Abstract

Research on the National Spherical Torus Experiment (NSTX) has studied the stability of resistive wall modes (RWMs) in high-beta fusion plasmas for disruption avoidance. Stabilizing mechanisms for RWMs have been identified as the transfer of energy from the mode to thermal particles through rotational resonances and the effect of energetic particles to resist distortion of the magnetic field lines. These kinetic effects have been implemented in the MISK code and results have compared favorably with NSTX experiments including prediction of the marginal stability point and agreement with the trends of low-frequency MHD spectroscopy experiments. Further improvement of the already close agreement of MISK to experimental results is being pursued by comparison to a large database of NSTX discharges and implementation of additional physics in the code, including rotational effects on the fluid stability and the effect of pressure anisotropy. An ITPA MHD Stability Group joint analysis task verified several kinetic RWM codes, including MISK, and generally good agreement between the codes was achieved. A new disruption avoidance algorithm in NSTX-Upgrade will utilize the knowledge gained by kinetic stability physics insight, calculation, and comparison with experiment.

Supported by the U.S. Department of Energy under contracts DE-FG02-99ER54524, DE-AC02-09CH11466, and DE-FG02-93ER54215.

Kinetic resistive wall mode stability evaluation gives physics insight, which will be used in NSTX-U

Motivation

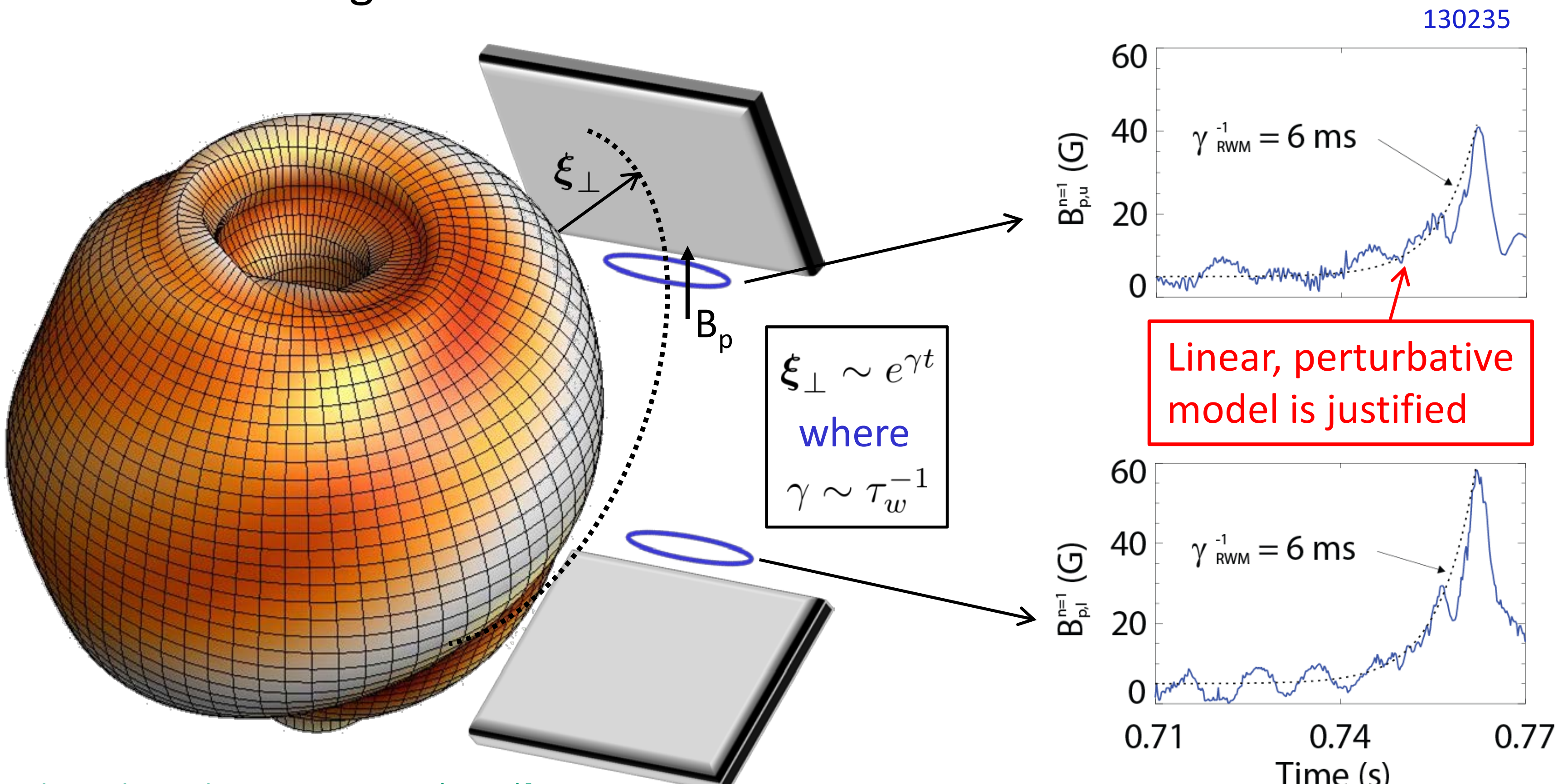
- Kinetic theory has been successful in determining RWM marginal stability in both NSTX and DIII-D experiments
- Attention is now turning to projected ITER stability, and application of kinetic stability physics insight for disruption avoidance in NSTX-U

Outline

- Introduction: resistive wall mode and kinetic stabilizing effects
- NSTX MHD spectroscopy experiments are explained by kinetic theory
- MISK calculations compare well with marginal stability point
- Unified analysis of DIII-D and NSTX improves RWM understanding
- MISK has been benchmarked, now focusing on ITER stability
- NSTX-U disruption avoidance system will use kinetic physics

An unstable RWM is an exponential growth of magnetic field line kinking that can be studied with a linear model

- The resistive wall mode (RWM) is a kinking of magnetic field lines slowed by penetration through vessel structures



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

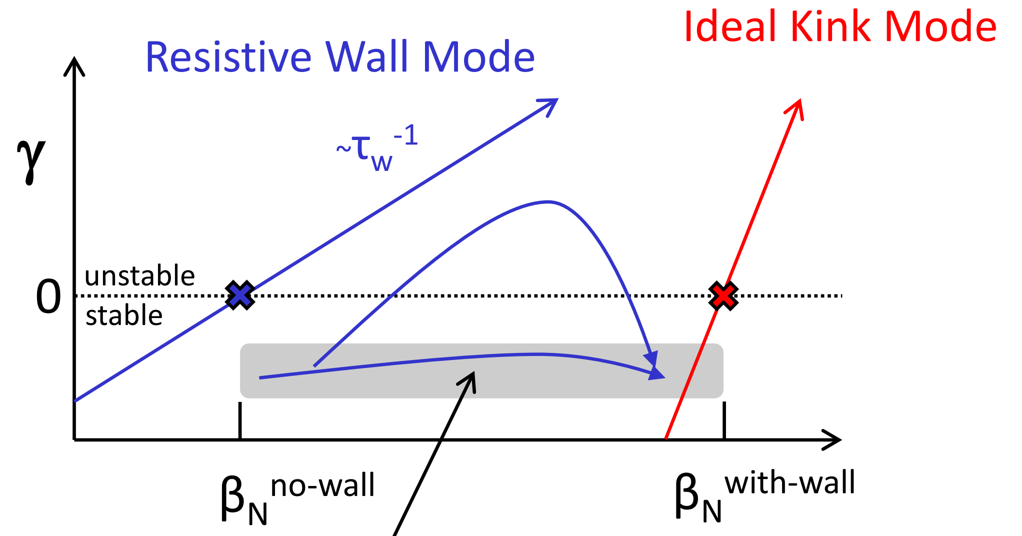
RWMs in NSTX cause a collapse in β, disruption, and termination of the plasma

Kinetic effects in the RWM dispersion relation allows for passive stabilization of the RWM, can explain experiments

Resistive Wall Mode (RWM) fluid dispersion relation:

$$\gamma_f \tau_w = -\frac{\delta W_\infty}{\delta W_b}$$

τ_w^{-1} is slow enough that <u>active</u> stabilization (feedback) can keep the plasma stable



However, NSTX experiments have often operated in this range <u>without active control</u>!

- <u>Passive stabilization</u>
  - Collisional dissipation
  - Rotational stabilization
    - Simple models with a scalar "critical rotation" level for stability could not explain experiments

[S. Sabbagh *et al.*, Nucl. Fusion **50**, 025020 (2010)]

Kinetic Effects

$$(\gamma - i\omega_r)\,\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$$

[B. Hu *et al.*, Phys. Rev. Lett. **93**, 105002 (2004)]

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:

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

Kinetic Energy

Fluid terms

Change in potential energy due to perturbed kinetic pressure is:

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

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

~ Plasma Rotation

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

Precession Drift

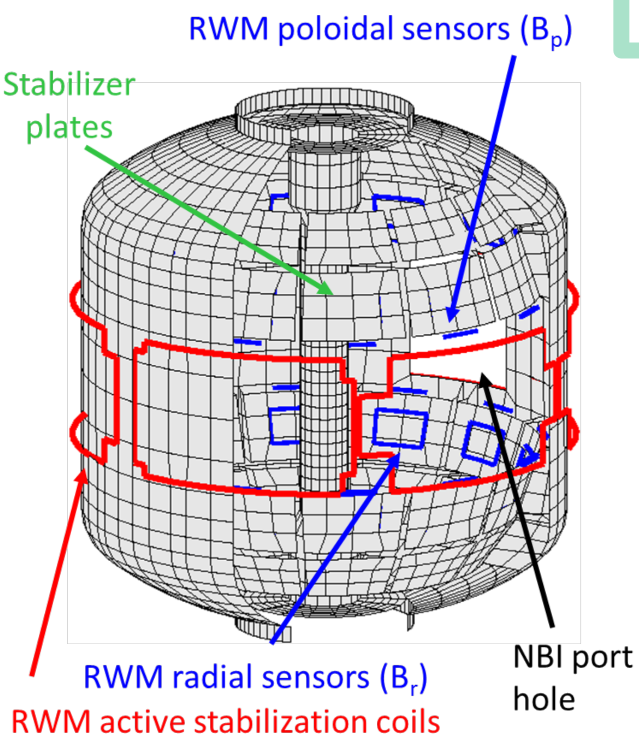
Collisionality

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

High beta plasma stability is directly measured to test experimental trend of disruptivity

- Active MHD spectroscopy measures RWM stability when modes are stable
  - Resonant field amplification (RFA) of n=1 applied AC field is measured in 20 high beta NSTX plasmas with rotation slowed by n=3 magnetic braking

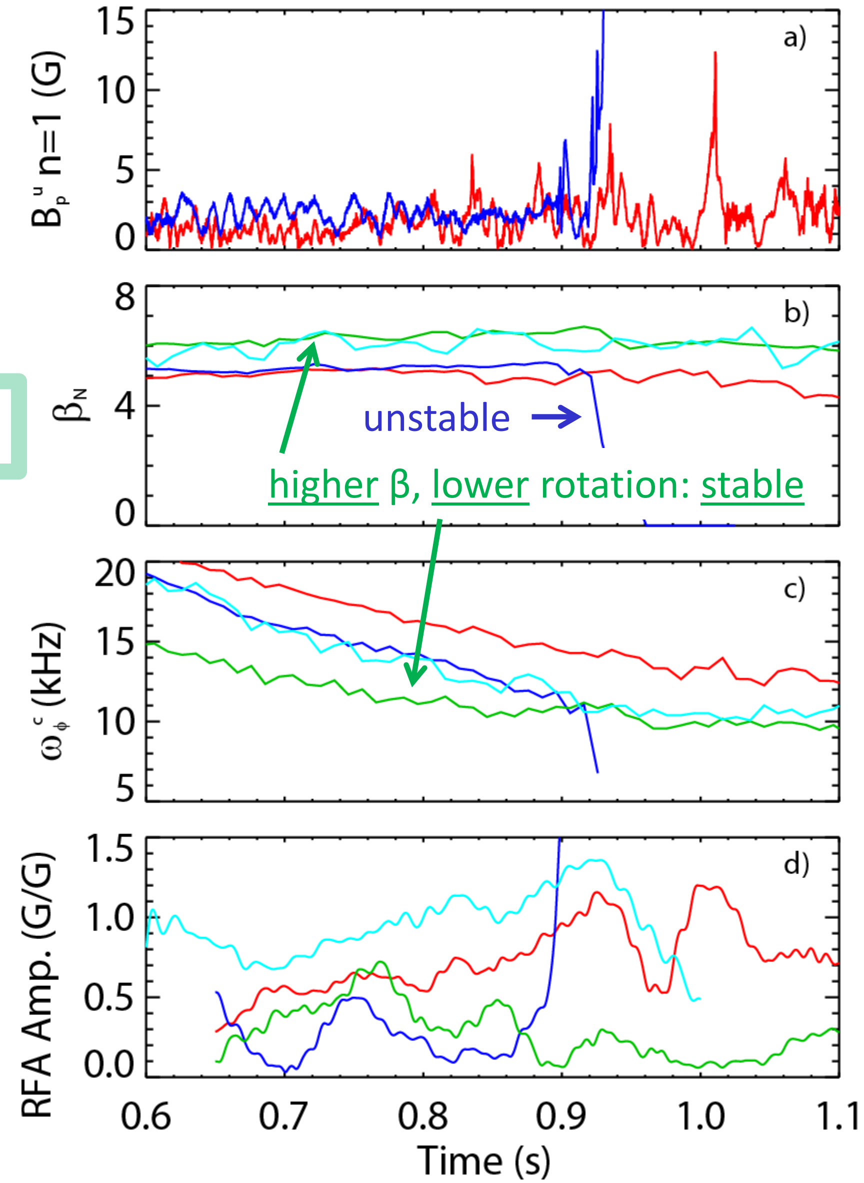
$$\text{RFA} = B_{plasma}/B_{applied}$$



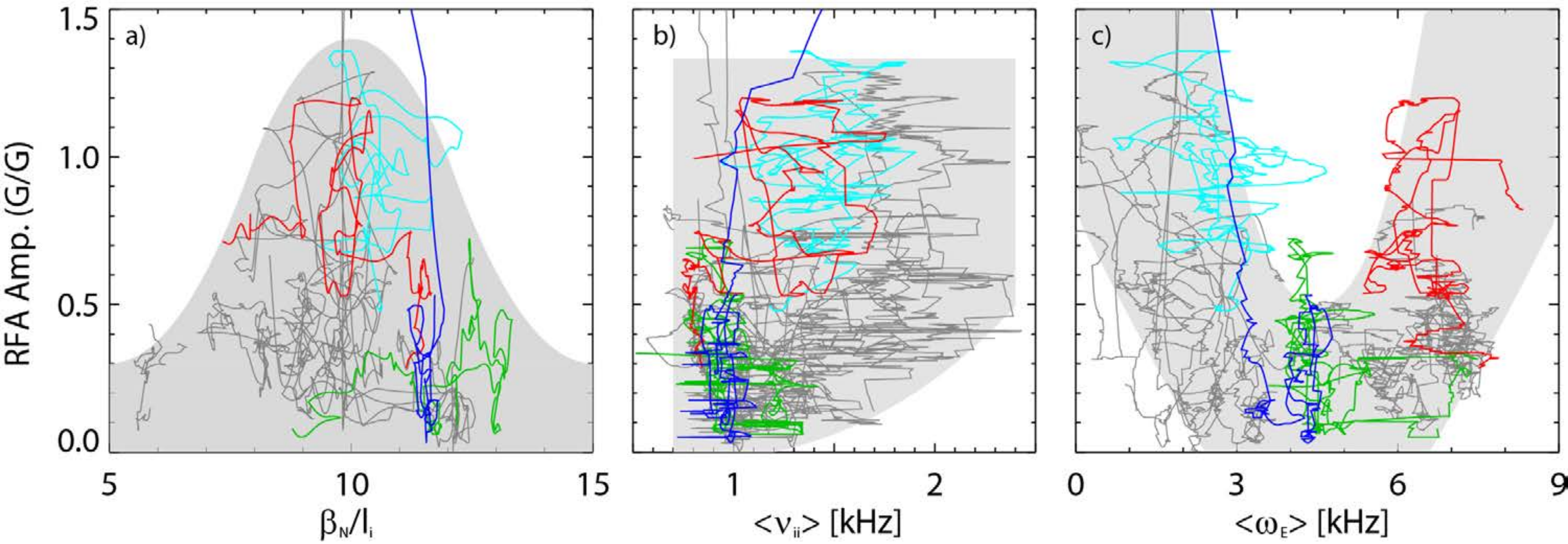
Increased RFA indicates decreased stability

[H. Reimerdes *et al.*, Phys. Rev. Lett. **93**, 135002 (2004)]

[J. Berkery *et al.*, Phys. Plasmas **21**, 056112 (2014)]



Stability boundaries in NSTX from MHD spectroscopy are explained by kinetic theory, have favorable dependencies



Discharge trajectories for 20 plasmas

a) Stability vs. β_N/l_i

Stability *increases* at the highest β_N/l_i due to kinetic effects

b) Stability vs. collisionality

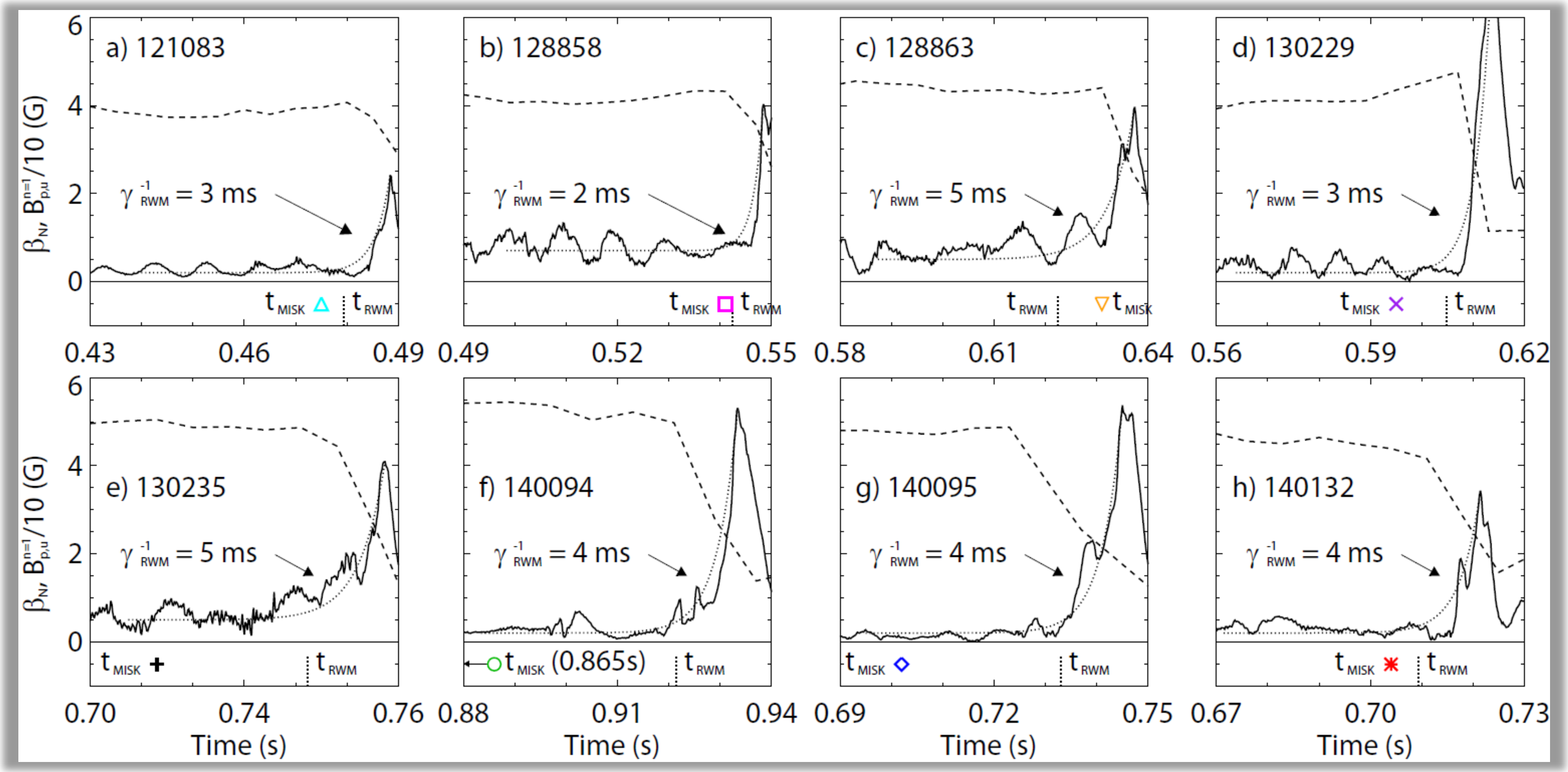
Stable plasmas appear to benefit further from reduced collisionality

c) Stability vs. rotation

Precession drift resonance is stabilizing, useful for disruption avoidance

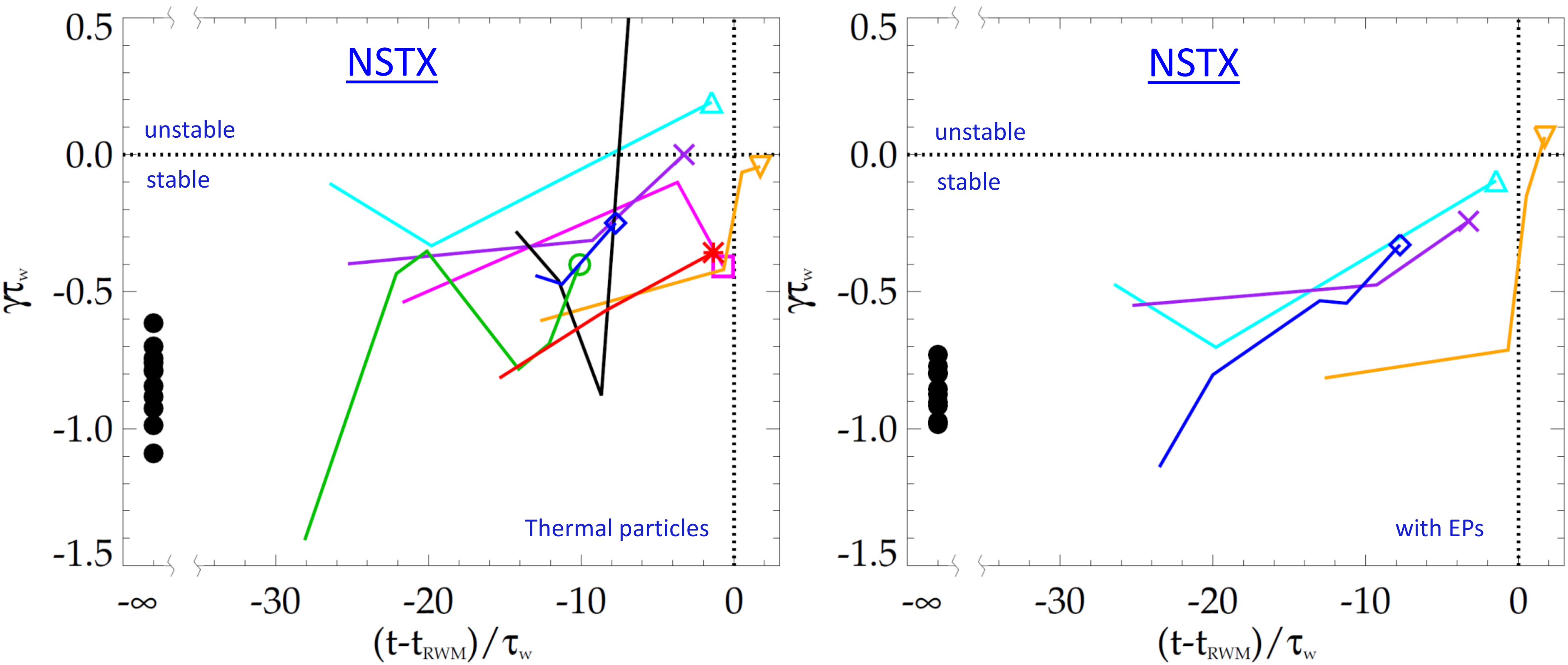
[J. Berkery *et al.*, Phys. Plasmas **21**, 056112 (2014)]

MISK calculations are grounded in validation against unstable experimental plasmas



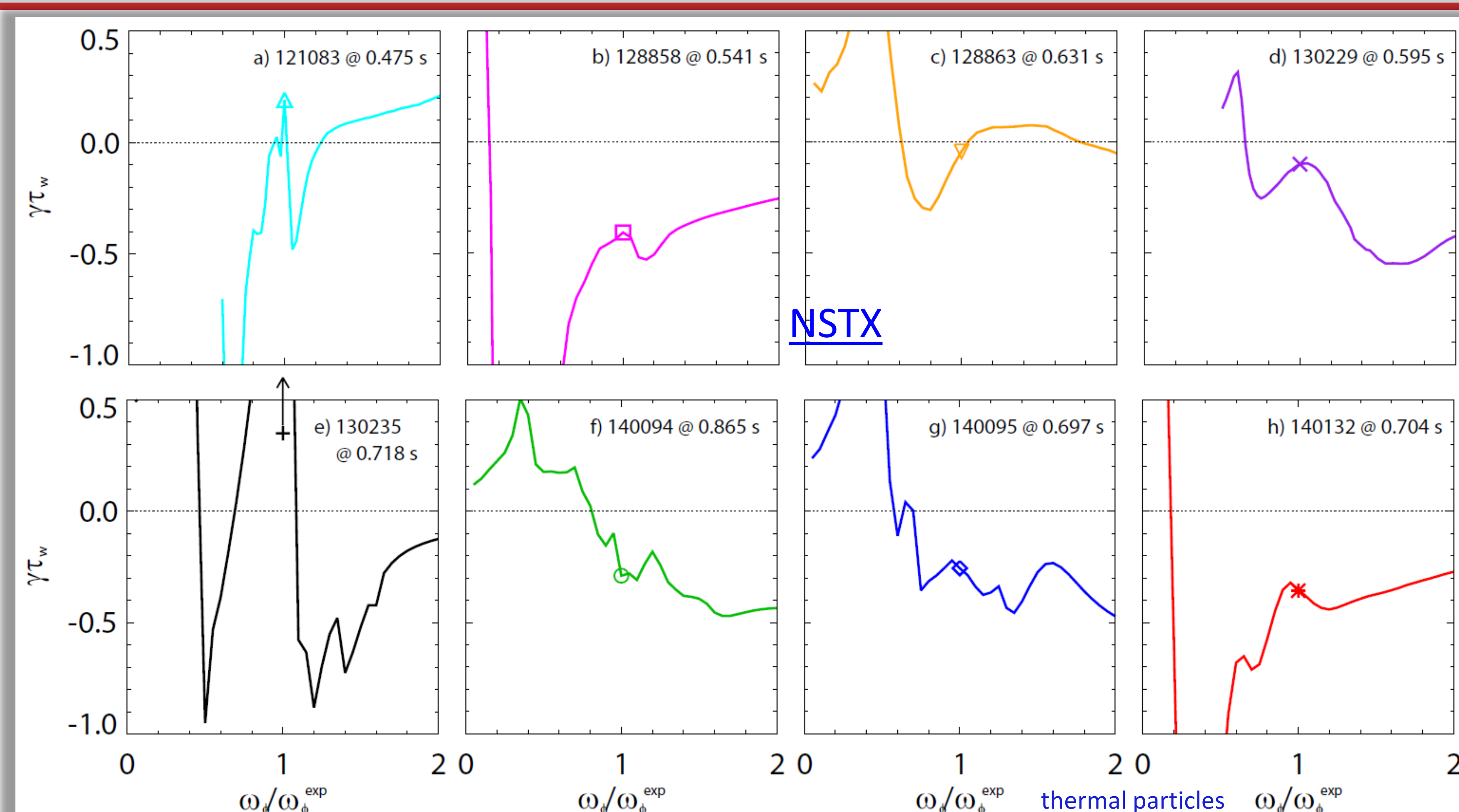
- MISK is being tested by comparison to many NSTX (and DIII-D) cases
  - Goal: operate MISK as a “turnkey” tool for NSTX-U

MISK calculations generally reproduce the approach towards marginal stability seen in experiments



- In each case, the calculations trend towards instability ($\gamma\tau_w = 0$) as the time approaches the time of experimental RWM instability growth
  - Twelve equilibria from discharges with no RWM show no trend and are more stable in the calculations

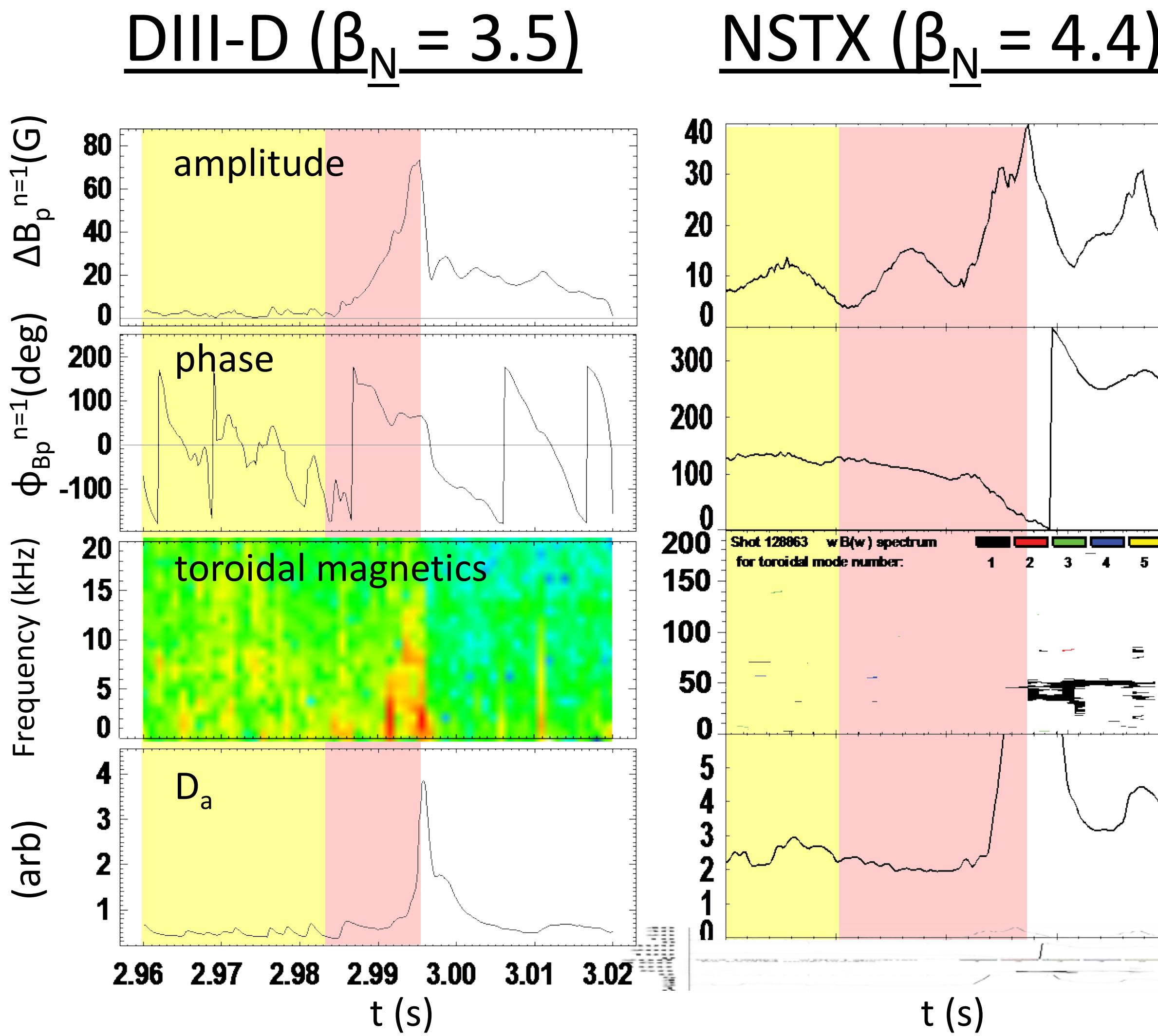
MISK calculations of kinetic RWM growth rates for individual equilibria compare well with marginal stability points



- MISK calculations with scaled experimental rotation profiles (ω_ϕ^{exp}) show:
  - Marginally stable discharges predicted unstable or close to marginal, sometimes in local stability minima or getting less stable with slightly further reduced rotation

RWM growth and dynamics and kinetic RWM marginal stability boundaries were examined in DIII-D and NSTX

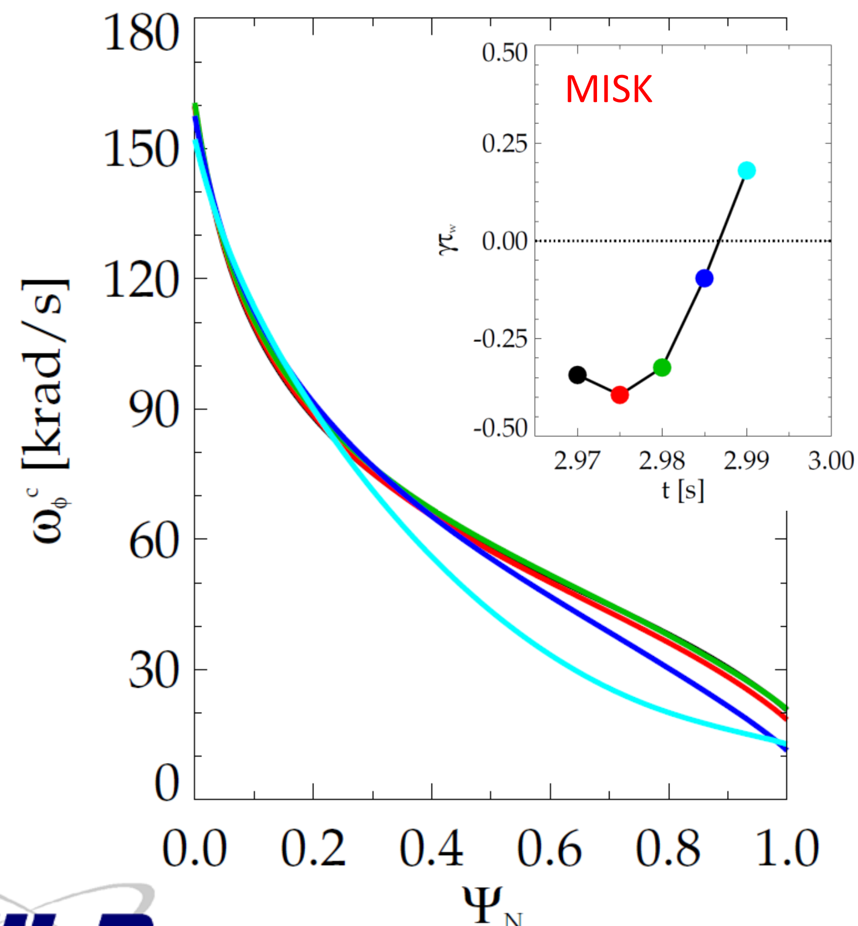
- Elements
  - RWM rotation and mode growth observed
  - No strong NTM activity
  - Some weak bursting MHD in DIII-D plasma
    - Alters RWM phase
  - No bursting MHD in NSTX plasma



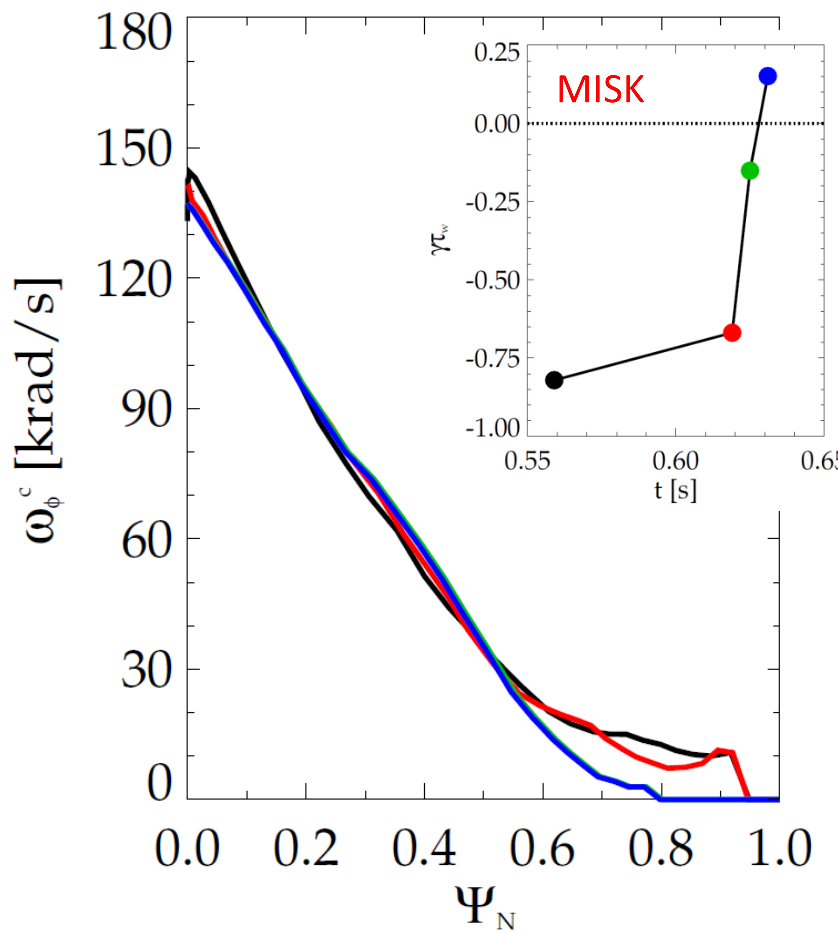
[S. Sabbagh invited talk, Thursday 3:30pm]

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

DIII-D (minor disruption)



NSTX (major disruption)



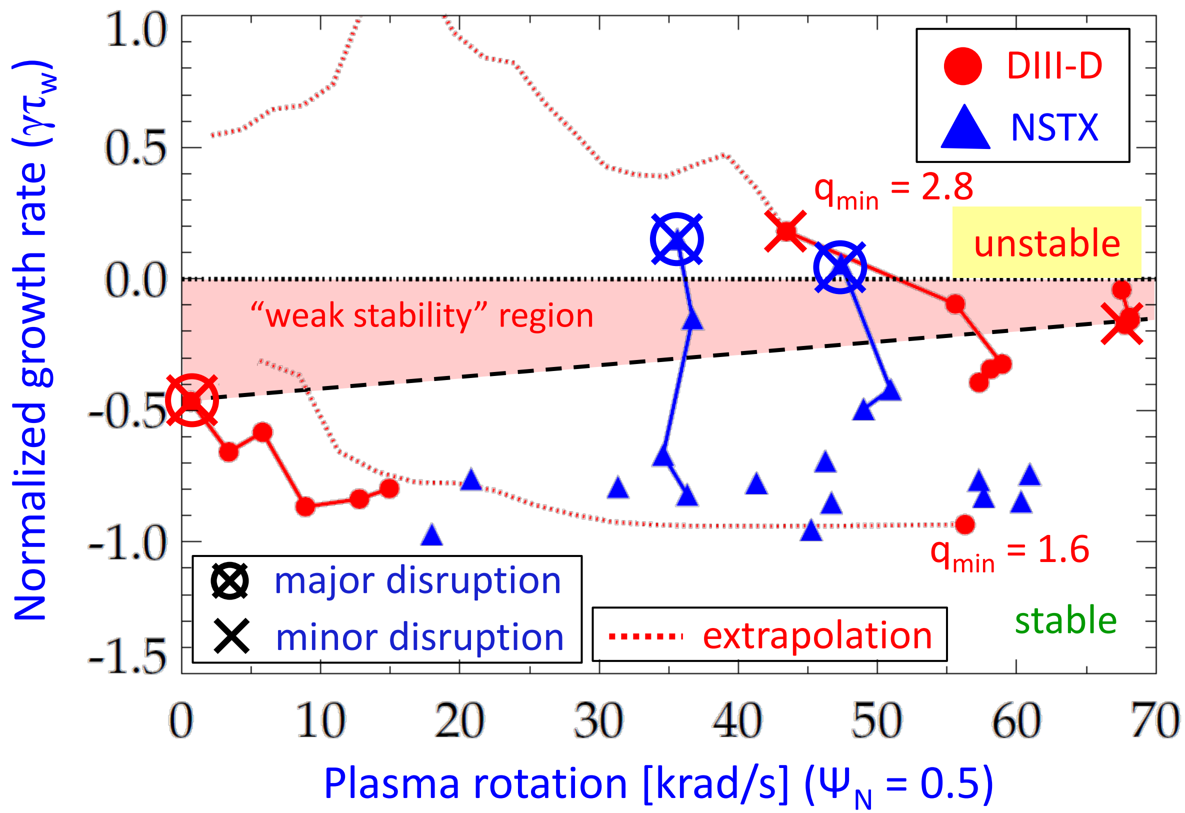
Kinetic RWM stability analysis evaluated for DIII-D and NSTX plasmas

- Plasmas free of other MHD modes can reach performance that approaches or exceeds linear kinetic RWM stability theory

- Strong bursting MHD modes can lead to non-linear destabilization before linear stability limits are reached

- Extrapolations of DIII-D plasmas to different ω_ϕ show marginal stability is bounded by $1.6 < q_{min} < 2.8$

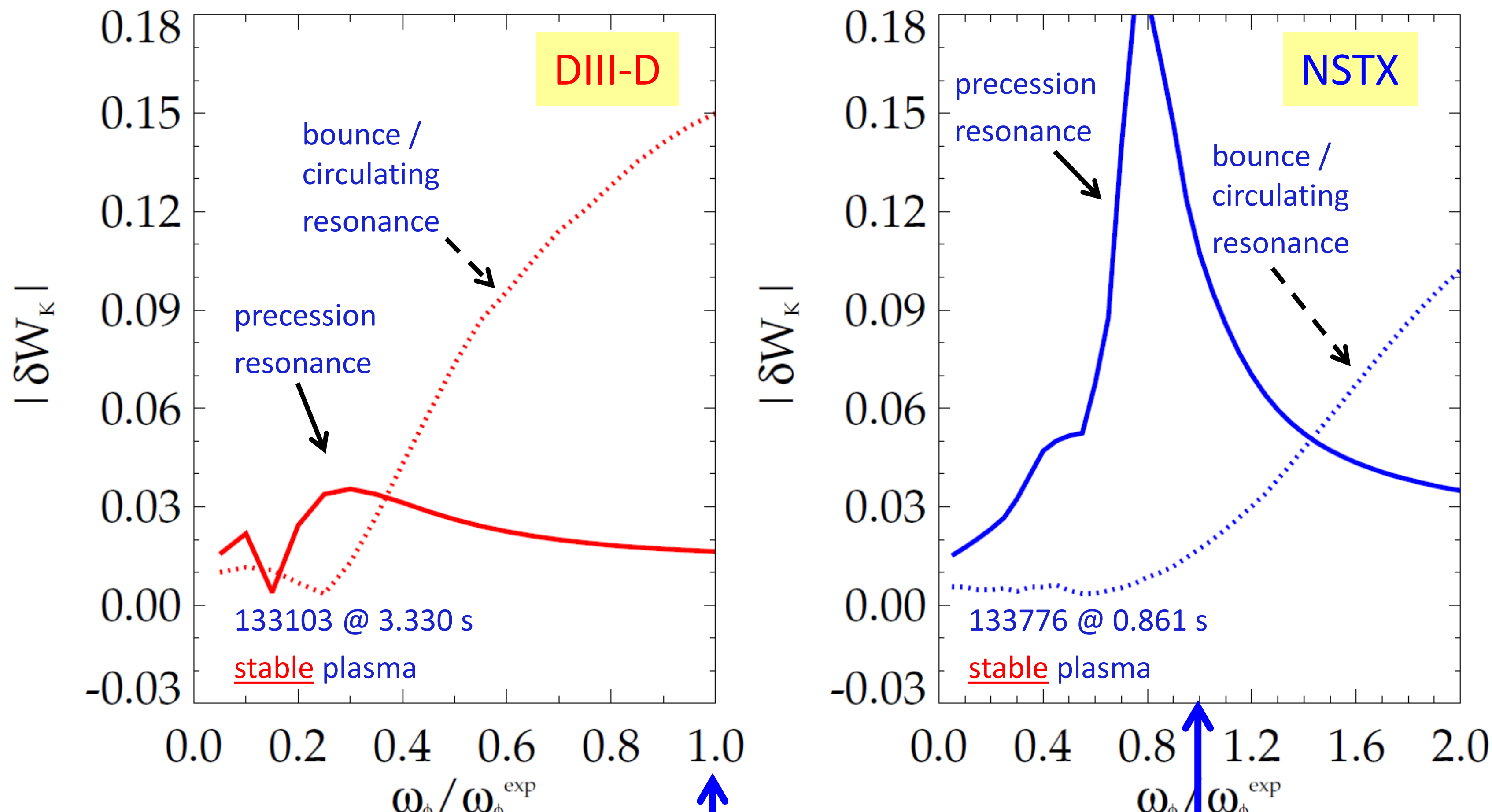
Kinetic RWM stability analysis for experiments (MISK)



[S. Sabbagh invited talk, Thursday 3:30pm]

Bounce resonance dominates for DIII-D at high rotation, while precession drift resonance is typical for NSTX

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

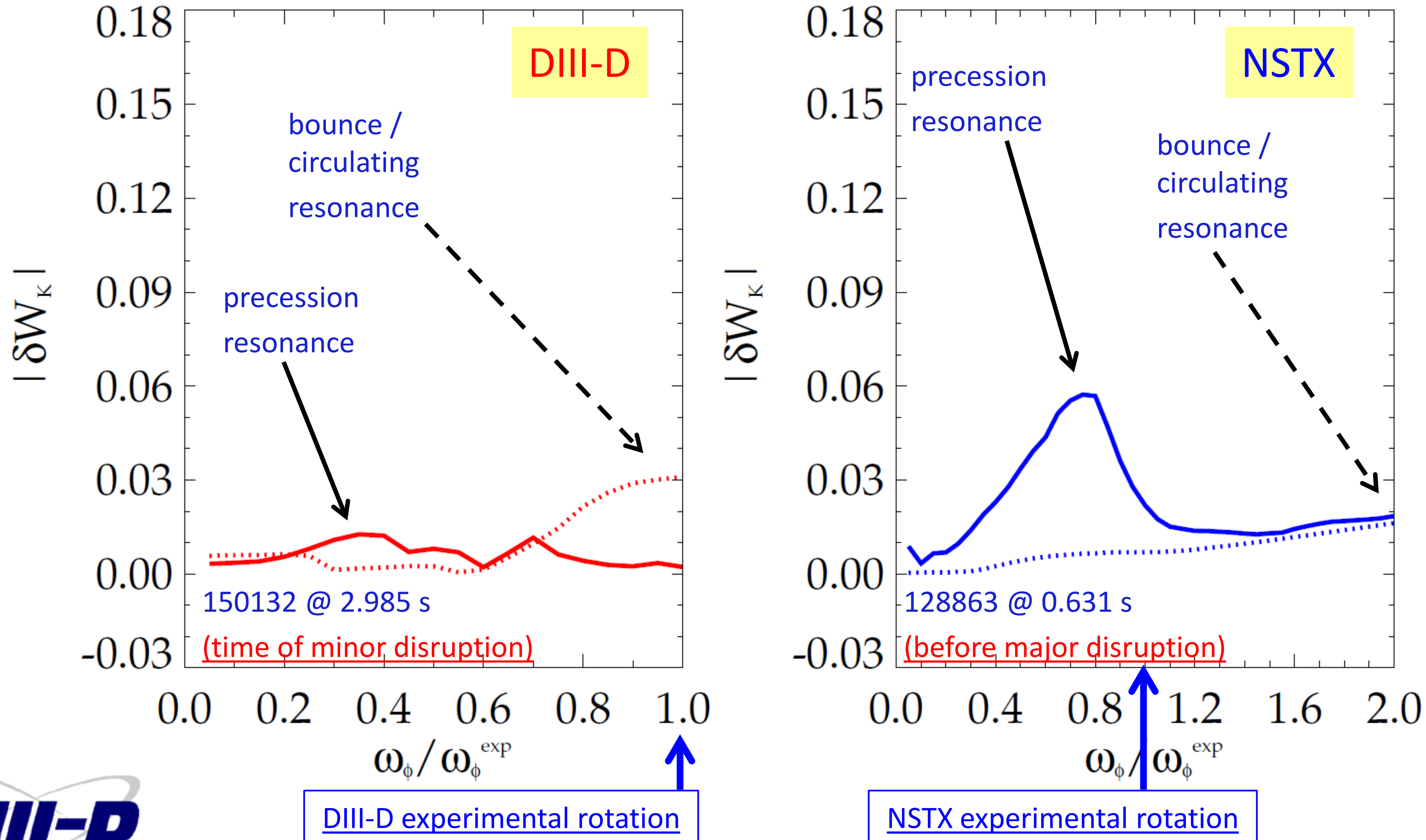


DIII-D experimental rotation

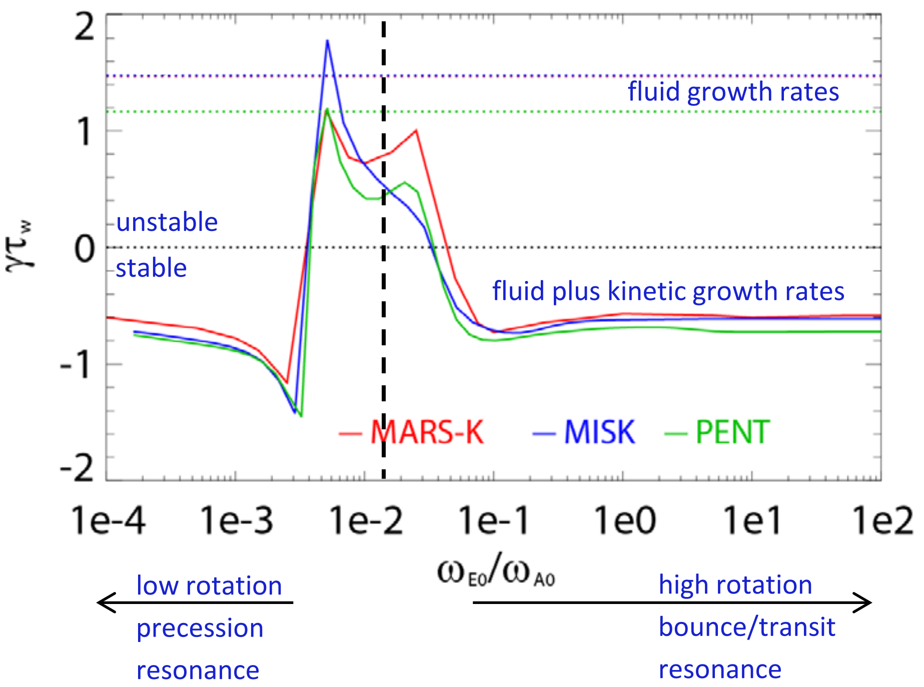
NSTX experimental rotation

Bounce resonance dominates for DIII-D at high rotation, while precession drift resonance is typical for NSTX

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



Benchmarking:
MARS-K, MISK, and PENT agree in $\gamma\tau_w$ vs ω_E for ITER



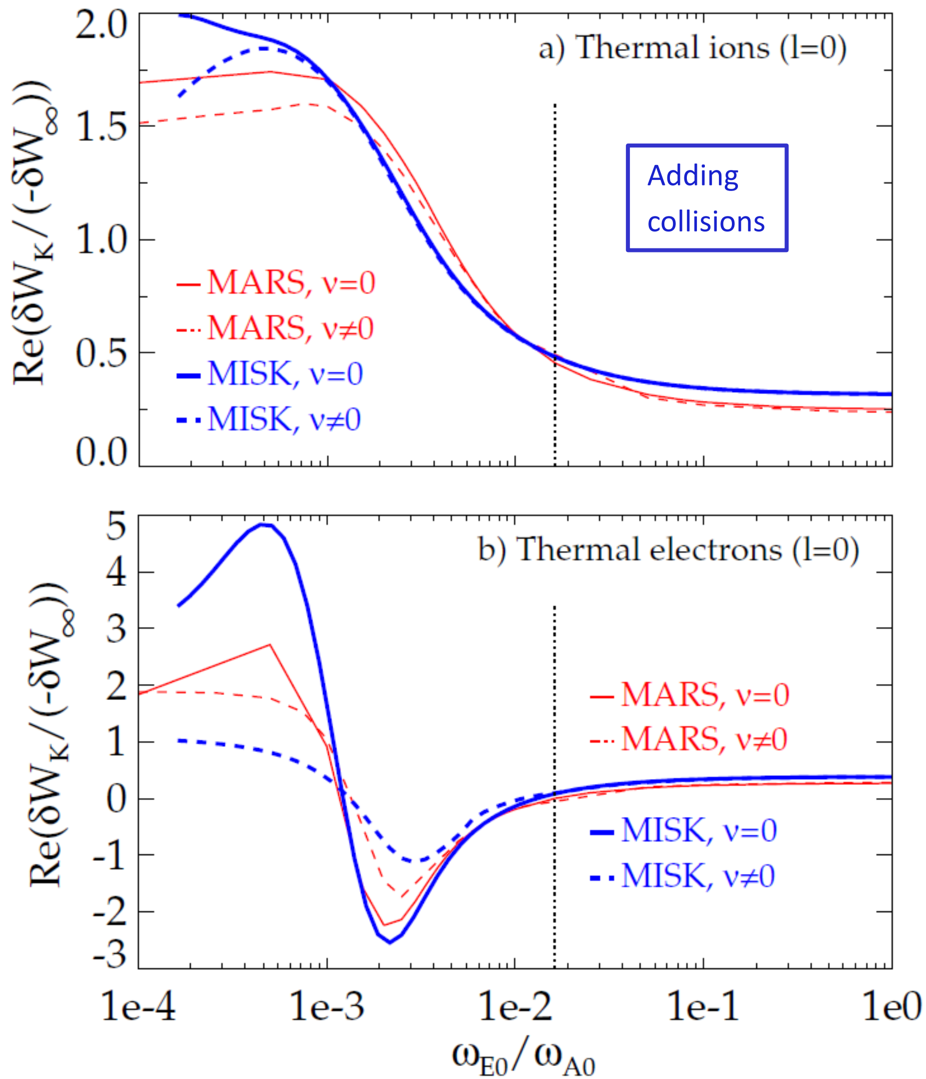
[J. Berkery *et al.*, Phys. Plasmas **21**, 052505 (2014)]

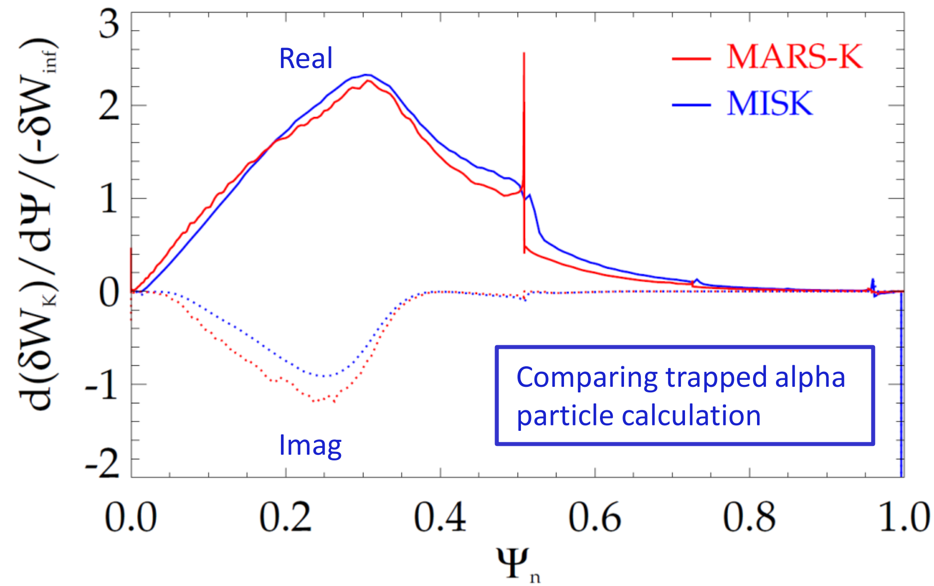
- The codes support the present understanding that RWM stability can be increased by kinetic effects
  - At low rotation through precession drift resonance
  - At high rotation by bounce and transit resonances
  - Intermediate rotation can remain susceptible to instability

Benchmarking gives confidence that the codes are calculating kinetic effects equivalently for ITER case when rational surfaces handled equally

To the extent that this model is validated against *experimental* evidence of RWM stability, one can then project the stability of future devices with greater confidence

MARS-K and MISK benchmarking continues, focusing on presenting a realistic projection of ITER stability

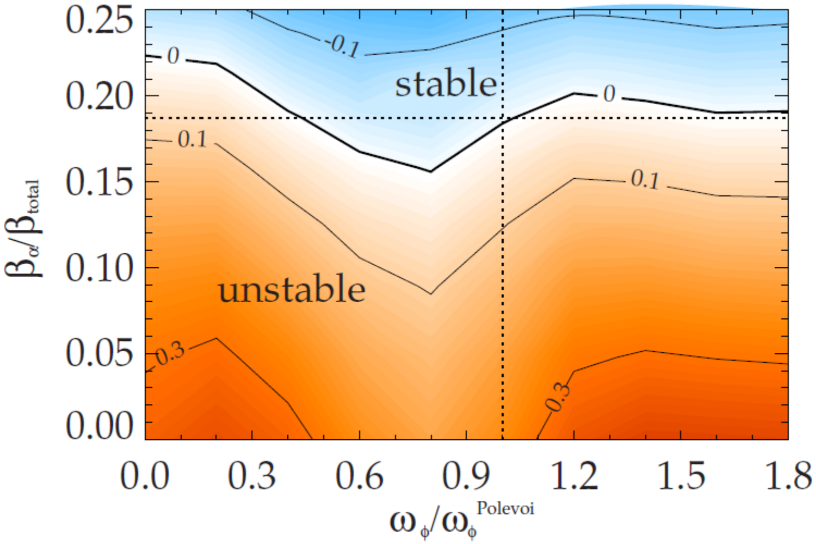




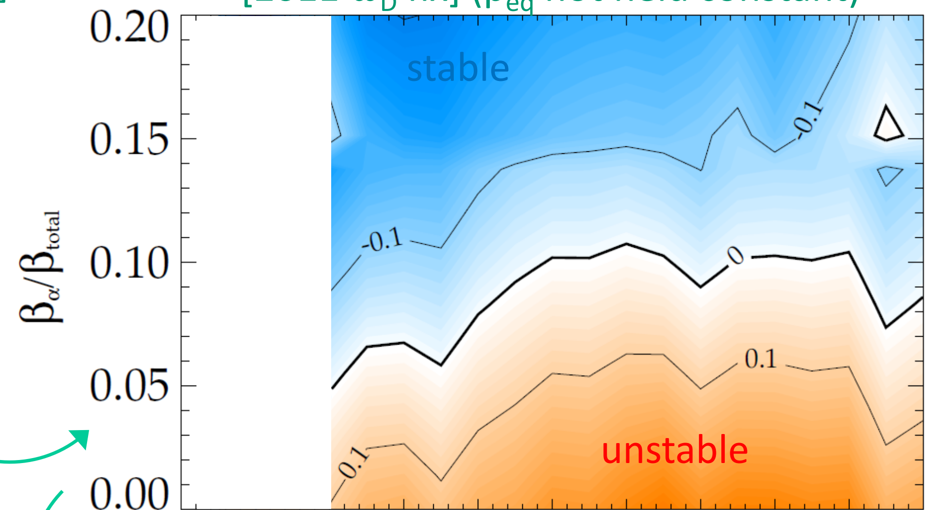
- Collisionality is low in ITER, but still reduces electrons' contribution to stability
- Alpha particle calculations agree between MISK and MARS-K, are crucial to ITER stability

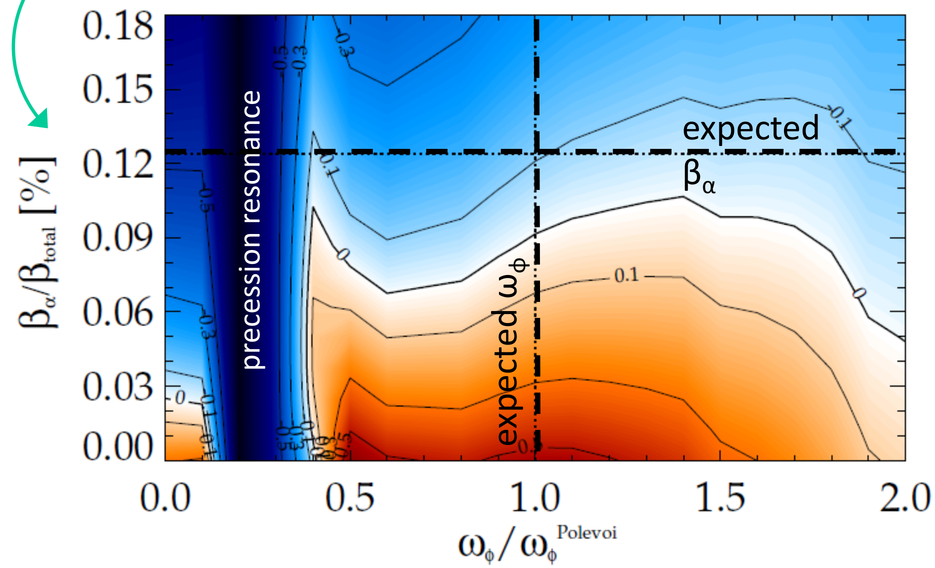
Present MISK calculations for ITER consistent with past results, show somewhat greater stabilization from alphas

[J. Berkery *et al.*, Phys. Plasmas **17**, 082504 (2010)]
(equilibrium pressure not held constant)



[2011 ω_D fix] (p_{eq} not held constant)





[Present analysis] (p_{eq} held constant)

- Evolution of analysis
  - Original calculations showed large α population required for stabilization
  - Calculations with a new equilibrium, new profiles, benchmarking fixes, and collisionality are generally consistent, show further stability and a strong precession drift resonance

Rotational terms in the force balance have previously not been considered in RWM kinetic stability

$$\rho_0(\gamma + i(n\omega_\phi - \omega_r))\tilde{\mathbf{v}} = \mathbf{j_0} \times \tilde{\mathbf{B}} + \tilde{\mathbf{j}} \times \mathbf{B_0} - \nabla \cdot \tilde{\mathbb{P}} - 2\rho_0 \left(\mathbf{v_0} \cdot \nabla\right) \tilde{\mathbf{v}} - \rho_0 \left(\tilde{\mathbf{v}} \cdot \nabla \mathbf{v_0}\right) - \tilde{\rho} \left(\mathbf{v_0} \cdot \nabla\right) \mathbf{v_0}$$

Inertia | Usual fluid terms | Kinetic effects | Coriolis - ω_ϕ | Coriolis - $d\omega_\phi$ | Centrifugal

$$(\gamma - i\omega_r)\tau_w = -\frac{\delta W_\infty + \delta W_K + \delta W_{\rm rot}}{\delta W_b + \delta W_K + \delta W_{\rm rot}}$$

(Note: rotation effects on equilibrium not considered here)

Inertia: $$\delta I = \frac{1}{2}\int \rho_0(\gamma + i(n\omega_\phi - \omega_r))^2 \left|\boldsymbol{\xi}\right|^2 d\mathbf{V}$$

Coriolis – ω_ϕ: $$\delta W_\Omega = \frac{1}{2}\int 2\rho_0\omega_\phi(\gamma + i(n\omega_\phi - \omega_r))(\hat{\mathbf{z}} \times \boldsymbol{\xi}) \cdot \boldsymbol{\xi}^* d\mathbf{V}$$

Coriolis – $d\omega_\phi$: $$\delta W_{d\Omega} = \frac{1}{2}\int 2\rho_0\omega_\phi(\boldsymbol{\xi}_\perp \cdot \nabla\omega_\phi)R(\hat{\mathbf{R}} \cdot \boldsymbol{\xi}^*)d\mathbf{V}$$

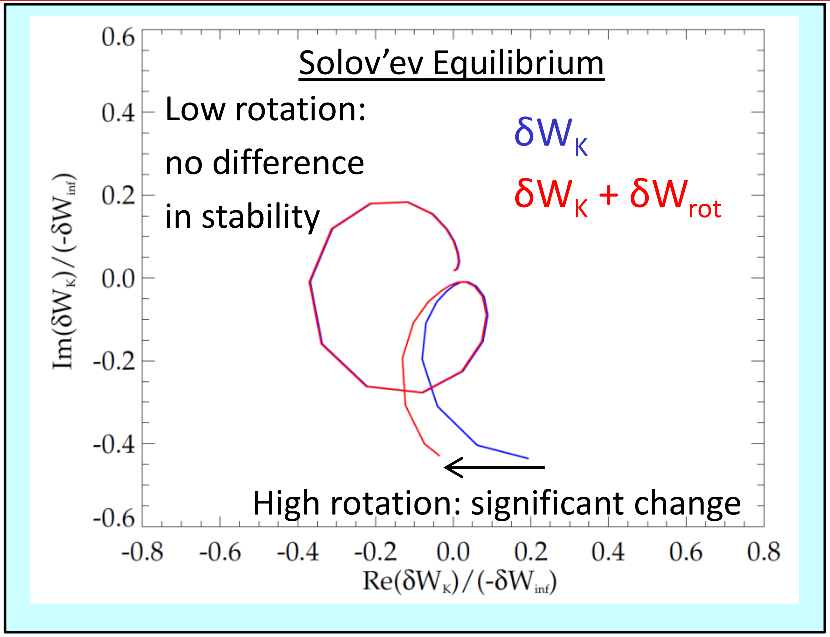
Centrifugal: $$\delta W_{\rm cf} = \frac{1}{2}\int \nabla \cdot (\rho_0\boldsymbol{\xi})\omega_\phi^2 R(\hat{\mathbf{R}} \cdot \boldsymbol{\xi}^*)d\mathbf{V}$$

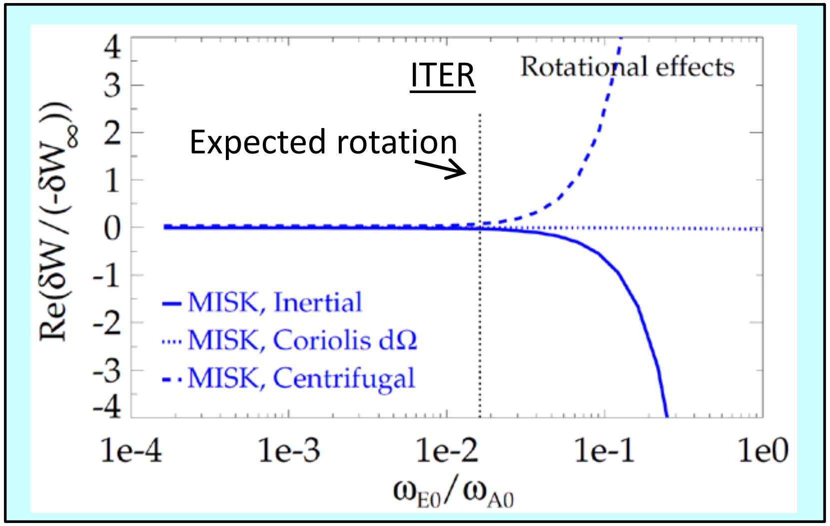
[J. Menard et al., APS (2013)]

Preliminary indications are that rotational terms could impact stability calculations; further testing required

- Preliminary results
  - Tested on a Solov'ev analytical equilibrium and an ITER test case
  - Currently benchmarking with MARS-K
- Rotational terms could impact stability
  - No effect at low rotation
  - Significant effect at "high" rotation
  - May impact NSTX calculations at experimental rotation levels (destabilizing?)

[Z. Wang invited talk, Thursday 10:30am]





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

NSTX-U

(General framework & algorithms applicable to ITER)

Plasma Operations

Predictors (Measurements)
Shape/position
Eq. properties (β, l_i, V_{loop},)
Profiles (p(r), j(r), v_ϕ(r), ..)
Plasma response (n=0-3, RFA,)
Divertor heat flux

Control Algorithms: Steer Towards Stable Operation
Isoflux and vertical position ctl
LM, NTM avoidance
RWM and dynamic EF control
RWMSC (plasma response)
Divertor radiation control

Avoidance Actuators
PF coils
2nd NBI: q, v_ϕ, p control
3D fields (upgraded + NCC):
EF, v_ϕ control
n=1-3 feedback
Divertor gas injection

Loss of Control

Disruption Warning System

Mitigation
Early shutdown
Massive Gas Injection

NSTX-U is planning a disruption avoidance system, in which real-time MHD spectroscopy or kinetic physics can be used

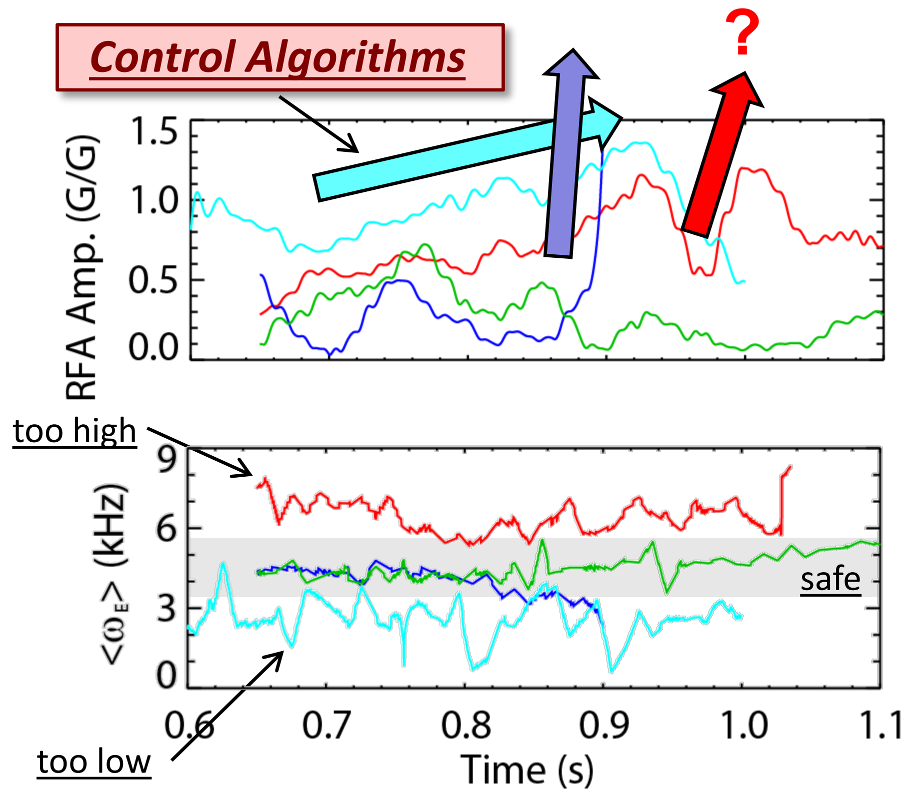
- MHD Spectroscopy
  - Experiments in NSTX-U: Use real-time MHD spectroscopy while varying rotation and β_N to predict disruptions
  - Apply as a ***Predictor*** in control scheme
  - Disadvantage: plasma stability can change when kinetic profiles change, but MHD spectroscopy is limited in frequency.
    - Active control still necessary

- Kinetic Physics
  - Real-time measurement of plasma rotation not good enough!
  - Evaluate simple physics criteria for global mode marginal stability in real-time
  - Can obtain $\langle\omega_E\rangle$ inside the pedestal from real-time ω_ϕ and modeled density and temperature profiles (future work)

Disruption Warning System

[S. Gerhardt *et al.*, Nucl. Fusion **53**, 063021 (2013)]

Need to maximize warning time, minimize false positives



Conclusions

- Active measurement of RWM stability with MHD spectroscopy experiments in NSTX are explained by kinetic theory
- MISK calculations compare well with marginal stability point for a large database of NSTX unstable discharges
- Unified analysis of DIII-D and NSTX experiments gives improved RWM understanding
  - S. Sabbagh invited talk, Thursday 3:30pm
- MISK has been benchmarked, now focusing on ITER stability
- NSTX-U disruption avoidance system will use kinetic physics

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