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Global MHD Mode Stabilization for Disruption Avoidance in Tokamaks

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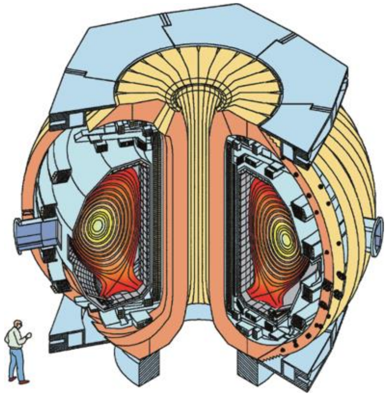
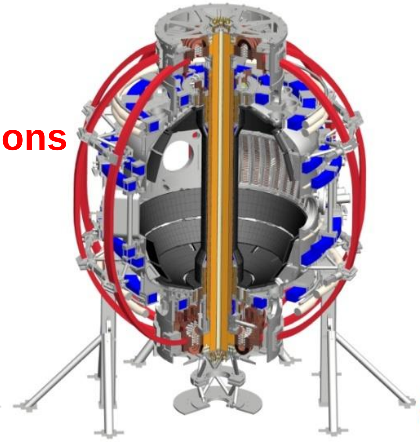


Theory/Simulation of Disruptions
July 15, 2015
PPPL



DIII-D NATIONAL FUSION FACILITY

V1.4

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

PPPL

To prevent disruptions in tokamaks, past stability/control achievements need to be exploited; research needs to evolve

- ☐ Multi-faceted research plan includes
  - ☐ Advance/validate theoretical stability understanding
  - ☐ Utilize prediction/control capabilities, develop new systems
  - ☐ Evolve experiments toward focused, integrated prediction/avoidance research
  - ☐ Pursue/validate comprehensive research on disruption event chains and related disruption forecasting
- ☐ These research elements now being brought together as part of a disruption prediction/avoidance system for NSTX-U

- ☐ THIS TALK – two parts
  - ☐ Kinetic RWM stabilization physics - unification between NSTX, DIII-D
  - ☐ Disruption event chain characterization capability started for NSTX-U

Talk PART 1: Kinetic RWM stabilization physics unification

- ☐ RWM phenomenology and characteristics in theory and experiment (DIII-D and NSTX)

- ☐ RWM kinetic stabilization analysis / proximity of plasmas to stability boundaries

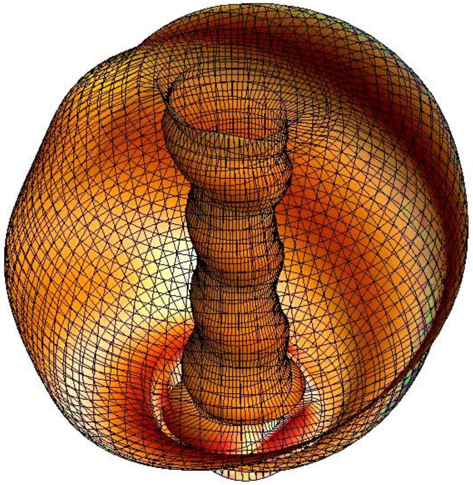
(portion of S.A. Sabbagh, et al. APS DPP 2014 Invited talk)

Analysis of DIII-D and NSTX experiments has unified understanding of resistive wall mode (RWM) stability physics

❑ Importance: Strongly growing RWMs cause disruptions

- ❑ Also cause large stored energy collapse (minor disruption) with ΔWtot ~ 60% (~ 200 MJ in ITER)
  - For comparison, large ELMs have ΔWtot ~ 6% (20 MJ in ITER)
- ❑ RWM is a kink/ballooning mode with growth rate and rotation slowed by conducting wall (~ $1/\tau_{wall}$)
- ❑ RWM typically doesn't occur when strong tearing modes (TM) appear
  - But, what happens when TMs are avoided / controlled (ITER)?
- ❑ RWM evolution is also dangerous as it can itself trigger TMs

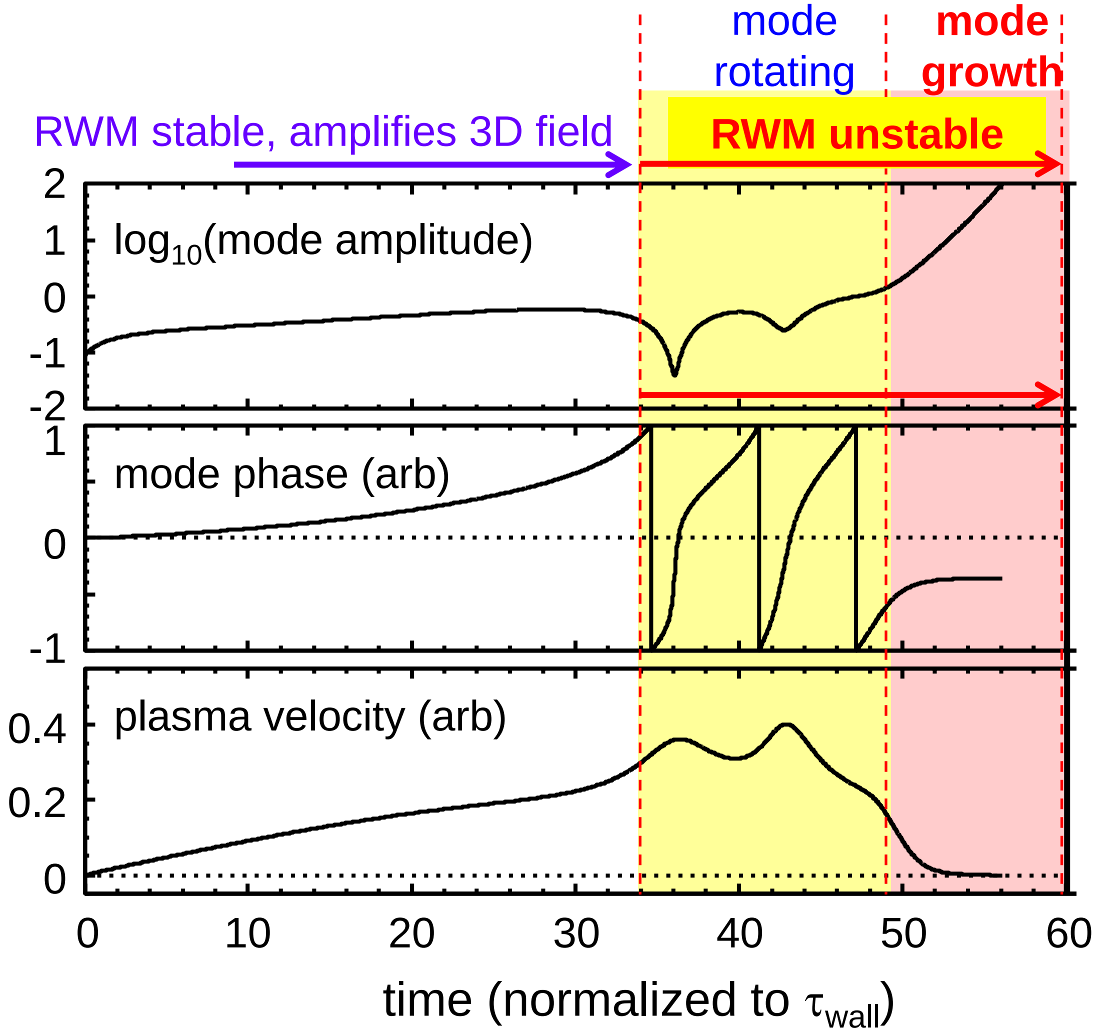
RWM reconstruction in NSTX



(S.A. Sabbagh, et al., Nucl. Fusion **46** (2006) 635)

RWM stability physics must be understood to best assess techniques for **disruption avoidance**

A classic, simple RWM model illustrates basic mode dynamics



R. Fitzpatrick, Phys. Plasmas **9** (2002) 3459

- ❑ Simulation with error field, and increasing mode drive
- ❑ Stable RWM amplifies error field (resonant field amplification (RFA))
- ❑ When RWM becomes unstable, it first unlocks, rotates in co-NBI direction
  - ❑ Amplitude is not strongly growing during this period
- ❑ Eventually unstable mode amplitude increase causes RWM to re-lock, mode grows strongly
- ❑ RWM growth rate, rotation frequency is O(1/τ_{wall})

DIII-D and NSTX provide excellent laboratories to study kinetic RWM stability characteristics

DIII-D High β_N, q_{min} plasmas

- Candidates for steady-state, high β_N operation
- Can have high probability of significant RWM activity with $q_{min} > 2$
  - RWMs and TMs cause strong β collapses in 82% of a database of 50 shots examined, with an average of 3 collapses every 2 shots
  - RWMs cause collapse 60% of the time, TMs 40% of the time
- Employ high $q_{min} > 2$ to avoid 2/1 TM instability (TM precludes RWM)
  - Used ECCD control of 3/1 TM to provide further control of strong n = 1 TMs
- Unique 1 ms resolution of ω_ϕ and T_i measurement captures profile detail in timescale < RWM growth time

NSTX

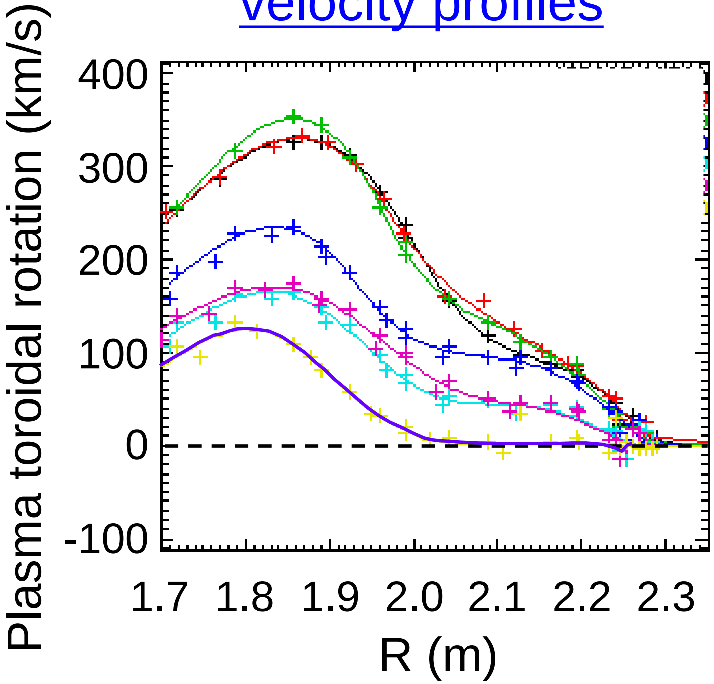
- Strong RWM drive: Maximum $\beta_N > 7$, $\beta_N / l_i > 13.5$
- Strong TMs eliminated by high elongation (> 2.6) or Li wall conditioning

Kinetic RWM marginal stability boundaries were examined over a wide range of plasma rotation profiles

- RWM marginal stability examined for major and minor disruptions

1. Found at high β_N and high rotation
2. Found at high β_N and low rotation
   - Low rotation expected in ITER
3. At moderate β_N and high rotation with increased profile peaking
   - similar loss of profile broadness might easily occur in ITER

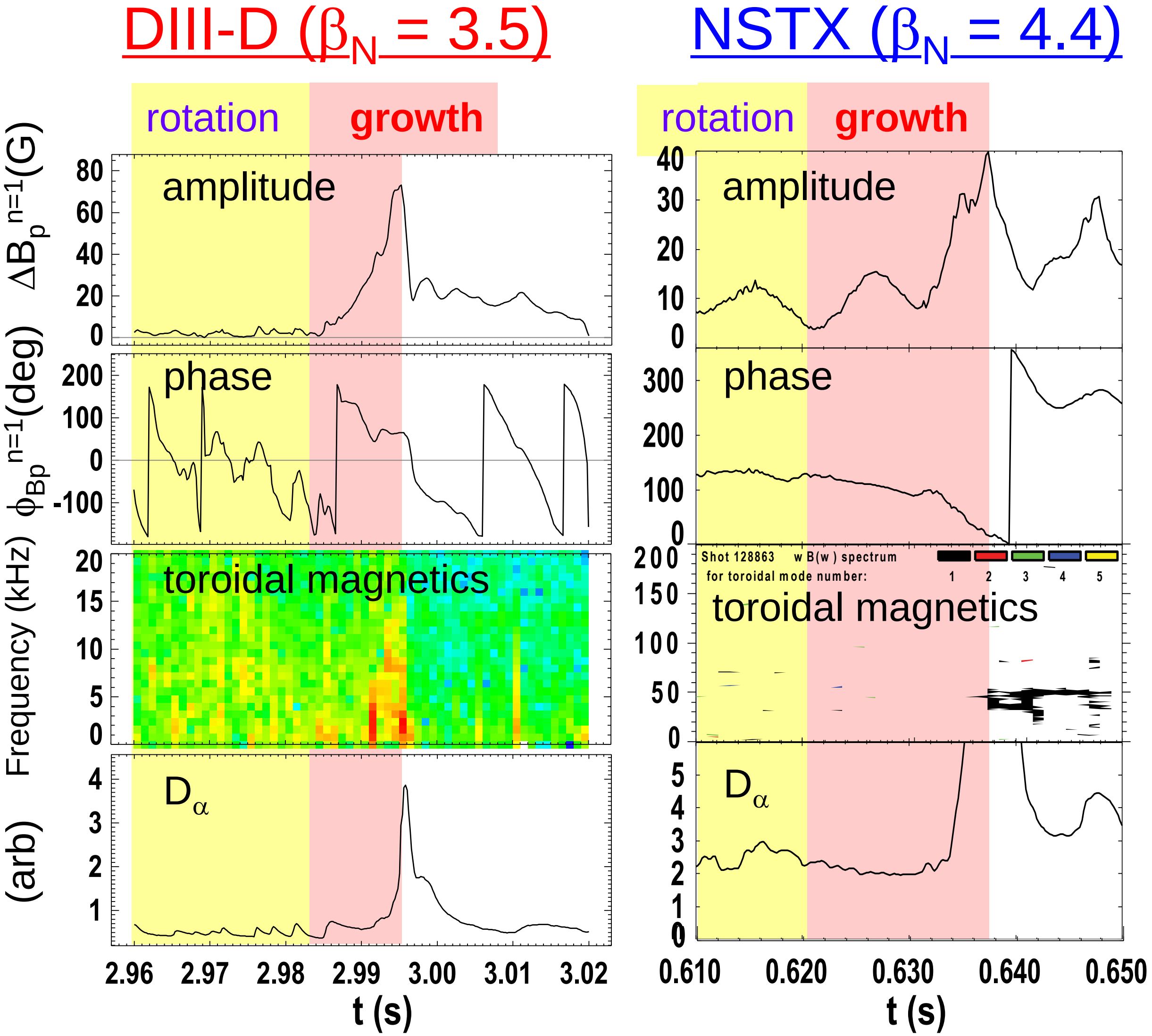
Wide range of DIII-D toroidal plasma velocity profiles



➔In this presentation, variables V_ϕ and ω_ϕ both indicate plasma toroidal rotation

1. Comparison of RWM growth and dynamics in high β_N shots with high plasma rotation

- Elements
  - 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)

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)

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

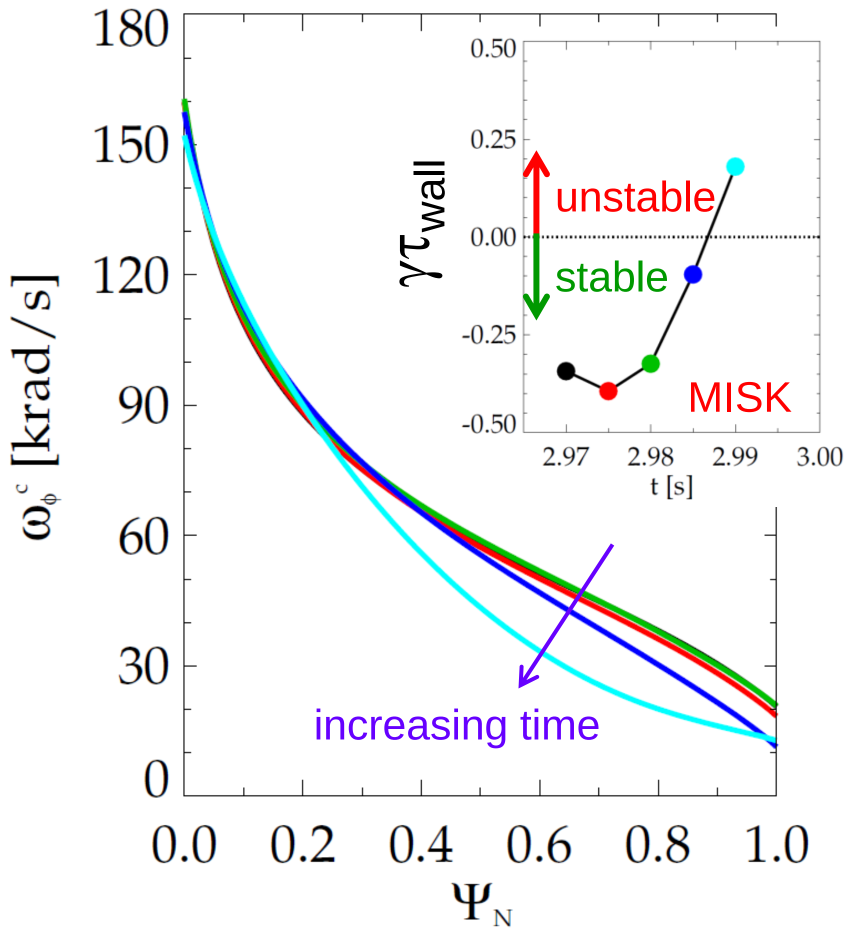
precession drift bounce collisionality

Some NSTX / MISK analysis references

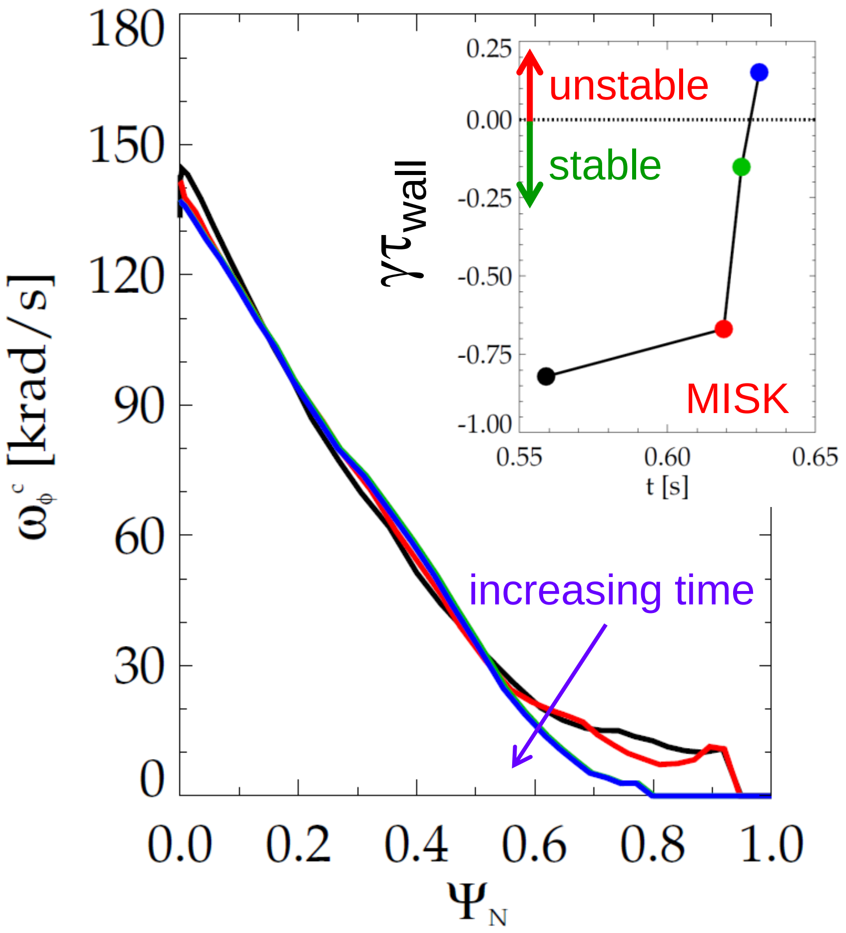
J. Berkery *et al.*, PRL **104**, 035003 (2010)
S. Sabbagh, et al., NF **50**, 025020 (2010)
J. Berkery *et al.*, PRL **106**, 075004 (2011)
J. Berkery *et al.*, PoP **21**, 056112 (2014)
J. Berkery *et al.*, PoP **21**, 052505 (2014) (benchmarking paper)

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

DIII-D (minor disruption)

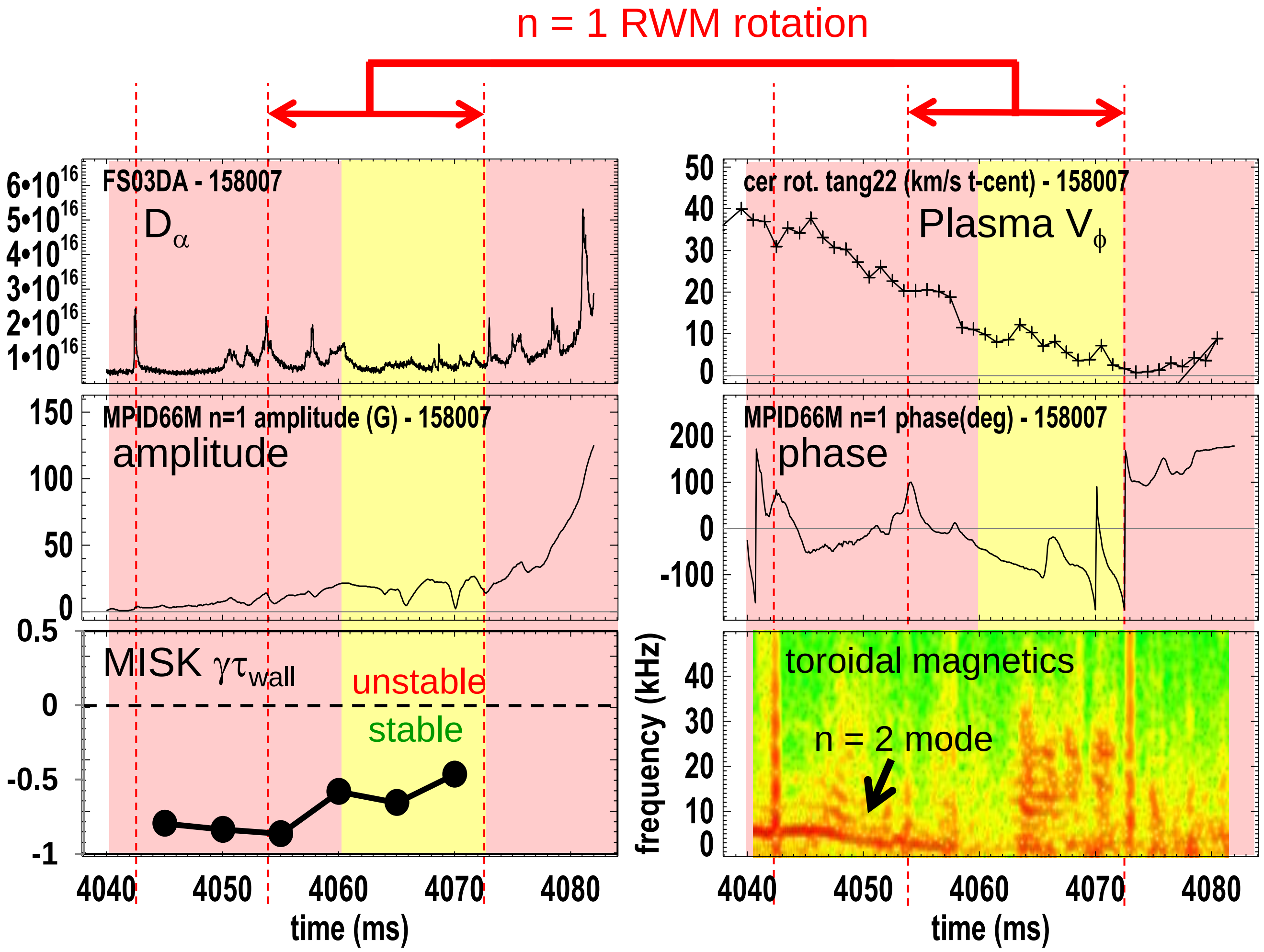


NSTX (major disruption)



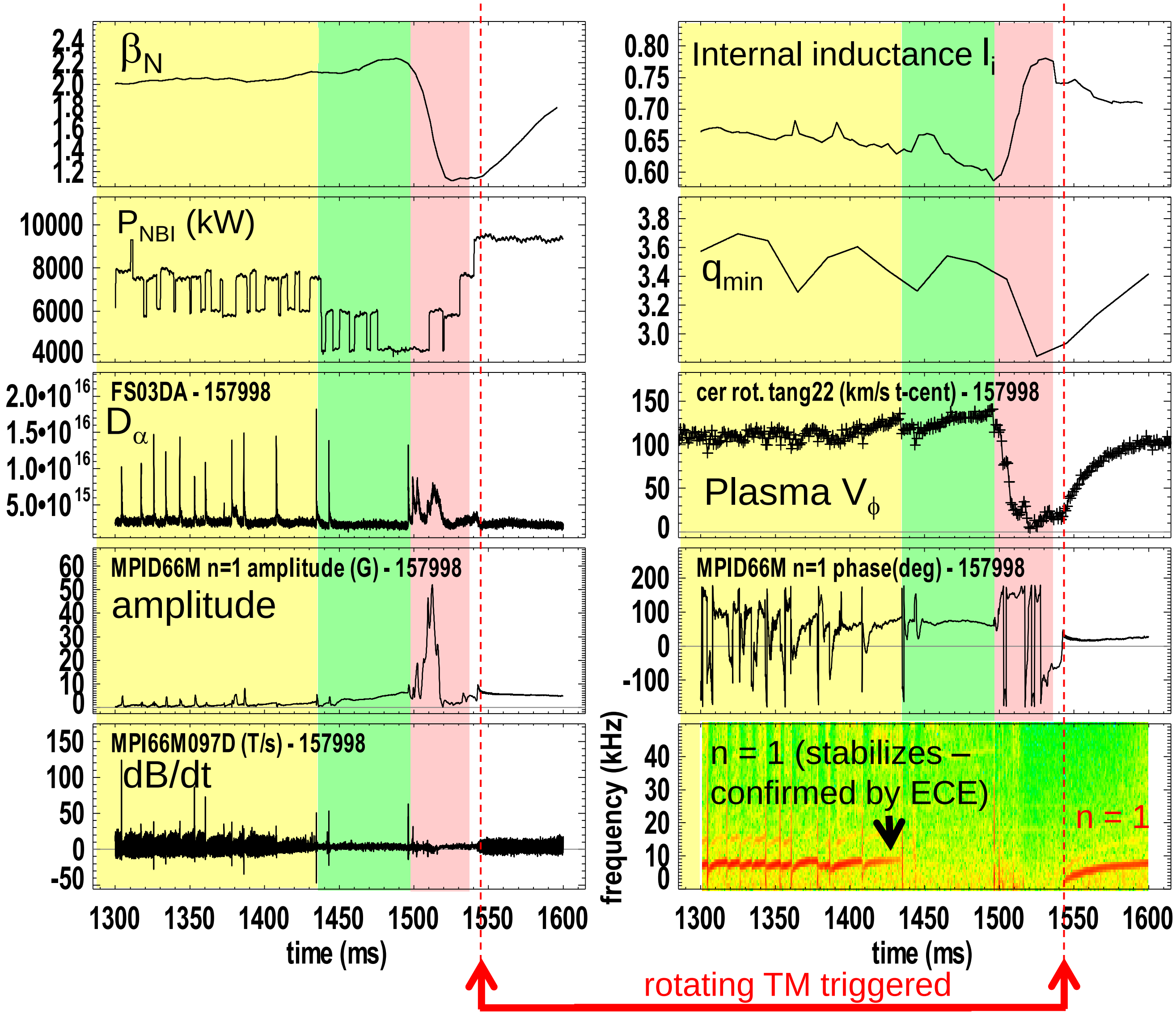
2. Full current quench disruption occurs as RWM grows following mode rotation at high β_N and low V_ϕ

- RWM evolution (β_N=3.3)
  - No n = 1 rotating TM present
    - n = 2 mode stabilizes
- RWM grows to large amplitude (21 G)
- RWM then rotates, increasing rotation speed at later times
  - Rotation > $1/\tau_w$ can stabilize RWM, but…
- RWM grows strongly after bursting MHD event locks the rotating RWM
  - Linear computation indicates stability

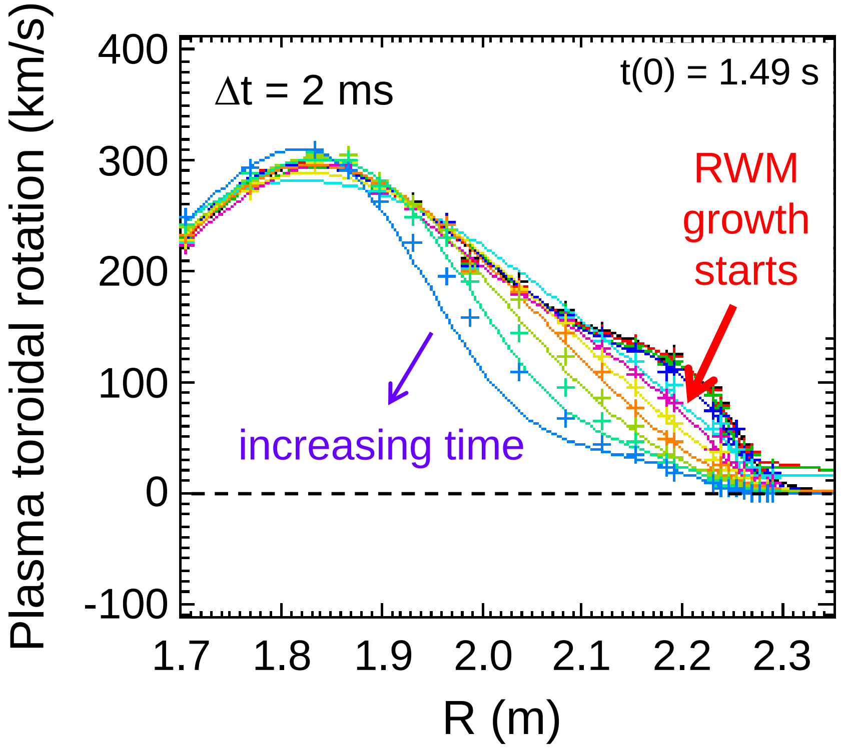


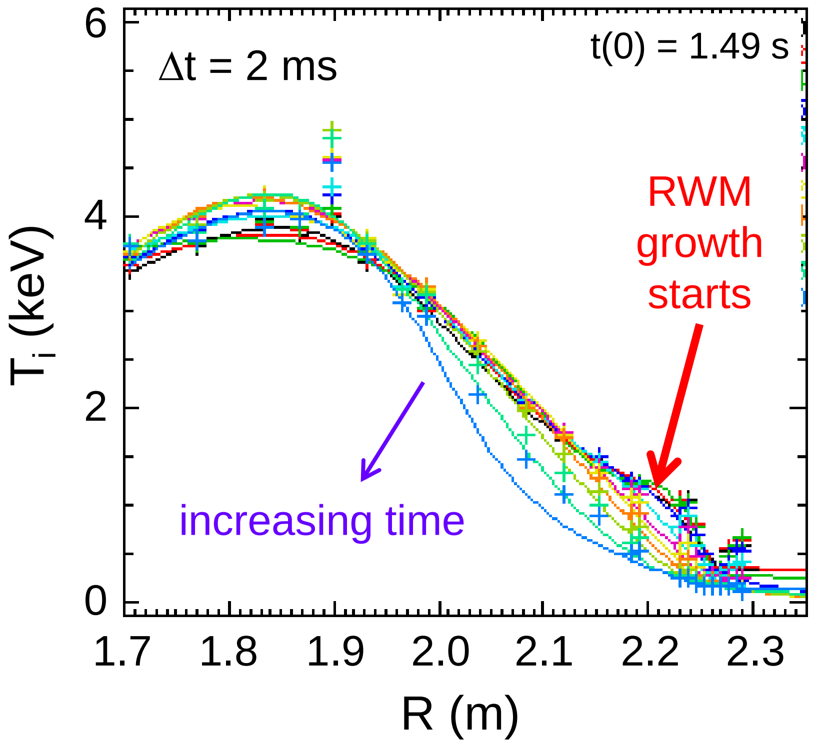
3. Minor disruption occurs as RWM grows at moderate β_N correlated with profile peaking

- ❑ RWM evolution
  - ❑ n = 1 rotating TM decays / stabilizes
  - ❑ Injected NBI power drops (by β_N control)
  - ❑ Frequency of "ELMs" decreases, β_N rises
  - ❑ n = 1 locked mode (RWM) increases
  - ❑ RWM then grows strongly (q_{min} > 3)
- ❑ TM triggered after RWM evolution



Rotation profile evolves toward a more peaked profile, T_i pedestal lost as minor disruption is approached

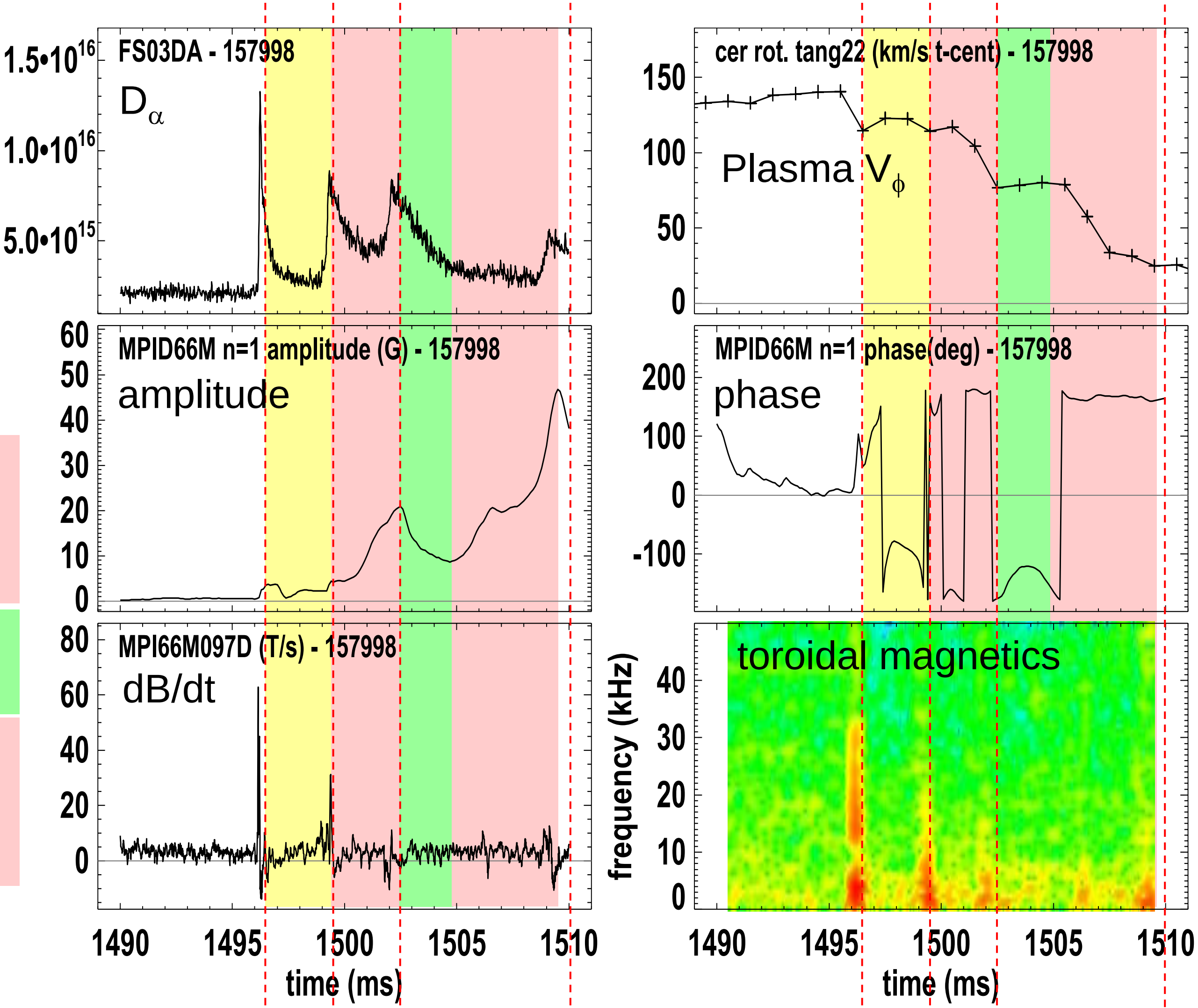




- ❑ Loss of pedestal causes profile peaking, correlates with RWM growth
  - ❑ Example of transport phenomena that can lead to instability and minor disruption, but can also be used as an indicator for disruption avoidance

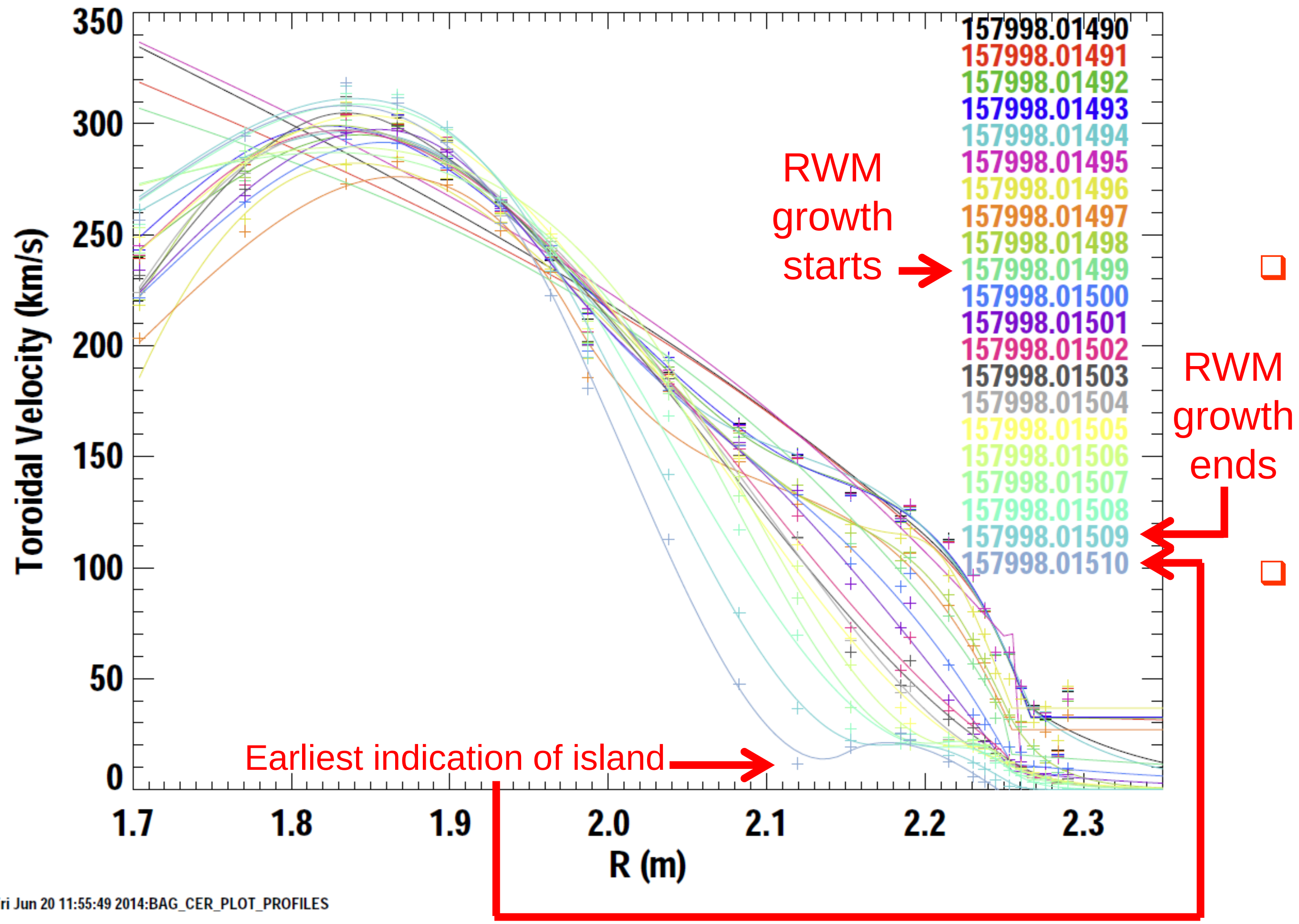
3. Periods of RWM growth and decay leading to minor disruption correlate with bursting MHD events

- ❑ First bursting MHD event causes small ω_ϕ drop
- ❑ RWM rotation starts, small V_ϕ drop and partial recovery
- ❑ Strong RWM growth after second bursting event, strong V_ϕ drop
- ❑ RWM amplitude drops after 3rd bursting event
- ❑ RWM grows strongly again without an obvious trigger



Earliest indication of significant island forming

The earliest potential indication of a locking island (from CER) comes after the n = 1 RWM has fully grown



RWM growth starts

RWM growth ends

Earliest indication of island

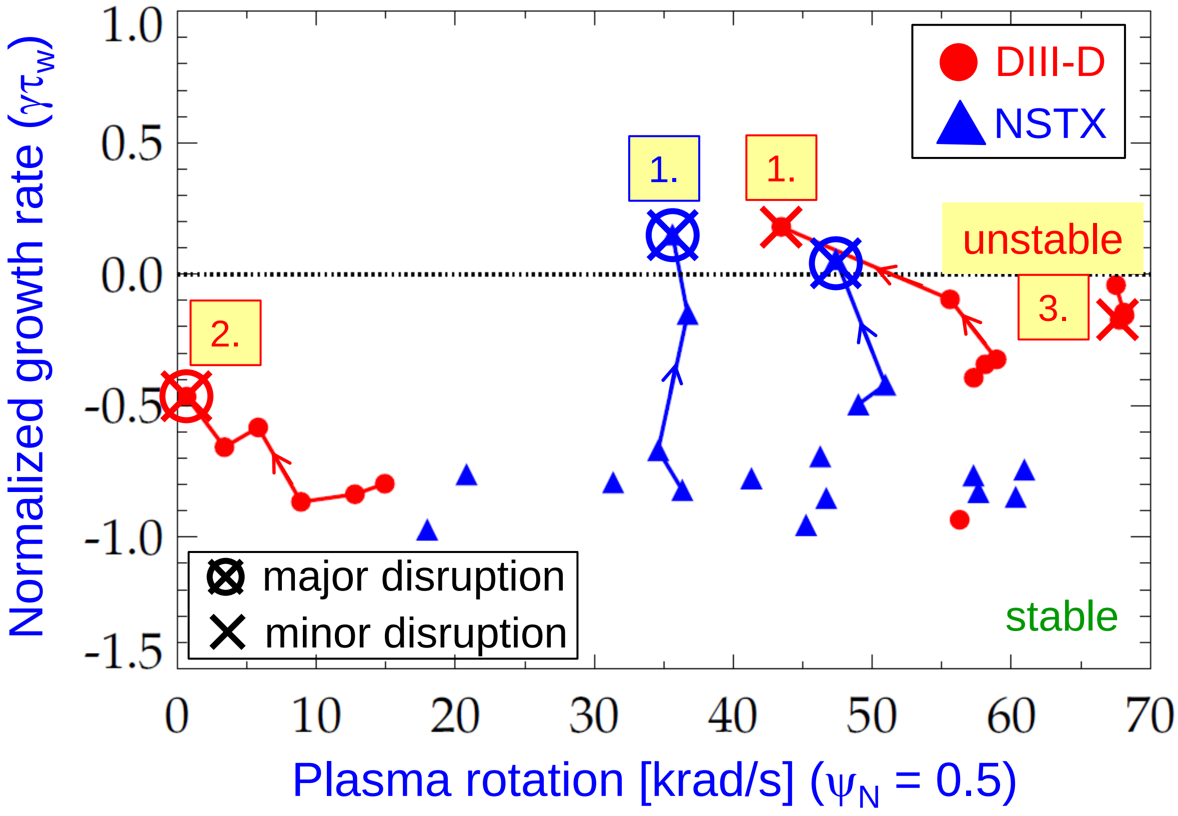
grierson Fri Jun 20 11:55:49 2014:BAG_CER_PLOT_PROFILES

- 1 ms CER indicates that an island may be forming and locking by 1.510s
- Magnetics show that n = 1 RWM reaches full amplitude by 1.509s
- Conclude that this dynamic is not caused by an island-induced loss of torque balance

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

Kinetic RWM stability analysis for experiments (MISK)



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

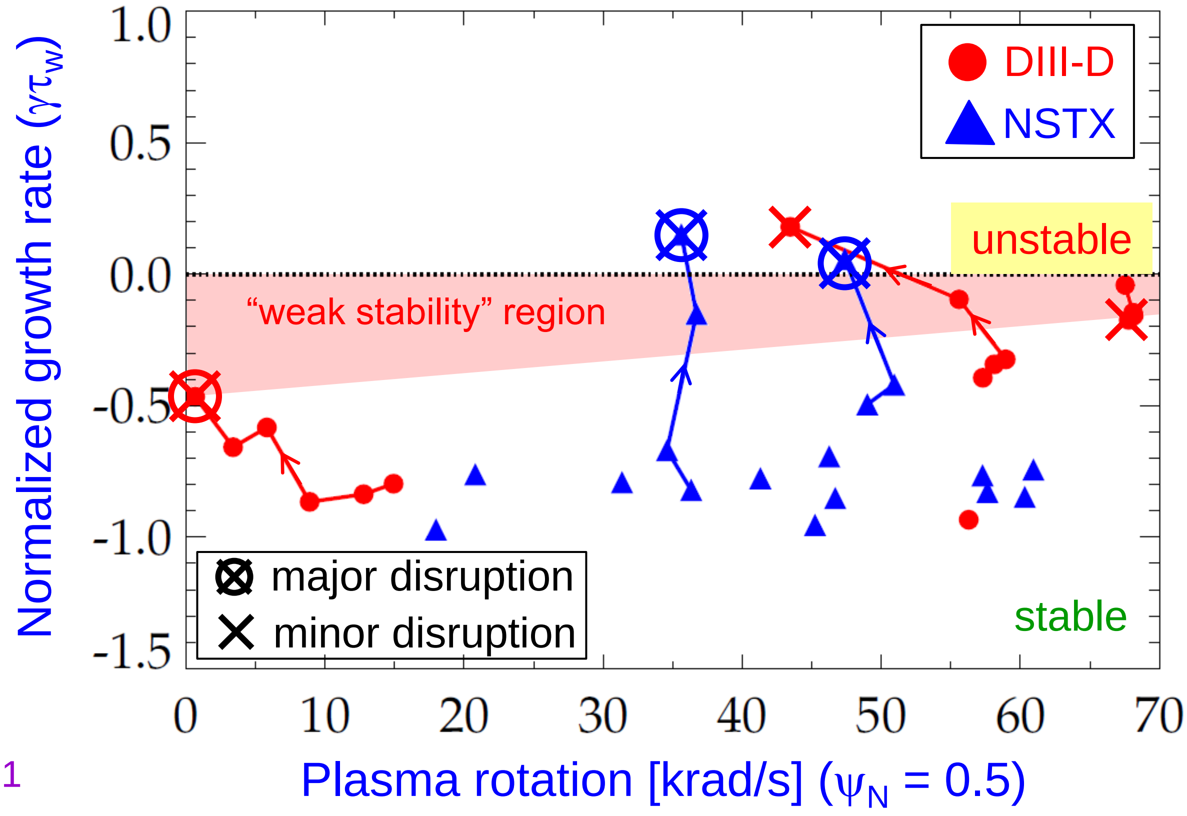
- Summary of results
  - Plasmas free of other MHD modes can reach or exceed linear kinetic RWM marginal stability
  - Bursting MHD modes can lead to non-linear destabilization before linear stability limits are reached

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

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

    - $\Delta\gamma\tau_w$ due to bursting MHD depends on plasma rotation

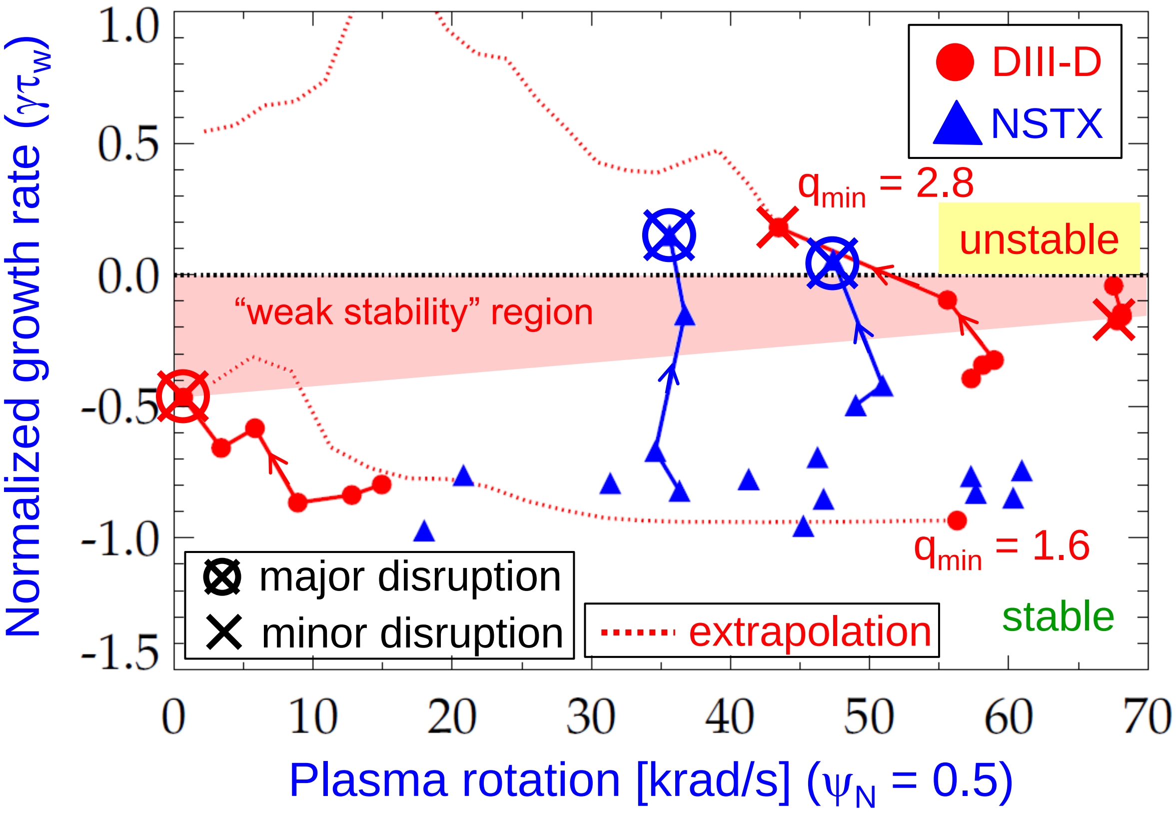
Kinetic RWM stability analysis for experiments (MISK)



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

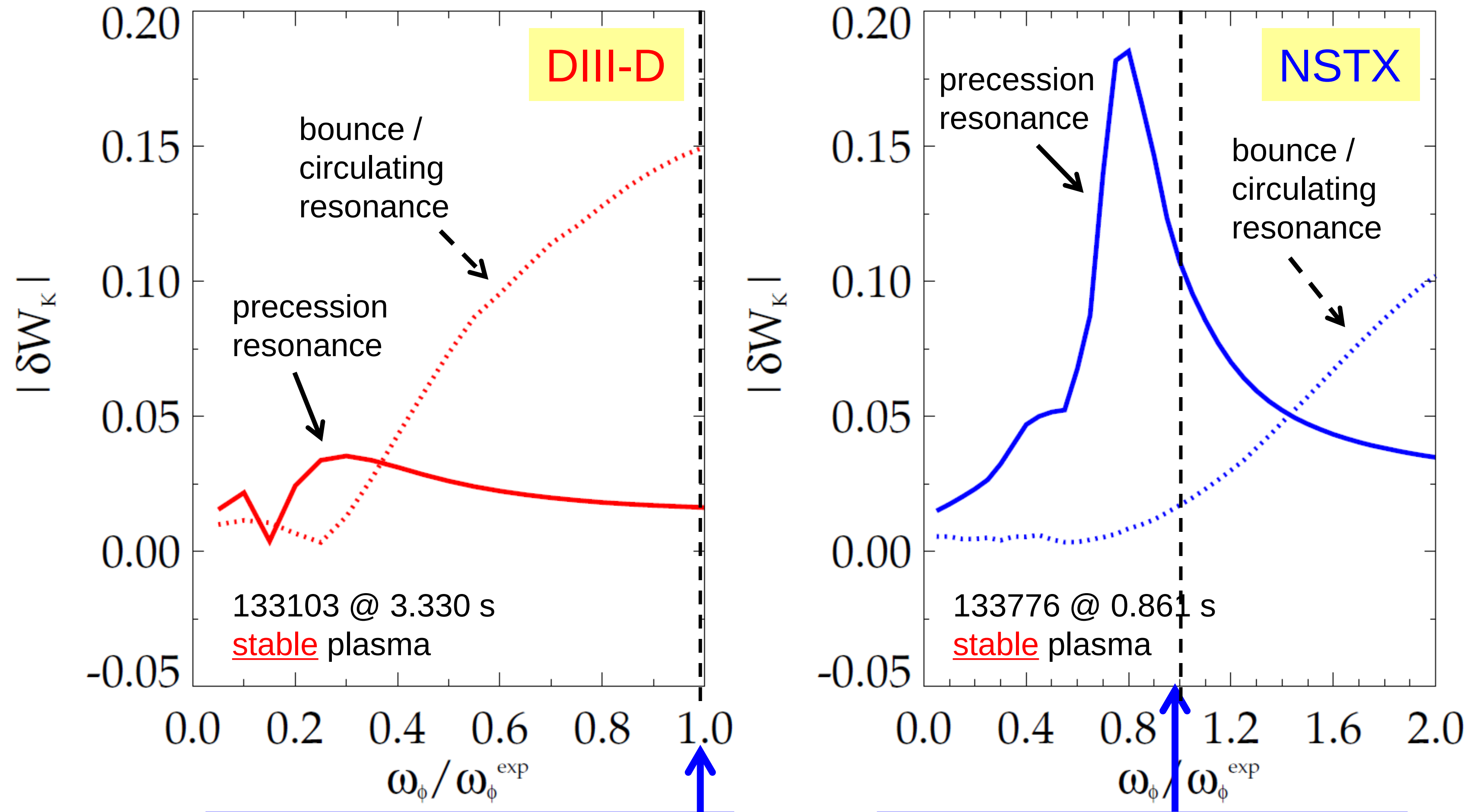
- Summary of results
  - Plasmas free of other MHD modes can reach or exceed linear kinetic RWM marginal stability
  - Bursting MHD modes can lead to non-linear destabilization before linear stability limits are reached
  - Extrapolations of DIII-D plasmas to different V_ϕ show marginal stability is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

Kinetic RWM stability analysis for experiments (MISK)



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)

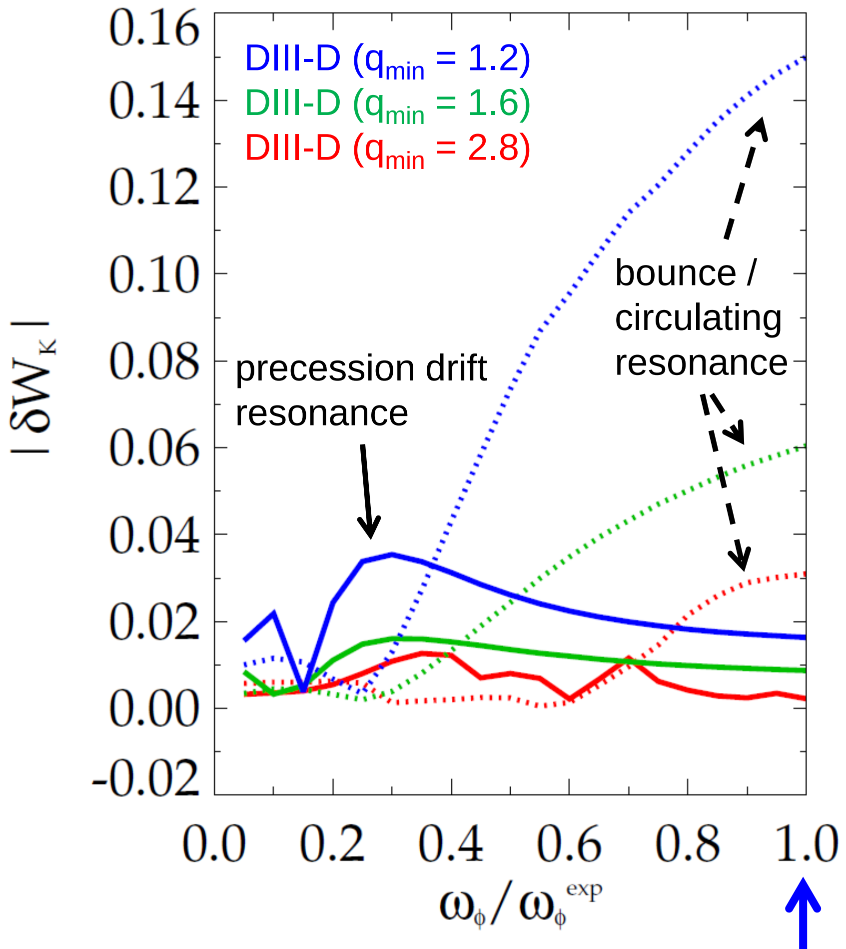


DIII-D experimental rotation profile

NSTX experimental rotation profile

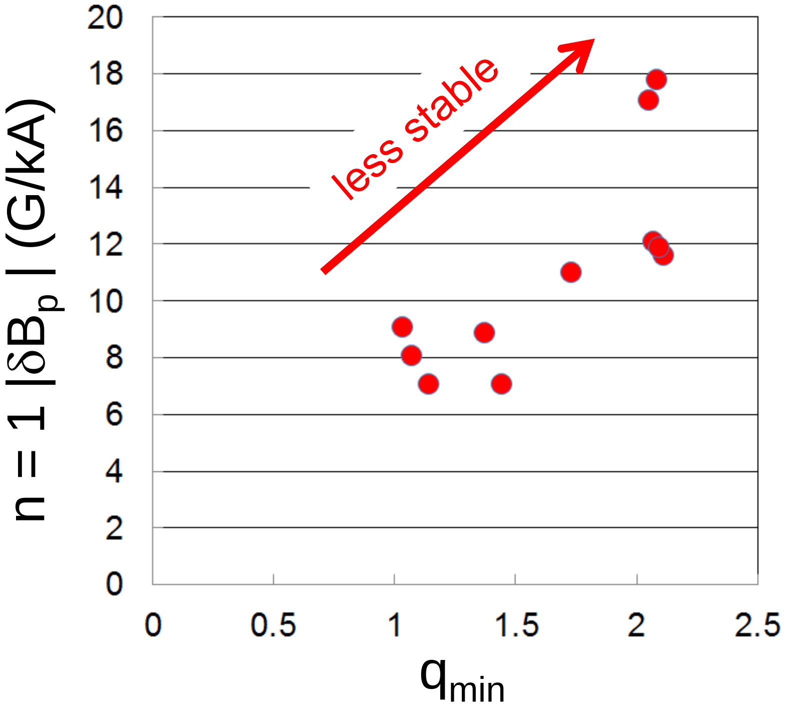
Increased RWM stability measured in DIII-D plasmas as q_{min} is reduced is consistent with kinetic RWM theory

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



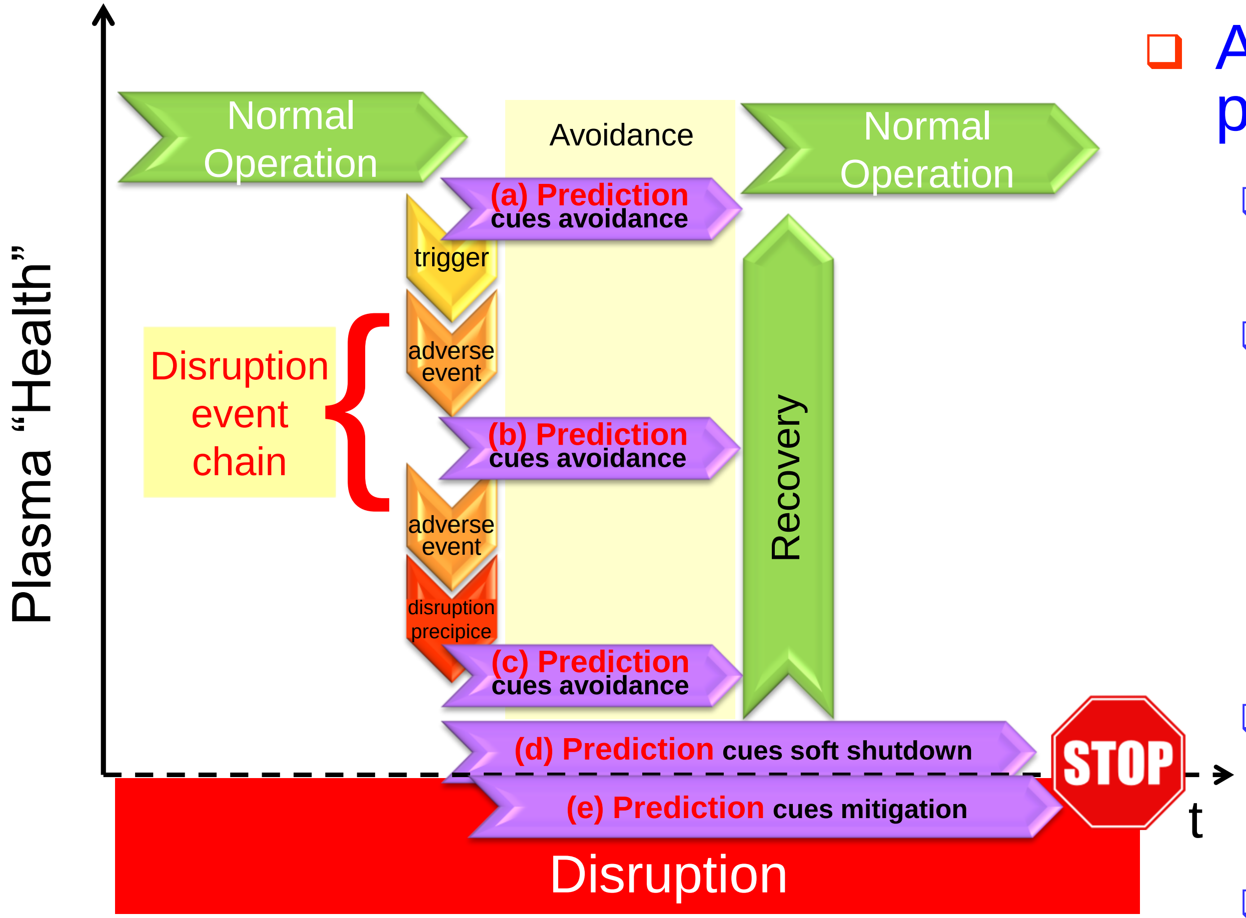
DIII-D experimental rotation profile

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

Talk PART 2: Disruption event chain characterization capability started for NSTX-U

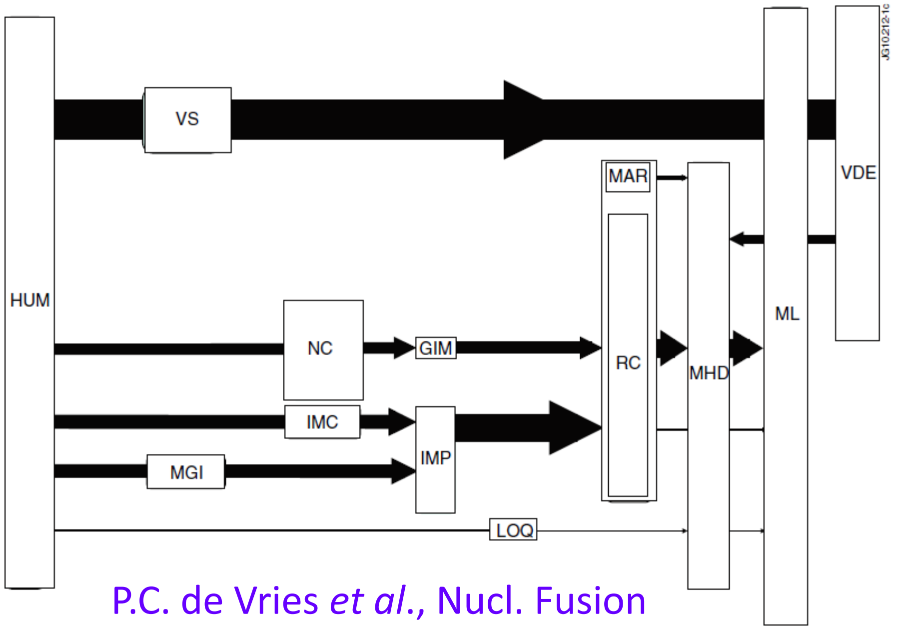


General code written (Python) to address the first step – initial test runs started using NSTX data

- 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

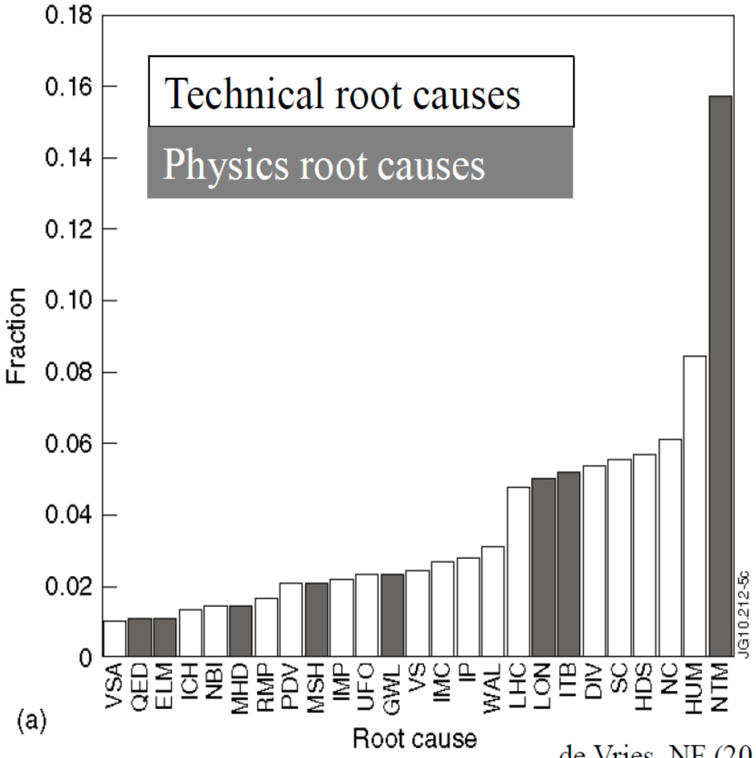
JET disruption event characterization – pioneering effort (de Vries) which provides a strong precedent

JET disruption event chains



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

Related disruption event statistics



de Vries, NF (2011)

P. de Vries disruption event chain analysis for JET performed by hand – need to automate

NSTX-U DPAM Working Group Mtg: List of disruption chain events defined (~ P. deVries), interested individuals identified

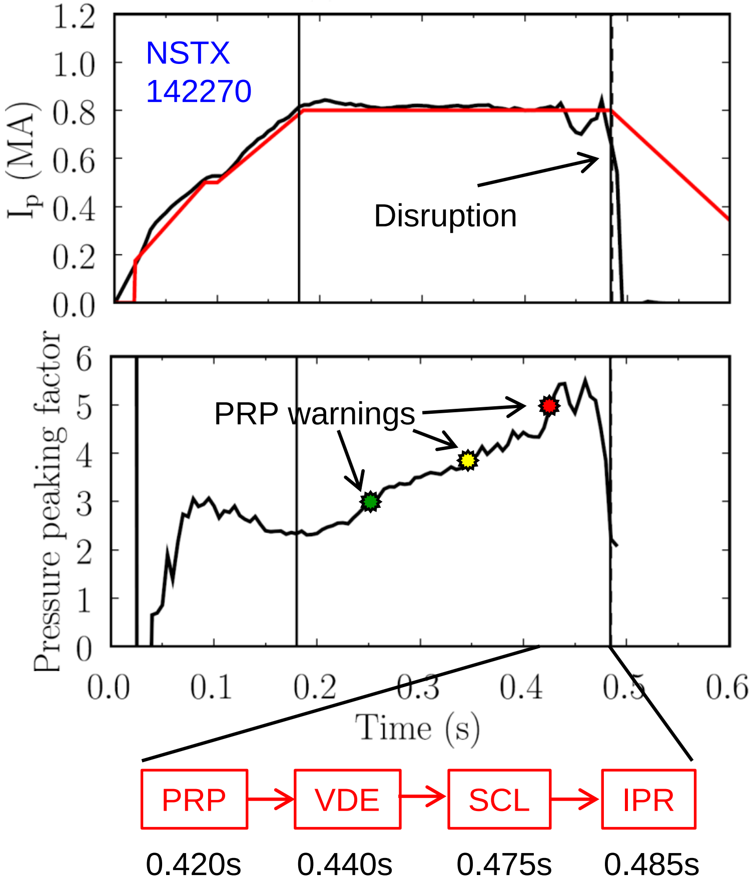
- Impurity control (NC)
  - bolometry-triggered shutdown (SPG); "tailoring" radiation-induced TM onset (LD, DG)
  - change plasma operational state / excite ELMs, etc. (TBD – perhaps JC)
- Greenwald limit (GWL)
  - density/power feedback, etc. (DB)
- Locked TM (LTM)
  - TM onset and stabilization conditions, 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
raman@pppl.gov

Disruption Characterization Code now yielding initial results: disruption event chains, with related quantitative warnings (1)

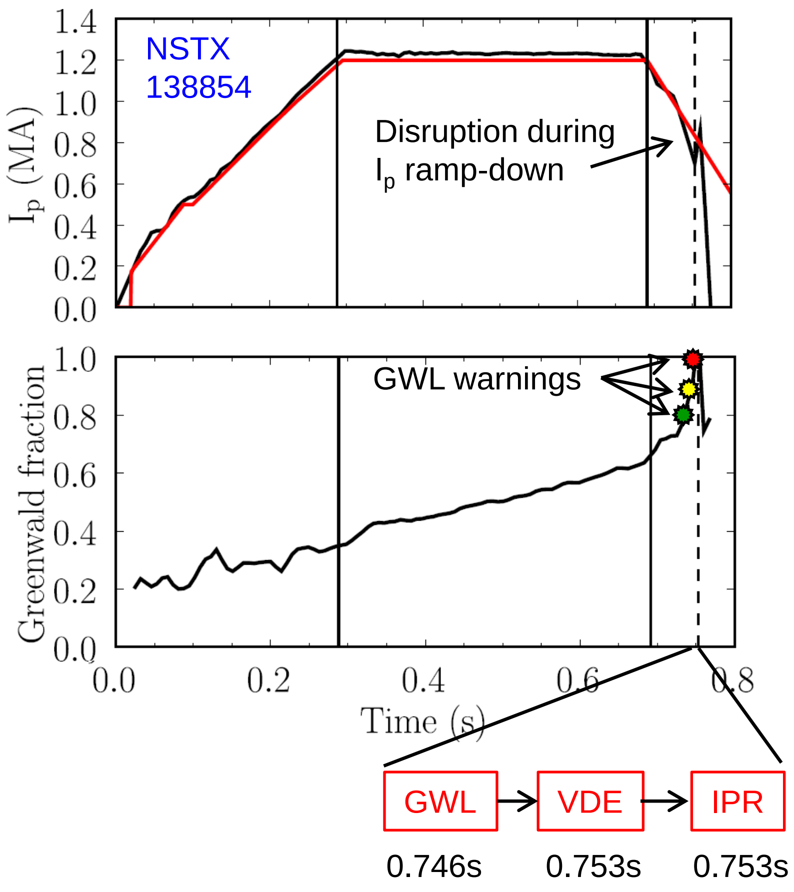


- 10 physical disruption chain events and related quantitative warning points are presently defined in code
  - Easily expandable, portable

- 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. Berkery, S.A. Sabbagh, Y.S. Park

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



GWL → VDE → IPR

0.746s 0.753s 0.753s

- <u>This example</u>: 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. Berkery, S.A. Sabbagh, Y.S. Park

Unification of DIII-D / NSTX experiments and analysis gives improved RWM understanding for disruption avoidance

- ❑ Growing RWM amplitude found at significant levels of plasma rotation in both devices, the underlying basic dynamics shown in simple models
- ❑ Linear kinetic RWM marginal stability limits can describe disruptive limits in plasmas free of other MHD modes
- ❑ Complementarity found: at similar high rotation, kinetic RWM stabilization physics is dominated by bounce orbit resonance in DIII-D, and by ion precession drift resonance in NSTX
- ❑ Strong bursting MHD modes can lead to non-linear mode destabilization before linear stability limits are reached
- ❑ **Disruption avoidance may be aided by this understanding, e.g.**
  - ❑ Use plasma rotation control to avoid unfavorable V_ϕ profiles based on kinetic RWM analysis
  - ❑ Avoid or control slow RWM rotation that indicates a dangerous state of "weak stability" leading to growth
  - ❑ Avoid computed "weak stability" region when strong bursting MHD is observed, OR stabilize the bursting modes

Research in today's presentation is part of NSTX-U's evolving capabilities for disruption prediction/avoidance

Sensor/predictor (CY available)	Control/Actuator (CY available)
Low frequency MHD (n=1,2,3): 2003	Physics model-based RWM state-space control (2010)
Low frequency MHD spectroscopy (open loop: 2005)	Dual-component RWM sensor control (closed loop: 2008)
r/t RWM state-space controller observer (2010)	NTV rotation control (open loop: 2003) (+NBI closed loop ~ 2017)
Real-time rotation measurement (2015)	Safety factor control (closed loop ~ 2016-17)
Kinetic RWM stabilization real-time model (2016-17)	Control of β_N (closed loop: 2007)
MHD spectroscopy (r/t) (in NSTX-U 5 Year Plan)	Upgraded 3D coils (NCC) (in NSTX-U 5 Year Plan)

- ❑ Back-up slides give further details on some of these existing/planned capabilities

Backup slides

Near 100% disruption avoidance is an urgent need for ITER, FNSF, and future tokamaks

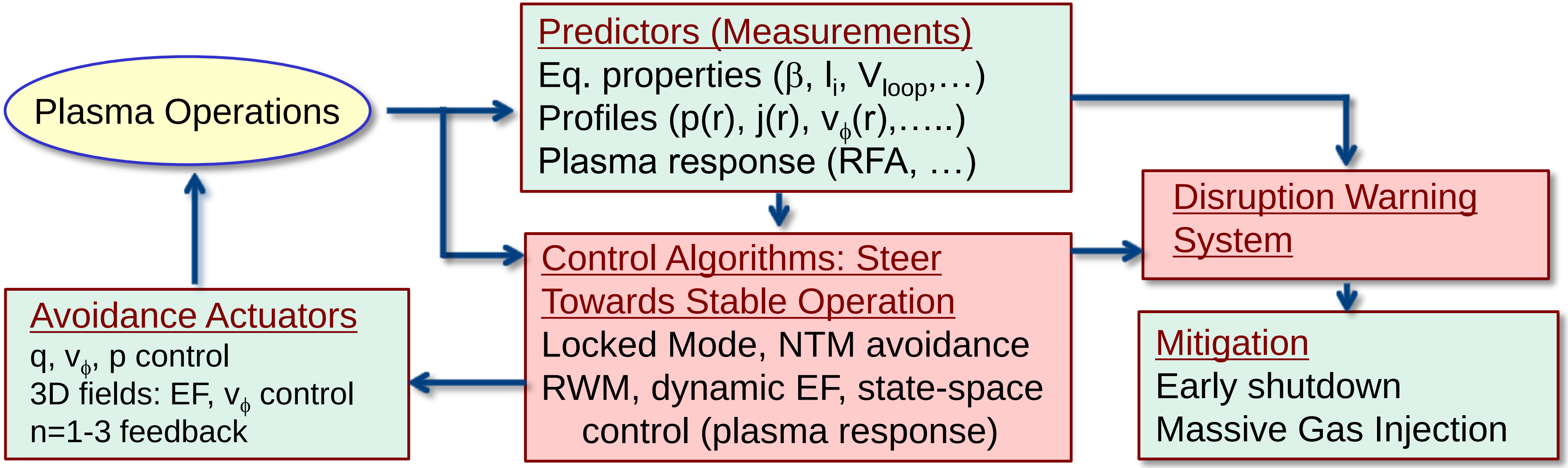
- This is the new “grand challenge” in tokamak stability research
  - ❑ Can be done! (JET: < 4% disruptions w/C wall, < 10% w/ITER-like wall)
    - ITER disruption rate: < 1 - 2% (energy load, halo current); << 1% (runaways)
  - ❑ Disruption prediction, avoidance, and mitigation (*PAM*) is multi-faceted, best addressed by focused, national effort (multiple devices/institutions)
  - ❑ Serves FES strategic planning charge; pervades 3 of 5 ReNeW themes
- Strategic plan summary: Utilize and expand upon successes in stability and control research – synergize elements
  - ❑ Add focused, incremental support for US research programs to show near 100% disruption PAM success using quantifiable figures of merit
  - ❑ Leverage upgraded facilities with heightened focus on disruption PAM
- Leverage US university expertise, international collaborations
  - ❑ e.g. JET high power operation, KSTAR long-pulse operation above ideal MHD stability limits, US university scientists, post-docs, and students

A relatively modest incremental investment will greatly enhance quantifiable progress

Near 100% disruption avoidance is an urgent need for ITER; NSTX-U is developing disruption avoidance research

- 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)
  - Disruption prediction, avoidance, and mitigation (*PAM*) is multi-faceted, best addressed by a focused, (inter)national effort (multiple devices/institutions)

- Disruption prediction by multiple means will enable avoidance via profile or mode control or mitigation by MGI



Plasma Operations

Predictors (Measurements)
Eq. properties (β, l_i, V_{loop},…)
Profiles ($p(r)$, $j(r)$, $v_\phi(r)$,…..)
Plasma response (RFA, …)

Control Algorithms: Steer Towards Stable Operation
Locked Mode, NTM avoidance
RWM, dynamic EF, state-space control (plasma response)

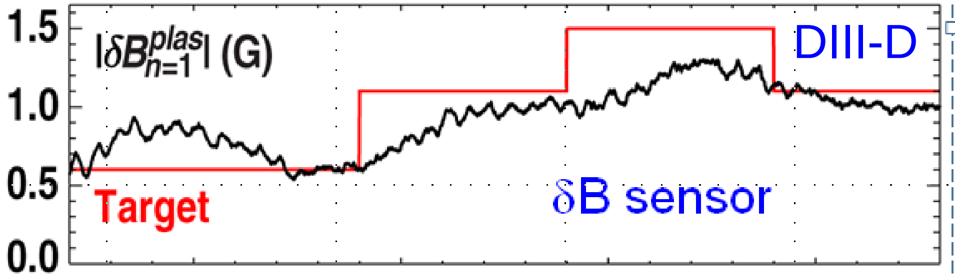
Disruption Warning System

Mitigation
Early shutdown
Massive Gas Injection

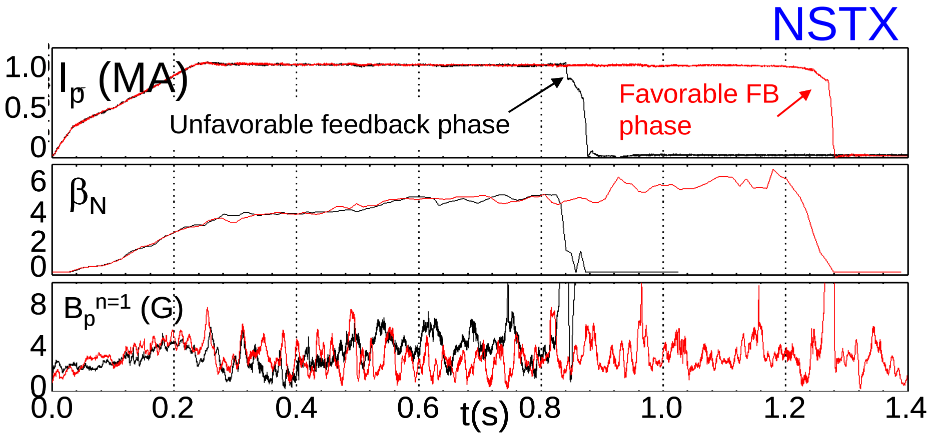
Avoidance Actuators
q, v_ϕ, p control
3D fields: EF, v_ϕ control
n=1-3 feedback

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

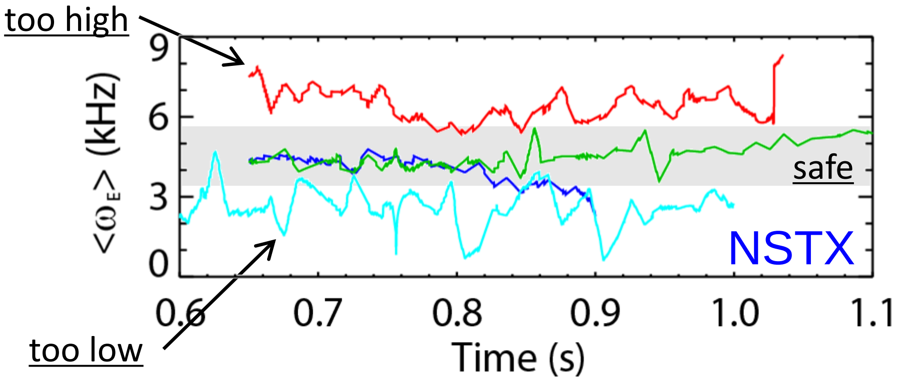
- ❑ MHD Spectroscopy
  - ❑ Use real-time measurement of plasma global mode stability to “steer” toward increased stability



- ❑ 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



Kinetic effects arise from the perturbed pressure, are calculated in MISK from the perturbed distribution function

Force balance:

$$\rho\frac{d\mathbf{v}}{dt} = \mathbf{j}\times\mathbf{B} - \boldsymbol{\nabla}\cdot\mathbb{P}$$

leads to an energy balance:

$$\underbrace{-\frac{1}{2}\int \rho\omega^2|\boldsymbol{\xi}_\perp|^2 d\mathbf{V}}_{\text{Kinetic Energy}} = \frac{1}{2}\int \boldsymbol{\xi}_\perp^*\cdot\Big[\underbrace{\tilde{\mathbf{j}}\times\mathbf{B_0} + \mathbf{j_0}\times\tilde{\mathbf{B}} - \boldsymbol{\nabla}\tilde{p}_F}_{\text{Fluid terms}} - \boldsymbol{\nabla}\cdot\tilde{\mathbb{P}}_K\Big]d\mathbf{V}$$

δW_K is solved for in the MISK code by using $\tilde{f}$ from the drift kinetic equation to solve for $\tilde{\mathbb{P}}_K$

Change in potential energy due to perturbed kinetic pressure is:

$$\delta W_K = -\frac{1}{2}\int \boldsymbol{\xi}_\perp^*\cdot\left(\boldsymbol{\nabla}\cdot\tilde{\mathbb{P}}_K\right)d\mathbf{V}$$

$$\delta W_K = \sum_{l=-\infty}^{\infty} 2\sqrt{2}\pi^2\int\int\int\left[|\langle H/\hat{\varepsilon}\rangle|^2\frac{(\omega-\omega_E)\frac{\partial f}{\partial\varepsilon} - \frac{n}{Ze}\frac{\partial f}{\partial\Psi}}{\langle\omega_D\rangle + l\omega_b - i\nu_{\text{eff}} + \omega_E - \omega}\right]\frac{\hat{\tau}}{m_j^{\frac{3}{2}}B}\left|\frac{v_\parallel}{v}\right|\hat{\varepsilon}^{\frac{5}{2}}d\hat{\varepsilon}d(v_\parallel/v)d\boldsymbol{\Psi}$$

Precession Drift resonance

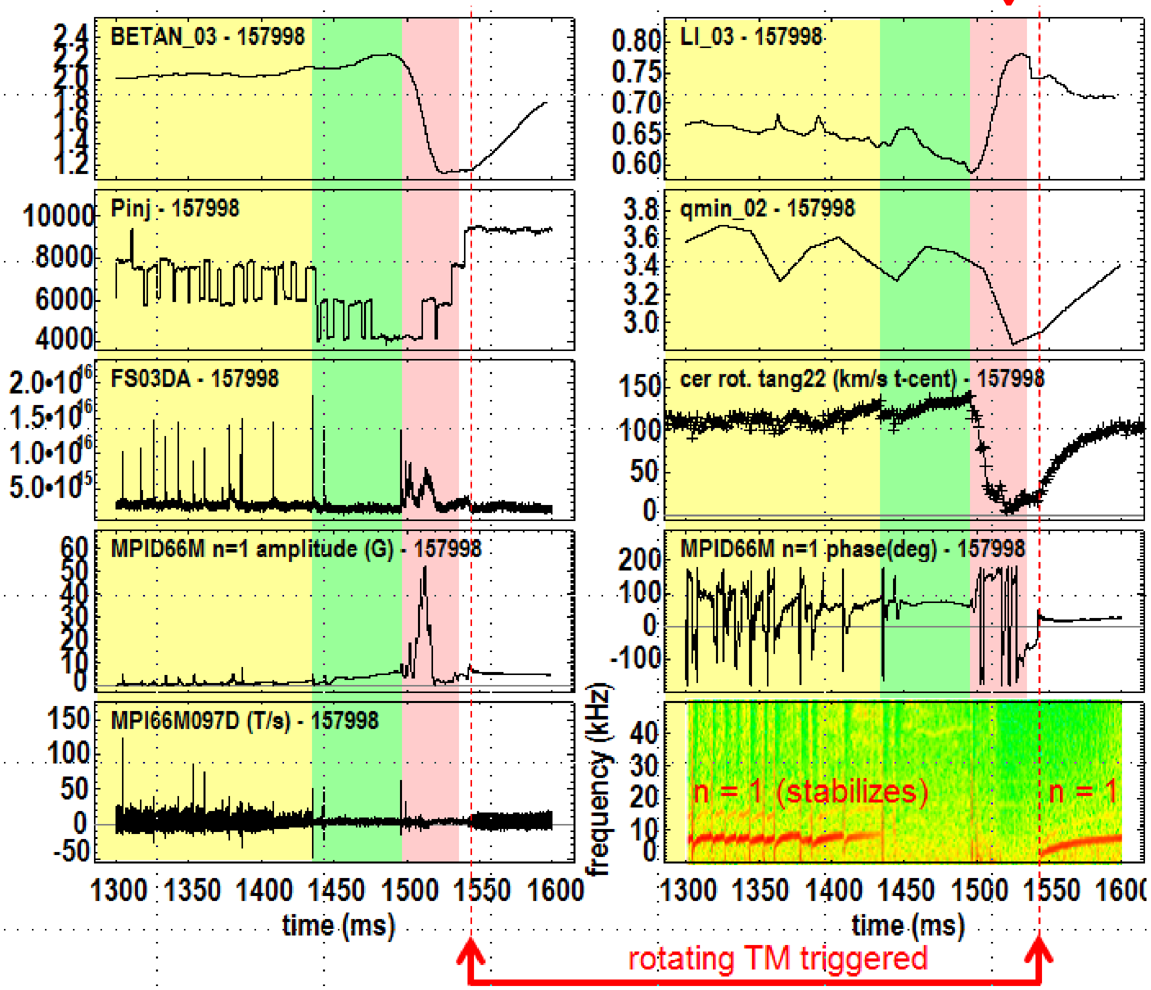
Bounce orbit resonances

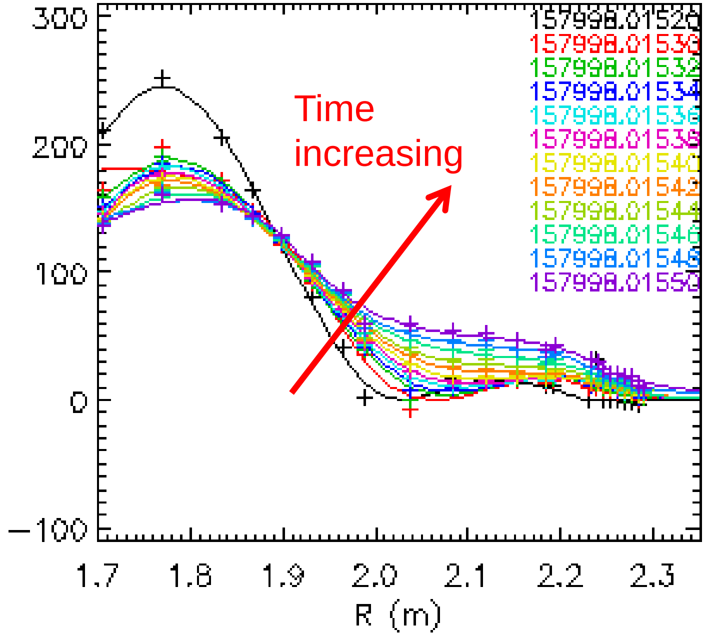
Collisionality

~ Plasma Rotation

$$\omega_E \approx \omega_\phi - \omega_{*i}$$

RWM triggers TM: CER profiles illustrate spin-up phase of the n = 1 locked tearing mode

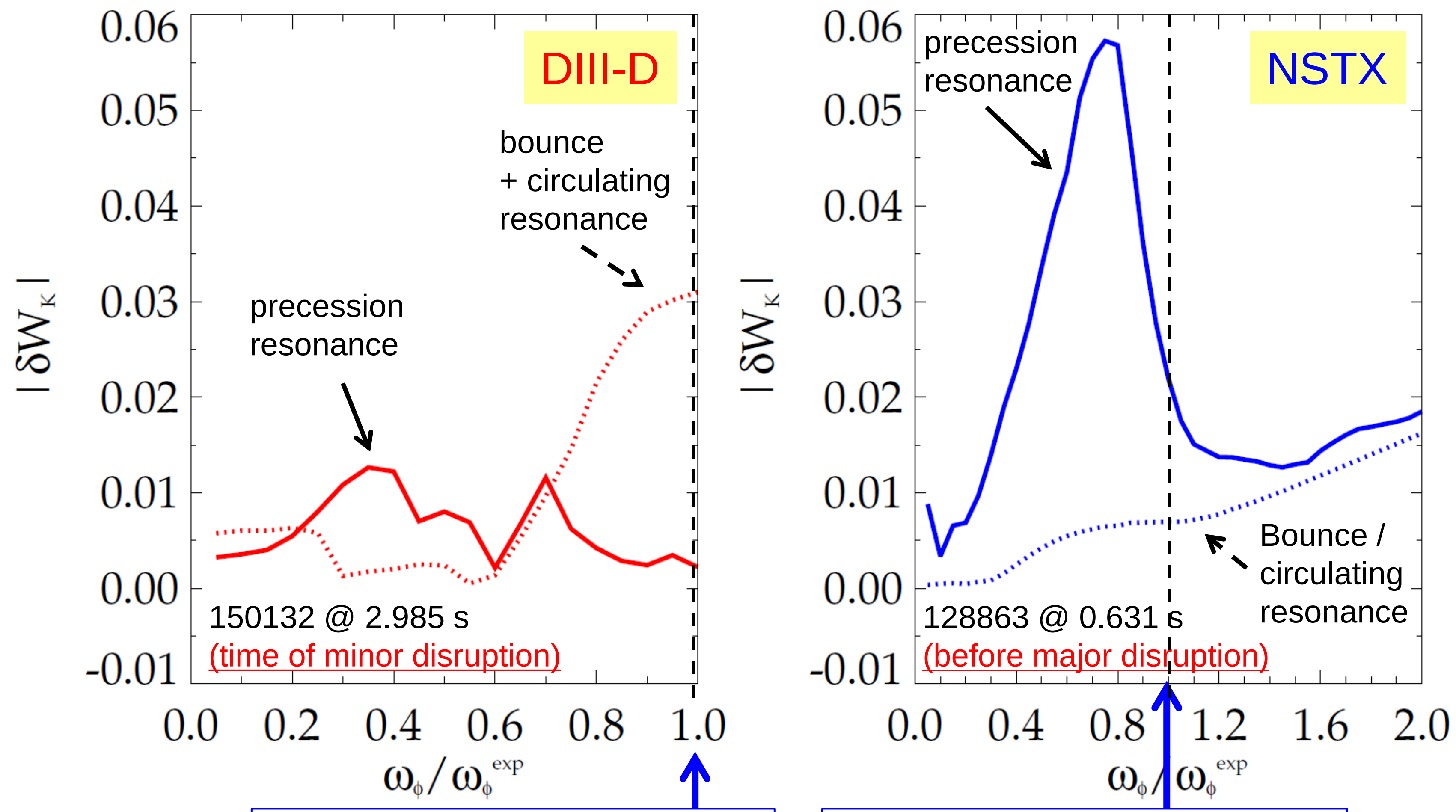




- n = 1 tearing mode initially forms as n = 1 RWM grows and decreases V_ϕ
- Locked n = 1 tearing mode spins up once n = 1 RWM decays and plasma spins back up

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

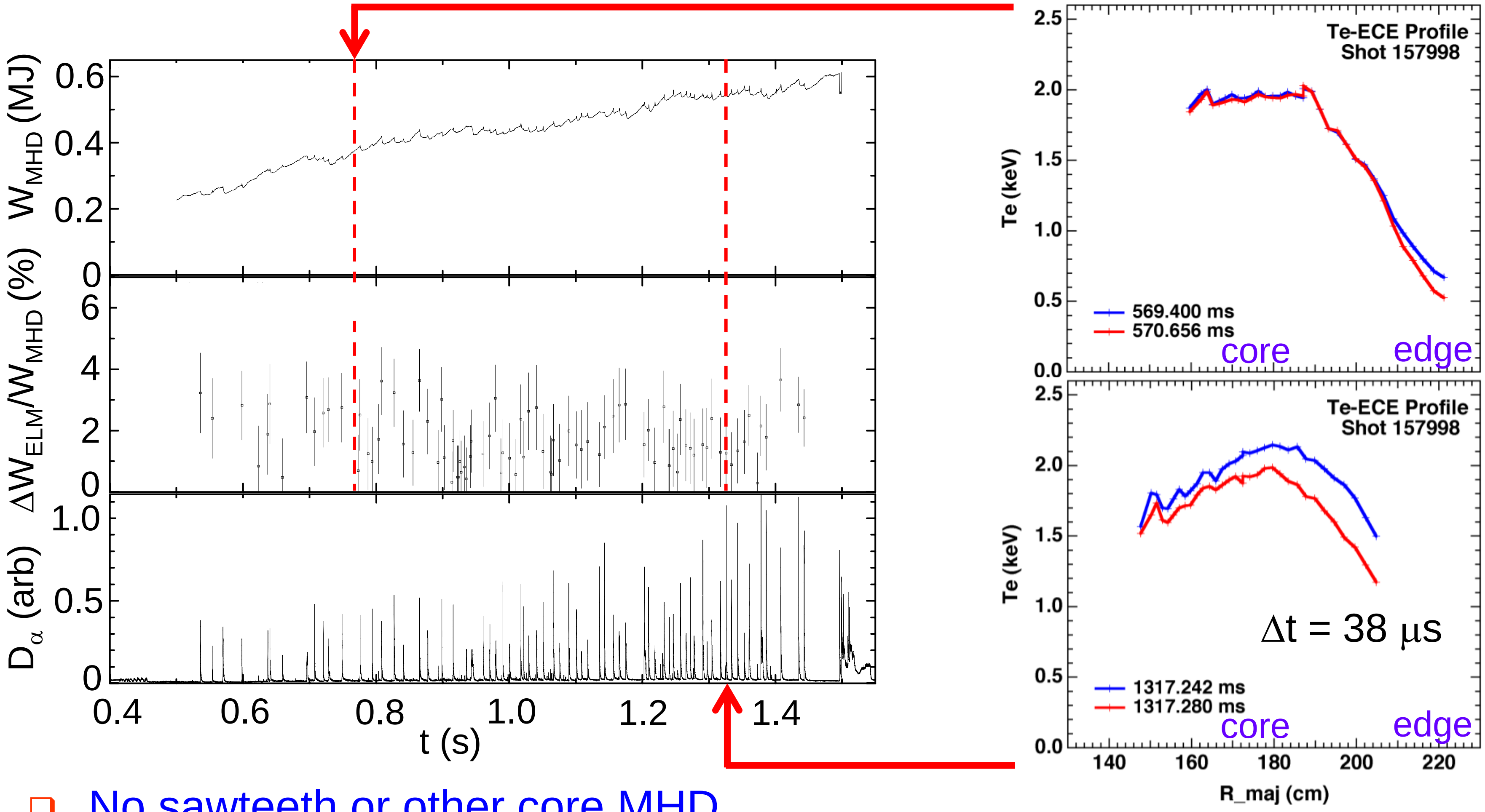
$|\delta W_K|$ for trapped resonant ions vs. scaled experimental rotation (MISK)



DIII-D experimental rotation profile

NSTX experimental rotation profile

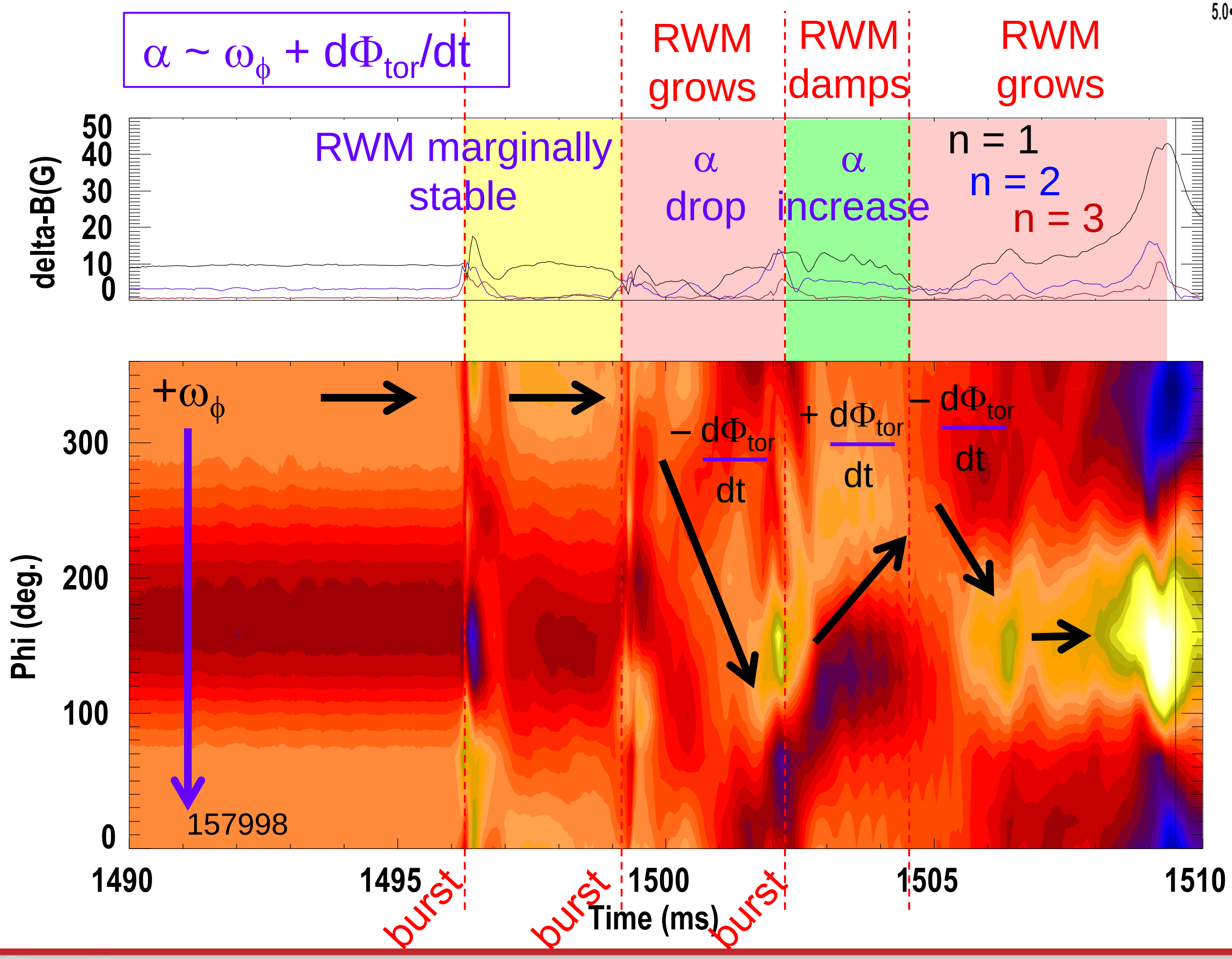
3. "ELMs" become radially extended at increased β_N; may have greater influence on RWM non-linear destabilization

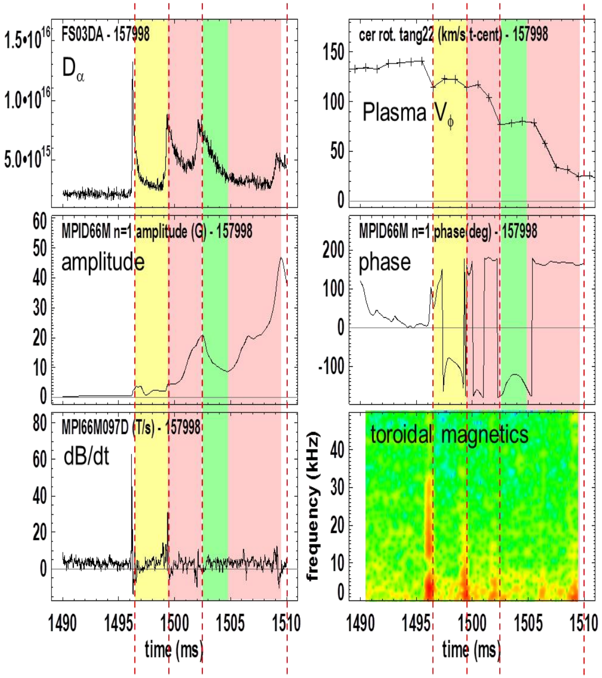


- No sawteeth or other core MHD
- Rapid bursting and quick "healing" ($\Delta t \sim 250\ \mu s$) may indicate that the internal perturbations are ideal

3. Detail of RWM marginal point toward instability or stability might be explained by mode/plasma differential rotation

- Boozer model: stability enhanced by increased differential rotation between mode and plasma ("α" parameter)





- Magnetics show n = 1,2,3 content in each bursting MHD event ("3D" mode)

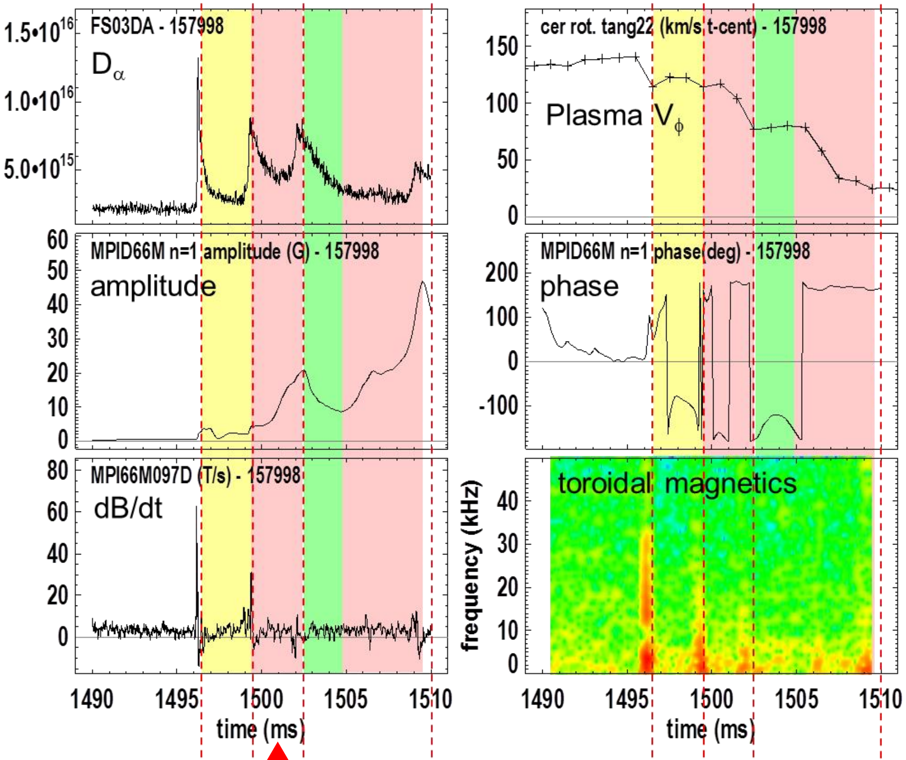
Another consistent, intriguing hypothesis is non-linear RWM destabilization caused by δB from bursting MHD event

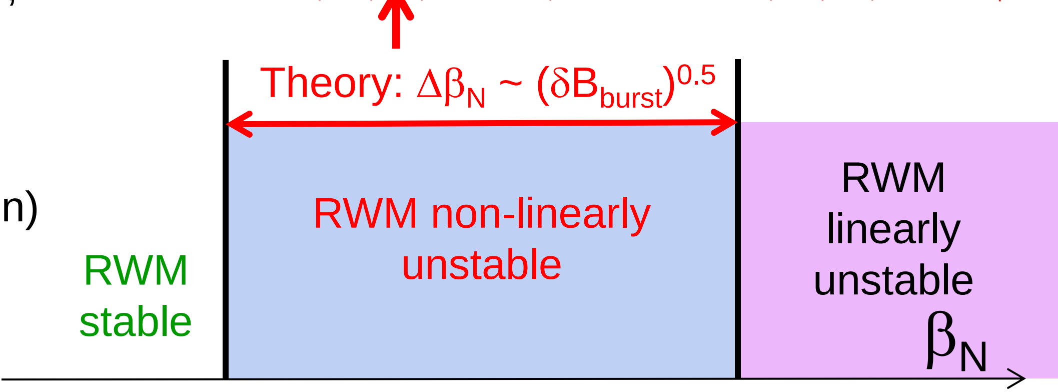
- Non-linear destabilization theory shows growth can occur below the linear instability point when other n = 1 field perturbation is present
  - Change in stability related to perturbation magnitude

    J. Bagaipo, et al., PoP **18** (2011) 122103

- Hypothesis
  - Due to δB from bursting MHD, marginally stable RWM becomes non-linearly unstable
  - As bursting MHD perturbation relaxes, RWM non-linearly destabilized region goes away
  - Finally, the RWM becomes linearly unstable, continues to grow (disruption)

What does the bursting MHD perturbation look like?





Theory: $\Delta\beta_N \sim (\delta B_{burst})^{0.5}$

RWM stable

RWM non-linearly unstable

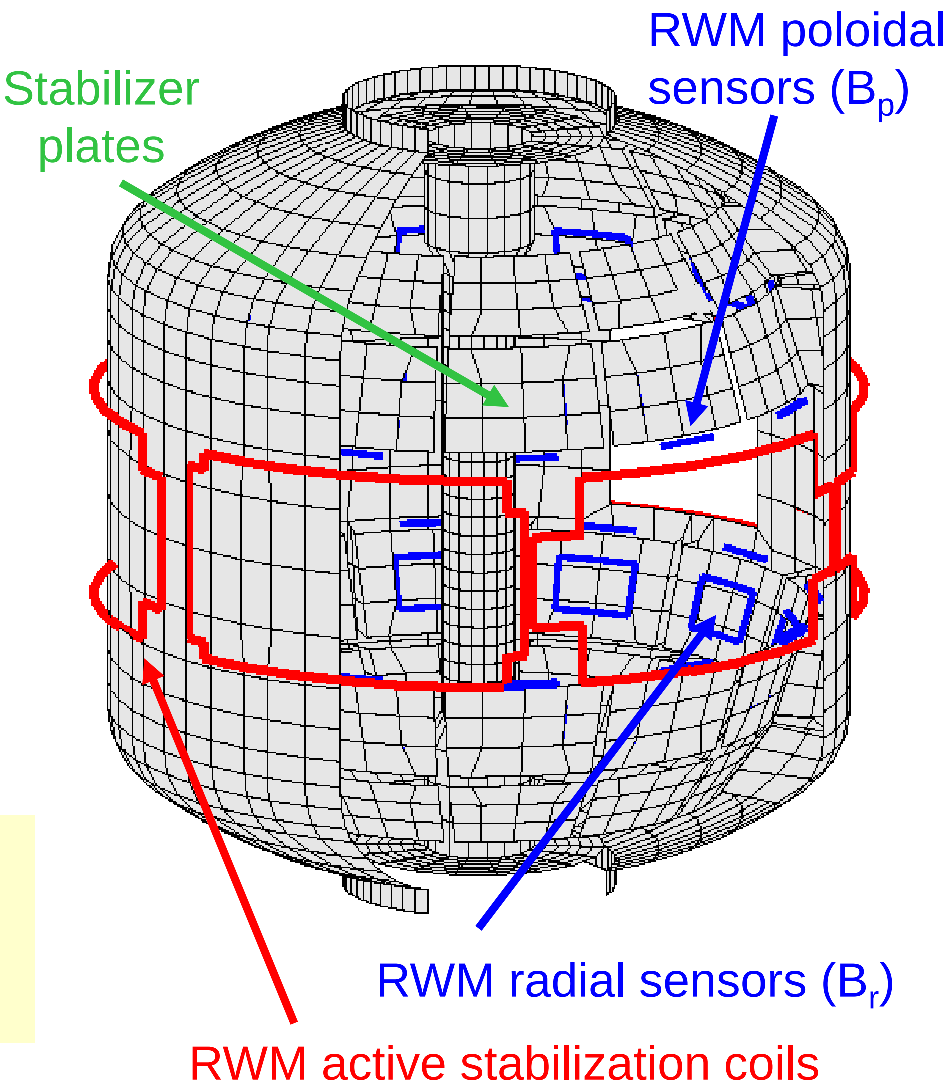
RWM linearly unstable

β_N

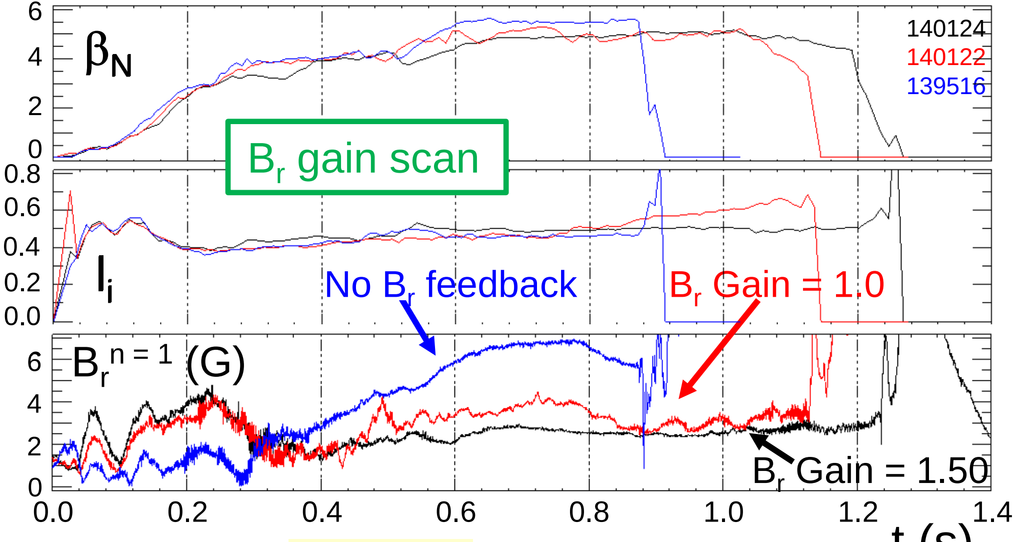
NSTX is a spherical torus equipped to study passive and active global MHD control

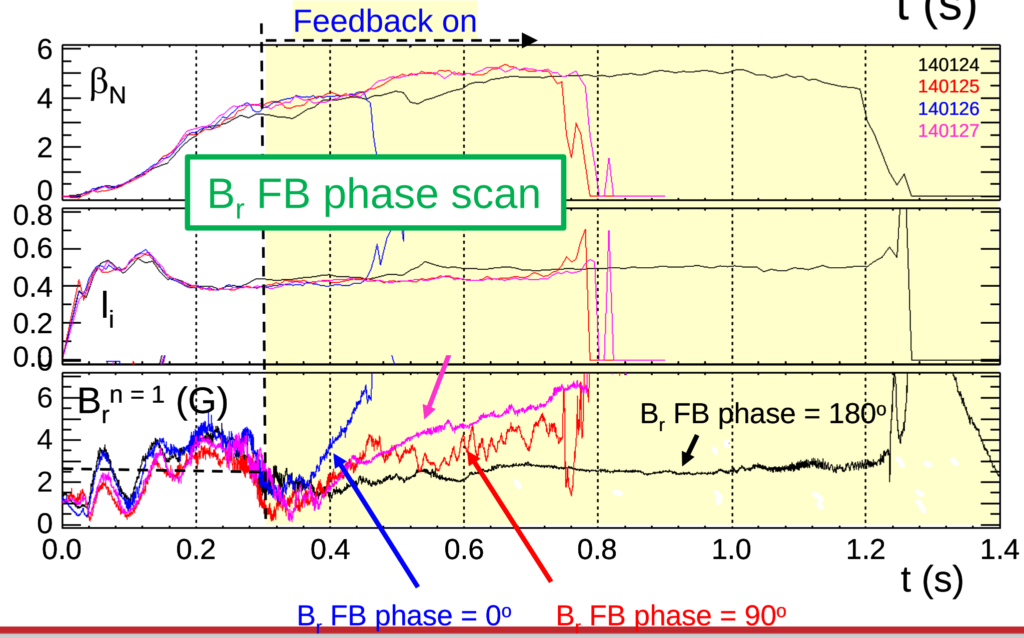
- High beta, low aspect ratio
  - R = 0.86 m, A > 1.27
  - I_p < 1.5 MA, B_t = 5.5 kG
  - $\beta_t < 40\%$, $\beta_N > 7$
- Copper stabilizer plates for kink mode stabilization
- Midplane control coils
  - n = 1 – 3 field correction, magnetic braking of ω_ϕ by NTV
  - n = 1 RWM control
- Combined sensor sets now used for RWM feedback
  - 48 upper/lower B_p, B_r

3D Structure Model



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

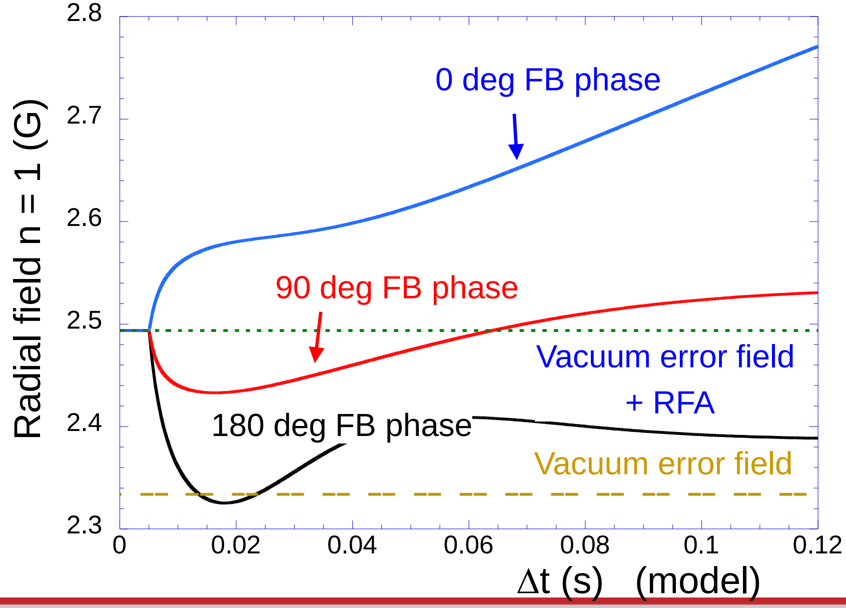




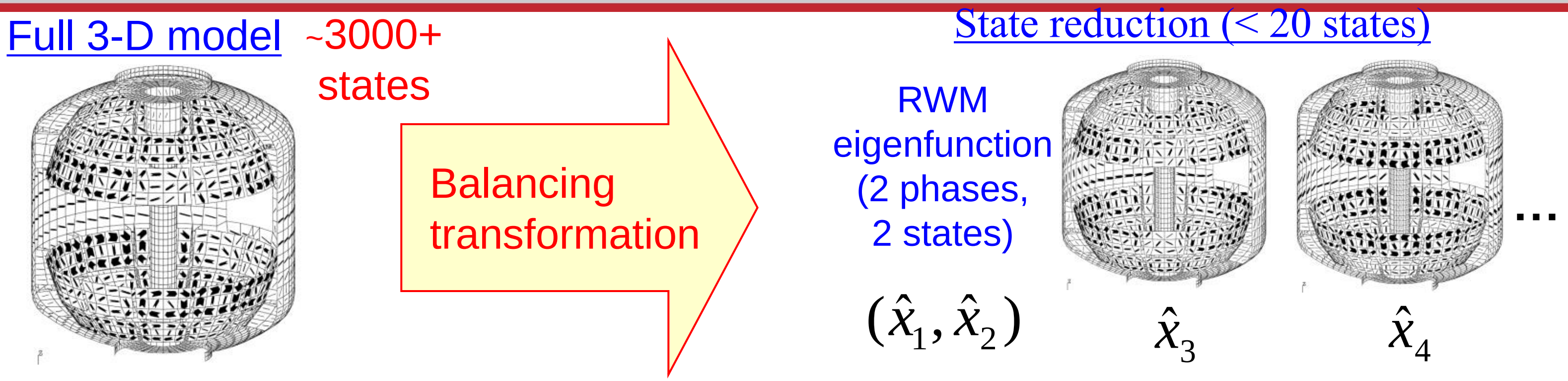
- ❑ Favorable B_p + B_r feedback (FB) settings found (low l_i plasmas)
  - ❑ Fast RWM growth ~ 2 - 3 ms control by B_p
  - ❑ B_r FB controls (~10 ms ~ $\tau_{w\text{-radial}}$) n=1 field amplification, modes
- ❑ Time-evolved theory simulation of B_r+B_p feedback follows experiment

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

Simulation of B_r + B_p control (VALEN)



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)

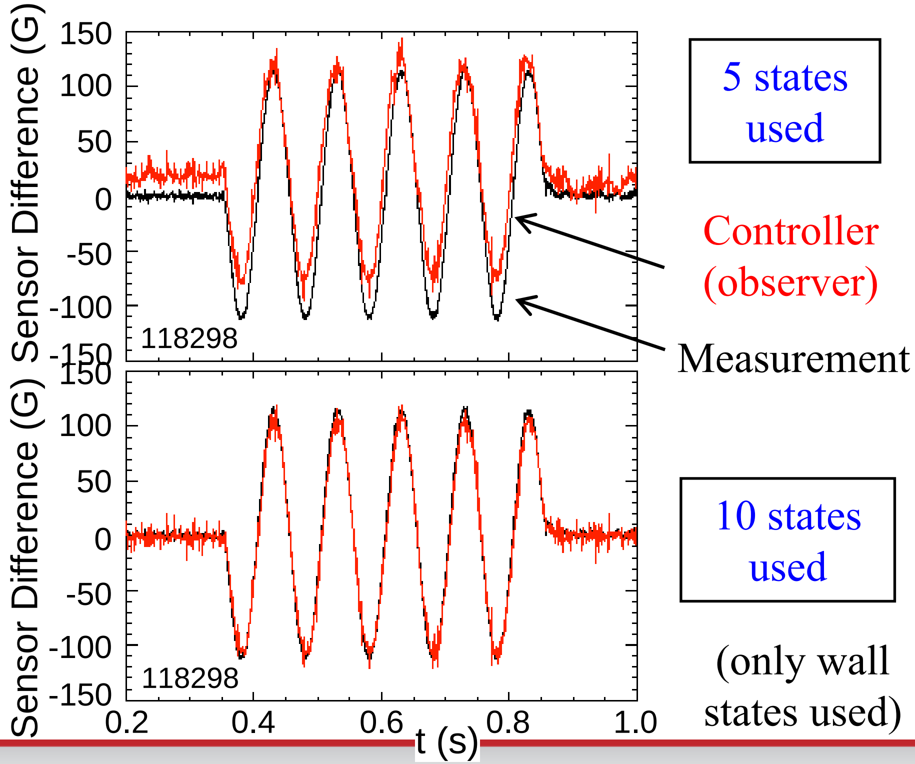
RWM eigenfunction (2 phases, 2 states)

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

- 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



New State Derivative Feedback Algorithm needed for Current Control

- State equations to advance

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

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

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

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

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

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

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

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

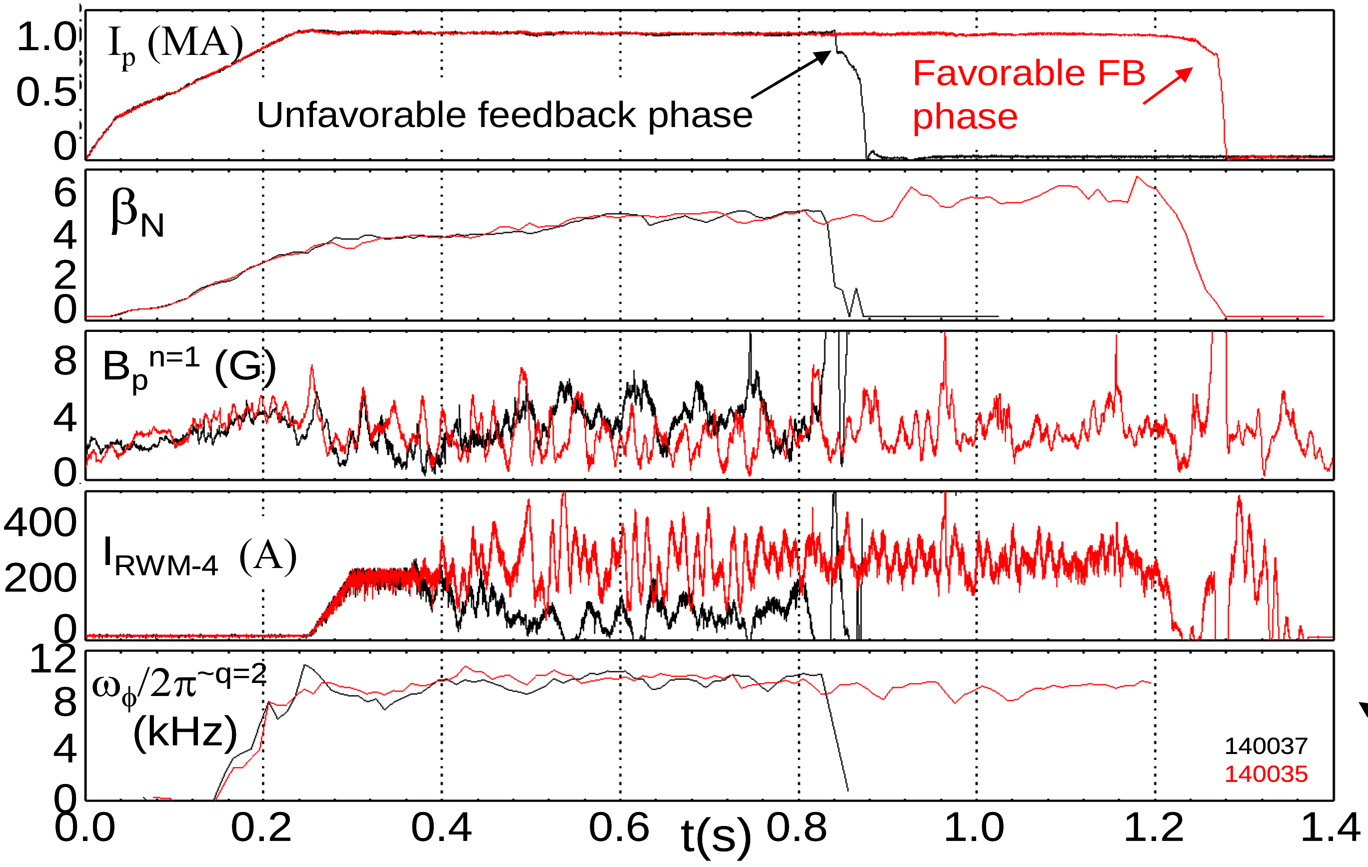
Written into the NSTX PCS

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

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

RWM state space feedback (12 states)

NSTX Experiments (Year 2010)



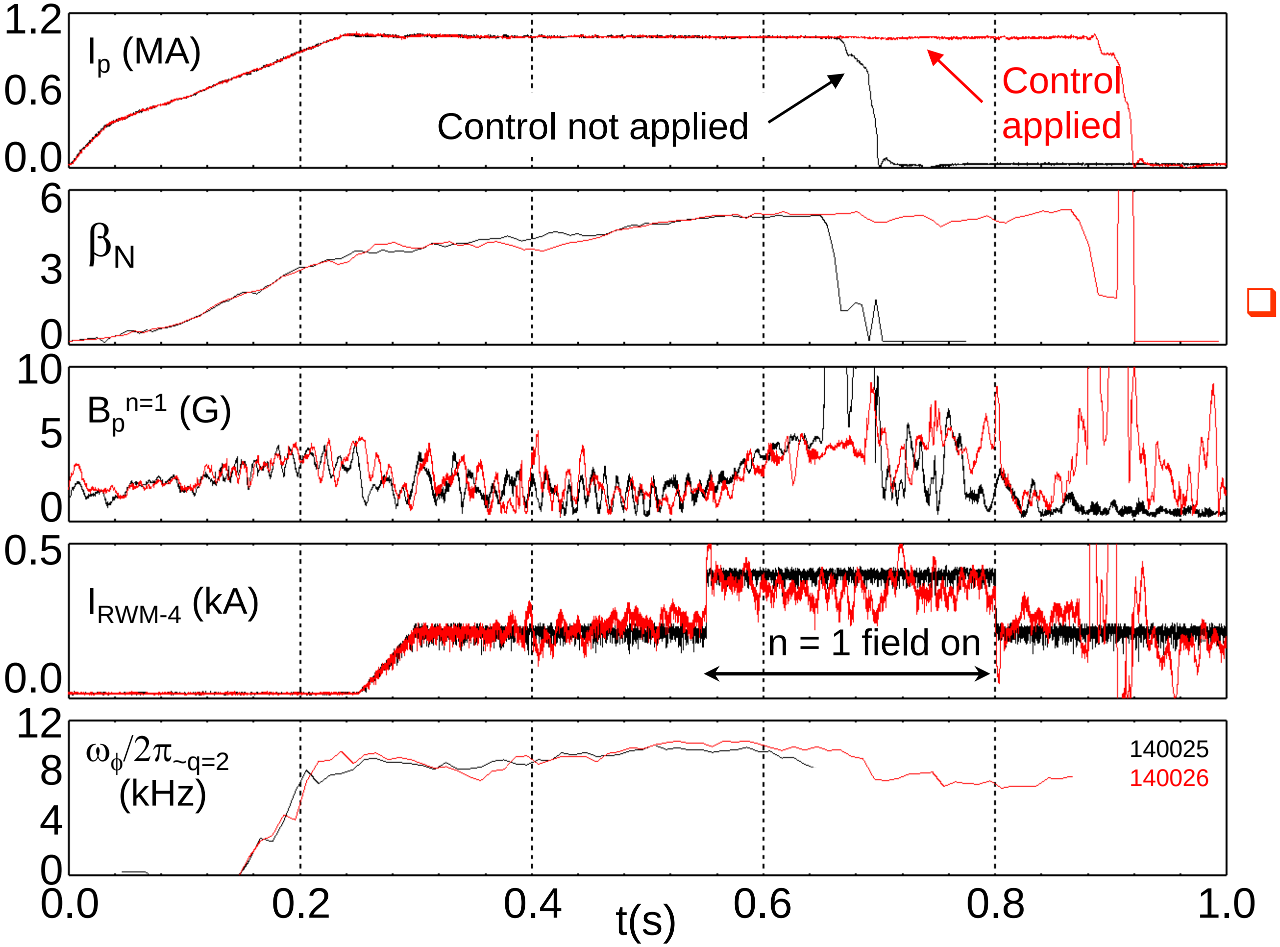
- n = 1 applied field suppression
  - Suppressed disruption due to n = 1 field
- Feedback phase scan
  - Best feedback phase produced long pulse, β_N = 6.4, β_N/l_i = 13

- Run time has been allocated for continued experiments on NSTX-U in 2015

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

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

RWM state space feedback (12 states)



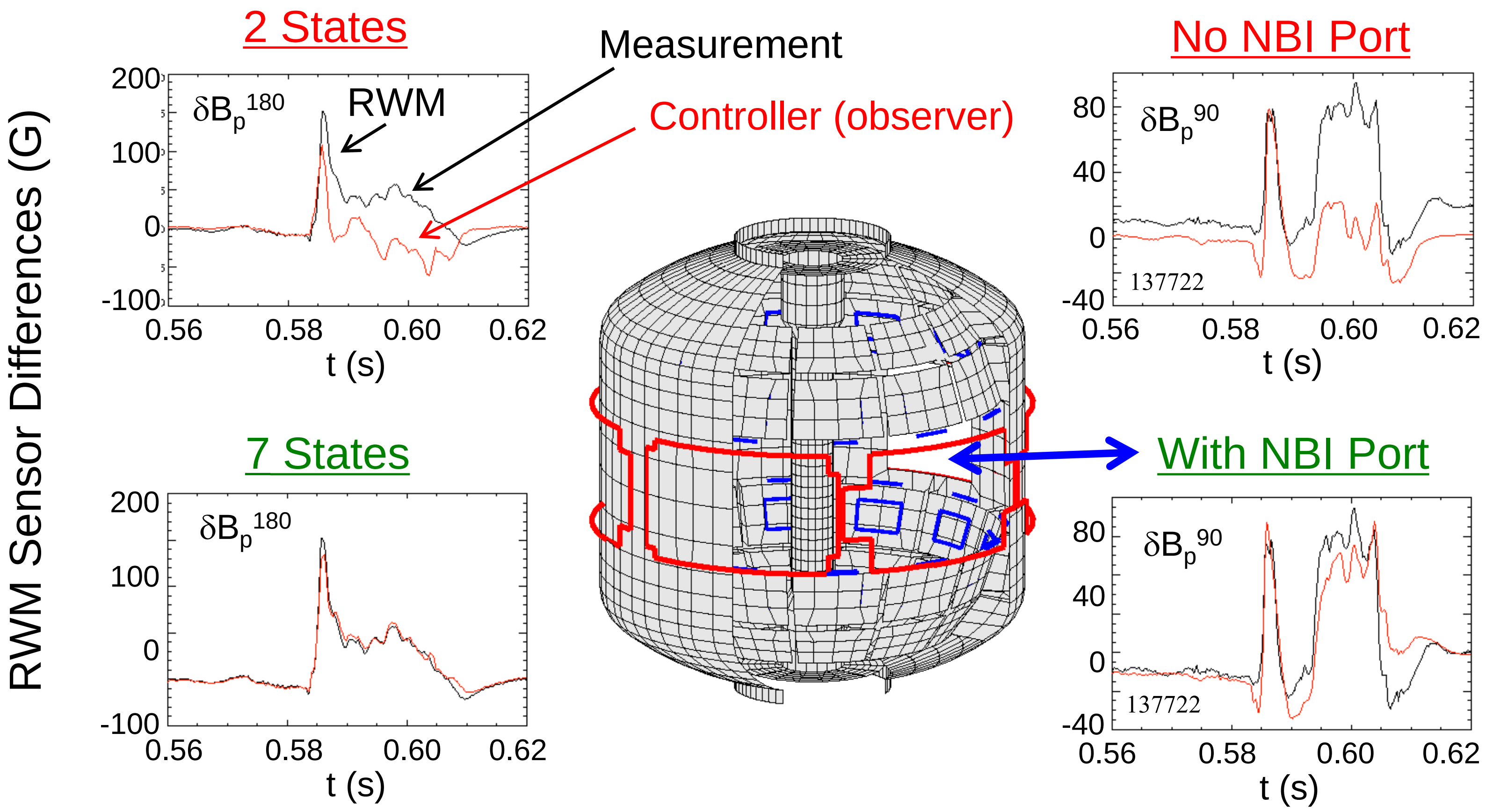
S. Sabbagh et al., Nucl. Fusion **53** (2013) 104007

- n = 1 DC applied field
  - Simple method to generate resonant field amplication
  - Can lead to mode onset, disruption
- RWM state space controller sustains discharge
  - With control, plasma survives n = 1 pulse
  - n = 1 DC field reduced
  - Transients controlled and do not lead to disruption
  - NOTE: initial run – gains NOT optimized

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


2 States

7 States

Measurement

Controller (observer)

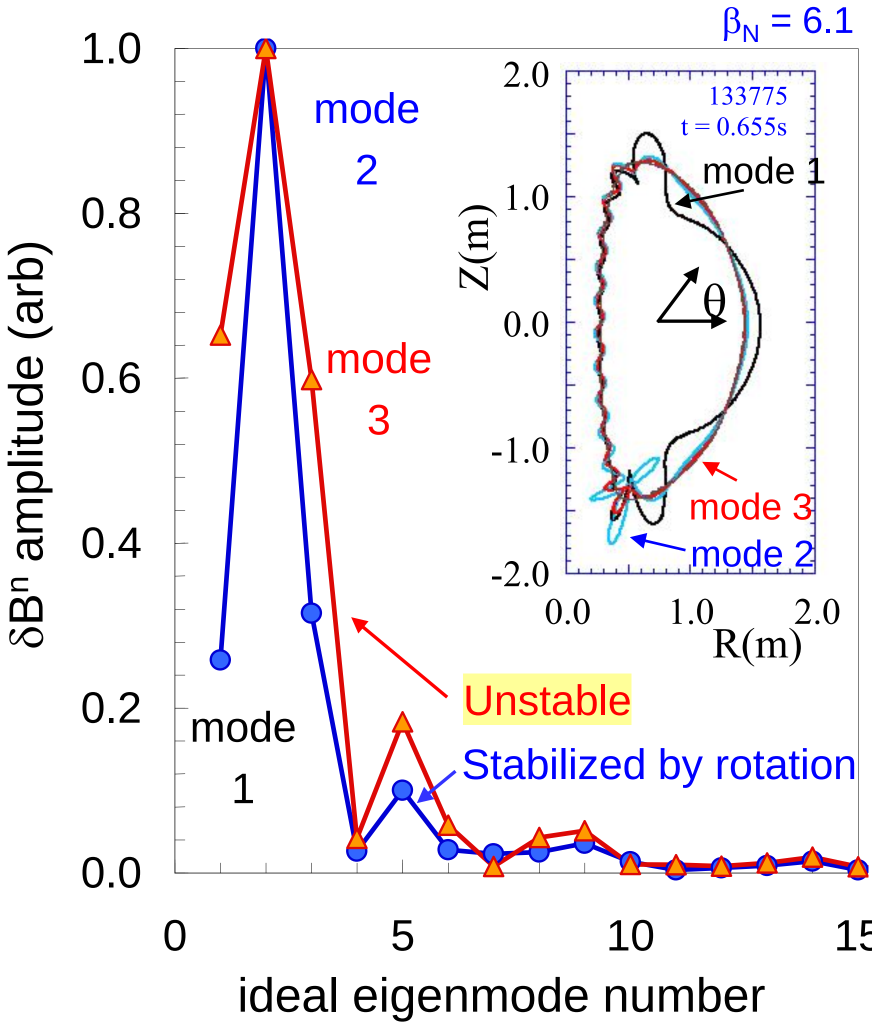
No NBI Port

With NBI Port

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

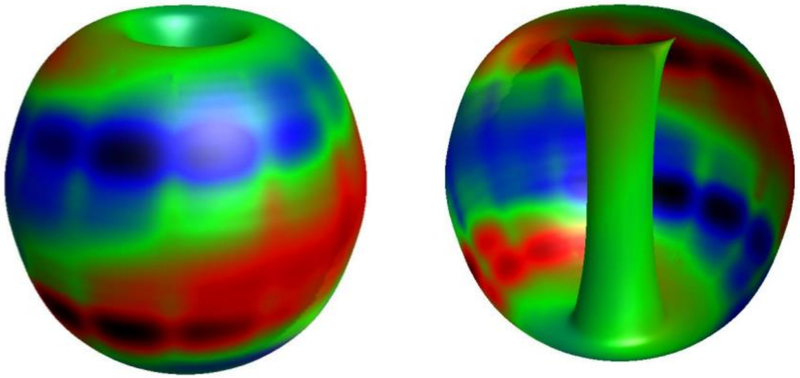
Multi-mode computation for RWM: 2nd eigenmode component has dominant amplitude at high β_N in NSTX 3D stabilizing structure

δB^n RWM multi-mode composition



mmVALEN code

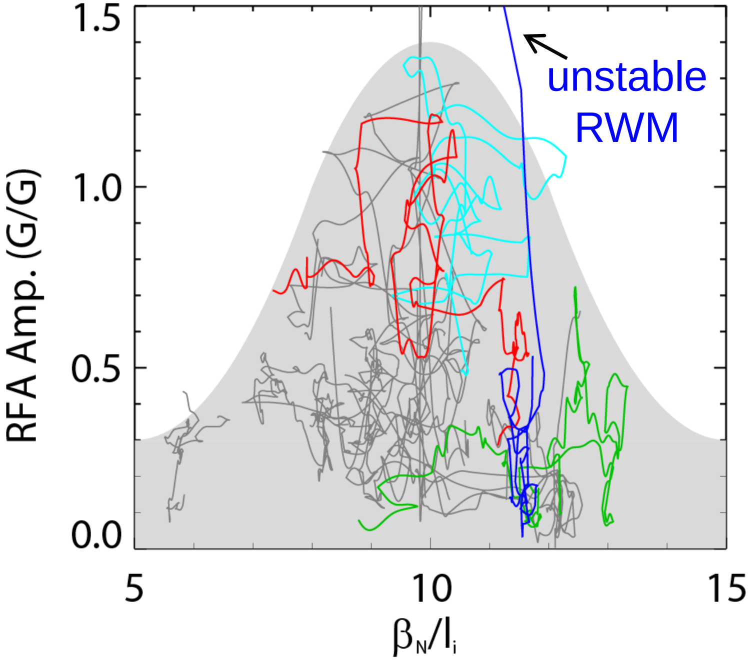
δB^n from wall, multi-mode response



- 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
- NSTX-U RWM state space controller will assess effectiveness multi-mode eigenfunctions in real-time feedback

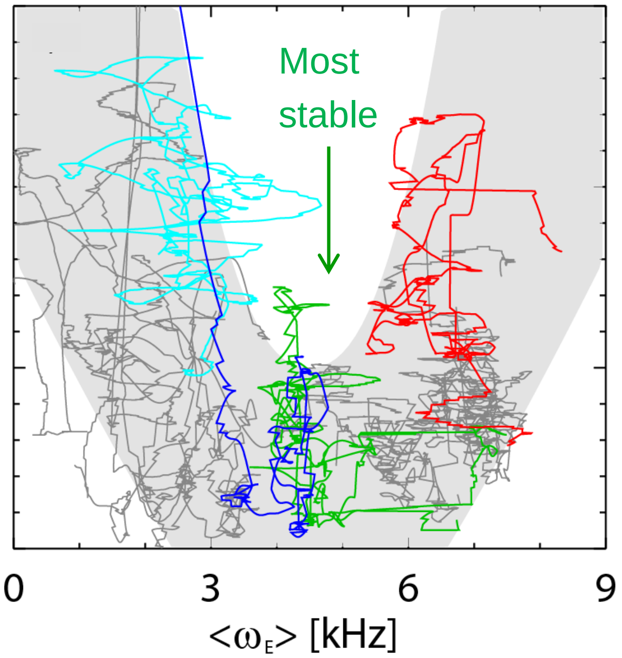
Experiments directly measuring global stability using MHD spectroscopy (RFA) support kinetic RWM stability theory

Resonant Field Amplification vs. β_N/l_i



(trajectories of 20 experimental plasmas)

RFA vs. rotation (ω_E)



NSTX experiments

- 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

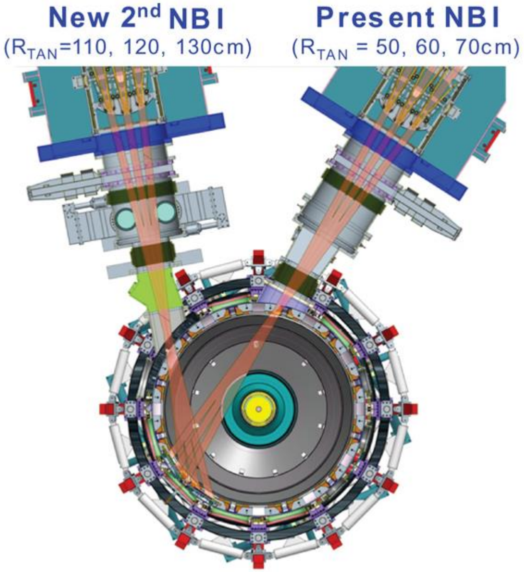
- Stability vs. rotation
  - Largest stabilizing effect from ion precession drift resonance with ω_ϕ

- 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

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

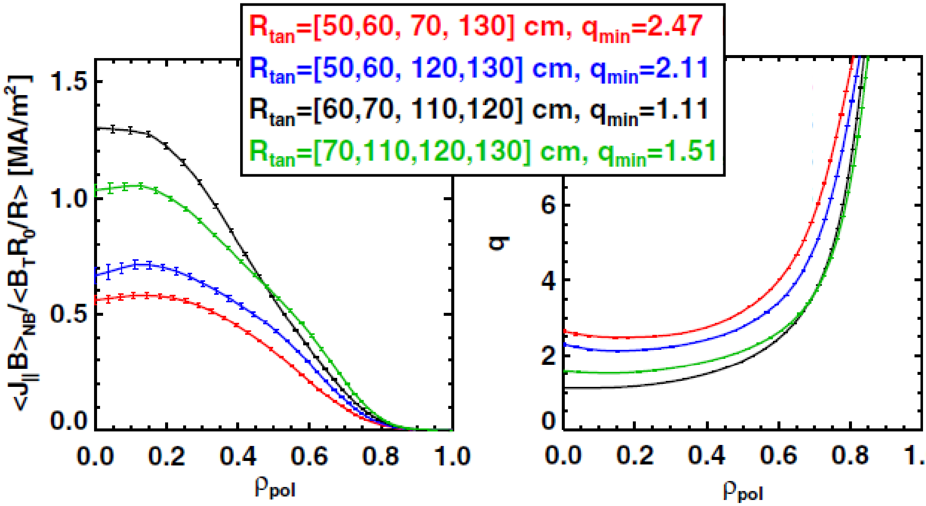
$$\delta W_k \sim \frac{1}{\langle\omega_D\rangle + \omega_E - i\nu_{eff}}$$

NSTX-U has new capabilities that impact stability and will be utilized for disruption avoidance

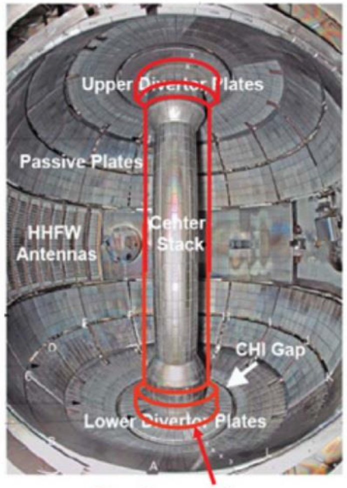


New neutral beams:

- Higher power
- Broader current and pressure profiles



(S.P. Gerhardt *et al*., Nucl. Fusion **52**, 083020 (2012))

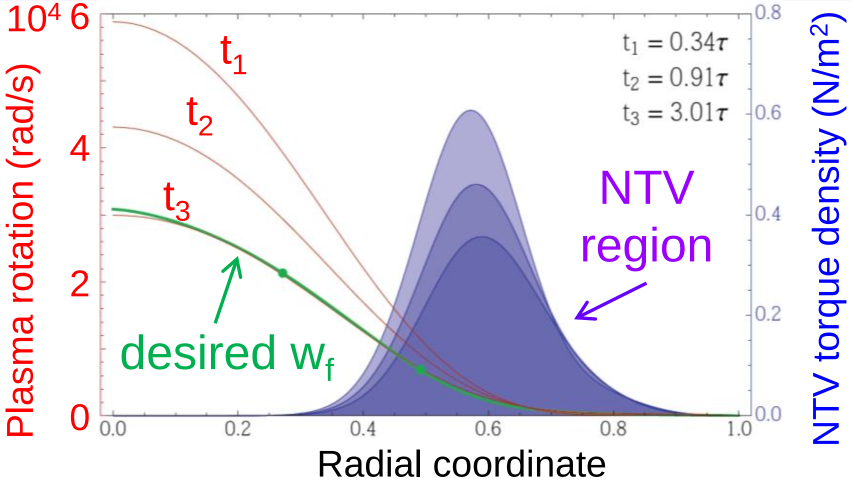


Outline of new center-stack (CS)

New center stack:

- Higher current, field yields lower collisionality
- Test physics at larger aspect ratio

NSTX-U state-space w_f controller w/NTV as actuator



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

Non-resonant NTV and NBI used as actuators in state-space rotation feedback controller designed for NSTX-U

- Momentum force balance – ω_ϕ decomposed into Bessel function states

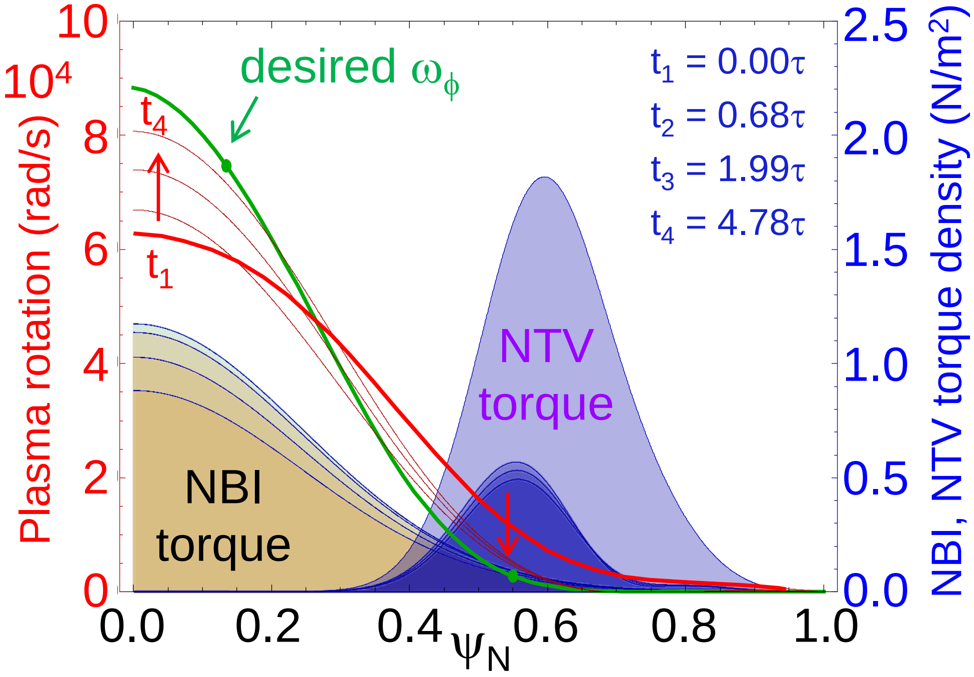
$$\sum_i n_i m_i \left\langle R^2 \right\rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho}\right)^{-1} \frac{\partial}{\partial \rho}\left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \chi_\phi \left\langle \left(R \nabla \rho\right)^2 \right\rangle \frac{\partial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

- NTV torque:

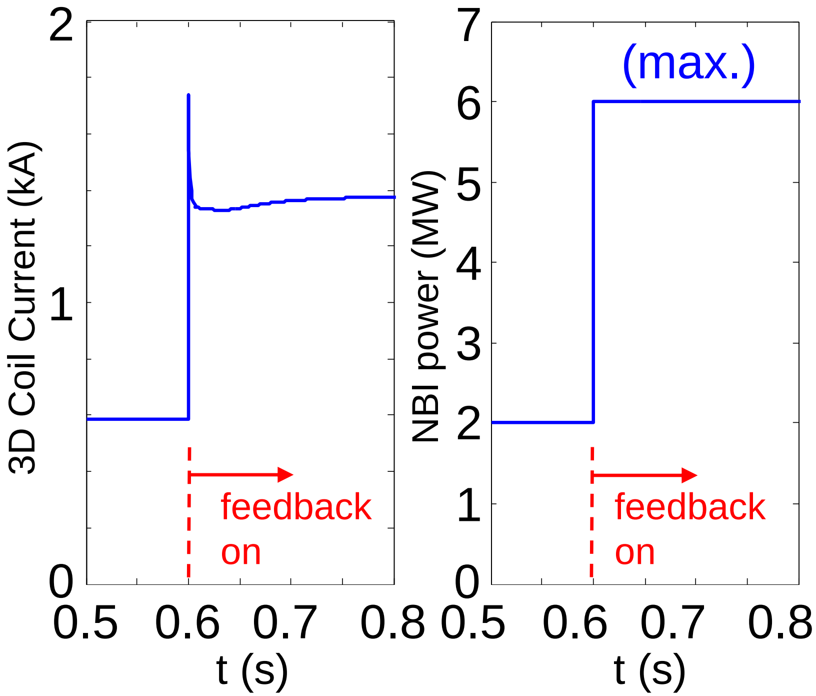
$$T_{NTV} \propto K \times f\left(n_{e,i}{}^{K1} T_{e,i}{}^{K2}\right) g\left(\delta B\left(\rho\right)\right)\left[I_{coil}{}^{2} \omega\right]$$

(non-linear)

Rotation evolution and NBI and NTV torque profiles



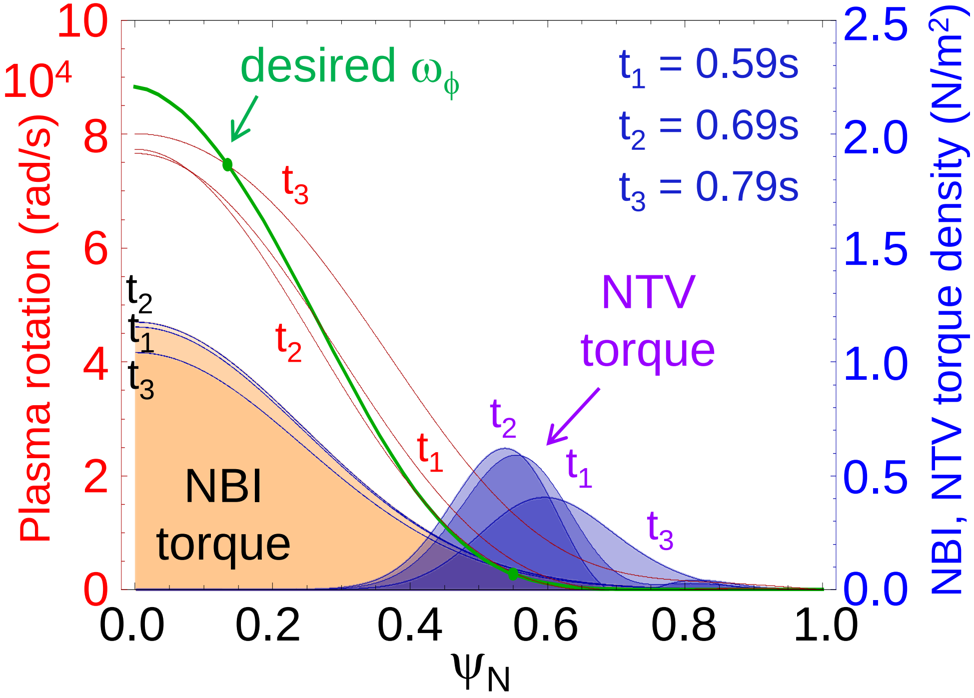
3D coil current and NBI power (actuators)



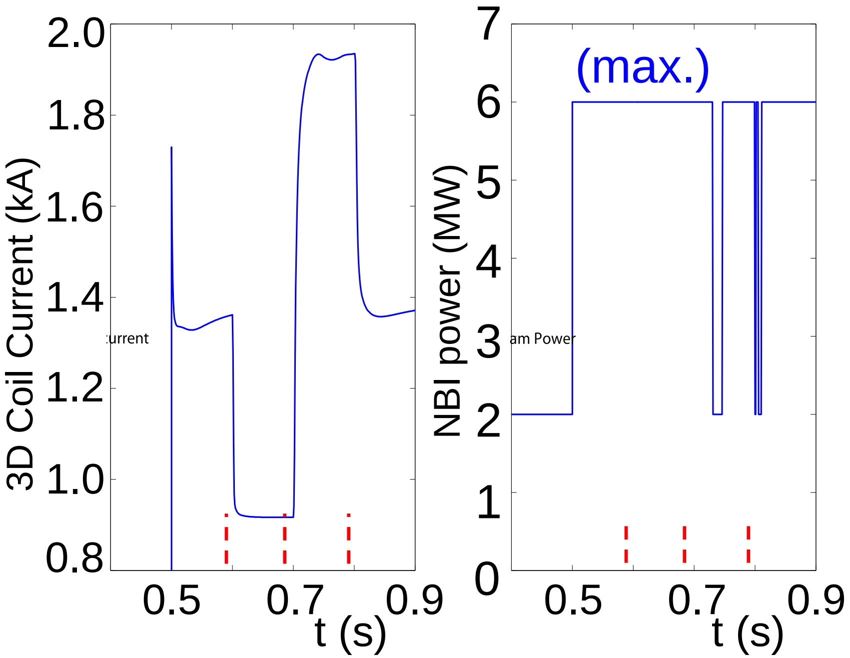
I. Goumiri, et al., PP8.053 (Wed. PM)

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



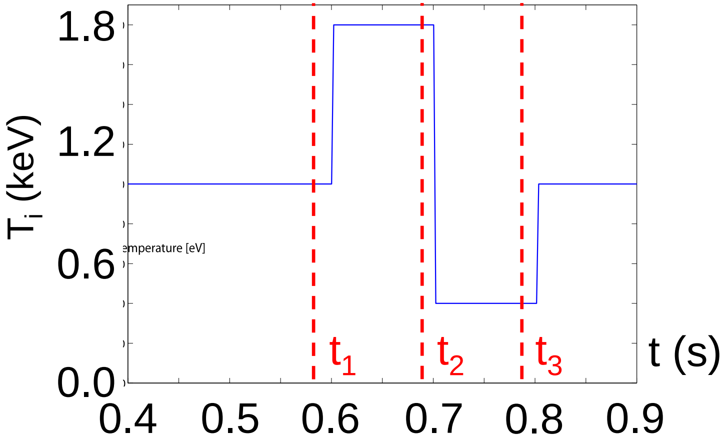
3D coil current and NBI power (actuators)



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

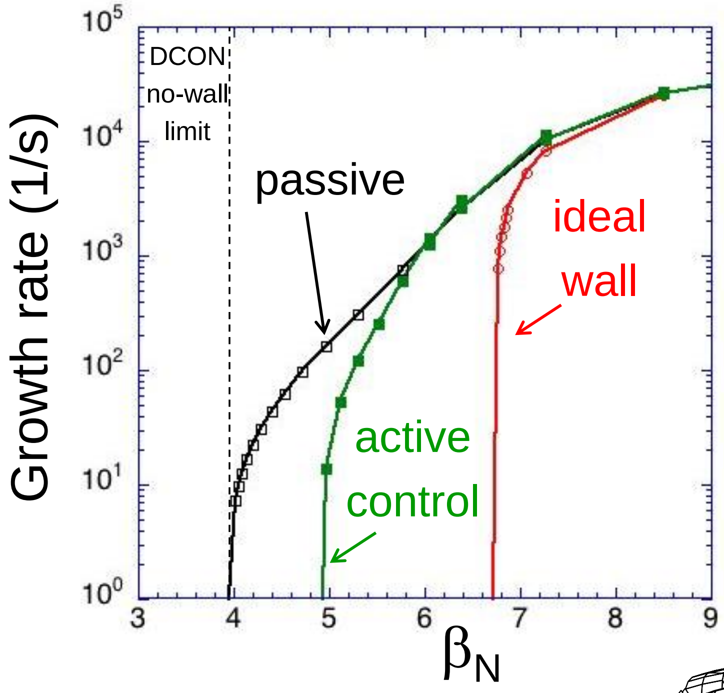
K1 = 0, K2 = 2.5

- NTV torque profile model for feedback dependent on ion temperature

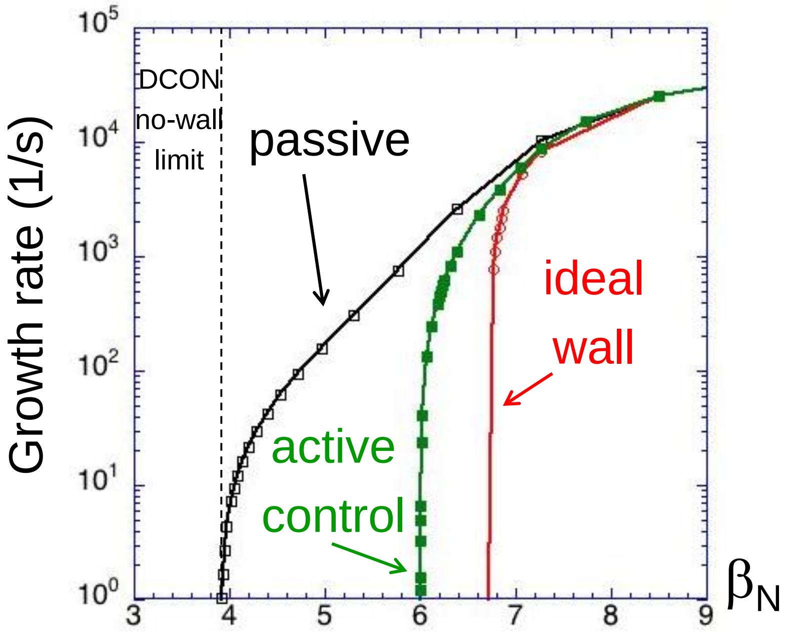


NSTX-U: RWM active control capability increases as proposed 3D coils upgrade (NCC coils) are added

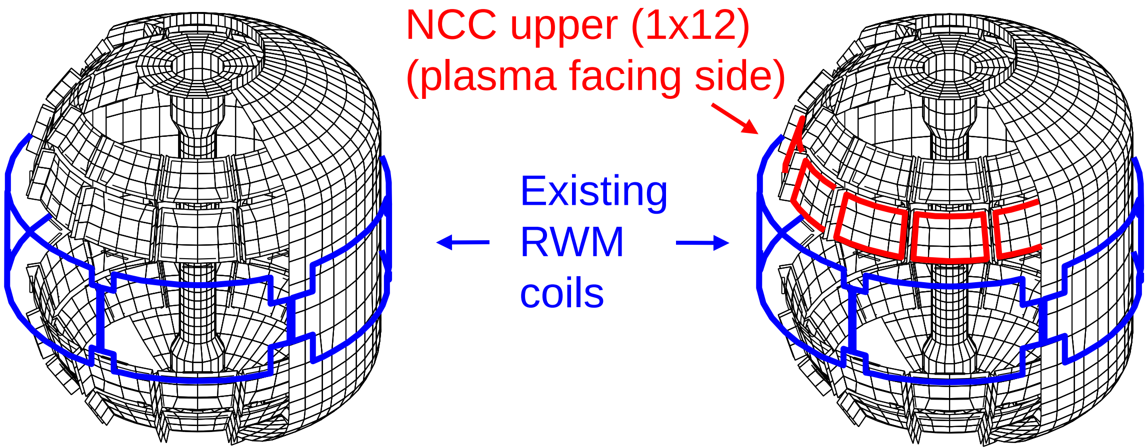
Using present midplane RWM coils



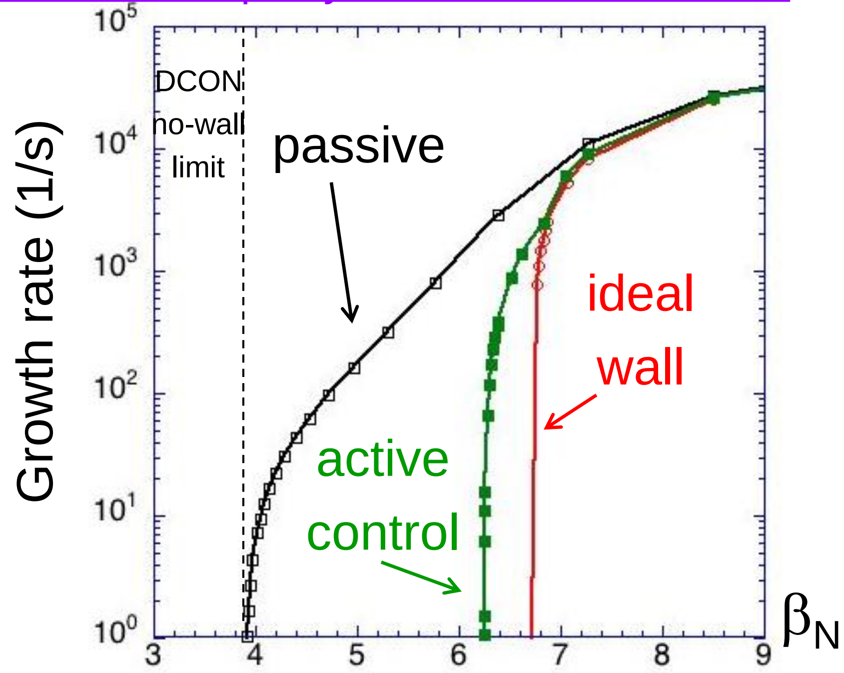
Partial NCC 1x12 (upper), favorable sensors

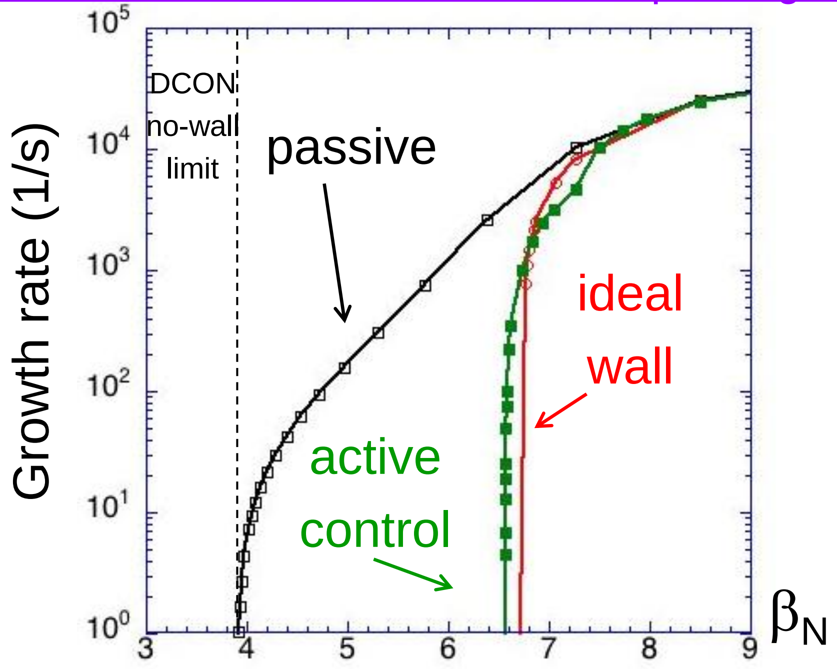


- Partial 1x12 NCC coil set significantly enhances control
  - Present RWM coils: active control to $\beta_N/\beta_N^{no\text{-}wall} = 1.25$
  - NCC 1x12 coils: active control to $\beta_N/\beta_N^{no\text{-}wall} = 1.52$



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


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 $\beta_N/\beta_N^{\text{no-wall}} = 1.58$
  - NCC 2x12 coils, optimal sensors: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.67$