Understanding Magnetic Field Error Correction in DIII–D

by

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with

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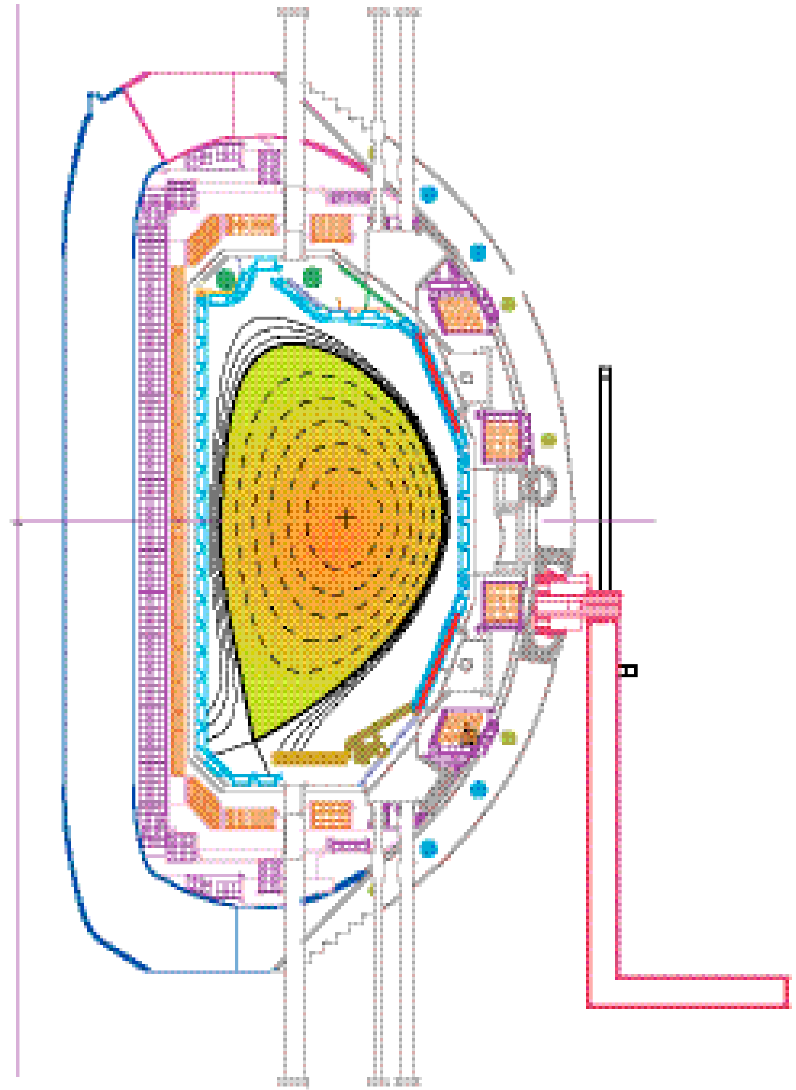

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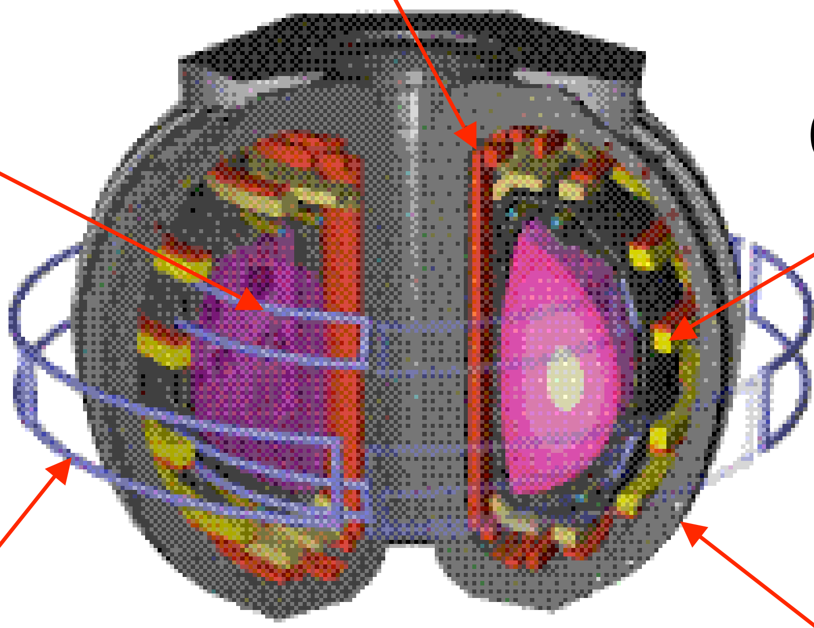
DIII–D Magnet Coils



Motivation & Key Points

- Error δB → makes weakly non-axisymmetric stable equilibrium
  → brakes plasma rotation → weakens screening currents
  → δB penetration → island → loss of nested magnetic surfaces
  - Compounded by plasma amplification of δB
- RESONANT error at q = 2 in DIII–D left-handed ("normal") plasmas is *very* small … $\delta B_{2/1} \approx 0.5 \times 10^{-4}$, but it still needs error correction!
- Additional error search at DIII–D → no appreciable new n=1 errors
  - Must confront n = 1 error correction paradoxes!
- Ideal Perturbed Equilibrium Code (IPEC) resolves many DIII–D and NSTX error correction paradoxes [Jong-kyu Park et al, PRL, 2007 Nov 9]
  - Plasma response is large, dominated by least stable ideal mode
  - Internal δB is mainly from coupling external δB to this mode
    - Not an amplification of external vacuum field

OUTLINE

- DIII–D ERROR STATUS
  - One TF coil feed modified in 2005–6 → reduced error
  - Results after reduced TF coil error
  - Error Search: Found other errors associated with TF coil
- EMPIRICAL ERROR CORRECTION
  - New method
  - Local correction at a local error
  - Correcting error of right-handed plasmas
- COMPARISON WITH IDEAL MHD PERTURBED EQUILIBRIUM MODEL
  - Experimental evidence
  - Some properties of ideal perturbed equilibrium
  - Model results from IPEC
- SUMMARY & CONCLUSIONS

ERROR STATUS

TF coil current feed modified for lower error in 2006, reduced effective error. I-coil better than C-coil.

RESULTS OF BEST EMPIRICAL CORRECTIONS in 2006

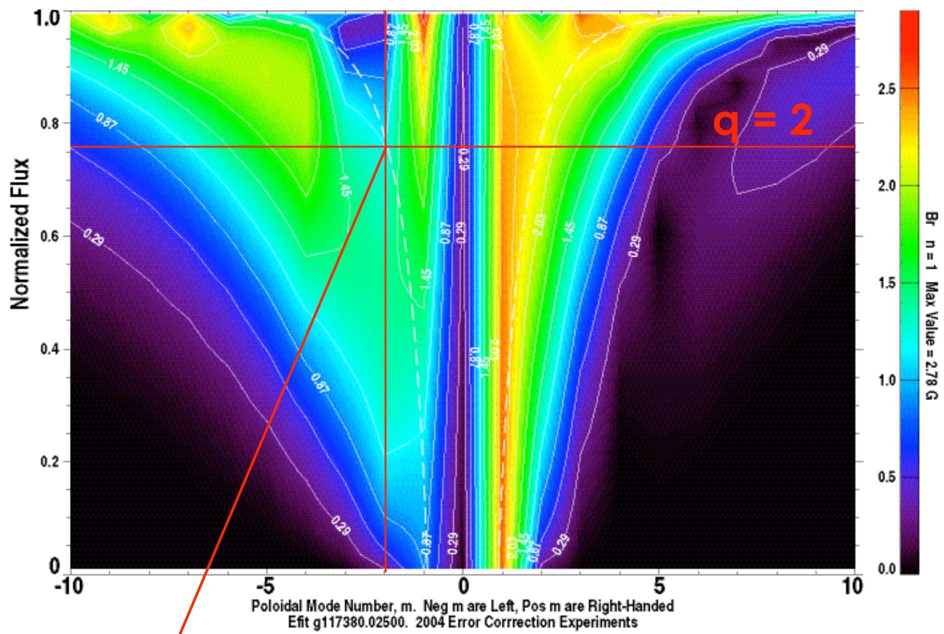
TF-coil Feed Status	Density at Lock Onset (10^{19} m^{-3})		
	Uncorrected DIII–D Error	With C-coil Correction	With I-coil* Correction
≤ 2005	1.2	0.8	never tested
2006	0.85	0.60	0.36

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

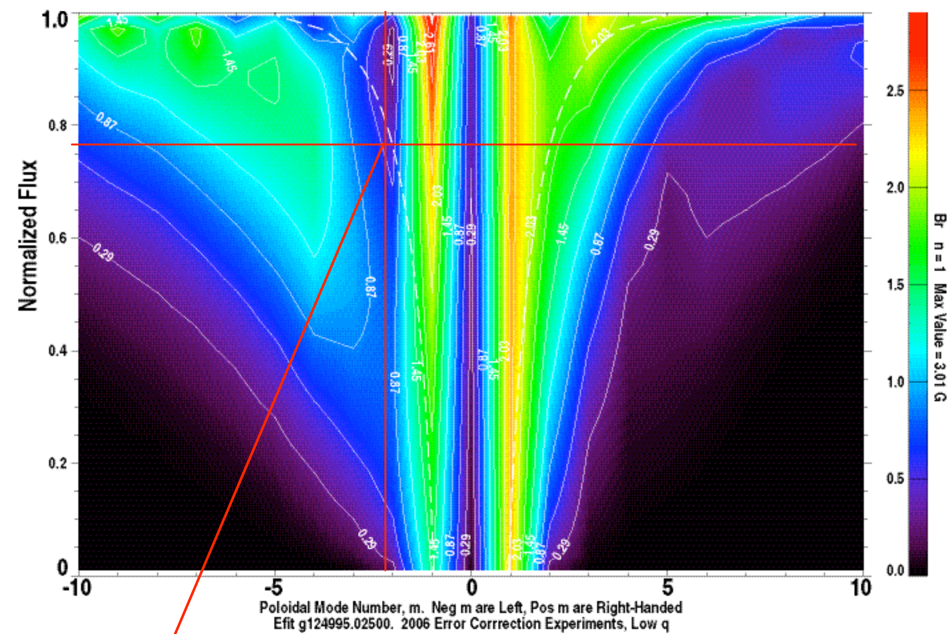
- Removing this error from DIII–D yields better locked mode avoidance
  - … as expected
- Optimized C-coil still gives additional improvement after the change
  - But, C-coil still overcorrects known errors
- Optimized I-coil error correction (never tested before) is best
  - Empirical I-coil field reduces known error … no puzzle

Poloidal harmonics of DIII–D n=1 vacuum field errors reduced from ≤ 2005 to ≥ 2006

n = 1 error field ≤ 2005, Br



n = 1 error field ≥ 2006, Br

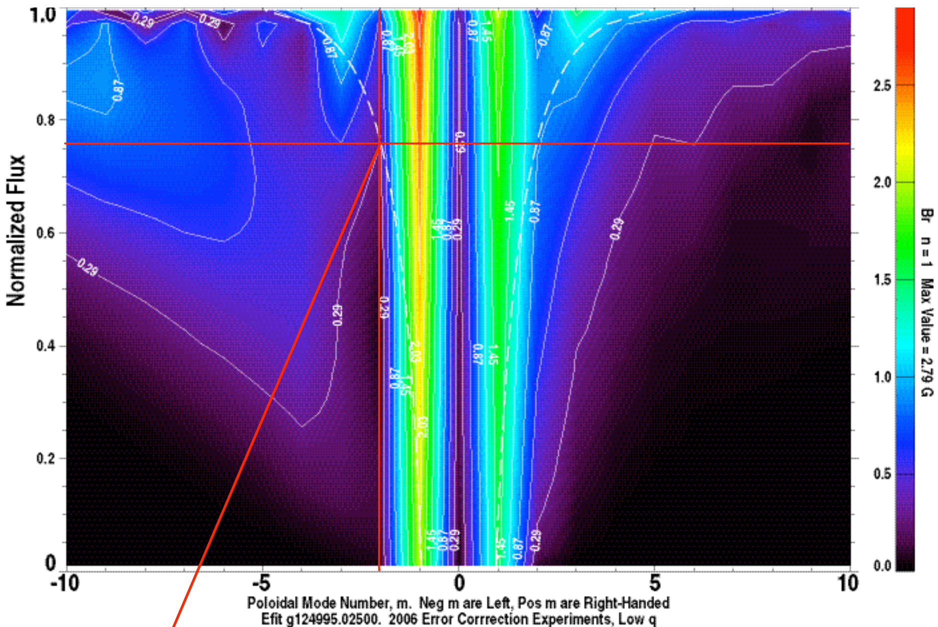


- $\delta B_{r(-2/1)}$ = 1.19×10^{-4} at q=2
- δB_r field is “chiral” (left and right handed harmonics not equal)

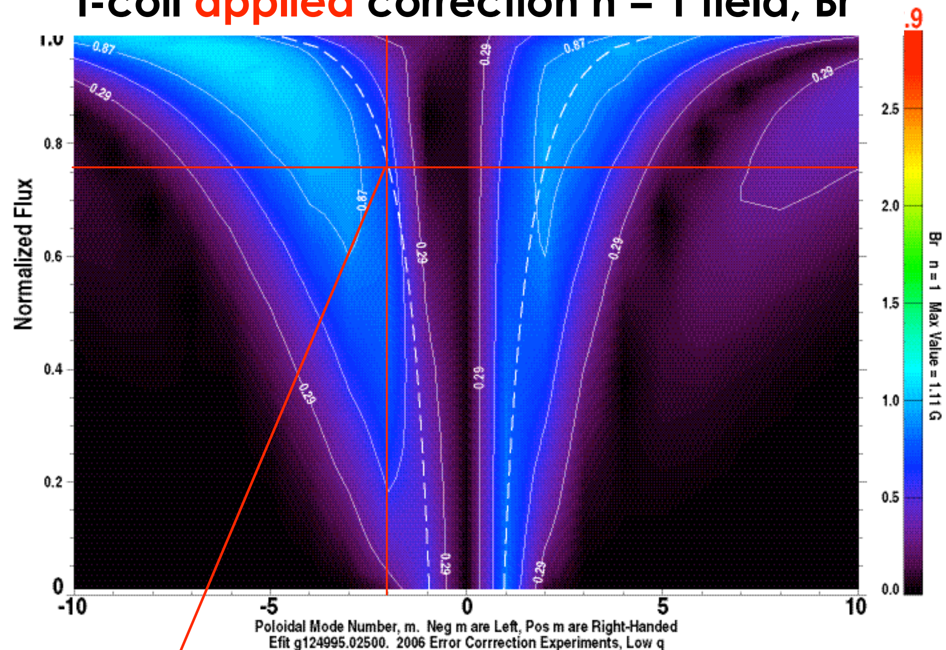
- $\delta B_{r(-2/1)}$ = 0.48×10^{-4} at q=2
- Pitch resonance is in an error valley, especially at q = 2, 3
- δB_r is now weaker at |m| ≥ 2

Empirical correction by I-coil in ≥ 2006 dramatically reduces the vacuum field errors

n = 1 error empirically corrected by I-coil, Br



I-coil applied correction n = 1 field, Br



- $\delta B_{r(-2/1)}$ = 0.29×10^{-4} at q=2
- δB_r is reduced everywhere by I-coil, except m = –1 at q = 1

- $\delta B_{r(-2/1)}$ = 0.70×10^{-4} at q=2
- $\delta B_{r(-2/1)}$ resonant I-coil field is 180° from its -2/1 error counterpart
- I-coil spectrum peaks at m ~ 2 nq

- I-coil had 240° top-bottom current phase difference, a choice based on reduced plasma rotation braking in beam-driven H-mode plasmas [A. Garofalo]

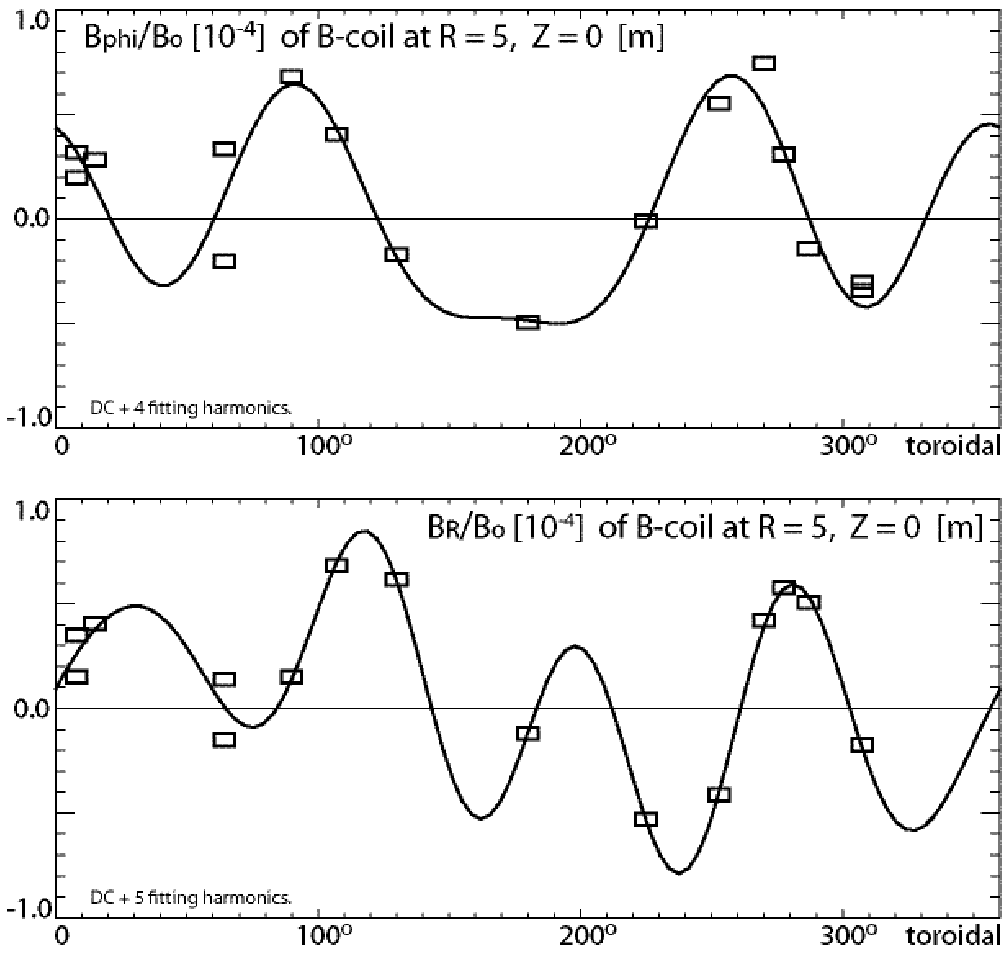
ERROR SEARCH

New measurements show one significant Ferromagnetic source associated with TF coil

- **Must know all significant machine errors to test theory predictions**
- **There is ~130° toroidally outside of TF coil midplane where almost no reliable data could be taken,**
  - **and saw an unexplainable "large" vertical B error there.**
  - **Took good data densely in the one accessible region**
  - **Anomaly source identified as ferromagnetic steel supports intercepting flux from high current TF-coil feed where they passed close to each other**
    - **The ferromagnetic steel *reduced* far field of current feed**
- **After including ferromagnetic steel effect, measured midplane TF coil error could be interpreted plausibly**

Measurements revealed TF coil δB from wider-than-specified inter-bundle gaps

Data and Fits, 2 m outside B-coil



- Three δB_ϕ peaks are close to:
  - wider TF coil inter-bundle gaps at 15 °, 90°, 270 °
  - Gap excesses ≈ 4, 6, 6 mm
- Narrow peaks; resolve n = 1–4

  $B_{n=1}$ ~ 1.3x10^{-4} at R_o = 1.7 m

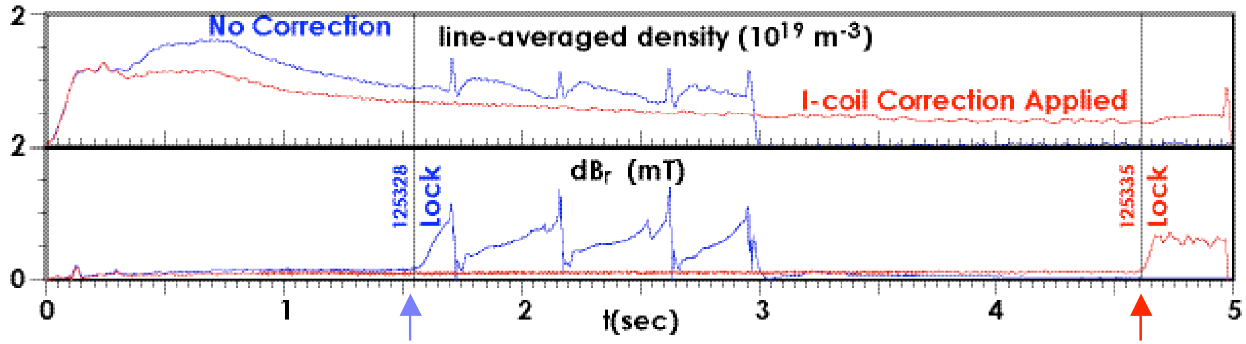
  $B_{n=2}$ ~ 1.5x10^{-4} at " "
- $B_{n=1}$ is much smaller than ~ 5x10^{-4} "unknown error" implied by large C-coil empirical correction field
- Effects of higher-n errors not yet known

EMPIRICAL ERROR CORRECTION

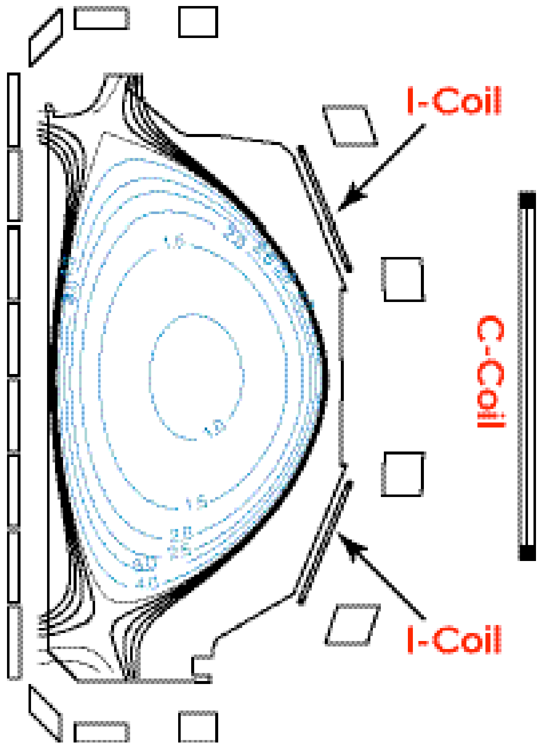
Same Low-Density Locked-Mode Technique Used in New (>2005) and Old (<2005) Experiments

- Ohmic, low-density plasma is a "standard candle" to evaluate tokamak error status.
  - Sensitive to locked mode instability.
  - Effective ERROR ~ DENSITY at lock onset.
  - Verified in several tokamaks.
- Upper null avoids Ohmic H-mode in shots with downward ion ∇B drift.

Density Rampdowns to Lock

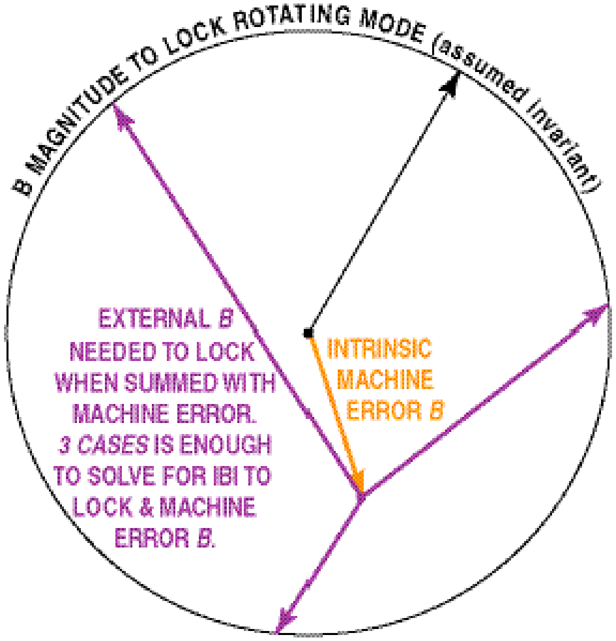


Test Plasma

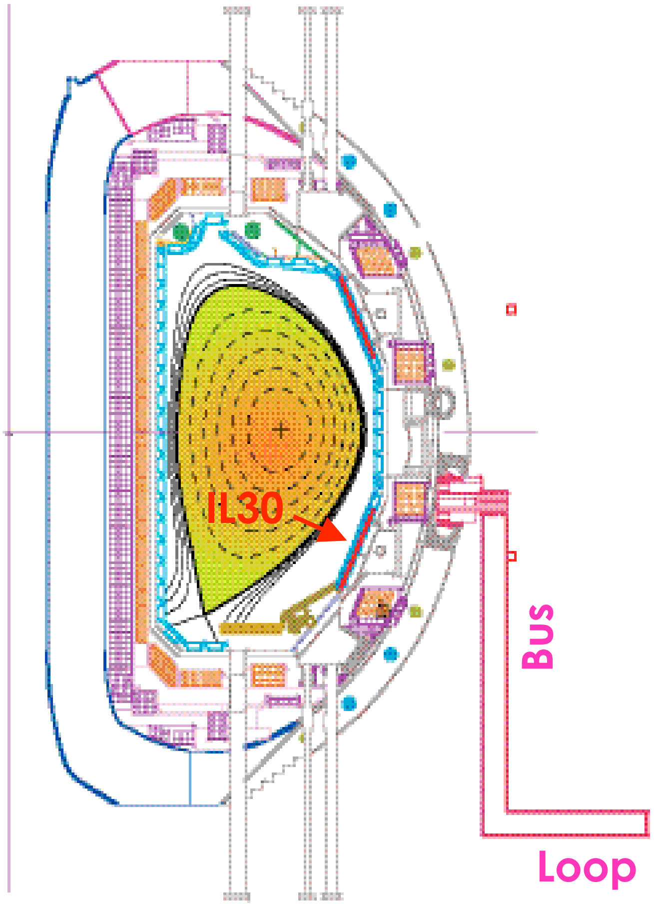


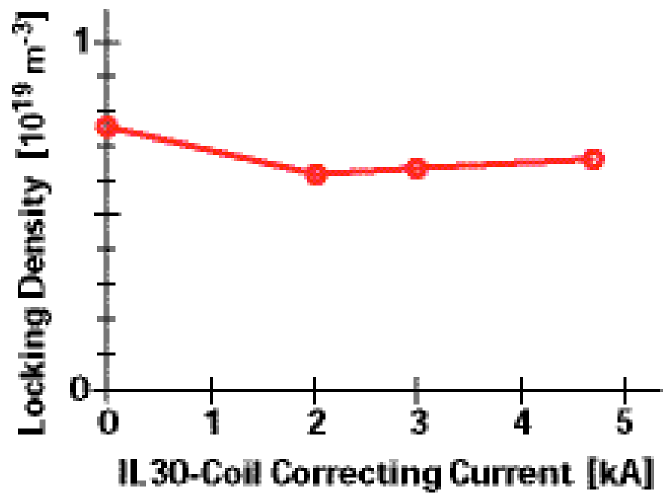
New Empirical Correction Search Strategy Was Developed in 2006

- Years of experience show that in DIII–D:
  - An n=1 correction field combines with an n=1 *effective* error field like vectors
  - Mode locking occurs when vector sum reaches a determined magnitude
  - I.e., n=1 behaves like a rigid "mode"
- Correction coil *current ramp-ups* to locking at 3 different toroidal phases at a *fixed density* are sufficient to *calculate* an n=1 effective erro
  - In practice we ramp current at 4 different phases for redundancy
- Finally, a *density ramp-down* shot is taken with the newly found correction, to quantify the locking density, hence the residual effective error
- Used in 2006 & 07
- The one test of "goodness of minimum lock density" indicates that further refinement is possible … the n=1 "mode" may not be perfectly rigid



Exploratory experiment that actively reduced 30° feed bus error postponed locked mode

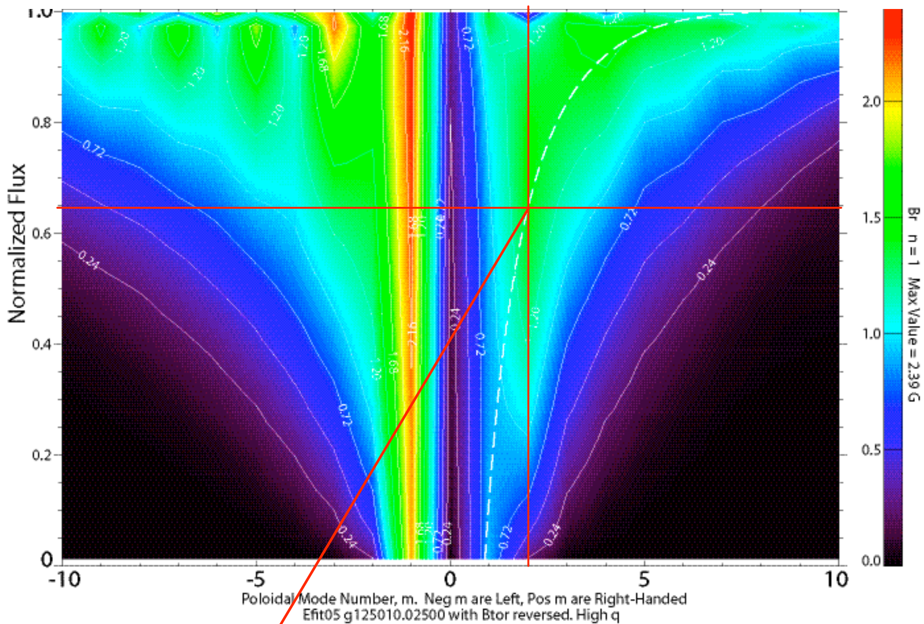




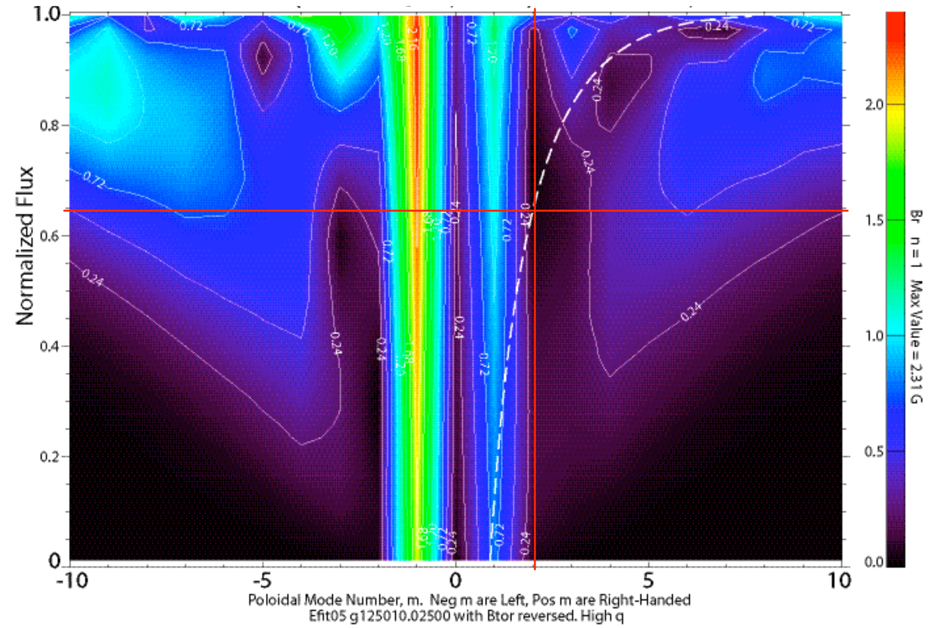
- TF coil feed bus error at machine 30° was partially corrected by nearest I-coil, IL30
  - Not a pure test; IL30 was correcting mixed local bus multi-n error and PF coil n=1 offset
- For future, plan to combine corrections of feed and PF coil errors

New correction of RIGHT-HANDED plasmas was developed with 180° top-bottom phase difference

Intrinsic error field, RT-handed test plasma, Br



PREDICTED corrected field using I-coil @Δ180

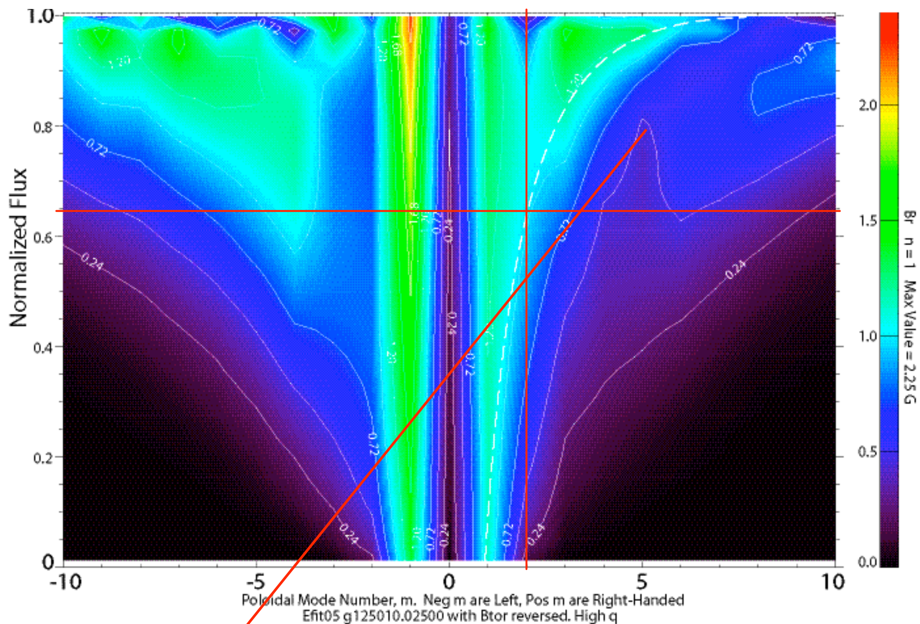


- Intrinsic n=1 error spectral peak in right-handed plasma is resonant, ≈1.5x10^{-4} at q = 2, 3, 4
  - Unlike left-handed plasmas, where resonant n=1 harmonics are < 0.5x10^{-4}

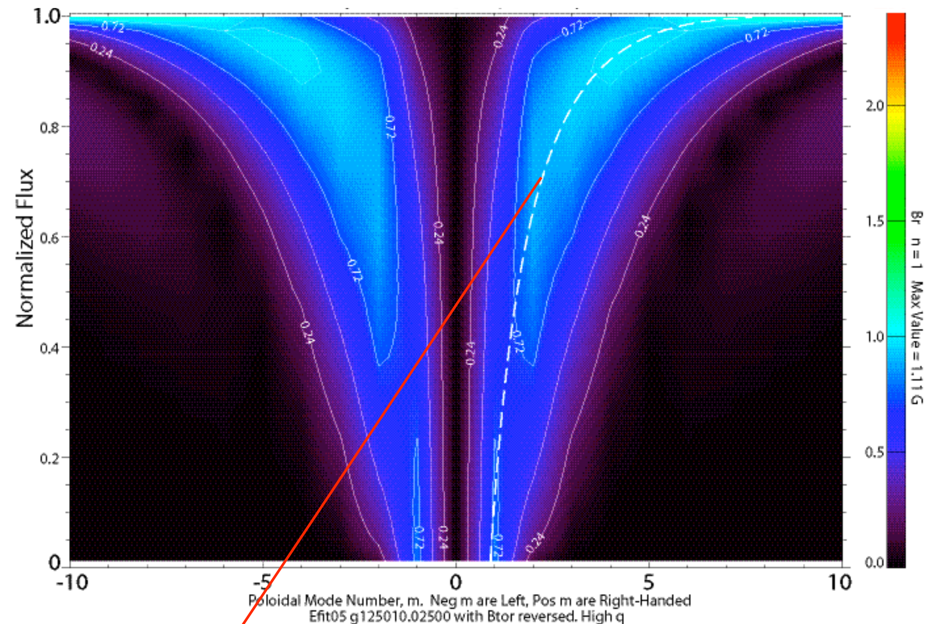
- Prior calculations showed that I-coil with 180° top-bottom difference gave “eyeball best” low resonant harmonics
  - Didn’t know how to weight
  - 1.22 kA n=1 current

Empirical correction of RIGHT-HANDED plasmas optimized quite differently than predicted

EMPIRICAL corrected field using I-coil @Δ180



EMPIRICAL I-coil @Δ180 correction field alone



- Empirical correction reduced spectrum at *higher* than resonant q
- Gave little gain in locked mode avoidance

- Although empirical I-coil field was aligned with q, plasma "wanted" only 0.77 kA peak, vs. 1.22 "predicted"

- Subsequently, perturbed equilibrium model suggests applying correction to its dominant mode, whose spectral peak has m > nq (see later)
- Will try I-coil top-bot difference = 120°, better coupling to dominant mode

COMPARISON WITH IDEAL MHD PERTURBED EQUILIBRIUM THEORY

Many data contradict the model of vacuum error field negligibly affected by plasma

Using calculated n=1 vacuum error field in DIII–D:

- Resonant intrinsic error (left handed, normal) is already small ~ 0.5×10^{-4}
- Optimum C-coil overcorrects resonant errors by 2~3 times, yet significantly reduces locking,
  in both left- and right-handed plasmas
- All my designed resonant correction fields made mode locking worse
- The commonality among all optimum empirical corrections I've analyzed

  I-coil, C-coil, I +C-coils

  "N=1"coil + C-coil; dynamic error feedback

  left- and right-handed plasmas

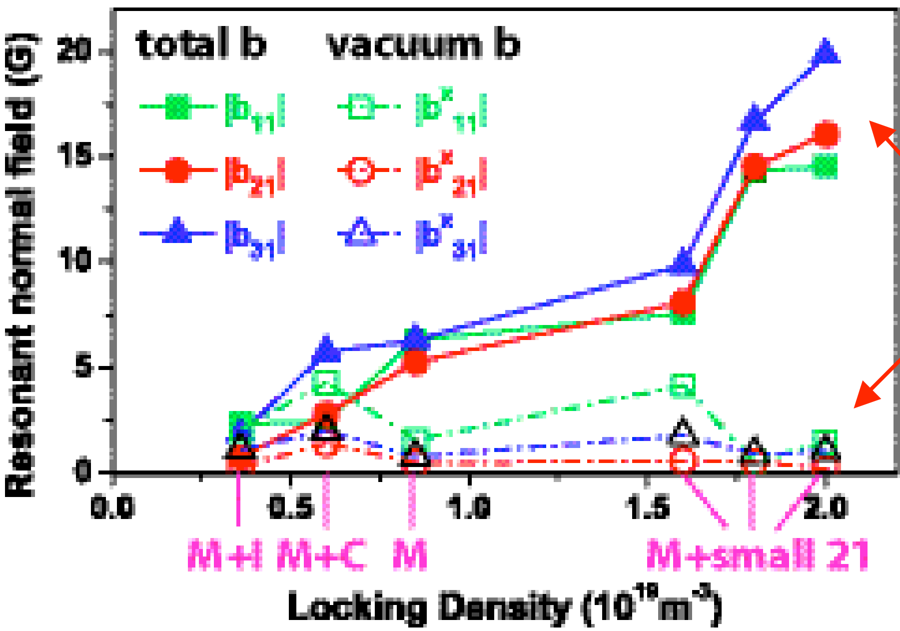
  before & after 2005 error change

  is reduced $m \sim 2nq$ (i.e., higher $|m|$)*, not resonant harmonics

- VACUUM MODEL FAILS. PLASMA RESPONSE MUST BE IMPORTANT

*(m and q have signs here)

IPEC calculations: Small/Large TOTAL resonant δB associate with Good/Bad locking avoidance



total b = δB including plasma response

M = machine intrinsic error

M+C = error + C-coil empirical correction

M+I = error + I-coil " "

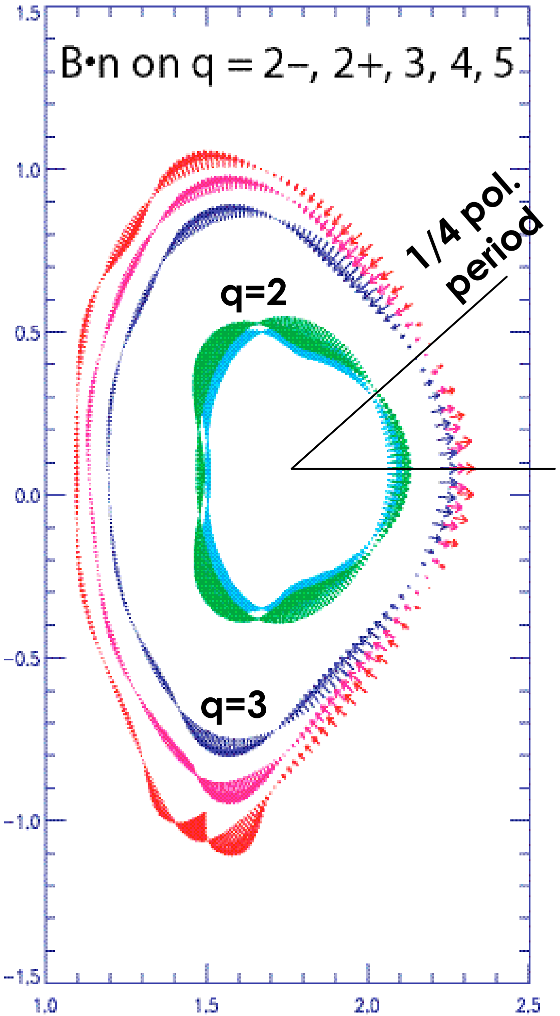
M+small 21 = error + *designed* for small vacuum 2/1

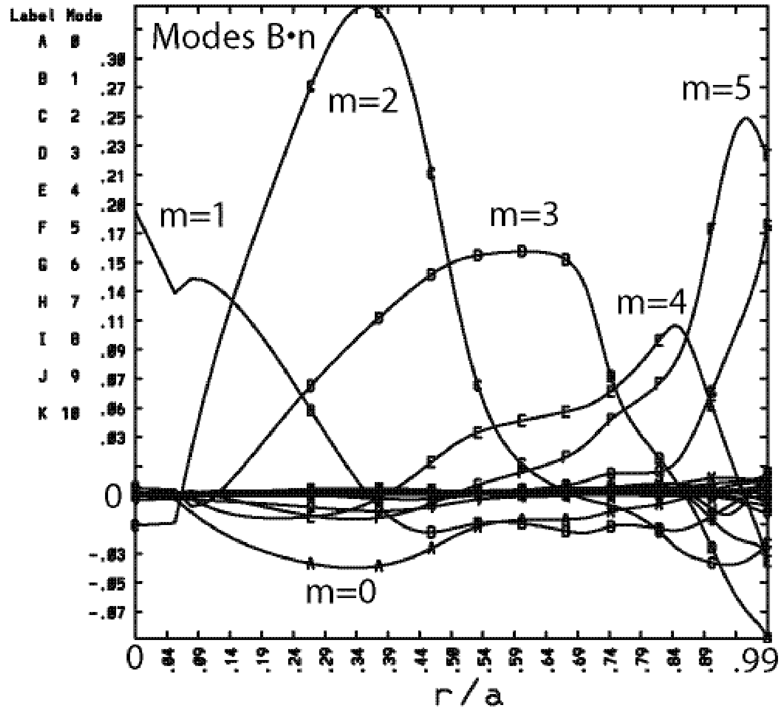
Low locking density means better lock avoidance

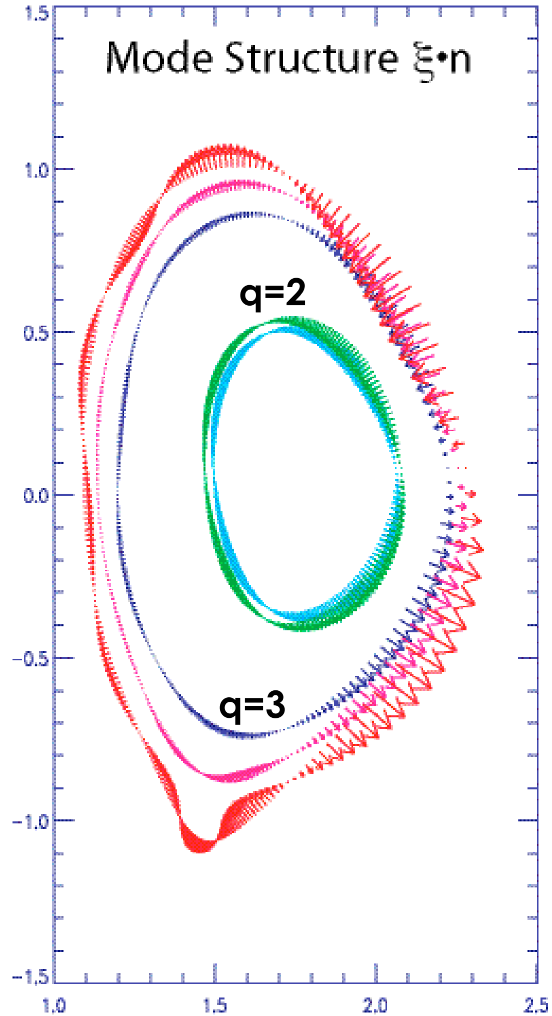
- Locking density is monotonic with TOTAL δB · n for varied cases
- Naïvely *designed* correction fields achieved small vacuum δB · n, but they over-drove the plasma mode to the extreme
- Machine vacuum error δB · n are small, but amplified ~5 times.
- Total δB · n of machine + C-coil correction ≤ total machine error
- Total δB · n of machine + I-coil correction << total machine error

Jong-kyu Park et al, PRL, 2007 Nov 9

The Ideal MHD n=1 external kink generates many poloidal harmonics inside plasma







Figures courtesy of
M. Okabayashi and J. Manickam

- Note that m=3 is not shielded inside of q=3…it's amplified
  - Potential for non-resonant braking

DIII-D
NATIONAL FUSION FACILITY

Ideal n=1 mode has a characteristic geometry on outboard side. Mode phase NOT resonant with B lines.

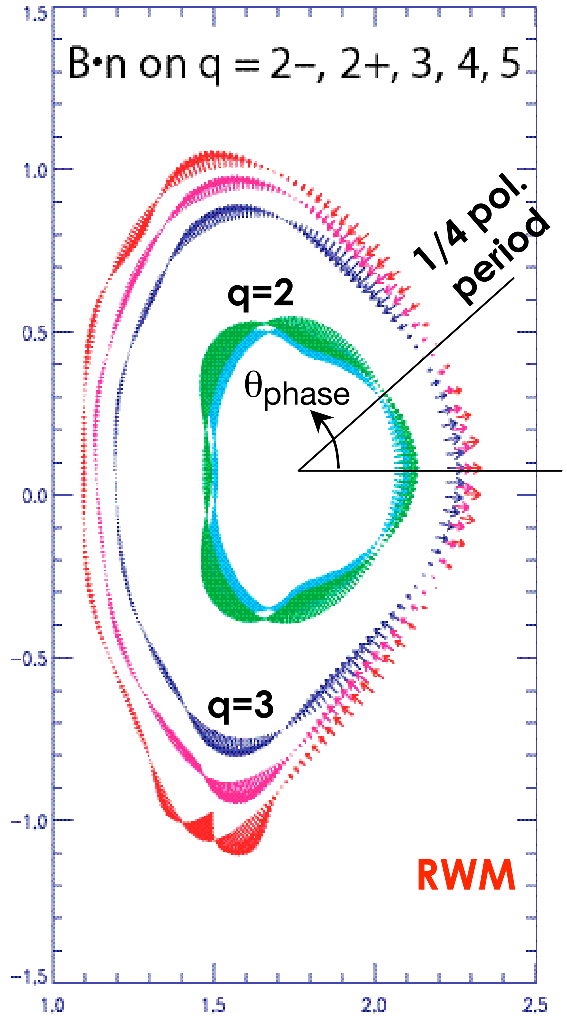
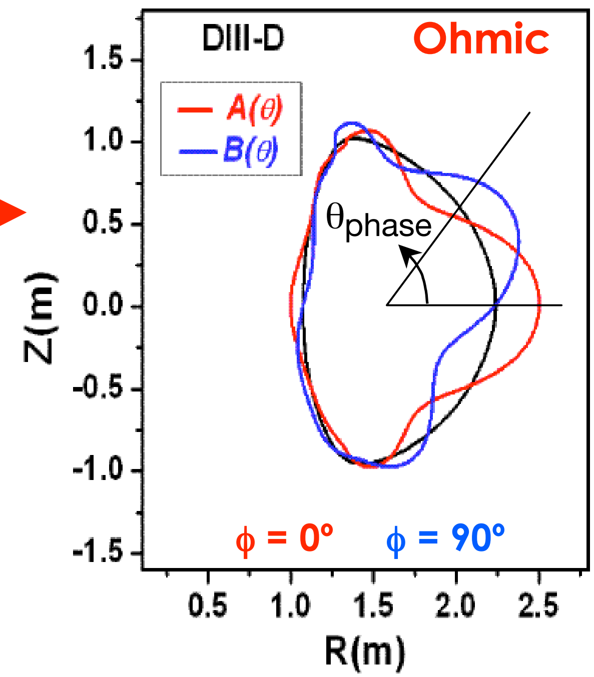


Figure courtesy of
M. Okabayashi and J. Manickam

B · n of m/n = 2/1 RWM mode (q_{95} ~ 5)

B · n of 1st ideal mode at edge of Ohmic test plasma (q_{95} ~ 3.5)

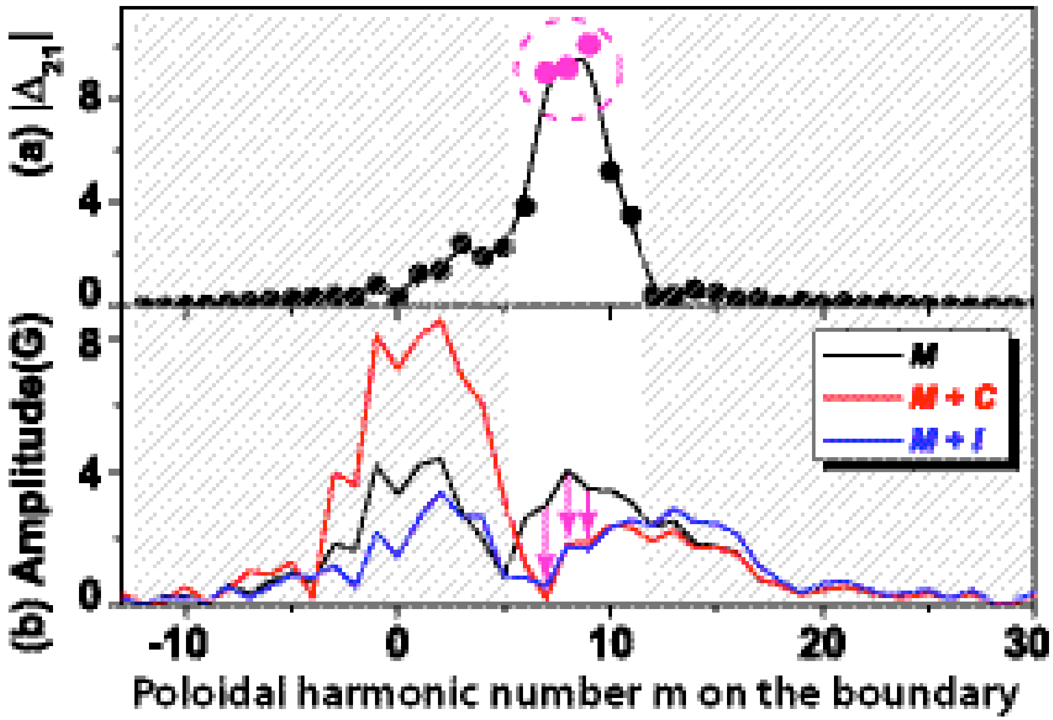


- On outboard side of A ≈ 3 tokamaks, ideal kink poloidal/toroidal phase advance is ~ half the local magnetic line pitch:

$$\frac{d\theta_{phase}}{d\phi_{toroidal}} = 0.5 \sim 0.7 \qquad \frac{d\theta_{B\text{-line}}}{d\phi_{toroidal}} = 1 \sim 1.4$$

- I-coil with 240° top-bottom difference matches kink phase well, and it avoids locking better, too!

Edge δB harmonics m = 7, 8, 9 couple most strongly to 2/1 resonance at q = 2



a) Higher-m edge harmonics 7,8,9 couple most strongly to m/n = 2/1 resonance at q=2
   - $\delta B_{2/1}|_{q=2} \sim \Delta_{2/1}$

b) On boundary, empirical corrections M+I and M+C reduce TOTAL $\delta B_{m/1}$ from machine M levels, for $6 \le m \le 10$
   - M+C increases low-|m| boundary harmonics
   - Enough non-resonant braking to explain why C-coil is less effective than I-coil at locked mode avoidance?

Sign of m was inverted in this figure in order to decrease and/or increase reader confusion.

Jong-kyu Park et al, PRL, 2007 Nov 9

DIII-D NATIONAL FUSION FACILITY

The ideal perturbed plasma equilibrium model fits many features of DIII–D error correction experience

- m ~ 2q is very suggestive of ideal MHD n=1 external kink
  - Stable in most tokamak plasmas, but not by much
- Ideal Perturbed Equilibrium Code IPEC calculations* of plasma responses to external error and correction fields show:
  - Small external perturbation drives large internal plasma response. Makes large helical currents on low-rational surfaces*
    (new result; large, cannot ignore)
    (corrections *designed* to null resonant *vacuum* errors *WILL* fail)
  - Dominant equilibrium mode is insensitive to perturbation geometry*
    (new result, response rigidity)
    - Combined error + perturbation responds almost like a single mode (seen in locked mode experiments everywhere)
    - Response depends on coupling of external field to plasma mode (Consistent with I-coil coupling well, C-coil poorly)
  - Non-resonant m ~ 2q perturbations couple best to non-resonant dominant plasma mode
    (consistent with DIII–D empirical corrections)

*Jong-kyu Park et al, PRL (2007 Nov 9)

SUMMARY

- DIII–D magnetic errors are well characterized
- TF coil bus modification reduced DIII–D error
- I-coil correction was developed — better than C-coil
- Demonstrated local correction at a local error
- Correction of a right handed plasma by I-coil @ Δ=180° was not very effective
  - Consistent with Ideal MHD Perturbed Equilibrium theory
- Common feature of all good correction in DIII–D is reduced error in $m \sim 2q$ part of $n = 1$, B_r poloidal harmonic spectrum
- Comparison of DIII–D data with Ideal MHD Perturbed Equilibrium theory computed by IPEC code yields good qualitative and semiquantitative agreement
  - In my opinion, this is paradigm-changing progress