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Toroidal Rotation Damping Physics in High Beta NSTX Plasmas

W. Zhu[1], S. A. Sabbagh[1], A. Sontag[1], R.E. Bell[2], J. Menard[2], B. LeBlanc[2], D. Stutman[3]

[1]*Department of Applied Physics and Applied Mathematics, Columbia University, New York, NY, USA*

[2]*Plasma Physics Laboratory, Princeton University, Princeton, NJ, USA*

[3]*Johns Hopkins University*

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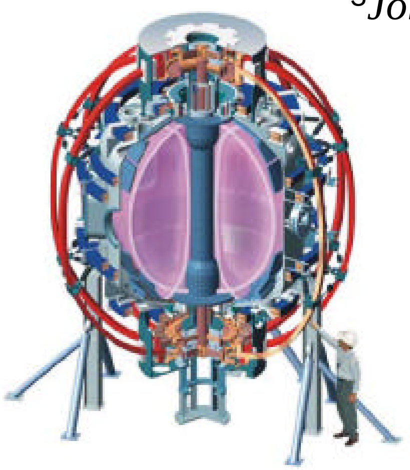

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NSTX

Abstract

Tokamak and spherical torus experiments show that the combination of sufficient plasma rotation and a resistive wall can stabilize ideal kink/ballooning modes at high plasma beta. However, rapid toroidal rotation damping has been observed in high beta plasmas, eliminating passive wall stabilization. Resonant electromagnetic drag may explain the localized rotation damping caused by resistive perturbations, while a global, non-resonant fluid drag in the helically perturbed field due to neoclassical toroidal viscosity qualitatively agrees with the global rotation damping observed during resistive wall mode activity. These characteristics are observed in NSTX, with relatively rapid and global damping occurring when beta exceeds the ideal MHD no-wall beta limit. Global damping experimentally expedites localized mode locking and plasma beta collapse. Quantitative comparison is made between theory and experiment to determine the physics and parameter dependence of this complex damping evolution.

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Rotation Damping Physics Investigated with a Variety of Models

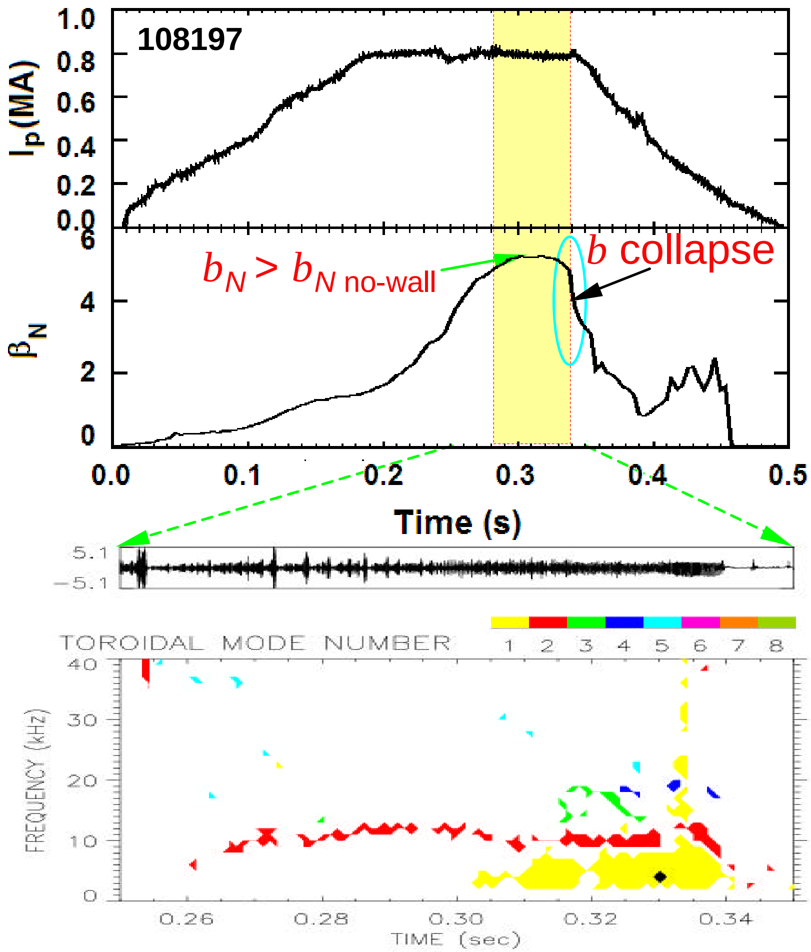
Motivation

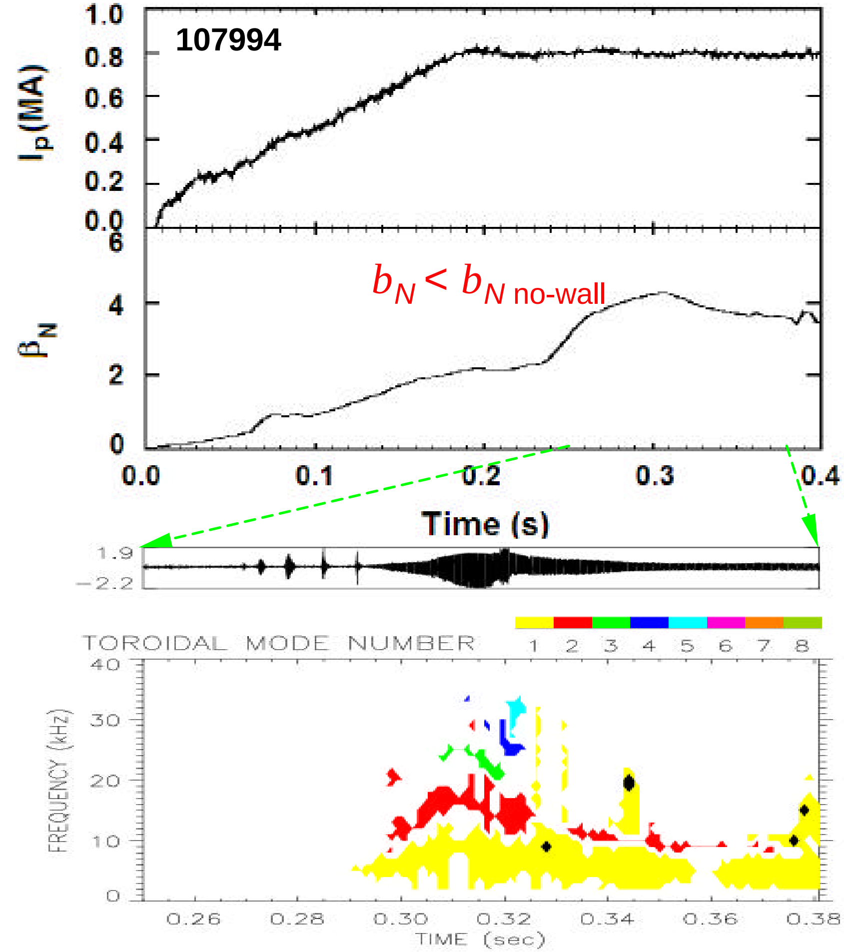
- Rotation damping impedes achievement of high plasma beta
- Quantitative comparison of experiment and physical models above and below $b_{N\ \text{no-wall}}$ can give critical understanding of rotation damping

Outline

- Resonant electromagnetic torque: mode and error field
- Resonant electromagnetic torque: mode and conducting wall
- Plasma inertia and viscosity
- Other modes: non-resonant ideal perturbation

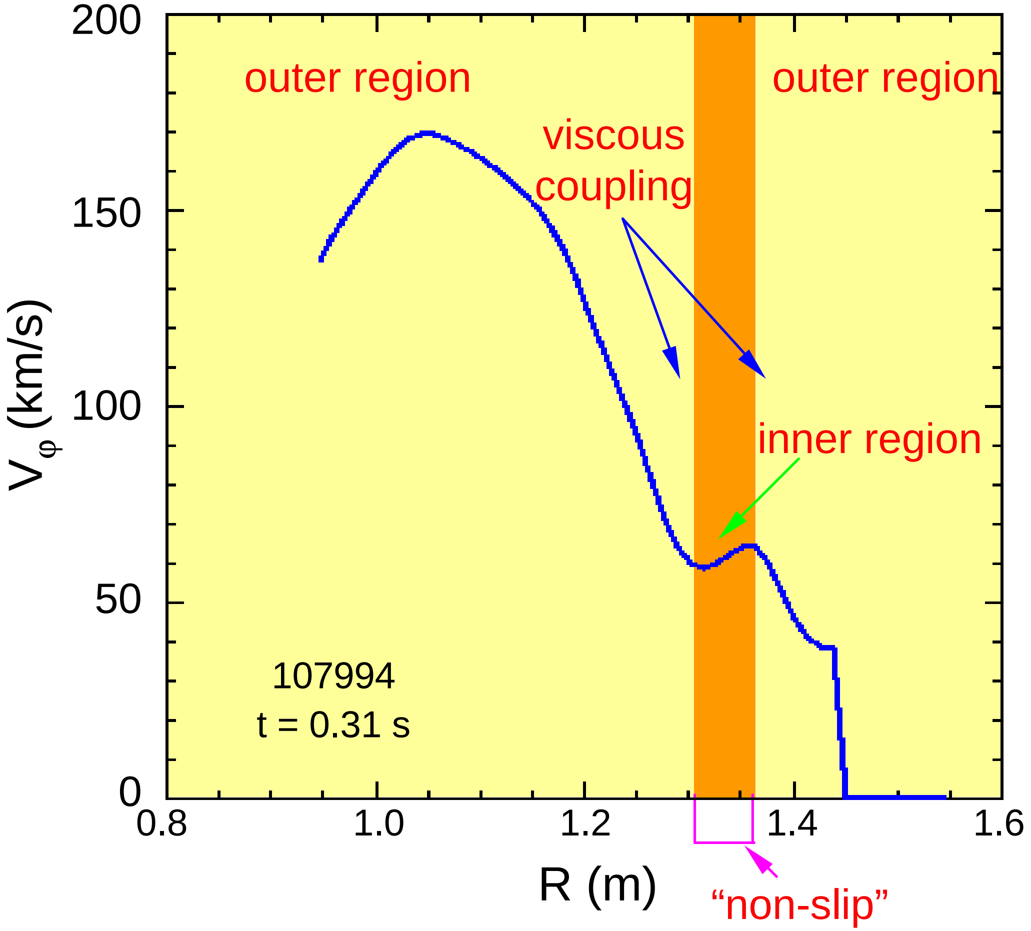
Resistive Perturbations Occur Above and Below $b_{N\ \text{no-wall}}$





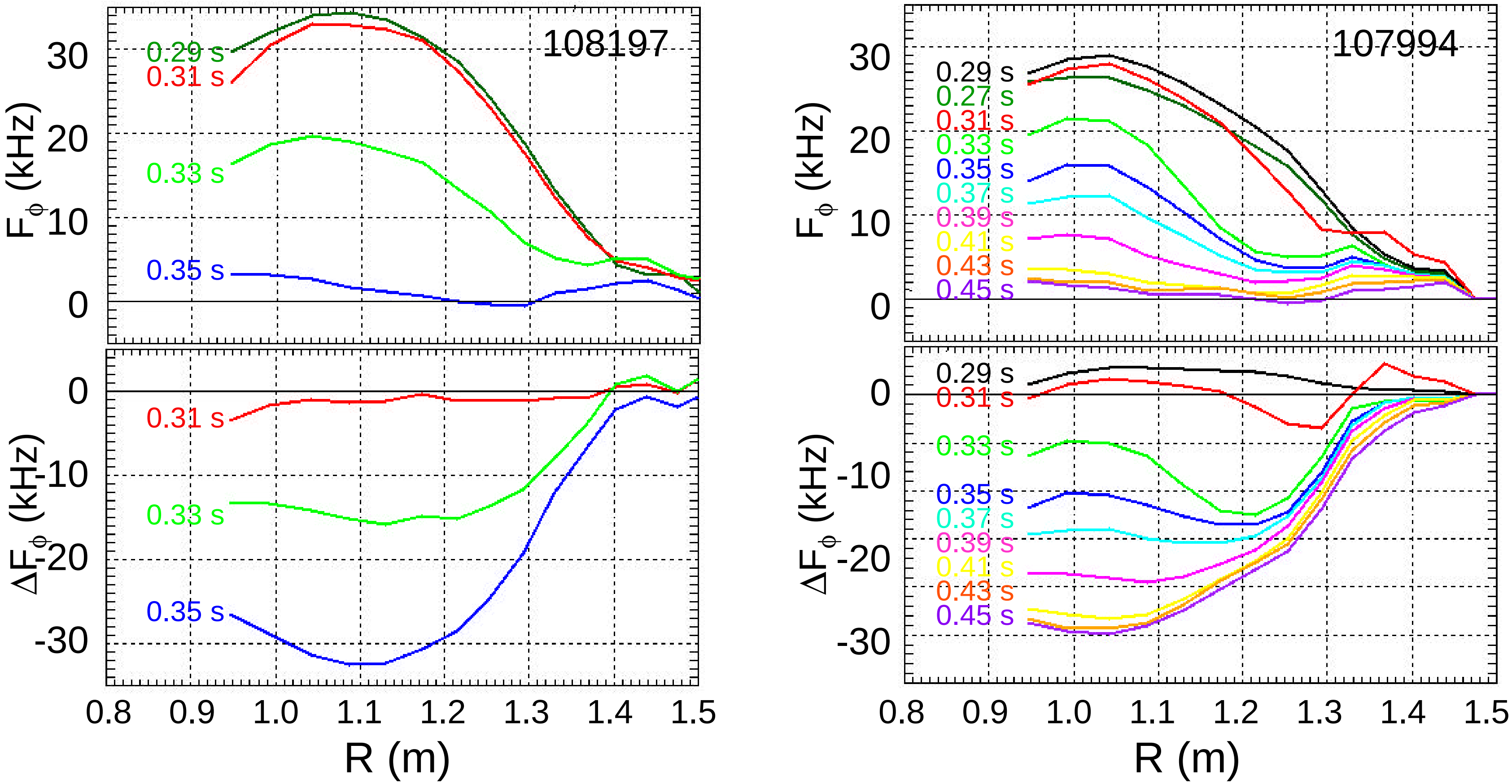
- When $b_N > b_{N\ \text{no-wall}}$ tearing mode can co-exist with resistive wall mode(RWM)

Analyze Torque Balance with Resonant and other Physical Mechanisms



- Electromagnetic resonant torque within inner region
- Viscous coupling to outer region
- Additional torques
  - Non-resonant ideal perturbation torque

Large Increase in Rotation Damping When $b_N > b_N$ no-wall



- RWM cause global rotation damping that is ~3 times faster in the core than that of rotating modes alone
- Rotating modes cause rotation damping that is localized and diffusive

Analysis of Electromagnetic Torques Exerted on the Plasma

- Plasma toroidal torque balance equation

$$r\,r\left(\frac{\partial\Omega_j}{\partial t}\right)-\frac{\partial}{\partial r}\left(r\,m_\perp r\frac{\partial\Omega_j}{\partial r}\right)=r f_{non\_resonant}+\frac{T_{j\ EM}}{4p^2 wR_0^3}d\left(r-r_s\right)$$

Inertia | Viscosity | Non-resonant torque | Resonant J×B torque

- Ω_j : Plasma rotation from charge exchange recombination spectroscopy (CHERS)
- r_{s+}, r_{s-} : Island inner/outer radii from Thomson scattering and CHERS
- $r=nm$: Plasma density from Thomson scattering
- R_0 : Plasma major radius from EFIT
- $m_\perp$: Plasma viscous coefficient

Two Types of Resonant Torques Analyzed

- Interaction of tearing mode with NSTX static error field

$$T_{\varphi\, EM_{err}} = 4\pi^2 R_0 \frac{r_s^2}{\mu_0}\frac{n}{m}\left|\delta B_{r\_island}\right|\left|\delta B_{r\_error\_field}\right|^{*}$$

- Interaction of tearing mode with NSTX conducting wall

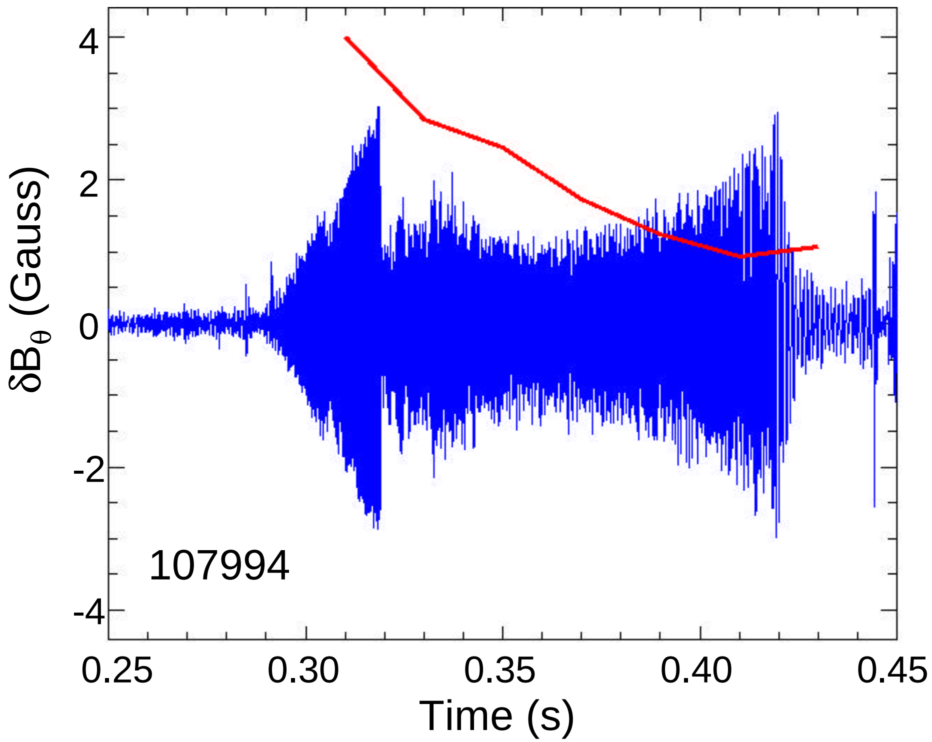
$$T_{\varphi\, EM_{wall}} = 4\pi^2 R_0 \frac{r_s^2}{\mu_0}\frac{n}{m}\frac{(\omega\tau_w)(r_{s+}/r_w)^{2m}}{1+(\omega\tau_w)^2\left[1-(r_{s+}/r_w)^{2m}\right]^2}\left|\delta B_{r\_island}\right|^{2*}$$

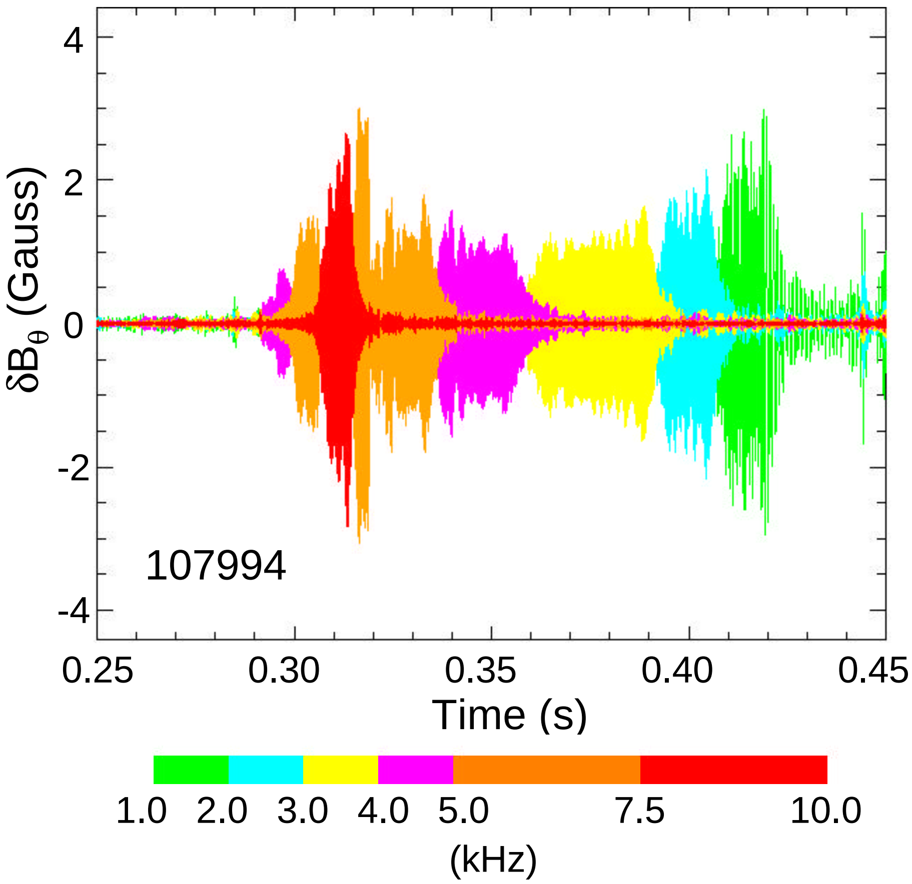
- *m,n* : mode numbers from toroidal Mirnov array and EFIT

* R. Fitzpatrick, Nuclear Fusion 33 (1993) 1049.

Resonant Mode Interaction with NSTX Static Error Field

Computed *dB* Required to Generate Observed Rotation Damping in Reasonable Agreement

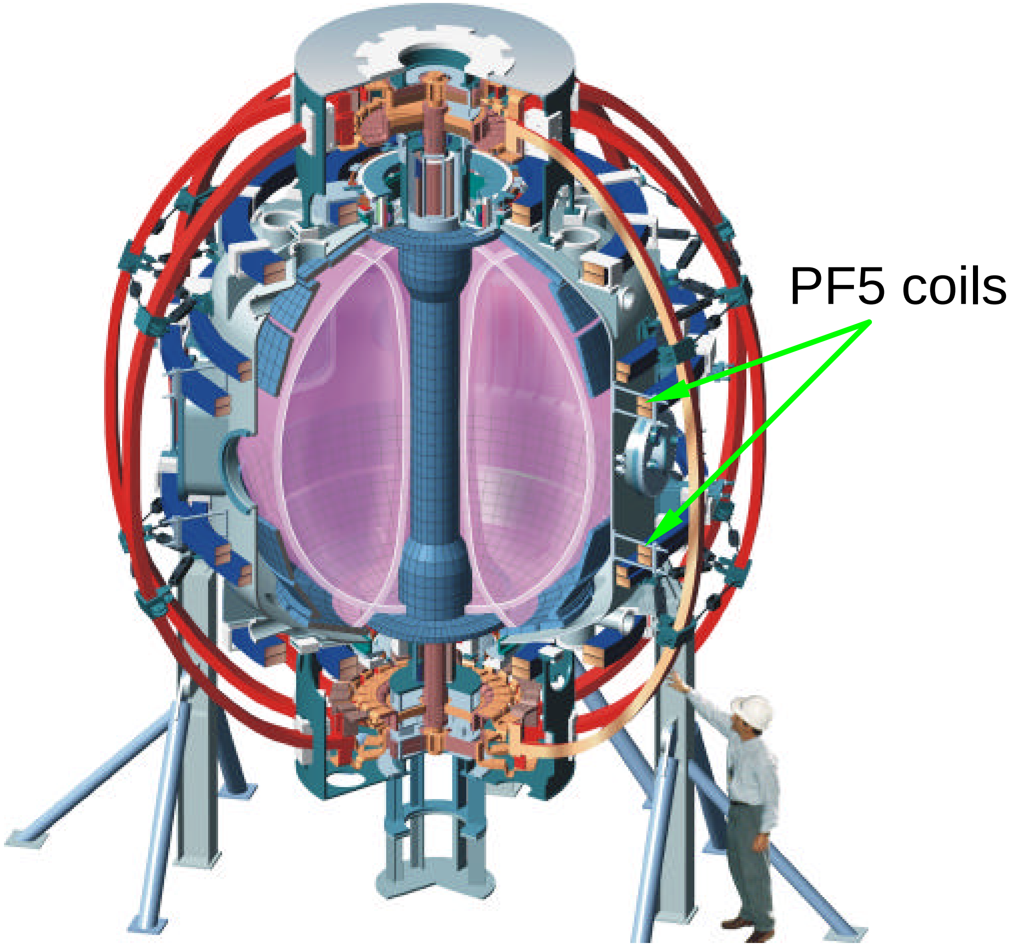




- Post-error field correction shots with *m* /*n* = 2/1 tearing modes
- Red line: calculated required *dB* to cause measured rotation damping
- Blue signal: *dB* measured by Mirnov coil

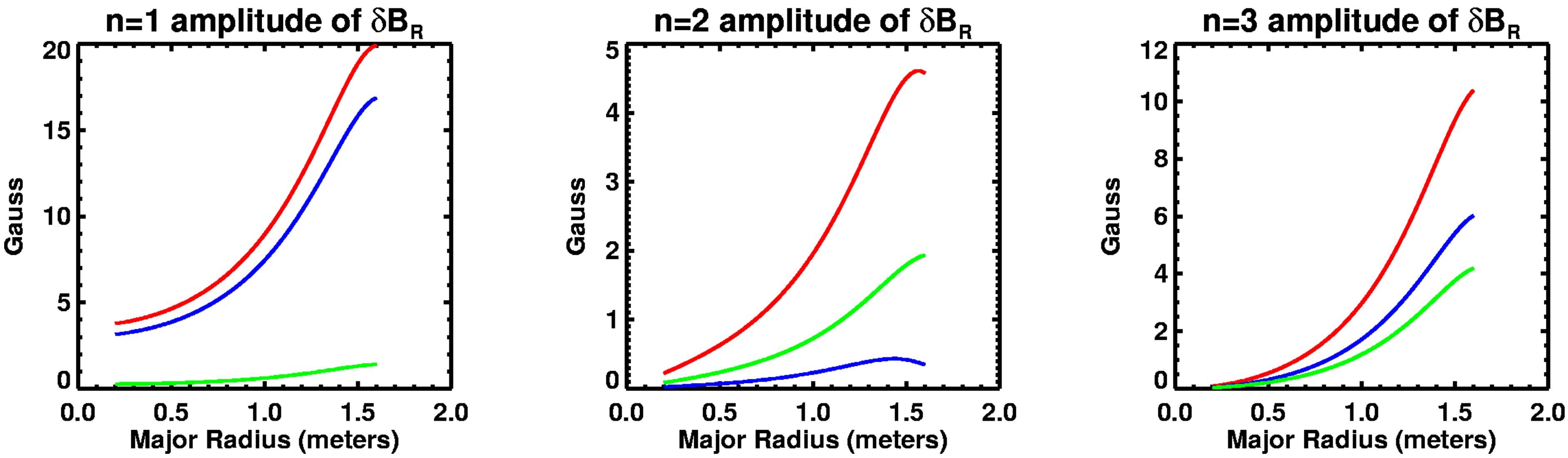
- Mode slows and grows in time

NSTX Error Field Primarily Caused by Misalignment of PF5 Coils



- PF5 is one set of the poloidal field coils placed symmetrically above and below the midplane outside the vacuum vessel for equilibrium control
- PF5 re-aligned in December 2001

PF5 Alignment Greatly Reduces n = 1 Error Field



- **n=1 amplitude reduced by factor of 12**
- n=2 amplitude increased slightly
  - Still only 2 Gauss at plasma edge
- n=3 is largest predicted amplitude
  - 4 Gauss at plasma boundary
  - Localized effect from coil feeds

RED = magnetic measurements **before correction**

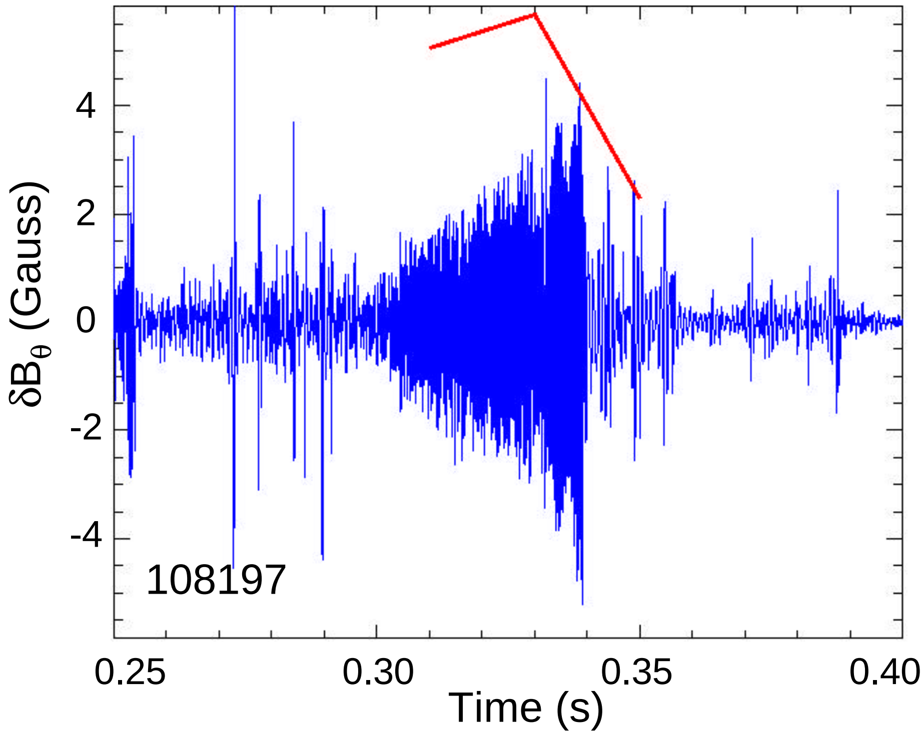
Blue = using measured coil radius **before correction**

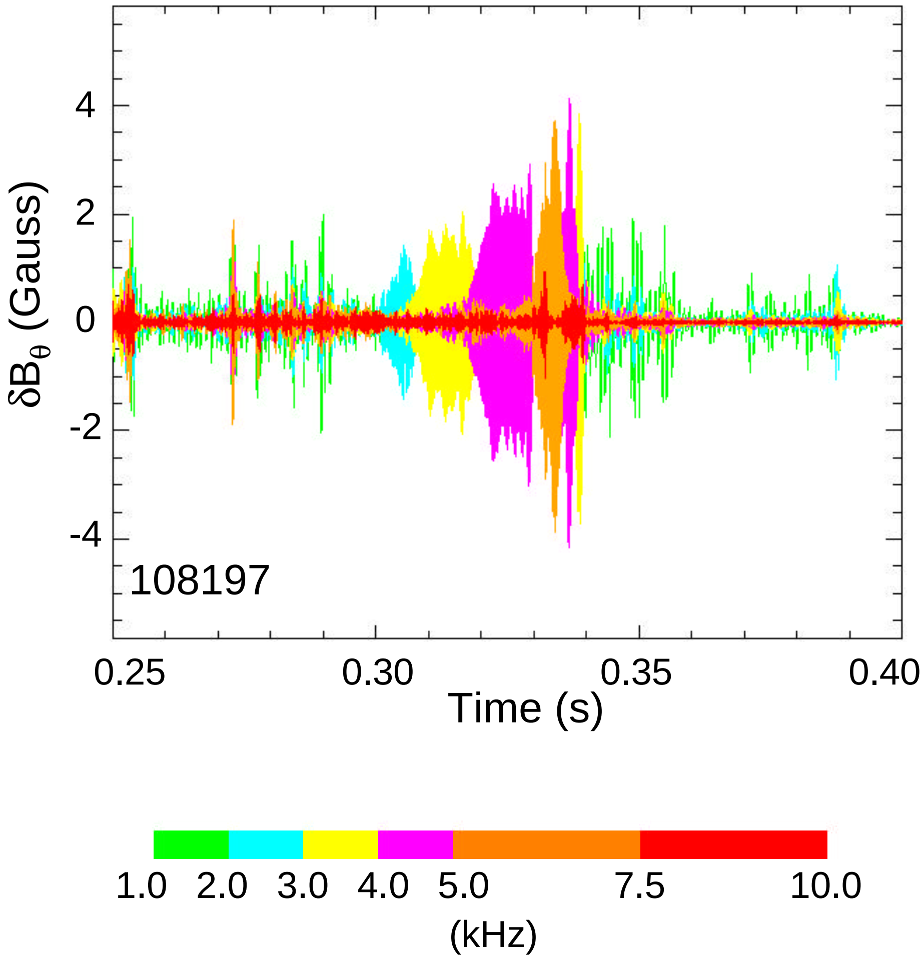
Green = using measured coil radius **after correction**

Calculations assume I_{PF5}=10kA

J. Menard

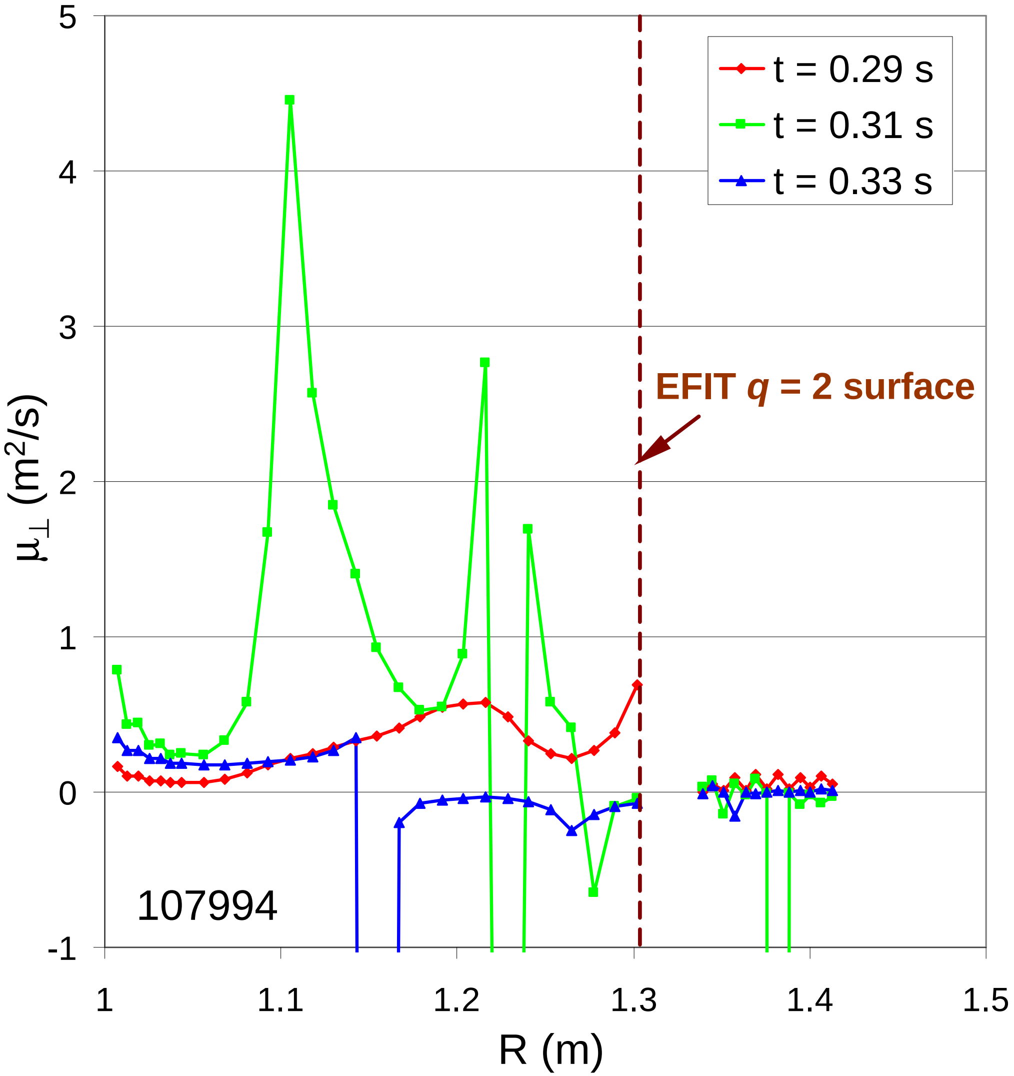
J´B Torque Balanced by Viscosity and Inertia can Account for the Local Rotation Damping near the Island





- Red line: calculated required *dB* to cause measured rotation damping
- Blue signal: *dB* measured by Mirnov coil

Viscosity Calculated in Near the Island



- Equation of motion in the outer region

$$\frac{\partial V}{\partial t} = m_\perp \frac{\partial^2 V}{\partial r^2}$$

- For shot #107994

$$r < r_s : m_\perp \simeq 0.6 - 0.8\, m^2/s$$

$$r > r_s : m_\perp \simeq 0.0 - 0.2\, m^2/s$$

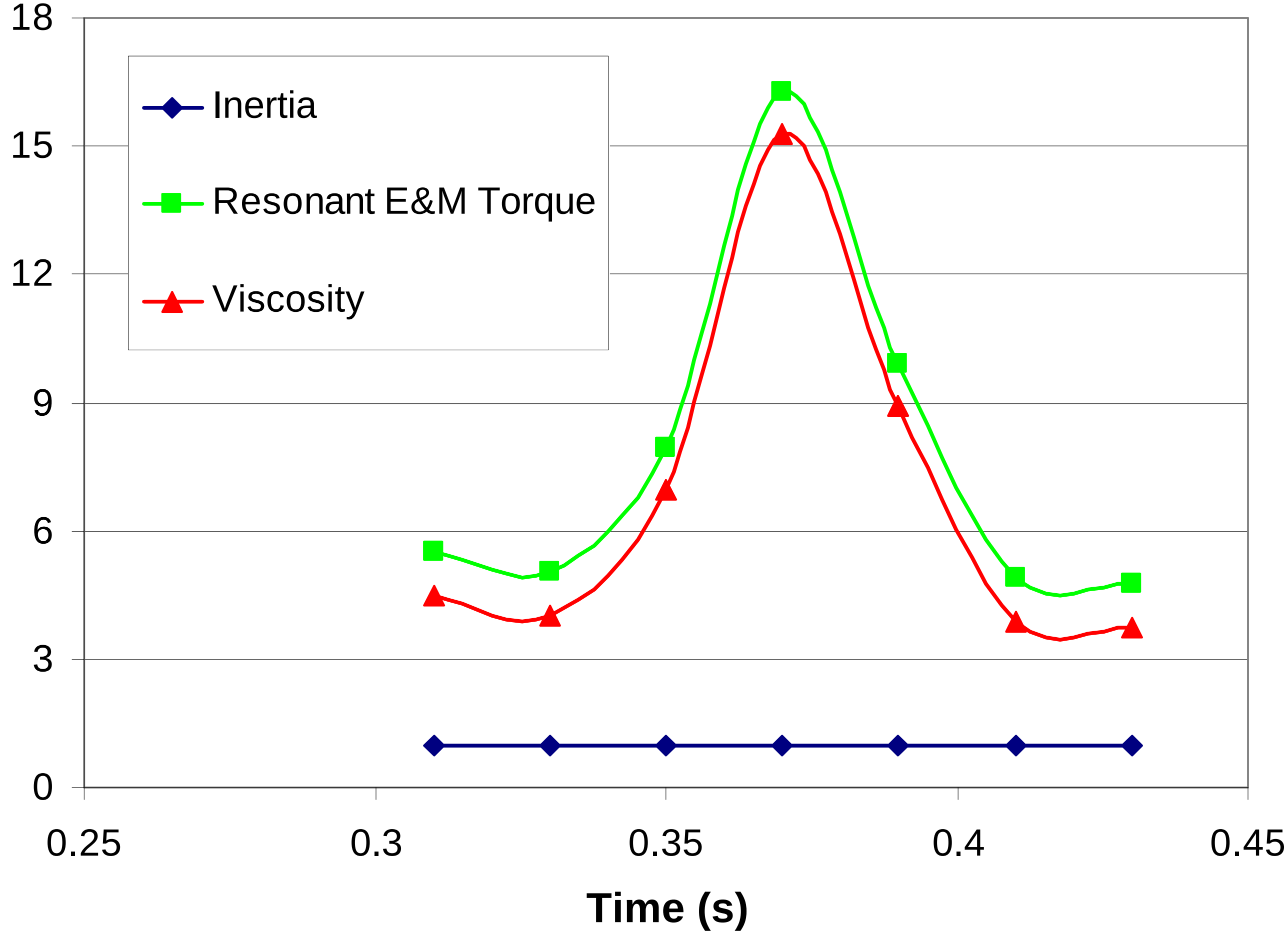
- “Global” model*

$$m_\perp = \begin{cases} \infty & r < r_c \\ m_c & r_c \le r \le a \end{cases}$$

$$m_c \simeq \frac{a^2 - r_c^2}{4t_E} = 1.5\, m^2/s$$

* R. Fitzpatrick, et. al, Phys. Plasmas 6 (1999) 3878.

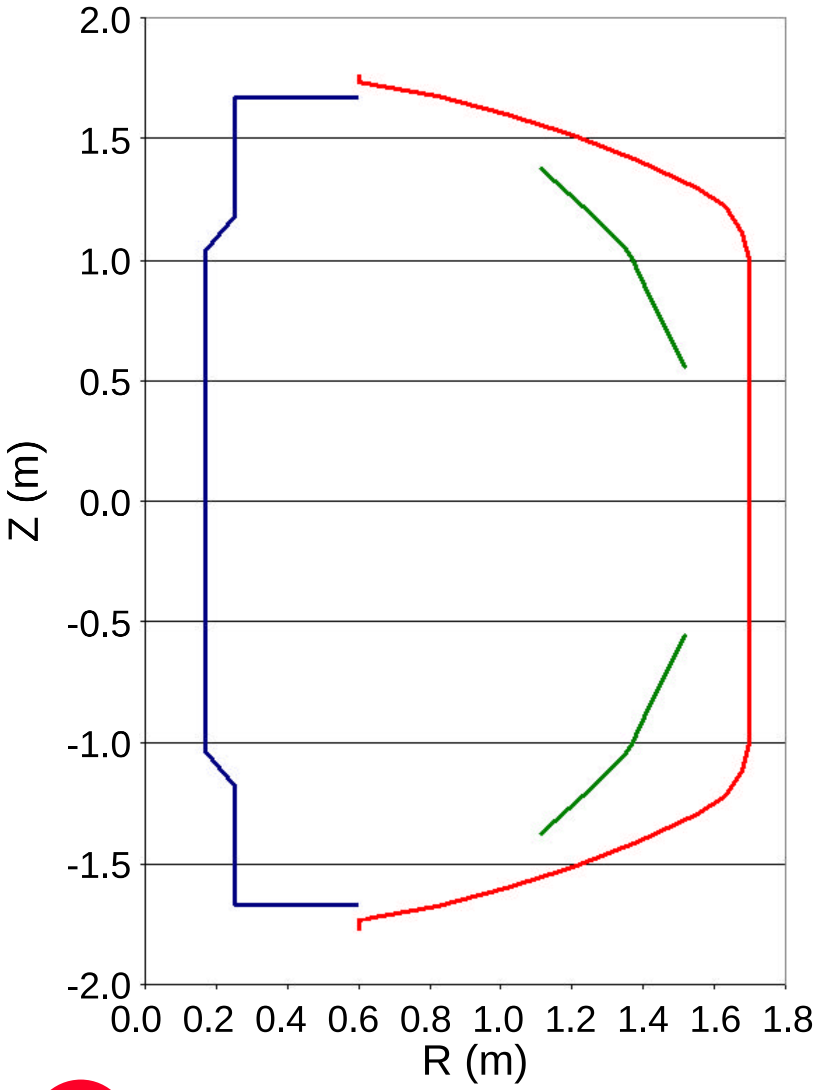
Viscosity Plays an Important Role in Local Torque Balance



- Magnitude of each term normalized to inertia term

Resonant Mode Interaction with NSTX Conducting Wall

NSTX Conducting Wall Made of Stainless Steel and Inconel



- Red: stainless steel

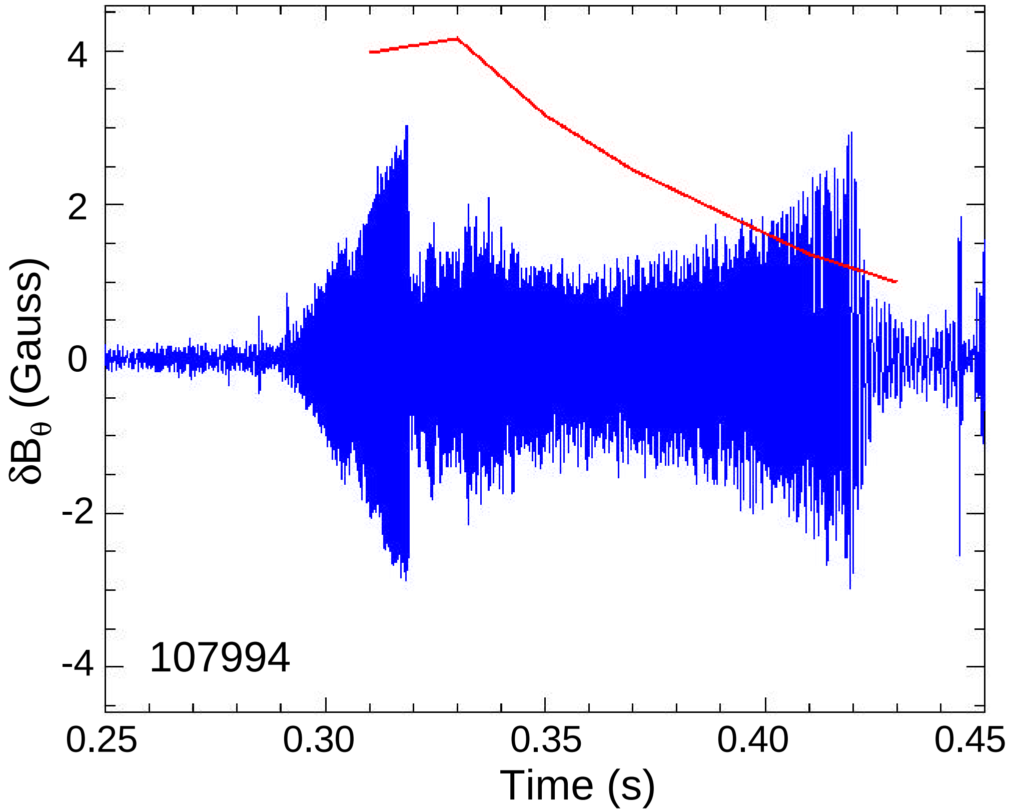
  $h = 77 \times 10^{-8}$ ohm meters
- Blue: Inconel

  $h = 130 \times 10^{-8}$ ohm meters
- Green(passive plates): copper

  $h = 2.1 \times 10^{-8}$ ohm meters
- Ignore all ports
- $t_w \simeq m_0 s_w d_w r_w / 2m^*$
- $t_{w\,eff}$ = 0.0133/*m* seconds
- $r_{w\,eff}$ = 1.43 meters
- Passive plates not included when computing $t_{w\,eff}$ and $r_{w\,eff}$

* R. Fitzpatrick, Nuclear Fusion 33 (1993) 1049.

Qualitatively Agreement before Mode Locking Phase

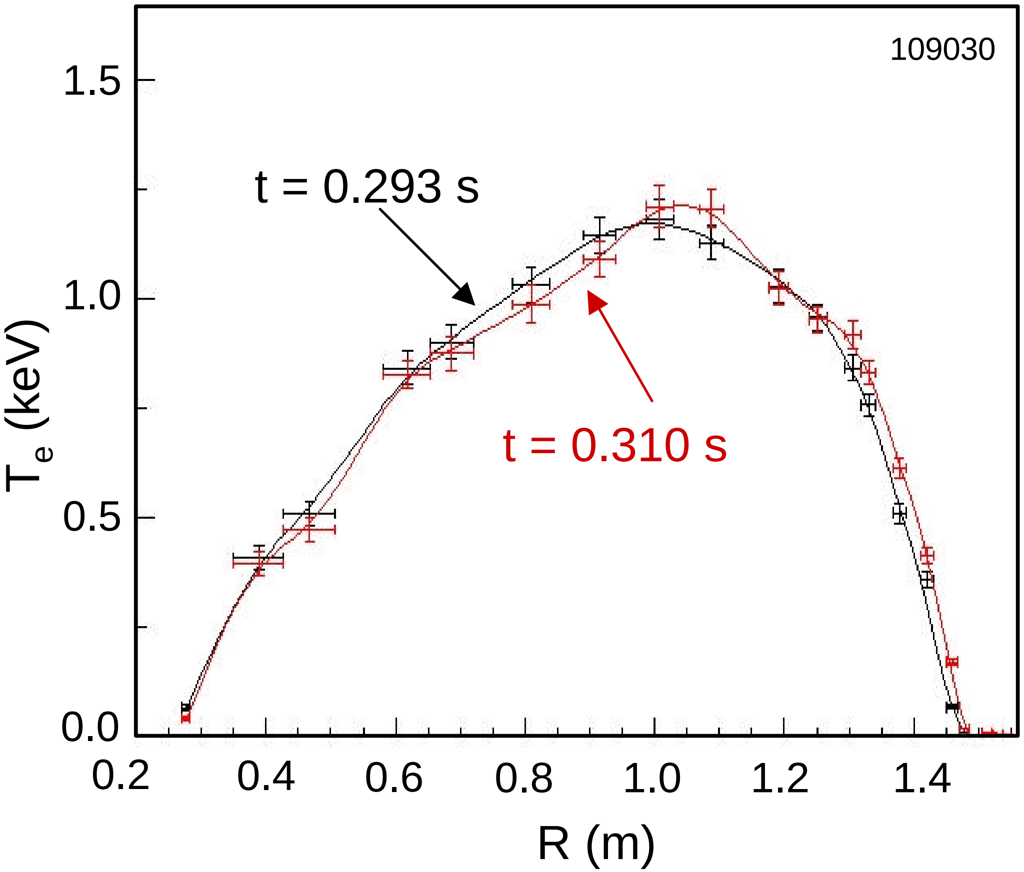


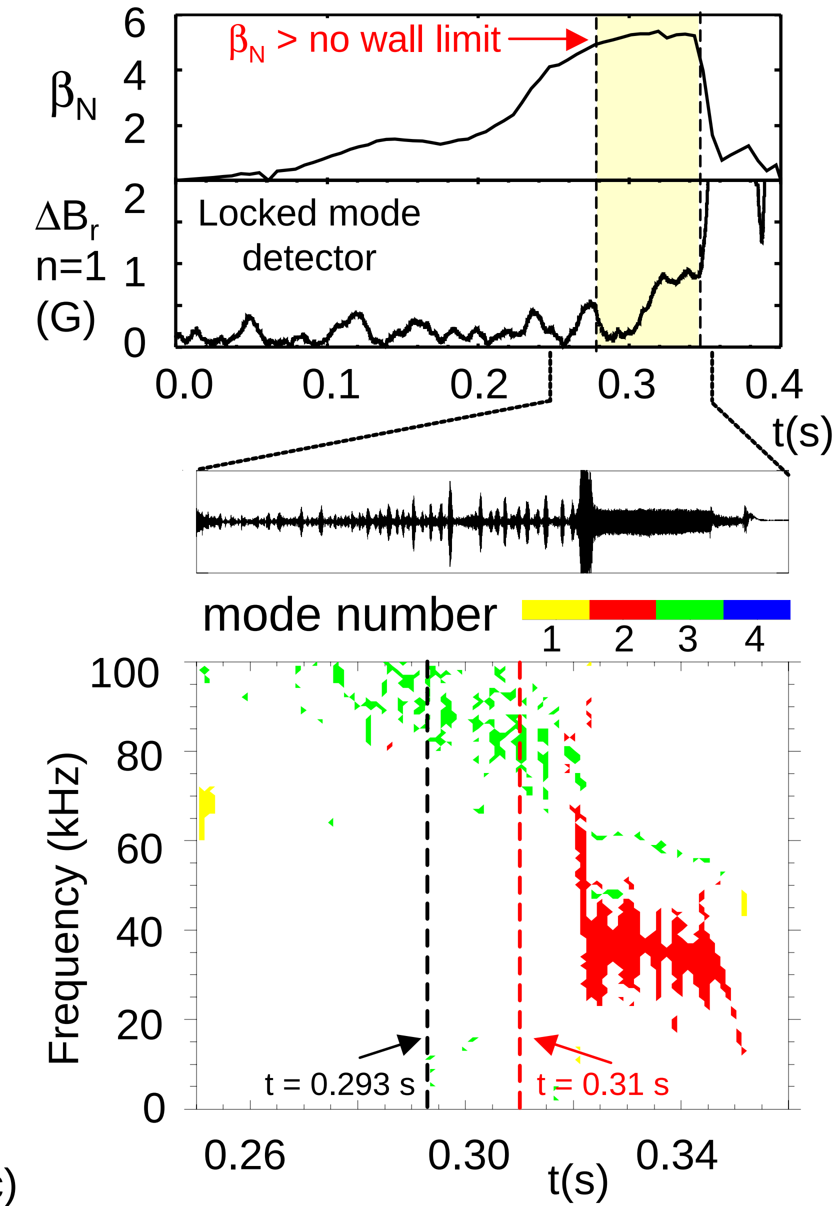
- Red line: 1/30 of calculated required *dB* to cause measured rotation damping
- Blue signal: *B* measured by Mirnov coil

- Quantitatively ~30 times measured δB
- Disagreement entering locking phase

Non-resonant Ideal Perturbation

T_e perturbation measured during RWM



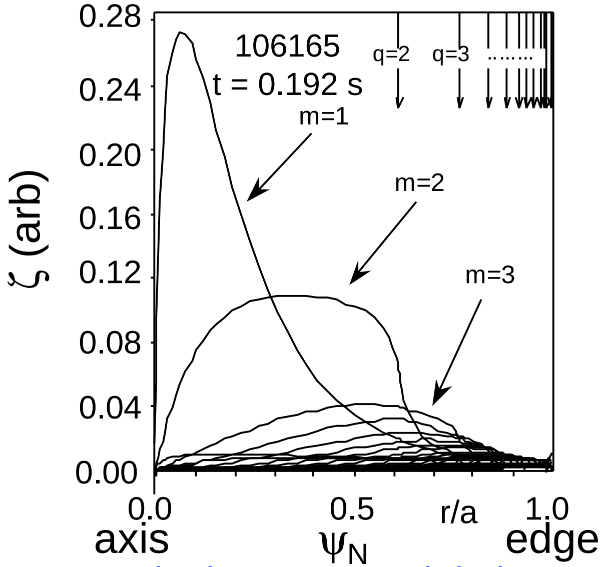


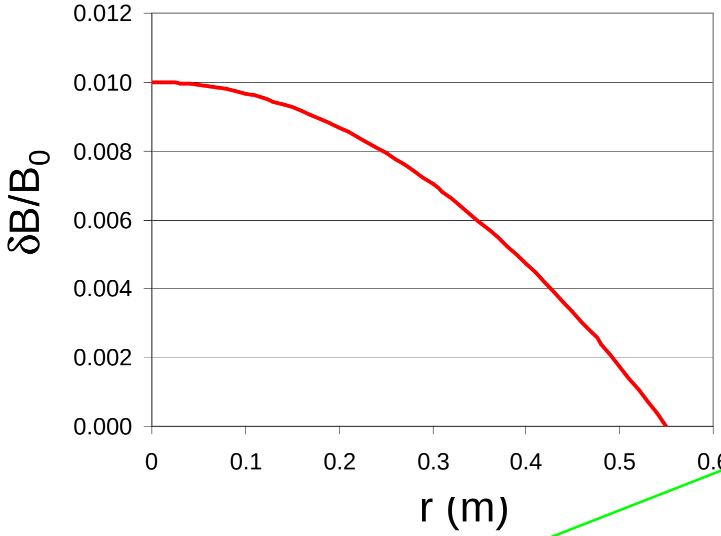
- No low frequency (< 80 kHz) rotating modes observed during measured δT_e
- δT_e displacement precedes n=2 rotating mode

Thomson scattering (LeBlanc)

Non-resonant Neoclassical Viscous Force Exerted Across Plasma Core

Mode decomposition



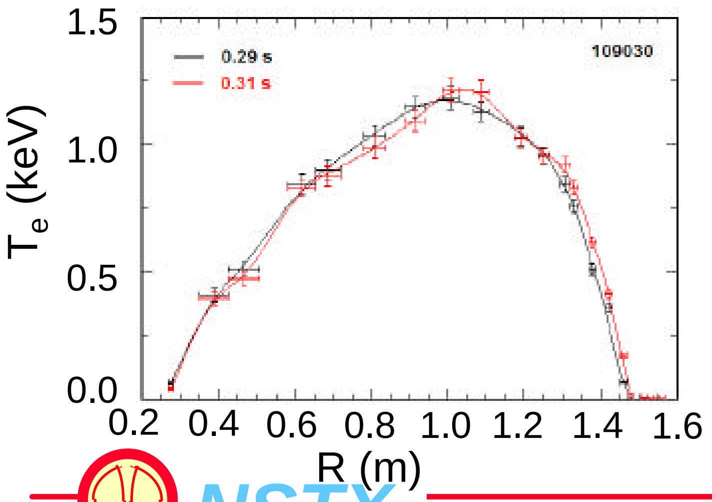


- Assume rough estimate of dB/B_0

$$\sim T_i^{1/2} \text{ (measured)} \qquad \left(\frac{dB}{B_0}\right)^2$$

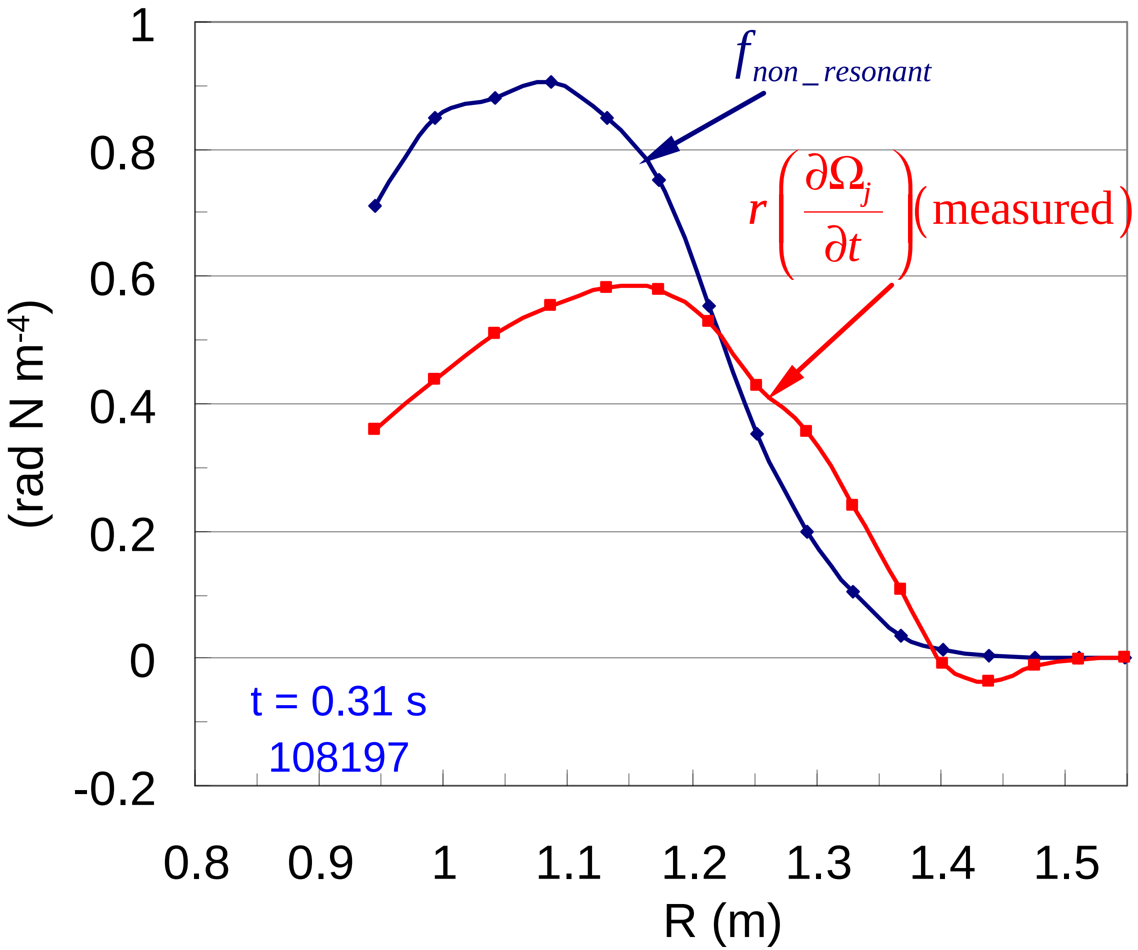
$$f_{non\_resonant} = \frac{p^{1/2} p_i}{R_0 v_{T_i}} \Omega_j \sum_{m,n\neq 0} \frac{\left(B_{0q} b_q^{m,n} + B_{0j} b_j^{m,n}\right)^2}{B_0^4} \frac{n^2 q}{|m-nq|}$$

T_e perturbation measured during RWM



- Assume $dB/B_0 \simeq dr_{T_e}/a$
- $dr_{T_e}/a \sim 10^{-2}$
- Take the form of $dB(r)/B_0 = -0.033r^2 + 0.01$
- Assume $n^2 q/|m-nq| \sim O(1)$ away from rational surfaces

Non-resonant Viscous Physics Model Matches the Measured Global Damping Profile in RWM Plasma



- Force Balance

$$r\left(\frac{\partial \Omega_j}{\partial t}\right) = f_{non\_resonant}$$

- Neoclassical viscous torque has good agreement with observed global damping in RWM plasma

Physics Models Are Being Applied to Understand Rotation Damping in High b ST Plasmas

- Resonant mode interaction with NSTX static error field balanced by viscosity and inertia in reasonable quantitative agreement with local rotation evolution near rational surface

- The wall eddy currents in NSTX are too weak to cause observed rotation damping by themselves

- Higher than required *dB* observed in final locking phase

- Non-resonant neoclassical viscous drag model estimate in good quantitative agreement with measured global damping in RWM plasma

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