Understanding Magnetic Field Error Correction in DIII-D

by

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with

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DIII-D Magnet Coils

- **E-Coil** (Electric Field Induction Coil)
- **2 x 6 I-Coils** (Internal Coils)
- **6 C-Coils** ("Correction Coils")
- **18 F-Coils** (Poloidal Field Coils)
- **B-Coil (24 bundles)** (Toroidal Field Coil)
Motivation & Key Points

• Error $\delta B \rightarrow$ makes weakly non-axisymmetric stable equilibrium
  $\rightarrow$ brakes plasma rotation $\rightarrow$ weakens screening currents
  $\rightarrow$ $\delta B$ penetration $\rightarrow$ island $\rightarrow$ loss of nested magnetic surfaces
• Compounded by plasma amplification of $\delta B$

• **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 $\rightarrow$ 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 $\delta B$ is mainly from coupling external $\delta B$ to this mode
  • Not an amplification of external vacuum field
• **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**
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

<table>
<thead>
<tr>
<th>TF-coil Feed Status</th>
<th>Density at Lock Onset (10^{19} \text{ m}^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uncorrected DIII–D Error</td>
</tr>
<tr>
<td>≤ 2005</td>
<td>1.2</td>
</tr>
<tr>
<td>2006</td>
<td>0.85</td>
</tr>
</tbody>
</table>

*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 $\leq 2005$ to $\geq 2006$

- $\delta B_r(-2/1) = 1.19 \times 10^{-4}$ at $q=2$
- $\delta B_r$ field is “chiral” (left and right handed harmonics not equal)
- Pitch resonance is in an error valley, especially at $q = 2, 3$
- $\delta B_r$ is now weaker at $|m| \geq 2$
Empirical correction by I-coil in ≥ 2006 dramatically reduces the vacuum field errors

- $\delta B_{r(-2/1)} = 0.29 \times 10^{-4}$ at $q=2$
- $\delta B_r$ is reduced everywhere by I-coil, except $m = -1$ at $q = 1$
- $\delta B_{r(-2/1)} = 0.70 \times 10^{-4}$ 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 $m \sim 2nq$
- 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]
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 $\delta B$ from wider-than-specified inter-bundle gaps

- Three $\delta B_\phi$ peaks are close to:
  - wider TF coil inter-bundle gaps at 15°, 90°, 270°
  - Gap excesses $\approx 4, 6, 6$ mm

- Narrow peaks; resolve $n = 1$–4
  - $B_{n=1} \sim 1.3 \times 10^{-4}$ at $R_o = 1.7$ m
  - $B_{n=2} \sim 1.5 \times 10^{-4}$ at $\ldots$

- $B_{n=1}$ is much smaller than $\sim 5 \times 10^{-4}$ “unknown error” implied by large C-coil empirical correction field

- Effects of higher-$n$ errors not yet known
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 \( \text{ERROR} \sim \text{DENSITY} \) at lock onset.
  - Verified in several tokamaks.
- Upper null avoids Ohmic H-mode in shots with downward ion \( \nabla B \) drift.

![Test Plasma](image)

**Density Rampdowns to Lock**
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 error
  - 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

- 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

- Intrinsic $n=1$ error spectral peak in right-handed plasma is resonant, $\approx 1.5 \times 10^{-4}$ at $q = 2, 3, 4$
  - Unlike left-handed plasmas, where resonant $n=1$ harmonics are $< 0.5 \times 10^{-4}$
Empirical correction of RIGHT-HANDED plasmas optimized quite differently than predicted

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

Although empirical I-coil field was aligned with $q$, plasma “wanted” only 0.77 kA peak, vs. 1.22 “predicted”
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 $\sim 0.5 \times 10^{-4}$
- 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 $\delta B$ associate with Good/Bad locking avoidance

- Locking density is monotonic with TOTAL $\delta B \cdot n$ for varied cases
- Naively designed correction fields achieved small vacuum $\delta B \cdot n$, but they overdrove the plasma mode to the extreme
- Machine vacuum error $\delta B \cdot n$ are small, but amplified ~5 times.
- Total $\delta B \cdot n$ of machine + C-coil correction $\leq$ total machine error
- Total $\delta B \cdot n$ of machine + I-coil correction $<<$ total machine error

Low locking density means better lock avoidance

\[ \text{total } b = \delta B \text{ including plasma response} \]
\[ M = \text{machine intrinsic error} \]
\[ M+C = \text{error + C-coil empirical correction} \]
\[ M+I = \text{error + I-coil """"} \]
\[ M+\text{small } 21 = \text{error + designed for small vacuum 2/1} \]

Jong-kyu Park et al, PRL, 2007 Nov 9
The Ideal MHD n=1 external kink generates many poloidal harmonics inside plasma

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

Figures courtesy of M. Okabayashi and J. Manickam
Ideal n=1 mode has a characteristic geometry on outboard side. Mode phase NOT resonant with B lines.

- **B \cdot n of m/n = 2/1**
  - **RWM mode (q_{95} \sim 5)**

- **B \cdot n of 1st ideal mode at edge of Ohmic test plasma (q_{95} \sim 3.5)**

  - On outboard side of A \approx 3 tokamaks, ideal kink poloidal/toroidal phase advance is \sim half the local magnetic line pitch:
    \[
    \frac{d\theta_{phase}}{d\phi_{toroidal}} = 0.5 \sim 0.7 \\
    \frac{d\theta_{B-line}}{d\phi_{toroidal}} = 1 \sim 1.4
    \]

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

Figure courtesy of M. Okabayashi and J. Manickam
Edge $\delta B$ 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 $q = 2$

- $\delta B_{2/1} \mid q=2 \sim \Delta_{2/1}$

(b) On boundary, empirical corrections $M+I$ and $M+C$ reduce TOTAL $\delta B_{m/1}$ from machine M levels, for $6 \leq m \leq 10$

- $M+C$ 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
The ideal perturbed plasma equilibrium model fits many features of DIII-D error correction experience

- \(m \sim 2q\) 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 \(m \sim 2q\) 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 @ \( \Delta = 180^\circ \) 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