Results from New Error Control Experiments in DIII-D

By M. Schaffer

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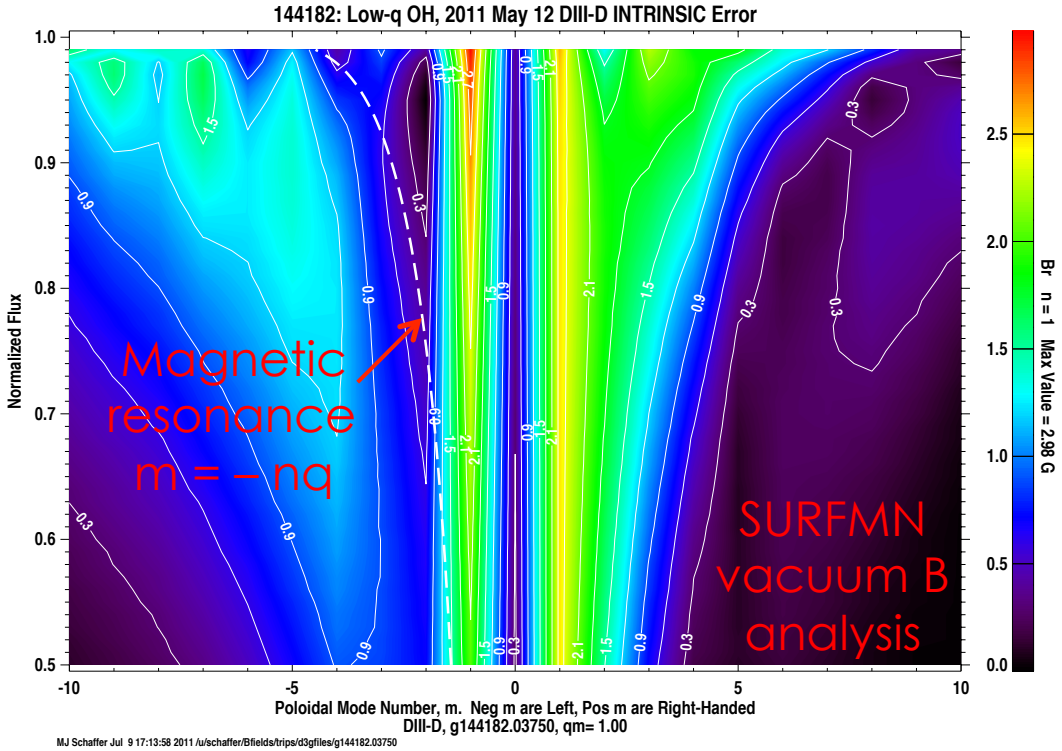
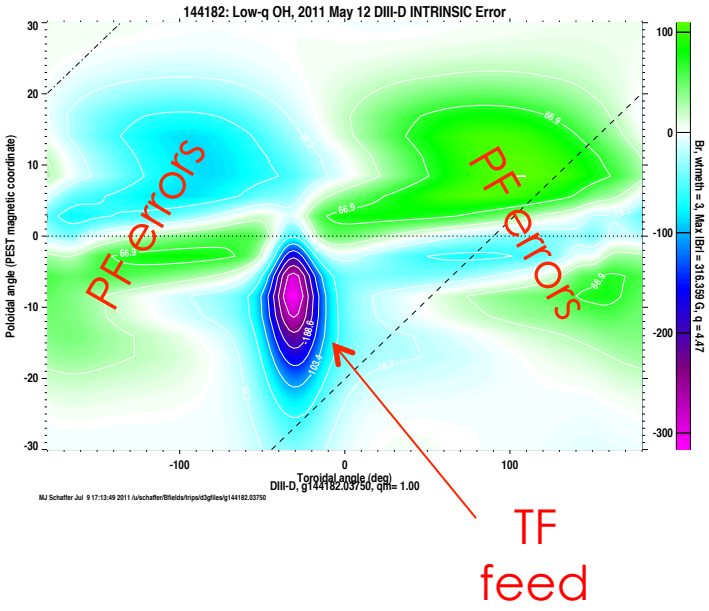
Preliminary results presented in this talk

- **Compensation of n=1 harmonics of a simple artificial (proxy) error**
- **Compensation of actual (complicated) DIII-D n=1 intrinsic error**
- **Measurement of low-n errors from DIII-D TF coil**

COMPENSATION OF A SIMPLE PROXY ERROR

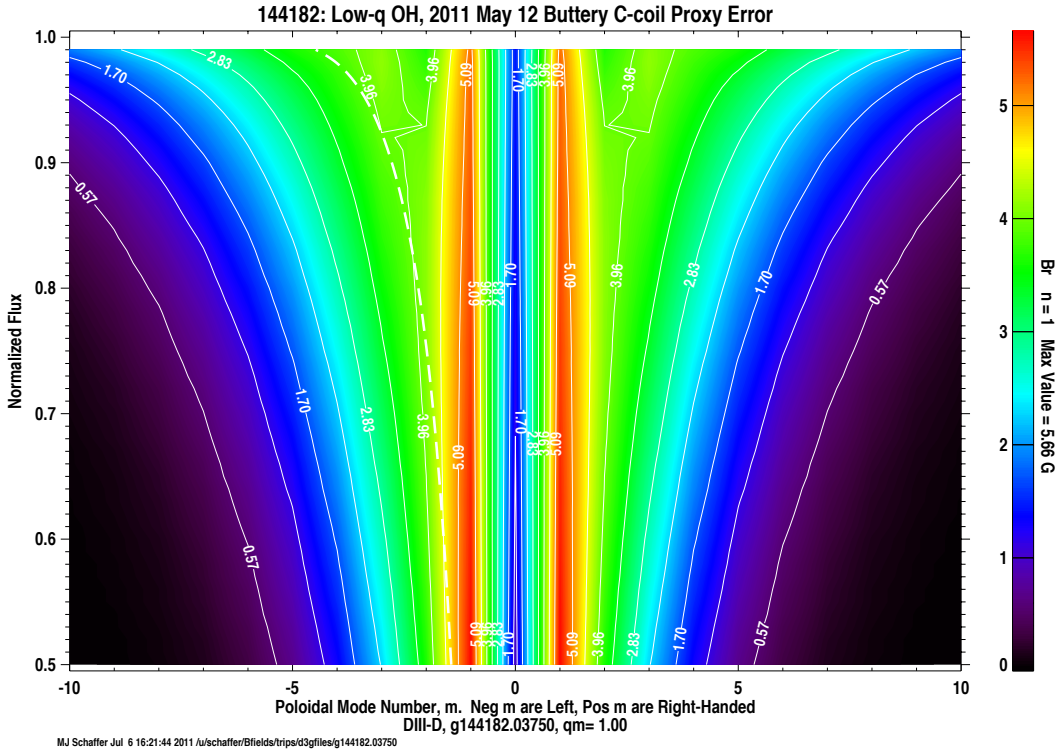
DIII-D Intrinsic Errors are generated mainly by PF-coil shifts and tilts and a TF-coil current feed

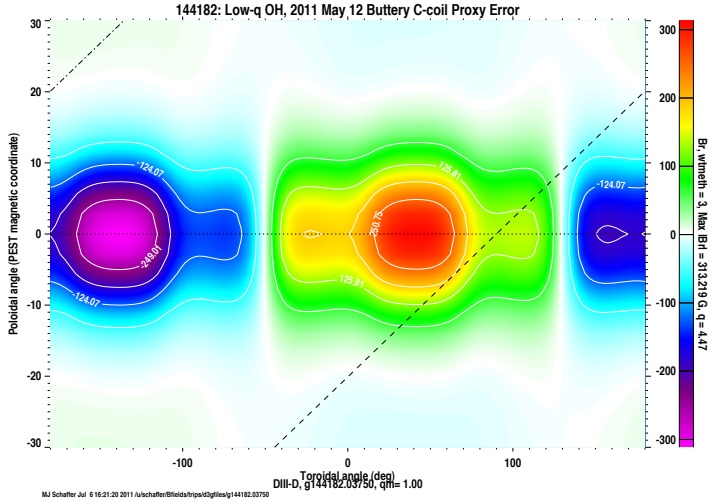




- **18 PF coils have dominantly n=1 error harmonics**
  - Many poloidal amplitudes and phases interfere, notably at high |m|
- **Localized TF error has many slowly decaying m, n harmonics**
  - This talk considers only n=1

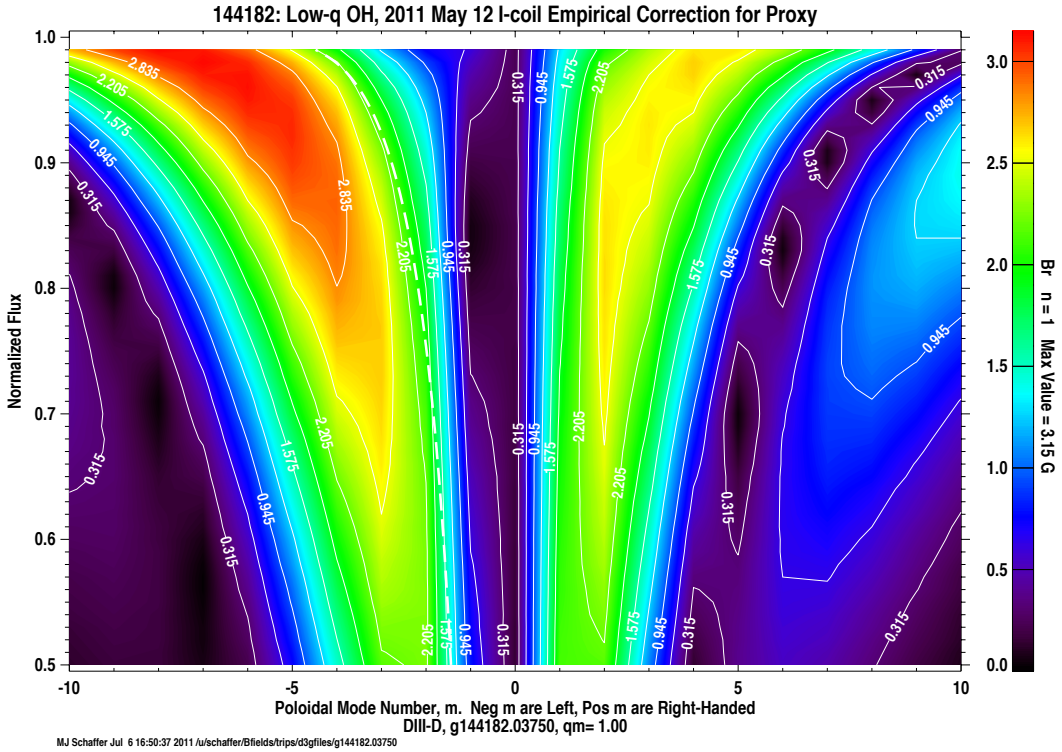
The DIII-D C-coil magnetic field is much simpler. Used it as an 'artificial' or 'proxy' error

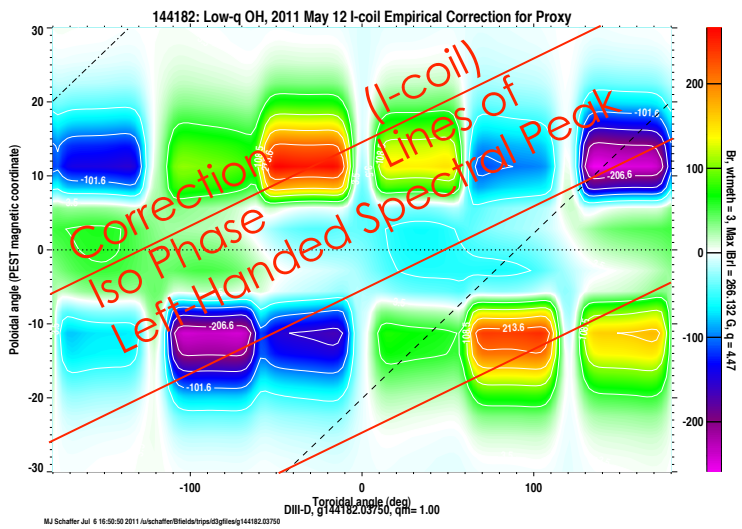




- **C-coil helical harmonics are concentrated at low m and n, and n=1 spectrum is mostly smooth**
  - Easier to study the physics of n=1 error compensation

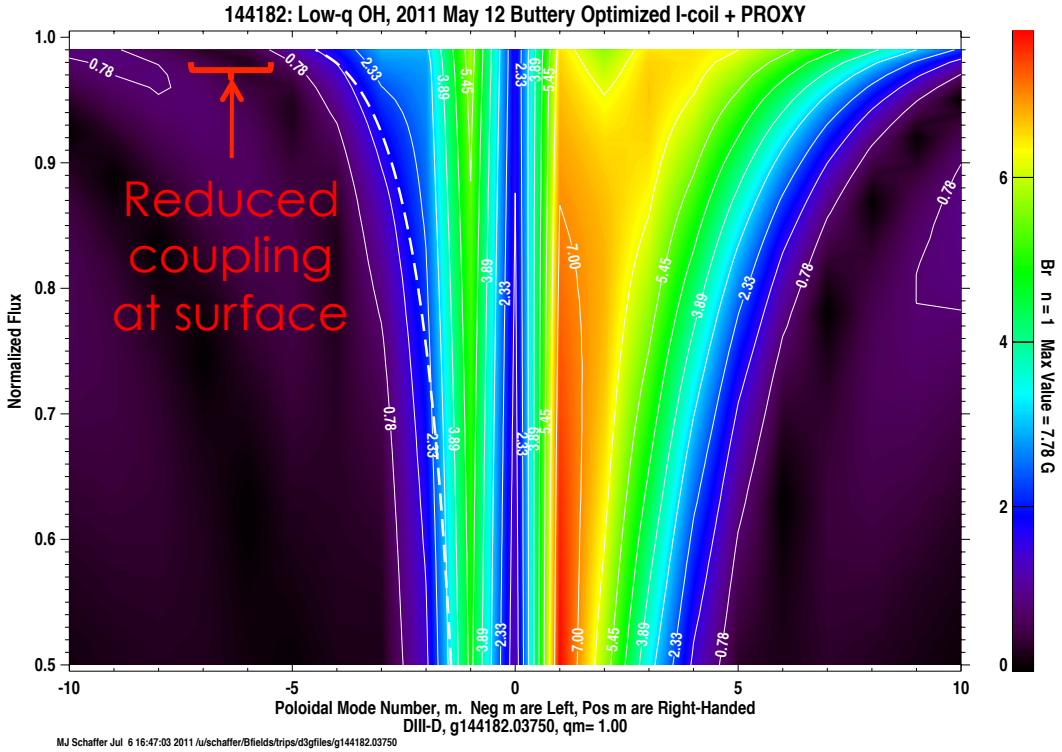
I-coil n=1 that compensated the C-coil proxy error

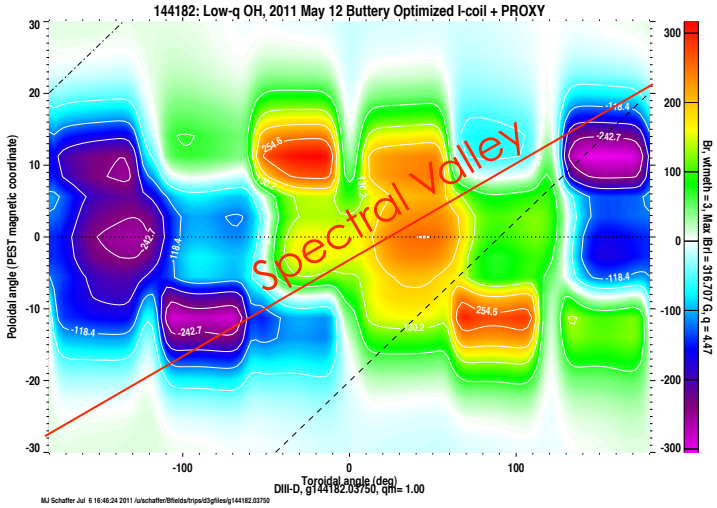




- **240° phase difference between the 6 upper and 6 lower I-coils yields a spectral peak to the high –|m| side of magnetic resonance (-m=nq)**
  - Also a 'smooth' spectrum

Consistent with the new paradigm, I-coil compensated the proxy error at the high –|m| side of resonance





$q_{99} \approx 4.5$ at 0.99 surface

- **New paradigm: External vacuum n=1 fields couple across plasma surface to the least stable, ideal-MHD-like, external kink mode, whose amplitude is much larger inside the plasma**
  - This n=1 mode has |m| ~ 2 q near plasma edge
  - Other non-resonant harmonics were strengthened

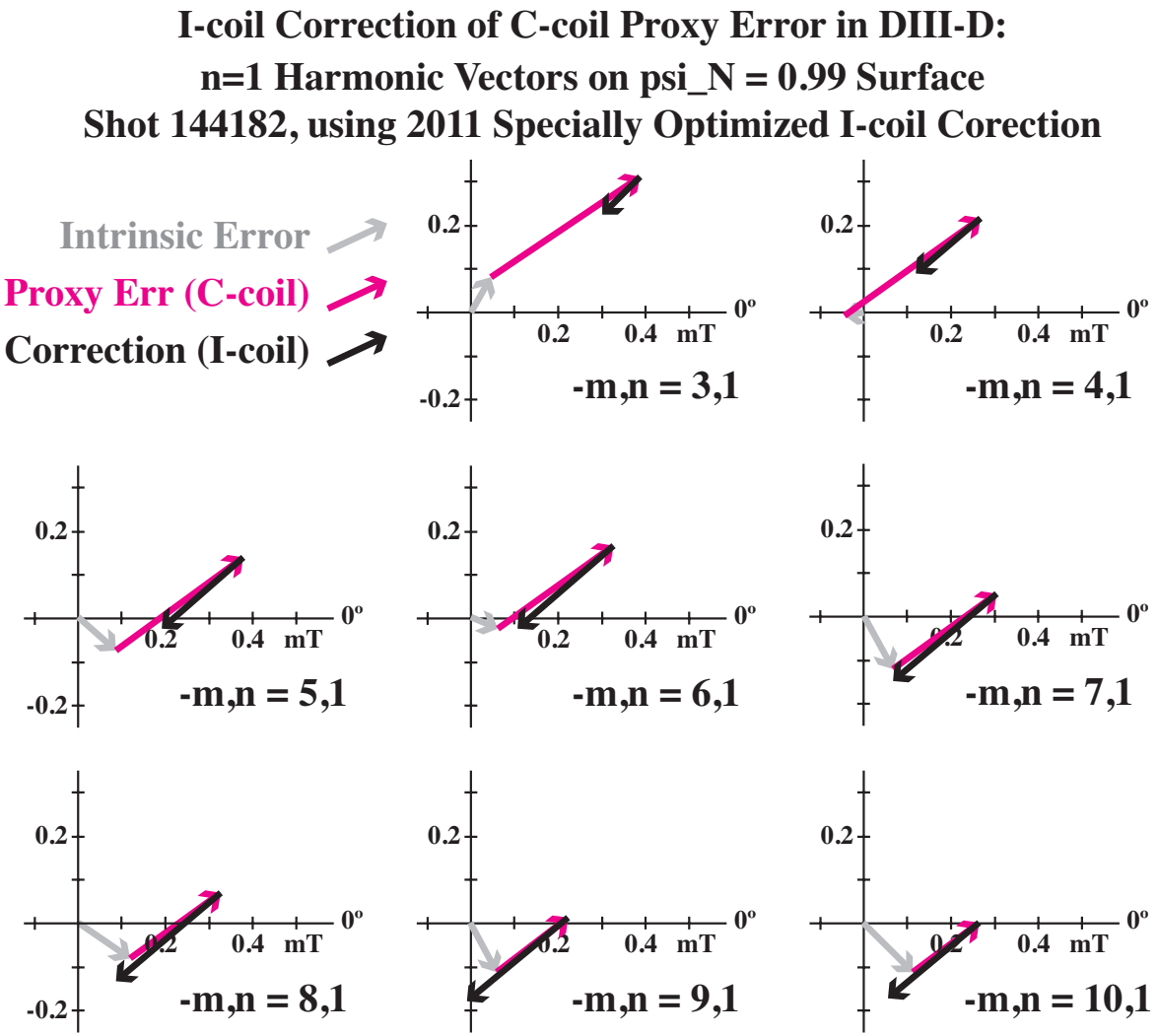
Empirical correction harmonics –m = 6 – 8 do best canceling of proxy error at the plasma surface

$q_{99} \approx 4.5$ at 0.99 surface

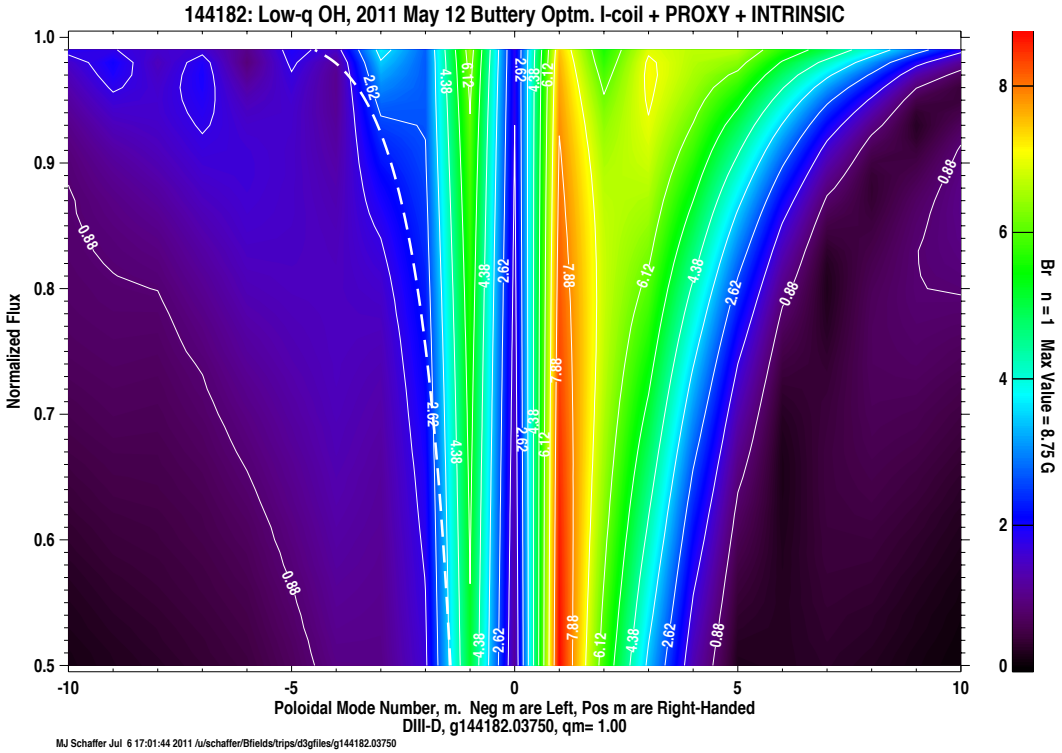
Experimental technique found a best correction amplitude and toroidal phase for locked mode avoidance in low-density Ohmic test plasmas

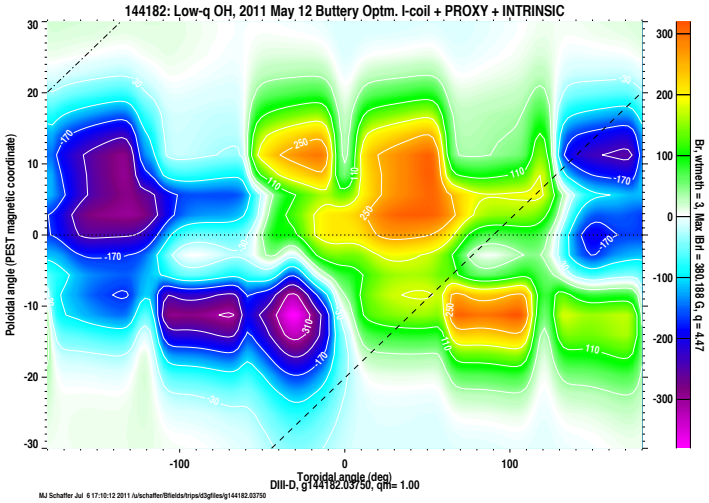
By experimental design, DIII-D intrinsic error was decoupled from the compensation

C-coil (proxy) phase was rotated among 4 orthogonal phases



Intrinsic error spectrum (absolute amplitude) was little reduced in the MHD coupling range, – m > q_{99}





Intrinsic error was little affected on the left side of resonance.

However, total nonaxisymmetric field increased markedly on the right side of the spectrum.

SUMMARY of Correction of a Simple Proxy Error Field

- **DIII-D C-coil**
  - Achiral and smooth
  - Simple artificial error for basic studies
  - Very different from real intrinsic error field
- **DIII-D I-coil**
  - Chiral and smooth
  - Proven effective at DIII-D over 6 years
- **Consistent with the new paradigm, I-coil compensated the proxy error at the high –|m| side of magnetic line resonance**

COMPENSATION OF DIII-D INTRINSIC ERROR

Compare & Contrast different I-coil compensations of DIII-D intrinsic error field

- **From 2006 to 2011, the n=1 I-coil correction of DIII-D intrinsic error appears to have varied . . . gotten worse**
  - Our low-density Ohmic "standard candle" test plasma "flickers"
    - PF coil currents, and thus intrinsic error, changes despite nominally "identical" plasmas
      - Feedback control system? Power supply control boards? . . .
    - "Wall, pumping and/or recycling change"
      - Fact or superstition?
- **Especially bad day-to-day in 2011**
- **"Opportunity!"**
  - Analyze the differences for clues to the most sensitive n=1 feature(s)

Three examples of I-coil empirical compensation of DIII-D intrinsic error

Shot	Year	I-coil error compensation method	Density at lock onset (1019 m-3	Optimum I-coil current & phase
125335	2006	"Standard 2006 algorithm"	0.36	0.71 kA, 231°
144432	2011	"Standard 2006 algorithm"	0.5	0.76 kA, 229°
144564	2011	New re-optimization of empirical compensation	0.8	0.97 kA, 222°

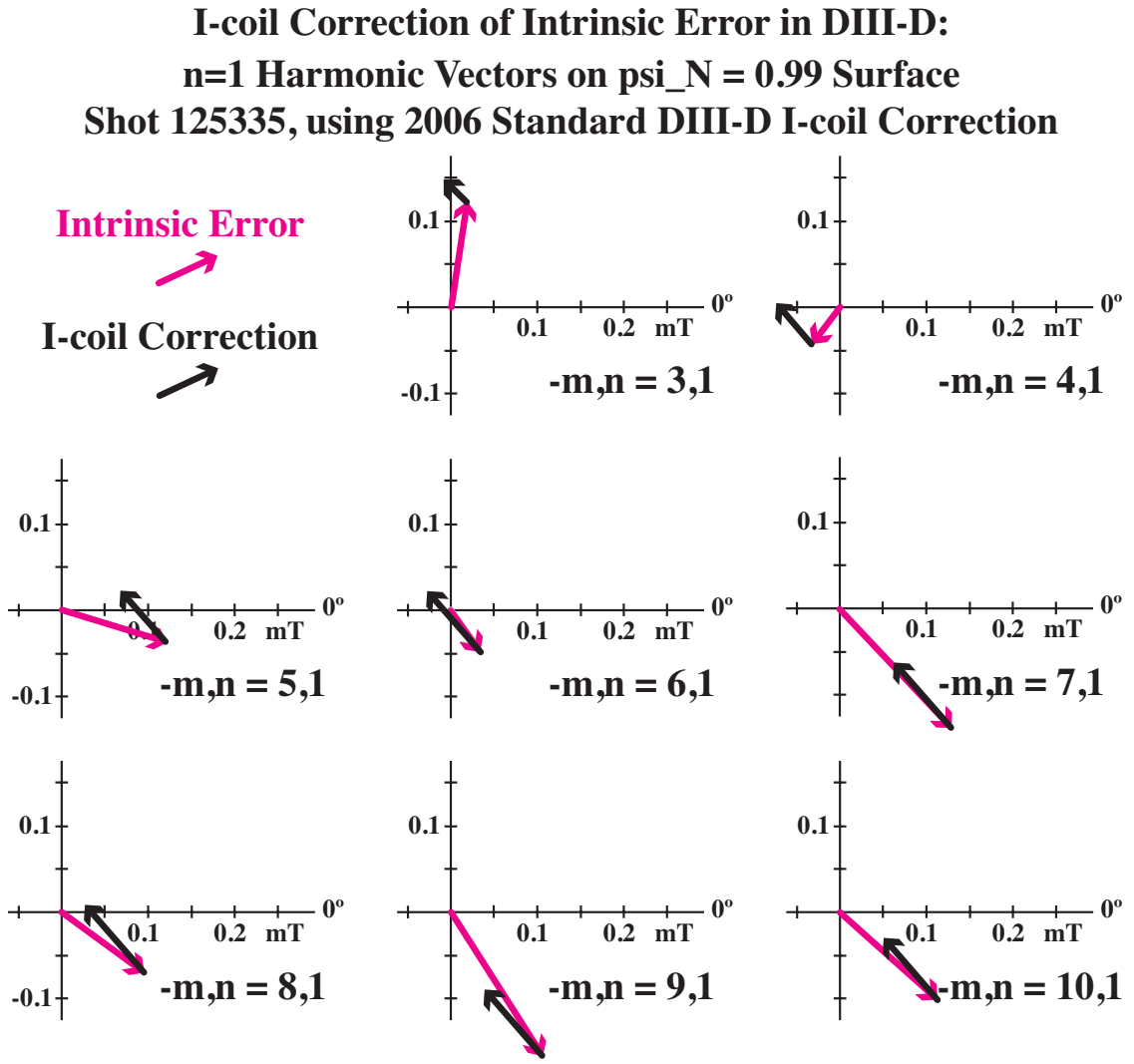
Original 2006 best n=1 compensation by I-coil

All I-coil harmonics from m = -3 to beyond m = -10 have same phase within ±1°

A property of the I-coil configuration used

Intrinsic error harmonic amplitudes, and especially phases, vary

Here m = -6 and -8 appear to be best corrected



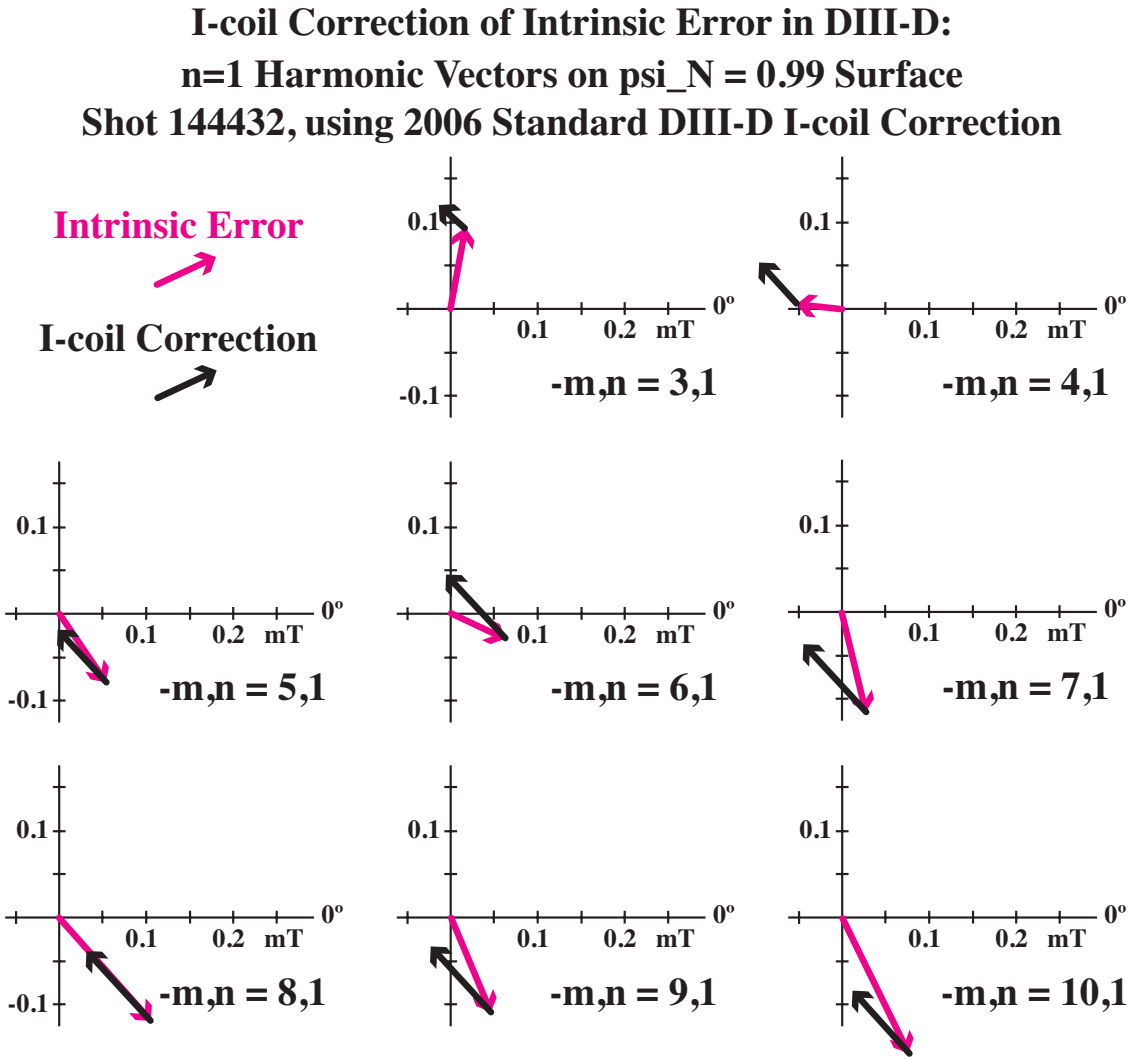
The same 2006 correction formula used in 2011 was less effective

The distribution of the intrinsic amplitudes and phases is different in 2011

Caused by different PF coil current distribution, despite nominally identical plasmas

<u>Intrinsic</u> error harmonic amplitudes, and especially phases, vary

Here m = -5, -6 and -9 appear to be best corrected



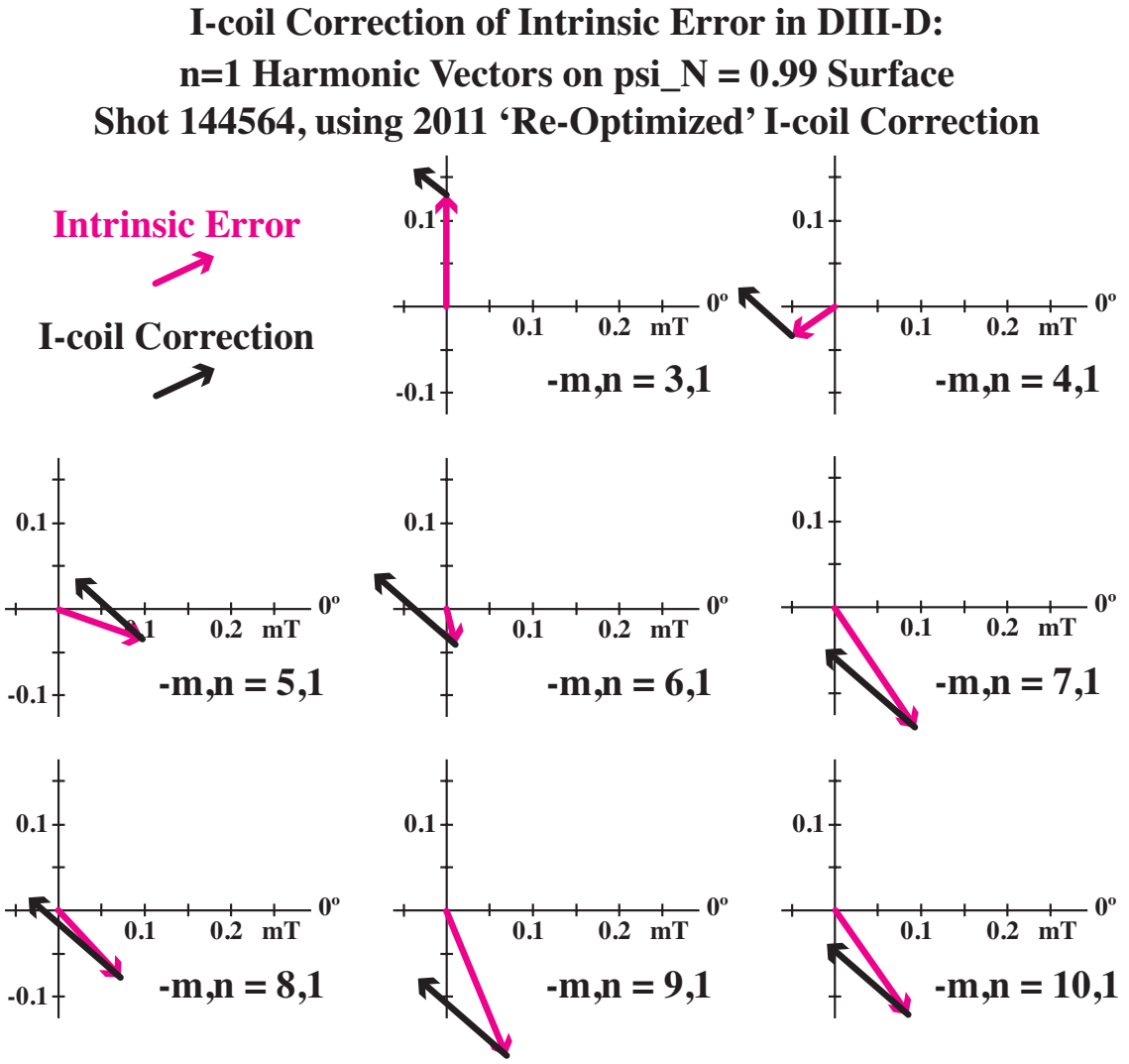
A new re-optimization in 2011 was even less effective for locked mode avoidance

The distribution of the intrinsic amplitudes and phases is different in 2011

Caused by different PF coil current distribution, despite nominally identical plasmas

<u>Intrinsic</u> error harmonic amplitudes, and especially phases, vary

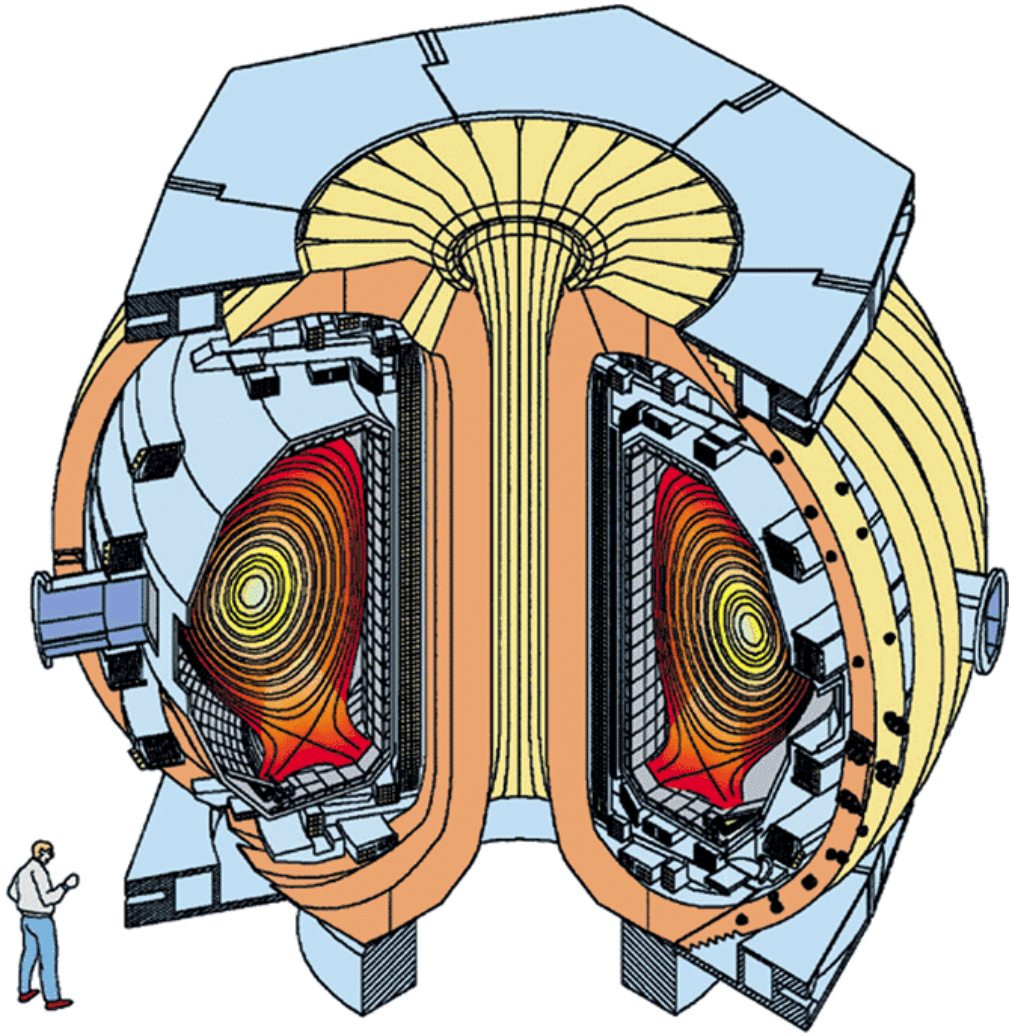
Here m = -8 is the only harmonic that appears well-corrected



SUMMARY of I-coil Compensation of Intrinsic Errors

- **Intrinsic error field sources, geometry and helical harmonic structure are not simple.**
  - Neighboring harmonics can have significantly different amplitudes and phases
  - No practical set of error compensation coils can reduce more than a few of the largest dangerous harmonics
  - Most practical compensation coils will strengthen many of the less dangerous harmonics
- **In DIII-D, best intrinsic error field compensation so far has reduced only 2 or 3 harmonics to low amplitudes at the plasma surface**
- **Empirical compensation techniques continue to be important**
- **More research is needed before first principles error correction will be practical**

LOW-n ERRORS FROM THE DIII-D TF-COIL



Low-n error field of the DIII-D TF-coil was measured at midplane (Z = 0)

Measured B at R = 5m, 2m out from TF-coil

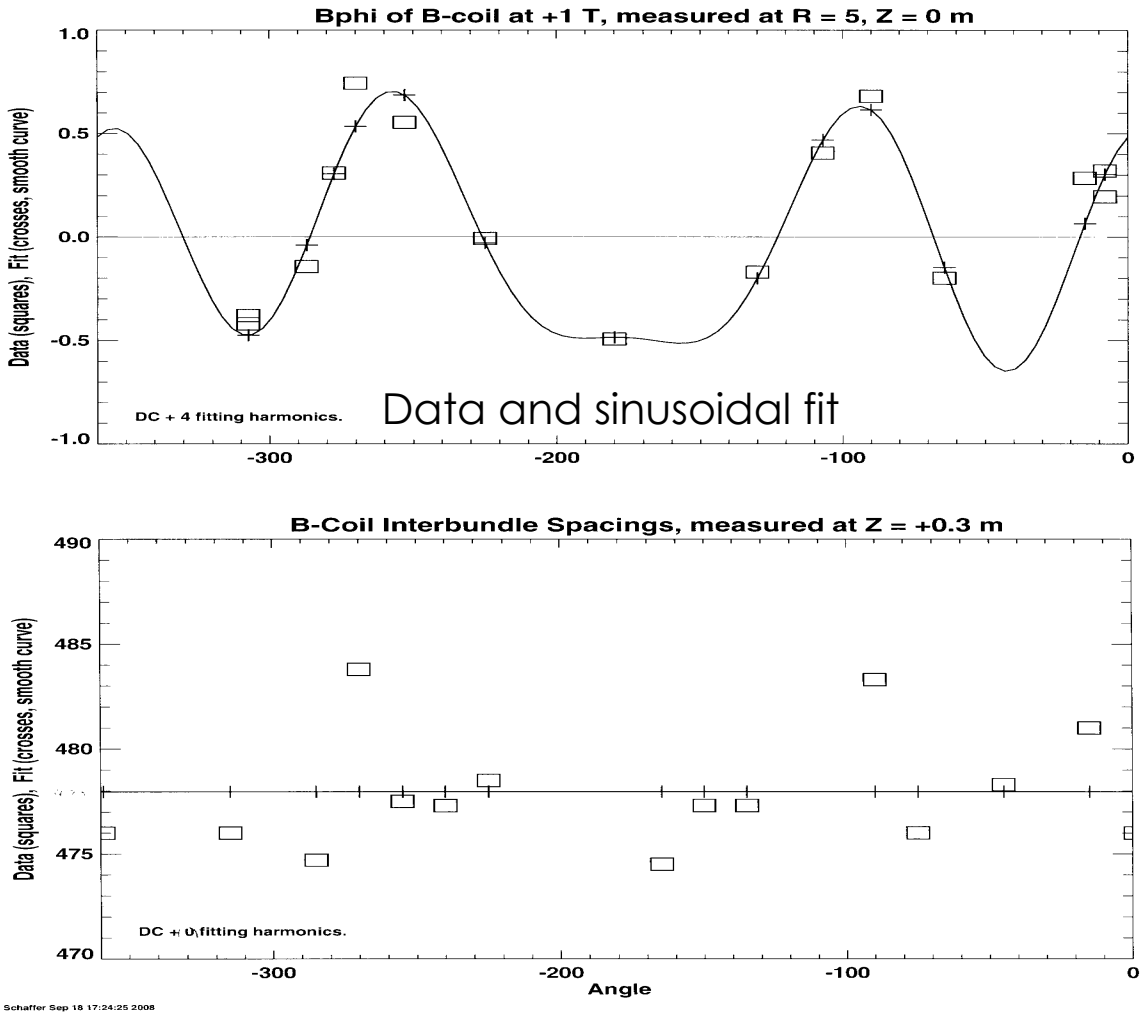
Avoid n=24 ripple

Subtracted known error field of TF current feeds.

Measured separation between coil bundles.

Limited access, gaps in data.

B_{Tor} positive peaks correlate with widest spacing between coil bundles.



The main features of the measured B_{Tor} can be approximated by a physically motivated model

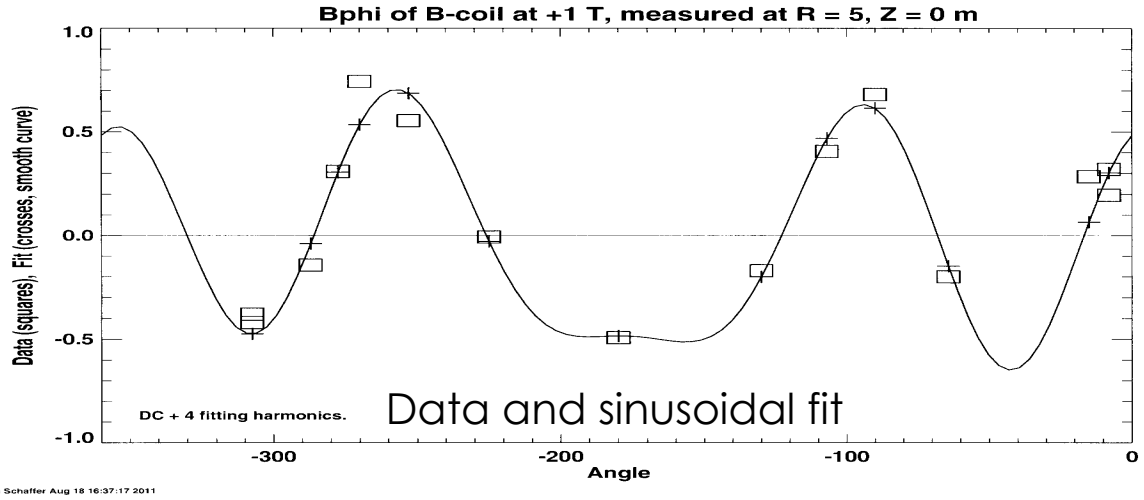
The pair of B_{Tor} peaks at 90° and 270° are approximated by:

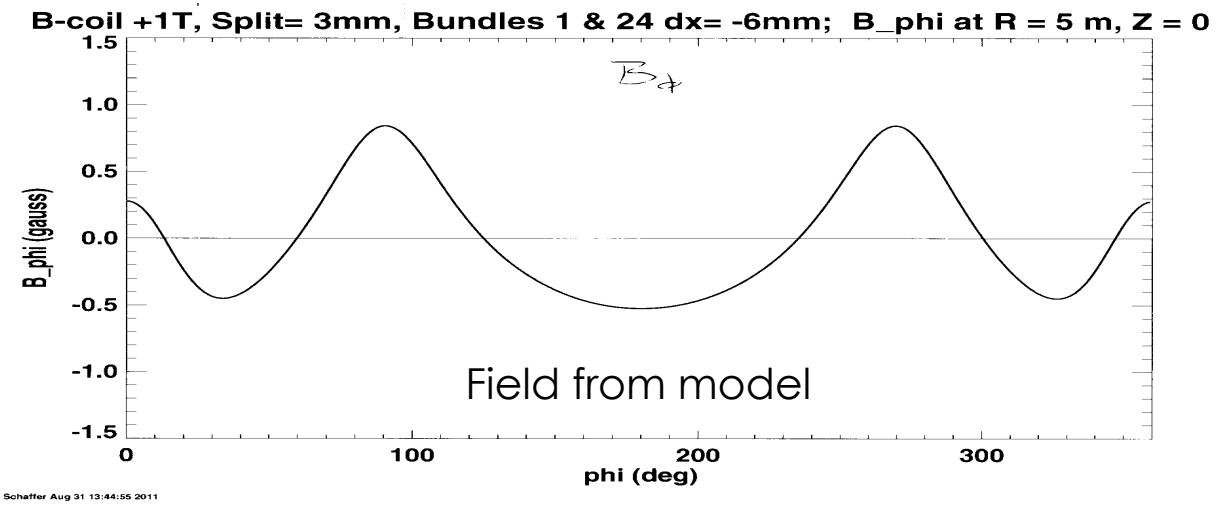
1) divide the TF-coils into two halves by the 90° – 270° vertical plane;

2) shift the halves horizontally apart to leave a 3mm gap.

The smaller B_{Tor} peak at 0° is approximated by:

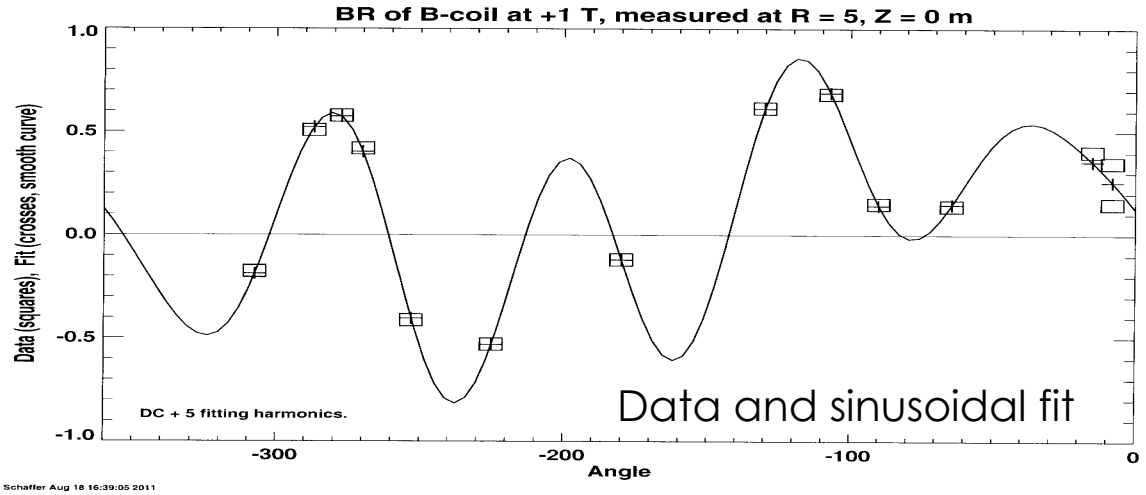
3) further adjustment of the two bundles nearest to 0°.



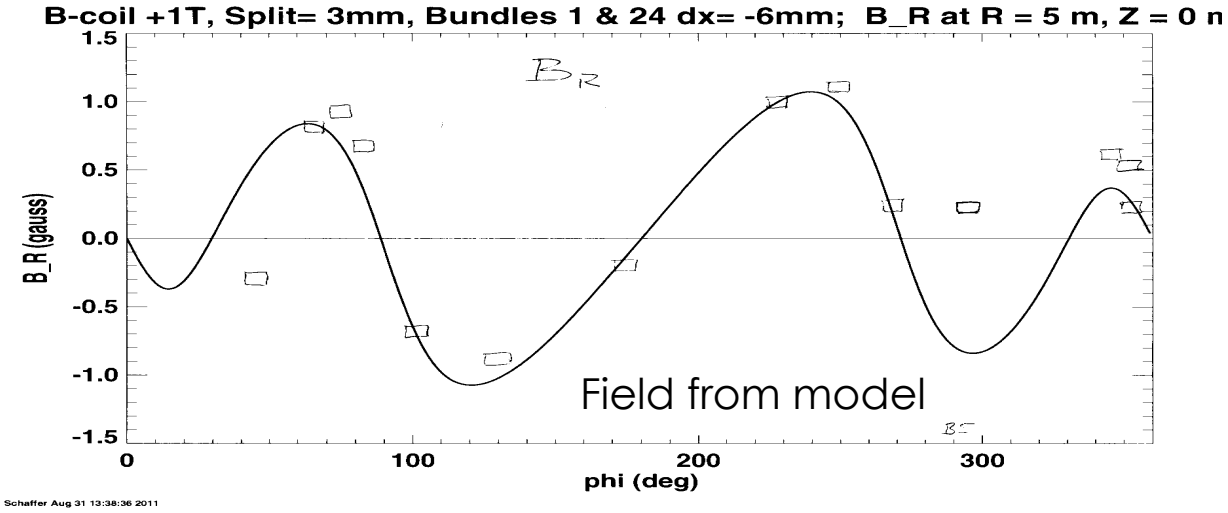


B_R dependence is not as well approximated by this model

B_R data have more high frequency content than does B_{Tor}



The model appears plausible but it needs more high frequency (smaller size) source elements



SUMMARY of Low-n Error Fields from DIII-D TF-coil

- **In DIII-D there are TF-coil irregularities that make low-n error field components**
  - In particular, n=1 and n=3
- **Plausible sources have been identified**
- **SURFMN analysis shows that these error fields have little resonant component of any kind**
- **There are smaller and higher-n sources than have been identified**