Issues of Error Field Control for ITER

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Low Magnetic Error Field is Wanted in ITER

"As Low As Reasonably Achievable"

- Magnetic error control important in ITER because:
  - Errors introduce magnetic drag torque (braking) and slow plasma rotation
    - But, rotation improves confinement
      - Especially by velocity shear
    - And, rotation stabilizes some MHD modes
      - Especially RWM, tearing, NTM
- How to control magnetic errors in ITER?
  - Design for low error
  - Design an error correction coil system
  - Meet error specifications during component fabrication and assembly
    - Doublet–III $\Rightarrow$ DIII–D story
  - Plan and perform error measurements
  - Plan and perform empirical error correction with plasmas

ITER Design Includes Error Correction Coils

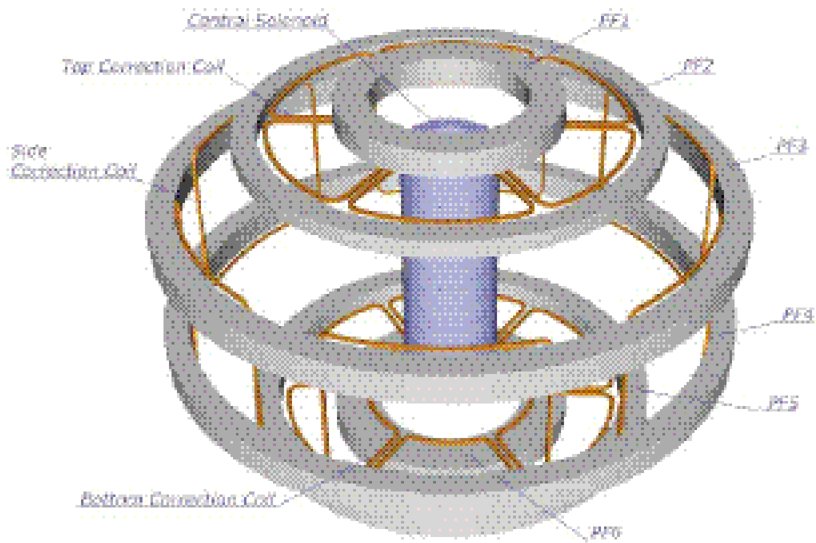
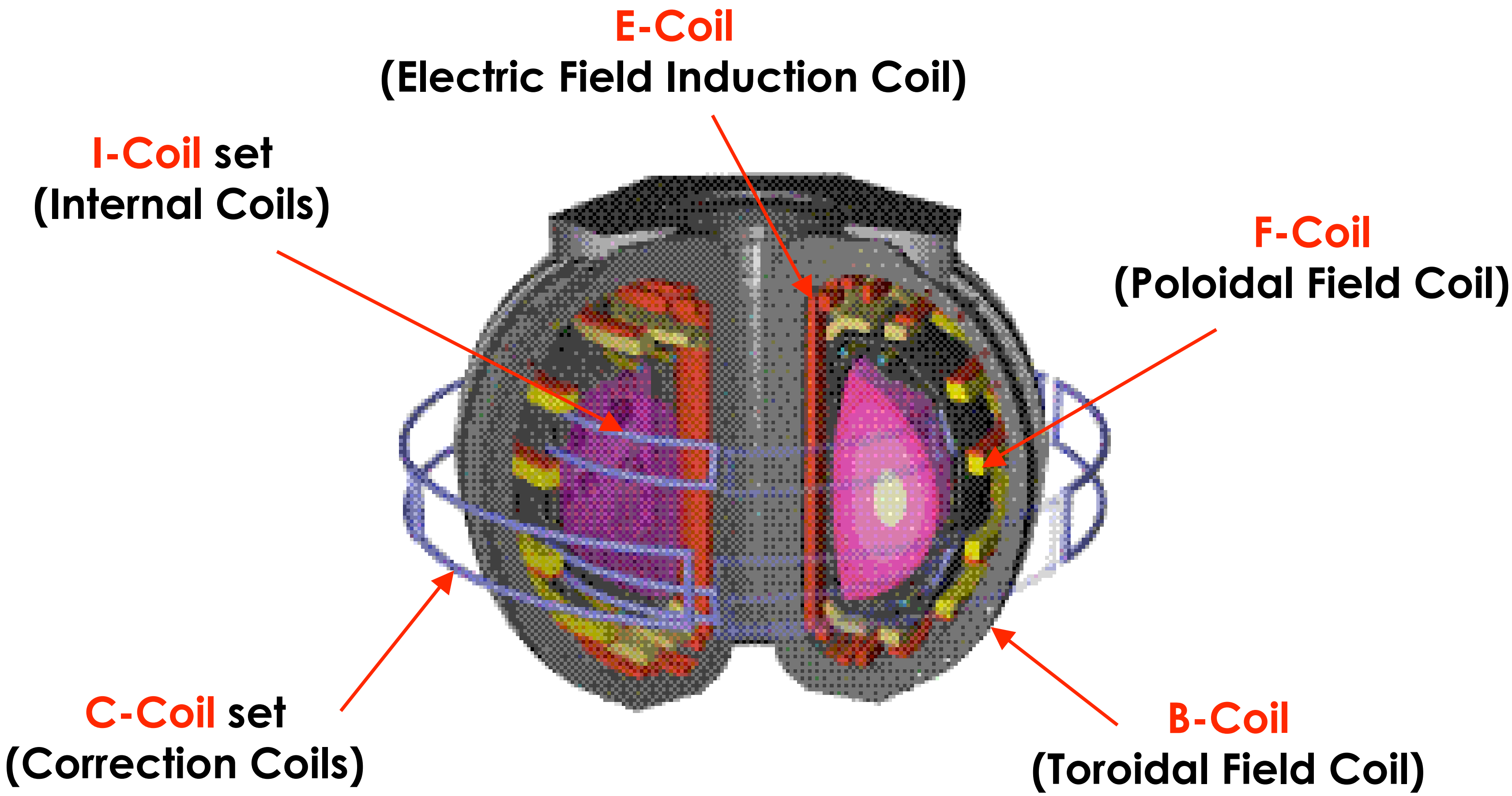


Figure 4.1-3 ITER Poloidal Field Coils and Error Field Correction Coils

- **Designed for currents needed to correct calculated expected, low-m, n = 1, pitch-resonant errors from PF & TF coil mechanical errors.**
- **Other error harmonics not considered, but one expects comparable magnitudes.**
- **ITER coils are different at 4 K than at 300 K, how to know errors from 4 K coils?**

DIII–D C-Coils and I-Coils Have Now *Both* Been Used for Error Correction



DIII–D error correction experience has been at odds with theory.
Suggests precautions that might be taken by ITER.

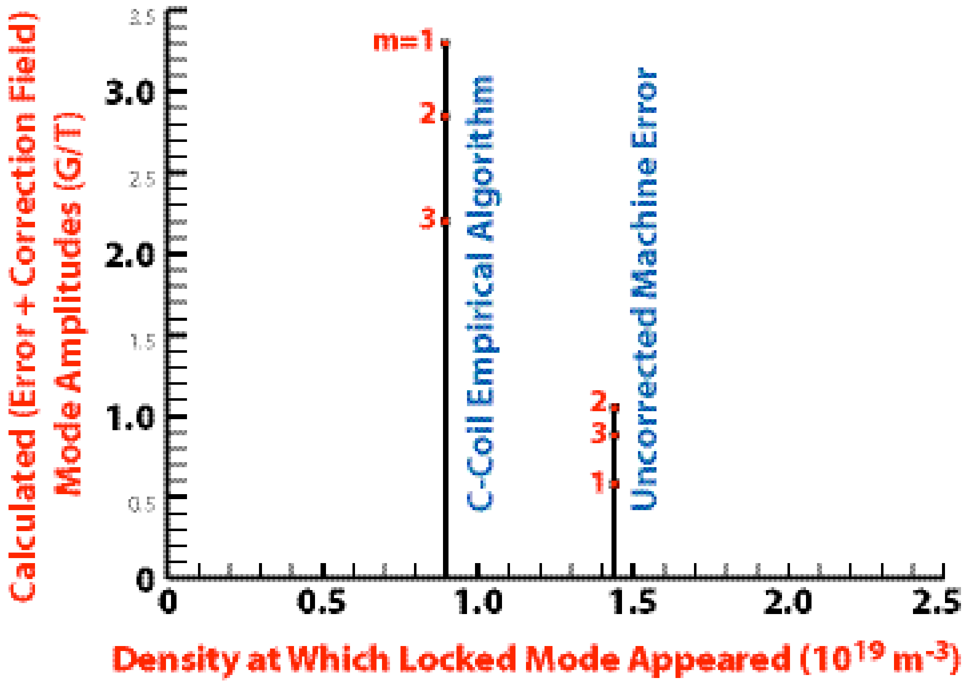
Empirical C-Coil Correction of DIII–D Error Field *Overcorrects* the *Known* Machine Errors

- Empirically corrected field

  (known error + correction)

  increases the pitch-resonant m = 1,2,3 Fourier amplitudes by 2~4 times.

- This puzzling result was interpreted as possibly an unknown machine error...
  - Machine error had been measured well in 1990
  - C-coil installed in 1995

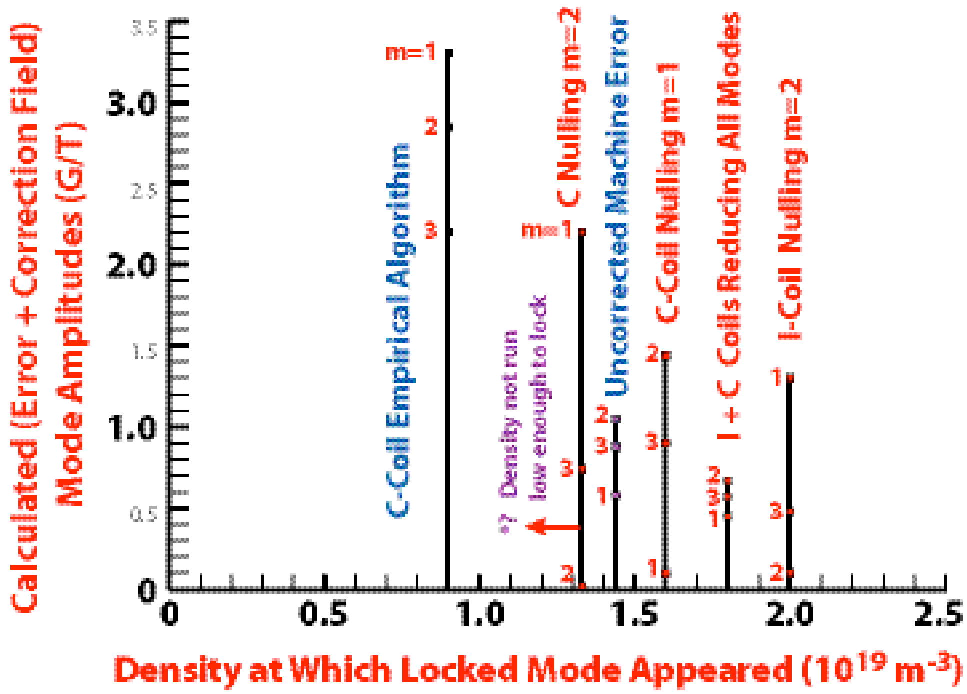


With increasing experimental demands for low operating error fields, new measurements of DIII–D errors were made in 2001.

- No errors of the missing magnitude were found

__Designed__ Corrections of *Known* DIII–D *Resonant* Error Did *NOT* Improve Locked Mode Avoidance (2004)

- Empirical C-Coil correction performed best, ‘corrected’ field has largest m = 1,2,3.
- C-coil nulling m = 2 gave improvement…
    - …unfortunately, not fully tested.
- I-coil similarly __nulling__ m = 2 is *worst*…
    - …but an EMPIRICALLY-found I-coil correction in 2006 is much better than empirical C-coil correction (see later).
- Using NO error correction worked better than 3 of 4 *designed* resonant error corrections.



__Conclusions__:

- We do not know how empirical error correction works.
    - Something may be missing in present theories of error effects.
    - Blindly canceling pitch-resonant error components is a futile idea.
- Or, maybe we do not know the true DIII–D error well (see later).

Apparent m/n = 2/1 Error is *Very* Dependent on Geometry (I-Coil top-bottom phasing) in Locking Expts. (2004)

Single Mode (m/n = 2/1) Critical Locking and Apparent Error Fields (G/T) at q=2 Surface

case —>	I-Coil 300º phasing	I-Coil 240º phasing	I-Coil 180º phasing	I-Coil 120º phasing	I-Coil 60º phasing	I-Coil 0º ** phasing	C-Coil Algo-rithm	Known DIII-D Error
Left-Hand* B_lock	1.05	2.11	2.98	4.5	6.9	1.3		
Left-Hand* B_error	0.61 54º	1.14 62º	1.58 58º	2.6 63º	3.5 49º	0.36 235º	2.3 52º	1.19 61º

* Left-handed modes are resonant, right non resonant ** 0º phasing has very different B geometry

- Values in a row should be constant if the same single pitch-resonant mode dominates for all I-coil geometries (phasings)
- Behavior does *not* conform to "single dominant pitch-resonant" model
    - Some other error(s) more important

TF Coil Current Feed Modification Reduced Effective Error in 2006 — Opportunity

RESULTS OF BEST EMPIRICAL CORRECTIONS in 2006

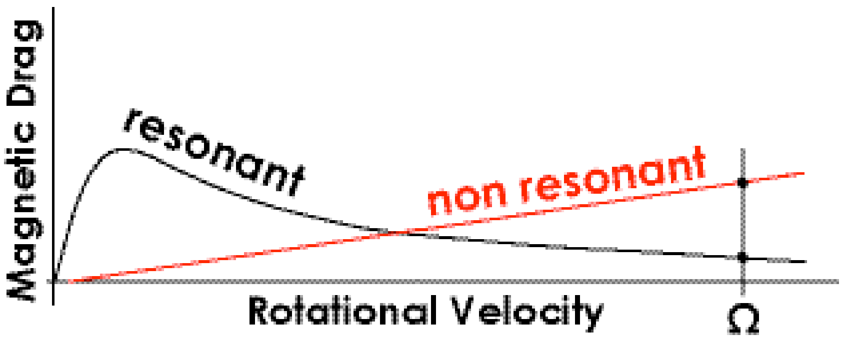
TF-coil Feed Status	Density at Lock Onset (10^{19} m^{-3})		
	Uncorrected DIII–D Error	With C-coil Correction	With I-coil⁺ Correction
≤ 2005	1.2	0.8	not tested
2006	0.85	0.60	0.36

⁺So far, I-coil was tested only for 240° phasing between top & bottom sections

- It is encouraging that removing a significant error from DIII–D yielded better performance (locked mode avoidance).
- It is encouraging that I-coil has better empirical correction than C-coil, because I-coil field is the better match to known error (see later).

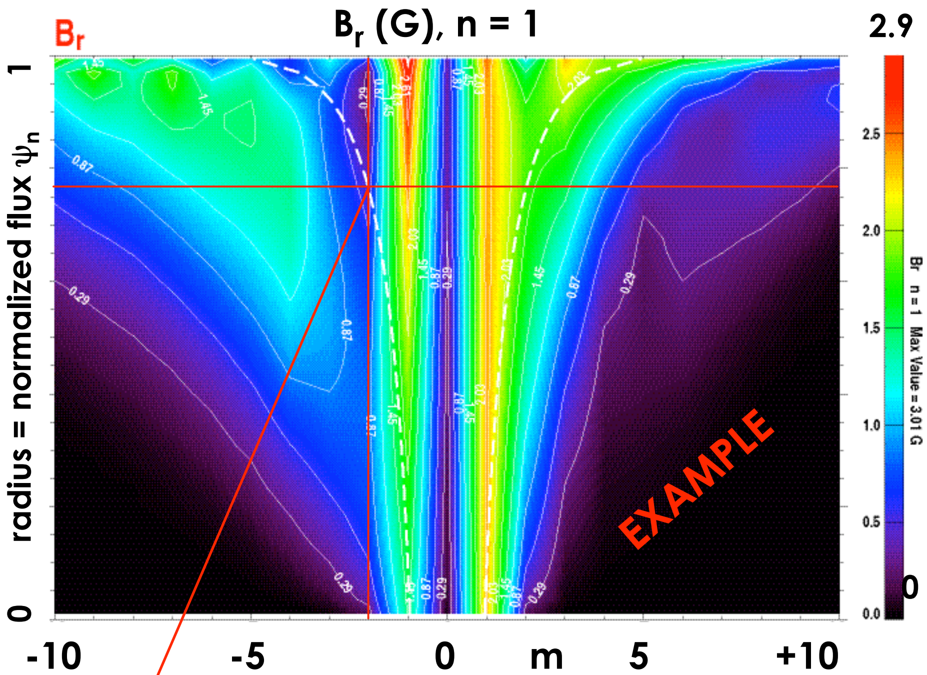
Perhaps Non Resonant Error Harmonics Slow Rotation to Where Resonant Braking Takes Over

- Non resonant magnetic braking ~ $\Omega\ \delta B^2$
  - Present throughout plasma volume
  - Both δB_r and δB_{tor} contribute
  - Most error field spatial spectrum power is non resonant
  - Rough estimates show non resonant braking might be comparable to resonant at high Ω



- Non resonant braking might initiate plasma slowing, even if final slowdown and nonlinear growth are dominated by resonant braking
  - Might not observe initiating non resonant effects casually in experiments when not looking for them

Nonaxisymmetric Fields Are Analyzed by SURFMN Code

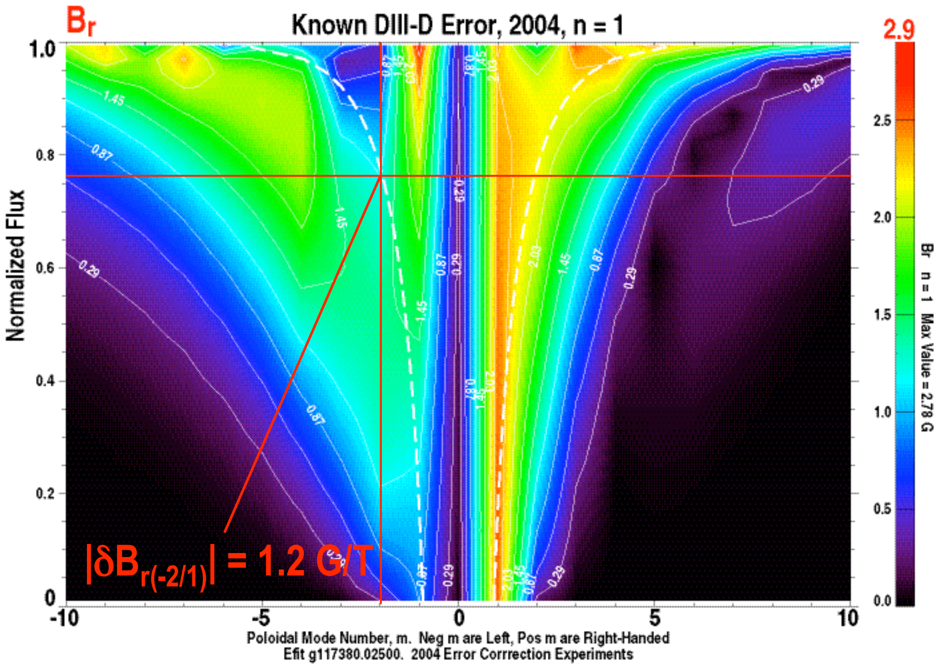


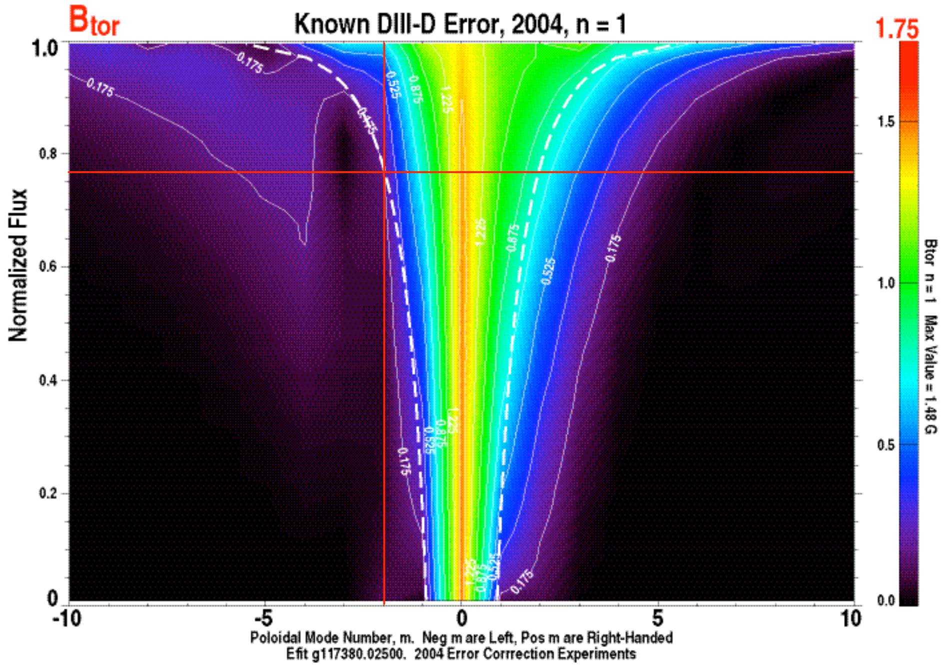
q = 2 at ψ_n = 0.77,
$|\delta B_r|$ = 0.48 G/T
at m/n = -2/1,
pitch resonance
in valley

Contouring shows mode magnitudes, $|\delta B_{m/n}|$

- SURFMN Fourier analyzes magnetic perturbations on the magnetic surfaces of a given EFIT equilibrium
  - Adds vacuum magnetic errors from source models to the equilibrium
- Mode naming convention:
  n = toroidal mode number, positive
  m = poloidal, m < 0 is left handed
  m > 0 is right "
- n is fixed in any one spectral plot.
- White dash lines show possible pitch resonance, $|m/n| = q(\psi)$:
  - Read m from bottom axis
  - DIII–D plasmas here are LEFT handed so pitch resonance is for m < 0.
  - Right handed $q(\psi)$ dash curve guides eye to equivalent positive m.

The Pre-2006 *Known* Machine Errors Had Small 2/1 and 3/1 Pitch-Resonant Errors (~10^{-4})

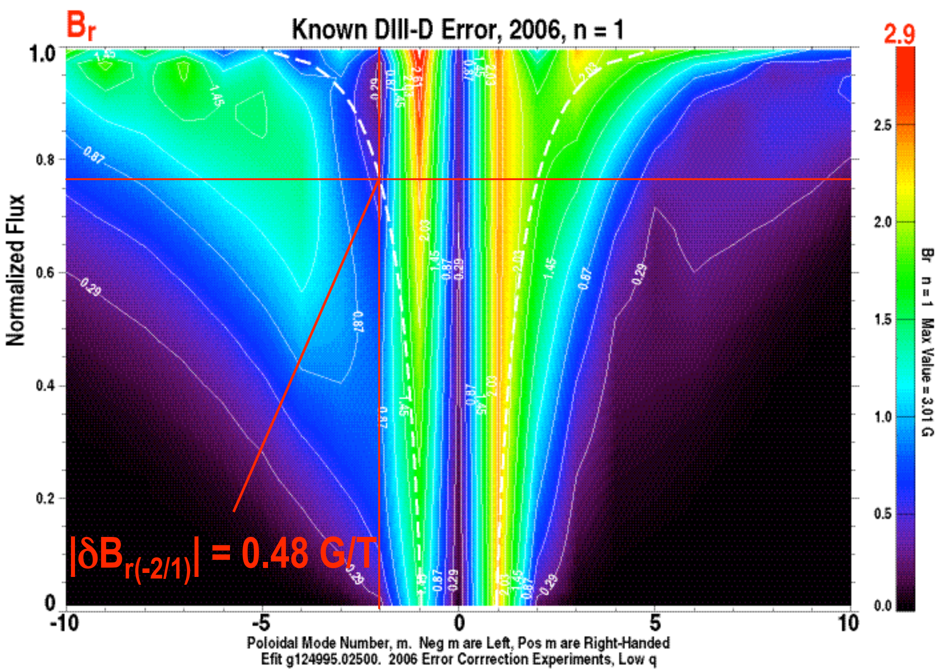


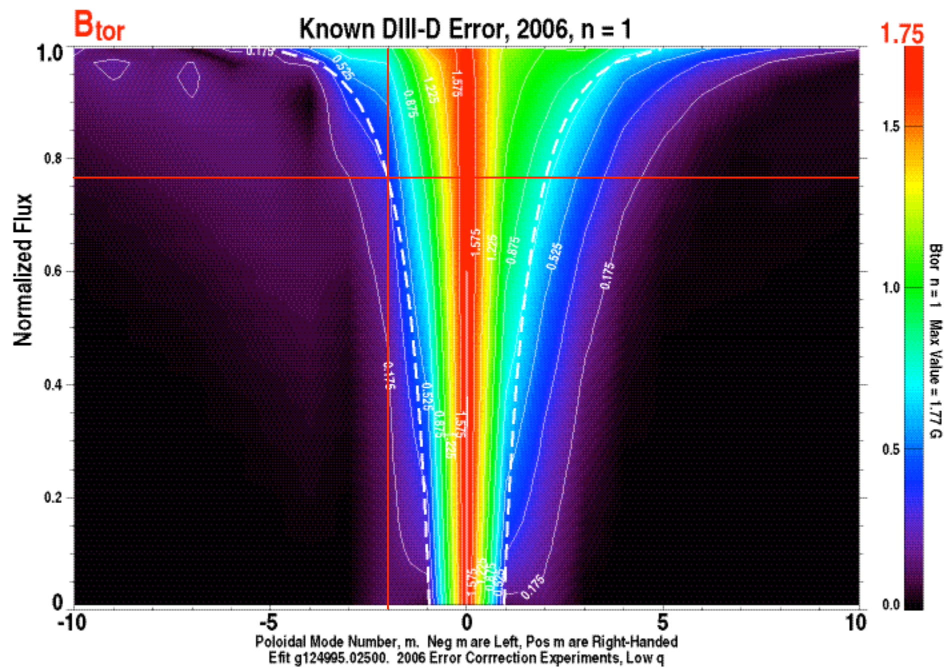


- Resonant δB_r is near a valley of mode amplitude topography
- Many larger non resonant modes
- Is why correcting just resonant mode(s) is ineffective in DIII–D?

- Known δB_{tor} is mostly m/n = 0/1 mode penetrating the whole plasma
  - Like a uniform horizontal B field

The New (2006) *Known* Machine Errors Have *Smaller* -2/1 Pitch-Resonant Errors After TF Coil Feed Change





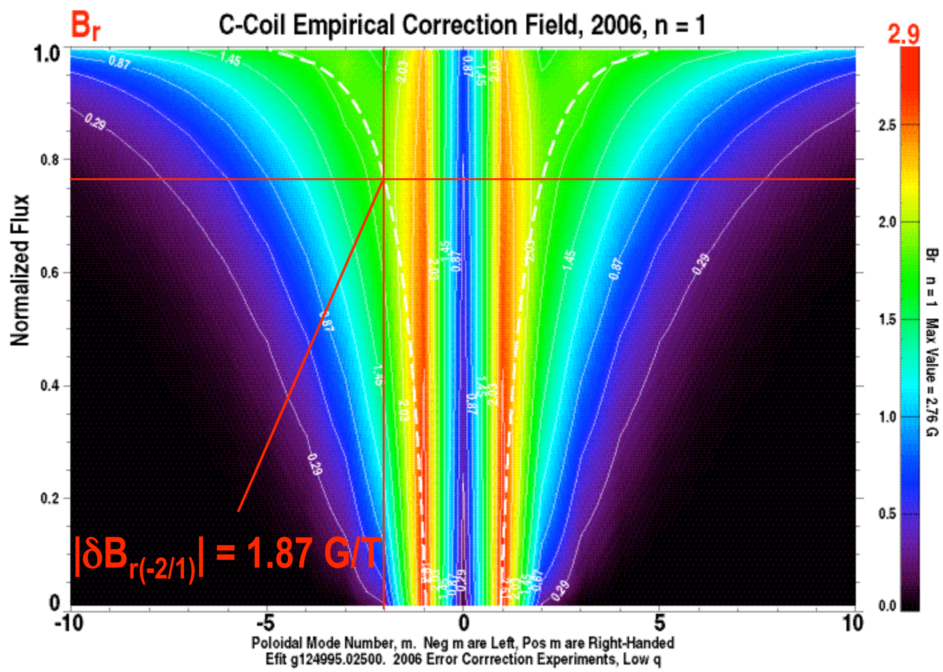
- Deeper pitch-resonant valley
- *Smaller* resonant δB_r after TF feed change
- δB_r also reduced at higher |-m|, but not at other non resonant modes

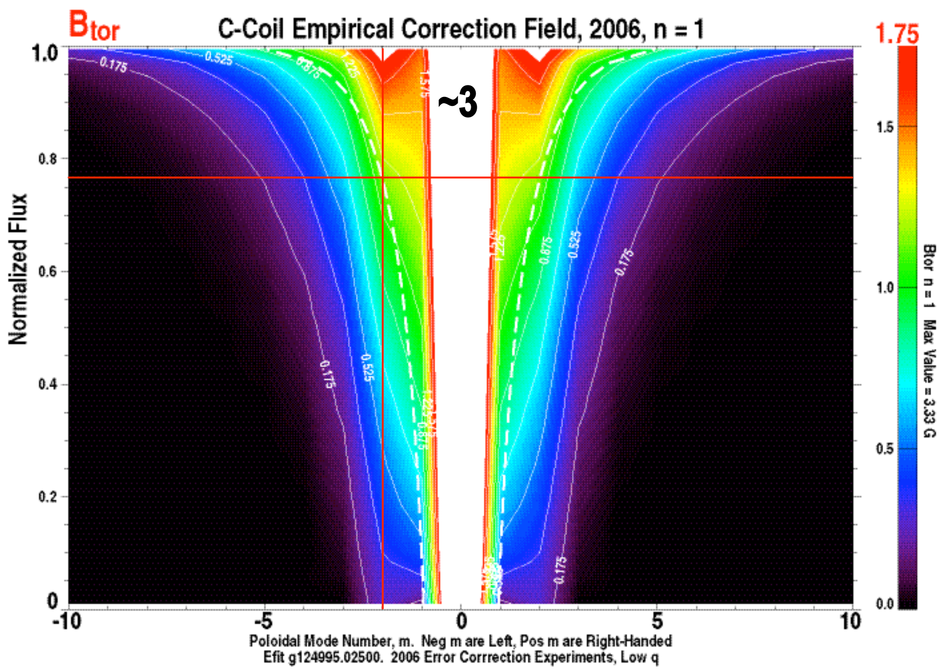
- But the toroidal vector component δB_{tor} mode amplitudes are *larger* after TF feed change

- Encouraging that *smaller* δB_r field is qualitatively associated with *smaller empirical* error

DIII-D NATIONAL FUSION FACILITY

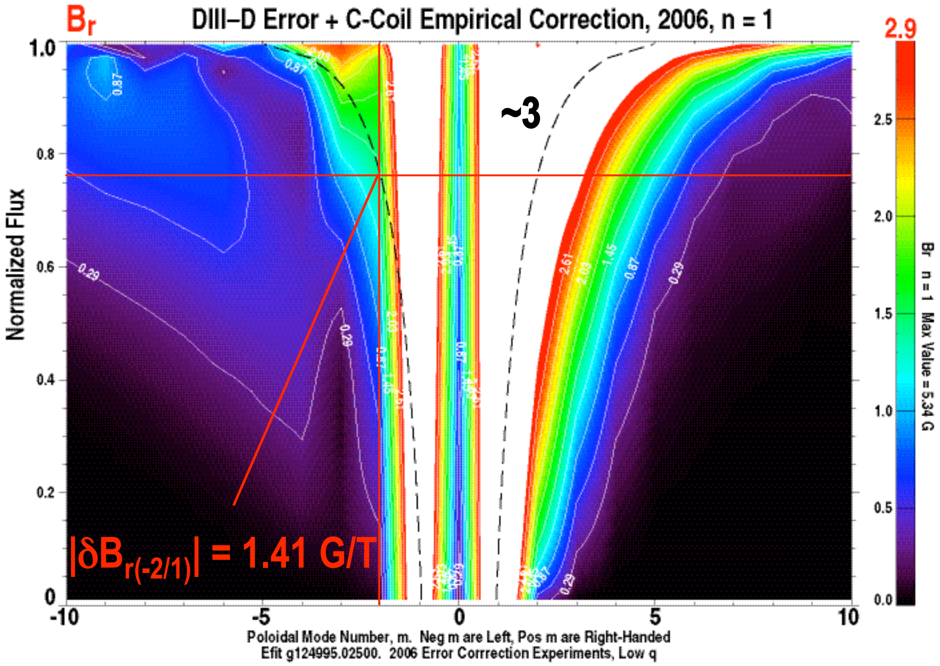
Empirical C-Coil Correction Does Not Match *Known* Error in Spectral Shapes or Magnitudes

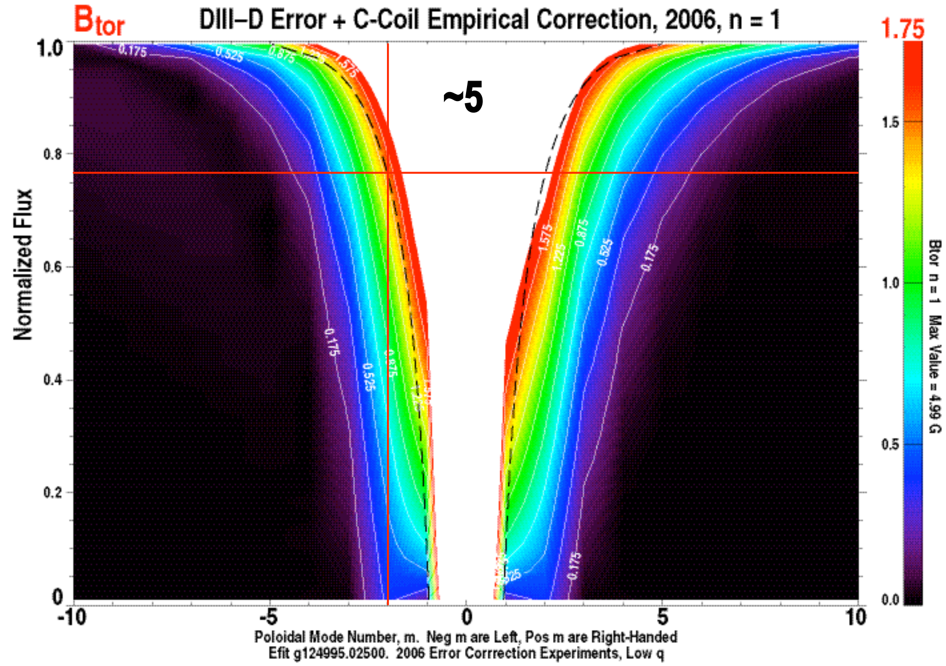




- DIII–D error is chiral, C-coil is achiral

C-Coil *Empirical* Correction Always Leaves Most *Known* Error Components Greatly *Overcorrected*



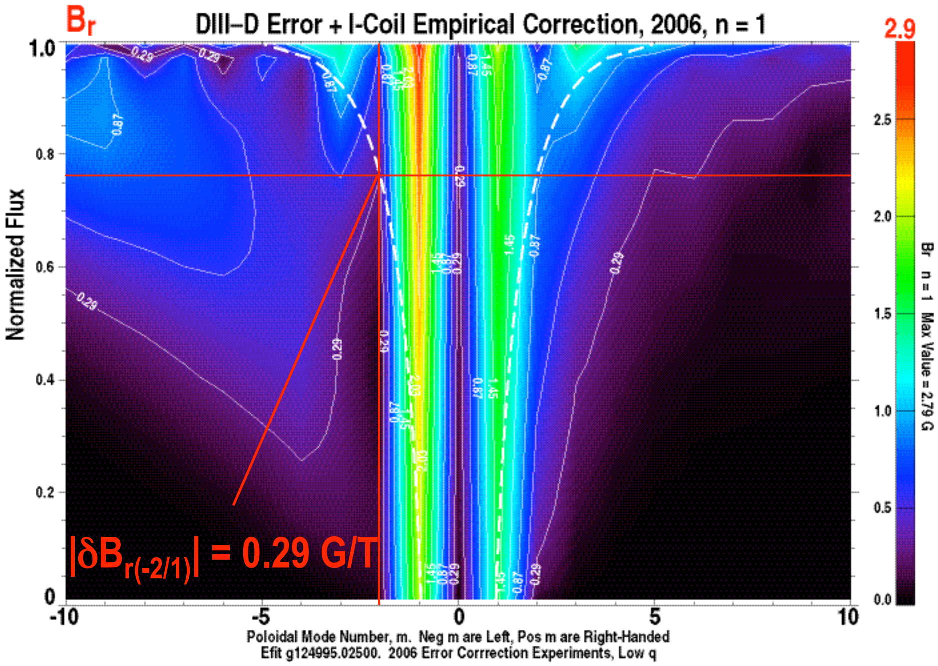


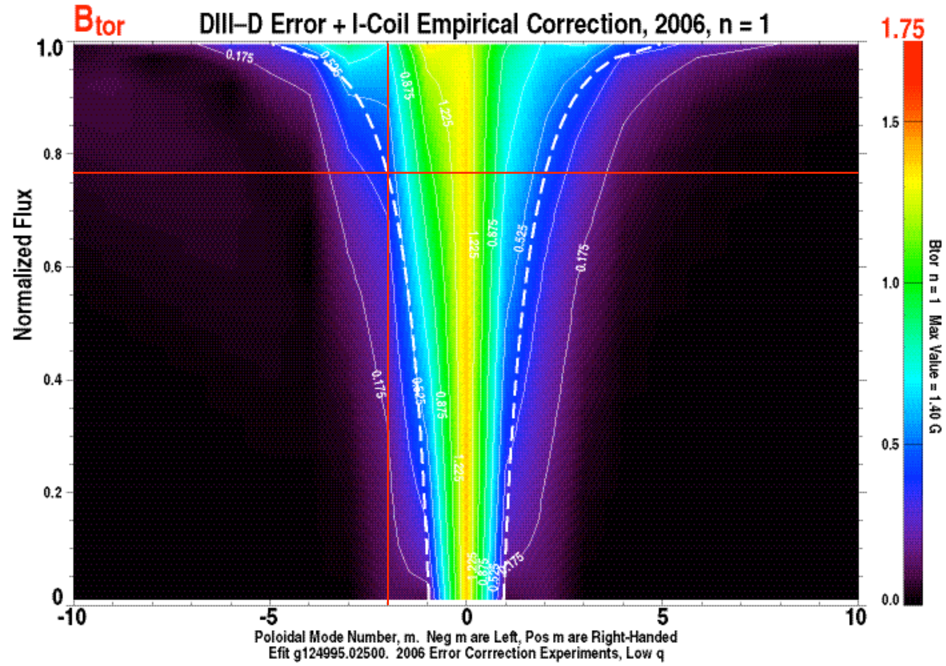
- Only high- (-m) left-handed harmonics are reduced by empirical C-coil correction
  - Also true before 2006
  - A clue?

- C-coil and machine δB_{tor} add in phase
- Either large δB_{tor} doesn't matter, or there is an unknown machine error
  - This motivated new search for horizontal B error from TF coil

2006 empirical data shown here

I-Coil *Empirical* Correction Amplitudes and Phases Match Most *Known* Error Components Quite Well





- Almost all δB_r components reduced
- Left-handed resonant and non resonant modes made especially small
  - As with C-coil correction
  - A pattern?
- δB_{tor} is reduced everywhere by I-coil

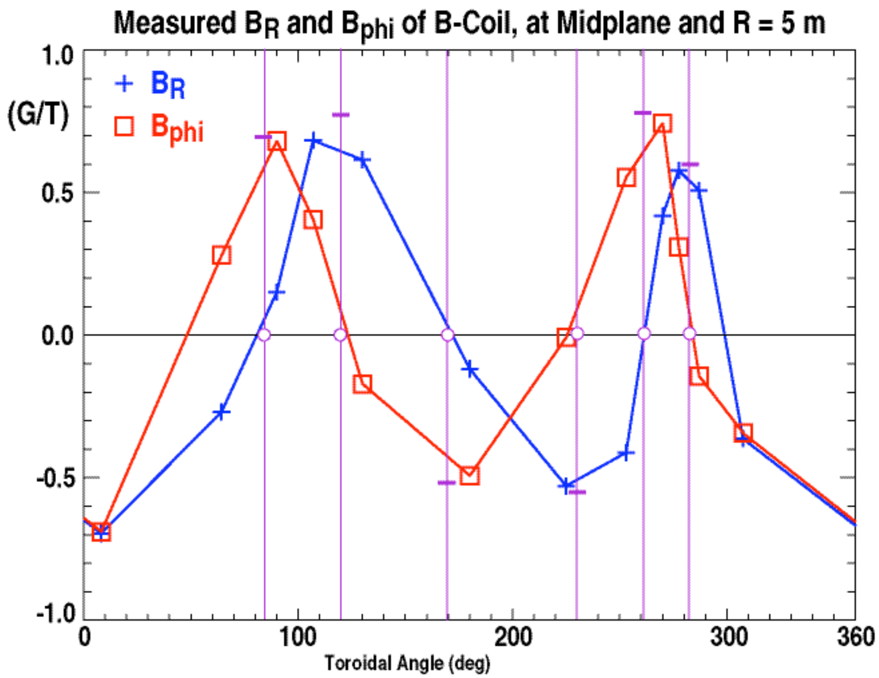
2006 machine error with empirical I-coil correction

Discussion: Is There a Pattern in the Data?

- Among these and other DIII–D data, the low-|m| and opposite-handed modes do not seem to be the critical components, whether δB_r or δB_{tor} are examined.
  - Furthermore, a new search has not found any ‘missing’ horizontal B (see later).
- The strongest commonality I have seen among all DIII–D empirical corrections is the reduction of high-|m| left-handed error field harmonics.
  - More consistent than reducing resonant modes to low levels.
- Jong-kyu Park suggested an explanation:
  - His calculations of ideal plasma response to a generic low-m “push” at outer midplane contain substantial high-m response.
- Perhaps, for best results, one must correct BOTH kinds of δB_r errors:

  same-handed, high-|m|, non resonant AND resonant 2/1.

TF Coil Correction System Should Accommodate More Than Just n = 1



- DIII–D TF coil has n = 2 error
  - Measured for 1st time
- No large 'missing' n = 1 error
- Measured δB may be systematic n = 2 variation of coil spacing around the torus
- Calculate local $\delta B \approx 3\times10^{-4}$ at minor axis
- There has been no attempt to empirically correct n = 2 at DIII–D

- ITER correction coils can make n = 2 field, but they need 3x6 independent power supplies, assuming n = 1 correction needed, too

  (Misaligned PF coils make n = 1 errors)

Error Control Considerations for ITER

- Error correction is poorly understood, even qualitatively
  - Cannot predict how much is tolerable
  - Do not know which components of error are important, unimportant
  - May lead to over- or under-design of correction system
  - Without knowledge, empirical adjustment of error correction is a slow, many-parameter search
- ITER correction coil system is designed to correct n = 1 pitch-resonant errors
  - Probably has sufficient flexibility to also correct likely non resonant n = 1 errors
  - Needs independent power supply for each of 18 coils for n = 2
- An alternate coil set closer to plasma could do about as well
  - A midplane-only set might be inadequate
  - If high-|m| correction is important, then a midplane correction coil set should be vertically narrow, to increase high-|m|.

Summary and Conclusions

- Empirical error correction works, but DIII–D data show we do not know how
  - Designed corrections of resonant errors fail
  - Getting less probable that there are significant unknown errors
  - Perhaps because resonant errors already quite small in DIII–D
    - Opportunity to discover the most important errors
- Non resonant errors could have significant effects
  - Low-|m| and opposite-handed δB_r and δB_{tor} do not seem to have strong deleterious effects
  - Small same-handed high-|m| modes are associated with low apparent errors
- Higher-n modes can arise e.g. from systematic assembly errors
- Knowing which error components to target may improve effectiveness of ITER error correction.

Extras

On Fourier Mode Analysis on a Magnetic Surface

- I want Fourier analysis of $B \cdot \hat{n}$ on a surface to correspond to magnetic island properties:
  - A null of B·n from Fourier analysis on a resonant surface must correspond to absence of an island in Poincaré plots of magnetic line trajectories.
- Procedure:
  - Set up straight-magnetic-line coordinate system on the surface: $\theta = \phi/q$
    - θ and ϕ are, respectively, poloidal and toroidal angle variables; interval = $[0,2\pi]$
  - Must use the corresponding Jacobian when integrating over the surface:

$$J = \left(\frac{q}{R_0 B_0}\right)\left(R^3 B_\theta\right)$$

where $R_0 B_0$ = product of R_0 and toroidal B at $R = R_0$ on the surface
R = local major radius
B_θ = local poloidal B

First parenthesis factor of J is constant on a magnetic surface, but R^3 and B_θ vary. They reduce contributions from high field side & tips, respectively.

Thus,

$$B \cdot \hat{n}\Big|_{mn} = \iint 2\cos(m\theta + n\phi)\,(B \cdot \hat{n})\left(B_\theta R^3\right) d\theta d\varphi \Big/ \iint \left(B_\theta R^3\right) d\theta d\varphi$$