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# Global MHD Mode Stabilization for Disruption Avoidance in Tokamaks

At PPPL

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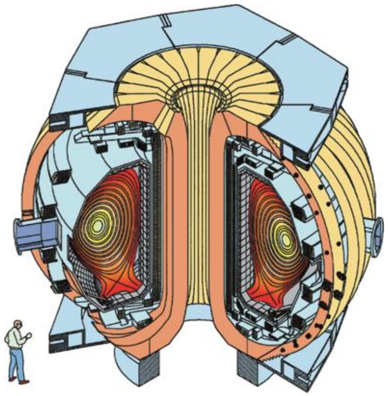
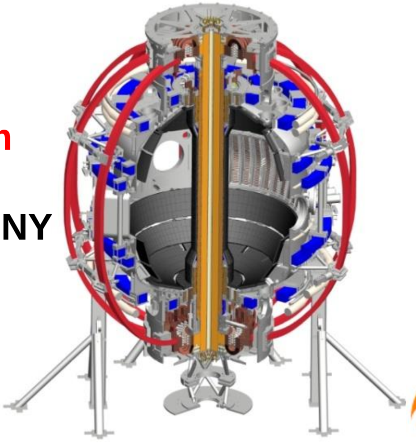


**Plasma Physics Colloquium**
**May 8, 2015**
**Columbia U. APAM Dept., NY, NY**



DIII-D NATIONAL FUSION FACILITY

V1.0

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

PPPL

# Near 100% disruption avoidance is an urgent need for ITER; NSTX-U is planning a disruption avoidance system

- 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)

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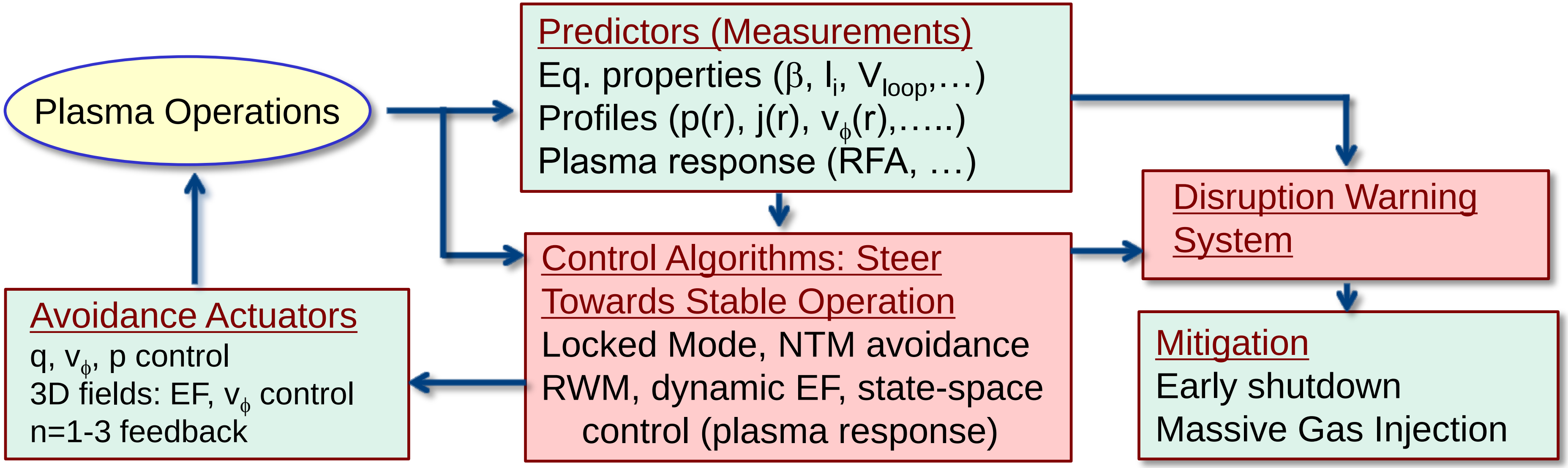
- Disruption prediction by multiple means will enable avoidance via profile or mode control or mitigation by MGI



Plasma Operations

Predictors (Measurements)
Eq. properties ($\beta$, $l_i$, $V_{loop}$,…)
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)

Avoidance Actuators
q, $v_\phi$, p control
3D fields: EF, $v_\phi$ control
n=1-3 feedback

Disruption Warning System

Mitigation
Early shutdown
Massive Gas Injection

# Research by the Columbia Group at PPPL provides key disruption avoidance elements by global mode stabilization

- ☐ Elements (Outline)
  - ☐ Kinetic RWM stabilization - unification between NSTX and DIII-D
  - ☐ NTV in closed loop rotation control
  - ☐ Dual-component RWM sensor control
  - ☐ Physics model-based RWM state-space controller
  - ☐ High normalized beta and NTV experiments on KSTAR
  - ☐ Analysis of upgraded 3D coils for NSTX-U

- ☐ These research elements now being brought together as part of a disruption prediction/avoidance system for NSTX-U

# Joint experiments/analysis on Global Mode Stabilization Physics and Control comprise International Tokamak Physics Activity MDC-21

From April 14th ITPA MHD meeting

- Tasks (both underway)
  1. MDC-21.1: "Comparison of kinetic RWM stabilization code calculations with experiments"
     - Unification of kinetic RWM stability theory application to RWM marginal stability points in NSTX and DIII-D high $\beta_N$, high $q_{min}$ plasmas
     - Kinetic RWM stability theory application to plasma response in DIII-D
     - Initial examination of further theoretical extensions
  2. MDC-21.2: "Comparison of global mode feedback stabilization models with experiments"
     - How are mode control models / techniques / detection working in tokamaks?
     - NSTX advanced RWM state-space control; recent advanced control in DIII-D
     - Future plans (AUG, NSTX-U, KSTAR)

the way to new energy iter ITPA MHD Meeting (Cadarache, France: Apr 14-17, 2015) ITPA MHD Group: MDC-21 Global Mode Stabilization – S.A. Sabbagh, et al. 4

# By the way, the April 2015 ITPA MHD Stability Meeting was held at ITER Headquarters for 1st time – a LOT of activity!....

- ITER HQ building completed
  - Great meeting venue
- Six large cranes, humming with activity
  - Center stack crane "C1" gives a good sense of scale
- Tokamak assembly building going up quickly
  - Impressive structure directly adjacent to main torus hall
- Lots of action in the "pit"

# Outline of ITPA MDC-21.1 section of talk

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

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

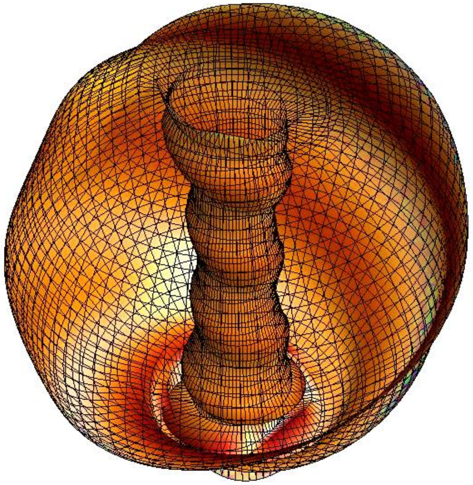
- ❑ Further implications and research opportunities

# Analysis of DIII-D and NSTX experiments gives an improved 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

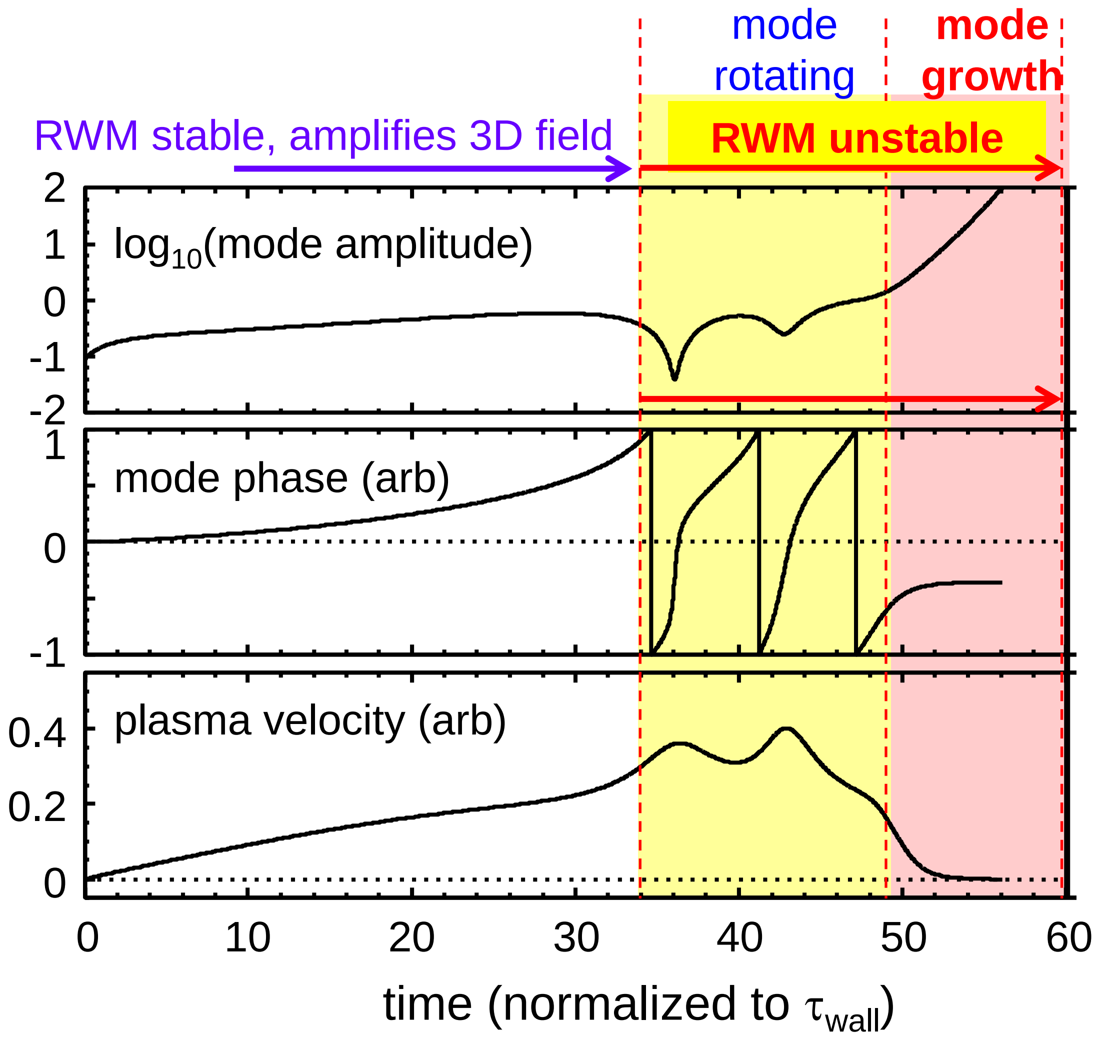
RWM reconstruction in NSTX



(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 $O(1/\tau_{wall})$

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

## DIII-D High $\beta_N$, $q_{min}$ plasmas

- Candidates for steady-state, high $\beta_N$ operation
- Can have high probability of significant RWM activity with $q_{min} > 2$
  - RWMs and TMs cause strong $\beta$ 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 $\omega_\phi$ and $T_i$ measurement captures profile detail in timescale < RWM growth time

## NSTX

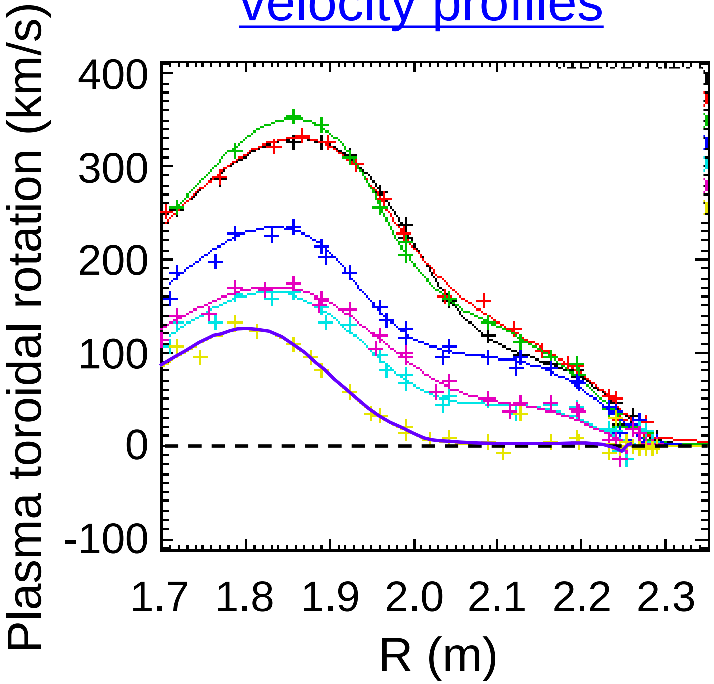
- Strong RWM drive: Maximum $\beta_N > 7$, $\beta_N / l_i > 13.5$
- Strong TMs eliminated by high elongation (> 2.6) or Li wall conditioning

# 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 $\beta_N$ and high rotation
  2. Found at high $\beta_N$ and low rotation
     - Low rotation expected in ITER
  3. At moderate $\beta_N$ 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

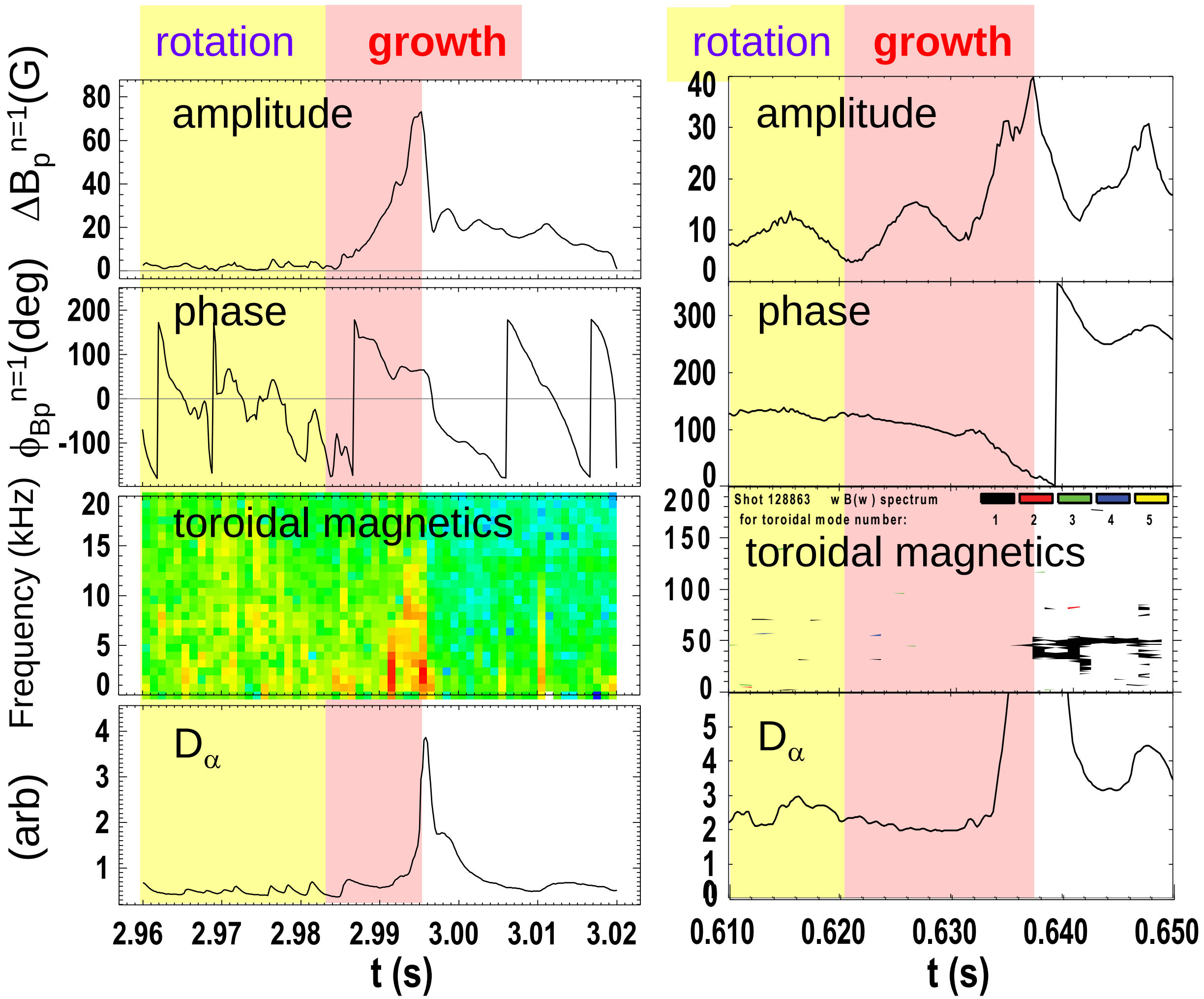


➔In this presentation, variables $V_\phi$ and $\omega_\phi$ both indicate plasma toroidal rotation

# 1. Comparison of RWM growth and dynamics in high $\beta_N$ 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 ($\beta_N$ = 3.5) NSTX ($\beta_N$ = 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 $\omega_\phi$ 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 $\omega_\phi$ profile: resonances in $\delta W_K$ (e.g. ion precession drift)
  - Particle collisionality, EP fraction

$\omega_\phi$ profile (enters through ExB frequency)

Trapped ion component of $\delta W_K$ (plasma integral over energy)

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

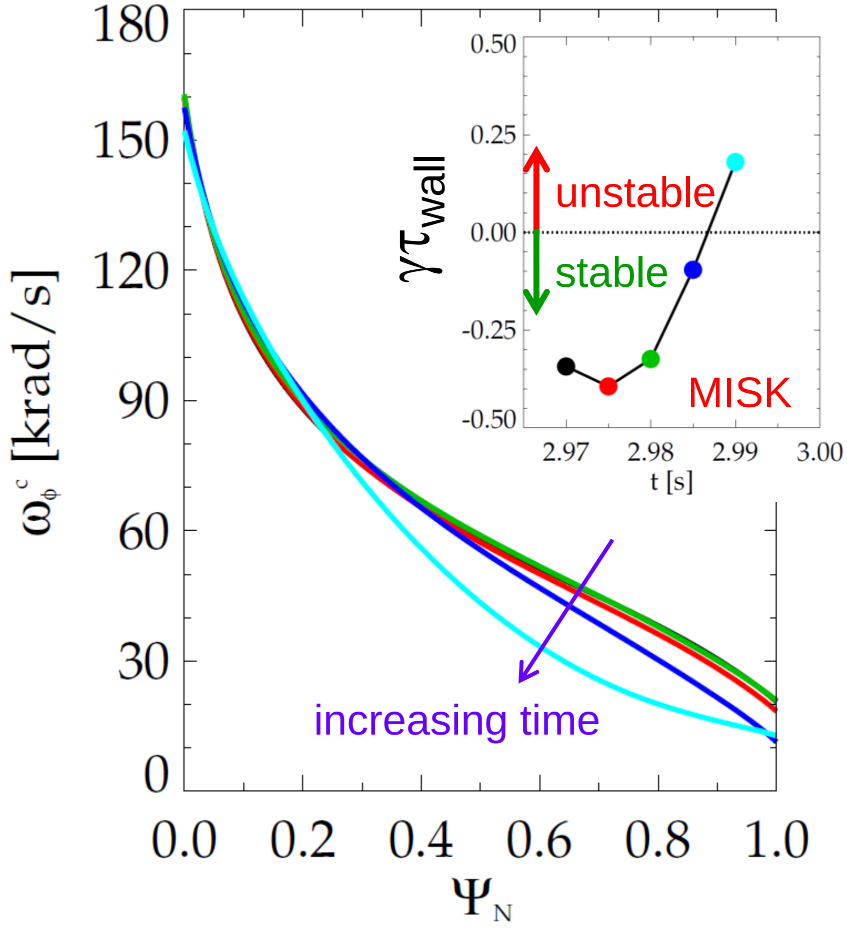
precession drift　bounce　collisionality

Some NSTX / MISK analysis references

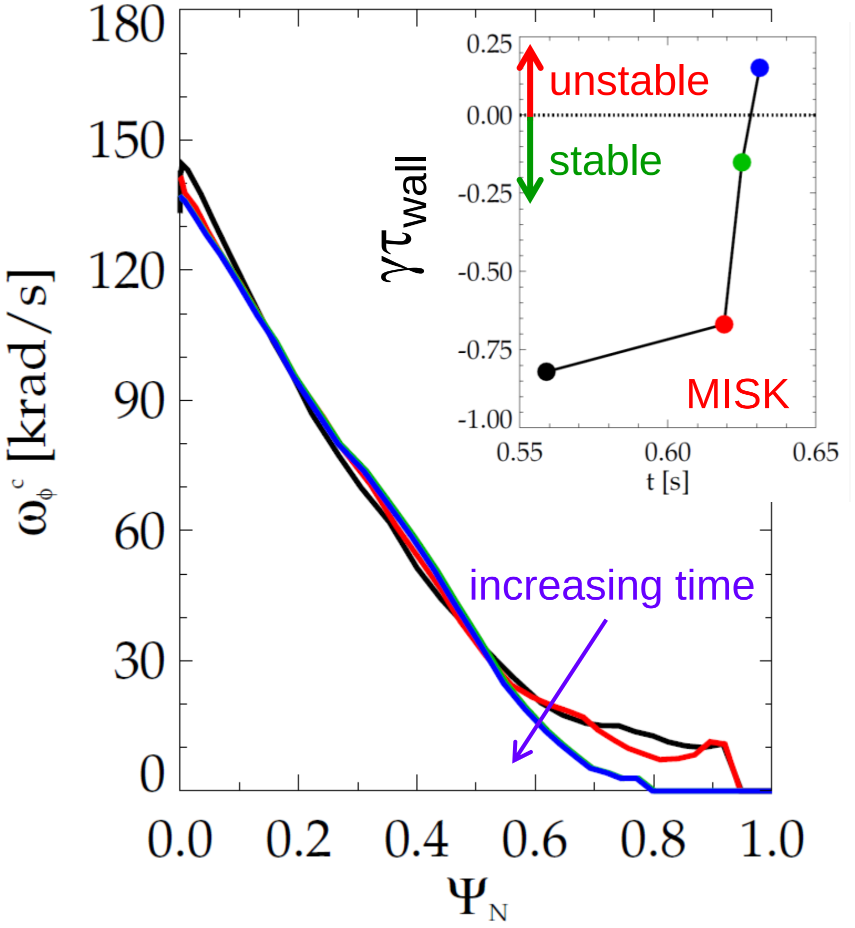
J. Berkery *et al.*, PRL **104**, 035003 (2010)
S. Sabbagh, et al., NF **50**, 025020 (2010)
J. Berkery *et al.*, PRL **106**, 075004 (2011)
J. Berkery *et al.*, PoP **21**, 056112 (2014)
J. Berkery *et al.*, PoP **21**, 052505 (2014)
(benchmarking paper)

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

DIII-D (minor disruption)

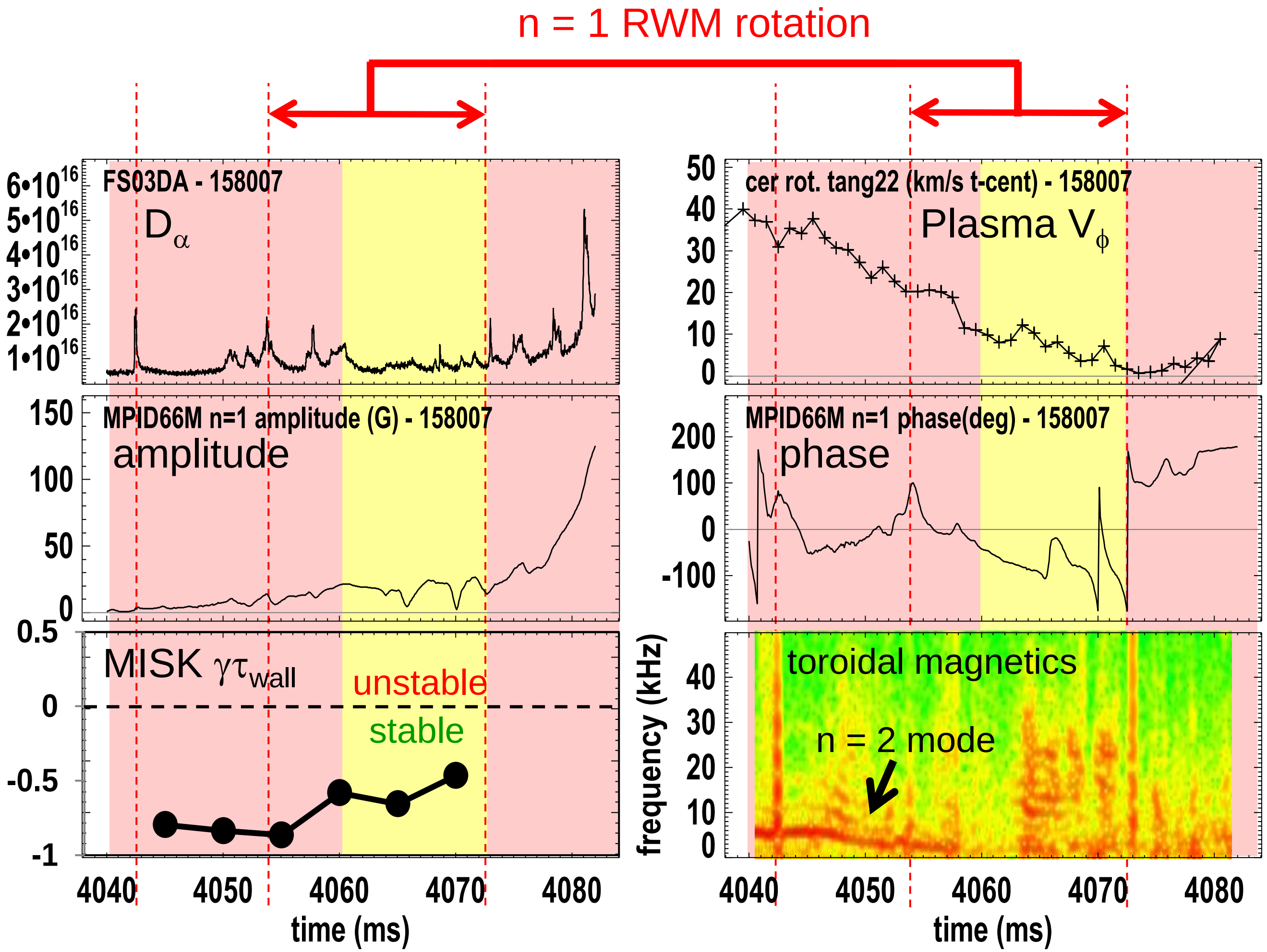


NSTX (major disruption)



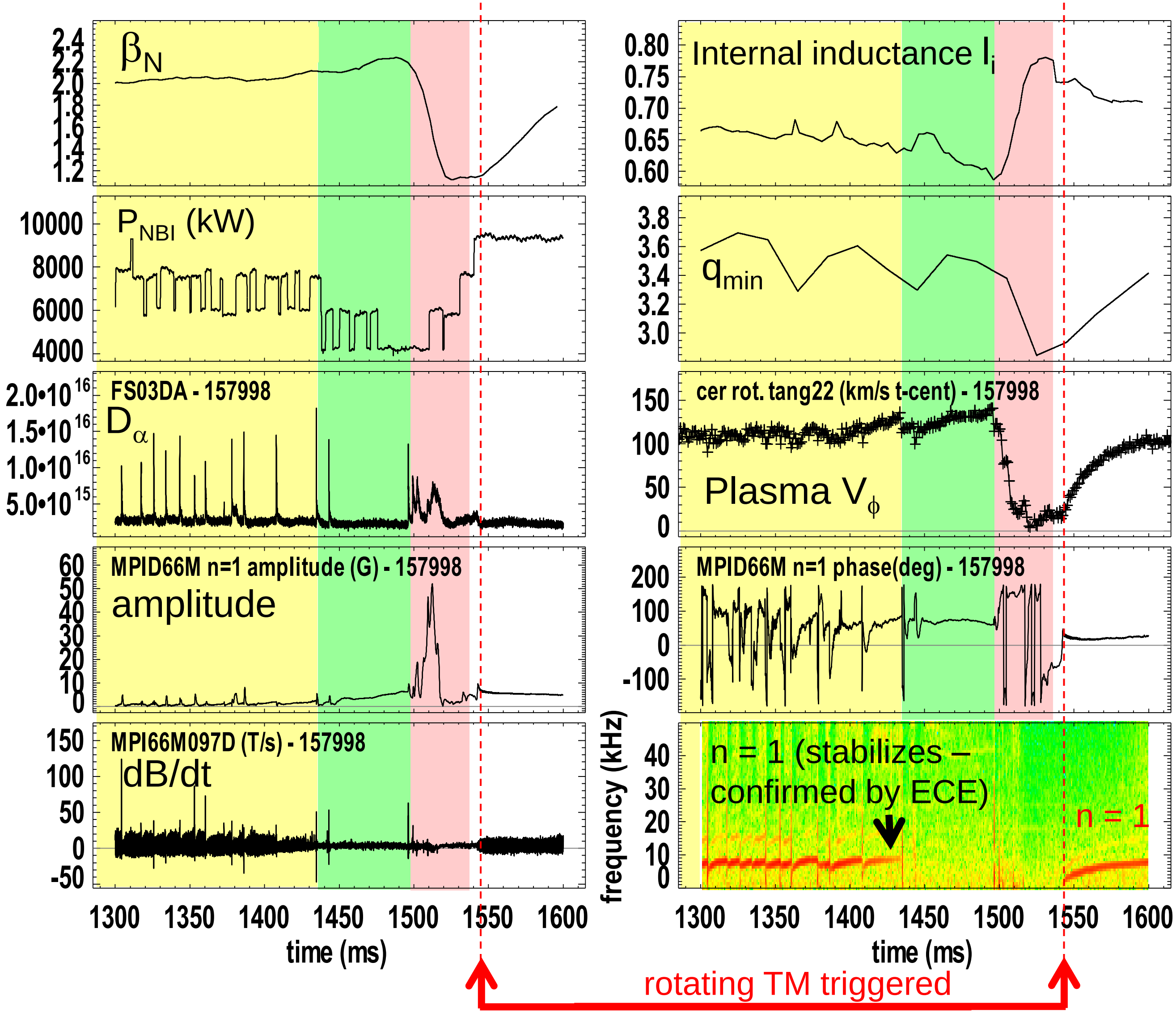
# 2. Full current quench disruption occurs as RWM grows following mode rotation at high $\beta_N$ and low $V_\phi$

- RWM evolution ($\beta_N$=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

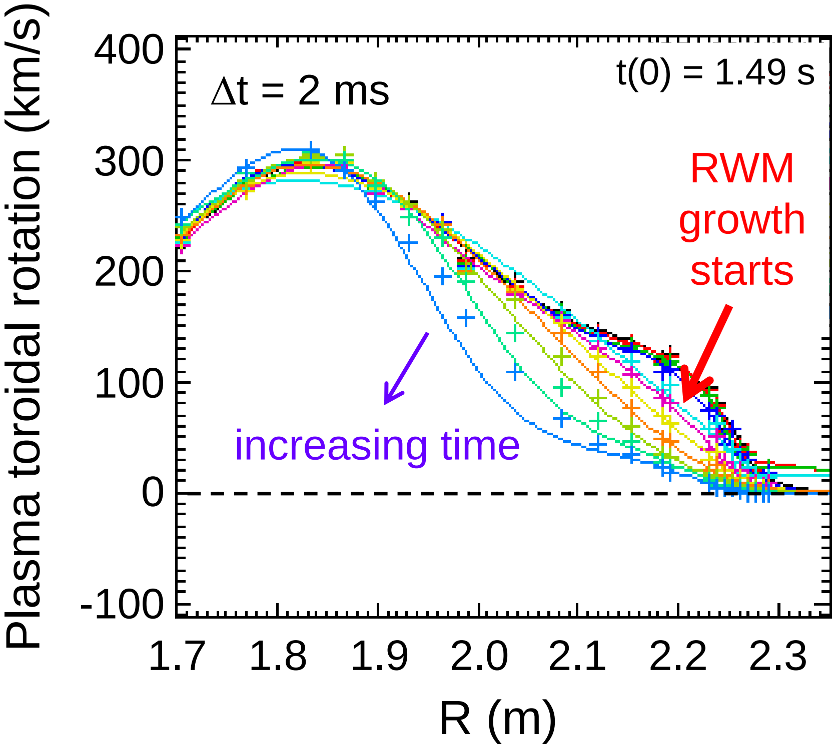


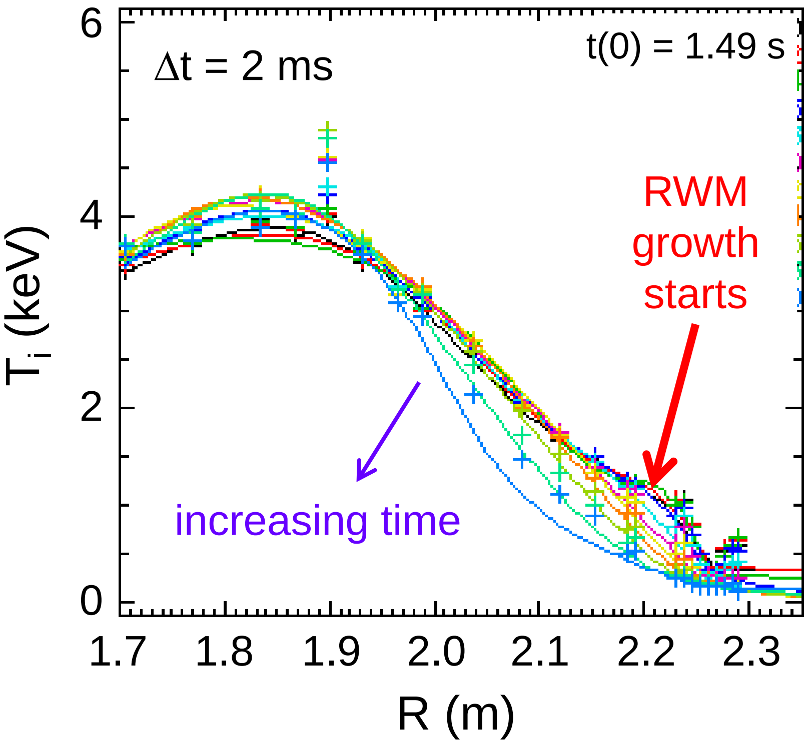
# 3. Minor disruption occurs as RWM grows at moderate $\beta_N$ correlated with profile peaking

- RWM evolution
  - n = 1 rotating TM decays / stabilizes
  - Injected NBI power drops (by $\beta_N$ control)
  - Frequency of “ELMs” decreases, $\beta_N$ 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



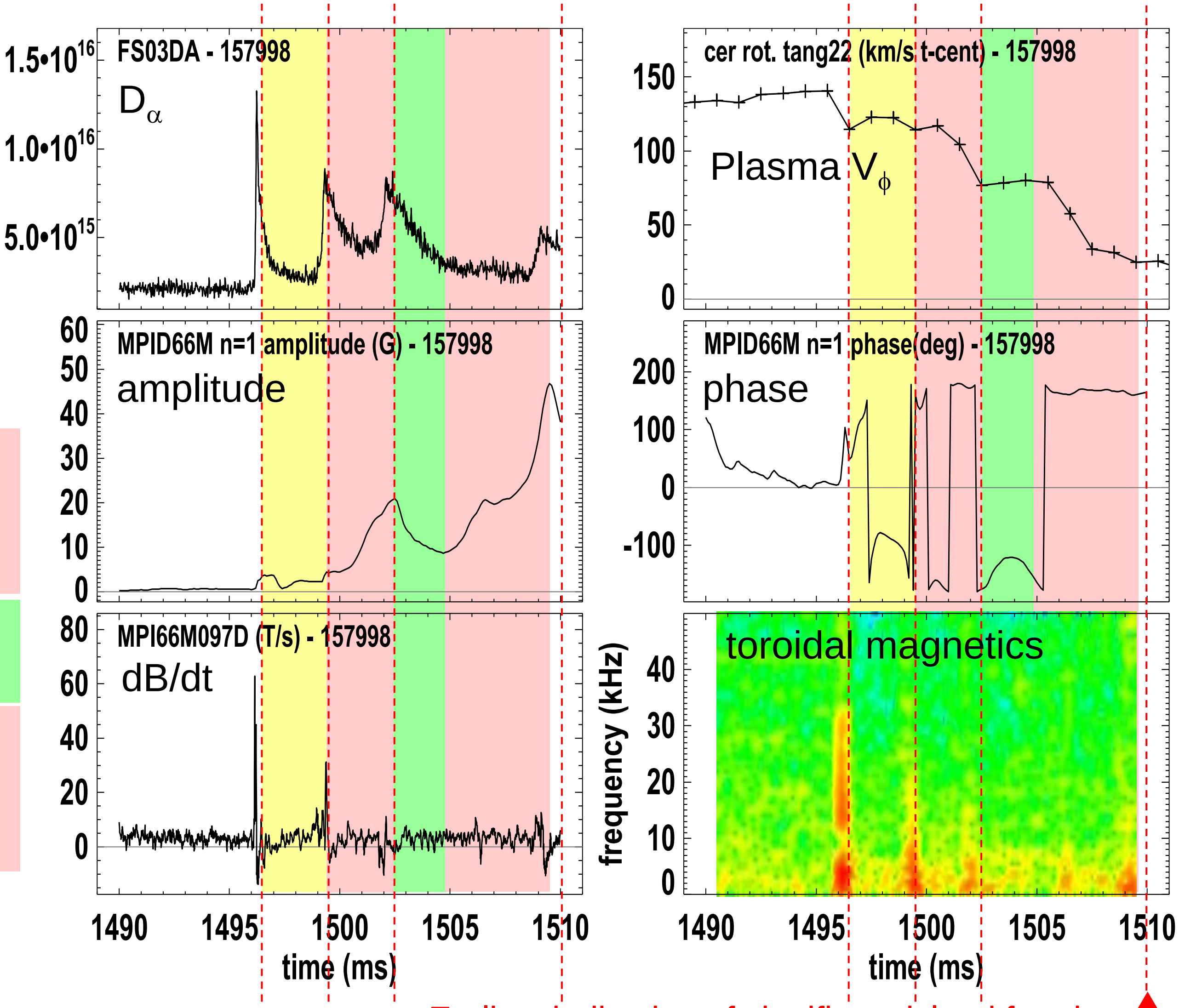


- ❑ Loss of pedestal causes profile peaking, correlates with RWM growth
  - ❑ Example of transport phenomena that can lead to instability and minor disruption, but can also be used as an indicator for disruption avoidance

3.

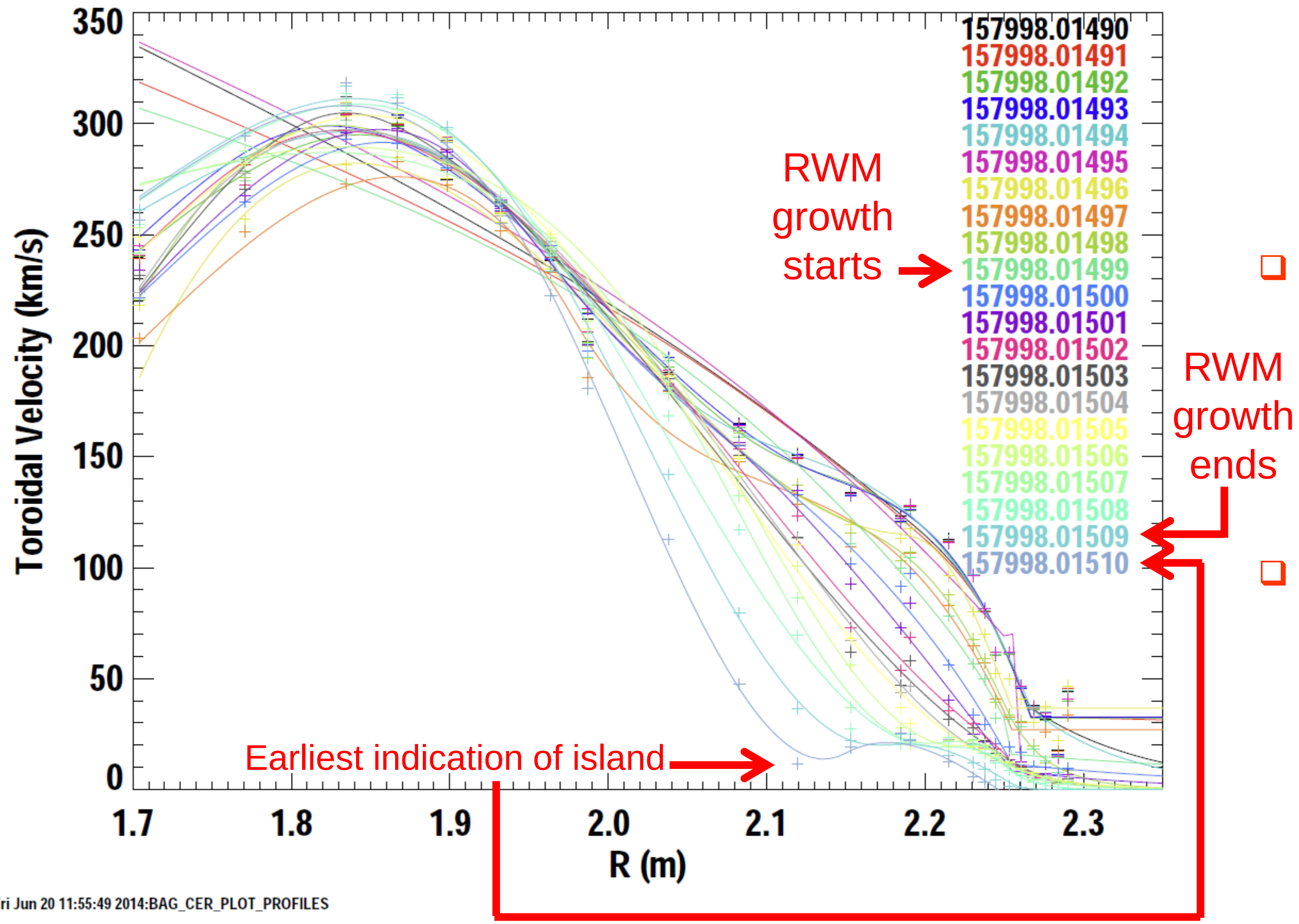
# Periods of RWM growth and decay leading to minor disruption correlate with bursting MHD events

- First bursting MHD event causes small $\omega_\phi$ drop
- RWM rotation starts, small $V_\phi$ drop and partial recovery
- Strong RWM growth after second bursting event, strong $V_\phi$ 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

# Outline

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

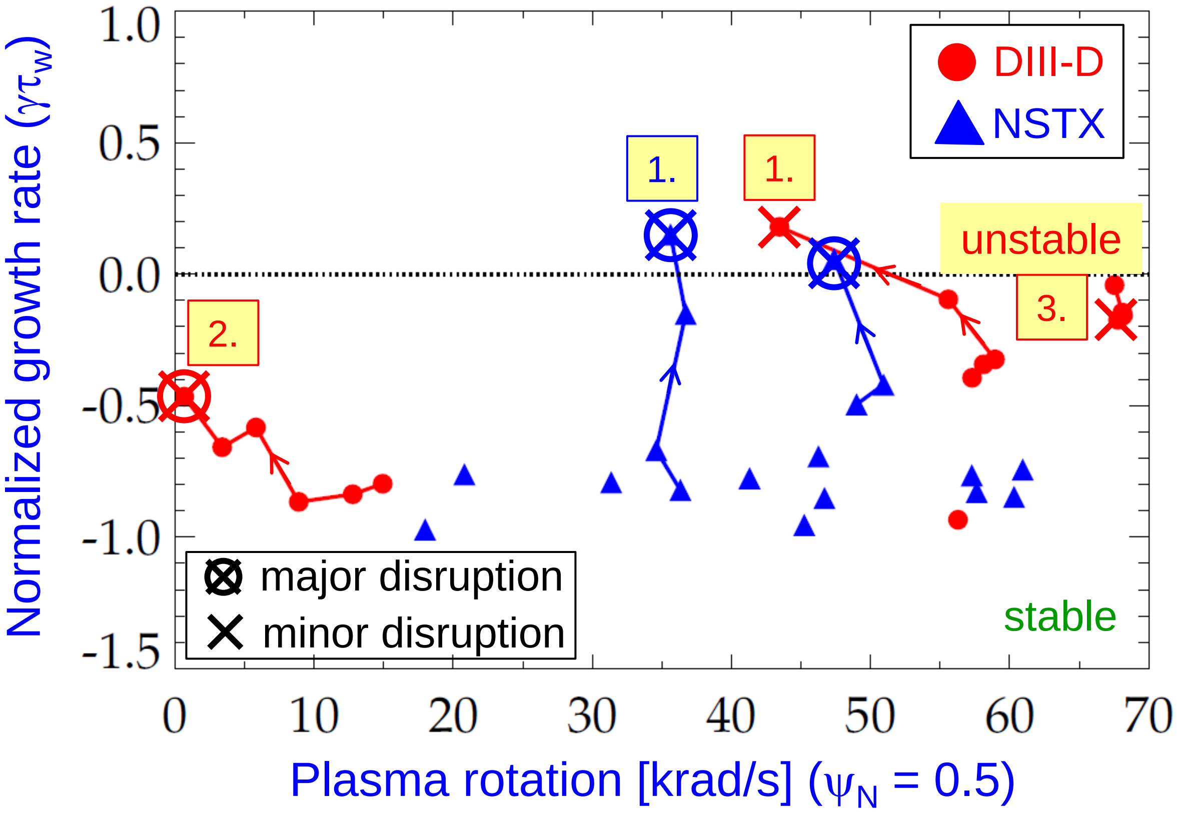
- ☐ RWM kinetic stabilization analysis / proximity of plasmas to stability boundaries

- ☐ Further implications and research opportunities

# 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

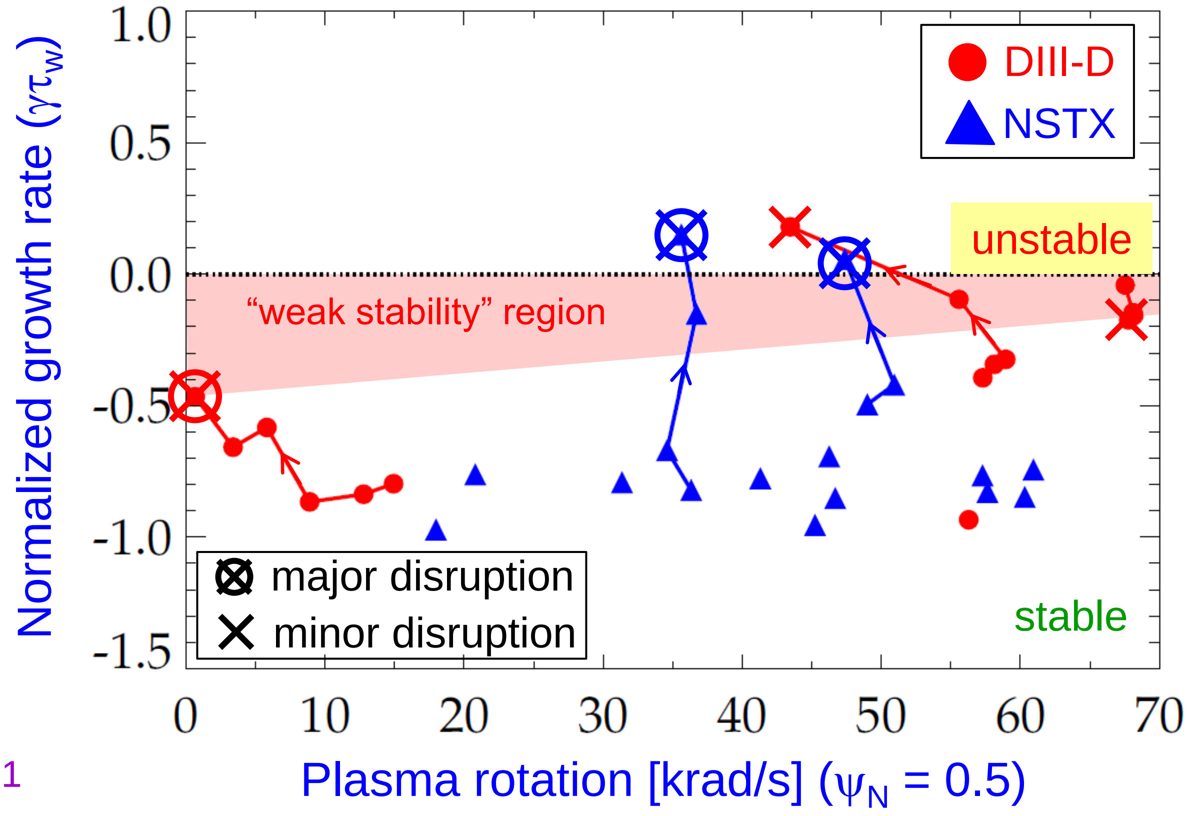
- Summary of results
  - Plasmas free of other MHD modes can reach or exceed linear kinetic RWM marginal stability
  - Bursting MHD modes can lead to non-linear destabilization before linear stability limits are reached

- 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

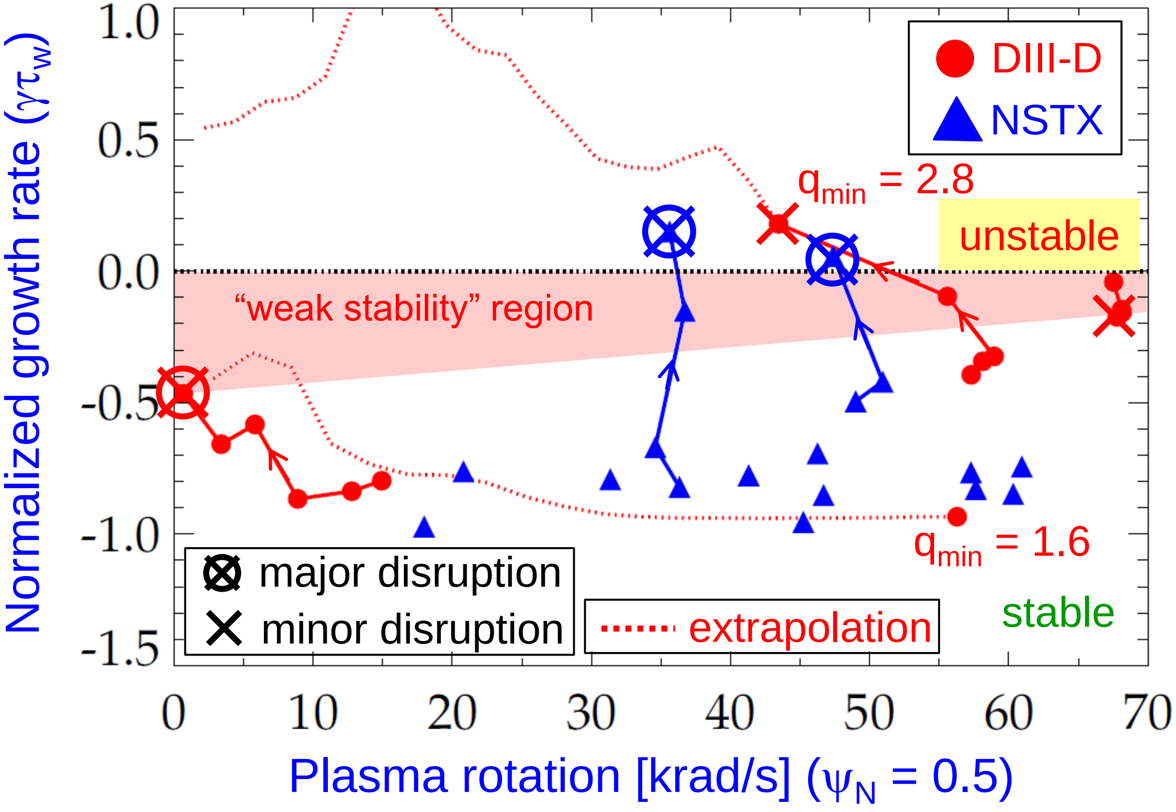
Kinetic RWM stability analysis for experiments (MISK)



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

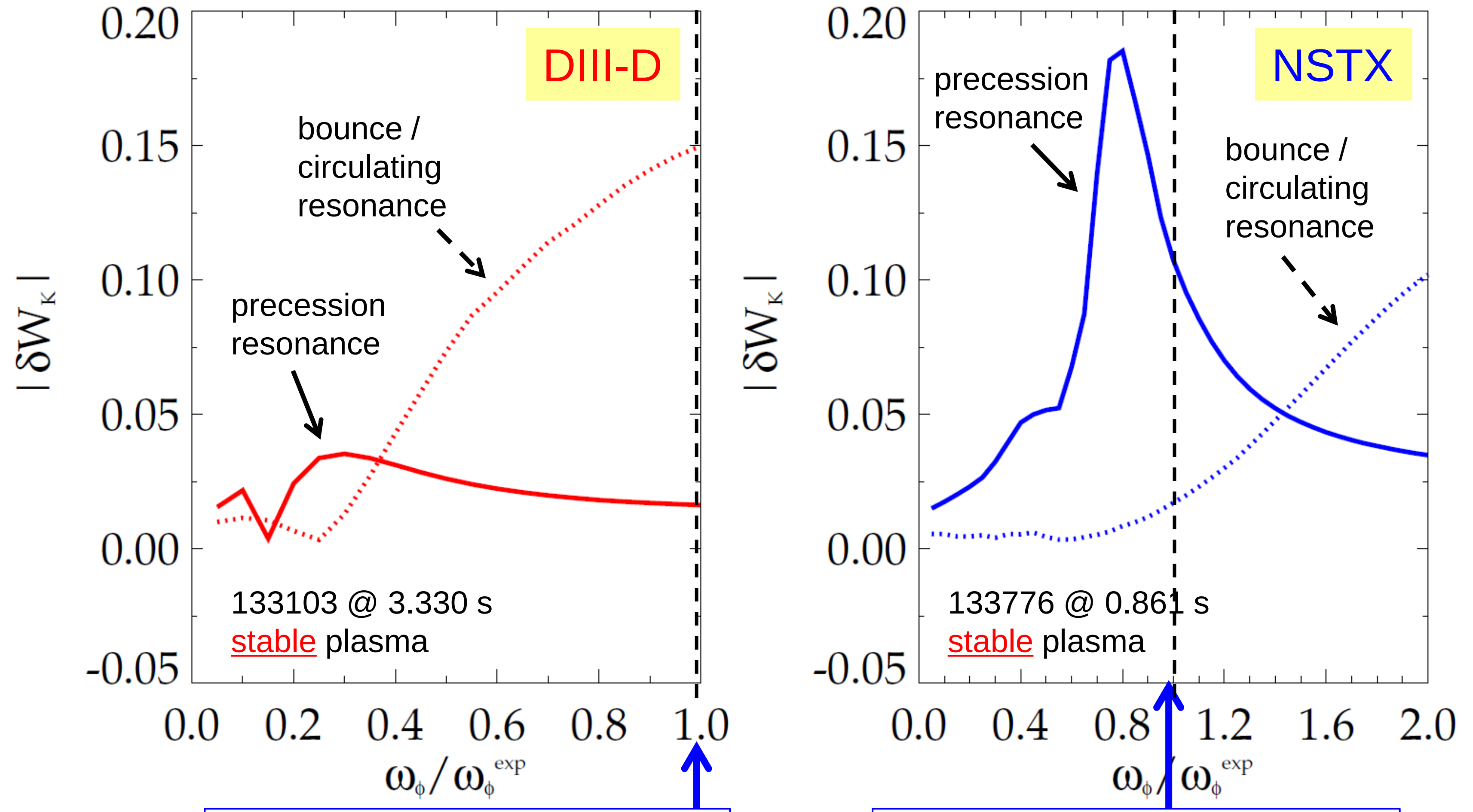
- Summary of results
  - Plasmas free of other MHD modes can reach or exceed linear kinetic RWM marginal stability
  - Bursting MHD modes can lead to non-linear destabilization before linear stability limits are reached
  - Extrapolations of DIII-D plasmas to different $V_\phi$ show marginal stability 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)

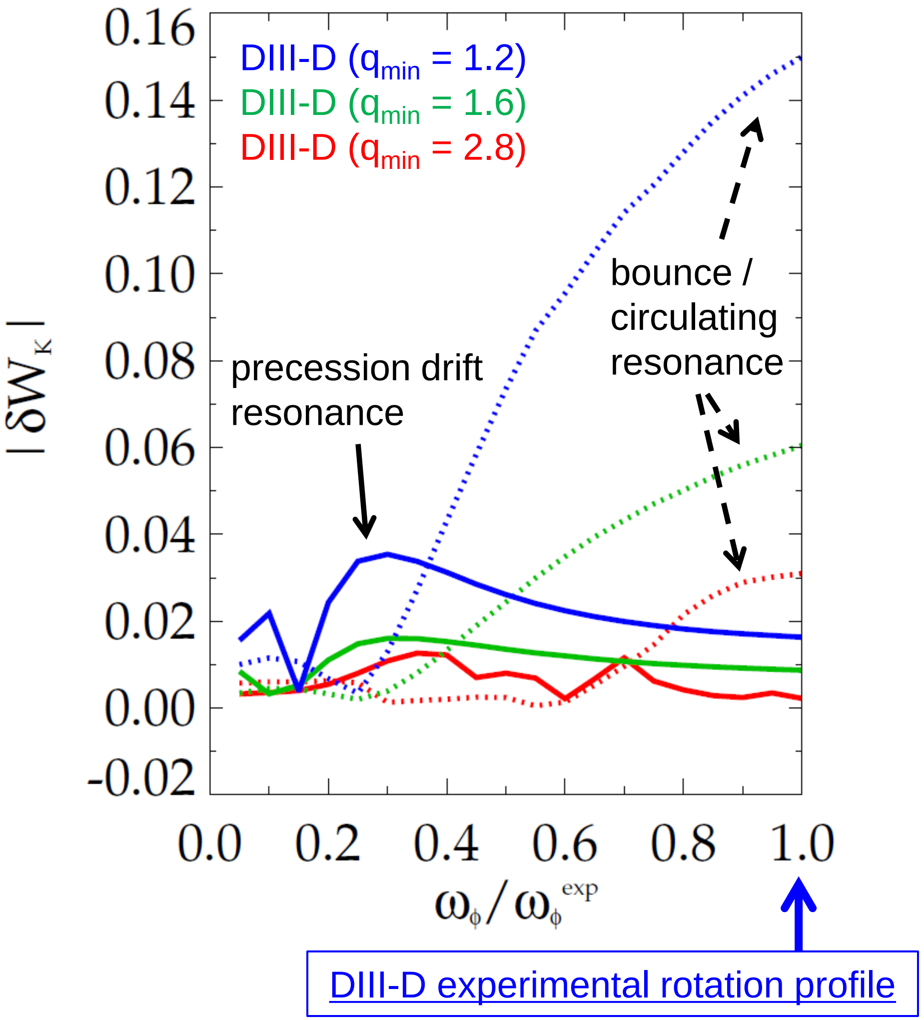


DIII-D experimental rotation profile

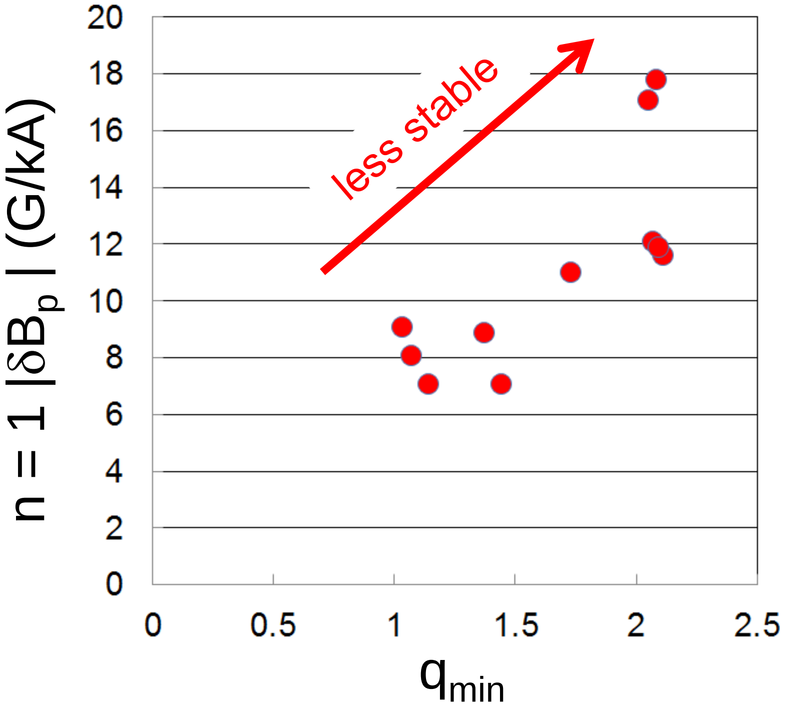
NSTX experimental rotation profile

# 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)



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

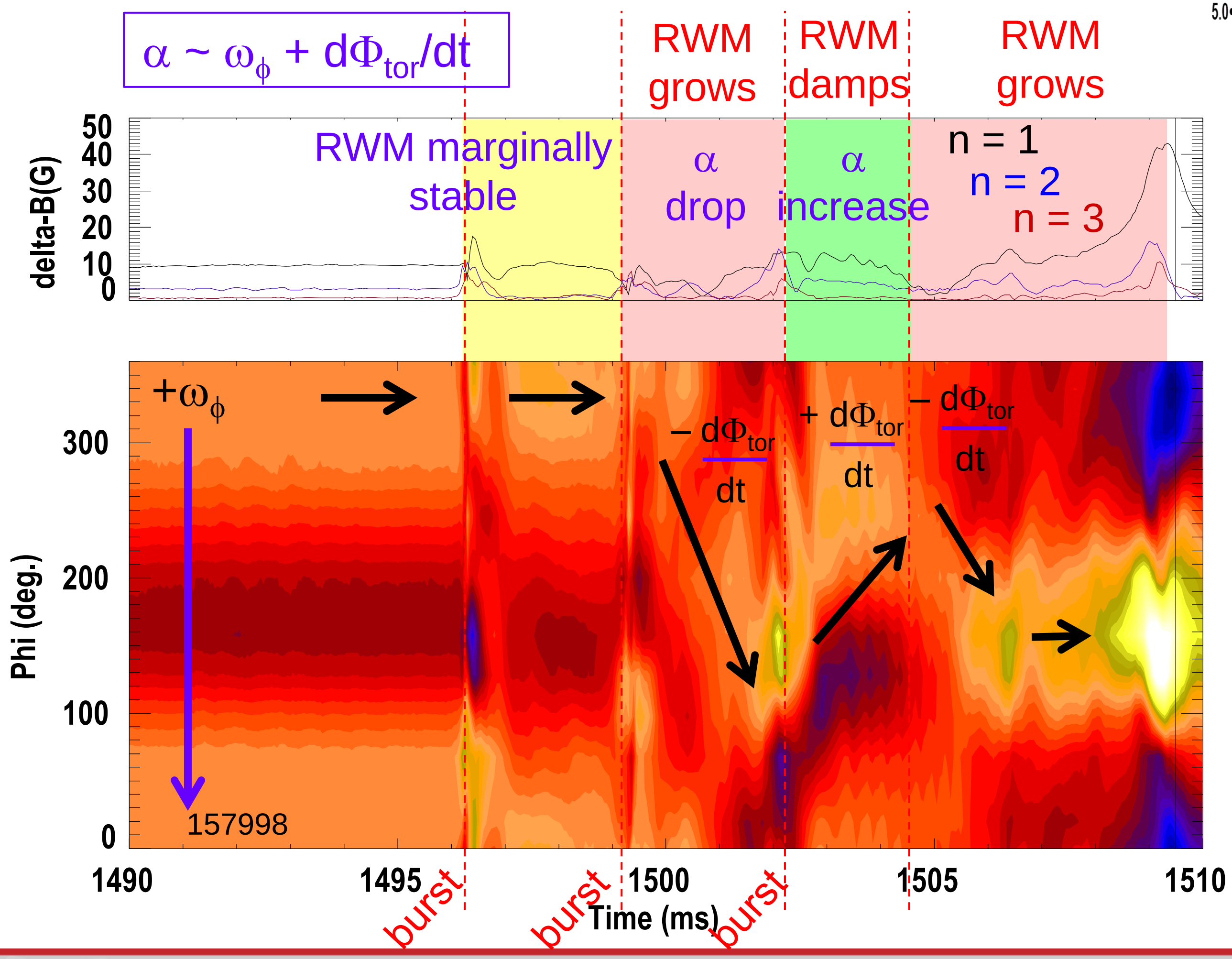
# Outline

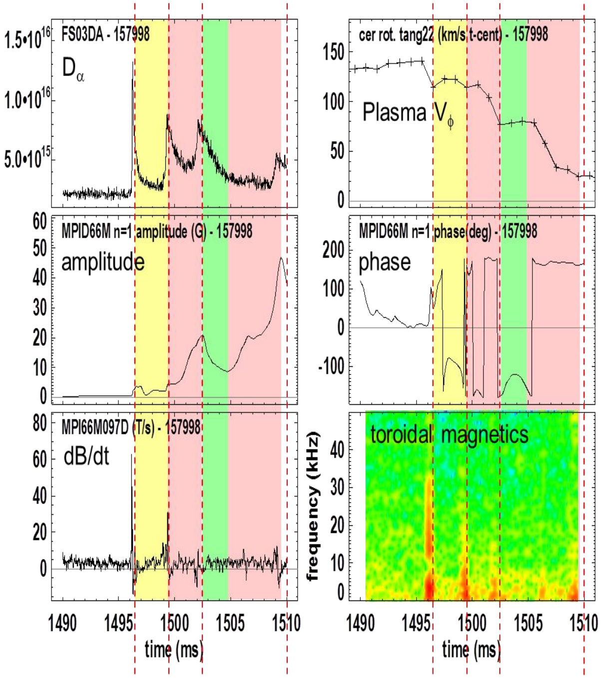
- ❑ RWM phenomenology and characteristics in theory and experiment (DIII-D and NSTX)
- ❑ RWM kinetic stabilization analysis / proximity of plasmas to stability boundaries
- ❑ Further implications and research opportunities

# 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)

$\alpha \sim \omega_{\phi} + d\Phi_{tor}/dt$





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

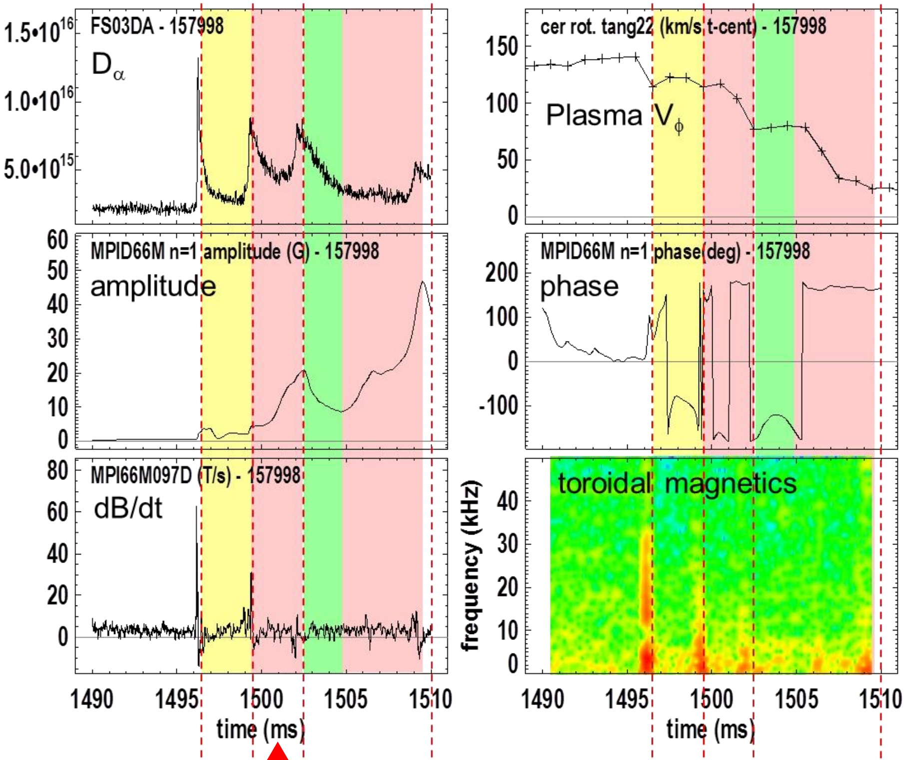
# Another consistent, intriguing hypothesis is non-linear RWM destabilization caused by $\delta$B from bursting MHD event

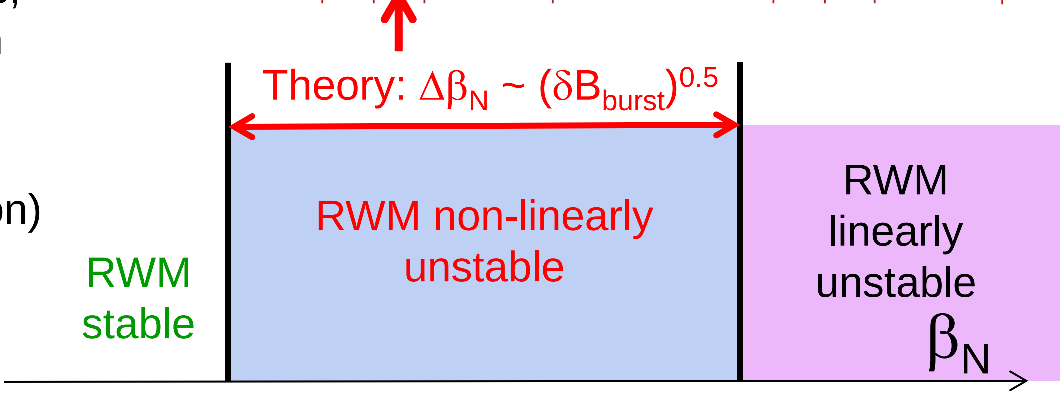
- Non-linear destabilization theory shows growth can occur below the linear instability point when other n = 1 field perturbation is present
  - Change in stability related to perturbation magnitude

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

- Hypothesis
  - Due to $\delta$B 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: $\Delta\beta_N \sim (\delta B_{burst})^{0.5}$

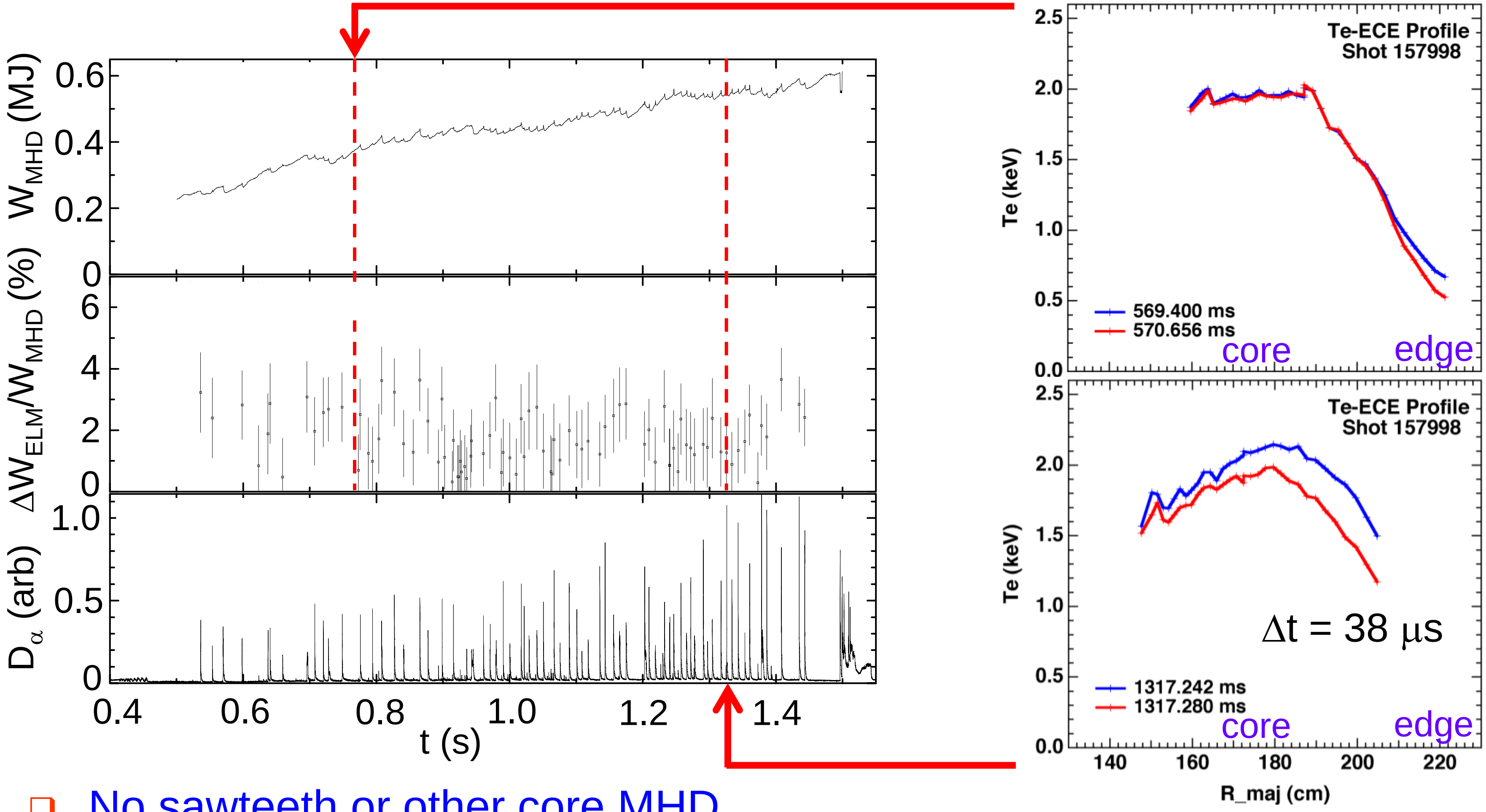
RWM stable

RWM non-linearly unstable

RWM linearly unstable

$\beta_N$

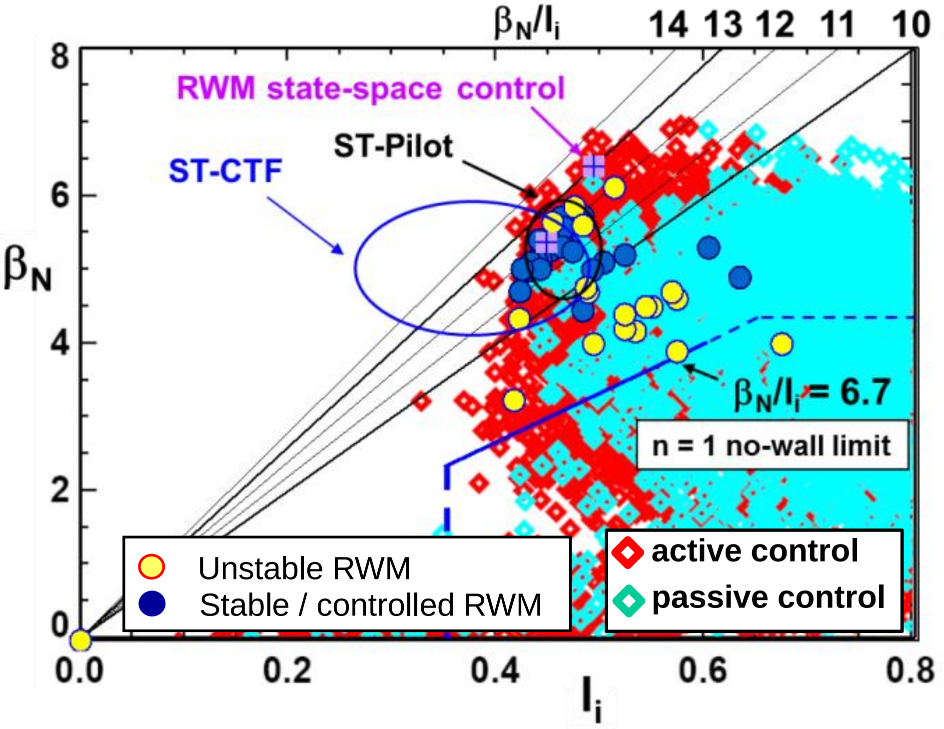
# 3. "ELMs" become radially extended at increased $\beta_N$; may have greater influence on RWM non-linear destabilization



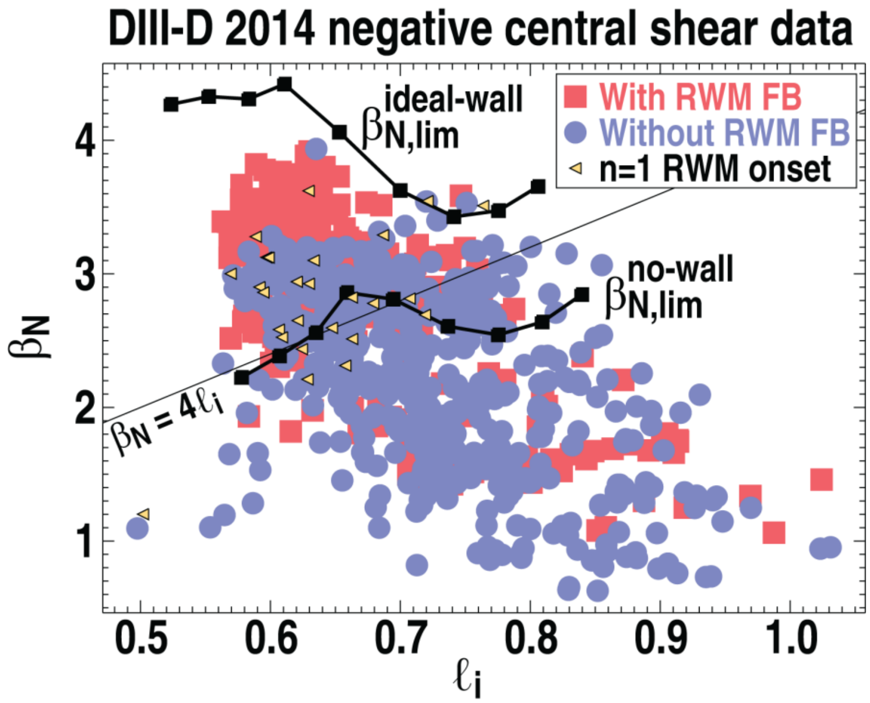
- No sawteeth or other core MHD
- Rapid bursting and quick "healing" ($\Delta t$ ~ 250 $\mu$s) may indicate that the internal perturbations are ideal

# Subtopic MDC-21.2: Active RWM feedback control has expanded the stable operating space in tokamaks

NSTX Database



DIII-D Database



- NSTX routine operation at 2x $\beta_N^{\text{no-wall}}$
  - At the highest $\beta_N$ values attained in device
  - Very high $\beta_N$, and $\beta_N$/li accessed
  - Intermediate $\beta_N$ suffers most disruptions

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

- **RWM feedback allows access to higher $\beta_N$ values**
- **Some cases where control is lost, indicating room for improvement.**

J.M. Hanson, C. Holcomb, et al., 2015

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

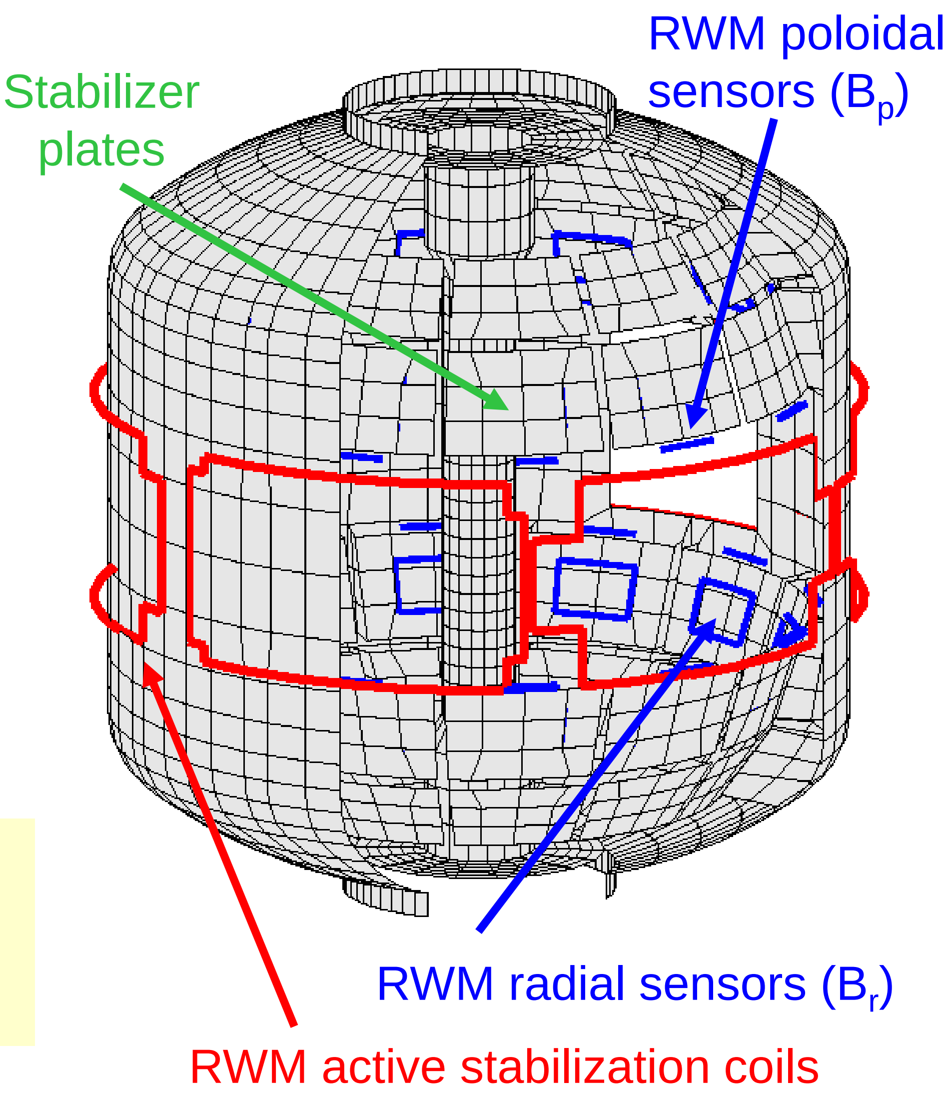
- High beta, low aspect ratio
  - R = 0.86 m, A > 1.27
  - $I_p < 1.5$ MA, $B_t = 5.5$ kG
  - $\beta_t < 40\%$, $\beta_N > 7$

- Copper stabilizer plates for kink mode stabilization

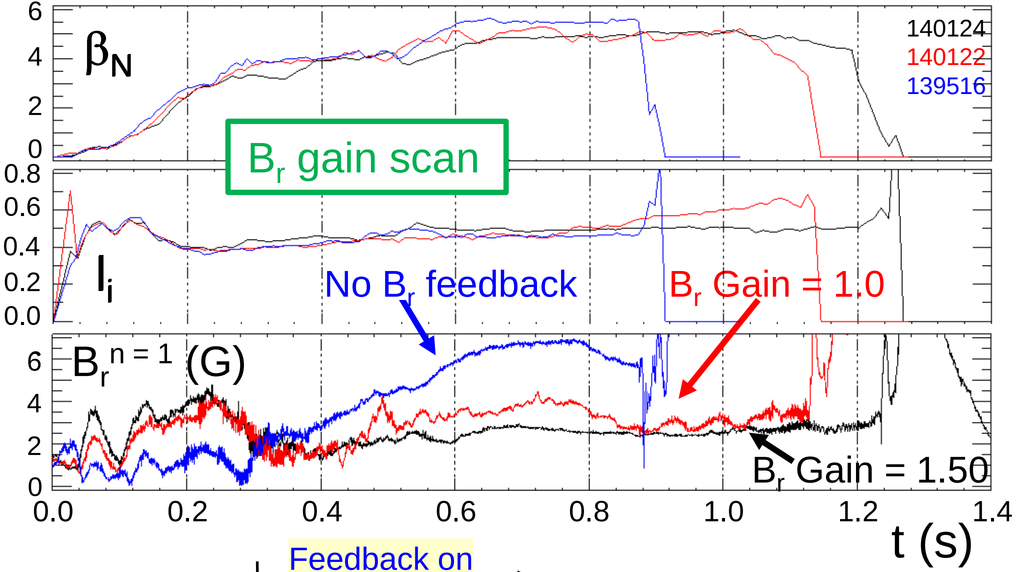
- Midplane control coils
  - n = 1 – 3 field correction, magnetic braking of $\omega_\phi$ by NTV
  - n = 1 RWM control

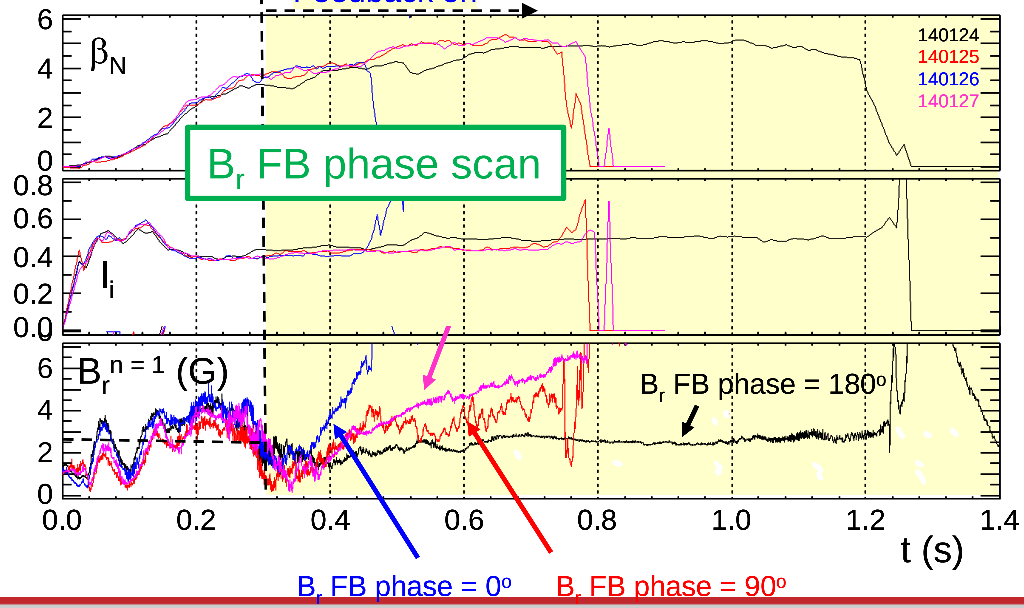
- Combined sensor sets now used for RWM feedback
  - 48 upper/lower $B_p$, $B_r$

3D Structure Model



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

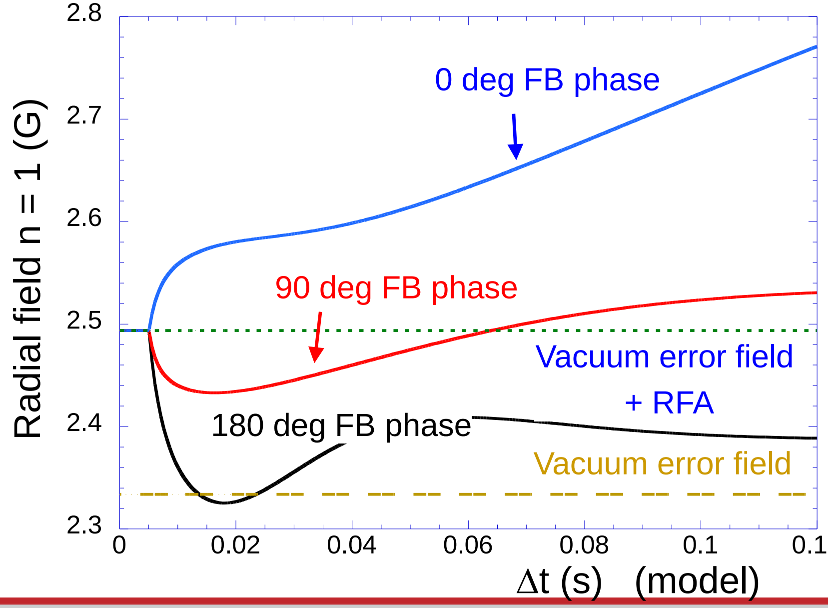




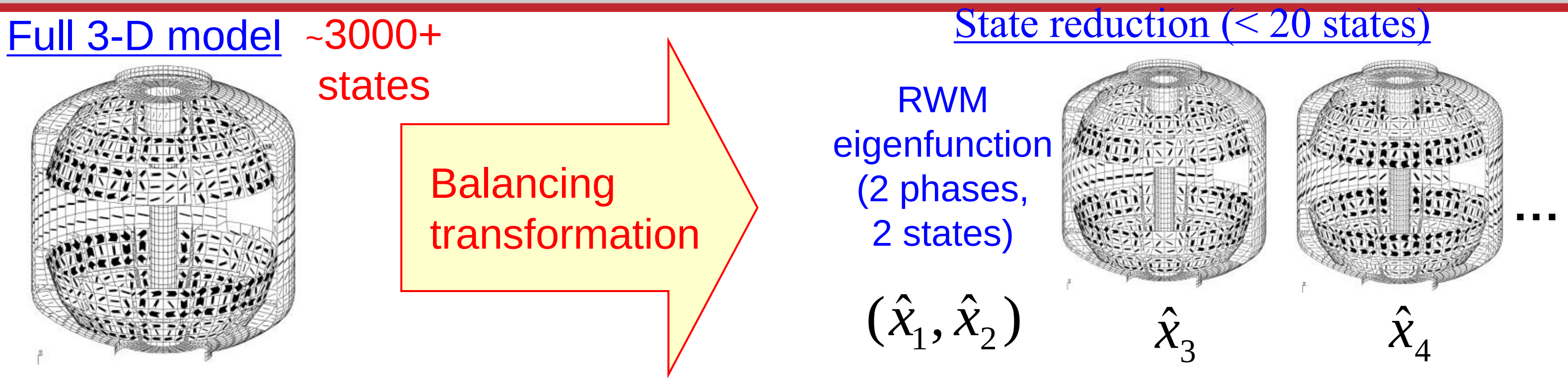
- Favorable $B_p$ + $B_r$ feedback (FB) settings found (low $l_i$ plasmas)
  - Fast RWM growth ~ 2 - 3 ms control by $B_p$
  - $B_r$ FB controls (~10 ms ~ $\tau_{w\text{-radial}}$) n=1 field amplification, modes
- Time-evolved theory simulation of $B_r$+$B_p$ feedback follows experiment

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

Simulation of $B_r$ + $B_p$ control (VALEN)



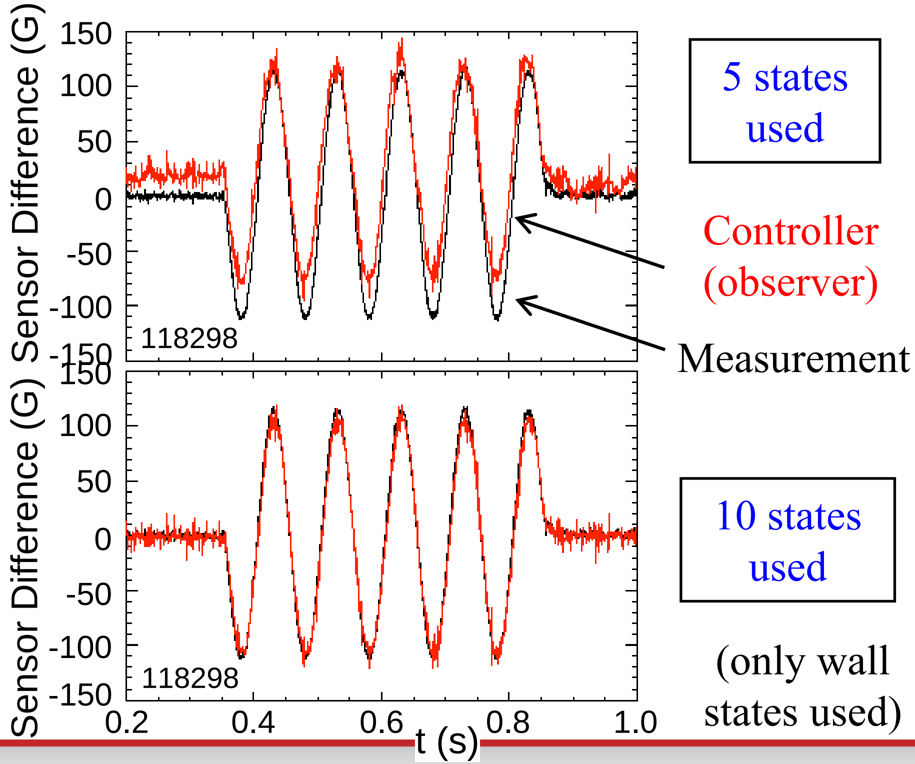
# Model-based RWM state space controller including 3D model of plasma and wall currents used at high $\beta_N$



- ❑ 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



5 states used

Controller (observer)

Measurement

10 states used

(only wall states used)

# 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

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

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

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

$$\hat{\vec{x}}_t = A\vec{x}_{t-1} + B\vec{u}_{t-1}; \hat{\vec{y}}_t = C\hat{\vec{x}}_t$$

(time update)

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

(measurement update)

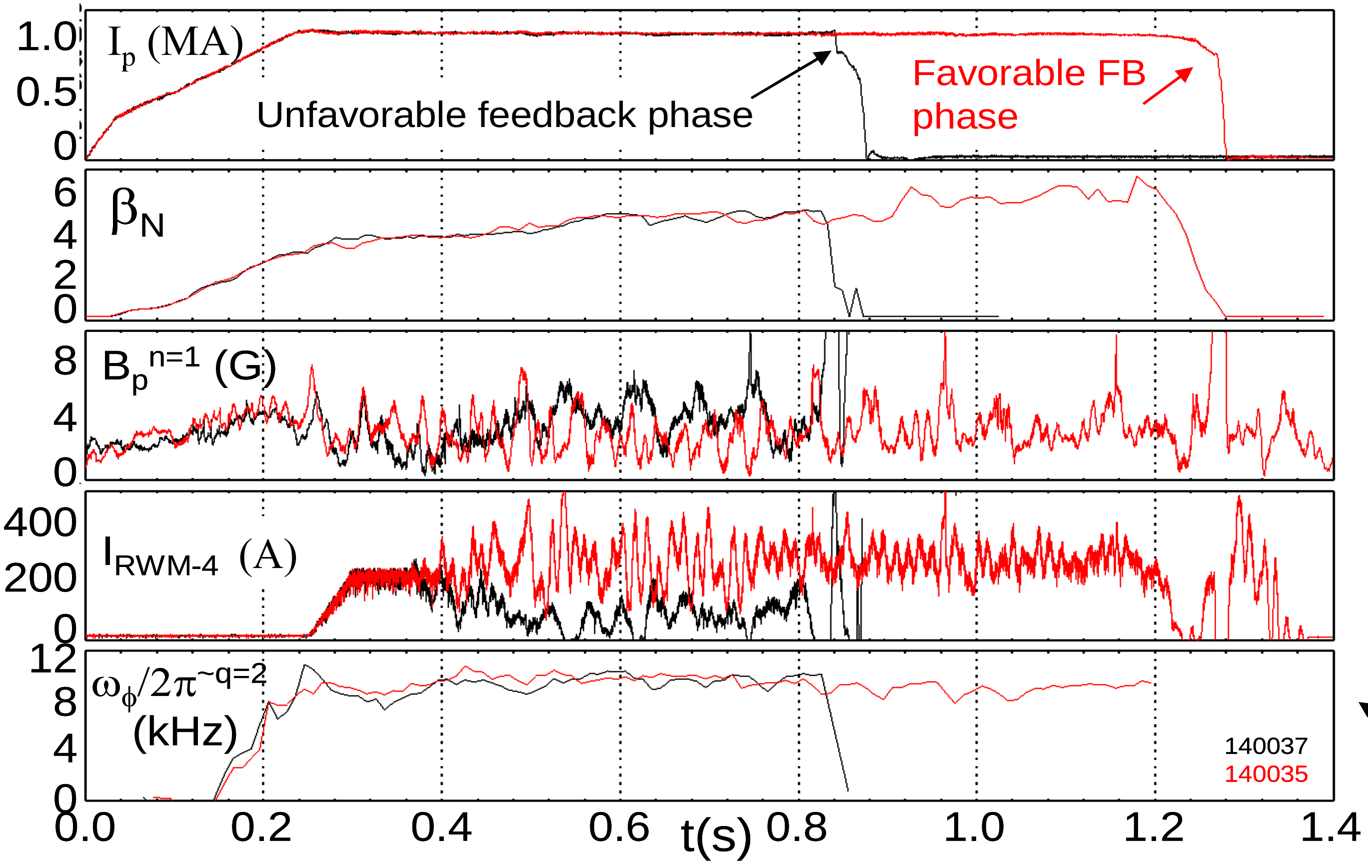
Written into the NSTX PCS

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

# NSTX RWM state space controller sustains high $\beta_N$, low $l_i$ plasma

RWM state space feedback (12 states)

NSTX Experiments (Year 2010)



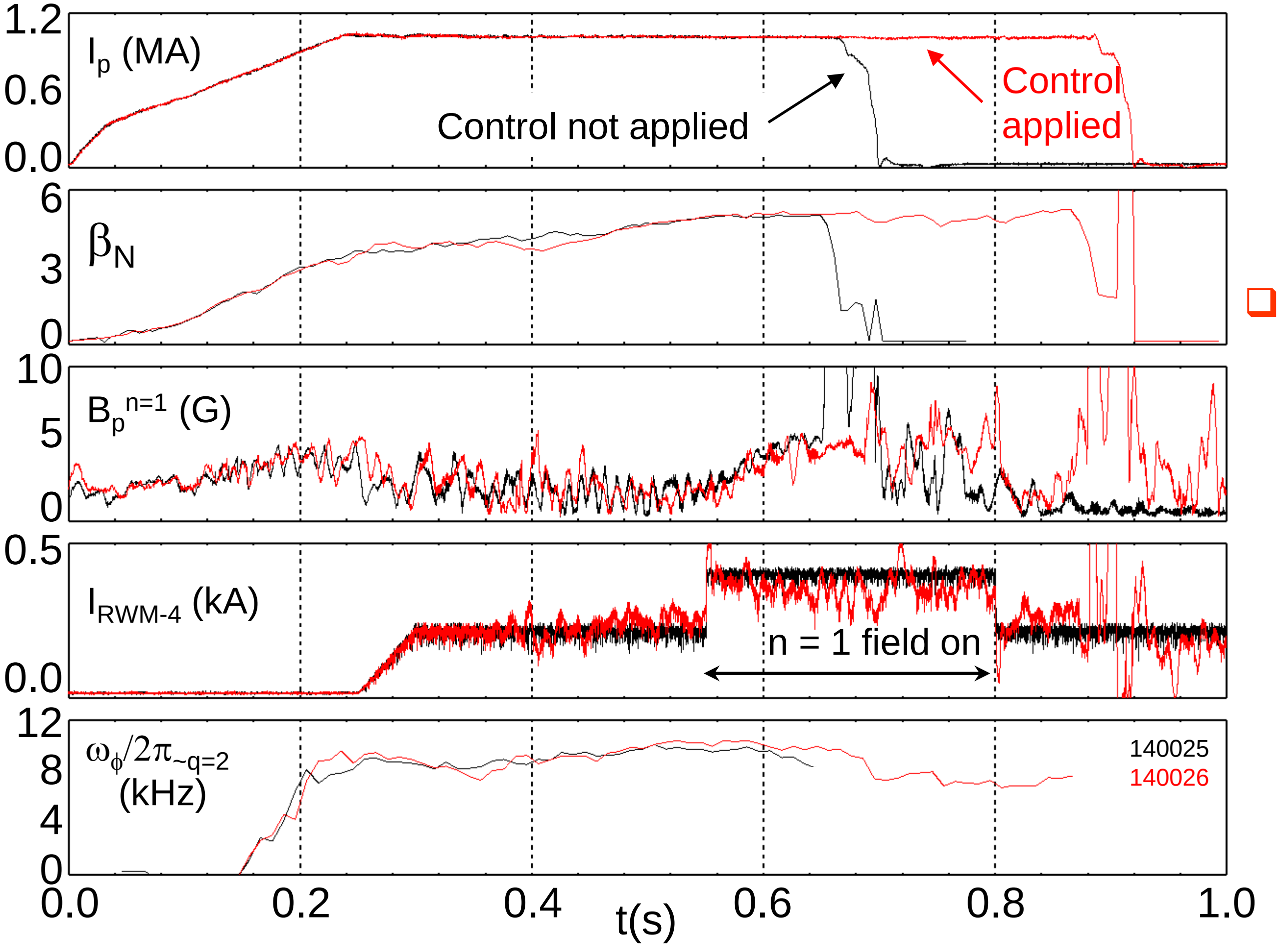
- n = 1 applied field suppression
  - Suppressed disruption due to n = 1 field
- Feedback phase scan
  - Best feedback phase produced long pulse, $\beta_N$ = 6.4, $\beta_N/l_i$ = 13

- 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)



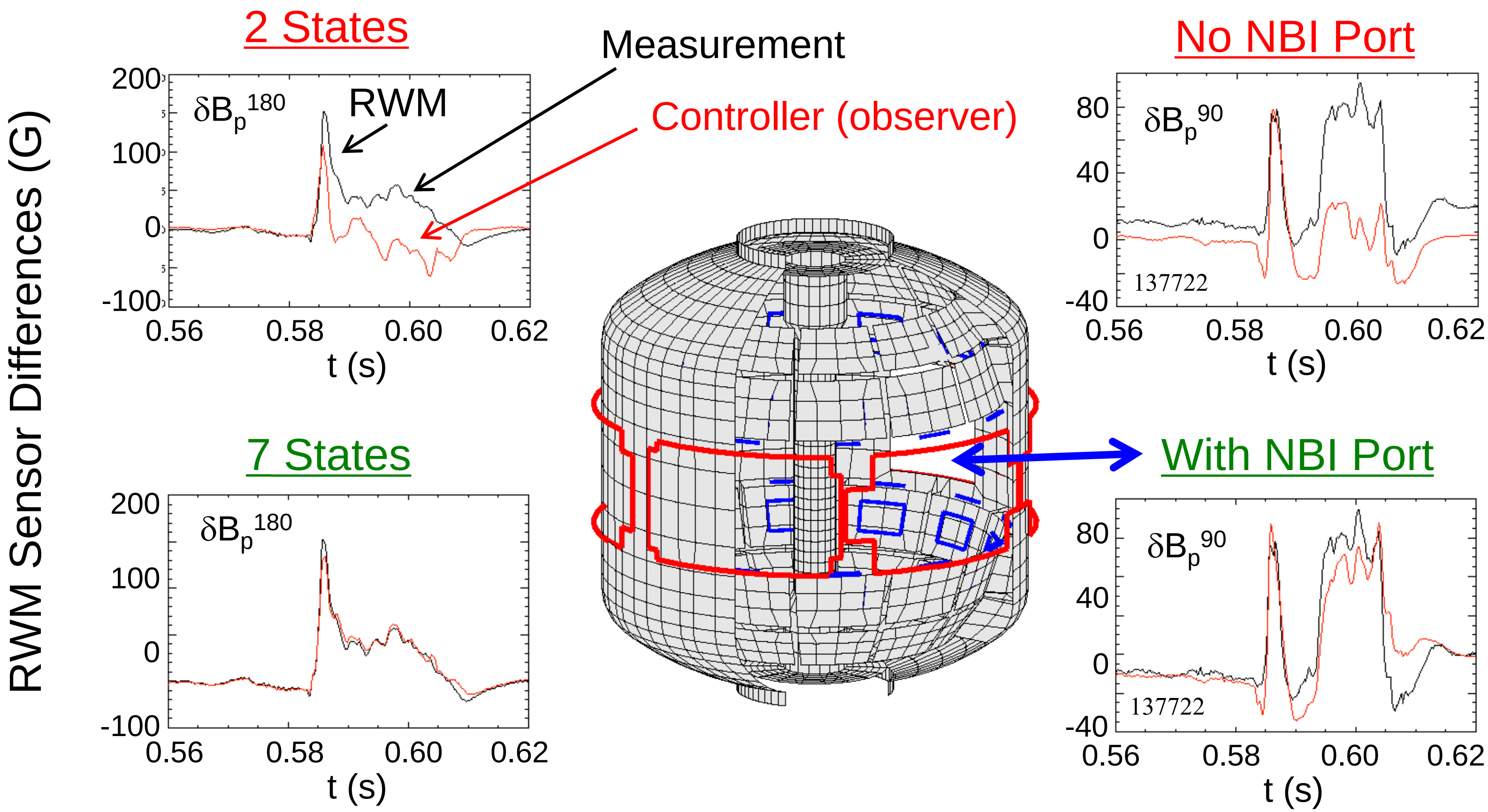
S. Sabbagh et al., Nucl. Fusion **53** (2013) 104007

- 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

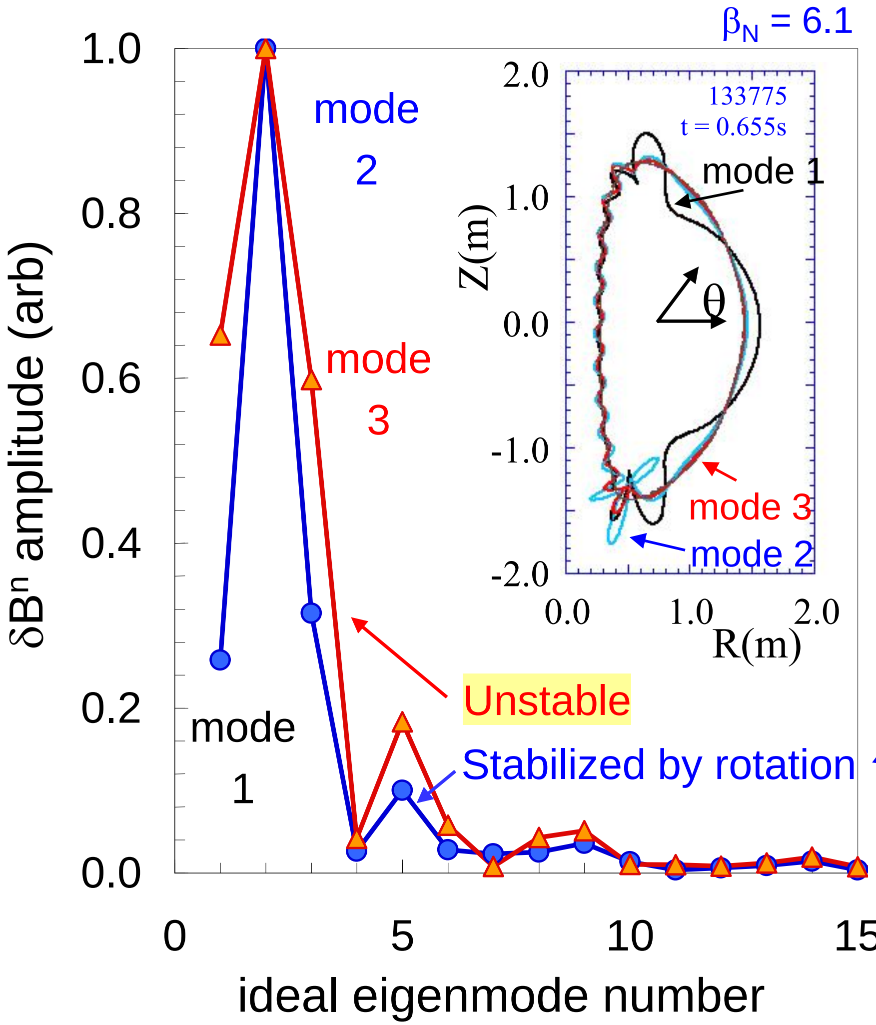
No NBI Port

With NBI Port

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

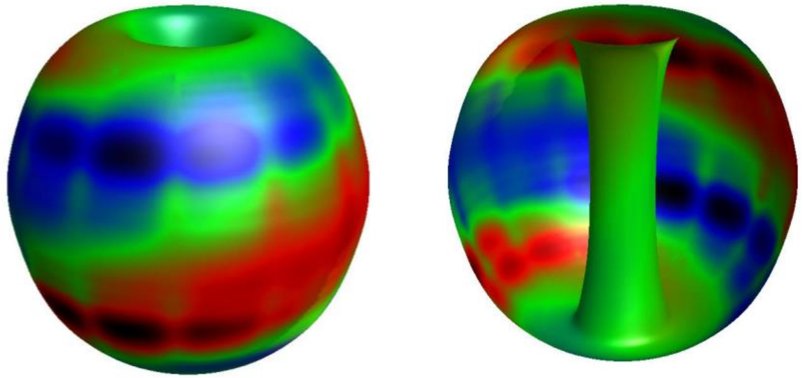
# Multi-mode computation for RWM: 2nd eigenmode component has dominant amplitude at high $\beta_N$ in NSTX 3D stabilizing structure

**$\delta B^n$ RWM multi-mode composition**



mmVALEN code

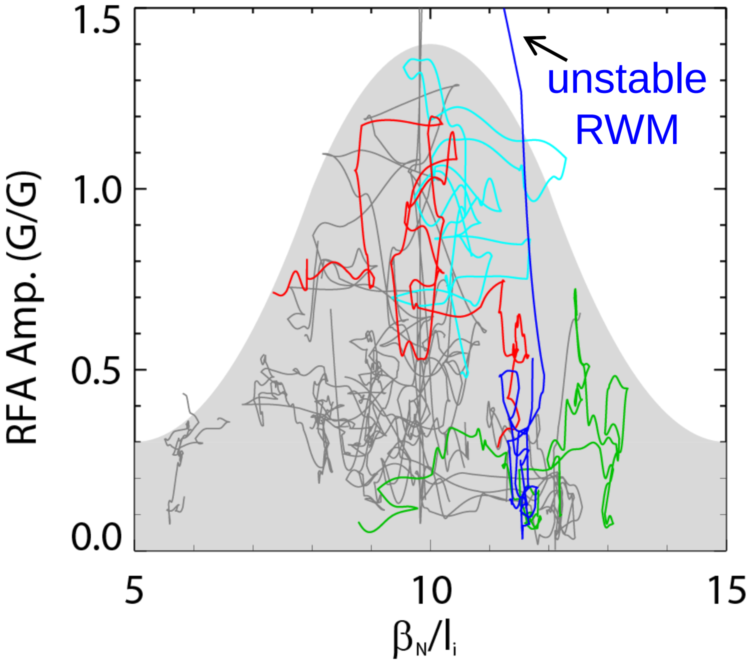
**$\delta B^n$ from wall, multi-mode response**



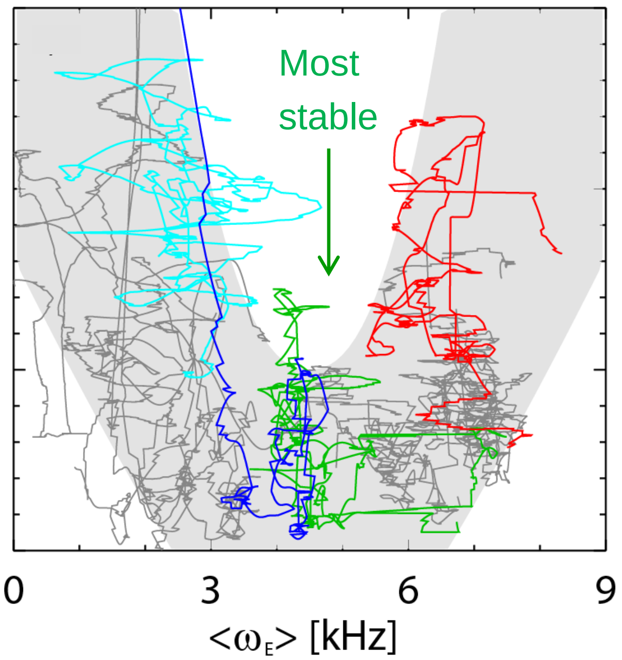
- NSTX RWM not stabilized by $\omega_\phi$
  - Computed growth time consistent with experiment
  - 2nd eigenmode ("divertor") has larger amplitude than ballooning eigenmode
- NSTX RWM stabilized by $\omega_\phi$ (or "$\alpha$")
  - Ballooning eigenmode amplitude decreases relative to "divertor" mode
  - 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. $\beta_N/l_i$



RFA vs. rotation ($\omega_E$)



(trajectories of 20 experimental plasmas)

- Stability vs. $\beta_N/l_i$
  - decreases up to $\beta_N/l_i = 10$, ***increases*** at higher $\beta_N/l_i$
  - 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 $\omega_\phi$

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

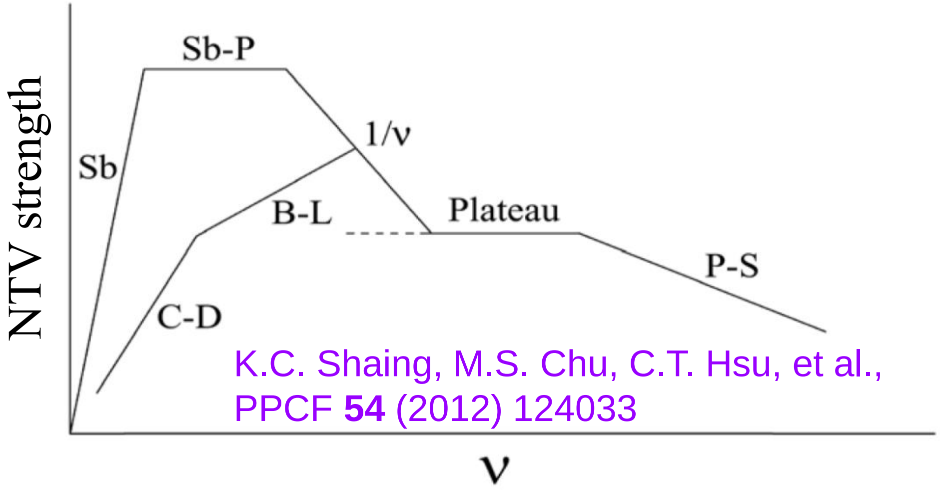
$$\delta W_k \sim \frac{1}{\langle\omega_D\rangle + \omega_E - i\nu_{eff}}$$

## NSTX experiments

- Stability at lower $\nu$
  - Collisional dissipation is reduced
  - Stabilizing resonant kinetic effects are enhanced
  - Stabilization when near broad $\omega_\varphi$ resonances; almost no effect off-resonance

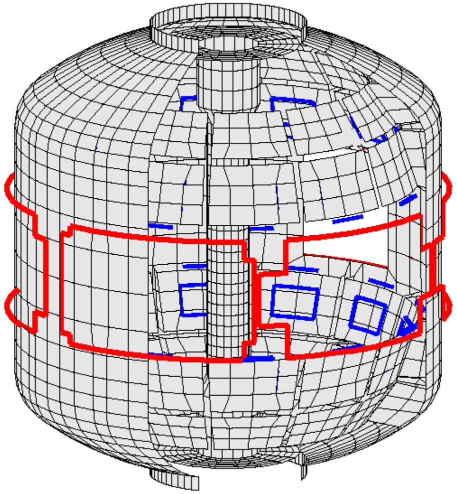
# Neoclassical Toroidal Viscosity (NTV) studied through the application of 3D fields in NSTX and KSTAR

- Theory: NTV strength varies with plasma collisionality $\nu$, $\delta B^2$, rotation

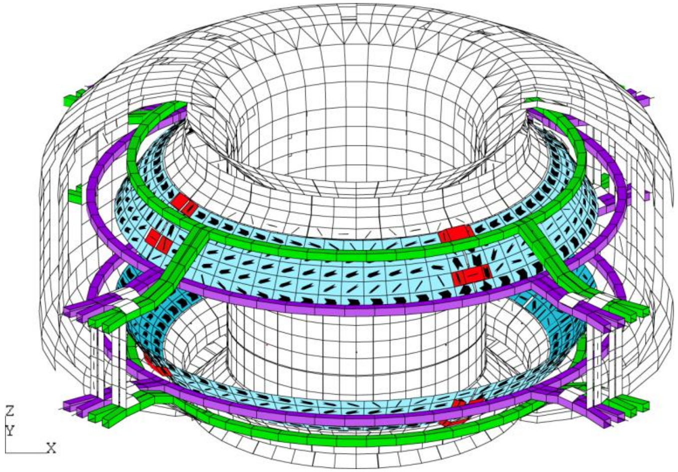


K.C. Shaing, M.S. Chu, C.T. Hsu, et al.,
PPCF **54** (2012) 124033

NSTX 3D coils



KSTAR 3D coils



NTV force in "1/ν" collisionality regime

$\delta B^2$

$$\boxed{\left\langle \hat{e}_t \bullet \vec{\nabla} \bullet \overleftrightarrow{\Pi} \right\rangle_{(1/\nu)} = B_t R \left\langle \frac{1}{B_t} \right\rangle \left\langle \frac{1}{R^2} \right\rangle \frac{\lambda_{1i} p_i}{\pi^{3/2} \nu_i} \varepsilon^{3/2} (\omega_\phi - \omega_{NC}) I_\lambda}$$

K.C. Shaing, et al.,
PPCF **51** (2009) 035004

$T_i^{5/2}$

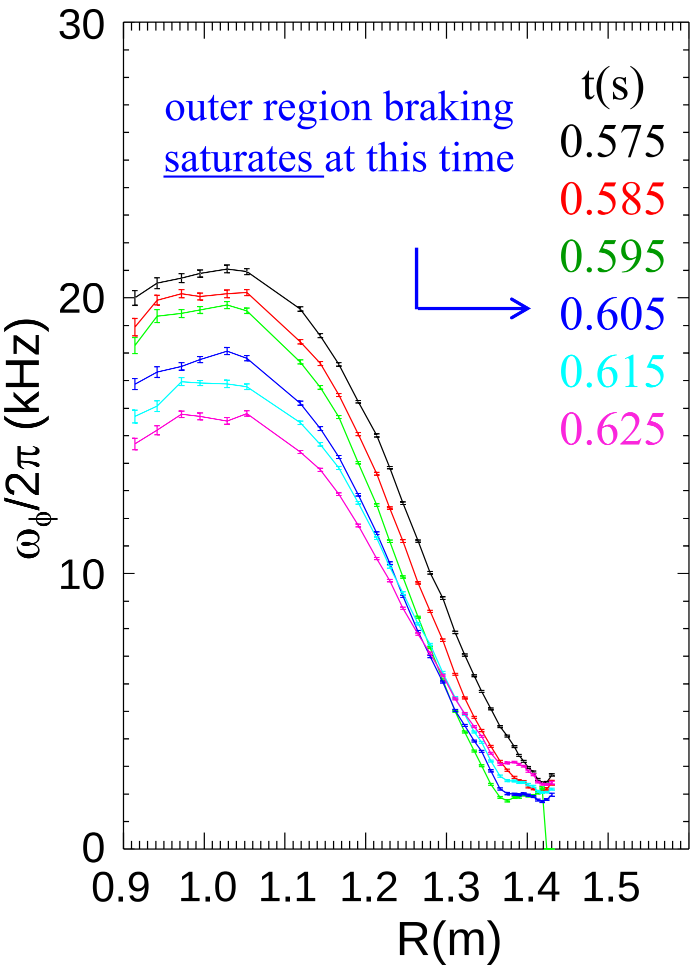
plasma rotation

# NTV physical characteristics are generally favorable for rotation control

- ❑ Non-resonant NTV characteristics (e.g. in NSTX and KSTAR)
  - ❑ Experimentally, NTV torque, $T_{NTV}$, is radially extended, with a relatively smooth profile
  - ❑ NTV changes continuously as the applied 3D field is increased
  - ❑ Can alter the $\omega_\phi$ profile without mode locking
  - ❑ $T_{NTV}$ is not simply an integrated torque applied at the plasma boundary, but a radial profile – e.g. $\omega_\phi$ shear can be changed
    - ● potential for mode control
- ❑ Questions remain
  - ❑ e.g. Is there hysteresis when $\omega_\phi$ is altered by NTV?

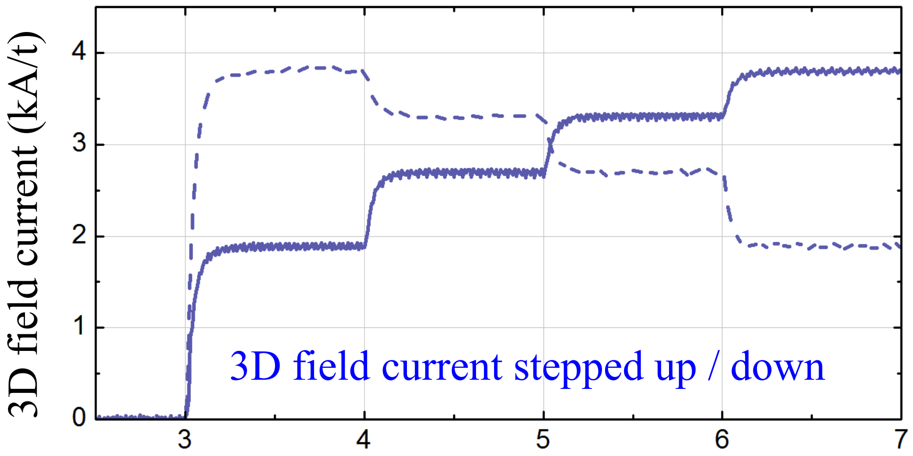
    Suggested in: Y. Liang, et al., NF **50** (2010) 025013

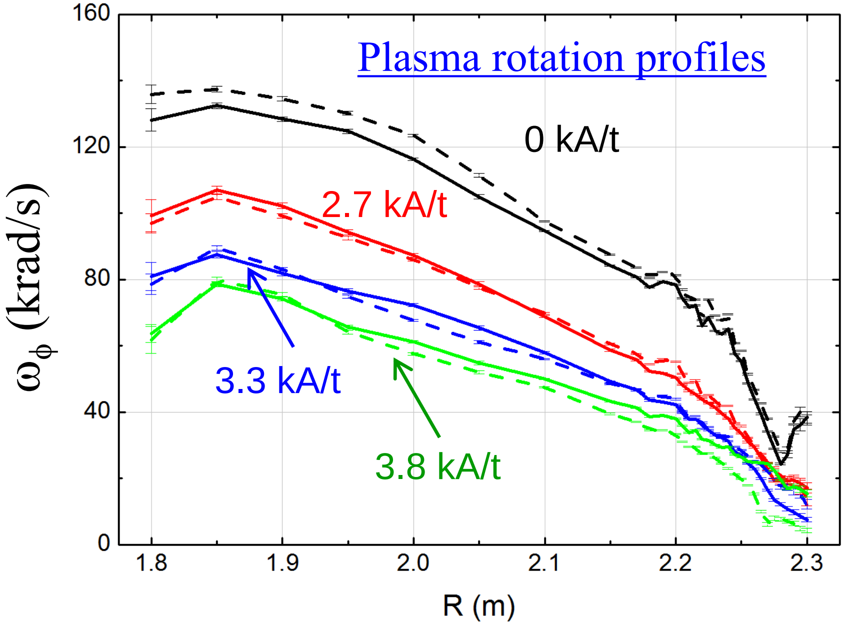
$\omega_\phi$ alteration by n = 2 applied field configuration in NSTX



# KSTAR experiments show essentially no hysteresis in steady-state $\omega_\phi$ profile vs. applied 3D field strength

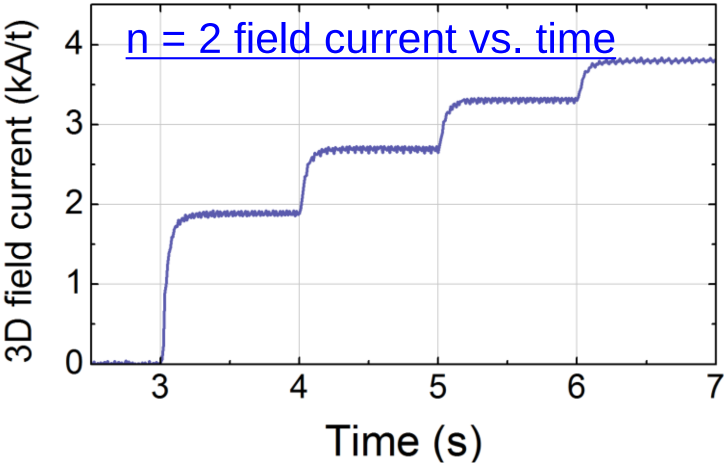
KSTAR non-resonant ("n = 2") NTV experiments

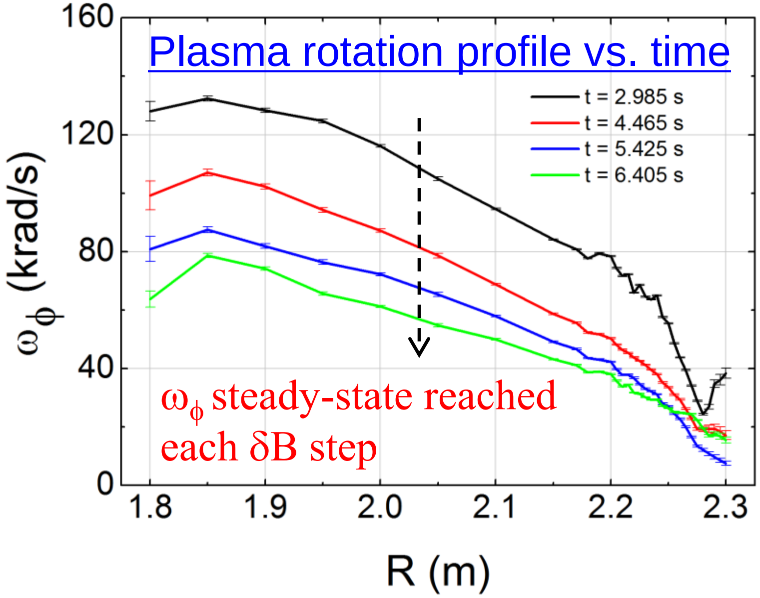




- Experiment run to produce various steady-state $\omega_\phi$ with different 3D field evolution
- The steady-state rotation profile reached is generally independent of the starting point of $\omega_\phi$
  - depends just on the applied 3D field current level
  - important for rotation control
- Absence of hysteresis further confirmed in very recent experiments with 6 steps in 3D field current

# KSTAR experiments show Neoclassical Toroidal Viscosity varies as $\delta B^2$, and $T_i^{2.27}$, expected by theory

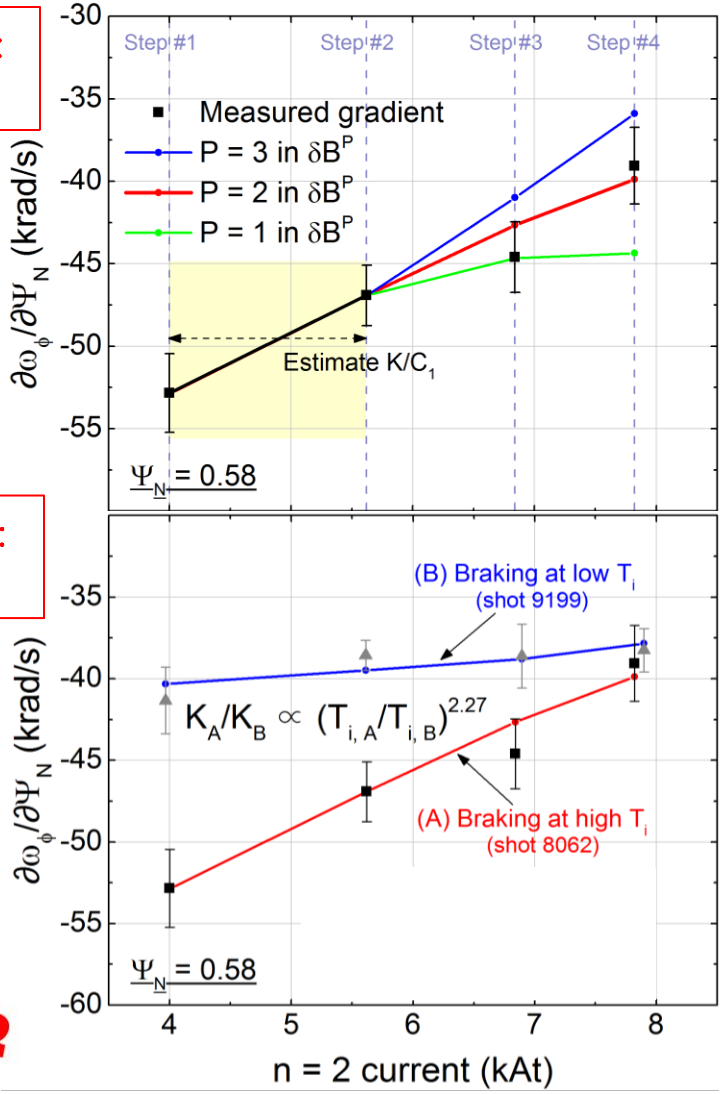




$\omega_\phi$ steady-state reached each $\delta B$ step

Best fit:
$\propto \delta B^2$

Best fit:
$\propto T_i^{2.27}$



- $T_i$ scaling confirms NSTX results

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

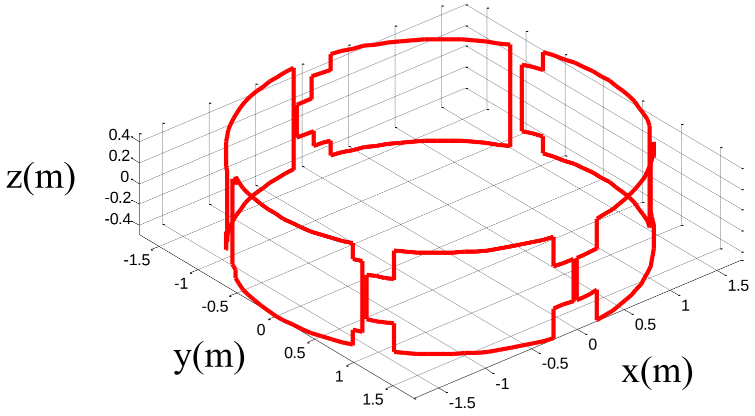
Y.S Park, et al., IAEA FEC 2014 paper EX/P8-05

# 3D field perturbation experiments measure the $T_{NTV}$ profile in NSTX

- High normalized beta plasma targets typically chosen
  - Typically near or above n = 1 no-wall limit (for higher $T_i$)
- Apply/change 3D field on a timescale significantly faster than momentum diffusion time, $\tau_m$
  - Analysis before/after 3D field application isolates $T_{NTV}$ in the momentum diffusion equation; $-dL/dt = T_{NTV}$ (other parameters ~ constant)
- $dL/dt$ measured experimentally and compared to theoretically computed $T_{NTV}$ on this timescale
  - Important, as $dL/dt$ profile changes significantly on timescales > $\tau_m$, (diffuses radially, broadens, leads to significant error compared to $T_{NTV}$)
- Focus on non-resonant applied 3D field configurations to avoid driving strong MHD modes

# Theoretical NTV torque density profiles, $T_{NTV}$ are computed for NSTX using theory applicable to all collisionality regimes

## Non-axisymmetric coils fully modelled in 3D



## 3D field definition

$$\delta B = \vec{b} \bullet \left(\vec{B} / B\right) + \left(\vec{\xi} \bullet \nabla B\right)$$

plasma displacement

- General considerations
  - In tokamaks, $\xi$ not measured in detail, can lead to large error
  - "Fully-penetrated field constraint" used to define $\xi$ $\left(\vec{B}_{2D} \bullet \nabla\vec{\xi} = \vec{b}\right)$
  - Computed $|\xi|$ ~ 0.3 cm << $\varepsilon^{0.5}\rho_i$, therefore, ion banana width-averaging is used for ion channel
    - Can explain why strong resonant peaks in NTV profile are not observed in experiment

- NTV analysis of NSTX – data interfaced to NTVTOK

  (Y. Sun, Liang, Shaing, et al., NF **51** (2011) 053015)

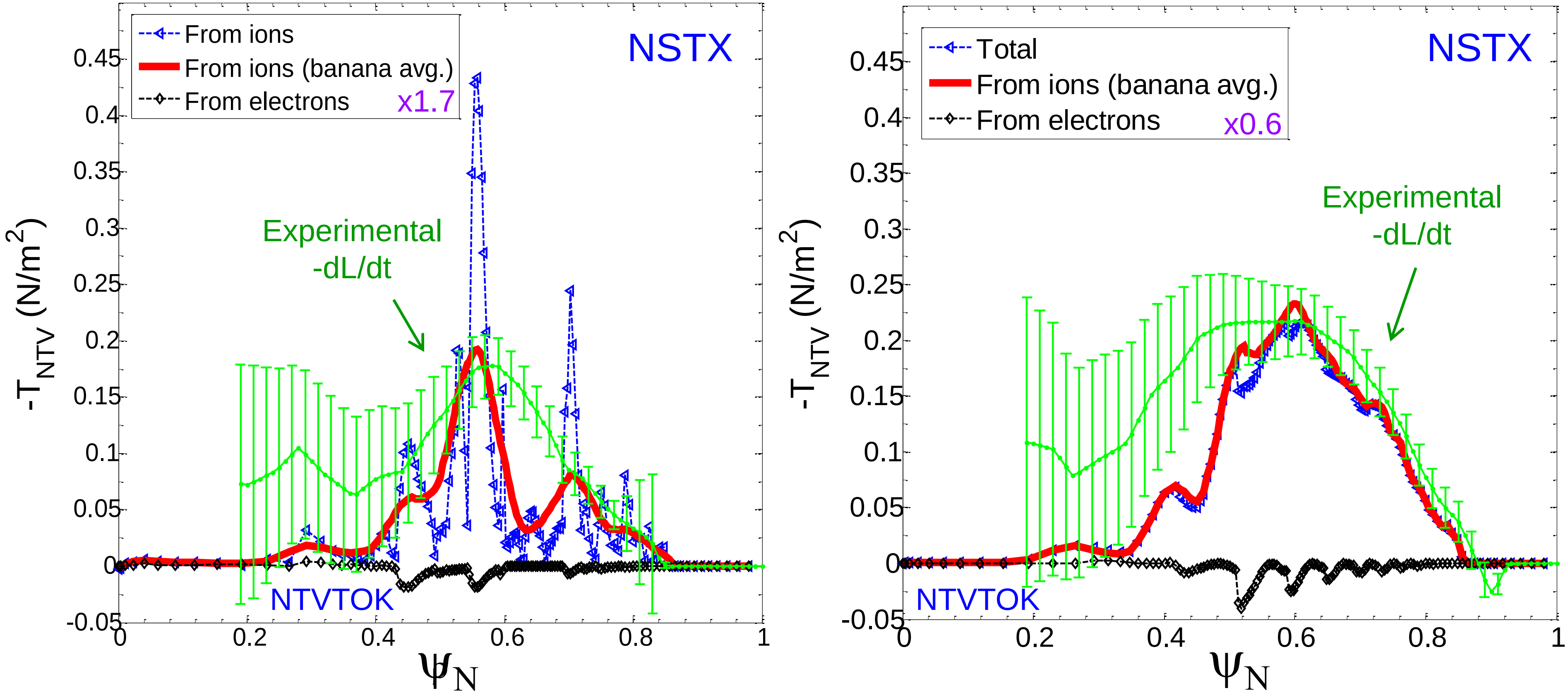
  - Use Shaing's "connected NTV model", covers all ν, superbanana plateau regimes

    (K.C. Shaing, Sabbagh, Chu, NF **50** (2010) 025022)
  - Full 3D coil specification and $\delta B$ spectrum, ion and electron components computed

# Measured NTV torque density profiles quantitatively compare well to computed $T_{NTV}$ using fully-penetrated 3D field

n = 2 coil configuration

n = 3 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
  - O(1) agreement using “fully-penetrated 3D field” indicates that plasma response is *not* strongly amplified from this “vacuum field assumption” ($T_{NTV} \sim \delta B^2$)

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

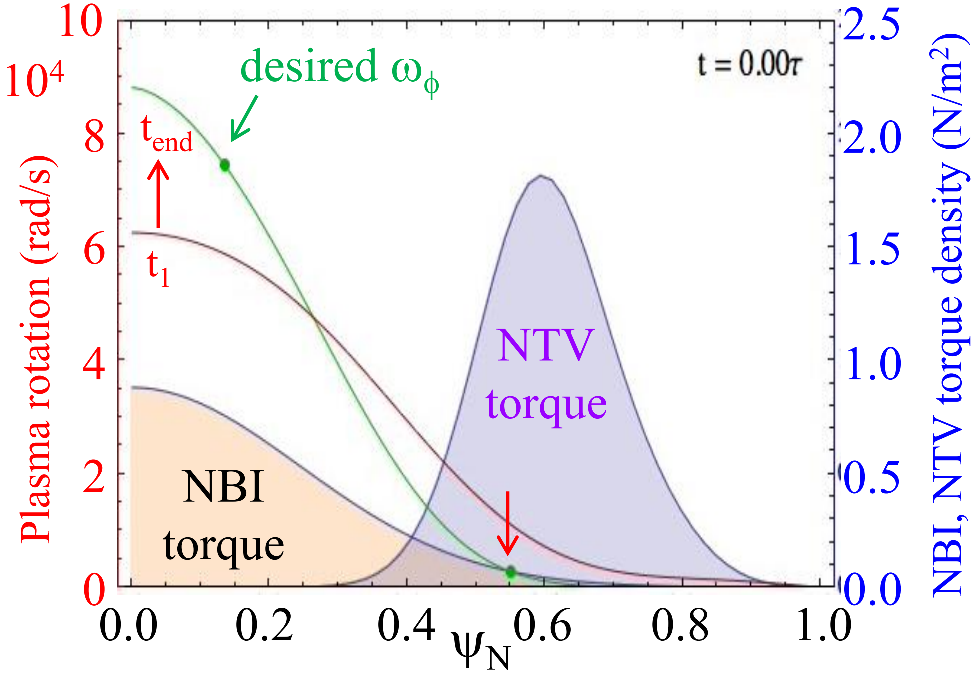
- Momentum force balance – $\omega_\phi$ decomposed into Bessel function states

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

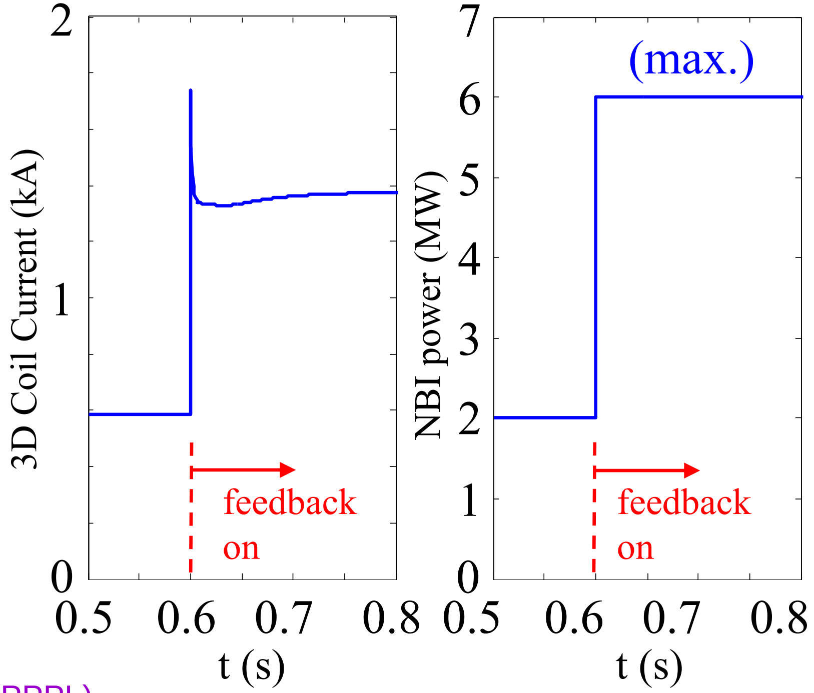
- NTV torque:

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

Rotation evolution and NBI and NTV torque profiles



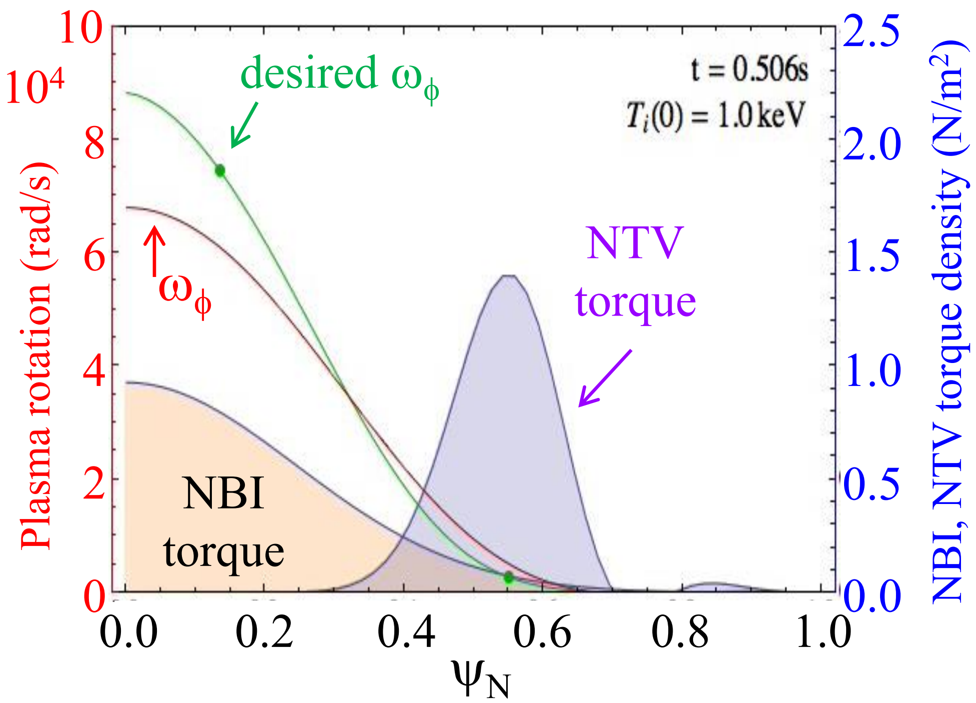
3D coil current and NBI power (actuators)



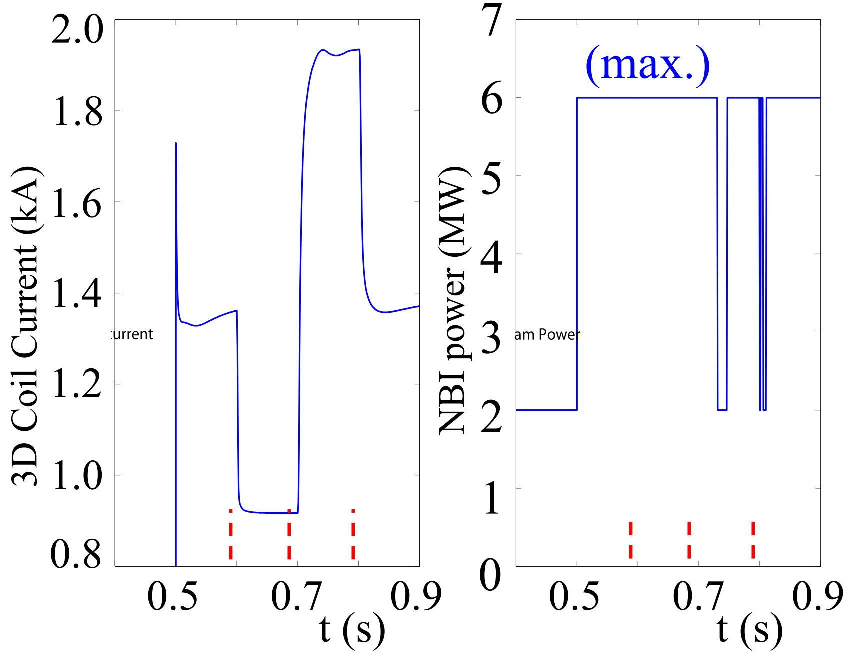
I. Goumiri (PU), S.A. Sabbagh (Columbia U.), D.A. Gates, S.P. Gerhardt (PPPL)

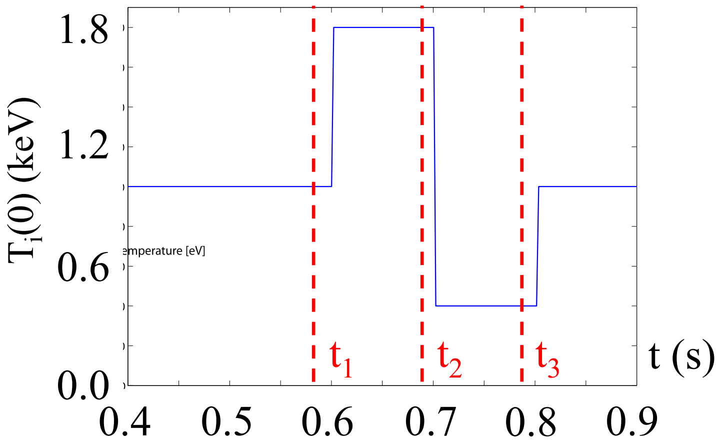
# When $T_i$ is included in NTV rotation controller model, 3D field current and NBI power can compensate for $T_i$ variations

Rotation evolution and NBI and NTV torque profiles



3D coil current and NBI power (actuators)



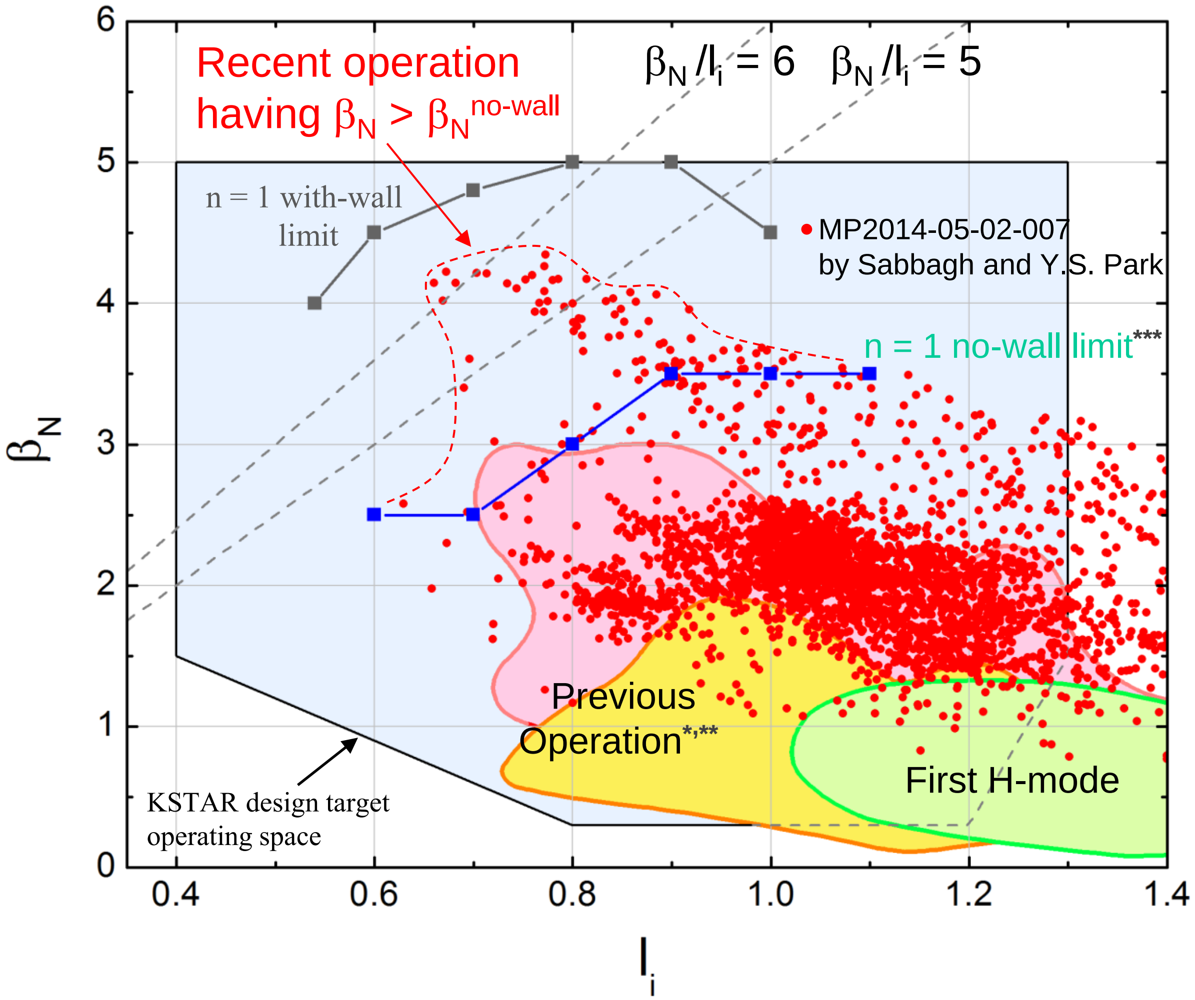


- NTV torque: depends in Ti

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

K1 = 0, K2 = 2.5

# KSTAR plasmas have 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

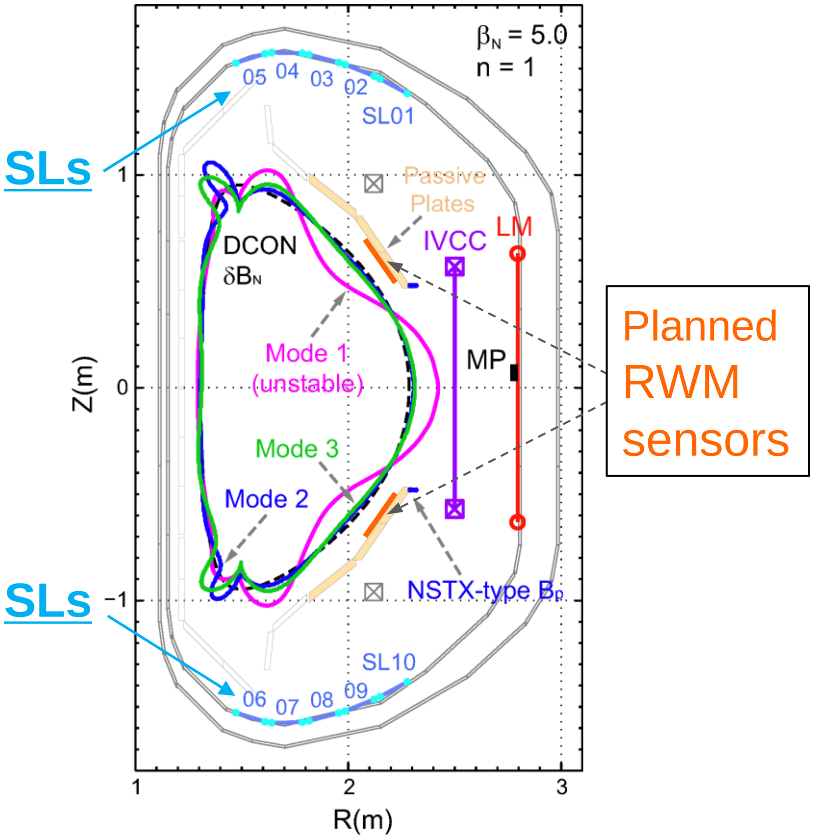
**Y.S. Park, et al., Phys. Plasmas **21** (2014) 012513

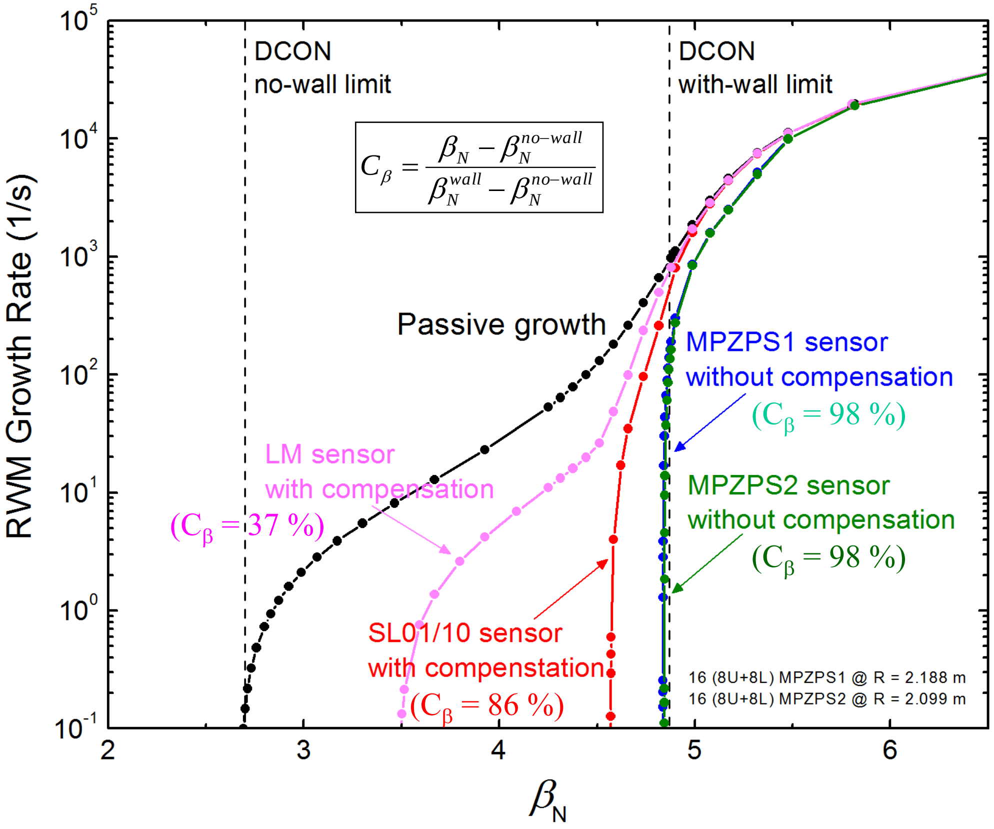
** O. Katsuro-Hopkins, et al., Nucl. Fusion **50** (2010) 025019

- 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
  - $\beta_N$ up to 4.3
  - $l_i$ ranging 0.66 - 0.87 with $\beta_N > 4$
  - Discharge $\beta_N$ was **not** limited by n > 0 events

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

# New (2015) KSTAR RWM sensors show superior theoretical control performance over the existing device sensors

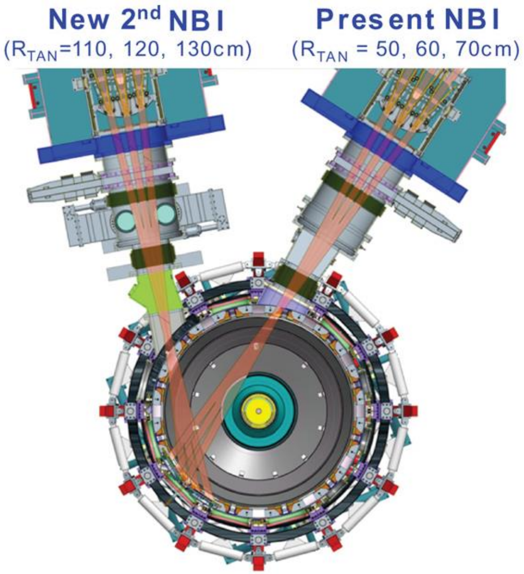




- Plans for KSTAR research and experiment in 2015
  - Examine data from new RWM sensors in 2015 experiments
  - Begin to use new high-bandwidth power supply for 3D field coils (various purposes)

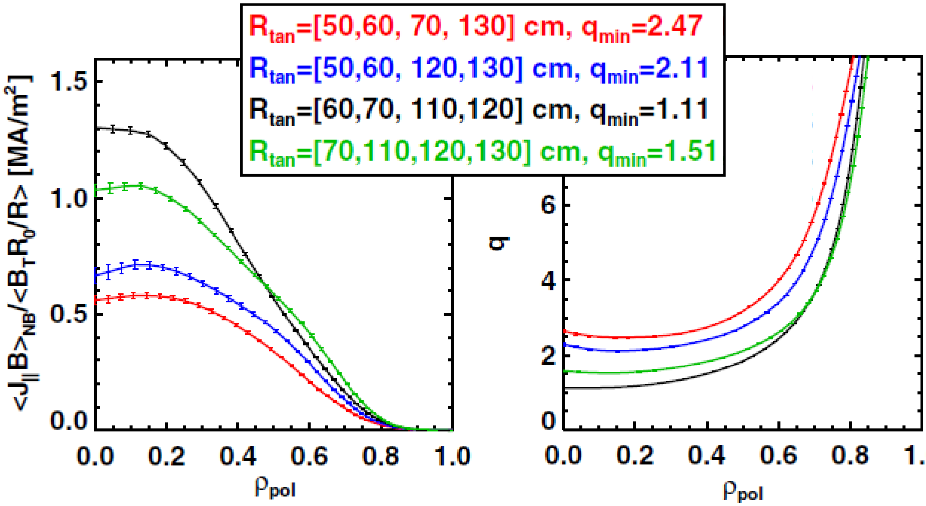
Y.S. Park, S.A. Sabbagh, et al., KSTAR Conference 2015

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

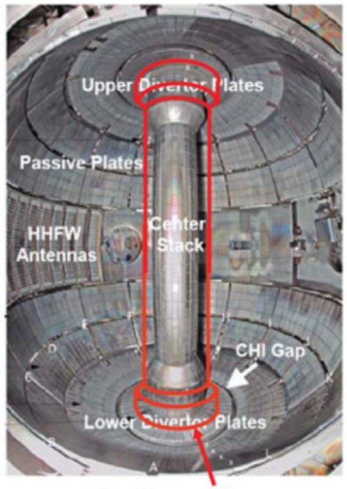


New neutral beams:

- Higher power
- Broader current and pressure profiles



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

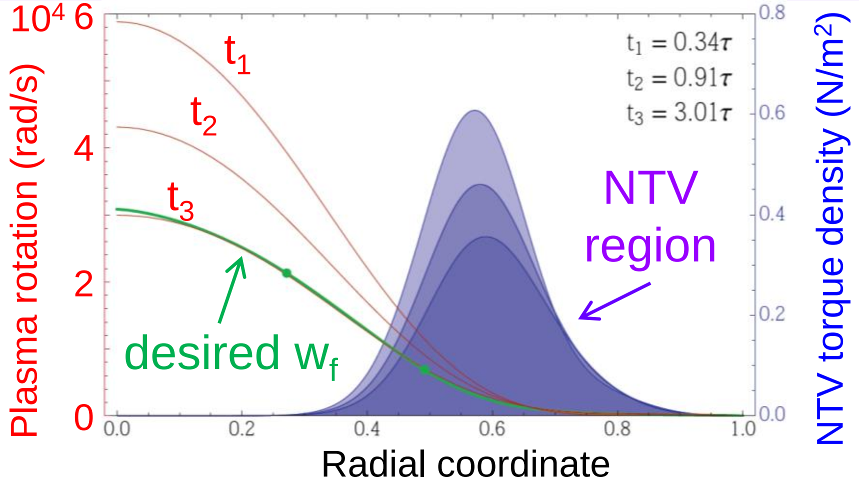


Outline of new center-stack (CS)

New center stack:

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

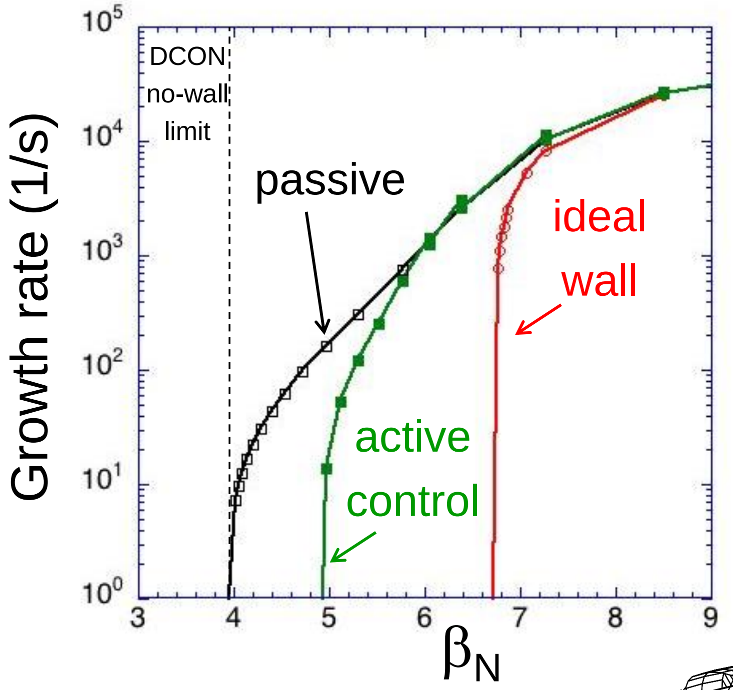
NSTX-U state-space $w_f$ controller w/NTV as actuator



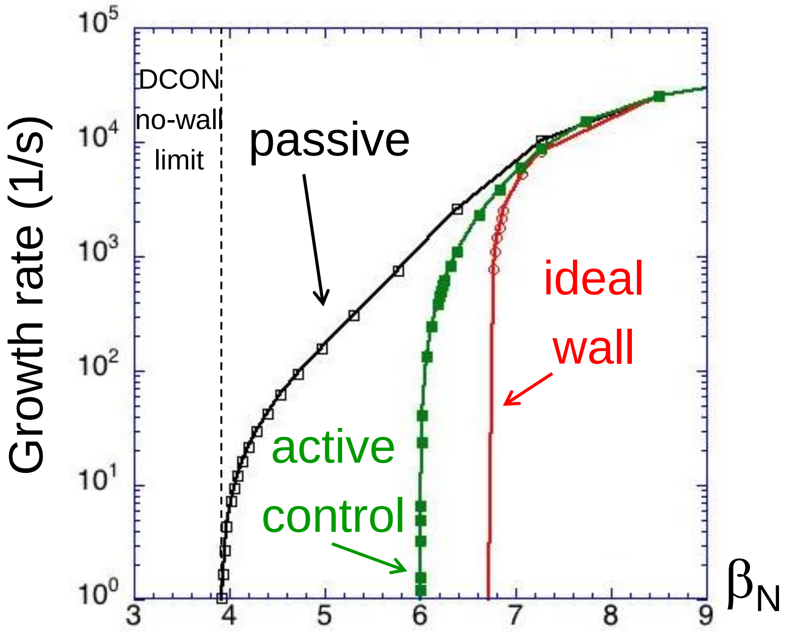
S.A. Sabbagh *et al.*, IAEA FEC paper EX/1-4 (2014)

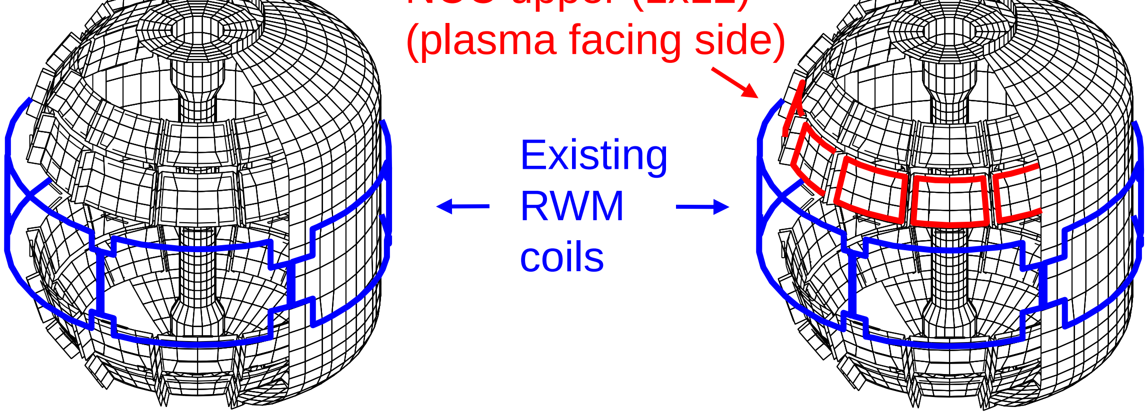
# NSTX-U: RWM active control capability increases as proposed 3D coils upgrade (NCC coils) are added

Using present midplane RWM coils



Partial NCC 1x12 (upper), favorable sensors

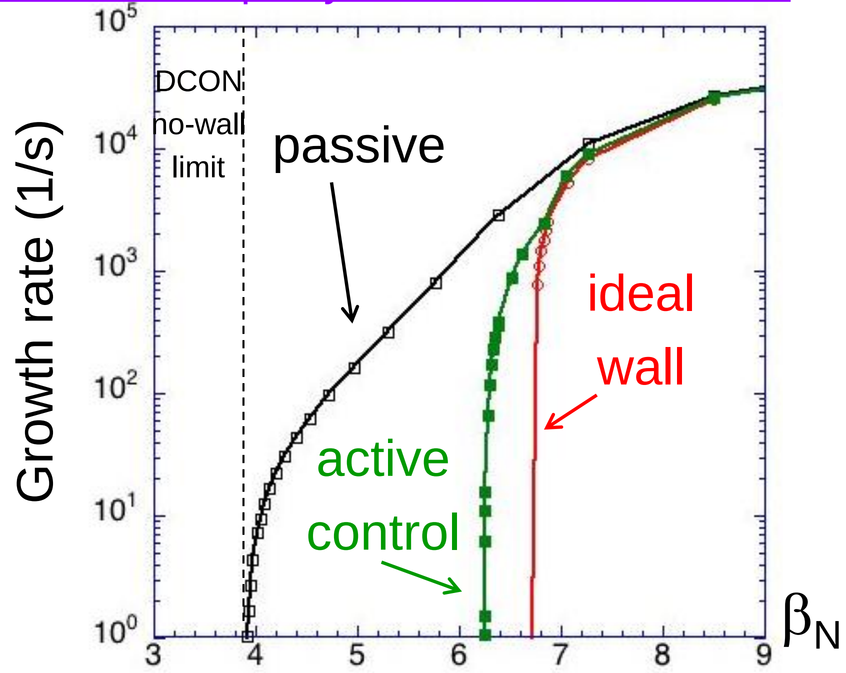




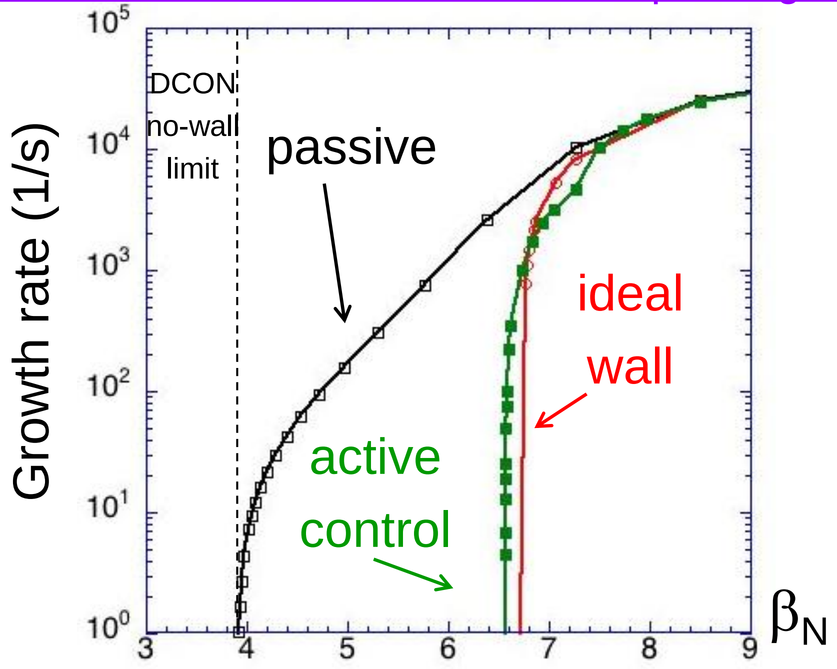
- Partial 1x12 NCC coil set significantly enhances control
  - Present RWM coils: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.25$
  - NCC 1x12 coils: active control to $\beta_N/\beta_N^{\text{no-wall}} = 1.52$

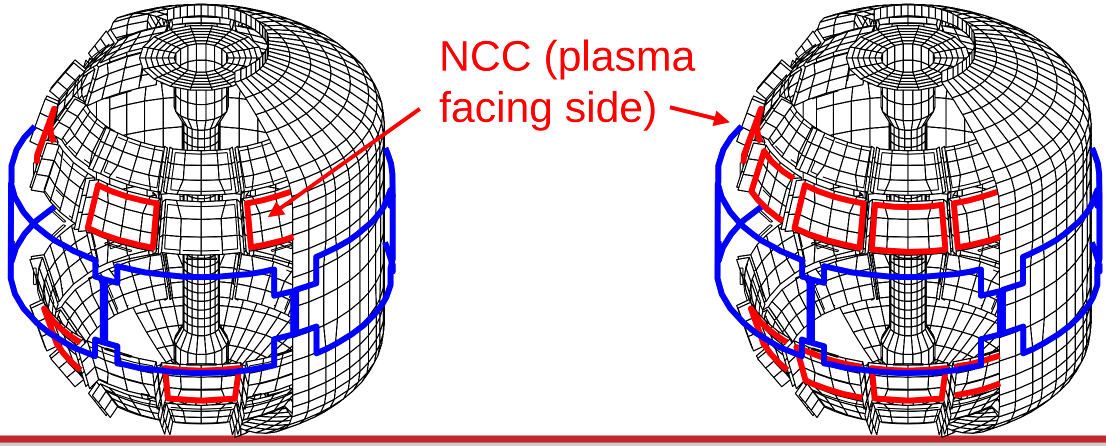
# NSTX-U: RWM active control capability increases as proposed 3D coils upgrade (NCC coils) are added

NCC 2x6 odd parity, with favorable sensors



NCC 2x12 with favorable sensors, optimal gain



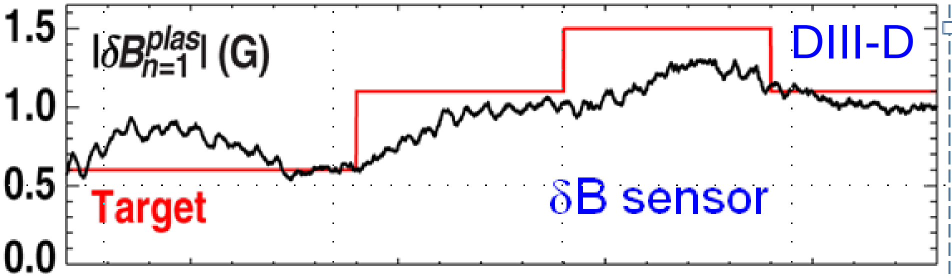


NCC (plasma facing side)

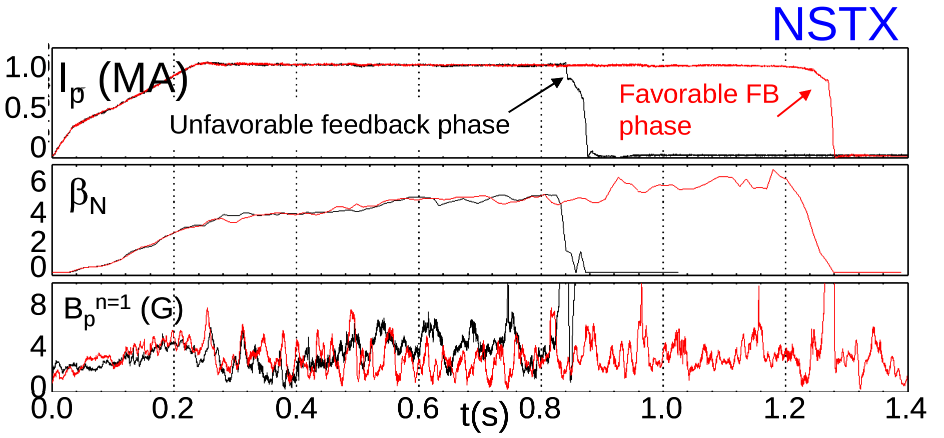
- Full NCC coil set allows control close to ideal wall limit
  - NCC 2x6 odd parity coils: active control to $\beta_N/\beta_N^{\text{no-wall}}$ = 1.58
  - NCC 2x12 coils, optimal sensors: active control to $\beta_N/\beta_N^{\text{no-wall}}$ = 1.67

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

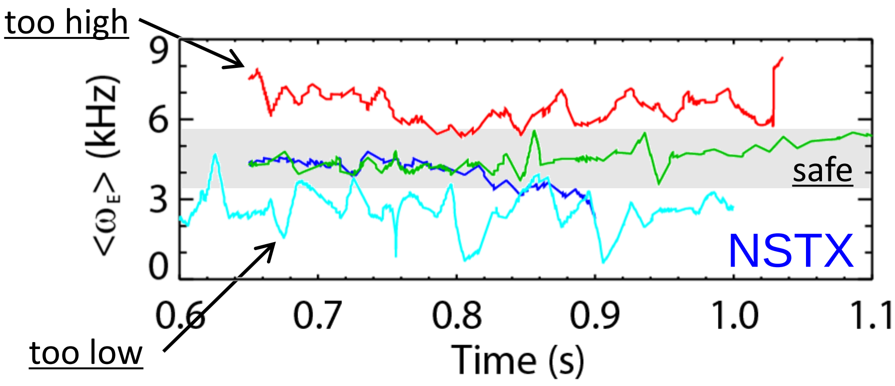
- MHD Spectroscopy
  - Use real-time measurement of plasma global mode stability to “steer” toward increased stability



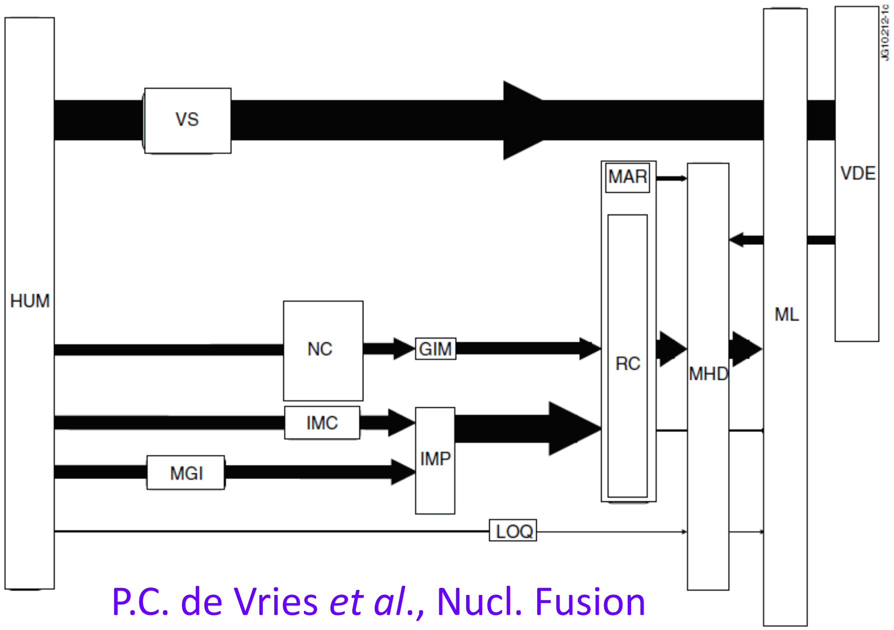
- Advanced active control
  - Combined Br + Bp feedback reduces n = 1 field amplitude, improves stability
  - RWM state space controller sustains low $l_i$, high $\beta_N$ plasma



- Simplified kinetic physics models
  - “steer” profiles (e.g. plasma toroidal rotation) toward increased stability in real-time



# NSTX-U Initial step to disruption prediction and avoidance – characterize physics elements (list incomplete)



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

- Impurity control (NC)
  - change plasma operational state / excite ELMs, etc.
- Greenwald limit (GWL)
  - density/power feedback, etc.
- Locked TM (LTM)
  - TM entrainment
- Error Field Correction
  - NSTX-U EF assessment and correction optimization
- Current ramp-up (IPR)
  - Active aux. power / CD alteration to change q
- Shape control issues (SC)
  - Active alteration of squareness, triangularity, elongation
- Approaching vertical instability (VSC)
  - Plasma shape change, etc.
- Resistive wall mode (RWM)
  - Active global parameter, $V_{\phi}$, etc. alteration techniques
  - Active mode control
- Ideal wall mode (IWM)
  - Active global parameter, $V_{\phi}$, etc. alteration techniques
- Internal kink/Ballooning mode (IKB)
  - Active global parameter, $V_{\phi}$, etc. alteration techniques

- ❑ Define a characterization for disruption causes, with related quantitative evaluations
  - ❑ Adopt a formalization similar to JET, which includes connections between categorized elements

Columbia NSTX-U research on includes applying global mode stabilization physics in model-based controllers

# (Incomplete) List of physics elements tied to disruption prediction, avoidance (highlighting individual involvement)

- 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, $V_\phi$, etc. alteration techniques (SAS,JWB,EK)
- H-L mode back-transition (HLB)
  - Active global parameter, $V_\phi$, etc. alteration techniques (SAS,JWB,EK)
- Approaching vertical instability (VSC)
  - Plasma shape change, etc. (SPG, MDB)
- Resistive wall mode (RWM)
  - Active global parameter, $V_\phi$, etc. alteration techniques (SAS,JWB)
  - Active multi-mode control (SAS,YSP,KT)
- Ideal wall mode (IWM)
  - Active global parameter, $V_\phi$, etc. alteration techniques (JEM)
- Internal kink/Ballooning mode (IKB)
  - Active global parameter, $V_\phi$, 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

# Disruption prediction and avoidance is a grand challenge problem – help make the solution a reality

## ❖ Status (NSTX-U

- NSTX-U disruption prediction and avoidance research efforts have already started among individuals and small groups on the NSTX-U Team

## ❖ Action Items

- Please contact Steve and Roger (sabbagh@pppl.gov; rraman@pppl.gov) to join and contribute to the group
- Open discussion (now) regarding the Disruption Prediction, Avoidance Mitigation Working Group
  - Please send further constructive comments to Steve and Roger by email as desired

## ❖ Next Step

- Meeting to discuss DPAM physics elements related to NSTX and initial NSTX-U operation (focus on 5 Year Plan) (to be announced)

# 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 $V_\phi$ 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

# Physical characteristics of NTV are investigated in tokamaks for rotation control and the evaluation of plasma response

- NTV characteristics / comparison to theory
  - Non-resonant NTV torque is radially extended, relatively smooth profile
  - KSTAR shows $T_{NTV} \propto (\delta B_{3D})^2$; $T_{NTV} \propto T_i^{2.27}$; no hysteresis on the rotation profile (key for control), confirms NSTX
  - Measured $T_{NTV}$ profile in NSTX quantitatively compares well between experiment and Shaing's "connected NTV theory"

K.C. Shaing, et al., NF **50** (2010) 025022)

- Plasma response
  - Non-resonant $T_{NTV}$ profile in NSTX quantitatively consistent with "fully-penetrated field" assumption without amplification
  - Flux surface-averaged 3D field profile from M3D-$C^1$ single fluid model consistent with field used for quantitative NTV agreement in experiment
- Rotation control
  - Model-based, rotation controller using NTV and NBI designed/tested for NSTX-U

# 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

**Critical Need for Disruption PAM in Tokamaks (FESAC 2014): S.A. Sabbagh, N. Commaux, N. Eidietis, S.P. Gerhardt, et al. (July 9th, 2014)** **61**

# 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:

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

$\delta W_K$ 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:

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

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

Precession Drift resonance

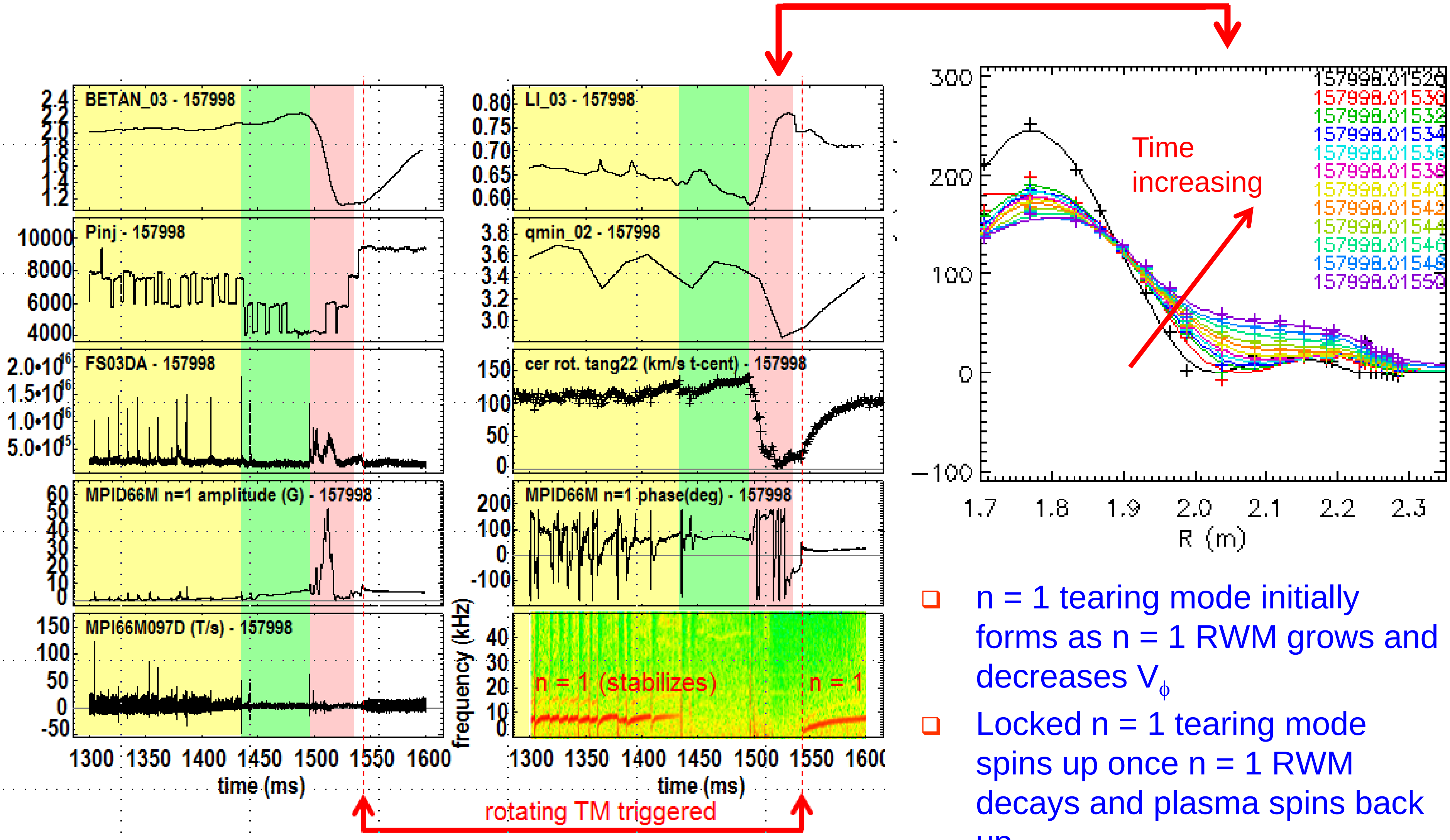
~ Plasma Rotation

Bounce orbit resonances

Collisionality

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

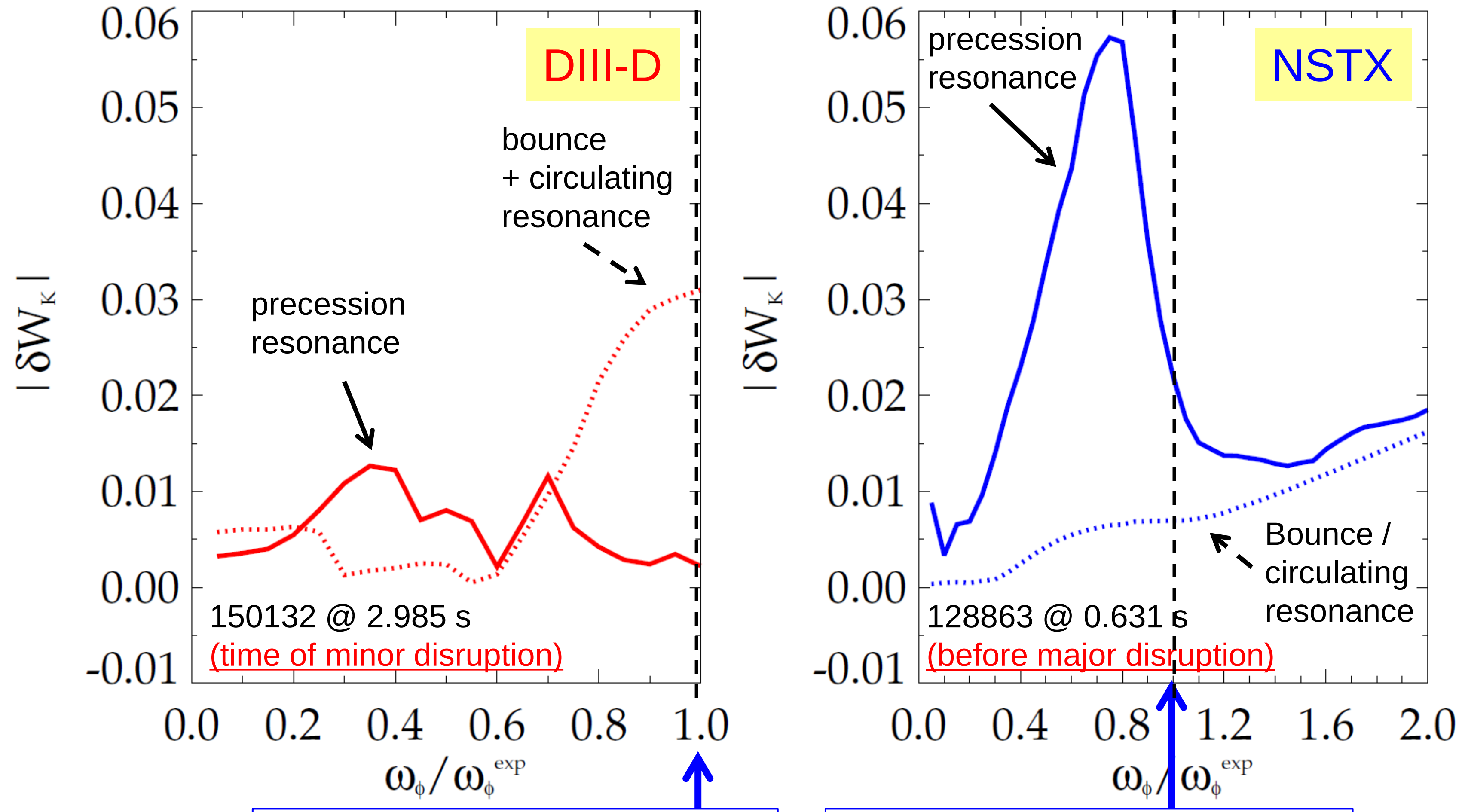
# RWM triggers TM: CER profiles illustrate spin-up phase of the n = 1 locked tearing mode



- n = 1 tearing mode initially forms as n = 1 RWM grows and decreases $V_{\phi}$
- 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)



precession resonance

bounce + circulating resonance

150132 @ 2.985 s
(time of minor disruption)

precession resonance

Bounce / circulating resonance

128863 @ 0.631 s
(before major disruption)

DIII-D experimental rotation profile

NSTX experimental rotation profile

# Several ordered publications by K.C. Shaing, et al. led to the "Combined" NTV Formulation

| Publications (chronological order) | Topic |
|---|---|
| 1) K.C. Shaing, S.P. Hirschman, and J.D. Callen, Phys. Fluids **29** (1986) 521. | Plateau transport |
| 2) K.C. Shaing, Phys. Rev. Lett., **87** (2001) 245003. | Island NTV |
| 3) K.C. Shaing, Phys. Plasmas **10** (2003) 1443. | Collisional, $1/\nu$ regimes |
| 4) K.C. Shaing, Phys. Plasmas **13** (2006) 052505. | Banana, $1/\nu$ regimes |
| 5) K.C. Shaing, S. A. Sabbagh, and M. Peng, Phys. Plasmas **14** (2007) 024501. | Multiple trapping |
| 6) K.C. Shaing, S. A. Sabbagh, M.S. Chu, et al., Phys. Plasmas **15** (2008) 082505. | Orbit squeezing |
| 7) K.C. Shaing, P. Cahyna, M. Becoulet, et al., Phys. Plasmas **15** (2008) 082506. | Coll. b'dary layer, $\nu^{0.5}$ |
| 8) K.C. Shaing, S. A. Sabbagh, and M. S. Chu, PPCF **51** (2009) 035004. | Low $\nu$ regimes |
| 9) K.C. Shaing, S. A. Sabbagh, and M. S. Chu, PPCF **51** (2009) 035009. | Superbanana plateau |
| 10) K.C. Shaing, S. A. Sabbagh, and M. S. Chu, PPCF **51** (2009) 055003. | Superbanana regime |
| 11) K.C. Shaing, M. S. Chu, and S. A. Sabbagh, PPCF **51** (2009) 075015. | Bounce/transit/drift res. |
| 12) K.C. Shaing, M. S. Chu, and S. A. Sabbagh, PPCF **52** (2010) 025005. | $J_{bootstrap}$ w/resonances |
| 13) K.C. Shaing, S. A. Sabbagh, and M. S. Chu, Nucl. Fusion **50** (2010) 025022. | Combined NTV formula |
| 14) K.C. Shaing, J. Seol, Y.W. Sun, et al., Nucl. Fusion **50** (2010) 125008. | $\nabla B$ drift in CBL analysis |
| 15) K.C. Shaing, M. S. Chu, and S. A. Sabbagh, Nucl. Fusion **50** (2010) 125012. | Flux/force gen. coords. |
| 16) K.C. Shaing, T.H. Tsai, M.S. Chu, et al., Nucl. Fusion **51** (2011) 073043. | SBP regime refinement |
| 17) K.C. Shaing, M.S. Chu, C.T. Hsu, et al., PPCF **54** (2012) 124033. | NTV brief overview |