Investigation of Resonant and Non-resonant Magnetic Braking in Plasmas Above the No-wall Beta Limit

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Abstract - In the DIII-D tokamak, stabilization of the $n=1$ ideal kink resistive wall mode (RWM) is achieved by sustaining toroidal plasma rotation above a critical threshold. The toroidal axisymmetry of the magnetic field is important for maintaining rotation and allowing sustained access to regimes with beta significantly above the no-wall limit. To help elucidate the role of rotation in RWM stability, magnetic braking is used as a tool to modify the rotation profile. The effects of the non-axisymmetric field perturbations are studied for three cases:
(1) resonant $m/n = 2/1$ perturbations with $q_{min} < 2$,
(2) non-resonant $m/n = 2/1$ perturbations with $q_{min} > 2$,
and (3) non-resonant $n = 3$ perturbations with $q_{min} > 1.5$.
Comparisons are made to theories such as the "induction motor model" and "transit time magnetic pumping".

INTRODUCTION

- The stability of high beta plasmas ($\beta_N > \beta_N^{\text{no-wall}}$) is critically dependent on plasma rotation.

- The presence of nonaxisymmetric magnetic fields (error fields) can lead to the decay of plasma rotation and loss of stability.

- Modifying the plasma rotation in a controlled way is useful for studying the stability of high beta plasmas.

- Three different types of external field perturbations were applied to plasmas to effect rotation:

  1) resonant $m/n = 2/1$ fields with $q_{min} < 2$

  2) non-resonant $m/n = 2/1$ fields with $q_{min} > 2$

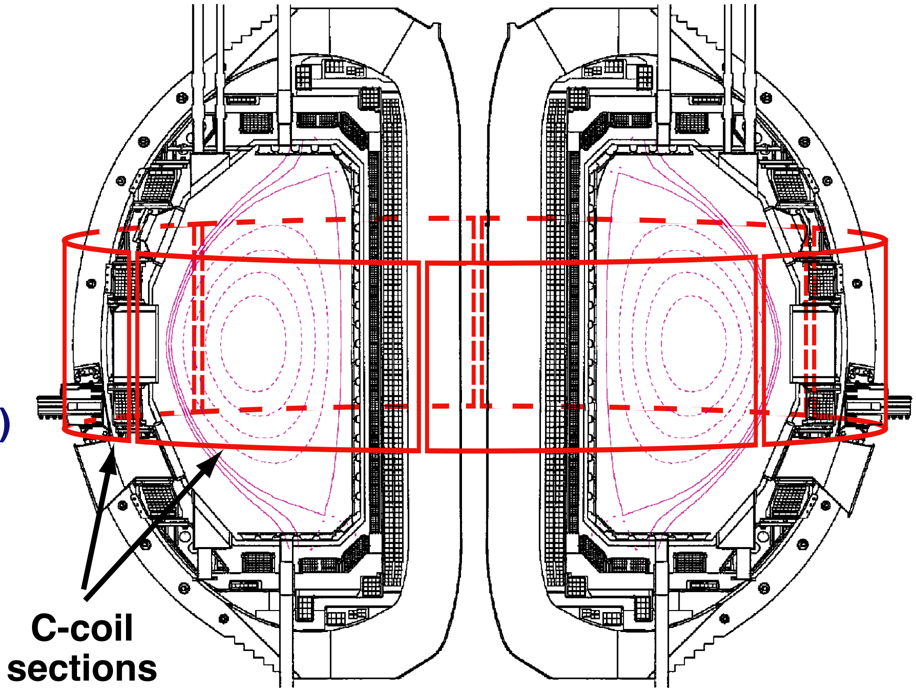
  3) non-resonant $n = 3$ fields with $q_{min} > 1.5$

- Each method of magnetic braking is modeled and comparisons are made of the relative field strengths required to effect the rotation.

ERROR FIELD CORRECTION AND ACTIVE RWM FEEDBACK CONTROL COIL SYSTEM

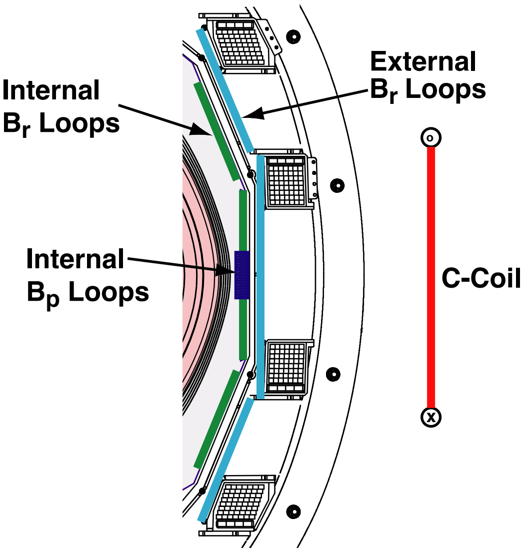
Excitation Coils

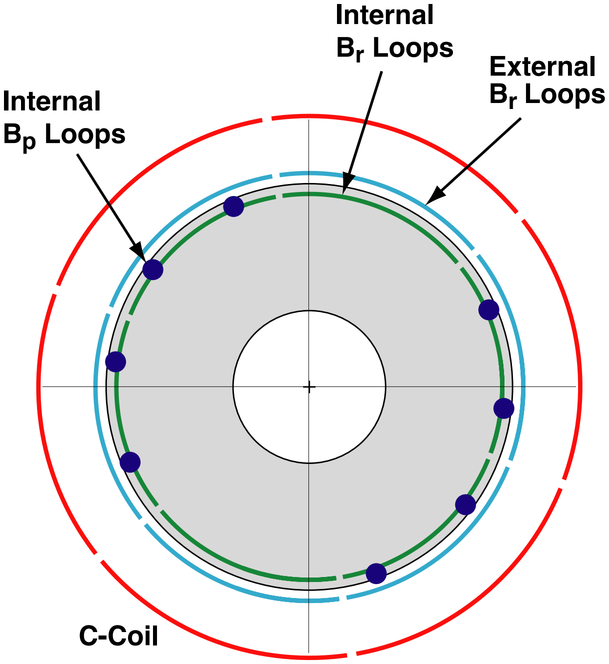
- C-coil consists of 6 sections centered around the midplane
- C-coil is driven in 3 independent pairs
- 12 internal coils (I-coils) installed this summer (see Jackson, QP1.080)



Detection Coils

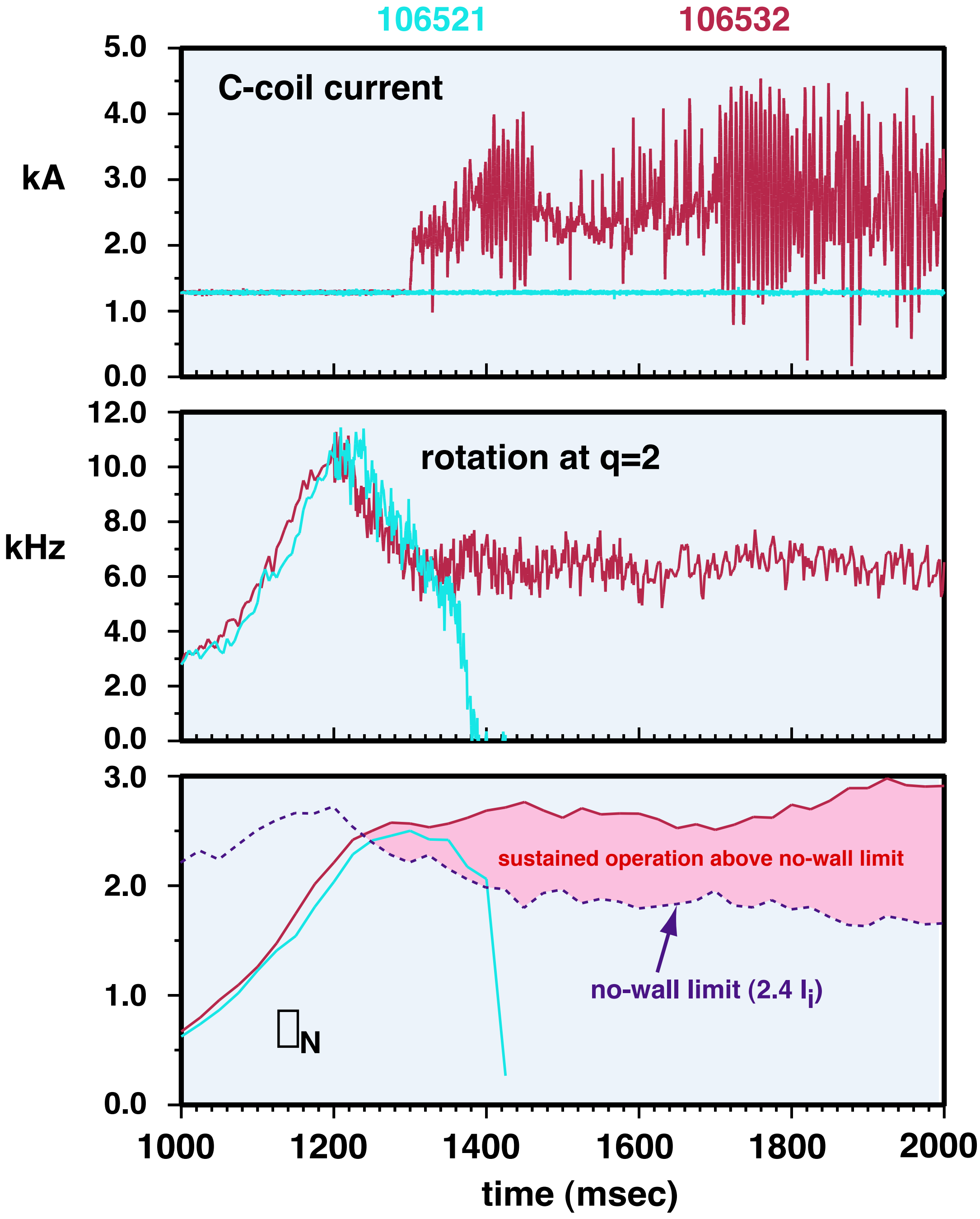
- 30 external saddle loops
  18 internal saddle loops
  8 internal poloidal field loops





SUSTAINED OPERATION WITH β_N ABOVE NO-WALL LIMIT ACHIEVED BY MAINTAINING PLASMA ROTATION

- **Reducing error field using C-coil maintains plasma rotation**



RESONANT $m/n = 2/1$ MAGNETIC BRAKING

THE INDUCTION MOTOR MODEL PREDICTS THE DEGRADATION OF PLASMA ROTATION BY A RESONANT EXTERNAL ERROR FIELD

- The physics of the degradation of plasma rotation by an external static error field is analagous to that of a conventional induction motor model (Fitzpatrick, Phys. Plasmas, 1998)

- In equilibrium, the driving torque, T_D, (from beams, etc.) is balanced by the viscous torque and the torque from the error field:

$$T_D - T_{visc} - T_{ef} = 0$$

Viscosity produces a torque T_{visc} μ f

The error field drag is T_{ef} μ $\frac{B_{ef}^2}{f}$

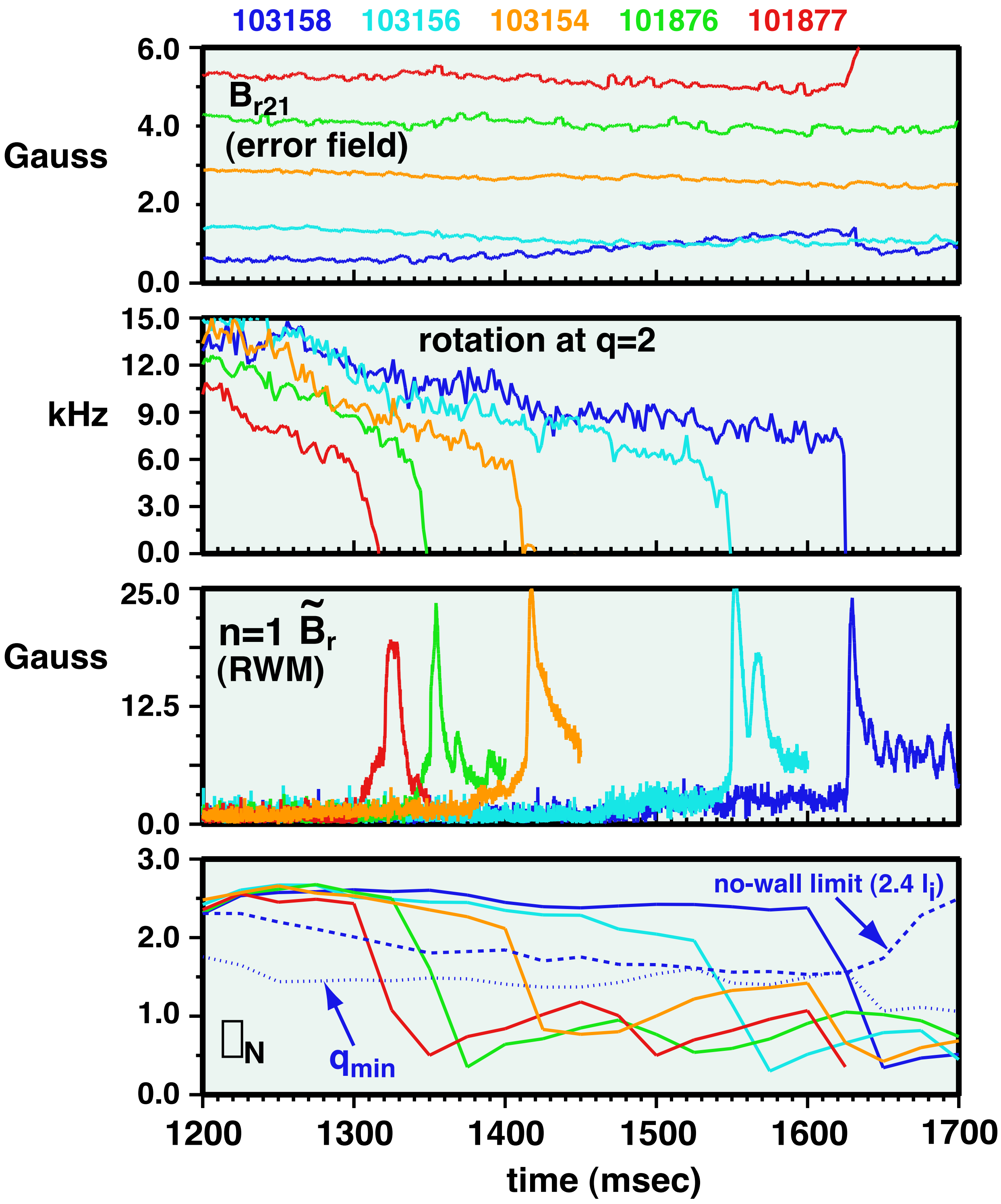
- Torque balance - induction motor model:

$$\frac{df}{dt} = \frac{f_0 - f}{\square_M} - C\,\frac{B_{ef}^2}{f}$$

where f_0 is the result of drive terms, $\square_M$ is the momentum confinement time, and C is a coefficient measuring the error field drag.

SCAN OF RESONANT m/n=2/1 ERROR FIELD WITH $q_{min} < 2$

- **Increased resonant error field causes faster rotation decay and earlier RWM onset**

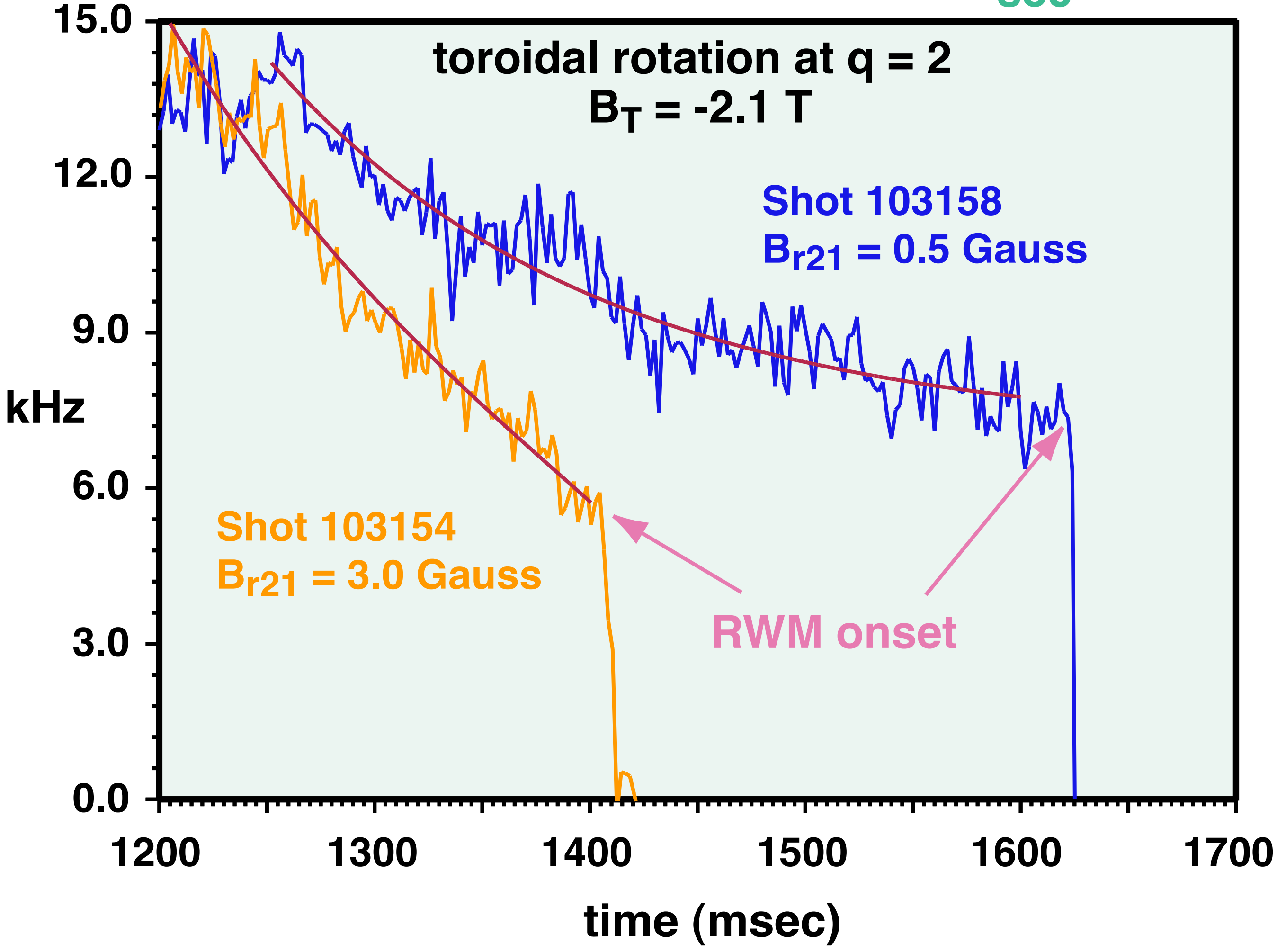


ROTATION DECAY FOR TWO SHOTS WITH DIFFERENT LEVELS OF ERROR FIELD IS FIT TO THE INDUCTION MOTOR MODEL

- Higher m/n = 2/1 resonant error field in plasmas with $q_{min} < 2$ results in faster rotation decay
- Induction motor model:

$$\frac{df}{dt} = \frac{f_0 - f}{\tau_M} - C_r \frac{B_{r21}^2}{f}$$

fit results: $f_0 = 7.2$ kHz , $C_r = 30 \frac{(\mathrm{kHz/Gauss})^2}{\mathrm{sec}}$



- For similar analysis of a large group of shots, see Garofalo, to be published in Nucl. Fus.

NON-RESONANT $m/n = 2/1$ MAGNETIC BRAKING

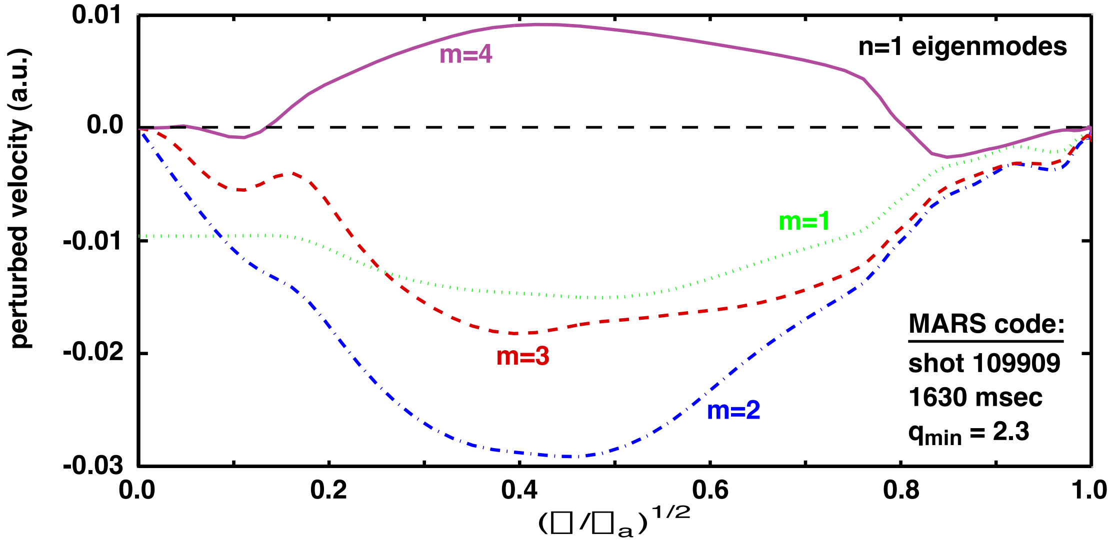
NON-RESONANT m/n = 2/1 PERTURBATIONS REDUCE ROTATION BY COUPLING TO A STABLE RESISTIVE WALL MODE

- Discharges with $\beta_N > \beta_N^{\text{no-wall}}$ and $q_{min} > 2$. No resonance surface for m/n = 2/1 component.

  - induction motor model should not apply

- The n=1 ideal kink (RWM) is stable, but close to marginal.

  - large m/n = 2/1 component of the displacement



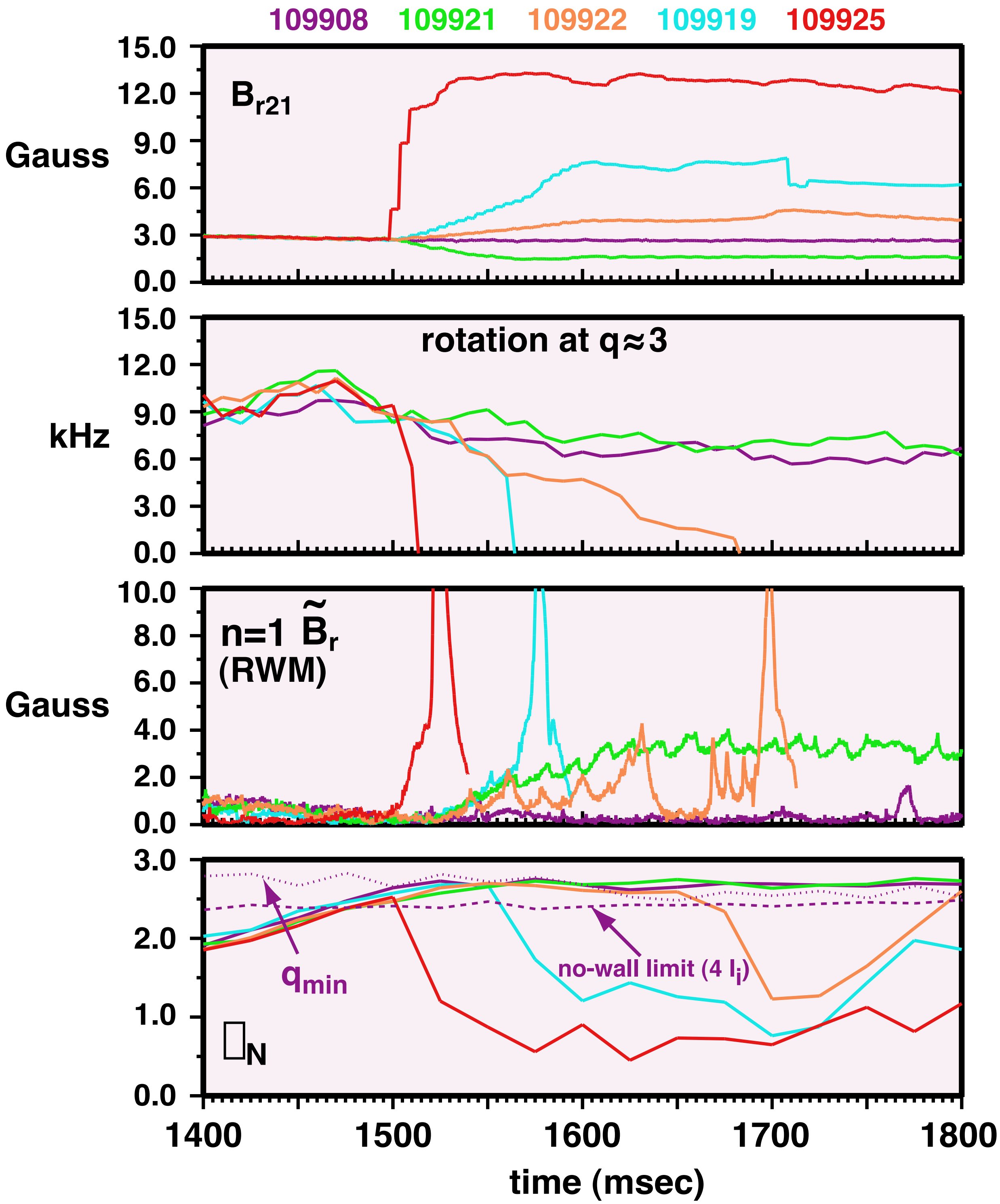
- m/n = 2/1 component of error field couples with RWM. Response is like a "forced oscillator" near marginal stability, exerting drag on rotation.

- Expect rotation decay of the form

$$\frac{df}{dt} = \frac{f_0 - f}{\tau_M} - C\, f\, B_{r21}^2$$

SCAN OF NON-RESONANT m/n=2/1 ERROR FIELD WITH $q_{min} > 2$

- **Increased non-resonant error field causes faster rotation decay and earlier RWM onset**



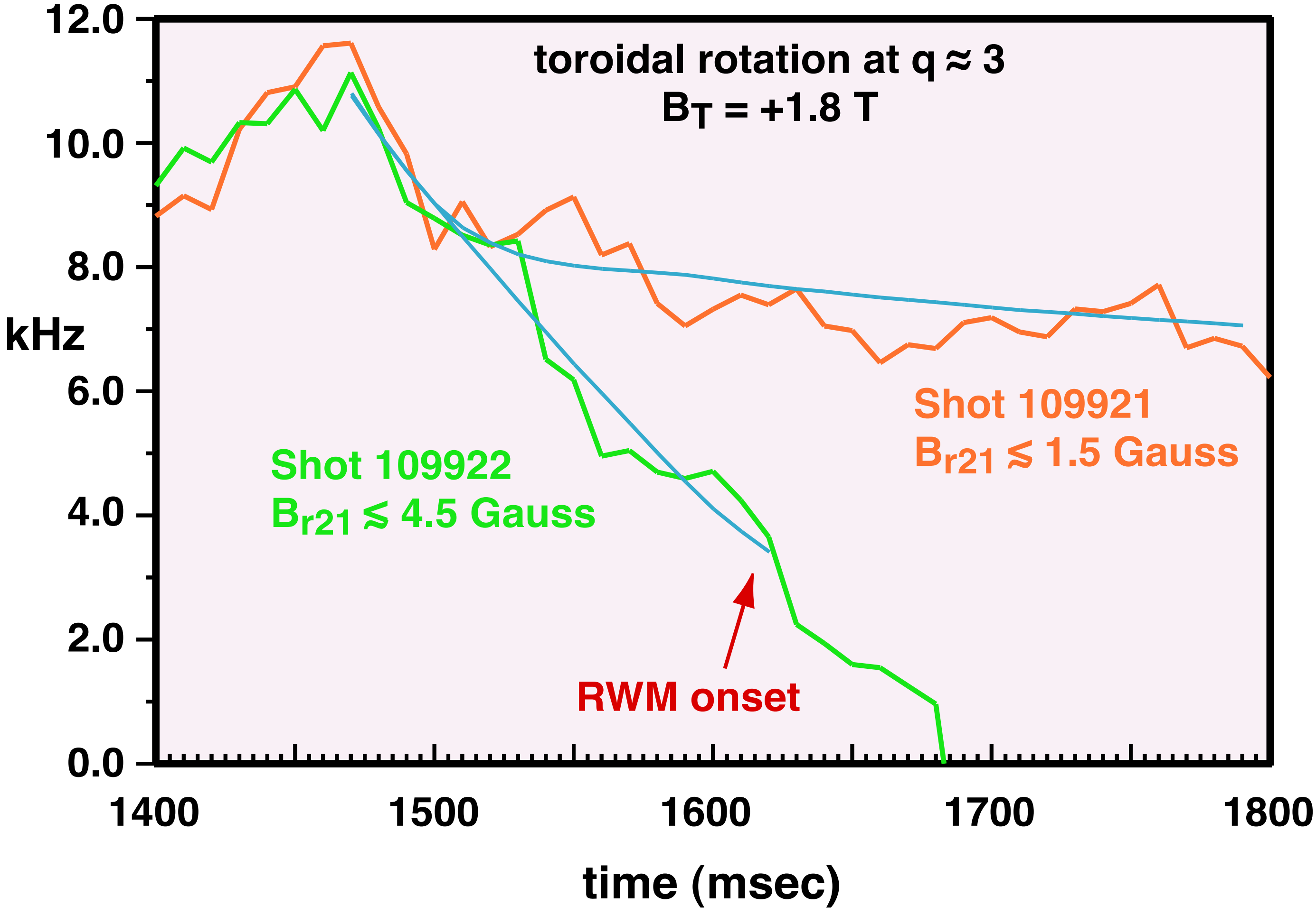
ROTATION DECAY FOR TWO SHOTS WITH DIFFERENT LEVELS OF ERROR FIELD IS FIT TO THE TTMP MODEL

- Higher non-resonant m/n = 2/1 error field results in slower rotation

- Drag from non-resonant 2/1 stable RWM:

$$\frac{df}{dt} = \frac{f_0 - f}{\tau_M} - C_{nr} f B_{r21}^2$$

fit results: $f_0 = 15.5$ kHz , $C_{nr} = 4.4 \frac{(1/\mathrm{Gauss})^2}{\mathrm{sec}}$



NON-RESONANT n = 3 MAGNETIC BRAKING

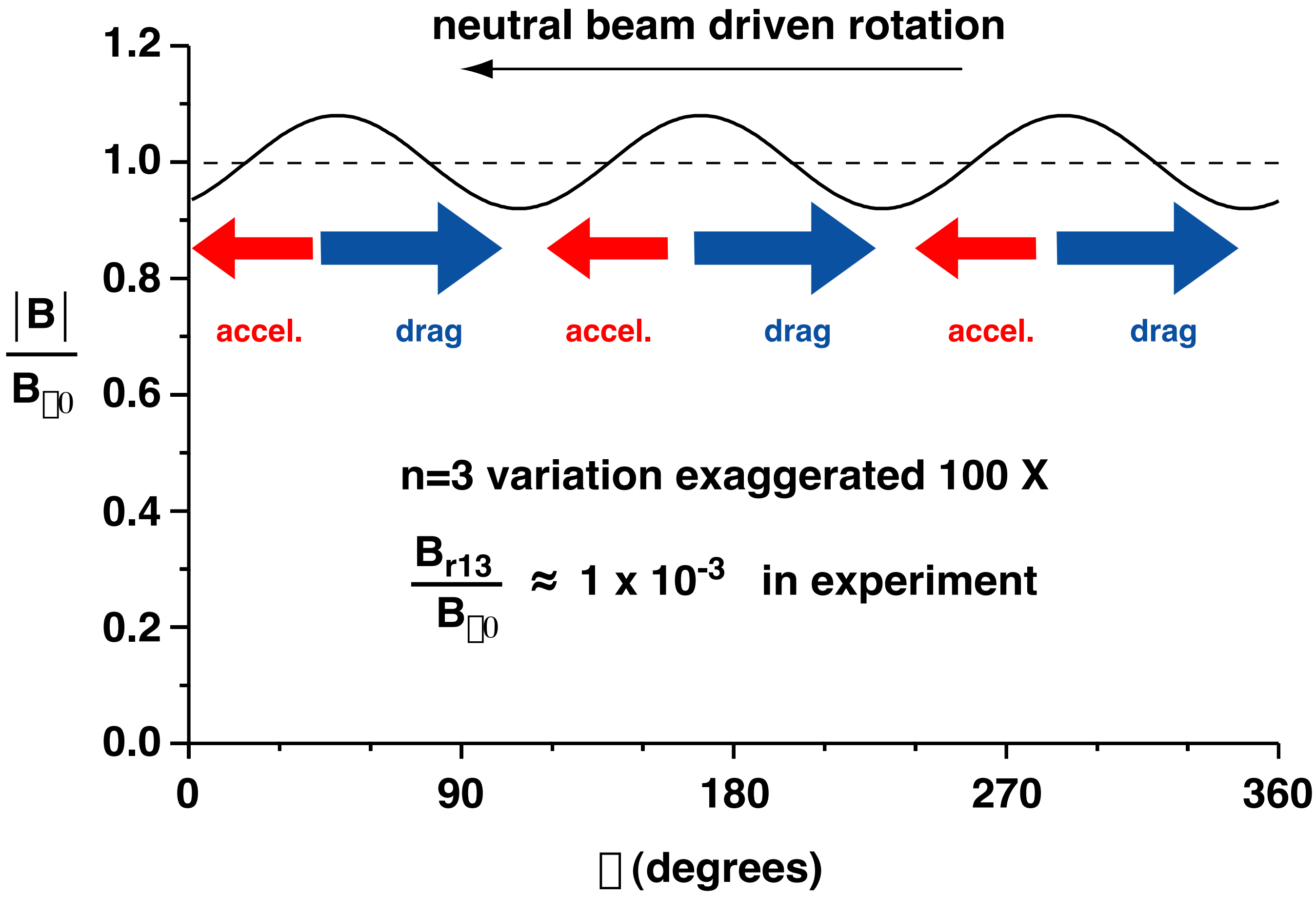
THE TRANSIT TIME MAGNETIC PUMPING MODEL PREDICTS ROTATION DECAY CAUSED BY A BUMPY MAGNETIC FIELD

- n=3 "bumpy" magnetic field, or n=3 field "ripple"

- C-coil applies m/n = 1/3 magnetic field
  - non-resonant, since q >> 1/3
  - n=3 ideal kink is very stable (not driven by n=3 field)

- Magnetic bumps in toroidal direction impede flow, causing a net drag:

$$\frac{df}{dt} \sim -\frac{v_{th,i}}{R_0}\left(\frac{B_{r13}}{B_{\phi 0}}\right)^2 f$$

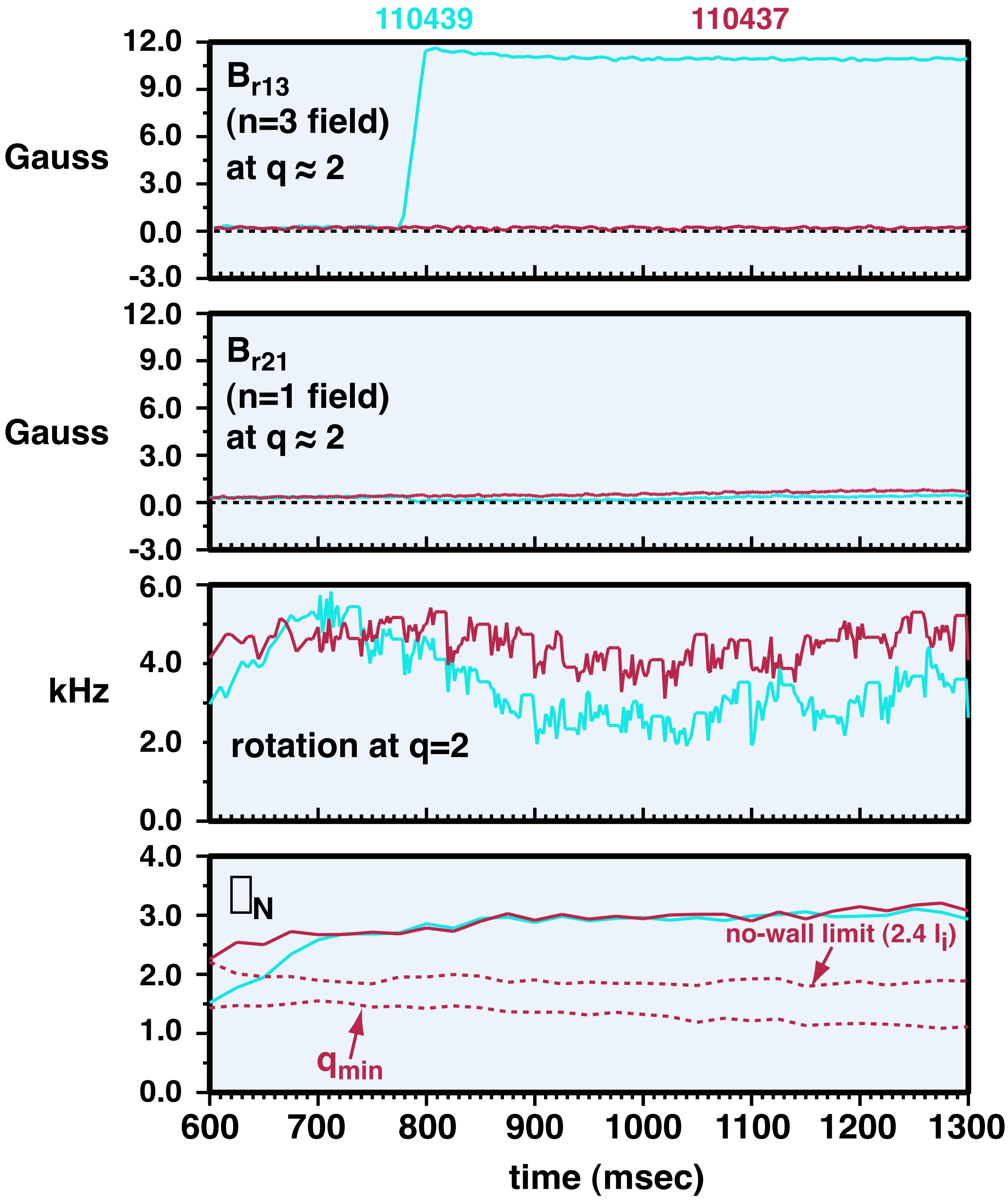


n=3 variation exaggerated 100 X

$\frac{B_{r13}}{B_{\phi 0}} \approx 1 \times 10^{-3}$ in experiment

NON-RESONANT n=3 ERROR FIELD REDUCES TOROIDAL ROTATION

- 110439 and 110437 both have negligible n=1 field. n=3 field applied to 110439.



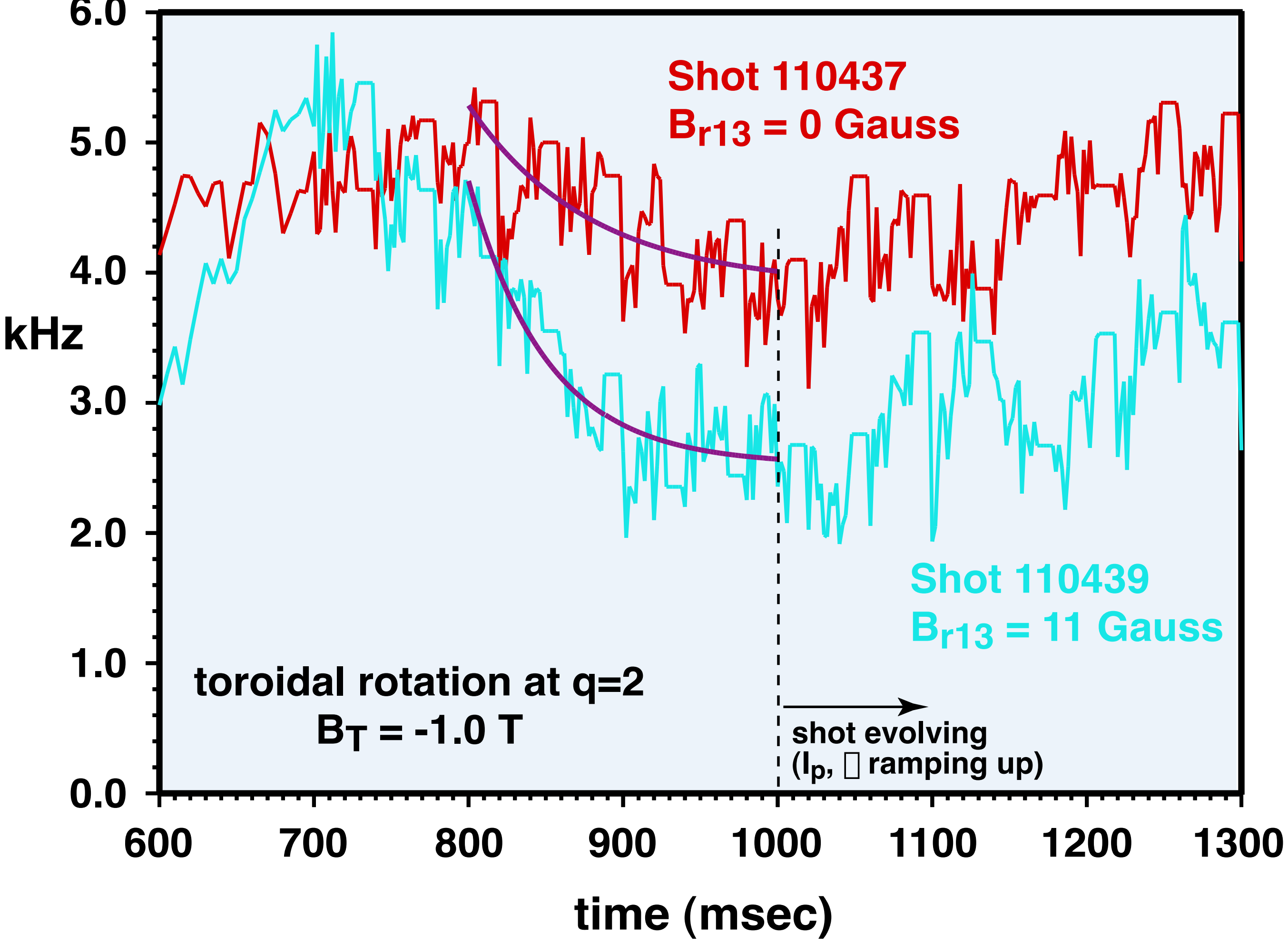
ROTATION DECAY FOR TWO SHOTS WITH DIFFERENT LEVELS OF ERROR FIELD IS FIT TO THE TTMP MODEL

- higher m/n = 1/3 non-resonant error field results in slower rotation (note $B_T = -1.0$ T)
  - both shots have good rotation and no RWM

- transit time magnetic pumping model:

$$\frac{df}{dt} = \frac{f_0 - f}{\square_M} - C_{ttmp} f\, B_{r13}^2$$

fit results: $f_0 = 3.9$ kHz , $C_{ttmp} = .057 \dfrac{(1/\mathrm{Gauss})^2}{\mathrm{sec}}$



COMPARISON OF BRAKING METHODS

- Results of the models for rotation decay are used to compare the three methods of magnetic braking.
- In equilibrium (df/dt = 0), what relative error field B_{ef}/B_T is required to reduce the rotation to half the frequency with no error field ($f_0/2$)?

1) resonant m/n = 2/1

$\tau_M = 0.15$ sec $\quad B_T = -2.1$ T

$f_0 = 7.2$ kHz $\quad C_r = 30$

$$f \longrightarrow \frac{f_0}{2} \quad \Rightarrow \quad \frac{B_{ef}}{B_T} = 8.1 \times 10^{-5}$$

2) non-resonant m/n = 2/1

$\tau_M = 0.125$ sec $\quad B_T = +1.86$ T

$f_0 = 15.5$ kHz $\quad C_{nr} = 4.4$

$$f \longrightarrow \frac{f_0}{2} \quad \Rightarrow \quad \frac{B_{ef}}{B_T} = 7.3 \times 10^{-5}$$

3) non-resonant n = 3

$\tau_M = 0.08$ sec $\quad B_T = -1.05$ T

$f_0 = 3.9$ kHz $\quad C_{ttmp} = .057$

$$f \longrightarrow \frac{f_0}{2} \quad \Rightarrow \quad \frac{B_{ef}}{B_T} = 1.4 \times 10^{-3}$$

CONCLUSIONS

- Three different types of magnetic braking were used in plasmas with $\beta_N > \beta_N^{\text{no-wall}}$ to modify the rotation profile and study the stability of high beta plasmas.

- Rotation decay data was fit using the induction motor model for resonant error fields and the transit time magnetic pumping or field ripple model for non-resonant error fields.

- For a 50% degradation of rotation, the level of relative error field required for non-resonant n=3 perturbations is approximately 20 times higher than the m/n = 2/1 field required.

- A surprising result is that the strength of the m/n = 2/1 error field required for rotation modification is comparable for resonant and non-resonant perturbations.

- Increased understanding of magnetic braking makes it a more useful tool in the study of high beta plasma rotation and stability.

FUTURE WORK

- **Installation of a set of 12 saddle coils (I-coils) inside the vacuum vessel has just been completed - 6 coils in the upper plane and 6 in the lower.**
- **Experiments in error field and RWM control using the I-coils will be carried out in the 2003 campaign.**

Tuesday, October 23, 2001 JPEG image 2048x1536 pixels