Disruption Event Characterization of Global MHD Modes in NSTX and Plans for Instability Avoidance in NSTX-U

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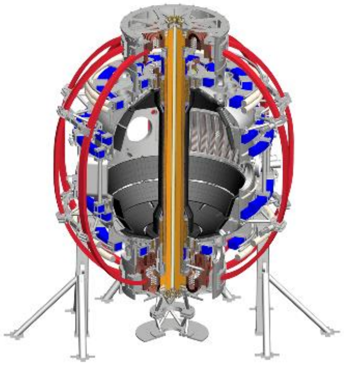
Theory/Simulation of Disruptions Workshop

July 20, 2016

PPPL

V1.4



OUTLINE

- Motivation and connection to DOE FES priorities
- Mission statement and scope
- Disruption Prediction: Characterization and forecasting approach, implementation, and development
- Disruption Avoidance: Mode stabilization and control plan summary, rotation controller and analysis

Disruption prediction and avoidance is a critical need for future tokamaks; NSTX-U is focusing research 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
  - Synergize and build upon disruption prediction and avoidance successes attained in present tokamaks (don't just repeat them!)
- FESAC 2014 Strategic Planning report defined "*Control of Deleterious Transient Events*" highest priority (Tier 1) initiative
- NSTX-U will produce focused research on disruption prediction and avoidance with quantitative measures of progress
  - Long-term goal: many sequential shots (~3 shot-mins) without disruption

DPAM Working Group - Mission Statement and Scope

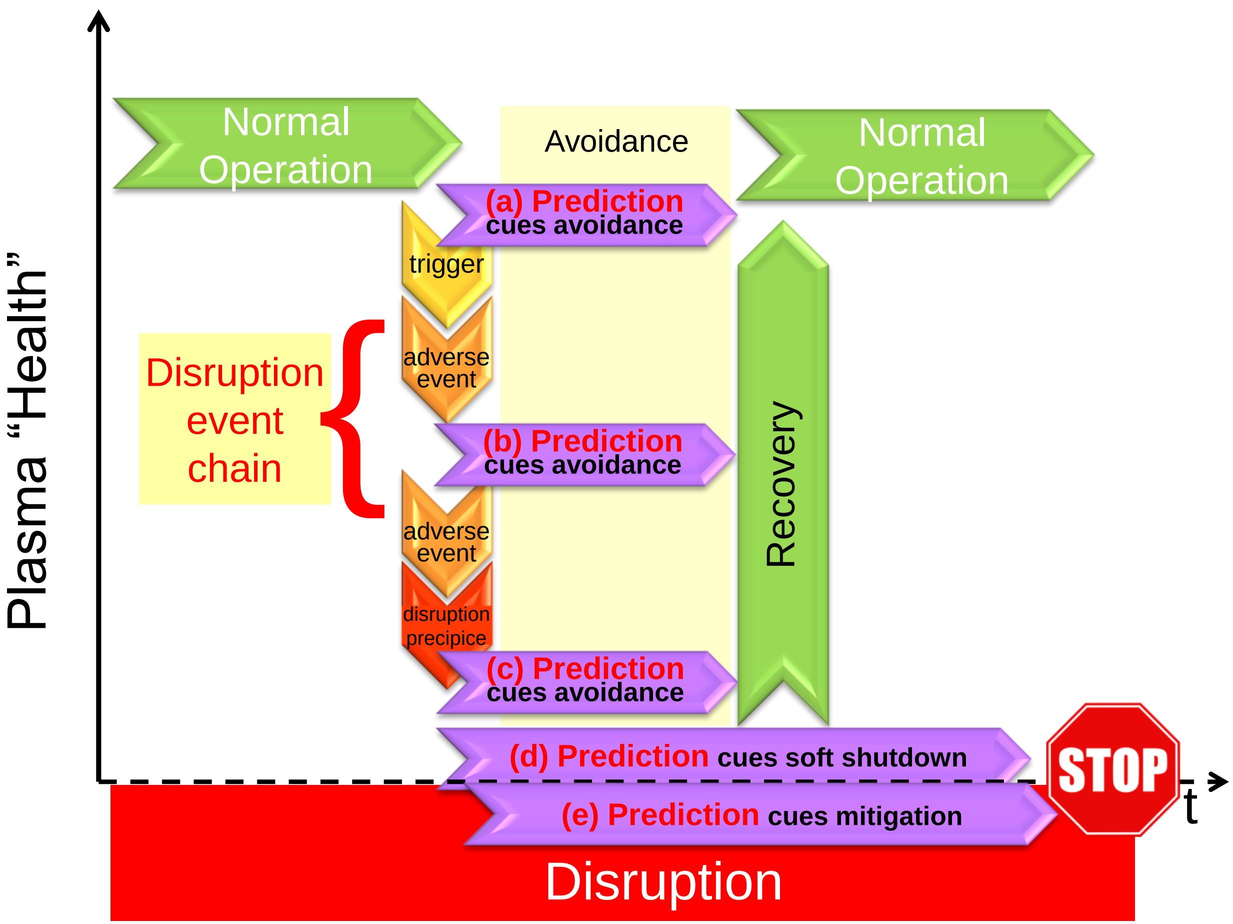
- Mission statement
  - Satisfy gaps in understanding prediction, avoidance, and mitigation of disruptions in tokamaks, applying this knowledge to move toward acceptable levels of disruption frequency/severity using quantified metrics

- Scope
  - Location: Initiate and base the study at NSTX-U, expand to a national program and international collaboration (multi-tokamak data)
  - Timescale: Multi-year effort, planning/executing experiments of various approaches (leveraging the 5 NSTX-U Year Plan) to reduce plasma disruptivity/severity at high performance
  - Breadth: High-level focus on quantified mission goal, with detailed physics areas expected to expand/evolve within the group, soliciting research input/efforts from new collaborations as needed

More than 50 members presently on email list

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

Disruption prediction/avoidance framework
(from DOE "Transient Events" report)



- Approach to disruption prevention
  - Identify disruption event chains and elements
  - Predict events in disruption chains
  - Cues disruption avoidance systems to break event chains
    - Attack events at several places with active control
  - Synergizes and builds upon both physics and control successes of NSTX

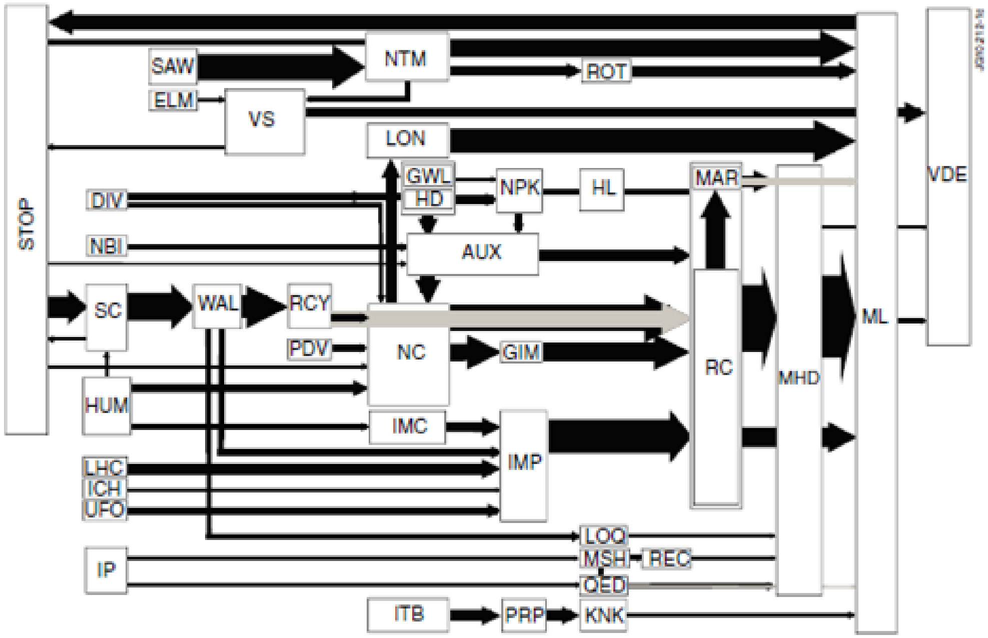
- New Disruption Event Characterization and Forecasting (DECAF) code created

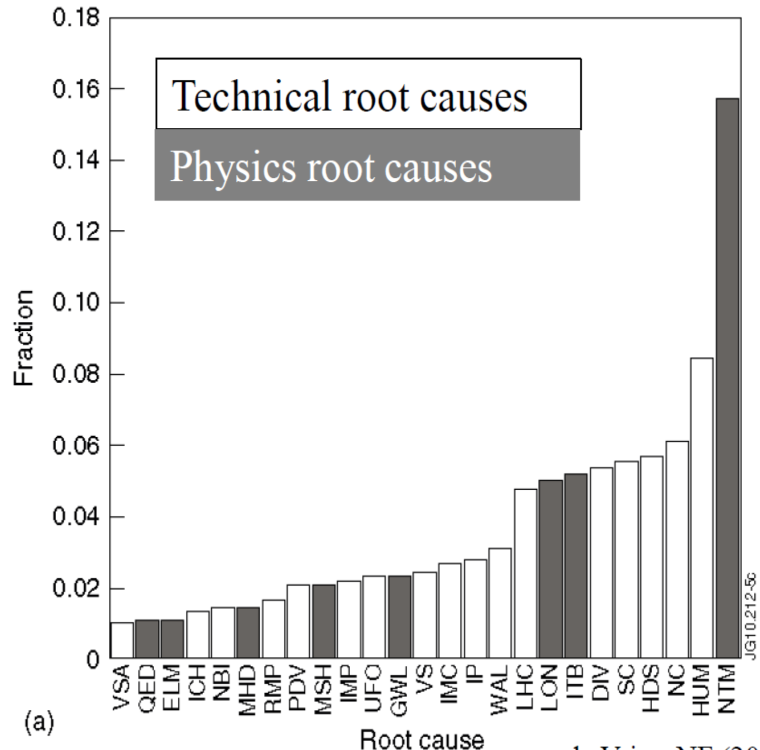
Disruption Prediction

JET disruption event characterization provides framework for understanding / quantifying disruption prediction

JET disruption event chains

Related disruption event statistics



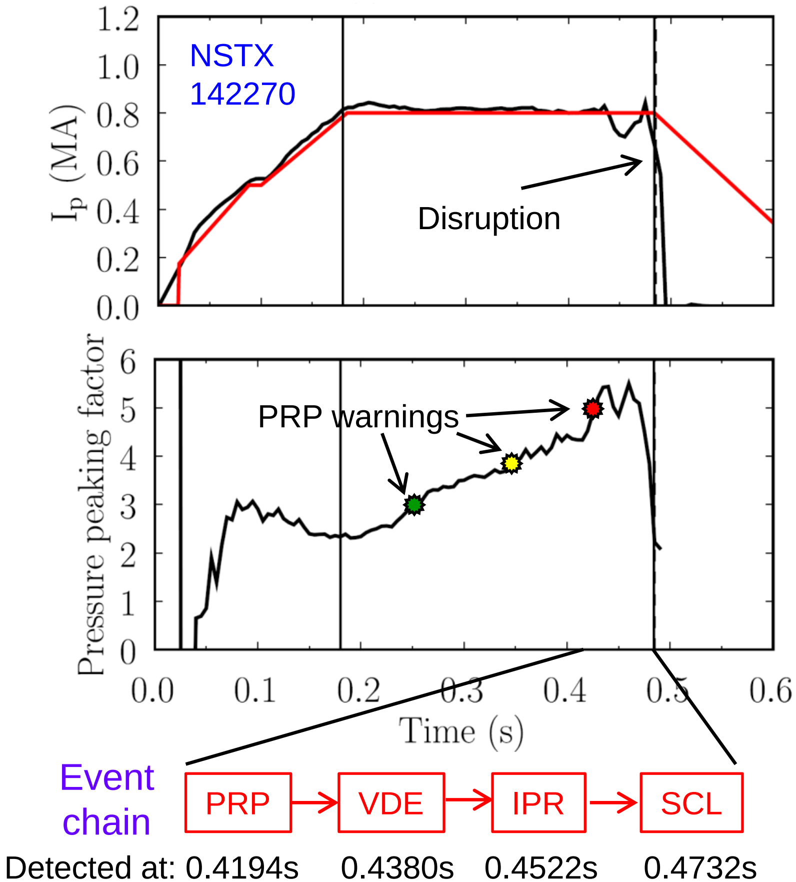


P.C. de Vries *et al*., Nucl. Fusion **51** (2011) 053018

de Vries, NF (2011)

- JET disruption event chain analysis performed by hand, desire to automate

Disruption Event Characterization And Forecasting Code (DECAF) yielding initial results (pressure peaking example)



- 10 physical events presently defined in code with quantitative warning points
  - Builds on manual analysis of de Vries

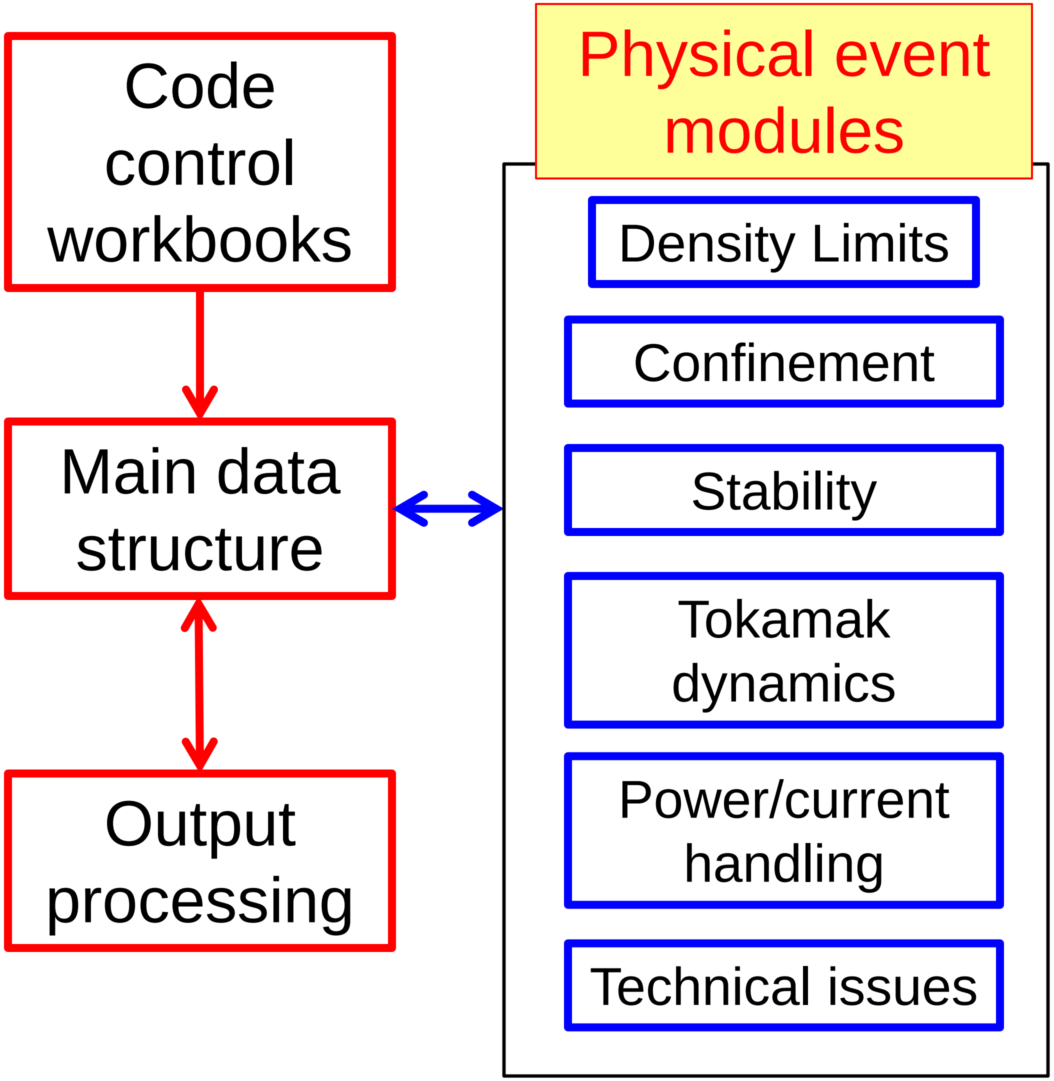
    P.C. de Vries *et al*., Nucl. Fusion **51** (2011) 053018
  - Builds on warning algorithm of Gerhardt

    S.P. Gerhardt *et al*., Nucl. Fusion **53** (2013) 063021
  - New code written (in Python), easily expandable, portable to other tokamaks (can now read DIII-D data)

- Example: Pressure peaking (PRP) disruption event chain identified by code before disruption
  1. (PRP) Pressure peaking warnings identified first
  2. (VDE) VDE condition subsequently found 19 ms after last PRP warning
  3. (IPR) Plasma current request not met
  4. (SCL) Shape control warning issued

J.W. Berkery, S.A. Sabbagh, Y.S. Park (Columbia U.)
and the NSTX-U Disruption PAM Working Group

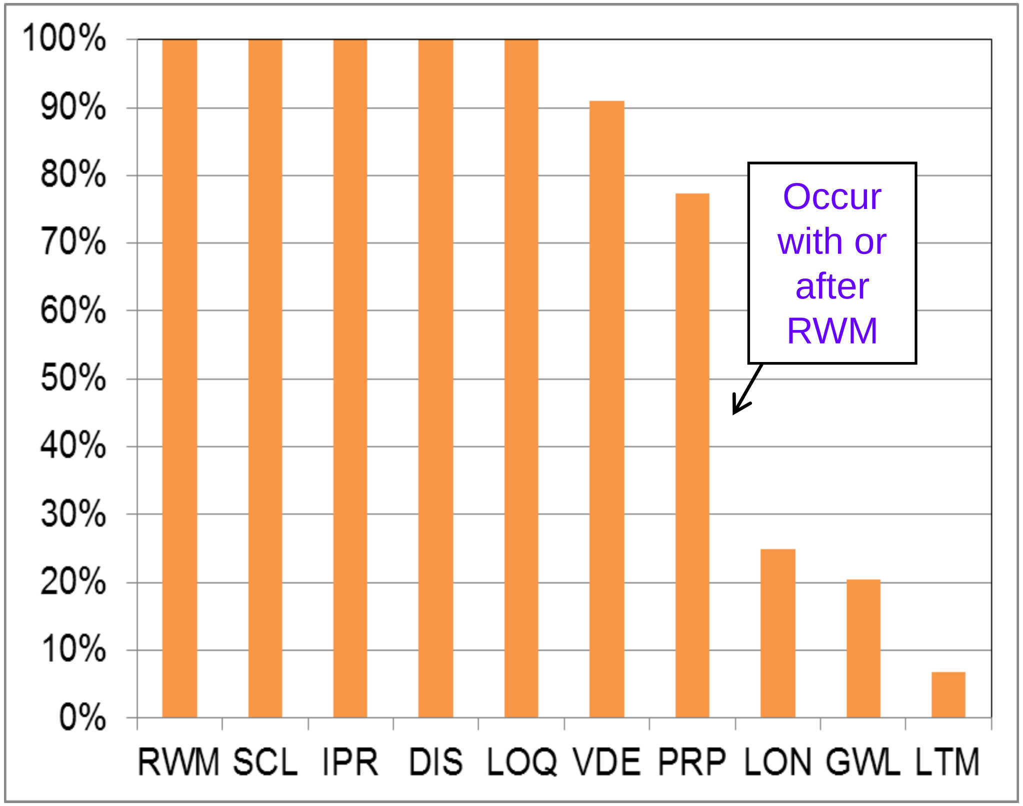
DECAF is structured to ease parallel development of disruption characterization, event criteria, and forecasting



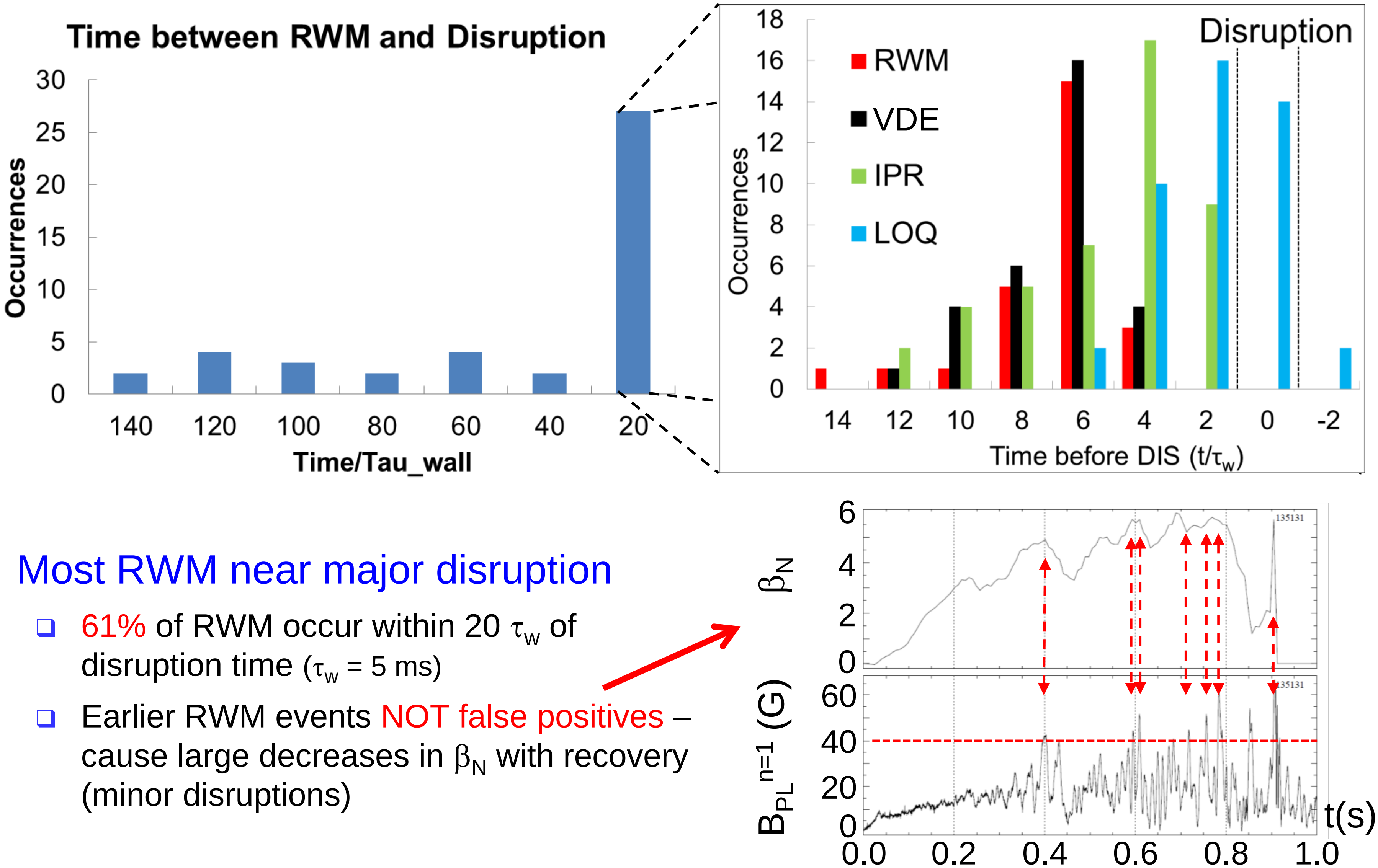
- Physical event modules encapsulate disruption chain events
  - Development focused on improving these modules
  - Structure eases development
    - E.g. separate code by C. Myers that improved disruption timing definition was quickly imported
- Physical events are objects in physics modules
  - e.g. VDE, LOQ, RWM are objects in "Stability"
  - Carry metadata, event forecasting criteria, event linkages, etc.

DECAF results detect disruption chain events when applied to dedicated 44 shot NSTX RWM disruption database

- Several events detected for all shots
  - RWM: RWM event warning
  - SCL: Loss of shape control
  - IPR: Plasma current request not met
  - DIS: Disruption occurred
  - LOQ: Low edge q warning
  - VDE: VDE warning (40 shots)
- Others:
  - PRP: Pressure peaking warning
  - GWL: Greenwald limit
  - LON: Low density warning
  - LTM: Locked tearing mode



DECAF results detect disruption chain events when applied to dedicated 44 shot NSTX RWM disruption database



- Most RWM near major disruption
  - 61% of RWM occur within 20 τ_w of disruption time (τ_w = 5 ms)
  - Earlier RWM events NOT false positives – cause large decreases in β_N with recovery (minor disruptions)

DECAF analysis already finding common disruption event chains (44 shot NSTX disruption database)

- Common disruption event chains (52.3%)

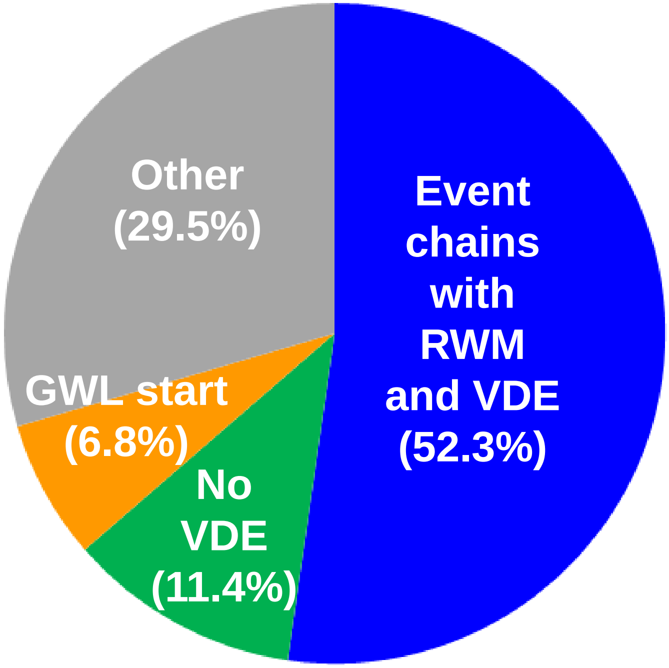
  RWM → VDE → SCL → IPR → DIS

  - Related chains
    - RWM ➔ SCL ➔ VDE ➔ IPR ➔ DIS
    - VDE ➔ RWM ➔ SCL ➔ IPR ➔ DIS
    - VDE ➔ RWM ➔ IPR ➔ DIS ➔ SCL
    - RWM ➔ SCL ➔ VDE ➔ GWL ➔ IPR ➔ DIS

- Disruption event chains w/o VDE (11.4%)

- New insights being gained
  - Chains starting with GWL are found that show rotation and β_N rollover before RWM (6.8%)
  - Related chains
    - GWL ➔ VDE ➔ RWM ➔ SCL ➔ IPR ➔ DIS
    - GWL ➔ SCL ➔ RWM ➔ IPR ➔ DIS

Disruption event chains with RWM

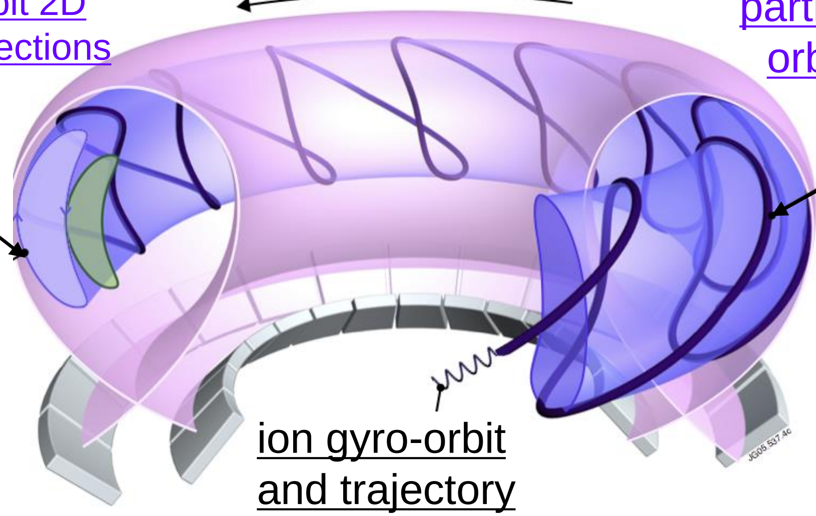


Global mode stability forecasting: build from success of drift kinetic theory modification to MHD as a model

- Kinetic modification to ideal MHD

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

- Stability depends on
  - Trapped / circulating ions, trapped electrons
  - Particle collisionality
  - Energetic particle (EP) population
  - Integrated ω_ϕ profile matters!!! : broad rotation resonances in δW_K



(Fig. adapted from R. Pitts et al., Physics World (Mar 2006))

(Hu, Betti, et al., PoP **12** (2005) 057301)

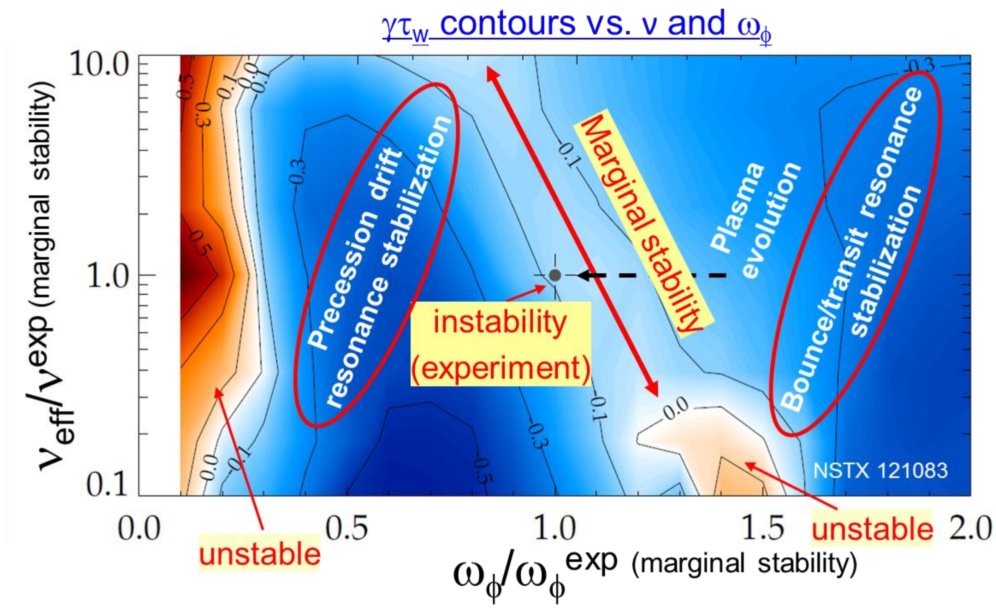
plasma integral over particle energy

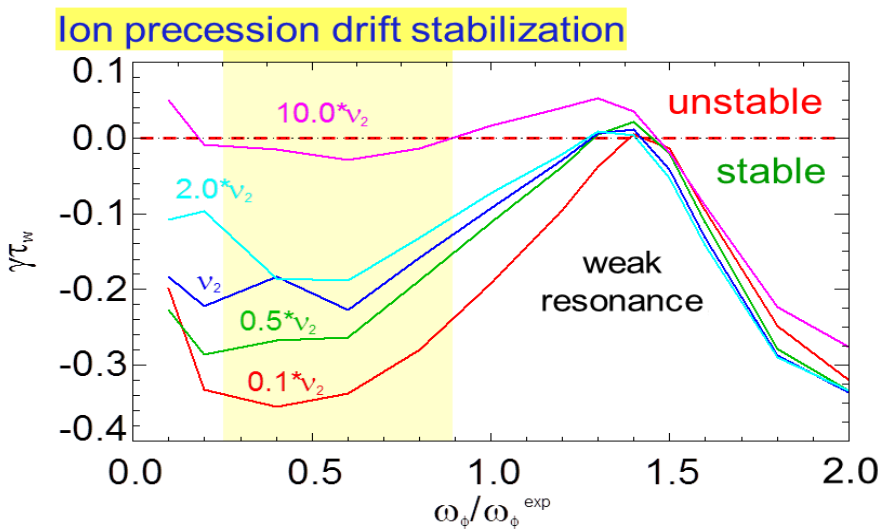
$$\delta W_K \propto \int \left[\frac{\omega_{*N} + \left(\hat{\varepsilon} - \frac{3}{2}\right)\omega_{*T} + \omega_E - \omega - i\gamma}{\langle \omega_D \rangle + l\omega_b - i\nu_{eff} + \omega_E - \omega - i\gamma} \right] \hat{\varepsilon}^{\frac{5}{2}} e^{-\hat{\varepsilon}} d\hat{\varepsilon}$$

← EP integral component is dominated by precession drift term

precession drift — bounce — collisionality — ω_ϕ profile (enters through ExB frequency)

Initial reduced kinetic RWM stability model for disruption prediction based on full MISK code calculations for NSTX





- Key stabilization physics
  - Precession drift resonance stabilization at lower rotation
  - Bounce/transit resonance stabilization at higher rotation
  - Collisionality
    - Earlier theory: collisions provided (sole) stabilization – unfavorable for future devices
    - Modern theory: Collisions spoil stabilizing resonances, Mode stabilization vs. ν depends on ω_ϕ
      - At strong resonance: mode stability **increases** with decreasing ν

Just some references:

J. Berkery *et al.*, PRL **104** (2010) 035003

S. Sabbagh, et al., NF **50** (2010) 025020

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

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

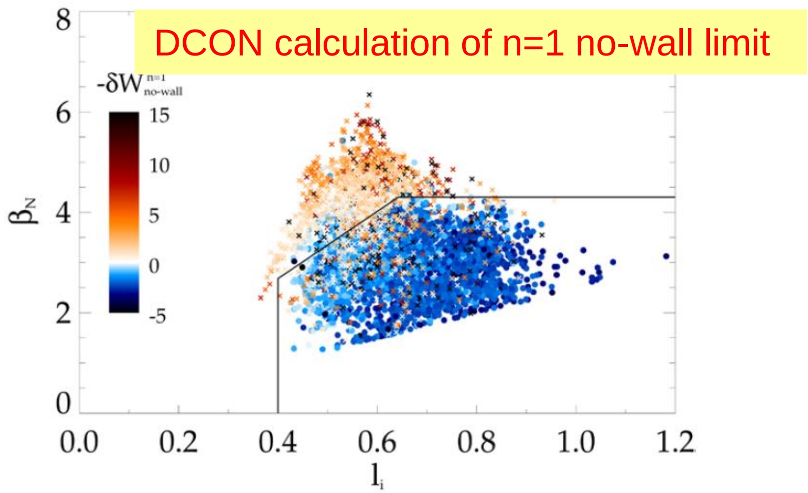
J. Berkery *et al.*, PoP **21** (2014) 056112

J. Berkery *et al.*, NF **55** (2015) 123007

Elements of the reduced kinetic RWM model in DECAF

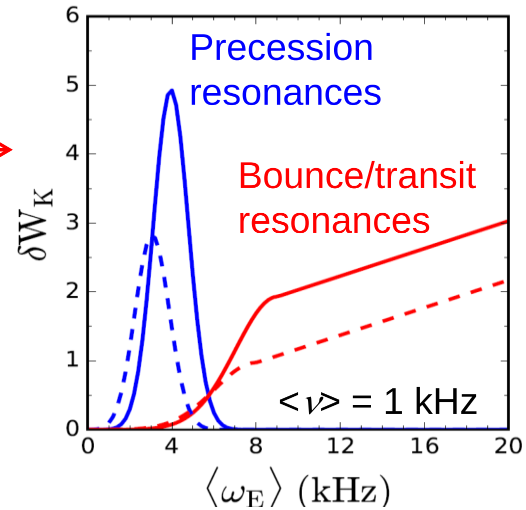
Mode growth rate calculation

- Ideal component δW
  - Equilibrium quantities including l_i, p_0/<p>, A, used in beta limit models for δW_b, δW_{inf}



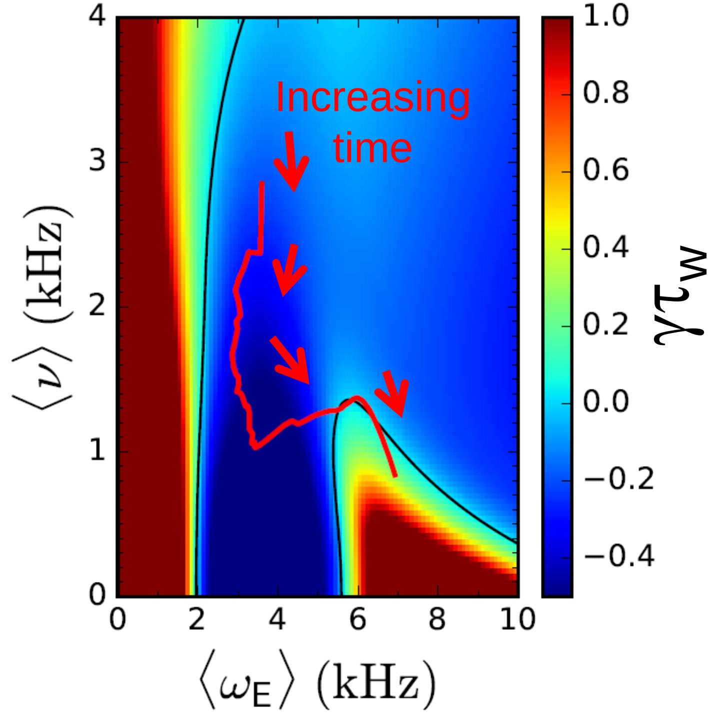
J.W. Berkery, S.A. Sabbagh, R.E. Bell, *et al.*, NF **55** (2015) 123007

- Kinetic component δW_k
  - Functional forms (mainly Gaussian) used to reproduce precession and bounce/transit resonances
  - Height, width, position of peak depend on collisionality

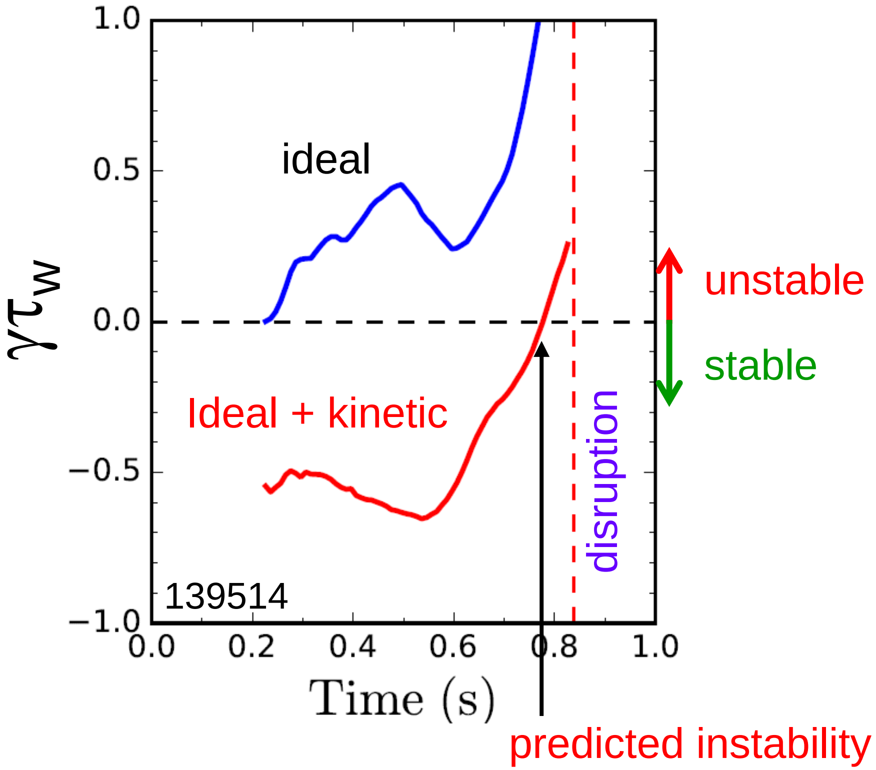


Reduced kinetic RWM model in DECAF results in a calculation of $\gamma\tau_w$ vs. time for each discharge

$\gamma\tau_w$ contours vs. ν and ω_ϕ



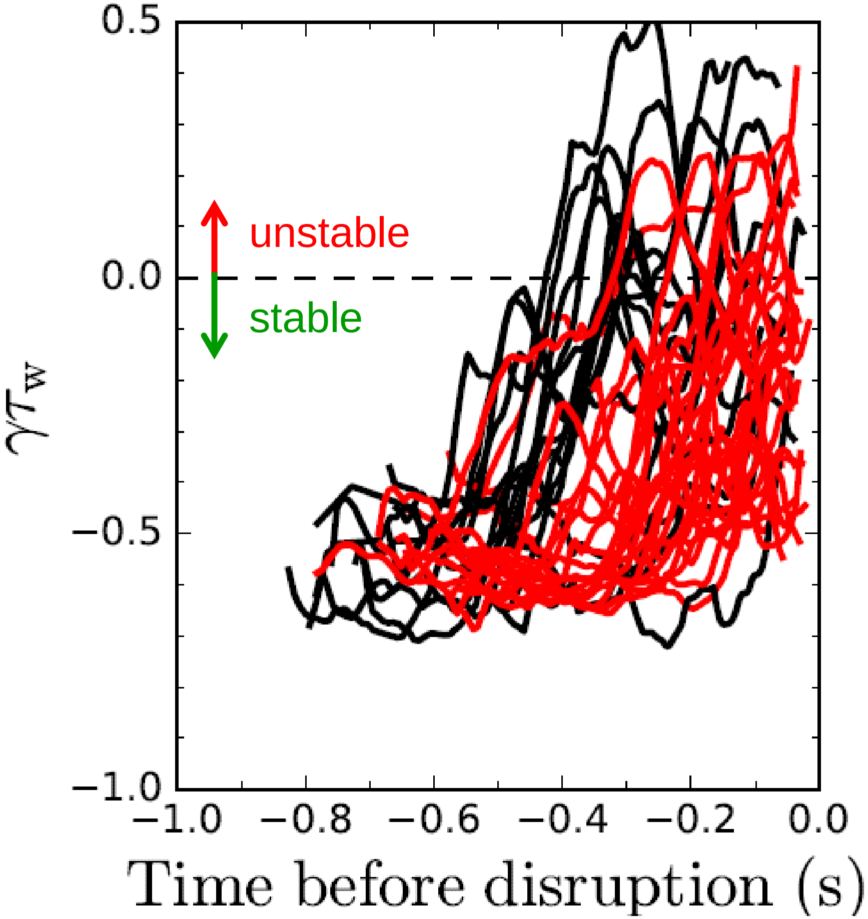
Normalized growth rate vs. time



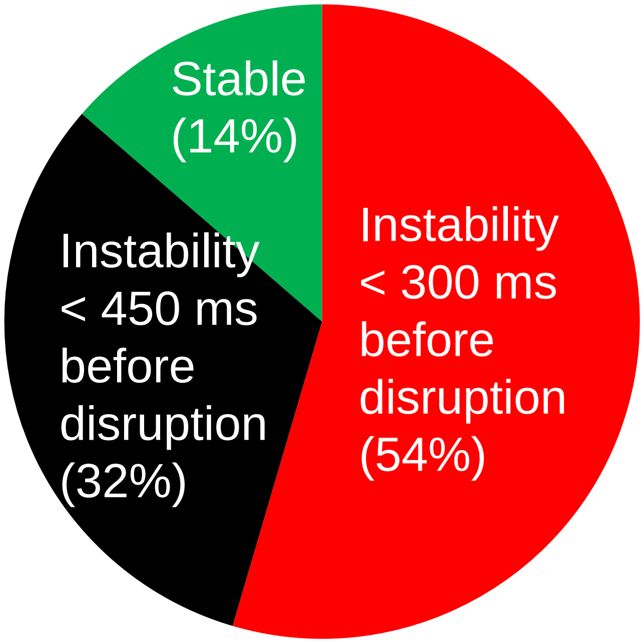
- Favorable characteristics
  - Stability contours CHANGE for each time point (last time point shown left frame)
  - Possible to compute growth rate prediction in real time

DECAF reduced kinetic model results initially tested on a database of NSTX discharges with unstable RWMs

Normalized growth rate vs. time



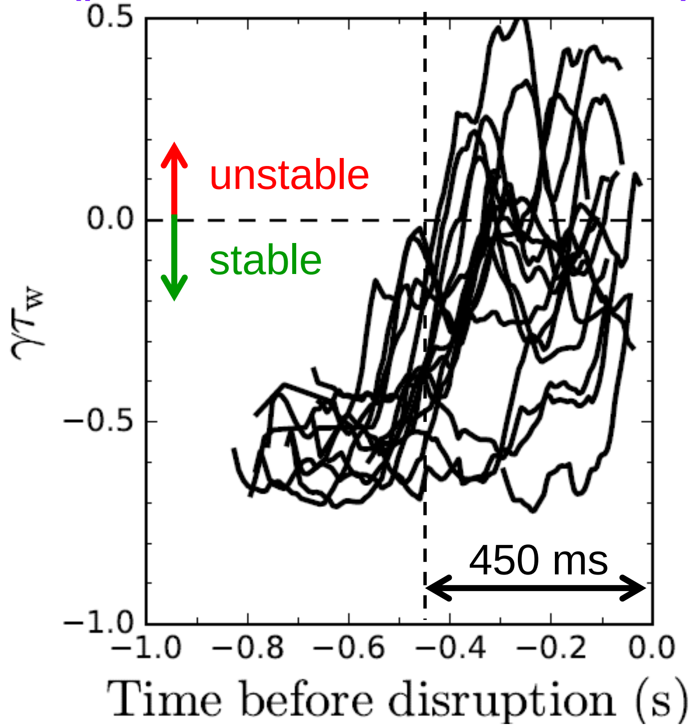
Predicted instability statistics (44 shots)



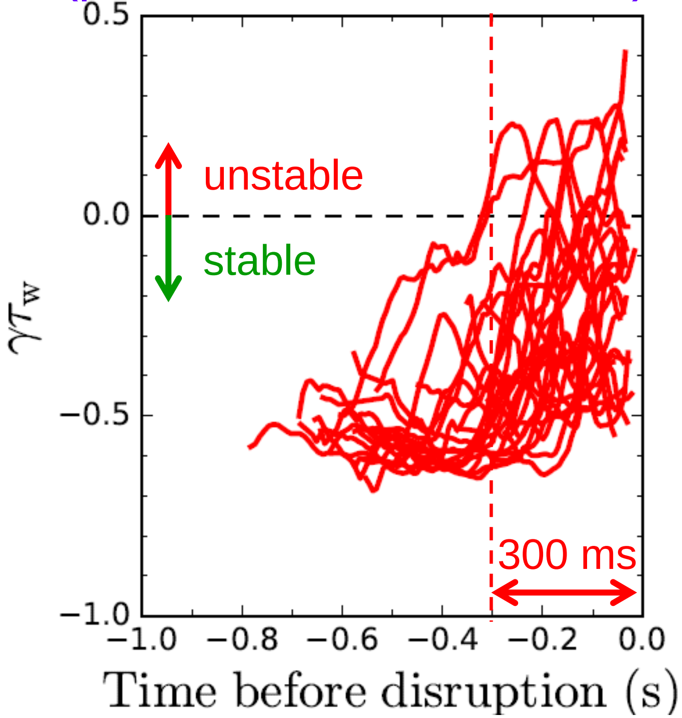
- 86% of shots are predicted unstable
- 54% predicted unstable < 300 ms (approx. $60\tau_w$) before current quench
- 32% predicted unstable < 450 ms before current quench
  - Mostly earlier cases are minor disruptions

DECAF reduced kinetic RWM initial model shows promise for greater accuracy with further analysis

Normalized growth rate vs. time (predicted unstable earlier)



Normalized growth rate vs. time (predicted unstable later)

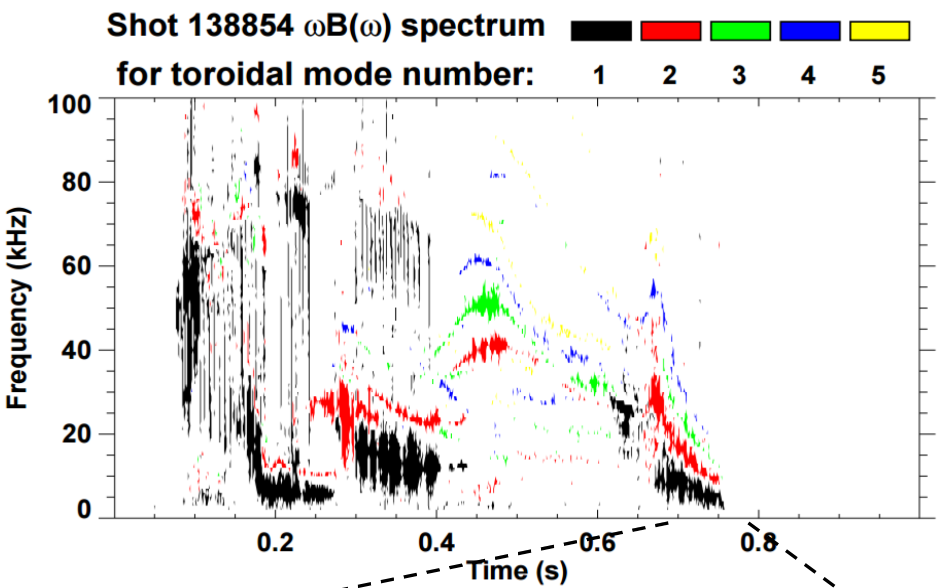


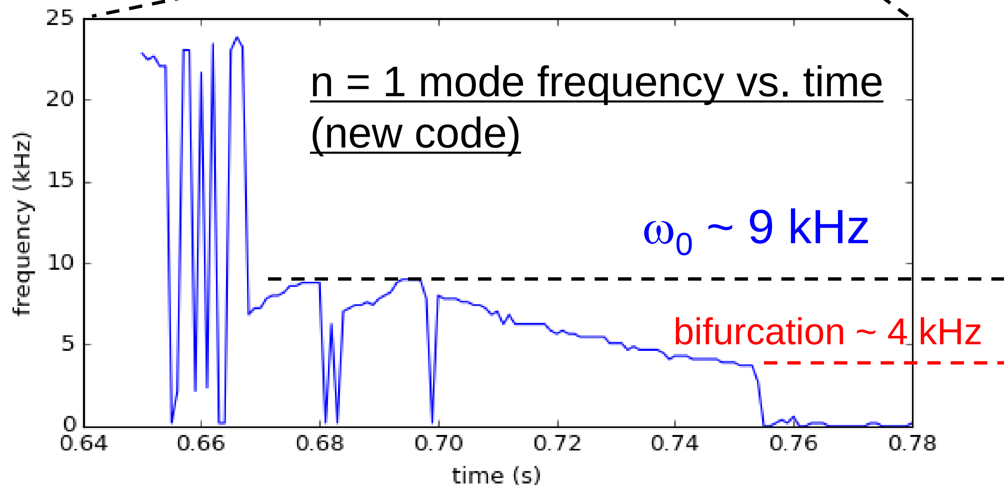
- Near-term analysis
  - Clarify proximity of predicted instability to full current quench vs. thermal quenches
  - Optimize parameters of reduced kinetic RWM model to best predict instability
  - Using the above, determine proper $-\gamma\tau_w$ WARNING LEVEL for instability

Essential step for DECAF analysis of general tokamak data: Identification of rotating MHD (e.g. NTMs)

- Initial goals
  - Create portable code to identify existence of rotating MHD modes
  - Track characteristics that lead to disruption
    - e.g. rotation bifurcation, mode lock
- Approach
  - Apply FFT analysis to determine mode frequency, bandwidth evolution
  - Determine bifurcation and mode locking

Magnetic spectrogram of rotating MHD in NSTX

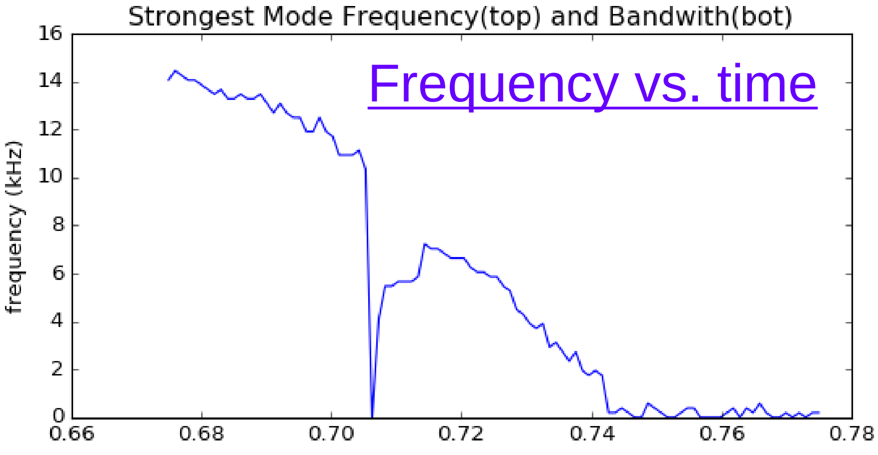




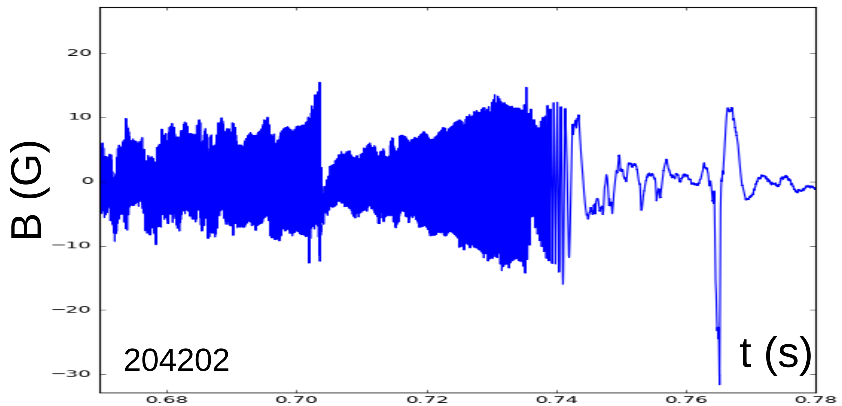
J. Riquezes (U. Michigan – SULI student)

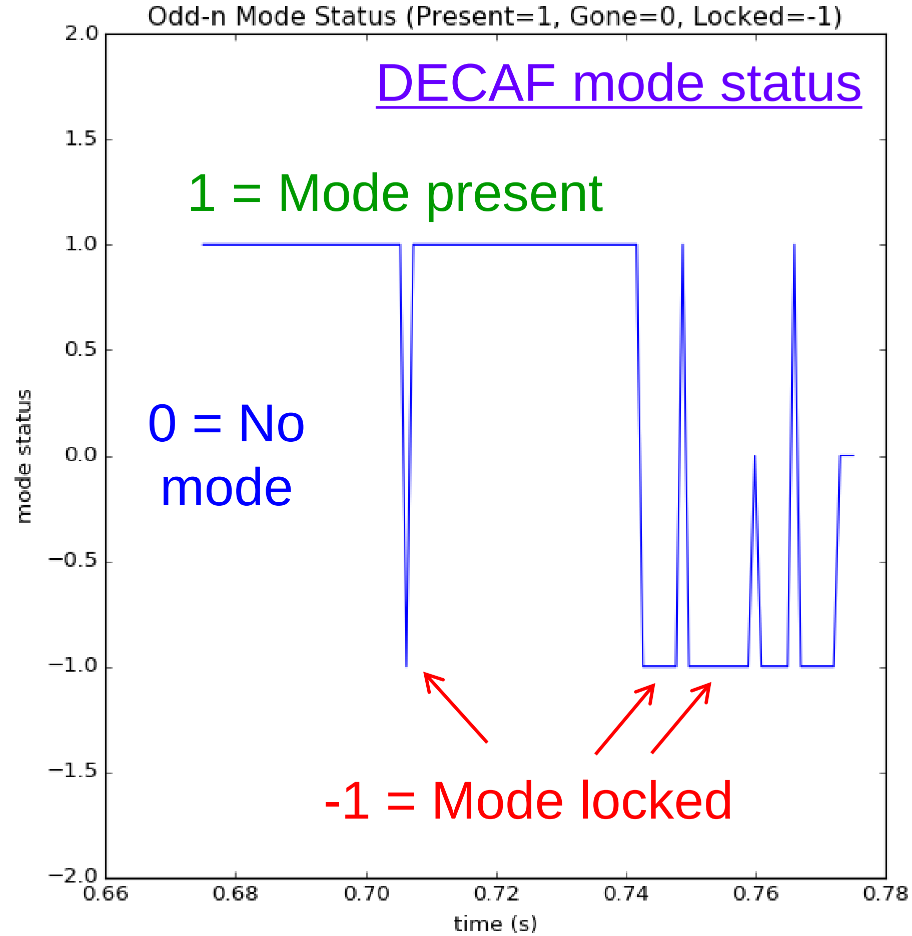
Continued analysis of rotating MHD for DECAF includes more complex cases examined in NSTX-U (I)

Odd-n magnetic signal / analysis (mode locking / unlocking)



Signal

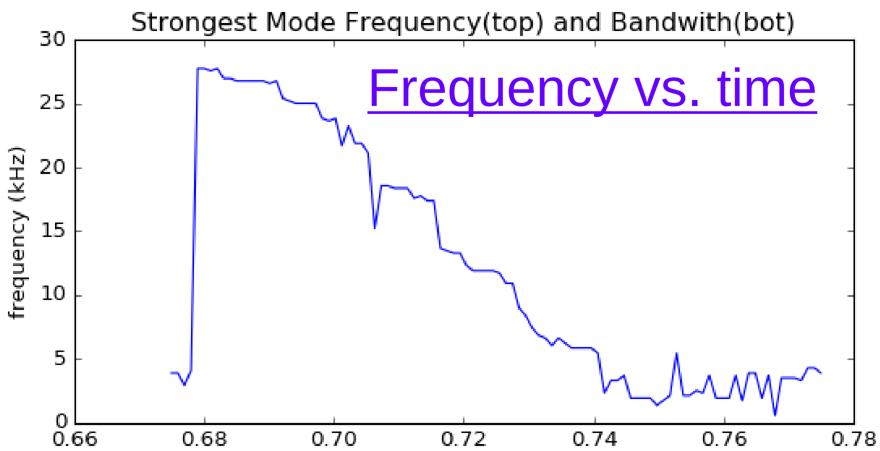




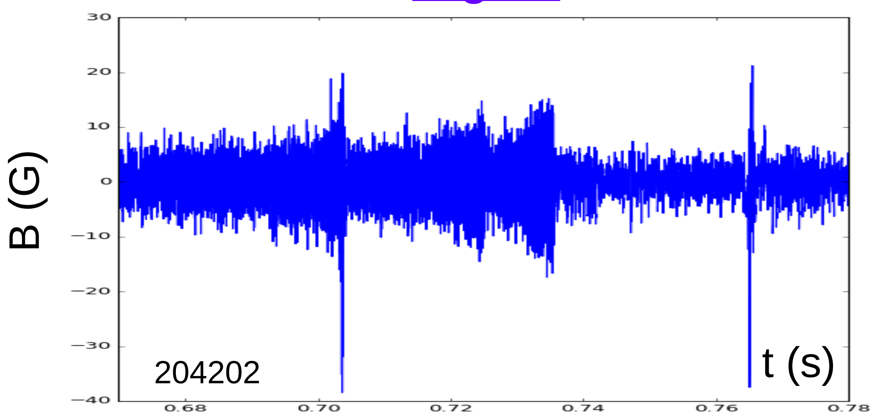
J. Riquezes (U. Michigan – SULI student)

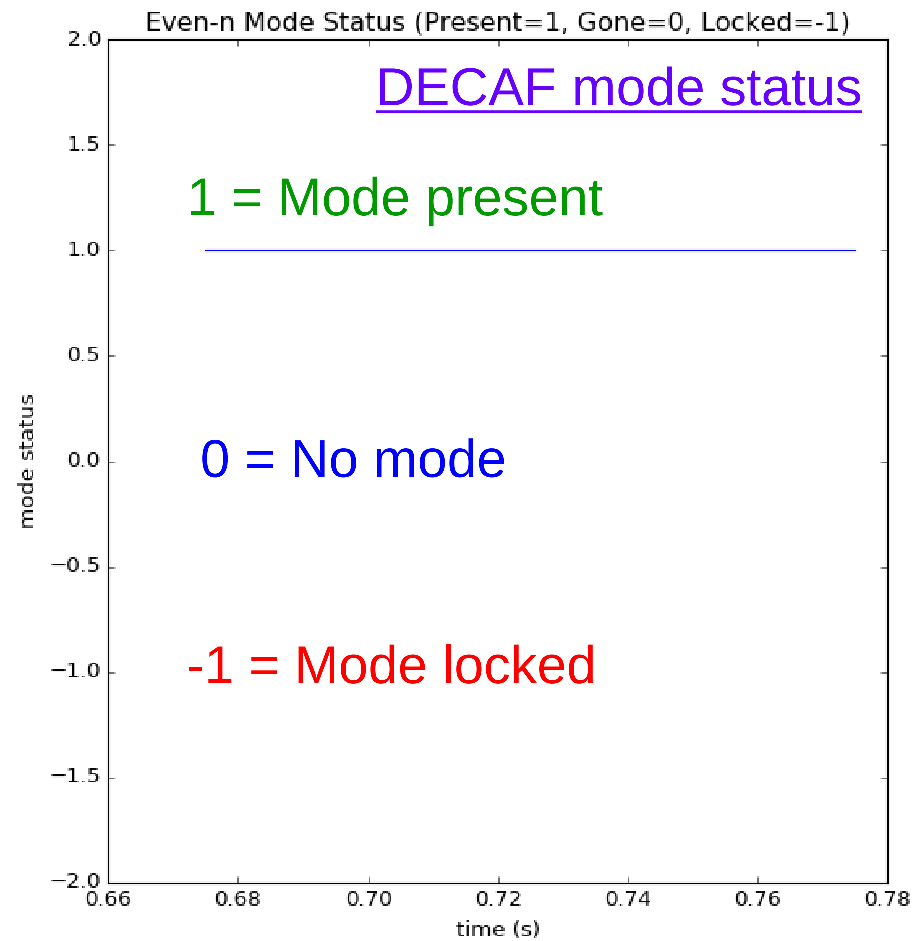
Continued analysis of rotating MHD for DECAF includes more complex cases examined in NSTX-U (II)

Even-n magnetic signal / analysis (mode present, not locked)



Signal





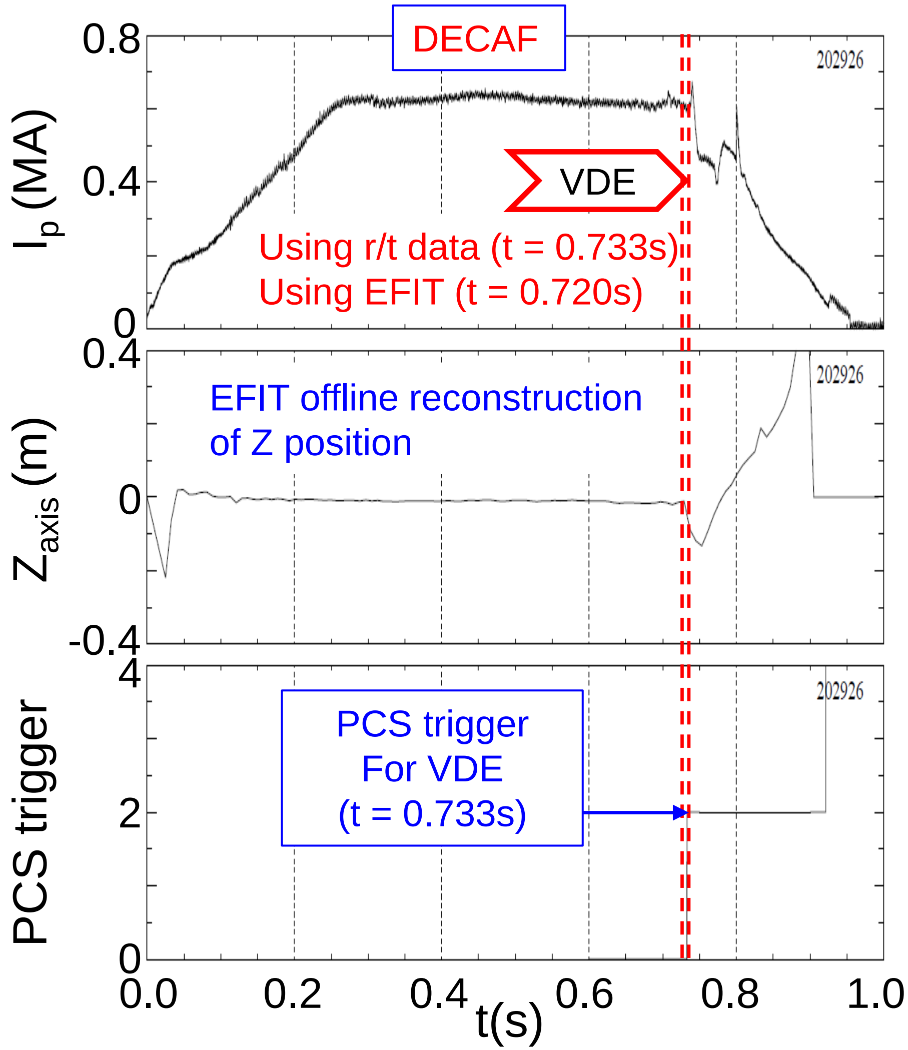
J. Riquezes (U. Michigan – SULI student)

First DECAF results for NSTX-U replicate the triggers found in new real-time state machine shutdown capability

- Important capability of DECAF to compare analysis using offline vs. real-time data
  - Simple, initial test

- PCS Shut-down conditions are analogous to DECAF events
  - PCS loss of vertical control
    ➔ DECAF VDE

- DECAF comparison:VDE event
  - Matches PCS when r/t signal used (1 criterion)
  - VDE event 13 ms earlier using offline EFIT signals (3 criteria)



- S.P. Gerhardt, et al. , NSTX-U shutdown handler

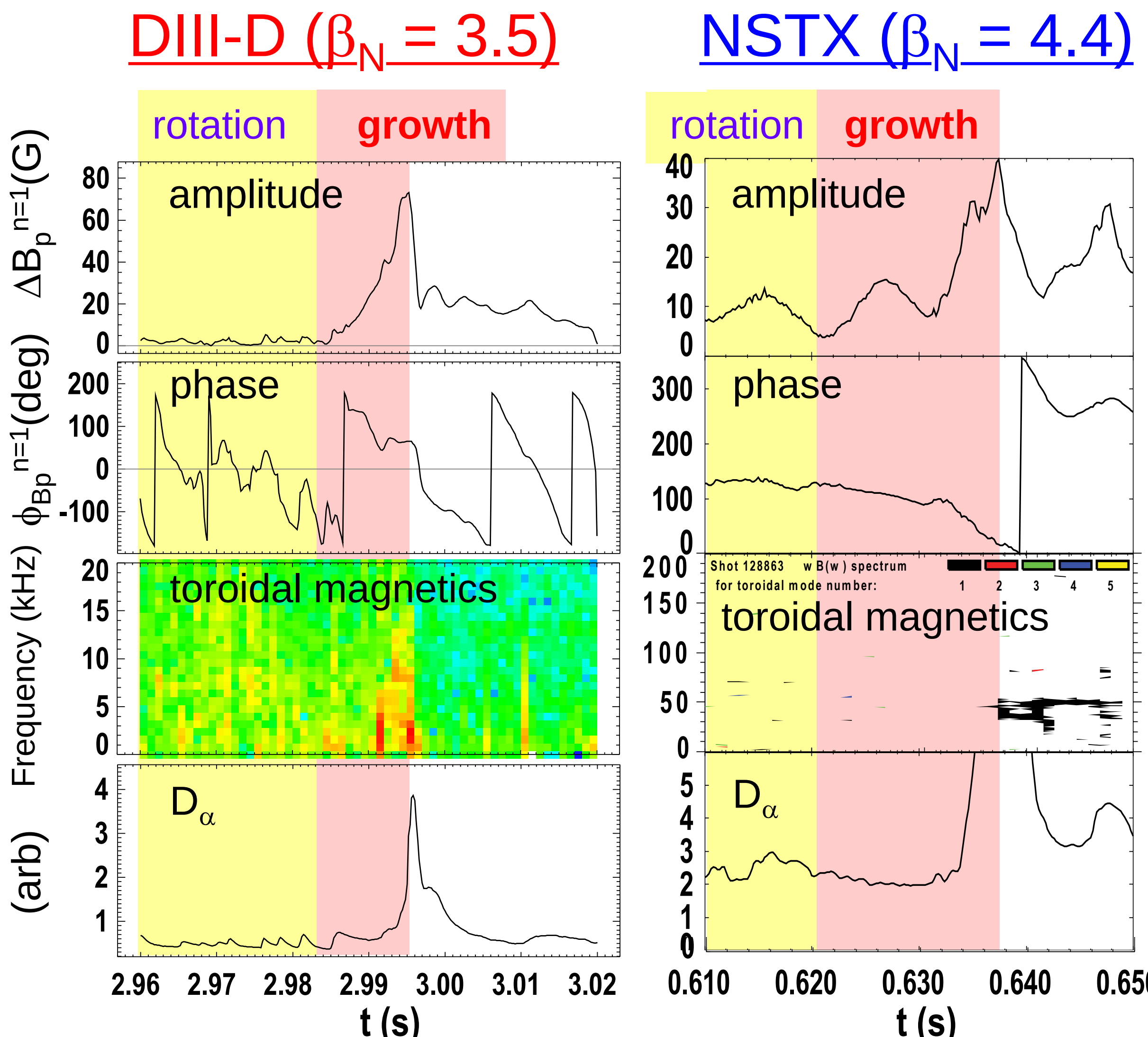
Disruption Avoidance

NSTX-U is building on past strength, creating an arsenal of capabilities for disruption avoidance

Predictor/Sensor (CY available)	Control/Actuator (CY available)	Modes	REFER TO
Rotating and low freq. MHD (n=1,2,3) 2003	Dual-component RWM sensor control (closed loop 2008)	NTM RWM	- Menard NF 2001 - Sabbagh NF 2013
Low freq. MHD spectroscopy (open loop 2005); Kinetic RWM modeling (2008)	Control of β_N (closed loop 2007)	Kink/ball RWM	- Sontag NF 2007 - Berkery (2009–15) - Gerhardt FST 2012
r/t RWM state-space controller observer (2010)	Physics model-based RWM state-space control (2010)	NTM, RWM Kink/ball, VDE	- Sabbagh NF 2013; + backup slides
Real-time V_ϕ measurement (2016)	Plasma V_ϕ control (NTV 2004) (NTV + NBI rotation control closed loop ~ 2017)	NTM Kink/ball RWM	- Podesta RSI 2012 - Zhu PRL 06 +backup - THIS TALK
Kinetic RWM stabilization real-time model (2016-17)	Safety factor, l_i control (closed loop ~ 2016-17)	NTM, RWM Kink/ball, VDE	- Berkery, NF 2015 (+ this talk) - D. Boyer, 2015
MHD spectroscopy (real-time) (in 5 Year Plan)	Upgraded 3D coils (NCC): improved V_ϕ and mode control (in 5 Year Plan)	NTM, RWM Kink/ball, VDE	- NSTX-U 5 Year Plan + this talk + backup slides

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

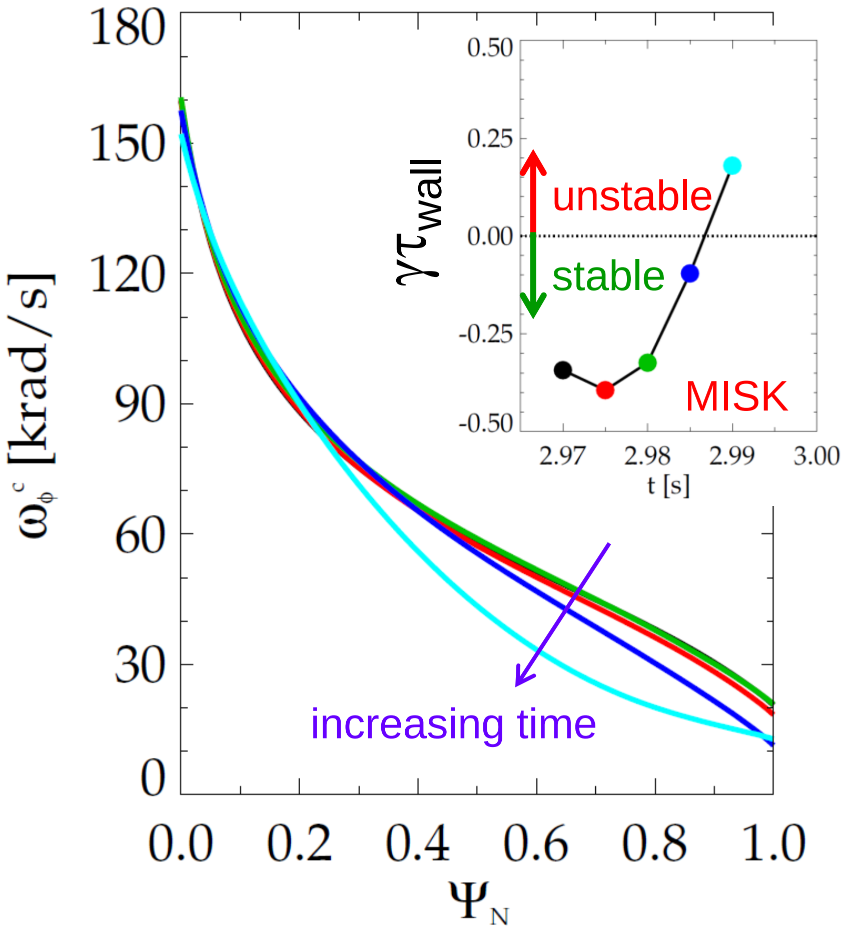
- RWM Dynamics
  - RWM rotation and mode growth observed
  - No strong NTM activity
  - Some weak bursting MHD in DIII-D plasma
    - Alters RWM phase
  - No bursting MHD in NSTX plasma



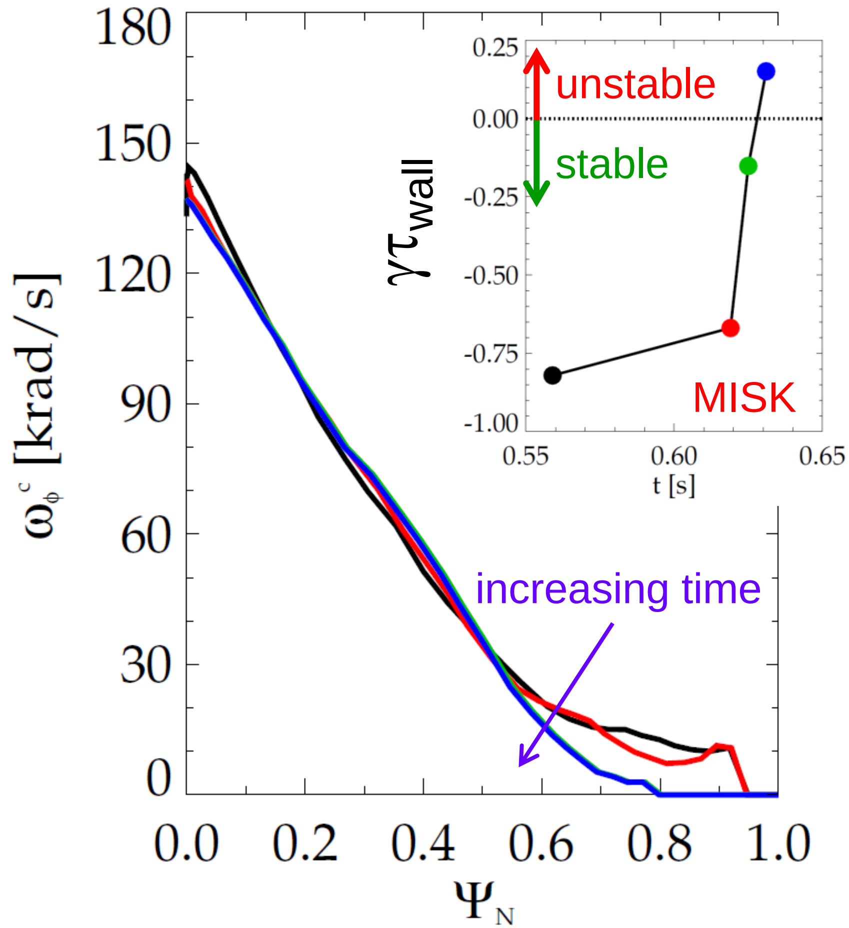
S. Sabbagh et al., APS Invited talk 2014

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

DIII-D (minor disruption)



NSTX (major disruption)

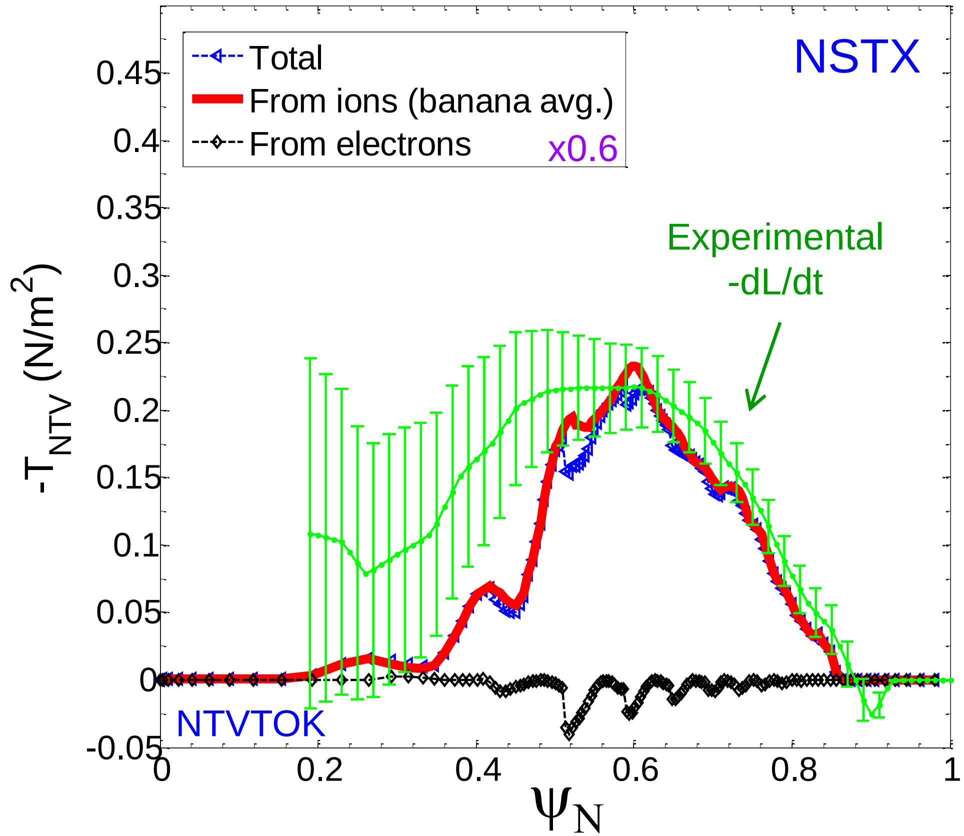


- Kinetic RWM stabilization occurs from broad resonances between plasma rotation and particle precession drift, bounce/circulating, and collision frequencies

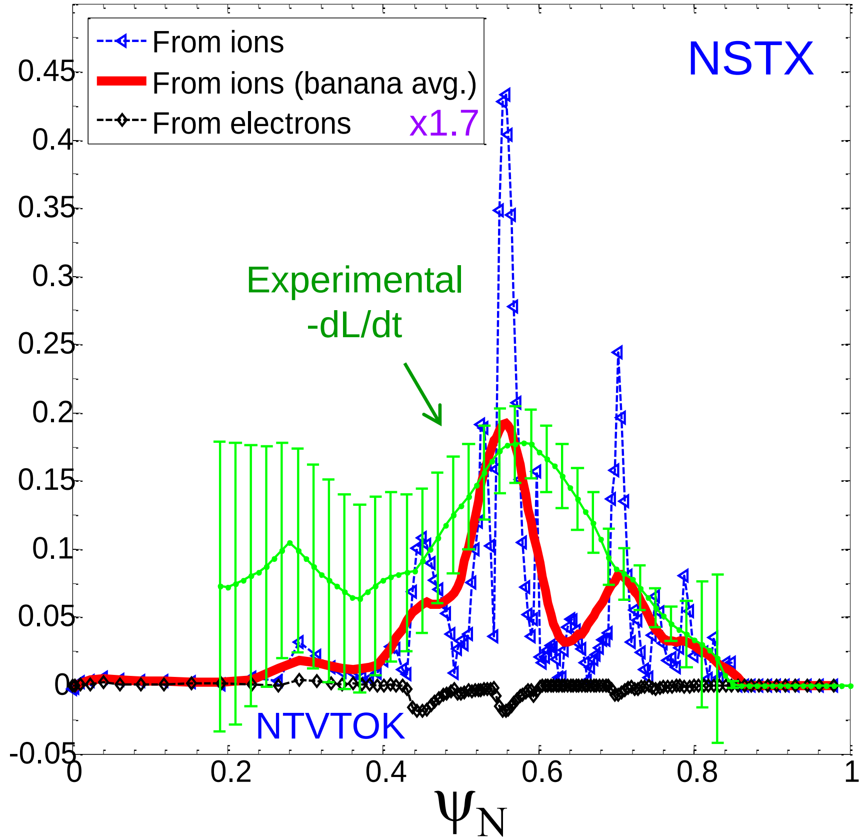
S. Sabbagh et al., APS Invited talk 2014

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

<u>n = 3 coil configuration</u>



<u>n = 2 coil configuration</u>



- 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
- KSTAR n = 2 NTV experiments <u>do not</u> exhibit hysteresis

See recent NTV review paper: K.C. Shaing, K. Ida, S.A. Sabbagh, et al., Nucl. Fusion **55** (2015) 125001

State space rotation controller designed for NSTX-U using non-resonant NTV and NBI to maintain stable profiles

- Momentum force balance – ω_ϕ decomposed into Bessel function states

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

- NTV torque:

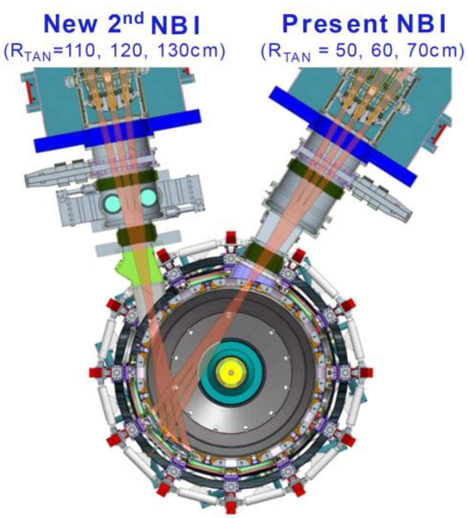
$$T_{NTV} \propto K \times f\left(n_{e,i}{}^{K1} T_{e,i}{}^{K2}\right) g\left(\delta B(\rho)\right)\left[I_{coil}{}^{2}\omega\right]$$

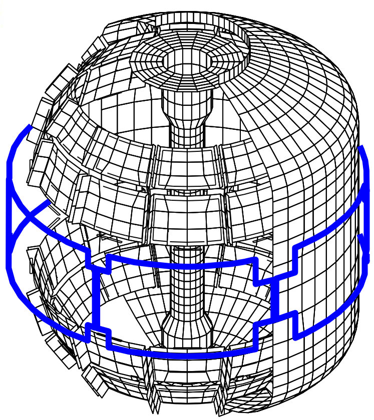
I. Goumiri, C. Rowley, S. Sabbagh, et al. NF **56** (2016) 036023)

Momentum Actuators

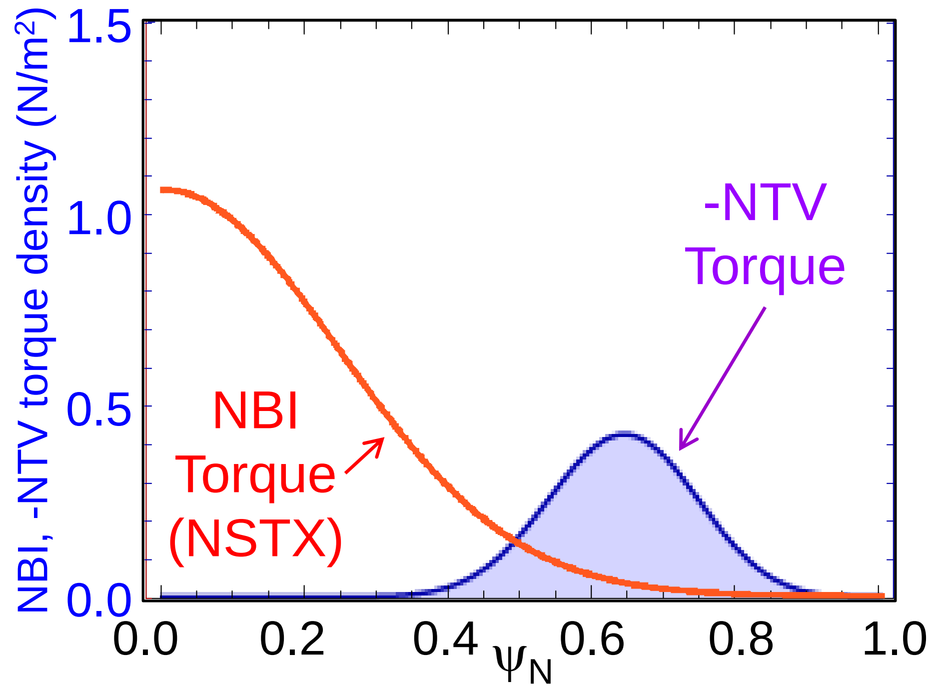
New NBI (broaden rotation)

3D Field Coil (shape ω_ϕ profile)





NBI and NTV torque profiles for NSTX-U



State space rotation controller designed for NSTX-U using non-resonant NTV and NBI to maintain stable profiles

- 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:

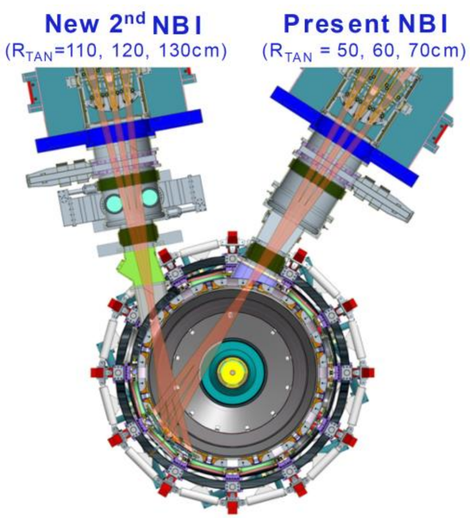
$$T_{NTV} \propto K \times f\left(n_{e,i}{}^{K1} T_{e,i}{}^{K2}\right) g\left(\delta B(\rho)\right)\left[I_{coil}{}^{2}\omega\right]$$

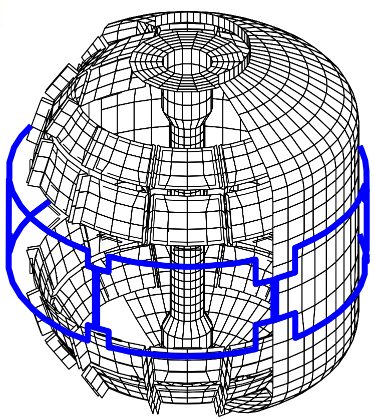
I. Goumiri, C. Rowley, S. Sabbagh, et al. NF **56** (2016) 036023)

Momentum Actuators

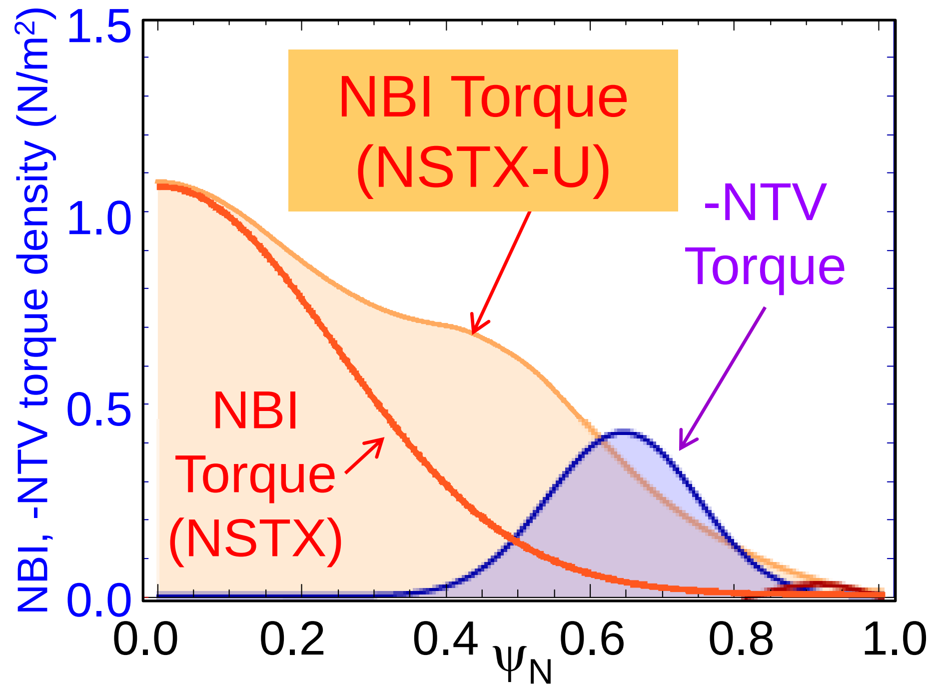
New NBI
(broaden rotation)

3D Field Coil
(shape ω_ϕ profile)



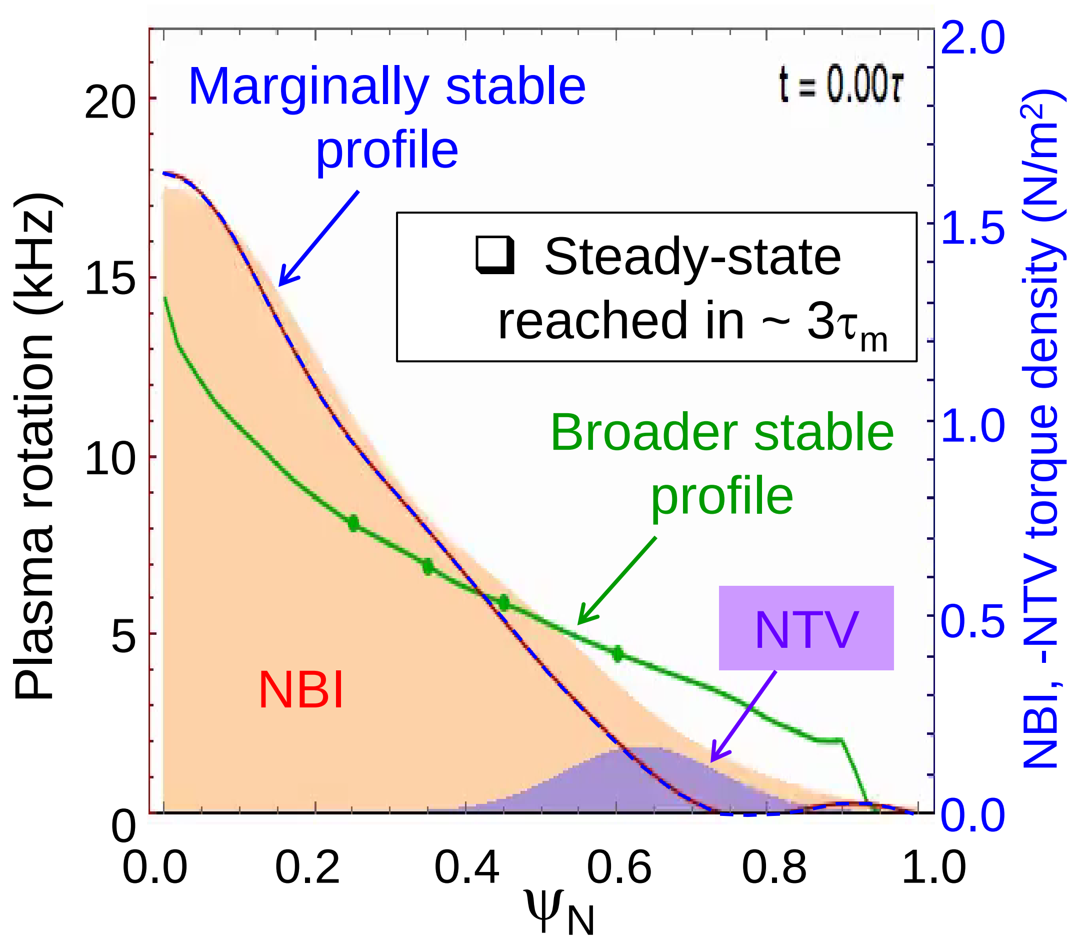


NBI and NTV torque profiles for NSTX-U

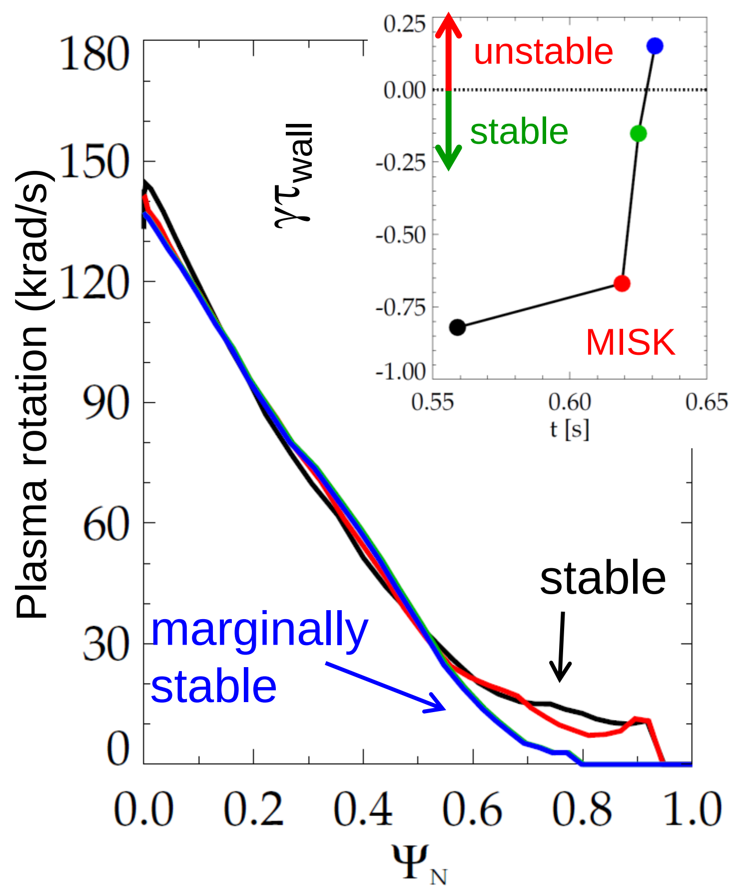


State space rotation controller designed for NSTX-U can evolve plasma rotation profile toward global mode stability

NSTX-U (6 NBI sources and n = 3 NTV)

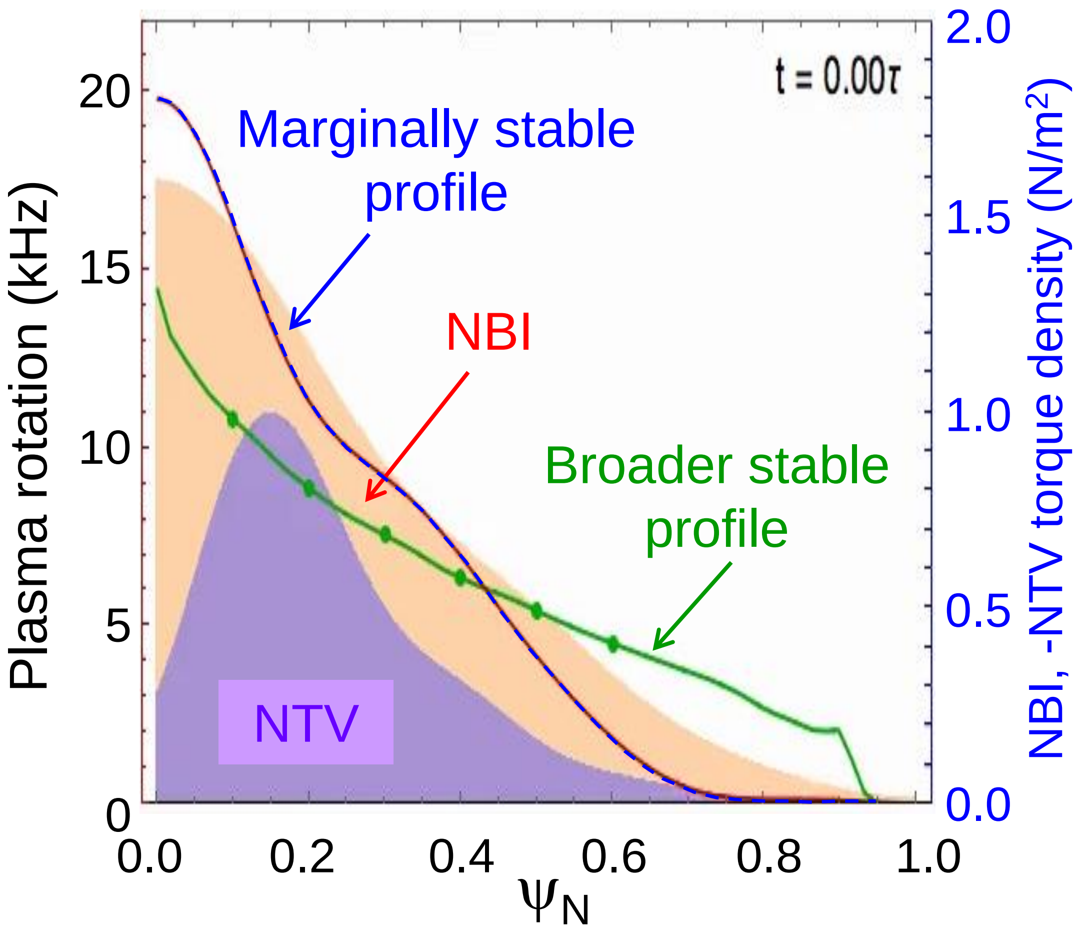


Recall:
NSTX (major disruption)



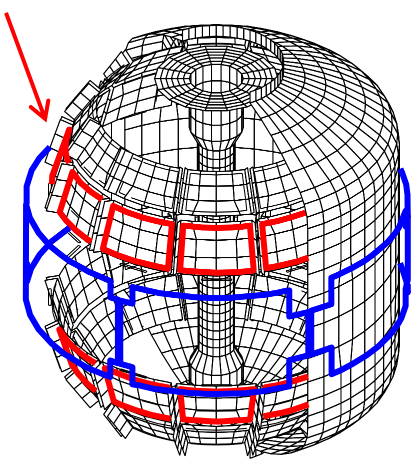
I. Goumiri (Princeton student), S.A. Sabbagh (Columbia U.), C. Rowley (P.U.), D.A. Gates, S.P. Gerhardt (PPPL)

With planned NCC coil upgrade, rotation controller can reach desired rotation profile faster, with greater fidelity



- NSTX-U ω_ϕ control with
  - 6 NBI sources
  - Greater core NTV from planned NCC upgrade
- Better performance
  - Faster to target t ~ $0.5\tau_m$
  - Matches target ω_ϕ better

Planned NCC upgrade



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

Global MHD mode stabilization understanding, forecasting, control will synergize in NSTX-U for disruption avoidance

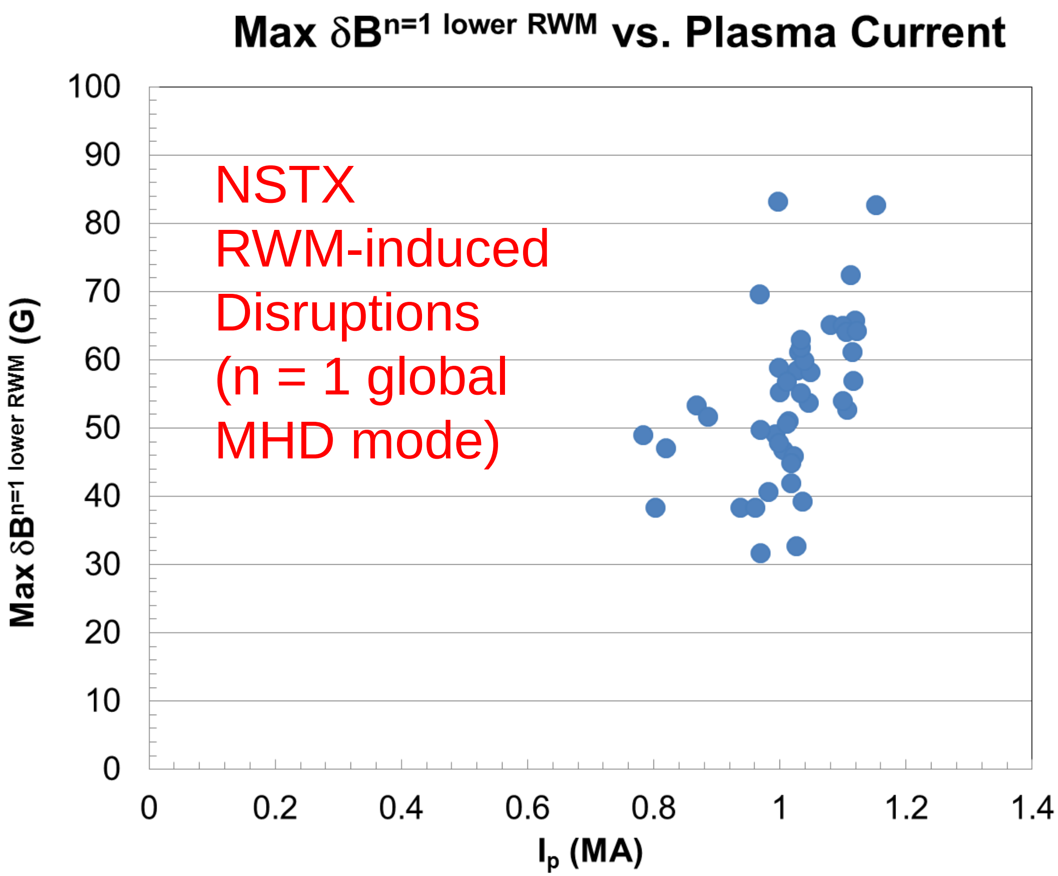
- Physics Understanding
  - Disruption Event Characterization and Forecasting code (DECAF) identifies RWM events and disruption event chains
  - Unification of DIII-D / NSTX experiments and analysis gives improved RWM understanding for disruption avoidance ➔ linear computations useful to determine marginal stability points
  - Recent DECAF development includes initial RWM forecasting, and initial identification of rotating MHD modes, bifurcation, and locking

- Stability Control
  - An arsenal of new profile control tools are planned for NSTX-U to add to existing mode control tools
  - Rotation profile controller has potential to steer away from unstable profiles
    - Non-resonant NTV quantitatively verified (circa 2006), well-behaved to alter plasma rotation without hysteresis along with NBI

Additional Slides Follow

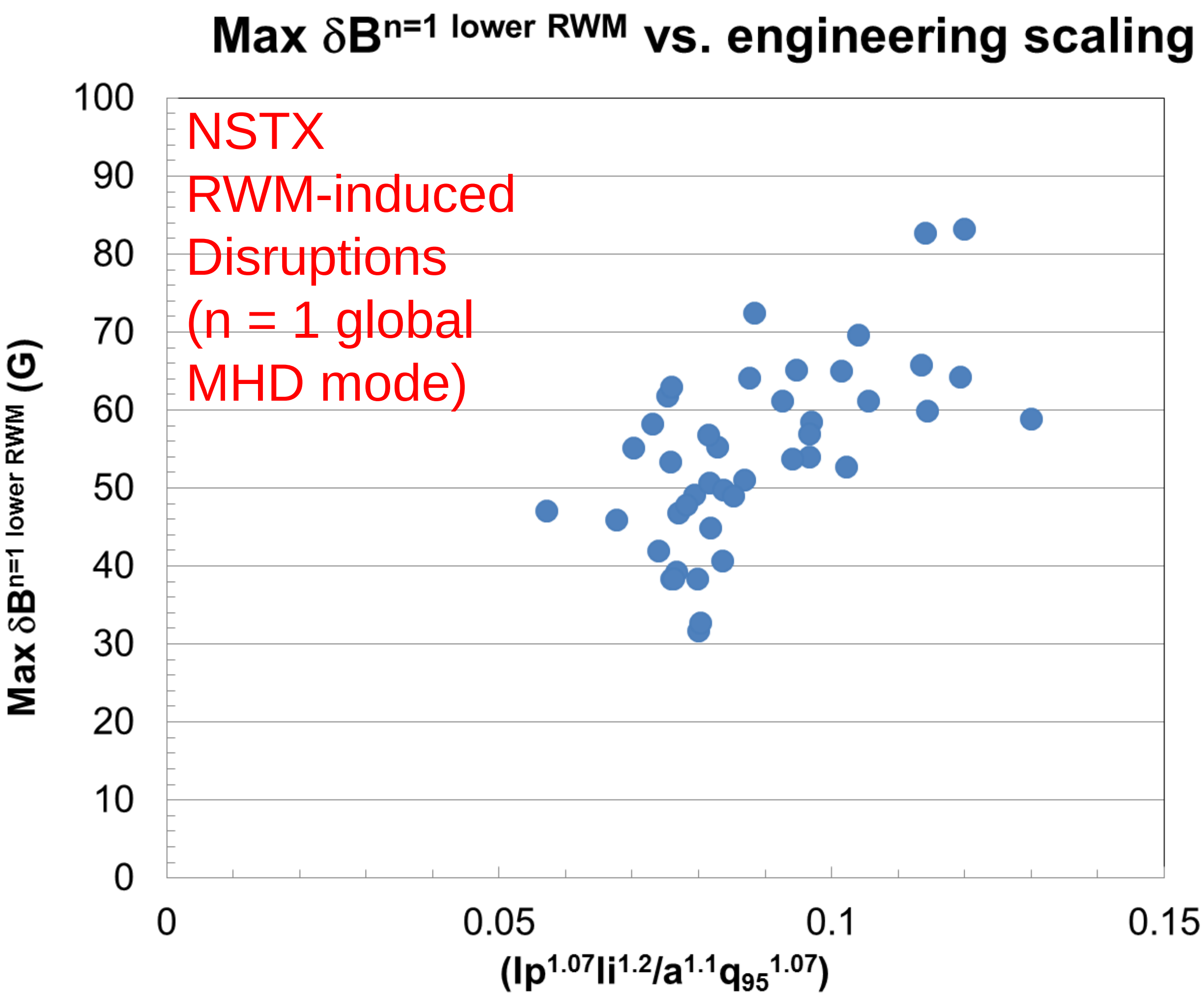
ITER High Priority need: What levels of plasma disturbances (δB_p; $\delta B_p/B_p(a)$) are permissible to avoid disruption?

- NSTX RWM-induced disruptions analyzed
  - Same database analyzed by DECAF in prior slides
- Compare maximum δB_p (n = 1 amplitude) causing disruption vs I_p
- Maximum δB_p increases with I_p



Maximum δB_p might follow a de Vries-style engineering scaling $I_p^{p1} l_i^{p2} / (a^{p3} q_{95}^{p4})$

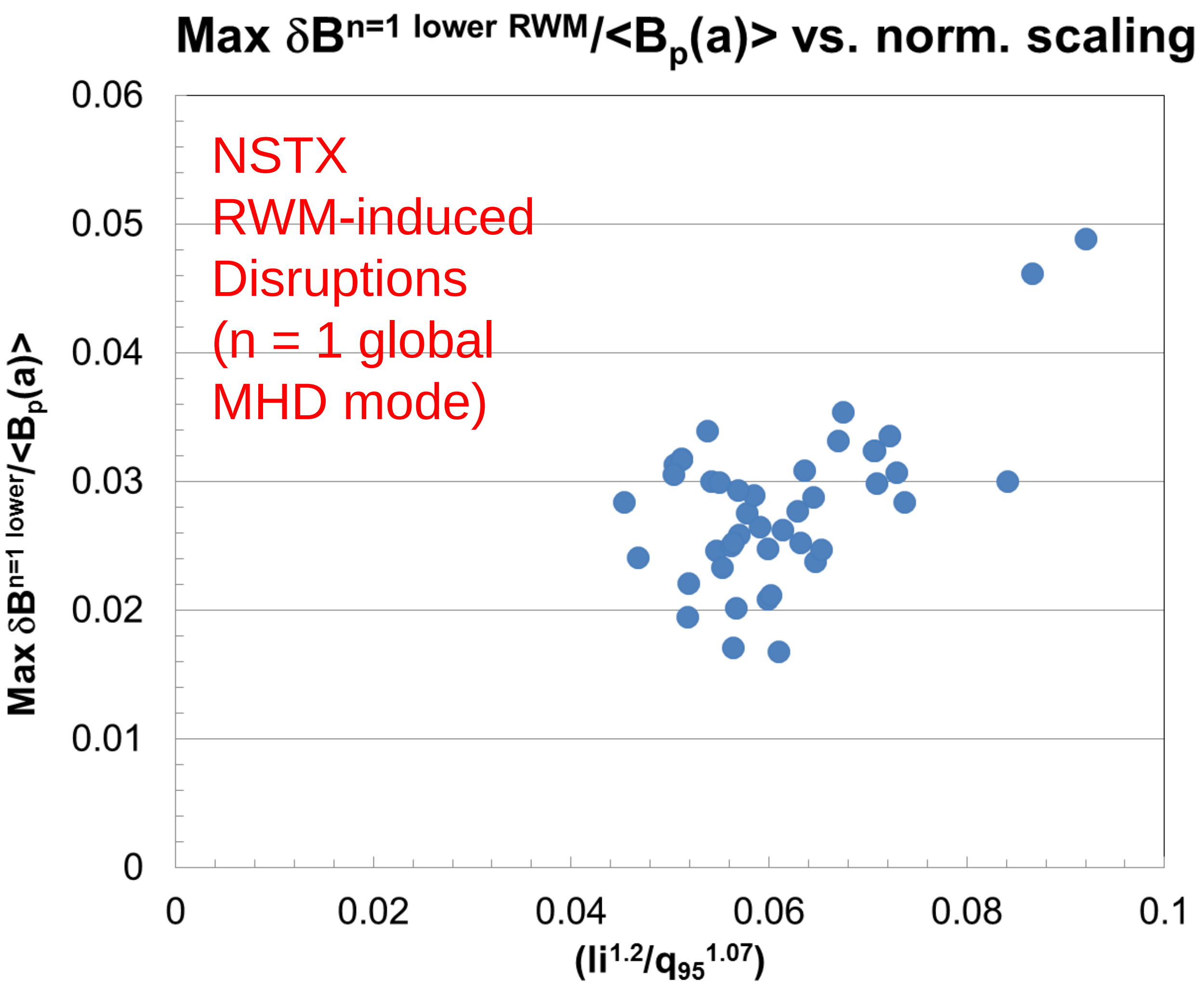
- NSTX RWM-induced disruptions
- Compare maximum δB_p causing disruption to de Vries locked NTM scaling
  - engineering parameters
  - Data shows significant scatter (as does de Vries' analysis for NTM)



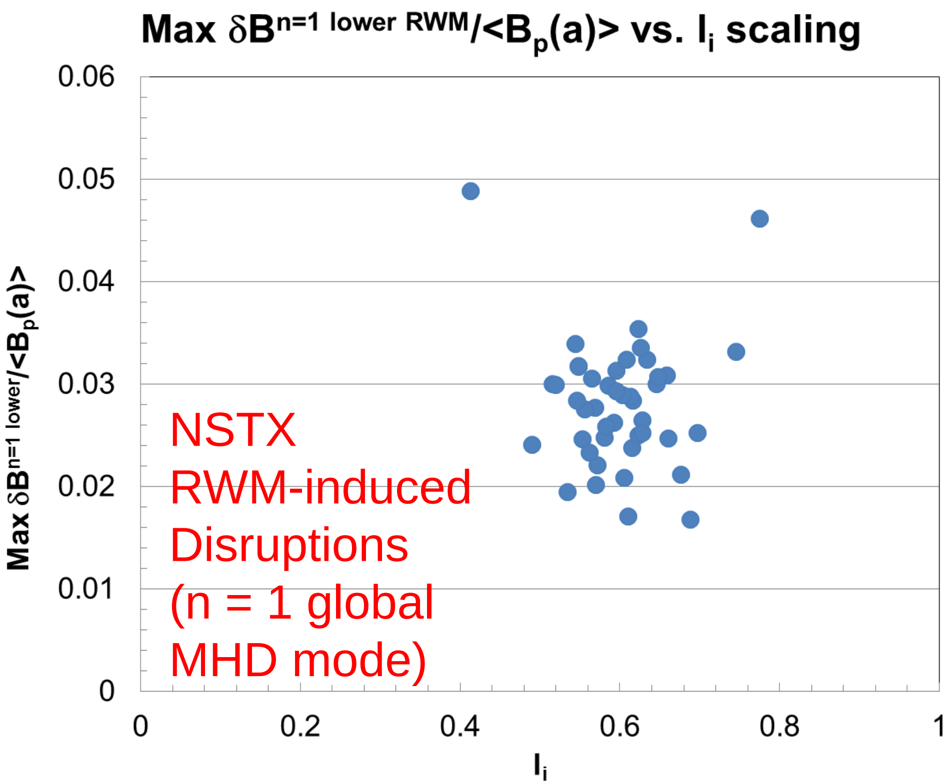
- P.C. de Vries, G. Pautasso, E. Nardon, et al., Nucl. Fusion **56** (2016) 026007

Maximum δB_p /<B_p(a)> might follow a de Vries-style scaling l_i^{p1}/q_{95}^{p2}

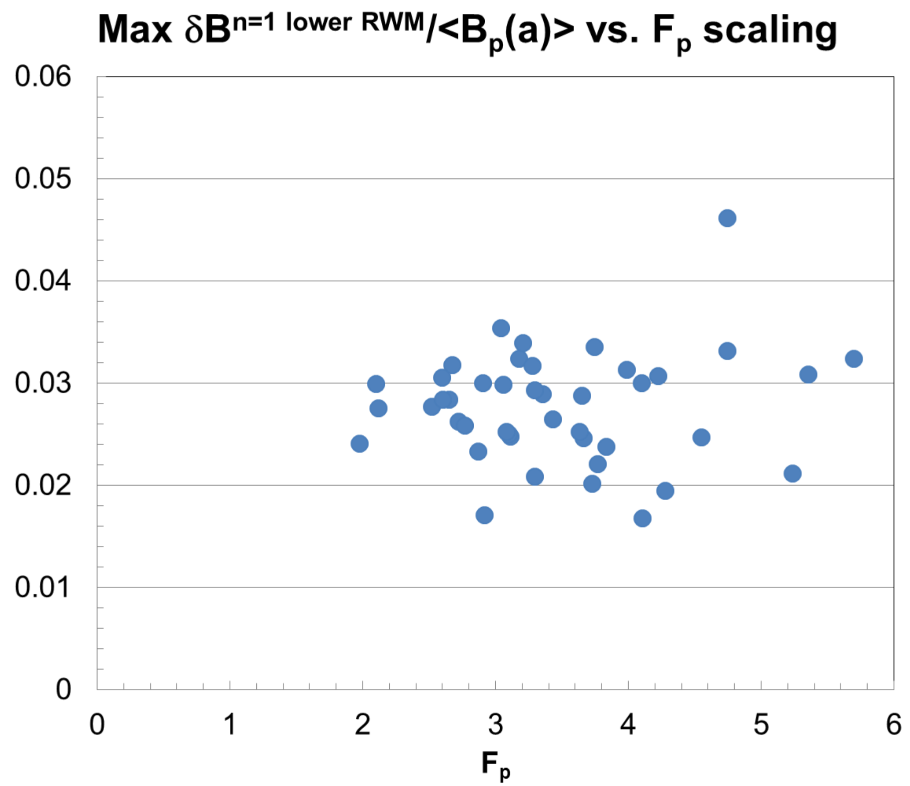
- NSTX RWM-induced disruptions
- Compare maximum δB_p causing disruption vs. de Vries locked NTM scaling
  - Normalized parameters
- NSTX analysis uses kinetic EFIT reconstructions
  - l_i instead of $l_i(3)$
  - $\langle B_p(a)\rangle_{fsa}$ used



In contrast, maximum $\delta B_p/\langle B_p(a)\rangle$ seems independent of scaling on (l_i) or (F_p) (or (F_p/l_i))



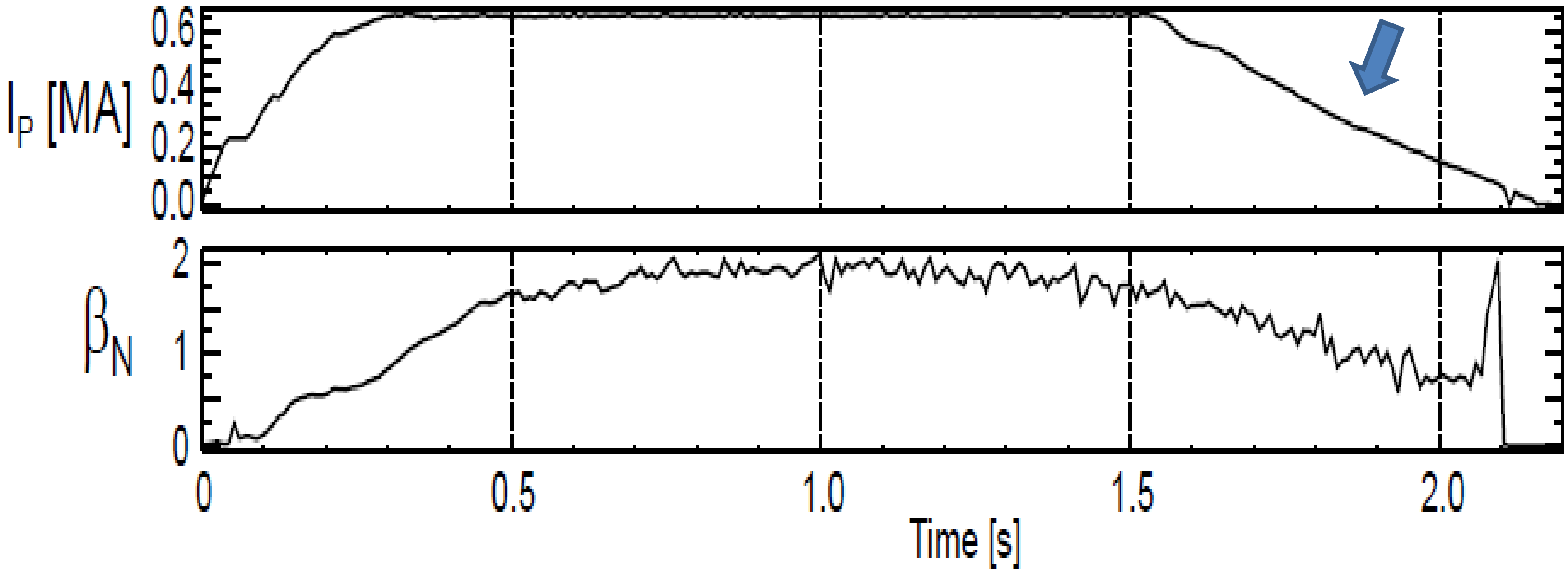
internal inductance



total pressure peaking factor

- $F_p = p_{tot}(0)/\langle p_{tot}\rangle_{vol}$ (from kinetic equilibrium reconstructions)
- Dependence on l_i, F_p expected for RWM marginal stability points

Recent NSTX-U controlled shutdown example

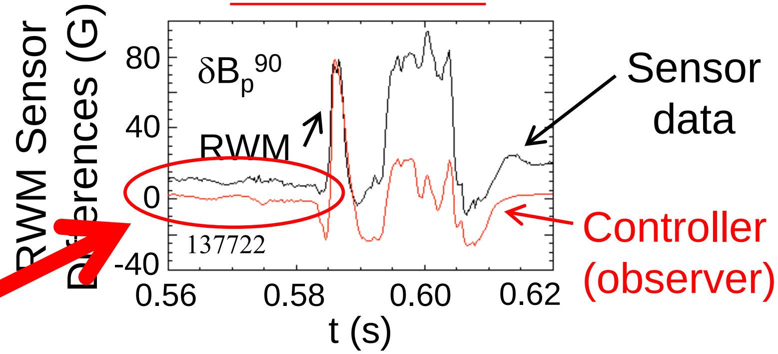


In addition to active mode control, the NSTX-U RWM state space controller can be used for real-time disruption warning

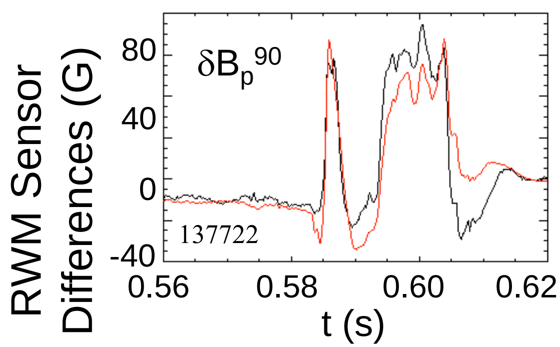
- The controller "observer" produces a physics model-based calculation of the expected sensor data – a synthetic diagnostic
- If the real-time synthetic diagnostic doesn't match the measured sensor data, a r/t disruption warning signal can be triggered
  - Technique will be assessed using the DECAF code

Effect of 3D Model Used

No NBI Port



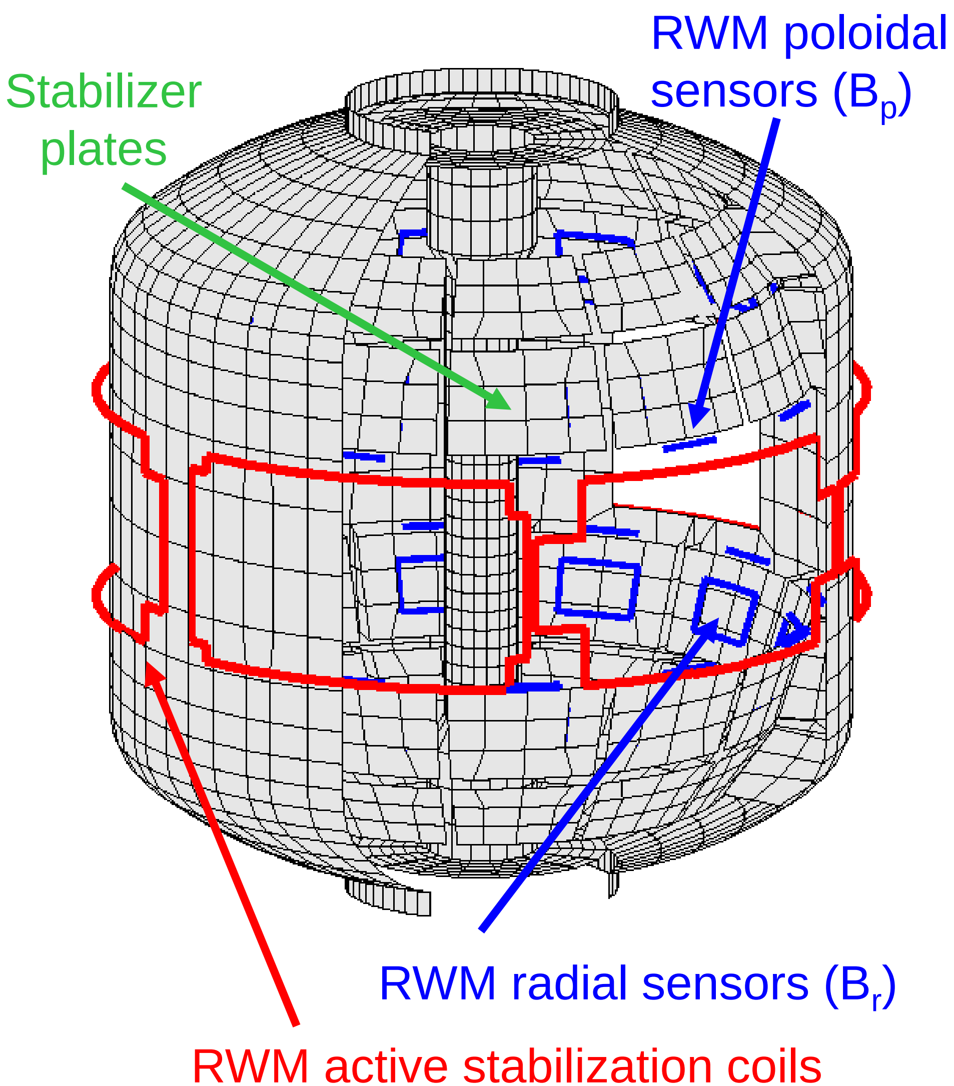
With NBI Port



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 Conducting Structure Model



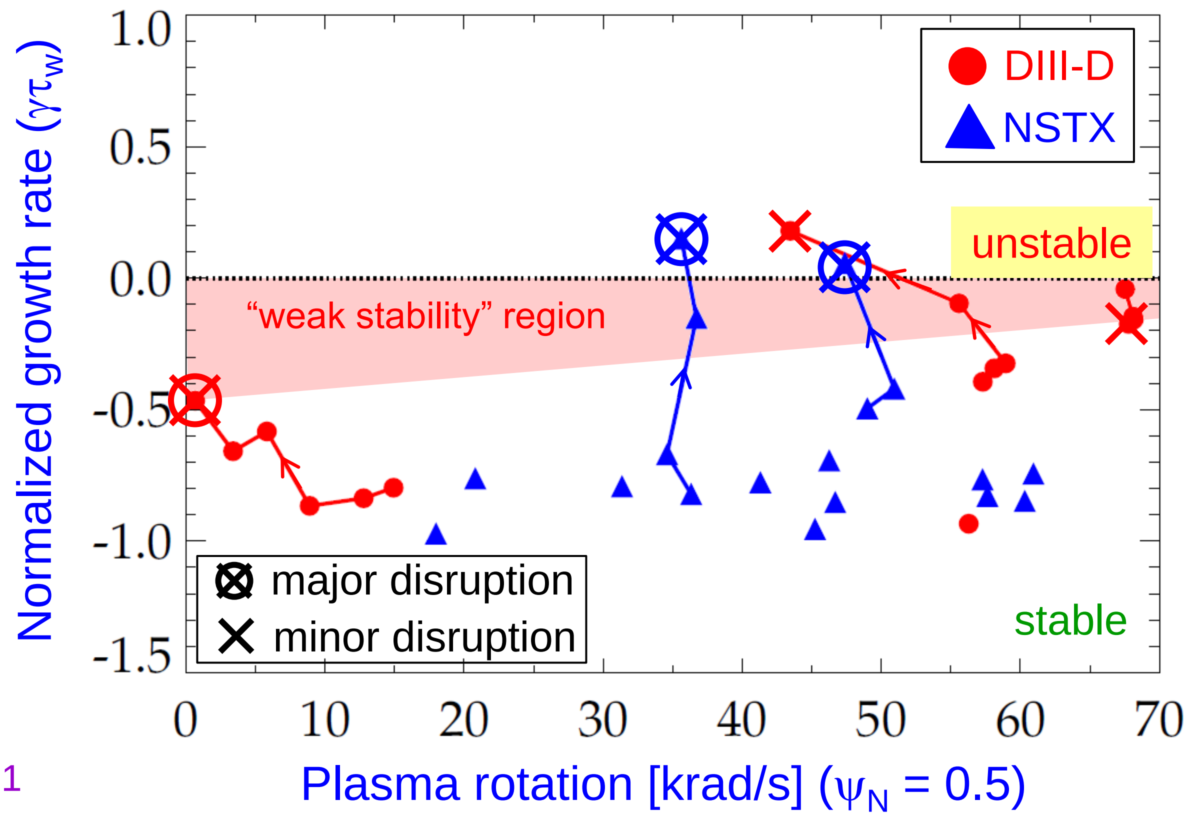
Kinetic RWM stability analysis evaluated for DIII-D and NSTX plasmas

- 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

    - Present analysis can quantitatively define a "weak stability" region below linear instability

    Strait, et al., PoP **14** (2007) 056101

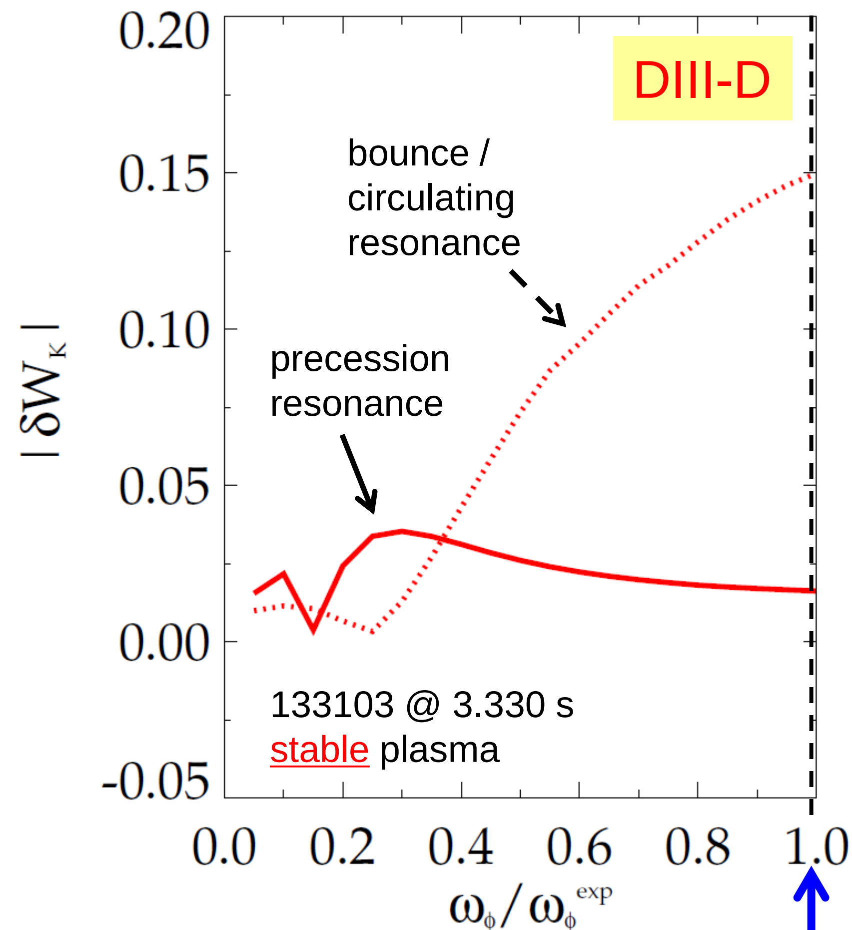
Kinetic RWM stability analysis for experiments (MISK)

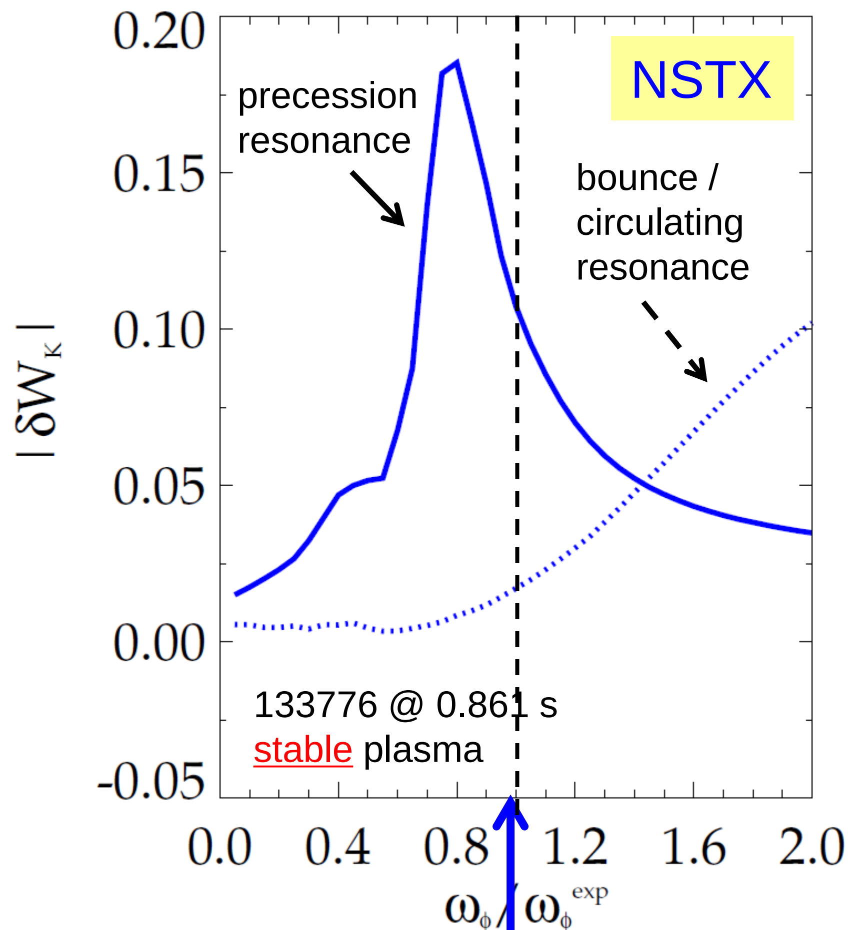


S.A. Sabbagh, J.W. Berkery, J. Hanson, et al. APS DPP Invited Talk VI2.0002 (2014)

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)



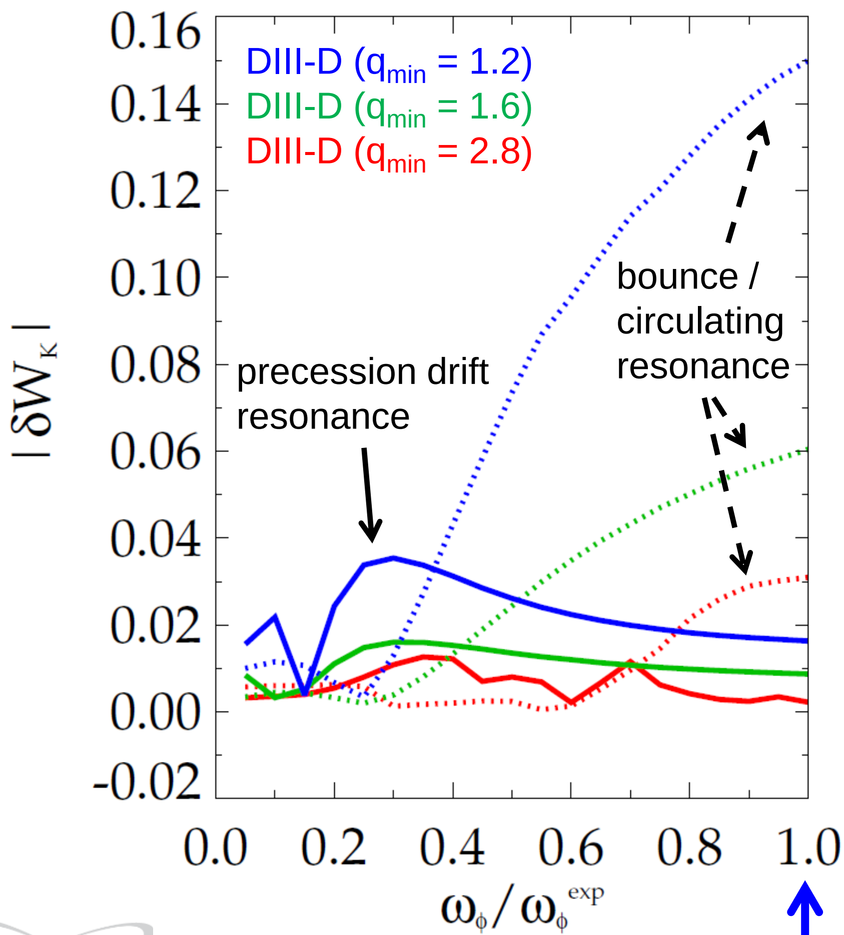


DIII-D experimental rotation profile

NSTX experimental rotation profile

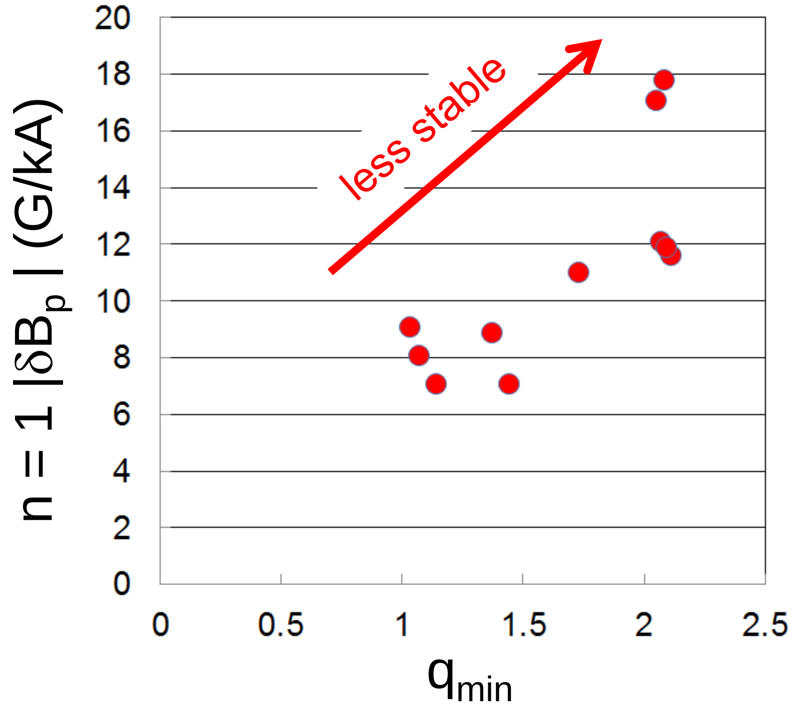
Increased RWM stability measured in DIII-D plasmas as q_{min} is reduced is consistent with kinetic RWM theory

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



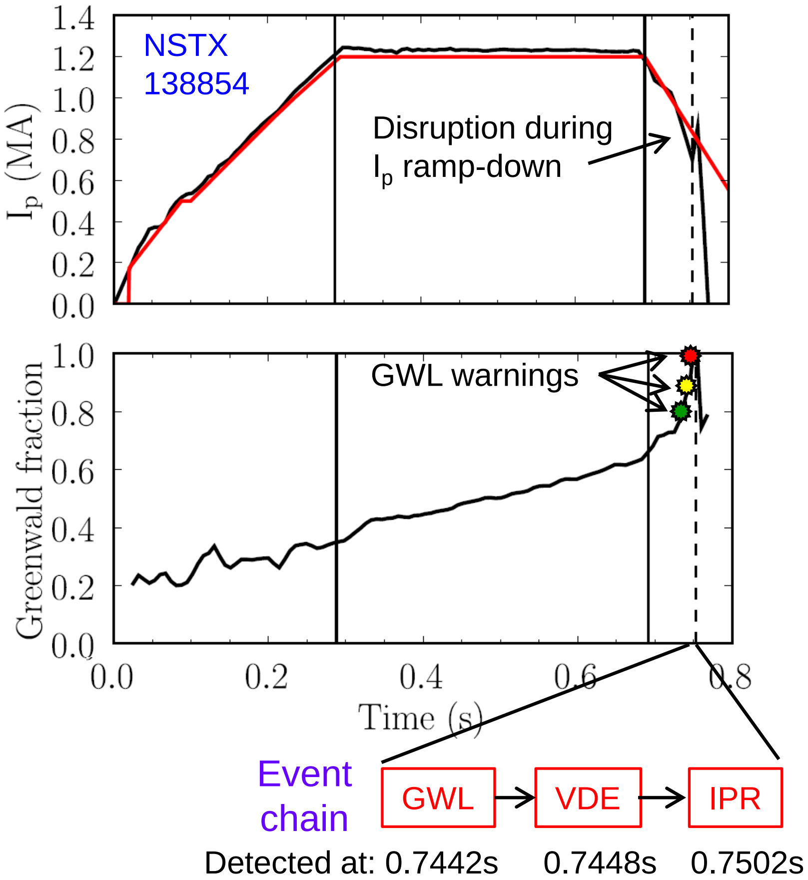
DIII-D experimental rotation profile

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

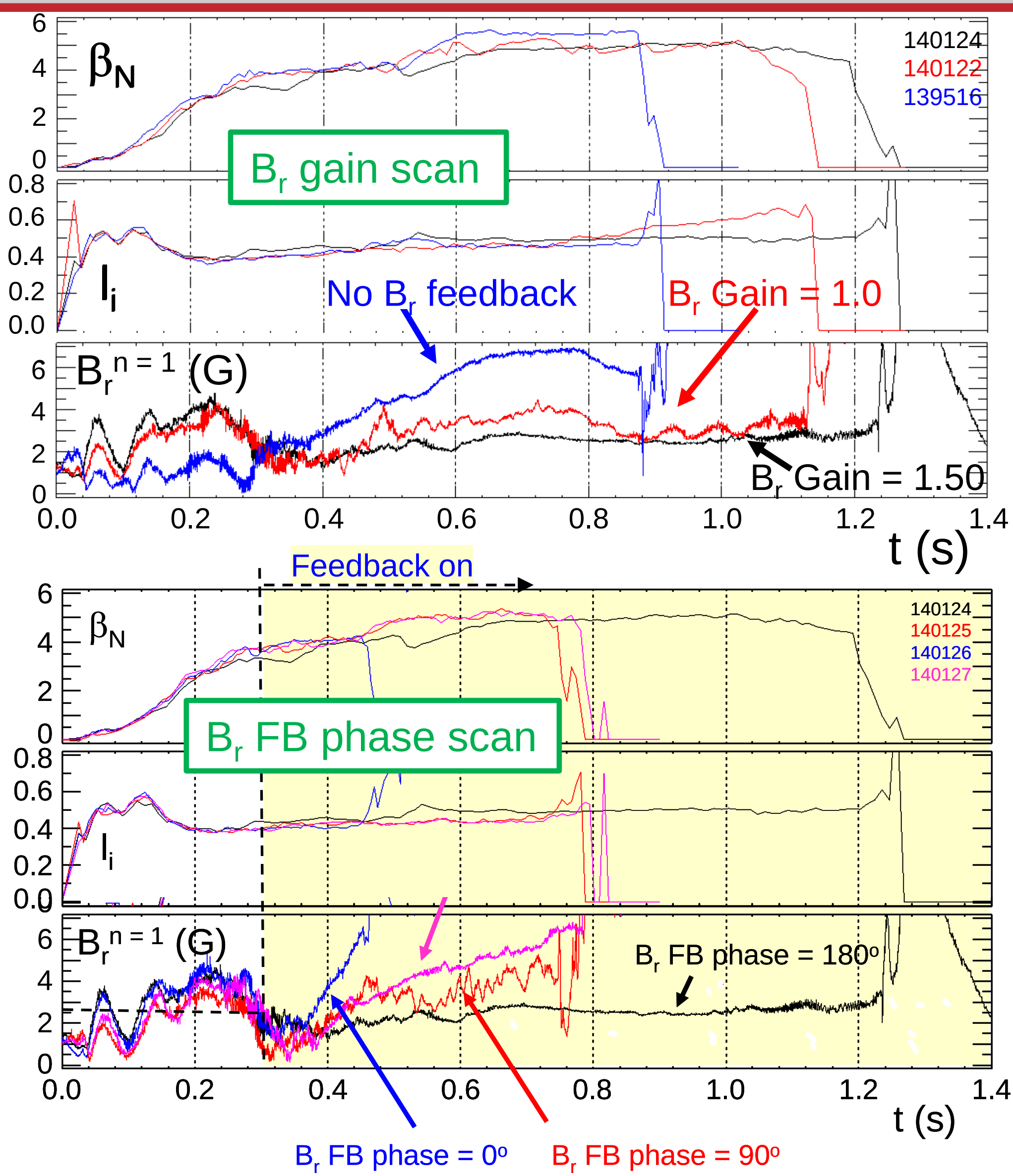
Disruption Characterization Code now yielding initial results: disruption event chains, with related quantitative warnings (2)



- This example: Greenwald limit warning during I_p rampdown
  1. (GWL) Greenwald limit warning issued
  2. (VDE) VDE condition then found 0.6 ms after GWL warning
  3. (IPR) Plasma current request not met

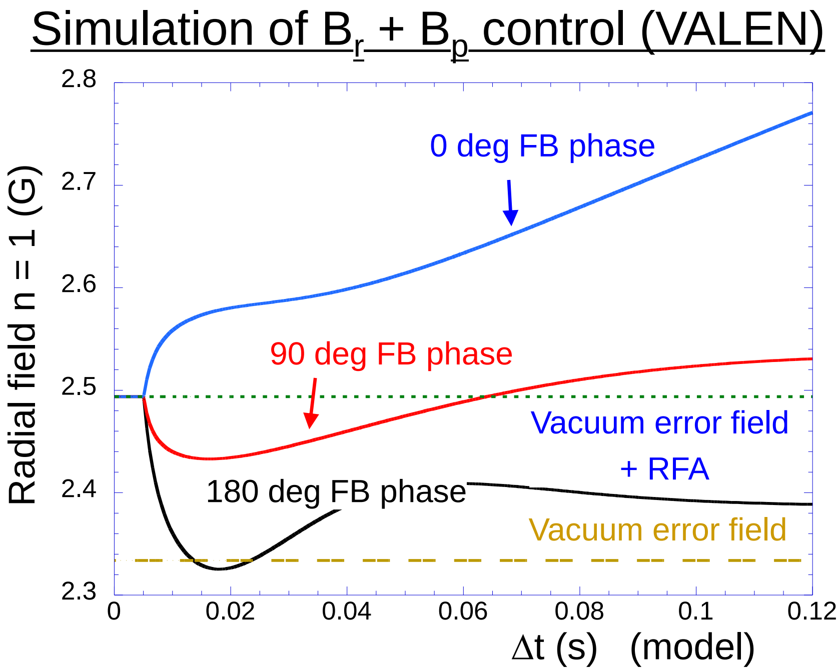
J.W. Berkery, S.A. Sabbagh, Y.S. Park

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



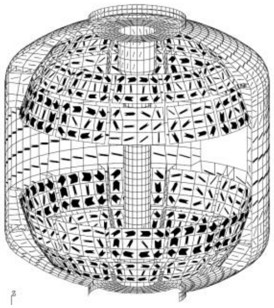
- Favorable B_p + B_r feedback (FB) settings found (low l_i plasmas)
- Time-evolved theory simulation of B_r+B_p feedback follows experiment

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



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

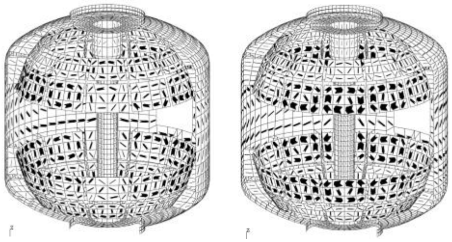
Full 3-D model ~3000+ states



Balancing transformation

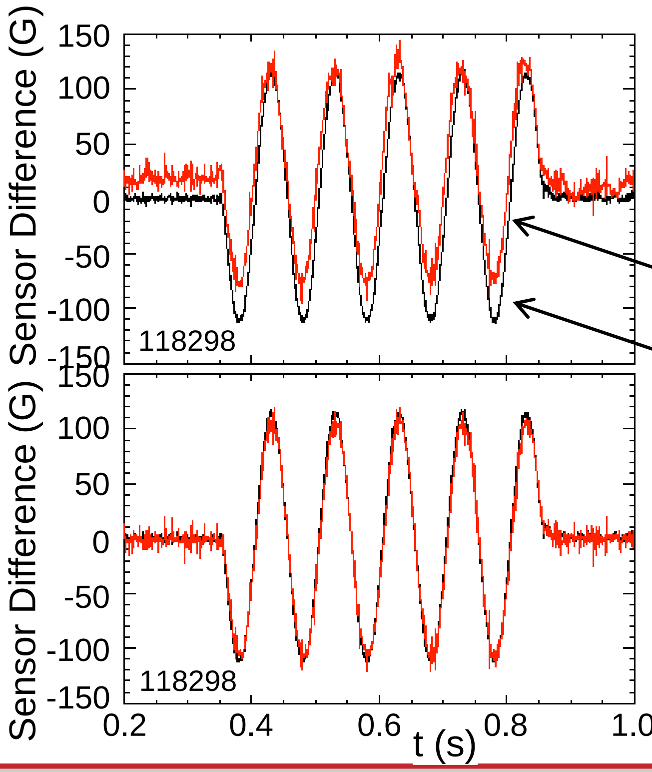
State reduction (< 20 states)

RWM eigenfunction (2 phases, 2 states)



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

Controller reproduction of n = 1 field in NSTX



5 states used

Controller (observer)

Measurement

10 states used

(only wall states used)

- Controller model can compensate for wall currents
  - Includes linear plasma mode-induced current model (DCON)
- Potential to 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, or n > 1)

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

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

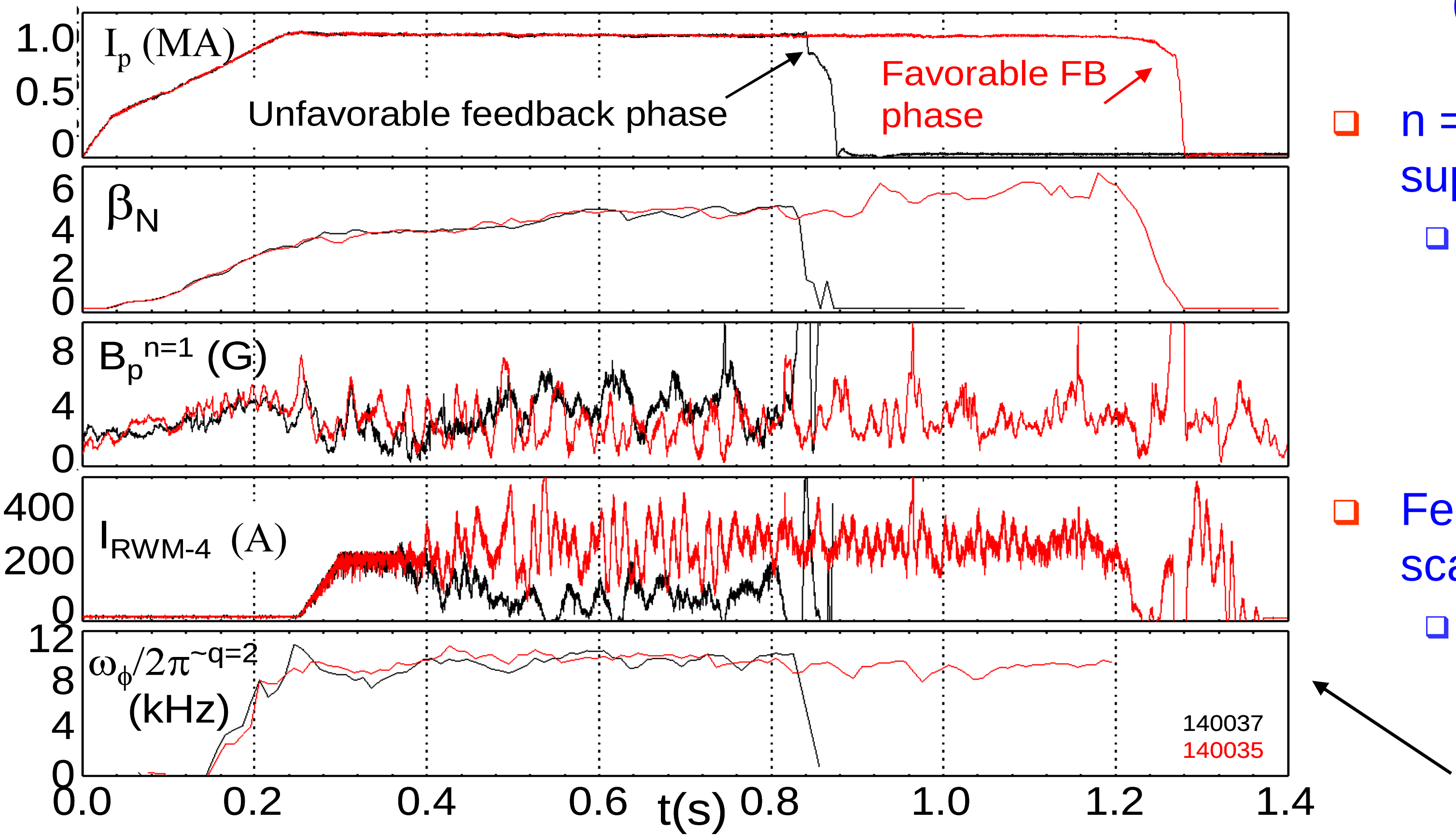
$$\vec{x}_{t+1} = \hat{\vec{x}}_t + A^{-1}K_o(\vec{y}_{sensors(t)} - \hat{\vec{y}}_t) \qquad \text{(measurement update)}$$

Written into the PCS

- General (portable) matrix output file for operator

NSTX RWM state space controller sustains high β_N, low l_i plasma – available for NSTX-U with independent coil control

RWM state space feedback (12 states)

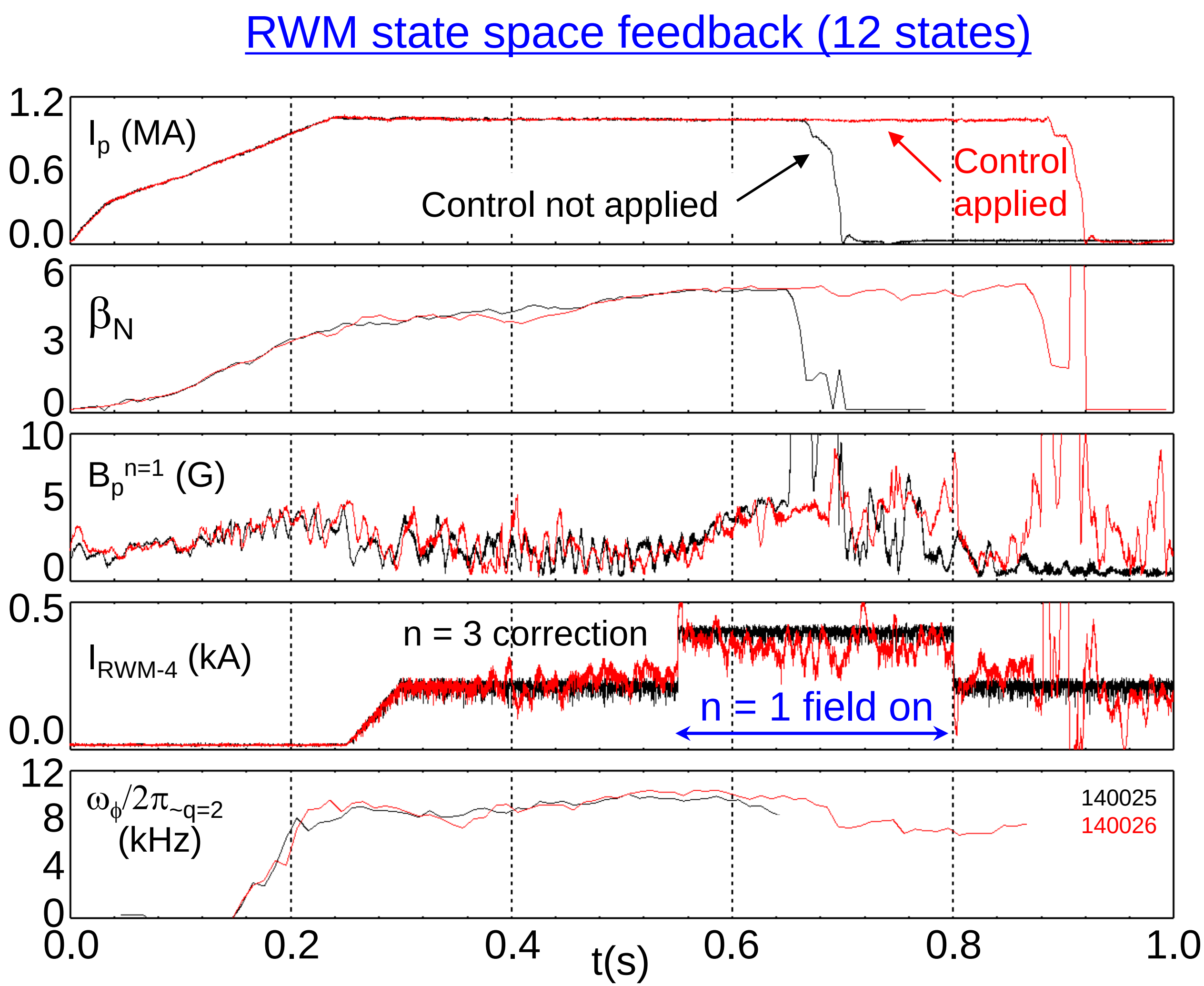


NSTX Experiments (from 2010)

- 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

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

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



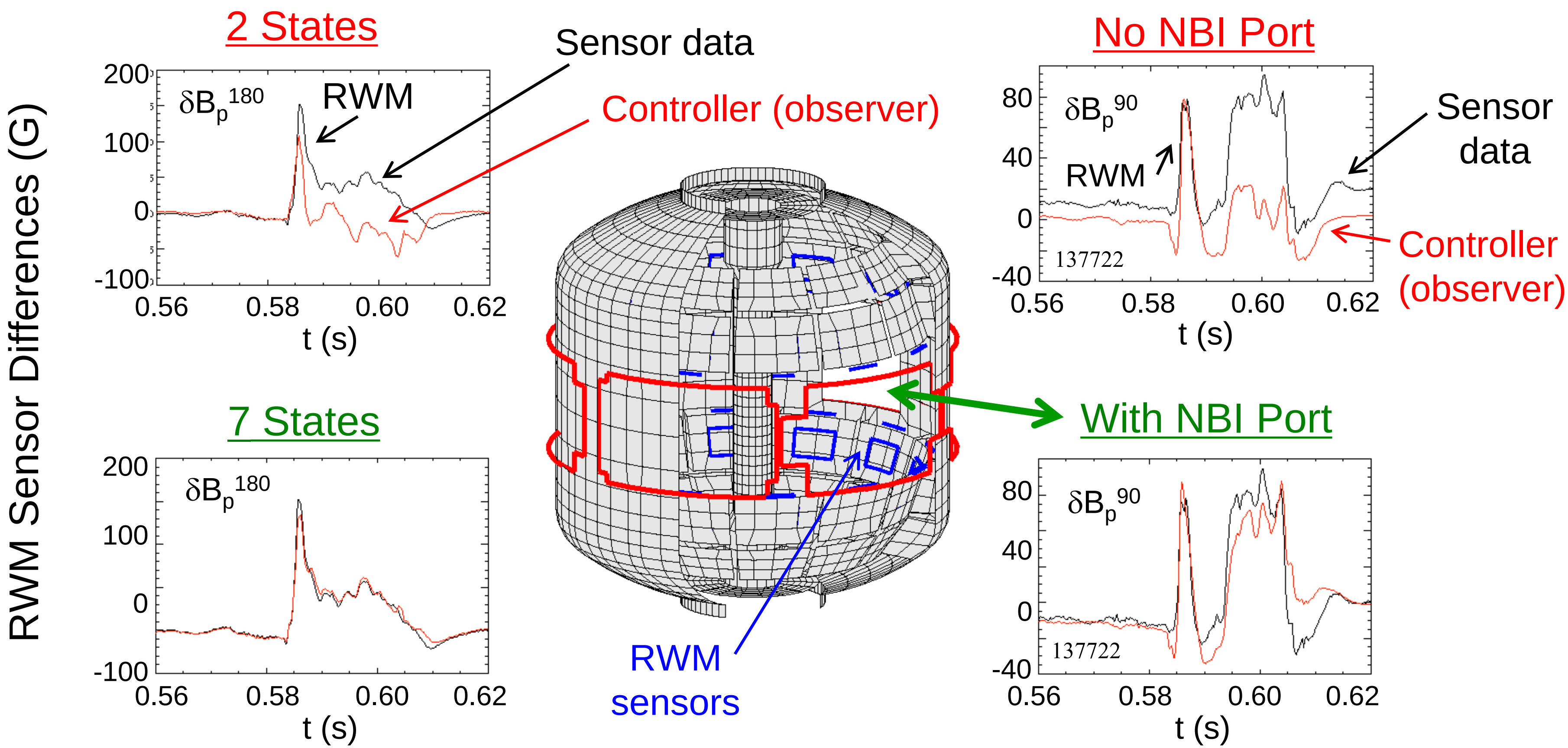
- n = 1 DC applied field test
  - Generate resonant field amplification, disruption
  - Use of RWM state space controller sustains discharge
- RWM state space controller sustains discharge at high β_N
  - Best feedback phase produced long pulse, β_N = 6.4, β_N/l_i = 13

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

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

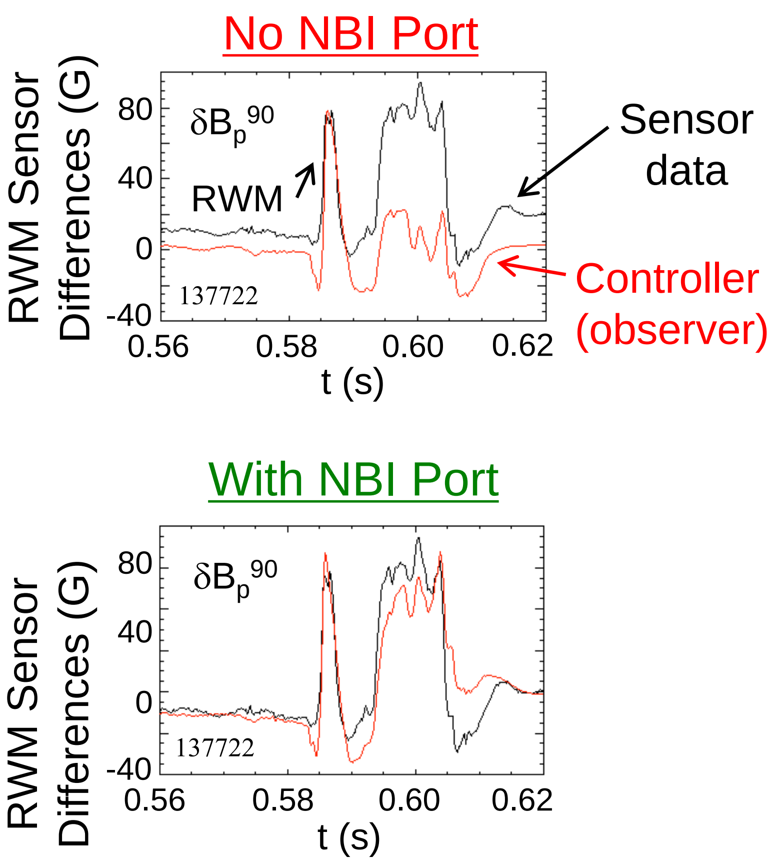


- Improved agreement with sufficient number of states (wall detail)
- 3D detail of model important to improve agreement

In addition to active mode control, the NSTX-U RWM state space controller can be used for r/t disruption warning

- The controller “observer” produces a physics model-based calculation of the expected sensor data – a synthetic diagnostic
- If the real-time synthetic diagnostic doesn’t match the measured sensor data, a r/t disruption warning signal can be triggered
  - Technique will be assessed using the DECAF code

Effect of 3D Model Used

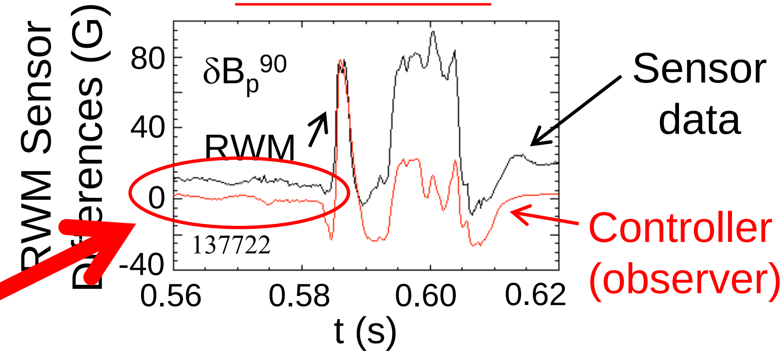


In addition to active mode control, the NSTX-U RWM state space controller can be used for real-time disruption warning

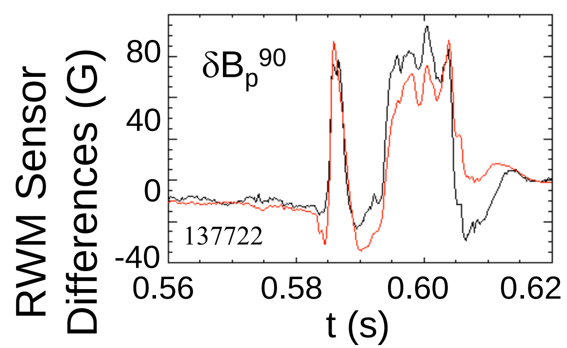
- The controller "observer" produces a physics model-based calculation of the expected sensor data – a synthetic diagnostic
- If the real-time synthetic diagnostic doesn't match the measured sensor data, a r/t disruption warning signal can be triggered
  - Technique will be assessed using the DECAF code

Effect of 3D Model Used

No NBI Port

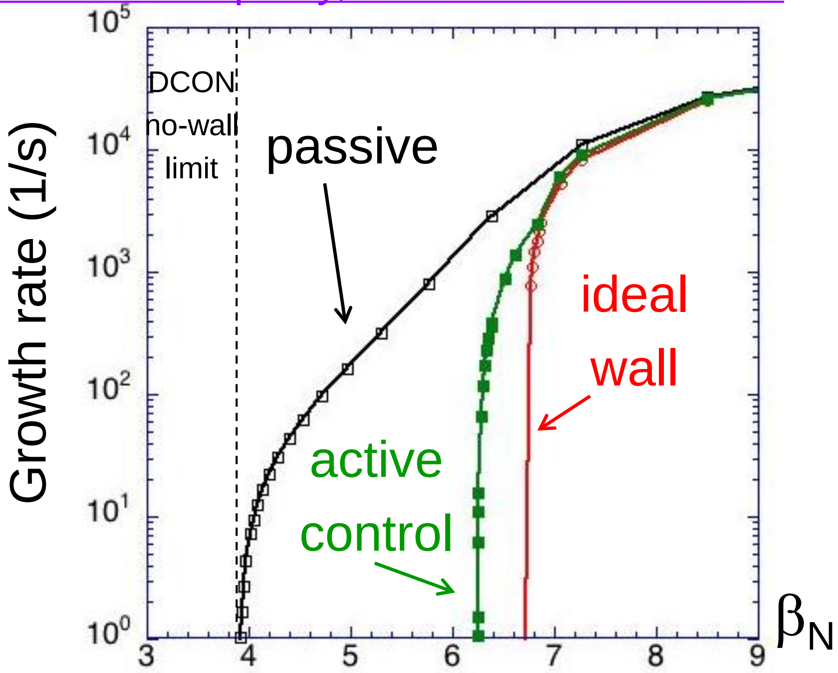


With NBI Port

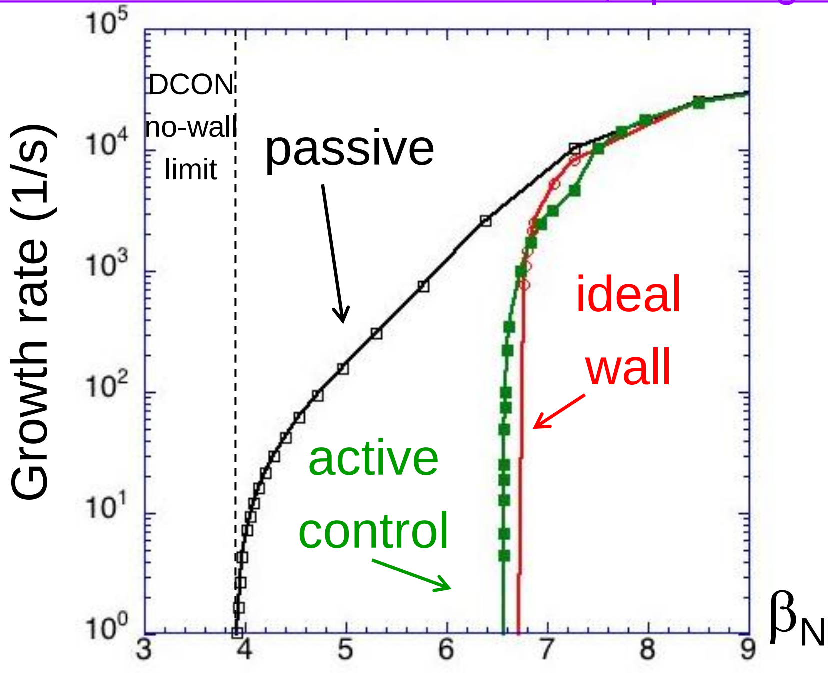


Active RWM control design study for proposed NSTX-U 3D coil upgrade (NCC coils) shows superior capability

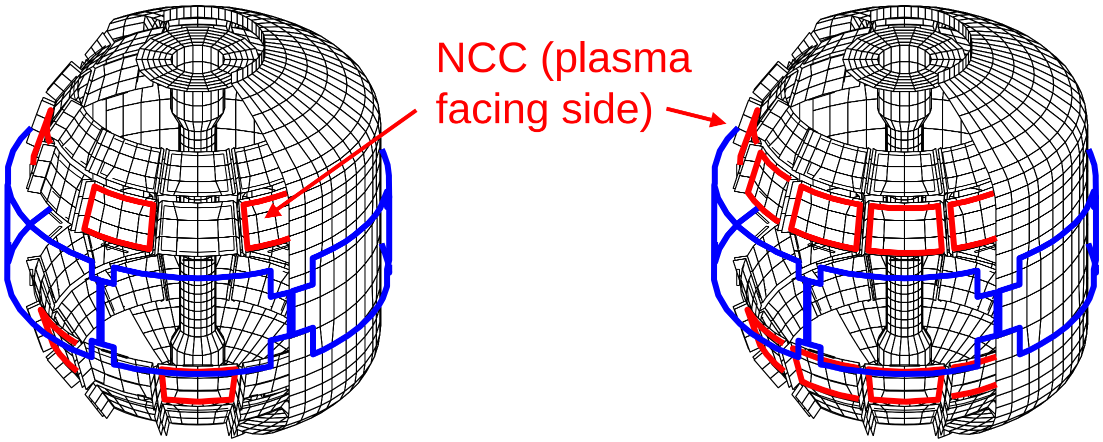
NCC 2x6 odd parity, with favorable sensors



NCC 2x12 with favorable sensors, optimal gain

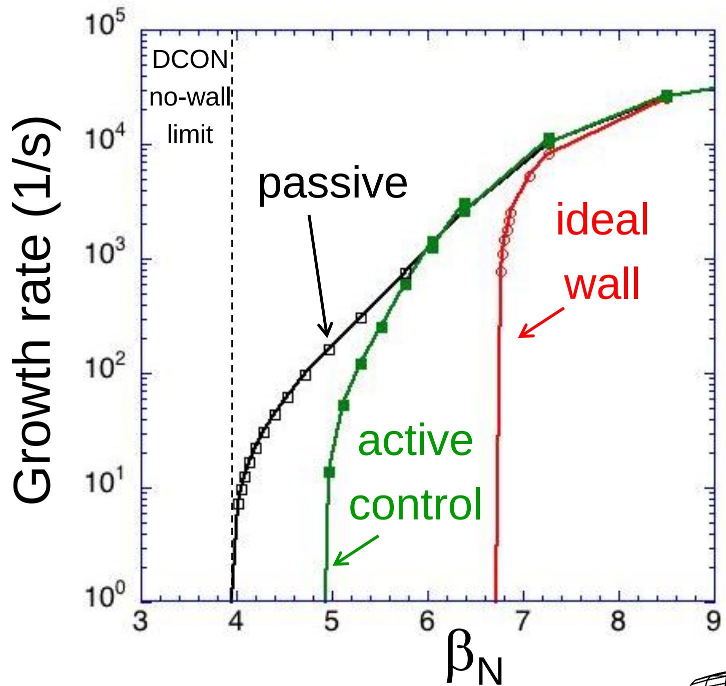


- Full NCC coil set allows control close to ideal wall limit
  - NCC 2x6 odd parity coils: active control to $\beta_N/\beta_N^{no\text{-}wall}$ = 1.58
  - NCC 2x12 coils, optimal sensors: active control to $\beta_N/\beta_N^{no\text{-}wall}$ = 1.67

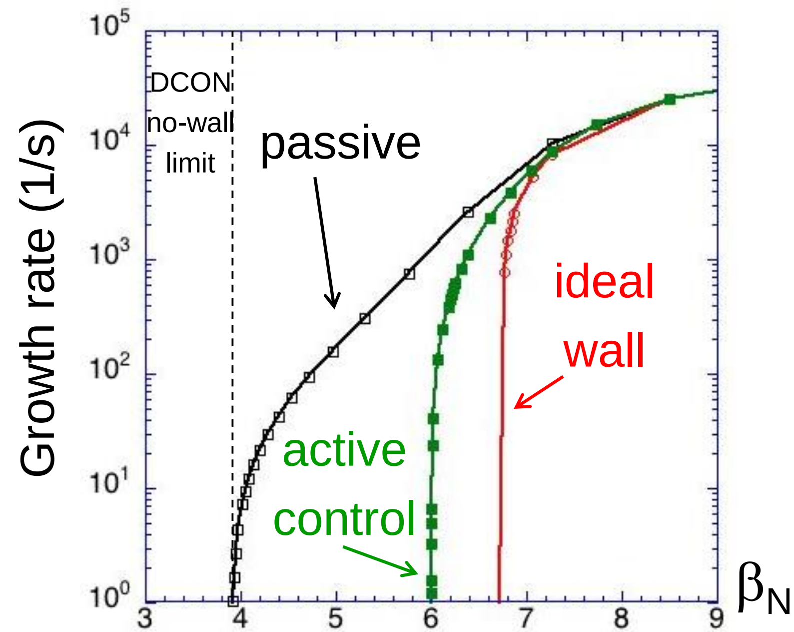


NSTX-U: RWM active control capability increases as proposed 3D coils upgrade (NCC coils) are added

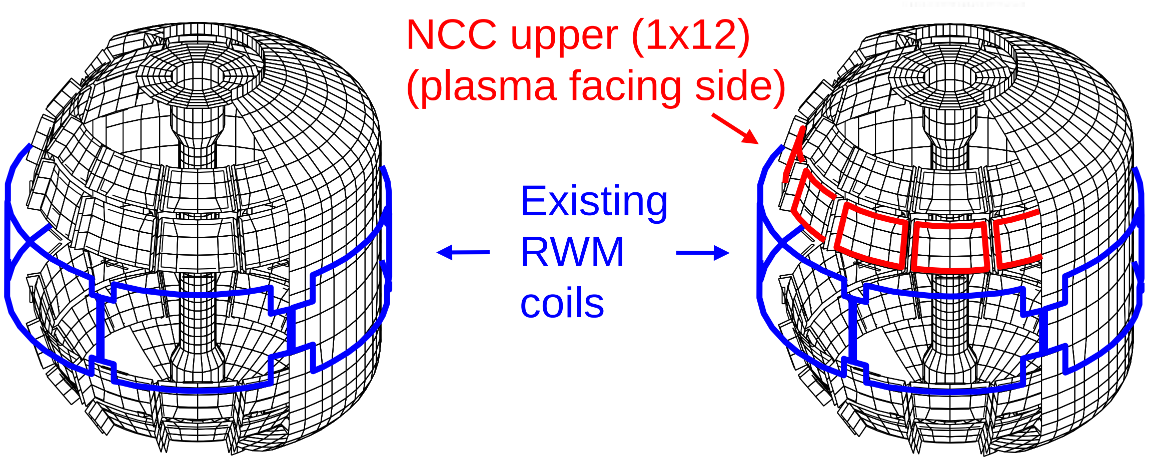
Using present midplane RWM coils



Partial NCC 1x12 (upper), favorable sensors

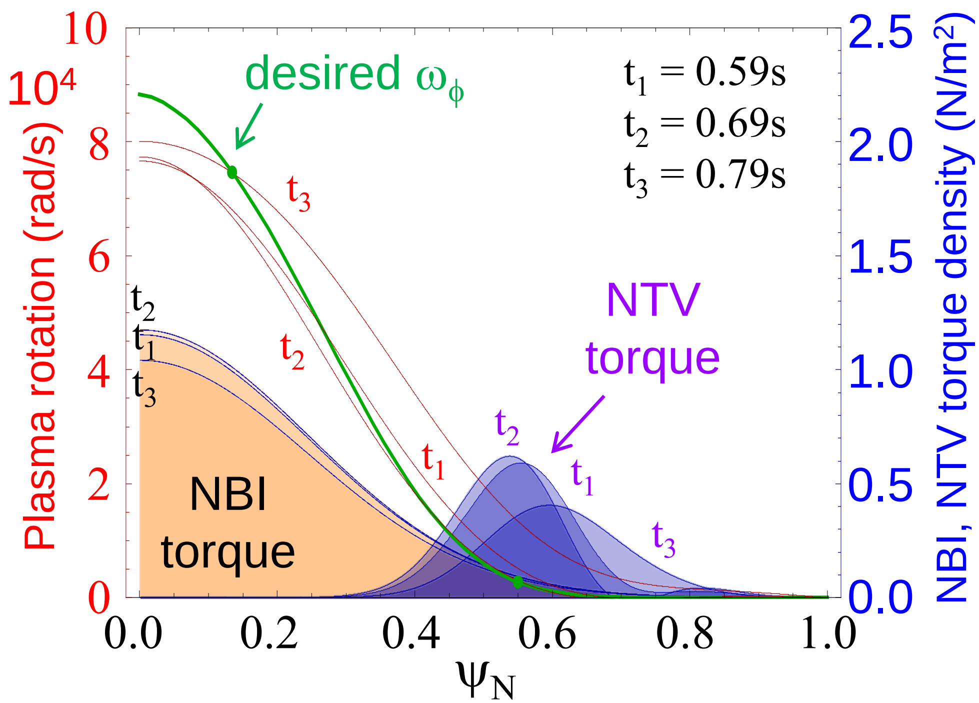


- Partial 1x12 NCC coil set significantly enhances control
  - Present RWM coils: active control to $\beta_N/\beta_N^{no\text{-}wall} = 1.25$
  - NCC 1x12 coils: active control to $\beta_N/\beta_N^{no\text{-}wall} = 1.52$

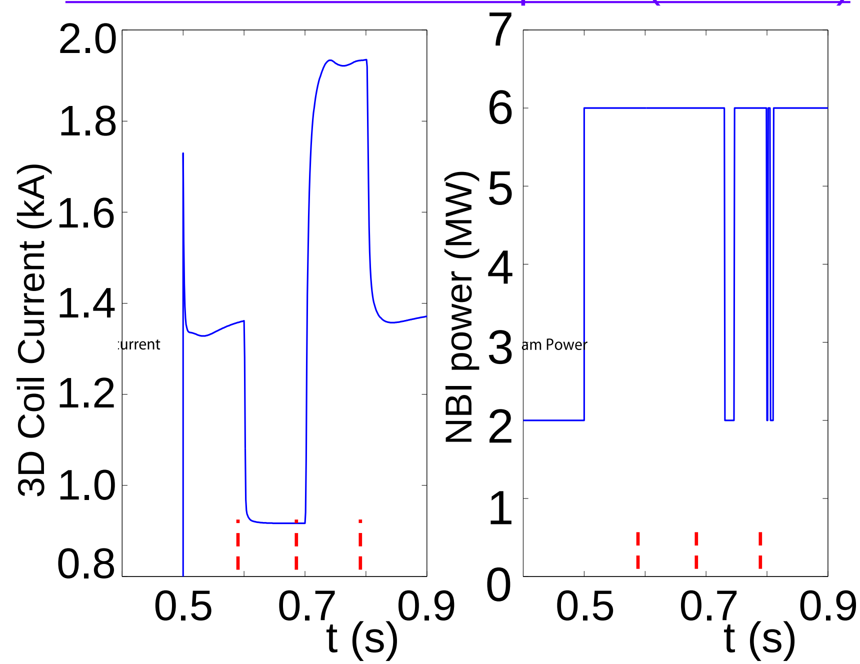


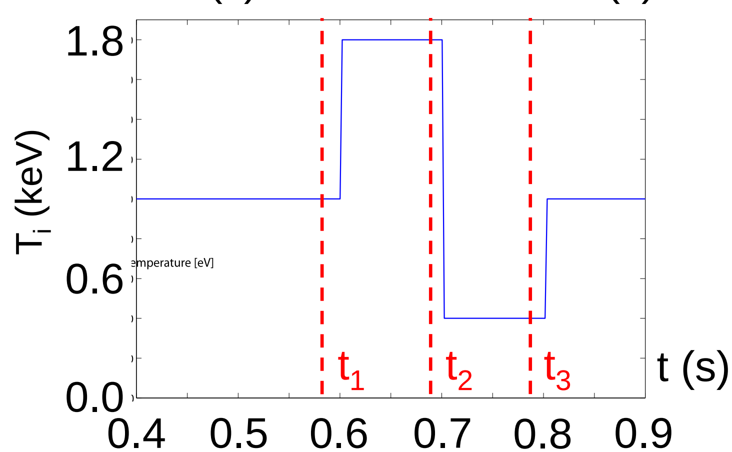
When T_i is included in NTV rotation controller model, 3D field current and NBI power can compensate for T_i variations

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