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Toroidal Rotation Damping Physics in NSTX

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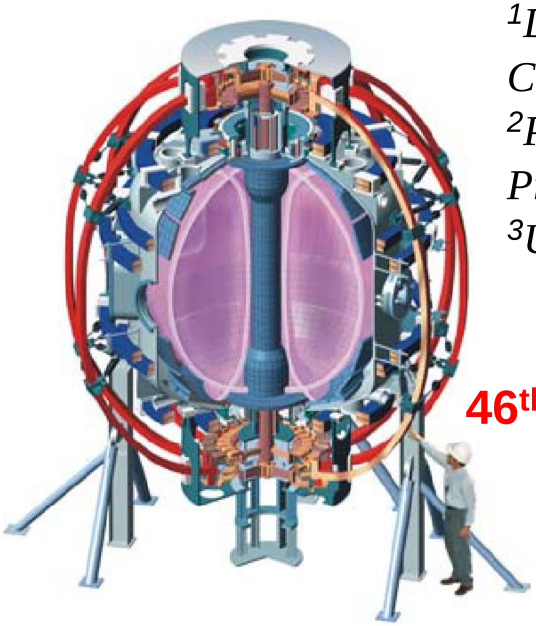

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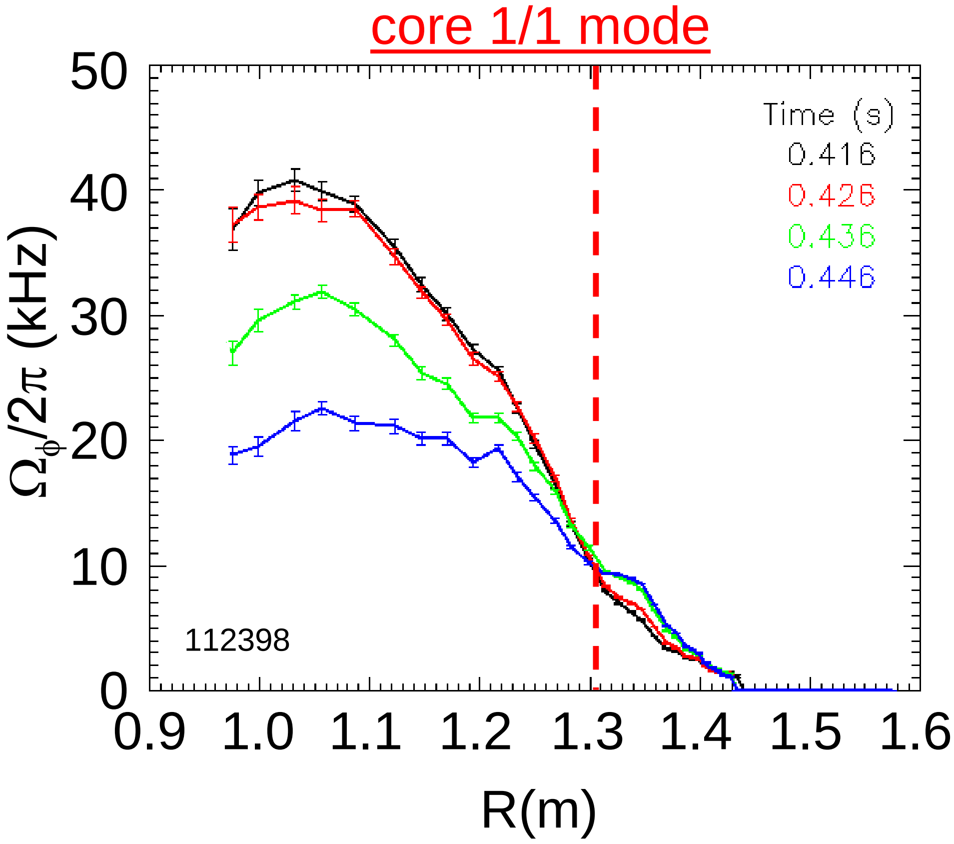
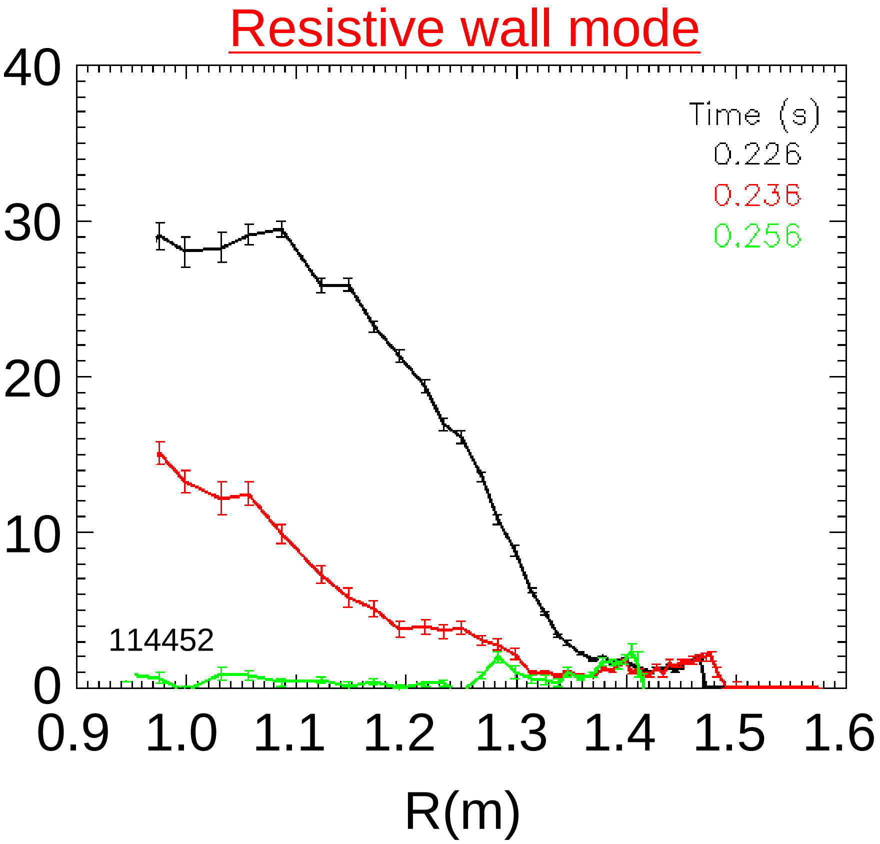
Theory / experiment comparison yields understanding of plasma rotation damping

- Motivation / Goal
  - Plasma rotation provides required stabilization to reach and maintain maximum plasma beta
  - Understand and minimize rotation damping
- Outline
  - Theoretical models of rotation damping
  - Experimental rotation damping sources
  - Comparison of theory to experiment

Rotation Damping Evolution Dependent on Mode Type

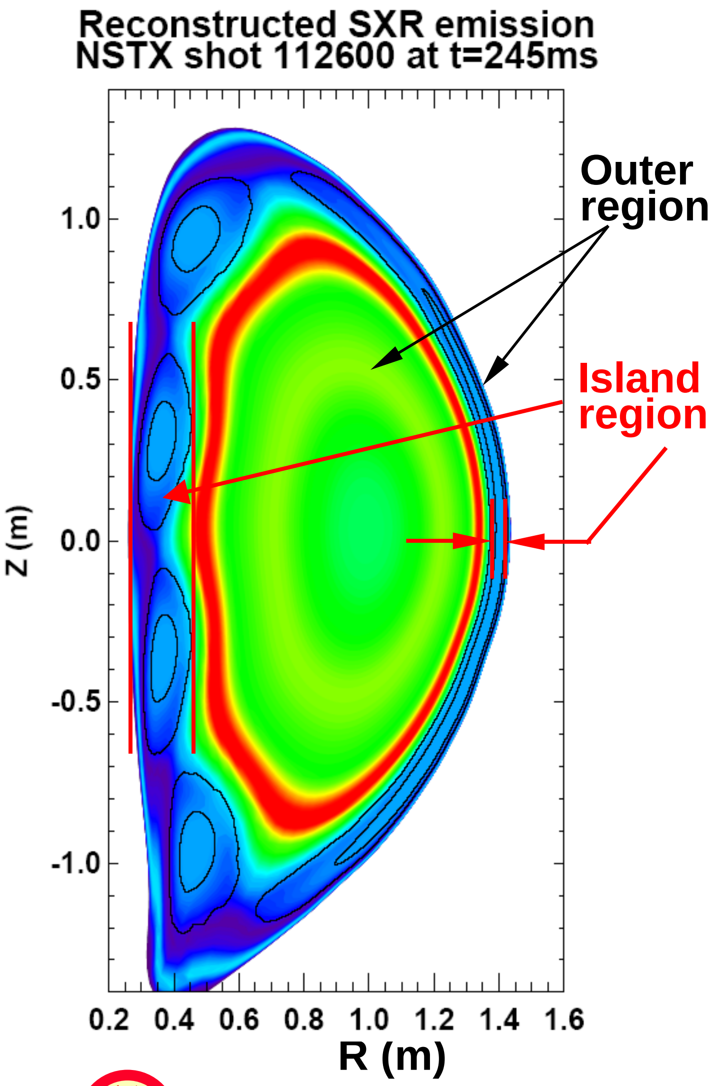

core 1/1 mode


Resistive wall mode

- Core rotation damping with 1/1
  - leads to "rigid rotor" plasma core
  - damping rate ~ $1/\tau_E$
- Momentum transfer across rational surface near R = 1.3m

- Rapid, global rotation damping by RWM
  - damping rate ~ $1/\tau_{wall}$
- Edge rotation maintained

Plasma Rotation Damping Physics Investigated with a Variety of Models



torque **mode**	Resonant EM* torque	Non-resonant NTV* torque
Small saturated island	Island separatrix	
Resistive wall mode (RWM)		Entire plasma
1/1 internal kink mode	Island separatrix	Plasma core
Edge localized mode (ELM)		Edge region

* EM – Electromagnetic

* NTV – Neoclassical toroidal viscosity

Rotation Evolution Equation used for Experimental Comparison

$$\underbrace{\rho R^2 \left(\frac{\partial \Omega_\phi}{\partial t} \right)}_{\textbf{Inertia term}} - T_{\text{viscosity}} - T_{\text{source}} = T_{\text{damping}} = T_{\text{NTV}} + T_{J\times B}$$

- Resonant EM torque on island (R. Fitzpatrick, et al.)
  - $$T_{J\times B_{wall}} = \frac{r_s}{w\mu_0} \frac{n}{m} \frac{(\Omega_\phi \tau_w)\left[1-(r_{s+}/r_w)^{2m}\right]}{1+(\Omega_\phi \tau_w)^2\left[1-(r_{s+}/r_w)^{2m}\right]^2} \left|\delta B_{r\_island}\right|^2$$
  - Average torque between island and static error field is small
- Non-resonant NTV torque (K.C. Shaing, et al.) – dominant *m* number
  - $$T_{NTV} = R \frac{\pi^{1/2} p_i}{v_{t_i}} \left(\Omega_\phi - \Omega_{\text{mode}}\right) \varepsilon^2 n^2 q \left(\frac{\delta B_r}{B_\phi}\right)^2$$

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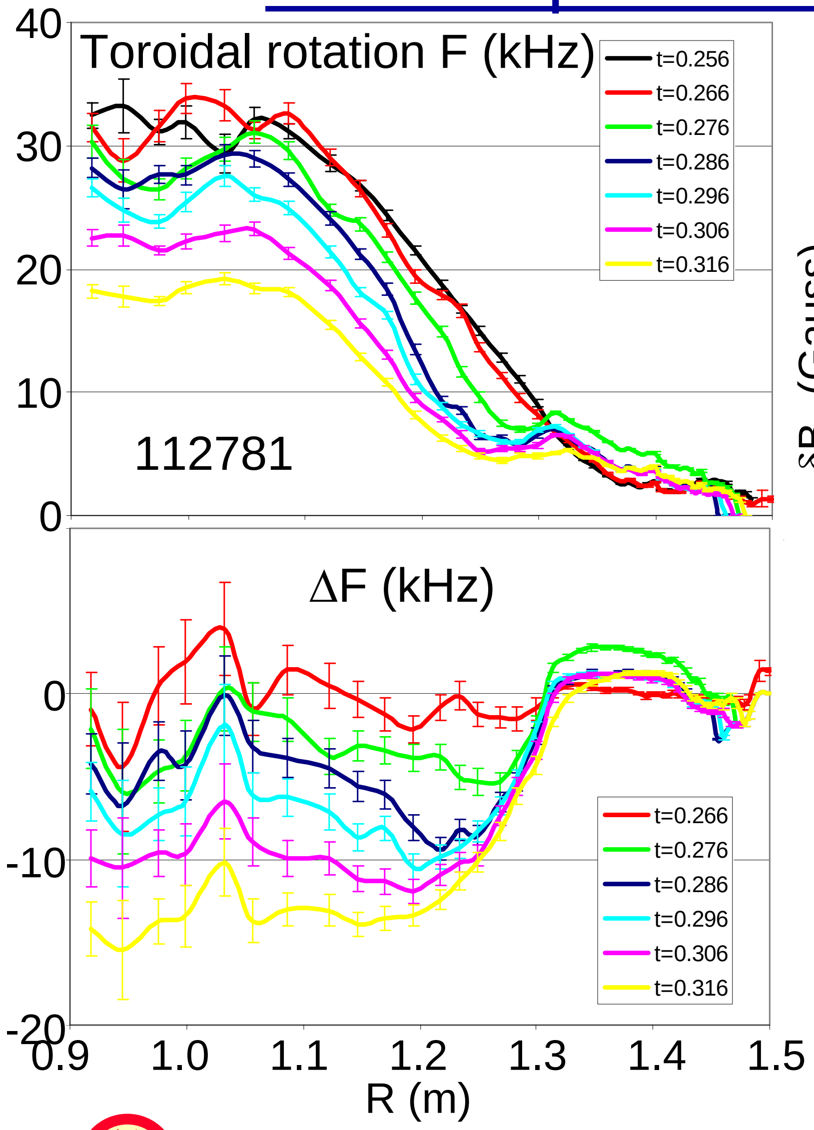
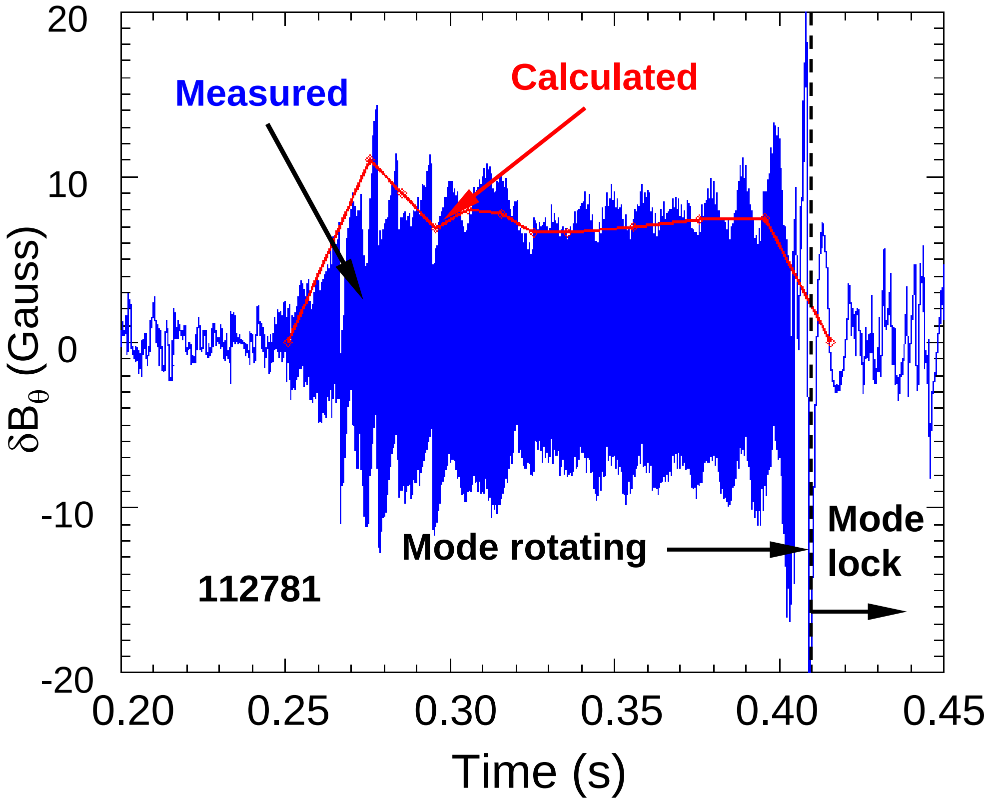
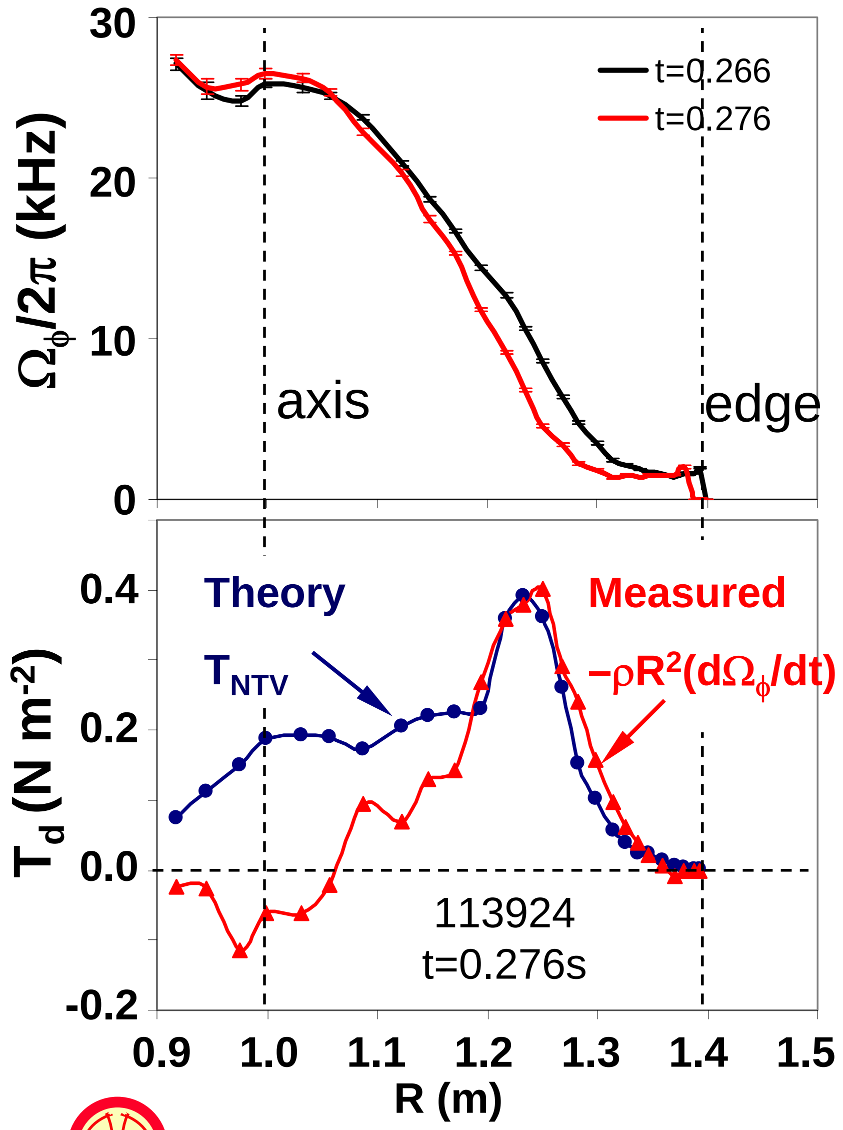
Measured Rotation Damping Matches Resonant JxB Torque from Small, Saturated Island

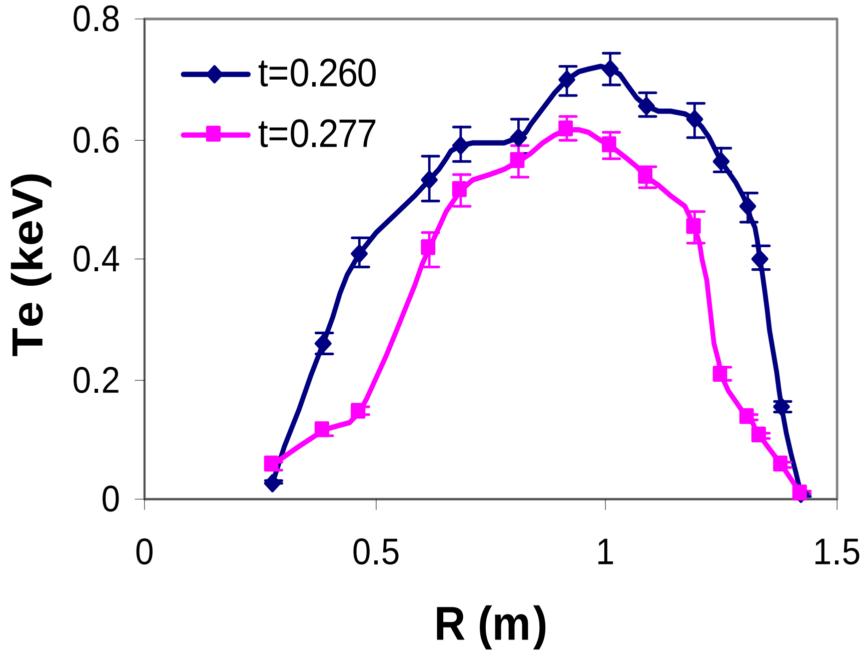




- Discharge with small island at R ~ 1.3m
- Damping localized and diffusive
- Momentum transfer across rational surface near R ~ 1.3m

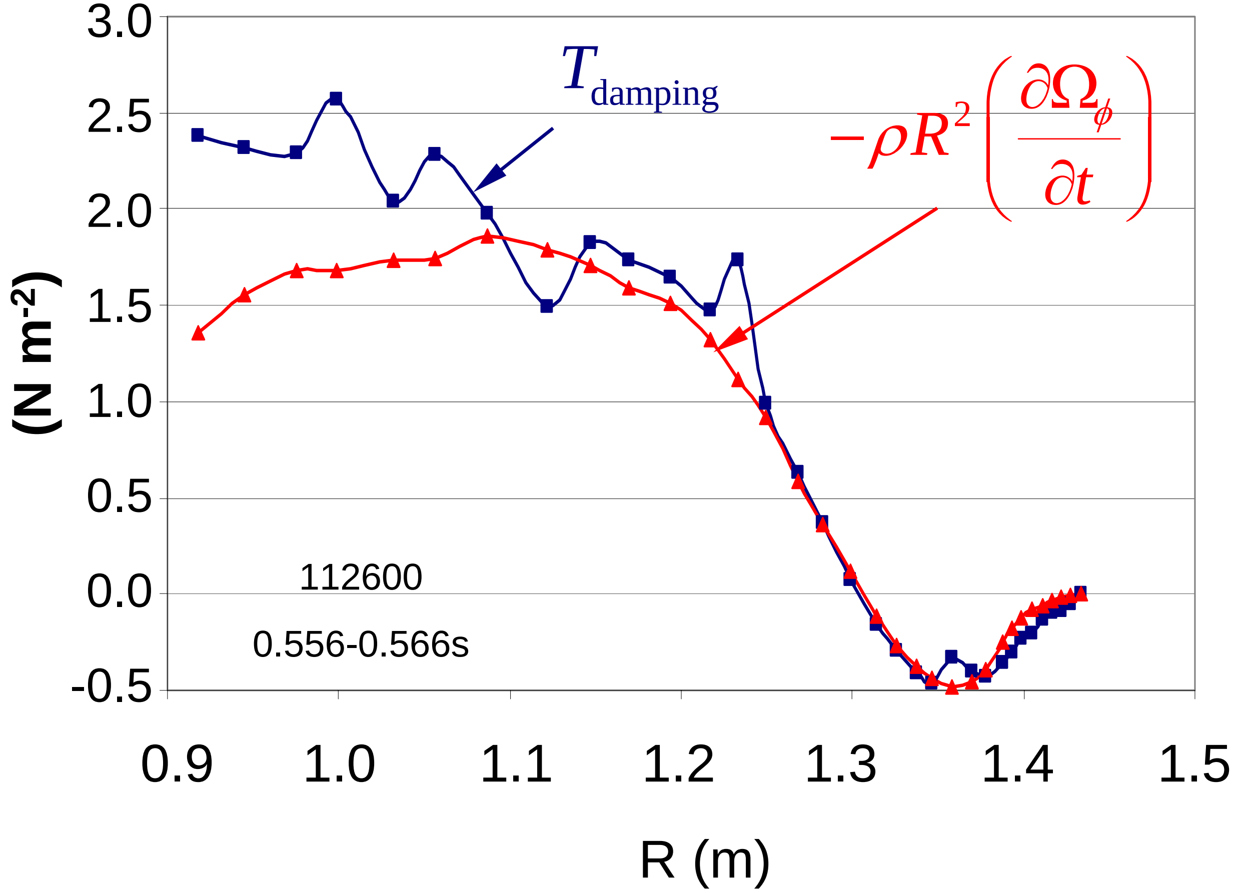
Non-resonant NTV Model in Good Agreement with Measured Global Damping during RWM



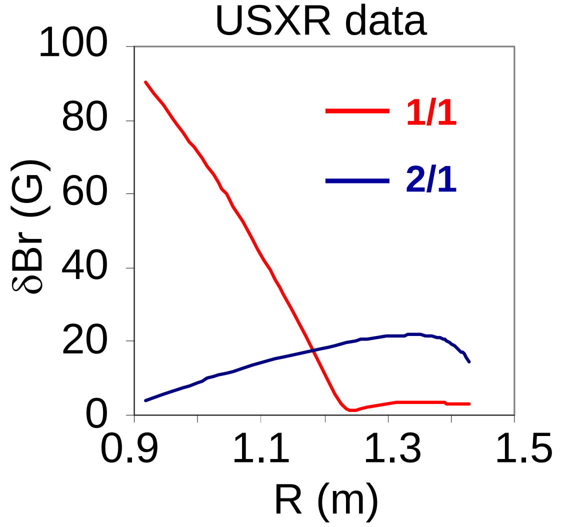


- NTV ~ $\delta B^{2}*T_i^{0.5}$
  - Edge rotation ~ 2kHz maintained
  - Measured δTe used to determine δB profile
- Low frequency tearing modes absent

NTV Torque Contributes to Measured Core Rotation Damping During Large 1/1 Mode

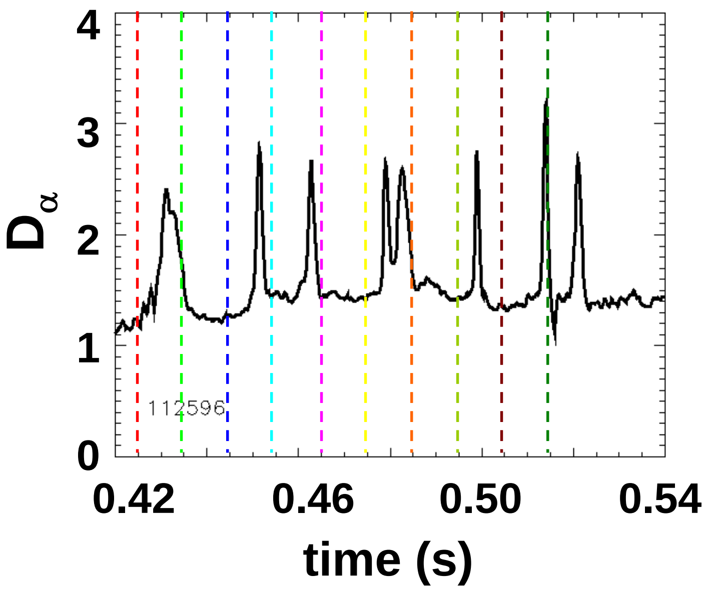


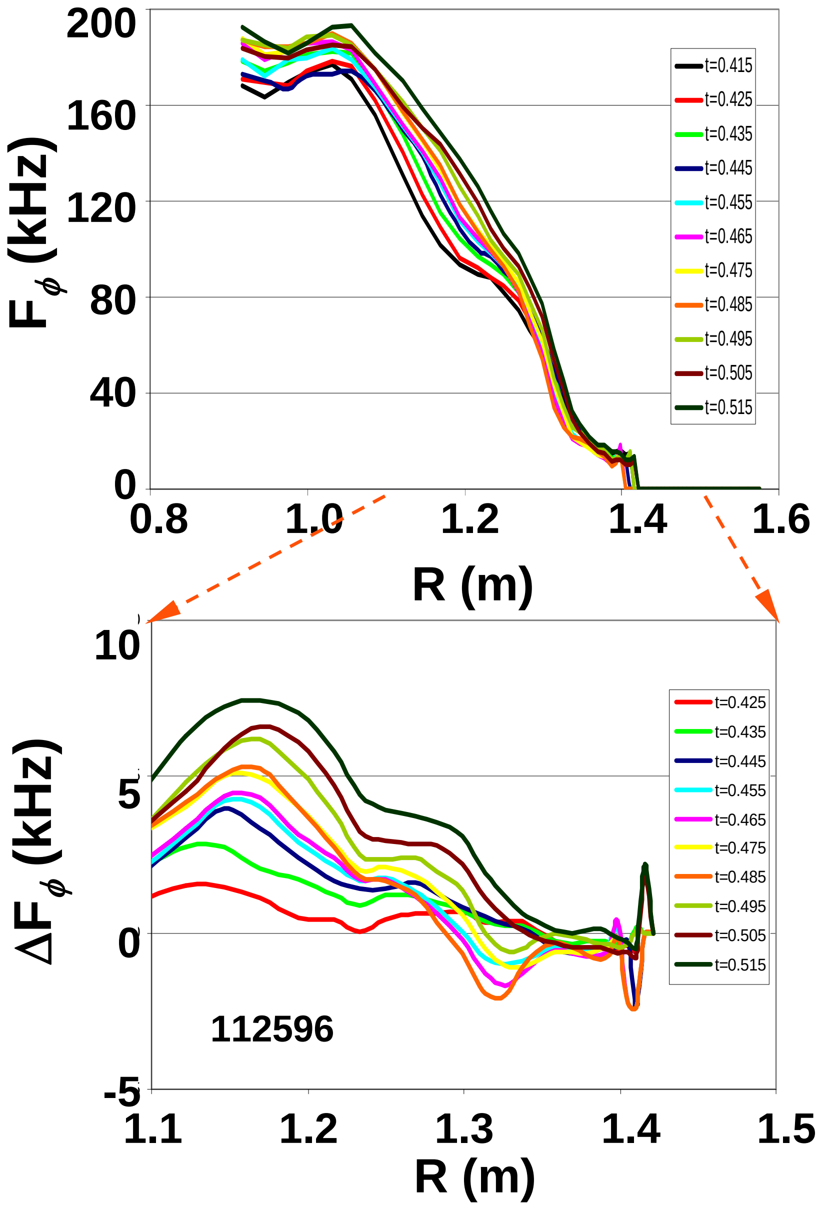
δBr derived from USXR data



- NTV torque applied to plasma core
    - Rotating mode Doppler shifted relative to q=1 surface
- Resonant EM torque applied on 2/1 island
- Fluid viscosity included

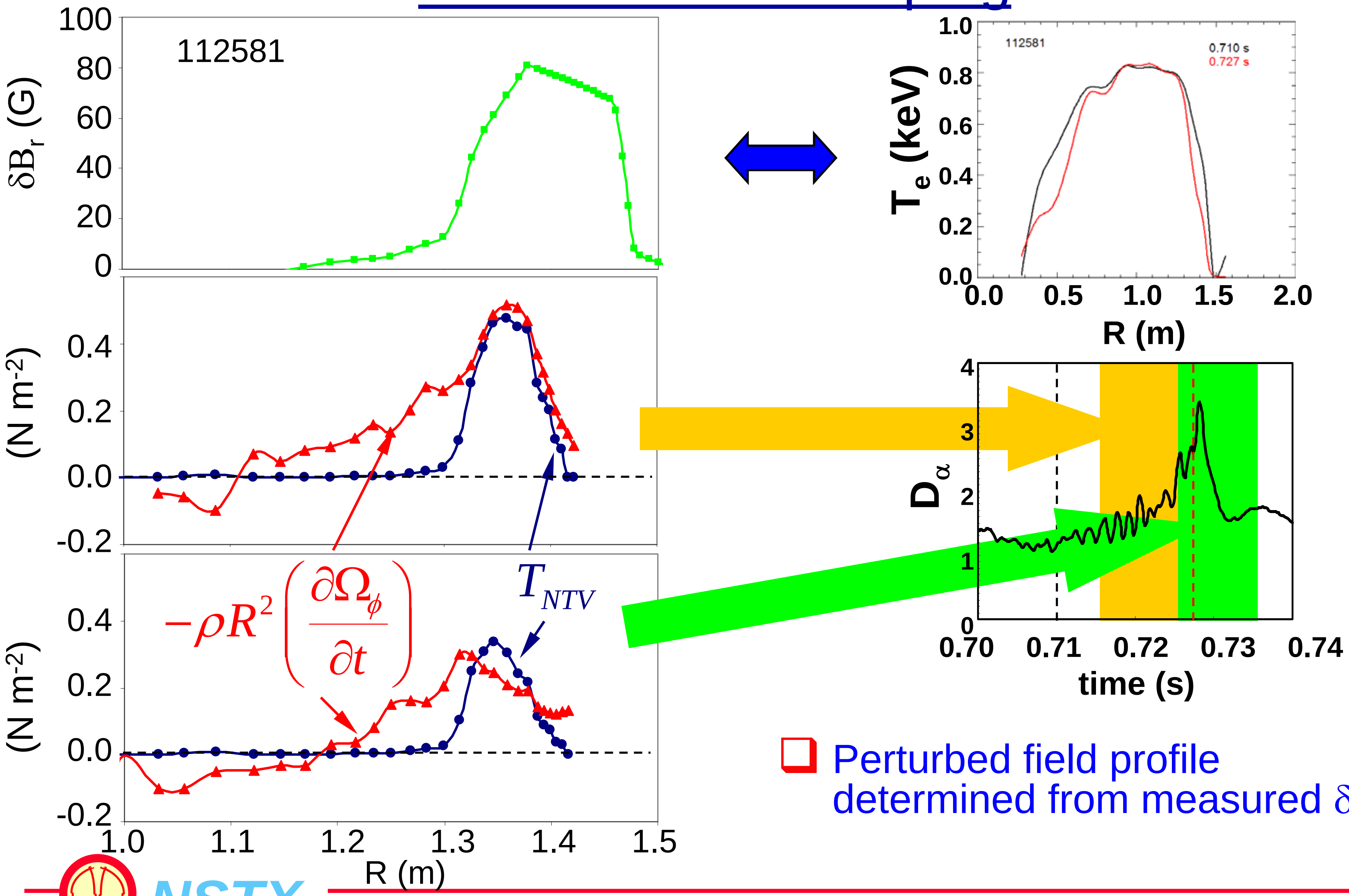
Small edge rotation decrease recovers after each ELM





- Repetitive ELMs can clamp edge rotation
  - Do not collapse rotation profile
  - Edge rotation decreases while core rotation increases
- Other low frequency modes (NTM, RWM, etc.) absent during ELM

Agreement between NTV Theory and Measured ELM Rotation Damping



- ❑ Perturbed field profile determined from measured δTe

Plasma Rotation Damping Explained by Resonant and Non-resonant Physics Mechanisms

- Resonant EM torque on island in quantitative agreement with local rotation evolution near rational surface
- Non-resonant NTV model in good agreement with global damping from RWM and internal 1/1 mode
- NTV model in good agreement with edge localized damping due to ELMs
- Maintenance of plasma rotation important for sustaining maximum beta
  - See poster JP1.005 by S.A. Sabbagh (Wed afternoon) for further detail