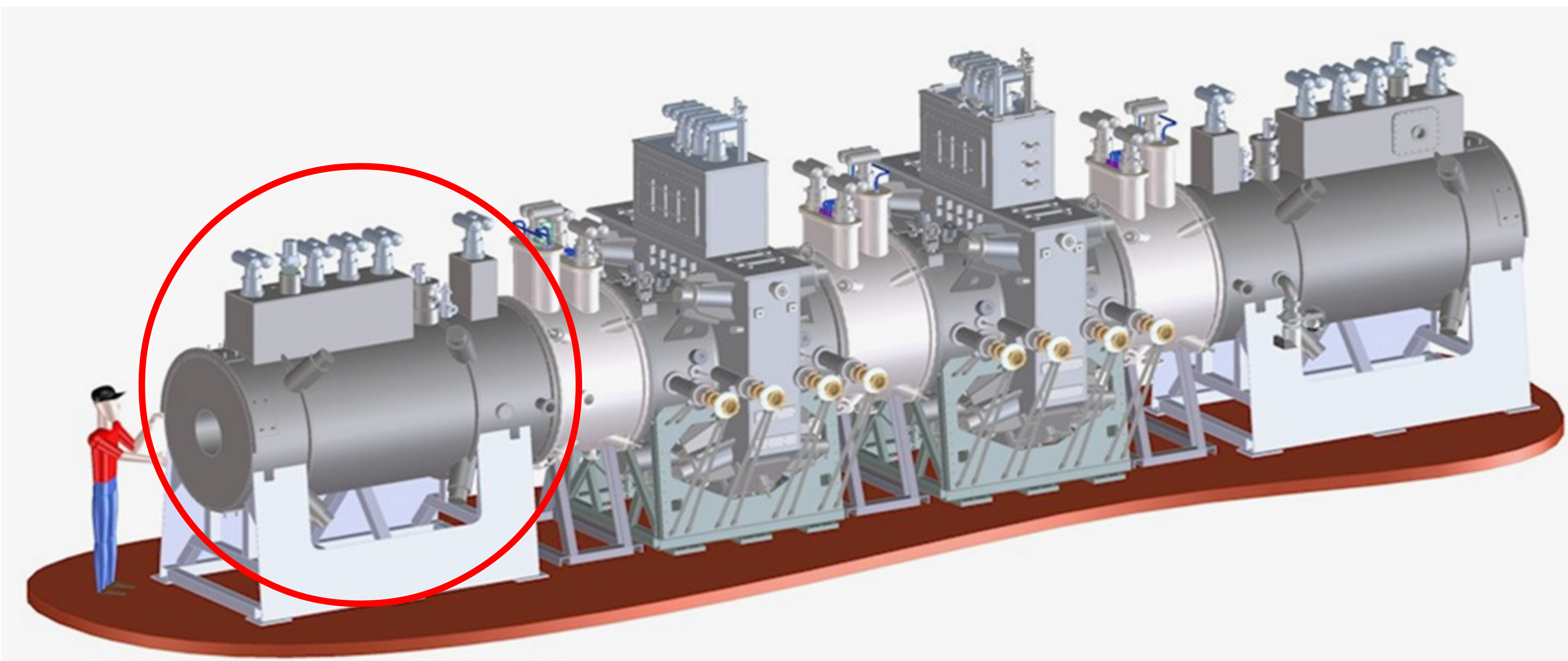
Magnetic Measurements of MICE Spectrometer Solenoid 2

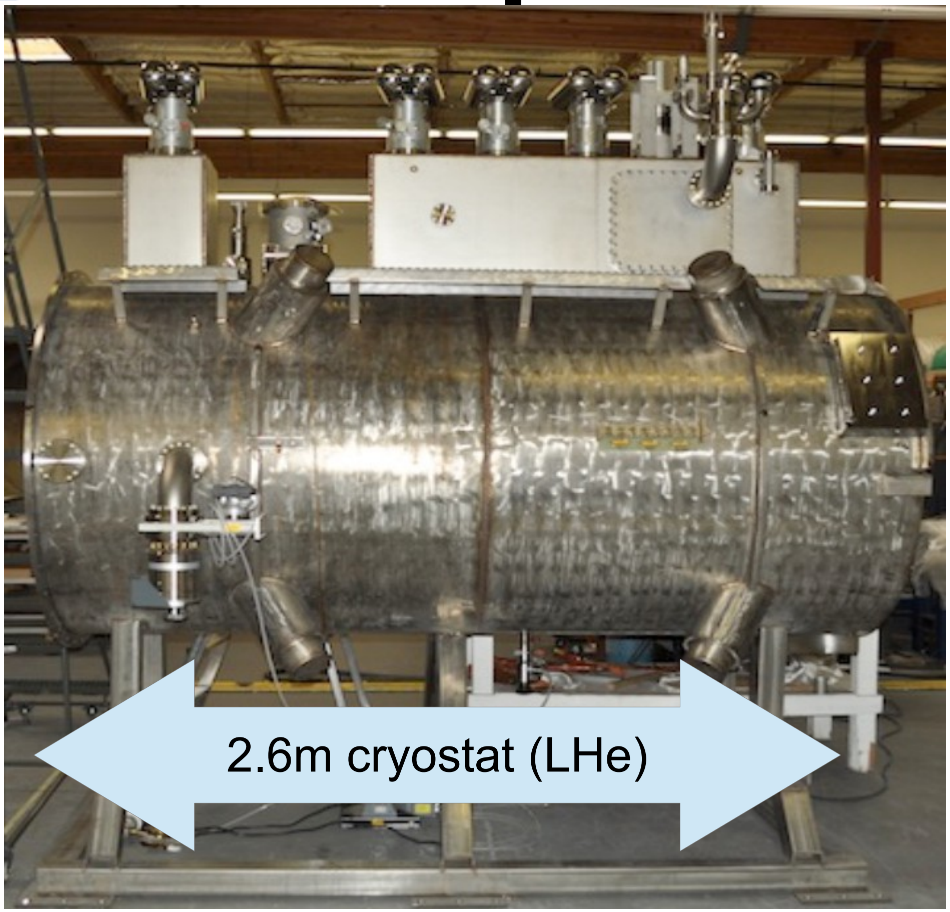
Marc Buehler, Mike Tartaglia, John Tompkins
(Fermilab TD – Magnet Systems Dept.)

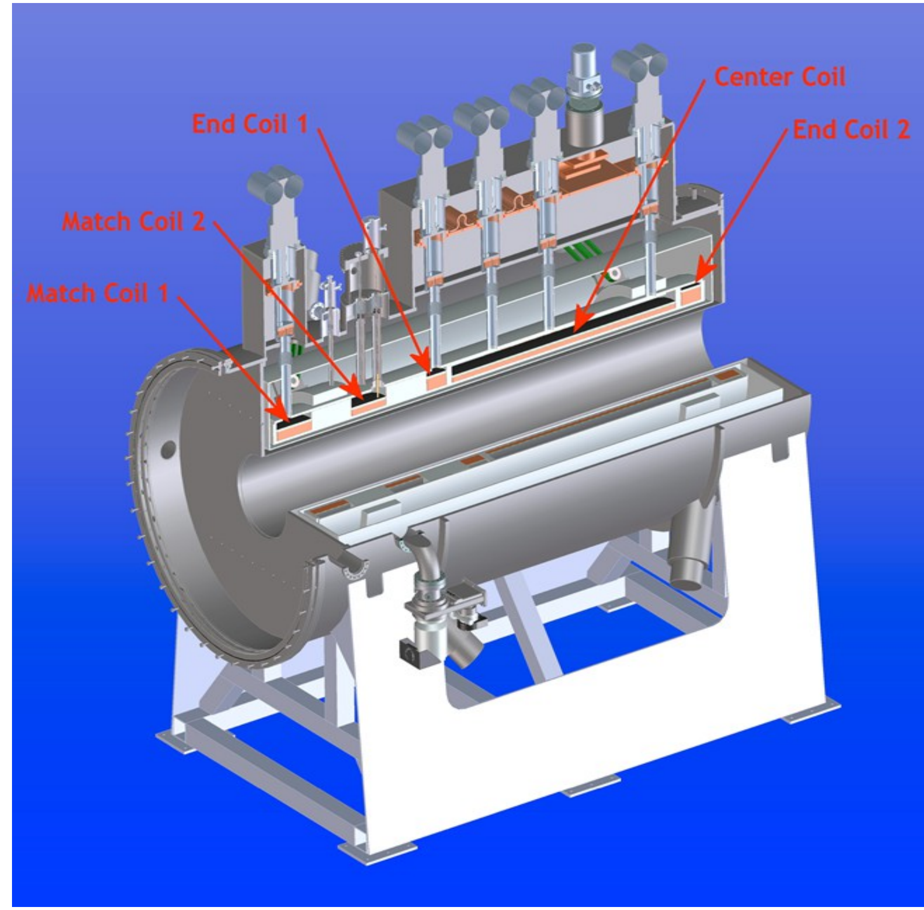


Overview

- Goal: Perform basic (not high-precision) verification measurement of Spectrometer Solenoid 2
- Developed a portable/shippable measurement system
- M. Buehler & M. Tartaglia performed measurement at Wang NMR in Livermore (CA) during the week of June 11-15 in 2012
- Data analysis with OPERA. Results shown in this talk.
- Current status of SS2:
  - Completed final training test run
  - Flip mode + hold, solenoid mode + hold

MICE Spectrometer Solenoid 2





- Nomenclature:
  - Matching coils: **M1 & M2**
  - End coils: **E1 & E2**
  - Center/Spectrometer coil: **C**
- M1, M2 powered separately
- ECE powered in series

- Nb-Ti conductor
- All coils wound on a single machined Aluminum mandrel (6061-T6-Al)
- No splices
- 40 cm diameter warm bore

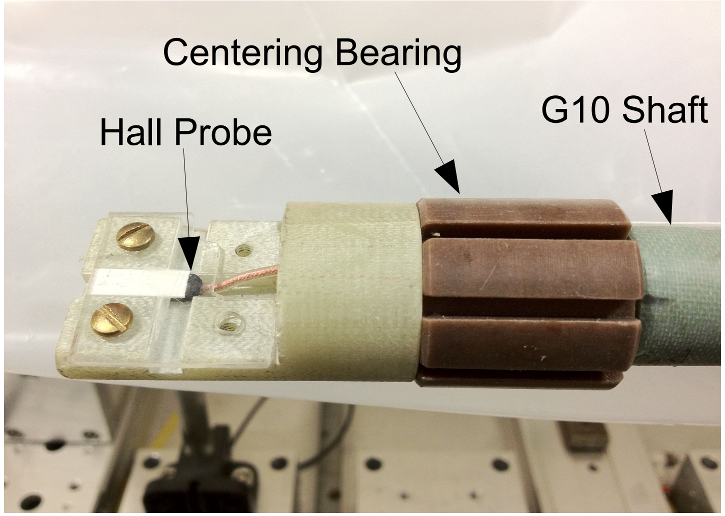
Geometry and Winding Info

As Built Dimensions and Turns (MICE Note 207, Table 5):

Parameter	Match 1	Match 2	End 1	Center	End 2
Inner Coil Radius (mm)	258	258	258	258	258
Coil Thickness (mm)	46.165	30.925	60.905	22.125	67.783
Coil Length (mm)	201.268	199.492	110.642	1314.30	110.642
Current Center Axial Position* (mm)	124.00	564.00	964.00	1714.00	2464.00
Current Center Radial Position* (mm)	281.083	273.463	288.453	269.063	291.891
Coil Average J (A mm^{-2})	137.67	147.77	124.28	147.66	127.09
Number of layers per Coil	42	28	56	20	62
Number of Turns per Layer	115	114	64	768	64
Total Number of Turns	4830	3192	3584	15360	3968
Design Current (A)**	264.83	285.60	233.68	275.52	240.21
Coil Self Inductance (H)^	12.0	5.0	9.0	40.0	11.3
Coil Stored Energy (MJ)**	0.42	0.20	0.26	1.55	0.32
Peak Field in Coil (T)**	5.30	4.32	5.68	4.24	5.86
Temperature Margin at 4.2 K (K)**	~1.6	~1.8	~1.5	~2.0	~1.5

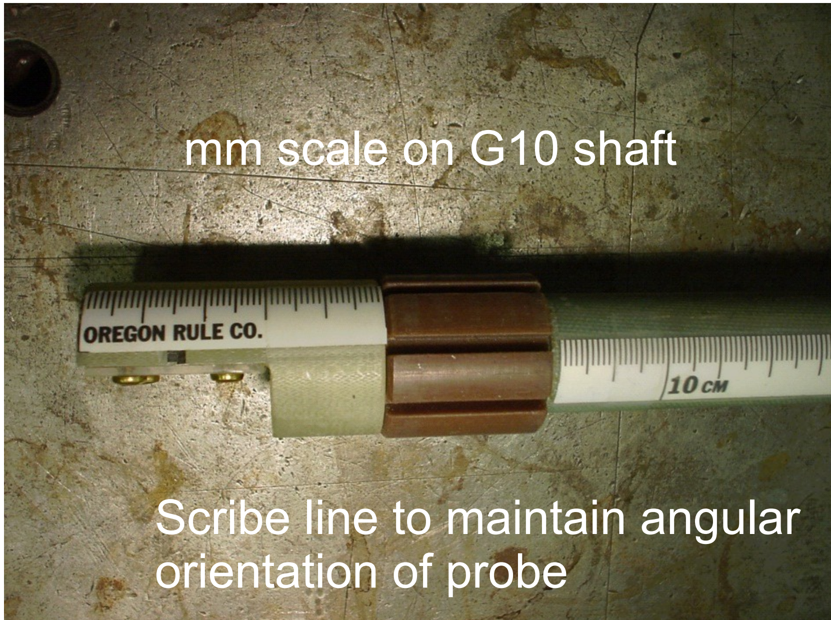
MICE Note 207

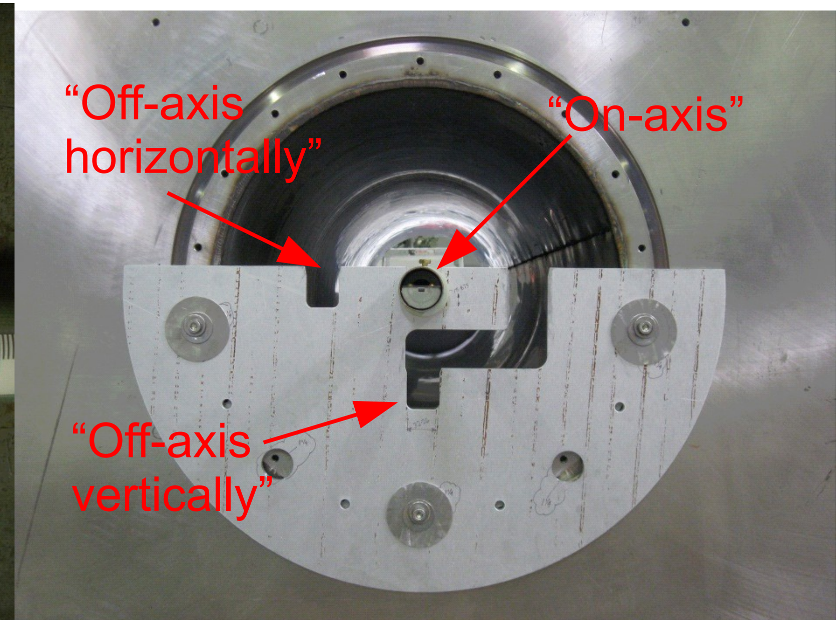
The Measurement System



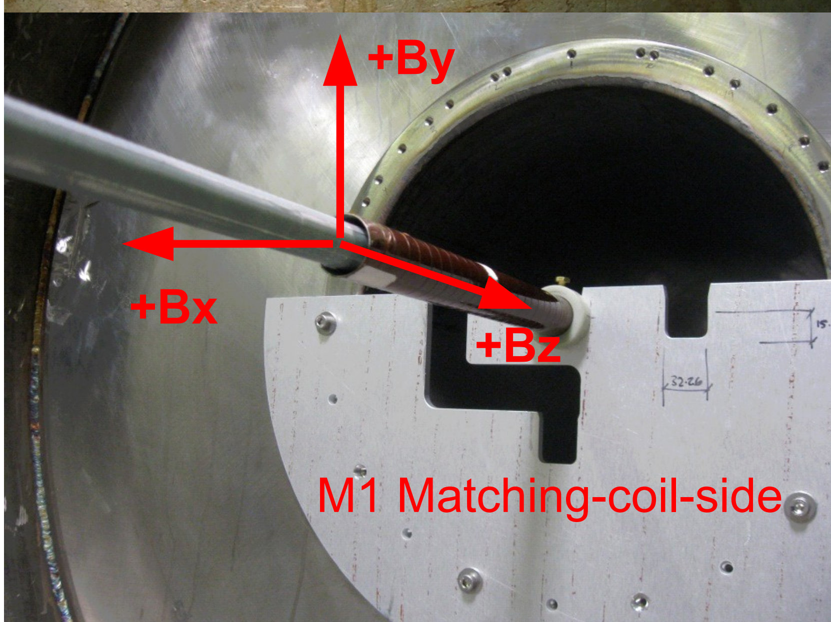
- 3D Hall Probe:
  - Senis 10T probe (S/N5406)
  - Calibrated against NMR probe using 4T Tevatron dipole at Fermilab's MTF
- Field Readout:
  - Keithley 2700 Mux/DMM
  - Automated with Labview
- Manual probe positioning:
  - Long G10 shaft
  - Stainless steel guide tube
  - Aluminum support plates

Measurement System



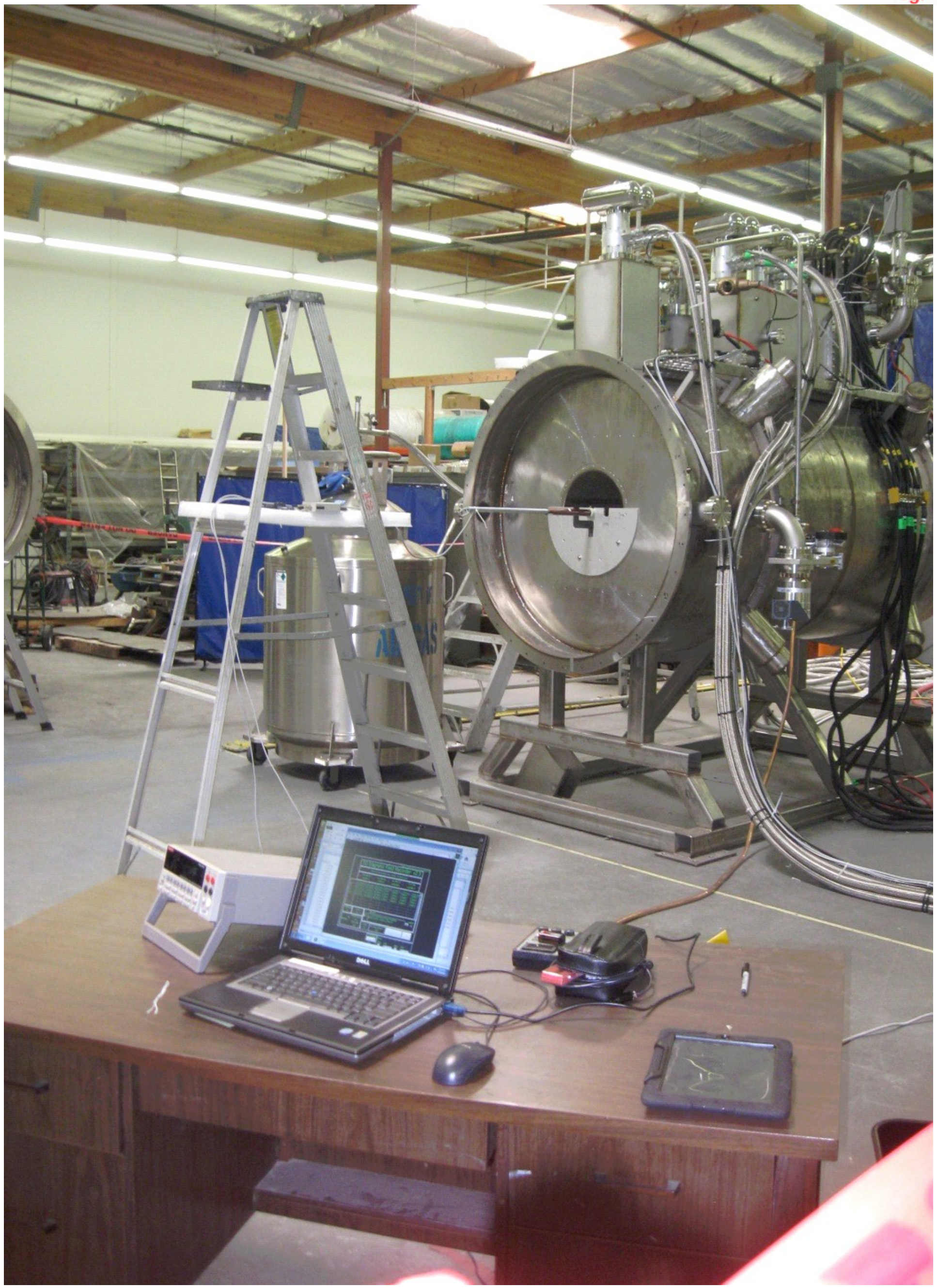


Al support plates at both ends of magnet warm bore. Surveyed in x and y. No absolute z reference. Used G10 capture rings to provide z position reference.



Stainless Steel guide tube. Tube bend/sag negligible. Manually move guide tube to facilitate on- and off-axis measure-ments.

Measurement Procedure



- **Person 1:**
  - Manually position probe along z, by pushing G10 shaft with attached Hall probe into the guide tube
  - 1-2 cm steps (except near centering bearings)
  - Adjust probe roll via scribe mark
- **Person 2:**
  - Manually record coil current and z position
  - Trigger Hall probe readout (records 10 meas.)
- ~3 z-positions per minute (~40 minutes for full z-scan)

Measurement History

- Monday (June 10, 2012):
  - Unpack, install, and test measurement system

Data discussed in this talk

- Tuesday (June 11, 2012):
  - M1-M2 @ 10A on-axis
- Wednesday (June 12, 2012):
  - M2 @ 50A on-axis and off-axis (vert. & hor.)
  - E1-C-E2 @ 50A on-axis and off-axis (hor.)

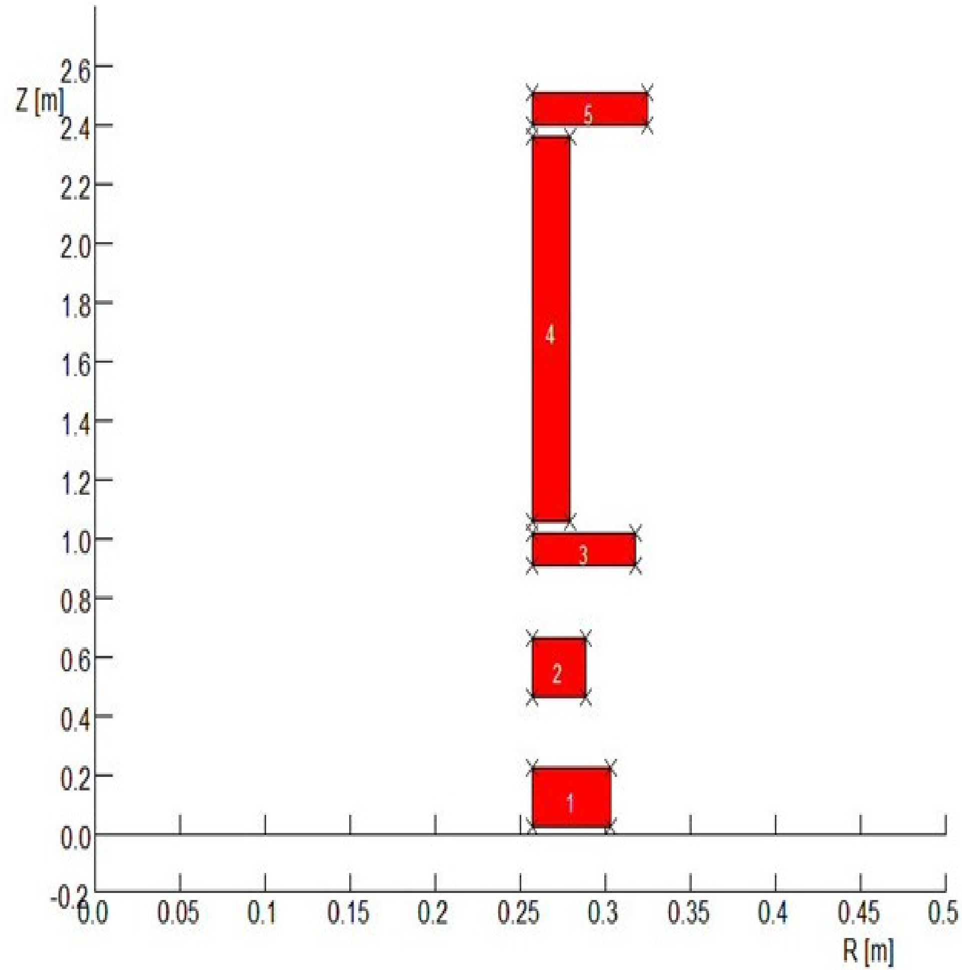
E1, C, E2 coils are powered in series. Could not measure individual coils.

- Thursday (June 13, 2012):
  - G10 shaft stuck in SS guide tube. Repaired.
  - M1 @ 50A on-axis
  - M1-M2-E1-C-E2 @ 185A started measurements, but quenched
- Friday (June 14, 2012):
  - M1-M2-E1-C-E2 @ 150A on-axis and off-axis (vert. & hor.)
- NB: Could not perform measurements at nominal magnet currents, since magnet training was still ongoing.

OPERA Modeling

We performed two independent data analyses using OPERA to calculate a model and then compare model vs data:

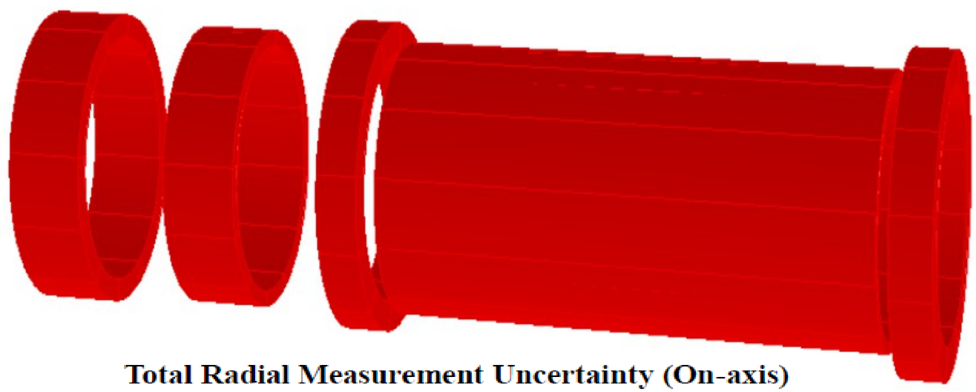
- Opera 2D (M. T.):
  - Assuming cylindrical symmetry
  - For each data set apply z offset that gives best agreement in B_z (by eye, ~2mm)
  - Based on as-built winding geometry (see slide 4)
  - Applied *a priori* thermal contraction coefficient 7.5mm shrinkage over the magnet length
  - Applied correction for small (~1 degree) and constant x-z tilt of probe
  - Calculate $dB=B_{data}-B_{model}$



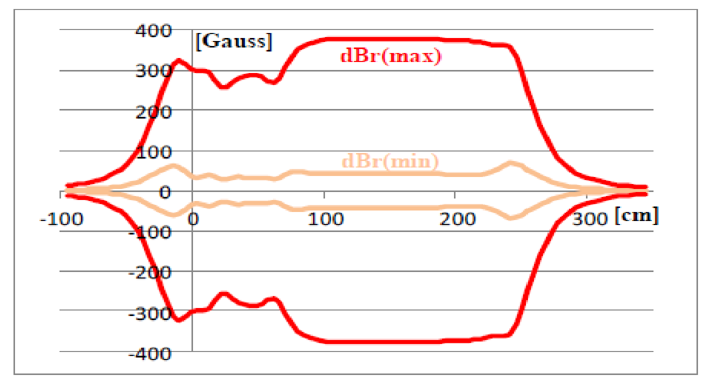
OPERA Modeling

We performed two independent data analyses using OPERA to calculate a model and then compare model vs data:

- Opera 3D (M. B.):
  - For each data set apply z offset that gives best agreement in B_z (by eye, ~2mm)
  - Based on as-built winding geometry (see slide 4)
  - Applied *a posteriori* correction for thermal shrinkage by matching single coil data with model ~2cm shrinkage over the magnet length
  - Applied correction for small (~1 degree) and constant x-z tilt of probe
  - Calculate $dB=B_{data}-B_{model}$
  - Estimate systematic uncertainties due to radial & axial displacement, as well as additional tilt of Hall probe
    - Radial disp.: 2.5-10mm
    - Axial disp.: 1-10mm
    - Tilt: 0.1-1deg

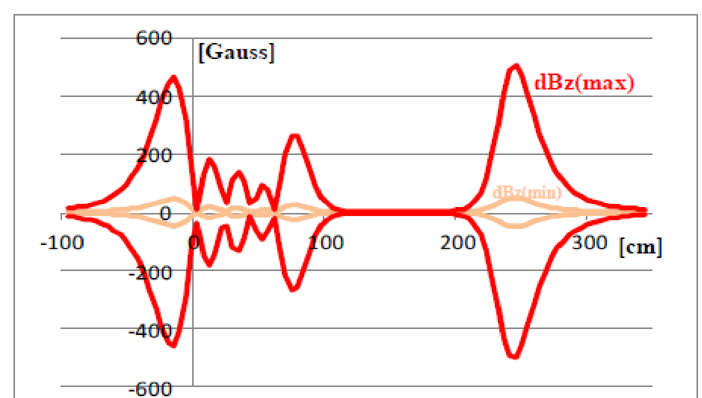


Total Radial Measurement Uncertainty (On-axis)



All coils at 150A

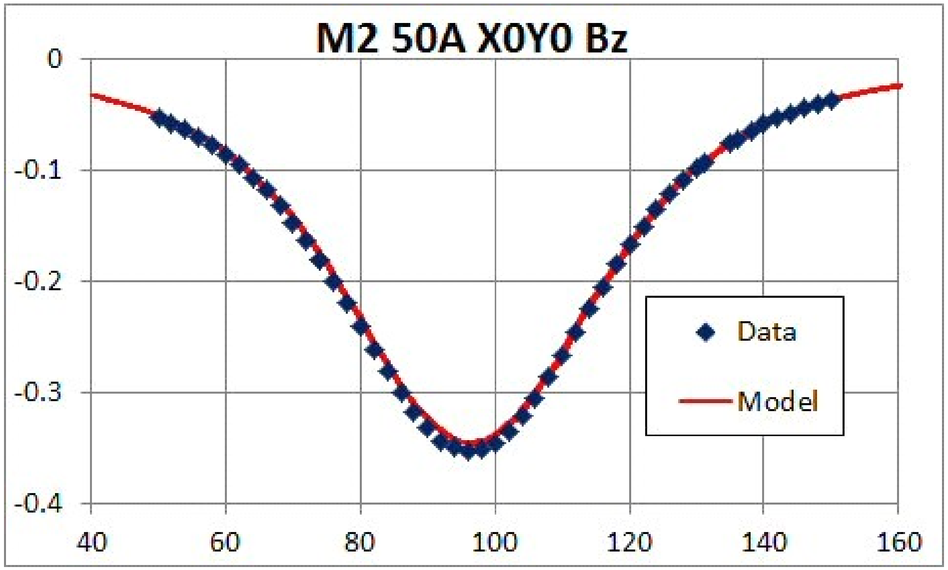
Total Axial Measurement Uncertainty (On-axis)

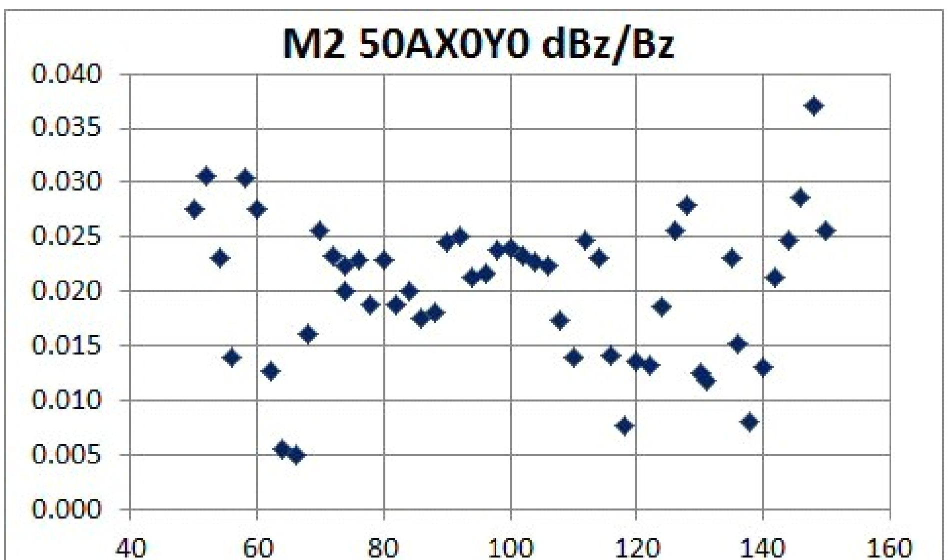


All coils at 150A

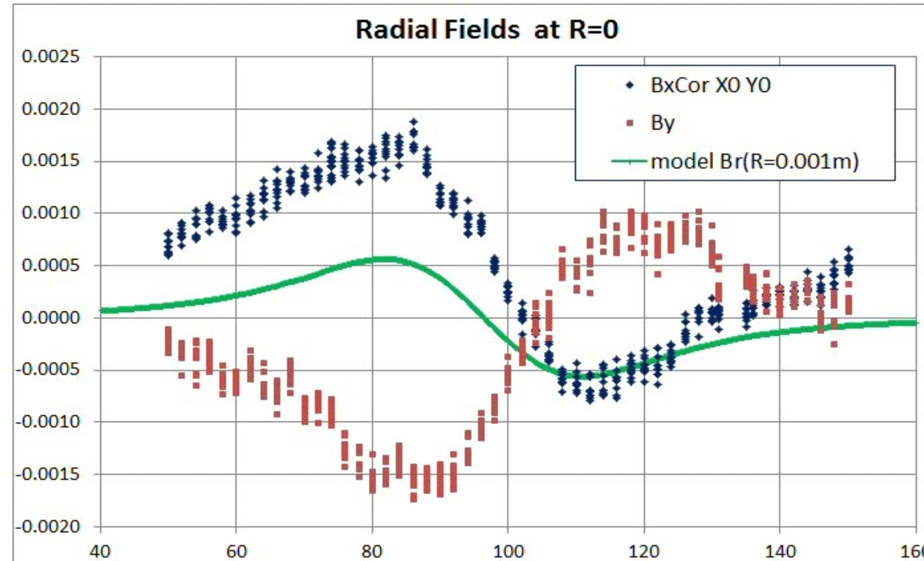
M2, 50A, On-Axis

$B_{Axial}(z)$





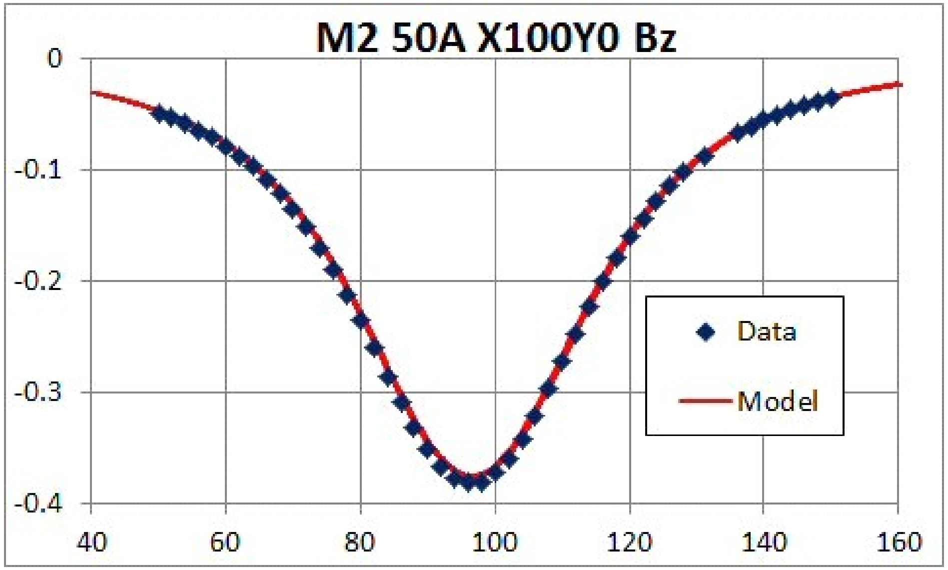
$B_{Radial}(z)$



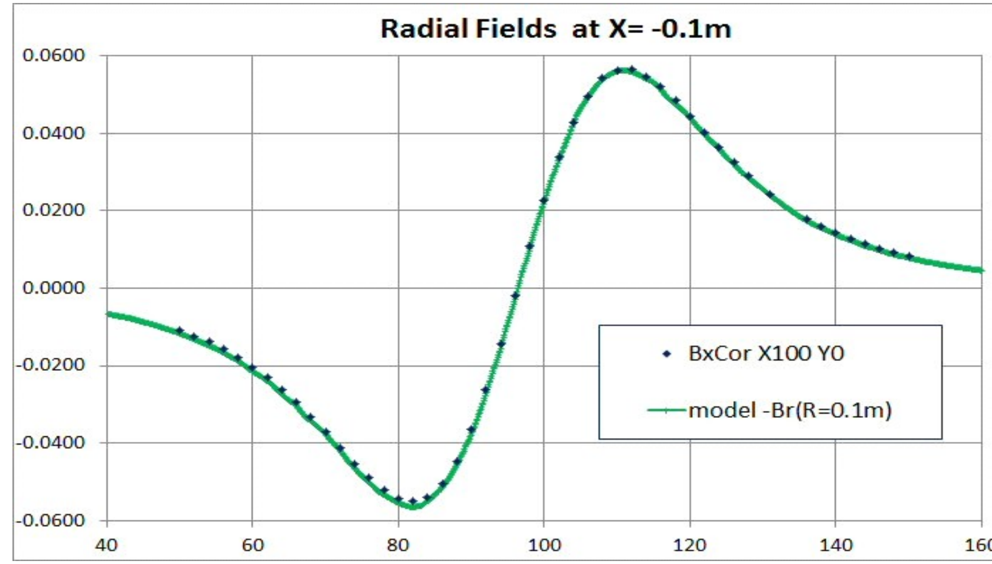
dx=+2mm, dy=-2.5mm

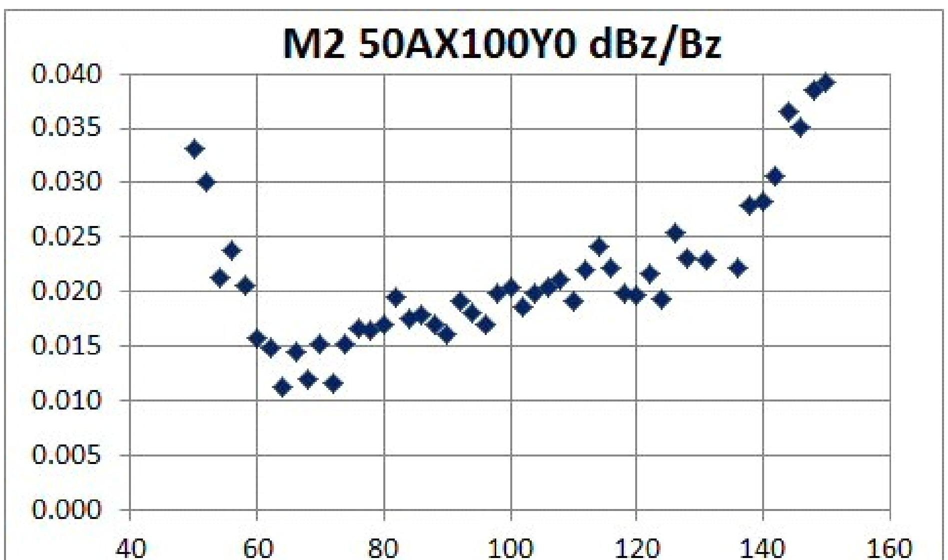
M2, 50A, Off-Axis

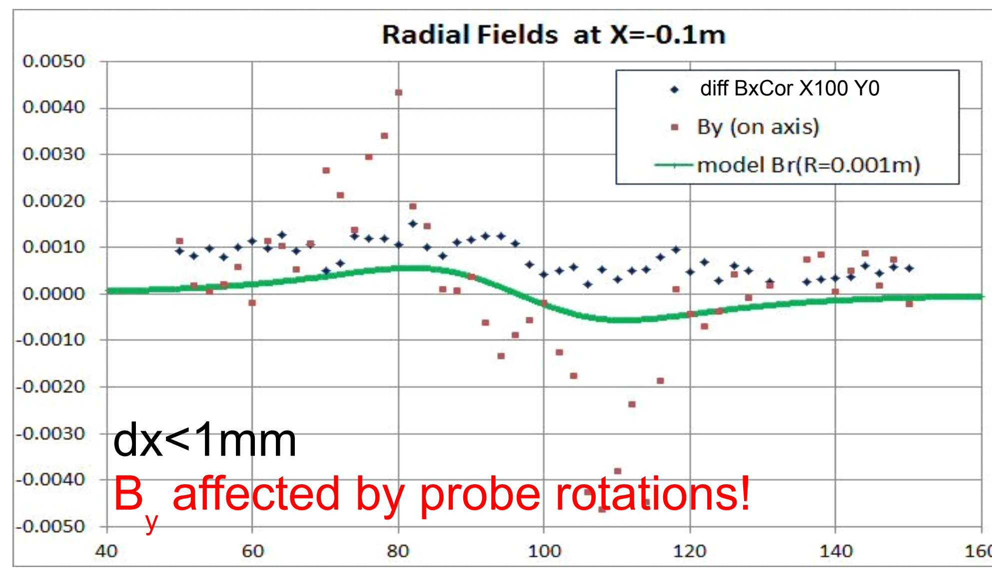
$B_{Axial}(z)$



$B_{Radial}(z)$

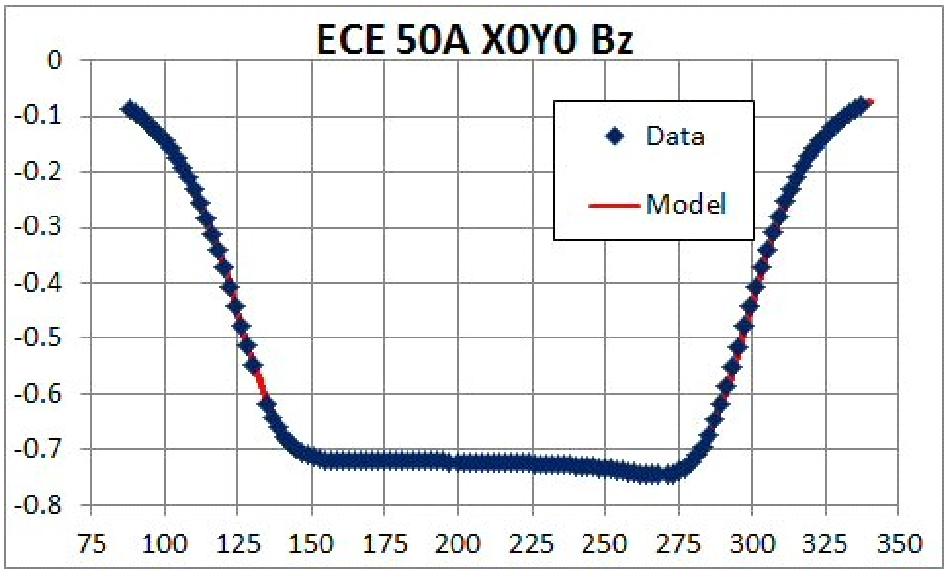


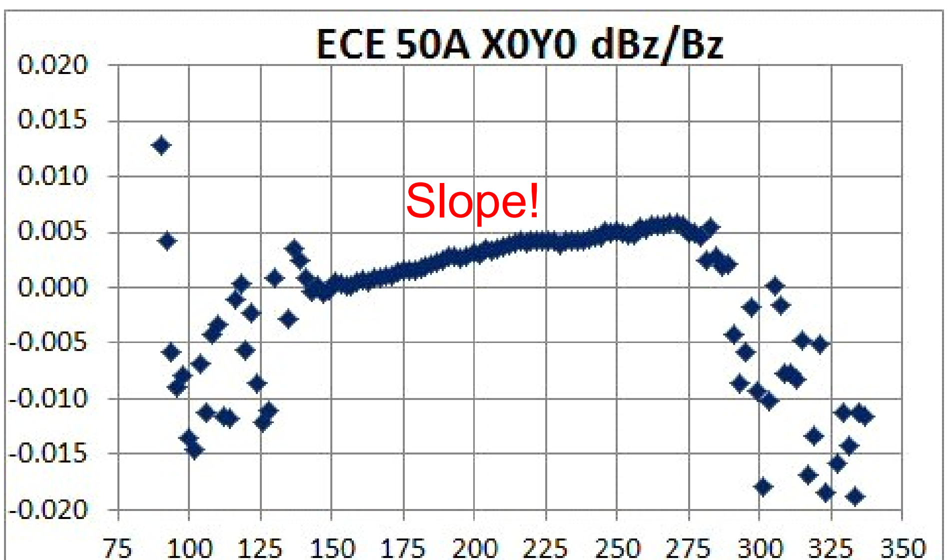




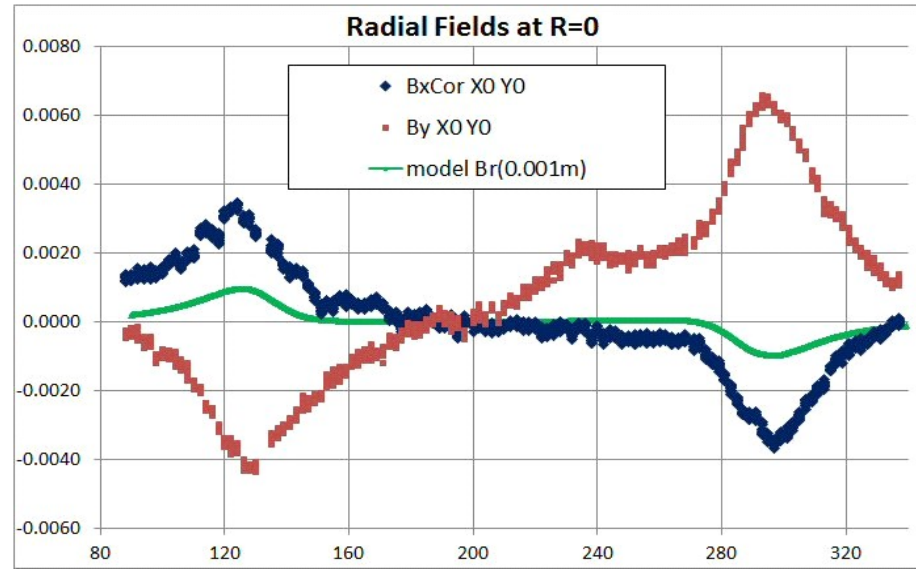
ECE, 50A, On-Axis

$B_{Axial}(z)$





$B_{Radial}(z)$

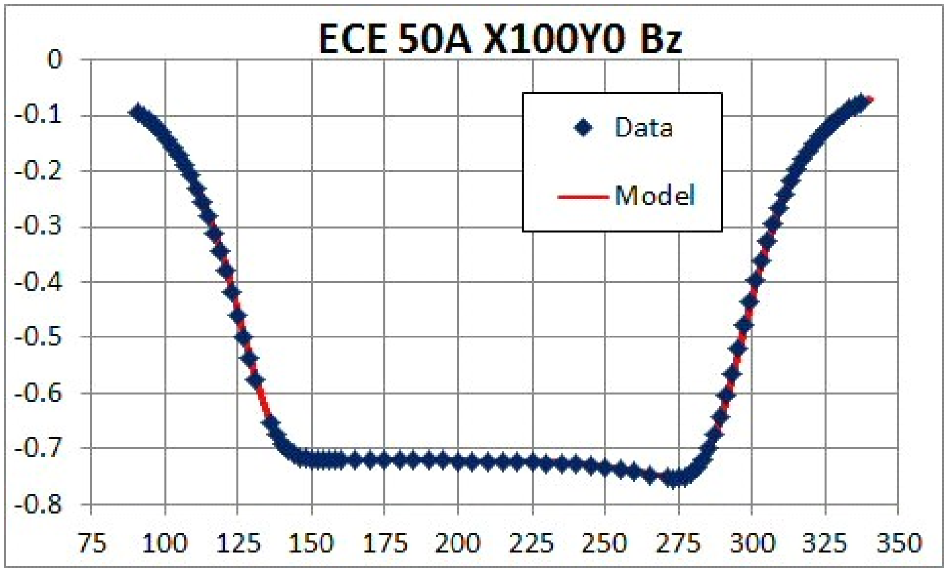


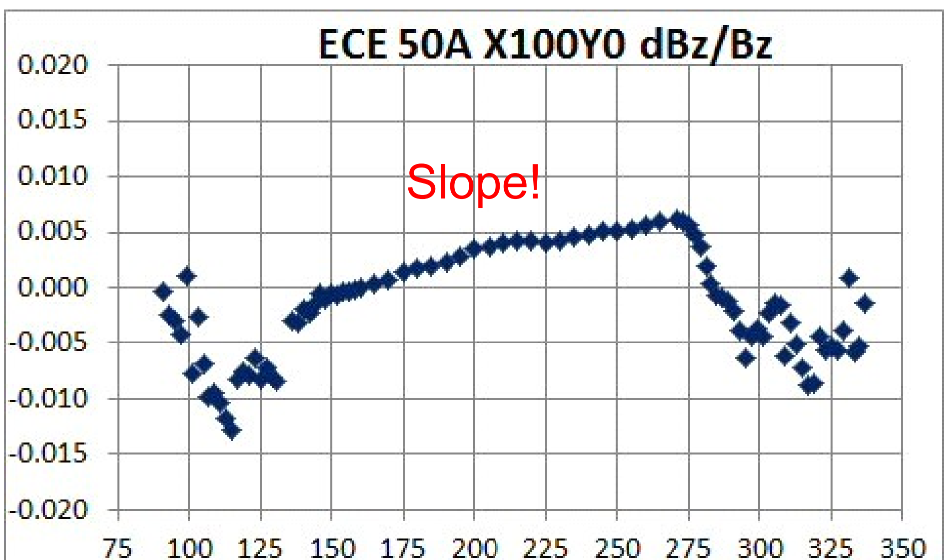
dx=+2mm, dy=-2.5mm

B_z slope in spectrometer coil could be due to non-uniform conductor winding density!

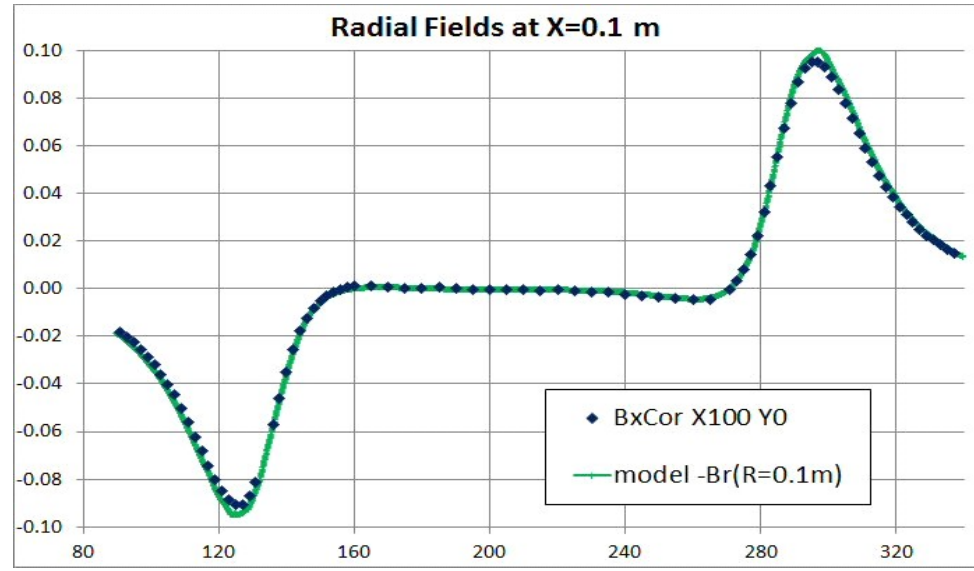
ECE, 50A, Off-Axis

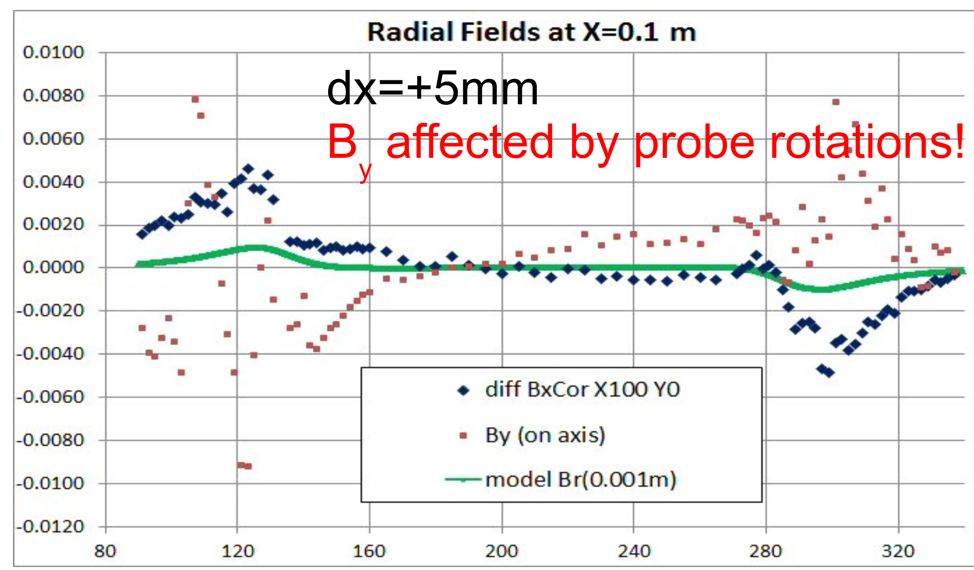
$B_{Axial}(z)$





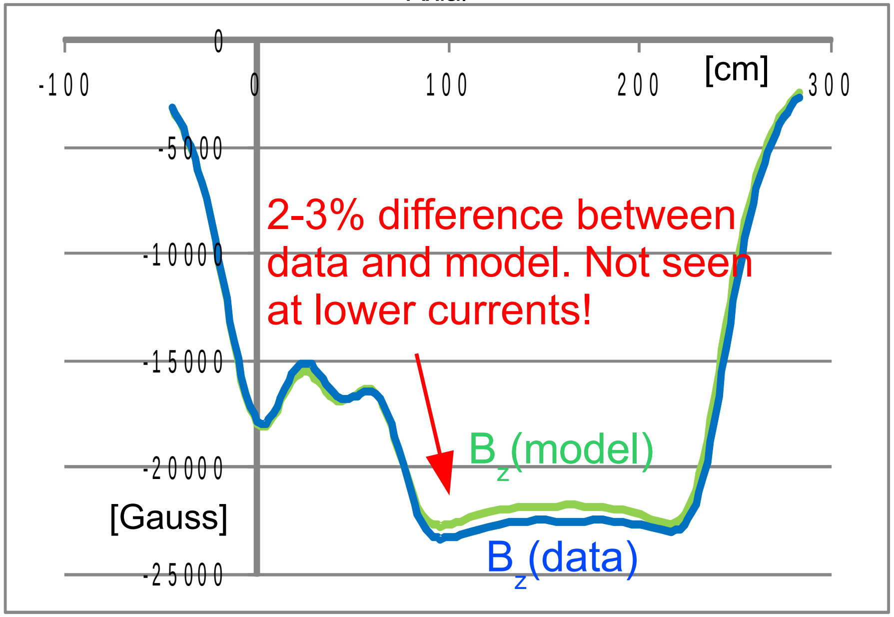
$B_{Radial}(z)$



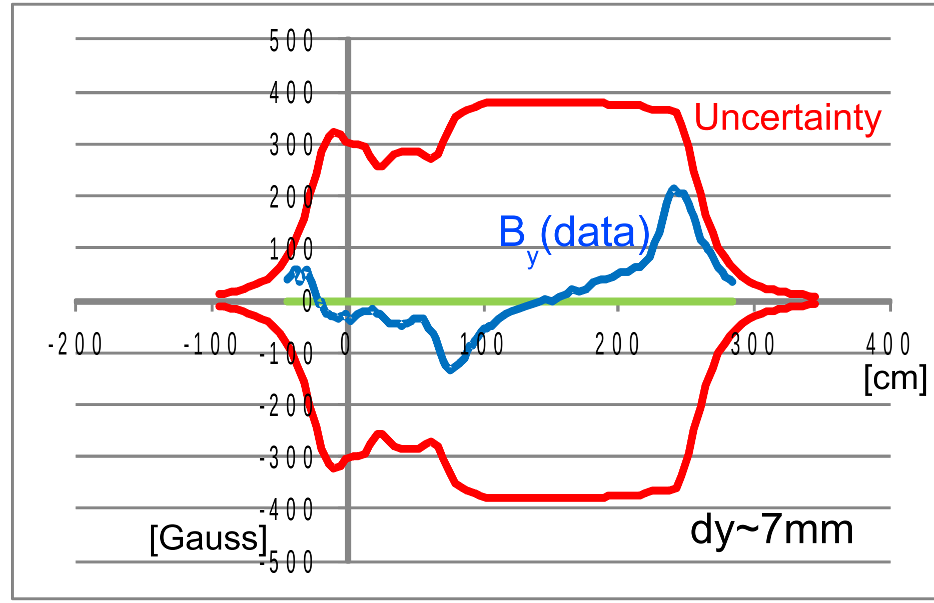


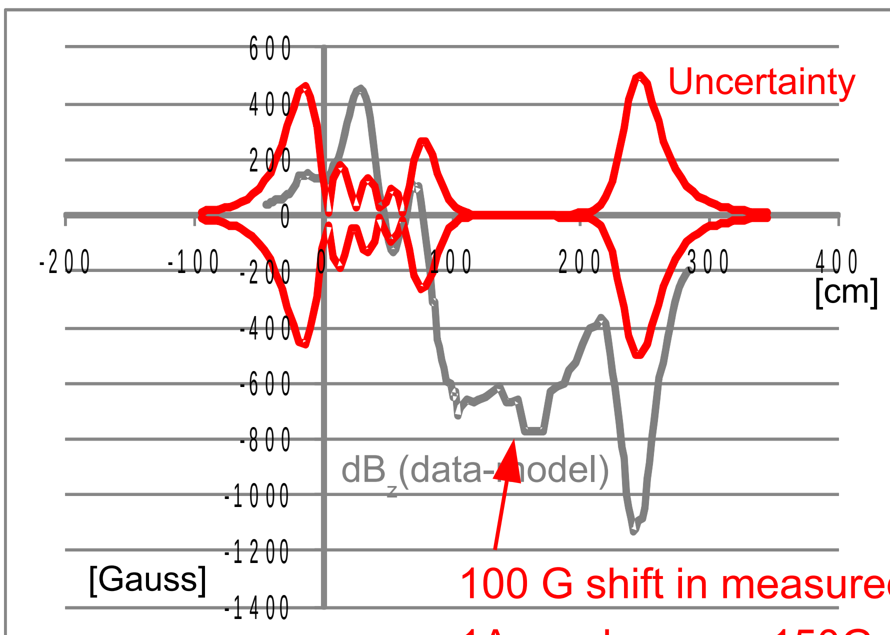
All Coils, 150A, On-Axis

$B_{Axial}(z)$

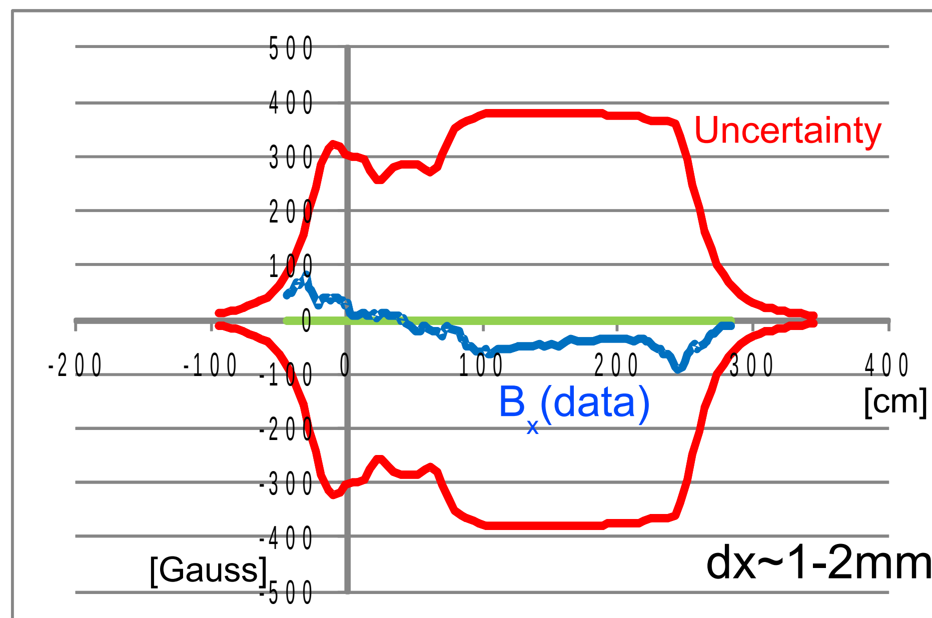


$B_{Radial}(z)$





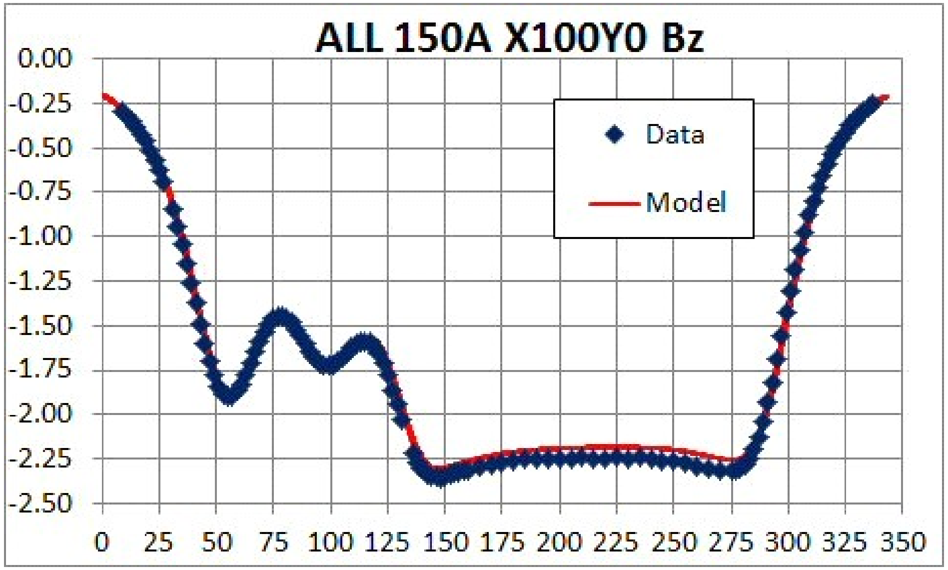
100 G shift in measured B_z
1Amp change = 150G
Power system fluctuation?

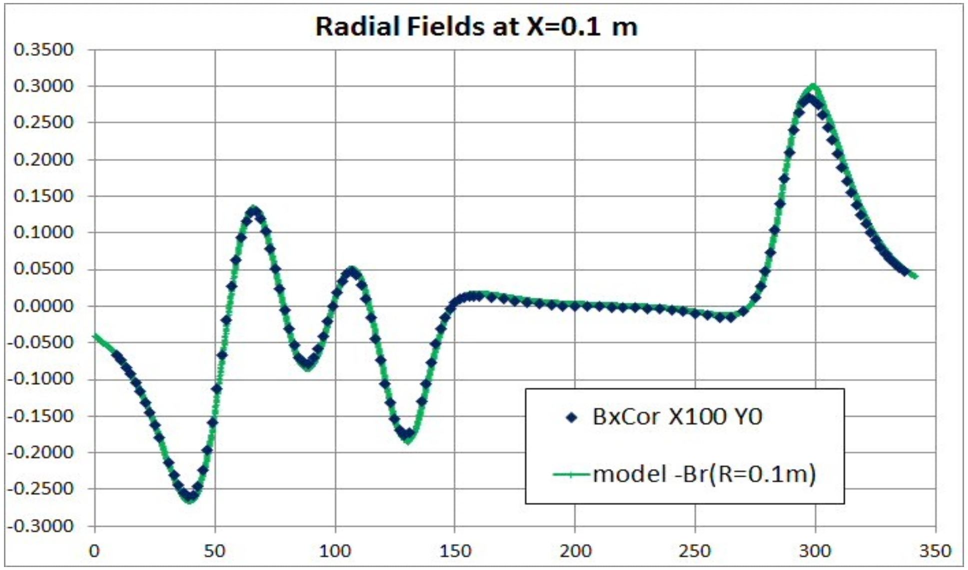


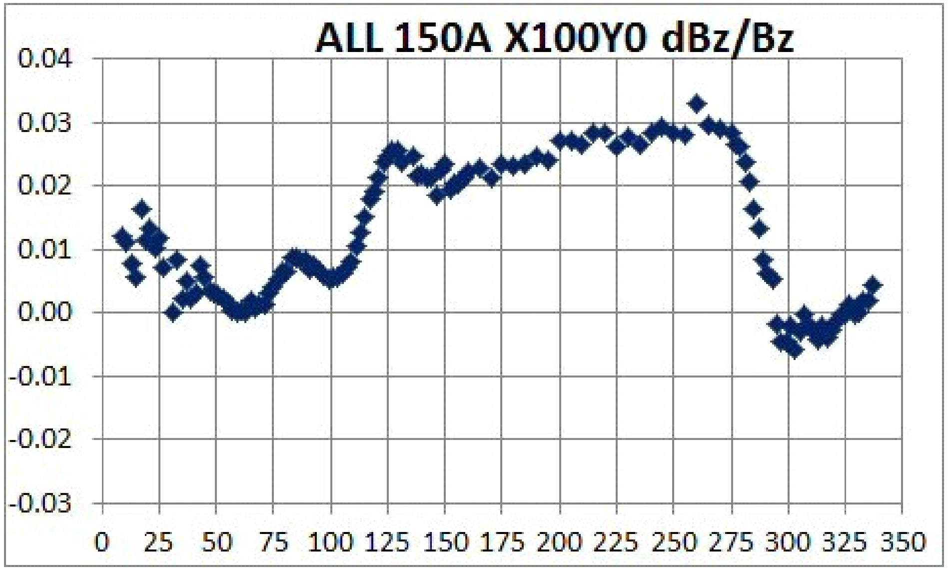
All Coils, 150A, Off-Axis

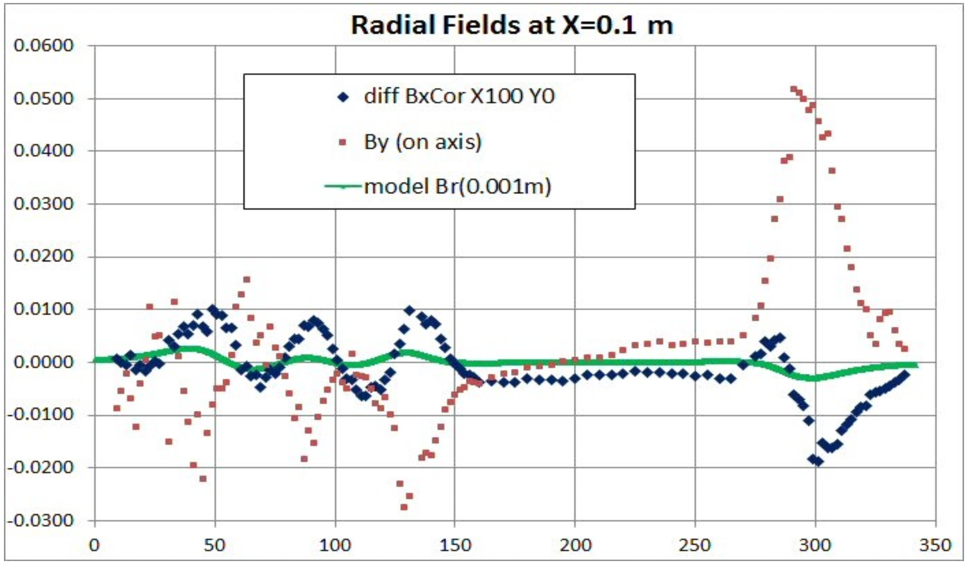
$B_{Axial}(z)$

$B_{Radial}(z)$









dx: mm-level shifts

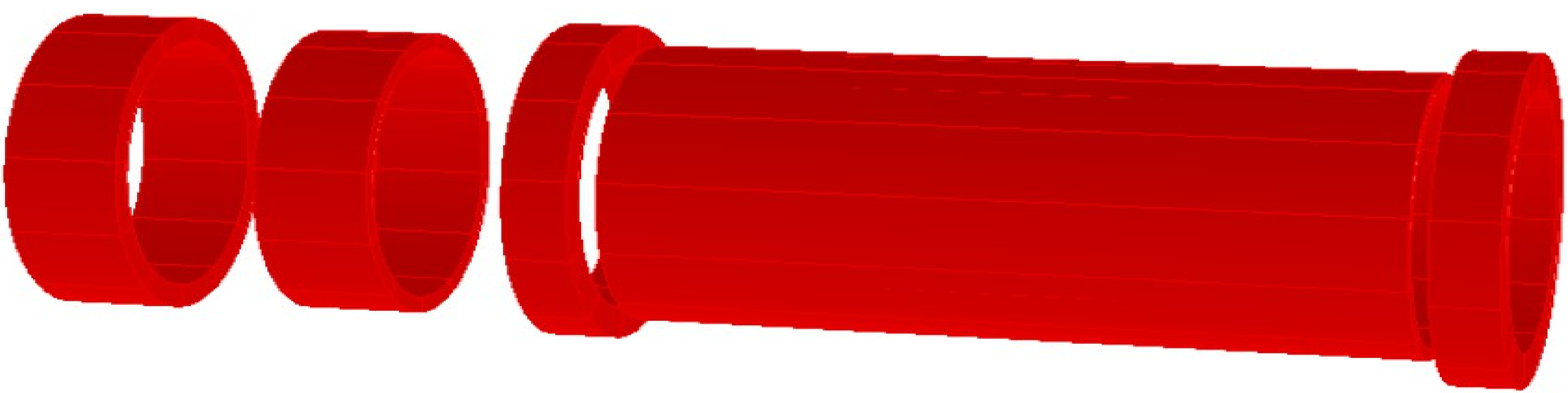
B_y affected by probe rotations!

Discussion of Results

- Axial field in spectrometer coil:
  - Uniform within ~1%
  - Small slope due to non-uniform winding density?
  - Model consistently below data at 150A (~2-3%). Power distribution issue?
- Radial field components:
  - It is difficult to maintain proper x-y-z alignment of Hall probe. B_y clearly affected.
  - Some data vs model discrepancies can be due to small (mm-level) shifts w.r.t. to ideal axis
    - NB: We see larger shifts in y than in x. Non-circular shape of coils?
- Thermal shrinkage effect needs to be taken into account for proper modeling

Lessons Learned

- Hall probe positioning and alignment is key:
  - Stiffer guide tube
  - Better shaft centering with bearings
  - Fix x-y-z alignment of probe with key/slot
  - Motorize probe motion along z-axis
  - Survey Al support plates w.r.t. z-axis
- Enable powering E1, C, and E2 coils individually
- Better current monitoring taking into account fringe field



Extra Slides

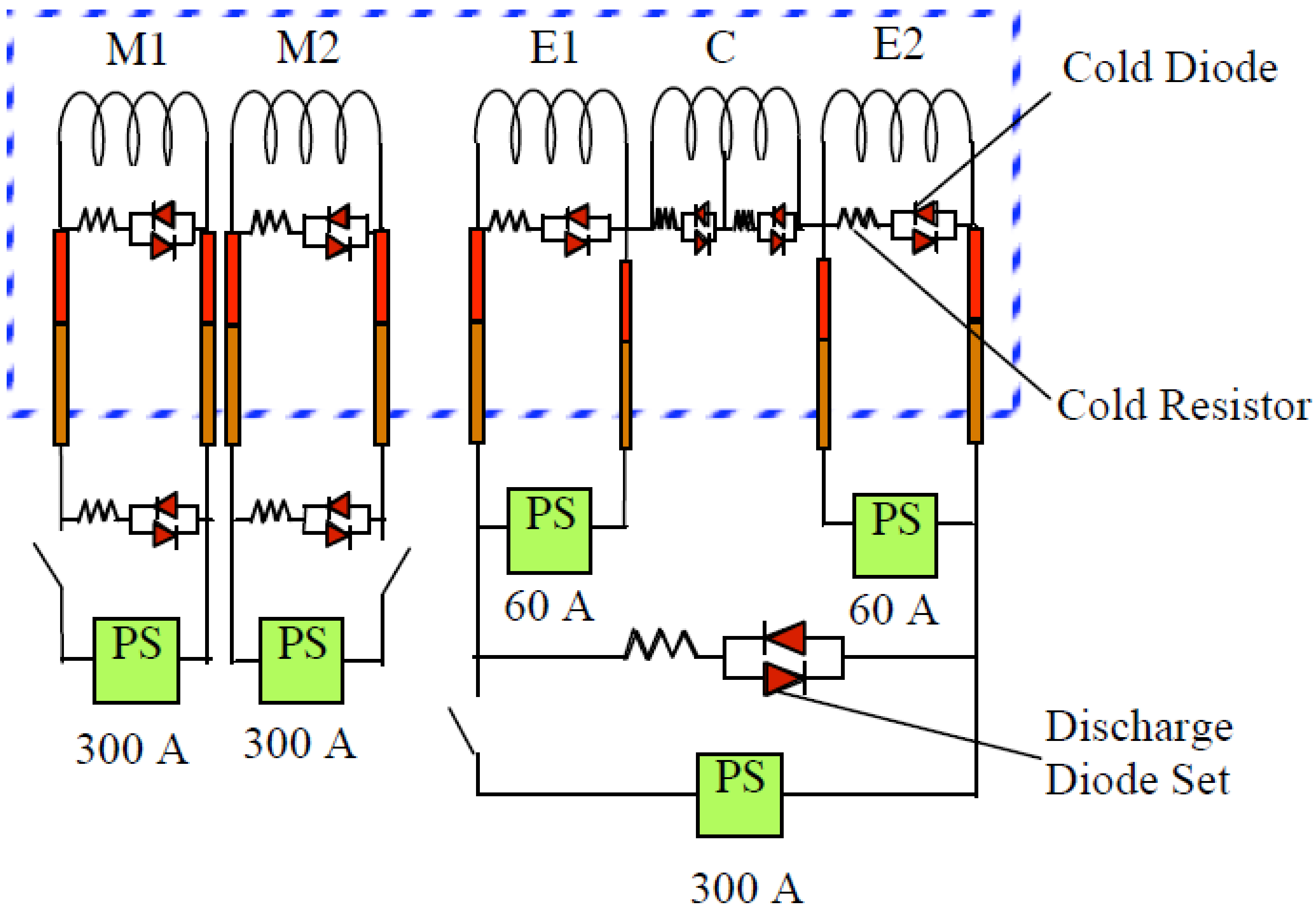
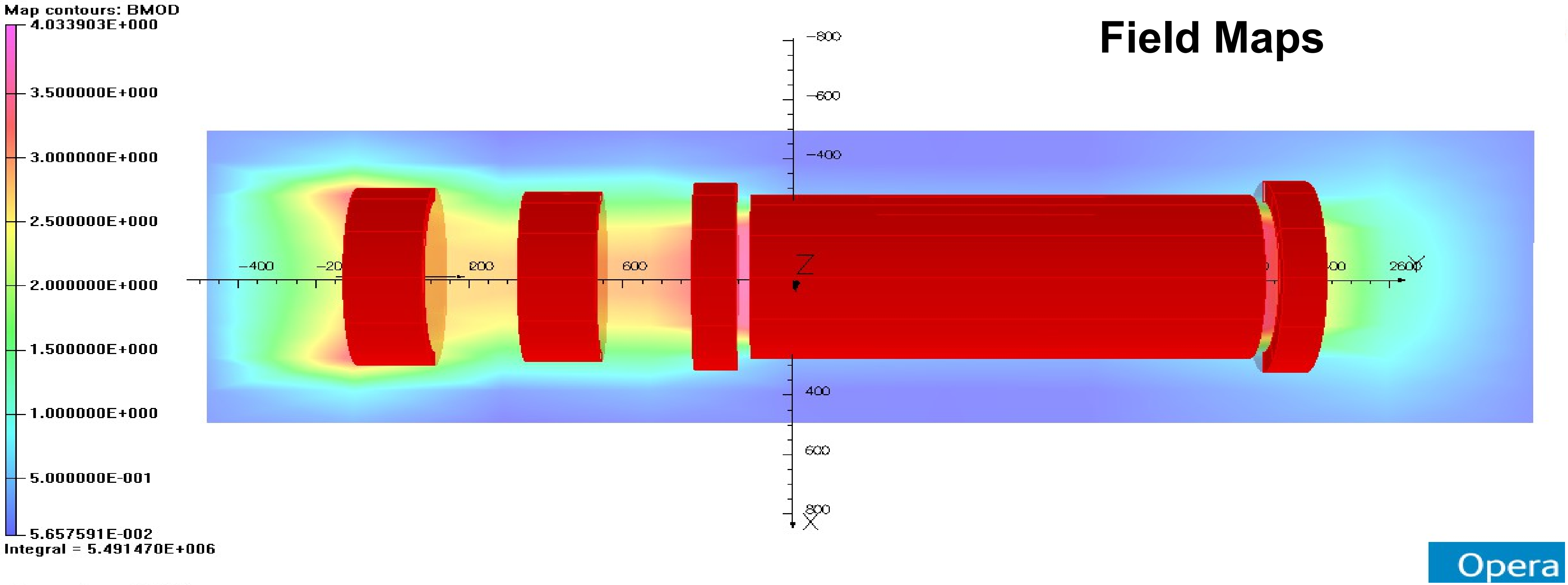
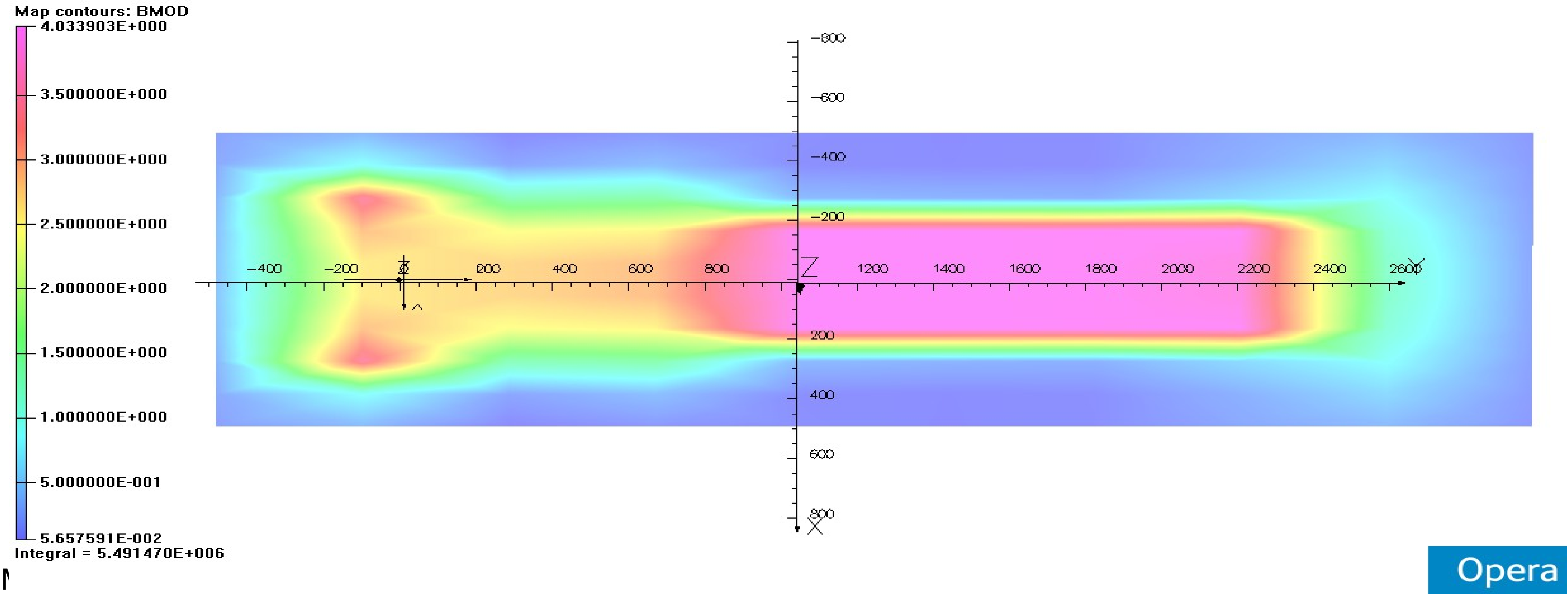


Fig.3 Quench protection circuit for the MICE spectrometer solenoids

Field Maps



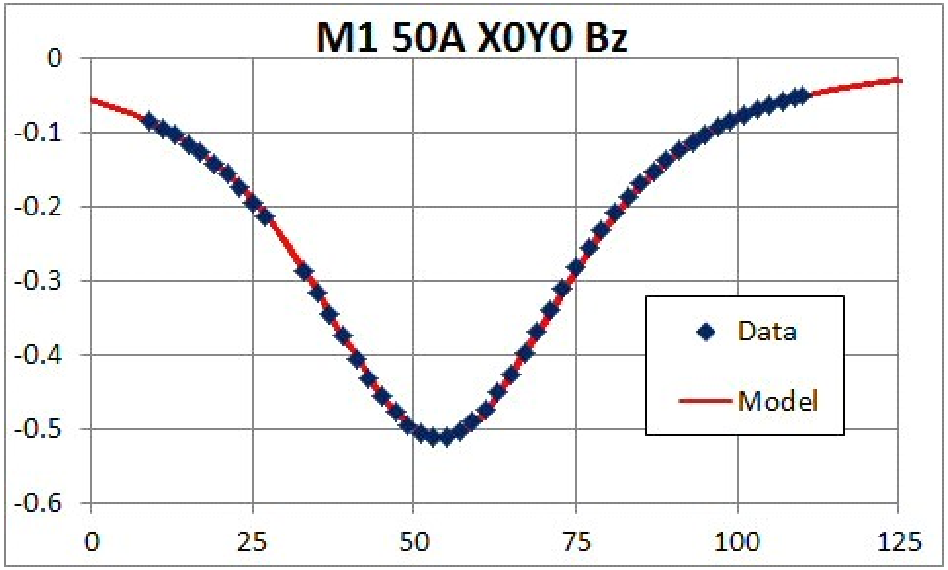
Map contours: BMOD
4.033903E+000
3.500000E+000
3.000000E+000
2.500000E+000
2.000000E+000
1.500000E+000
1.000000E+000
5.000000E-001
5.657591E-002
Integral = 5.491470E+006
Opera



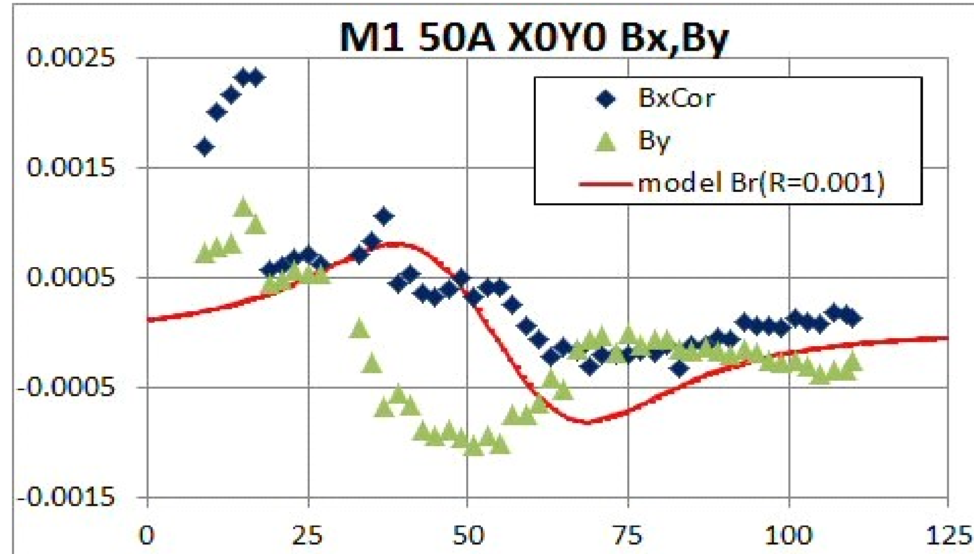
Map contours: BMOD
4.033903E+000
3.500000E+000
3.000000E+000
2.500000E+000
2.000000E+000
1.500000E+000
1.000000E+000
5.000000E-001
5.657591E-002
Integral = 5.491470E+006
Opera

M1, 50A, On-Axis

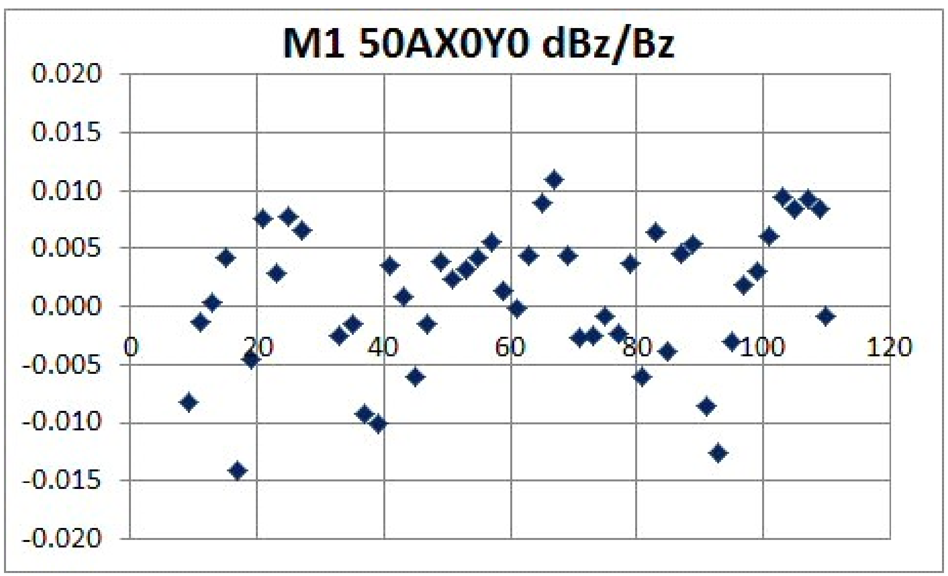
$B_{Axial}(z)$



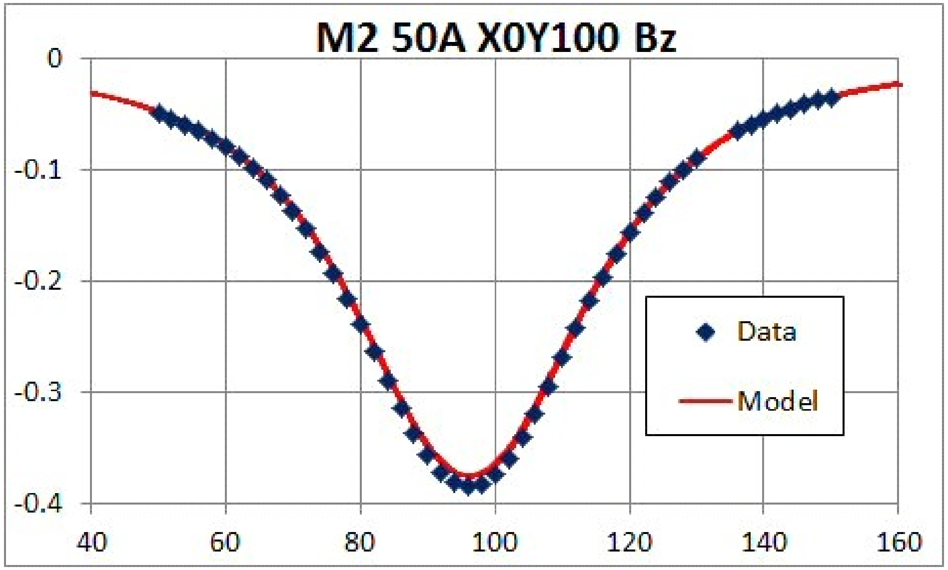
$B_{Radial}(z)$

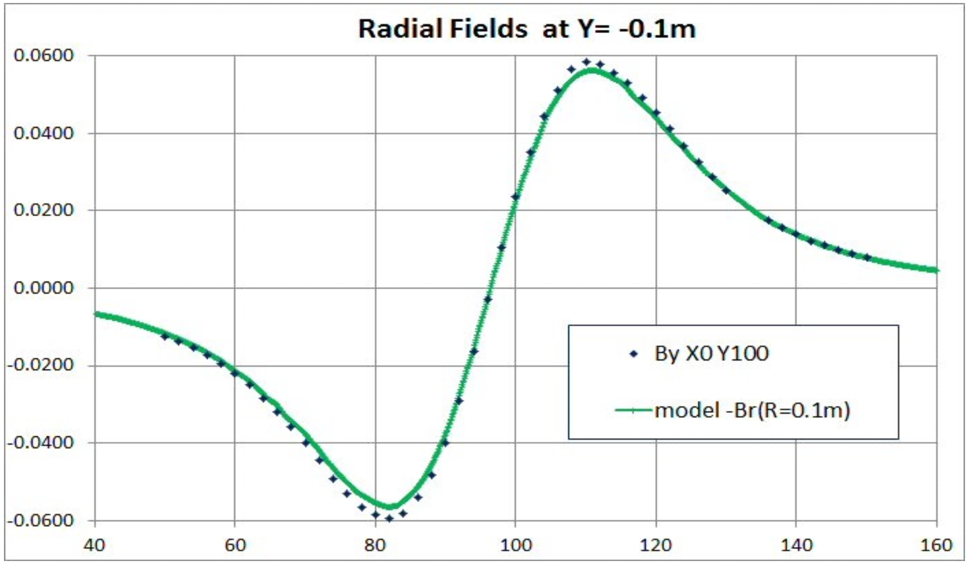


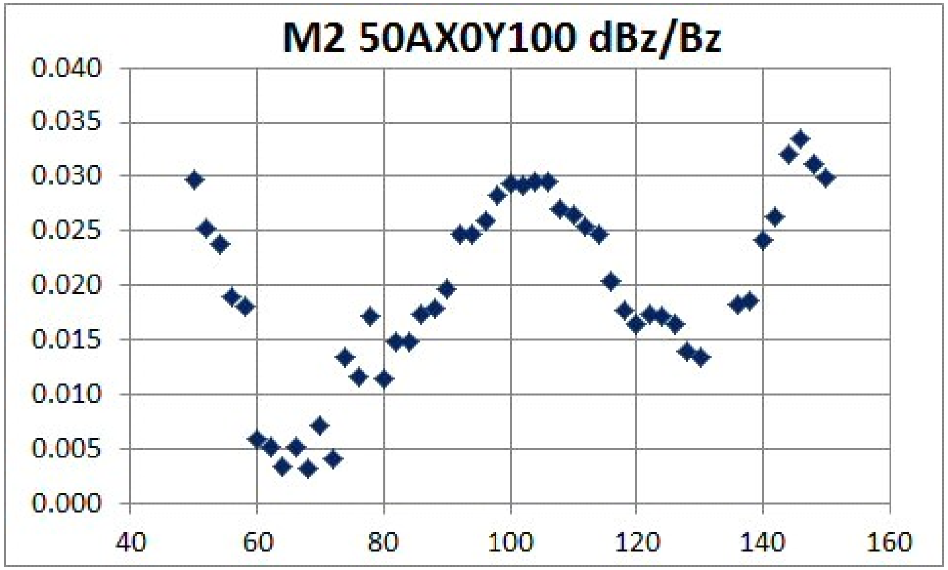
Small radial offset (~1mm)

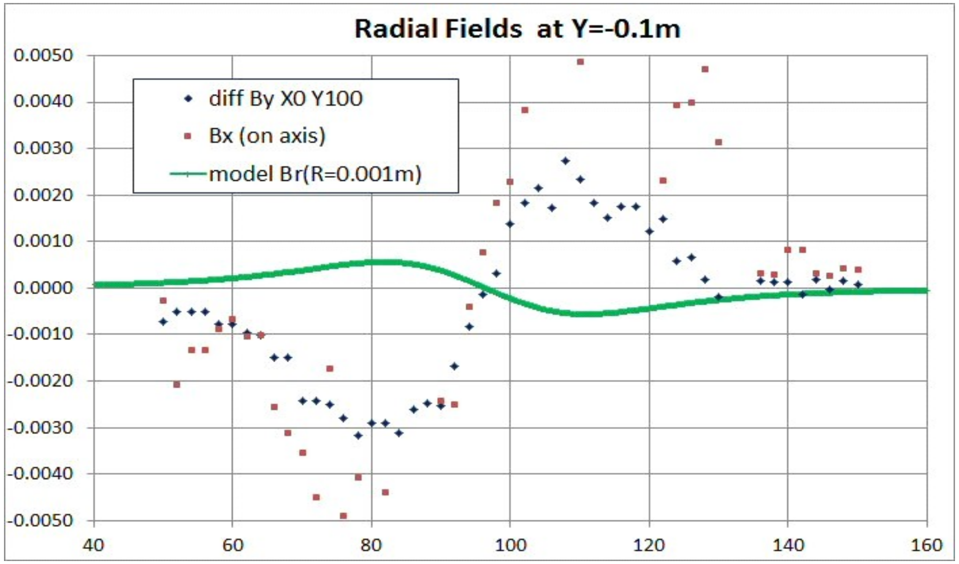


M2, 50A, Off-Axis









All Coils, 150A, Off-Axis