ABSTRACT

Improved Resistive Wall Mode Stability in DIII-D with Optimal Error Field Correction*

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In the development of an advanced tokamak plasma, beta may be limited by the Resistive Wall Mode (RWM). Sufficient plasma rotation can stabilize the RWM[1], but rotation can be reduced by the torque from error fields. In DIII-D plasmas with beta above the "no wall" limit, the rotation steadily drops and leads to an n=1 RWM when the rotation decreases below a critical value[2]. This is consistent with enhanced drag caused by a resonant response to an uncompensated n=1 error field once beta exceeds the no wall limit. A simple torque balance model that includes this effect will be compared with data. The experimental results show that careful error field correction leads to a much longer period of sustained rotation and RWM stability with beta above the no wall limit before the eventual RWM growth is observed.

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[1] A. Boozer, Phys. Plasmas **2**, 4521 (1995).

[2] A.M. Garofalo, *et. al.*, Phys. Rev. Lett. **82**, 3811 (1999).

INTRODUCTION

- Several recent experiments on DIII-D have focused on studying the stabilization of the resistive wall mode (RWM).

- In plasmas with β_N above the no-wall limit, a decrease in plasma rotation leads to the onset of the RWM.

- An enhanced plasma response to the external error field ("error field amplification") is observed as β_N exceeds the no-wall limit[1].

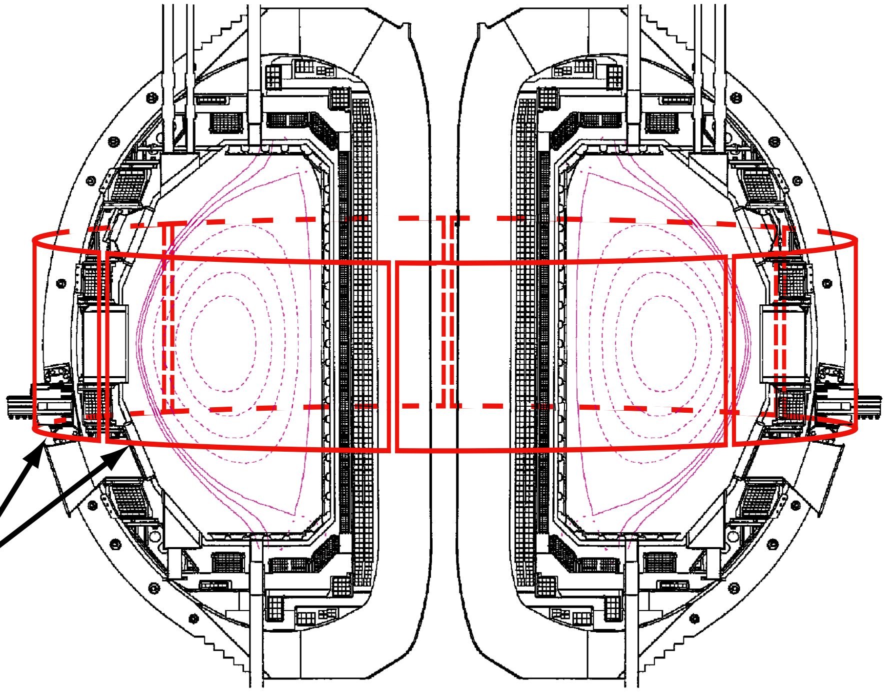
- The decay of plasma rotation is correlated with the error field. Better error field correction sustains plasma rotation and delays the RWM. Error field scans are fit well using the induction motor model of Fitzpatrick[2].

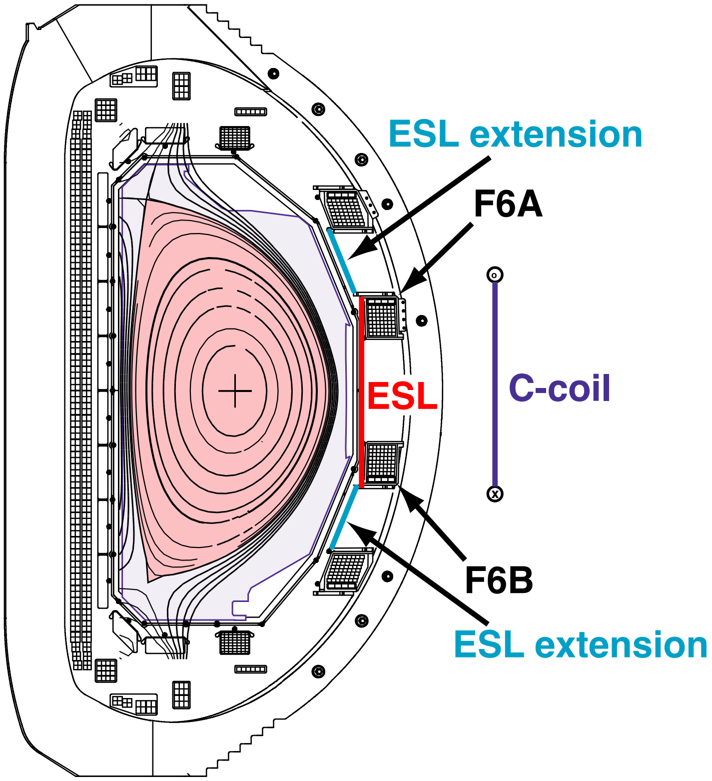
1 Garofalo, et. al., Phys. Rev. Lett. 82 (1999) 3811.
2 Fitzpatrick, Phys. Plasmas 5 (1998) 3325.

ACTIVE RWM STABILIZATION EXPERIMENTS IN DIII-D USE EXISTING 6-ELEMENT COIL SET

- C-coil consists of 6 sections centered around the midplane

- C-coil is driven in 3 independent pairs



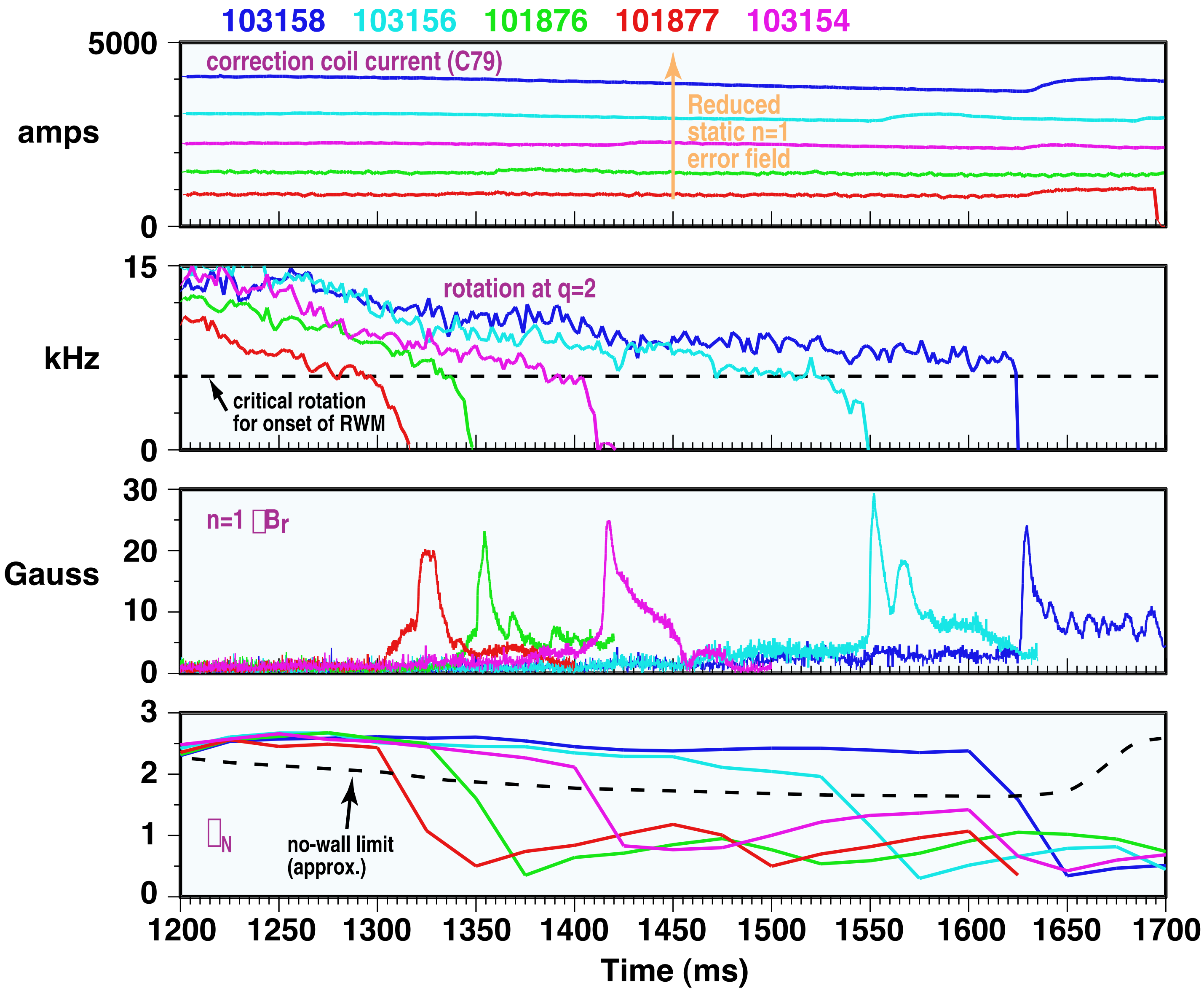


- RWM feedback uses 6 midplane external saddle loops (ESLs) on vessel wall

- Radial field sensed by ESLs is canceled by C-coil

BETTER CORRECTION OF THE m/n=2/1 ERROR FIELD SLOWS ROTATION DECAY AND POSTPONES THE ONSET OF THE RWM

- Rotation decay results from error field torque, which is enhanced when $\beta_N > \beta_N^{no\text{-}wall}$
- RWM onset when rotation drops to ~ 6 kHz
- Eventual growth rate of RWM, $\gamma\tau_W$, increases as delay in mode onset increases



ROTATION DECREASES AS β_N EXCEEDS THE NO-WALL LIMIT DUE TO INCREASED ERROR FIELD DRAG

- **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: $T_{visc} \propto \Omega$ **error field:** $T_{ef} \propto \frac{B_{ef}^2}{\Omega}$

In terms of Ω, torque balance can be written:

$$\frac{d\Omega}{dt} = \frac{\Omega_0 - \Omega}{\tau_M} - \frac{C_{ef} B_{ef}^2}{\Omega} \qquad (1)$$

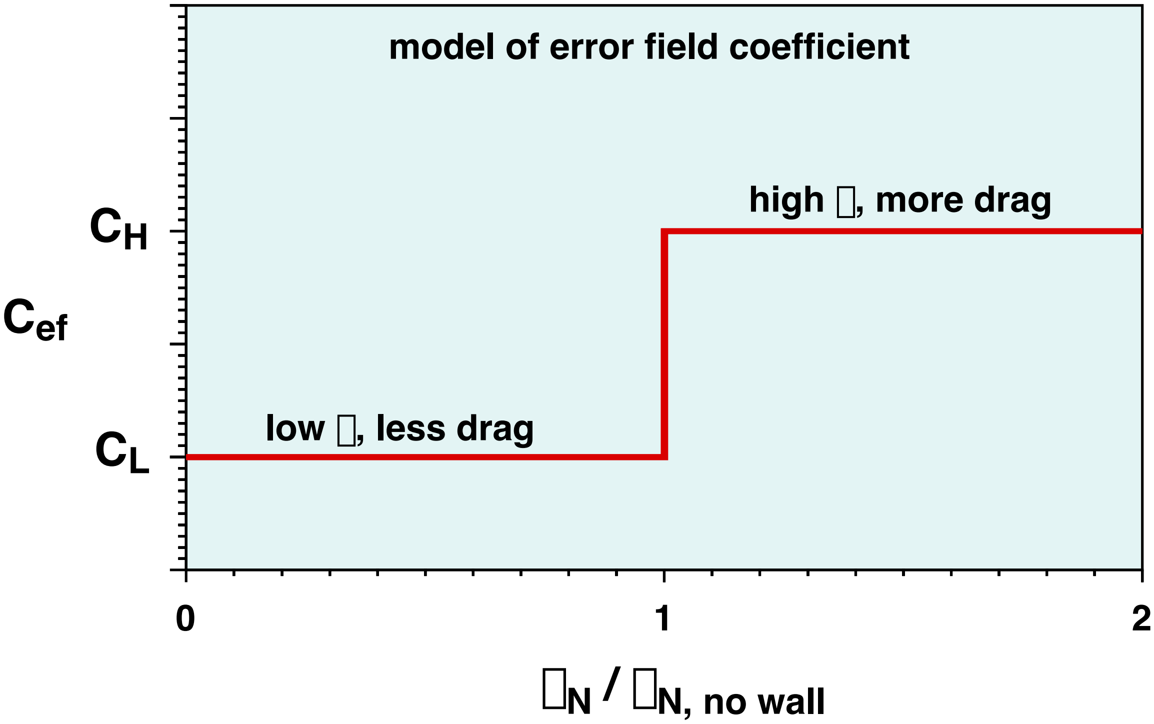
where Ω_0 is the result of drive terms, τ_M is the momentum confinement time, and C_{ef} is the coefficient of error field drag.

- **Equilibrium (dΩ/dt=0) gives a quadratic with solution**

$$\Omega = \frac{\Omega_0}{2} + \frac{\Omega_0}{2}\sqrt{1 - \frac{B_{ef}^2}{B_{crit}^2}} \quad , \qquad (2)$$

where $B_{crit}^2 \equiv \frac{\Omega_0^2}{4\tau_M C_{ef}}$ is the critical error field that reduces rotation by 1/2 and leads to a locked mode.

- As β_N increases and exceeds the no-wall limit, the plasma response to the error field suddenly increases. The error field coefficient, C_{ef} is modeled:



- The increase in error field drag for $\beta_N > \beta_{N,\text{ no-wall}}$ causes plasma rotation to decay. From eqn. (1),

$$\frac{d\Omega}{dt} = -\frac{(C_H - C_L)B_{ef}^2}{\Omega} \qquad (3)$$

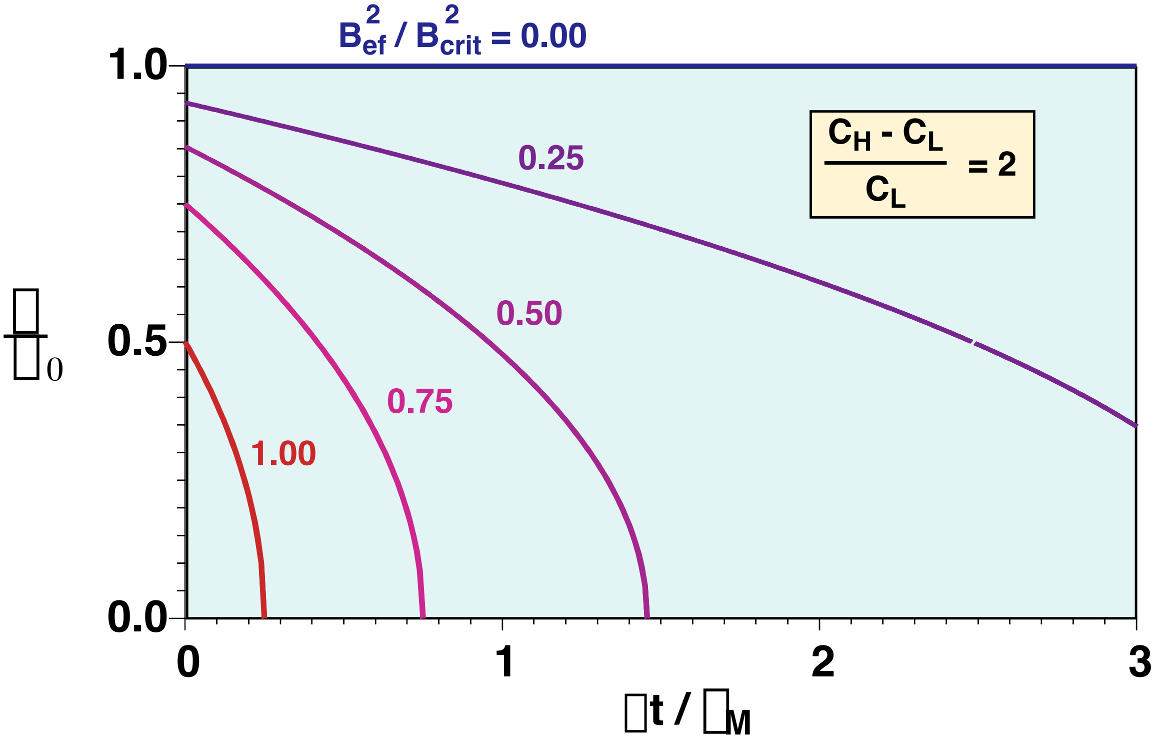
- Integrating eqn. (3) gives

$$\left.\frac{\Omega^2}{2}\right|_{\Omega_{init}}^{\Omega} = -(C_H - C_L)B_{ef}^2\Delta t$$

The rotation frequency prior to the $\square_N > \square_{N,\ \text{no-wall}}$ transition, $\square_{\text{init}}$, is defined by eqn. (2). The time from the transition is $\square t$. In terms of dimensionless ratios,

$$\frac{\square}{\square_0} = \left[\left(\frac{1}{2} + \frac{1}{2}\sqrt{1 - \frac{B_{ef}^2}{B_{crit}^2}} \right)^2 - \frac{C_H - C_L}{2C_L} \frac{B_{ef}^2}{B_{crit}^2} \frac{\square t}{\square_M} \right]^{1/2} \qquad (4)$$

- **A family of curves from eqn. (4) is generated by varying the strength of the error field and illustrates the effect on rotation decay.**



THE PHYSICS OF THE DEGRADATION OF PLASMA ROTATION BY AN EXTERNAL STATIC ERROR FIELD IS ANALOGOUS TO THAT OF A CONVENTIONAL INDUCTION MOTOR

- **Resonant components of an external magnetic error field can cause a bifurcation of the plasma state:**

  ⊟ the rotating state, where error field driven
  □ reconnection is suppressed

  ⊟ the fully reconnected state, where rotation
  □ is arrested at the rational surface

- **The transition between the rotating state and the reconnected state is determined by the error field.**

- **Scans show there are optimum values for the C-coil amplitude and phase, I_{opt} and $\square_{opt}$, that minimize the error field and the rotation decay.**

- **The rotation decay problem is linearized near the optimum values using eqn. (1). The result is the induction motor model.**

- Induction motor model - for a given C-coil amplitude and phase, I_c and ϕ_c , the rotation decay is:

$$\frac{df}{dt} = a_o + \frac{a_1}{2\pi f}\left[(I_c \sin \phi_c - I_{opt} \sin \phi_{opt})^2 + (I_c \cos \phi_c - I_{opt} \cos \phi_{opt})^2\right]$$

where a_0 , a_1 , I_{opt} and ϕ_{opt} are parameters determined by a multivariate fit.

- From fits of rotation data at the q=2 and q=3 surfaces, the optimum C-coil phase, ϕ_{opt} , is about 64° to minimize rotation decay. The predicted phase is the same for each of the surfaces.

- The optimum C-coil amplitude, I_{opt} , is approximately the same for each of the fits. I_c = 3.6 kA produces an m/n=2/1 correction field of about 7 Gauss.

- a_0 defines a rotation decay time, $\tau_{decay} = \frac{f_0}{a_0}$. where f_0 is the peak frequency.

	q=2 fit:	q=3 fit:
a_0 =	26.6 kHz/sec	19.4 kHz/sec
f_0 =	14 kHz	10.5 kHz
τ_{decay} =	0.53 sec	0.54 sec

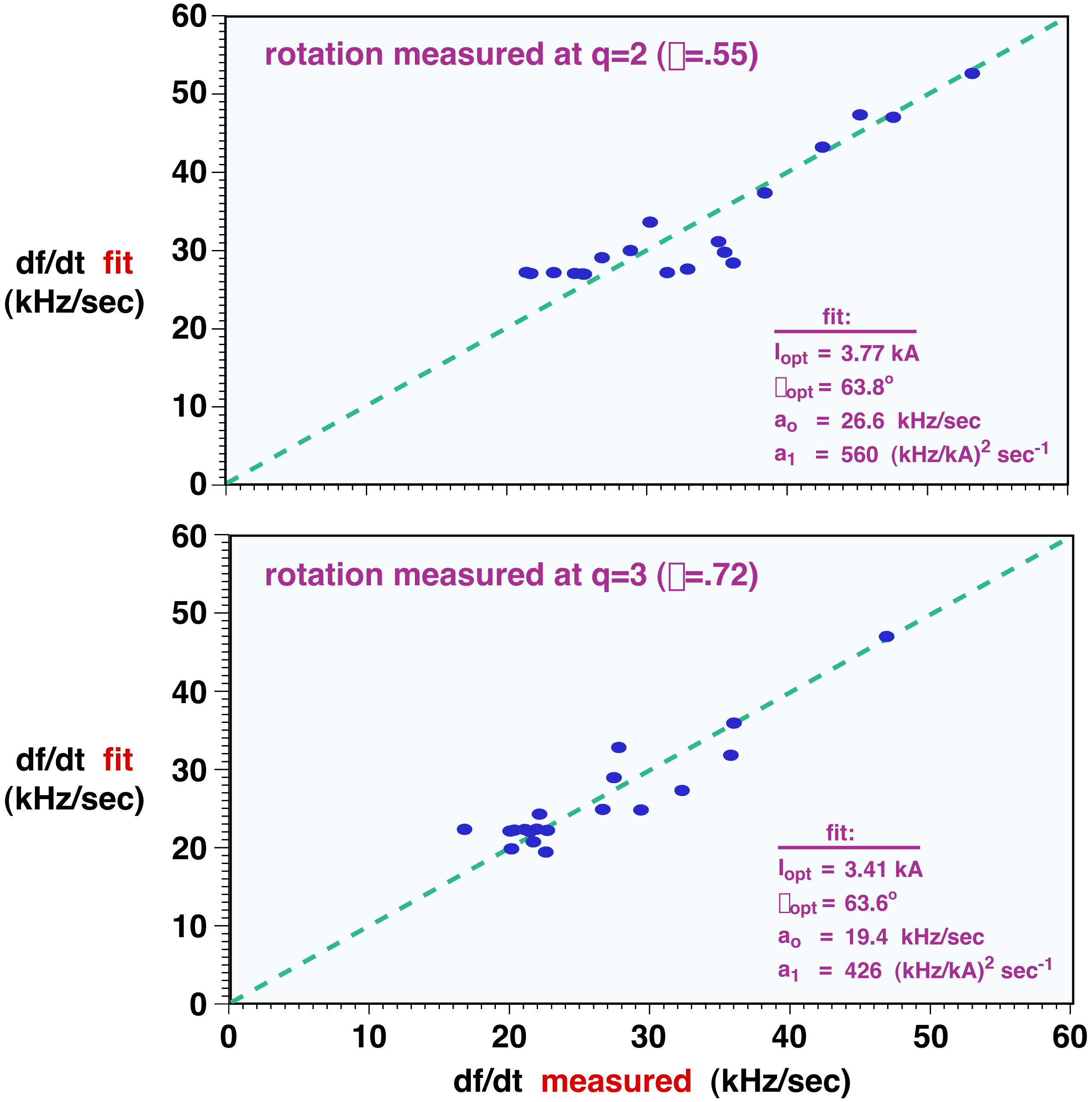
For comparison, the energy confinement time before RWM onset is approximately τ_E = 0.2 sec.

ROTATION DECAY DATA FITS THE INDUCTION MOTOR MODEL

- induction motor model:

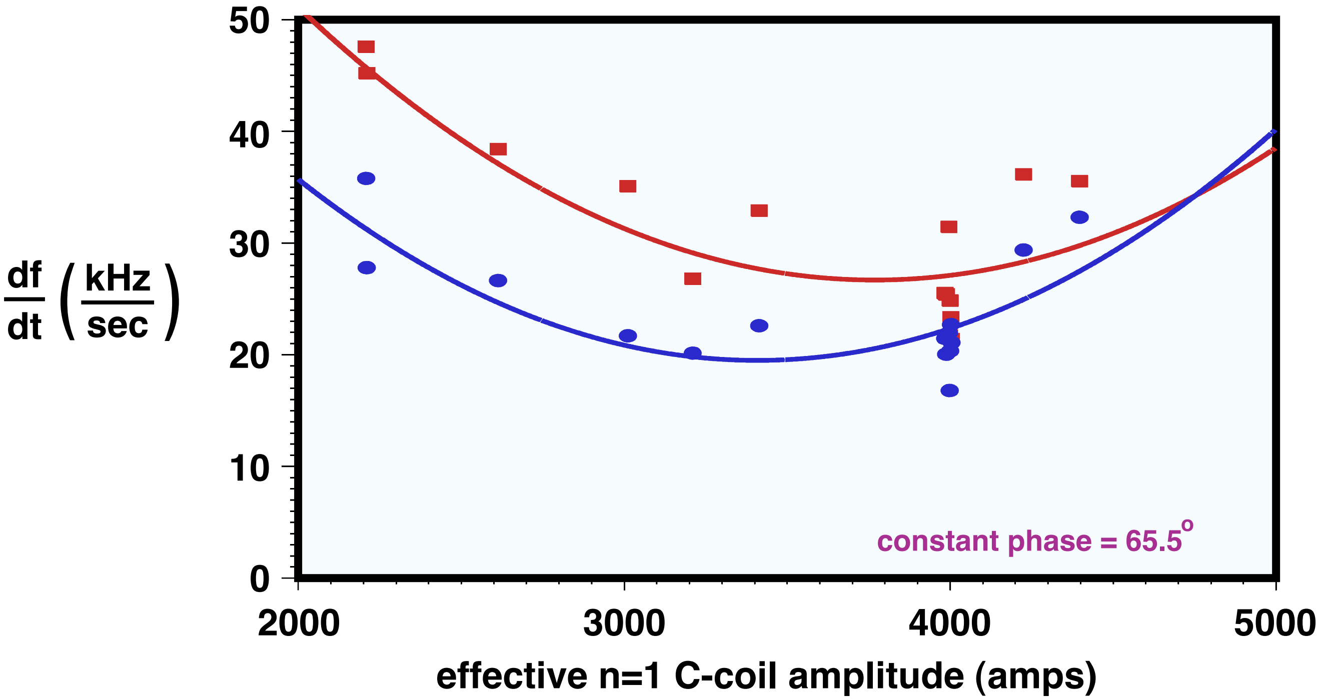
$$\frac{df}{dt} = a_o + \frac{a_1}{2\square f}\left[(I_c \sin \square_c - I_{opt} \sin \square_{opt})^2 + (I_c \cos \square_c - I_{opt} \cos \square_{opt})^2\right]$$

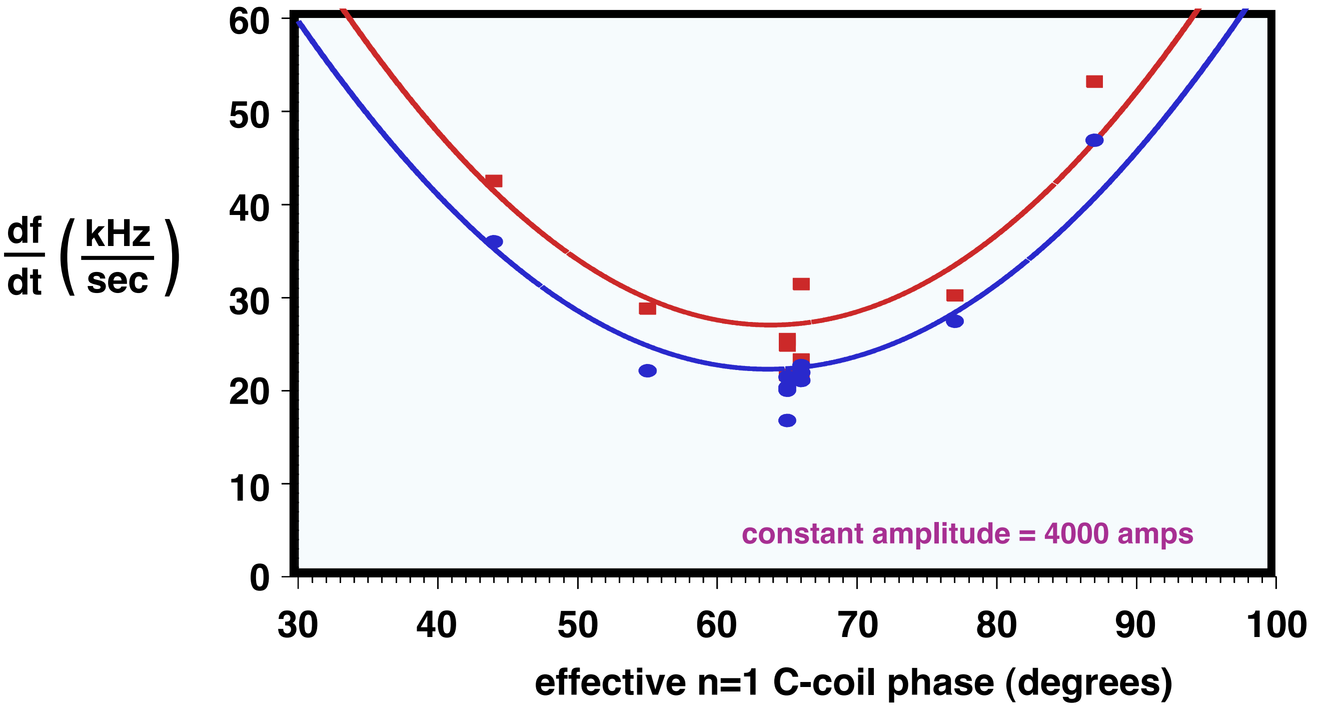
- nearly the same optimum error field amplitude and phase are predicted for two different radial positions
- faster decay rate at higher frequencies, lower □



ROTATION DECAY IS MINIMIZED WITH OPTIMUM ERROR FIELD CORRECTION CURRENT AND PHASE

- Rotation data at ■ ▯=.55 (q=2) ● ▯=.72 (q=3)
- Curves from fits to induction motor model





PULSED ERROR FIELD EXPERIMENTS STUDY PLASMA RESPONSE AT HIGH β_N

- In a series of discharges with varying β_N, the error field correction current was notched to simulate a pulsed external error field.

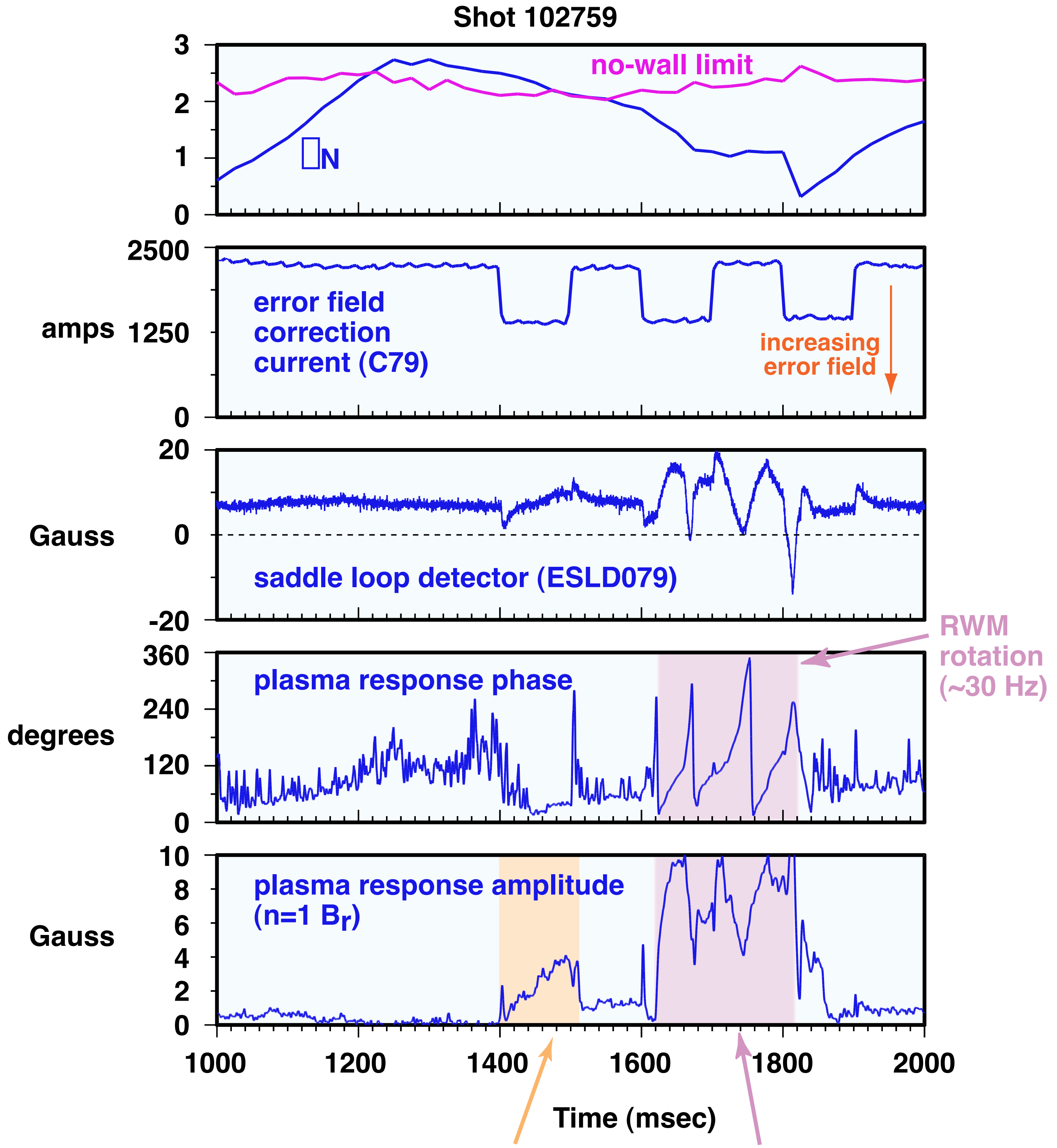
- The plasma response to the pulsed error field was deduced using the external saddle loops to measure the n=1 radial magnetic field, B_r, and subtracting the vacuum field.

- The amplitude of the plasma response is seen to increase as β_N approaches the no-wall limit.

- The measured B_r with plasma is approximately in phase with the vacuum field.

- The plasma response is primarily paramagnetic at high β_N and the phenomenon is sometimes called "error field amplification".

RESPONSE OF PLASMA TO PULSED ERROR FIELD NEAR RWM STABILITY BOUNDARY

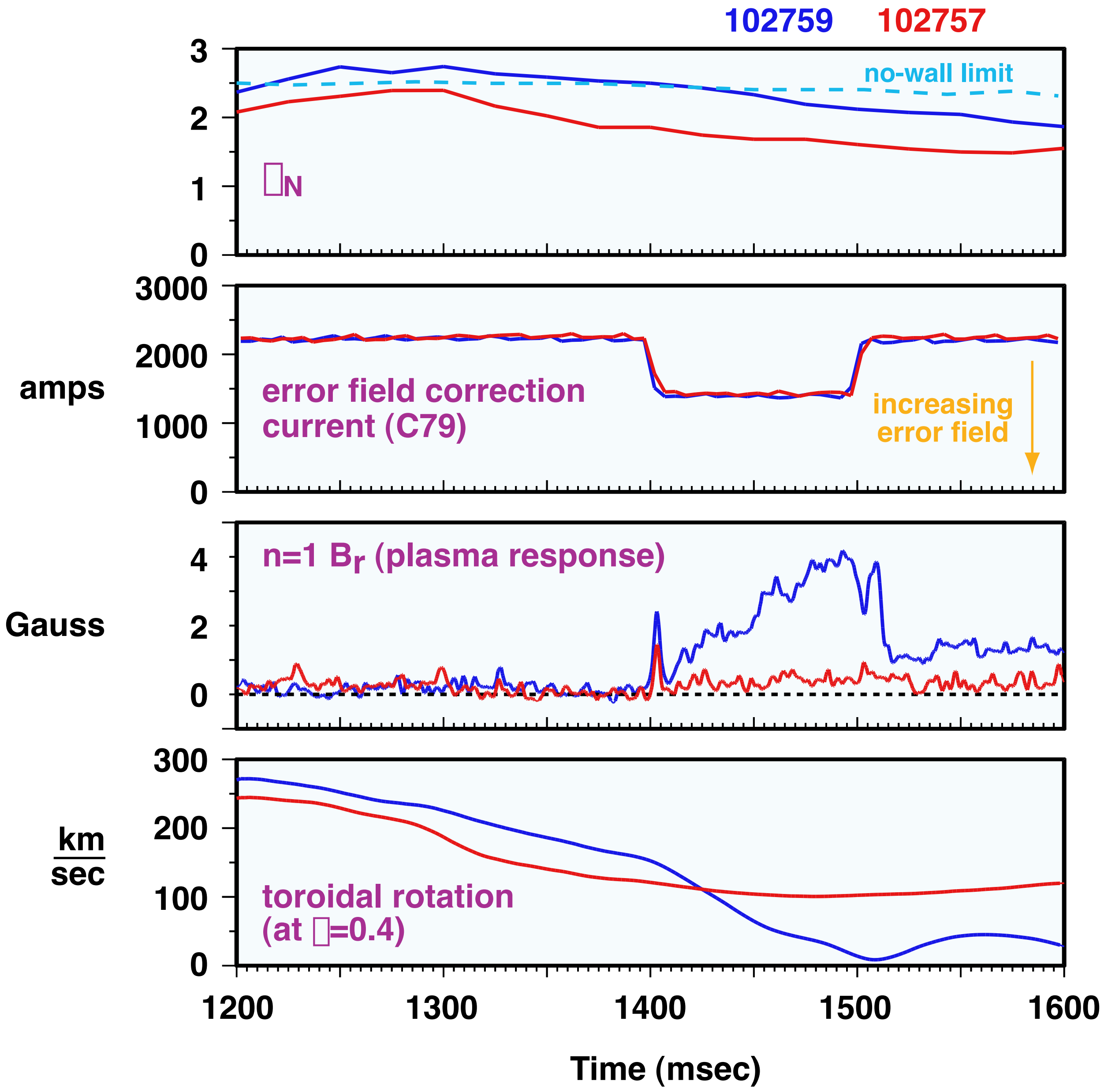


"error field amplification"

RWM, $B_r \sim 1/f$

A SENSITIVE FUNCTION OF $\square_N$, THE PLASMA RESPONSE TO THE ERROR FIELD INCREASES RAPIDLY AS $\square_N$ APPROACHES STABILITY LIMIT

- 102759 has higher $\square_N$, above the no-wall limit.
- Excitation of marginally stable RWM in 102759 suggested by decay of B_r after error field pulse is turned off.
- Rotation is significantly degraded by the plasma response.

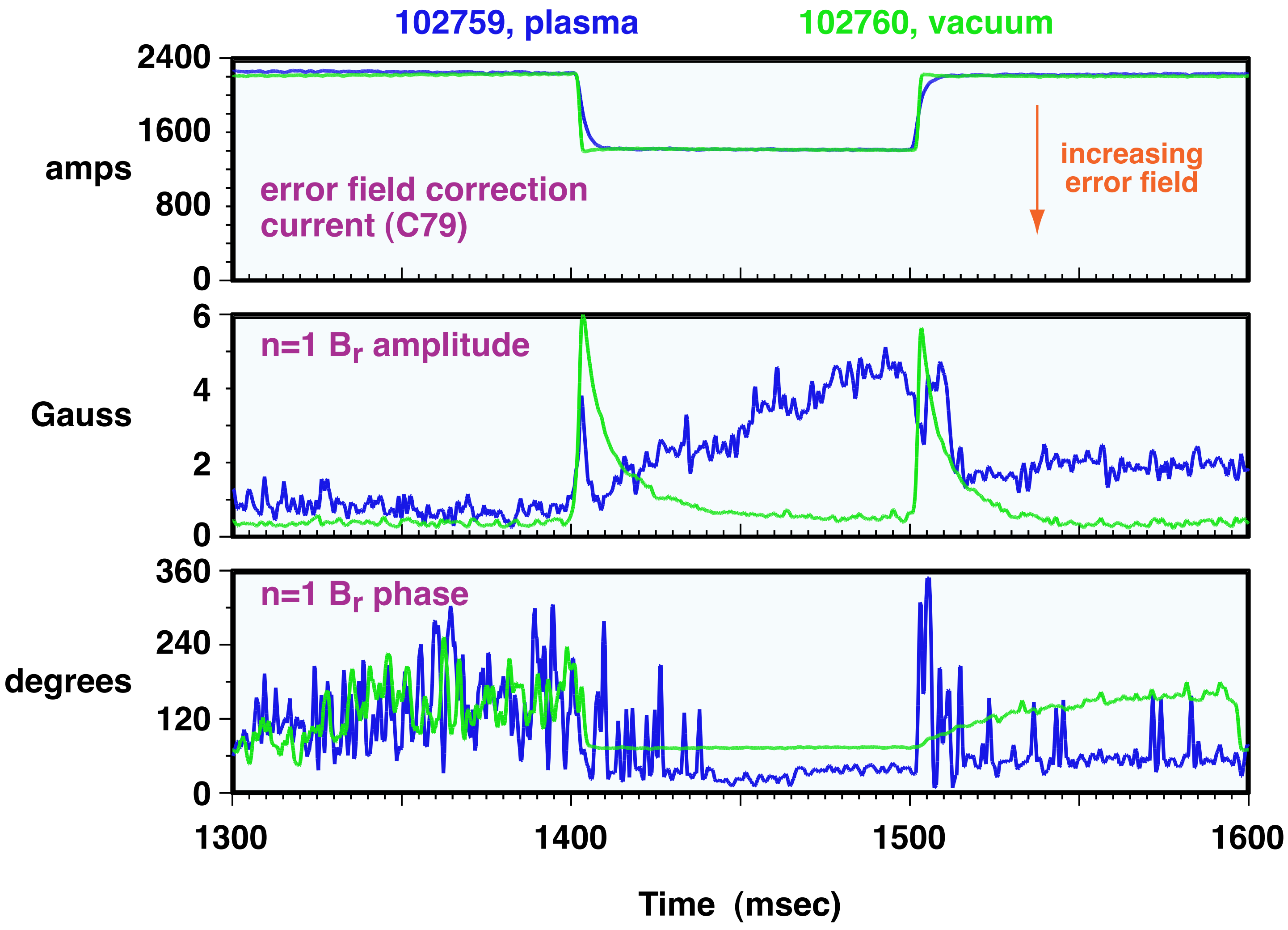


COMPARISON OF RADIAL FIELD AMPLITUDE AND PHASE IN VACUUM AND WITH PLASMA INDICATE A PARAMAGNETIC RESPONSE

- 102759, with plasma, shows slow increase in amplitude of the n=1 radial field measured by saddle loops (with vacuum field subtracted) during error field pulse.

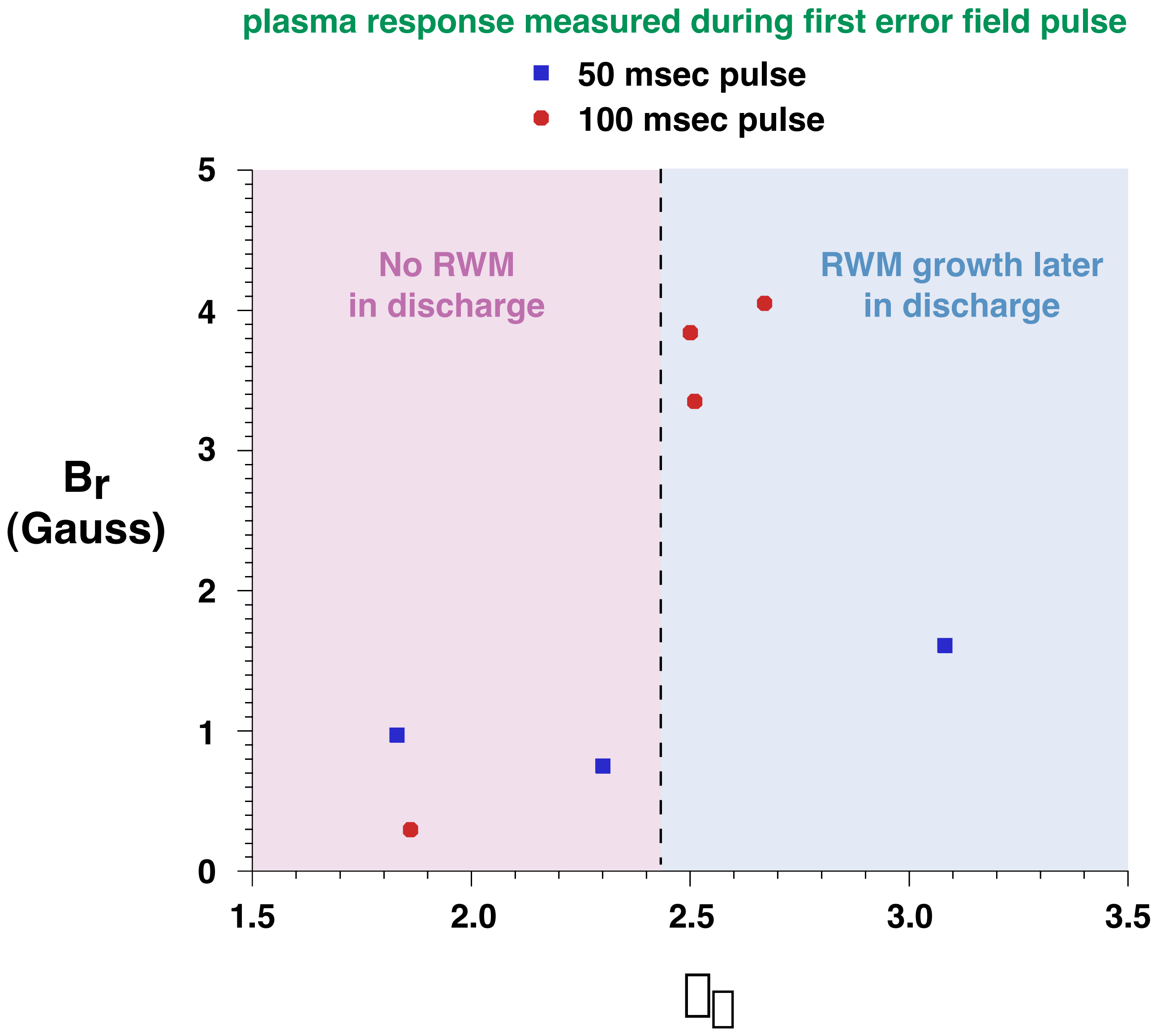
- Phase of n=1 radial field measured in error field pulse is approximately the same in vacuum and with plasma.

- Phase and amplitude indicate a primarily paramagnetic plasma response, or "error field amplification".



THE SCAN OF β_N IN THE PULSED ERROR FIELD EXPERIMENT SHOWS THE SENSITIVITY TO β_N AND THE PULSE WIDTH

- External error field pulsed on and off, 50 msec or 100 msec
- Plasma response, B_r, measured during first pulse
- RWM growth triggered in discharges with higher β_N
- Error field pulse width may define amplitude of plasma response



SUMMARY

- **Resistive wall mode experiments in DIII-D with β_N near the no-wall limit have shown the sensitivity of plasma rotation to the magnetic error field.**

- **Careful correction of the error field is crucial to maintaining plasma rotation and delaying the resistive wall mode.**

- **The decay of plasma rotation is described well by the induction motor model of Fitzpatrick, predicting the existence of an optimum error field correction current amplitude and phase.**

- **In stable plasmas with high β_N, the plasma exhibits a paramagnetic response to an uncorrected error field. This effect, sometimes called "error field amplification", may lead to reduced rotation and destablization of the RWM.**

RESISTIVE WALL MODE FEEDBACK CONTROL EXPERIMENTS REQUIRE THE INSTALLATION OF MORE DETECTION AND EXCITATION COILS

- **External saddle loops (ESLs) used for 2000 campaign**
- **New internal saddle loop (ISL) and B_p probe installation in progress for use in 2001 campaign**
- **Extensions to C-coil planned for 2002 campaign**