U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Columbia U. Group - Collaborative Research on NSTX-U for Disruption Avoidance

S.A. Sabbagh – for the Columbia U. / NSTX-U Group

(J.W. Berkery, J.M. Bialek, Y.S. Park)

Report to DOE and NSTX-U Program

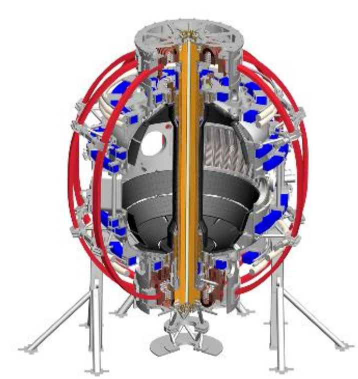
PPPL

7/23/15

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

PPPL

V1.1



Near 100% disruption avoidance is a critical need for future tokamaks; Columbia Research on NSTX-U is focused on this

- The new "grand challenge" in tokamak stability research
  - Can be done! (JET: < 4% disruptions w/C wall, < 10% w/ITER-like wall)
    - ITER disruption rate: < 1 - 2% (energy load, halo current); << 1% (runaways)

- Strategic plan: utilize/expand stability/control research success
  - Disruption prediction, avoidance, and mitigation (*DPAM*) is multi-faceted, best addressed by a focused, (inter)national effort (multiple devices/institutions)

- FESAC 2014 Strategic Planning report defined "*Control of Deleterious Transient Events*" highest priority (Tier 1) initiative

- NSTX-U is a world-leading laboratory for focused research on disruption avoidance with quantitative measures of progress
  - Columbia U. group endorsed by NSTX-U Program in a leadership role for this research, building on past success in MHD stability and control research

Columbia Group Research at PPPL provides key disruption avoidance research, emphasis on global mode stabilization

- Physics Elements
  - Kinetic RWM stabilization physics - unification between NSTX / DIII-D
  - NTV used in plasma rotation control (supports NSTX-U V_ϕ control)
  - Physics model-based active RWM state-space controller
  - Dual-component sensor RWM PID control
  - RWM control analysis of upgraded 3D coils for NSTX-U
  - NSTX-U equilibrium reconstruction – key basis for stability analysis
  - Planned real-time MHD spectroscopy for NSTX-U (in 5 Year Plan)
  - Related high normalized beta and NTV experiments on KSTAR

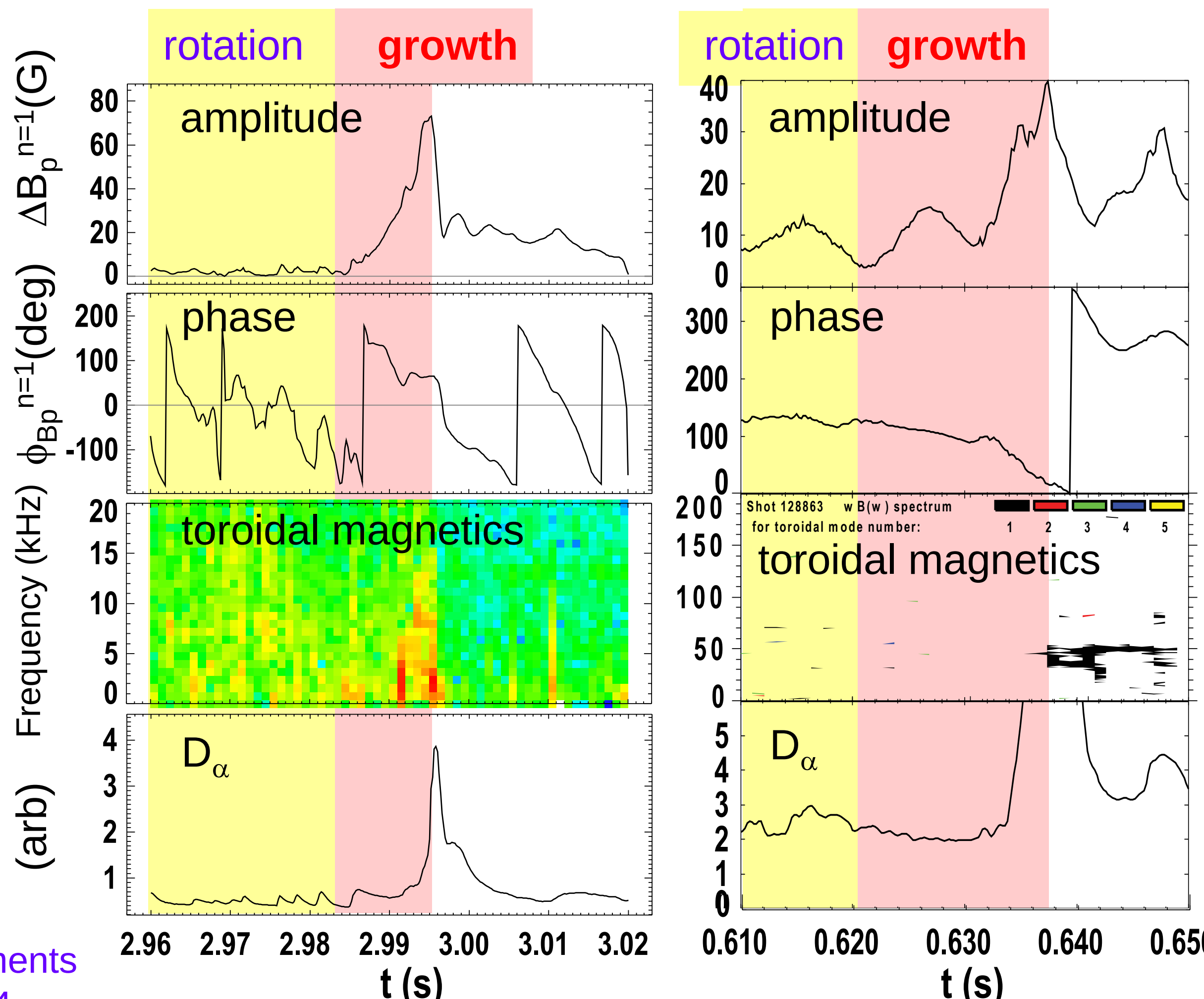
Princeton student

- Research synergism
  - These elements now being brought together as part of a disruption prediction/avoidance system; NSTX-U DPAM working group formed)
  - New Disruption Characterization and Prediction code / initial results
- Response to DOE call for enhanced university participation
  - CU-PPPL group outreach to Columbia U. APAM department; new diagnostic proposal to be submitted (Volpe/Sabbagh)

Joint NSTX / DIII-D experiments and analysis gives unified kinetic RWM physics understanding for disruption avoidance

- RWM Dynamics
  - RWM rotation and mode growth observed
  - No strong NTM activity
  - Some weak bursting MHD in DIII-D plasma
    - Alters RWM phase
  - No bursting MHD in NSTX plasma

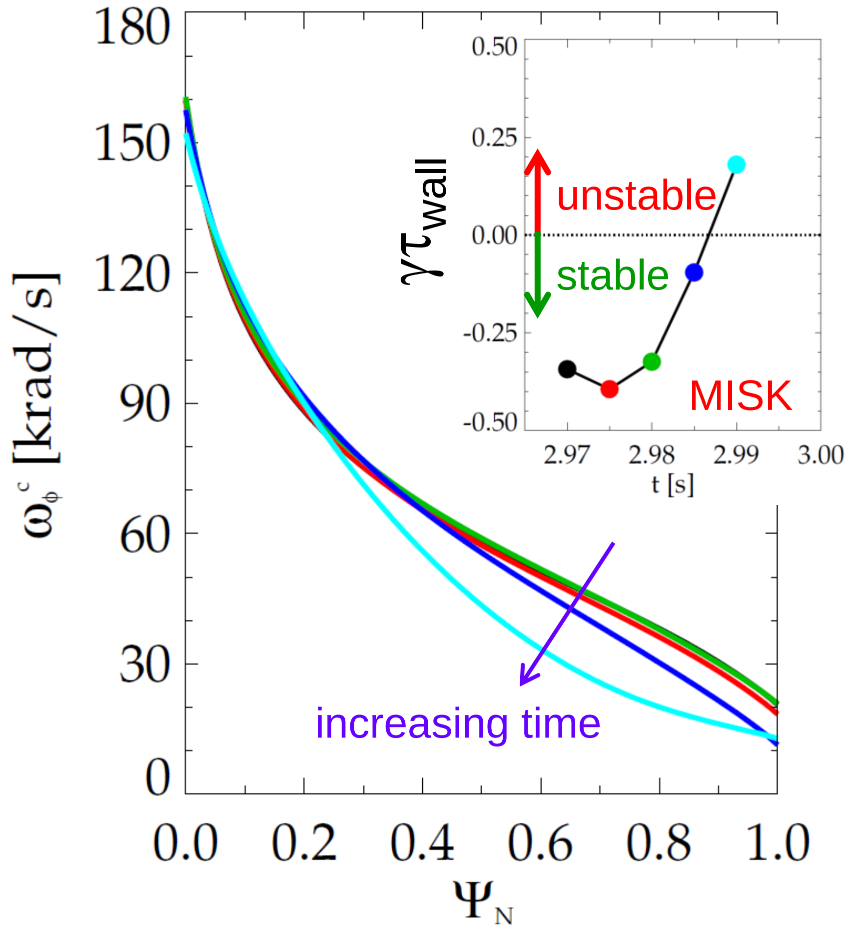
DIII-D (β_N = 3.5) NSTX (β_N = 4.4)



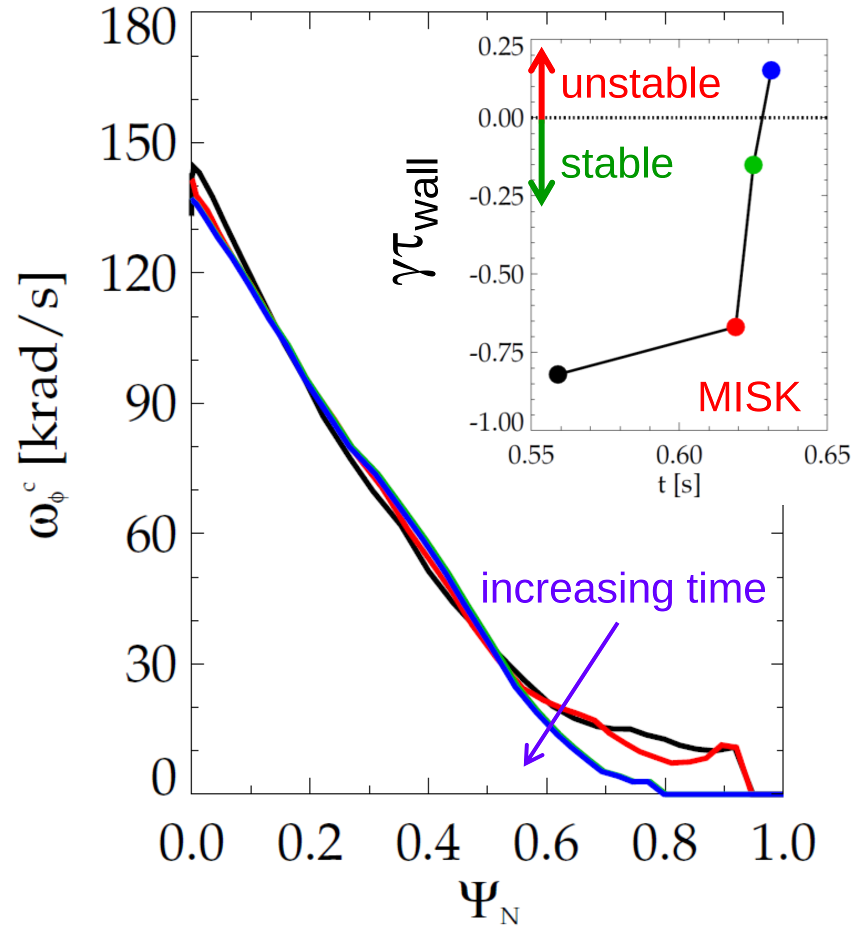
S. Sabbagh et al., DIII-D/NSTX experiments
S. Sabbagh et al., APS Invited talk 2014

Evolution of plasma rotation profile leads to linear kinetic RWM instability as disruption is approached

DIII-D (minor disruption)



NSTX (major disruption)

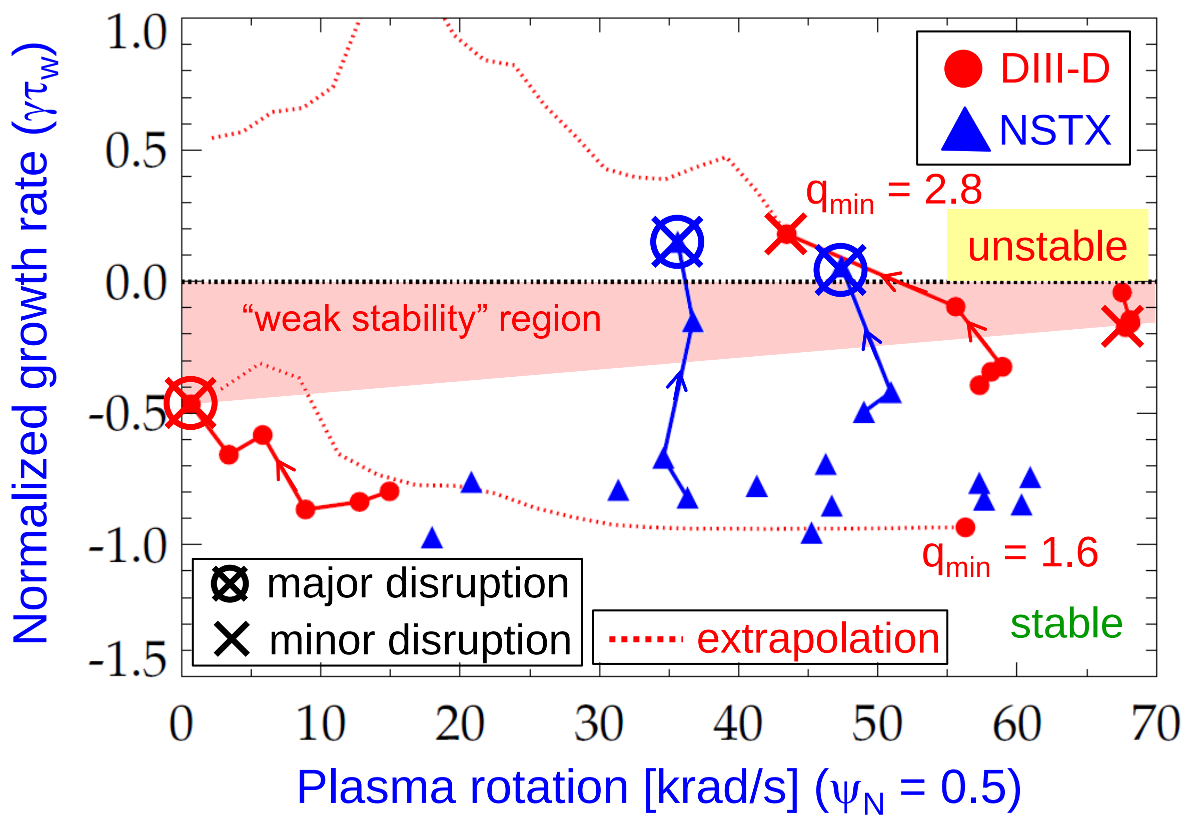


S. Sabbagh et al., DIII-D/NSTX experiments; S. Sabbagh et al., APS Invited talk 2014

Kinetic RWM stability evaluated for DIII-D and NSTX plasmas, reproduces experiments over wide rotation range

- Summary of results
  - Plasmas free of other MHD modes can reach or exceed linear kinetic RWM marginal stability
  - Bursting MHD modes can lead to non-linear destabilization before linear stability limits are reached
  - Extrapolations of DIII-D plasmas to different V_ϕ show marginal stability is bounded by $1.6 < q_{min} < 2.8$

Kinetic RWM stability analysis for experiments (MISK)



- Reduced models of kinetic RWM stability now being investigated to support real-time disruption avoidance (e.g. by rotation profile control)

J.W. Berkery, J.M. Hanson, S.A. Sabbagh (Columbia U.)

Rotation feedback controller designed for NSTX-U using non-resonant NTV and NBI used as actuators

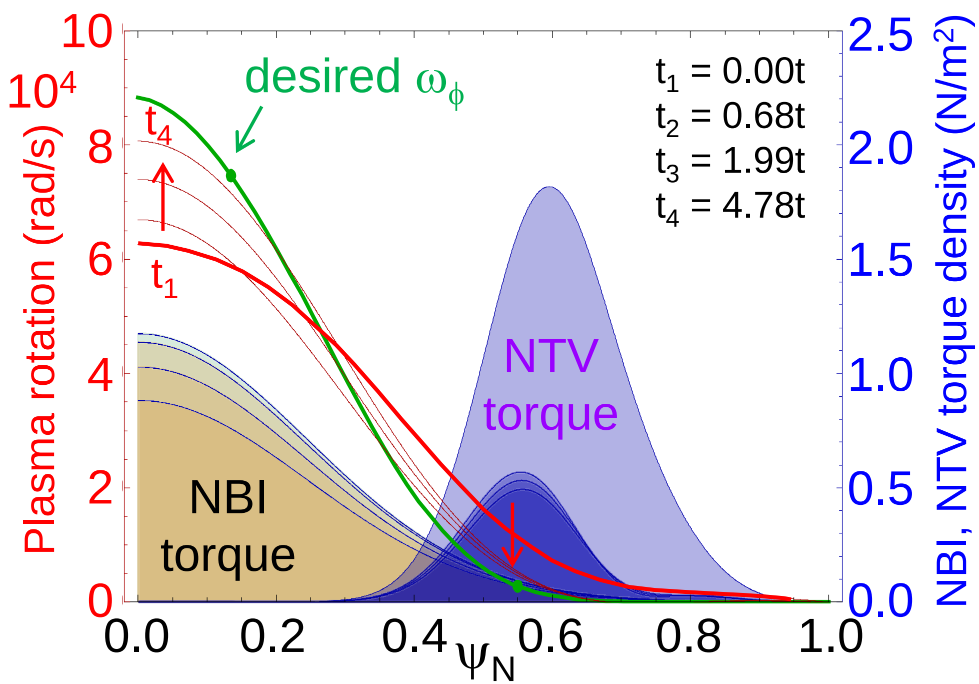
- Momentum force balance – ω_ϕ decomposed into Bessel function states

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

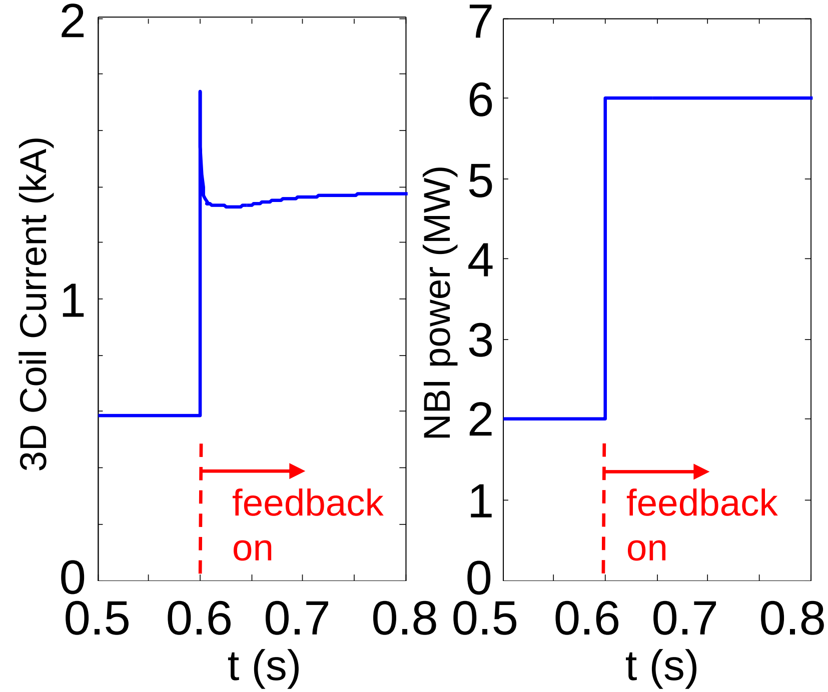
- NTV torque:

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

Rotation evolution and NBI and NTV torque profiles



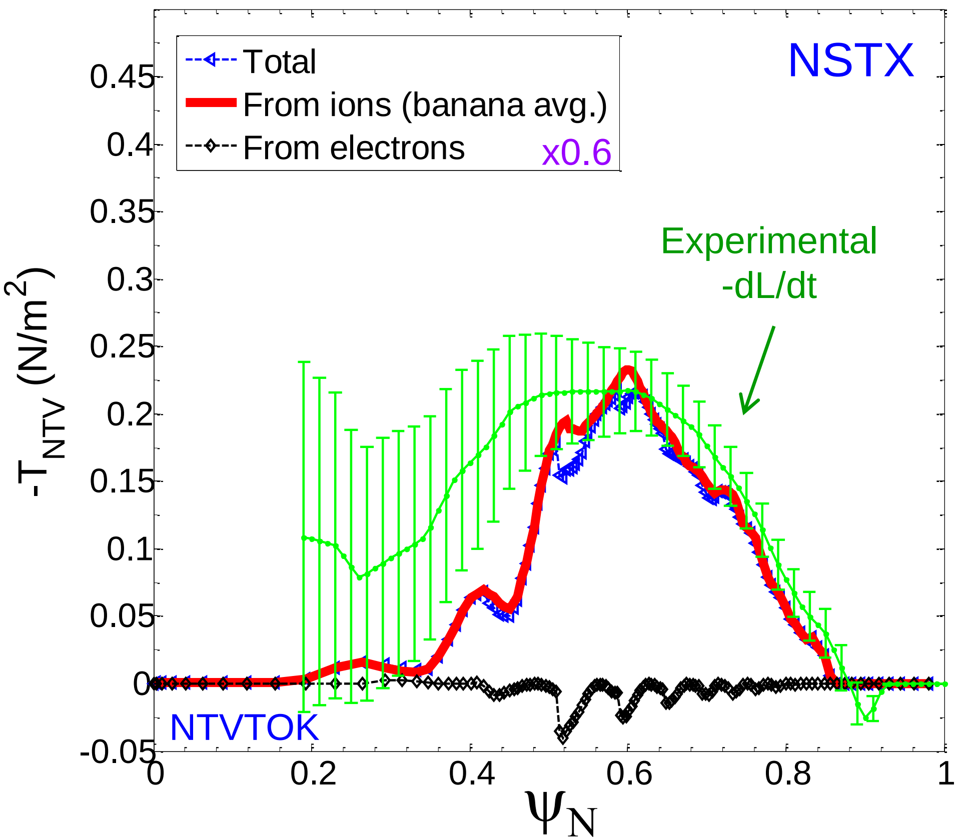
3D coil current and NBI power (actuators)



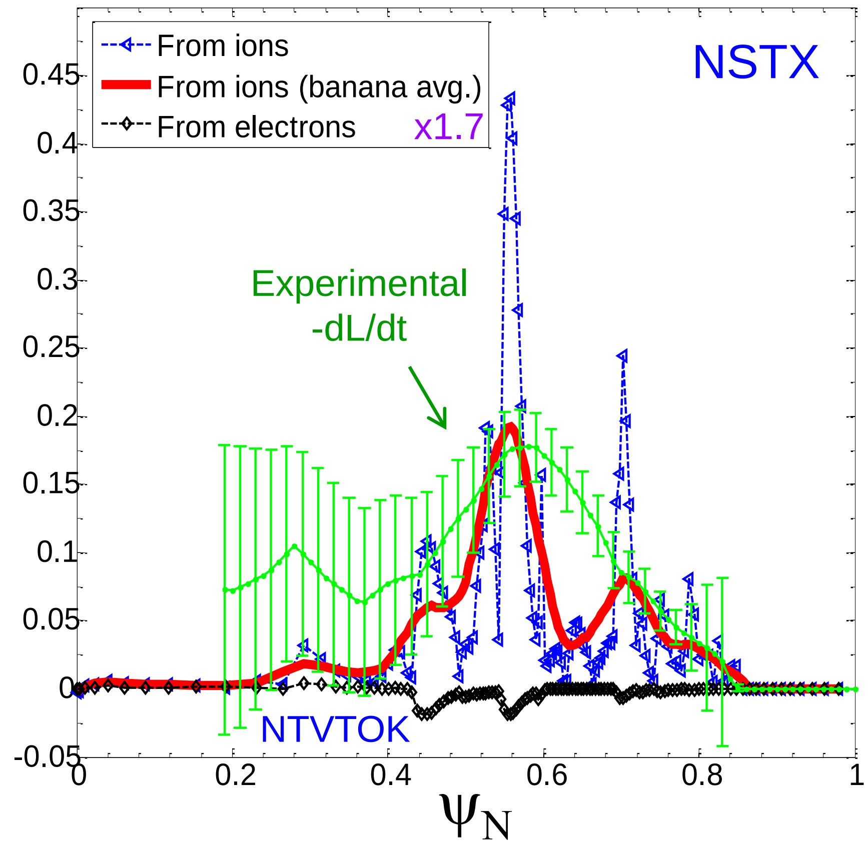
I. Goumiri (P.U. student), S.A. Sabbagh (Columbia U.), C. Rowley (P.U.), D.A. Gates, S.P. Gerhardt (PPPL)

NTV physics studies for rotation control: measured NTV torque density profiles quantitatively compare well to theory

n = 3 coil configuration



n = 2 coil configuration

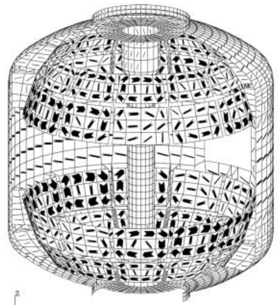


- T_{NTV} (theory) scaled to match *peak* value of measured *-dL/dt*
  - Scale factor ($(dL/dt)/T_{NTV}$) = 1.7 and 0.6 for cases shown above – O(1) agreement

S. Sabbagh et al., IAEA FEC 2014 (EX/1-4)

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

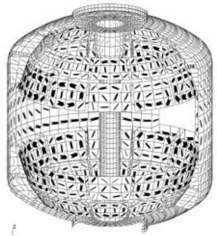
Full 3-D model ~3000+ states

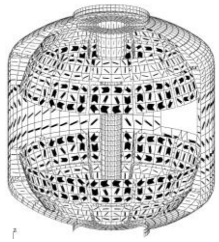


Balancing transformation

State reduction (< 20 states)

RWM eigenfunction (2 phases, 2 states)





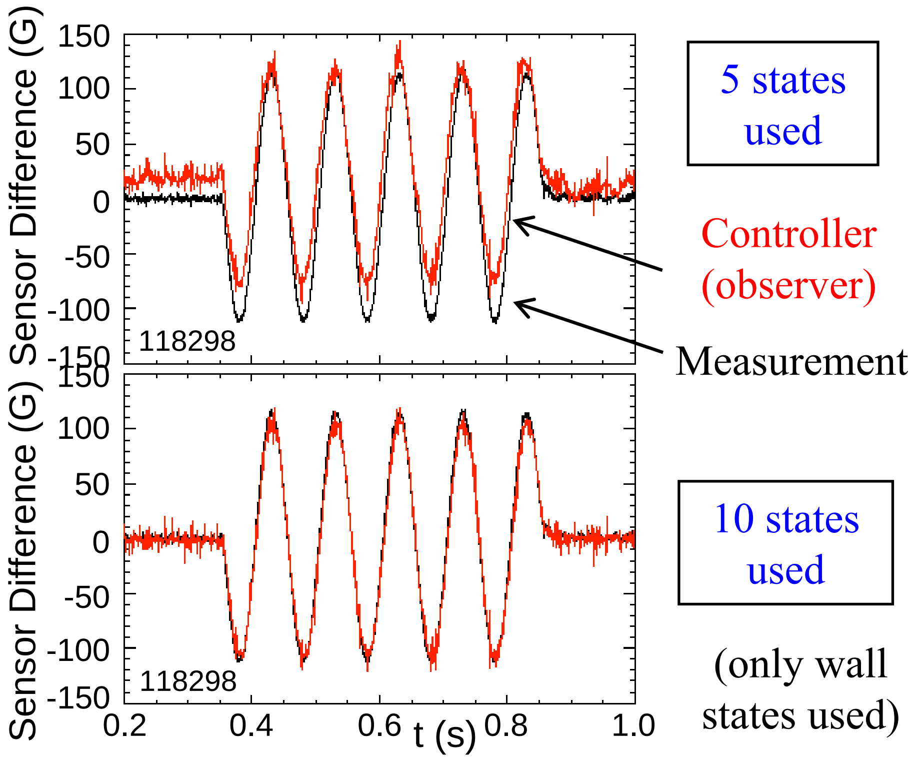
…

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

- Controller 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)

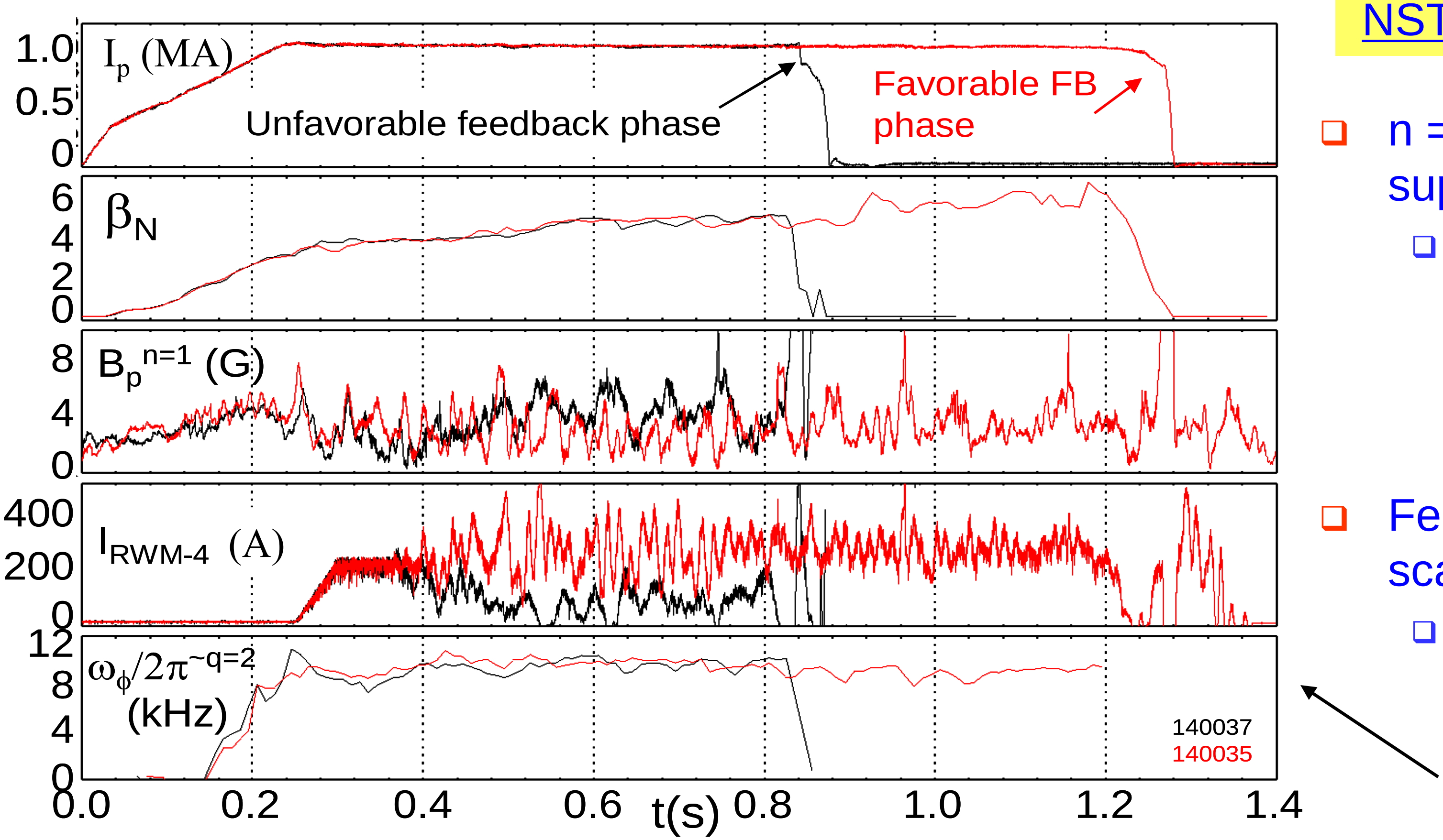
    Katsuro-Hopkins, et al., NF **47** (2007) 1157
- Straightforward inclusion of multiple modes (with n = 1, or n > 1) in feedback

Controller reproduction of n = 1 field in NSTX



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

RWM state space feedback (12 states)



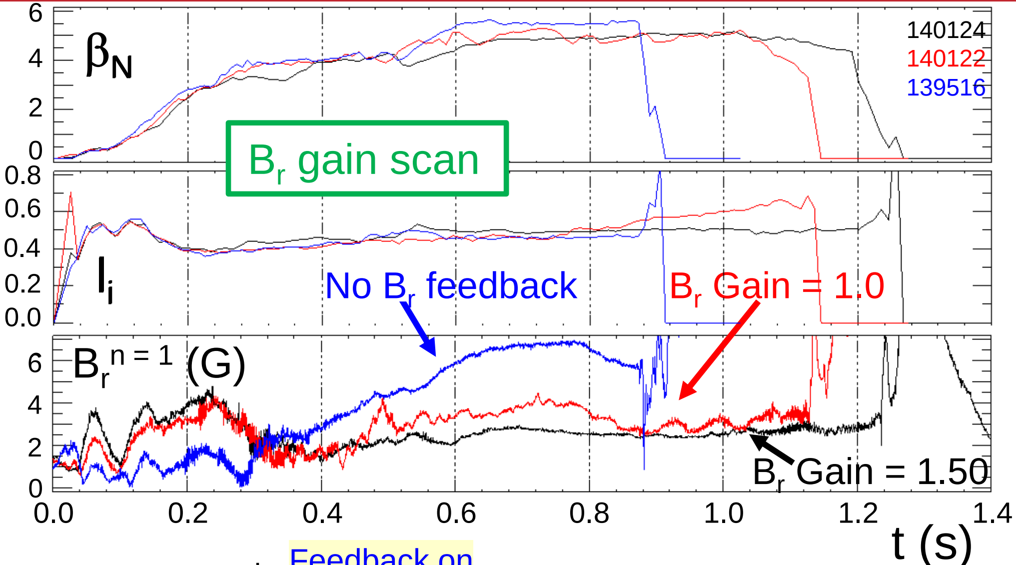
NSTX Experiments

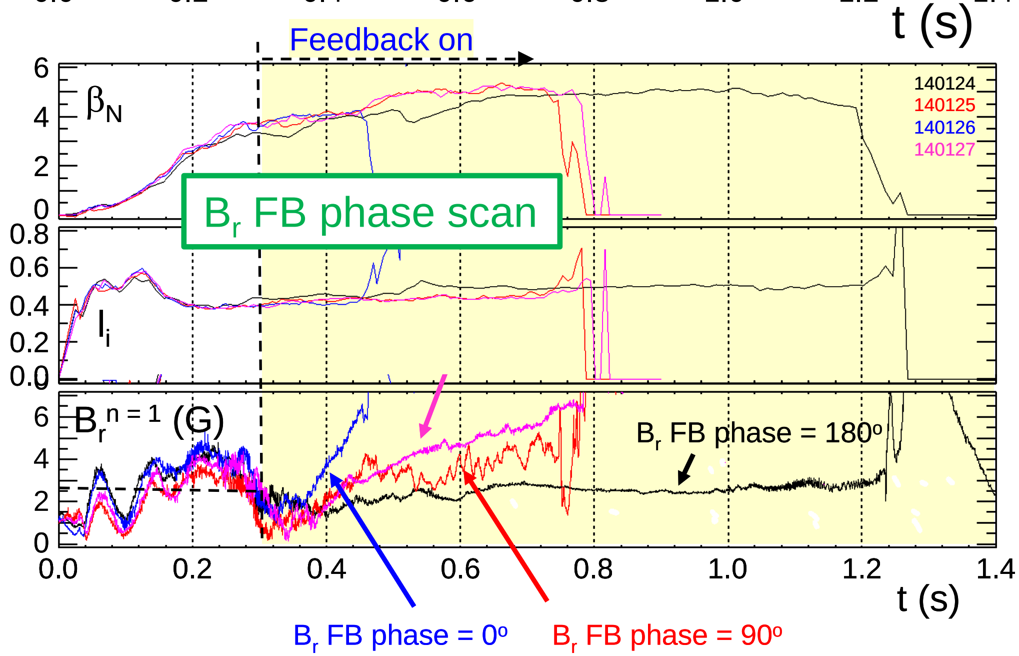
- n = 1 applied field suppression
  - Suppressed disruption due to n = 1 field
- Feedback phase scan
  - Best feedback phase produced long pulse, β_N = 6.4, β_N/l_i = 13

- Run time has been allocated for continued experiments on NSTX-U

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

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

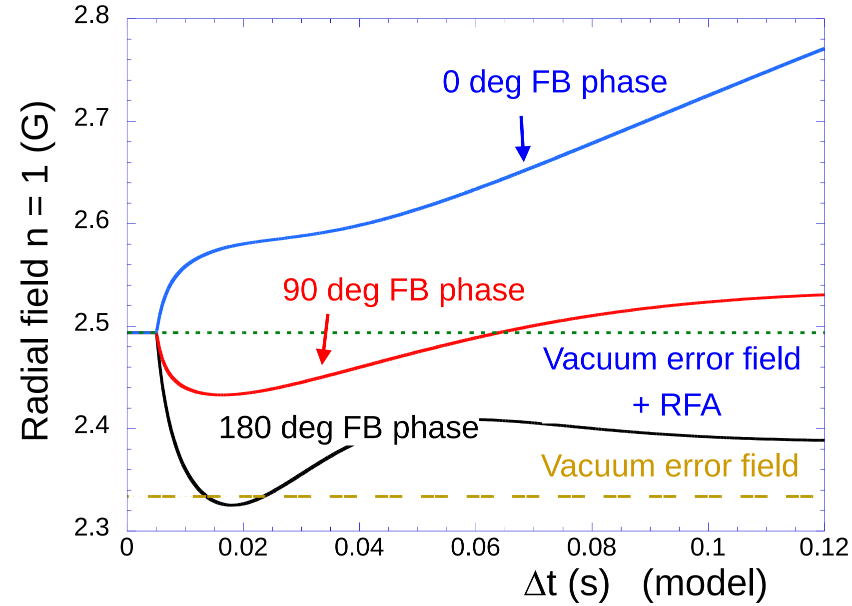




- Favorable B_p + B_r feedback (FB) settings found (low l_i plasmas)
- Time-evolved theory simulation of B_r+B_p feedback follows experiment

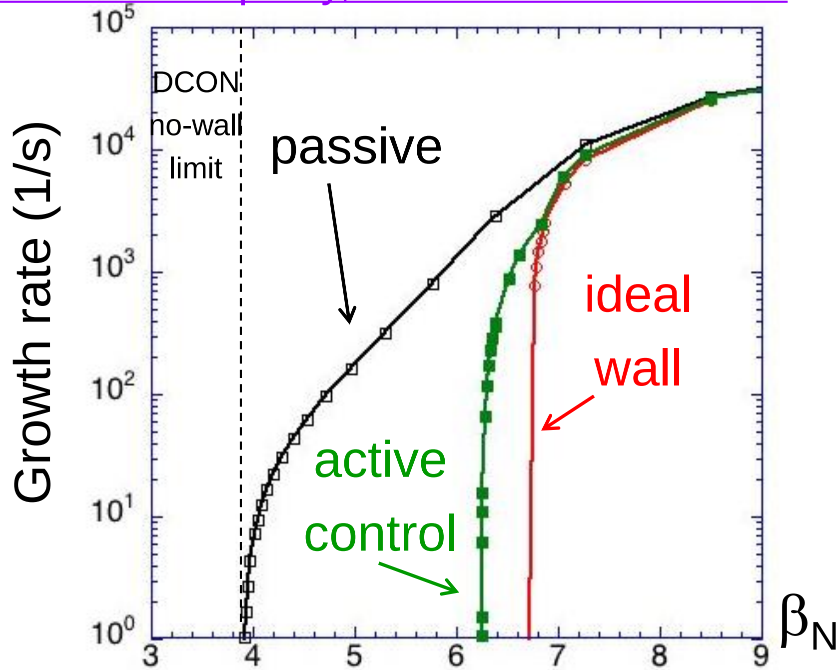
S. Sabbagh et al., Nucl. Fusion **53** (2013) 104007

Simulation of B_r + B_p control (VALEN)

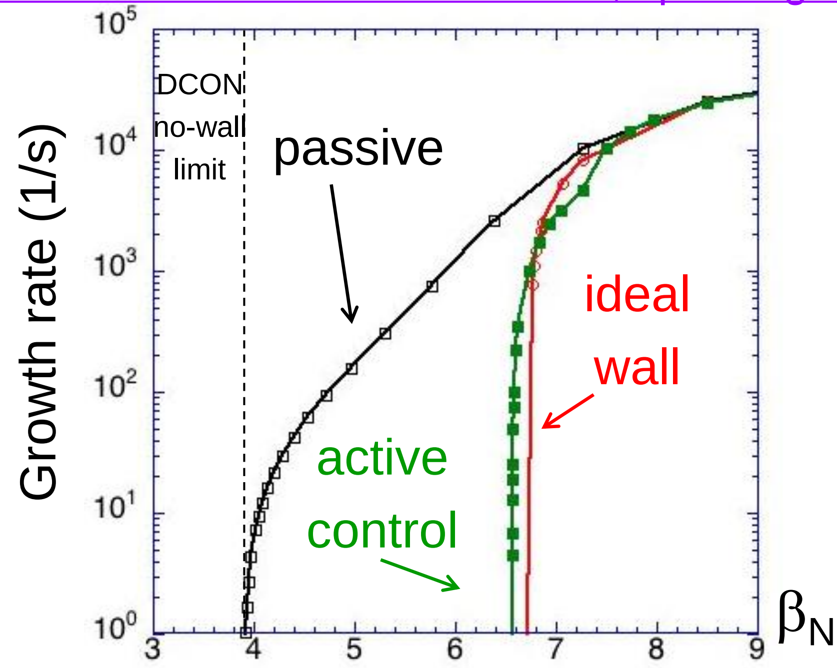


Active RWM control design study for proposed NSTX-U 3D coil upgrade (NCC coils) shows superior capability

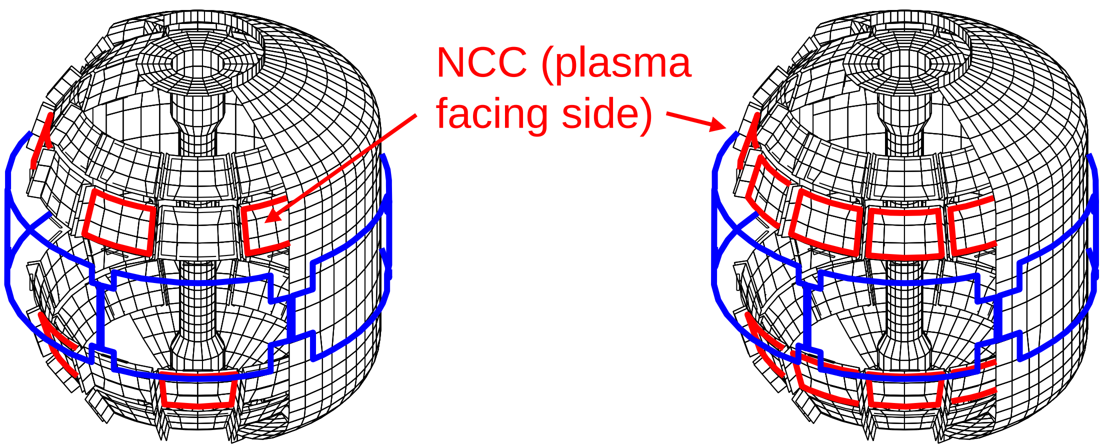
NCC 2x6 odd parity, with favorable sensors



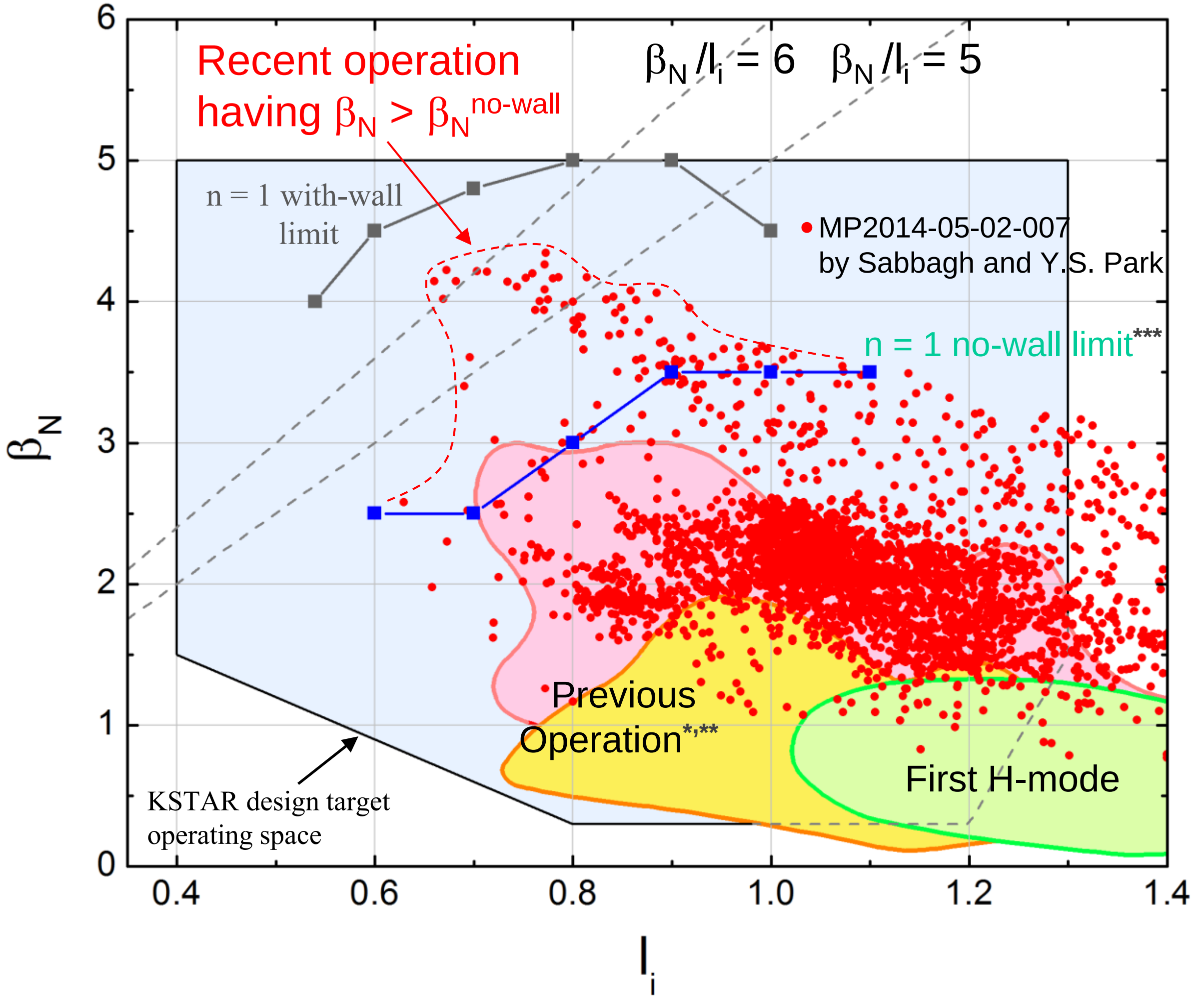
NCC 2x12 with favorable sensors, optimal gain



- Full NCC coil set allows control close to ideal wall limit
  - NCC 2x6 odd parity coils: active control to $\beta_N/\beta_N^{no-wall} = 1.58$
  - NCC 2x12 coils, optimal sensors: active control to $\beta_N/\beta_N^{no-wall} = 1.67$



Columbia U. experiments yield record β_N for KSTAR, significantly surpassed the ideal MHD *n* = 1 stability limit



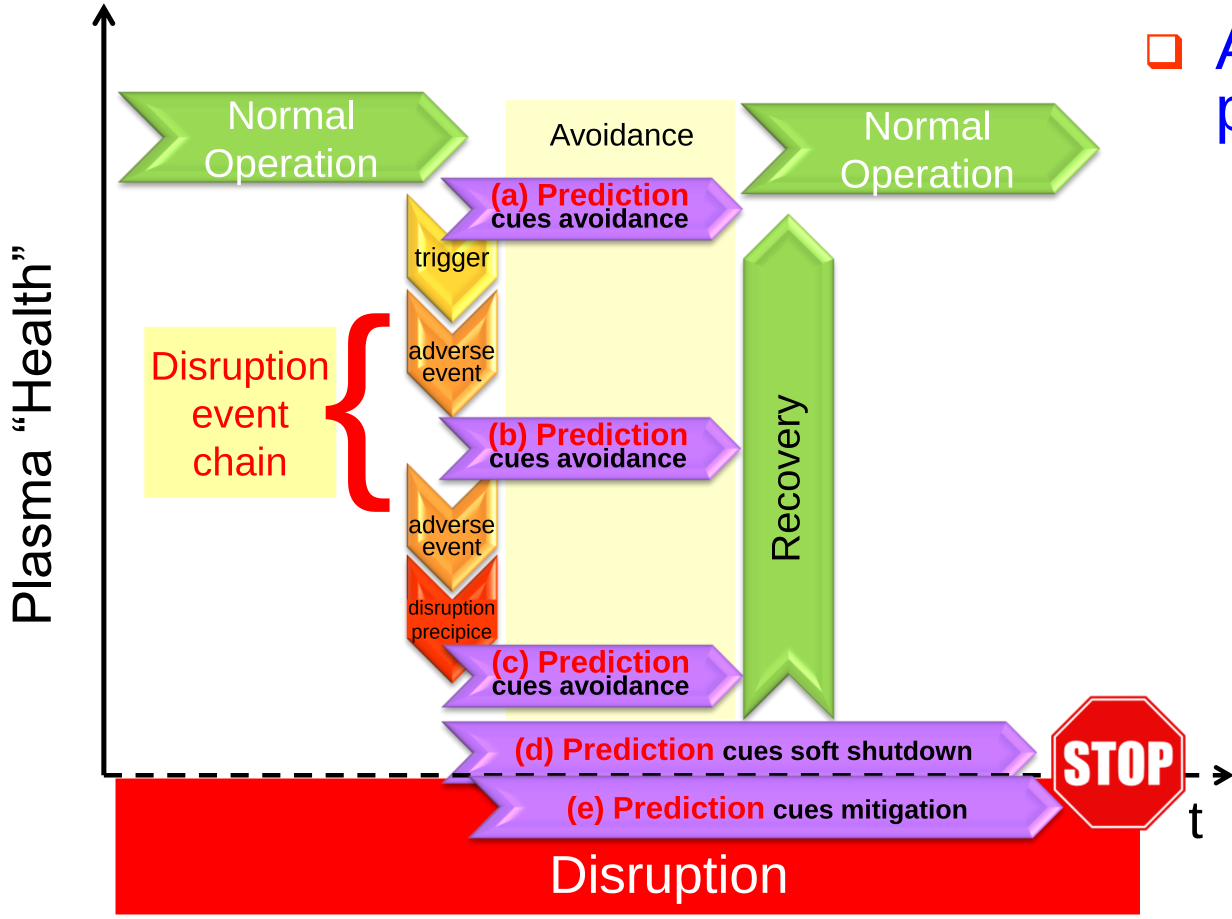
Normalized beta vs. internal inductance from KSTAR EFIT

*Y.S. Park, et al., Nucl. Fusion **53** (2013) 083029
Y.S. Park, et al., Phys. Plasmas **21 (2014) 012513
** O. Katsuro-Hopkins, et al., Nucl. Fusion **50** (2010) 025019

- Plasma parameters
  - q_{95} ~4.5
  - P_{NBI} = 2.7 - 4 MW (2 or 3 beam sources)
- $\beta_N/l_i > 6$ (50% increase from the highest values in previous operations)
  - A high value for advanced tokamaks
  - β_N up to 4.3
  - l_i ranging 0.66 - 0.87 with $\beta_N > 4$
  - Discharge β_N was **not** limited by n > 0 events

Y.S. Park, S.A. Sabbagh, et al., KSTAR Conference 2015

Disruption event chain characterization capability started for NSTX-U as next step in disruption avoidance plan

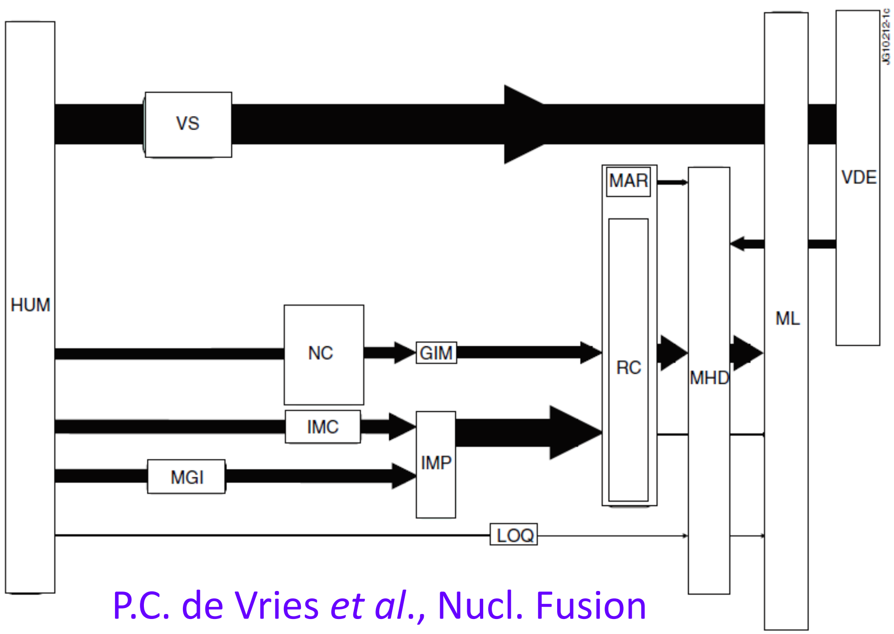


General code written (Python) to address the first step – initial test runs started using NSTX data

- Approach to disruption prevention
  - Identify disruption event chains and elements
  - Predict events in disruption chains
    - Attack events at several places
    - Give priority to early events
  - Provide cues to avoidance system to break the chain
  - Provide cue to mitigation system if avoidance deemed untenable

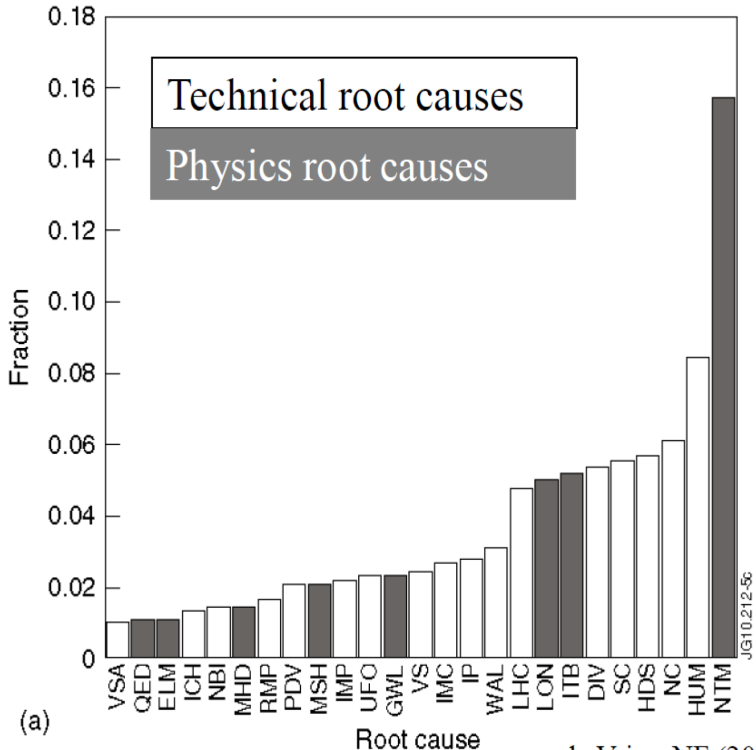
JET disruption event characterization provides framework to follow for understanding / quantifying DPAM progress

JET disruption event chains



P.C. de Vries *et al.*, Nucl. Fusion **51** (2011) 053018

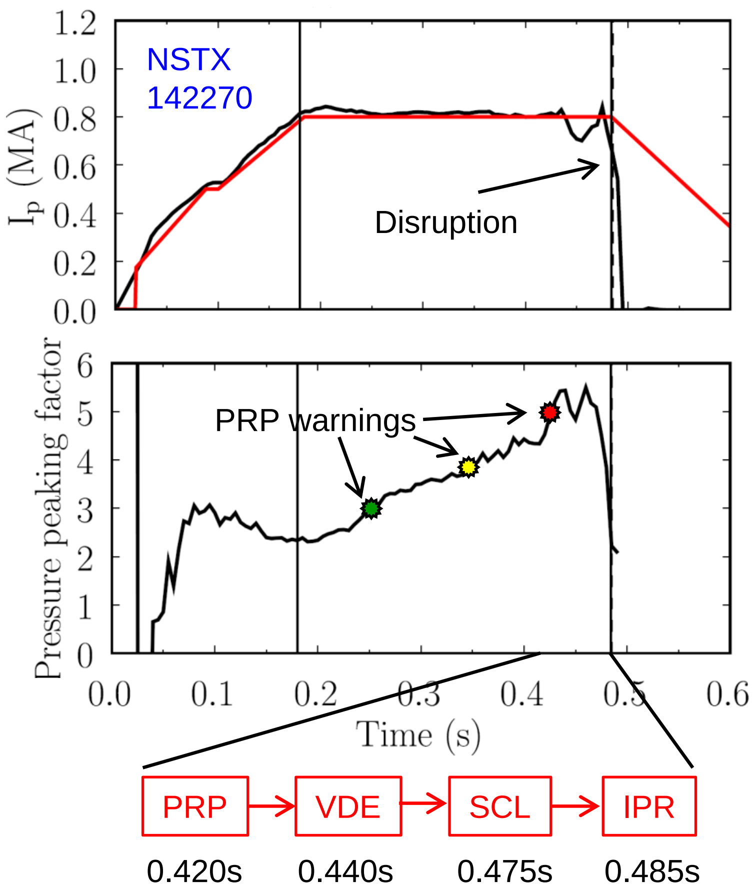
Related disruption event statistics



de Vries, NF (2011)

- JET disruption event chain analysis performed by hand, need to automate
- NSTX-U DPAM Working Group formed (w/ Columbia U. Group leadership): List of disruption chain events defined, interested individuals identified

Disruption Characterization Code now yielding initial results: disruption event chains, with related quantitative warnings



- 10 physical disruption chain events and related quantitative warning points are presently defined in code
  - Code is easily expandable, portable to other tokamaks
- This example: Pressure peaking (PRP) disruption even chain identified by code
  1. (PRP) Pressure peaking warnings identified first
  2. (VDE) VDE condition subsequently found 20 ms after last PRP warning
  3. (SCL) Shape control warning issued
  4. (IPR) Plasma current request not met

J.W. Berkery, S.A. Sabbagh, Y.S. Park (Columbia U.)

NSTX-U is a world leading program on disruption avoidance, Columbia U. Group Research providing a leadership role

- Physics Elements
  - Kinetic RWM stabilization physics
  - NTV physics for plasma rotation control (for instability avoidance)
  - Active RWM control (physics-based RWM state-space controller)
  - RWM control analysis of upgraded 3D coils for NSTX-U
  - NSTX-U equilibrium reconstruction – key basis for stability analysis
  - Planned real-time MHD spectroscopy for NSTX-U (in 5 Year Plan)
  - Related high normalized beta and NTV experiments on KSTAR

- Research synergism
  - Elements now being brought together as part of a disruption prediction/avoidance system; NSTX-U DPAM working group leadership
  - Disruption Characterization/Prediction code initiated

- Action to enhance university / student / post-doc participation
  - New diagnostic proposal to be submitted (Volpe/Sabbagh)

Supporting slides follow

Modification of Ideal Stability by Kinetic theory (MISK code) is used to determine proximity of plasmas to stability boundary

- Initially used for NSTX since simple critical scalar ω_ϕ threshold stability models did not describe RWM stability

  Sontag, et al., Nucl. Fusion **47** (2007) 1005

- Kinetic modification to ideal MHD growth rate
  - Trapped / circulating ions, trapped electrons, etc.
  - Energetic particle (EP) stabilization

$$\gamma\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_{wall} + \delta W_K}$$

Hu and Betti, Phys. Rev. Lett **93** (2004) 105002

- Stability depends on
  - Integrated ω_ϕ profile: resonances in δW_K (e.g. ion precession drift)
  - Particle collisionality, EP fraction

ω_ϕ profile (enters through ExB frequency)

Trapped ion component of δW_K (plasma integral over energy)

$$\delta W_K \propto \int \left[\frac{\omega_{*N} + \left(\hat{\varepsilon} - \frac{3}{2}\right)\omega_{*T} + \omega_E - \omega - i\gamma}{\langle\omega_D\rangle + l\omega_b - i\nu_{eff} + \omega_E - \omega - i\gamma} \right] \hat{\varepsilon}^{\frac{5}{2}} e^{-\hat{\varepsilon}} d\hat{\varepsilon}$$

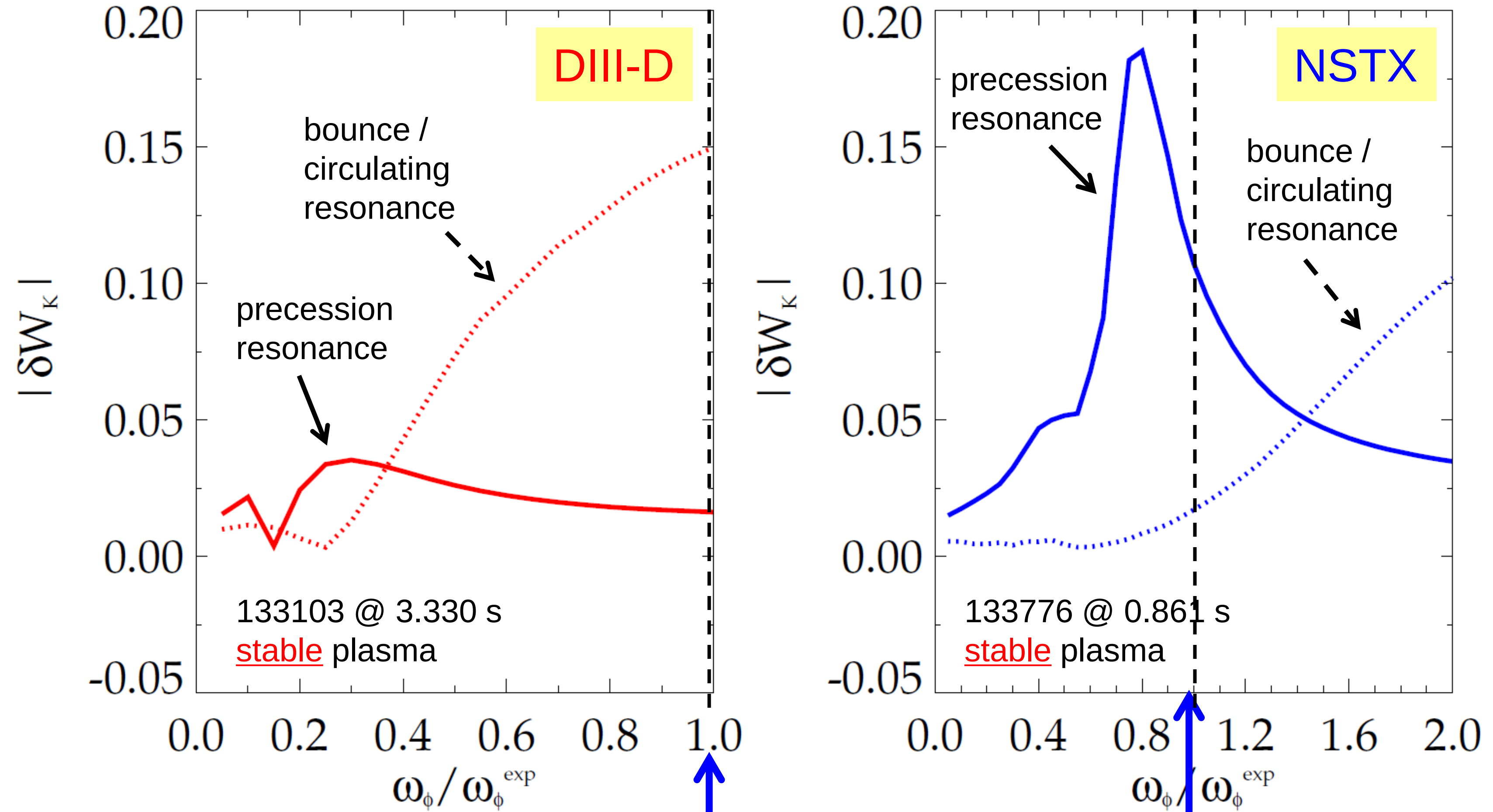
precession drift ($\langle\omega_D\rangle$) — bounce ($l\omega_b$) — collisionality (ν_{eff})

Some NSTX / MISK analysis references

- J. Berkery *et al.*, PRL **104**, 035003 (2010)
- S. Sabbagh, et al., NF **50**, 025020 (2010)
- J. Berkery *et al.*, PRL **106**, 075004 (2011)
- J. Berkery *et al.*, PoP **21**, 056112 (2014)
- J. Berkery *et al.*, PoP **21**, 052505 (2014) (benchmarking paper)

Bounce resonance stabilization dominates for DIII-D vs. precession drift resonance for NSTX at similar, high rotation

$|\delta W_K|$ for trapped resonant ions vs. scaled experimental rotation (MISK)

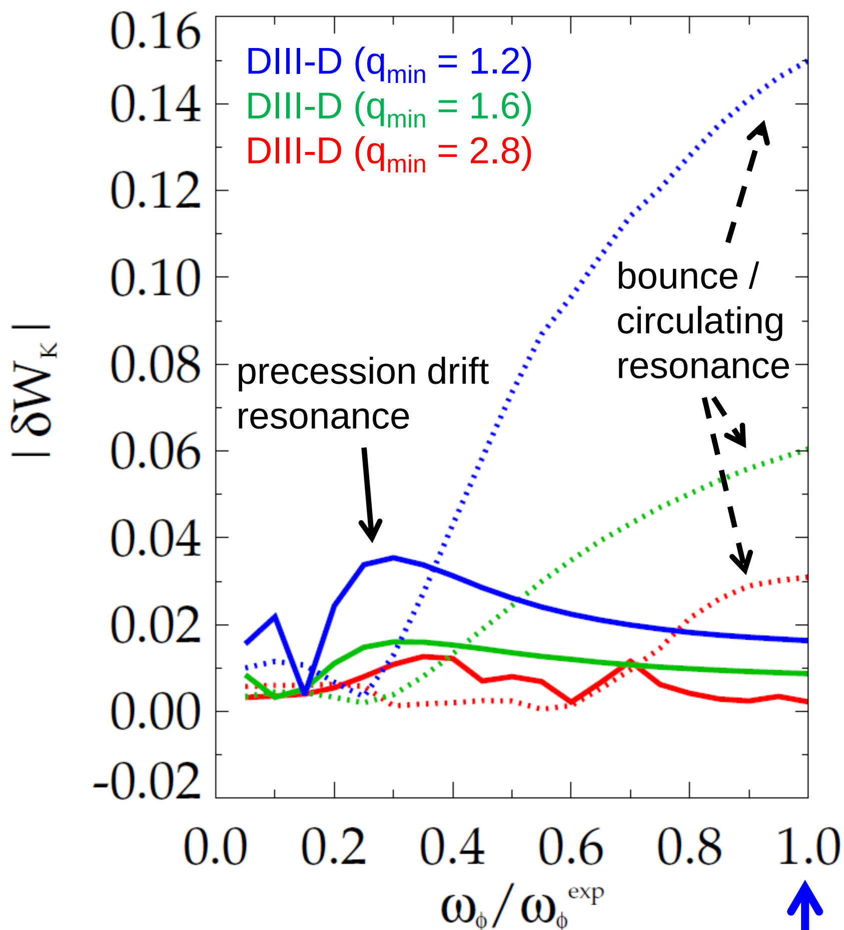


DIII-D experimental rotation profile

NSTX experimental rotation profile

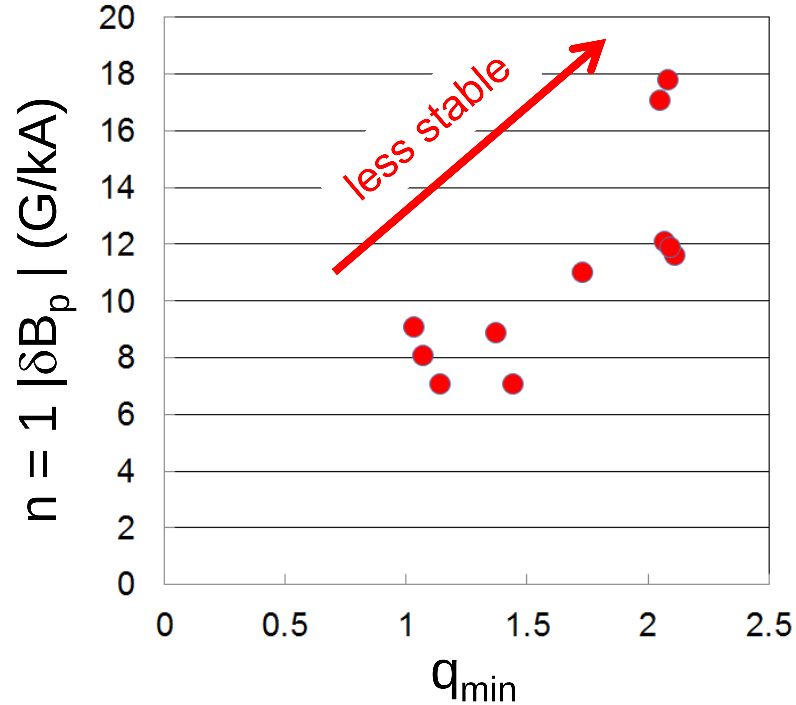
Increased RWM stability measured in DIII-D plasmas as q_{min} is reduced is consistent with kinetic RWM theory

$|\delta W_K|$ for trapped resonant ions vs. scaled experimental rotation (MISK)



DIII-D experimental rotation profile

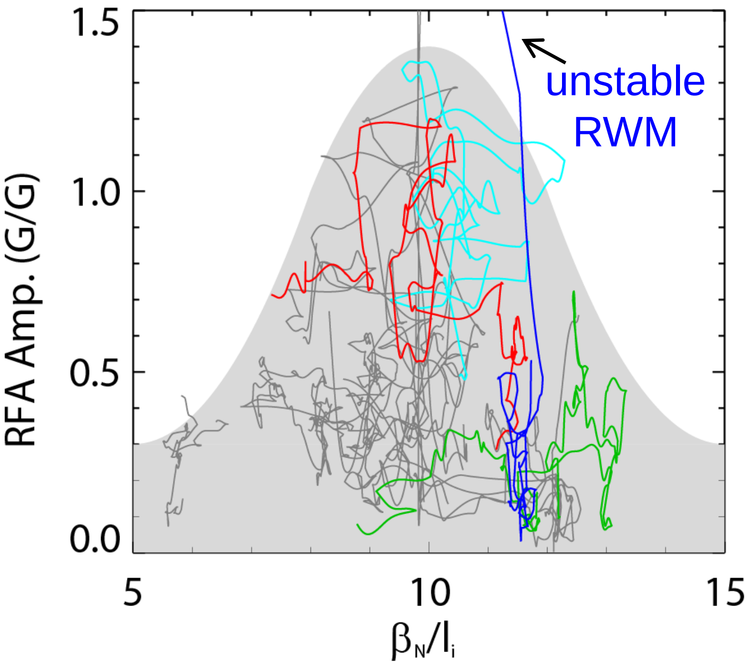
Measured plasma response to 20 Hz, n = 1 field vs q_{min}



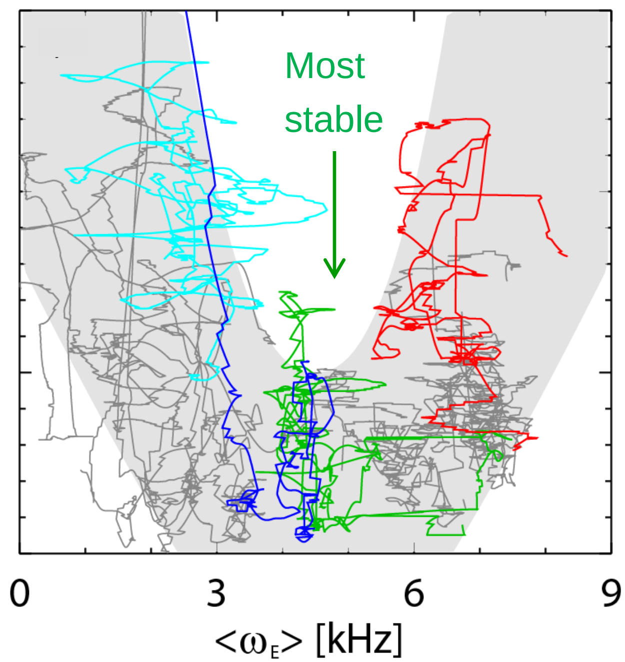
- Bounce resonance dominates precession drift resonance for all q_{min} examined at the experimental rotation

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)



NSTX experiments

(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

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

J. Berkery, et al., PoP **21** (2014) 056112

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

Minimize $|<\omega_D> + \omega_E|$

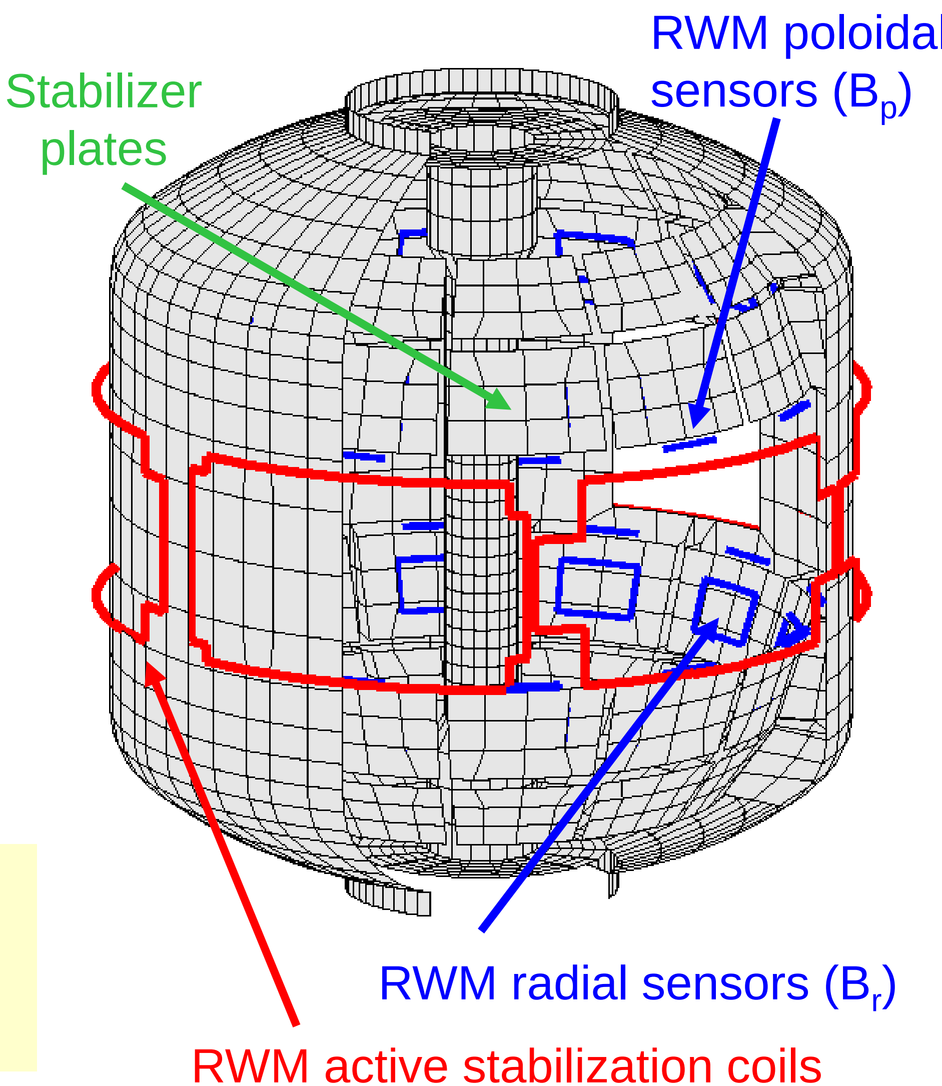
$$\delta W_k \sim \frac{1}{\langle \omega_D \rangle + \omega_E - i\nu_{eff}}$$

- 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

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

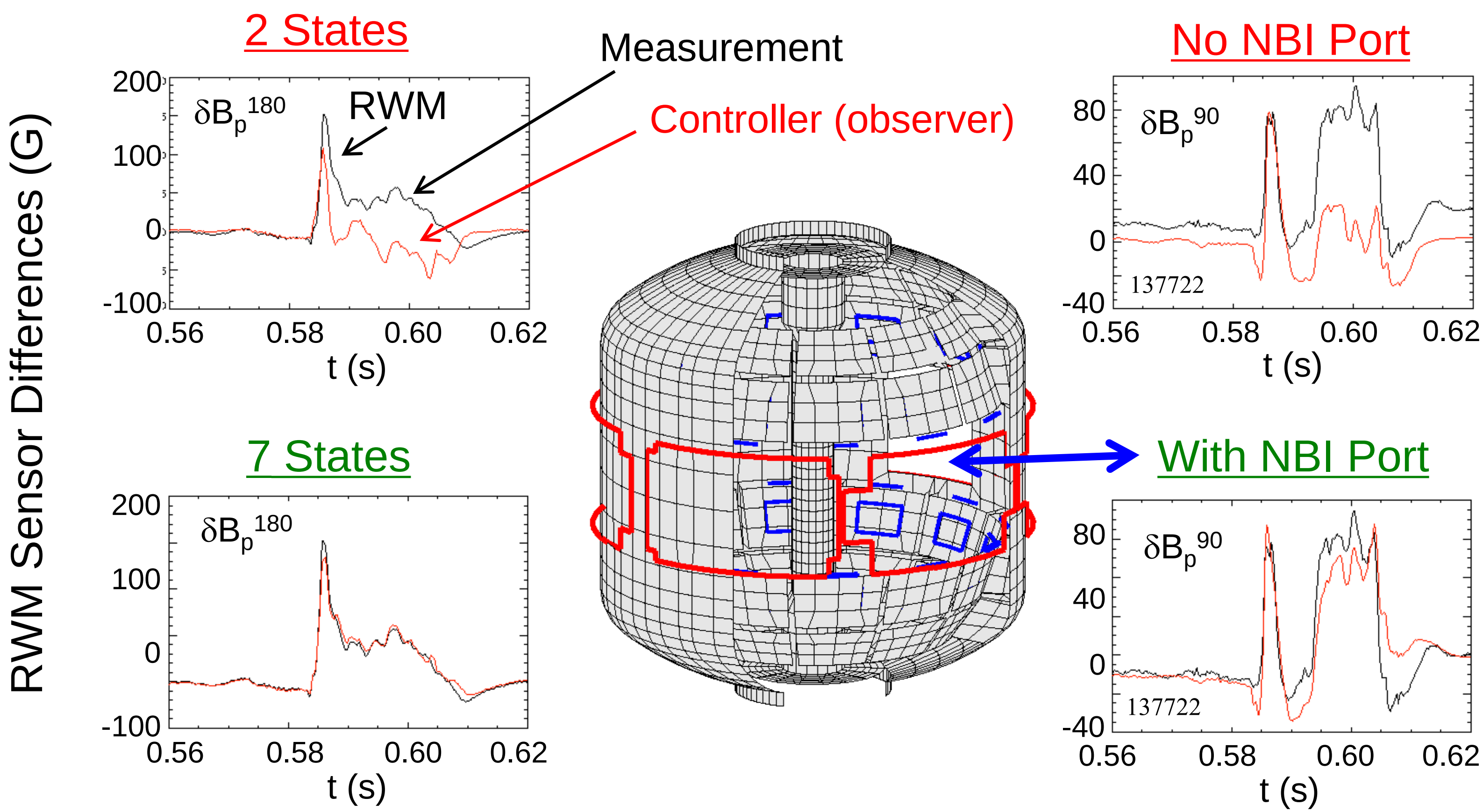
3D Structure Model



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

A) Effect of Number of States Used

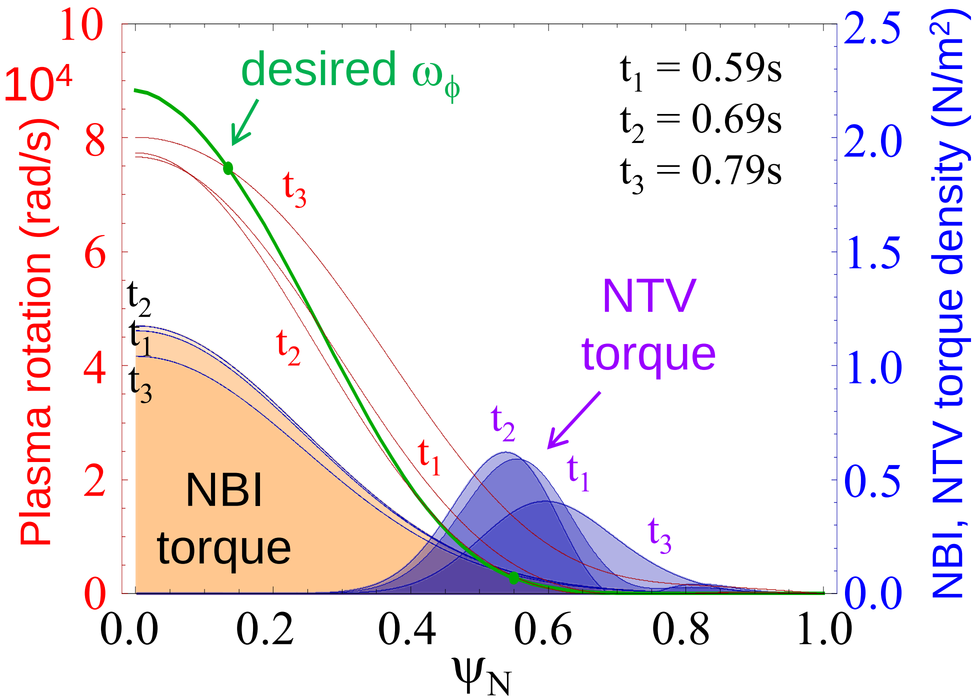
B) Effect of 3D Model Used



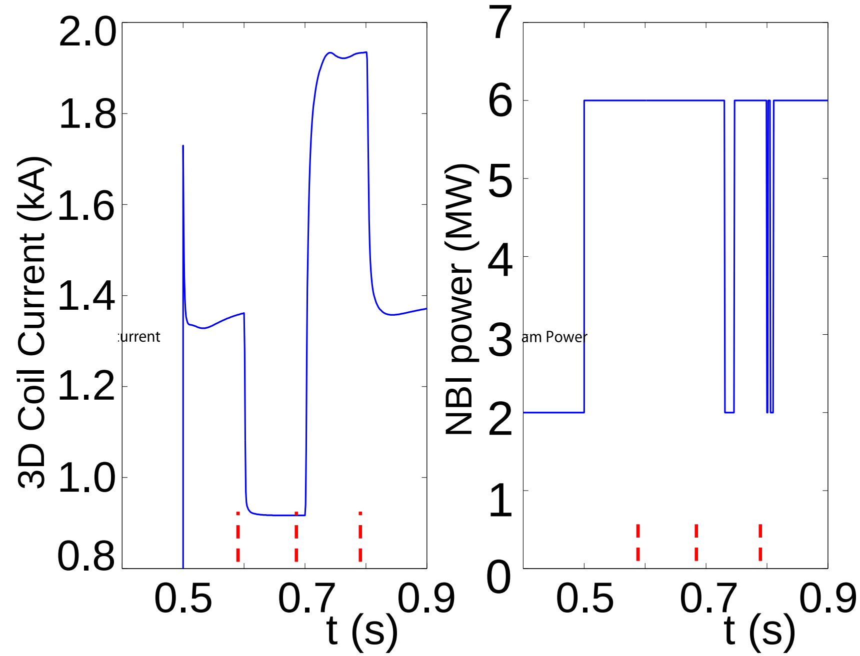
- Improved agreement with sufficient number of states (wall detail)
- 3D detail of model important to improve agreement

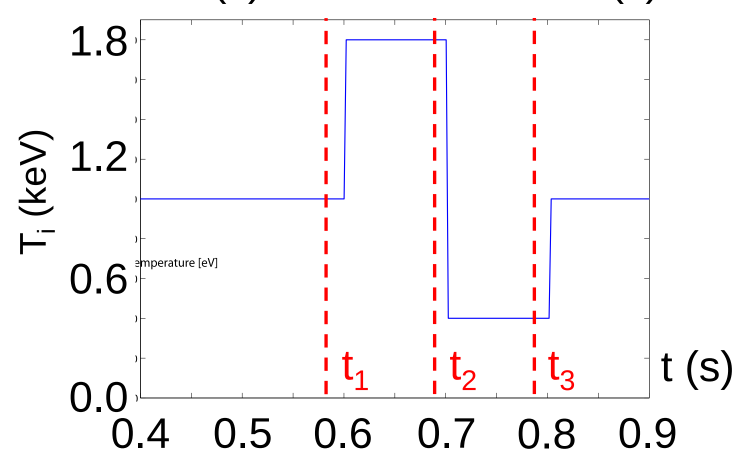
When T_i is included in NTV rotation controller model, 3D field current and NBI power can compensate for T_i variations

Rotation evolution and NBI and NTV torque profiles



3D coil current and NBI power (actuators)





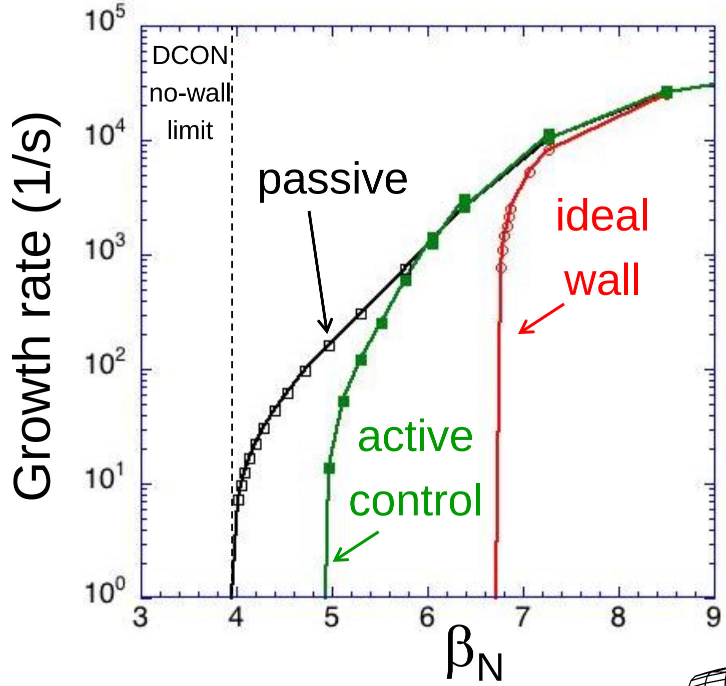
$$T_{NTV} \propto K \times f\left(n_{e,i}{}^{K1} T_i^{K2}\right) g\left(\delta B(\rho)\right)\left[I_{coil}{}^2 \omega\right]$$

K1 = 0, K2 = 2.5

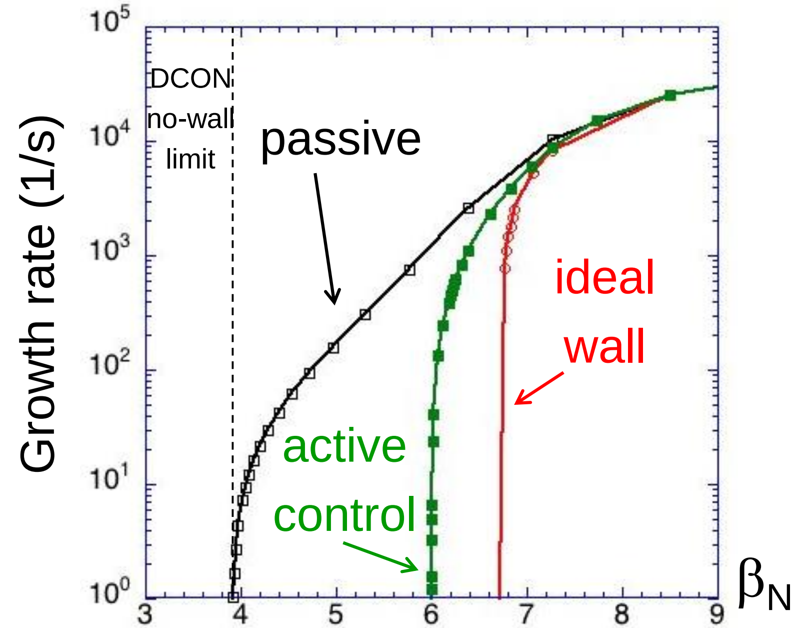
- NTV torque profile model for feedback dependent on ion temperature

NSTX-U: RWM active control capability increases as proposed 3D coils upgrade (NCC coils) are added

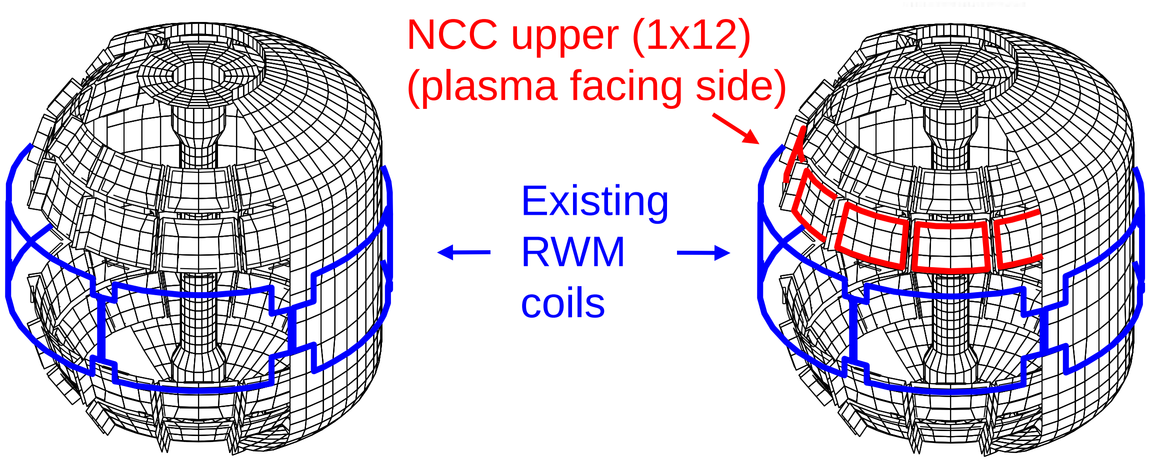
Using present midplane RWM coils



Partial NCC 1x12 (upper), favorable sensors

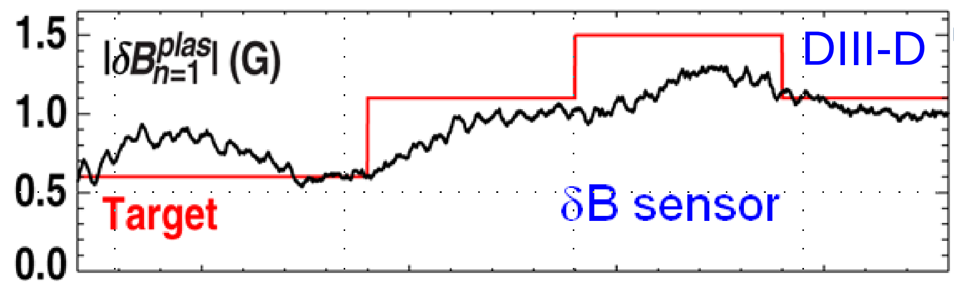


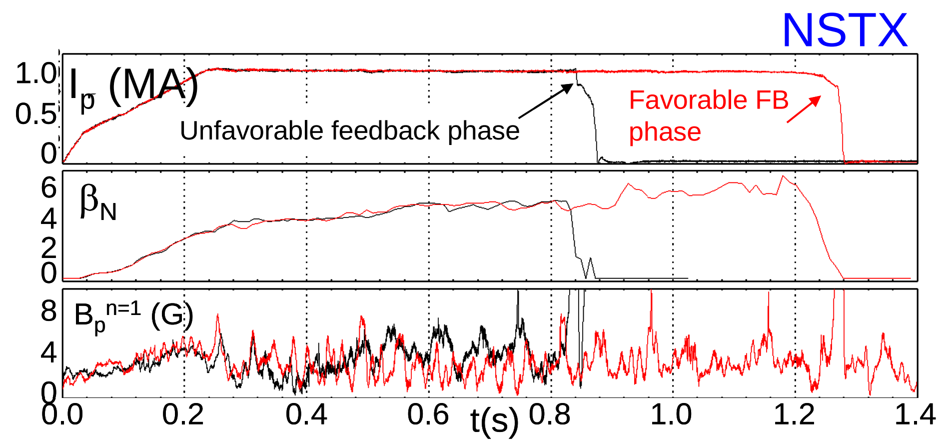
- Partial 1x12 NCC coil set significantly enhances control
  - Present RWM coils: active control to $\beta_N/\beta_N^{no\text{-}wall} = 1.25$
  - NCC 1x12 coils: active control to $\beta_N/\beta_N^{no\text{-}wall} = 1.52$

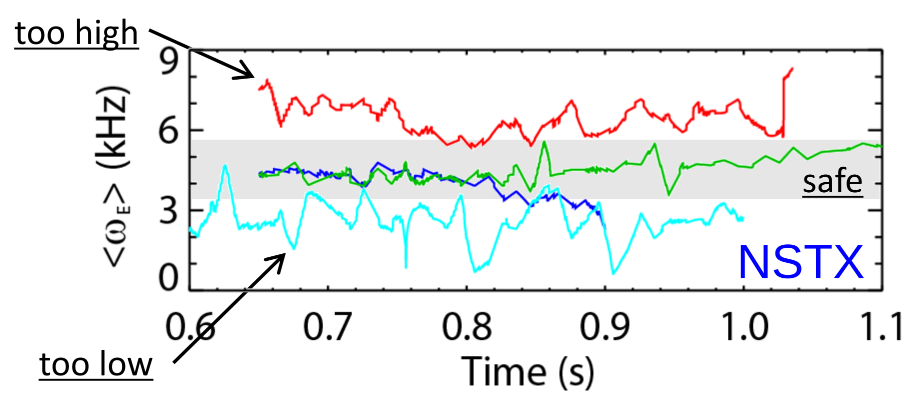


Real-time MHD spectroscopy, model-based active control, and kinetic physics will be used for disruption avoidance

- MHD Spectroscopy
  - Use real-time measurement of plasma global mode stability to "steer" toward increased stability
- Advanced active control
  - Combined Br + Bp feedback reduces n = 1 field amplitude, improves stability
  - RWM state space controller sustains low l_i, high β_N plasma
- Simplified kinetic physics models
  - "steer" profiles (e.g. plasma toroidal rotation) toward increased stability in real-time







NSTX-U DPAM Working Group meeting: List of disruption chain events defined, interested individuals identified

- Impurity control (NC)
  - bolometry-triggered shutdown (SPG); "tailoring" radiation-induced TM onset (LD, DG)
  - change plasma operational state / excite ELMs, etc. (TBD – perhaps JC)
- Greenwald limit (GWL)
  - density/power feedback, etc. (DB)
- Locked TM (LTM)
  - TM onset and stabilization conditions, locking thresholds (JKP,RLH,ZW)
  - TM entrainment (YSP)
- Error Field Correction (EFC)
  - NSTX-U EF assessment and correction optimization (CM,SPG)
  - NSTX-U EF multi-mode correction (SAS, YSP, EK)
- Current ramp-up (IPR)
  - Active aux. power / CD alteration to change q (MDB, SPG)
- Shape control issues (SC)
  - Active alteration of squareness, triangularity, elongation – RFA sensor (SPG,MDB)
- Transport barrier formation (ITB)
  - Active global parameter, V_ϕ, etc. alteration techniques (SAS,JWB,EK)
- H-L mode back-transition (HLB)
  - Active global parameter, V_ϕ, etc. alteration techniques (SAS,JWB,EK)
- Approaching vertical instability (VSC)
  - Plasma shape change, etc. (SPG, MDB)
- Resistive wall mode (RWM)
  - Active global parameter, V_ϕ, etc. alteration techniques (SAS,JWB)
  - Active multi-mode control (SAS,YSP,KT)
- Ideal wall mode (IWM)
  - Active global parameter, V_ϕ, etc. alteration techniques (JEM)
- Internal kink/Ballooning mode (IKB)
  - Active global parameter, V_ϕ, etc. alteration techniques (SAS,JWB)
  - Active multi-mode control (SAS, YSP, KT)

Abbreviations:
JWB: Jack Berkery
AB: Amitava Bhattacharjee
DB: Devon Battaglia
MDB: Dan Boyer
JC: John Canik
LD: Luis Delgado-Aparicio
DG: Dave Gates
SPG: Stefan Gerhardt
MJ: Mike Jaworski
EK: Egemen Kolemen
RLH: Rob La Haye
JEM: Jon Menard
CM: Clayton Myers
JKP: Jong-Kyu Park
YSP: Young-Seok Park
RR: Roger Raman
SAS: Steve Sabbagh
KT: Kevin Tritz
ZW: Zhirui Wang
TBD: (To be decided)

- Interest from Theory
  - Amitava Bhattacharjee, Allen Boozer, Dylan Brennan, Bill Tang have requested involvement

Interested? contact:
sabbagh@pppl.gov
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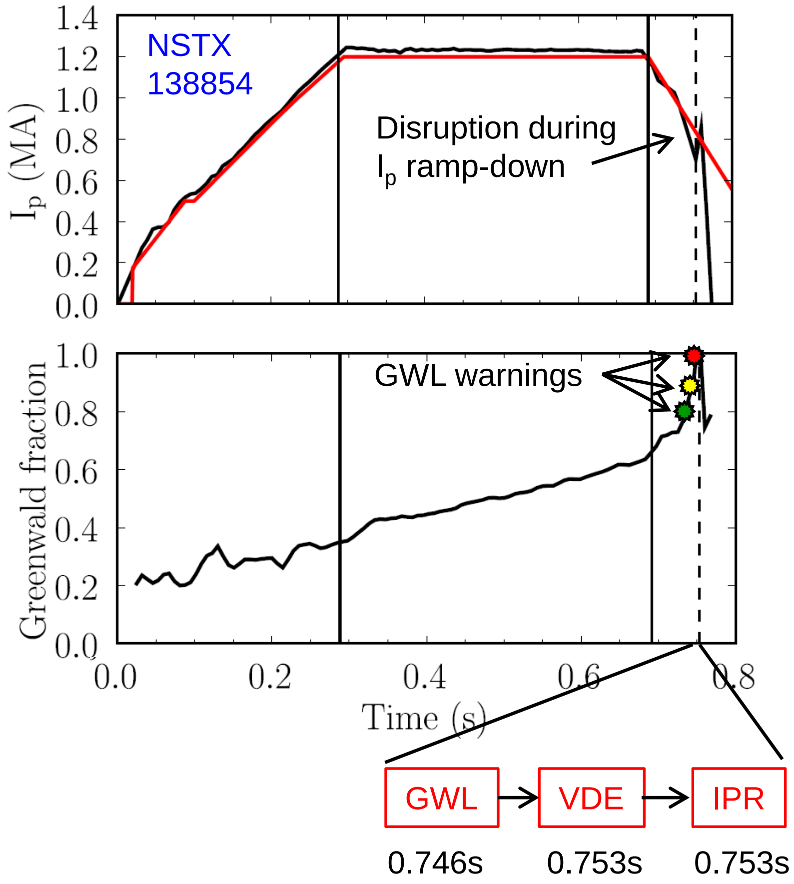
Disruption Characterization Code now yielding initial results: disruption event chains, with related quantitative warnings (2)



- This example: Greenwald limit warning during I_p rampdown
  1. (GWL) Greenwald limit warning issued
  2. (VDE) VDE condition then found 7 ms after GWL warning
  3. (IPR) Plasma current request not met

J.W. Berkery, S.A. Sabbagh, Y.S. Park