Resistive Wall Mode Physics and Control to Sustain High Normalized Beta in NSTX

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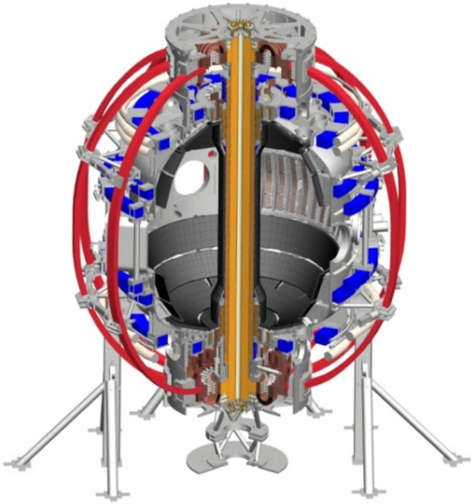

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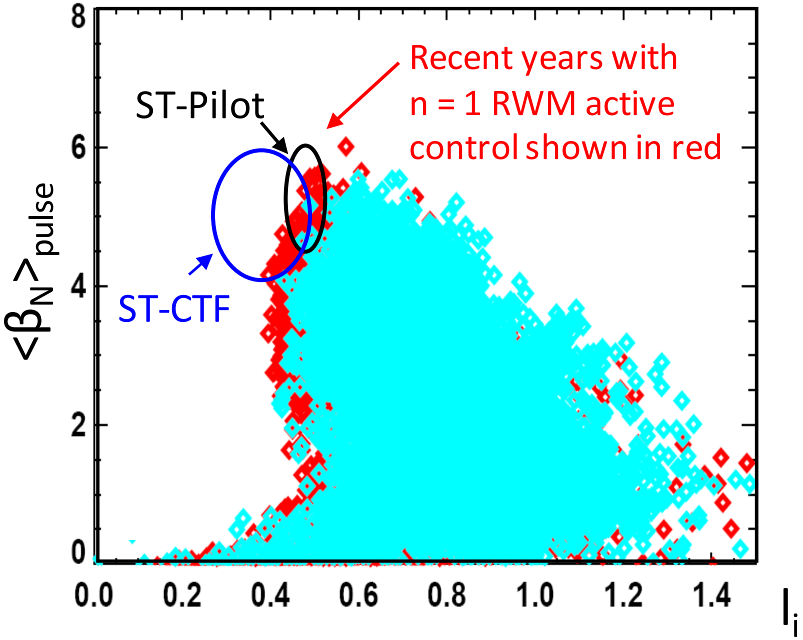
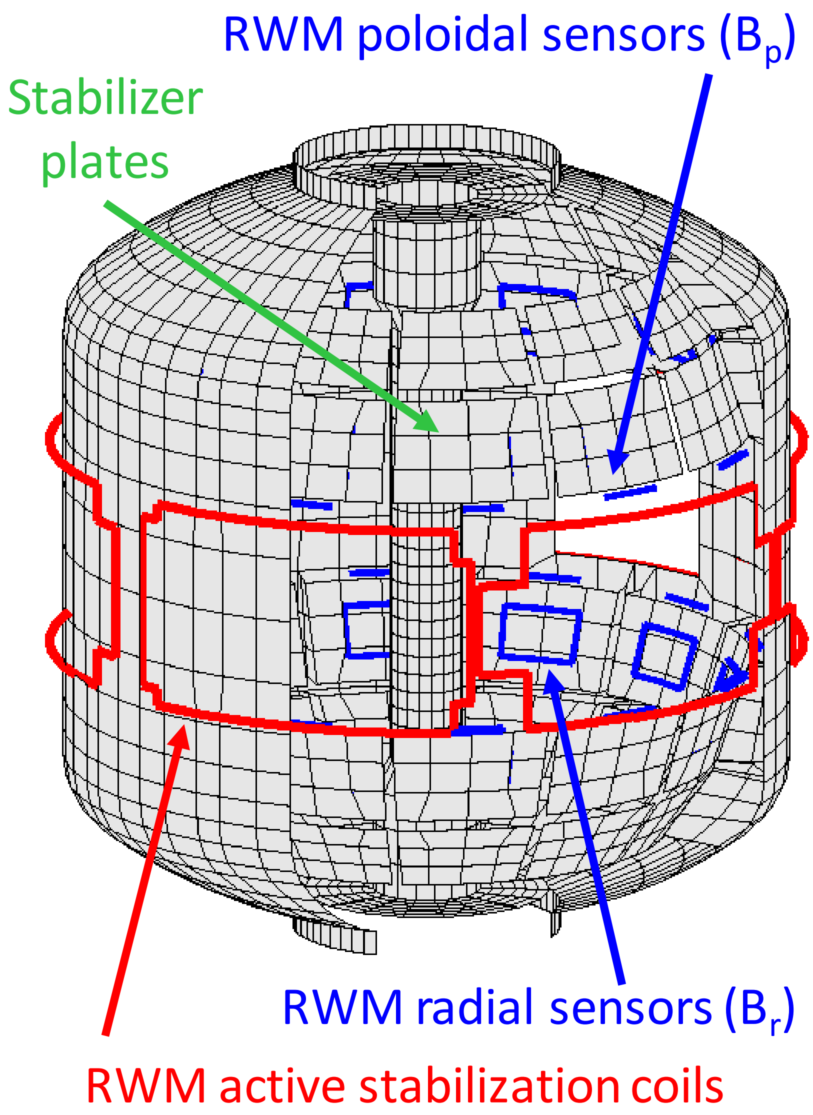
Long-wavelength MHD stability required for next-step high β_N, low l_i devices

- Motivation
  - Future fusion devices that operate at high non-inductive current fraction, have low plasma internal inductance, l_i.
  - The resistive wall mode (RWM) is a primary cause of disruption at high β
  - Understanding passive stabilization physics determining RWM stability is critical to extrapolate stability requirements for future devices
  - Active control of RWM required when passive stability is inadequate
- Outline
  - Introduction:
    - RWMs in NSTX
    - Kinetic stability theory
    - Active MHD spectroscopy
  - Resonant field amplification (RFA) vs. plasma rotation
  - RFA vs. collisionality
  - RFA vs. β_N/l_i



NSTX is equipped to study passive RWM stability in stable or unstable plasmas, and active global MHD control


RWM poloidal sensors (B_p)

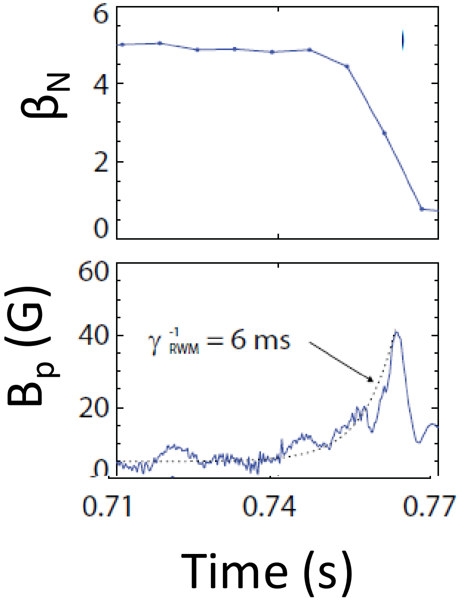
Stabilizer plates

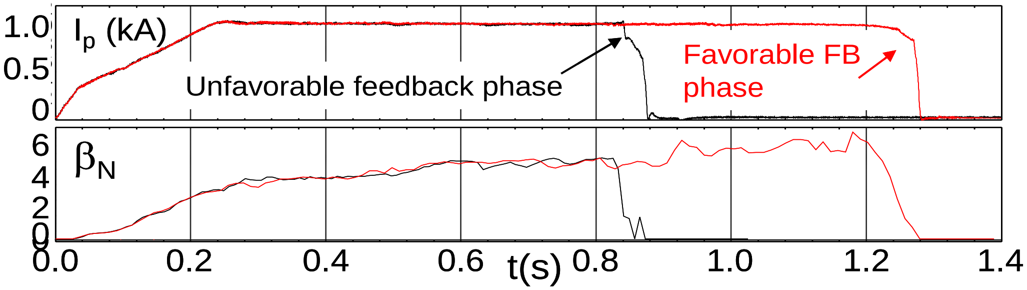
RWM radial sensors (B_r)

RWM active stabilization coils

- Unstable plasma causes β collapse, I_p disruption
  - Correlate marginal stability point with kinetic theory MISK calculations

    or
  - Use active control to stabilize: both dual component feedback and state space control





[Poster PP8.13, Wednesday afternoon]

Kinetic terms in the RWM dispersion relation enable stabilization; theory consistent with experimental results

Dissipation (Im(δW$_K$)) and restoring force (Re(δW$_K$)) from kinetic term enables stabilization of the RWM:

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

[B. Hu *et al.*, Phys. Plasmas **12**, 057301 (2005)]

MISK Code

$$\delta W_K \sim \left[\frac{1}{\langle\omega_D\rangle + l\omega_b - i\nu_{\text{eff}} + \omega_E}\right]$$

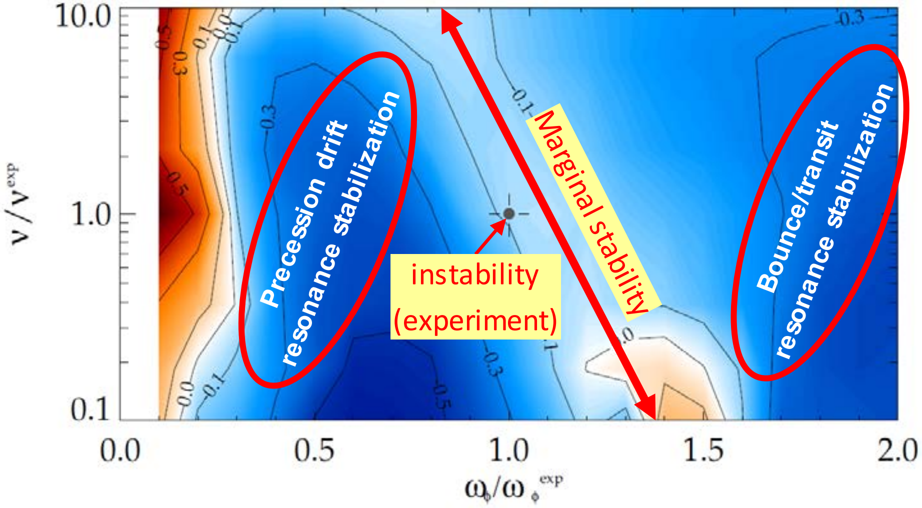
Precession Drift

Bounce

Collisionality

~ Plasma Rotation: $\omega_\phi \approx \omega_E + \omega_{*i}$

γτ$_w$ contours vs. ν and ω$_\phi$



[S. Sabbagh *et al.*, IAEA 2010, EXS/5-5]

- MISK calculations are consistent with RWM instability at intermediate plasma rotation between precession drift resonance at low ω$_\phi$, bounce/transit resonance at high ω$_\phi$

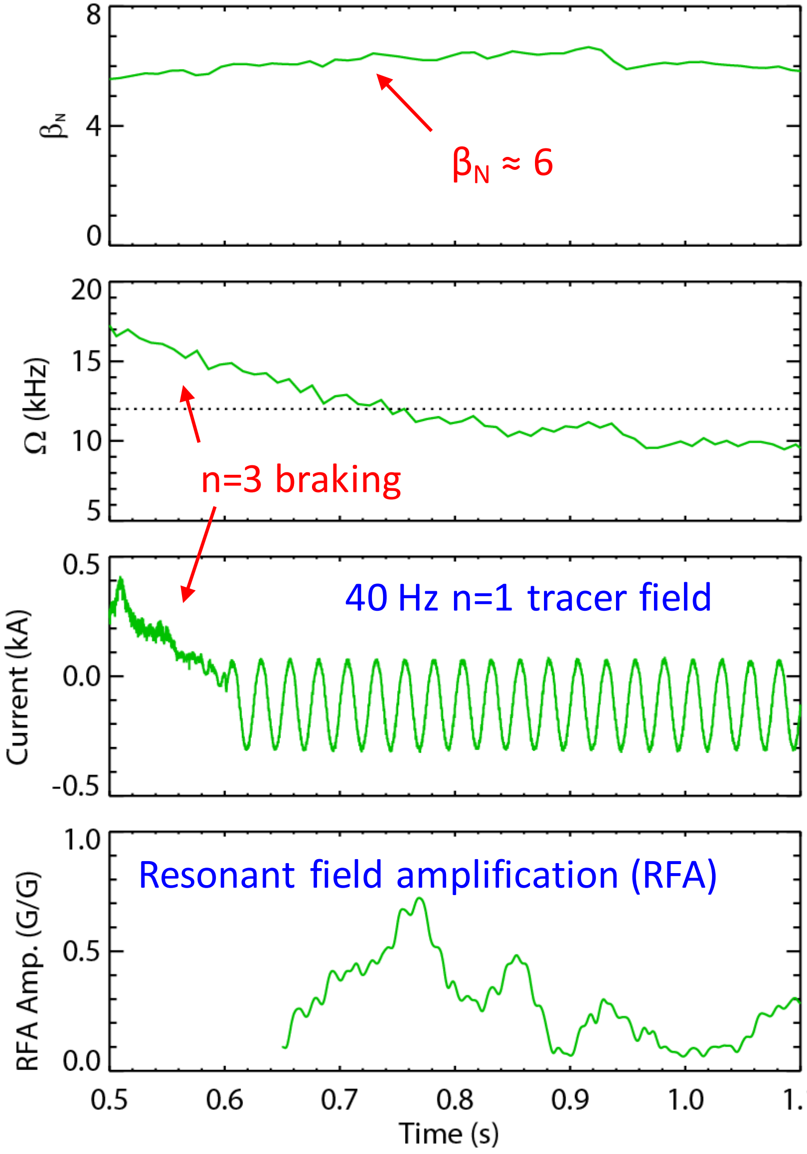
[S. Sabbagh *et al.*, Nucl. Fusion **50**, 025020 (2010)]
[J. Berkery *et al.*, Phys. Rev. Lett. **104**, 035003 (2010)]

Active MHD spectroscopy is used to probe plasma stability

- Active MHD spectroscopy used as a proxy for RWM stability when modes are stable
  - Resonant field amplification (RFA) of an n=1 applied AC field is measured.
  - Increased RFA indicates decreased stability

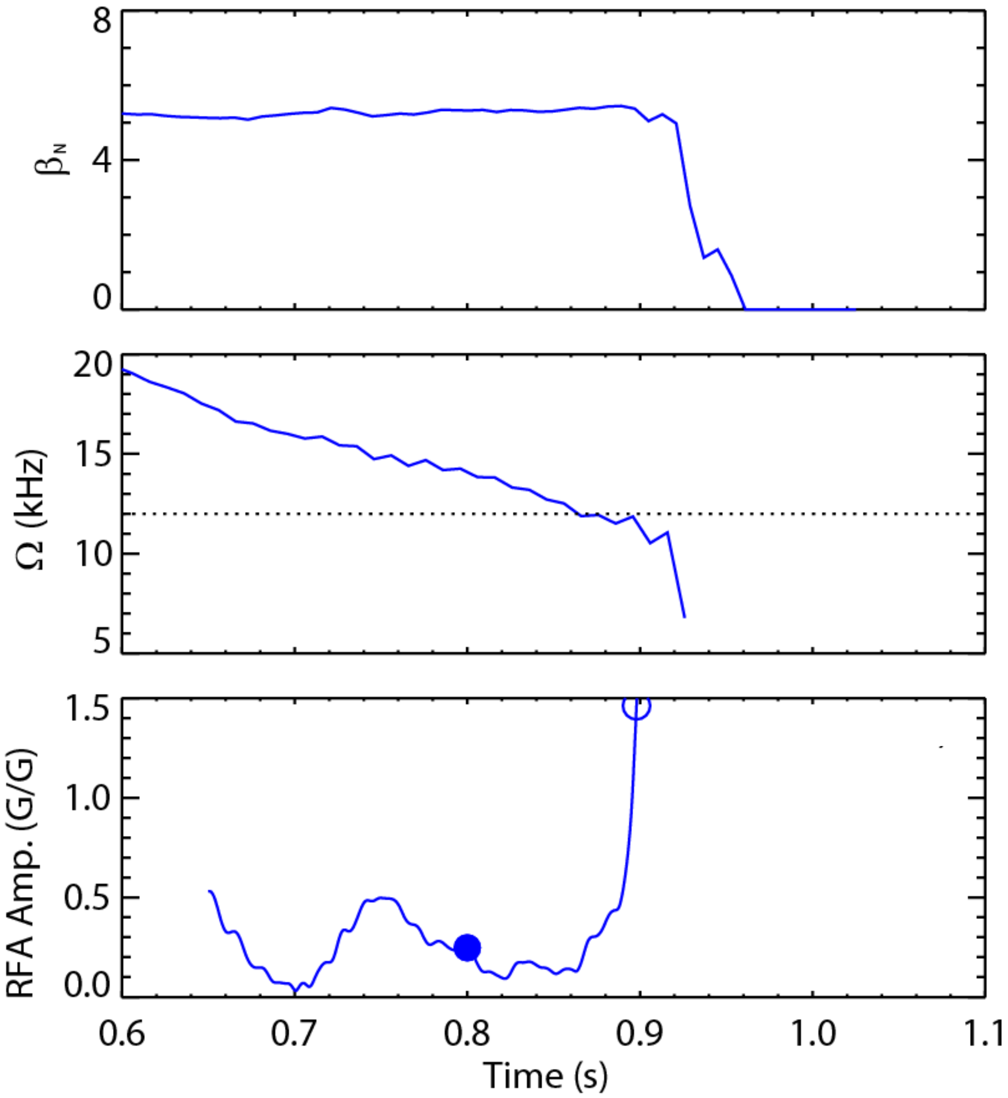
$$RFA = \frac{B_{plasma}}{B_{applied}}$$

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



Resonant field amplification experiments in NSTX gauge the stability of plasmas to compare to kinetic stability theory

- Experiments in NSTX measured RFA of high beta plasmas with rotation slowed by n=3 magnetic braking.
  - unstable at 0.9 s



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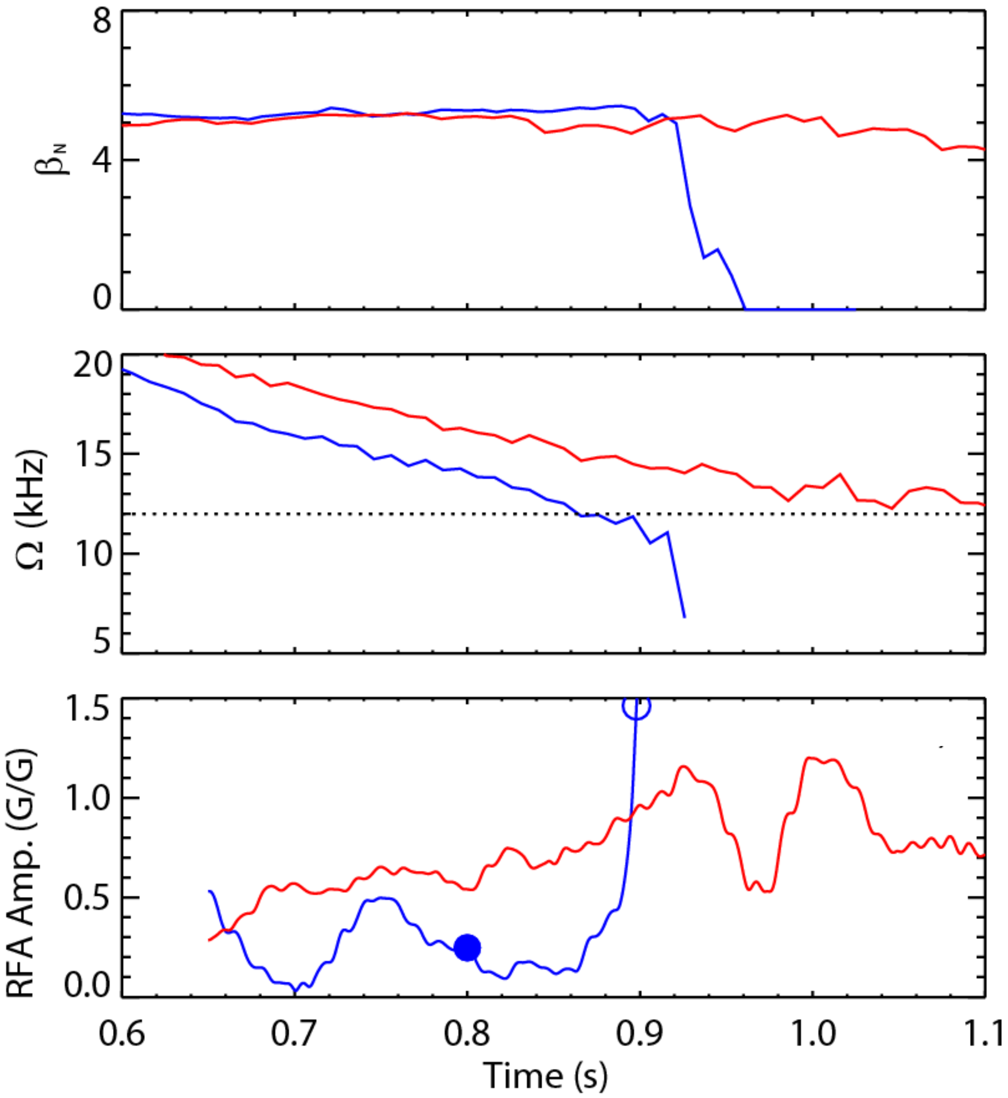
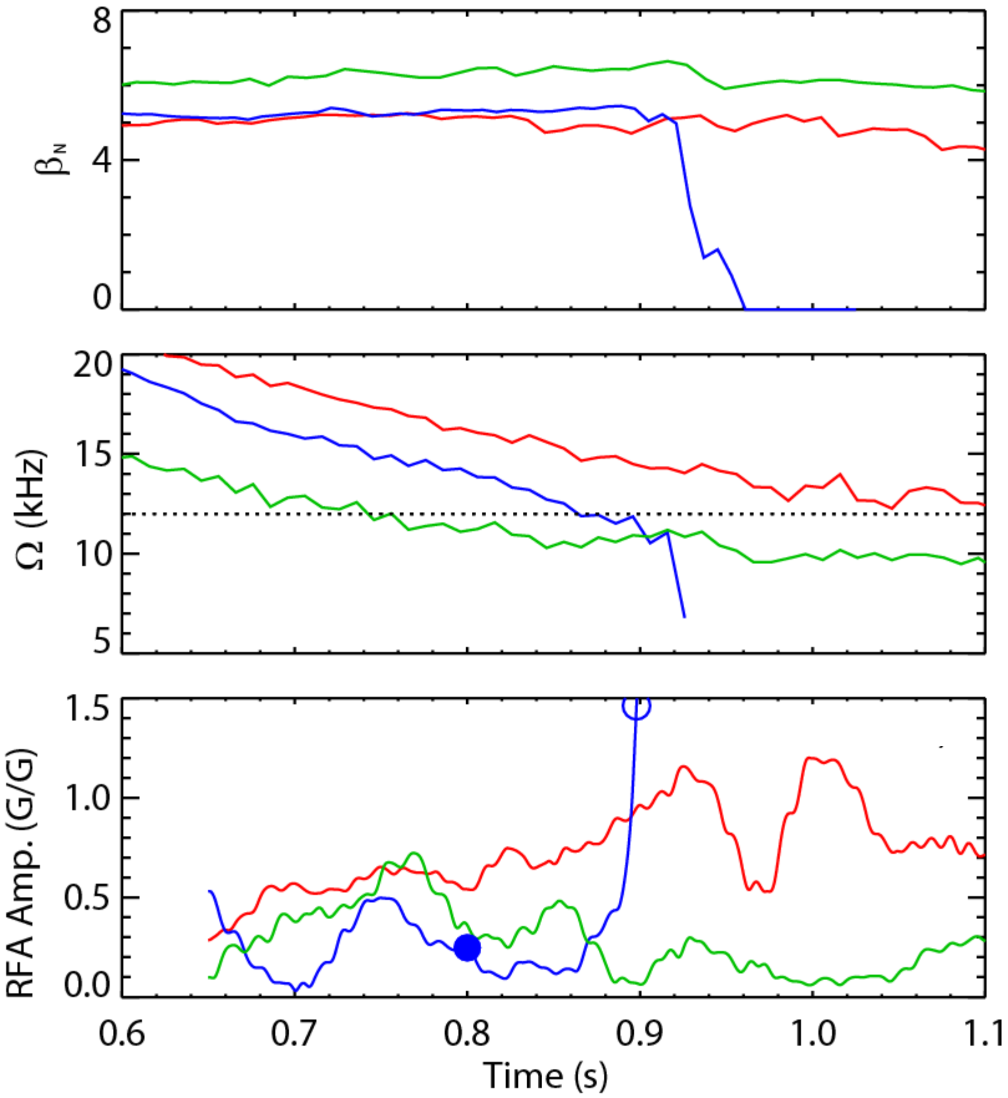
  - same β, higher rotation: marginally stable



Resonant field amplification experiments in NSTX gauge the stability of plasmas to compare to kinetic stabilty theory

- Experiments in NSTX measured RFA of high beta plasmas with rotation slowed by n=3 magnetic braking.
  - unstable at 0.9 s
  - same β, higher rotation: marginally stable
  - higher β, lower rotation: but stable! Counter-intuitive without invoking kinetic effects

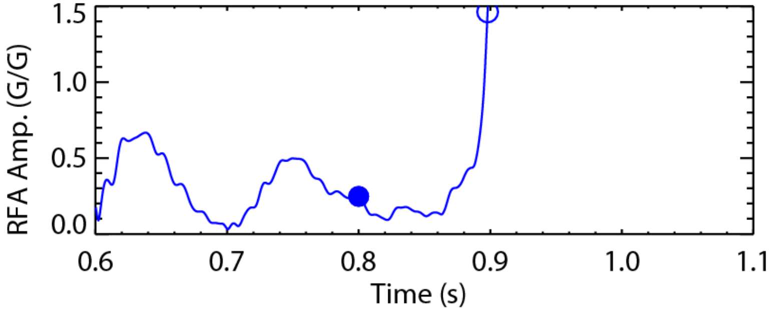


Experimental instability can be explained by kinetic theory and MISK calculation

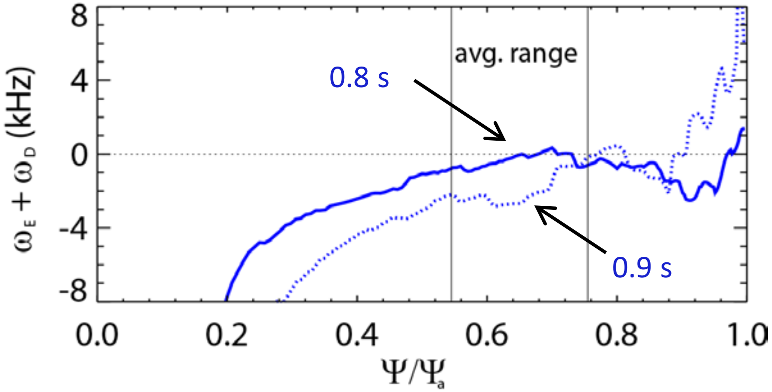
- Earlier time (0.8 s,●):
  $\omega_E + \omega_D \approx 0$
  - Experiment: stable
  - Theory: stabilizing
  - Calculation: stable
- Later time (0.9 s,○):
  $\omega_E + \omega_D < 0$
  - Experiment: unstable
  - Theory: destabilizing
  - Calculation: unstable at 10% lower rotation than marginal point

Effects of EPs still being evaluated

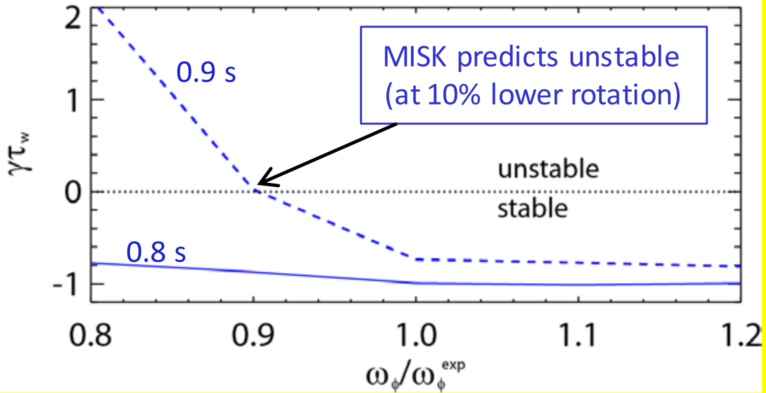
Experiment (RFA)



Theory (Profiles)



Calculation (MISK)



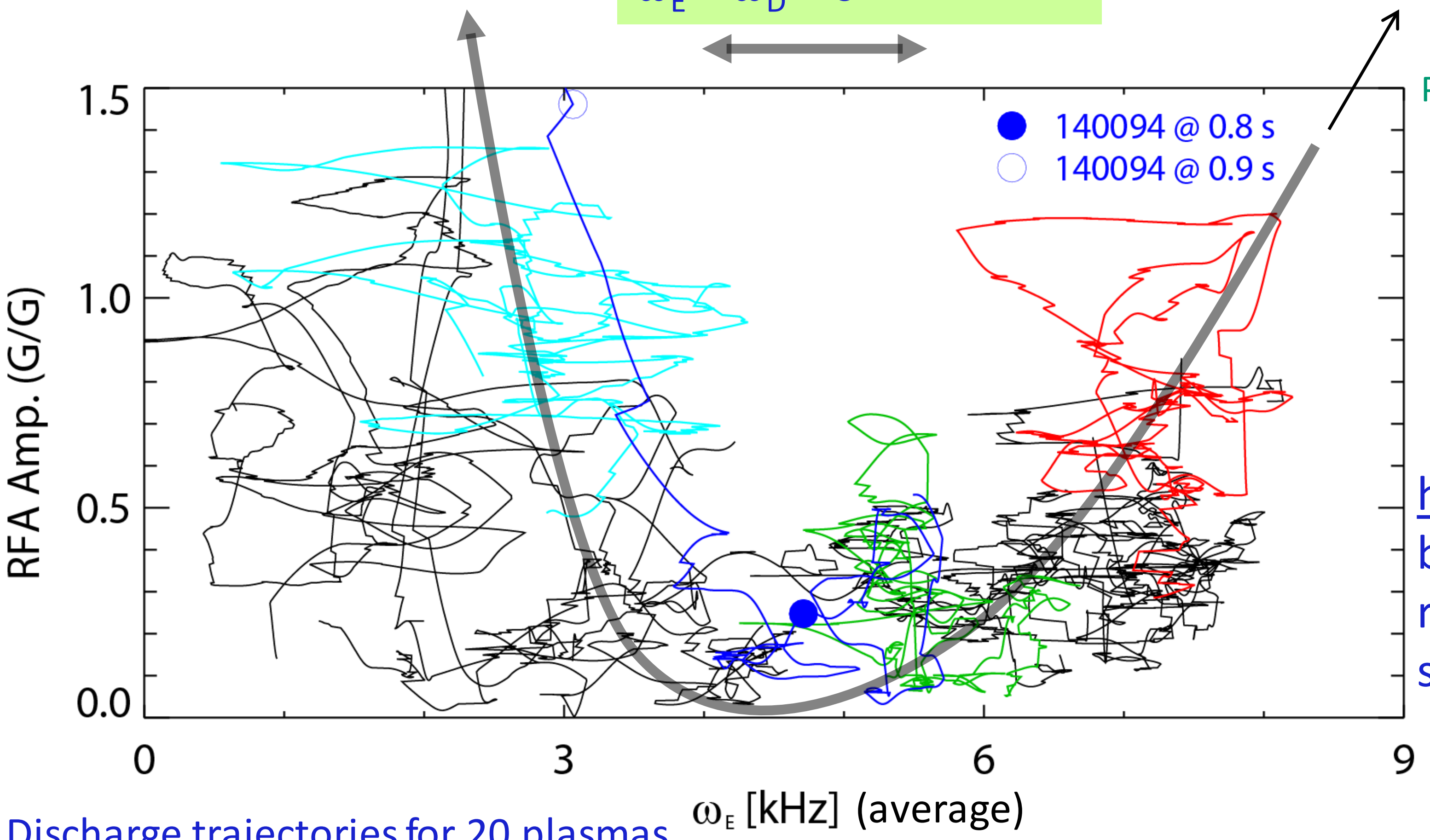
MISK predicts unstable (at 10% lower rotation)

RFA measurements add additional support to established theory of RWM stability through kinetic resonances

low rotation
unstable RWMs

precession drift resonance stabilization
$\omega_E - \omega_D \approx 0$

intermediate rotation
unstable RWMs
(not in present data set)

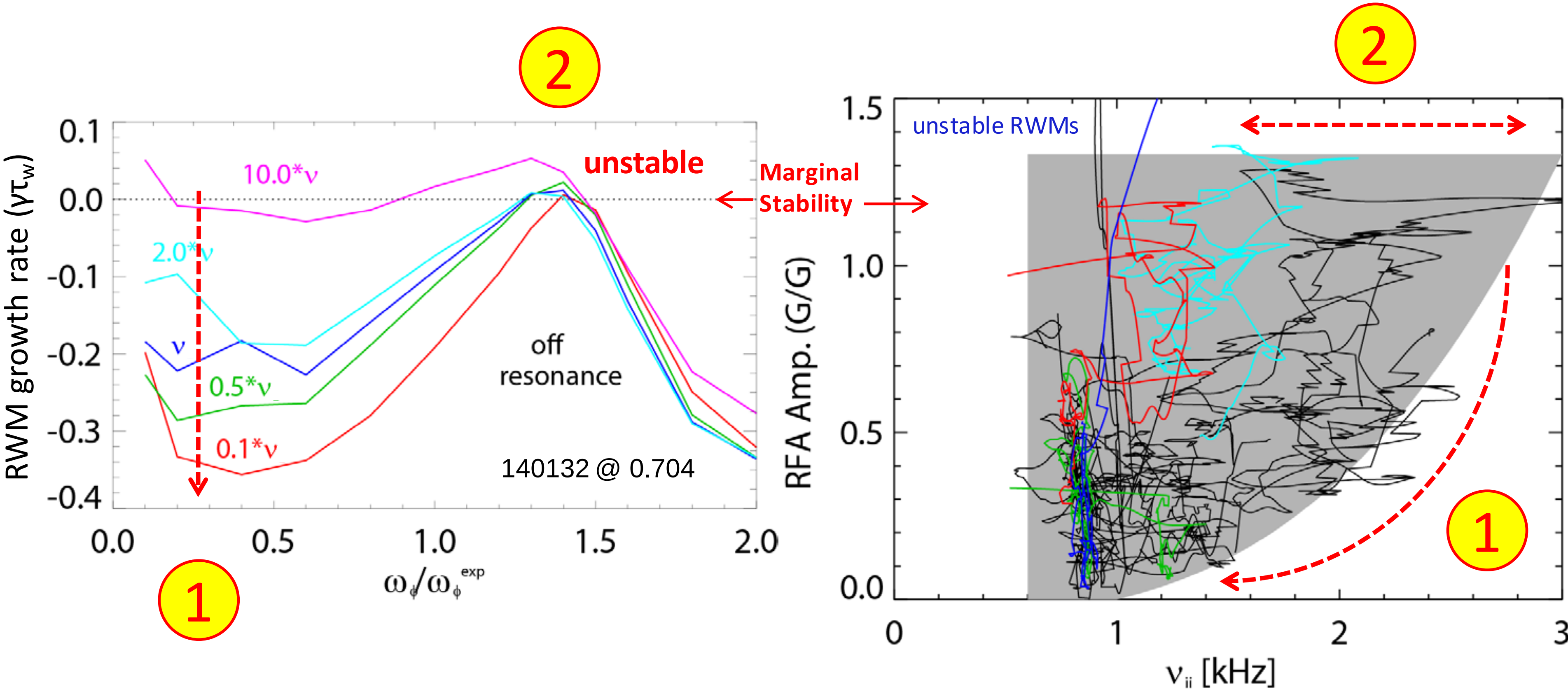


[J. Berkery *et al.*, Phys. Rev. Lett. **104**, 035003 (2010)]

high rotation
bounce resonances should stabilize

Discharge trajectories for 20 plasmas

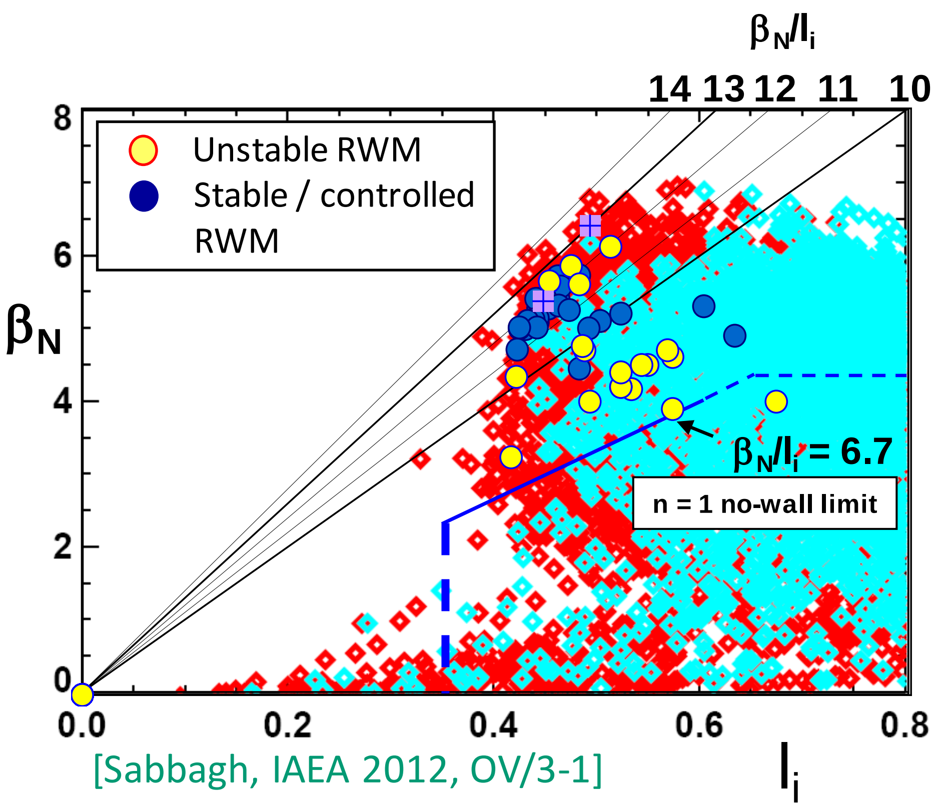
Theory: Reduced ν is stabilizing near kinetic resonances
Experimental Confirmation: Reduced ν -> reduced low RFA



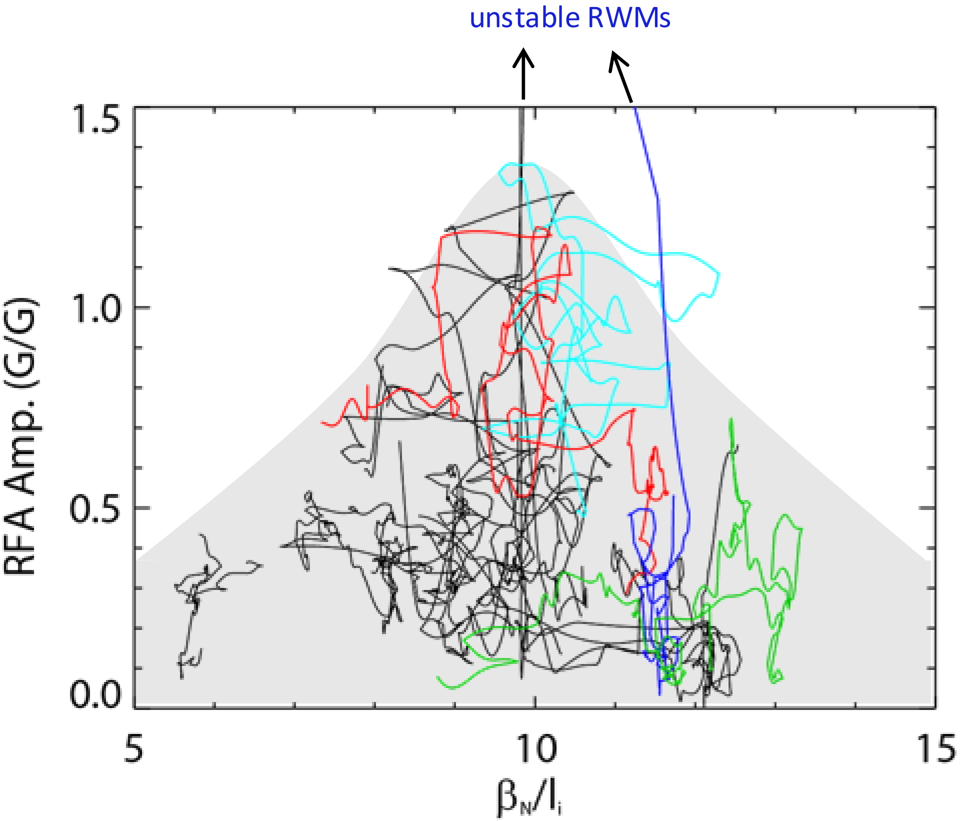
- RFA amplitude reduced at lower ν for low RFA (stable) plasmas, little effect on higher RFA (marginal) plasmas
- Expectations in NSTX-U, tokamaks at lower ν (ITER)
  - Stronger stabilization near ω_ϕ resonances; almost no effect off-resonance

[J. Berkery *et al.*, Phys. Rev. Lett. **106**, 075004 (2011)]

RFA measurements confirm previous NSTX result that the highest β_N/l_i is not the least stable



[Sabbagh, IAEA 2012, OV/3-1]



- Active control experiments reduced disruption probability from 48% to 14%, but mostly in high β_N/l_i [Poster PP8.13, Wednesday afternoon]
- RFA amplitude from 20-shot database also peaks at intermediate β_N/l_i
  - Increased stability at high β_N/l_i due to kinetic stabilization from resonances

Experimental and theoretical RWM stability studies in NSTX reveal dependencies on key plasma parameters

- RFA measurements add additional support to the established theory of RWM stability through kinetic mode-particle rotational resonances.

- Relatively stable plasmas appear to benefit from reduced collisionality, in agreement with expectation from kinetic theory.

- Stability is weakest at intermediate, not the highest, values of β_N/l_i, in agreement with other NSTX results.

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extra slides

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

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Bounce

Collisionality

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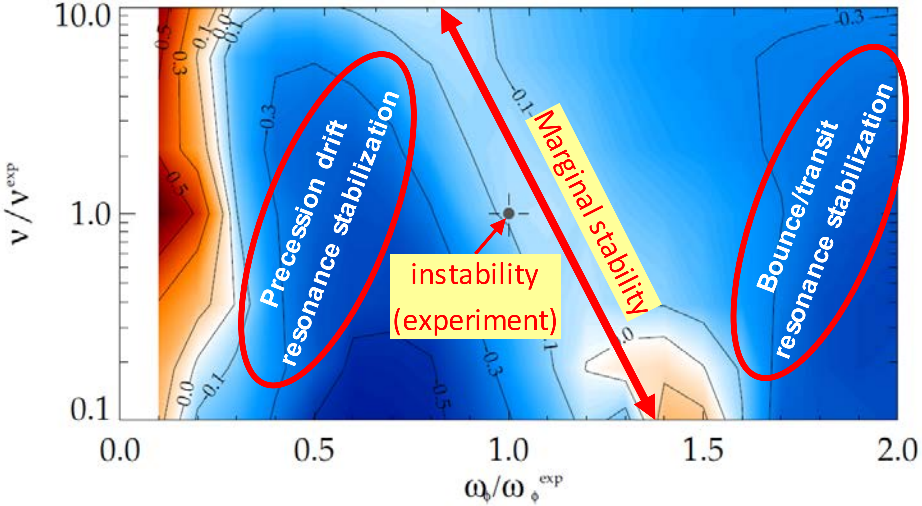
γτ$_w$ contours vs. ν and ω$_\phi$



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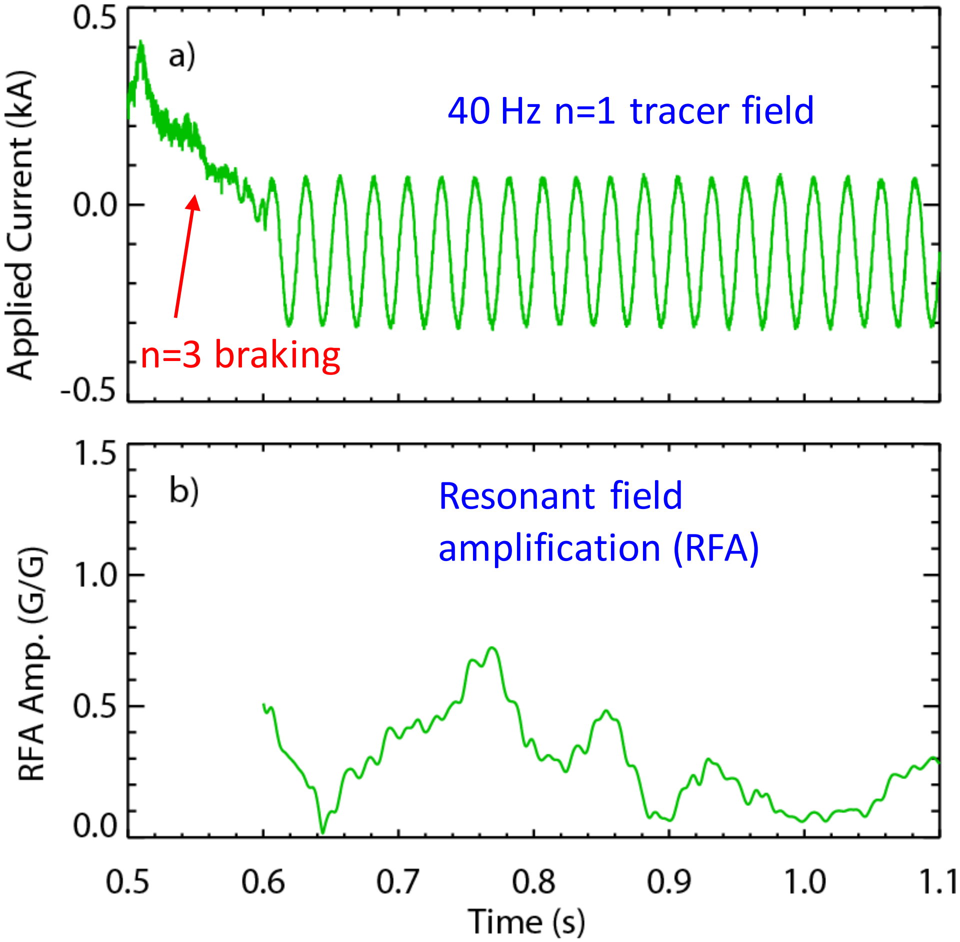

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