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XP408: Toroidal Rotation Damping Physics in NSTX

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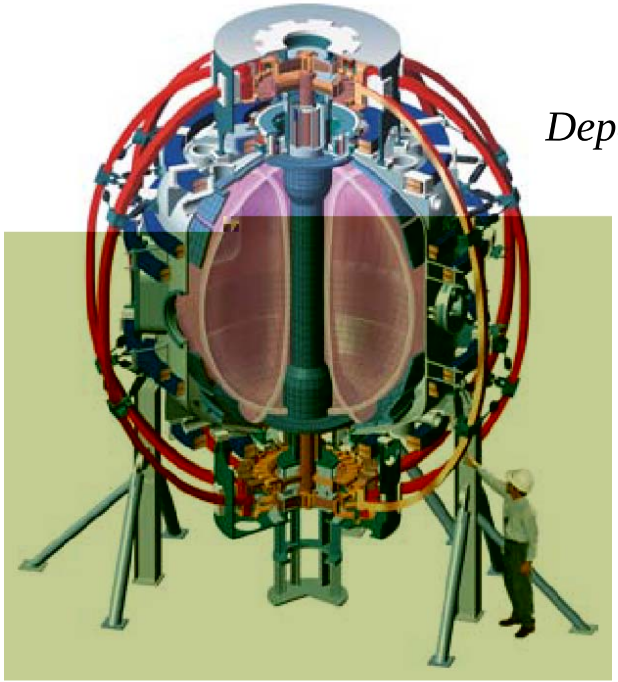

NSTX Result Review
Sept 20, 2004

Columbia U
Comp-X
General Atomics
INEL
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Lodestar
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Kyushu Tokai U
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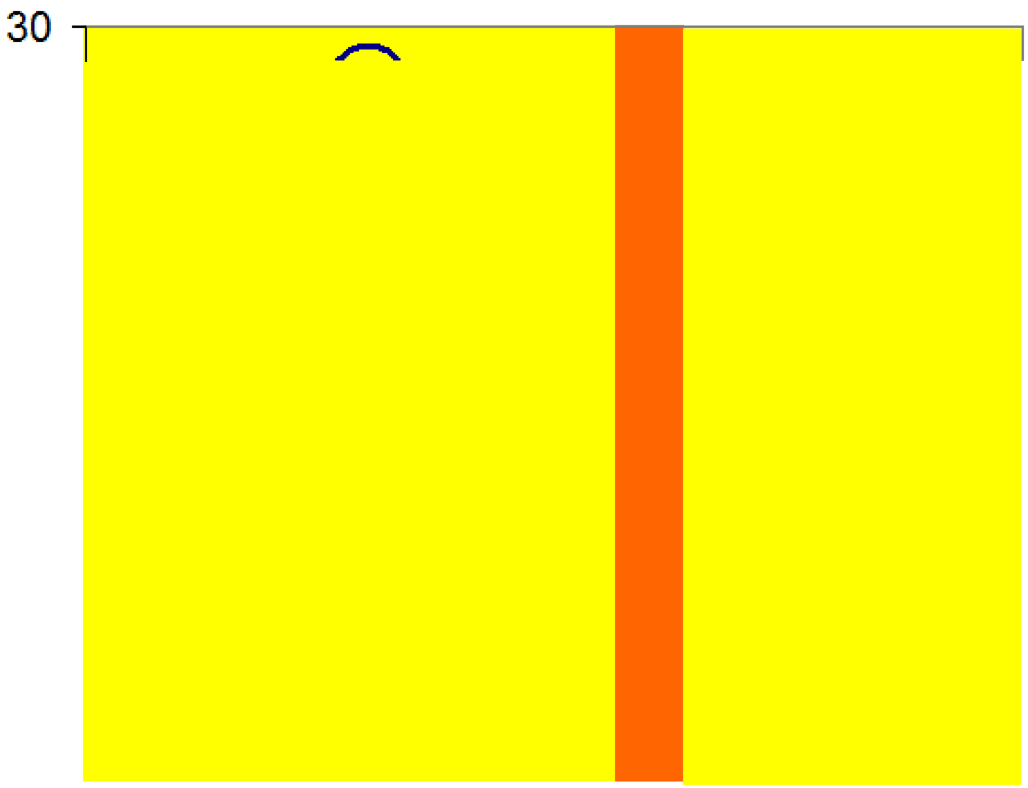
Rotation Damping Physics Investigated with a Variety of Models

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

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

Physics Model of Damping Torque Applies to Key Modes



- Small saturated island
  - Resonant EM torque inside inner region
  - Rotation relaxation term
- RWM with no islands
  - NTV applied to entire plasma
- 1/1 core tearing mode
  - Resonant EM torque at rational surface
  - NTV applied to outer region
  - torque Doppler shifted relative to q = 1 surface
- Edge localized mode
  - NTV applied to edge

Rotation Evolution Equation used for Experimental Comparison

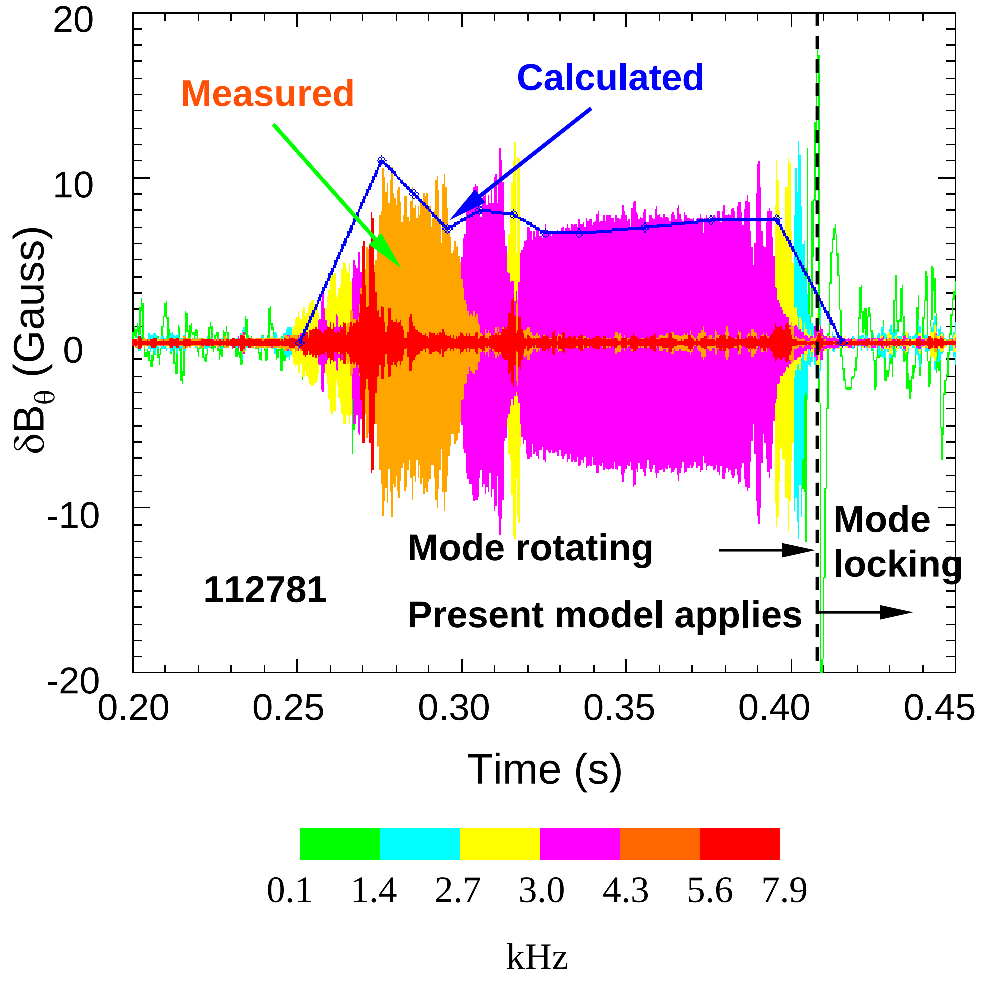
$$\rho R^2\left[\left(\frac{\partial\Omega_\phi}{\partial t}\right)+\frac{\Omega_\phi-\Omega_{\phi 0}}{\tau_v}\right]=T_{\text{damping}}=T_{\text{NTV}}+T_{J\times B}$$

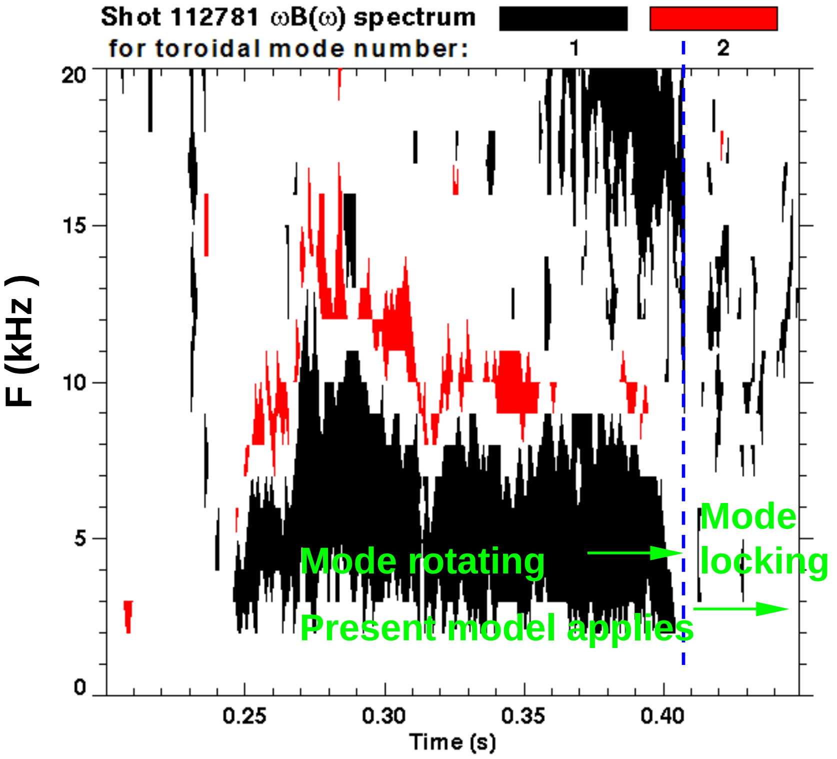
- Resonant EM force on island (R. Fitzpatrick, et al.)
  - Couple of island with static error field and NSTX conducting wall
  - $T_{\varphi EM_{err}}=4\pi^2R_0\frac{r_s^2}{\mu_0}\frac{n}{m}\boxed{\left|\delta B_{r\_island}\right|}\left|\delta B_{r\_error\_field}\right|\times Fac_{shielding}$ ~0
  - $T_{\varphi EM_{wall}}=4\pi^2R_0\frac{r_s^2}{\mu_0}\frac{n}{m}\frac{(\omega\tau_w)\left[1-\left(r_{s+}/r_w\right)^{2m}\right]}{1+(\omega\tau_w)^2\left[1-\left(r_{s+}/r_w\right)^{2m}\right]^2}\boxed{\left|\delta B_{r\_island}\right|^2}$
- Neo-classical toroidal viscosity (NTV) theory
  - $T_{NTV}\propto b_r^2\sqrt{T_i}$ K.C. Shaing et al.

unknown

- Inertia term and rotation relaxation term
  - Rotation relaxation time τ_v (use energy confinement time)

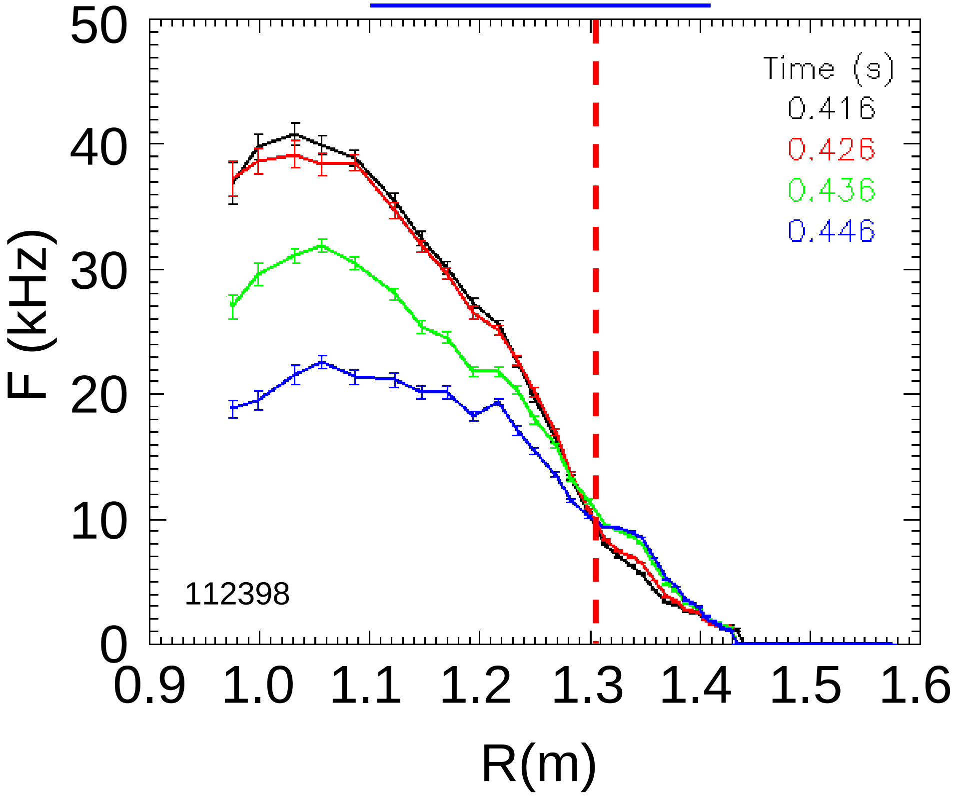
Resonant JâB Torque Matches Local Small Saturated Island Rotation Damping



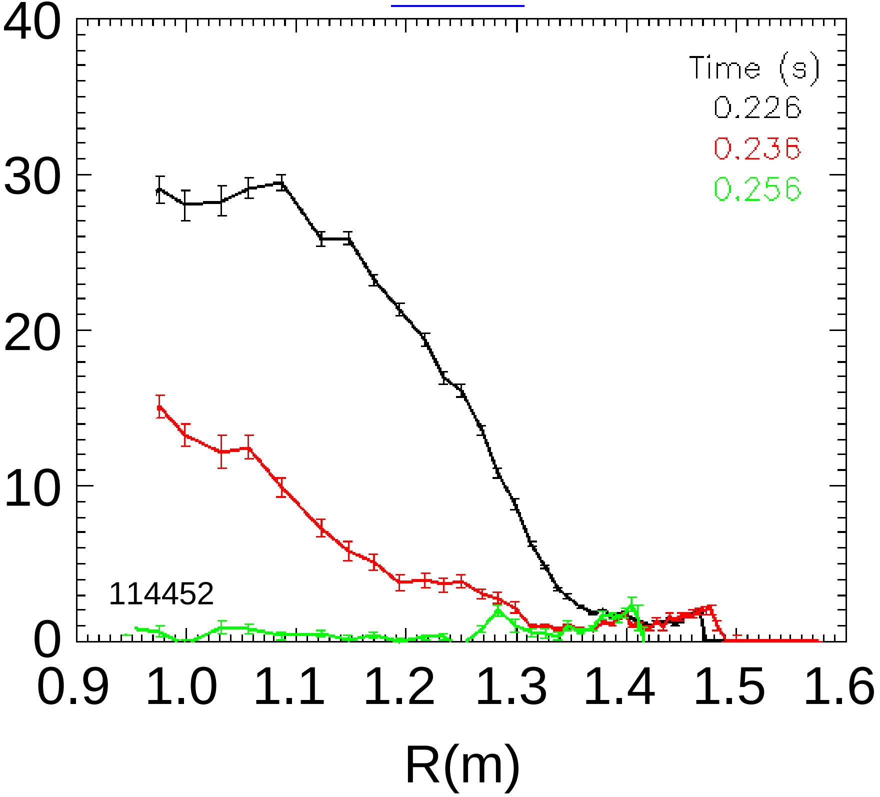


- Discharge with small island at R~1.3m
- Assume $m/n = 2/1$ in calculation

RWM rotation damping differs from other modes



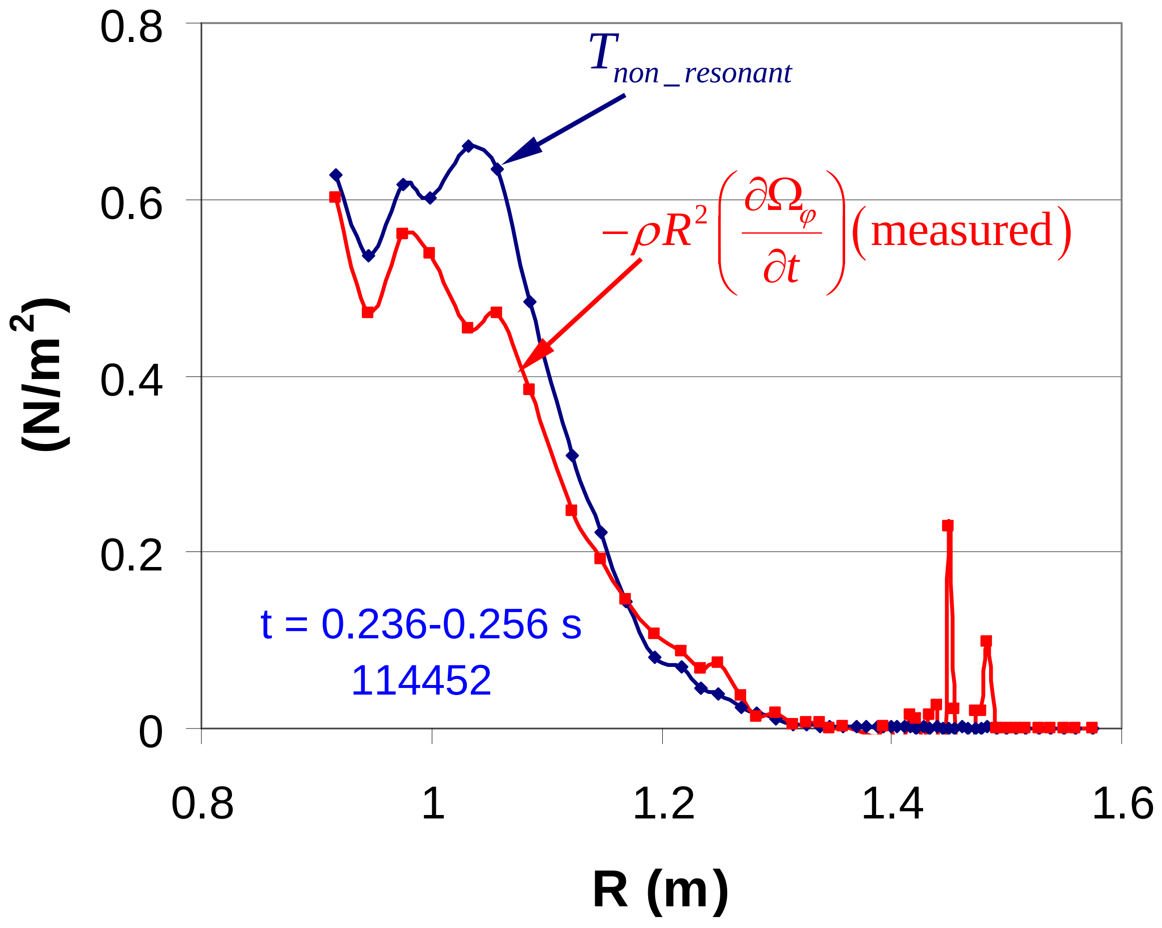
core 1/1 mode



RWM

- Core rotation damping when 1/1 mode onsets
  - leads to “rigid rotor” plasma core
- Clear momentum transfer across rational surface near R = 1.3m
- Global rotation damping by RWM
  - 1/1 tearing mode is absent
- Edge rotation does not halt
  - consistent with neoclassical toroidal viscosity ~ $\delta B^2 * Ti^{0.5}$
  - testing ideal δB as perturbation

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

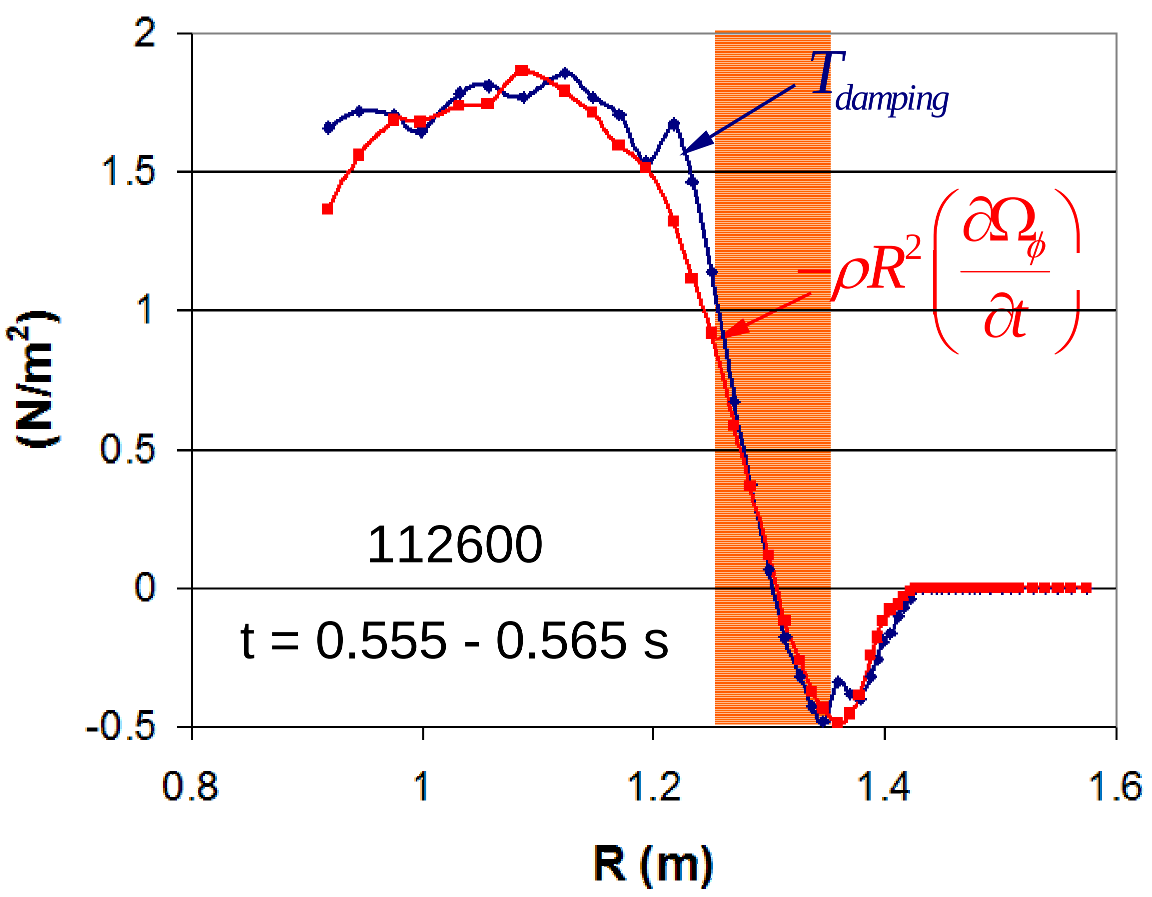


- Torque Balance

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

- Parabolic eigenfuction used
  - δb_{r_core} ~ 72.5 G
- No low frequency island was observed during this period
- To be compare with ideal MHD code calculation

Quantitative Agreement between NTV Theory for Large 1/1 Mode and Measurement



- NTV torque applied to entire plasma
  - Parabolic δb_r inside rational surface
  - 80 G at center[1]
- Mode rotating
  - Doppler shift
- Resonant EM torque applied at rational surface
  - 30G at rational surface[1]
- Momentum transfer across q=1

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

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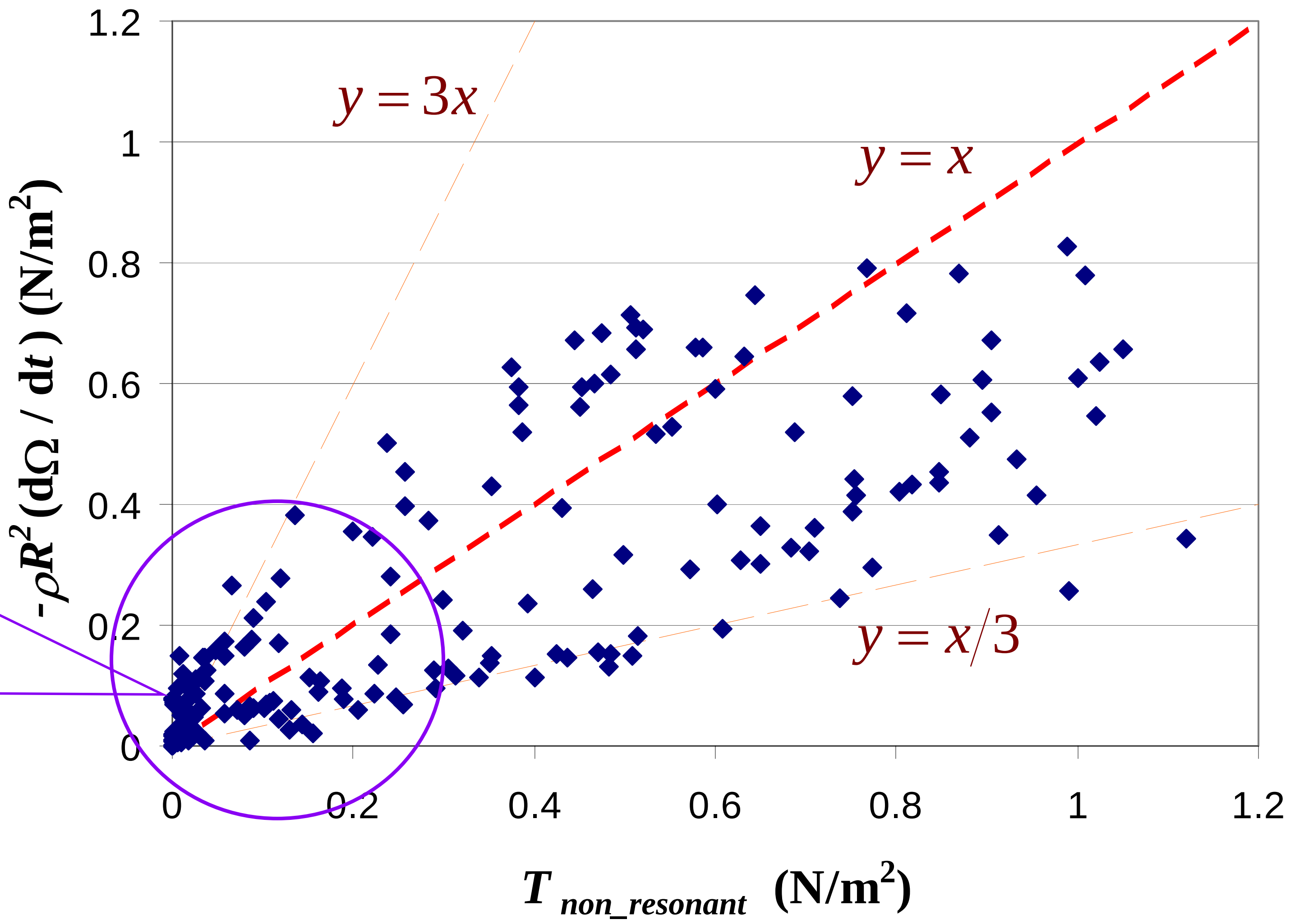
[1] J. Menard, ICC workshop, 2004

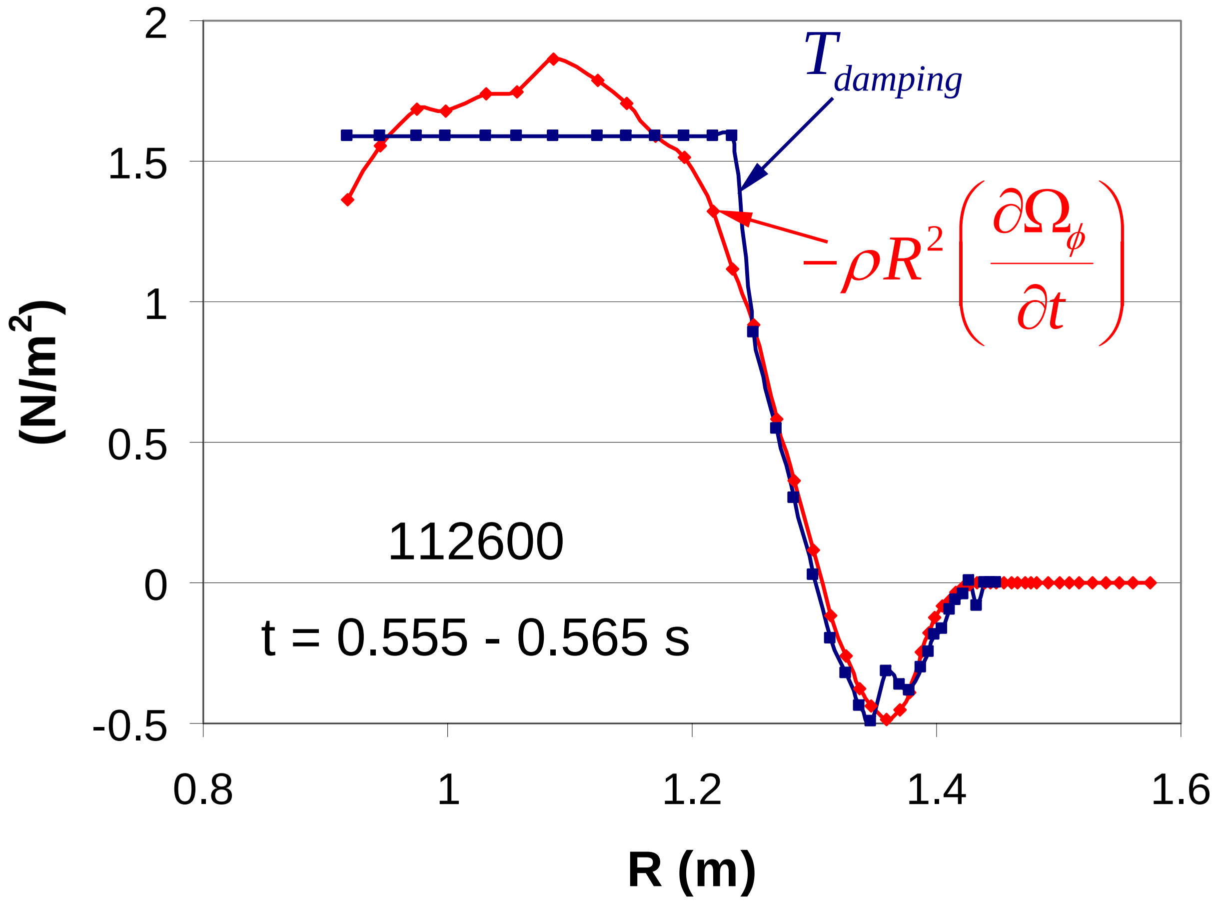
Quantitative Agreement within a Factor of 3 over Many Shots

- ☐ 12 shots
- ☐ 175 points



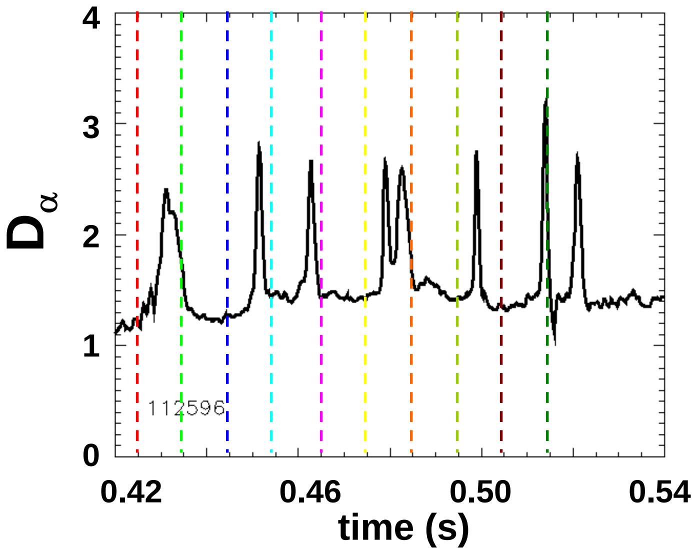
Islands account for the additional damping

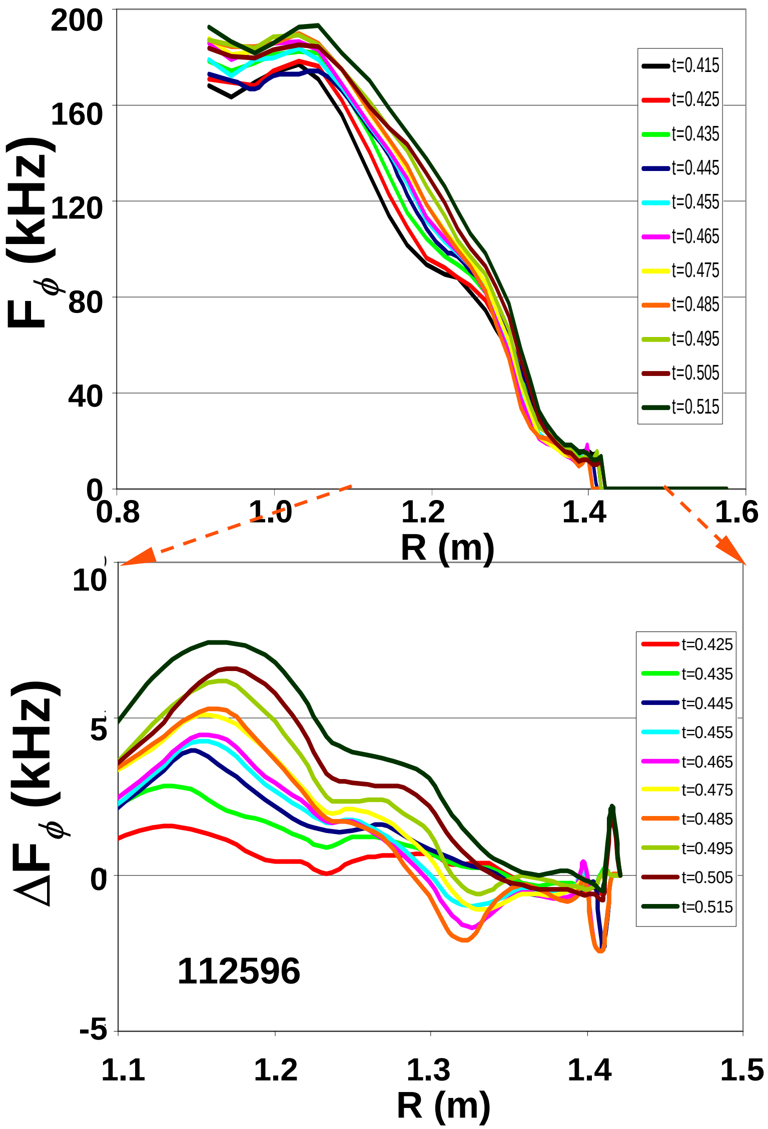
Electromagnetic Torque Alone Too Small to Quantitatively Explain Global Damping



- ❑ Assume only EM torque in plasma core
- ❑ Constant δb_r within *q*=1 rational surface
- ❑ Required δb_r for best fit is ~1550 G

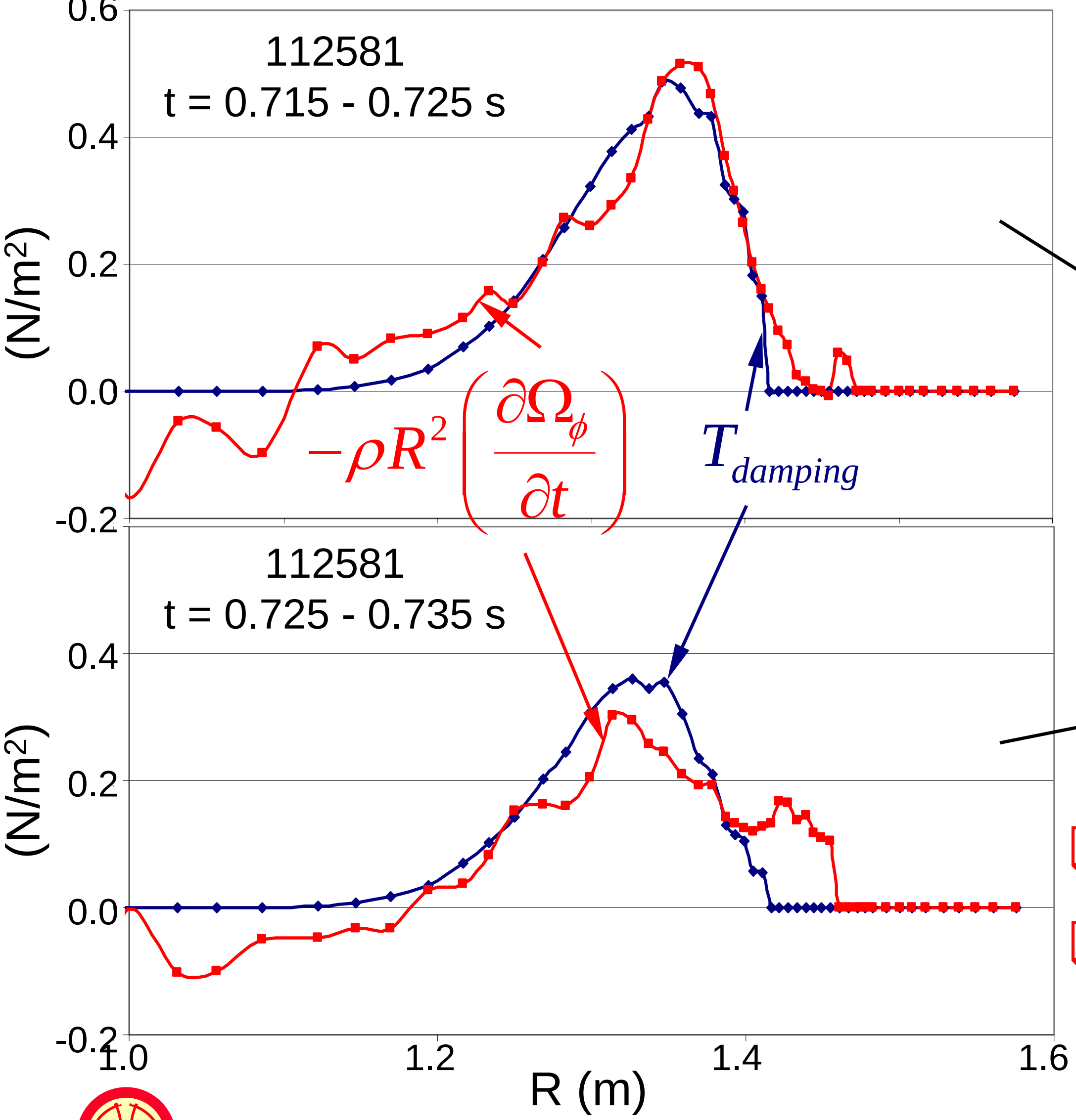
Edge Rotation Damping by ELM is Insignificant

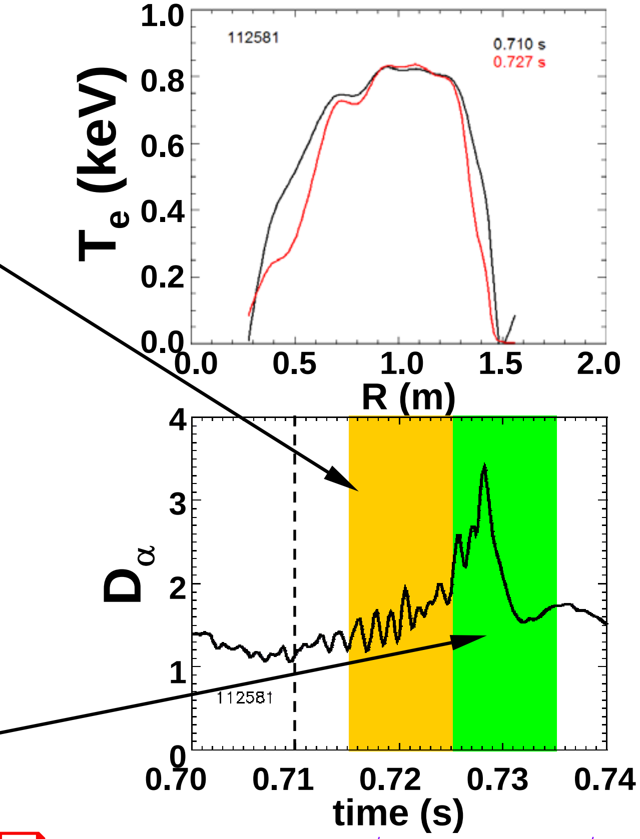




- Edge rotation decreases while plasma in the core speeds up
- Rotation recovers after each ELM
- Repetitive ELMs can clamp edge rotation
- No other low frequency modes (NTM, RWM, etc.) during ELM

Quantitative Agreement between NTV Theory and ELM Rotation Damping





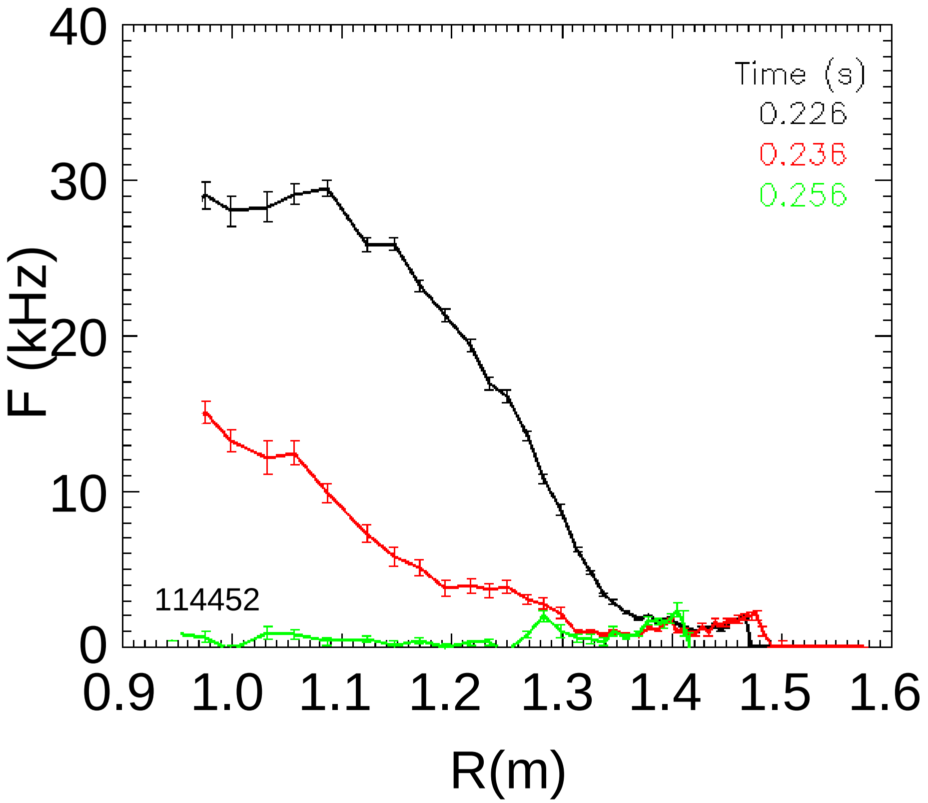
- Assume $\delta B/B_0 \simeq \delta r_{T_e}/a \sim 10\%$
- Assume the field perturbation decays fast into the plasma with $b = b_{edge}(r/a)^3$

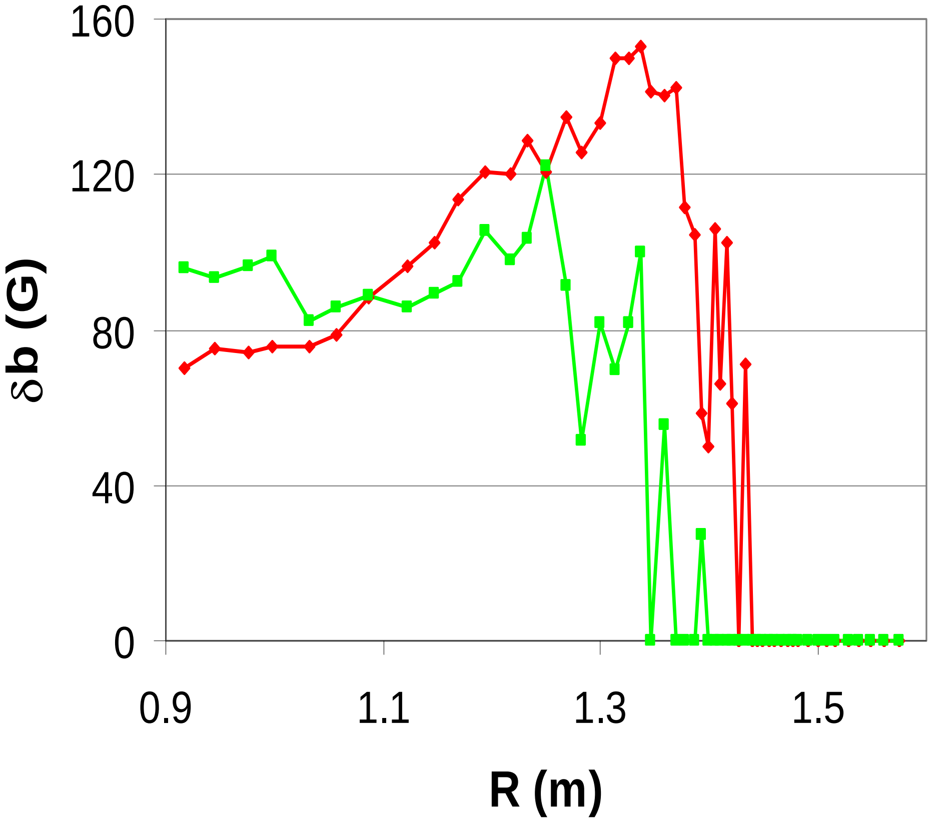
Rotation Damping Explained by Resonant and Non-resonant Physics Mechanisms

- Resonant mode interaction with NSTX conducting wall 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 work
  - Better RWM growth and rotation control (new active coils)
  - Acquire more CHERS data before plasma disrupts

Supporting Slides Follow

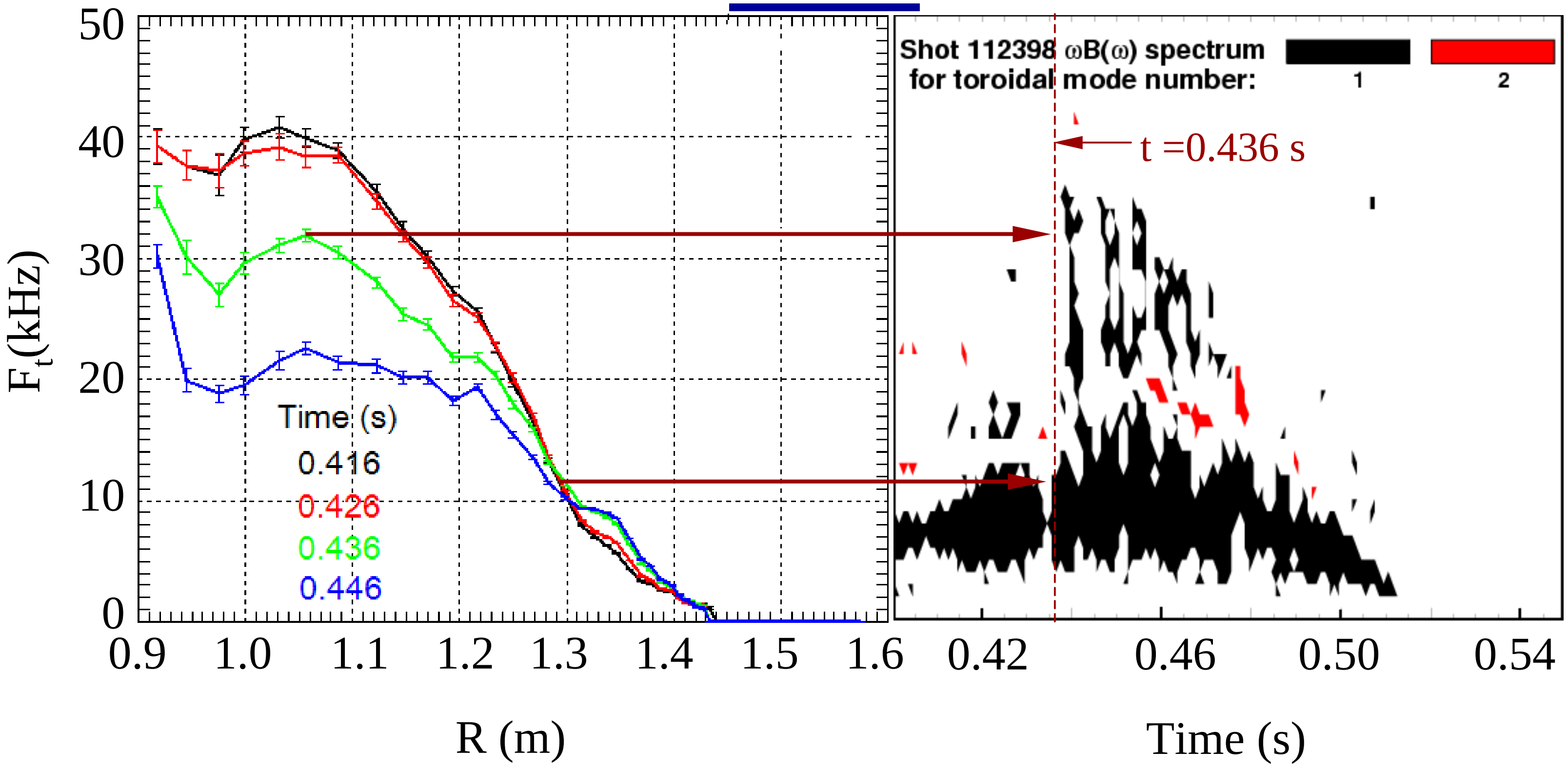
NTV Theory Predicts Global Characteristic of RWM





- ☐ To be compared with ideal MHD code result

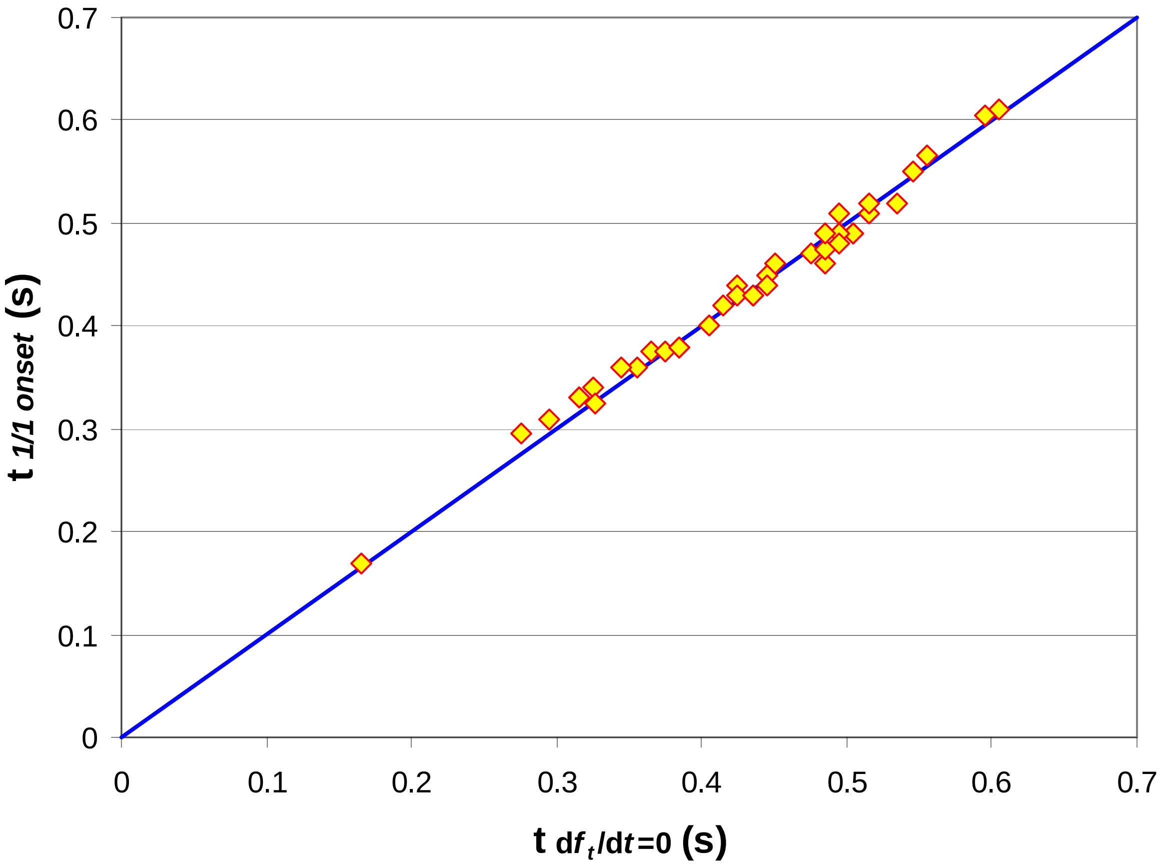
Mirnov Spectrum Indicate the Onset of 1/1 Mode



- Global rotation damping when large 1/1 mode onset
- Clear momentum transfer cross *q*=1
- Typical damping rate ~10^2kHz/s

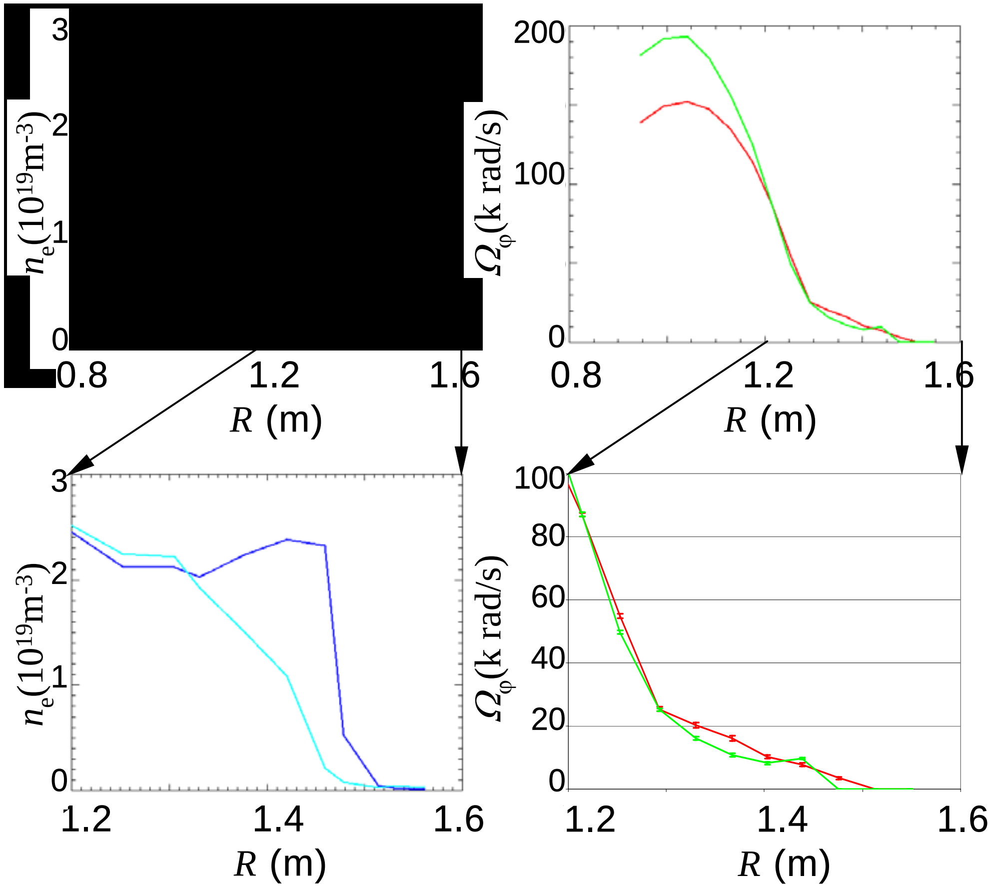
- *n*=1 Mirnov signal indicates the onset of 1/1 mode
  - Higher (plasma core) frequency
    - Intermittent or disappears quickly
  - Lower frequency
    - *q*=1 rational surface

Onset Time of 1/1 Mode Consistent with Core Rotation Damping

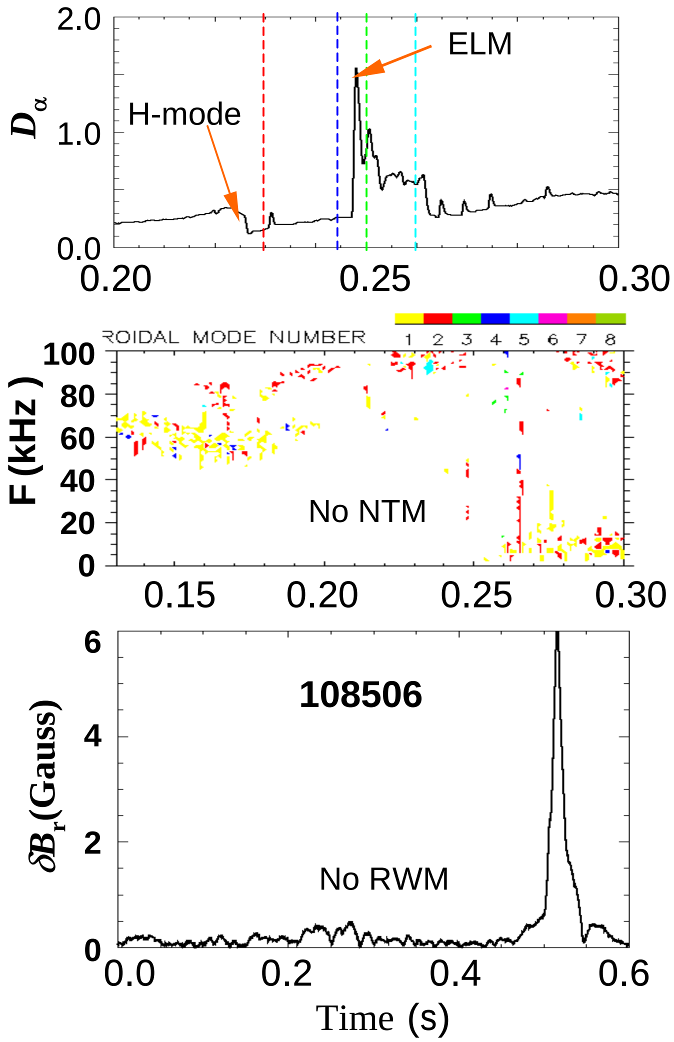


- 40 shots from FY 2004 data

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