Error Field Measurement Techniques for ITER using Plasma Response

by
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with
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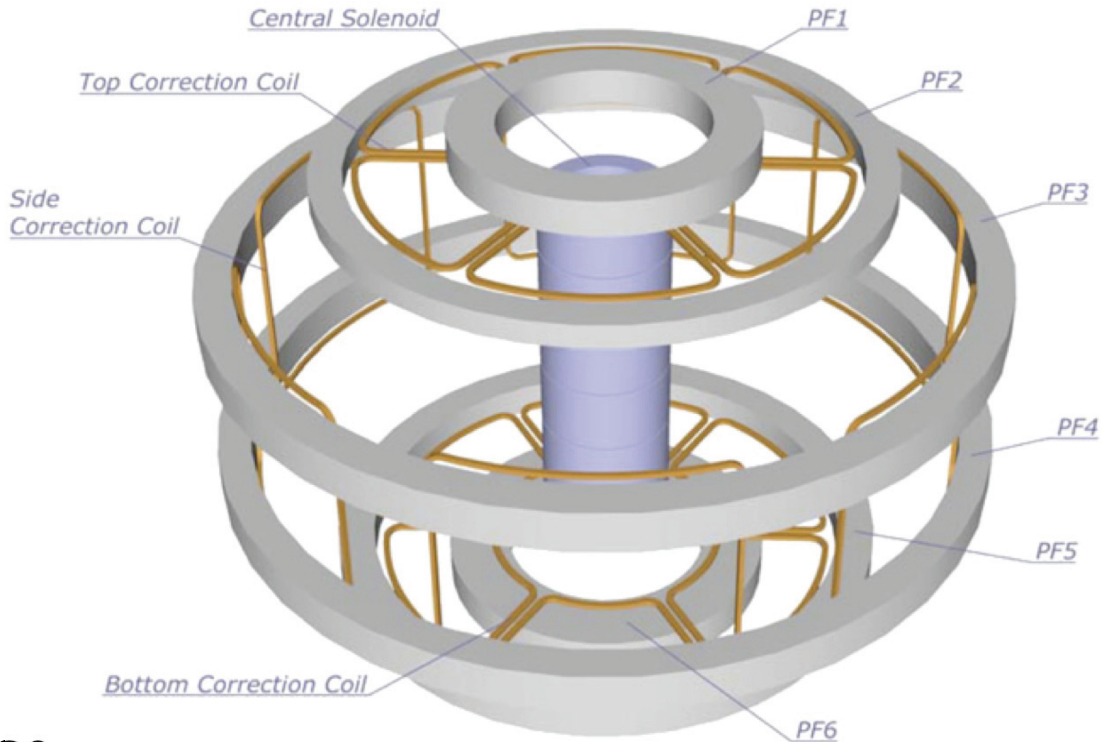

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Introduction

- **Error field measurement and correction will be essential in the early operation of ITER**
  - Avoid locked modes and disruptions
  - Optimize error correction during operation with reduced parameters

- **Error field sources are difficult to predict or measure directly**
  - Displaced coils, induced currents, ferromagnetic materials, …

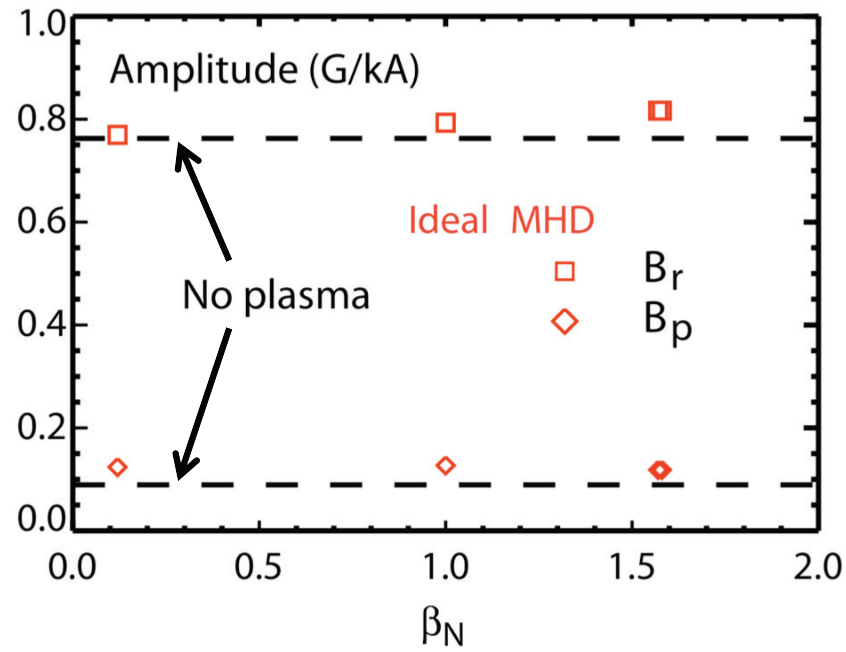
- **Plasma is a very sensitive error field detector**

- **We consider plasma-based approaches to error field measurement and correction in low-β plasmas**
  - Nonlinear magnetic plasma response
  - Braking of plasma rotation

Linear Ideal MHD Plasma Response is Unlikely to be Useful in Early ITER Operation

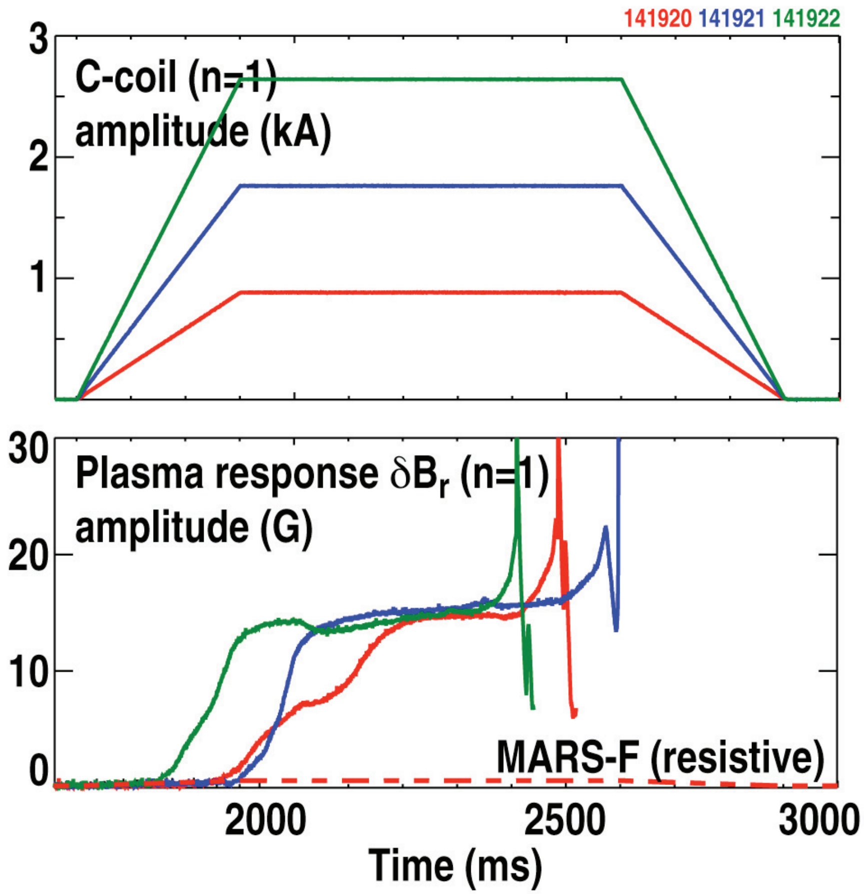
- **Plasma "amplification" of error fields is used in existing tokamaks at high β**
  - Can provide input for feedback control of error fields

- **Ideal MHD plasma response is small in ITER baseline scenario**
  - MARS-F study, based on CORSICA simulation of Scenario 2
  - Applied n=1 field from side EFC coil
  - Plasma response << applied field



Strong Non-linear, Resistive Plasma Response can be Used in Low-β Plasmas

- **Response to an increasing n=1 "error field"**

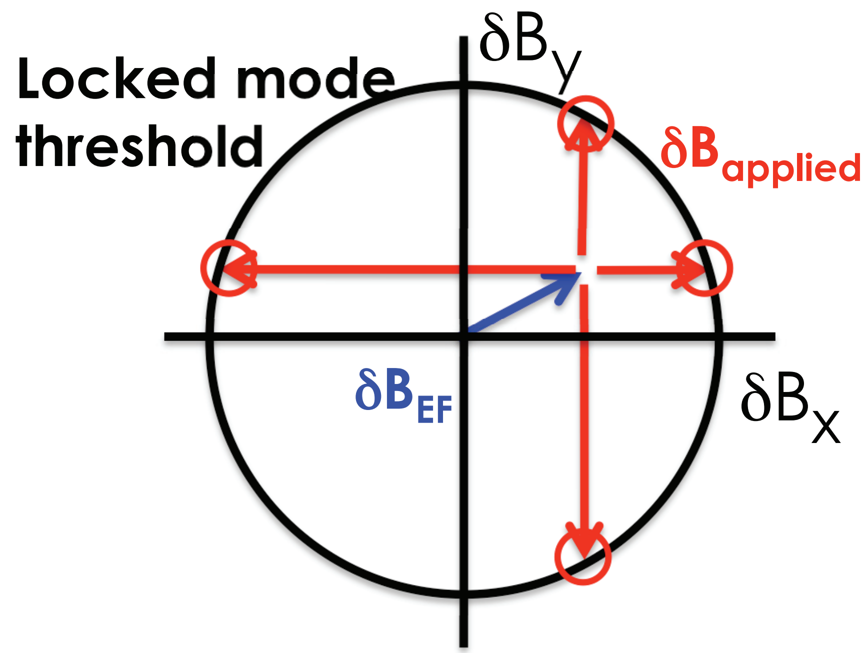


- **Locked mode response:**
  - Penetration of applied field, island growth, and saturation
  - Not described by linear model
- **Saturated amplitude is**
  - Independent of applied field
  - Much larger than linear resistive prediction (MARS-F)

➜ **Single-mode error correction**
  - Correct the component that drives the least stable mode
- **Error and correction fields are described by a 2-D phasor**
  - Amplitude and toroidal phase

Locked Mode Onset is a Standard Approach to Low-β Error Field Correction in Existing Tokamaks

- **Locked mode threshold forms a circle in the complex plane**
  - Depends on $|\delta \mathbf{B}_{ext}| = |\delta \mathbf{B}_{EF} + \delta \mathbf{B}_{applied}|$, independent of toroidal phase
- **Ramp an applied n=1 field in 4 quadrants, to find the threshold**
- **Offset of the fitted circle yields the "intrinsic" error field**



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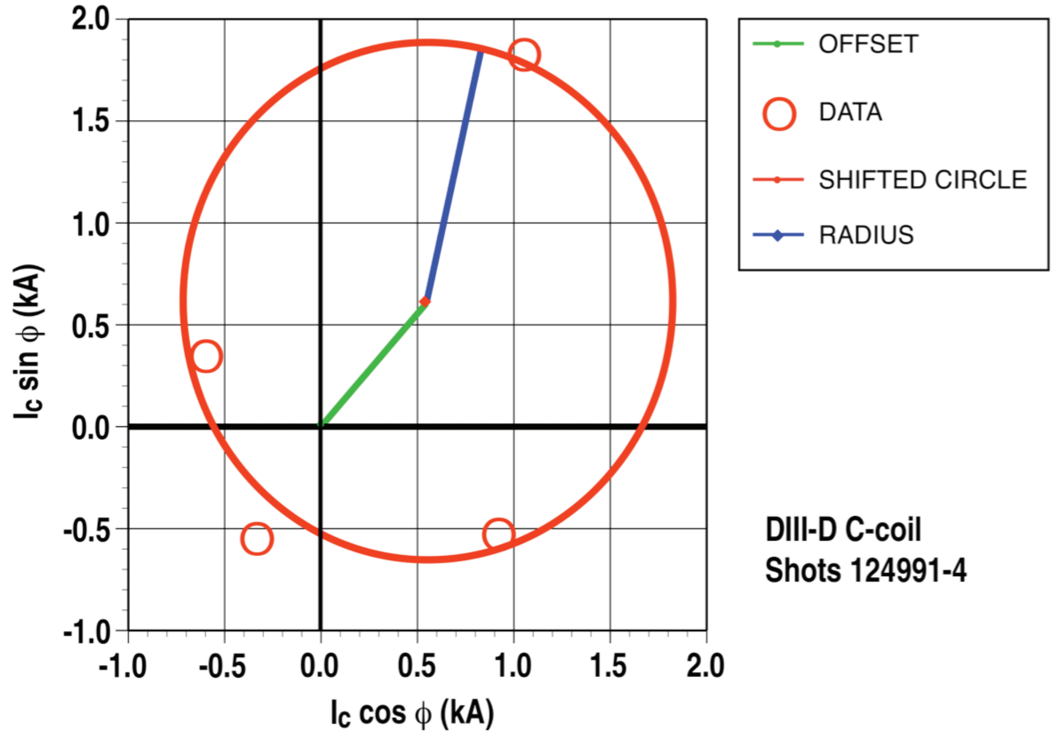
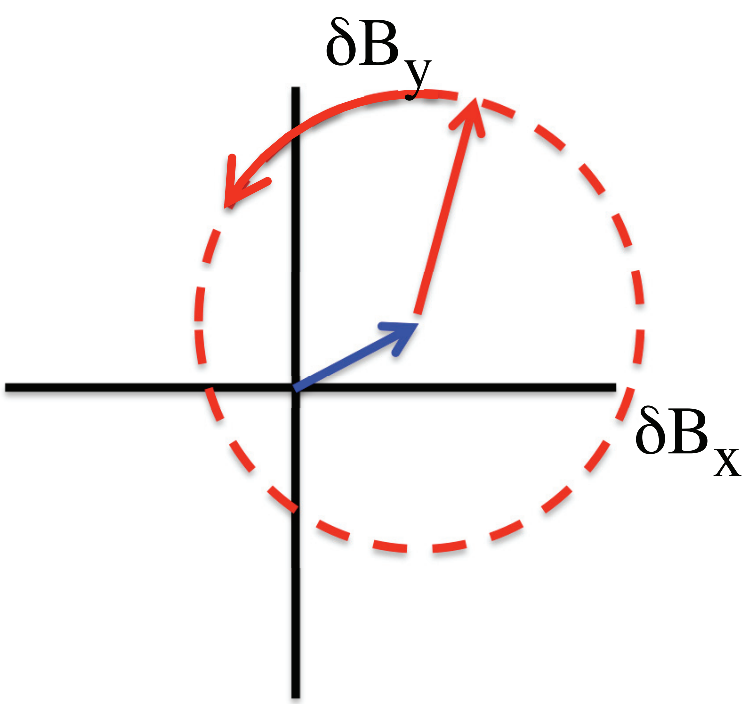
  - Standard method for DIII-D
- **Drawbacks for ITER:**
  - Time-consuming: requires several shots for one case
  - Not suitable for real-time control

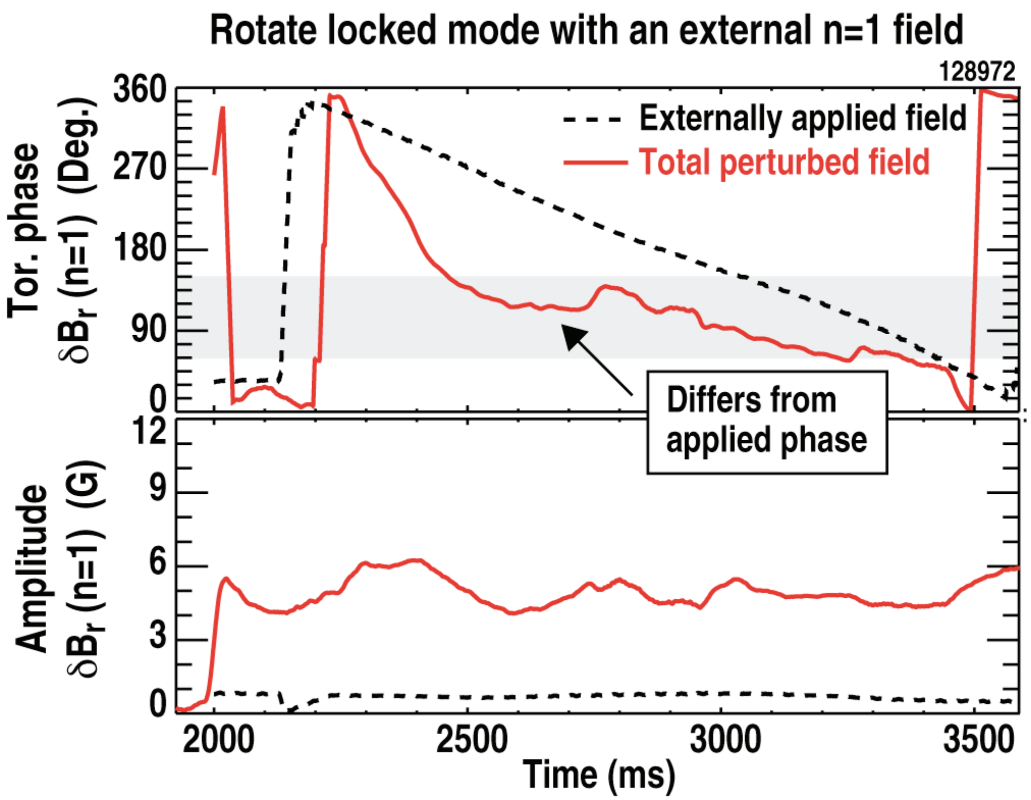


DIII-D C-coil
Shots 124991-4

Toroidal Phase of a Saturated Island Yields Error Field Measurement

- **Rotate the toroidal phase of an externally applied n=1 field**
  - Island phase depends on total external field $\delta\mathbf{B}_{ext} = \delta\mathbf{B}_{EF} + \delta\mathbf{B}_{applied}$
- **Measured island phase shows a preferred direction**





F. Volpe, et al., Phys. Plasmas 16, 102502 (2009).

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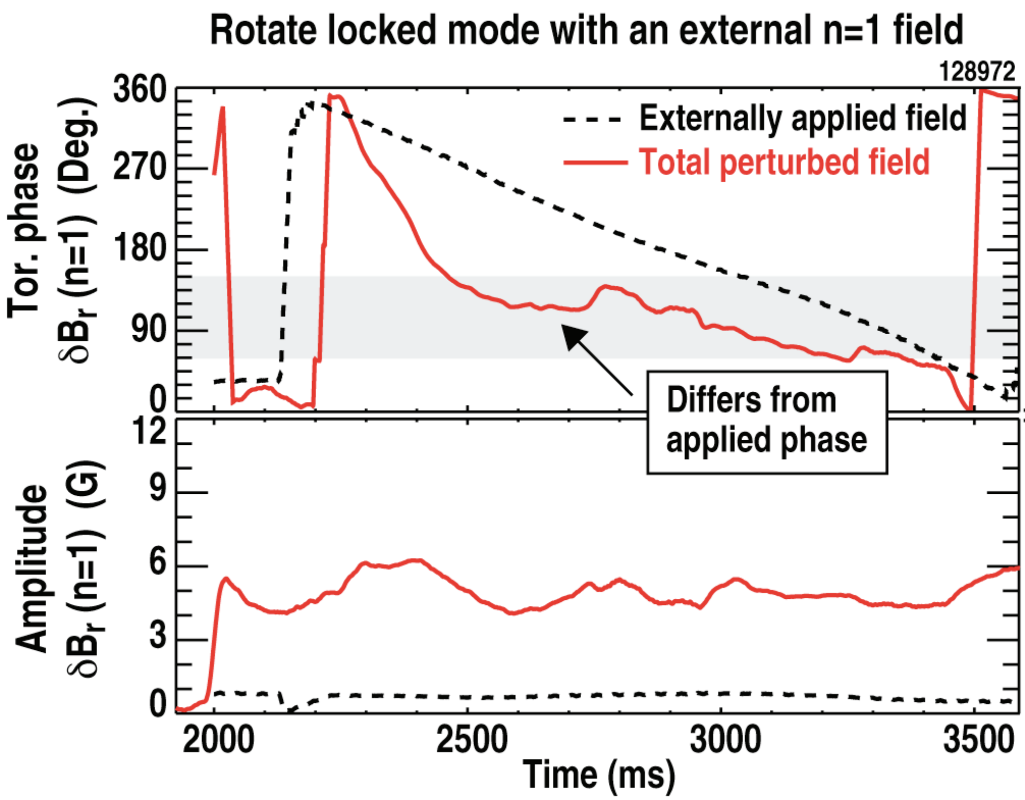
- **Measured island phase shows a preferred direction**
  - Analysis yields $\delta\mathbf{B}_{EF}$
- **Advantages for ITER:**
  - Continuous data
- **Drawbacks for ITER:**
  - Large island (high q_{95} can minimize risk of disruption)

Relation of mode phase to external field is still a subject of research



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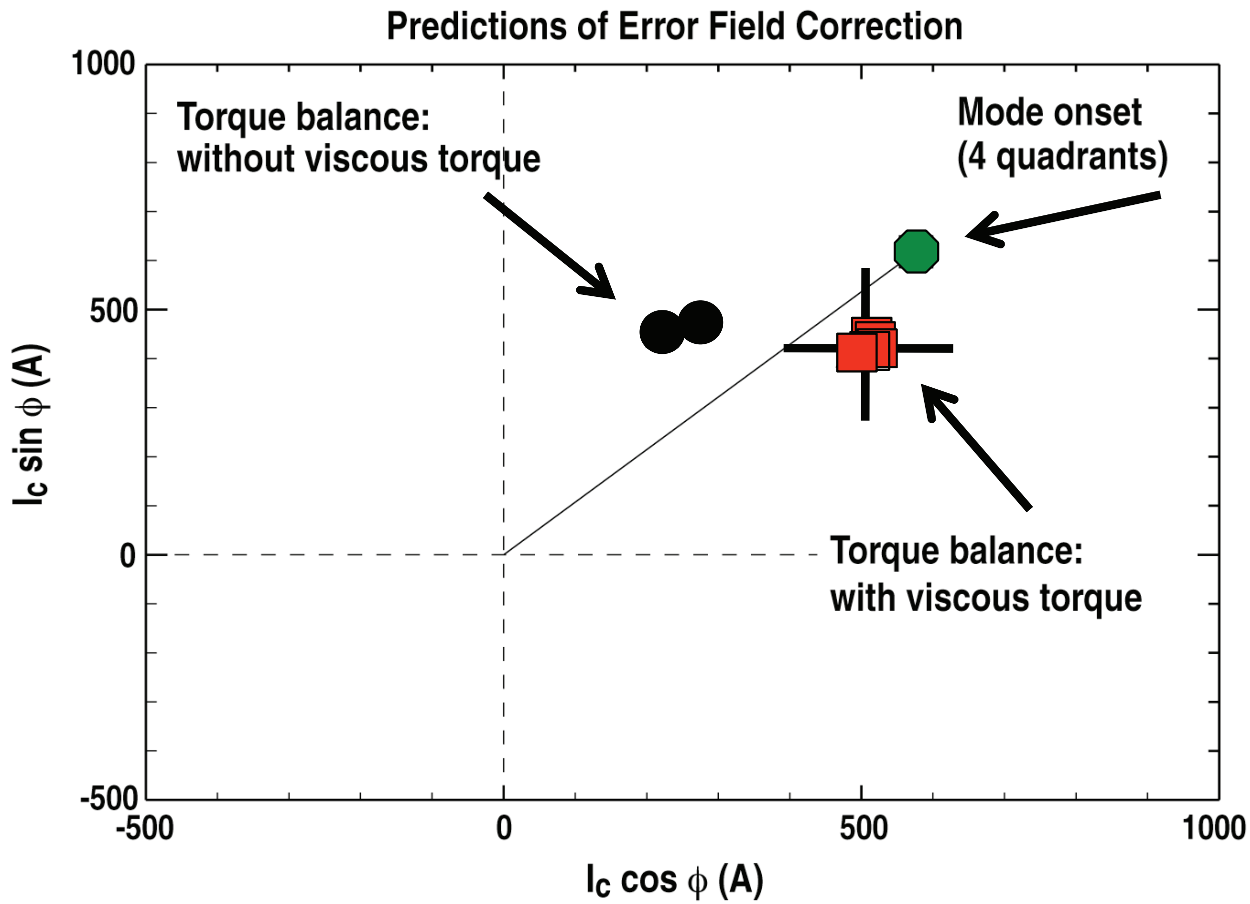
Torque Balance Model for Saturated Island Gives Reasonable Results

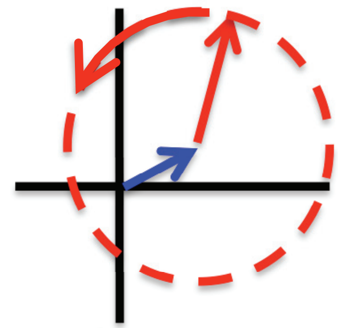
$$K_{EM}(I_{EF}+I_{COIL})\times B_m + K_V|B_m|^{\alpha} = 0$$

Electromagnetic torque — **Viscous torque**

- **Inclusion of viscous torque term yields:**
  - Better fit to data
  - Consistency with mode-onset method



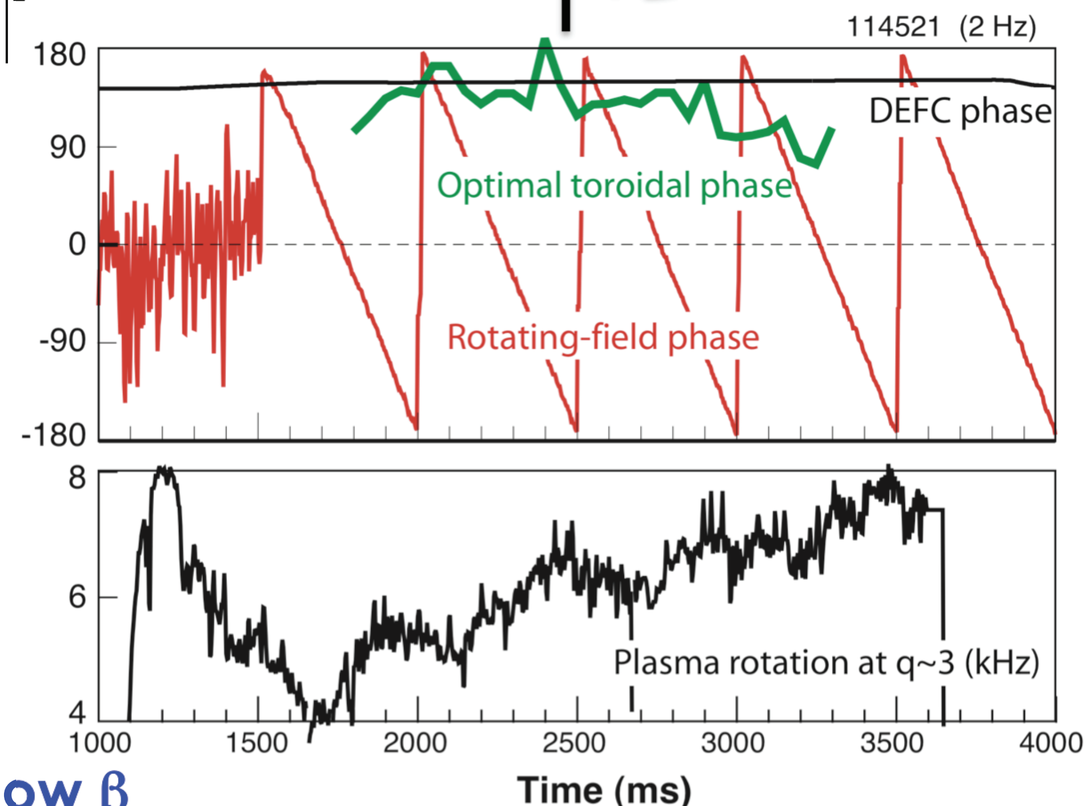
Braking of Plasma Rotation May be Suitable for Real-time Error Field Correction <u>Without</u> an Island



- **Apply n=1 field with rotating phase**
  - Observe modulation of plasma rotation
- **Solve equation of motion to obtain δB_{EF}:**

$$\frac{dL}{dt} = T_{NBI} - \frac{L}{\tau_L} - K\left|\delta\mathbf{B}_{EF} + \delta\mathbf{B}_{applied}\right|^2$$

  - Consistent with feedback controlled error correction

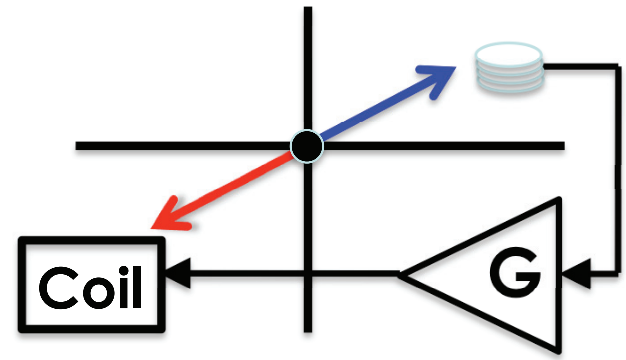


- **Advantages for ITER:**
  - Continuous data
  - No instabilities
- **Drawbacks for ITER:**
  - Requires NBI torque
  - Long integration time

Needs experimental test at low β

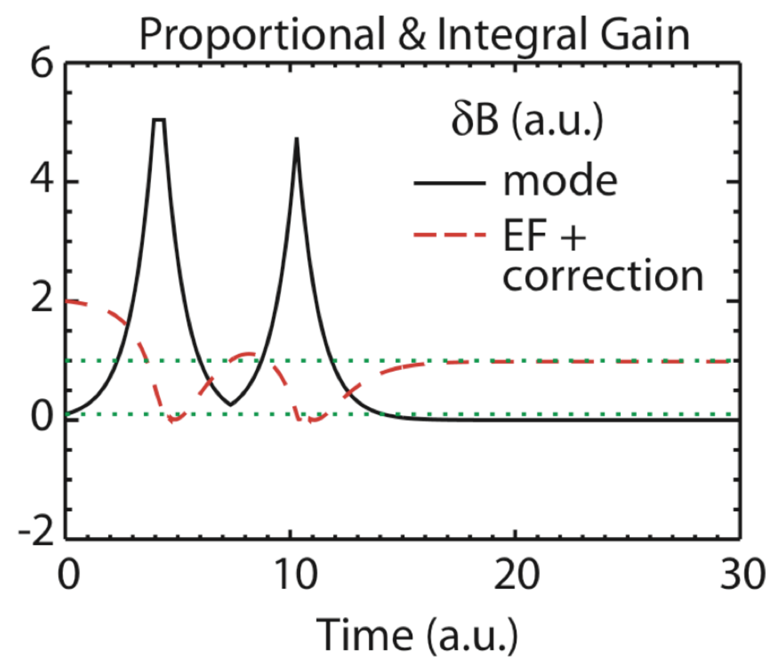
Direct Feedback Control of Locked Mode May Allow Error Field Correction

- **Simple model suggests that direct feedback control may be feasible**
- **Nonlinear, two-state model for locked mode island:**
  - Locked/Growing <u>or</u> Unlocked/Decaying
  - Two thresholds: δB (Unlock) << δB (Lock)



- **Result: converges to unlocked state**
  - Net error field is nonzero, but below the threshold for locking
  - Requires integral gain
- **Advantages for ITER:**
  - Continuous error field correction
  - Locked mode suppression

Needs experimental test



Several Plasma-response Methods are Candidates for Error Field Measurement and Correction at Low β

Method	Real-time	Island	Experimental Experience	Additional comments
Locked mode onset threshold	No	Transient	Extensive	Time-consuming
Toroidal phase of saturated island	Yes	Saturated	Limited	
Magnetic braking of plasma rotation	Yes (slow)	Stable	Limited	Requires NBI torque
Direct feedback control of locked mode	Yes	Suppressed	None	