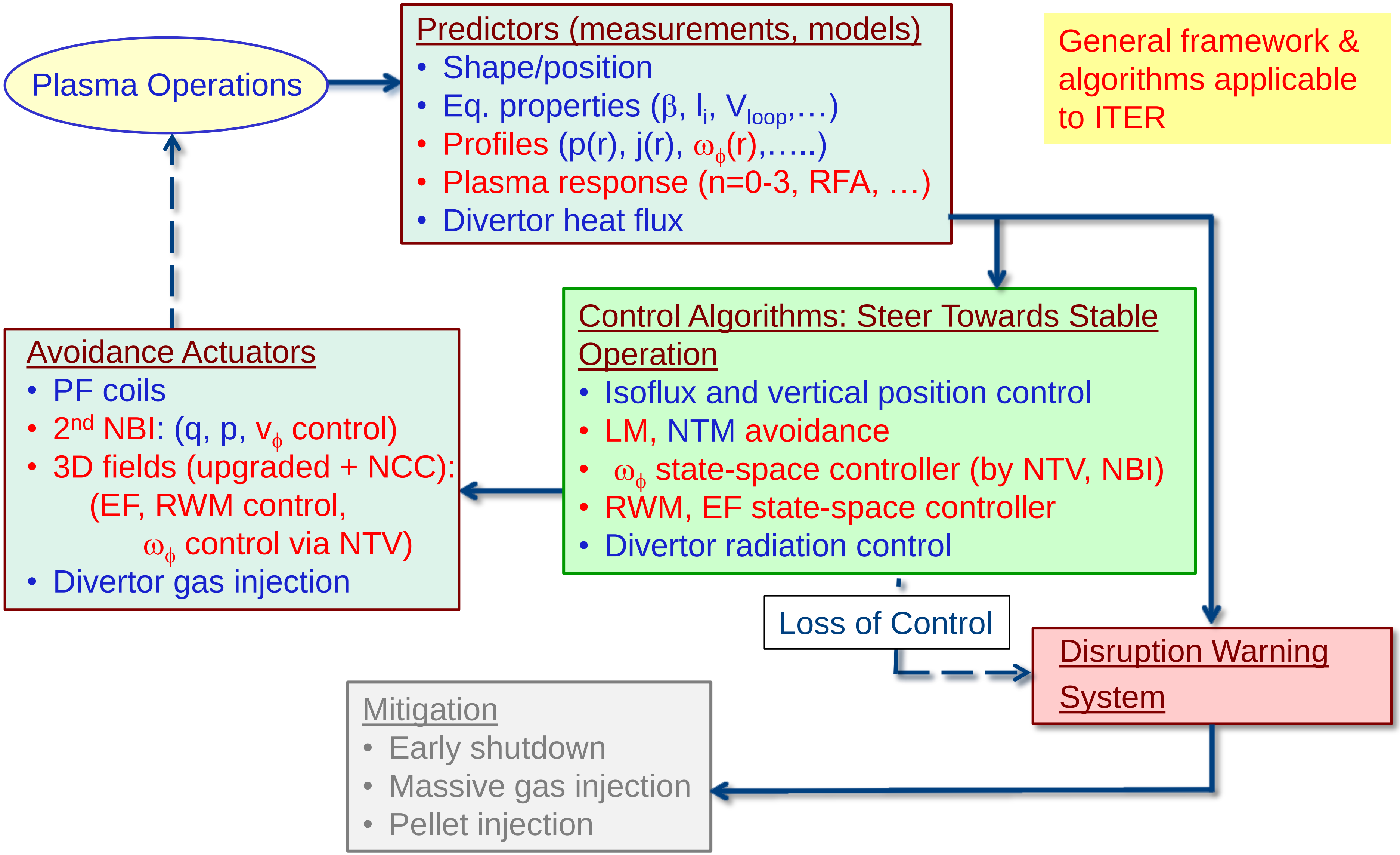
(C) Large amplitude instability

- Active instability control

(D) Instability saturation

- Profile control to damp mode

Research shown here is part of a sophisticated disruption prediction-avoidance-mitigation framework for NSTX-U



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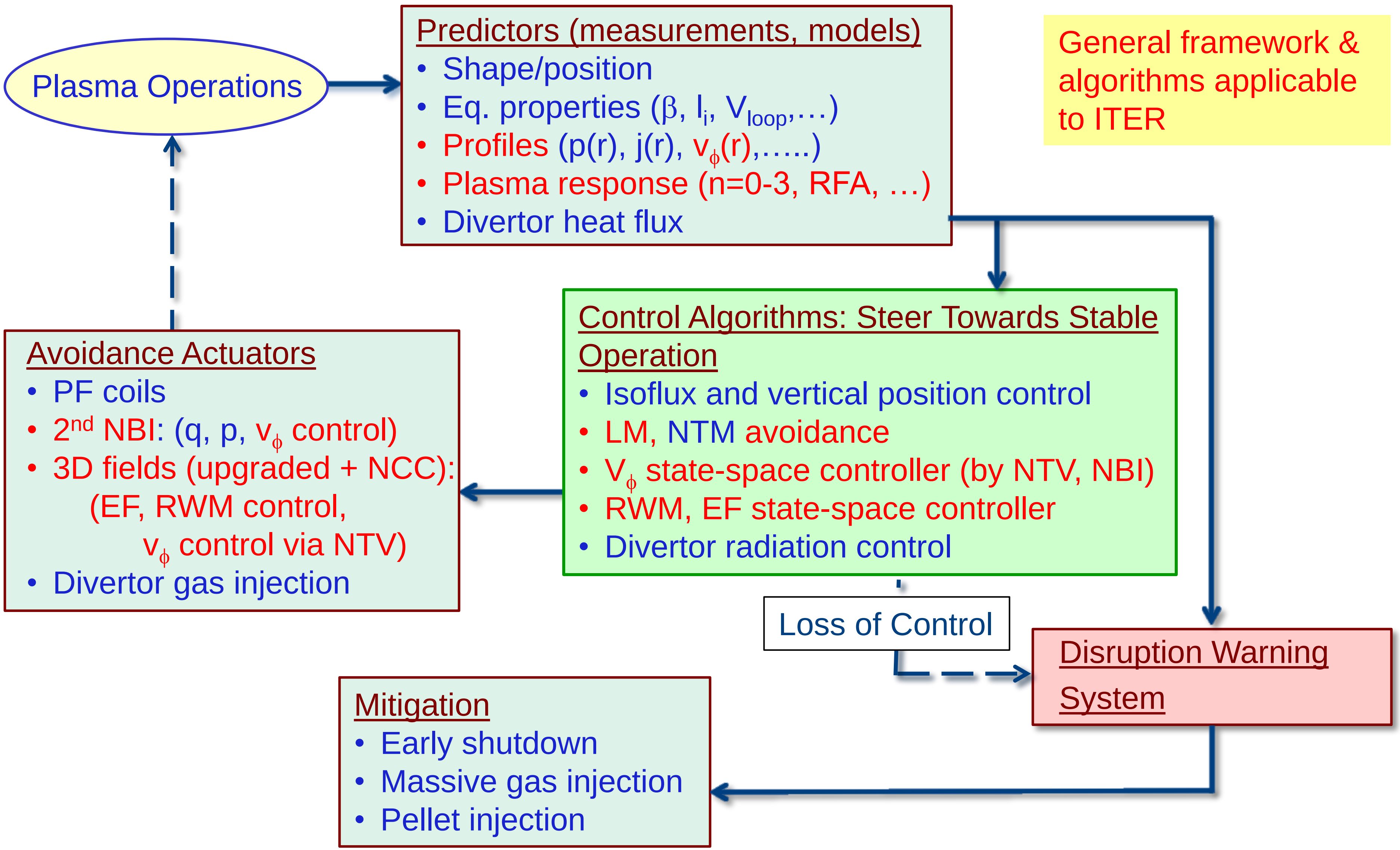
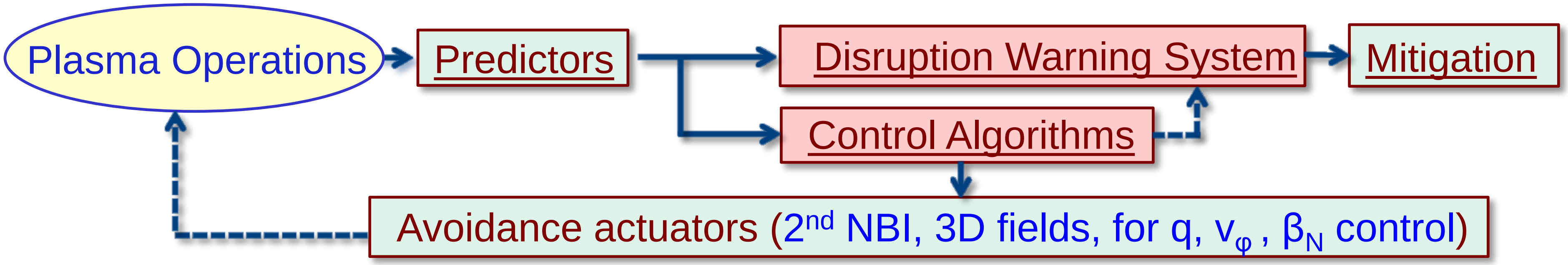


Dedicated MHD spectroscopy reveal stability dependencies that are non-intuitive based on early RWM stabilization theory



- MHD spectroscopy experiments
  - measured resonant field amplification (RFA) of high β_N plasmas at varied plasma rotation
- Counter-intuitive results:
  1. Highest β_N, lowest ω_ϕ (green): most stable
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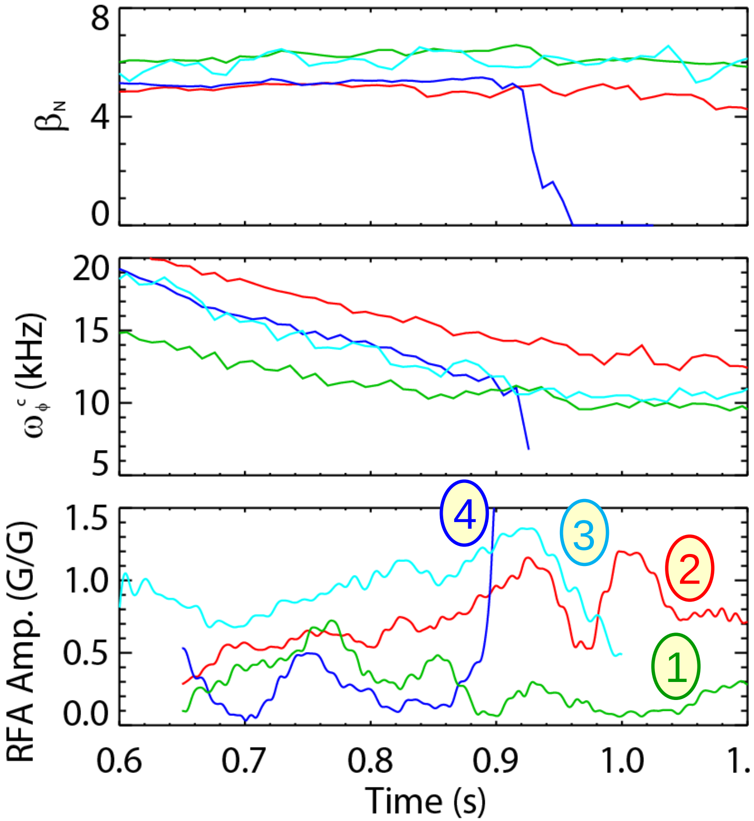
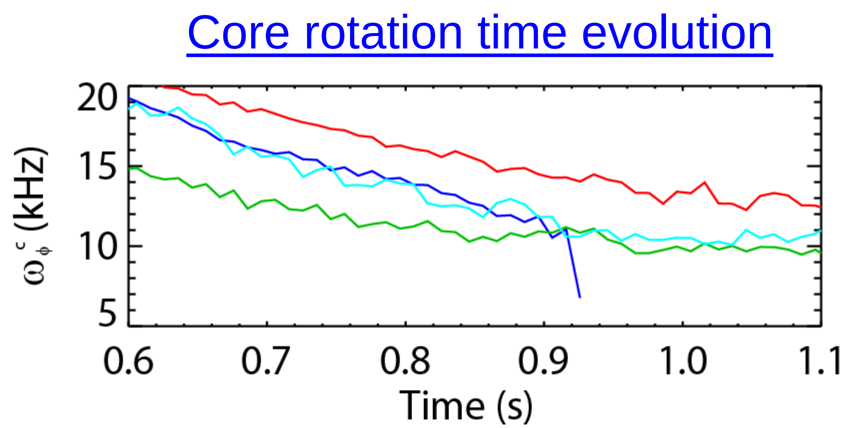
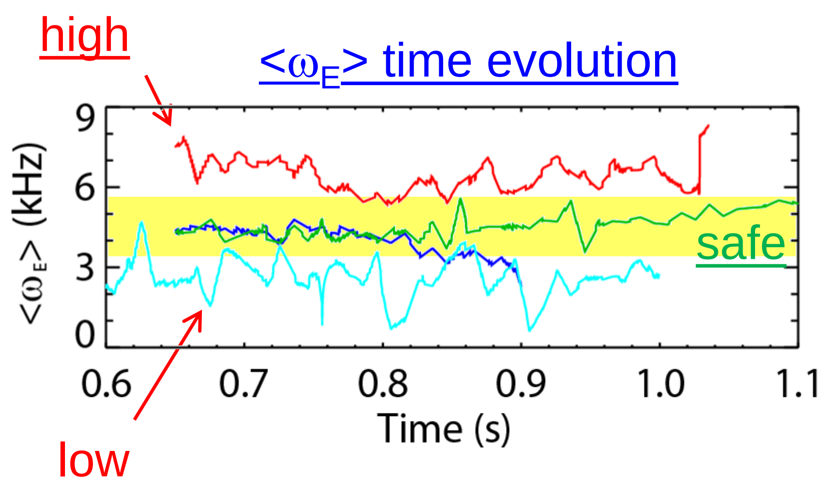


Simple models derived from kinetic RWM physics being developed for real-time disruption prediction / avoidance

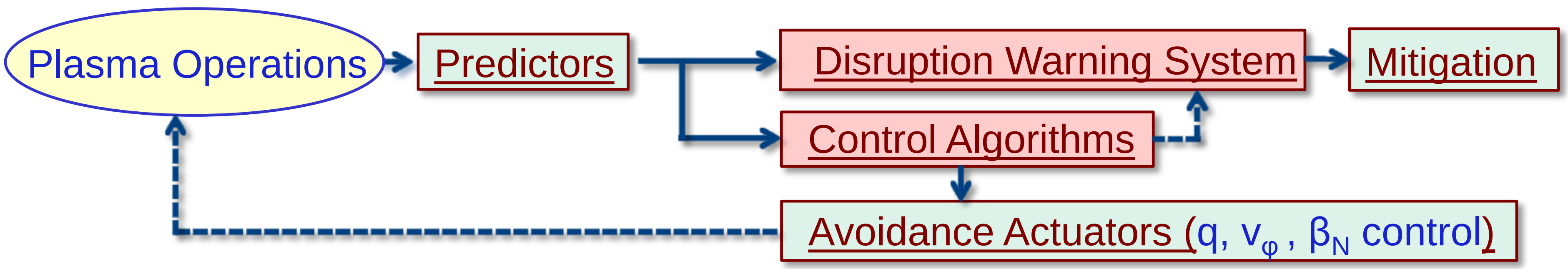
- Criteria to increase stability based on kinetic RWM physics
  - Real-time measurement of ω_ϕ (and β_N) alone is insufficient!
  - Precession drift stabilization criterion (minimize $|\omega_E + \omega_D|$) provides better guidance for global mode stability
    - Corresponds to $\langle\omega_E\rangle$ ~ 4 - 5 kHz
  - Avoid disruption by controlling plasma rotation profile toward this condition
    - obtain $\langle\omega_E\rangle$ from real-time ω_ϕ and modeled n and T profiles



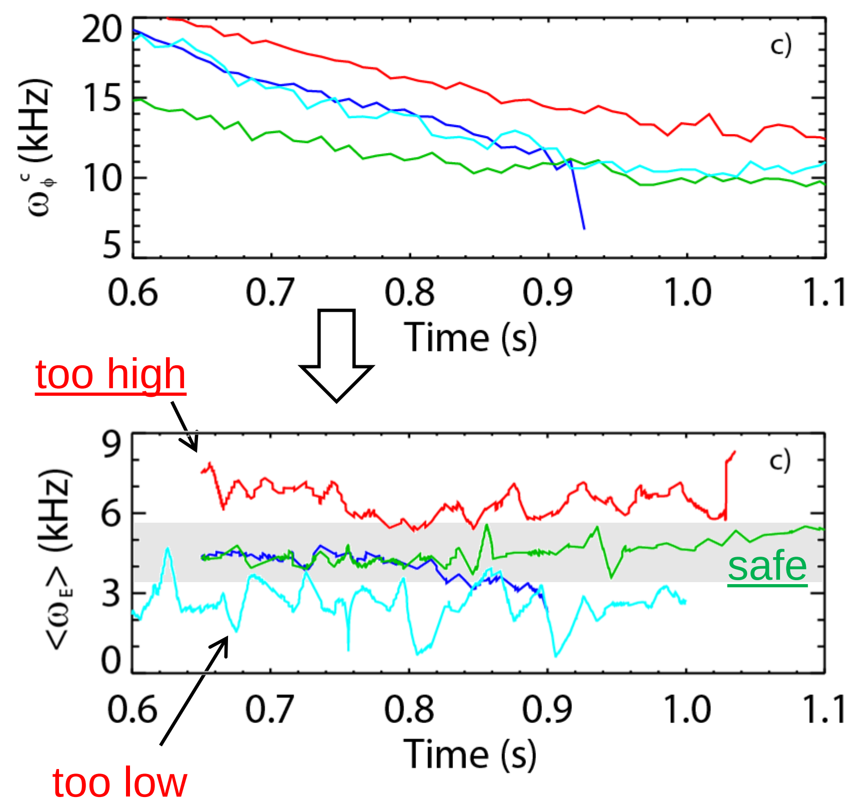


Berkery TI2.002 (Th)

2. Simple models derived from kinetic RWM physics being developed for real-time for disruption prediction / avoidance



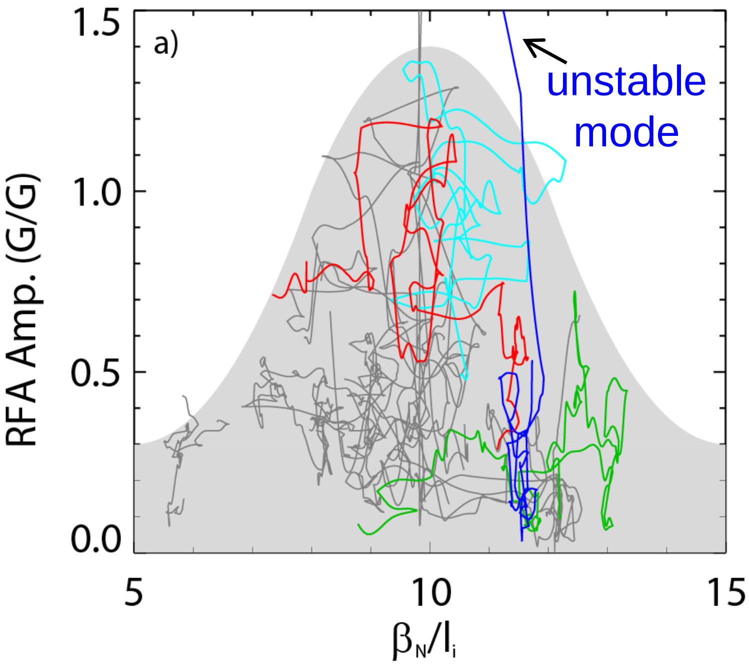
- **Criterion to increase stability based on kinetic RWM physics**
  - Real-time measurement of ω_ϕ (and β_N) alone is insufficient!
  - Simplified precession drift stabilization criterion (minimize $|\omega_E + \omega_D|$) provides better guidance for global mode stability
    - Corresponds to $\langle\omega_E\rangle$ ~ 5kHz in the range ($0.5 < \psi_N < 0.9$)
  - Avoid disruption by controlling plasma rotation profile toward this condition
    - obtain $\langle\omega_E\rangle$ from real-time ω_ϕ and modeled n and T profiles



Berkery TI2.002 (Th)

Experiments directly measuring global stability (RFA) using MHD spectroscopy support kinetic RWM stability theory

Resonant Field Amplification vs. β_N/l_i



(trajectories of 20 experimental plasmas)

- **Stability vs. β_N/l_i**
  - decreases up to β_N/l_i = 10, ***increases*** at higher β_N/l_i
  - Consistent with kinetic resonance stabilization

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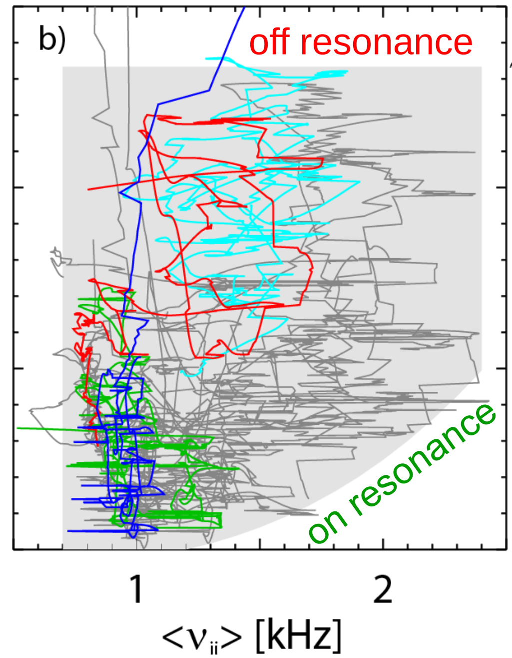
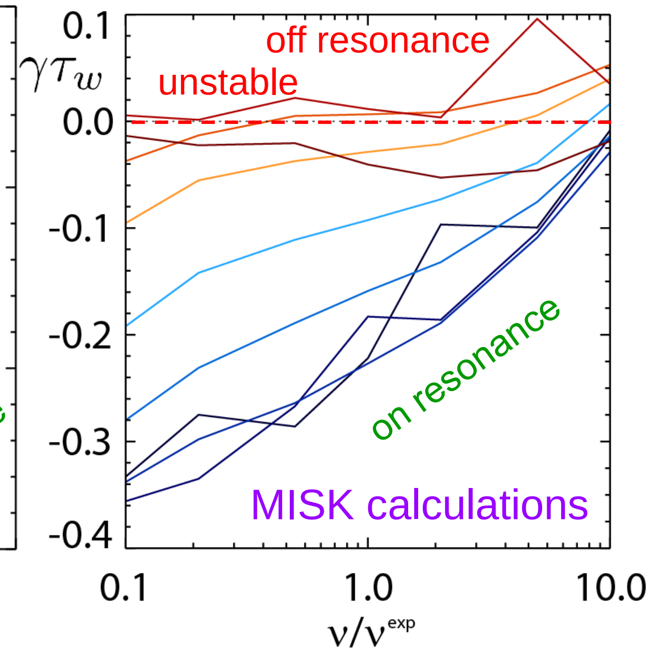
RFA vs collisionality



RFA vs collisionality (theory)



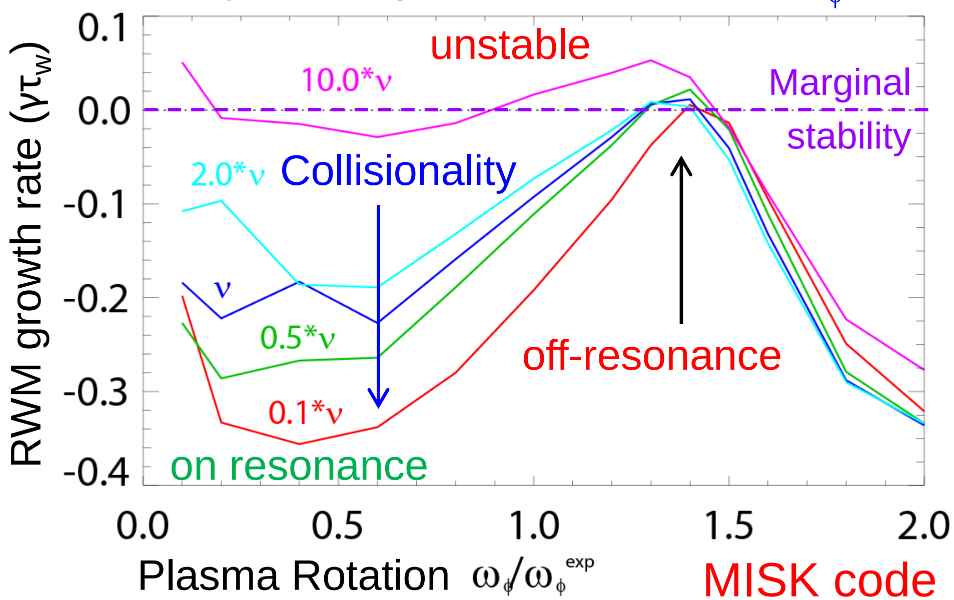
- **Stability at lower ν**
  - Collisional dissipation reduced
  - Stabilizing resonant kinetic effects enhanced
  - Stabilization near ω_φ resonances; almost no effect off-resonance

$$\delta W_k \sim \frac{1}{\langle \omega_D \rangle + \omega_E - i\nu_{eff}}$$

Berkery TI2.002 (Th)

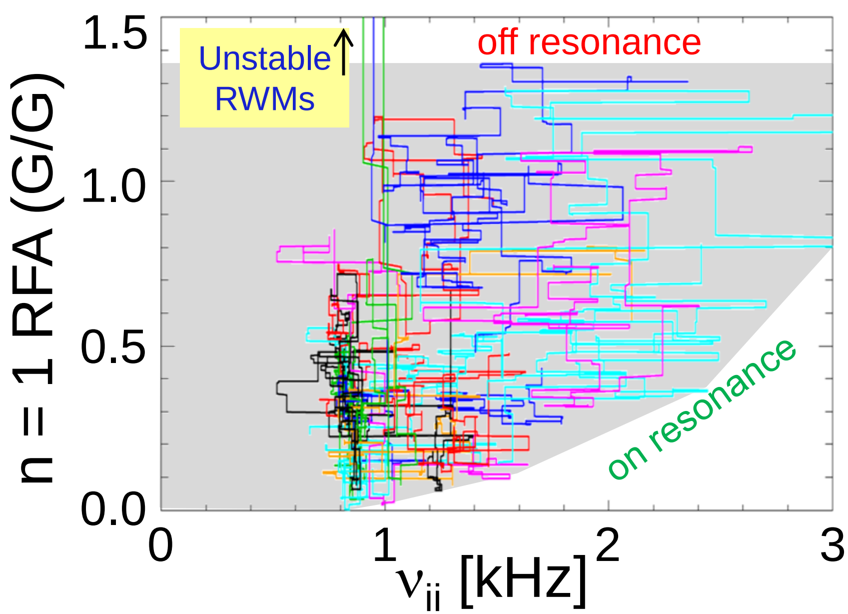
Experiments measuring global stability vs. ν further support kinetic RWM stability theory, provide guidance for NSTX-U

Theory: RWM growth rate vs. ν and ω_ϕ



MISK code

Exp: Resonant Field Amplification (RFA) vs ν



(trajectories of 20 experimental plasmas)

- Two competing effects at lower ν
  - Collisional dissipation reduced
  - Stabilizing resonant kinetic effects enhanced (contrasts early theory)
- Expectations at lower ν
  - More stabilization near ω_φ resonances; almost no effect off-resonance

- Mode stability directly measured in experiment using MHD spectroscopy
  - Decreases with ν at lower RFA ("on resonance")
  - Independent of ν at higher RFA ("off resonance")

$$\mathrm{RFA} = \frac{B_{plasma}}{B_{applied}}$$

Berkery #I#.## (Th)

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

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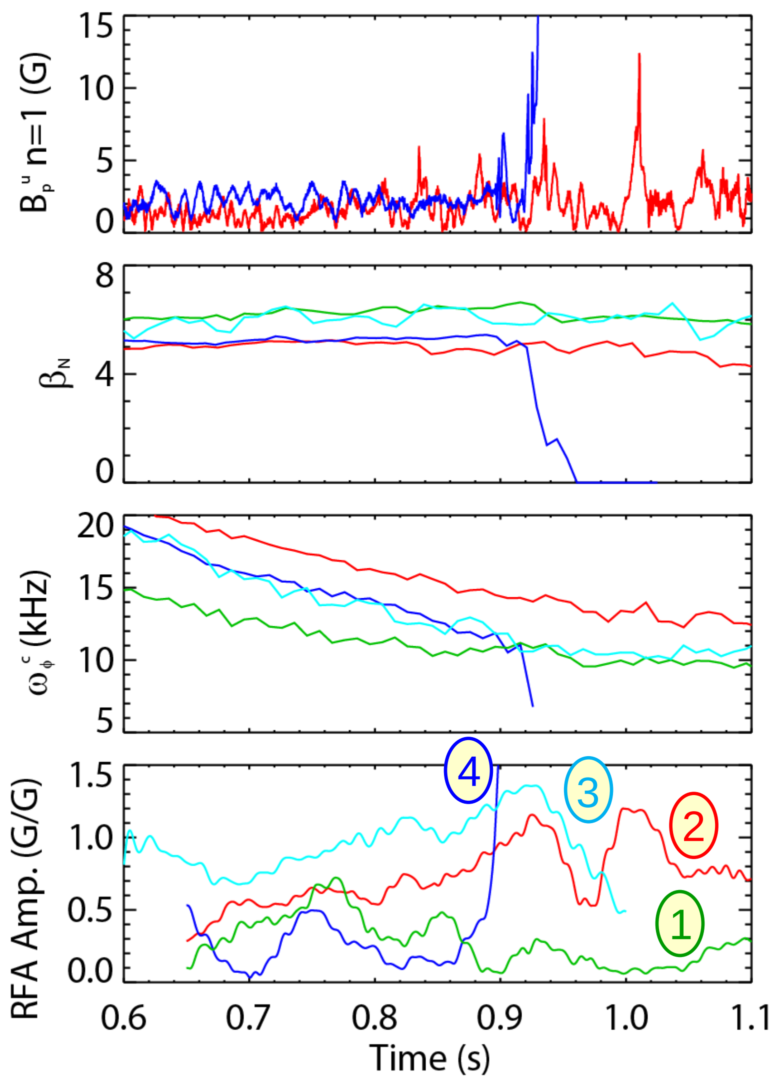
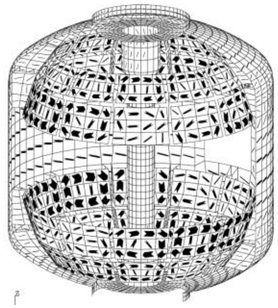


Model-based RWM state space controller including 3D plasma response and wall currents used at high β_N

Full 3-D model

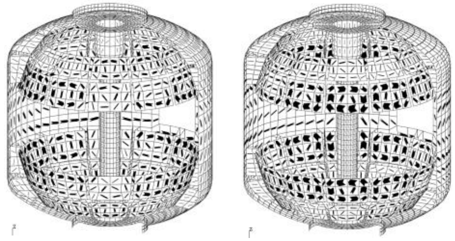
~4000 states



Balancing transformation

State reduction (< 20 states)

RWM eigenfunction (2 phases, 2 states)

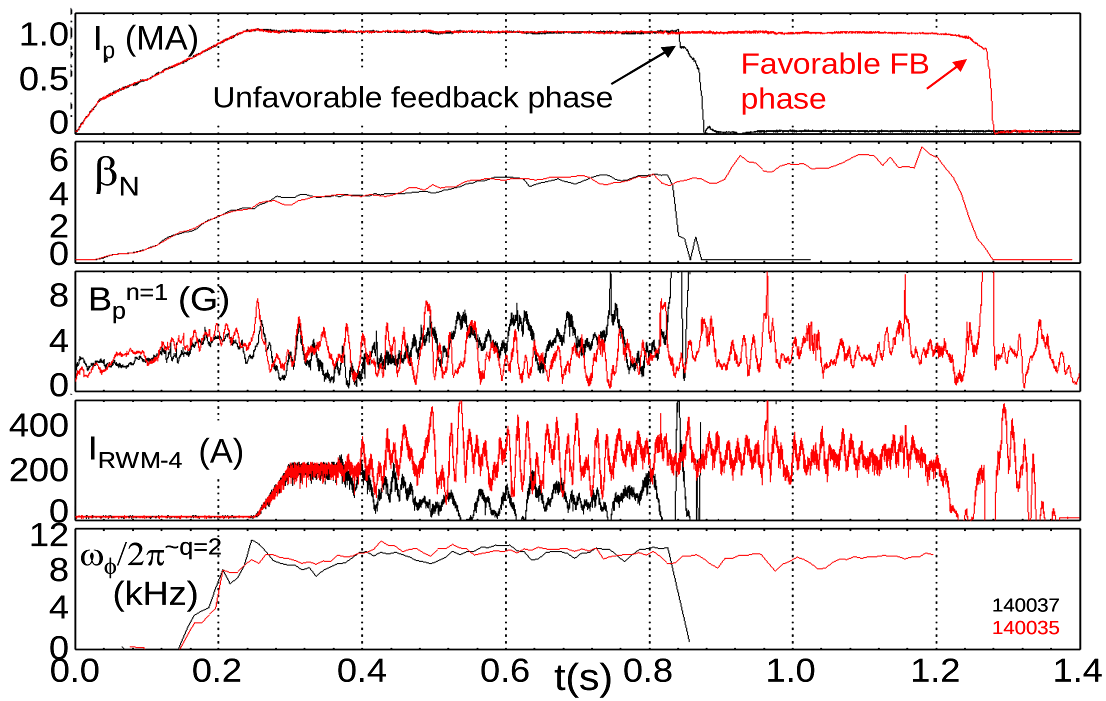


$(\hat{x}_1, \hat{x}_2)$ $\hat{x}_3$ $\hat{x}_4$ …

- Controller model includes
  - plasma response
  - 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

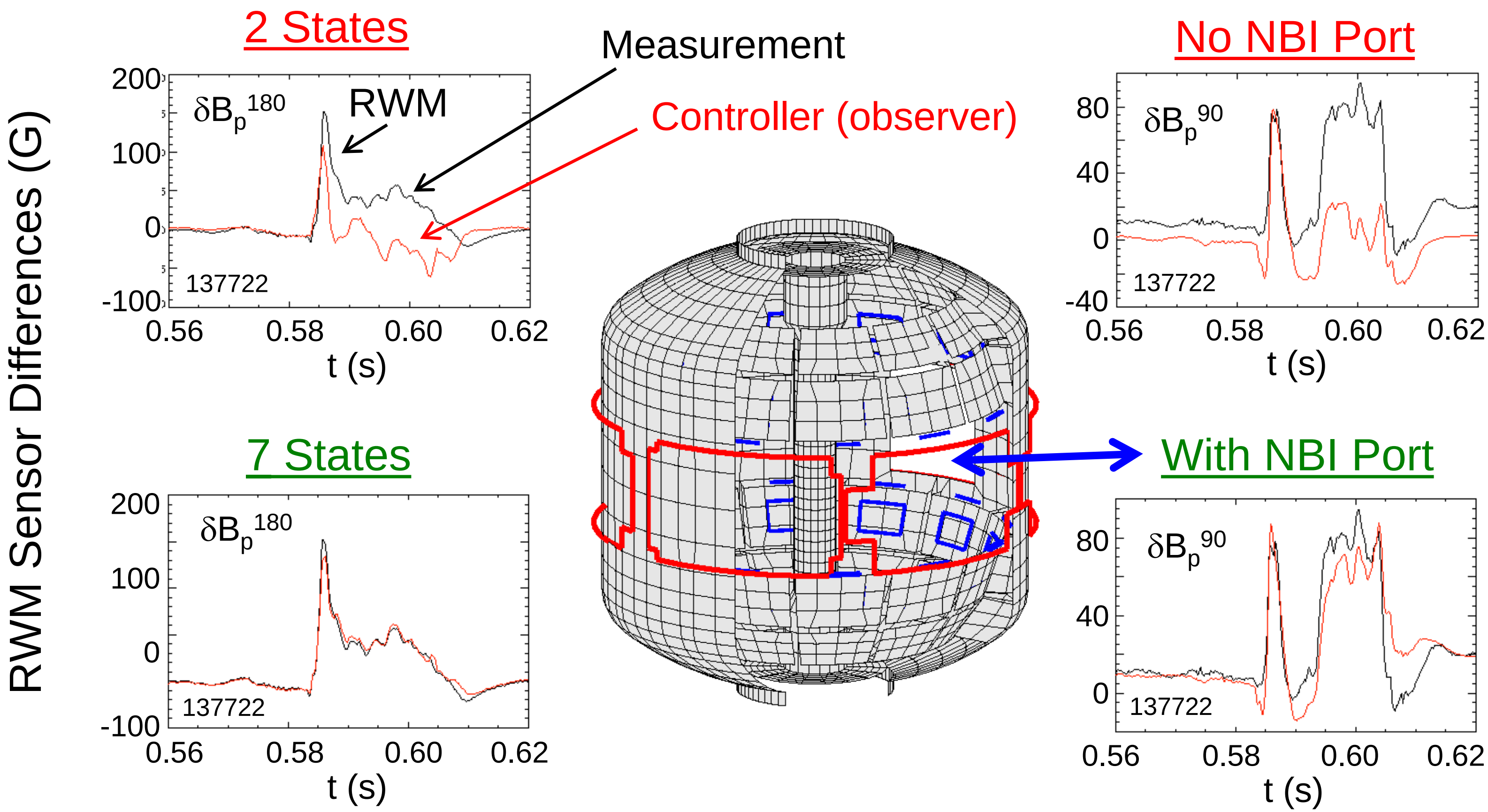
RWM state space controller in NSTX at high β_N



Comparisons between sensor measurements and state space controller show importance of states and 3D effects

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

S.A. Sabbagh, J.-W. Ahn, J. Allain, et al., Nucl. Fusion **53** (2013) 104007

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