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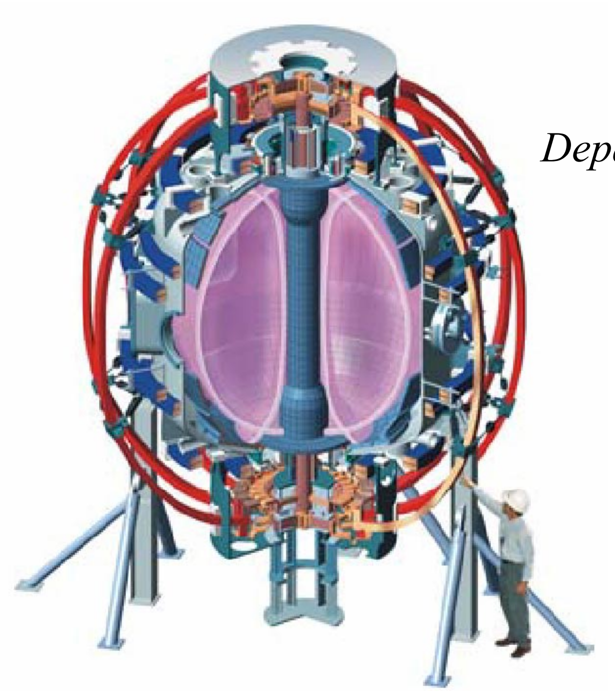
Toroidal Rotation Damping in NSTX Plasmas



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Columbia University

NSTX Physics Meeting

June 21, 2004

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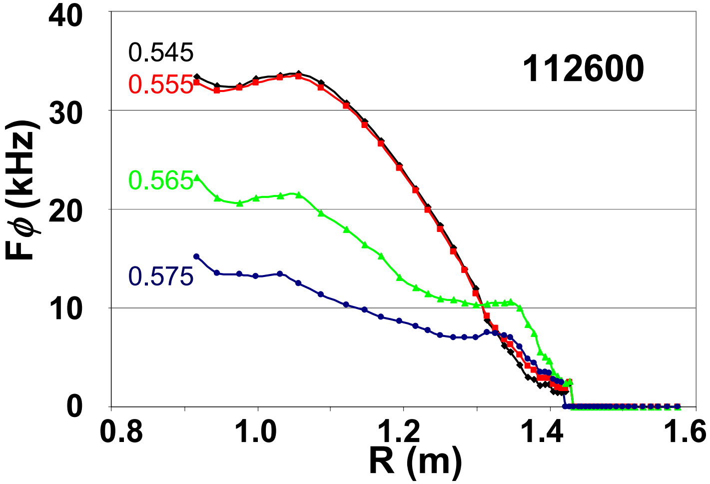
NSTX

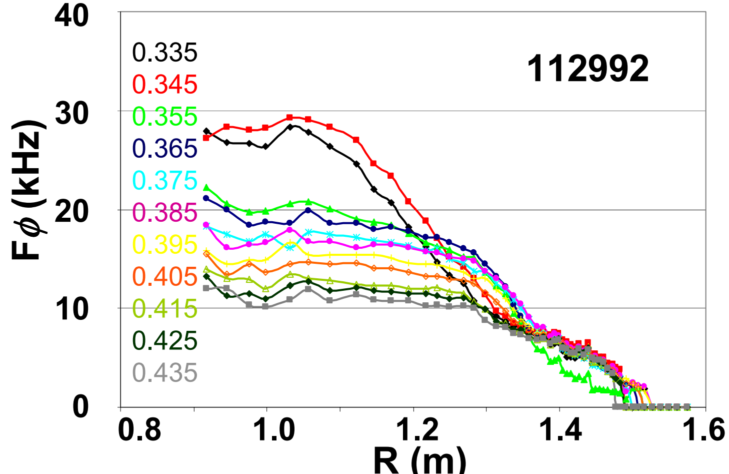
Physics Models Are Being Applied to Understand Rotation Damping in NSTX Plasmas

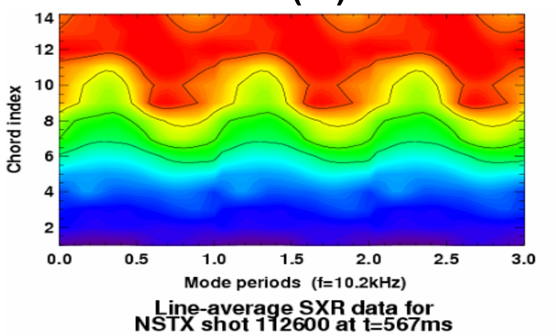
- Motivation
  - Rotation damping impedes achievement of high plasma beta
  - Comparison of theory and experiment can give critical understanding of rotation damping

- Outline
  - Survey of rotation damping observed
  - Theoretical models of rotation damping
  - Quantitative comparison of theory to experiment

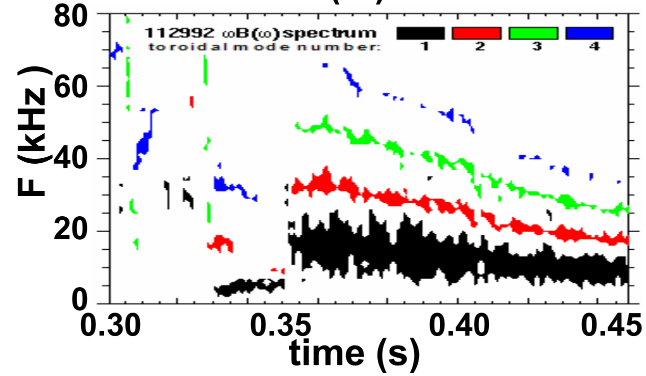
Large MHD Instabilities can Decrease Plasma Rotation Globally





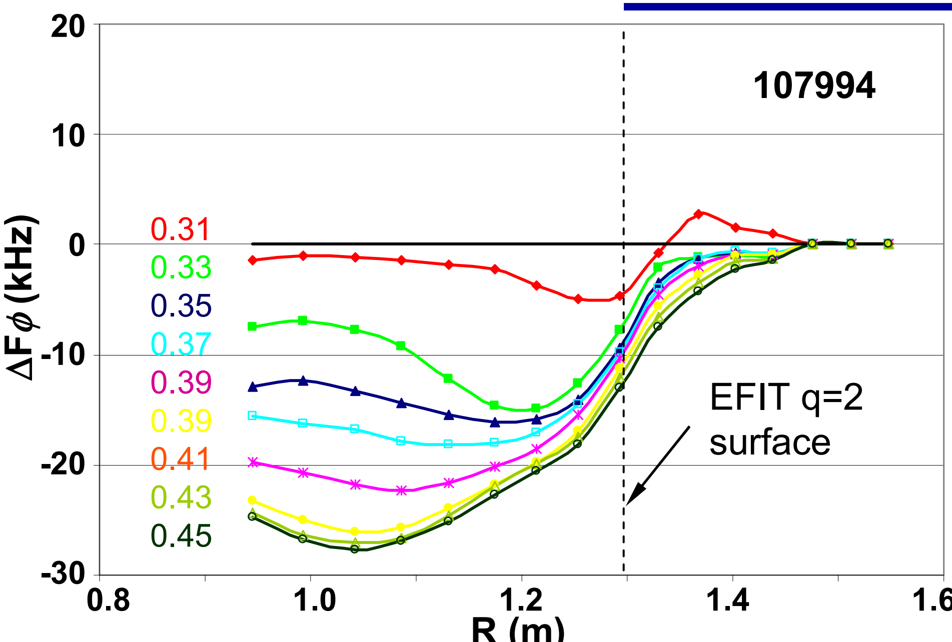


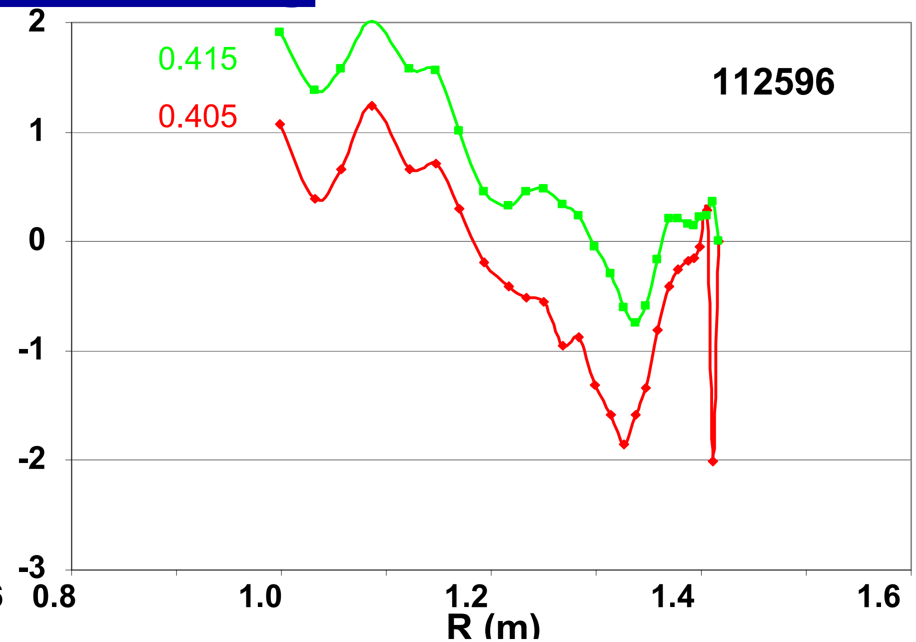
SXR plot by J. Menard

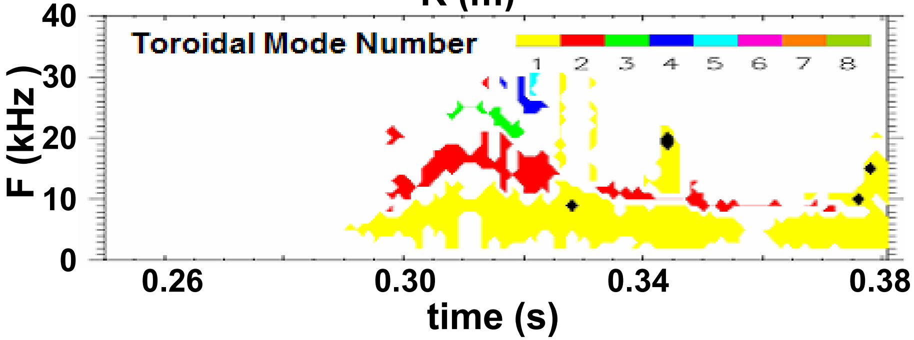


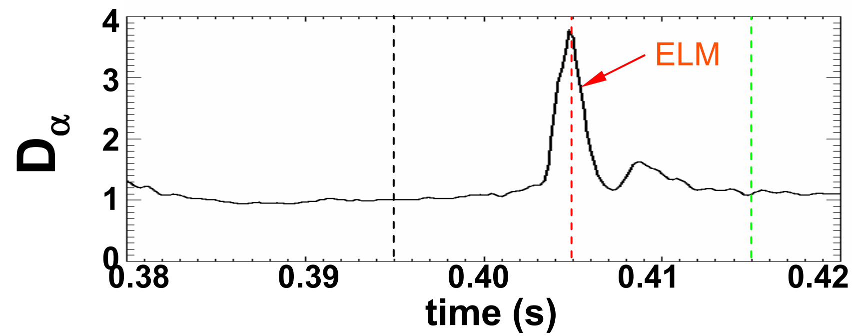
- 1/1 island causes fast global damping
- Momentum transfer across q=1
- Rotation flattens then damps slowly
- Large or multiple islands a candidate

Small Islands or ELMs Cause Localized Rotation Damping









- Rotation damping is diffusive from rational surface
- ELM rotation damping is ~8 times slower than for global mode; rotation recovers

Rotation Evolution Equation used for Experimental Comparison

$$\rho R^2\left(\frac{\partial\Omega_\phi}{\partial t}\right)=T_{\text{damping}}=T_{\text{NTV}}+T_{J\times B}+T_{\text{viscosity}}$$

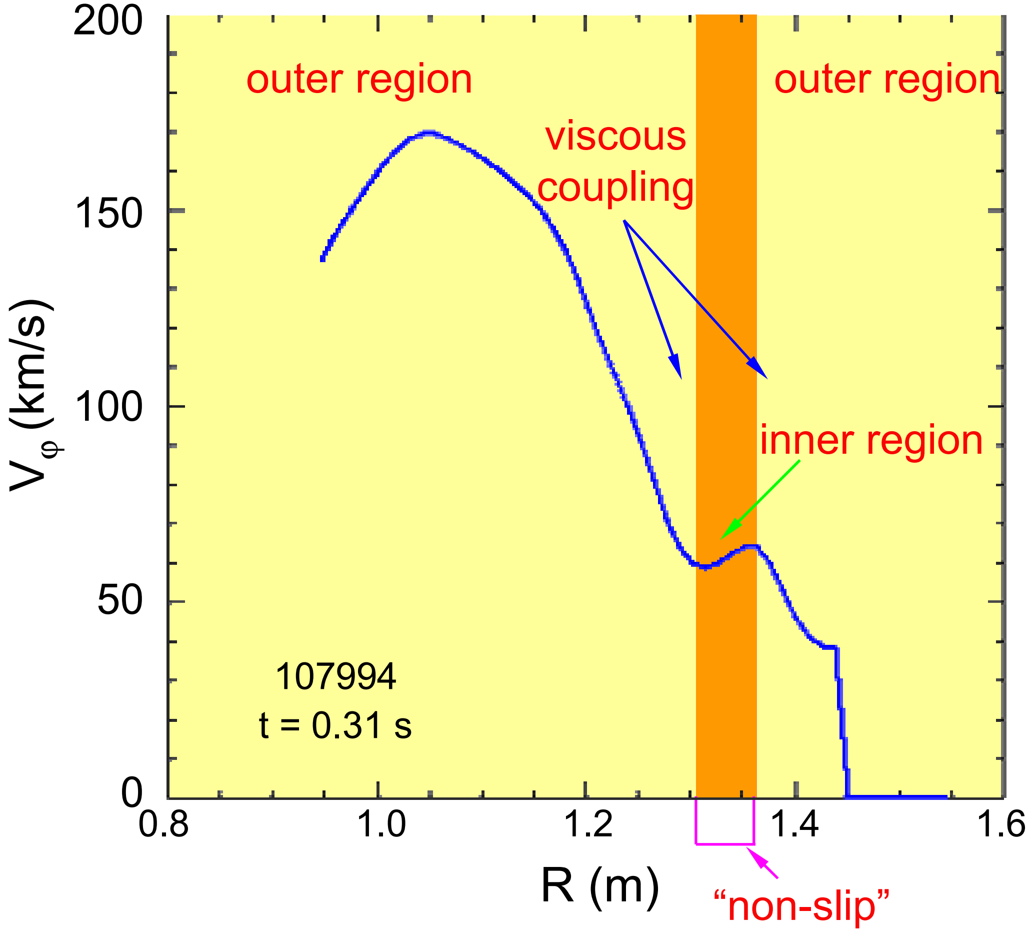
- Resonant EM force on island (R. Fitzpatrick, et al.)
  - Couple of island with static error field and NSTX conducting wall
  - $T_{\varphi EM_{err}}=4\pi^2R_0\frac{r_s^2}{\mu_0}\frac{n}{m}\left|\delta B_{r\_island}\right|\left|\delta B_{r\_error\_field}\right|\times Fac_{shielding}$
  - $T_{\varphi EM_{wall}}=4\pi^2R_0\frac{r_s^2}{\mu_0}\frac{n}{m}\frac{(\omega\tau_w)(r_{s+}/r_w)^{2m}}{1+(\omega\tau_w)^2\left[1-(r_{s+}/r_w)^{2m}\right]^2}\left|\delta B_{r\_island}\right|^2$

unknown

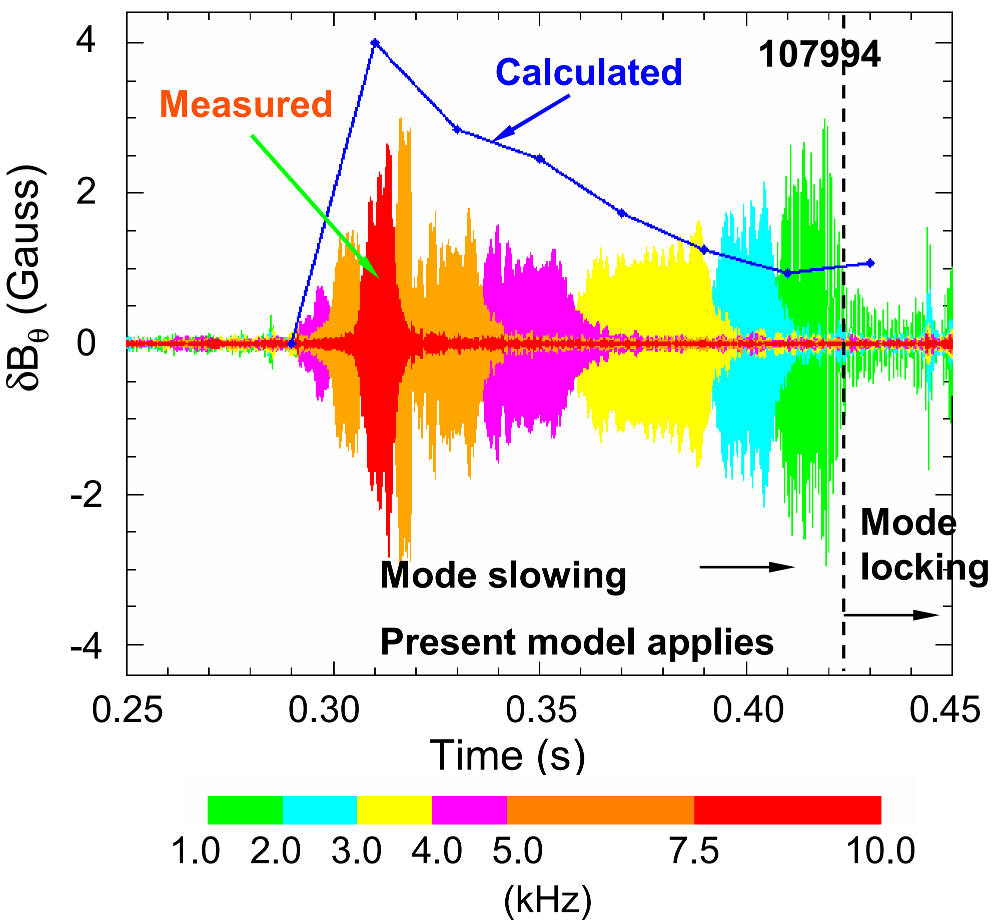
- Neo-classical toroidal viscosity (NTV) theory
  - K.C. Shaing et al.
  - $T_{NTV}\propto b_r^2\sqrt{T_i}$
- Plasma inertia and fluid viscosity included in analysis

Other Torques Included in Analysis

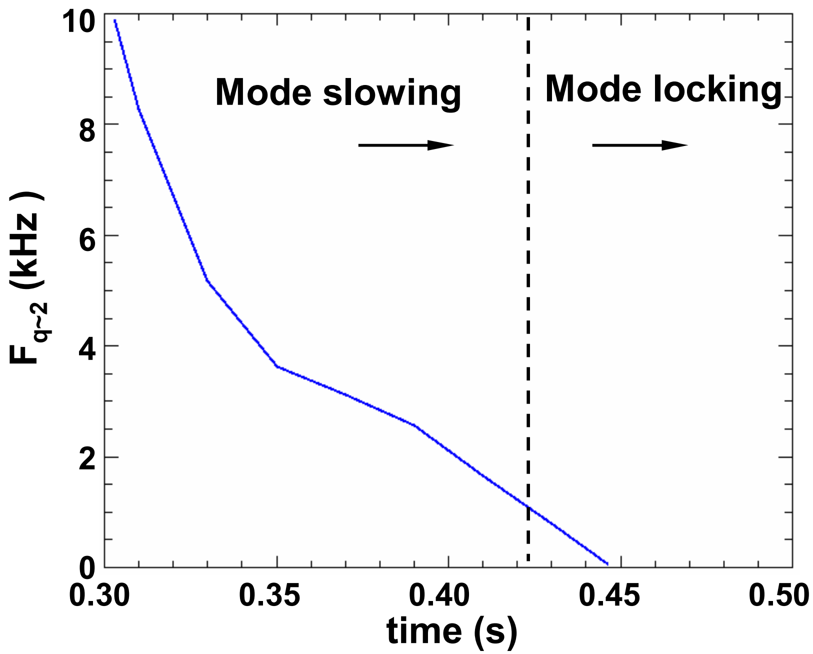
- JxB torque within inner region
- Fluid viscous coupling between inner and outer region
- 1/1 mode inner region extends across core
  - NTV torque Doppler shifted relative to q = 1 surface



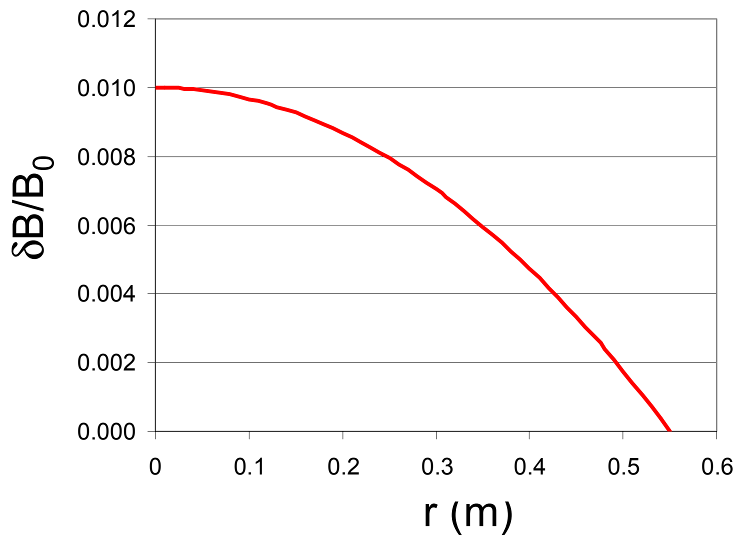
JxB Torque Balanced by Viscosity and Inertia Matches Local Island Rotation Damping



- Discharge with small 2/1 Island
  - Take $Fac_{shielding}$ = 1
- Mode grows as it slows in time



Non-resonant NTV Theory Used to Analyze Global Rotation Damping

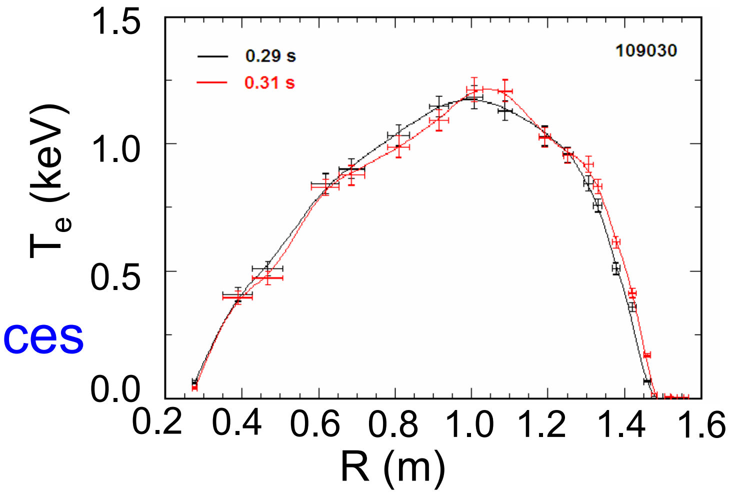


$$T_{non\_resonant} = R^2 \frac{\pi^{1/2} p_i}{v_{T_i}} \Omega_\varphi \sum_{m,n\neq 0} \frac{\left(B_{0\theta} b_\theta^{m,n} + B_{0\varphi} b_\varphi^{m,n}\right)^2}{B_0^4} \frac{n^2 q}{|m-nq|}$$

$\sim T_i^{1/2}$ (measured)

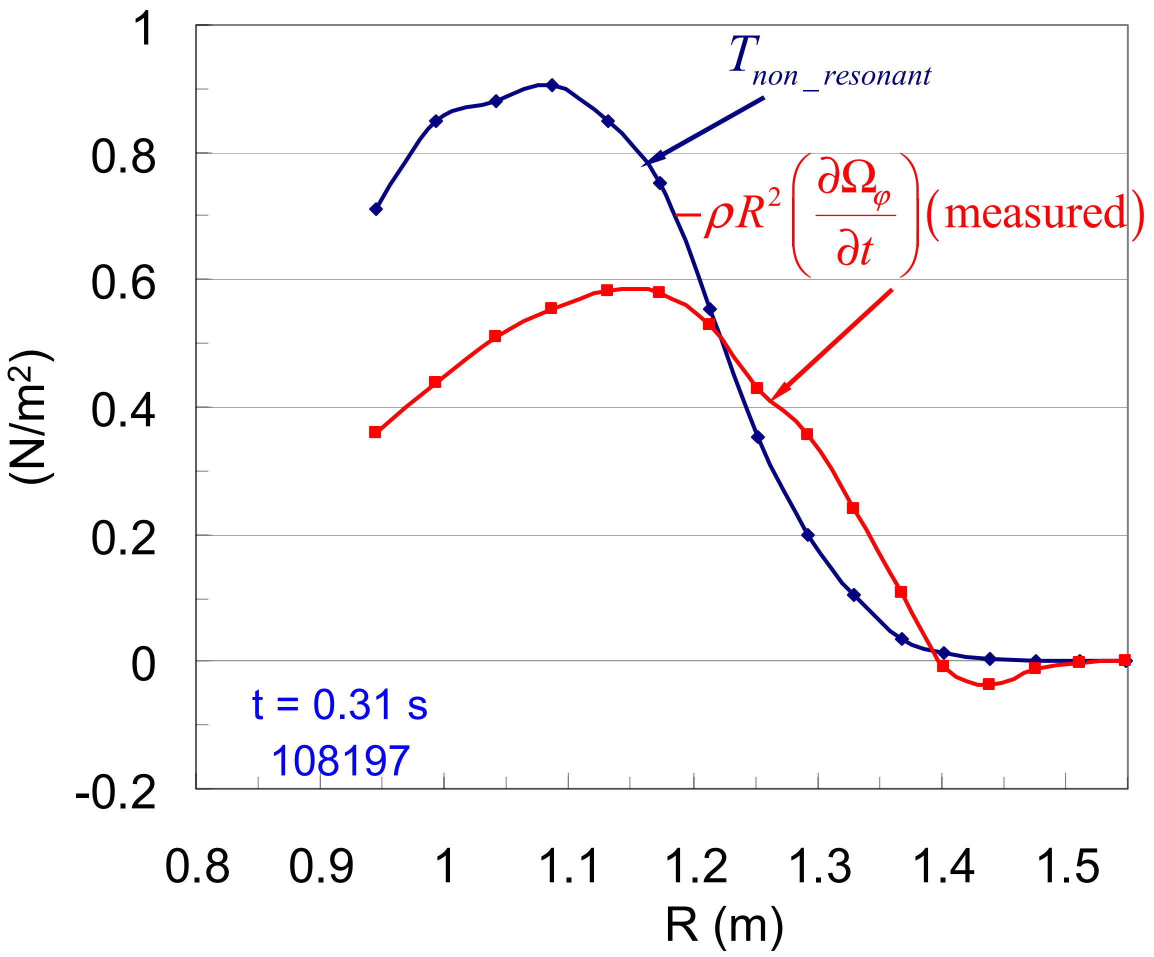
$\left(\frac{\delta B}{B_0}\right)^2$

Te perturbation measured during RWM



- Take parabolic form of $\delta B(r)/B_0$
- Assume $\delta B/B_0 \sim \delta r_{T_e}/a$
- $\delta r_{T_e}/a \sim 10^{-2}$
- $n^2 q/|m-nq| \sim O(1)$ away from rational surfaces
- Presently working to include ideal MHD eigenfunction for δB

Non-resonant NTV Physics Model Matches the Measured Global Damping Profile during RWM



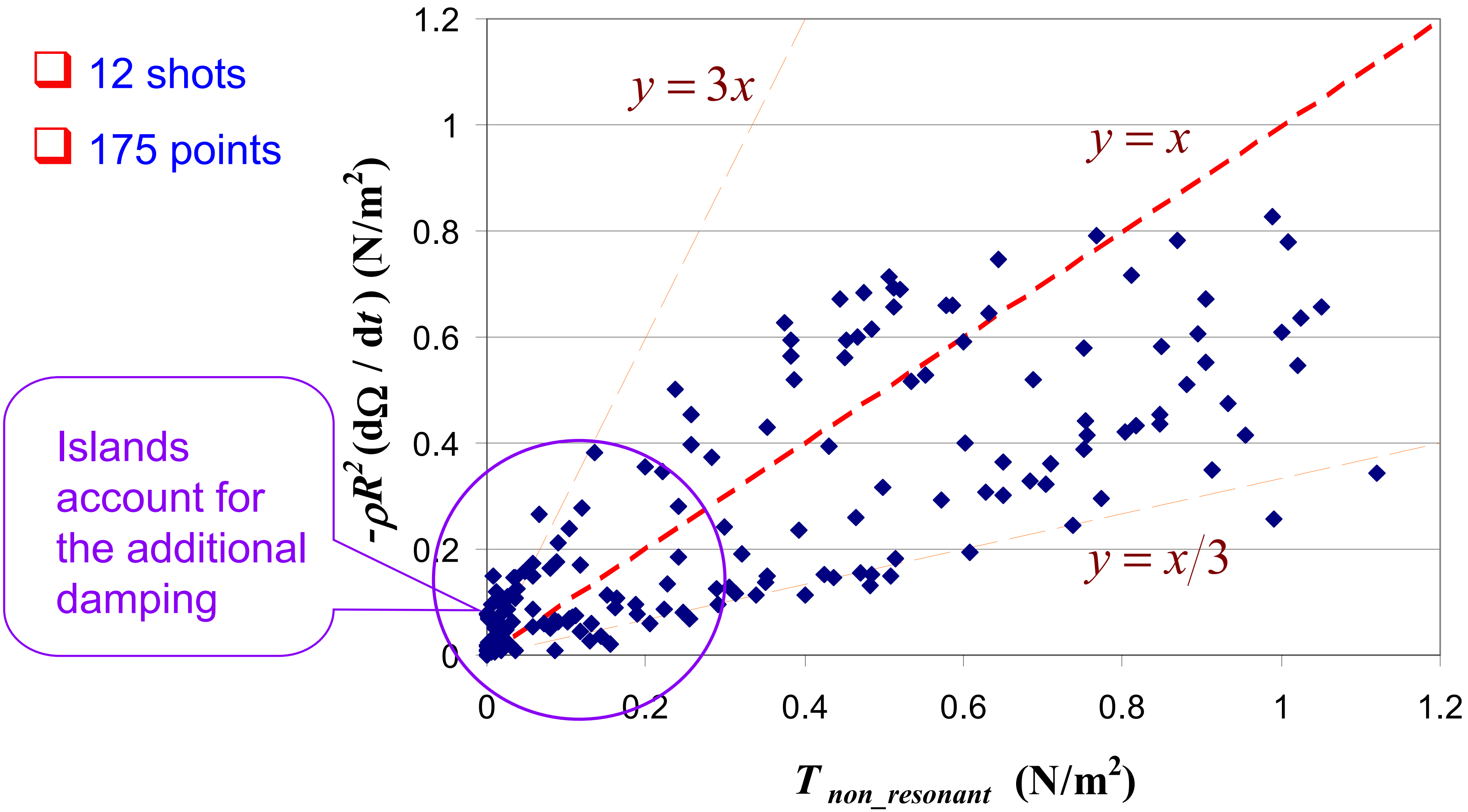
- Torque Balance

$$-\rho R^2 \left(\frac{\partial \Omega_\varphi}{\partial t}\right) = T_{non\_resonant}$$

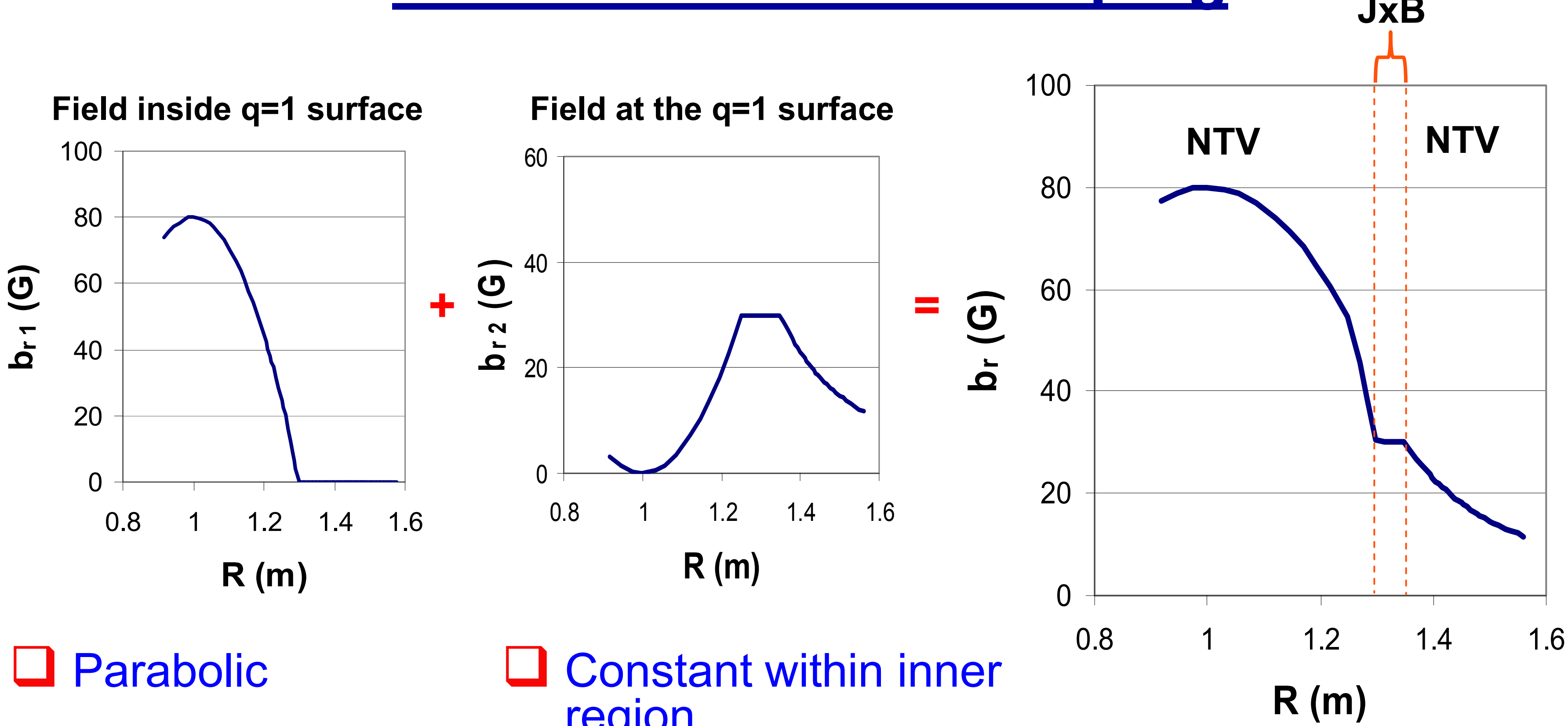
- Neoclassical viscous torque in good agreement with observed global damping
- Island at edge not modeled in calculation

Quantitative Agreement within a Factor of 3 over Many Shots

- 12 shots
- 175 points



NTV Theory Can Be Applied to 1/1 Mode Induced Rotation Damping

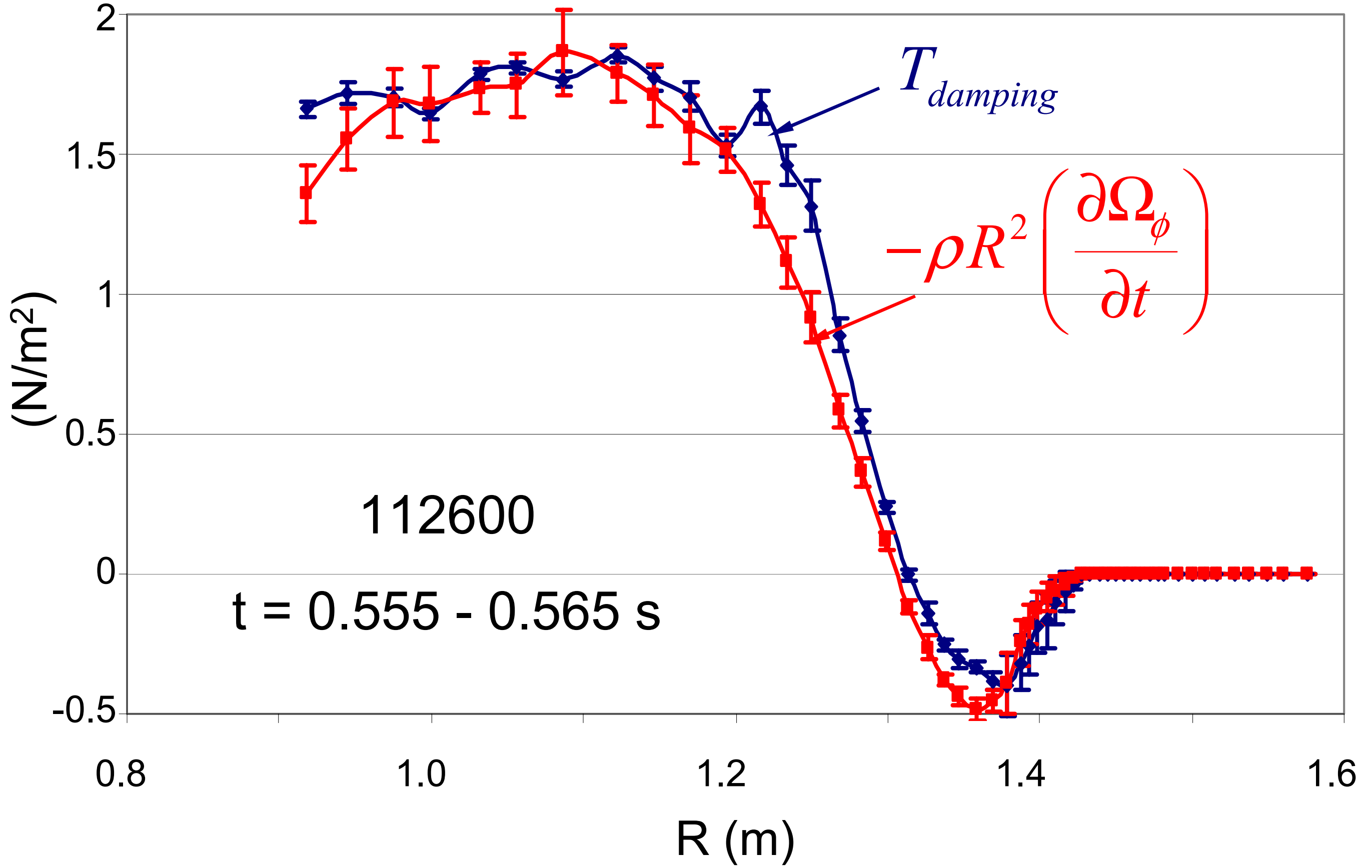


- Parabolic
- 80 G at plasma core[1,2]
- 0 G at q=1 surface
- Constant within inner region
- Decay at outer region
- 30 G at inner region[1,2]

[1] based on shot 112600

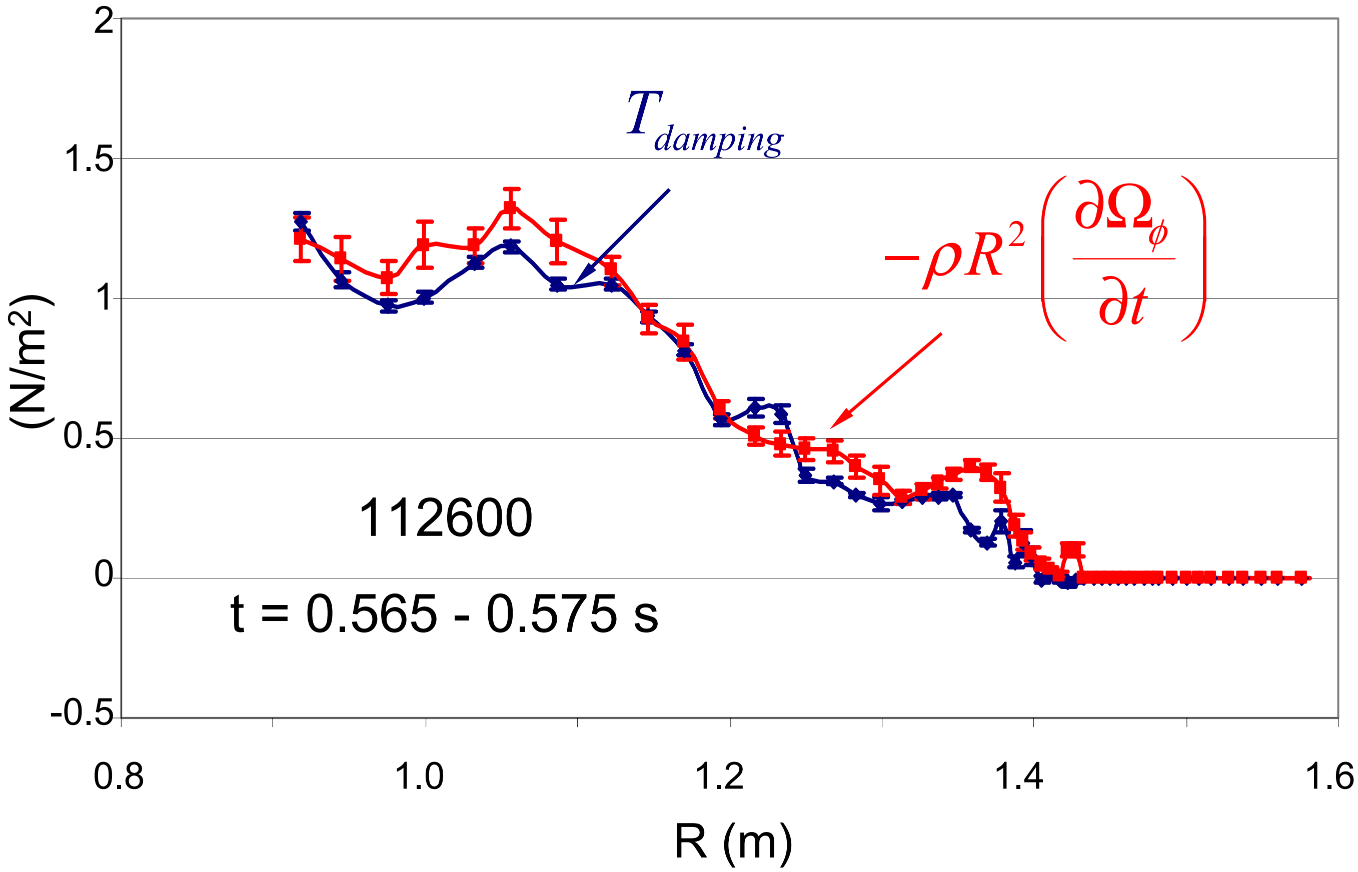
[2] J. Menard, ICC workshop, 2004

Quantitative Agreement between Rotation Damping Theory for Large 1/1 Mode and Measurement



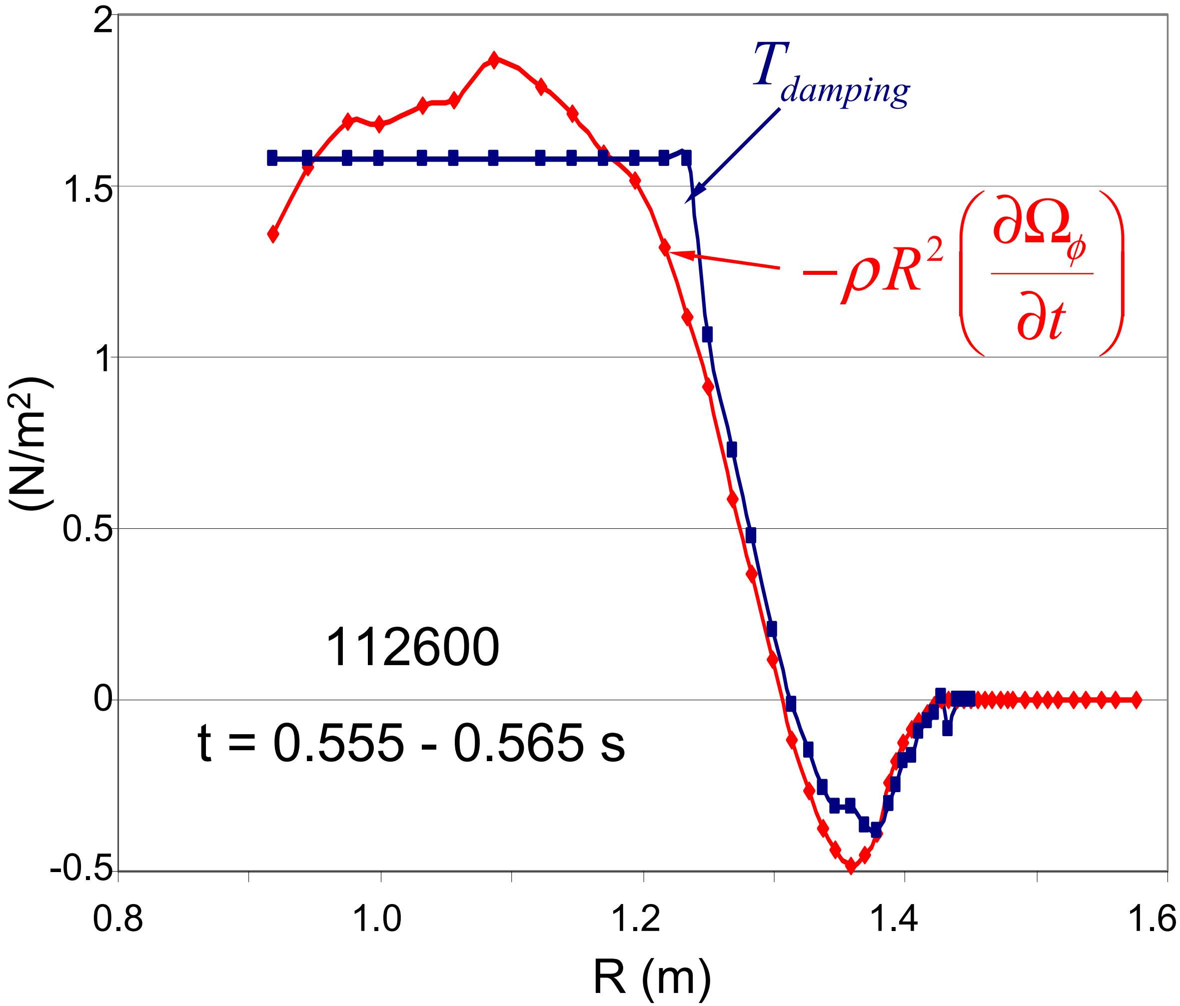
- Blue: Calculated torque density
- Red: Measured rotation damping profile

Quantitative Agreement between Rotation Damping Theory for Large 1/1 Mode and Measurement



- Blue: Calculated torque density
- Red: Measured rotation damping profile

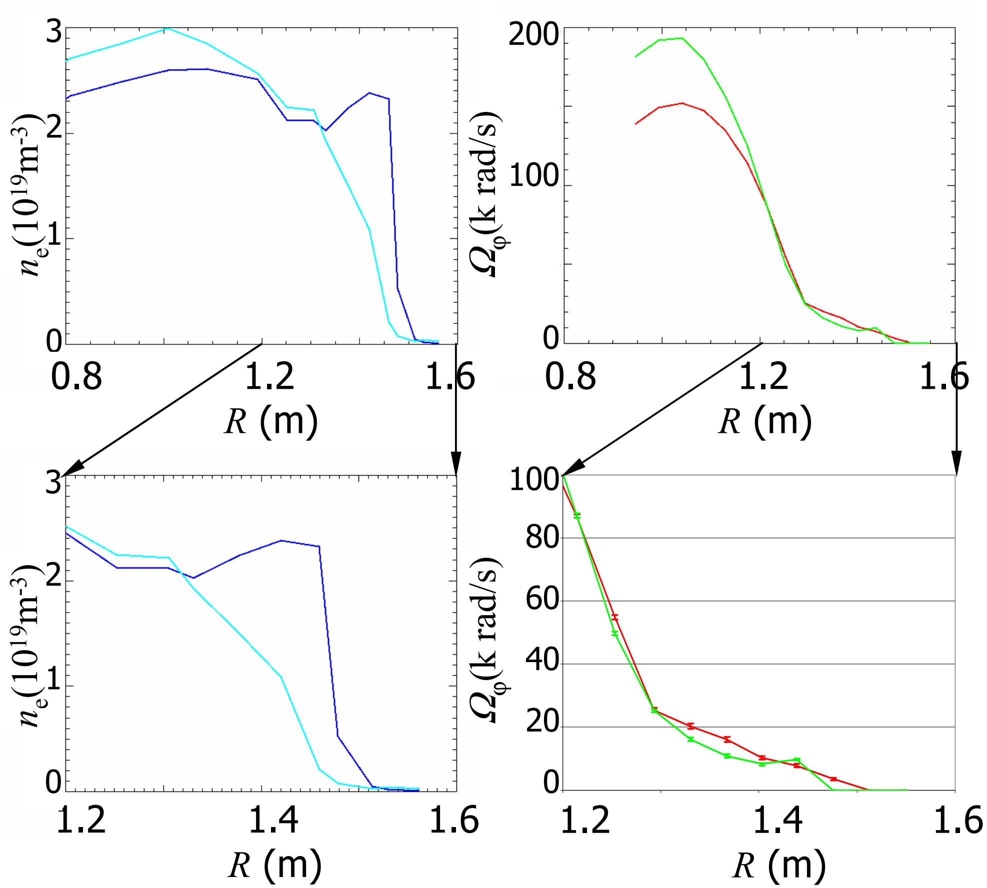
Electromagnetic Torque Alone Too Small to Quantitatively Explain Global Damping

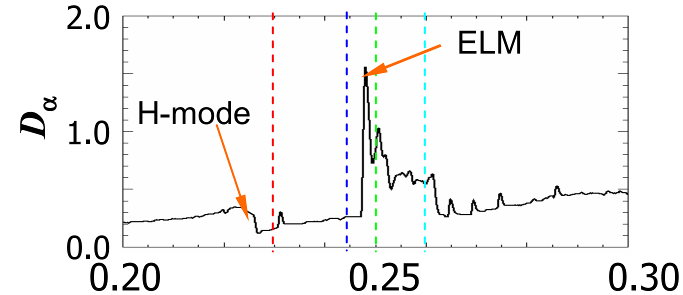


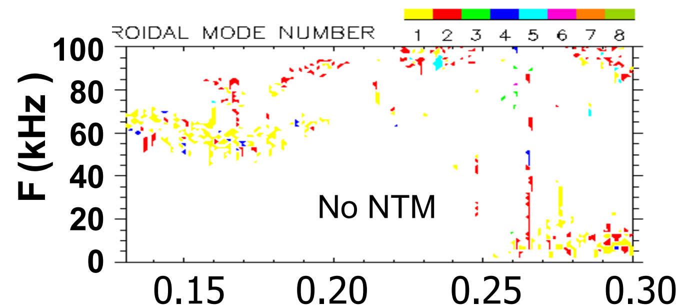
- Assume only EM torque in plasma core
- Constant δb_r within q=1 surface
- Include static error field and conducting wall drags
- Assume $Fac_{shielding}$=1
  - Conservative assumption
- Required δb_r for best fit is ~2300 G

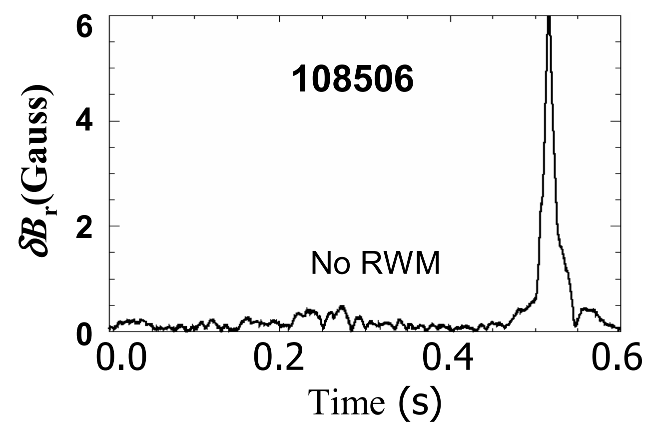
NSTX

Edge Rotation Damping by ELM is Insignificant



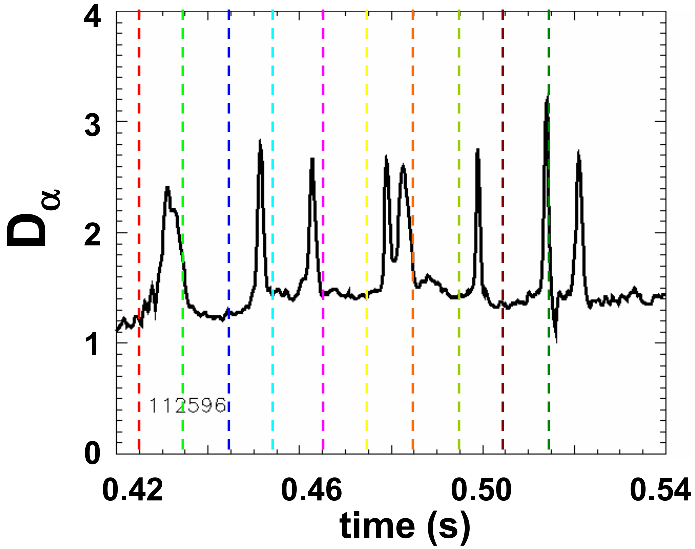


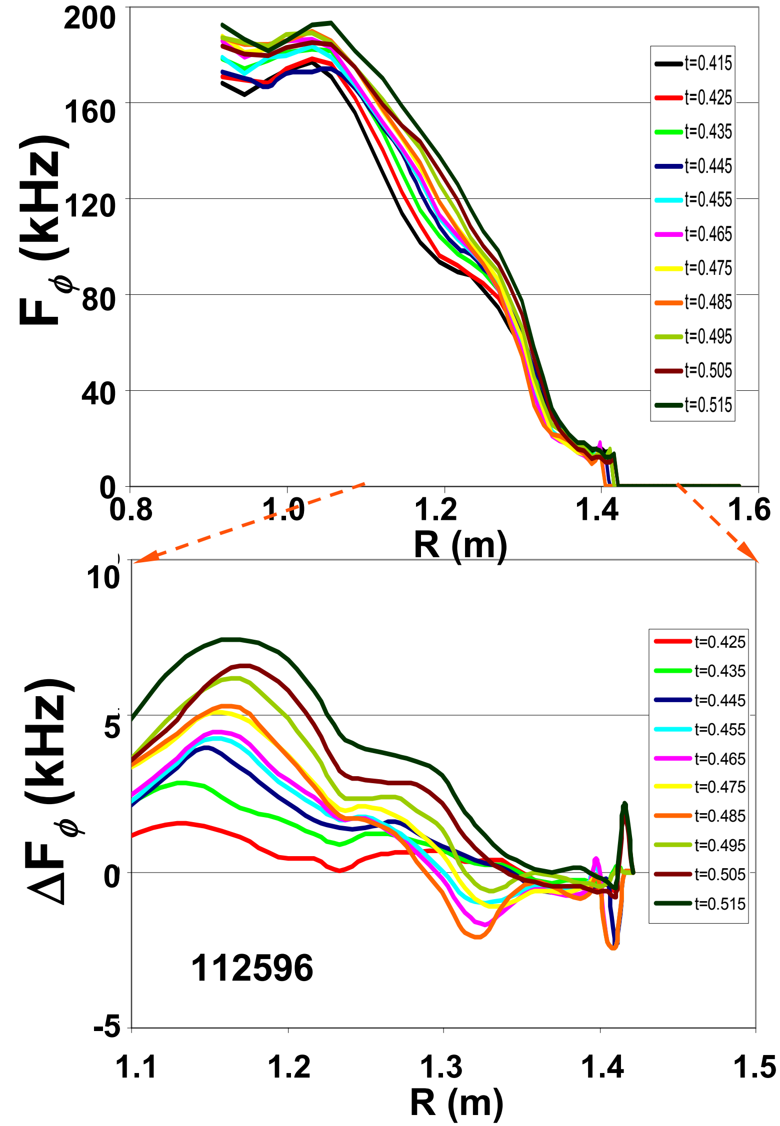




- Edge rotation decreases while plasma in the core speeds up
- Rotation affected width same as n_e affected width
- No other modes (NTM, RWM, etc.) during ELM

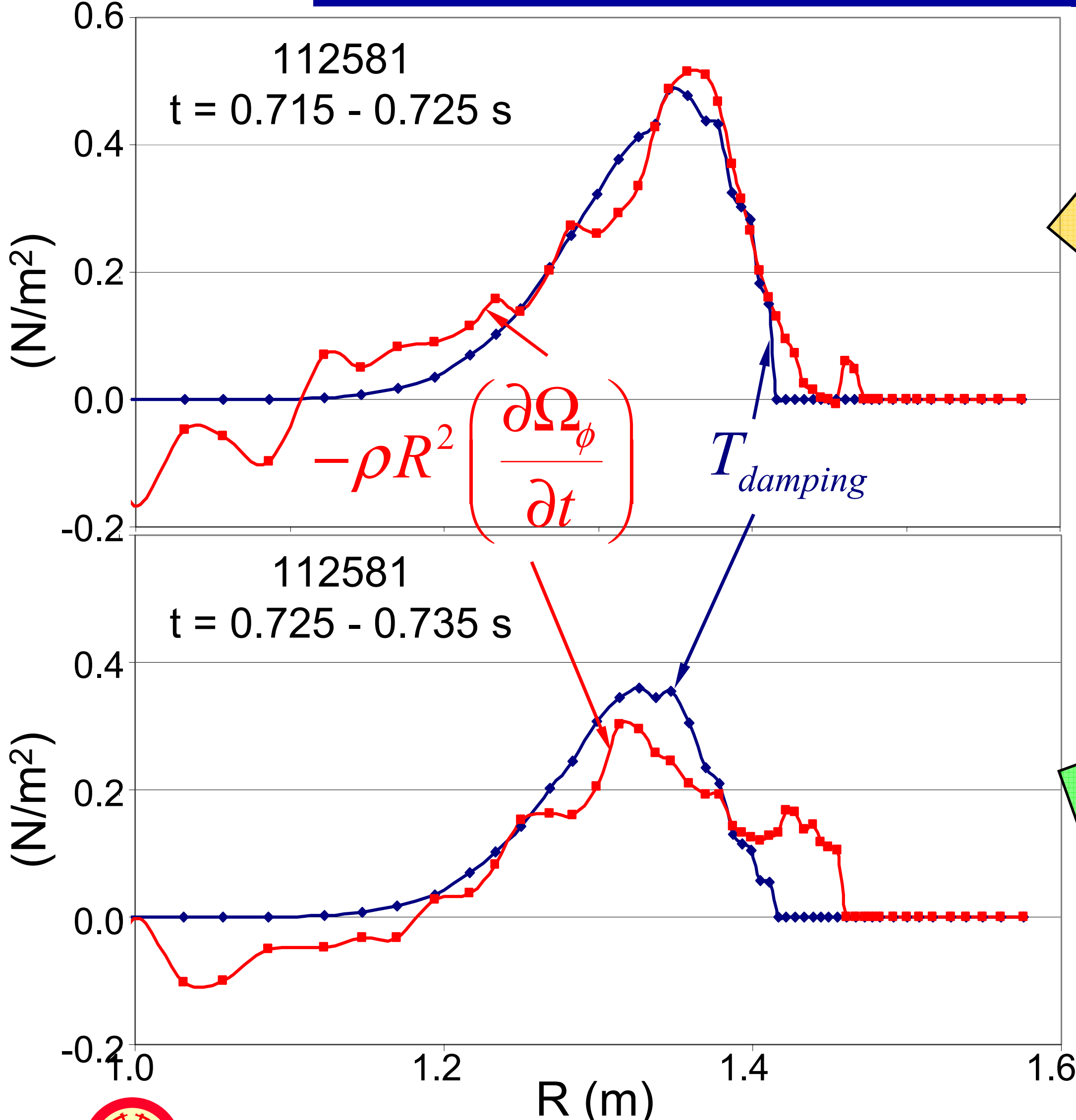
Repetitive ELMs Can Clamp Edge Rotation

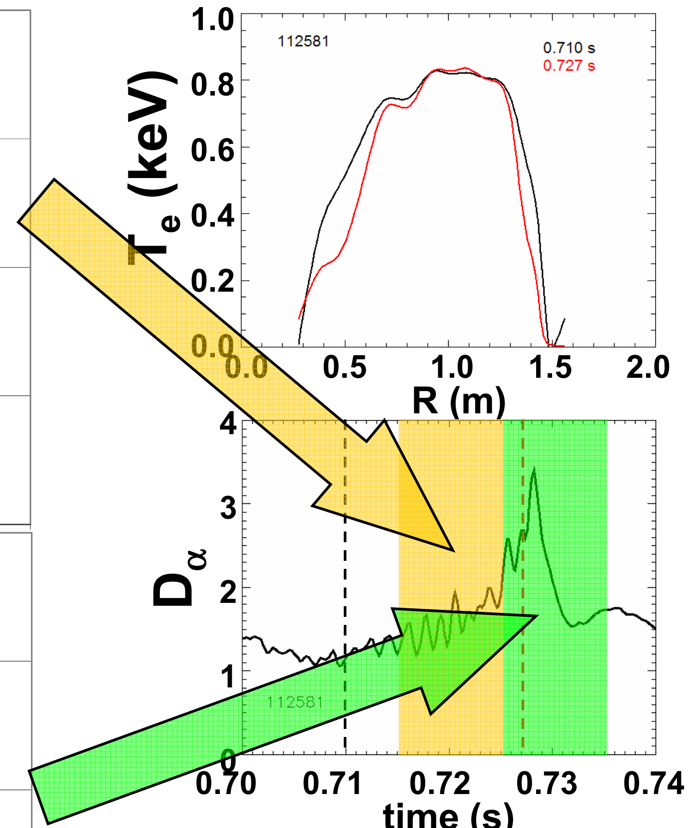




- Rotation recovers after each ELM
- ELMs do not prevent plasma core from speeding up

Quantitative Agreement between NTV Theory and ELM Rotation Damping





- Assume $\delta B/B_0 \approx \delta r_{T_e}/a \sim 10\%$
- Assume the field perturbation decays fast into the plasma with $b = b_{edge}(r/a)^3$

Rotation Damping Explained by Resonant and Non-resonant Physics Mechanisms

- Resonant mode interaction with NSTX static error field and conducting wall balanced by viscosity and inertia in reasonable quantitative agreement with local rotation evolution near rational surface
- Non-resonant NTV model estimate in good quantitative agreement with measured global damping in RWM and 1/1 mode plasmas, as well as local damping in ELMing plasma
- Electromagnetic drag alone is too weak to cause fast global damping
- Future analysis will continue to improve physics model
  - More CHERS data is needed