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Passive Stabilization at High Beta in NSTX

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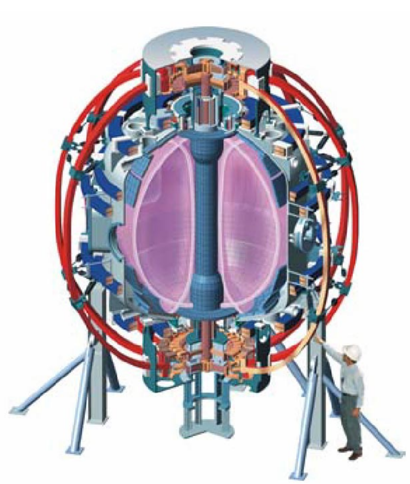

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Abstract

Rapidly rotating spherical torus plasmas at high normalized beta up to 6.8 exceed the ideal MHD no-wall beta limit and are passively stabilized when the rotation frequency profile exceeds the Bondeson and Chu critical profile $\omega/\omega_A = 1/(4q^2)$. Plasmas with insufficient rotation do not maintain high beta and may exhibit growing resistive wall modes (RWM). Two coils, of an eventual six to be used for active feedback stabilization, have been used to alter rotation by generating odd parity field perturbations. RWMs with 6 ms growth rates have been observed, in agreement with the VALEN code and frequencies of about 100 Hz have been measured. Rotation damping observed in plasmas exceeding the no-wall limit can be described by drag due to neoclassical toroidal viscosity (NTV) in the helically perturbed field. Rotating equilibria are reconstructed with ω/ω_A exceeding 0.45. Measured electron and ion pressure profiles, and a flux iso-surface constraint to the measured electron temperature are used.

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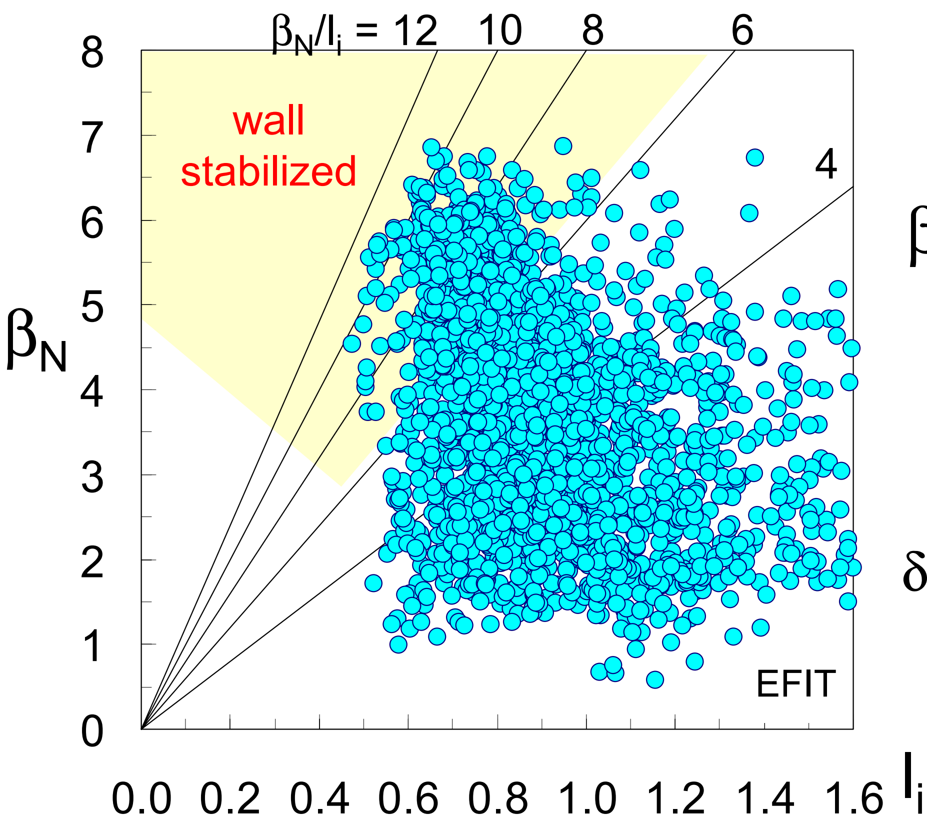
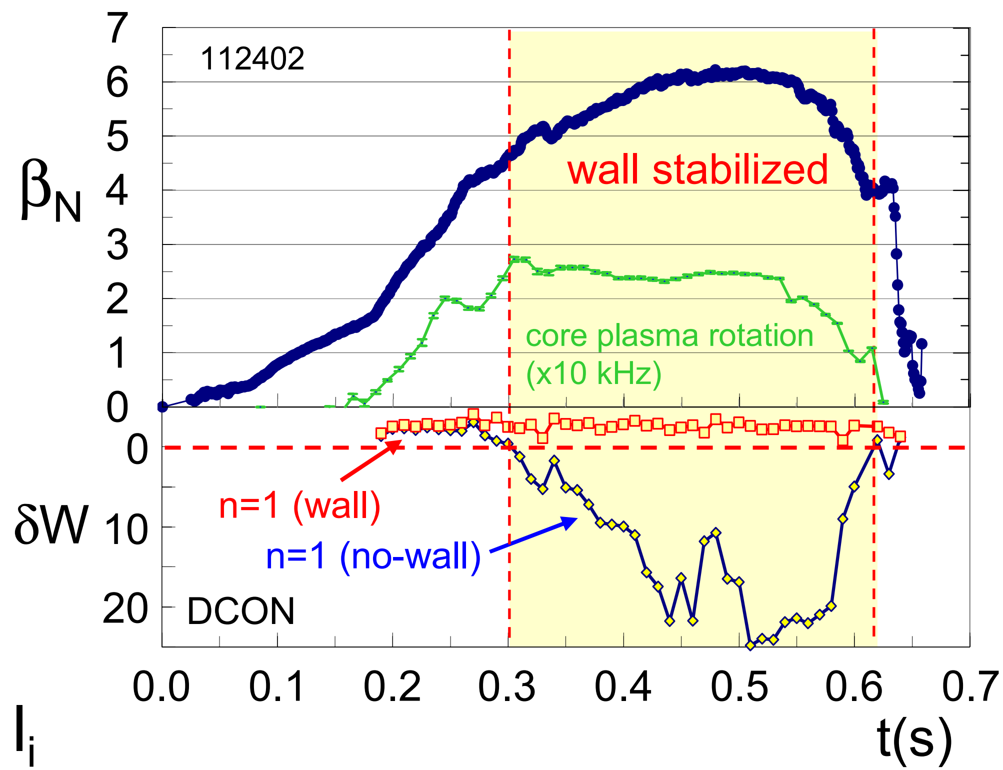
Wall stabilization physics understanding is key to sustained plasma operation at maximum β

- 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

Theory provides framework for wall stabilization study

- This poster: 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

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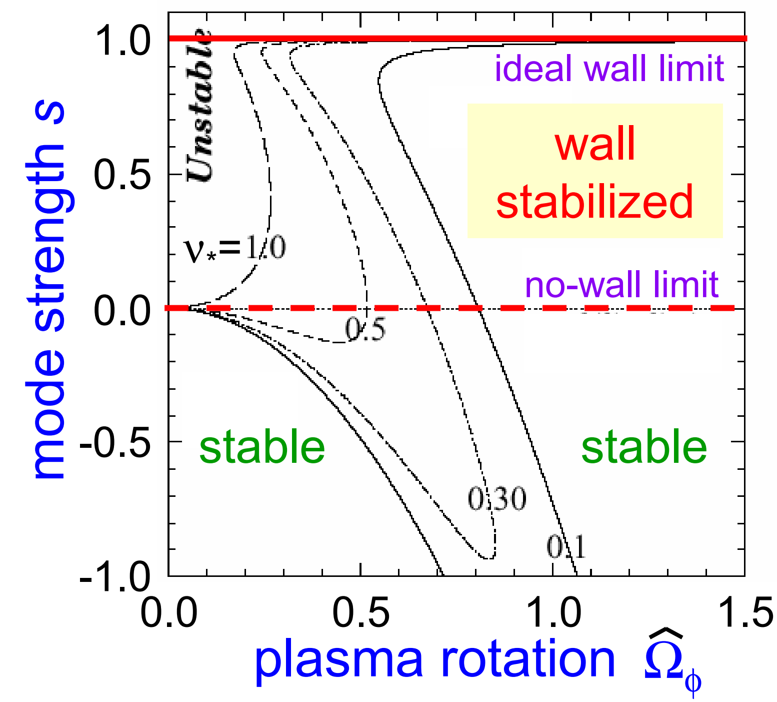

$$\left[\left(\hat{\gamma}-i\hat{\Omega}_\phi\right)^2+\nu_*\left(\hat{\gamma}-i\hat{\Omega}_\phi\right)+(1-s)(1-md)\right]\left(S_*\hat{\gamma}+(1+md)\right)=\left(1-(md)^2\right)$$

plasma inertia dissipation mode strength wall response wall/edge coupling

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

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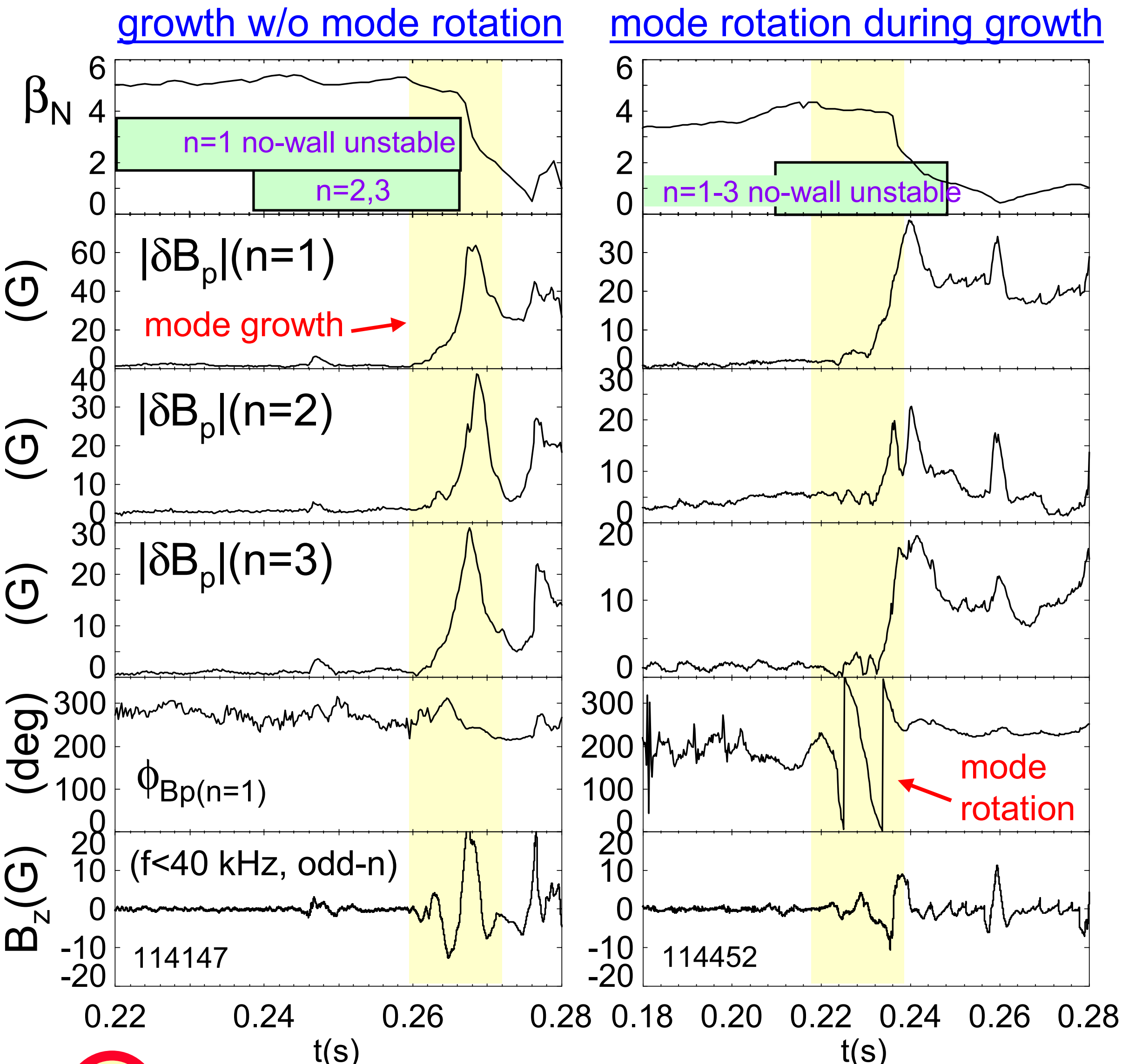
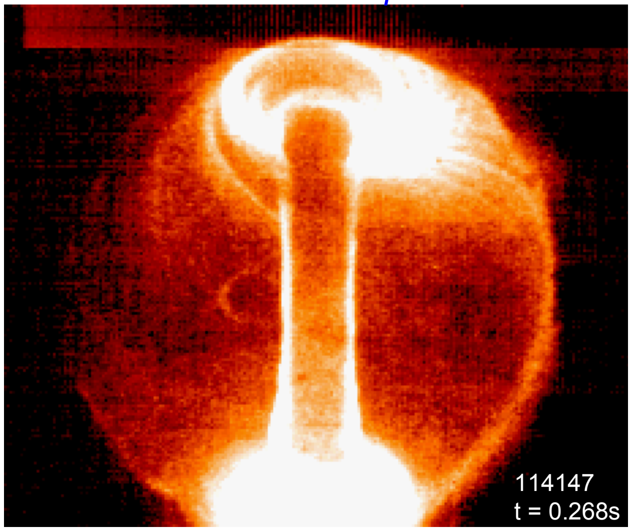
Unstable RWM dynamics follow theory



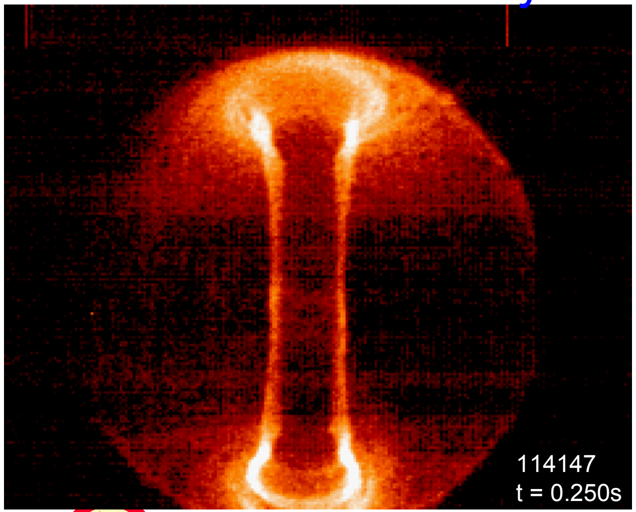
- Unstable n=1-3 RWM observed
  - ideal no-wall unstable at high β_N
  - n > 1 theoretically less stable at low A
- F-A theory / experiment show
  - mode rotation can occur during growth
  - growth rate, rotation frequency ~ $1/\tau_{wall}$
    - << edge Ω_ϕ > 1 kHz
  - RWM phase velocity follows plasma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

Camera shows scale/asymmetry of theoretical RWM

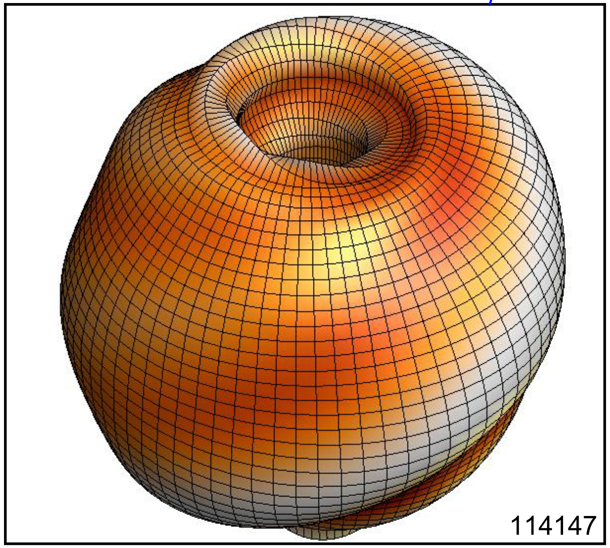
RWM with ΔB_p = 92 G



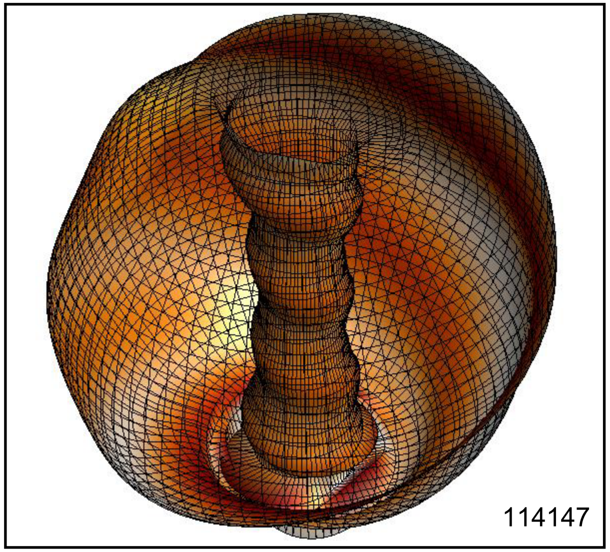
Before RWM activity



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



(exterior view)

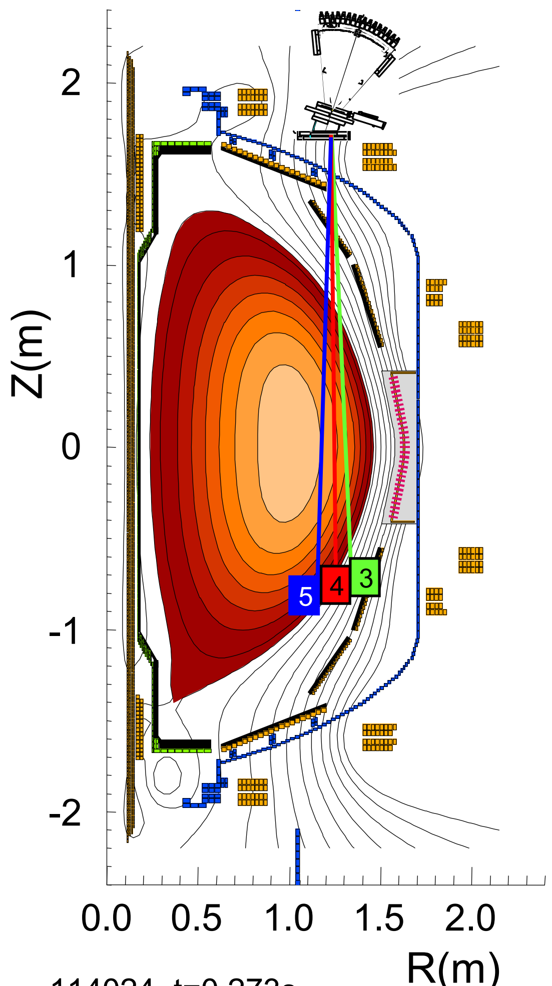


(interior view)

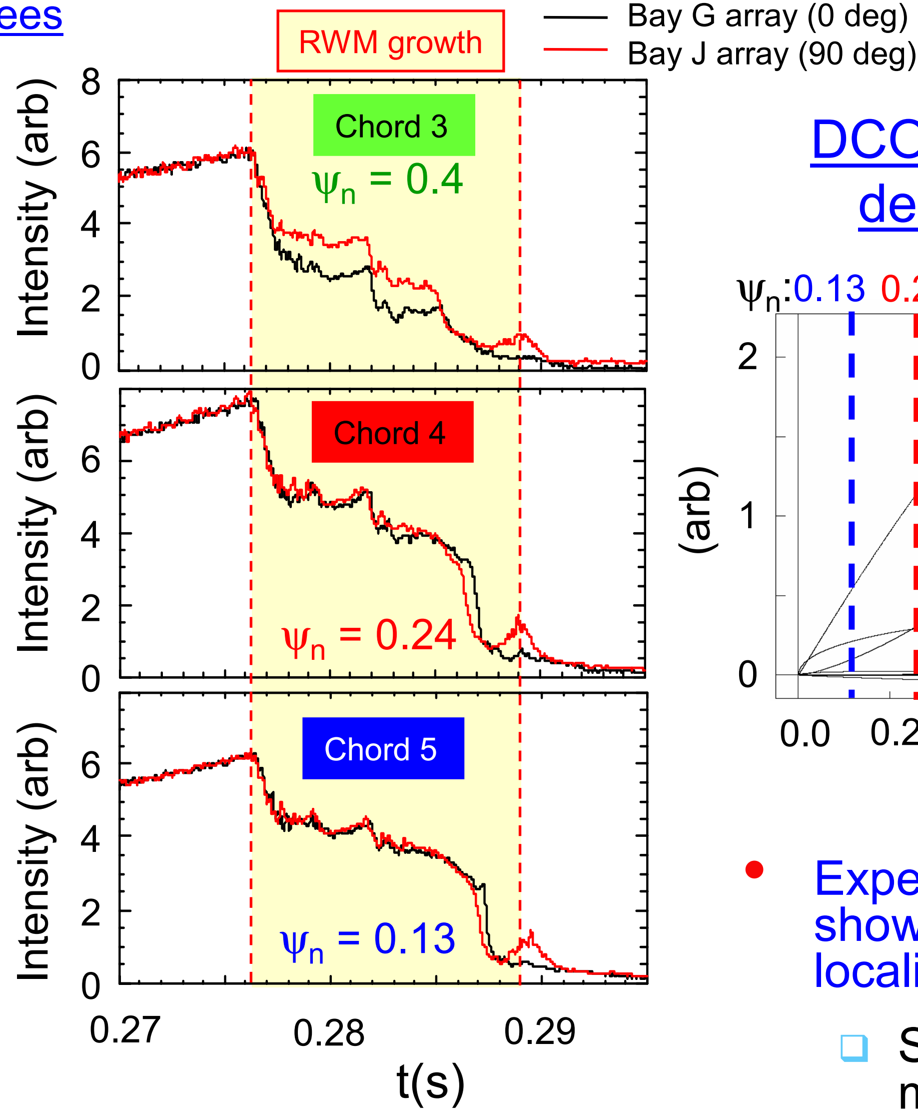
- Visible light emission is toroidally asymmetric during RWM
- DCON theory computation displays mode
  - uses experimental equilibrium reconstruction
  - includes n = 1 – 3 mode spectrum
  - uses relative amplitude / phase of n spectrum measured by RWM sensors

Soft X-ray emission shows toroidal asymmetry during RWM

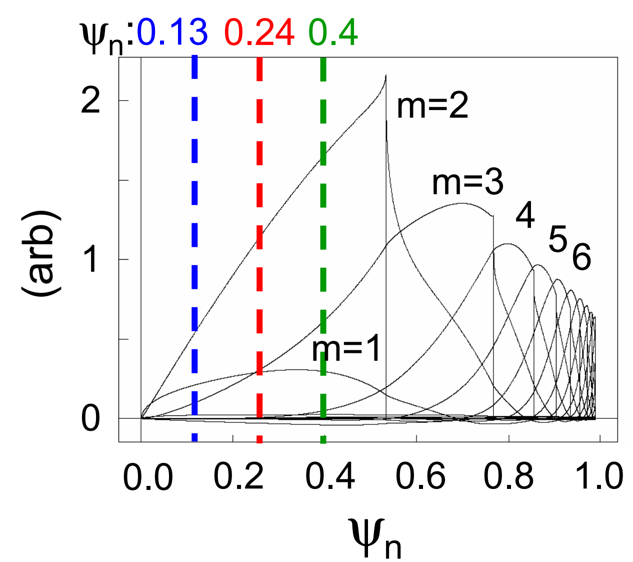
USXR separated by 90 degrees



114024, t=0.273s
β_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

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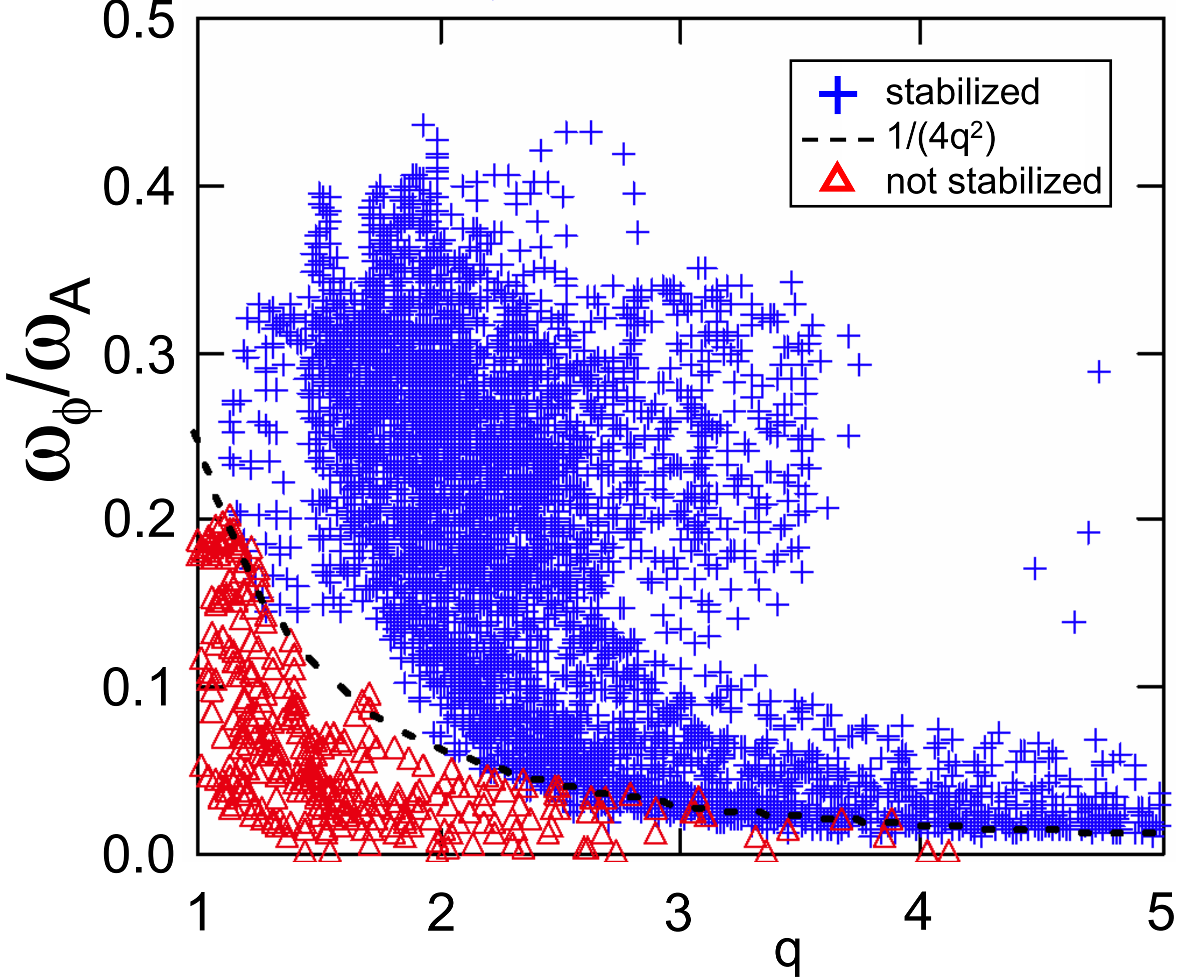
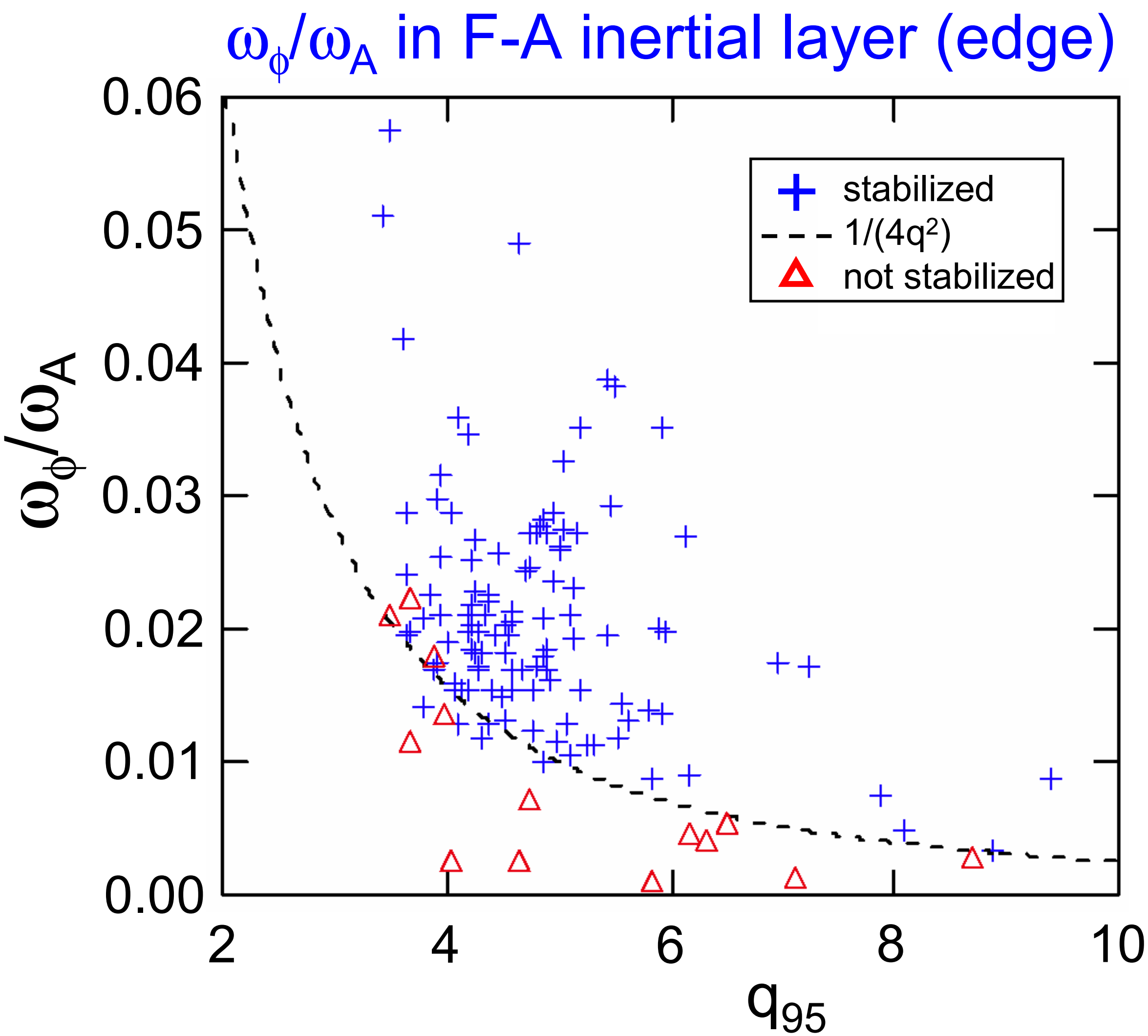
$\omega_\phi/\omega_A(q,t)$ profiles



- **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



- **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 $\Omega_{crit} \sim 1/q^2$

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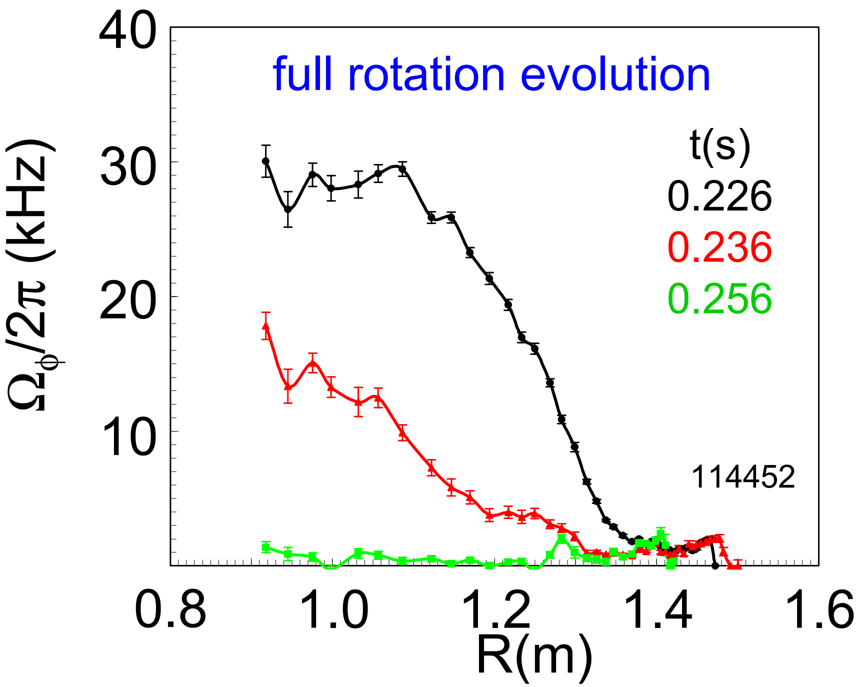
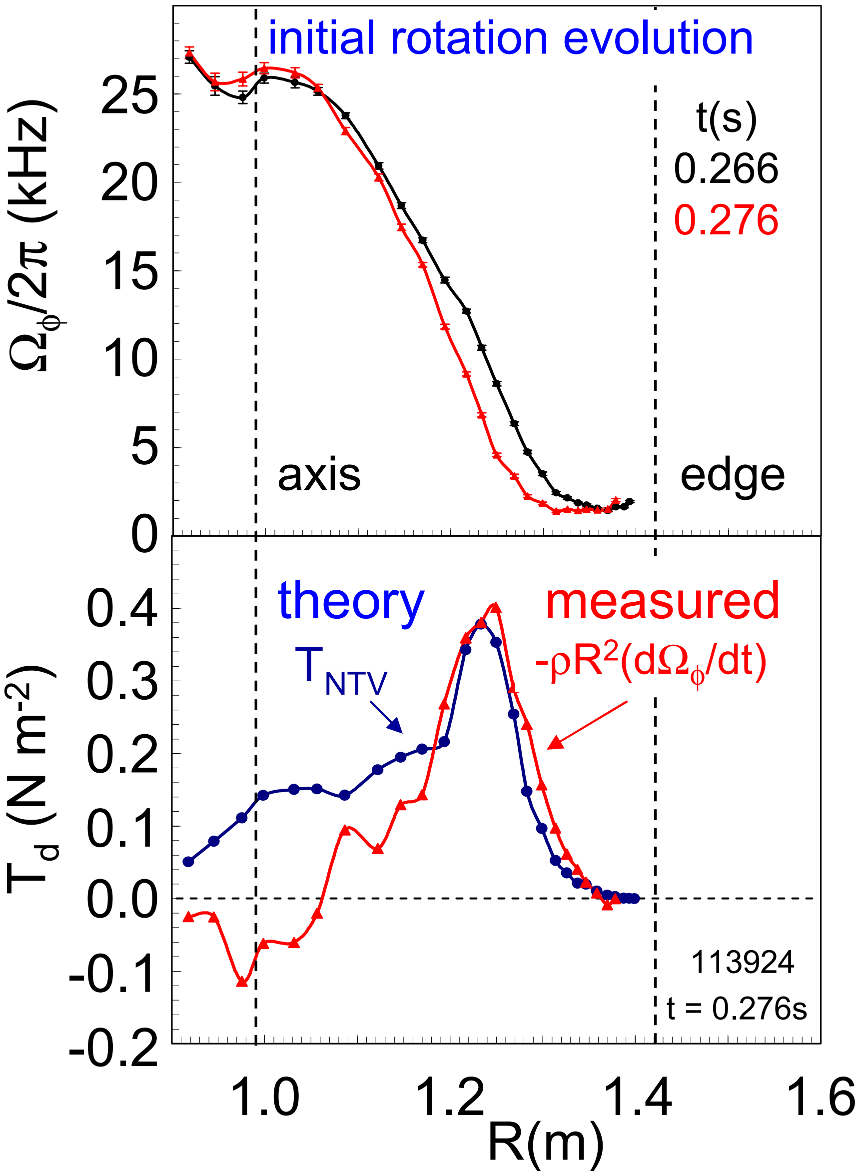
Plasma rotation damping described by NTV theory

- 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)

Toroidal Rotation Damping Torques

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

~0

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

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

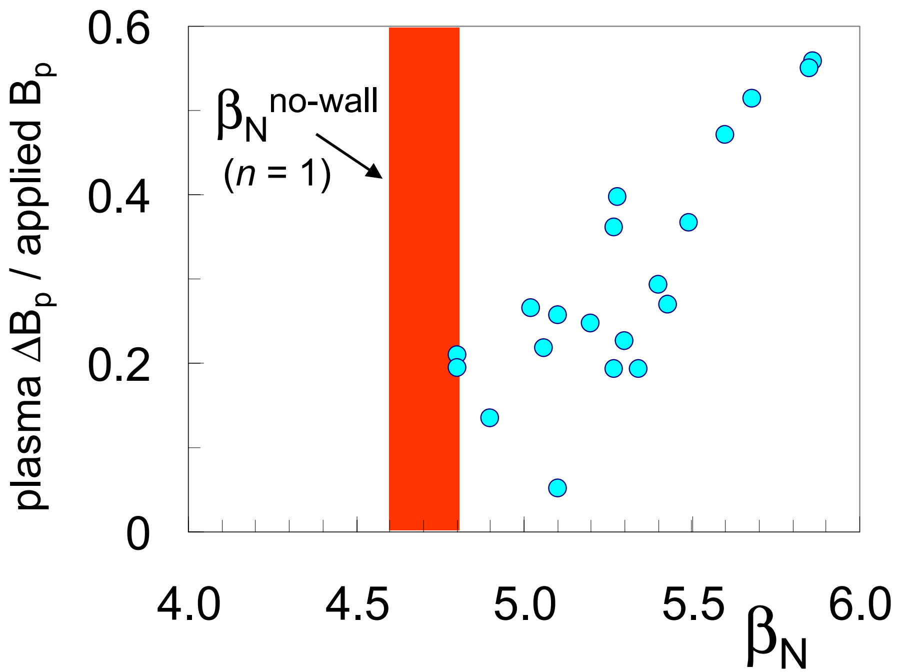
- Neoclassical toroidal viscosity (NTV) theory (K.C. Shaing et al.)

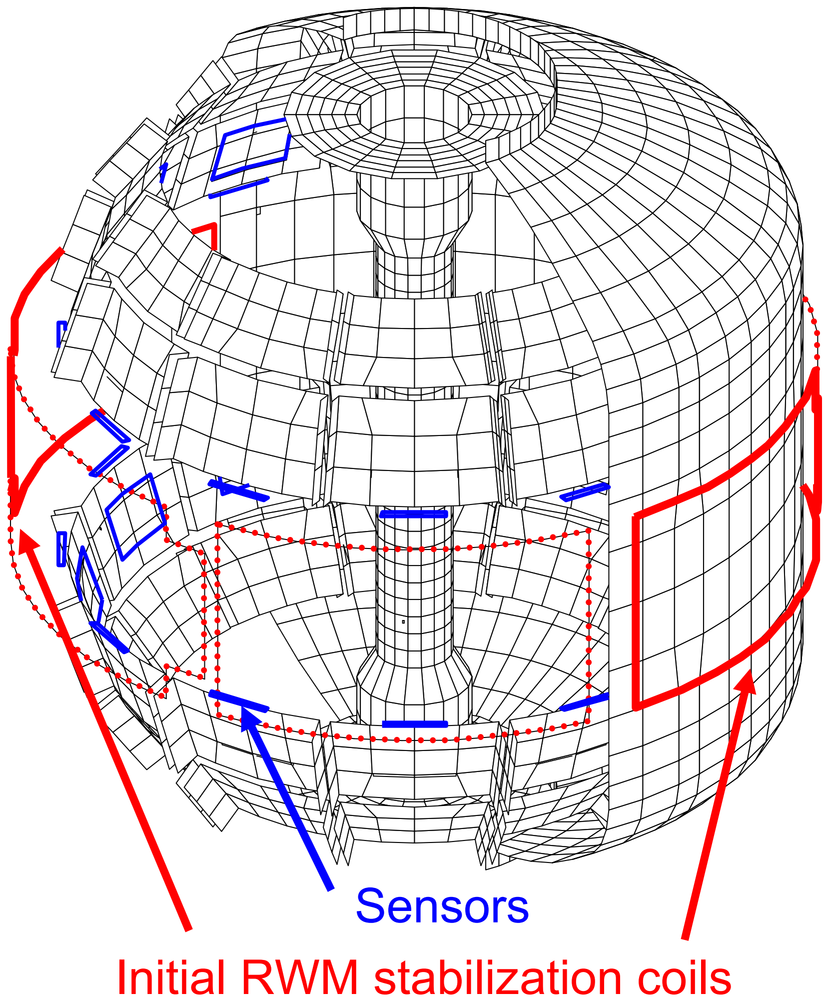
$$T_{NTV} = R\frac{\pi^{1/2}p_i}{v_{t_i}}\left(\Omega_\phi - \Omega_{\mathrm{mode}}\right)\varepsilon^2\sum_{m,n\neq 0}\left(\frac{\delta B_r^{mn}}{B_\phi}\right)^2\frac{1.365n^2q}{1.182+1.365\left|m-nq\right|}$$

dominant m:

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

Resonant Field Amplification increases at high β_N

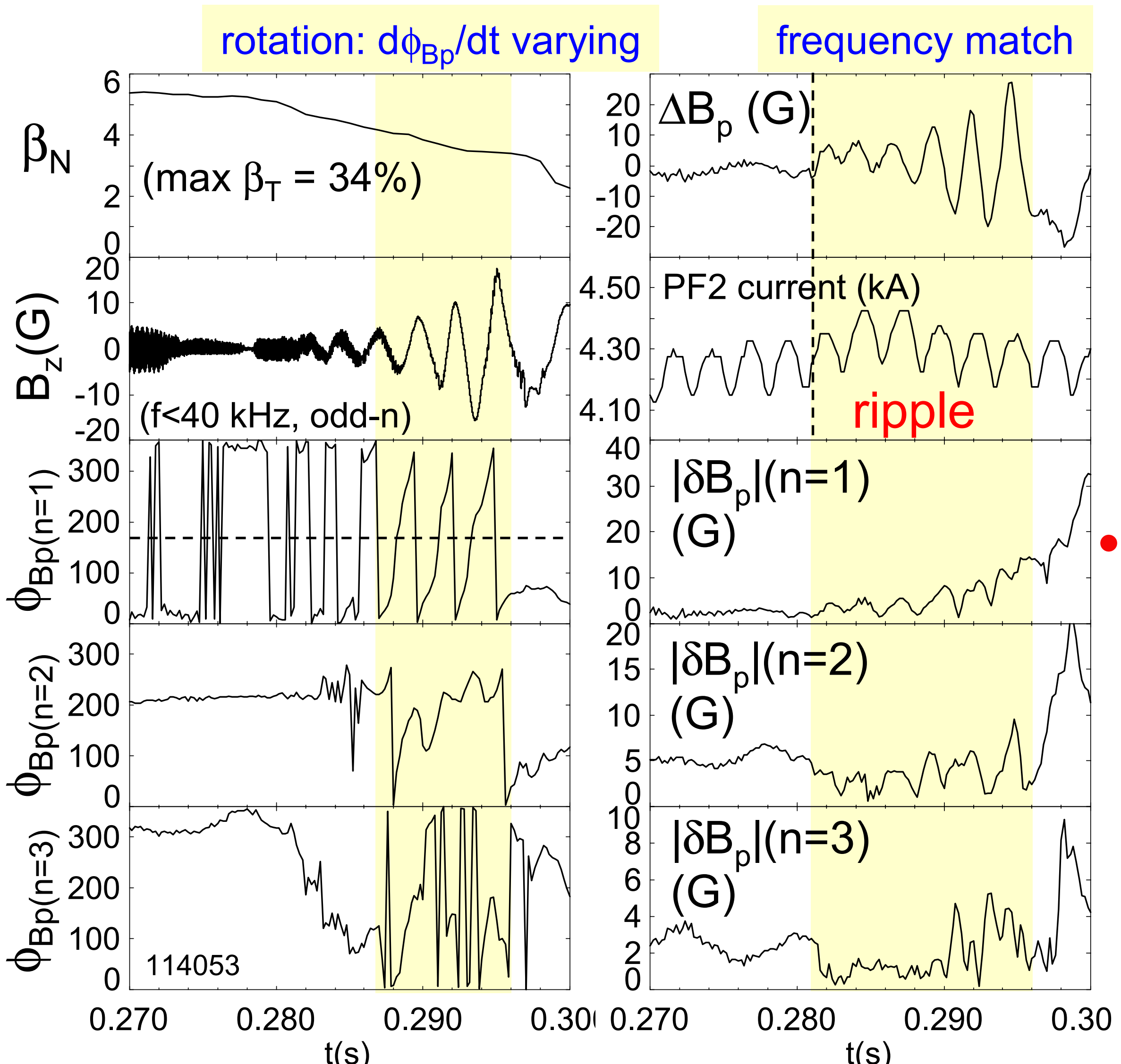




- Plasma response to applied field from initial RWM stabilization coil pair
  - AC and pulsed n = 1 field
- RFA increase consistent with DIII-D
- Stable RWM damping rate of 300s^{-1} measured

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

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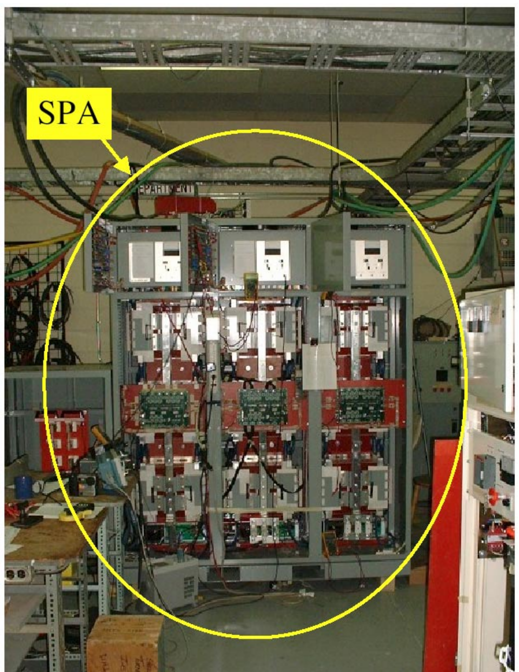
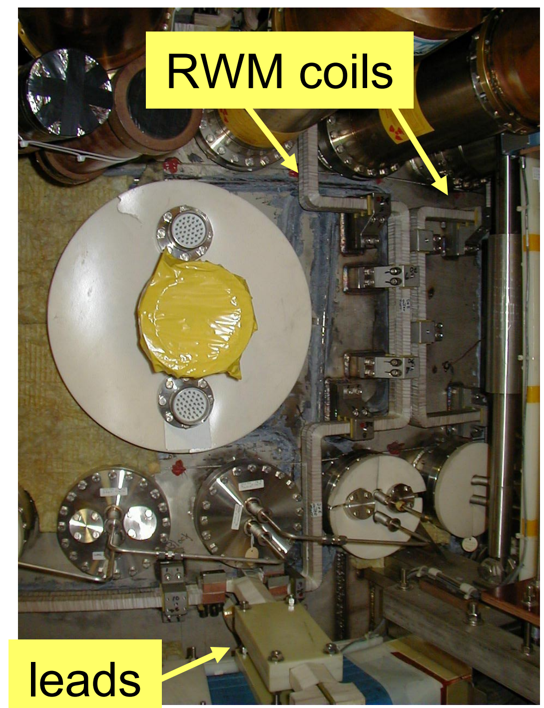
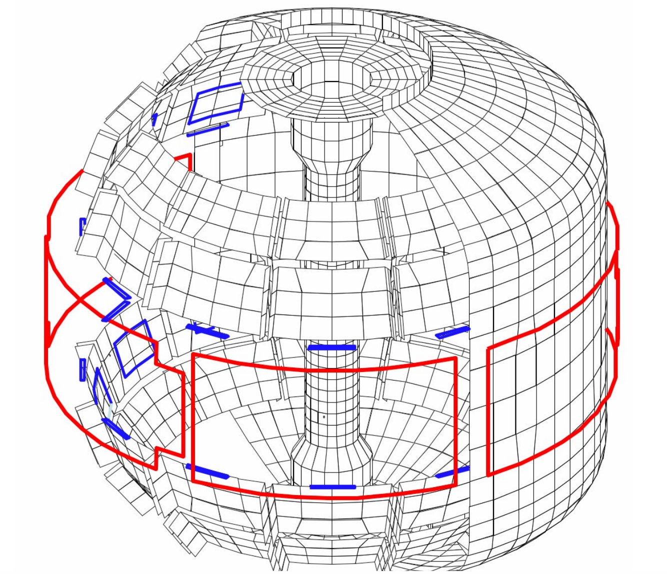
RWM stabilization system being installed for 2005 run

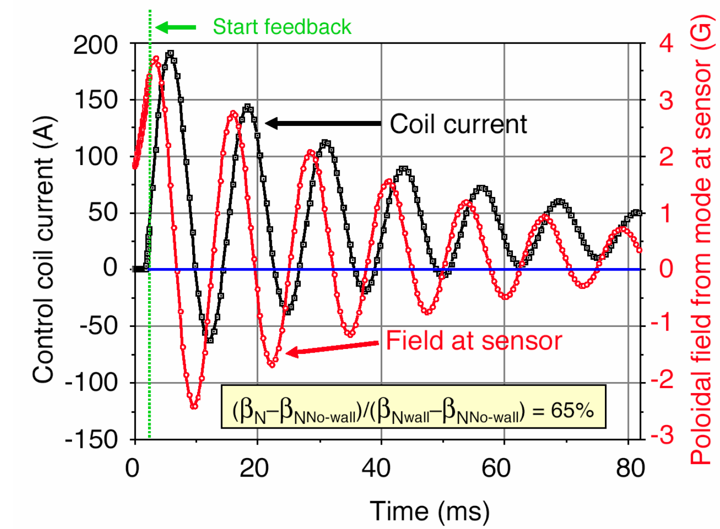
- RWM sensor array used in 2004 experiments
- 6 B_r coils now installed on NSTX
  - Pre-programmed capability in 2005 for RFA suppression / MHD spectroscopy experiments
- 3-channel switching power amplifier (SPA) on-site
- Real-time mode detection and control algorithm development in 2005 for feedback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





Physics design (VALEN code)



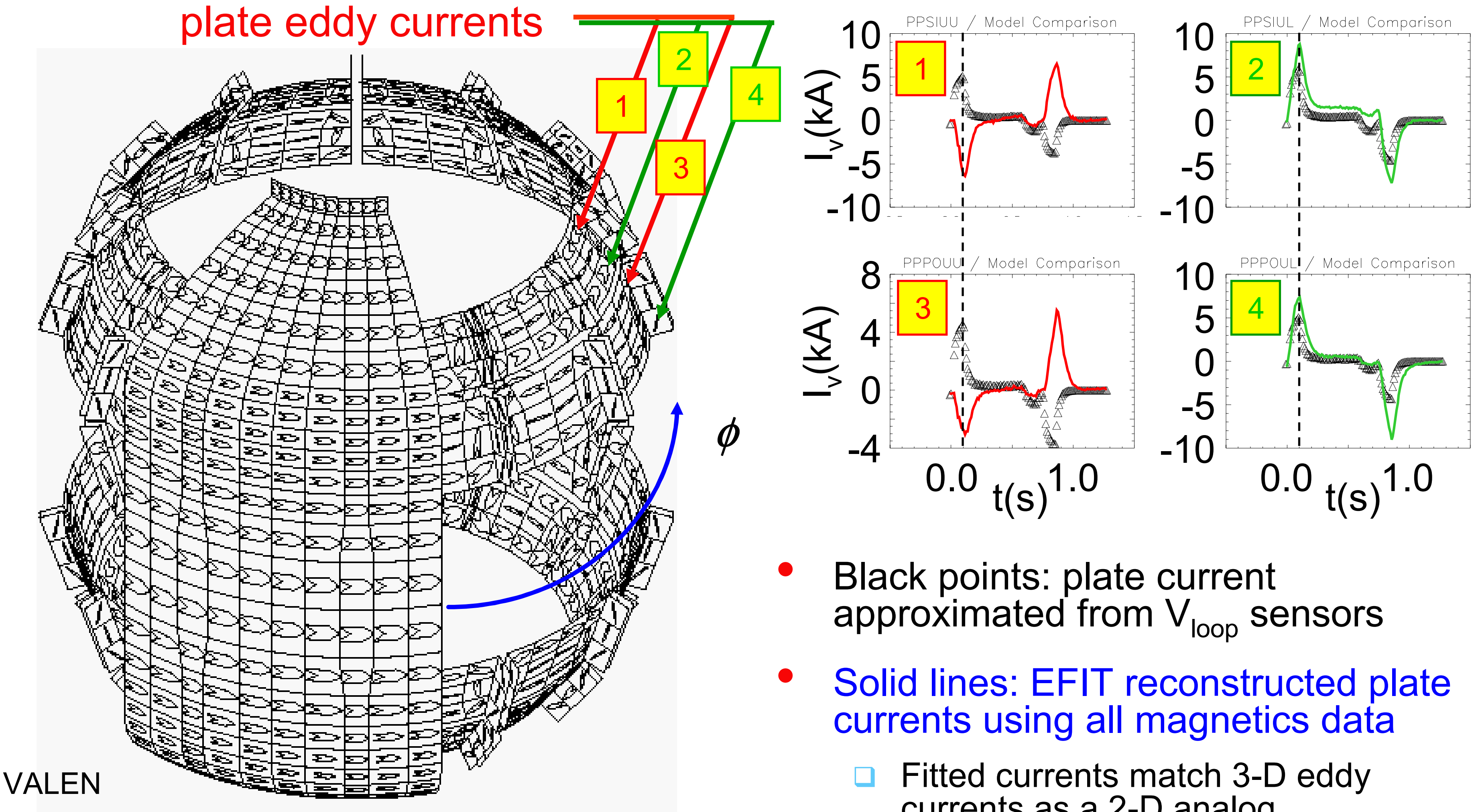


Between-shots equilibrium reconstruction with rotation introduced in 2004 (EFIT)*

- Data
  - 51 radial channel, Δt =10ms CHERS data generated between-shots
    - Dynamic (rotational) pressure $P_d(\psi,R)|_{z=0}$
    - P_i available – reduces error bars on "partial kinetic" $P(\psi,R)|_{z=0}$
  - Significant upgrade of divertor magnetics set / vessel voltage monitors
    - Reduces uncertainty in X-point position and plate currents
  - Over 350 total measurements are used per time point
    - Allows fit with *no* artificial constraints
    - One or two artificial constraints may be necessary to reduce noise
  - Over 11,000 shot*times run – further testing still needed for 100% reliability
- Physics constraints
  - Flux iso-surface constraint
    - Use $T_e = T_e(\psi(R)|_{z=0})$ *directly* from Thomson scattering data - rapid analysis
      - required to insure self-consistent solution with toroidal rotation
    - Better flux surface / q profile determination
    - Other data (e.g. soft X-ray emission) can be used as constraint

**in collaboration with Lang Lao (GA), C. Zhang (IPPCAS)*

Expanded magnetics set reproduces 3-D eddy currents as axisymmetric currents during OH ramp



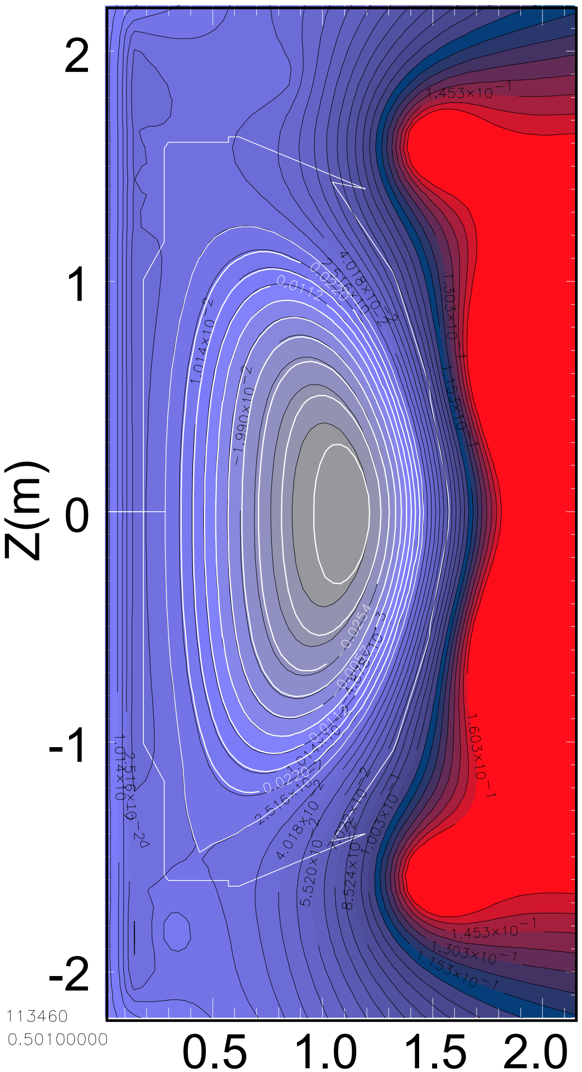
- Black points: plate current approximated from V_{loop} sensors
- Solid lines: EFIT reconstructed plate currents using all magnetics data
  - Fitted currents match 3-D eddy currents as a 2-D analog

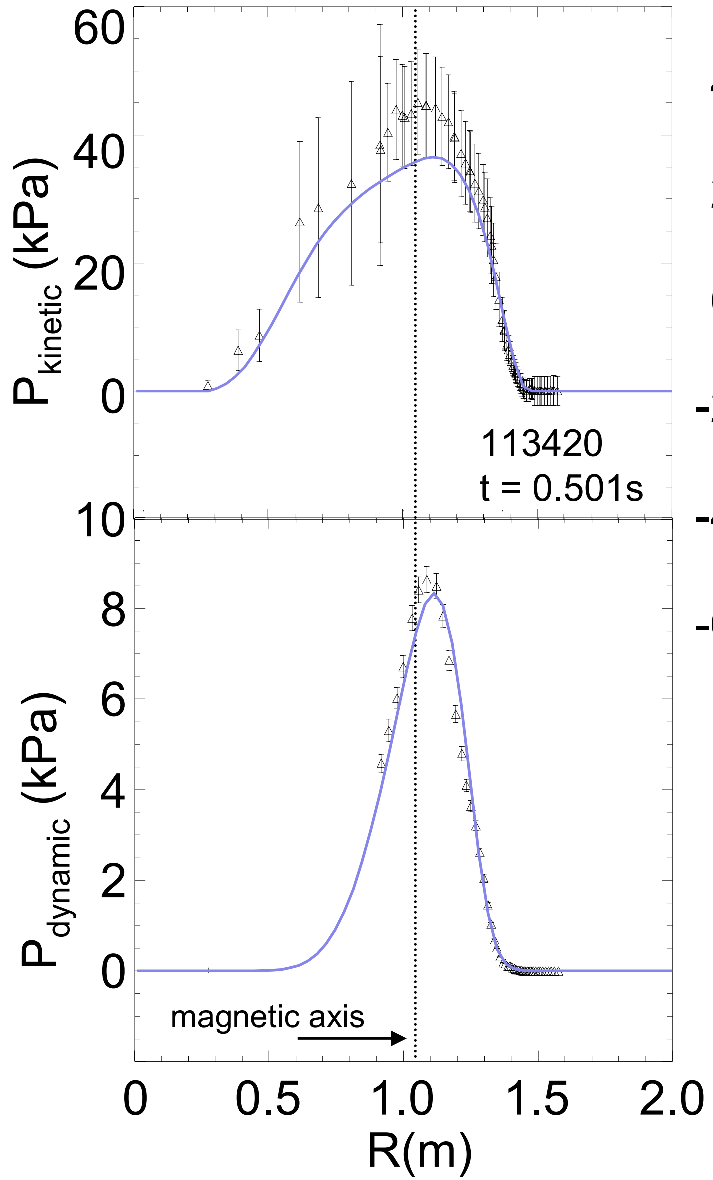
Pure toroidal flow allows a tractable equilibrium solution

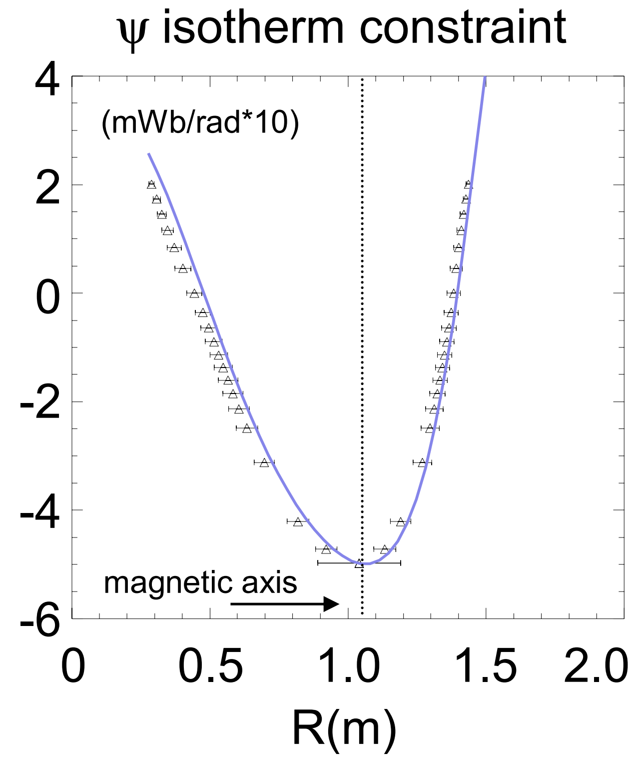
- Solve $\nabla\phi$, $\nabla\psi$, ∇R components of equilibrium equation
  - MHD: $\rho\mathbf{v} \bullet \nabla \mathbf{v} = J x B - \nabla p$; ρ = mass density
    - $\nabla\phi$: $f(\psi) = RB_t$
    - ∇R: $2P_d(\psi,R)/R = p'(\psi,R)|_\psi$; $P_d \equiv \rho(\psi,R)\omega^2(\psi)R^2/2$ (Bernoulli eq.)
    - $\nabla\psi$: $\Delta^*\psi = -\mu_0 R^2 p'(\psi,R)|_R - \mu_0{}^2 ff'(\psi)/(4\pi^2)$ (G.S. analog)
  - Pure toroidal rotation and $T = T(\psi)$ yields simple solution for p
    - $p(\psi,R) = p_0(\psi) \exp (m_{fluid}\, \omega^2(\psi)(R^2 - R_t{}^2)/2T(\psi))$

- Constraints for fit
  - EFIT reconstructs two new flux functions: $P_w(\psi)$, $P_0(\psi)$
    - $P_w(\psi) \equiv \rho(\psi)\, R_t{}^2\omega^2(\psi)/2$; $P_0(\psi)$ defined so that:
    - $p(\psi,R) = P_0(\psi) \exp (P_w(\psi)/P_0(\psi)\, (R^2 - R_t{}^2)/ R_t{}^2)$
  - Standard input: $P_w(\psi)$, $P_0(\psi)$ from approximation or transport code
  - New approach:
    - Solve for $P_w(\psi)$, $P_0(\psi)$ in terms of measured $P(\psi,R)|_{z=0}$, $P_d(\psi,R)|_{z=0}$

Significant shift of peak pressure off-axis due to rotation







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

NSTX

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)
- 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
- Effect of rotation on equilibrium reconstruction evaluated

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

Electronic reprints (please include EMAIL address)

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