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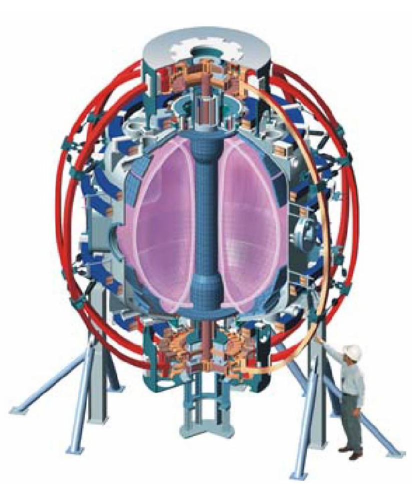
Wall Stabilized Operation in High Beta NSTX Plasmas

S. A. Sabbagh[1], A.C. Sontag[1], R. E. Bell[2], J. Bialek[1], D.A. Gates[2],A. H. Glasser[3], B.P. LeBlanc[2], J.E. Menard[2], W. Zhu[1], M.G. Bell[2], T.M. Biewer[2], A. Bondeson[4], C.E. Bush[5], J.D. Callen[6], M.S. Chu[7], C. Hegna[6], S. M. Kaye[2], L. L. Lao[7], Y. Liu[4], R. Maingi[5], D. Mueller[2], K.C. Shaing[6], D. Stutman[8], K. Tritz[8], C. Zhang[9]

[1]Department of Applied Physics, Columbia University, New York, NY, USA
[2]Plasma Physics Laboratory, Princeton University, Princeton, NJ, USA
[3]Los Alamos National Laboratory, Los Alamos, NM, USA
[4]Institute for Electromagnetic Field Theory, Chalmers U., Goteborg, Sweden
[5]Oak Ridge National Laboratory, Oak Ridge, TN, USA
[6]University of Wisconsin, Madison, WI, USA
[7]General Atomics, San Diego, CA, USA
[8]Johns Hopkins University, Baltimore, MD, USA
[9]Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China



20th IAEA Fusion Energy Conference
1-6 November 2004
Vilamoura, Portugal

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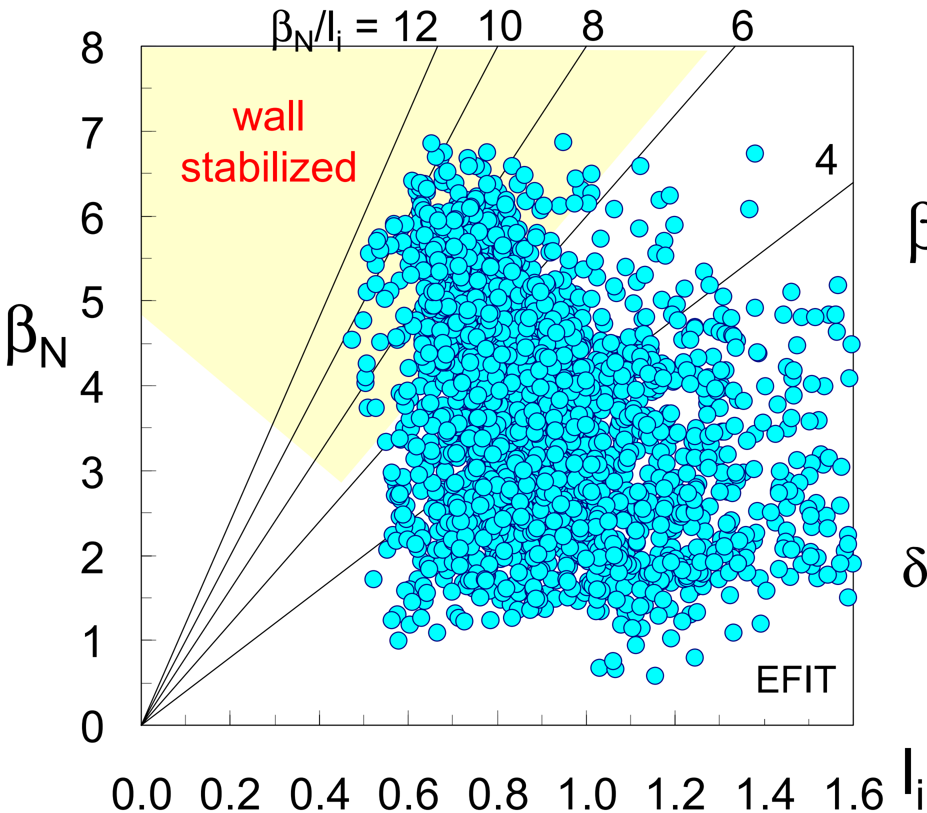
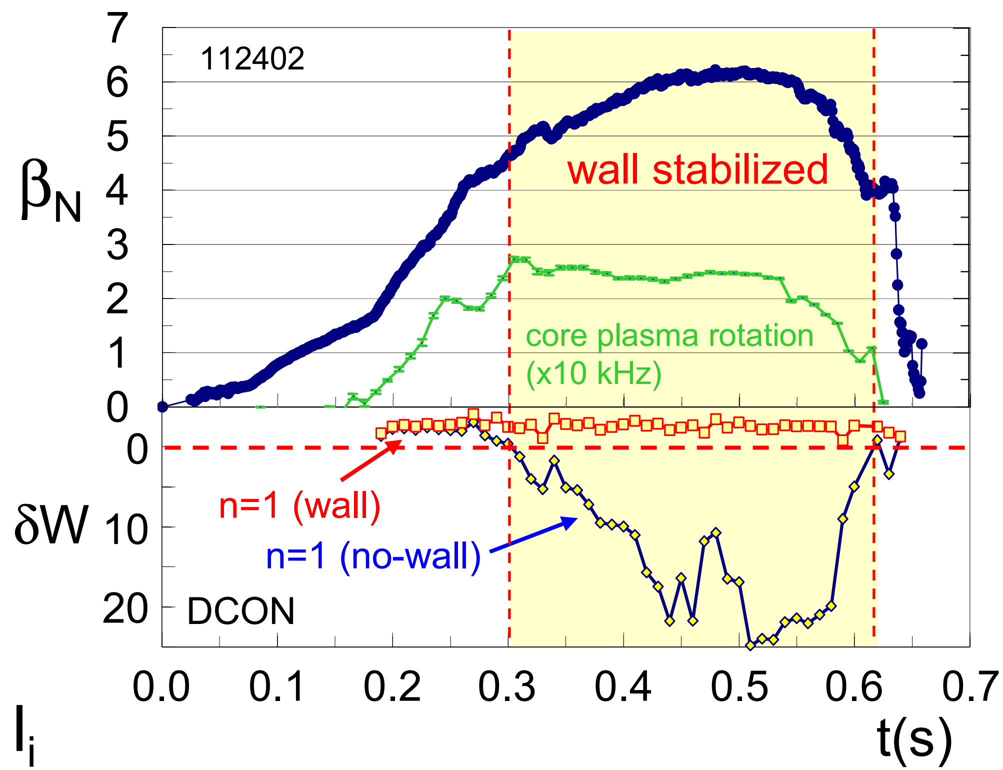
NSTX

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

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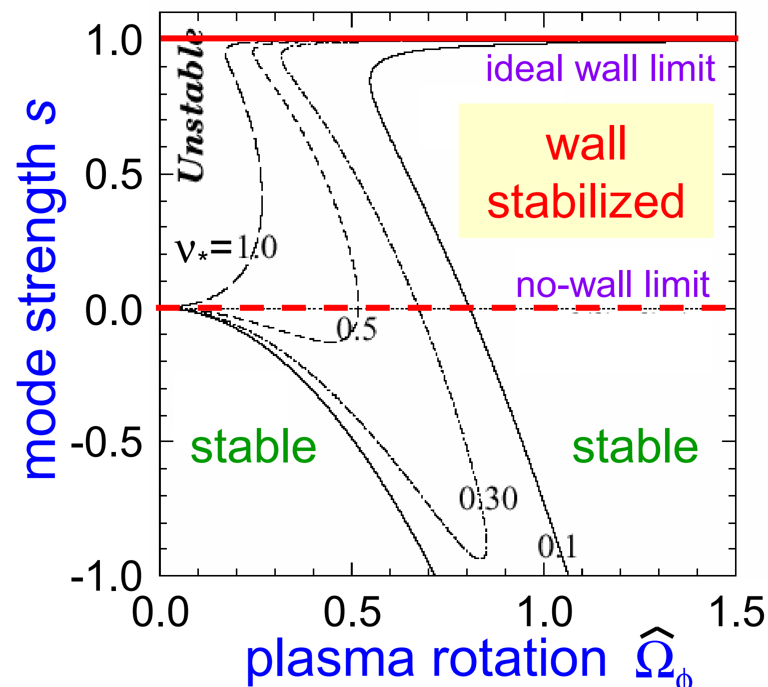
Theory provides framework for wall stabilization study

- This talk: Resistive Wall Mode physics
  - RWM toroidal mode spectrum
  - Critical rotation frequency, Ω_{crit}
  - Toroidal rotation damping
  - Resonant field amplification (RFA)

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

Fitzpatrick-Aydemir (F-A) stability curves

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

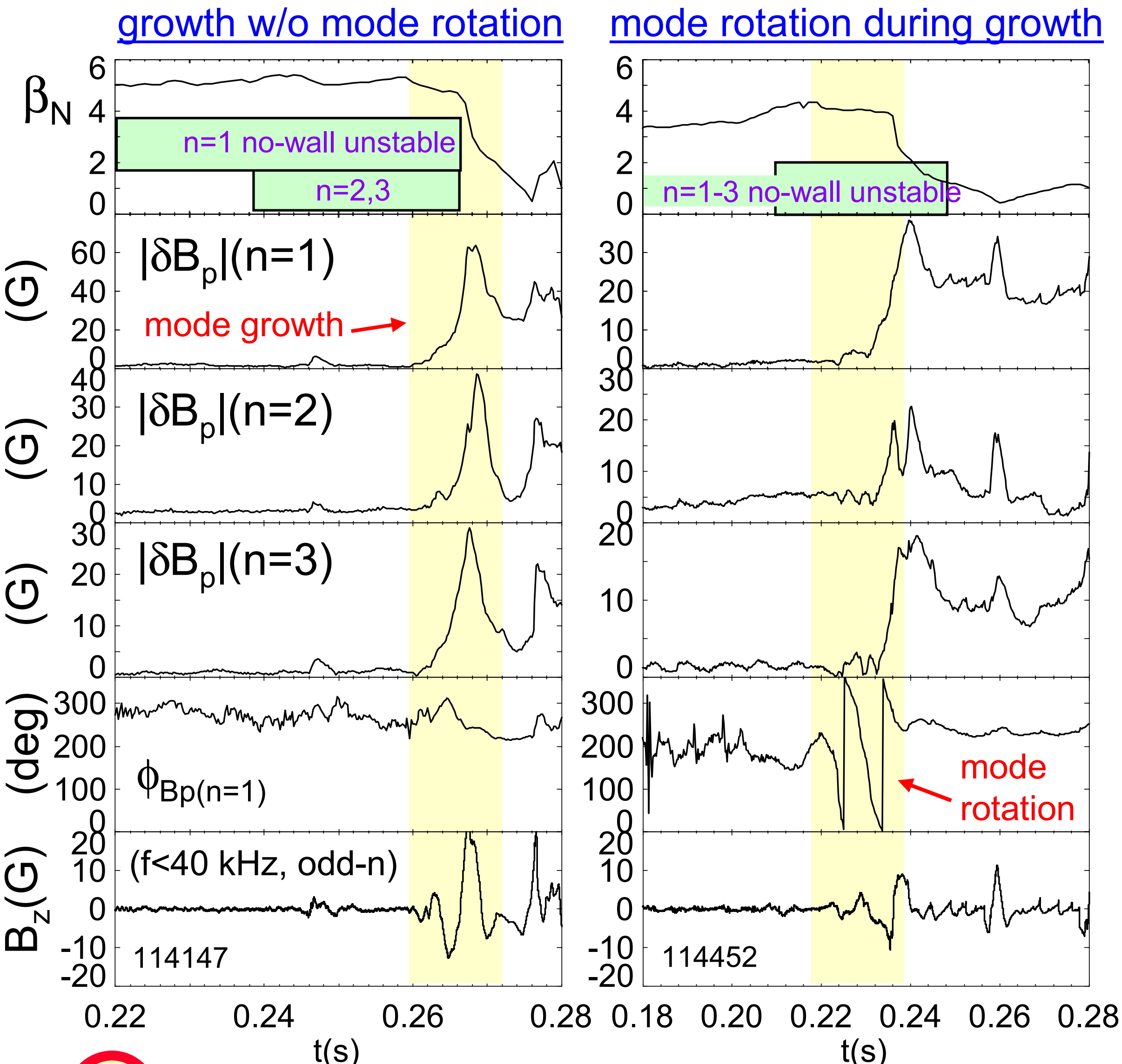


$$\left[\left(\hat{\gamma}-i\hat{\Omega}_\phi\right)^2+\nu_*\left(\hat{\gamma}-i\hat{\Omega}_\phi\right)+(1-s)(1-md)\right]\left(S_*\hat{\gamma}+(1+md)\right)=\left(1-(md)^2\right)$$

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

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

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

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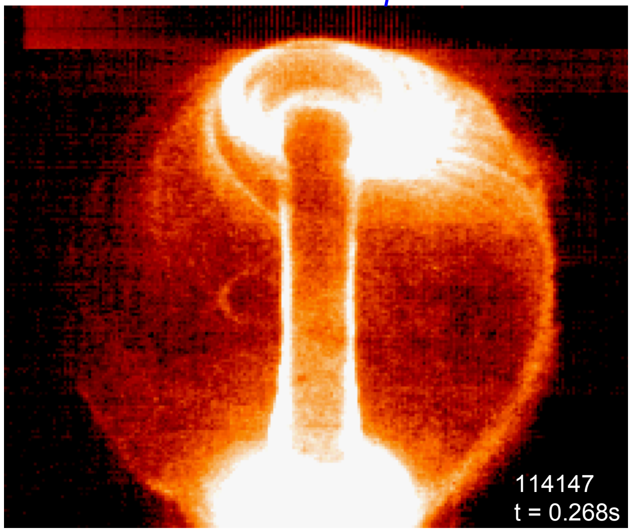
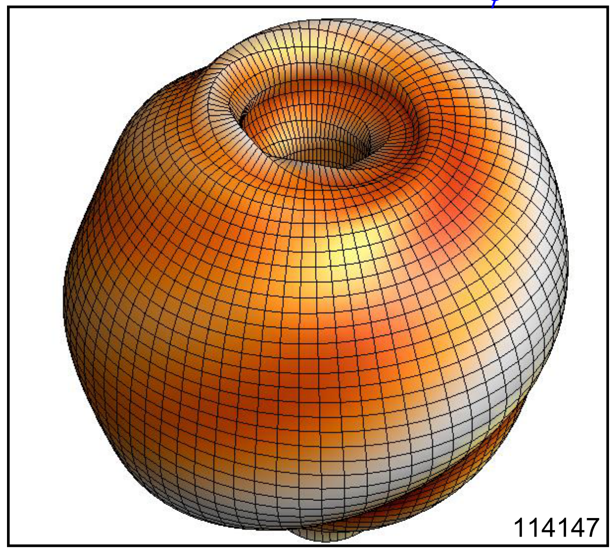
Camera shows scale/asymmetry of theoretical RWM

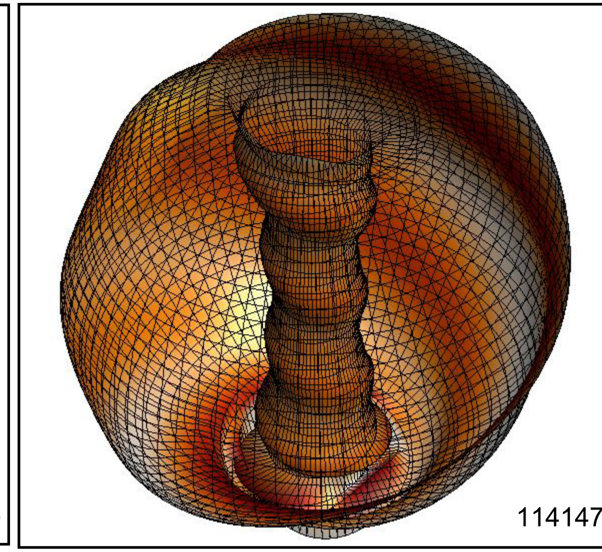
RWM with ΔB_p = 92 G



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

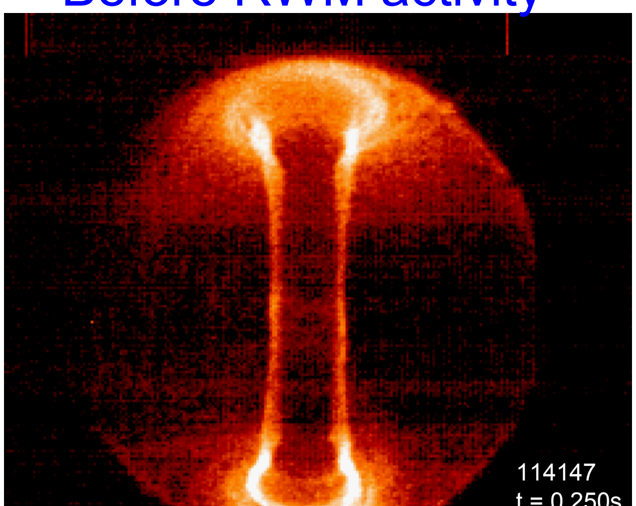


(exterior view)



(interior view)

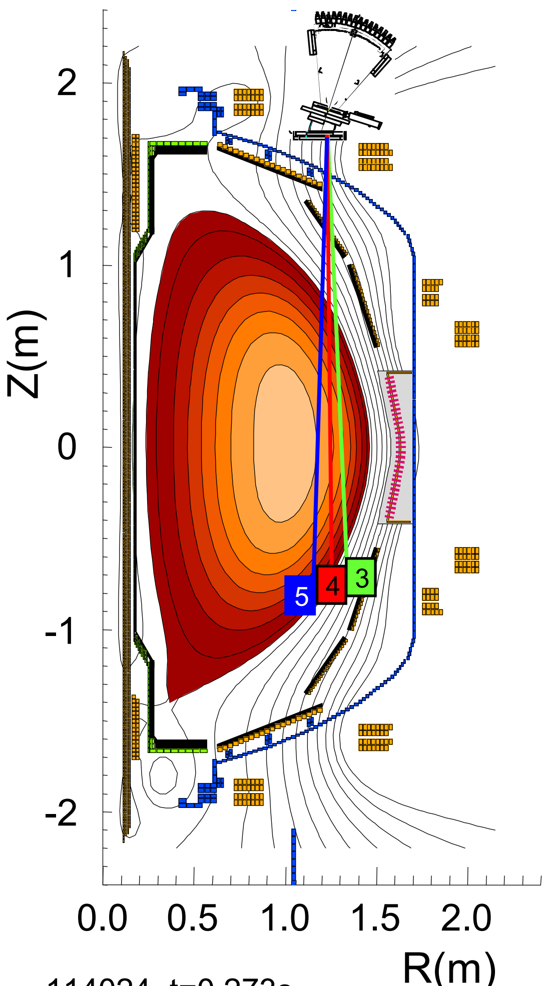
Before RWM activity



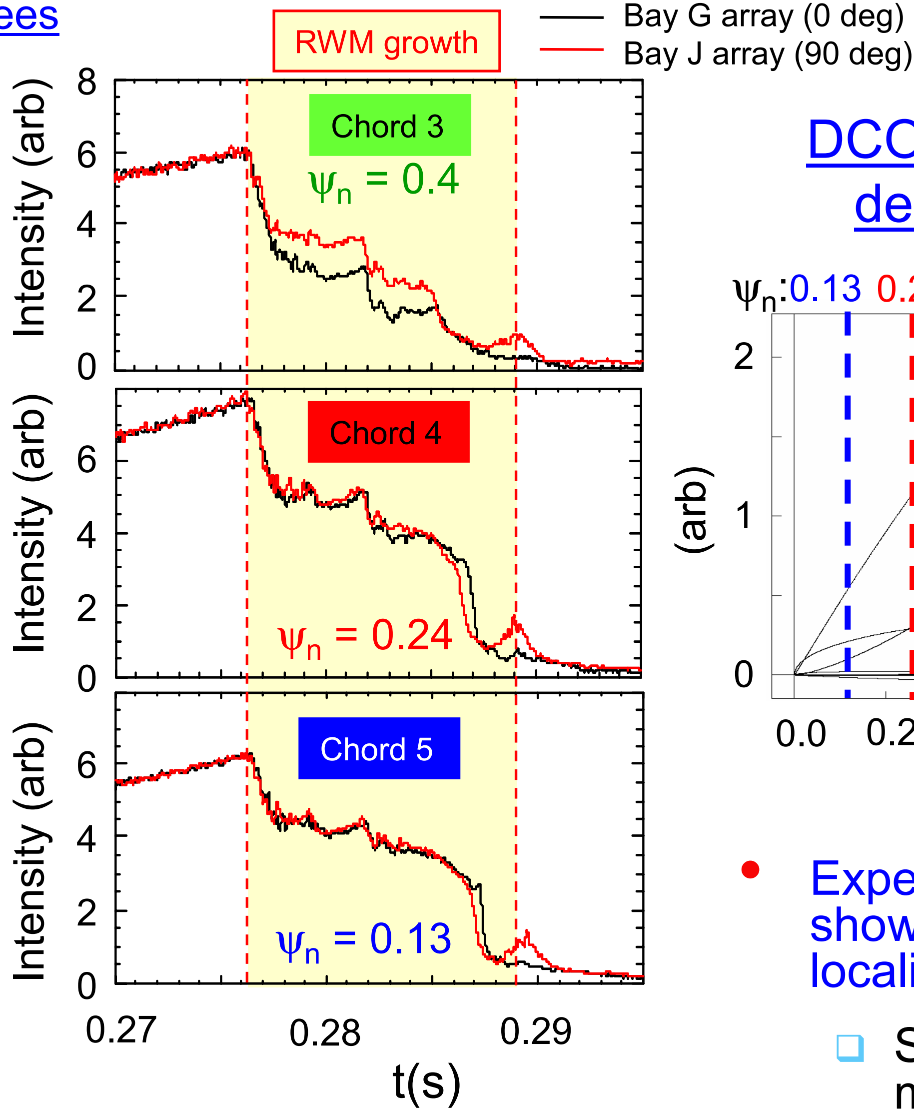
- Visible light emission is toroidally asymmetric during RWM
- DCON theory computation displays mode
  - uses experimental equilibrium reconstruction
  - includes n = 1 – 3 mode spectrum
  - uses relative amplitude / phase of n spectrum measured by RWM sensors

Soft X-ray emission shows toroidal asymmetry during RWM

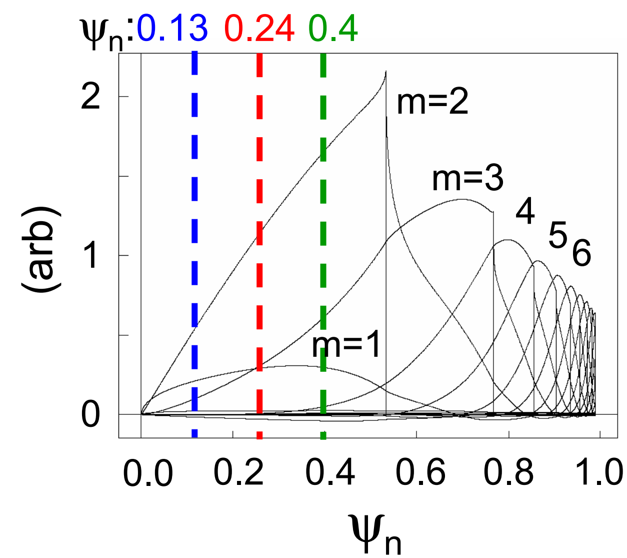
USXR separated by 90 degrees



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



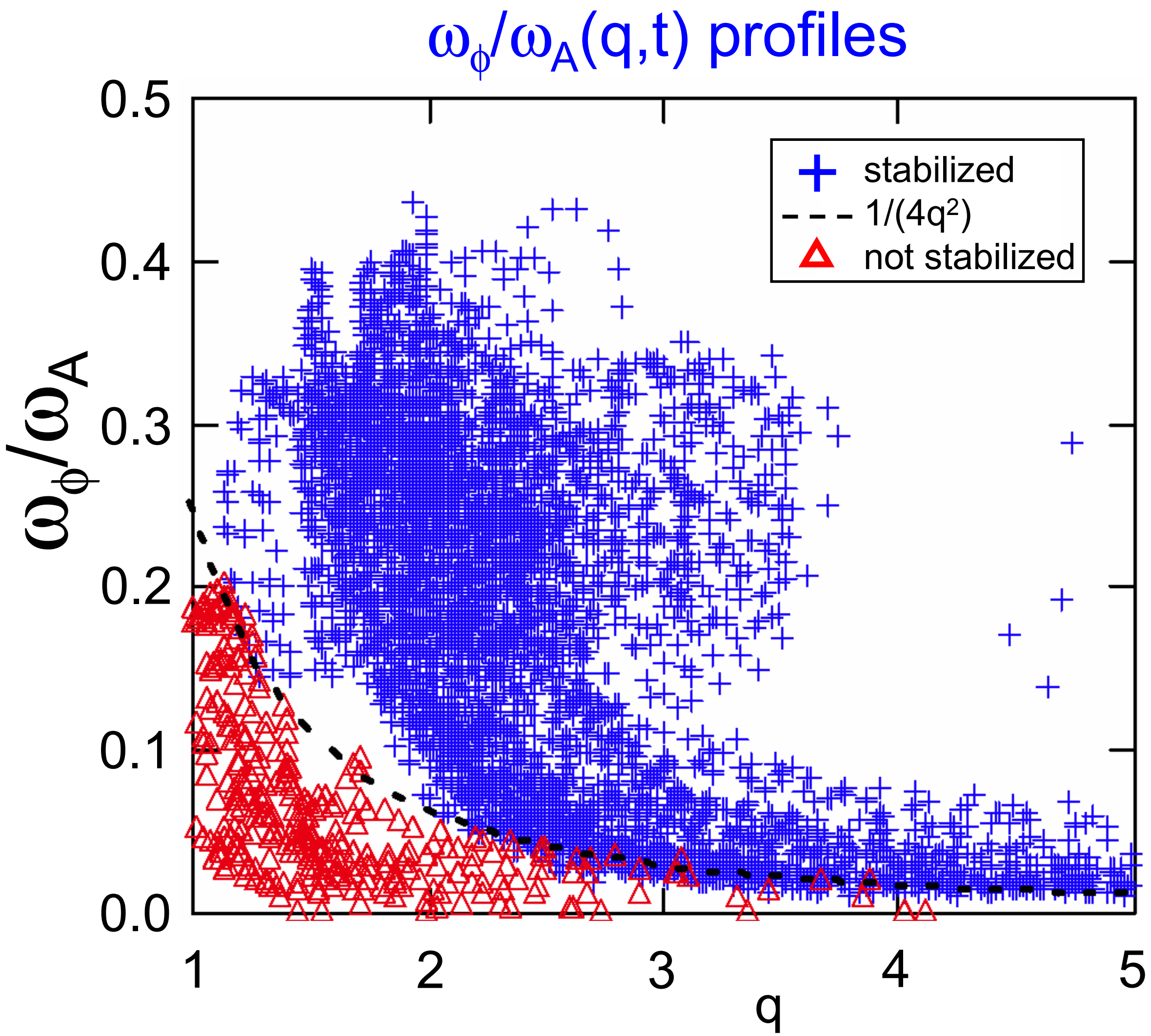
DCON n = 1 mode decomposition



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

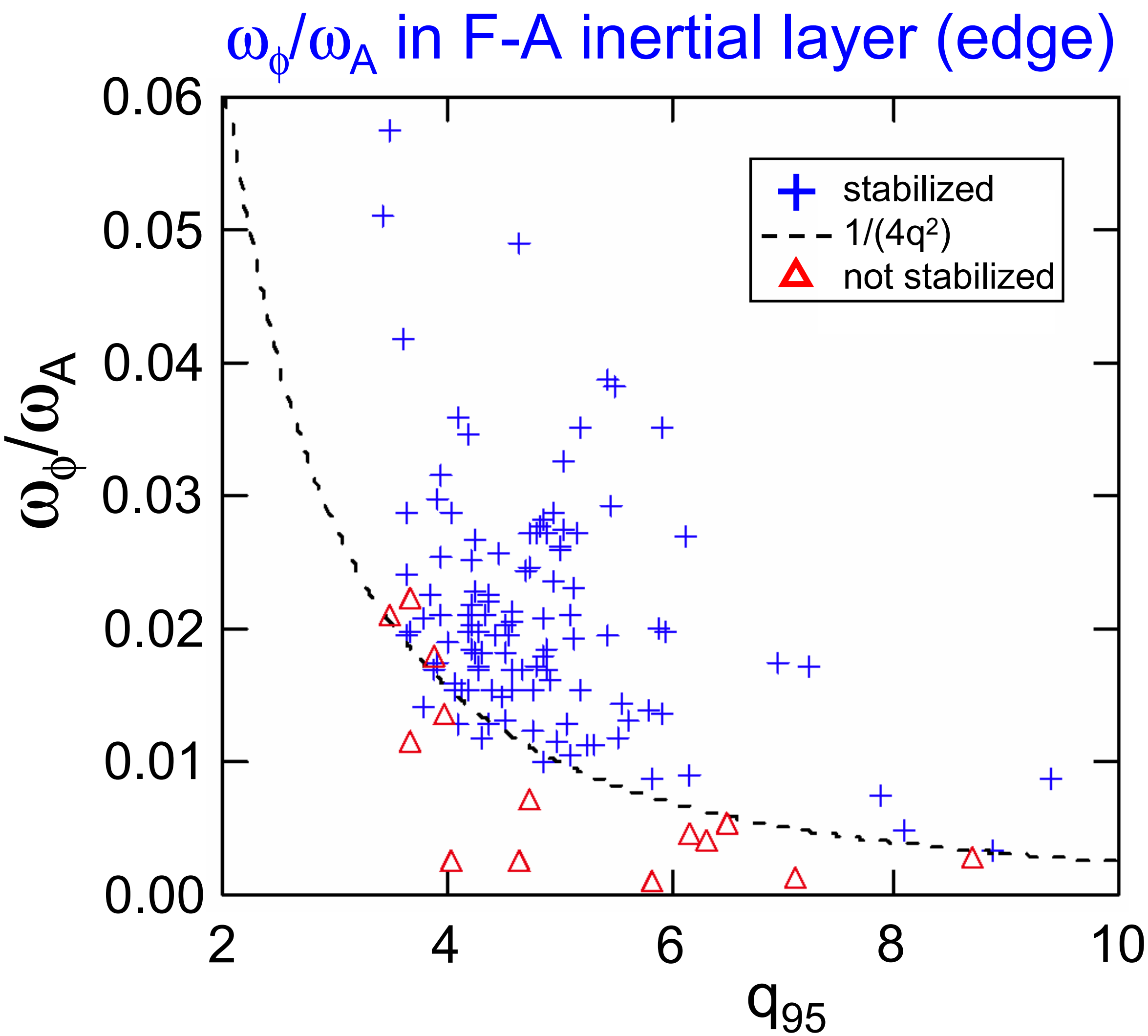
Experimental Ω_{crit} follows Bondeson-Chu theory

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



- 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 $\Omega_{crit} = \omega_A/(4q^2)$

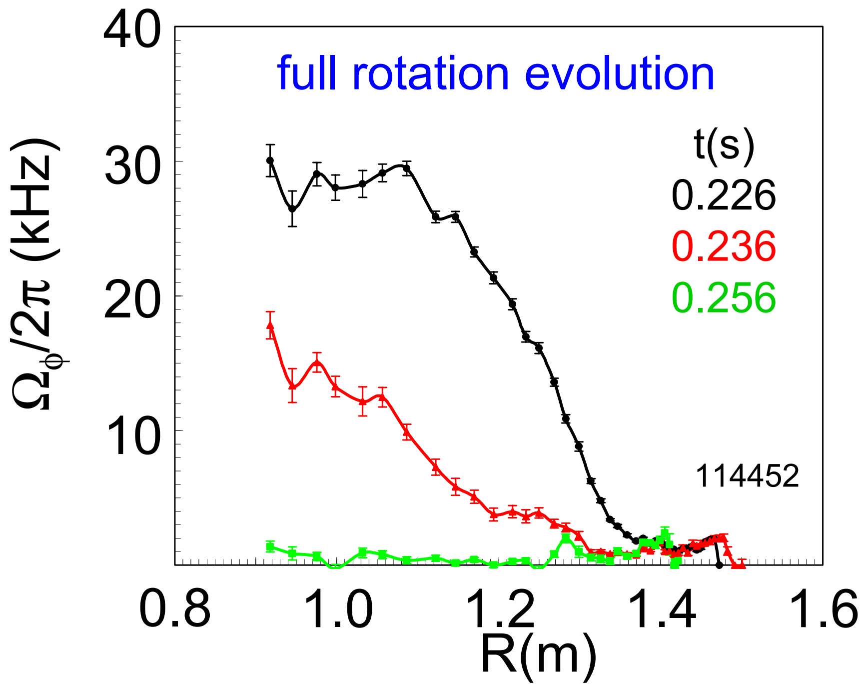
Ω_{crit} follows F-A theory with neoclassical viscosity

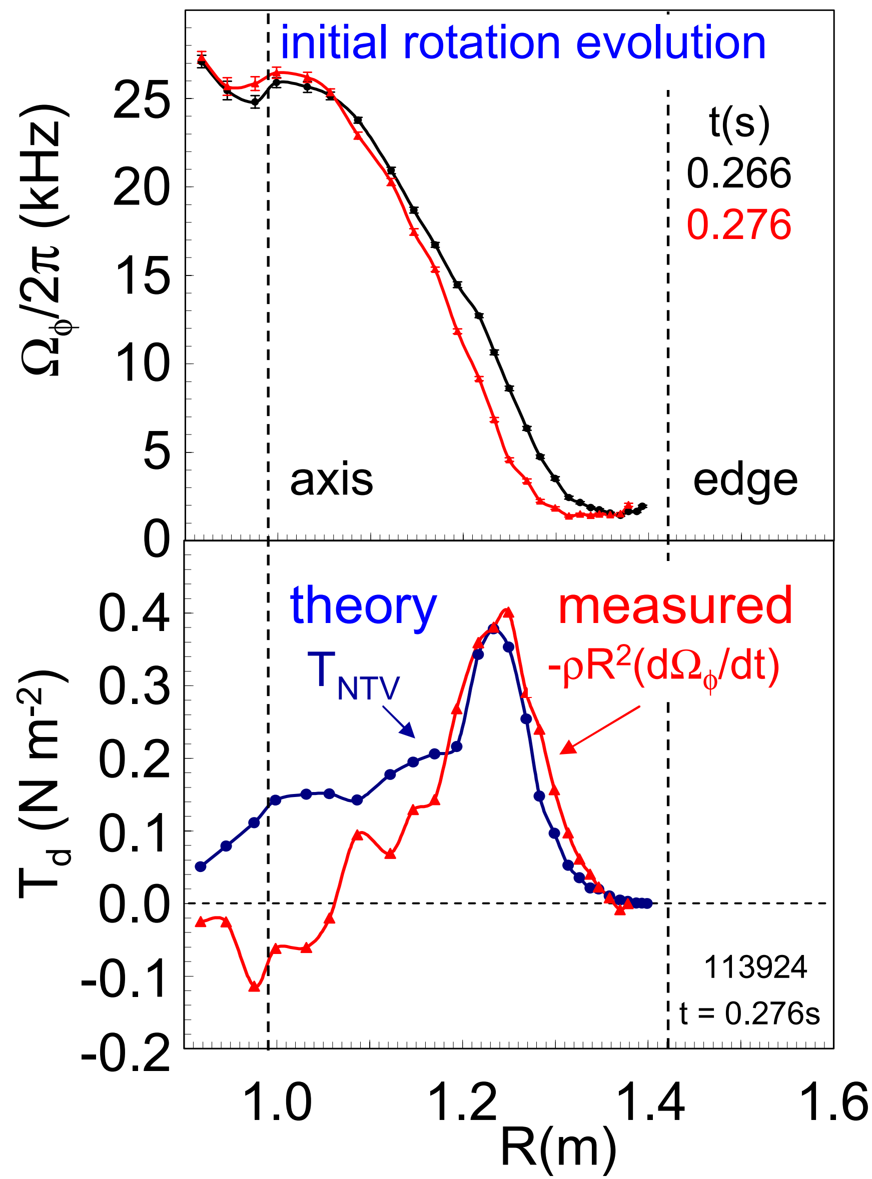


- Experimental Ω_{crit}
  - stabilized points: $\beta > \beta_N^{no\text{-}wall}$ (DCON)
  - points not stabilized cannot maintain $\beta > \beta_N^{no\text{-}wall}$
  - regions separated by $\omega_\phi/\omega_A = 1/(4q^2)$
- F-A Theory
  - Standard F-A theory has $\Omega_{crit} \sim 1/q$
  - neoclassical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

Plasma rotation damping described by NTV theory

- 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

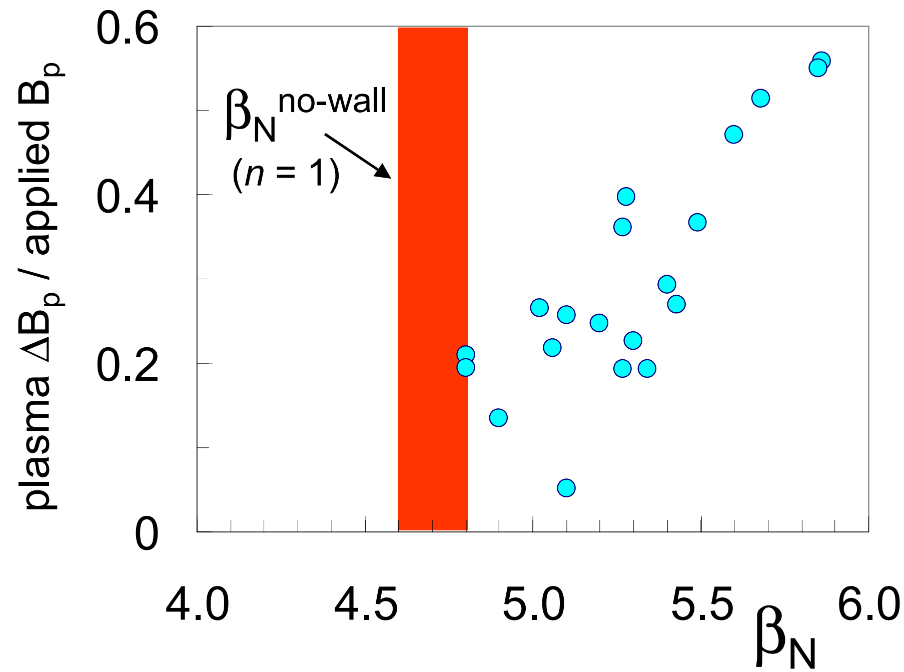


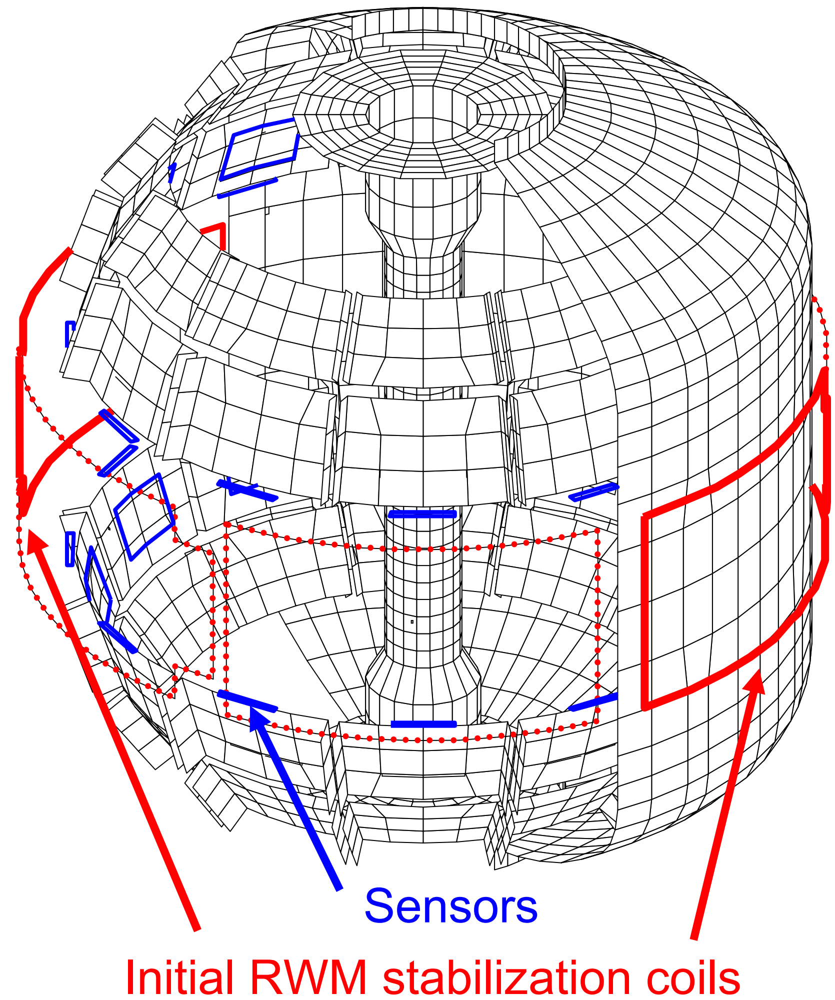


- Evolution detail differs for other modes
  - no momentum transfer across rational surfaces
  - no rigid rotor plasma core (internal 1/1 mode)

see EX/P2-26 Menard

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 $300 s^{-1}$ measured

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

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

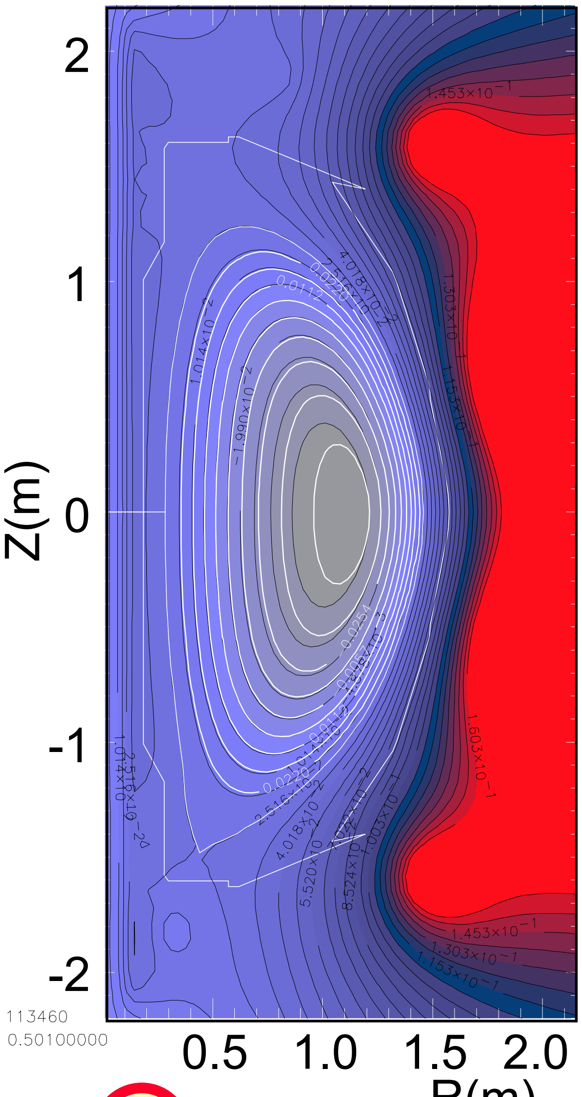
- Plasma β_t = 39%, β_N = 6.8, β_N/l_i = 11 reached; $\beta_N/\beta_N^{no\text{-}wall} > 1.3$
- Unstable n = 1-3 RWMs measured (n > 1 prominent at low A)
- Critical rotation frequency ~ ω_A/q^2 strongly influenced by toroidal inertia enhancement (prominent at low A)
- Rapid, global plasma rotation damping mechanism 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 (see poster)
- Effect of rotation on equilibrium reconstruction evaluated (see poster)

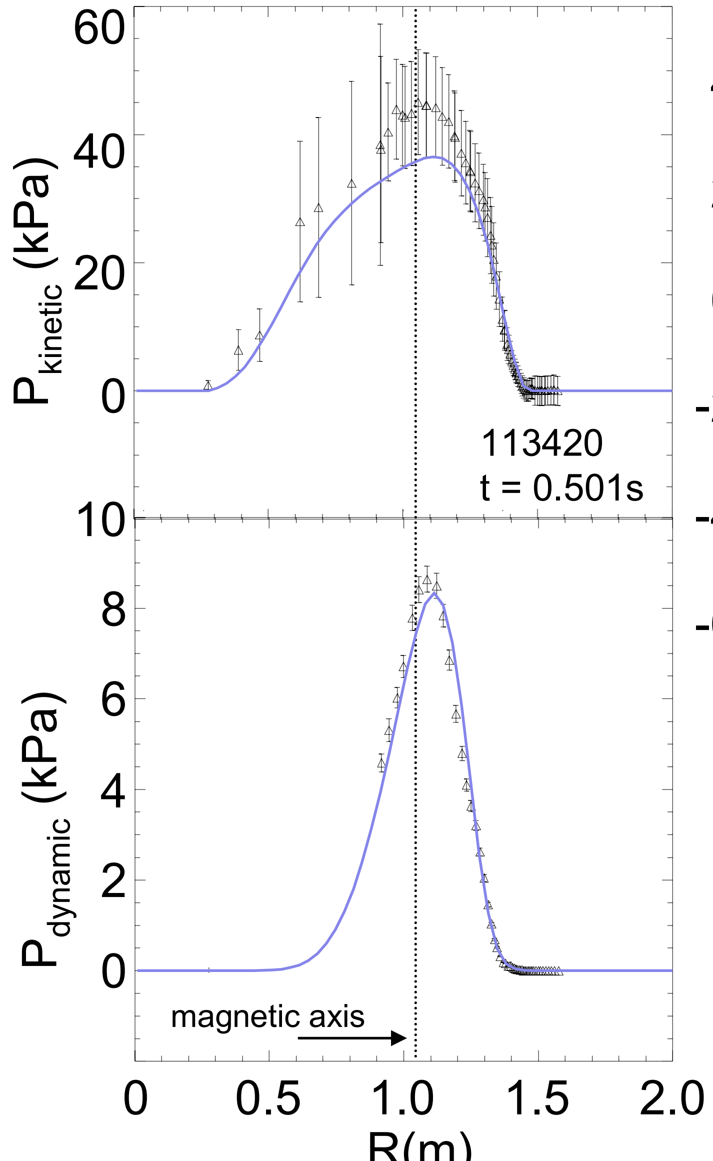
Completed RWM active stabilization coil to be used for research in 2005

Extra slides for poster follow

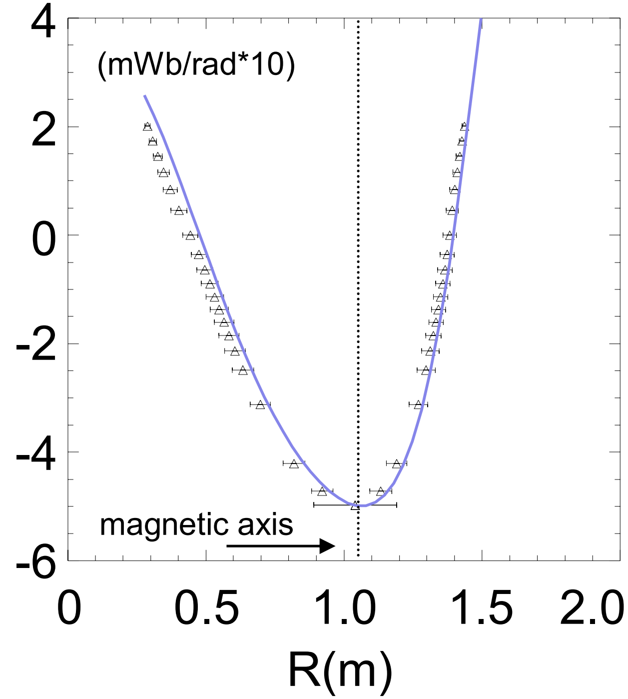
Significant shift of peak pressure off-axis due to rotation

Poloidal flux and pressure





ψ isotherm constraint



- $(R_{pmax} - R_{axis})/a = 11\%$
- V_ϕ broadens P profile and reduces q_0
- No significant reduction in reconstructed β compared to static case

Toroidal Rotation Damping Torques

- Resonant EM force on island (R. Fitzpatrick, et al.)

~0

$$T_{\varphi EM_{err}} = \frac{r_s}{w\mu_0}\frac{n}{m}\left|\delta B_{r\_island}\right|\left|\delta B_{r\_error\_field}\right| \times Fac_{shielding}$$

$$T_{\varphi EM_{wall}} = \frac{r_s}{w\mu_0}\frac{n}{m}\frac{(\omega\tau_w)\left[1-(r_{s+}/r_w)^{2m}\right]}{1+(\omega\tau_w)^2\left[1-(r_{s+}/r_w)^{2m}\right]^2}\left|\delta B_{r\_island}\right|^2$$

- Neoclassical toroidal viscosity (NTV) theory (K.C. Shaing et al.)

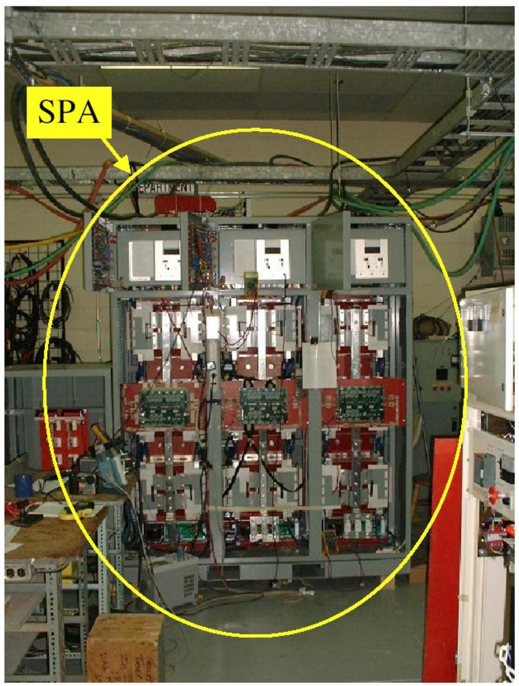
$$T_{NTV} = R\frac{\pi^{1/2}p_i}{v_{t_i}}\left(\Omega_\phi - \Omega_{\mathrm{mode}}\right)\varepsilon^2\sum_{m,n\neq 0}\left(\frac{\delta B_r^{mn}}{B_\phi}\right)^2\frac{1.365n^2q}{1.182+1.365\left|m-nq\right|}$$

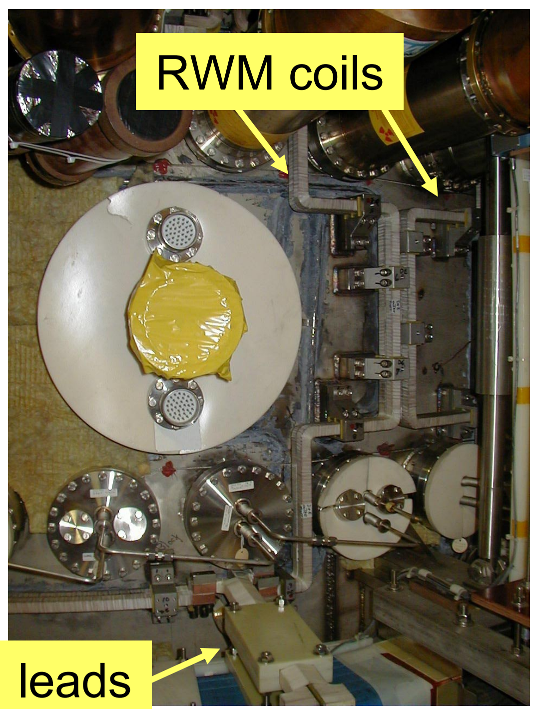
dominant m:

$$T_{NTV} = R\frac{\pi^{1/2}p_i}{v_{t_i}}\left(\Omega_\phi - \Omega_{\mathrm{mode}}\right)\varepsilon^2 n^2 q\left(\frac{\delta B_r}{B_\phi}\right)^2$$

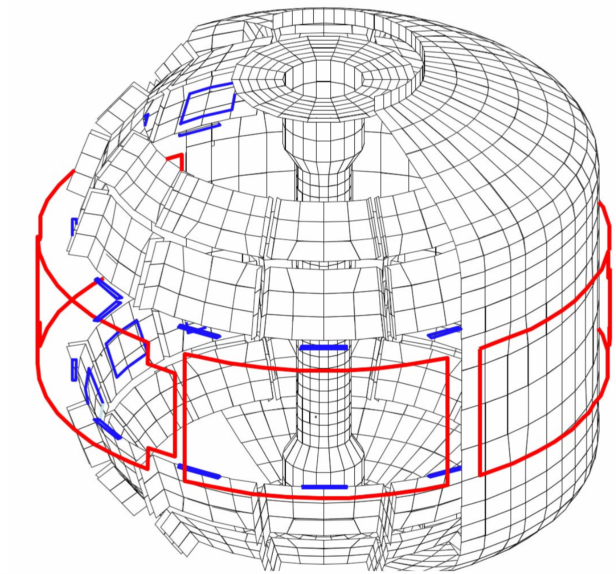
RWM stabilization system being installed for 2005 run

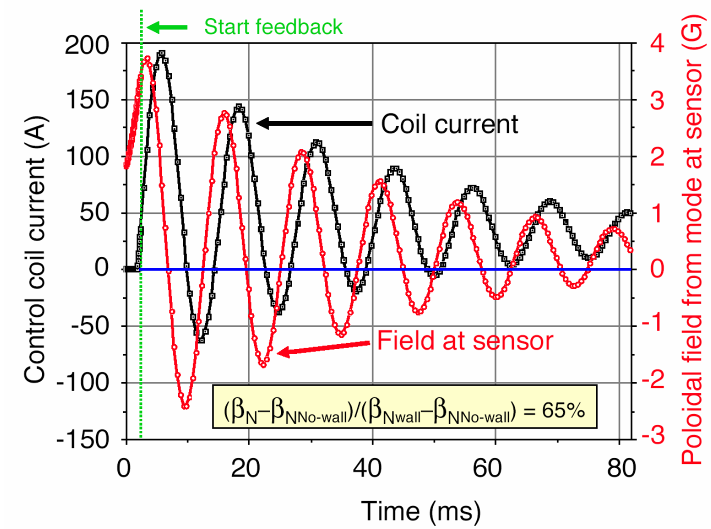
- RWM sensor array used in 2004 experiments
- 6 B_r coils now installed on NSTX
  - Pre-programmed capability in 2005 for RFA suppression / MHD spectroscopy experiments
- 3-channel switching power amplifier (SPA) on-site
- Real-time mode detection and control algorithm development in 2005 for feedback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



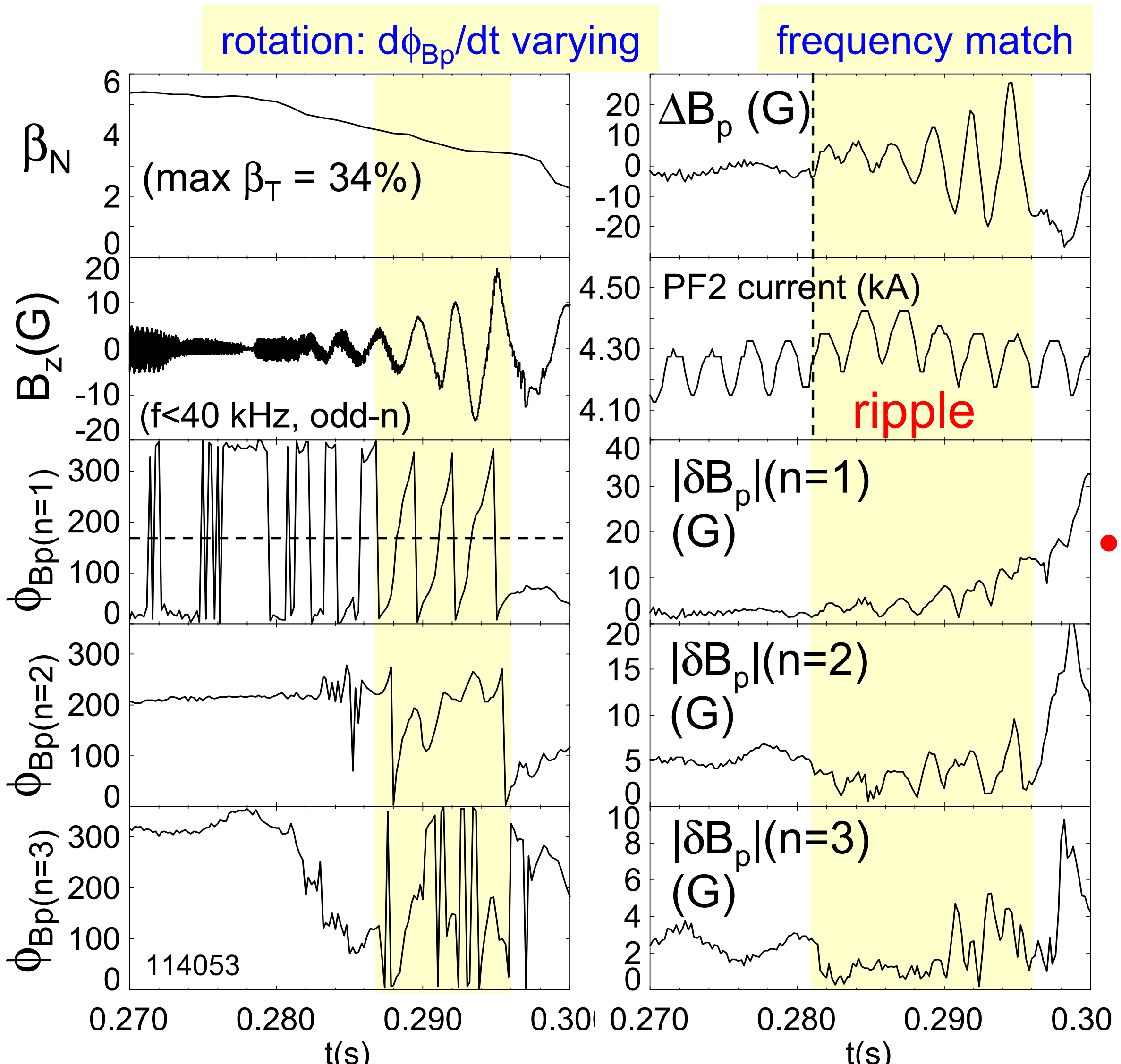


Physics design (VALEN code)





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

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