

---

# OPTIMIZATION OF THE PLASMA PERFORMANCE BY RWM STABILIZATION USING THE I-COIL IN DIII-D

*by A.M. Garofalo*

*with*

*H. Reimerdes (Columbia U.),*

*G.L. Jackson, T.H. Jensen, R.J. La Haye, M.J. Schaffer, J.T. Scoville, E.J. Strait*

*(General Atomics),*

*M. Okabayashi (PPPL), R.J. Jayakumar (LLNL), D.H. Edgell (FAR-Tech)*

**Post-APS Error Magnetic Field Workshop**

**October 31 - November 1, 2003**

**Albuquerque, New Mexico**



# Motivation/Background

---

- Stabilization of the resistive wall mode (RWM) by plasma rotation has opened access to reliable tokamak operation at pressure above the  $n=1$  free-boundary limit
  - To maintain the fluid rotation speed necessary for RWM stabilization it is critical to avoid the braking by magnetic field asymmetries
- Magnetic feedback using the C-coil in DIII-D provided a method to determine the optimal correction of these magnetic field errors
- The working paradigm was that the feedback system senses and opposes the resonant response of the stable RWM to the field asymmetries



# Goals and Key Questions

---

- The new internal control coil, the I-coil, affords us additional degrees of freedom for the poloidal and toroidal spectra of the correction fields
- Comparing the optimized magnetic configurations obtained with different spectra provides both a new test of our paradigm, and information that can illustrate the mechanism by which field asymmetries interact with the plasma
  - How does magnetic feedback correct this error field?
  - What is the intrinsic, magnetic error field in DIII-D?
  - How does it interact with the plasma?



# Outline

---

- Error field correction (EFC) using the C-coil:
    - Optimization w.r.t. plasma rotation
    - Feedback driven correction
    - Inferred error field (EF) structure
  - EFC using the I-coil:
    - RWM feedback driven
    - Inferred EF structure
  - Optimization w.r.t. plasma rotation
    - Toroidal phase scan
    - Amplitude scan
    - Helicity scan
    - Inferred EF structure
  - Measurement of resonant field amplification (RFA) internal structure using rotating I-coil field
- This poster
- Future work



# High Plasma Rotation May Be Crucial to Sustain High $\beta_N$ in DIII-D

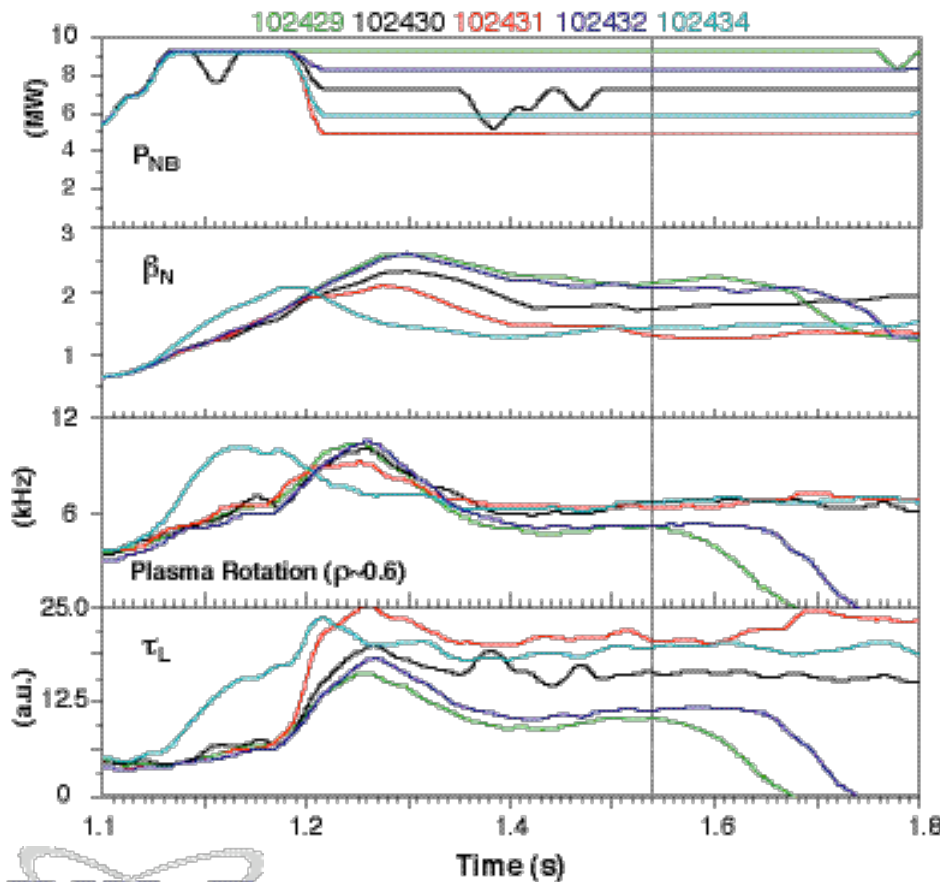
---

- High  $\beta_N$  requires high energy confinement
  - High rotation  $\Leftrightarrow$  high energy confinement
- Magnetic non-axisymmetries reduce the angular momentum confinement
- This work focuses on use of I-coil for optimization of the error field correction (EFC), not for direct feedback control of the resistive wall mode (RWM)
  - High rotation  $\Rightarrow$  RWM stabilization

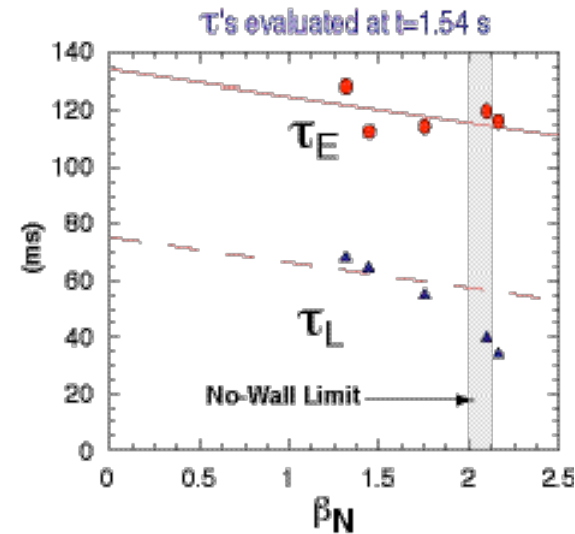


# Angular Momentum Confinement Time Decreases Anomally As $\beta_N$ Increases Above $\beta_N^{\text{no-wall}}$

- $\beta_N^{\text{no-wall}}$  = Ideal MHD stability limit for n=1 kink mode, with wall at infinity

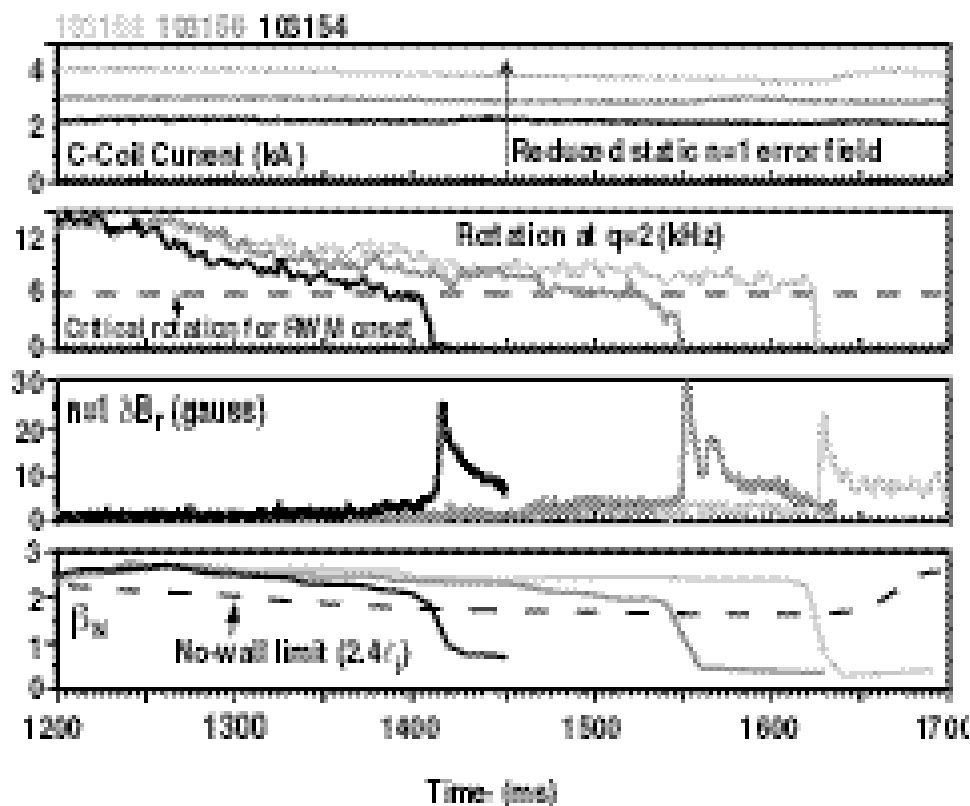


- Increased drag on rotation may be due to changes in plasma response to intrinsic magnetic error fields
  - Boozer, Phys. Rev. Lett. (2001)



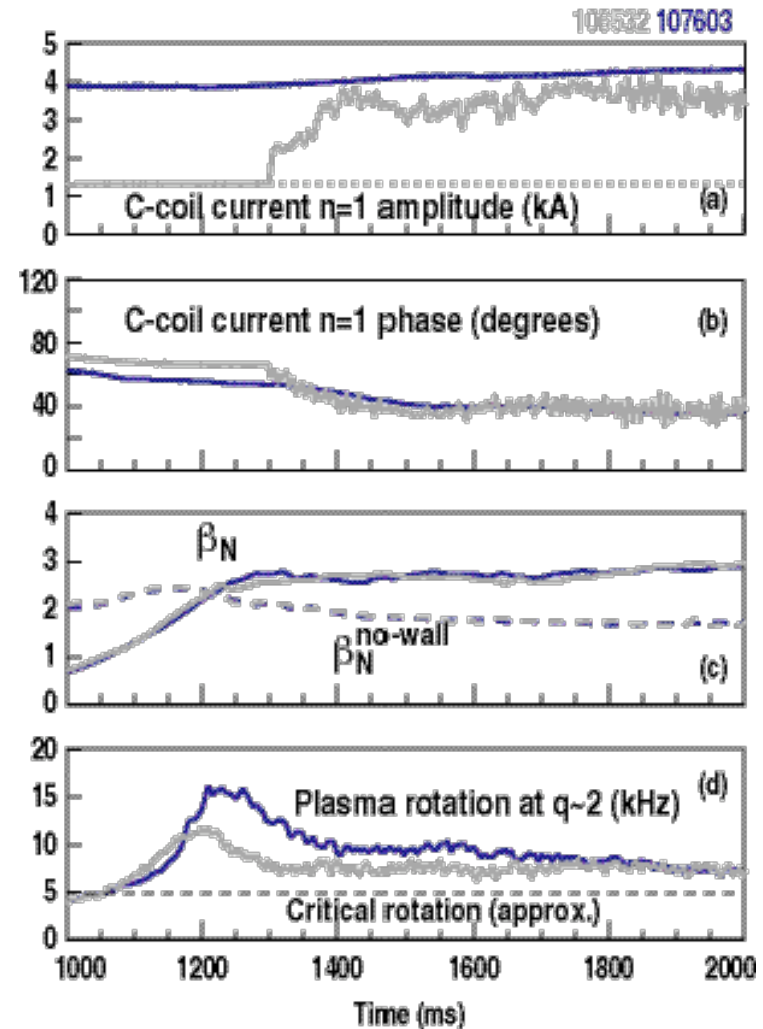
# Scan of C-coil n=1 Field Yields Amplitude and Phase which Minimizes Plasma Rotation Decay Rate

- Optimal correction  $\sim 2x$  standard correction determined for lower- $\beta$  plasmas



# RWM Feedback Can Work as Dynamic Error Field Correction System

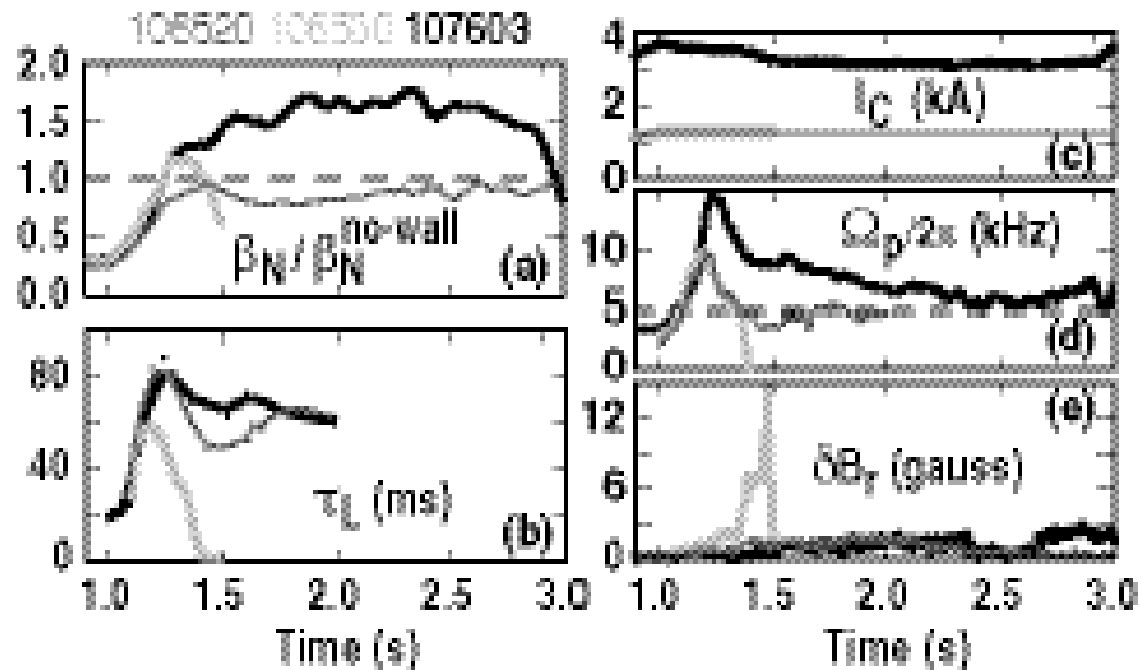
- Input to the feedback system:
  - Change of plasma response to the error field, as  $\beta_N$  increases above  $\beta_N^{\text{no-wall}}$
- Magnetic feedback and optimization w.r.t. plasma rotation converge to the same C-coil correction field
- Optimal C-coil field suggests amplitude of (2,1) intrinsic error field  $\sim 5\text{-}7$  Gauss



# Error Field Correction Optimization Allows High $\beta_L$ at High $\beta_N$

- RWM plasmas -

- Optimal EFC (107603) removes the decay of  $\beta_L$  observed when  $\beta_N$  exceeds the no-wall limit

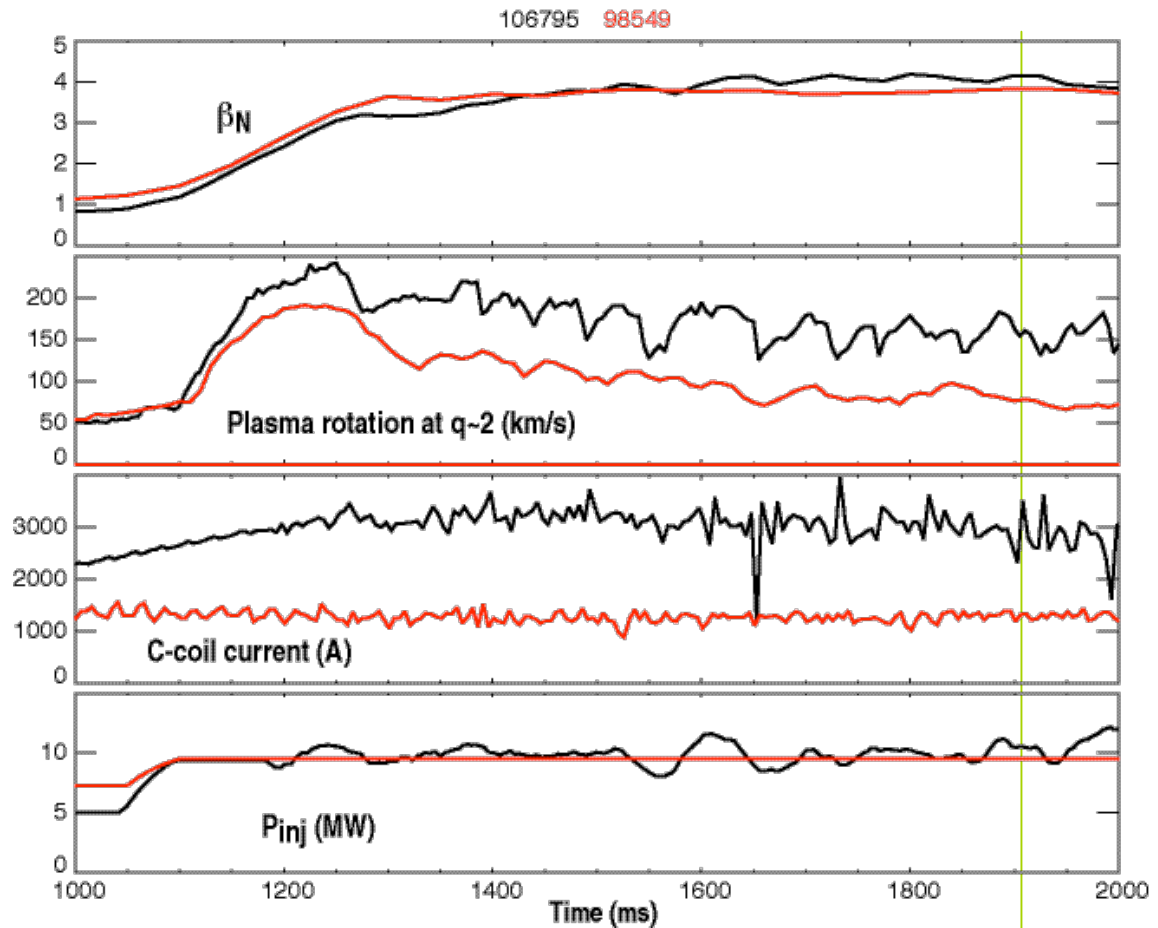


- Good error field correction gives  $\beta_L > 0.5 \beta_E$

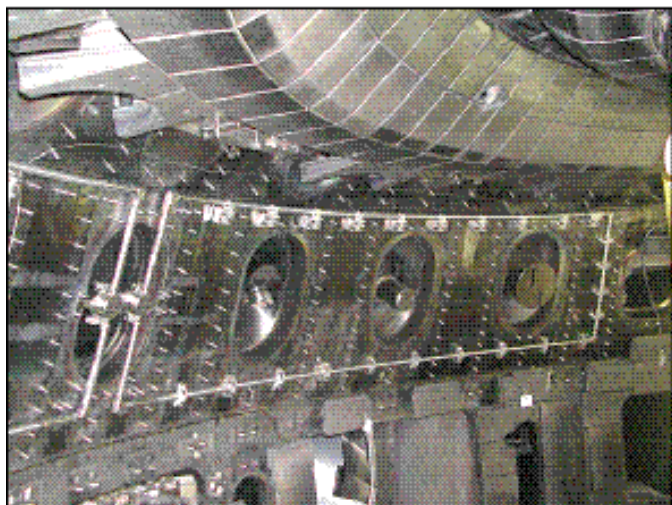
# EFC optimization allows high $\beta_L$ at high $\beta_N$

- AT plasmas -

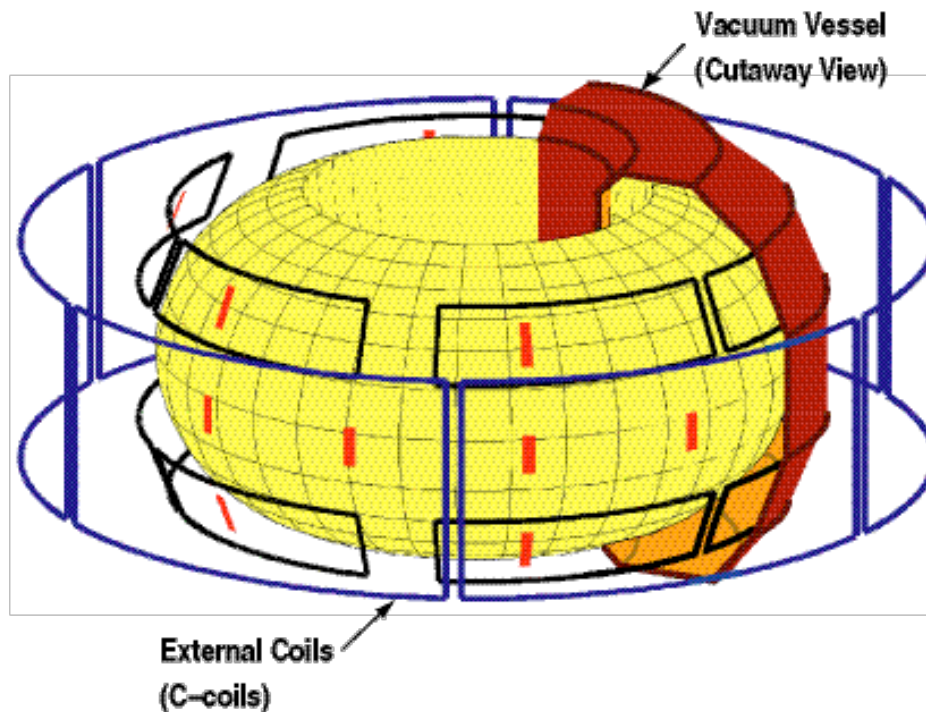
$\tau_E = 190$  ms,  
 $\tau_L = 130$  ms (=70% $\tau_E$ )  
 $\tau_E = 150$  ms,  
 $\tau_L = 50$  ms (=33% $\tau_E$ )



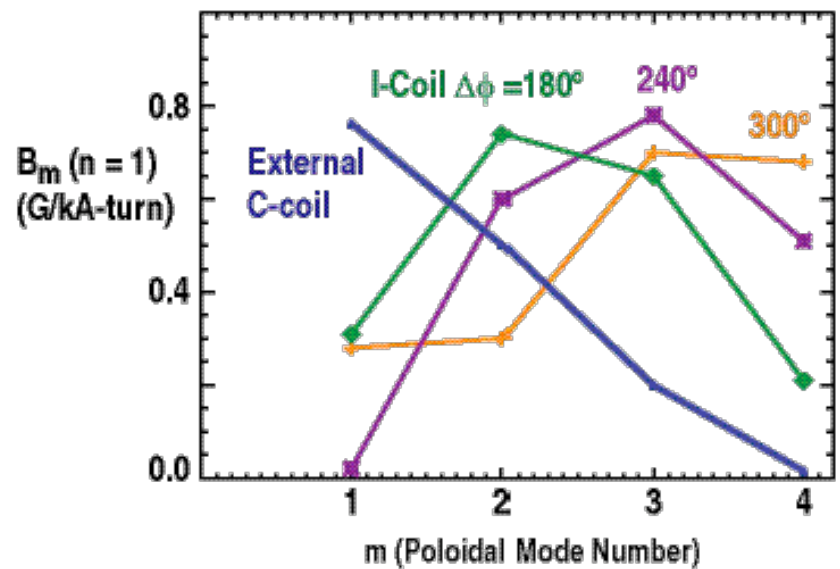
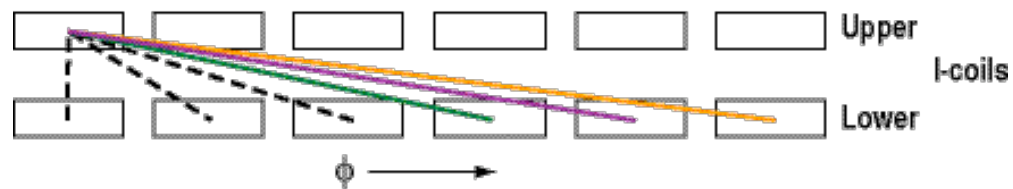
# RWM Feedback System Upgrades Include: New I-coils, New Off-mid Sensors



- 12 “picture-frame” coils
- Single-turn, water-cooled
- 7 kA max. rated current
- Protected by graphite tiles



# I-coil Connections Allow a Wide Range of (m,n) Spectra



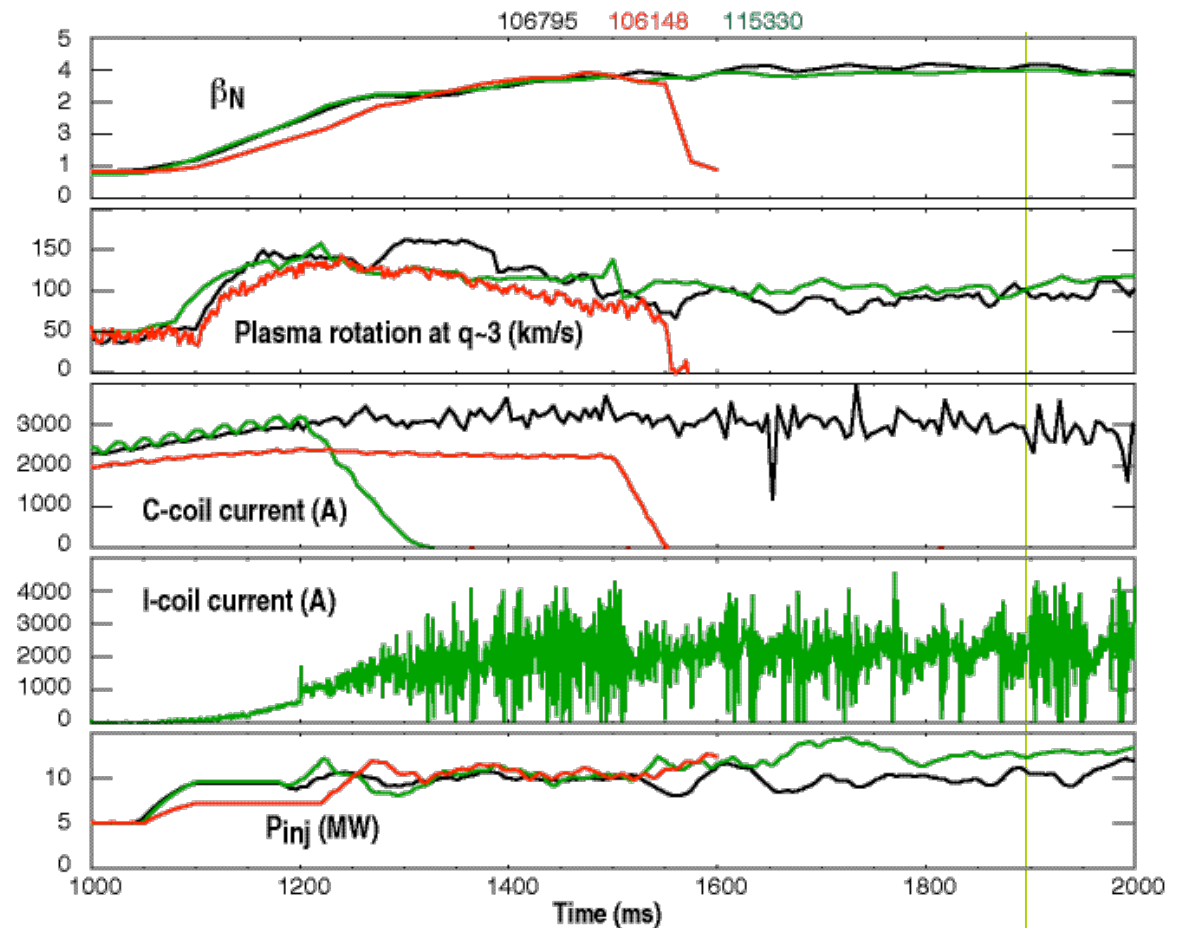
- Toroidal mode number:  $0 \leq n \leq 3$ 
  - Antisymmetric pairs ( $n = \text{odd}$ ) used for most experiments
- Poloidal mode number:  $0 \leq m < 4$ 
  - 240 degree upper-lower phase difference used for most experiments

# DEFC Using the I-coil Matches Plasma Performance Obtained Using the C-coil

$\beta_N = 70\% \beta_E$  (106795)

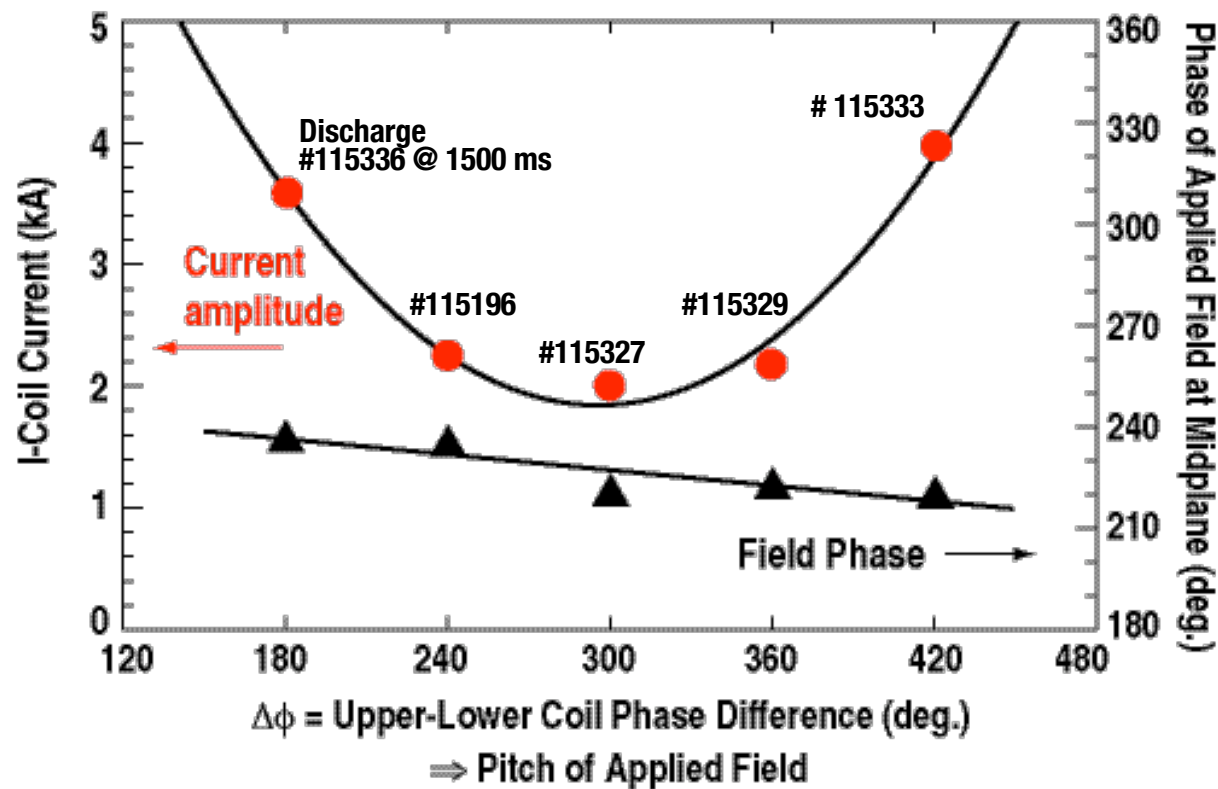
$\beta_N = 70\% \beta_E$  (115330)

- Scan of the I-coil helicity using RWM feedback with midplane sensors shows no improvement in terms of  $\beta_E$ ,  $\beta_N$  over C-coil correction
- Use of off-midplane sensors may be necessary for improvements



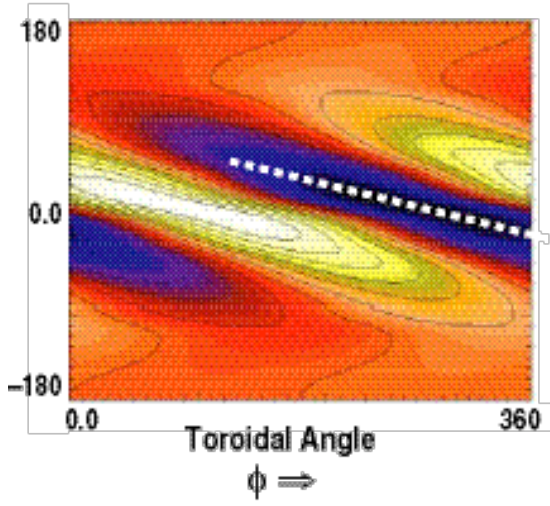
# Efficiency of DEFC Using the I-coil Depends on Helicity of Applied Field

- Correction field amplitude and phase determined by feedback control
- Constant phase is consistent with correcting a fixed error field
  - Consistent with vacuum error field measurements
- Optimal I-coil field  $m=2, 3, 4$  components  $\sim 1$  Gauss

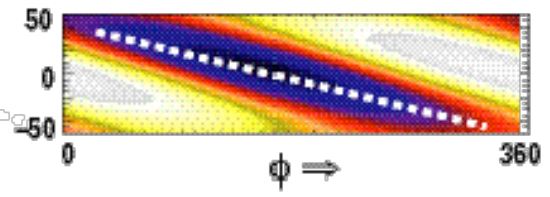


# Most Efficient DEFC Found When Applied Field Matches Helical Structure of the n=1 RWM

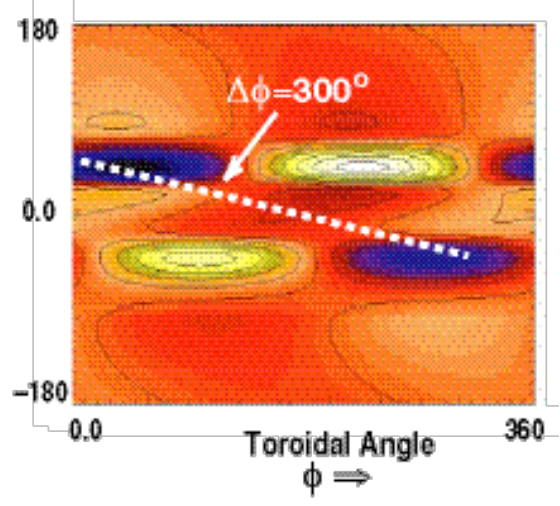
- Supports our working paradigm that the calculated ideal MHD kink mode is the intermediary between the intrinsic error field and the magnetic feedback system



Calculated Mode Structure at Plasma Surface



Measured Mode Structure at Vessel Wall

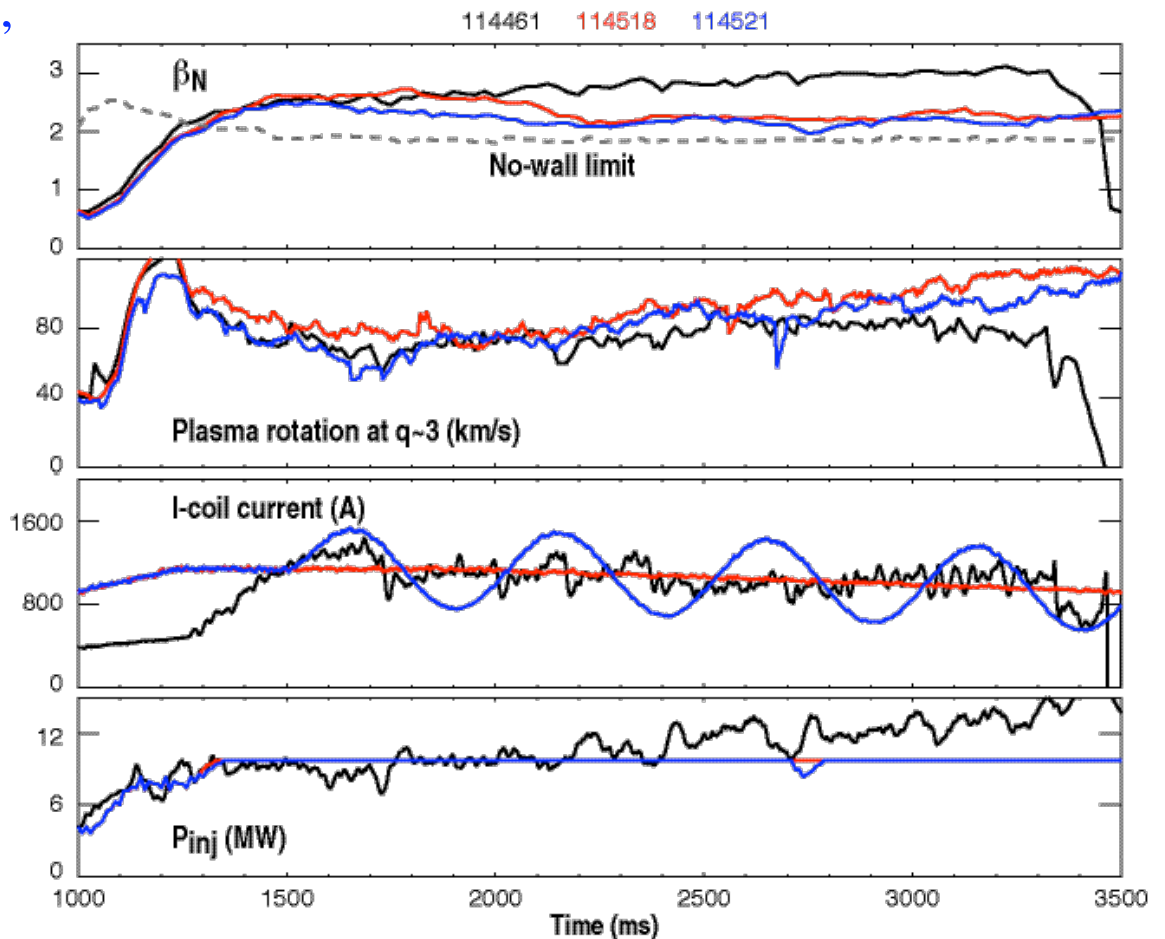


Calculated I-coil Field at Plasma Surface ( $\Delta\phi = 240^\circ$  Connection)



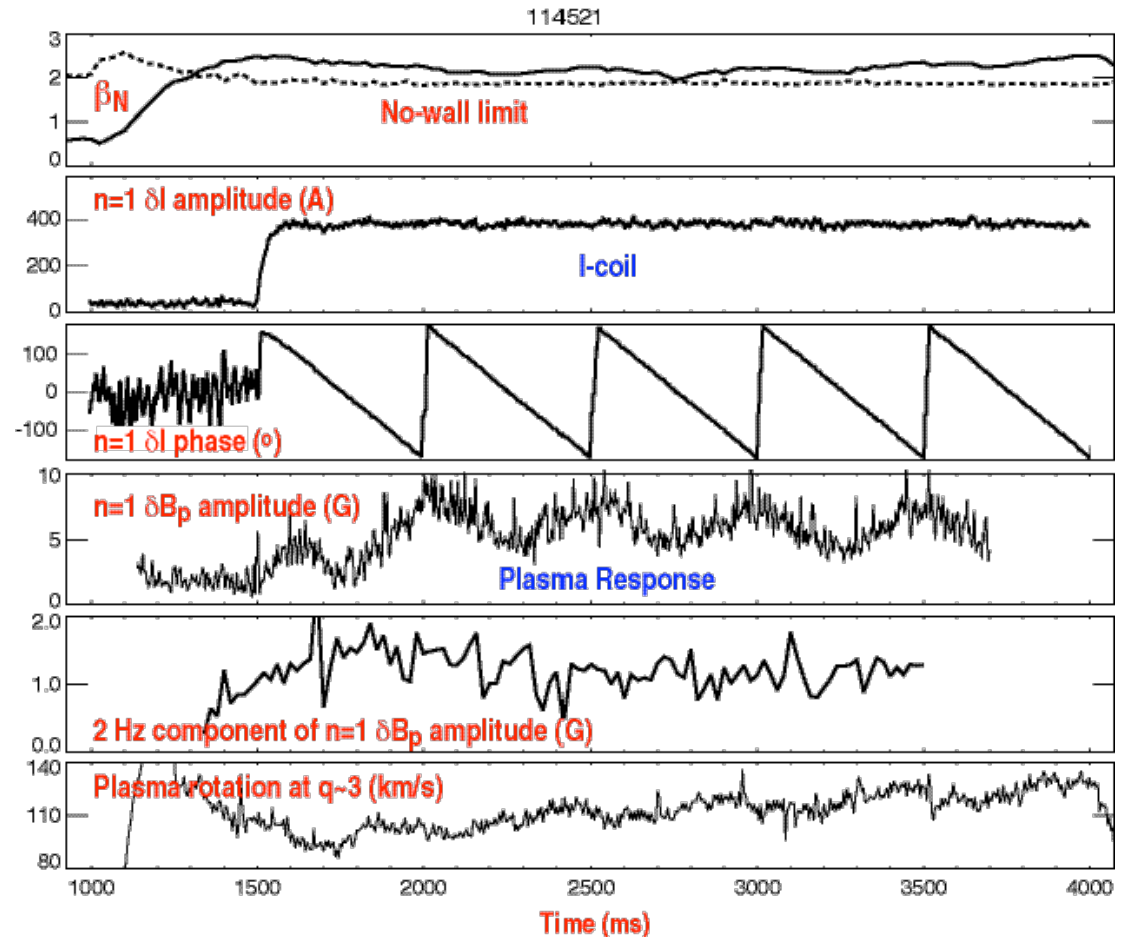
# Optimization w.r.t. Plasma Rotation - Toroidal Phase Scan in a Single Discharge

- $n=1$  rotating field (2 Hz), added to feedback-driven error field correction
  - $\square\square=240^\circ$  connection
- Scan results cannot be simply read from rotation time-traces



# Feedback-driven I-coil Current Does Not Cancel Intrinsic Error Field

- Amplitude of plasma response to rotating field of constant amplitude shows 2 Hz modulation
- If, without the  $n=1$  wave, the error correction were perfect, the plasma would be insensitive to the phase of an additional  $n=1$  field
- $n=0$  fluctuations are also measured on magnetics and CER

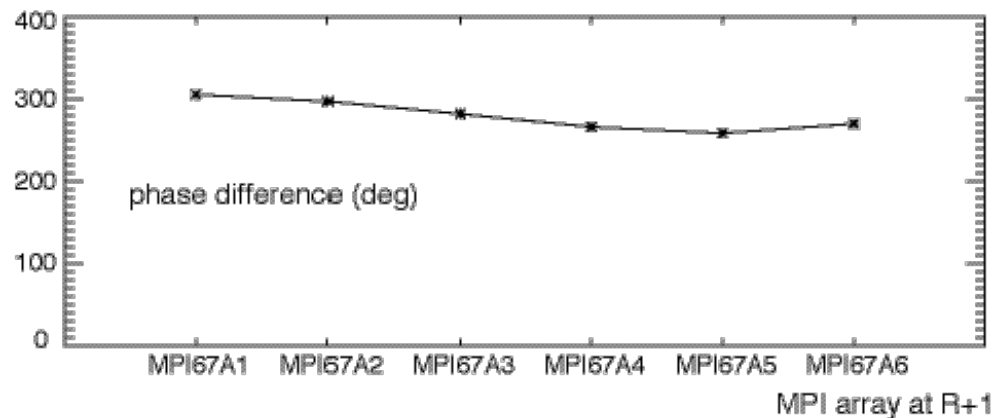
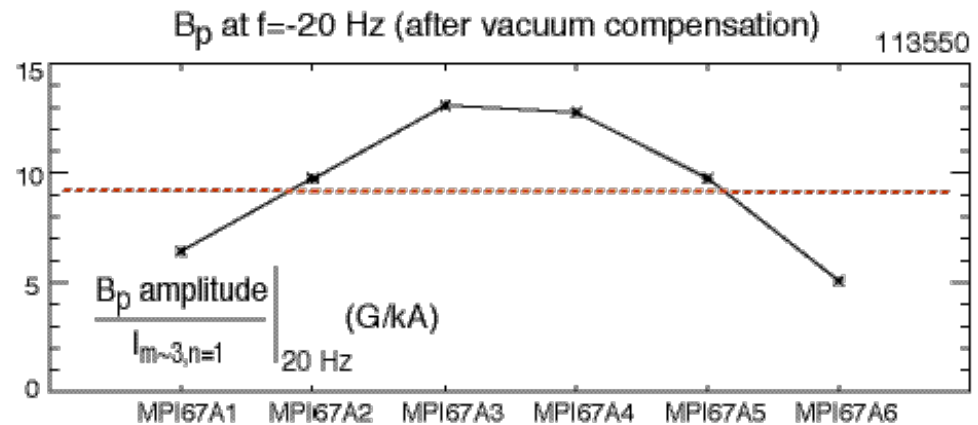


# Magnetics Show Both n=0 And n=1 Fluctuations at Frequency of Traveling n=1 Wave

- n=0 amplitude ~ twice n=1 amplitude

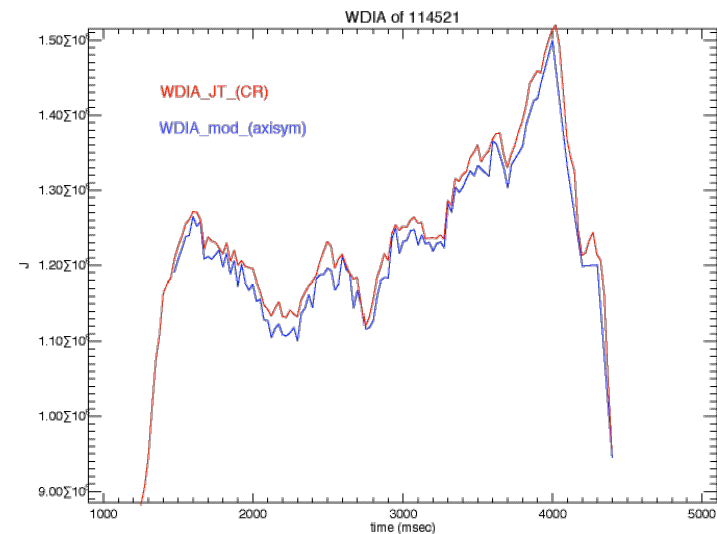
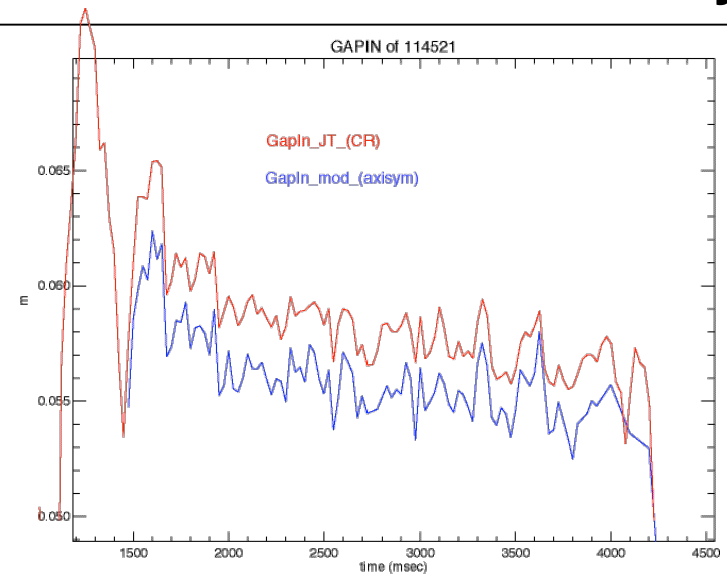
$\delta B_p(n=0) = 9.1$  Gauss

$\delta B_p(n=1) = 3.9$  Gauss



# Observed n=0 Fluctuations Due to Confinement Modulation Within Nearly Fixed Plasma Boundary

- Reconstructed equilibrium in a way that maximizes the weight of truly axisymmetric measurements, e.g. by setting:
  - Flux loops weight=10 (instead of 1)
  - Mirnov probes weight=0.1 (instead of 1)
- Time traces of quantities such as ChiSq, GapIn, GapOut, Aminor, Z0, and Volume, show no correlation with the n=1 perturbation
- Magnetic axis shows a  $\pm 1$  cm fluctuation at 2 Hz
- The stored-energy related quantities show the fluctuation as well.

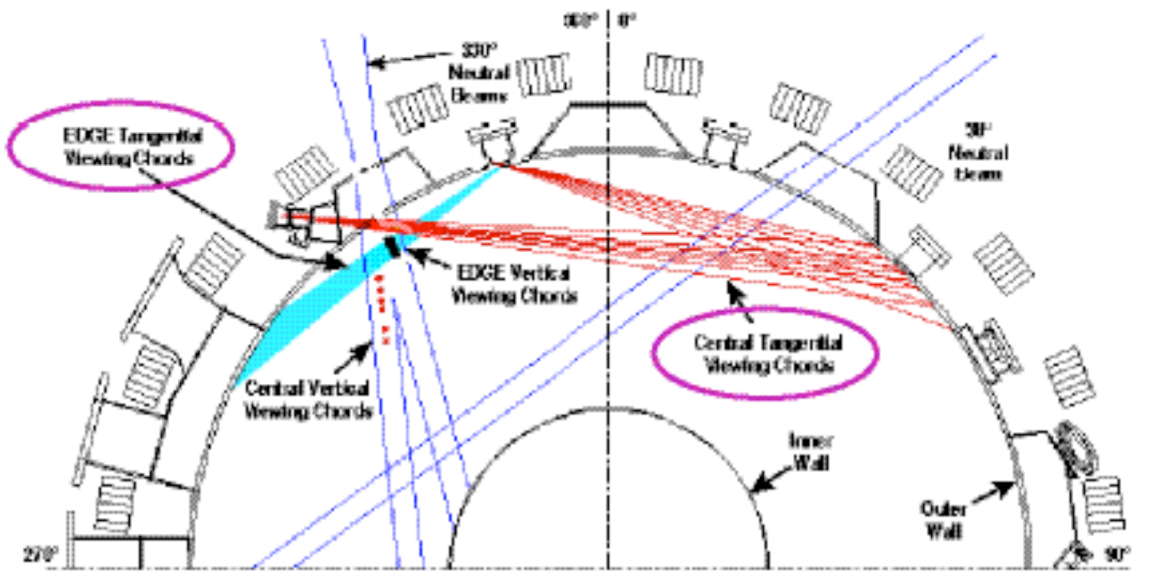


# Toroidally Displaced CER Measurements Allow Identification of n Number

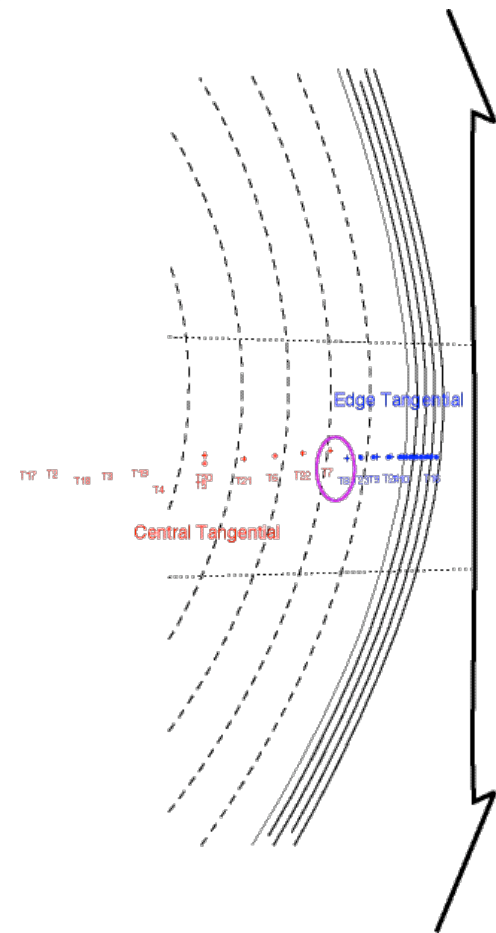
Channels T7 and T8:

- Two tangential channels separated toroidally by  $50^\circ$
- Nearly coincidental in the poloidal cross section

Plan View of CER Chords



 GENERAL ATOMICS



# Step 1: Determine the Phase (in Time) of the n=0 Fluctuation of Plasma Rotation

- Two CER channels give us 4 measurements:

- T7 amplitude and phase
- T8 amplitude and phase

- Can determine 4 unknowns:

- n=1 phase and amplitude
- n=0 phase and amplitude

$$T_7(t) = A_7 \cos(\omega t + \phi_7)$$

$$T_8(t) = A_8 \cos(\omega t + \phi_8)$$

$$T_7(t) = A_{7,1} \cos(\omega t + \phi_{7,1}) + A_{7,0} \cos(\omega t + \phi_{7,0})$$

$$T_8(t) = A_{8,1} \cos(\omega t + \phi_{8,1} + 50) + A_{8,0} \cos(\omega t + \phi_{8,0})$$

Since  $\phi = R(T_7) = R(T_8)$ :

$$A_{7,1} = A_{8,1} \equiv A_1$$

$$\phi_{7,1} = \phi_{8,1} \equiv \phi_1$$

$$A_{7,0} = A_{8,0} \equiv A_0$$

$$\phi_{7,0} = \phi_{8,0} \equiv \phi_0$$

$\phi_0 =$  Phase of n=0 fluctuation in plasma rotation measurements  
 $=$  Phase of fluctuation in angular momentum



## Step 2: Determining the Phase (in Time) of Minimum Error Field

$\varphi_{EF,0}$  = Phase of n=0 fluctuation in error field magnitude  
= Phase of fluctuation in error field torque

- Values of  $\varphi_0$  and  $\varphi_{EF,0}$  differ because of the finite angular momentum confinement time
- From the angular momentum balance equation

$$\frac{dL(t)}{dt} = T_{NB}(t) - \frac{L(t)}{\tau_L} - T_{EF}(t)$$

- The phase of the error field is

$$\varphi_{EF,0} = \arctan\left(\frac{T_{NB}}{L/\tau_L}\right) + \varphi_0$$

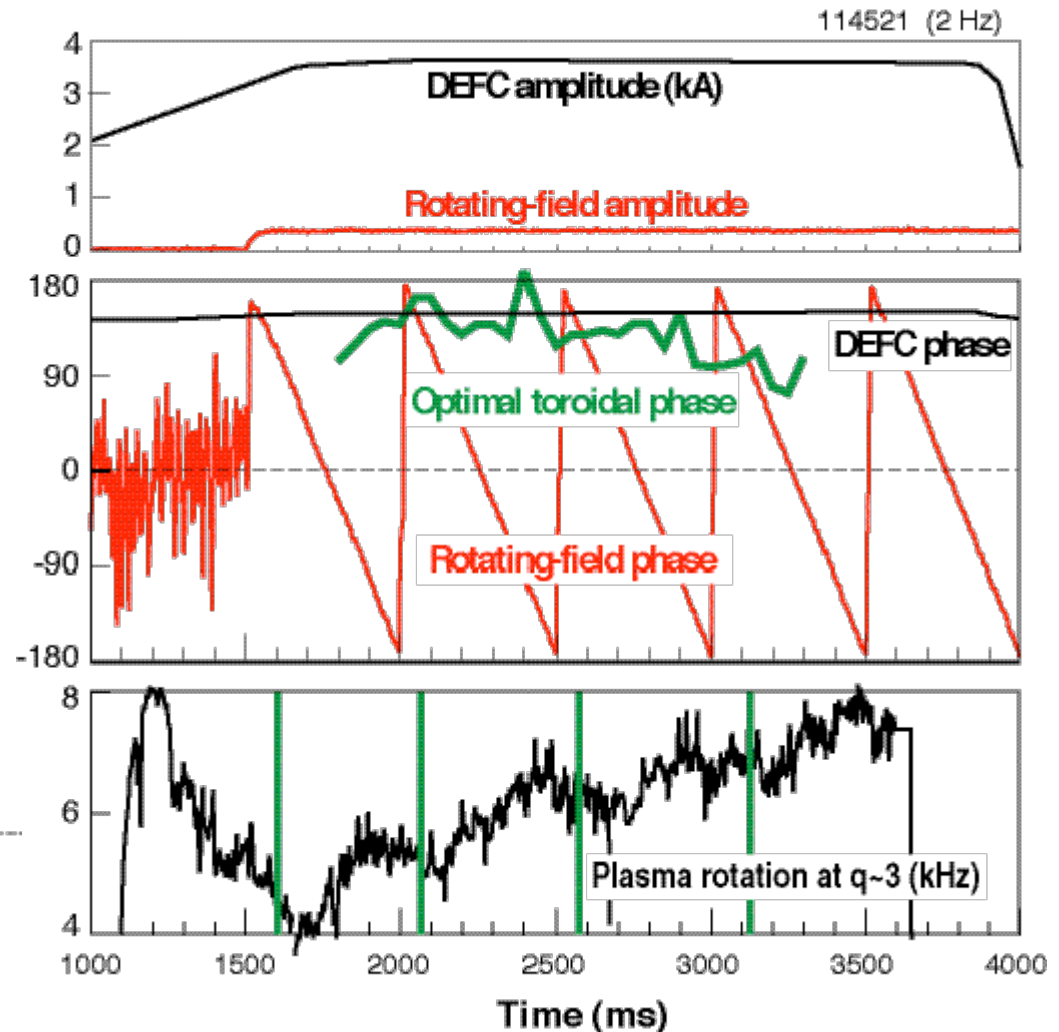
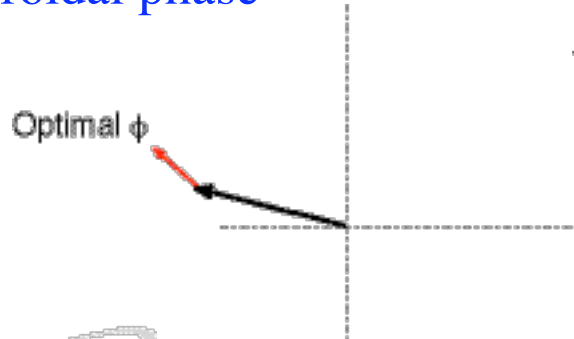


# Phase of Rotating n=1 Field Is Optimal at the Times When the Error Field Torque Is Minimal

- The phase of the applied rotating n=1 field is optimal at

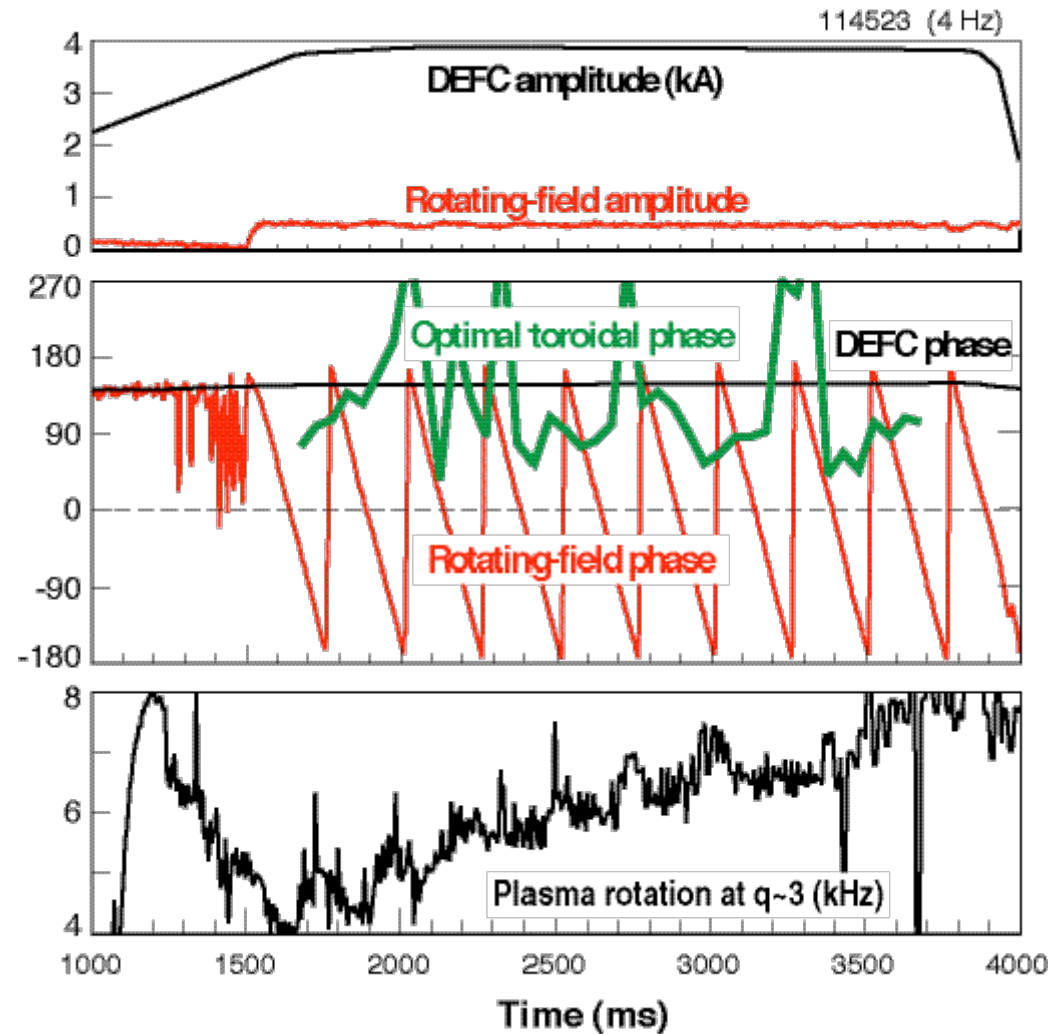
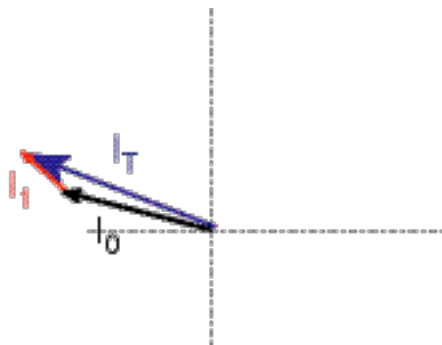
$$t = \frac{1}{f} (180^\circ \square \square_{EF,0})$$

- Moving time-interval ( $\square t = 1/f$ ) gives continuous measurement of optimal toroidal phase



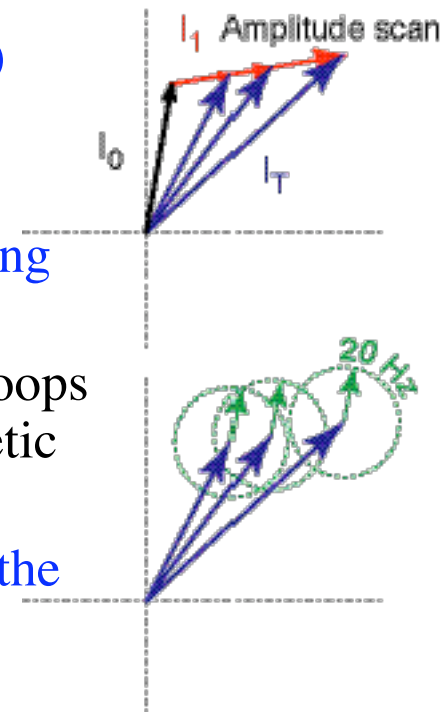
# Results of the Procedure Are Not Affected by Noise in the CER Signals

- Using a 4 Hz  $n=1$  traveling wave gives similar results as with 2 Hz, although with larger errors



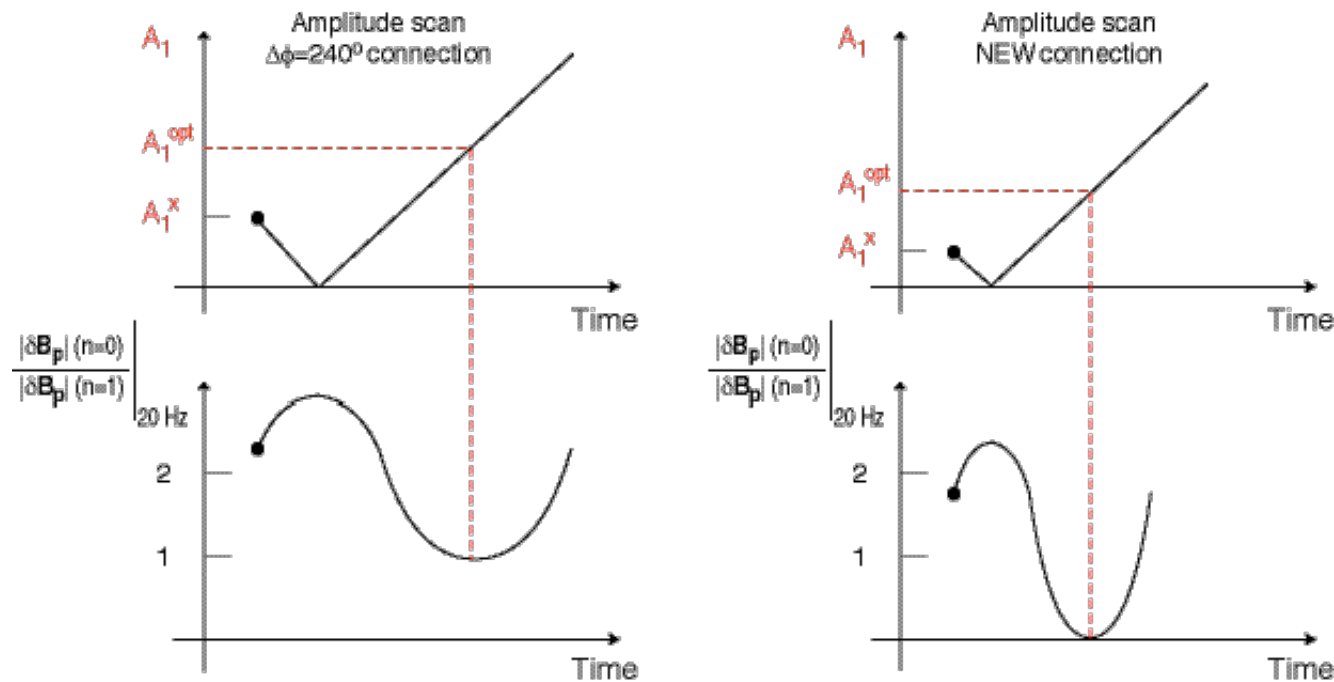
# Amplitude Scan Also Can Be Carried Out in a Single Discharge (Future Experiment)

- Phase scan: use analysis of the CER fluctuation to determine the times when the phase of the applied  $n=1$  I-coil field is the optimal correction phase
  - At these times the amplitude and phase of  $I_1$  are:  $A_1^x$ ,  $\phi_1^{\text{opt}}$
- Amplitude scan: vary  $A_1$  slowly (over several seconds) from  $A_1^x$  to zero and from zero to maximum allowed.
  - This gives an  $I_T$  with varying amplitude and phase
- In addition to this varying  $I_T$ , again apply an  $n=1$  rotating field, this time at higher frequency, e.g. 20 Hz
  - A time dependent Fourier analysis of the Mirnov loops will give the amplitudes of the  $n=0$  and  $n=1$  magnetic fluctuations.
- The time of minimum  $n=0/n=1$  amplitude should give the optimal error-field correction



# I-coil Helicity Scan May Improve Match to Intrinsic Error Field Structure

- Error correction is perfect when the plasma becomes insensitive to the phase of an additional, rotating  $n=1$  field



Traveling wave with ZERO  $n=0$  fluctuations would allow measurement of internal RFA structure using e.g. ECE radiometer, at single toroidal location

# Summary

---

- Dynamic error field correction (i.e. feedback driven) using the I-coil can efficiently replace the C-coil correction
  - Helicity scan results support paradigm that the calculated ideal MHD kink mode is the intermediary between the intrinsic error field and the magnetic feedback system
  - Optimal I-coil field phase agrees with vacuum measurements
  - Amplitude of (2,1), (3,1), (4,1) I-coil field  $\sim 1-2$  Gauss
- Phase of feedback-driven I-coil current and phase of empirically determined optimal correction are in good agreement
- Scan of I-coil correction-field phase, amplitude and helicity may yield significant improvements in both angular momentum and energy confinement times in high- $\beta$  plasmas
  - May also yield determination of intrinsic error field structure
  - And direct internal measurements of RFA structure

