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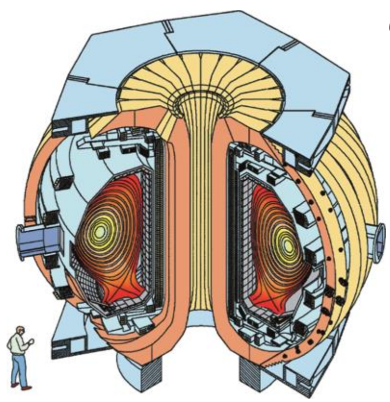
Unification of Kinetic Resistive Wall Mode Stabilization Physics in Tokamaks*

S.A. Sabbagh[1], J.W. Berkery[1], J.M. Hanson[1], C. Holcomb[2], M. Austin[3], D. Battaglia[4], R.E. Bell[4], K. Burrell[3], R. Buttery[3], N. Eidietis[3],S.P. Gerhardt[4], B. Grierson[4], G. Jackson[3], R. La Haye[3], J. King[3], E. Kolemen[4], M.J. Lanctot[2], M. Okabayashi[4], T. Osborne[3], E. Strait[3], B. Tobias[4], S. Zemedkun[6]

[1]Department of Applied Physics, Columbia University, New York, NY
[2]Lawrence Livermore National Laboratory, Livermore, CA
[3]General Atomics, San Diego, CA
[4]Princeton Plasma Physics Laboratory, Princeton, NJ
[5]University of California, Davis, CA
[6]University of Colorado, Boulder, CO



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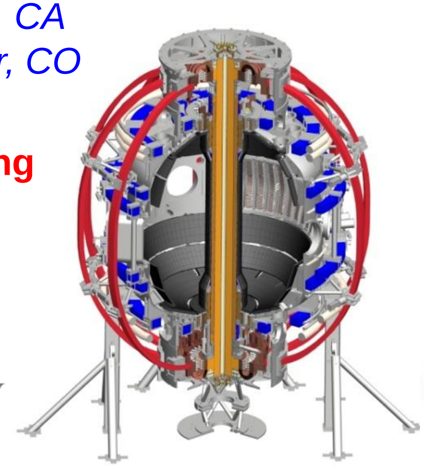

DIII-D NATIONAL FUSION FACILITY

v2.6t

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

PPPL

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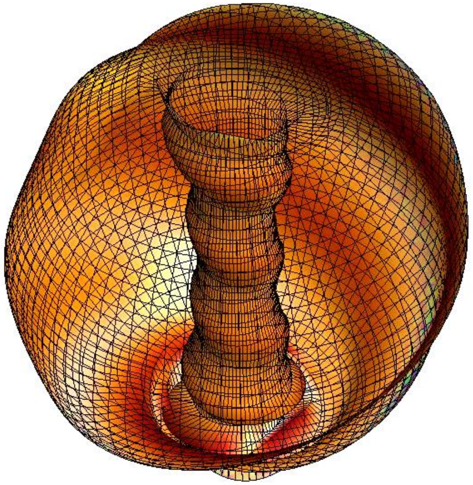
Analysis of DIII-D and NSTX experiments gives an improved understanding of resistive wall mode (RWM) stability physics

- **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**

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

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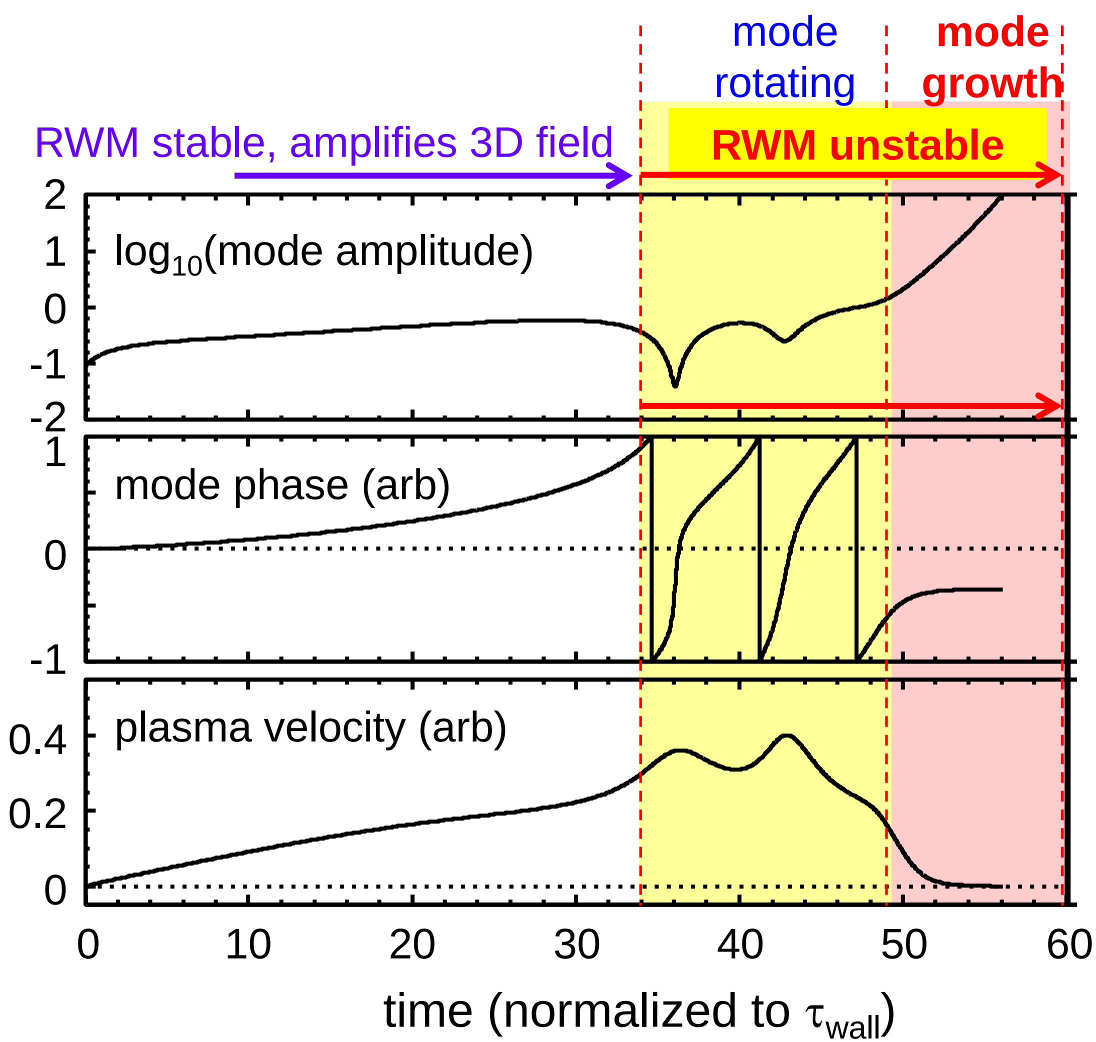
A classic, simple RWM model illustrates basic mode dynamics



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 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

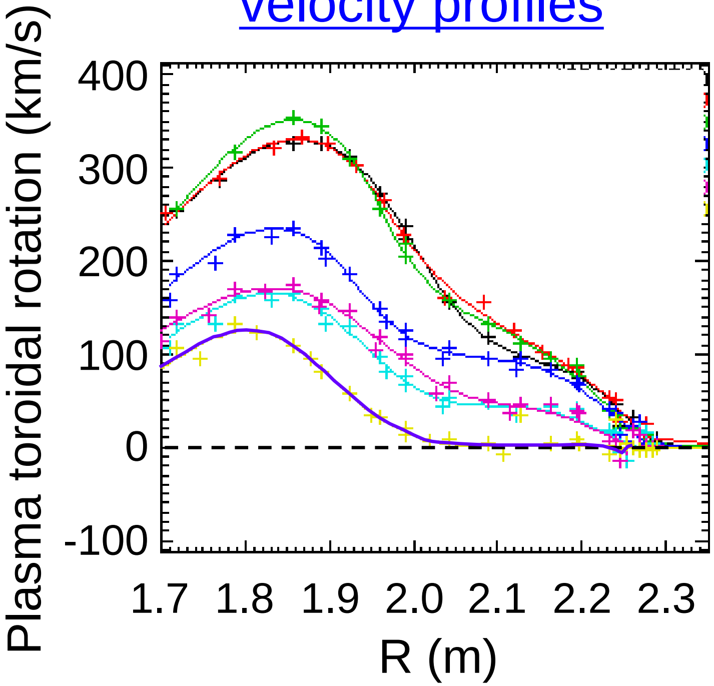
- Strong RWM drive: Maximum $\beta_N > 7$, $\beta_N / l_i > 13.5$
- Strong TMs eliminated by high elongation (> 2.6) or Li wall conditioning

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

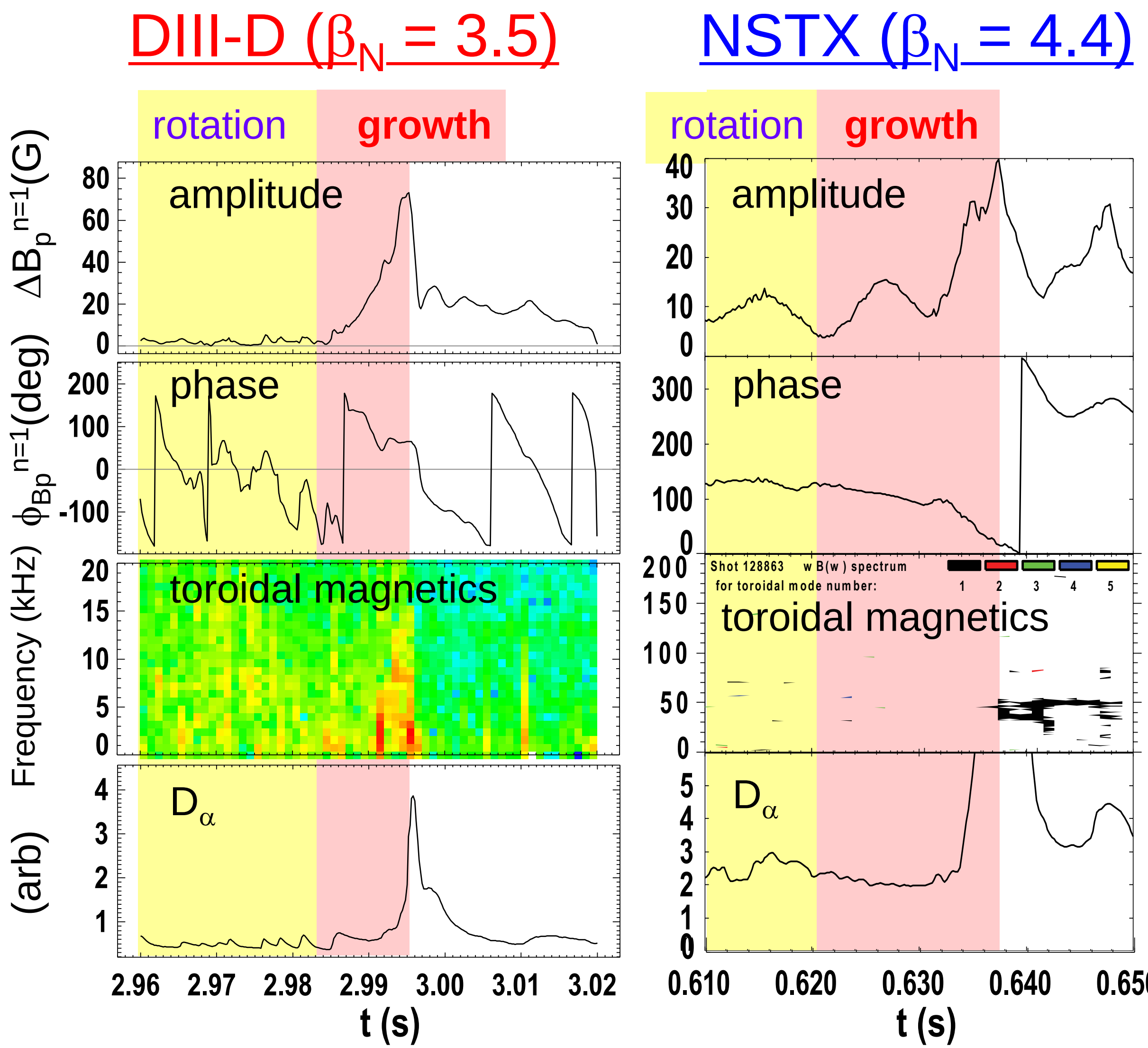
Wide range of DIII-D toroidal plasma velocity profiles



→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



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

- Initially used for NSTX since simple critical scalar ω_ϕ threshold stability models did not describe RWM stability
  Sontag, et al., Nucl. Fusion **47** (2007) 1005

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

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

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

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

ω_ϕ profile (enters through ExB frequency)

Trapped ion component of δW_K (plasma integral over energy)

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

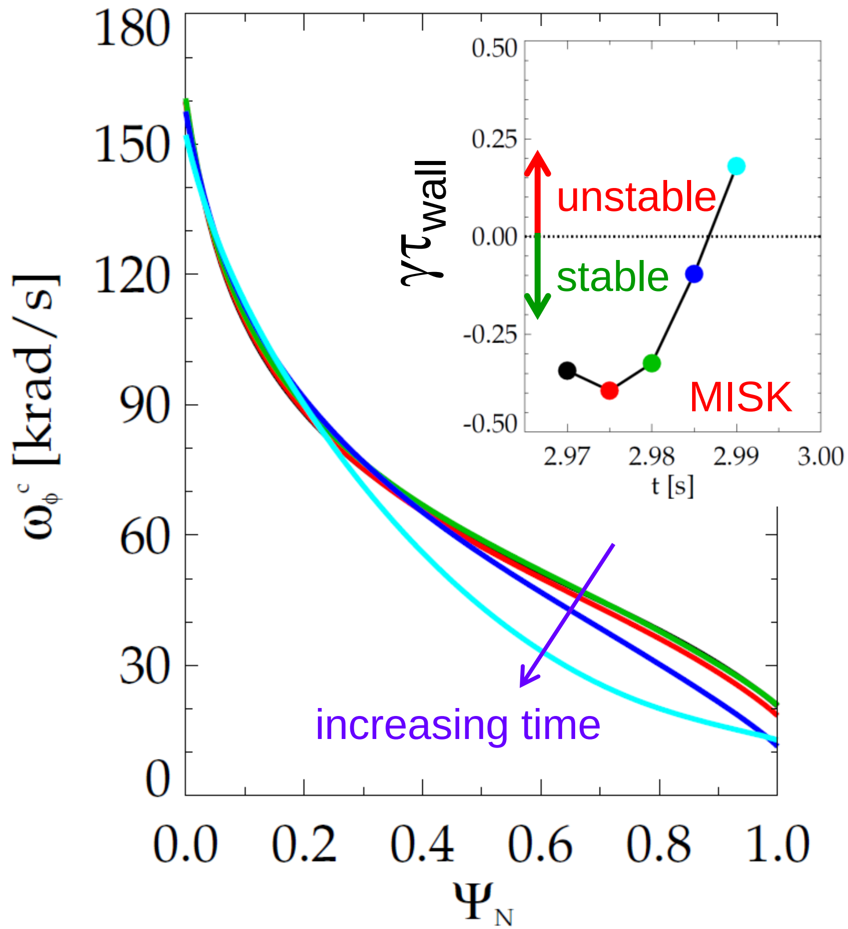
precession drift ($\langle \omega_D \rangle$) — bounce ($l\omega_b$) — collisionality (ν_{eff})

Some NSTX / MISK analysis references

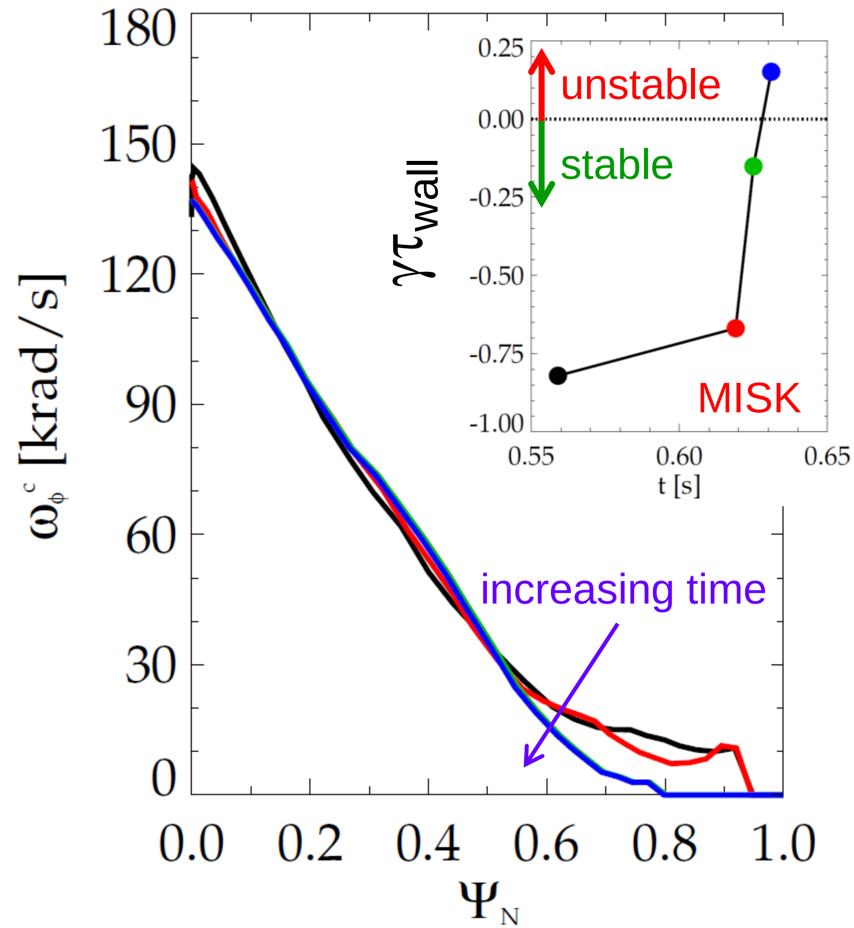
- J. Berkery *et al.*, PRL **104**, 035003 (2010)
- S. Sabbagh, et al., NF **50**, 025020 (2010)
- J. Berkery *et al.*, PRL **106**, 075004 (2011)
- J. Berkery *et al.*, PoP **21**, 056112 (2014)
- J. Berkery *et al.*, PoP **21**, 052505 (2014) (benchmarking paper)

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

DIII-D (minor disruption)

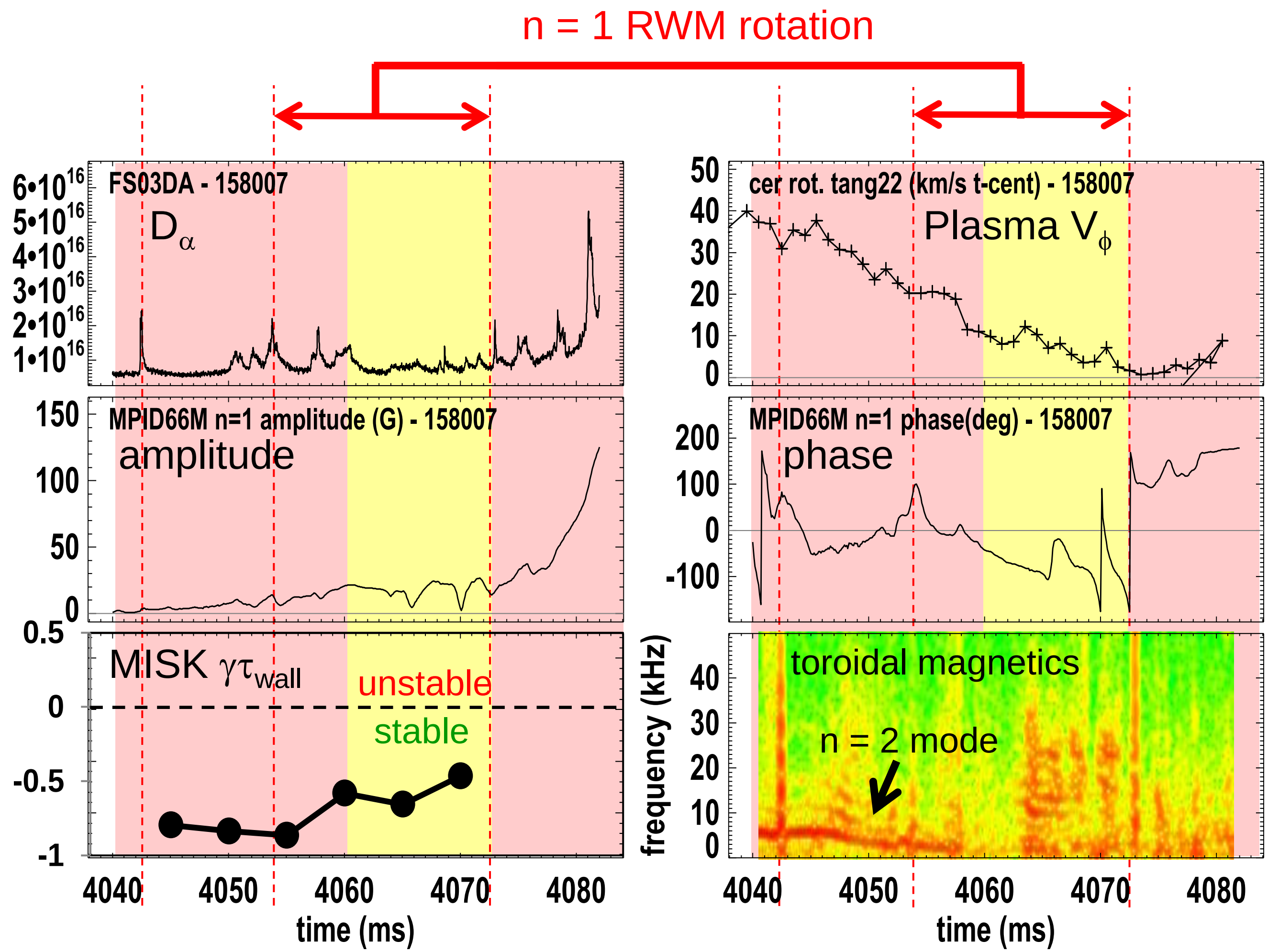


NSTX (major disruption)



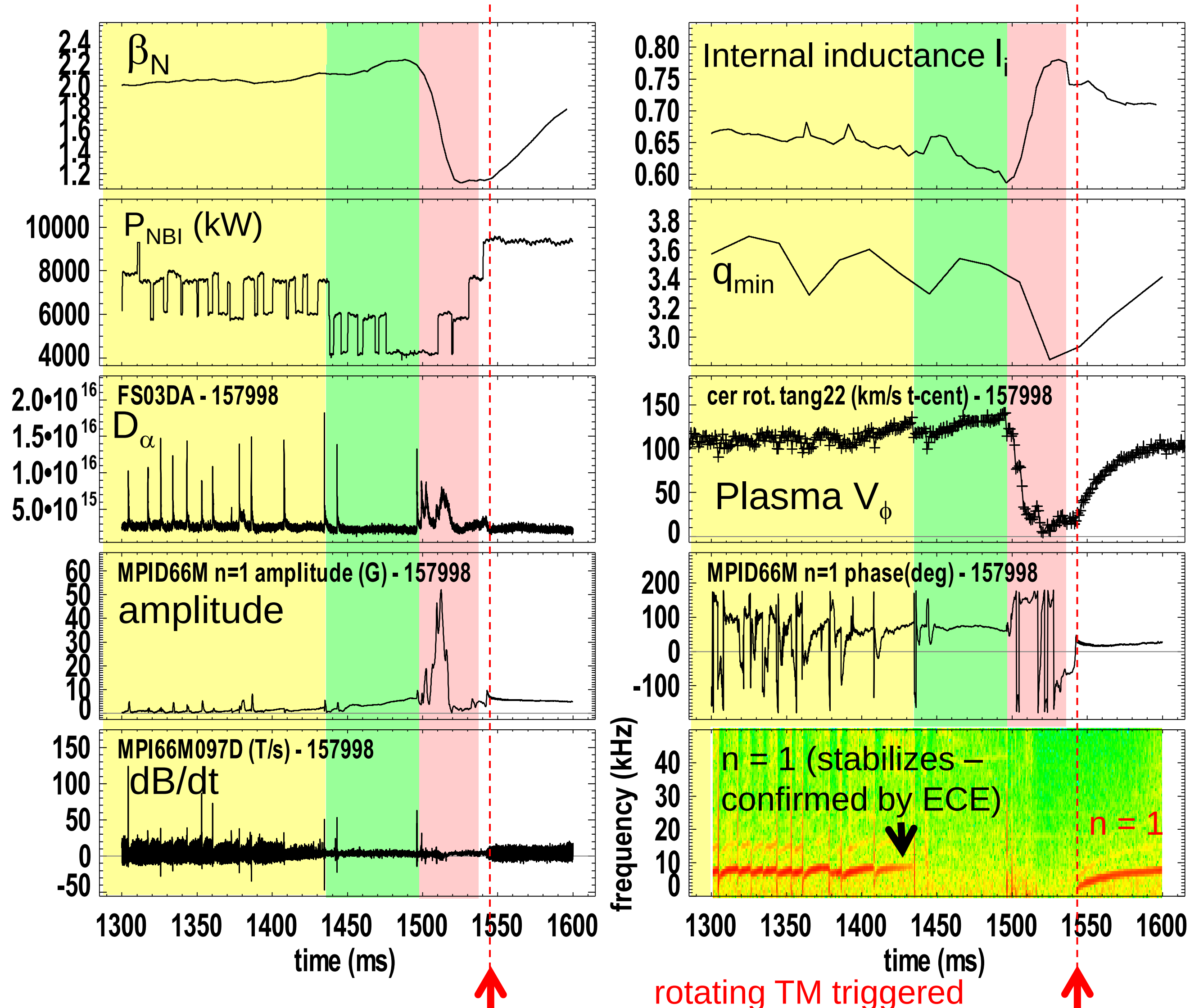
2. Full current quench disruption occurs as RWM grows following mode rotation at high β_N and low V_ϕ

- 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

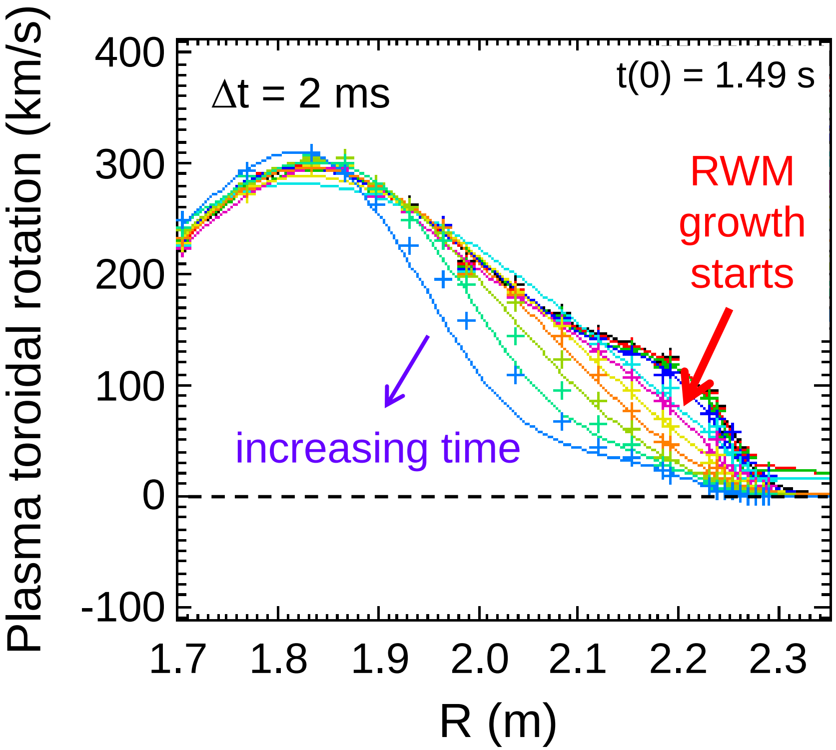


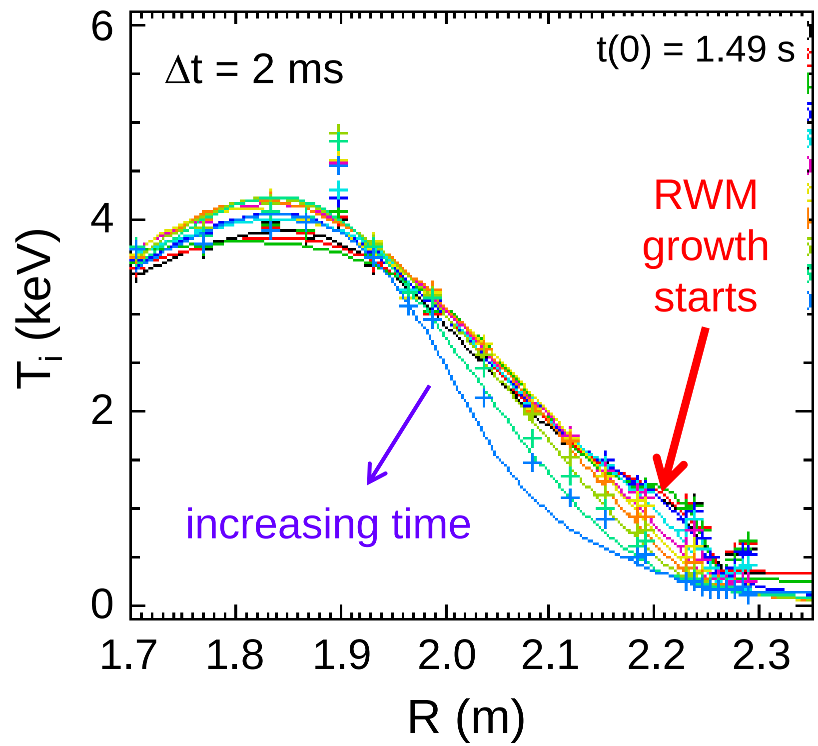
3. Minor disruption occurs as RWM grows at moderate β_N correlated with profile peaking

- 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

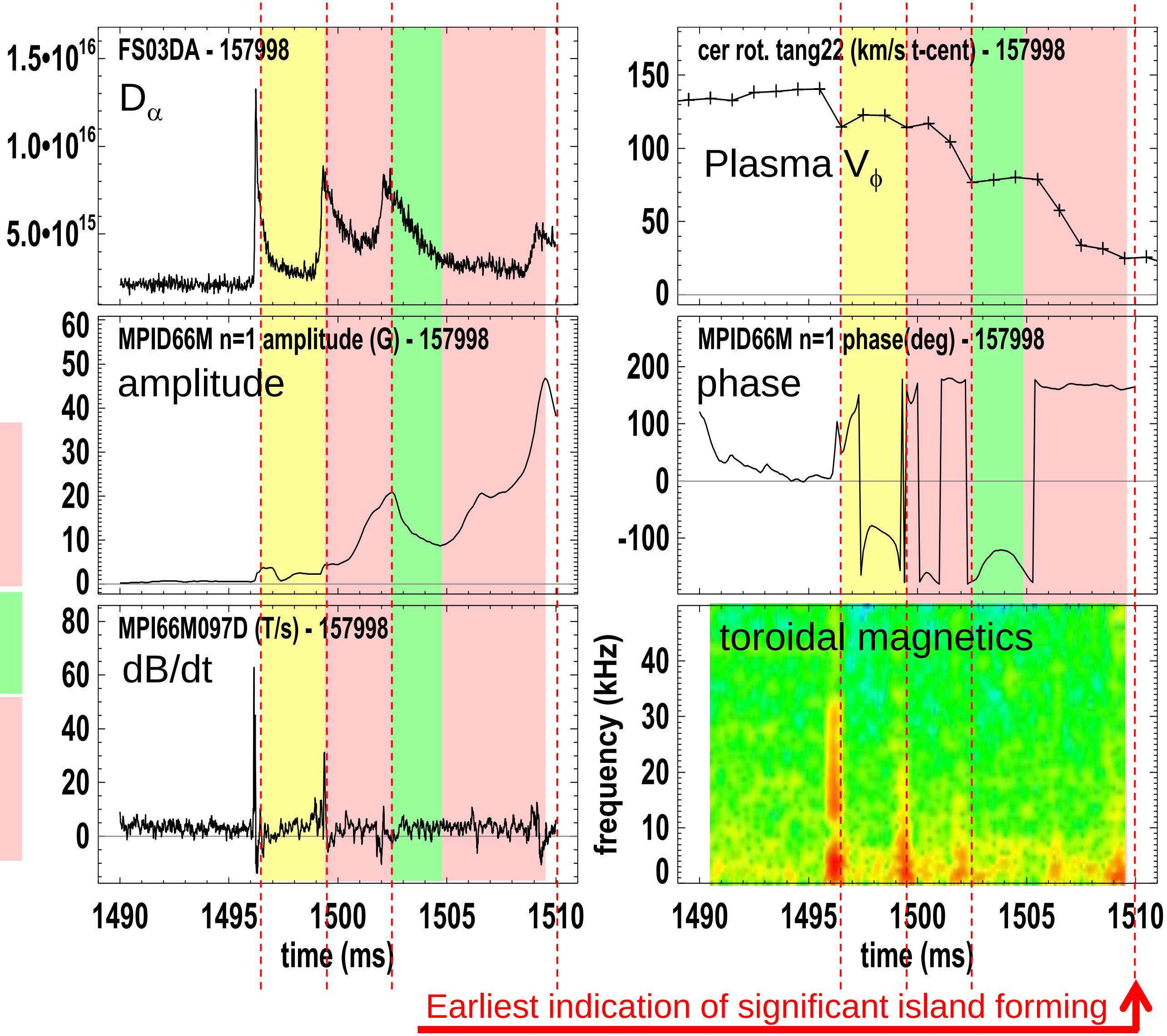




- Loss of pedestal causes profile peaking, correlates with RWM growth
  - Example of transport phenomena that can lead to instability and minor disruption, but can also be used as an indicator for disruption avoidance

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



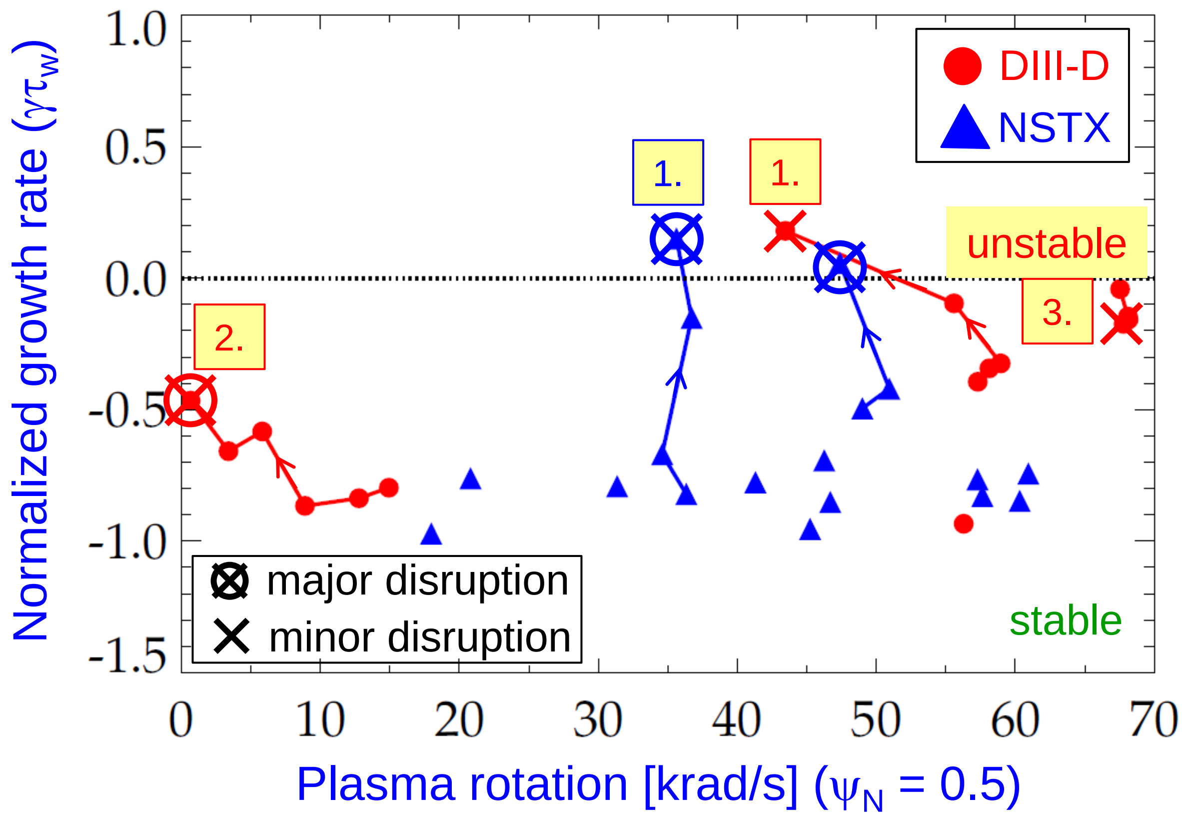
Outline

- 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

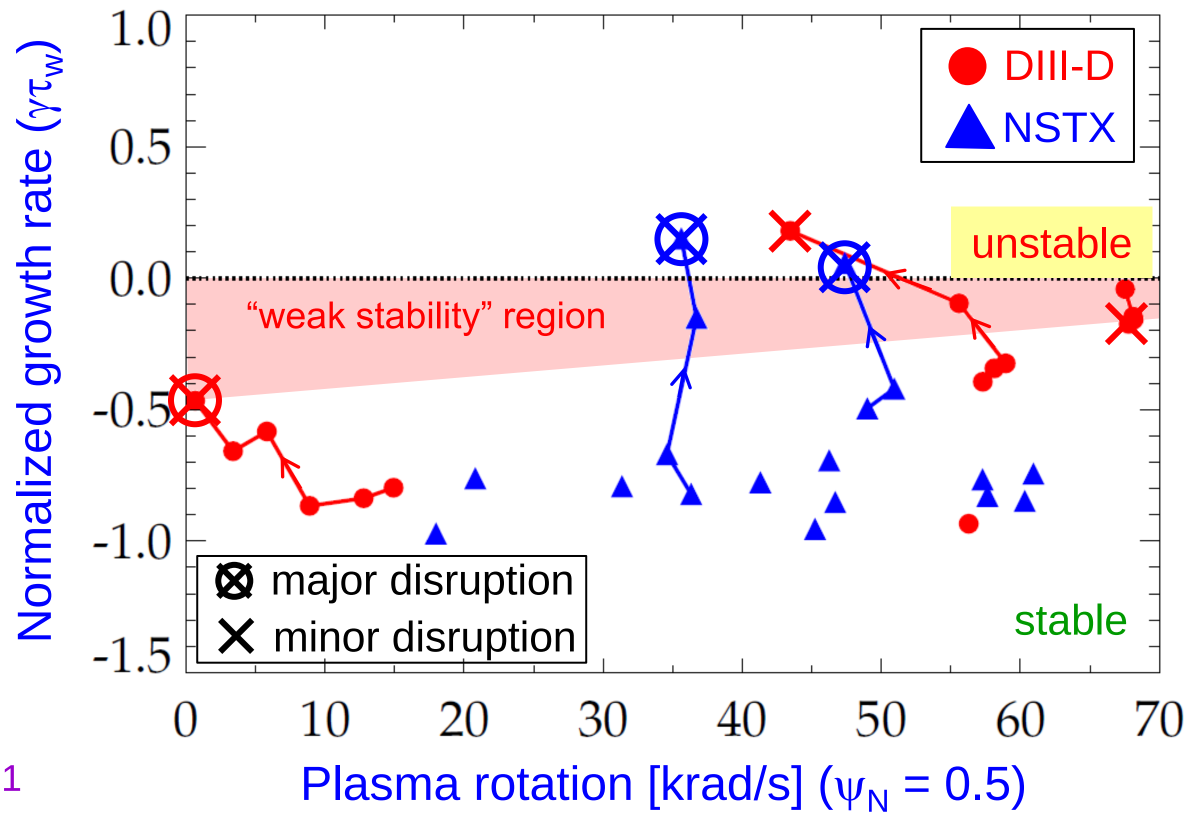
- Summary of results
  - Plasmas free of other MHD modes can reach or exceed linear kinetic RWM marginal stability
  - Bursting MHD modes can lead to non-linear destabilization before linear stability limits are reached

    - 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

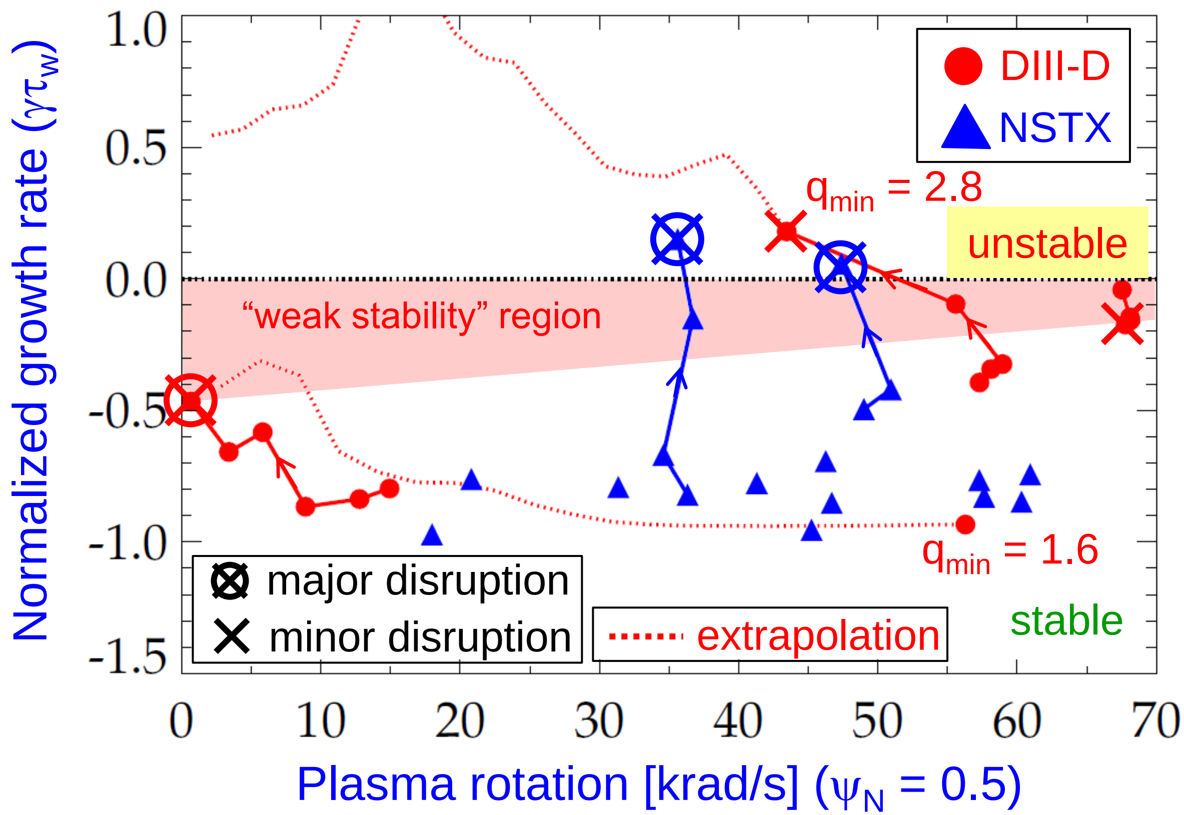
Kinetic RWM stability analysis for experiments (MISK)



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

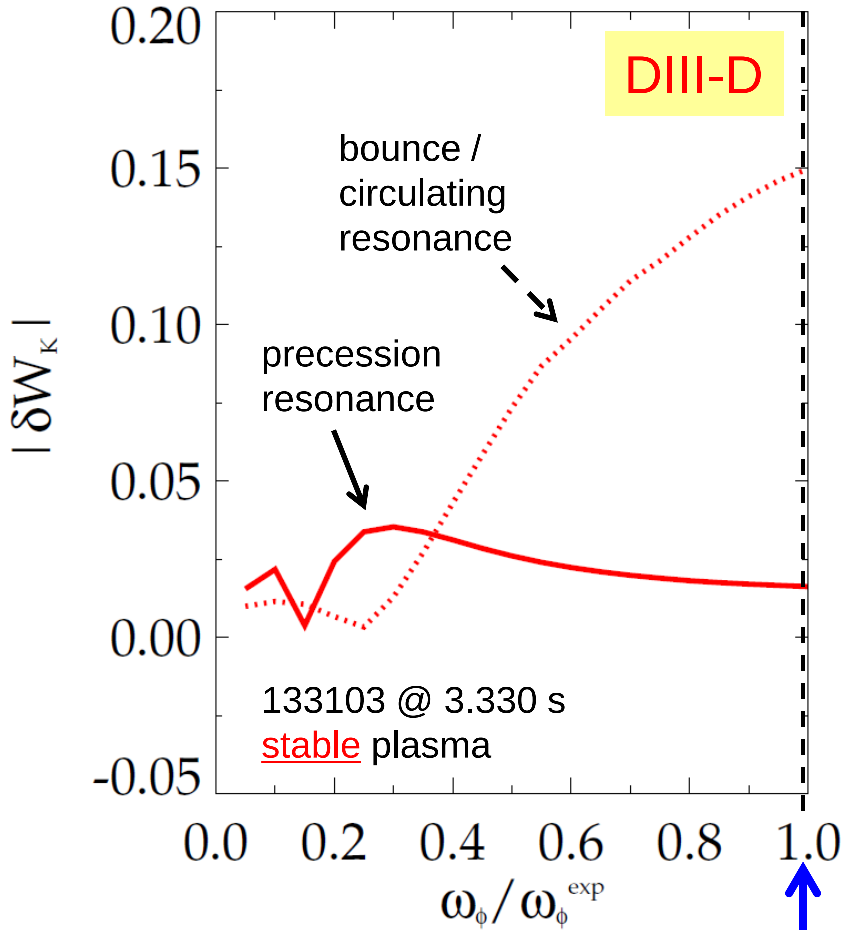
- **Summary of results**
  - Plasmas free of other MHD modes can reach or exceed linear kinetic RWM marginal stability
  - Bursting MHD modes can lead to non-linear destabilization before linear stability limits are reached
  - Extrapolations of DIII-D plasmas to different V_ϕ show marginal stability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

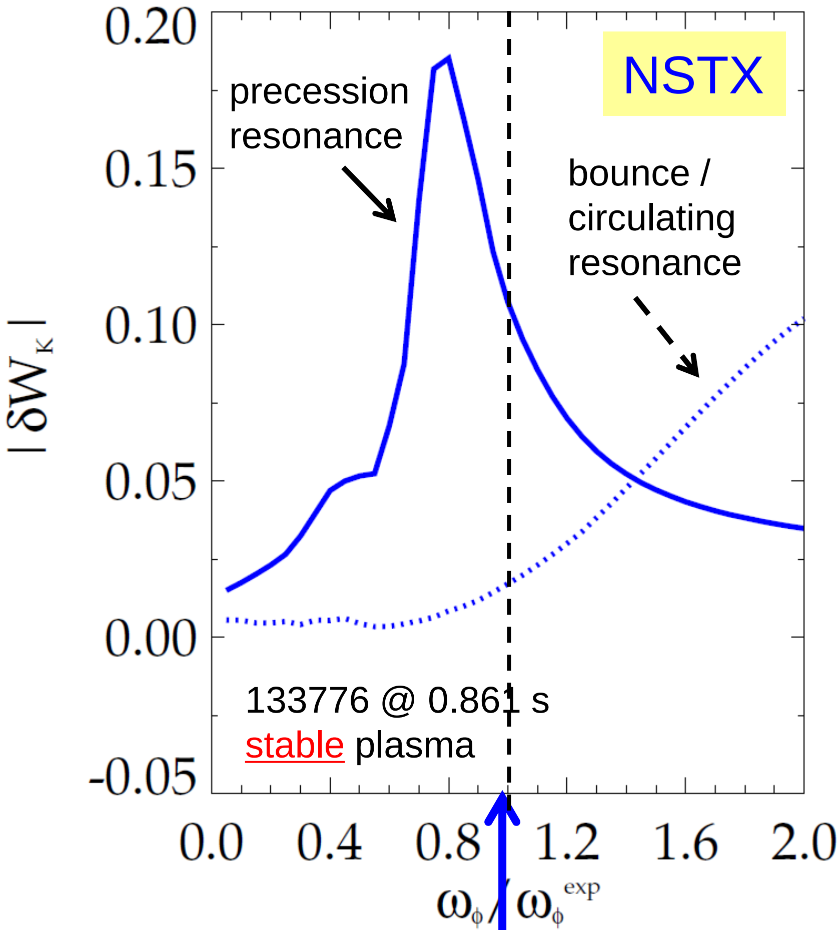
Kinetic RWM stability analysis for experiments (MISK)



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)



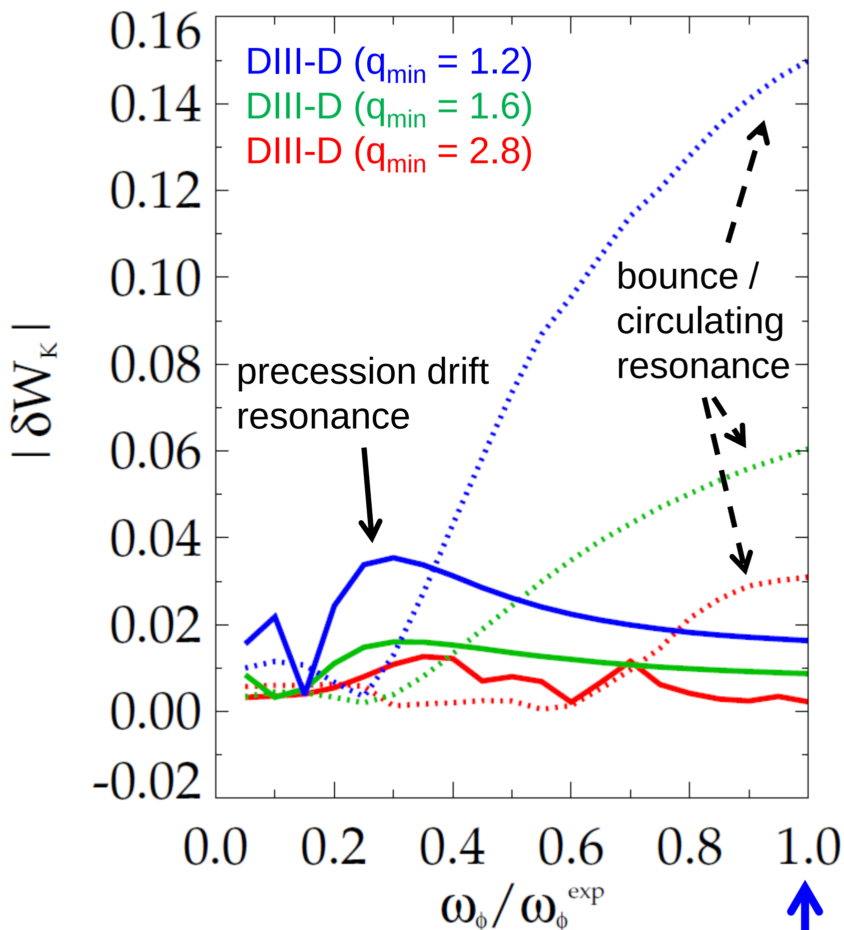


DIII-D experimental rotation profile

NSTX experimental rotation profile

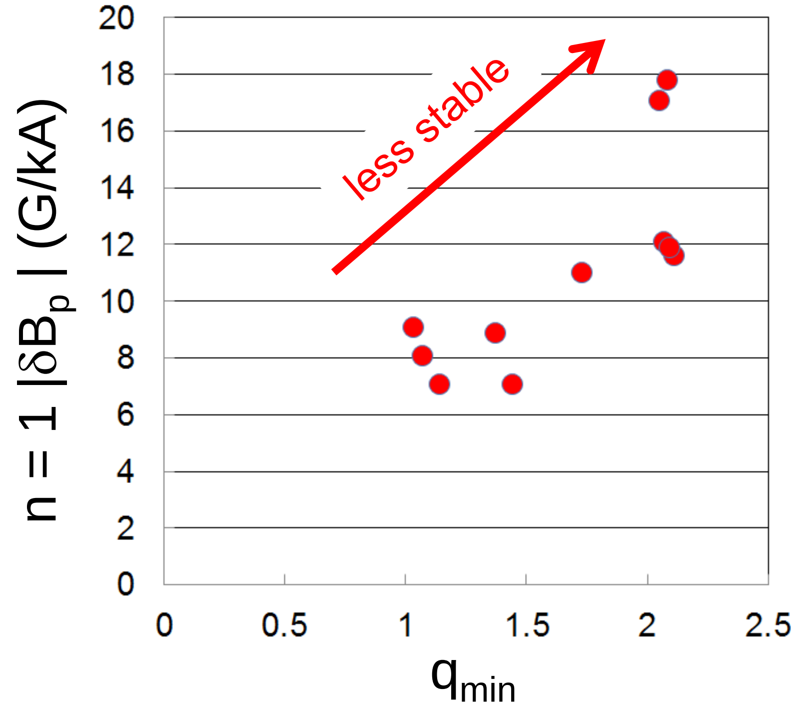
Increased RWM stability measured in DIII-D plasmas as q_{min} is reduced is consistent with kinetic RWM theory

$|\delta W_K|$ 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

Outline

- RWM phenomenology and characteristics in theory and experiment (DIII-D and NSTX)
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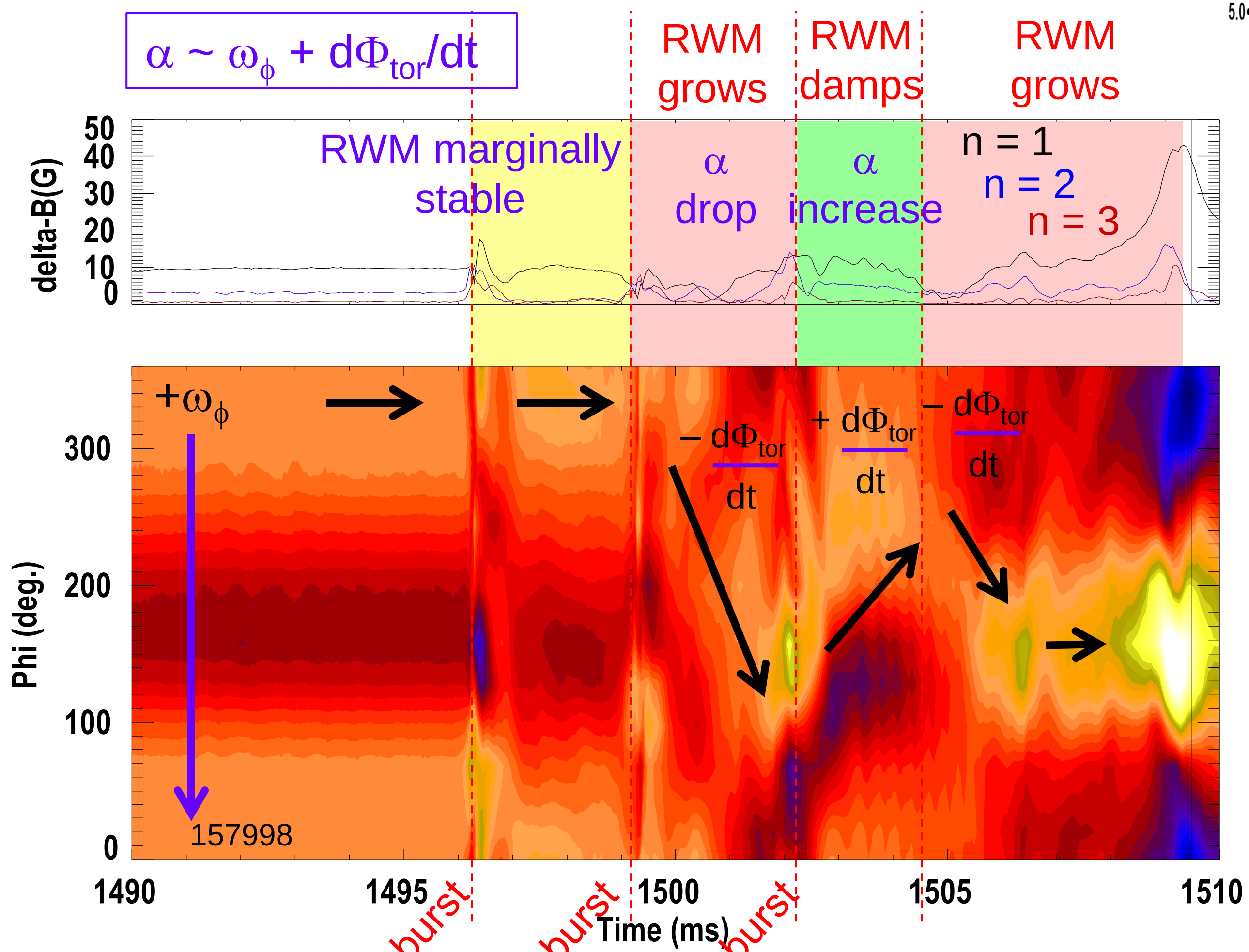
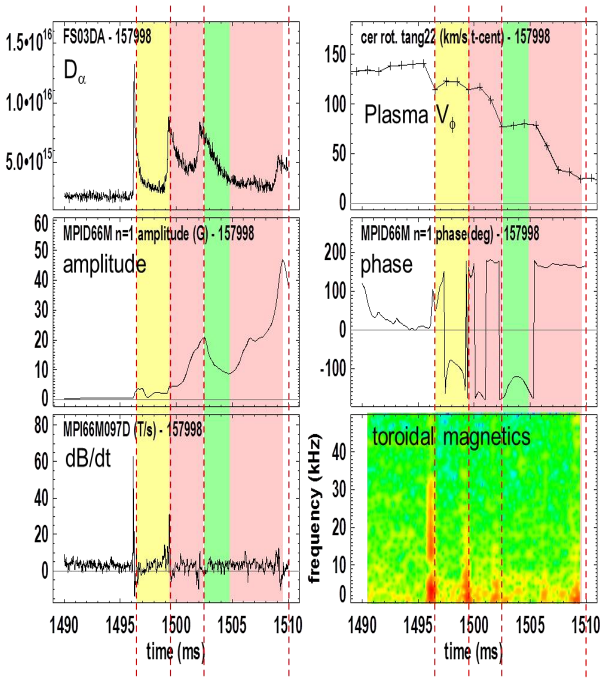
3. Detail of RWM marginal point toward instability or stability might be explained by mode/plasma differential rotation

- 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)

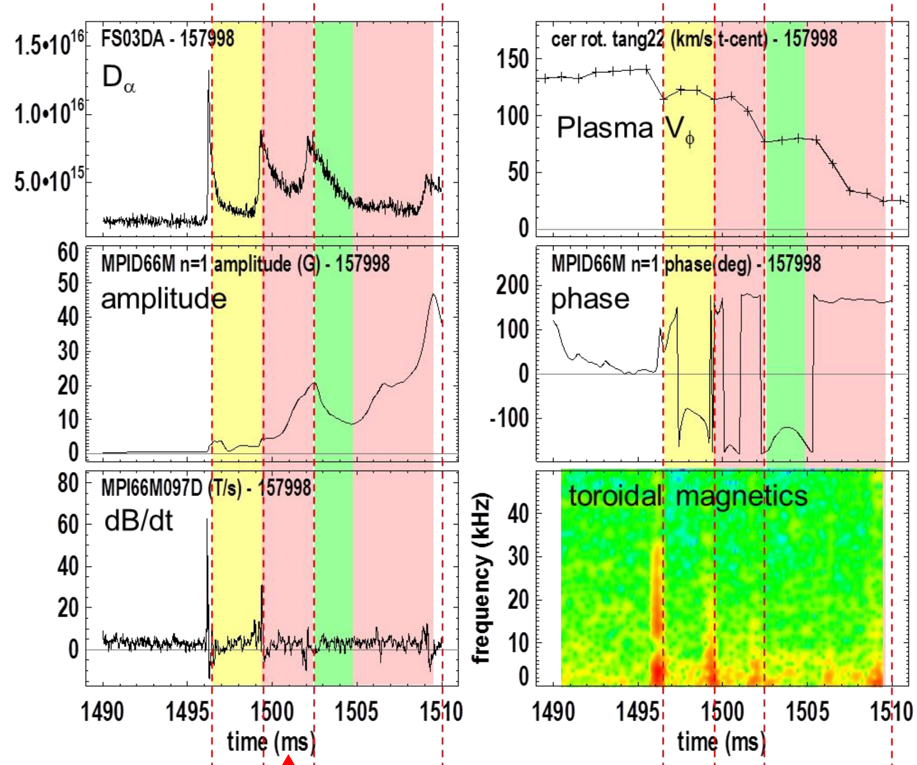
Another consistent, intriguing hypothesis is non-linear RWM destabilization caused by δB from bursting MHD event

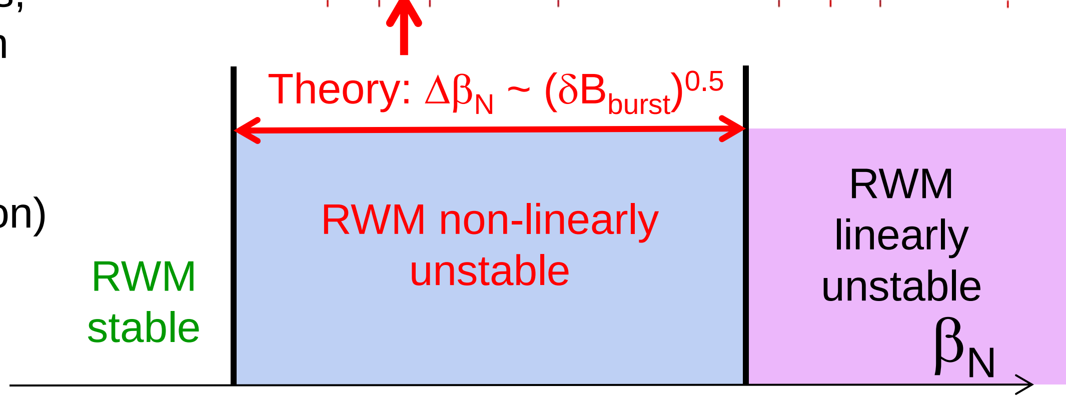
- Non-linear destabilization theory shows growth can occur below the linear instability point when other n = 1 field perturbation is present
  - Change in stability related to perturbation magnitude

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

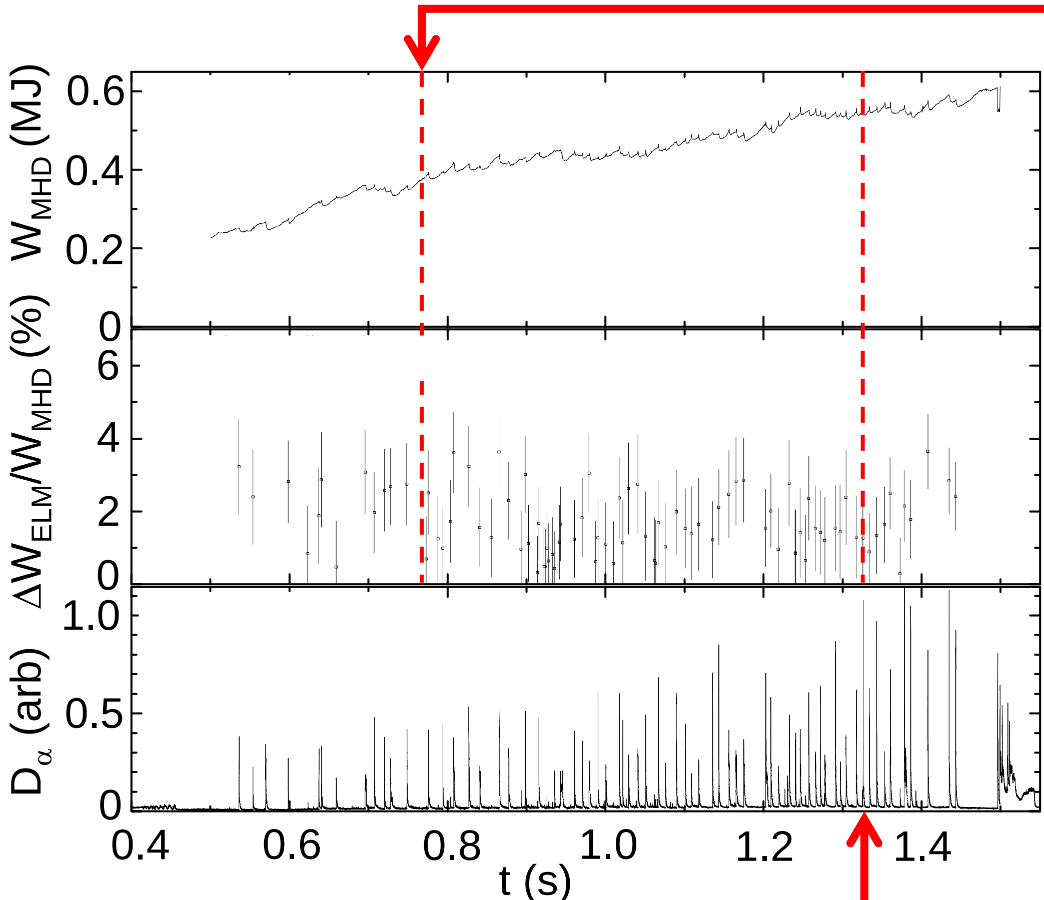
- Hypothesis
  - Due to δB from bursting MHD, marginally stable RWM becomes non-linearly unstable
  - As bursting MHD perturbation relaxes, RWM non-linearly destabilized region goes away
  - Finally, the RWM becomes linearly unstable, continues to grow (disruption)

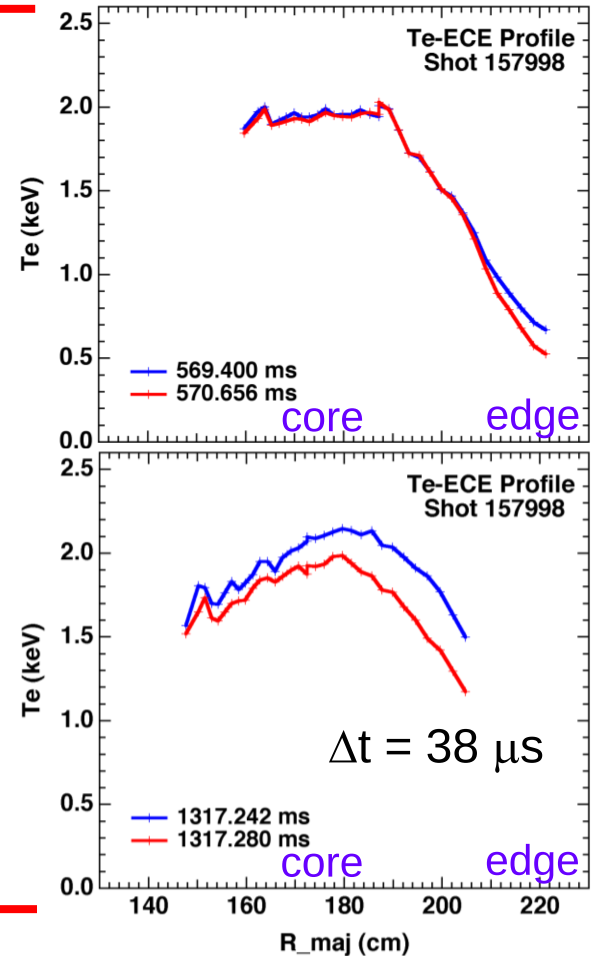
What does the bursting MHD perturbation look like?





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" (Δt ~ 250 μs) may indicate that the internal perturbations are ideal

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

Backup slides

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

Force balance:

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

leads to an energy balance:

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

Kinetic Energy — Fluid terms

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:

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

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

Precession Drift resonance

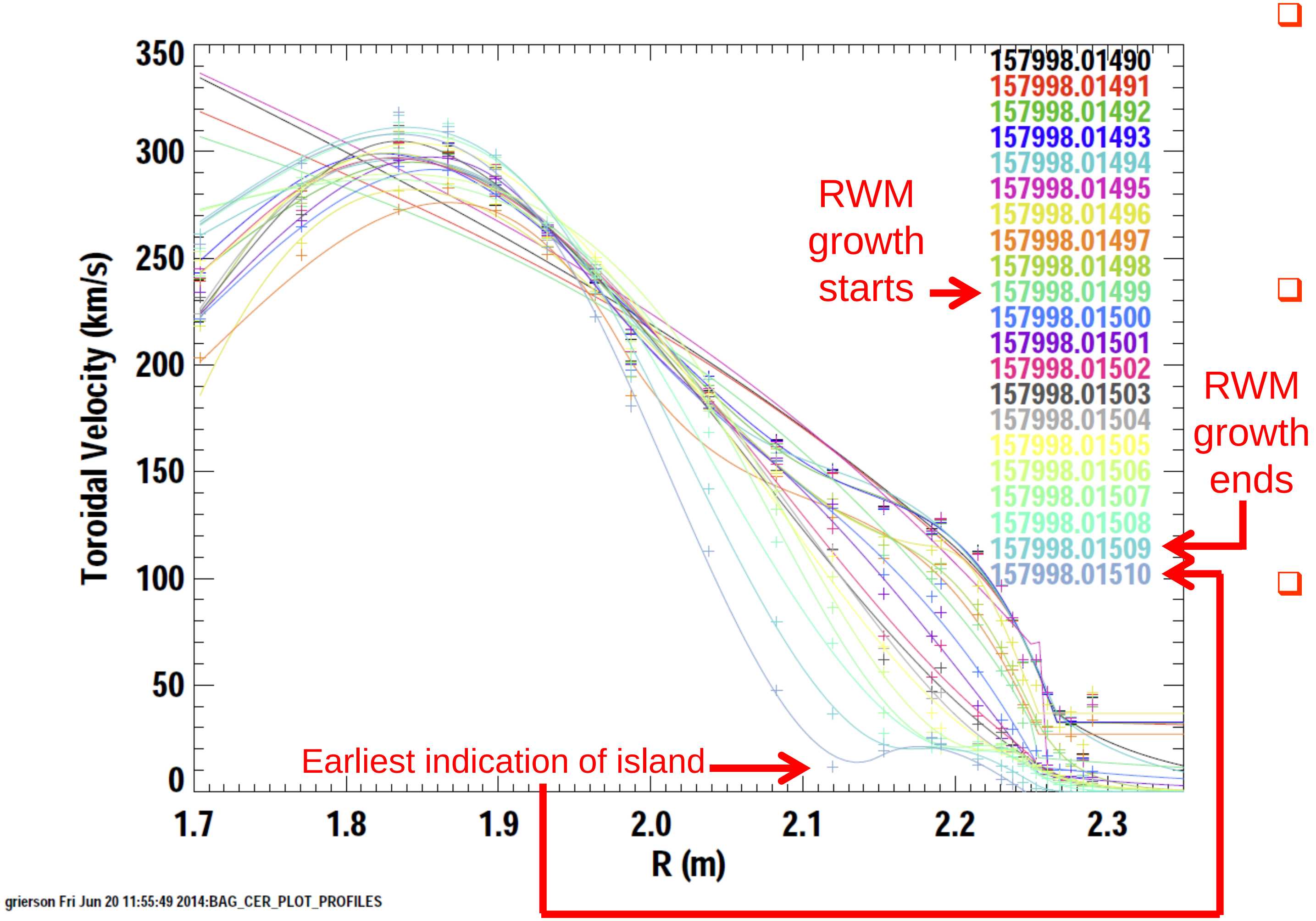
Bounce orbit resonances

Collisionality

~ Plasma Rotation

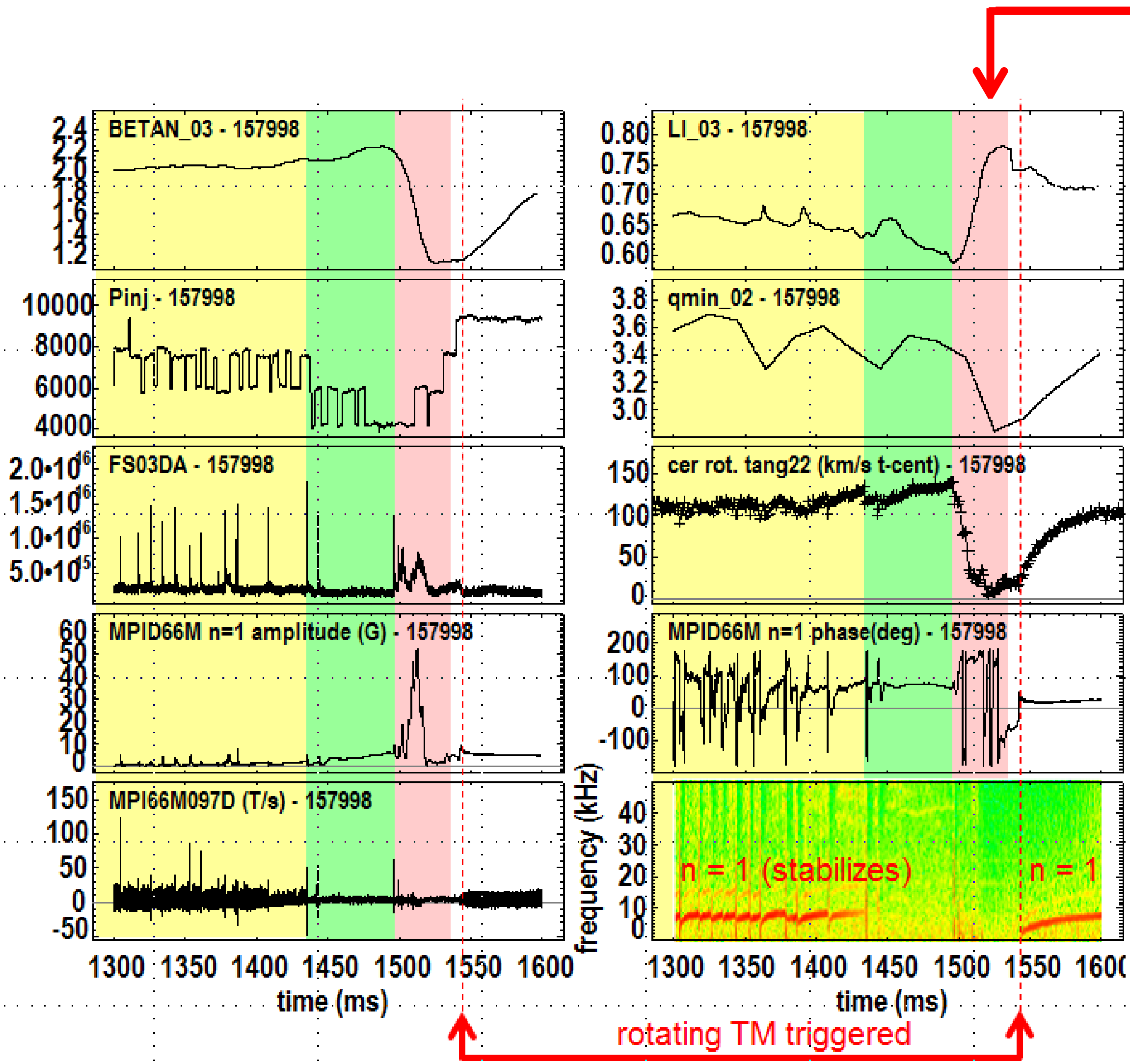
$$\omega_E \approx \omega_\phi - \omega_{*i}$$

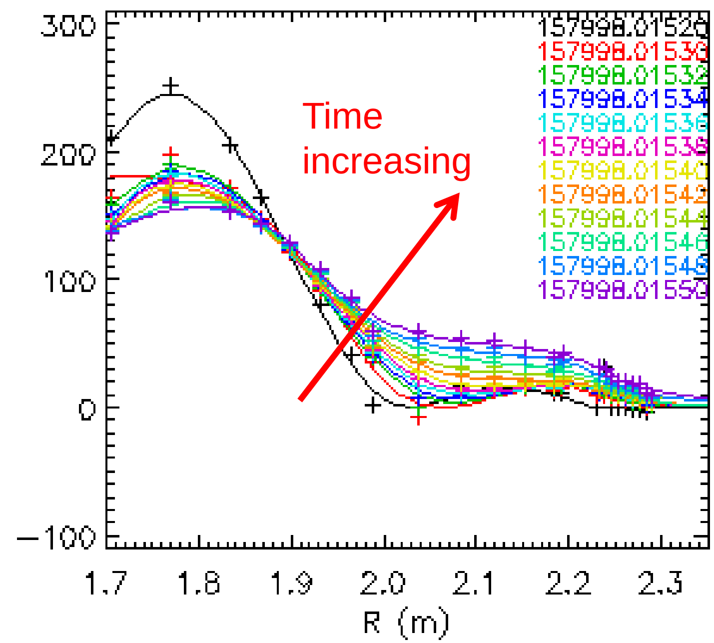
The earliest potential indication of a locking island (from CER) comes after the n = 1 RWM has fully grown



- 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

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)