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Wall Stabilization in High Beta Spherical Torus Plasmas

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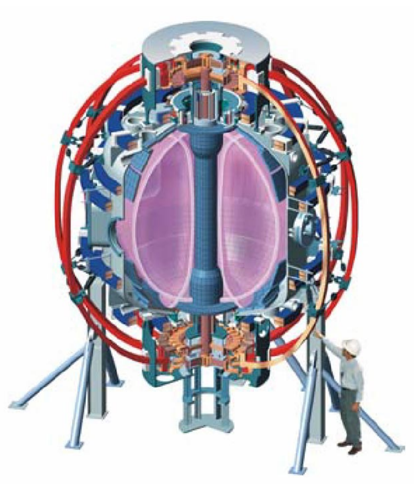

9th Workshop on MHD Stability Control
November 21 – 23, 2004
Princeton, NJ

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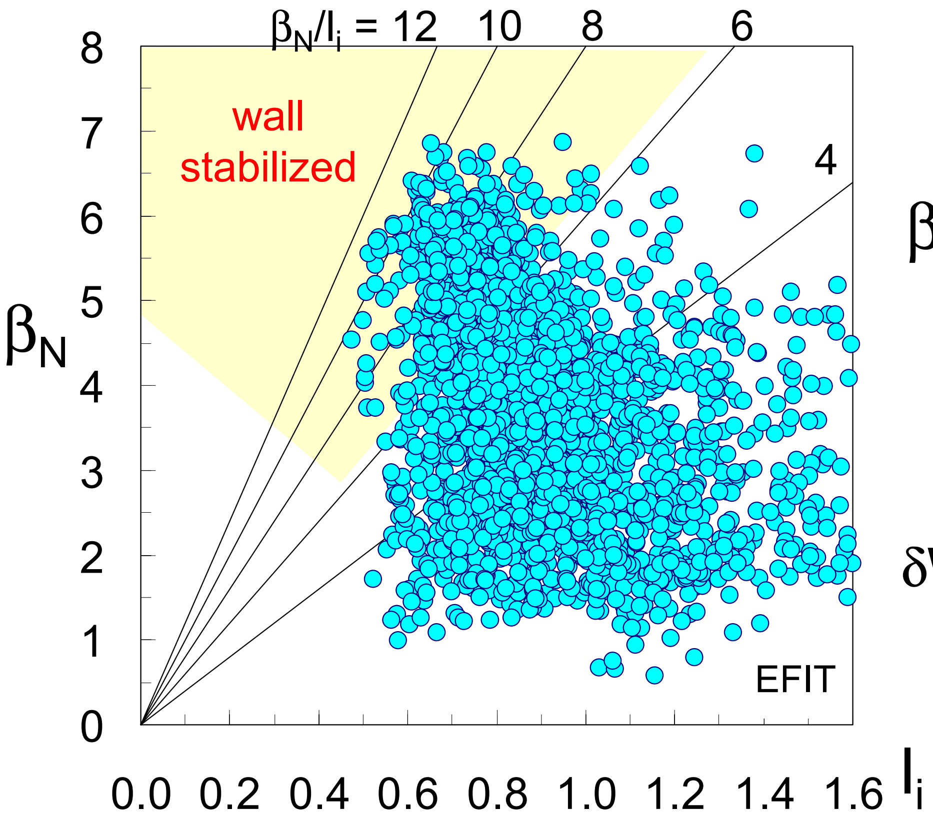
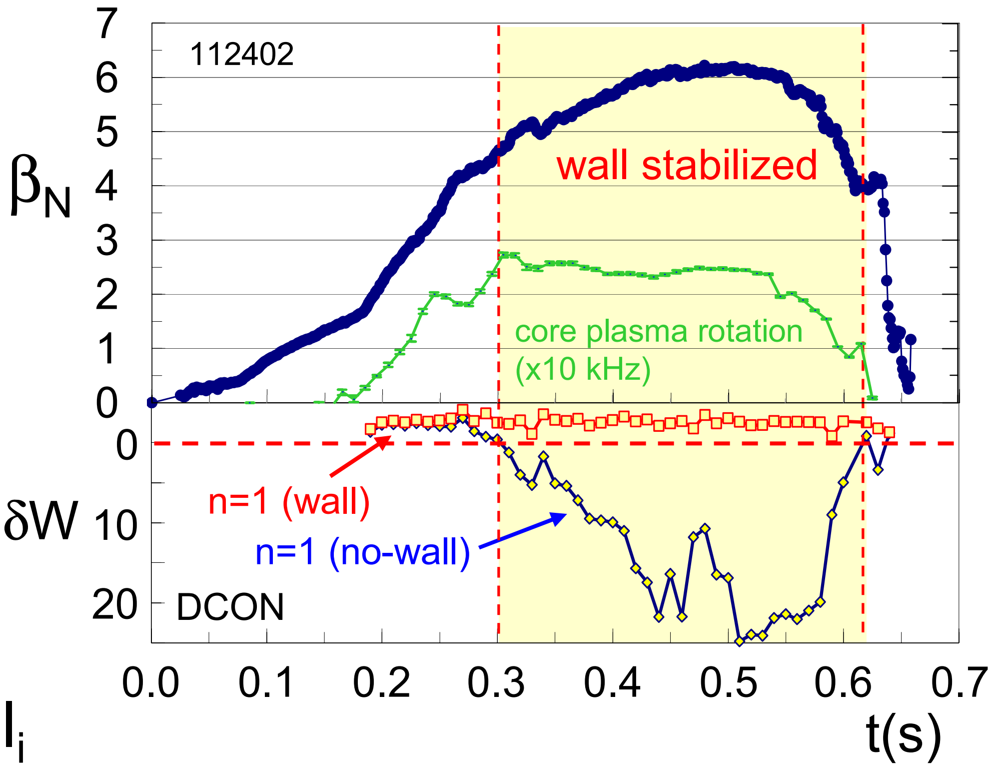
Wall stabilization physics understanding is key to sustained plasma operation at maximum β

- High β_t = 39%, β_N = 6.8 reached



- Operation with $\beta_N/\beta_N^{no\text{-}wall}$ > 1.3 at highest β_N for pulse >> τ_{wall}



- Global MHD modes can lead to rotation damping, β collapse
- Physics of sustained stabilization is applicable to ITER

NSTX

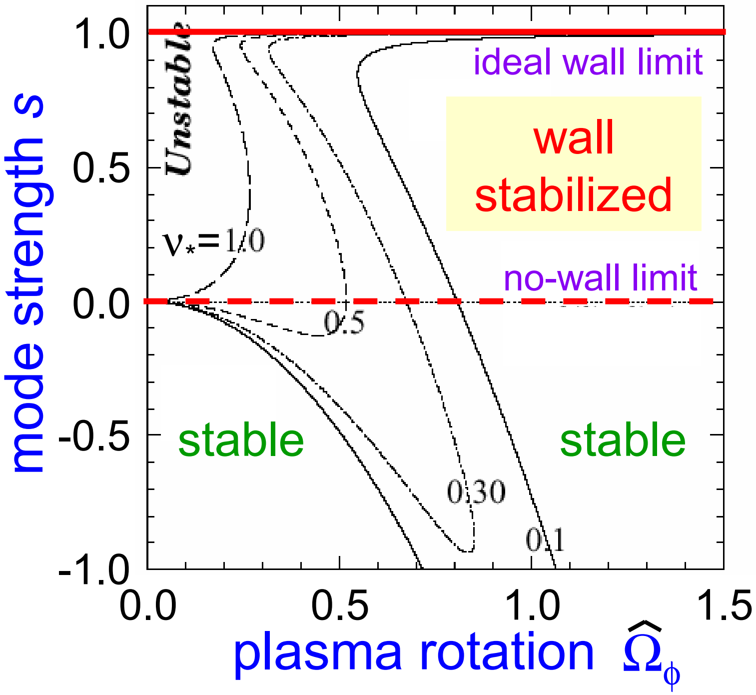
Latest experiments address basic Resistive Wall Mode physics

- Motivation
  - ☐ NSTX RWM first observed / published in 2001
  - ☐ Use new diagnostic and control capabilities to examine outstanding, basic RWM physics questions
- Outline
  - ☐ RWM dynamics and toroidal mode spectrum
  - ☐ Critical rotation frequency, Ω_{crit}
  - ☐ Toroidal rotation damping physics
  - ☐ Resonant field amplification (RFA)

Theory provides framework for wall stabilization study

- Theories
  - Ideal MHD stability – DCON (Glasser)
  - Drift kinetic theory (Bondeson – Chu)
  - RWM dynamics (Fitzpatrick – Aydemir)

Fitzpatrick-Aydemir (F-A) stability curves



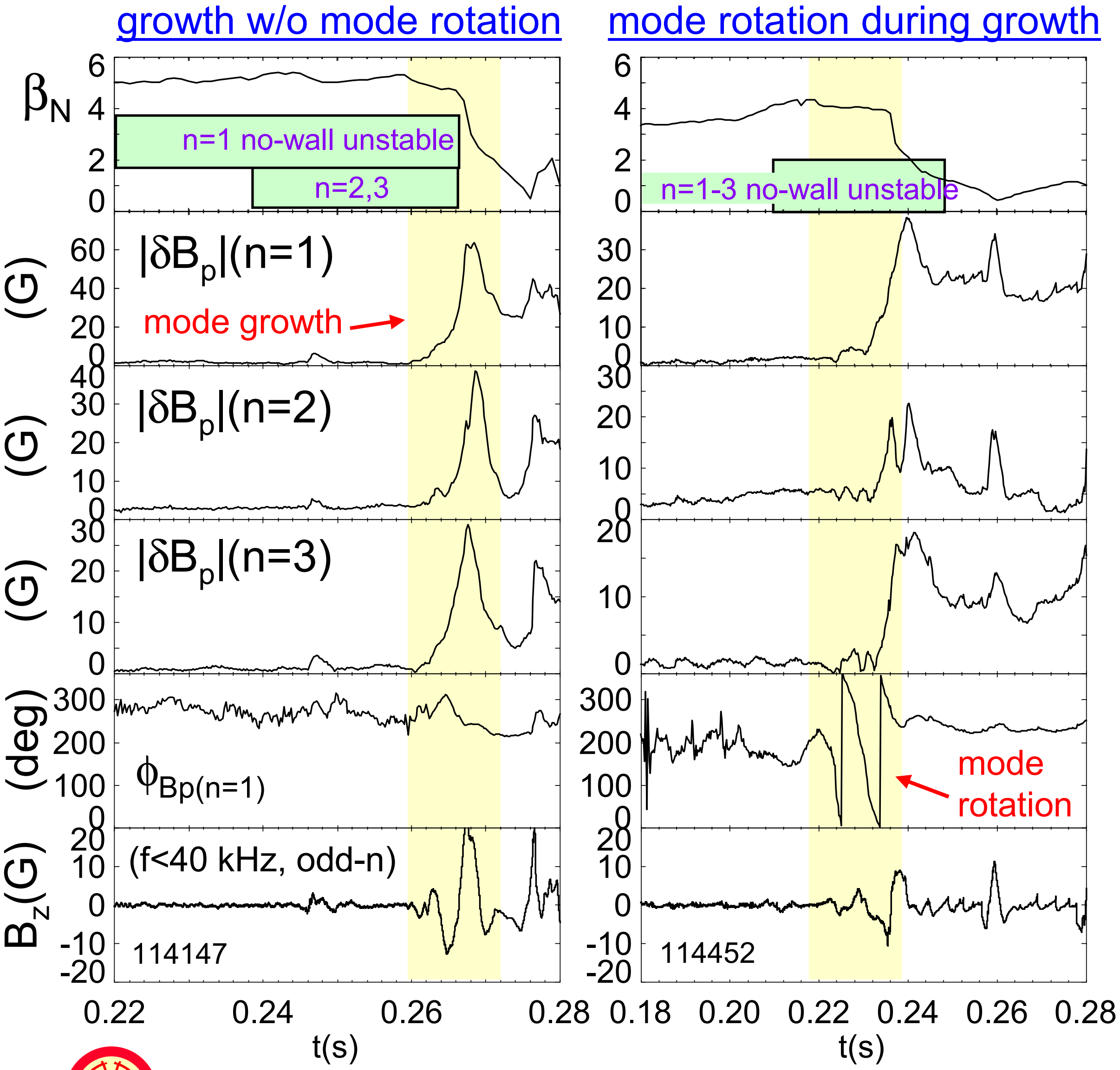
$$\left[\left(\hat{\gamma}-i\hat{\Omega}_{\phi}\right)^{2}+\nu_{*}\left(\hat{\gamma}-i\hat{\Omega}_{\phi}\right)+(1-s)(1-md)\right]\left(S_{*}\hat{\gamma}+(1+md)\right)=\left(1-(md)^{2}\right)$$

plasma inertia — dissipation — mode strength — wall response — wall/edge coupling

$S_* \sim 1/\tau_{wall}$

Phys. Plasmas **9** (2002) 3459

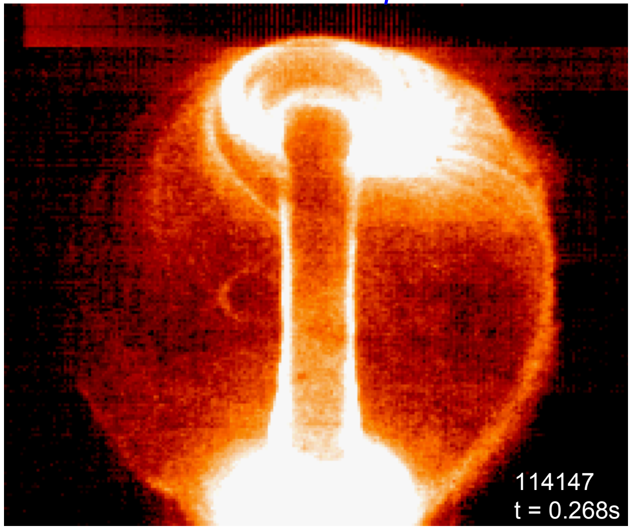
Unstable RWM dynamics follow theory



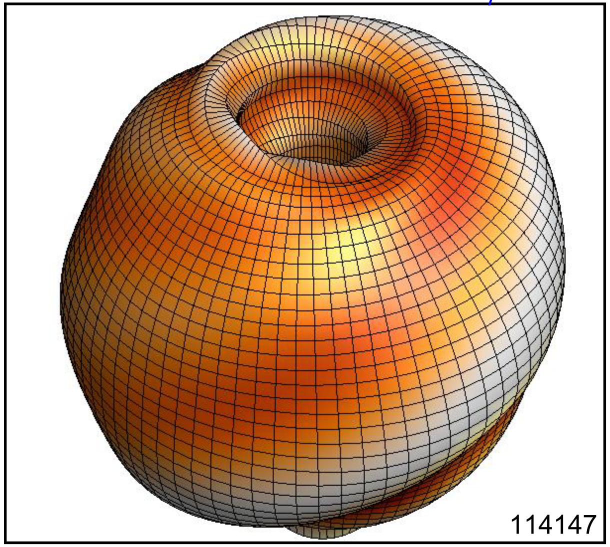
- Unstable n=1-3 RWM observed
  - ideal no-wall unstable at high β_N
  - n > 1 theoretically less stable at low A
- F-A theory / experiment show
  - mode rotation can occur during growth
  - growth rate, rotation frequency ~ $1/\tau_{wall}$
    - << edge Ω_ϕ > 1 kHz
  - RWM phase velocity follows plasma flow
  - n=1 phase velocity not constant due to error field
- Low frequency tearing modes absent

Camera shows scale/asymmetry of theoretical RWM

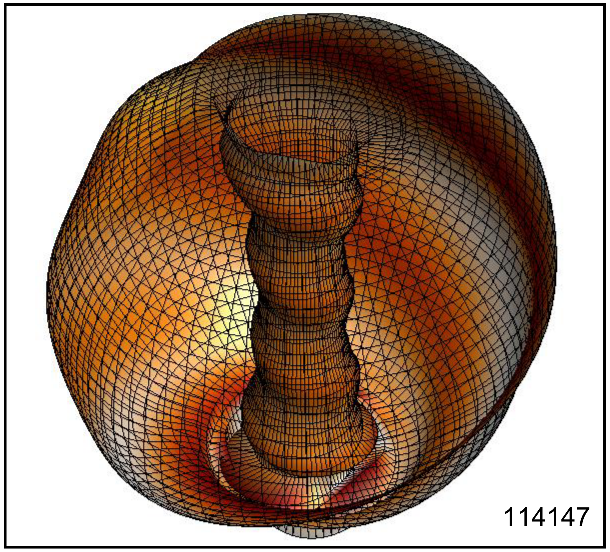
RWM with ΔB_p = 92 G



Theoretical ΔB_ψ (x10) with *n*=1-3 (DCON)

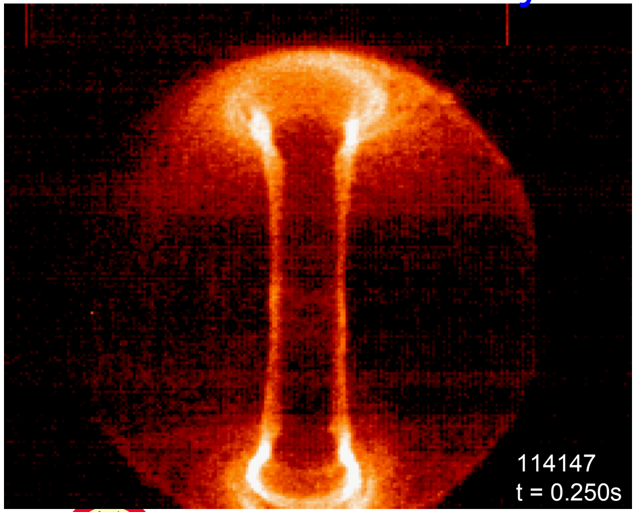


(exterior view)



(interior view)

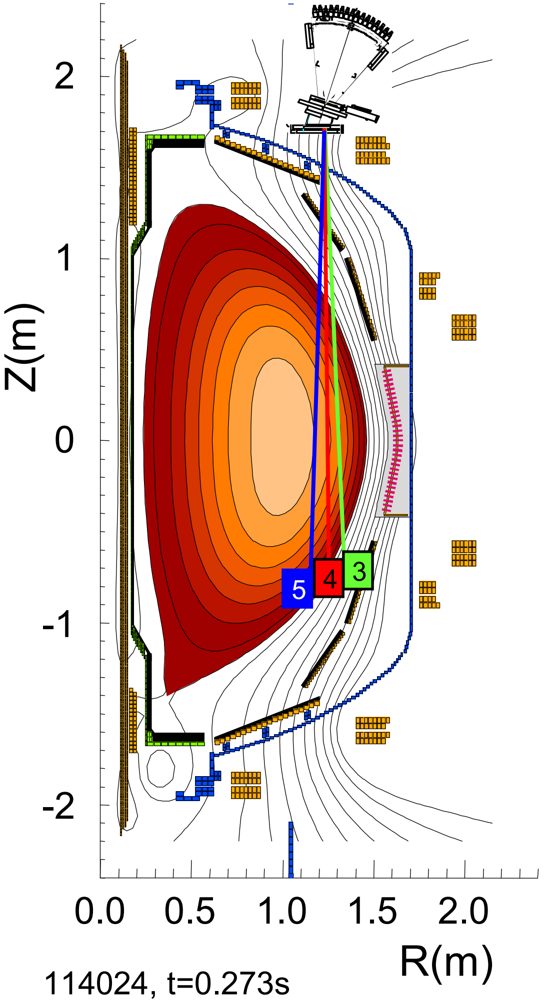
Before RWM activity



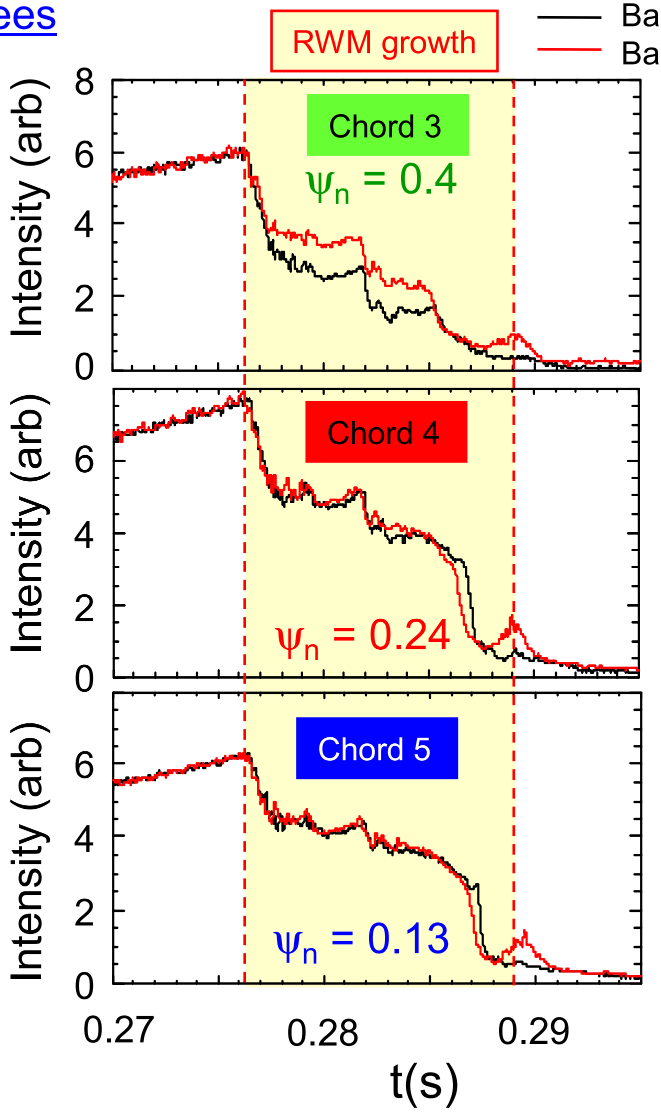
- Visible light emission is toroidally asymmetric during RWM
- DCON theory computation displays mode
  - uses experimental equilibrium reconstruction
  - includes *n* = 1 – 3 mode spectrum
  - uses relative amplitude / phase of *n* spectrum measured by RWM sensors

Soft X-ray emission shows toroidal asymmetry during RWM

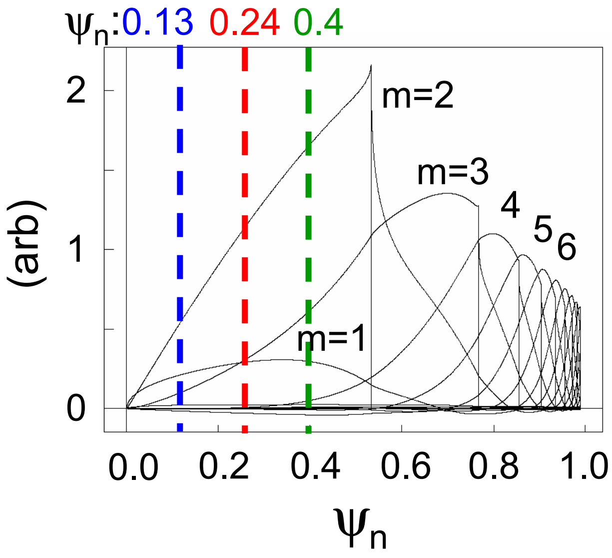
USXR separated by 90 degrees



114024, t=0.273s
$\beta_N = 5$



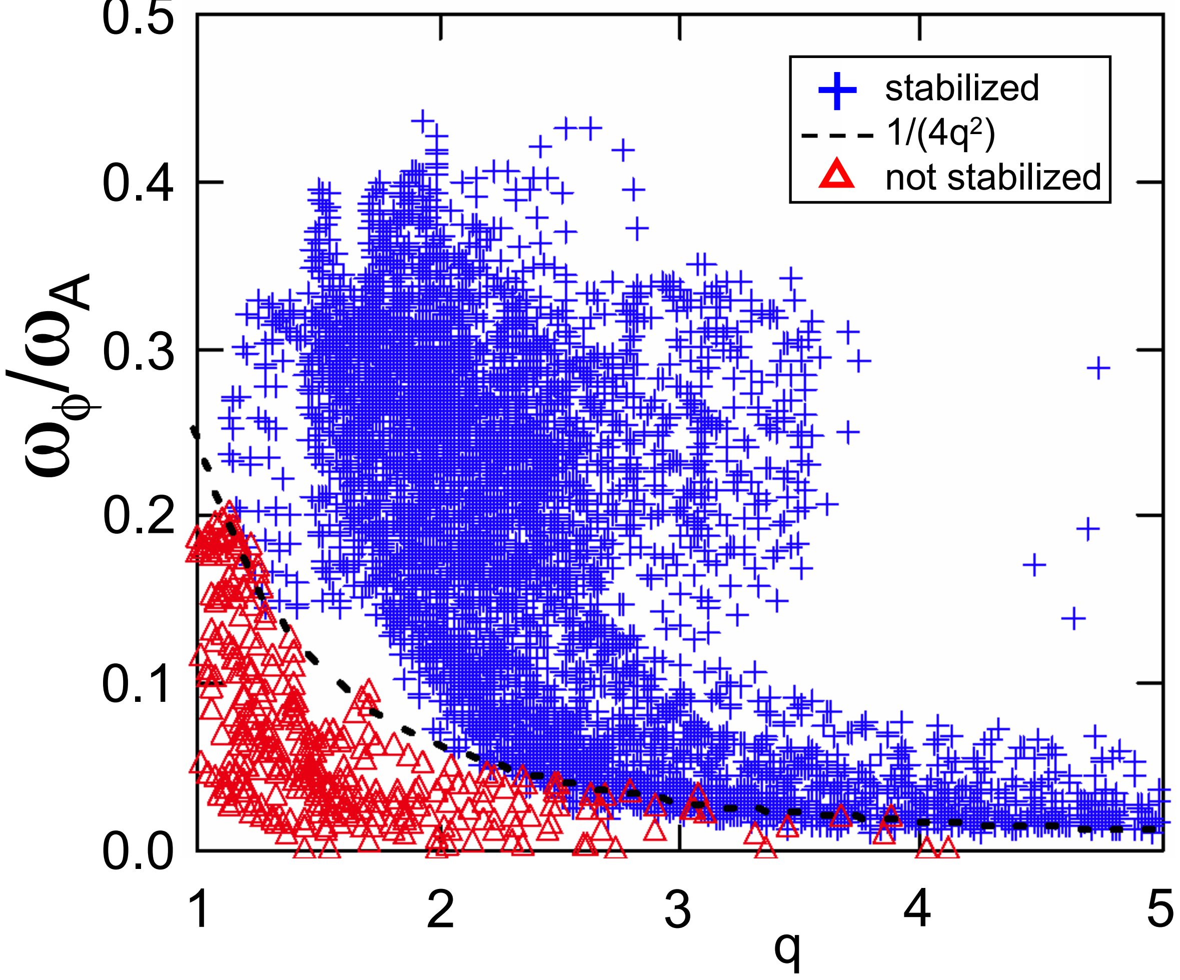
DCON *n* = 1 mode decomposition



- Experiment / theory show RWM not edge localized
  - Supported by measured ΔT_e

Experimental Ω_{crit} follows Bondeson-Chu theory

Phys. Plasmas **8** (1996) 3013

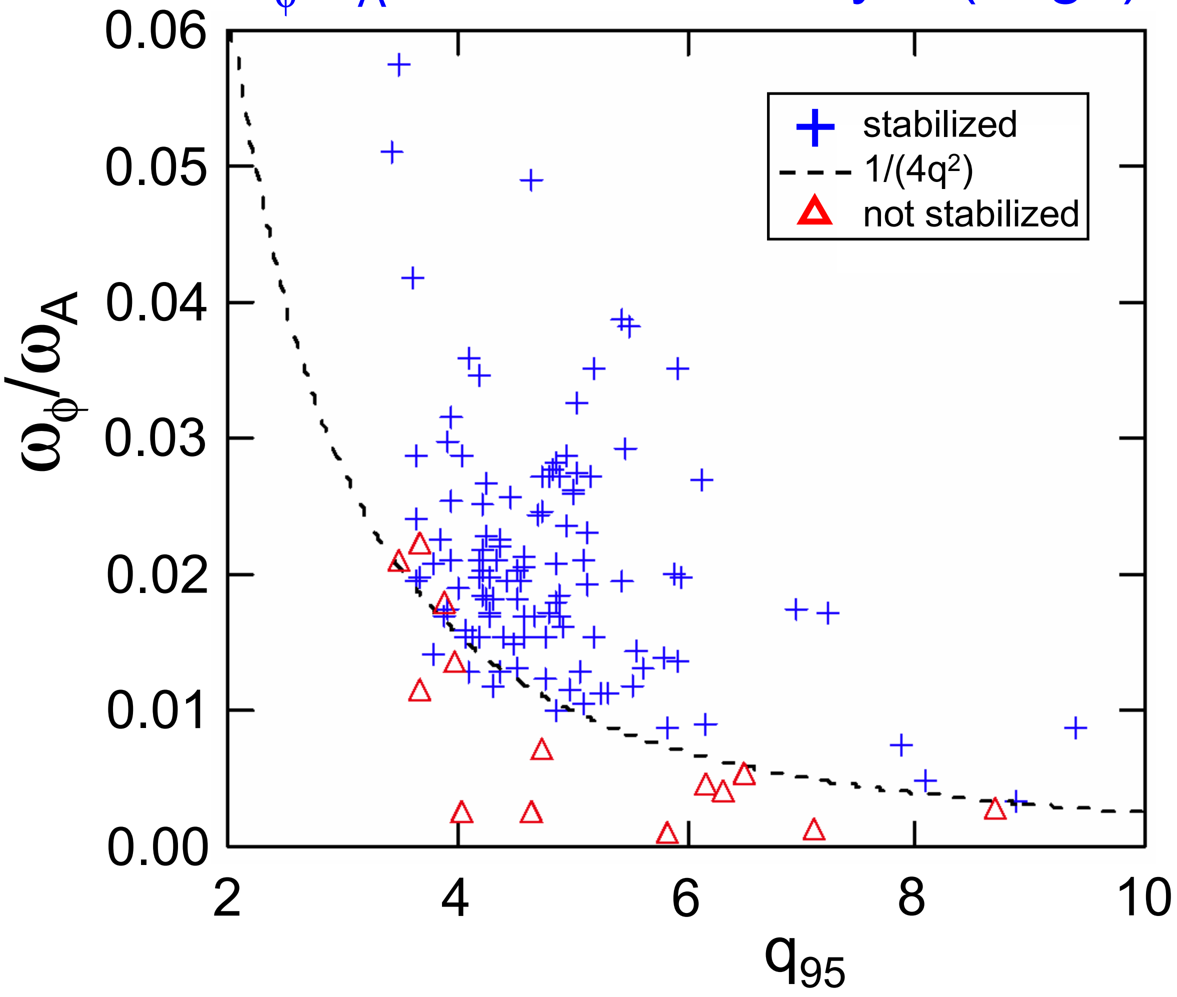


$\omega_\phi/\omega_A(q,t)$ profiles

- Experimental Ω_{crit}
  - stabilized profiles: $\beta > \beta_N^{no\text{-}wall}$ (DCON)
  - profiles not stabilized cannot maintain $\beta > \beta_N^{no\text{-}wall}$
  - regions separated by $\omega_\phi/\omega_A = 1/(4q^2)$
- Drift Kinetic Theory
  - Trapped particle effects significantly weaken stabilizing ion Landau damping
  - Toroidal inertia enhancement more important
    - Alfven wave dissipation yields $\Omega_{crit} = \omega_A/(4q^2)$

Ω_{crit} follows F-A theory with neoclassical viscosity

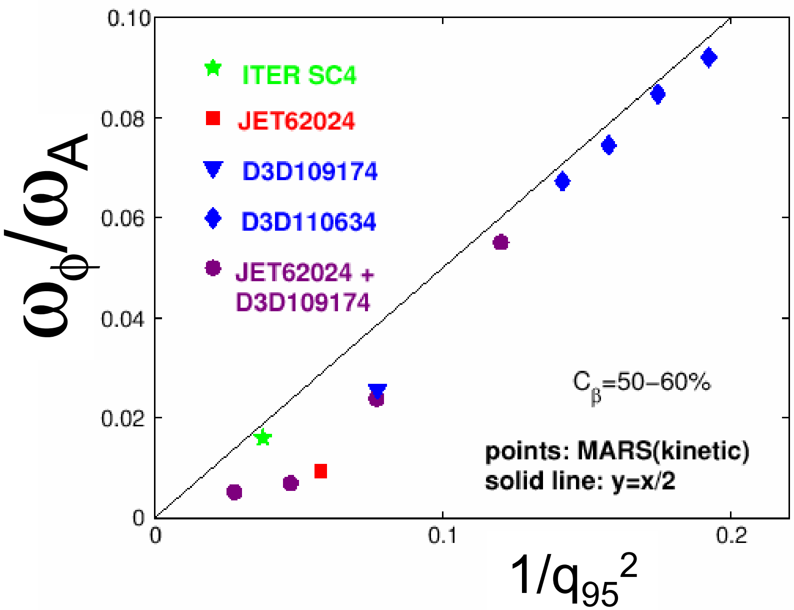
ω_ϕ/ω_A in F-A inertial layer (edge)

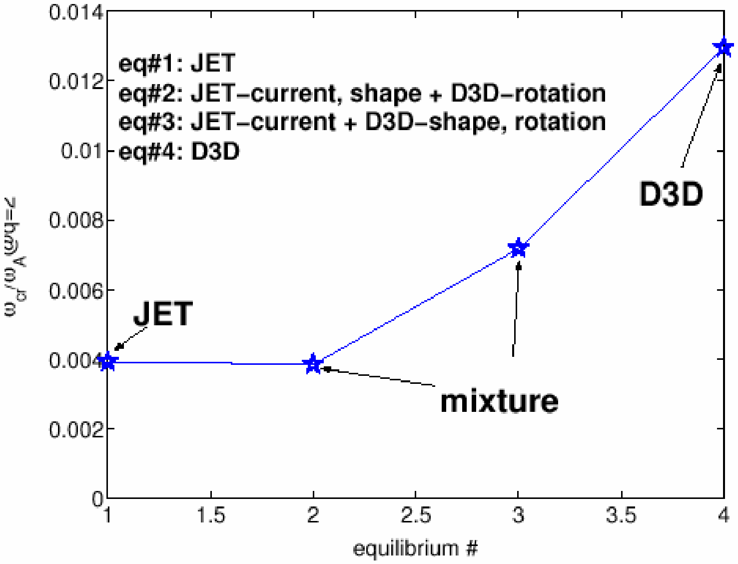


- Experimental Ω_{crit}
  - ❑ stabilized points: $\beta > \beta_N^{no\text{-}wall}$ (DCON)
  - ❑ points not stabilized cannot maintain $\beta > \beta_N^{no\text{-}wall}$
  - ❑ regions separated by $\omega_\phi/\omega_A = 1/(4q^2)$
- F-A Theory
  - ❑ Standard F-A theory has $\Omega_{crit} \sim 1/q$
  - ❑ neoclassical viscosity includes toroidal inertia enhancement (K. Shaing, PoP 2004)
    - yields $\Omega_{crit} \sim 1/q^2$

NSTX

MARS-F kinetic damping model computes $\Omega_{crit} \sim 1/q^2$

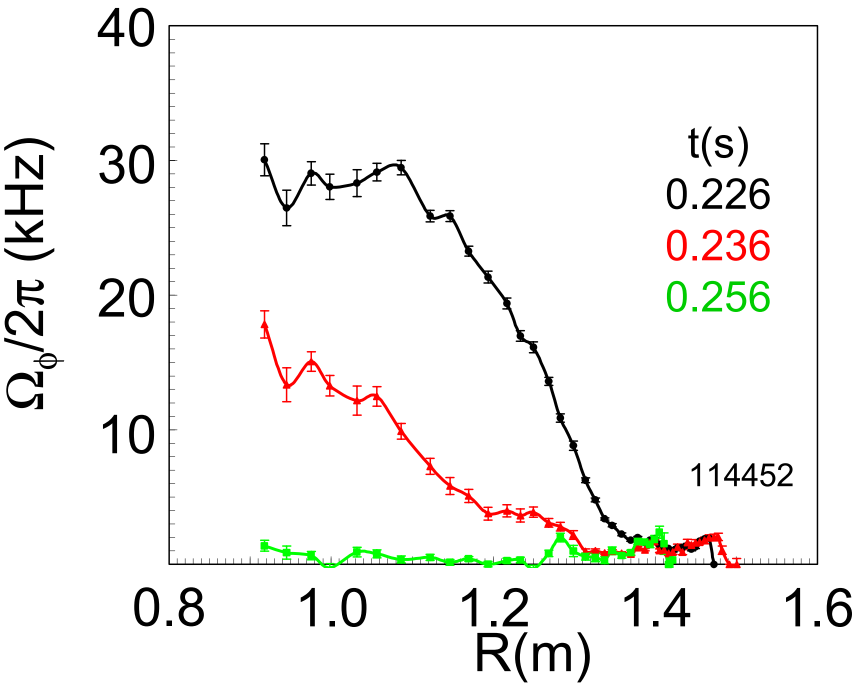


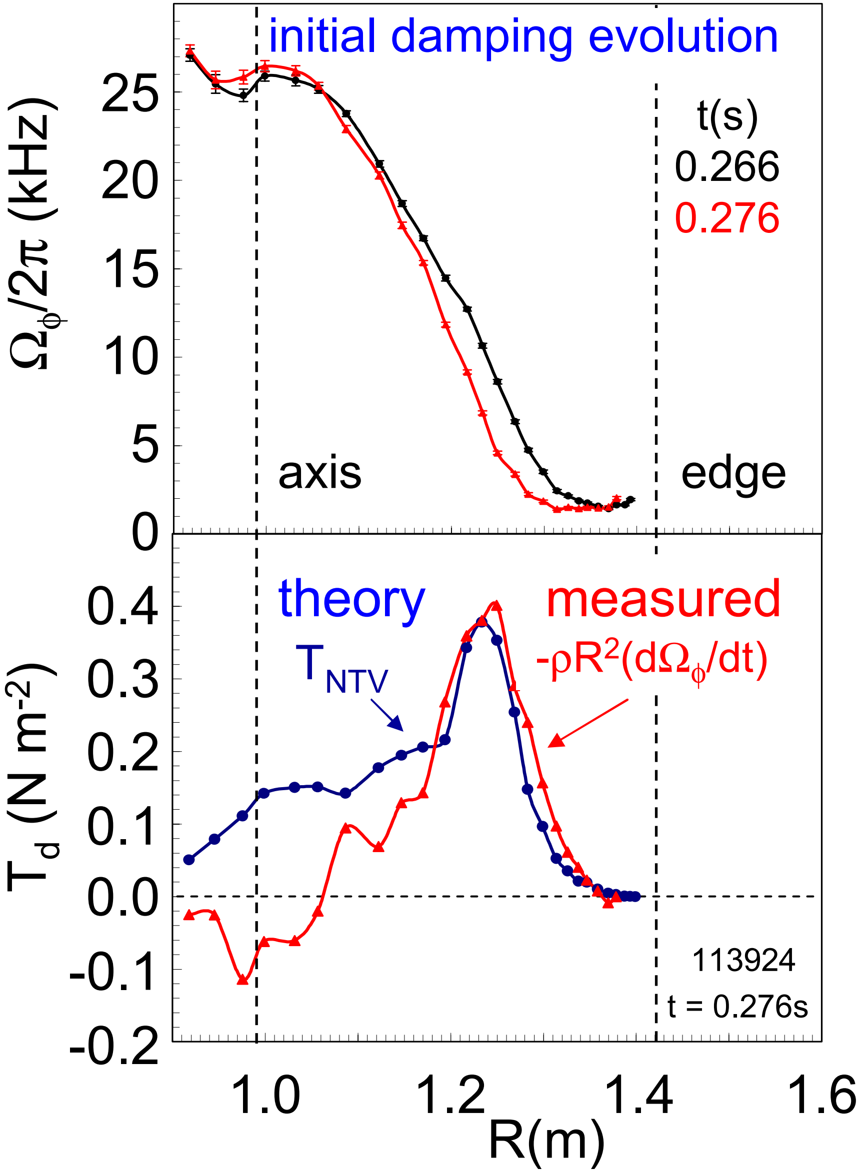


- Points are MARS-F predictions, not experimental data
- Theory (Bondeson&Chu, PoP96) predicts $\omega_{\rm rot}^{\rm cr} \propto 1/q^2$
- Rotational stabilization of RWM seems in favor of low-aspect-ratio (high-q)
- Difference between JET and DIII-D in equilibria profiles and plasma-wall shapes also change critical rotation

Plasma rotation damping described by NTV theory

Toroidal rotation profile evolution



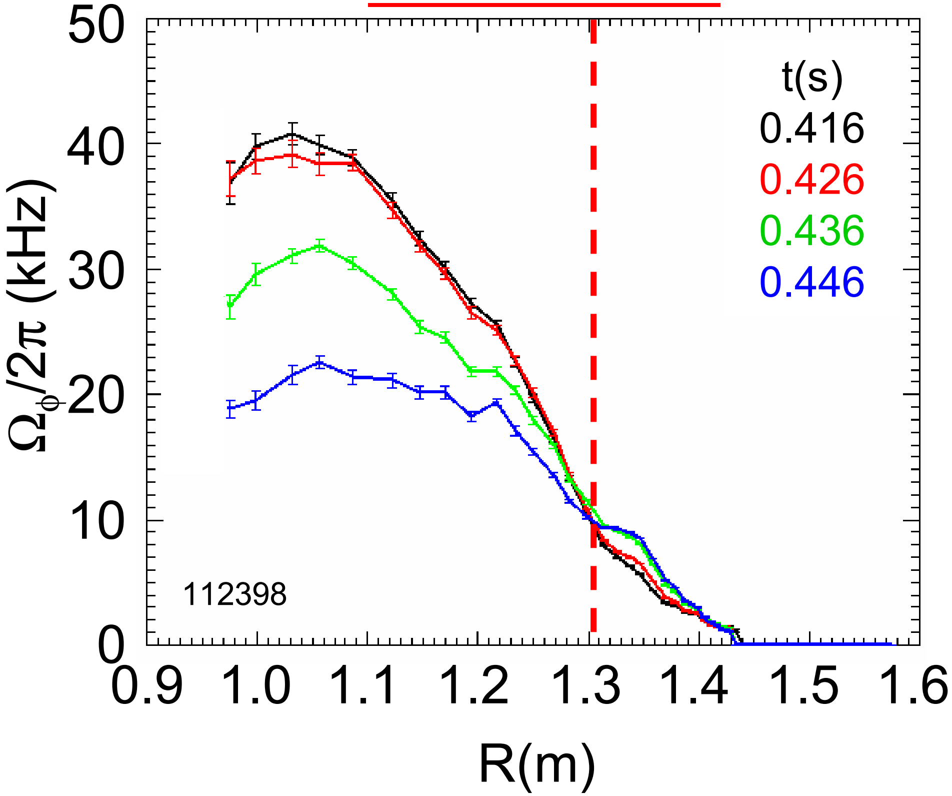


- Neoclassical toroidal viscosity (NTV) ~ $\delta B^2 * T_i^{0.5}$
- Rapid, global damping observed during RWM
  - Edge rotation ~ 2kHz maintained
  - Low frequency tearing modes absent

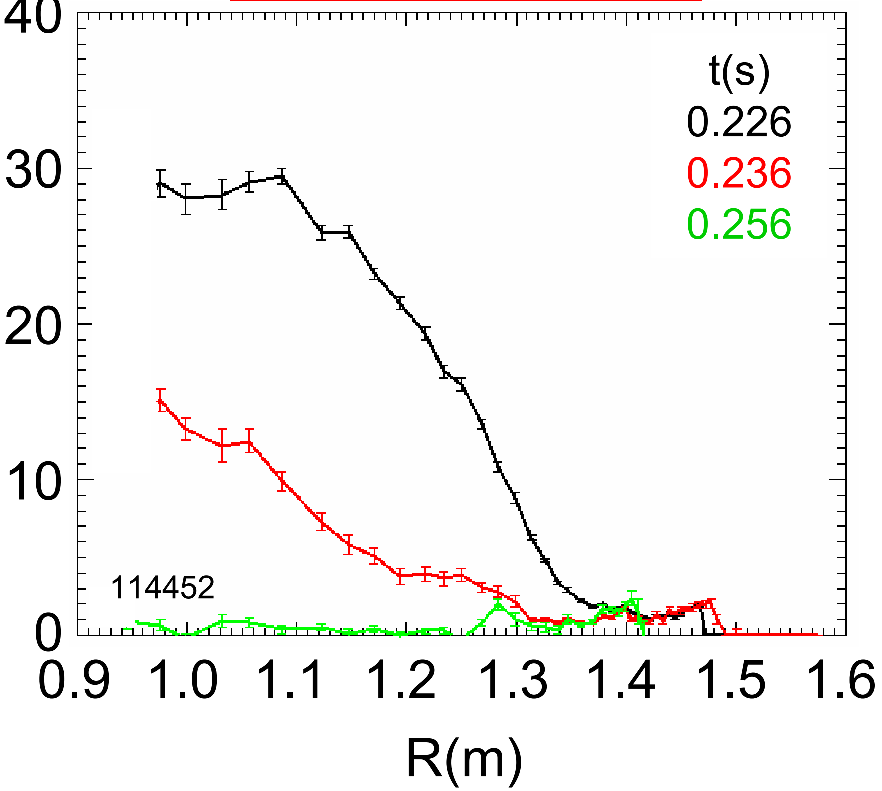
NSTX

Rotation Damping Evolution Depends on Mode Type

Core 1/1 mode



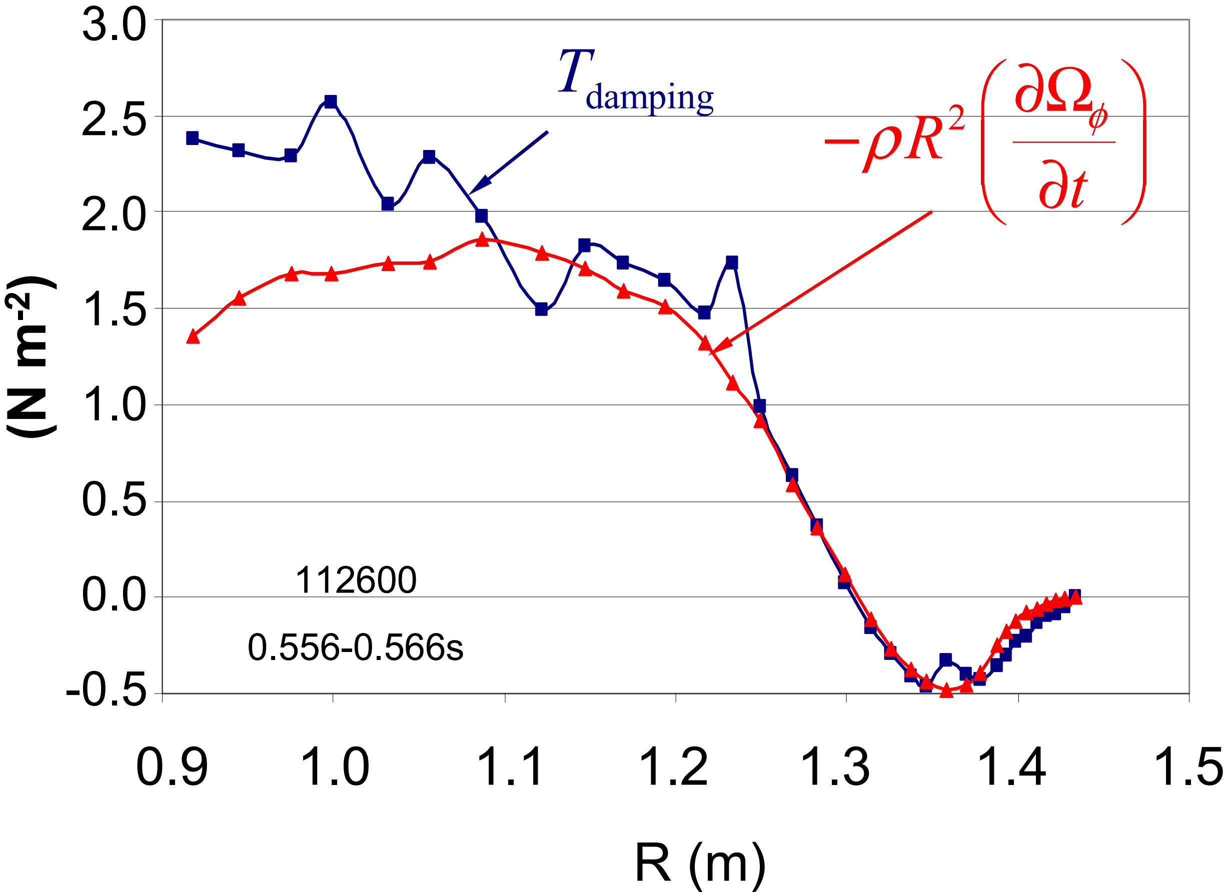
Resistive wall mode

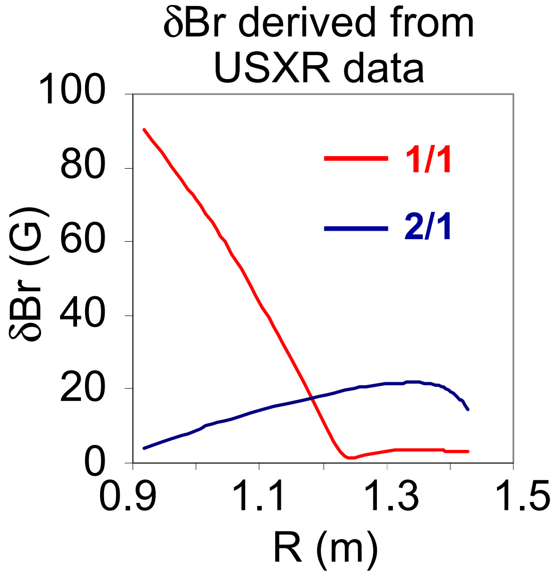


- Core rotation damping with 1/1
  - leads to “rigid rotor” plasma core
  - damping rate ~ $1/\tau_E$
- Momentum transfer across rational surface near R = 1.3m
- Rapid, global rotation damping by RWM
  - damping rate ~ $1/\tau_{wall}$
- Edge rotation maintained

NSTX

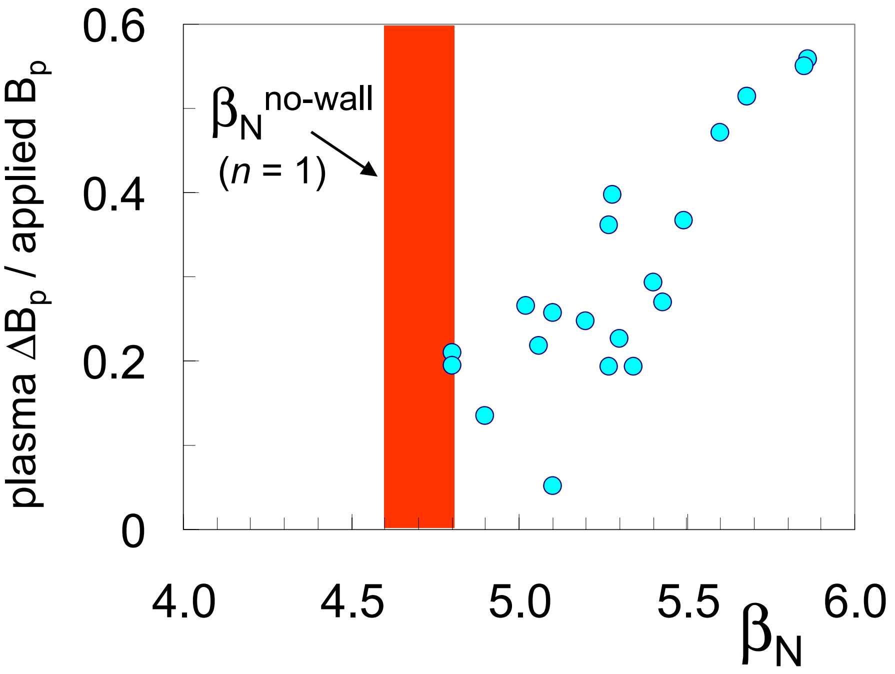
NTV Torque Contributes to Measured Core Rotation Damping During Large 1/1 Mode



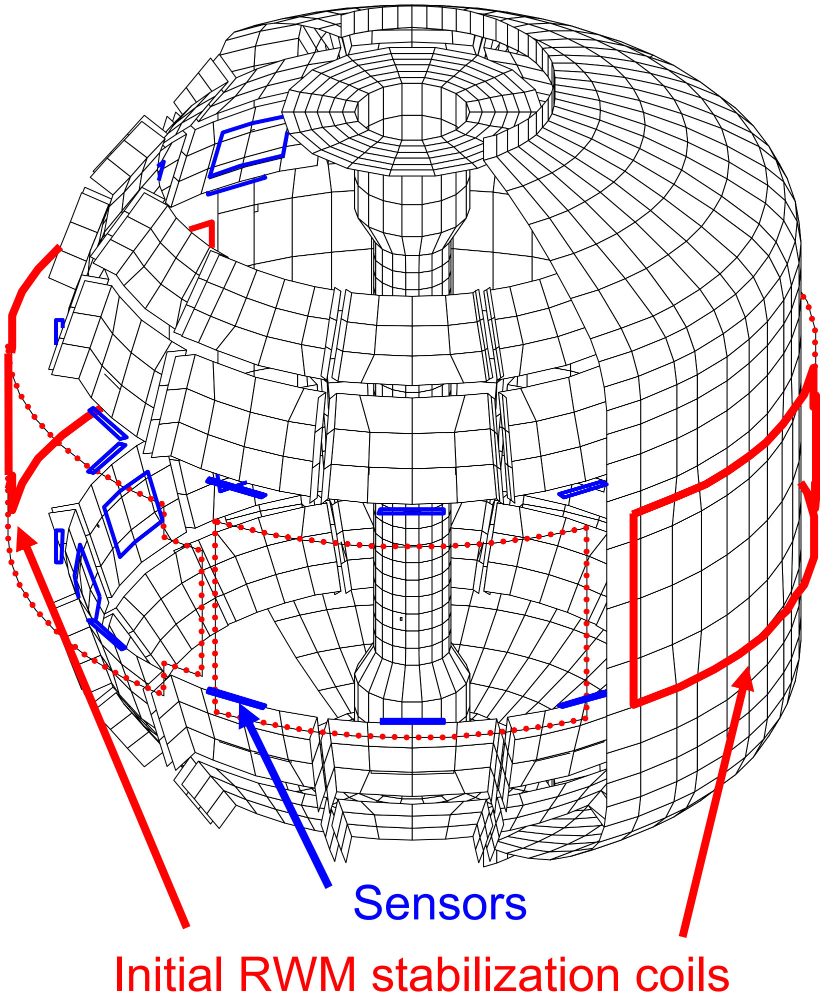


- NTV torque applied to plasma core
  - ❑ Rotating mode Doppler shifted relative to q=1 surface
- Resonant EM torque applied on 2/1 island
- Fluid viscosity included

Resonant Field Amplification increases at high β_N

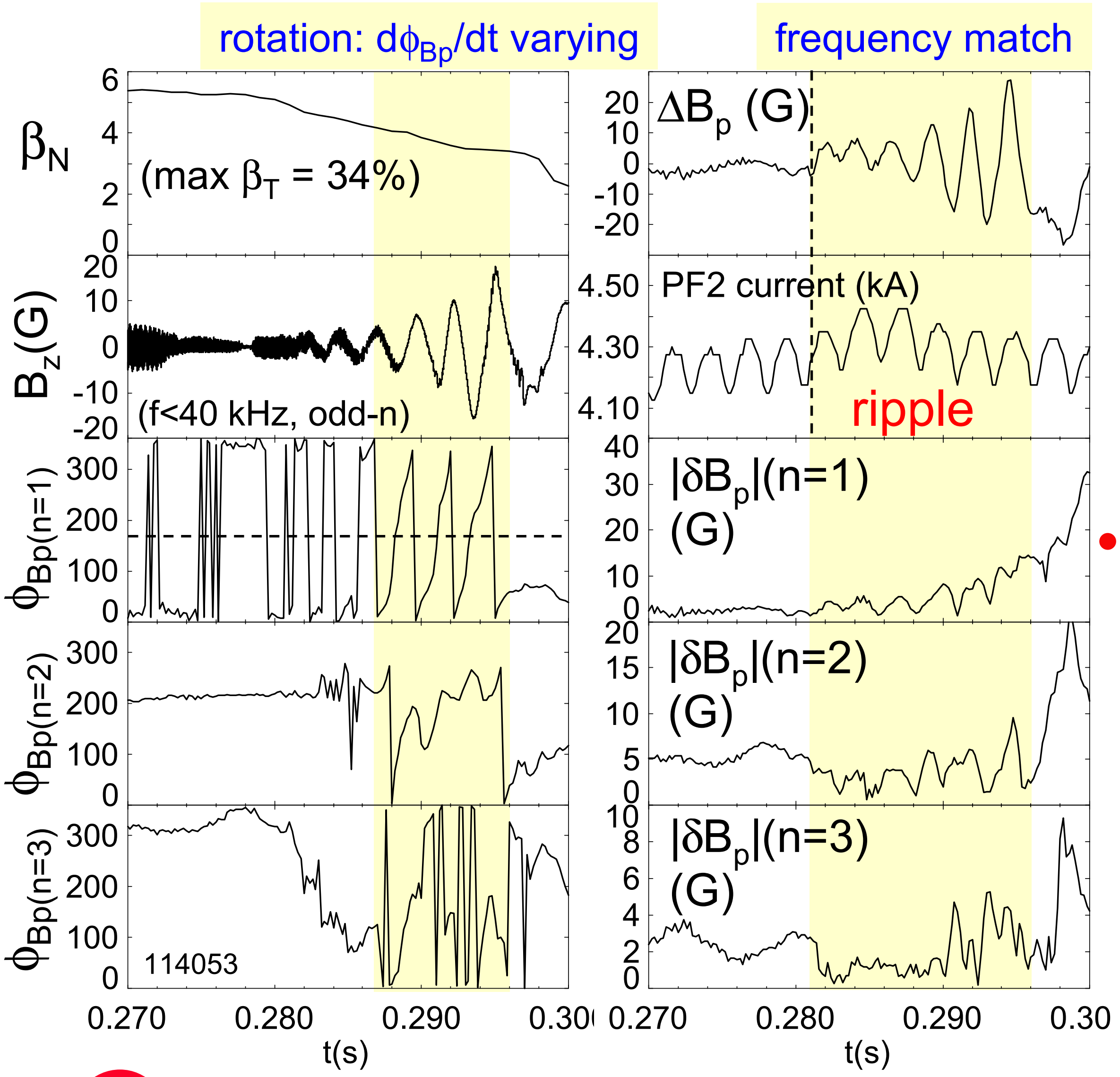


- Plasma response to applied field from initial RWM stabilization coil pair
  - AC and pulsed n = 1 field
- RFA increase consistent with DIII-D
- Stable RWM damping rate of 300s^{-1} measured



Completed coils will be used to suppress RFA, stabilize RWM, sustain high β

Evidence for resonance with AC error field observed



F-A modified resonance

$$\left(S_* \nu_* /(1+md)+1\right)\hat{\omega}_{AC}^2 + \left(s(1-md)+\Omega_\phi^2\right) = 0$$

"static error field" response

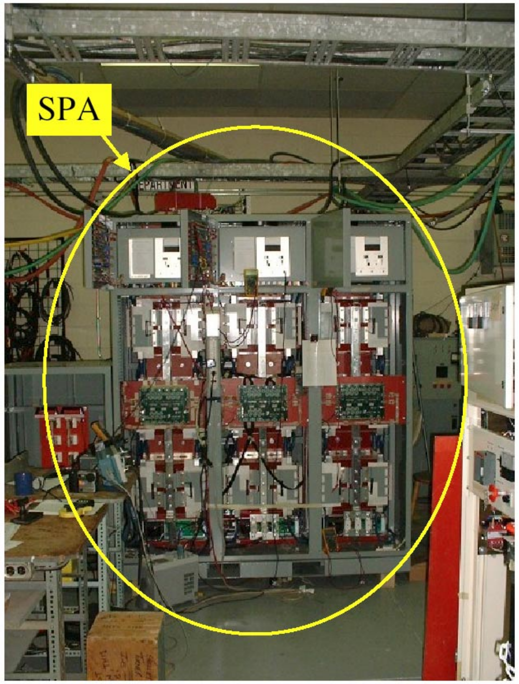
New condition

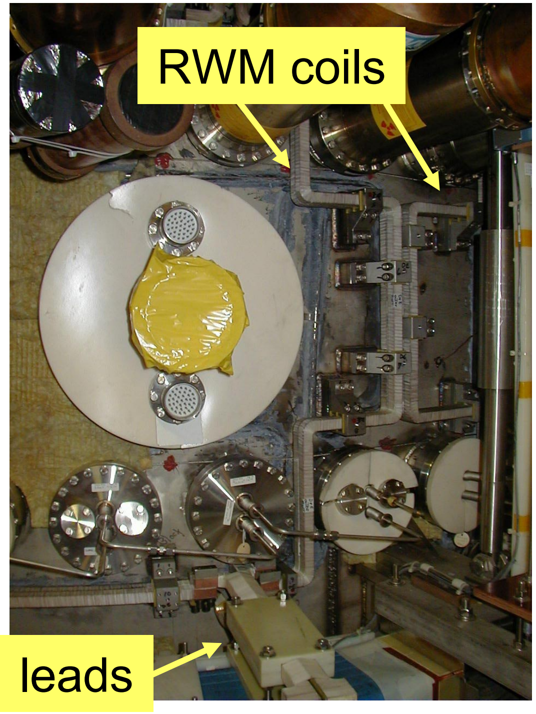
$$\hat{\omega}_{AC}^2 - \nu_*(1+md)/2S_* = 0$$

- Theory / experiment show
  - AC frequency match may be responsible for mode trigger
  - Mode rotates *counter* to plasma rotation
  - n=1 phase velocity not constant due to error field
  - Estimate of $\omega_{AC}/2\pi$ ~ 350 Hz consistent with PF coil ripple
  - Initial results – quantitative comparison continues

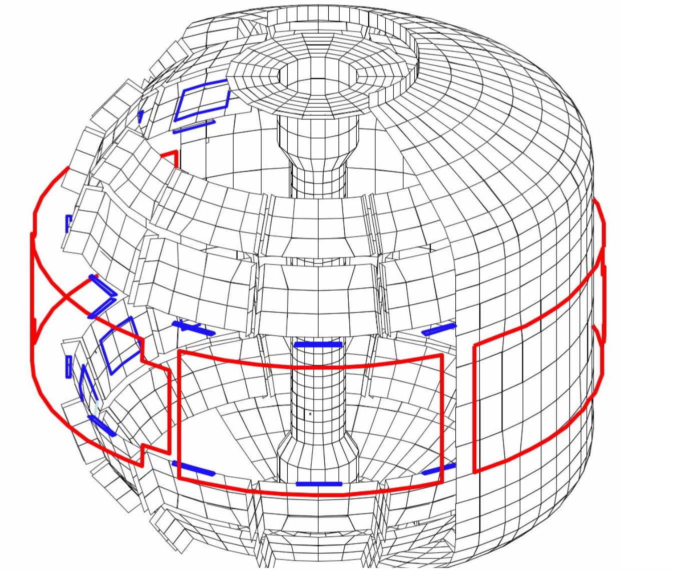
RWM stabilization system being installed for 2005 run

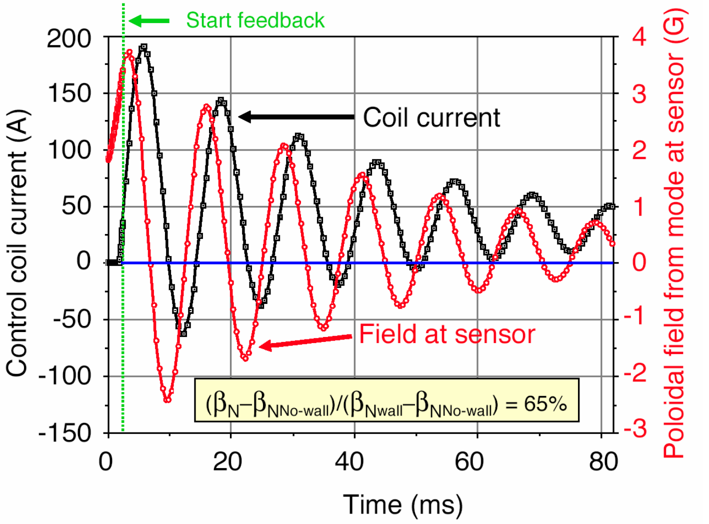
- RWM sensor array used in 2004 experiments
- 6 B_r coils now installed on NSTX
  - Pre-programmed capability in 2005 for RFA suppression / MHD spectroscopy experiments
- 3-channel switching power amplifier (SPA) on-site
- Real-time mode detection and control algorithm development in 2005 for feedback experiments





Physics design (VALEN code)





Passive stabilization research at low aspect ratio illuminates key physics for general high β operation

- Plasma β_t = 39%, β_N = 6.8, β_N/l_i = 11 reached; $\beta_N/\beta_N^{no\text{-}wall} > 1.3$
- Unstable n = 1-3 RWMs measured (n > 1 prominent at low A)
- Critical rotation frequency ~ ω_A/q^2 strongly influenced by toroidal inertia enhancement (prominent at low A)
- Measured rapid, global plasma rotation damping associated with neoclassical toroidal viscosity
- Resonant field amplification of stable RWM increases with increasing β_N (similar to higher A)
- Evidence for AC error field resonance observed

Completed RWM active stabilization coil to be used for research in 2005