Empirical Error Field Correction: Not Just Cancelling 1 or 2 Resonant Harmonic Components

by

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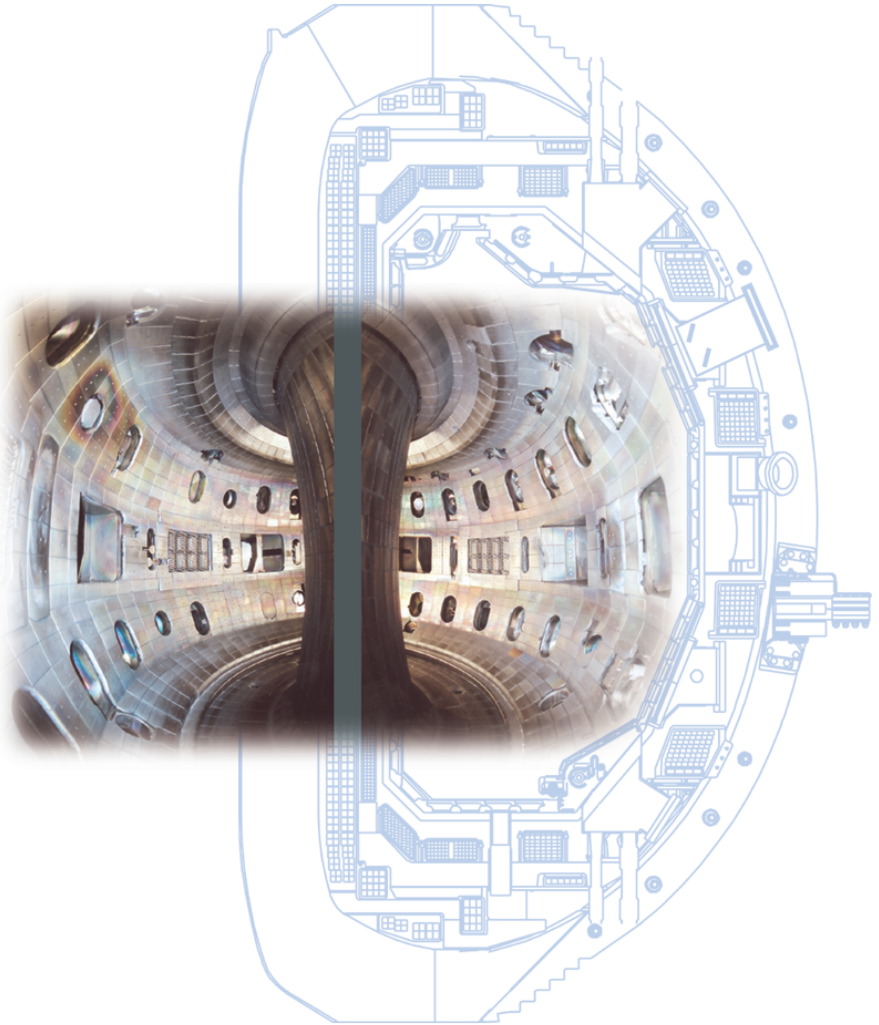

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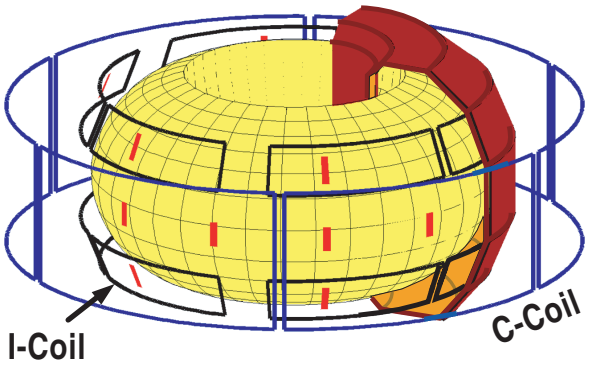
BACKGROUND and MOTIVATION

- Tokamak magnetic error correction is usually discussed in terms of cancelling just one pitch-resonant Fourier harmonic and maybe its two nearest sidebands.
- DIII–D C-Coil empirical "error correction" algorithm used routinely since 1994
  - It helps DIII–D avoid most Locked Mode problems
  - But empirical C-Coil field ~3 times larger than pitch-resonant n=1 error
    - DIII–D intrinsic magnetic error remeasured in 2001, is known[1]
- New I-Coil installed for Resistive Wall Mode feedback stabilization in 2003
- Some indications that I-Coil empirical "correction" ≈ negative of error (2003)[2]
- Experiments were performed in 2004 to investigate geometry effects of externally applied magnetic perturbation fields
  - Results presented and discussed in this poster
    - Geometry is very important
    - Non-resonant Fourier harmonics are important

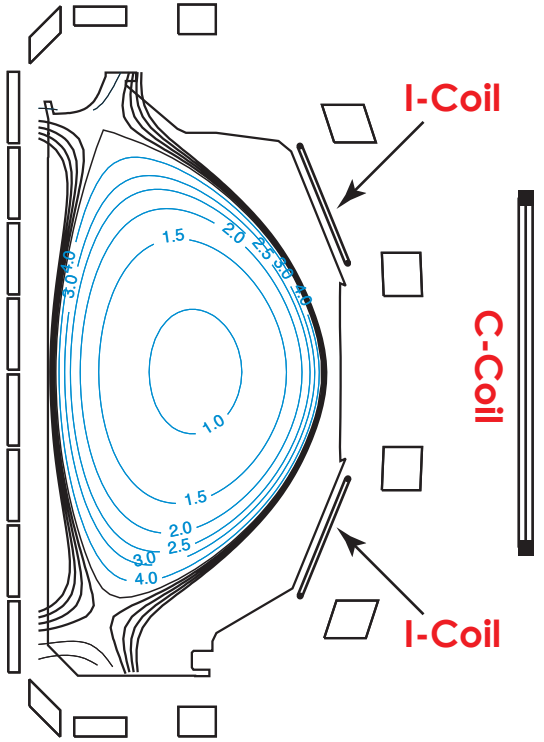


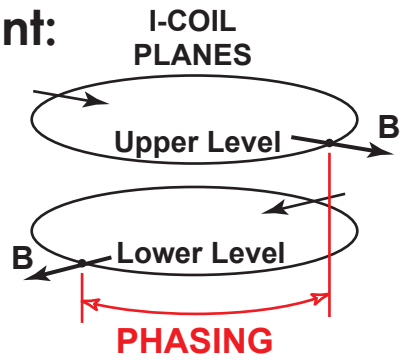
[1]Luxon et al., NF *43* (2003) 1813. [2]Schaffer et al., APS/DPP QP1.035 (2003).

Two Experiments:

1. Resonant Error Cancellation
2. Correction Geometry Scan

- Both experiments used Ohmic, low density, weakly rotating plasmas
  - reproducibly sensitive to Locked Mode onset as density is lowered
    or magnetic perturbations are increased.
  - Double-null diverted, 1.0 tesla, q_{95} ≈ 3.4
  - I-Coil + C-Coil apply prescribed
    test and correction perturbations.
  - Only n=1 toroidal mode studied here.
- Resonant Error Cancellation Experiment:
  - Apply a pre-calculated correction field,
    then reduce density to find Locked Mode.
- Correction Geometry Scan Experiment:
  - At constant density, ramp per-
    turbation to find Locked Mode.
  - Used I-Coil only, varied phasing
    between top and bottom halves.





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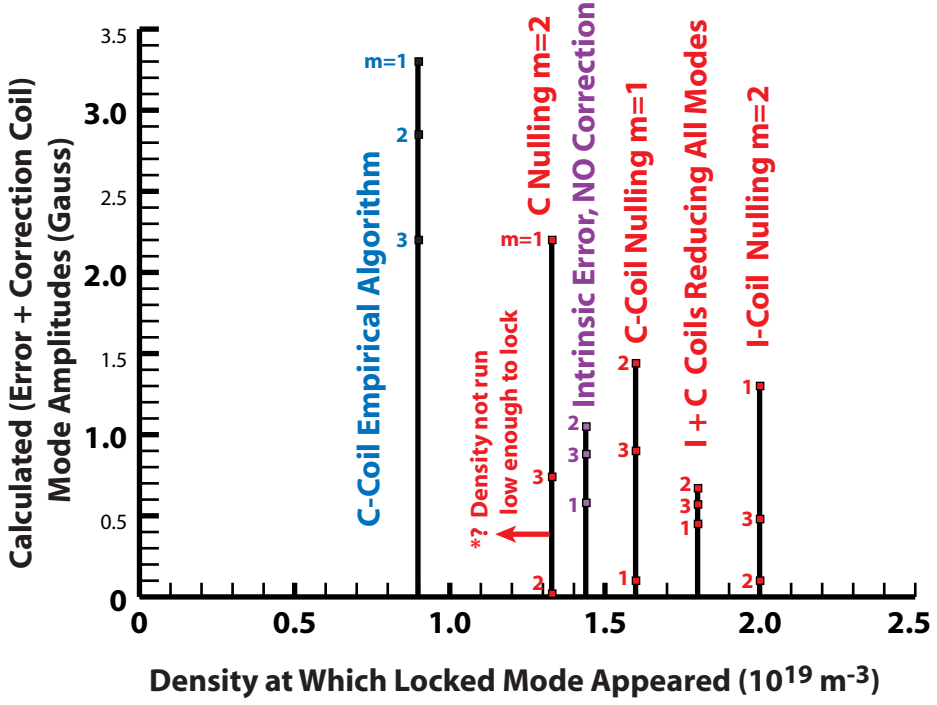
ERROR CANCELLATION: Locked Mode Avoidance Is NOT Achieved Just by Resonant Error Cancellation

Tested Applied Fields: Density at Time of Locked Mode and Mode Amplitudes



- DIII-D empirical C-Coil correction algorithm performs best, even though its low rational components are ~3 times larger than the known B-error.
- C-Coil nulling of m=2 resonant mode is next best (but not fully tested).
- I-Coil nulling same m=2 mode is worst.
- Nulling m=1 mode by the C-Coil, or reducing "all" m(=1, 2, 3) resonant modes together perform between the above extremes.
- NO correction at all is better than 3 out of 4 targeted corrections tested.

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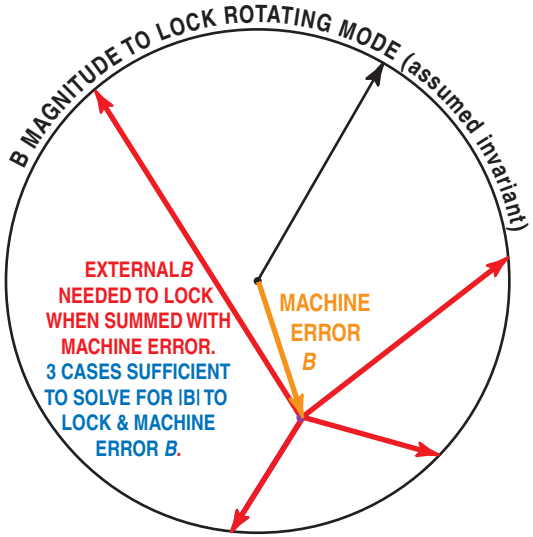
GEOMETRY SCAN: Apparent |B|-to-Lock and Resonant Error Field Vary Widely with Geometry. ⇒ No Single Sensitive Mode.



Assuming that the B magnitude-to-lock is unvarying, one can calculate the |B|-to-lock and the intrinsic B error magnitude and direction from 3 shots in which the external B is applied with differing toroidal phases.

The model holds only if a single Fourier harmonic e.g., m/n = 2/1, of the error and the external perturbation add to trigger locked mode. Otherwise, the resultant fields are not unique and depend on perturbing geometry.

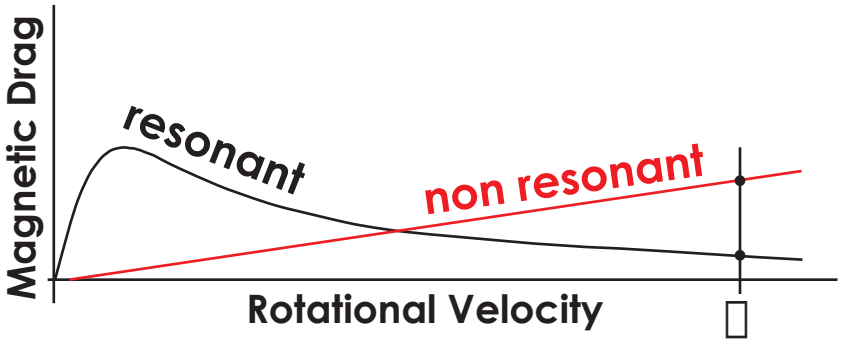
Single resonant mode (here m/n=2/1 at q=2 surface) locking magnitude & deduced error differ widely. Similarly for 1/1 and 3/1 modes on respective q surfaces. Therefore, there is no single responsible mode.

case →	I-Coil 300° phasing	I-Coil 240° phasing	I-Coil 180° phasing	I-Coil 120° phasing	I-Coil 60° phasing	I-Coil 0° phasing	Known DIII-D Error
|B| to Lock	1.05 G	2.11 G	2.98 G	4.5 G	6.9 G	1.3 G	n.a.
deduced Berror	0.61 G 54°	1.14 G 62°	1.58 G 58°	2.6 G 63°	3.5 G 49°	0.36 G 235°	1.19 G 61°

NON-RESONANT DRAG

CONJECTURE: NON-RESONANT Magnetic Perturbations May Be Important in Plasma Braking and Mode Locking

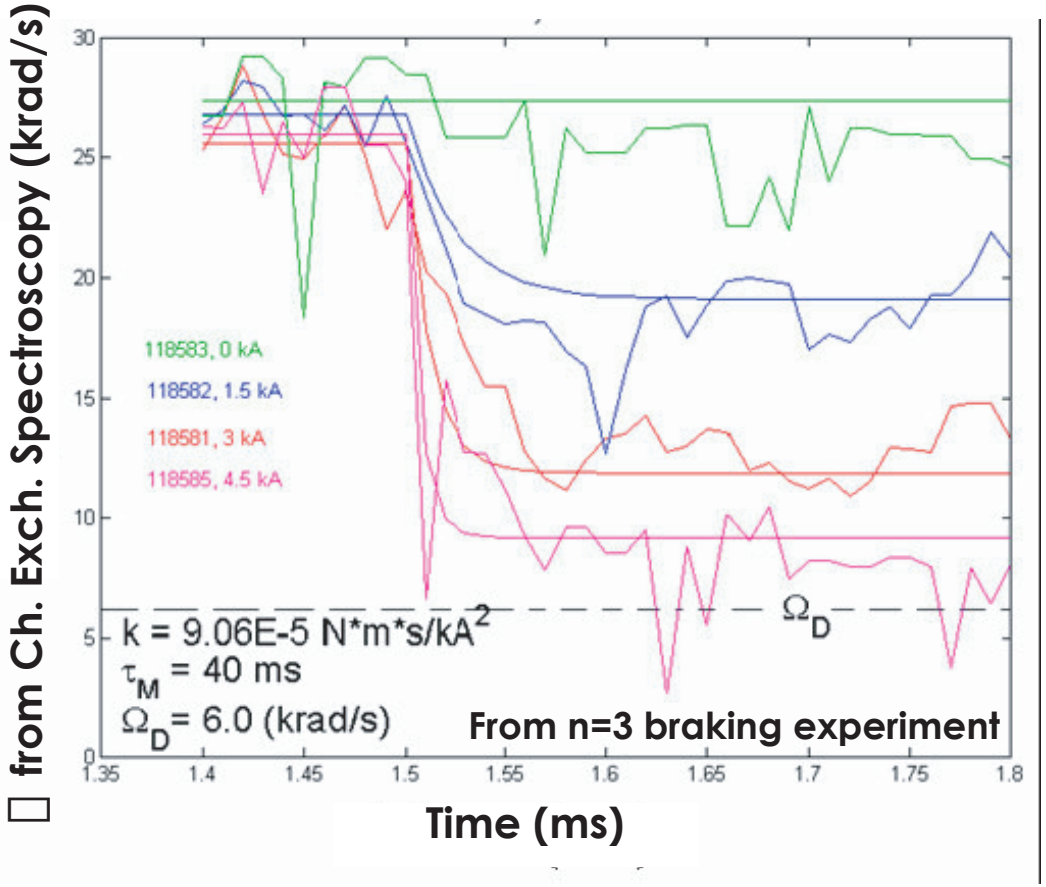
- Plasma starts in rotating state, so magnetic drag < driving torque.
- Rotating plasma shields resonant fields ($B_r \approx 0$ at resonance surface).
  - Resonant drag acts mainly in neighborhood of resonant surface.
  - Drag depends on pitch-resonant δB_r.
  - Peaks at low speed, decreases at high speed.
- Non-resonant fields not shielded.
  - Its drag acts throughout plasma volume.
  - Depends on δB_r and δB_{tor}.
  - Increases approximately linearly with speed.



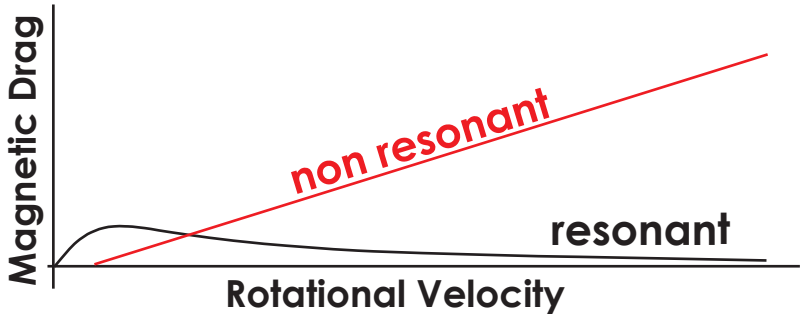
- The "Slippery Slope" to a Locked Mode can START with non-resonant drag, even though Locking eventually depends on a large resonant drag at end.
- Experimental "Locked Mode Scaling" with δB and n_e DEPENDS ON INITIAL DRAG. IT WILL NOT DEPEND ON JUST $\delta B_{resonant}$.

I-Coil Braking of NBI-Driven Plasma Rotation in DIII–D Exhibits NON-Resonant Scaling

Ion rotation decreases more rapidly as larger I-coil δB is applied shot by shot.

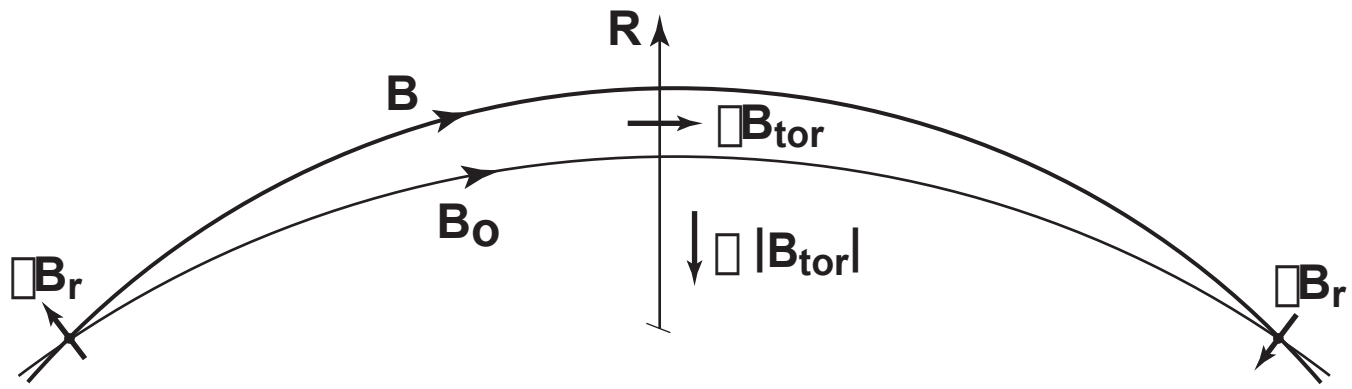


- Non-resonant torque scaling
  - Torque ~ k (ω – ω$_D$) δB^2
  - is observed in DIII-D plasmas.
  - ω(t) is fit by a single k and
  - ion drift frequency ω$_D$ for fixed
  - δB geometry and plasma.
- Resonant torque scales as
  - Torque ~ [c_1 ω + c_2/ω]$^{-1}$



See SA Driskill, Poster GP1.00040

δB_r and δB_{tor} Both Contribute to $\delta|B|$ and Non-Resonant Drag Around a Toroidal Drift Surface



δB_r bends a magnetic line in and out (out shown here).

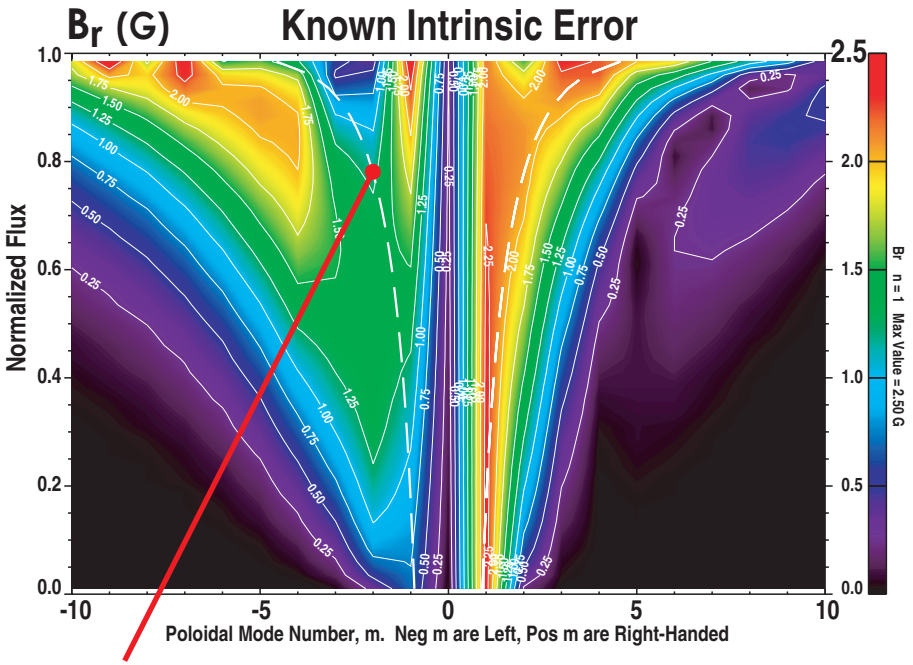
Helically perturbed surface displaced across gradient of background B_o.

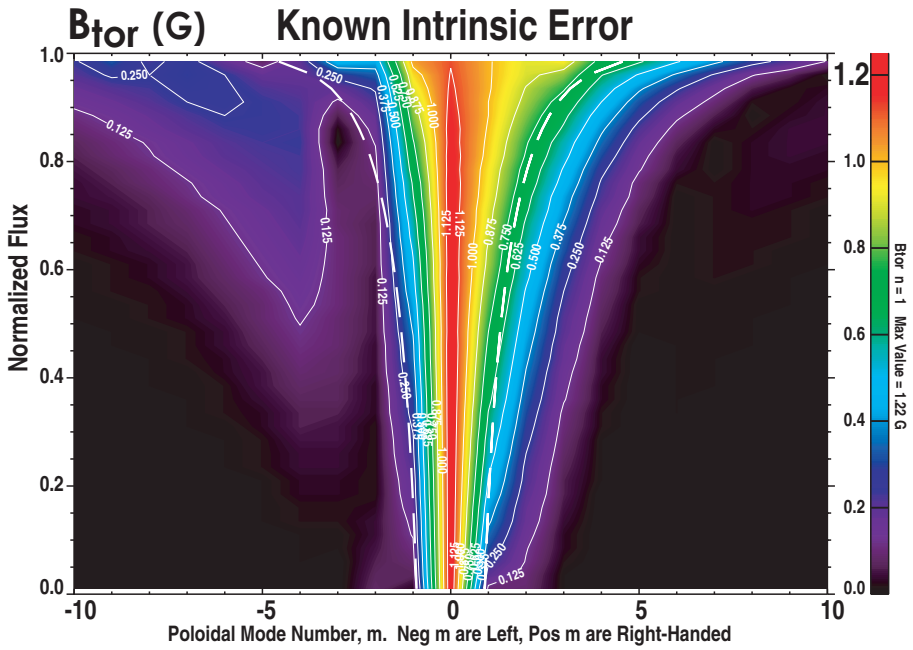
$B = B_o + (\delta B)(\delta B_r) + \delta B_{tor}$

Toroidally drifting particles encounter modulated field $\Rightarrow$ DRAG.

Look for correlations between δB_r, δB_{tor}, and experimental locking.

Non-Resonant Fourier Components Are Abundantly Present in Poloidal Spectrum of DIII–D Intrinsic Magnetic Error Field





m,n = –2,1 Resonance, 1.2 G
Surf. Avg. δB_r points out at equator 50–60

Pitch Resonance lies in Error Field Valley, relatively small $\delta B_{resonant}$

Poloidal/Toroidal mode numbers are **m/n**, respectively

All spectra in this poster are for toroidal mode **n=1 only**

White dash lines show possible pitch resonance, |m/n| = q(□):

- Read q(□) from bottom "poloidal mode number" axis
- Experimental plasmas had **LEFT Handed** magnetic line pitch
- Pitch-resonance corresponds to **negative** m
- Right-handed q(□) curve guides eye to equivalent positive m

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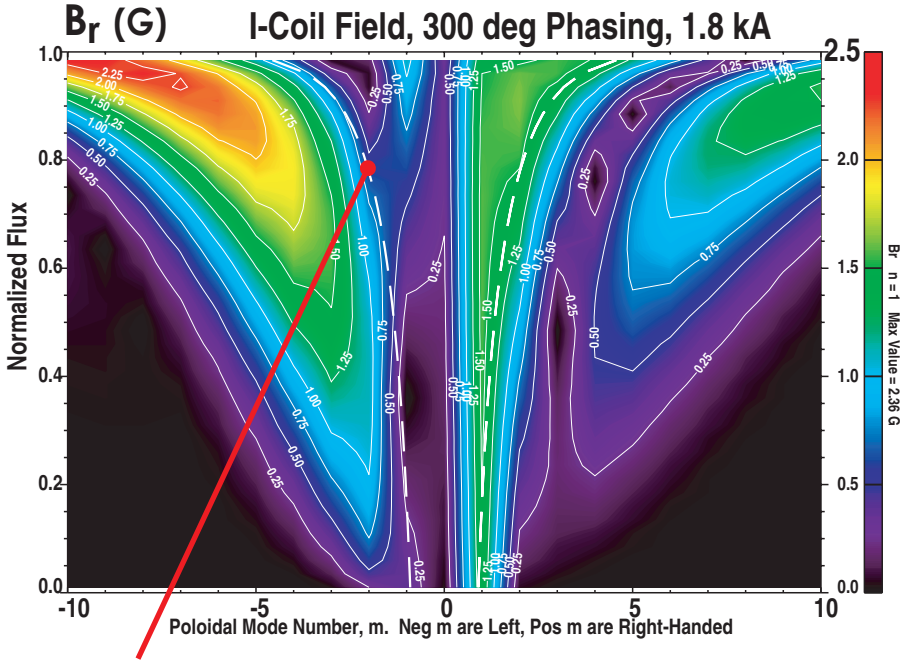
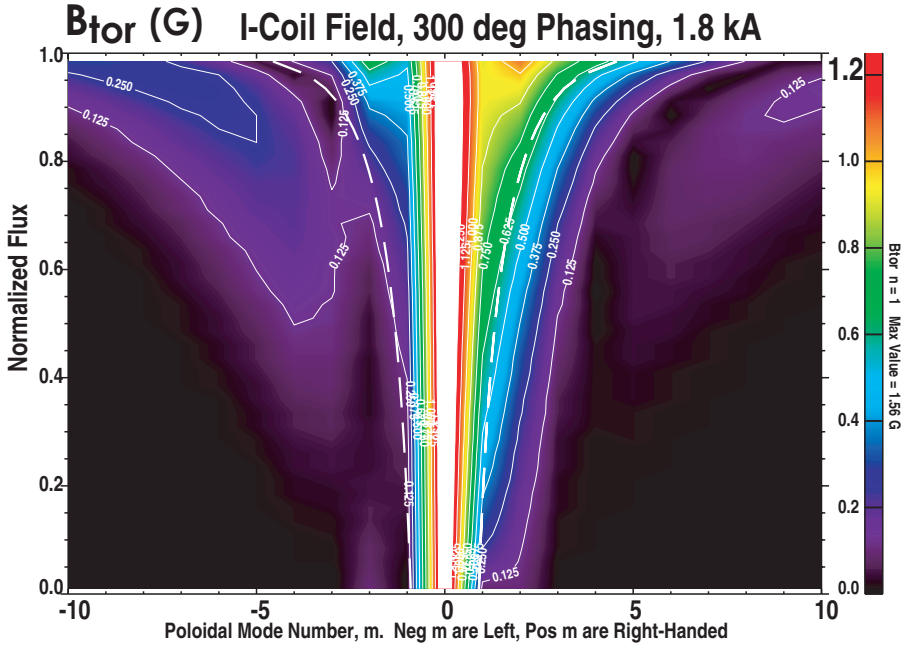
ERROR-LIKE □B GEOMETRY

Best Empirical Locked Mode Avoidance from I-Coil "Geometry Scan" at "300 Phasing" is 1.8 kA of n=1 Current





Pitch Resonance of m,n = (–2,1) at q = 2

- Empirical best avoidance derived from the 300 phasing part of the I-coil "Geometry Scan".
- Its poloidal mode spectrum roughly matches DIII–D Intrinsic Error spectrum.
- Toroidal B is mostly (m,n) = (0,1) Fourier harmonic at all radii.
- May be good example of "Nearly Complete" error correction.

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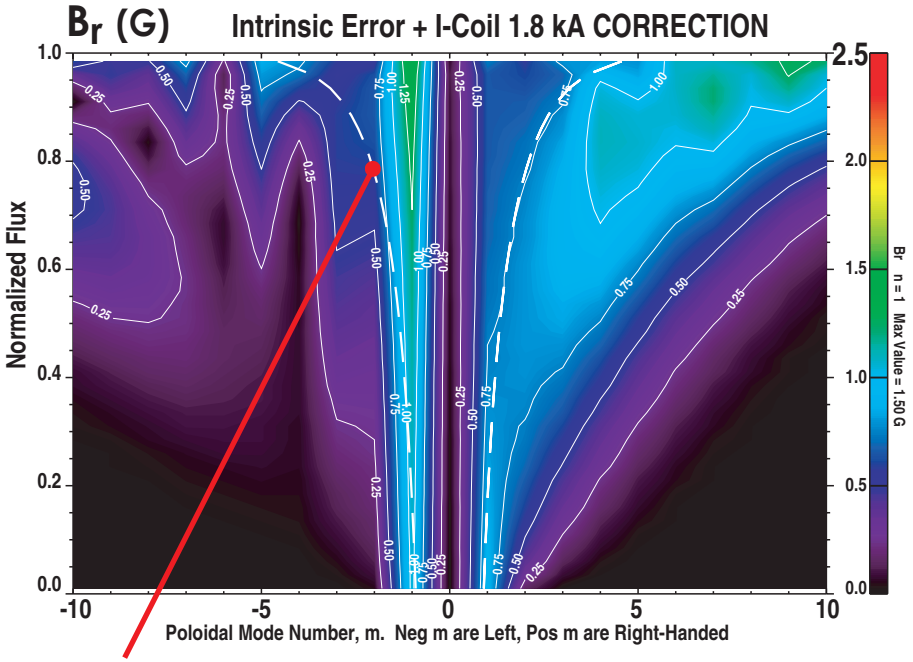
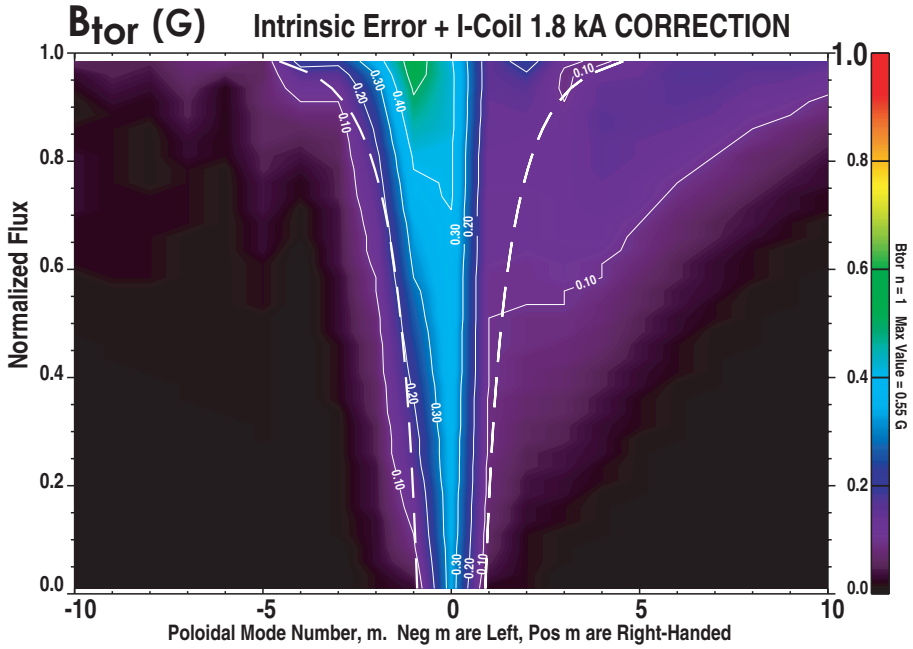
Remaining Non Axisymmetric B-Field after Empirical Correction by 1.8 kA "300 Phasing" I-Coil Field is SMALL





m,n = –2,1 Resonance 0.6 G

- Most B_r and all B_{tor} Fourier components reduced throughout all of plasma volume in these calculated spectra.
- I-Coil with 240 phasing yields more or less similar results.
- The "Geometry Scan" experiment did not include ramp downs to Locked Mode threshold.
  - Absolute Locked Mode performance is not yet known.

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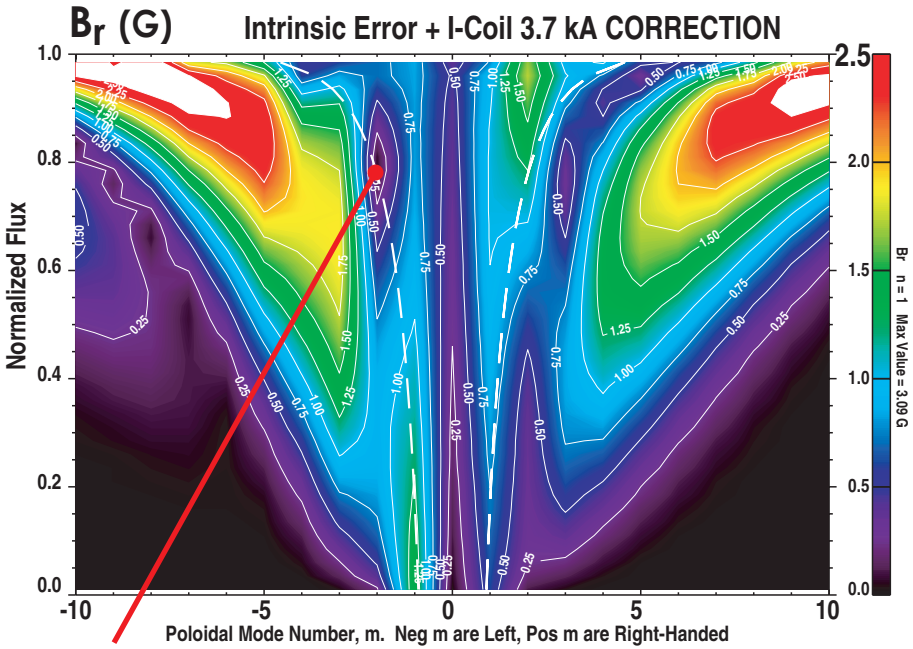
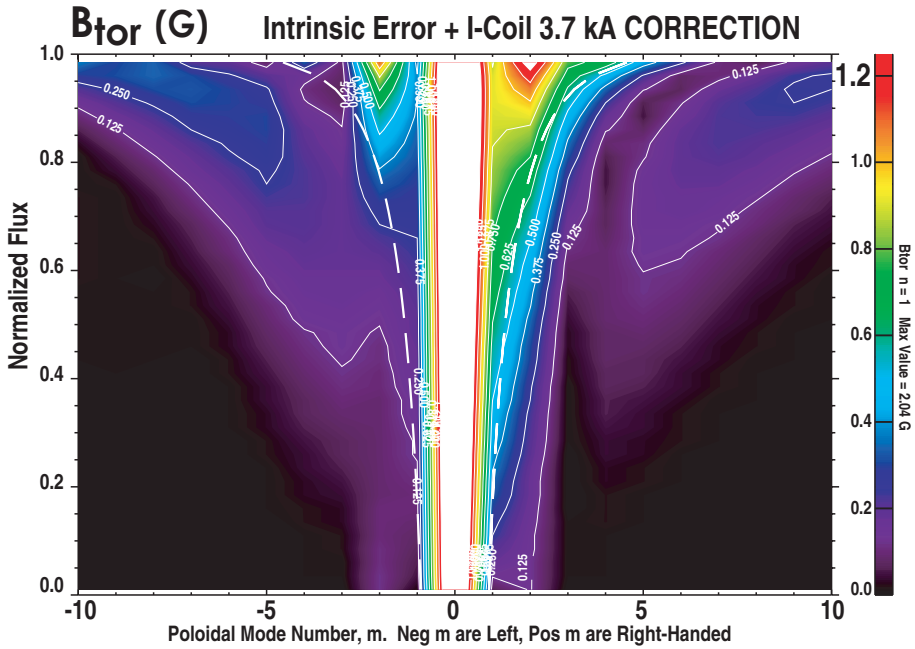
Also Used I-Coil with "300 Phasing" in the "Error Cancellation" Experiment to Null the δB_r m,n = (–2,1) Resonant Harmonic





B_r (–2,1) Null at q=2

- Pitch-resonant (-2,1) mode was 0 in this "Cancellation Experiment"
  yet it gave worst Locked Mode margin of all cases tested.
- Needed large I-coil current (3.7 kA) to make this null, thereby
  inadvertently applying increased non-resonant components.
- Result is consistent with non-resonant contribution to drag.

Lock onset is at $\bar{n}_e = 2.0 \times 10^{19}$ m^{-3}

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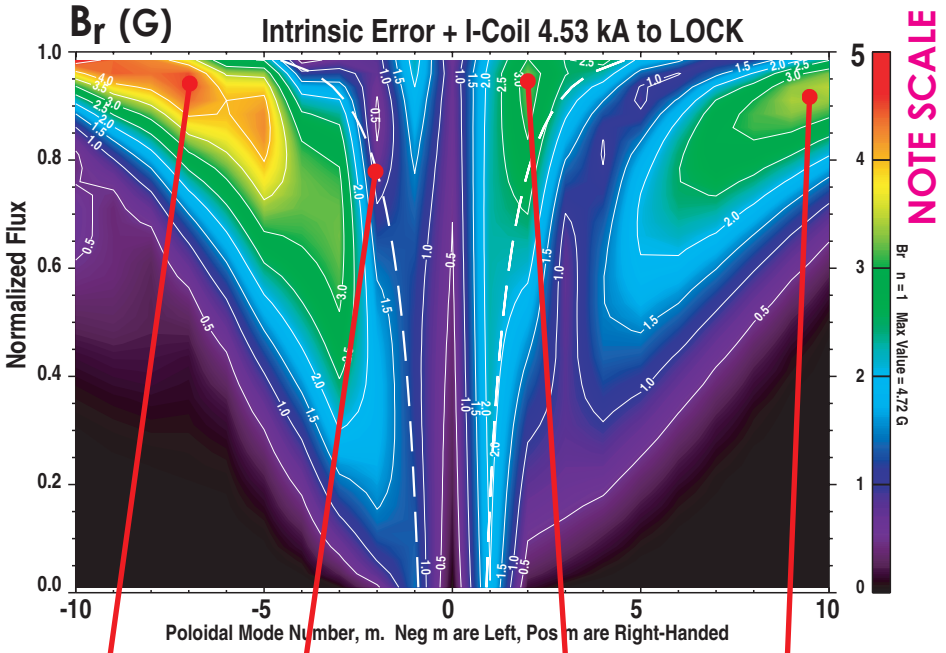
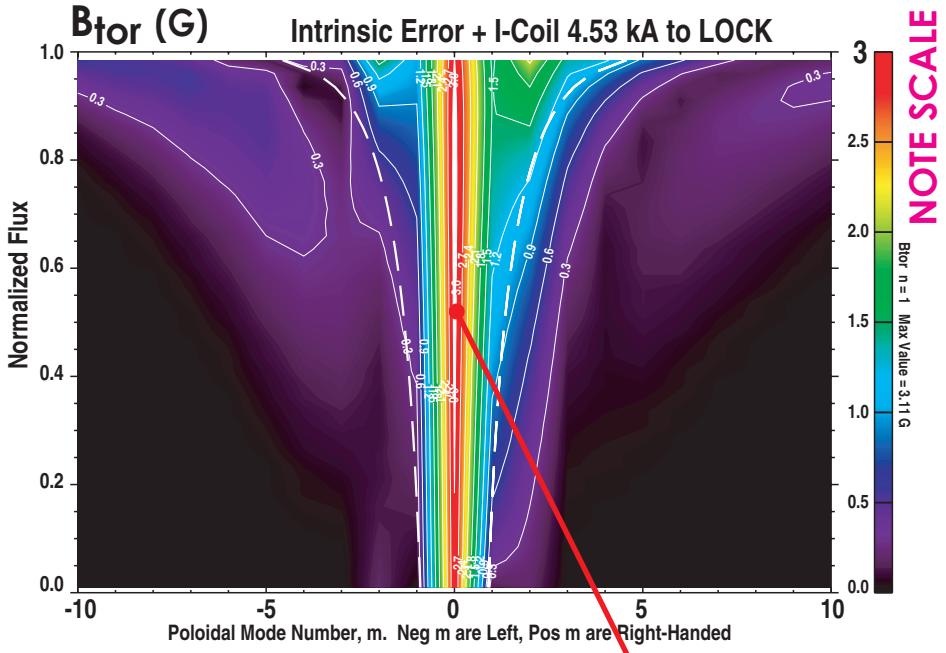
Total δB at LOCK Onset in "Geometry Scan" with Same "300 Phasing" Contains Large Non-Resonant Components





4.7 G

m,n = (–2,1) Resonance 0.8 G

3.2 G

3.4 G

3.1 G

- Pitch Resonant components at lock onset are SMALL.
- Non-Resonant components are LARGE.
- Data consistent with Non-Resonant contribution to drag.

$\bar{n}_e = 2.3 \times 10^{19}\ m^{-3}$

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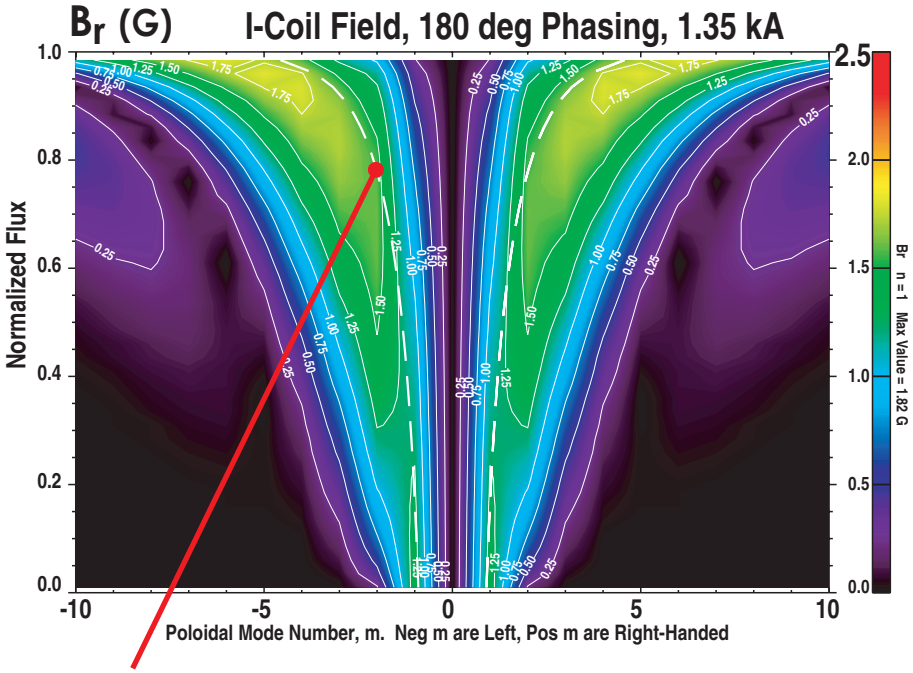
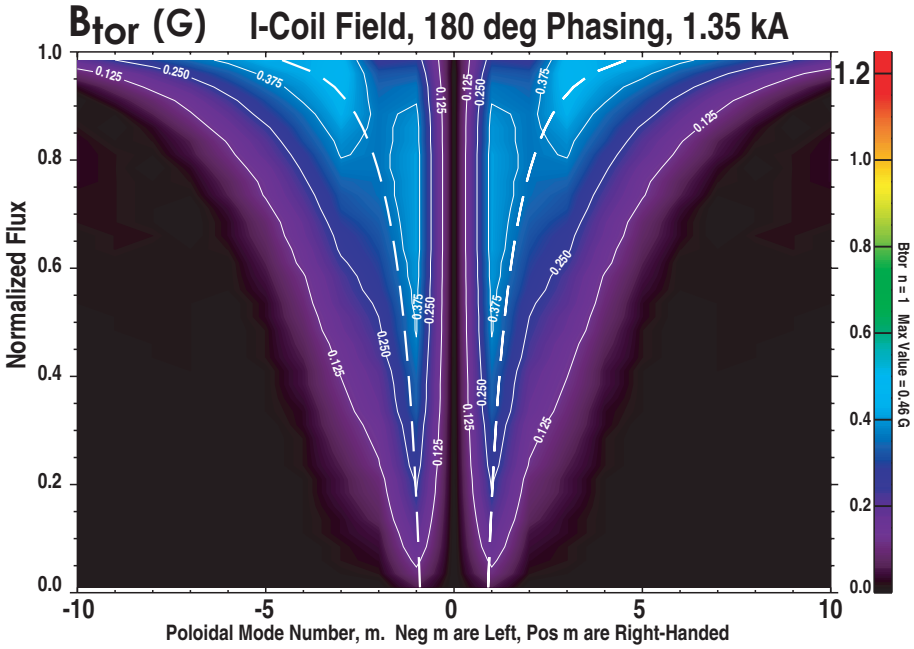
SMALL ∇B_{tor} GEOMETRY

I-Coil Toroidal B-Field with "180 Phasing" Is WEAK and Has NO m,n = (0,1) Fourier Component





m,n = (–2,1) Resonance

- Shown is empirically derived I-Coil best Locked Mode avoidance field from "Geometry Scan" with "180 Phasing".
- This case tests locking by B_r alone.
  - Mixed Resonant and Non-Resonant B_r Fourier harmonics.

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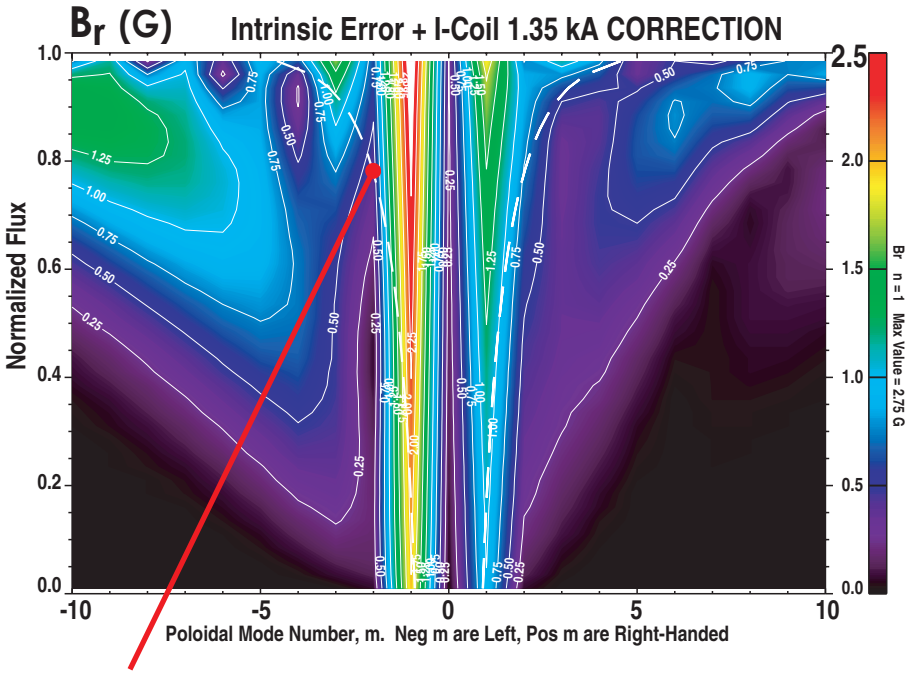
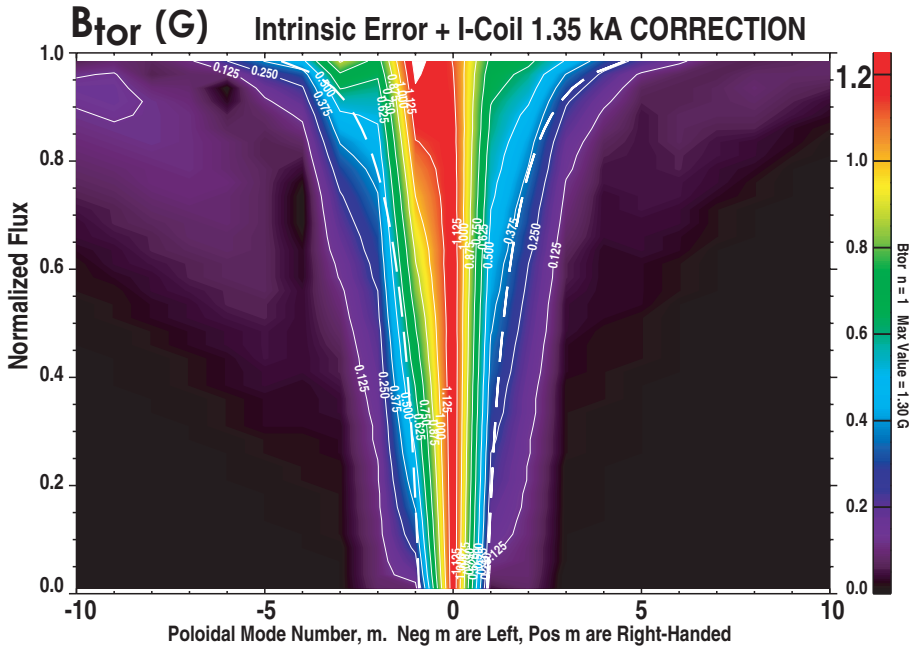
Remaining Non Axisymmetric B-Field with Empirical Correction by "180 Phasing" I-Coil Field is Mixed

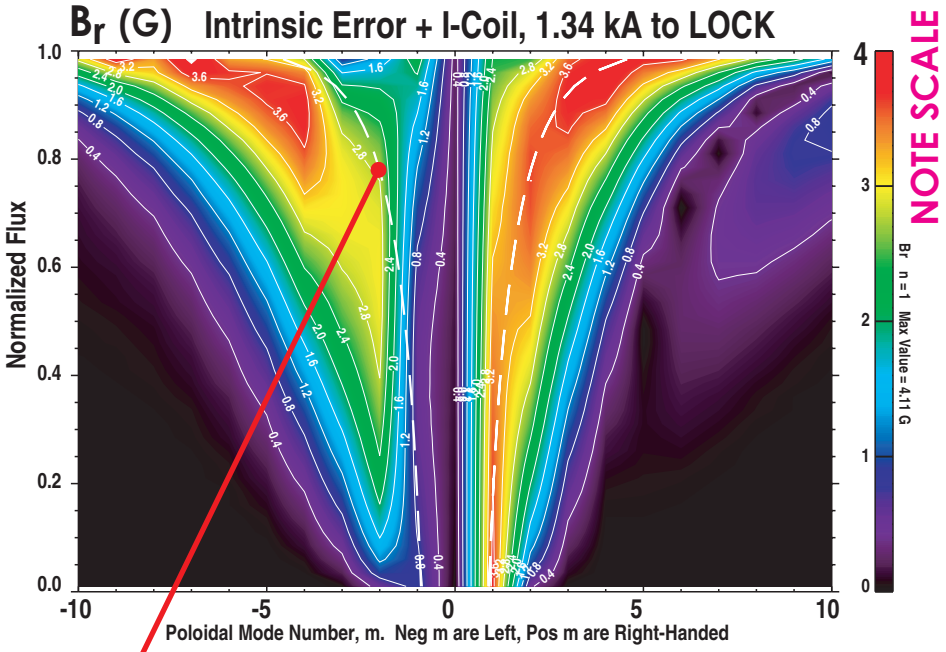


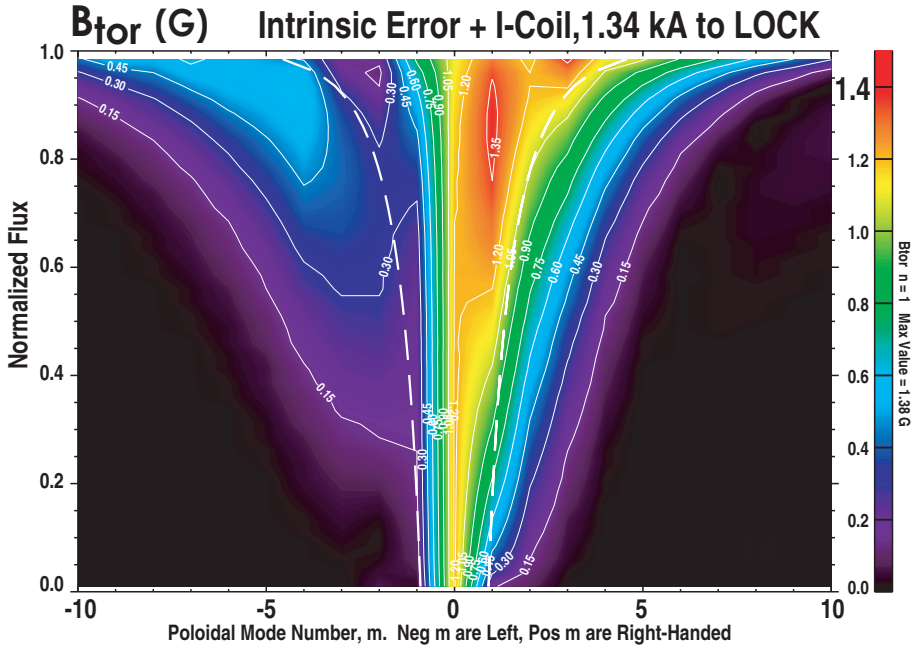


m,n = (–2,1) Resonance 0.4 G

- Most harmonics reduced or unchanged from intrinsic error, except:
  - B_r (-1,1) mode increased to 2.75 G and penetrates more
  - B_{tor} (-1,1) mode increased to 1.3 G, a small increase
- Absolute Locked Mode performance (density rampdown to lock) not yet done.

Total □B at LOCK Onset is Mostly RADIAL in "Geometry Scan" at "180 Phasing". NON-Resonant □B_r Drag May be Initiator.





m,n = (–2,1) Resonance 2.7 G

- □In this example, applied □B_r direction ADDED to intrinsic error.
- □□B_r has BOTH Non-Resonant (~4 G) + Resonant (2.7 G)
  - □–□Resonant □B_r may be shielded.
- □NON-Resonant □B_r larger, may have initiated the lock event.
- □□B_{tor} is mostly from the intrinsic error field.

$\bar{n}_e = 2.3 \times 10^{19}$ m^{-3}

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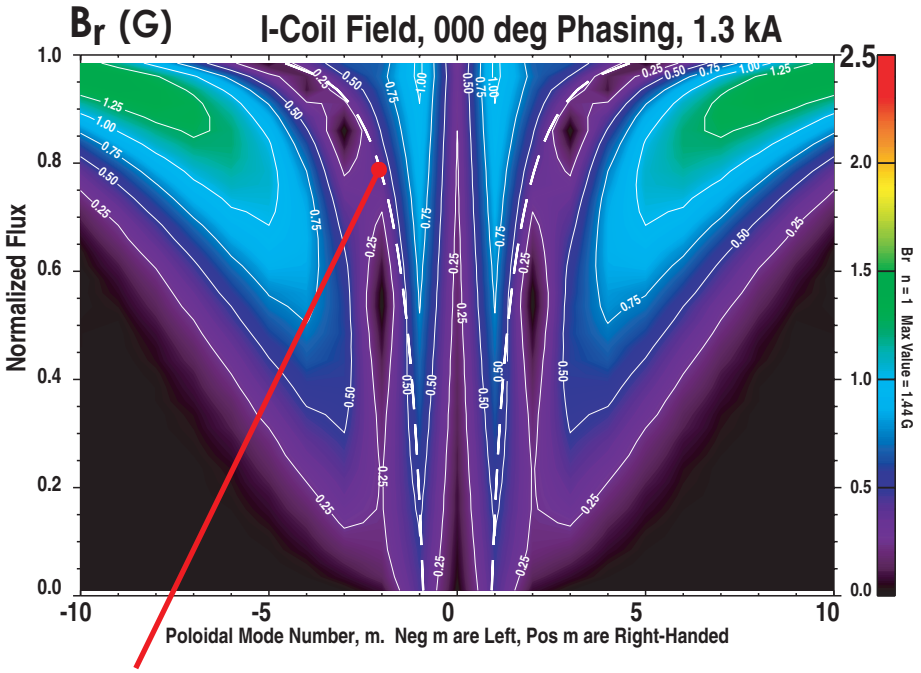
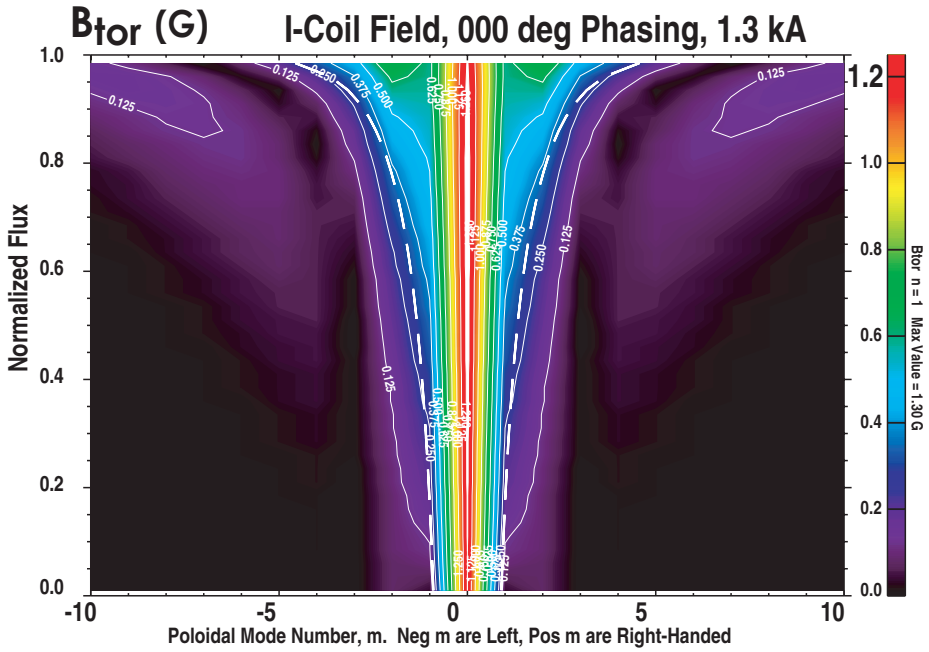
SMALL $\Delta B_{r,resonant}$ GEOMETRY

I-Coil Field with "0 Phasing" Has Small $\delta B_{r,resonant}$ and Approximately Equal δB_r and δB_{tor} Magnitudes

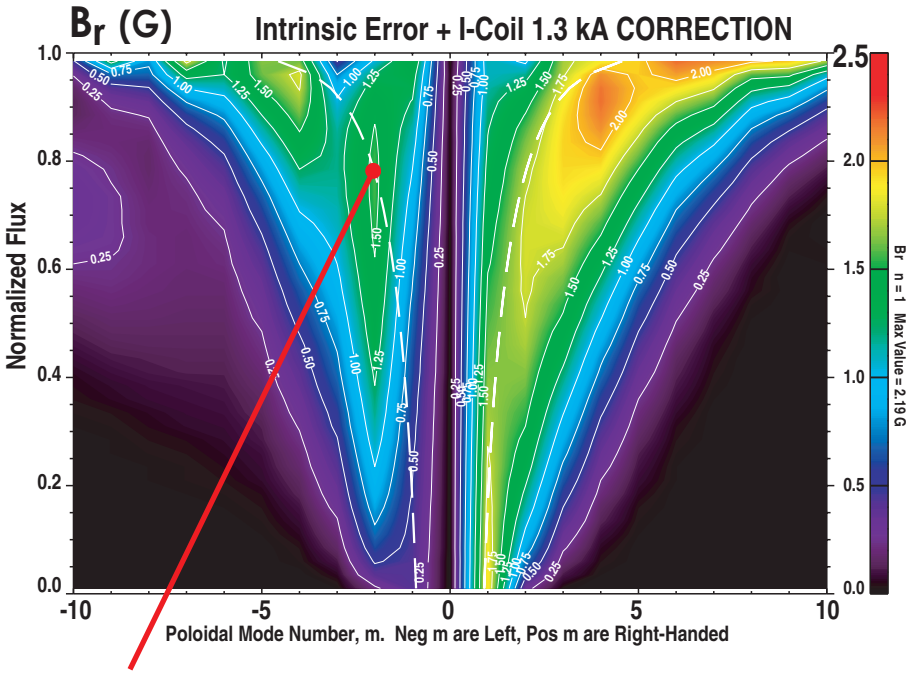


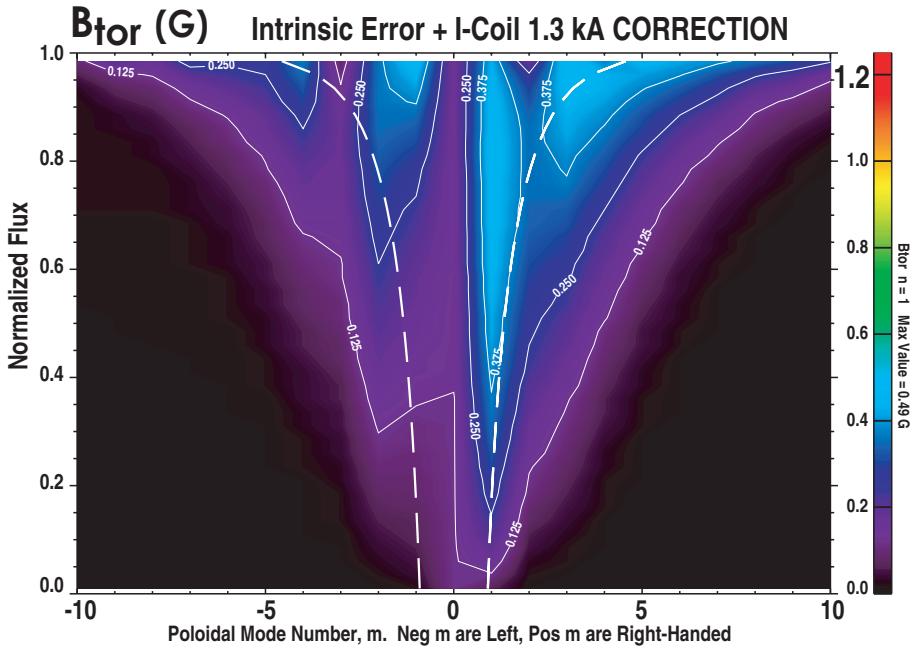


m,n = (–2,1) Resonance 0.4 G

- Shown is empirically derived I-Coil best Locked Mode avoidance field from "Geometry Scan" with "0 Phasing".
- Pitch resonance is along the edge of a δB_r valley.
  - This case tests locking with weak resonant δB_r.

Remaining Non Axisymmetric TOROIDAL □B with Empirical Correction by "0 Phasing" I-Coil Field is SMALL, but □B_r is Not





m,n = (–2,1) Resonance 1.55 G

- Net radial field □B_r components mixed, some larger, some smaller.
  - □□$B_{r,resonant}$ increased some with this correction.
  - □Resonant correction and error phase (both 55) ADD here.
  - □ – Phases oppose for all other empirical corrections tested.
- Empirical lock avoidance made □$B_{toroidal}$ small instead.
- Absolute Locked Mode performance not yet known

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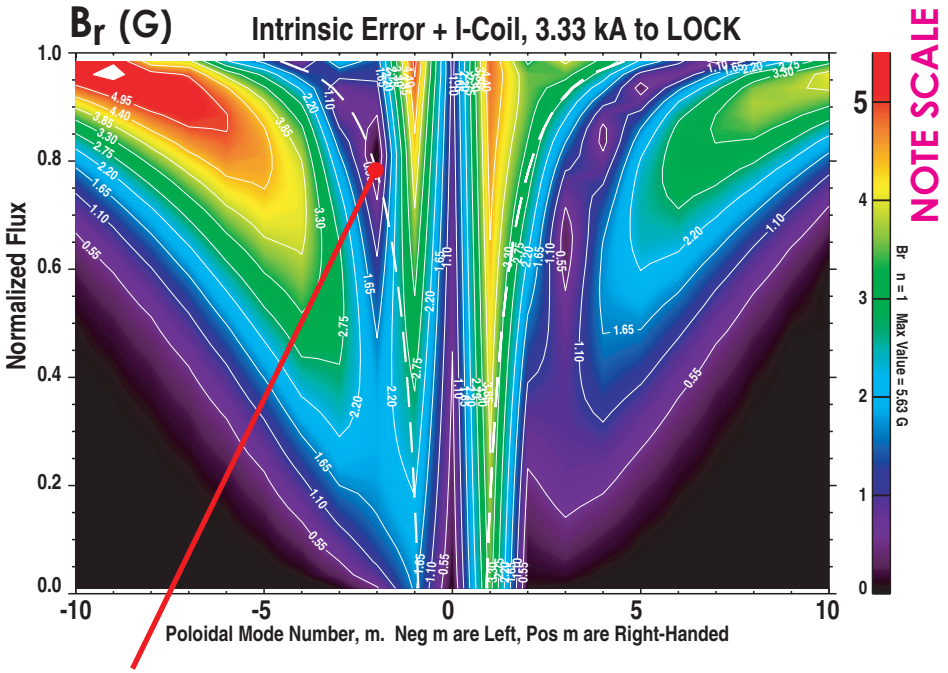
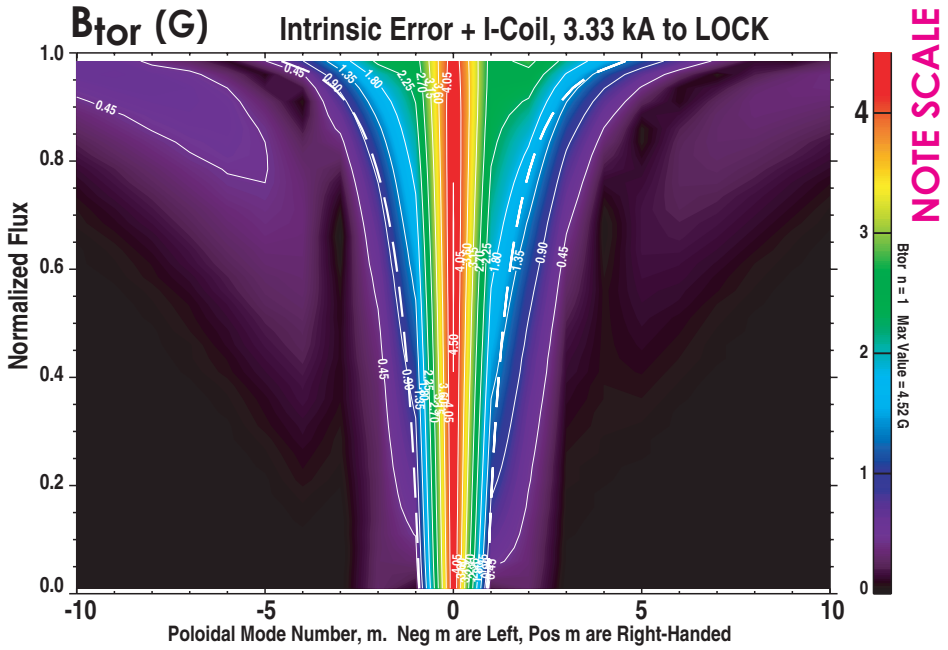
Resonant δB_r at LOCK Onset Is SMALL in "Geometry Scan" with "0 Phasing". Non-Resonant Harmonics are Large.





m,n = (–2,1) Resonance 0.3 G

- Pitch Resonant components at lock onset are SMALL.
- Non-Resonant components are LARGE.
- Data consistent with Non-Resonant contribution to drag.
- Applied resonant perturbation phase (240) here OPPOSES error phase (55), yet this I-Coil phase made Locked Mode with the least current of the "0 Phasing" tests.

$\bar{n}_e = 2.3 \times 10^{19}\ m^{-3}$

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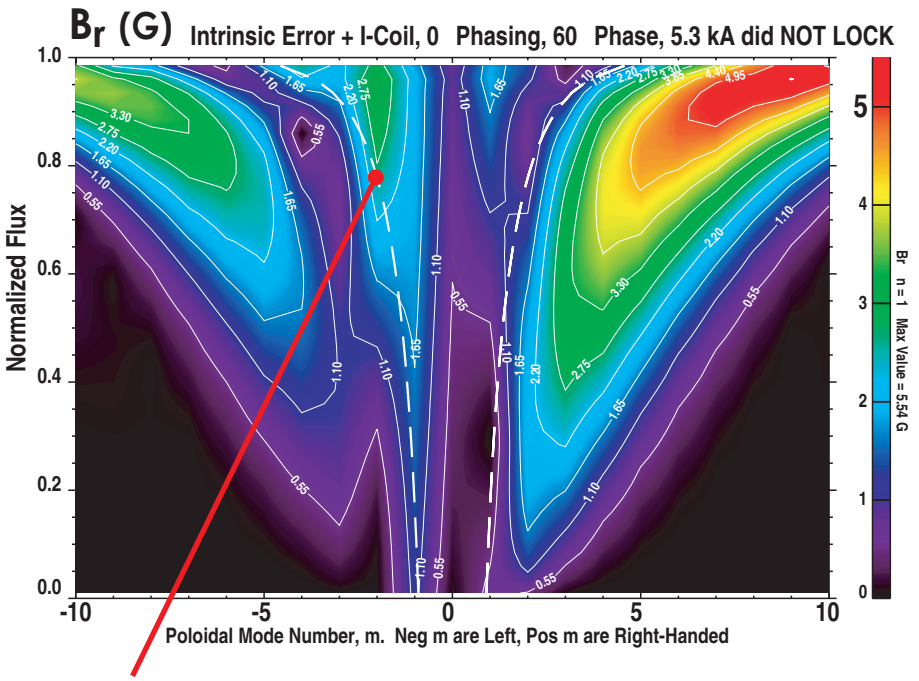
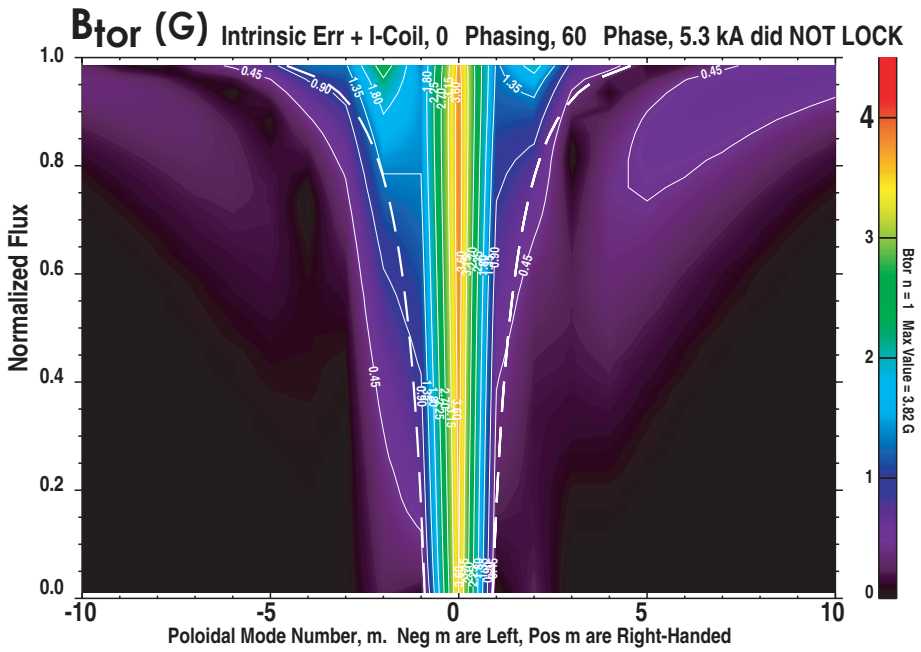
Maximum I-Coil Current (5.3 kA) Did NOT MAKE LOCKED MODE in "Geometry Scan" with "0 Phasing", Not Even at Lower n_e.





m,n = (–2,1) Resonance 2.7 G

- Total non axisymmetric field is large.
  - Resonant δB_r about double intrinsic error level.
  - Non-Resonant δB_r and δB_{tor} are both large.
- Does not fit into a simple explanation.

$\bar{n}_e = 1.5$ and 2.3×10^{19} m^{-3}

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DISCUSSION CONCLUSIONS RECOMMENDATIONS (1)

- Targeted "Error Cancellation" cases rule out just pitch-resonant δB components as the key to locked mode onset.
  - Resonant error cancellation not a viable strategy.
- "Geometry Scan" yields no necessary nor sufficient conditions for relative locked mode enhancement or postponement.
  - Postponement seen with generalized δB reduction, but also with mixes of reduced and increased δB components (some large).
  - Few absolute locking thresholds obtained; can't compare geometries.
- Locking is associated with at least one large harmonic in "Geometry Scan".
  - Even when $\delta B_{r,resonant}$ harmonics are small.
  - Nulling pitch-resonant harmonics does not guarentee lock avoidance.

DISCUSSION CONCLUSIONS RECOMMENDATIONS (2)

- We have no example where $\delta B_{r,resonant}$ dominates, to test resonant drag.
- Failure to lock with 0 phasing, 60 phase (even at 65% reduced density) despite large resonant and non-resonant components does not fit into a simple explanation.
  - Perhaps we need to understand weakly nonaxisymmetric drift surfaces and their torque on plasmas in detail.
- DIII–D TF-Coil's two current feeds contribute magnetic error.
  - Impulse-like: n = 1 and n > 1; Fourier spectrum goes to high |m| and |n|.
  - n > 1 components not affected by n = 1 correction fields.

DISCUSSION CONCLUSIONS RECOMMENDATIONS (3)

- Feed at 210 modified to accomodate reoriented neutral beam.
  - Also redesigned feed for low magnetic error, ~ 0.1 G on q=3 surface.
  - Feed at 30 unchanged for now.
  - DIII–D intrinsic error will be different starting in 2006.
    - Will develop new error correction algorithm.
- Need complete geometry scan data with density ramp-down.
  - New TF feed, have to do whole scan again for consistency.
- Change is an opportunity for new knowledge.
- MARS-F code now has DIII–D C- and I-Coil models.
  - To model, investigate interactions between plasma and external δB perturbations.
  - Has rotating plasma and viscous drag models.

SUMMARY

- Results of magnetic error correction and mode locking experiments using wide range of correcting field geometries are presented, discussed
  - Results not explained by just PITCH-RESONANT Fourier harmonics
- Propose braking by NON-RESONANT δB-field harmonics as an additional mechanism that can initiate plasma spin-down into lock
  - Non-Resonant braking effect is seen in unrelated DIII–D experiments
  - Due to δB variation along toroidal drift surface (theory)
  - δB_r and δB_{tor} may interfere, reinforce, cancel; complicated
- Showed examples of δB spectra for empirical correction and lock onset
  - CONSISTENT WITH NON-RESONANT δB HYPOTHESIS
- Data incomplete, theory incomplete; more work needed
- Magnetic error correction must include BOTH resonant and non-resonant components