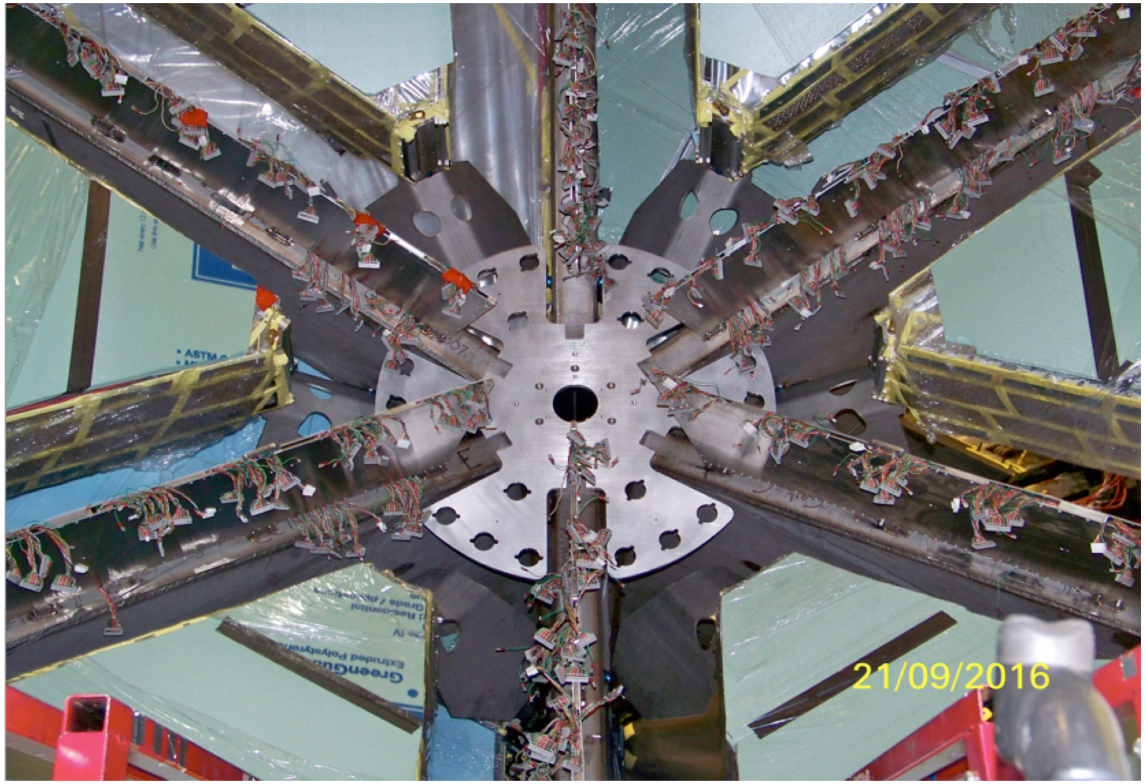


TORUS Field Mapping Update

Joseph Newton
CLAS Collaboration Meeting
July 11, 2018

Objectives and Physics Specifications

- **TORUS consists of six superconducting coils which produces a symmetric, mainly azimuthal field**
- **Joint-effort by Jefferson Lab and Fermilab**
- **Design allows for large acceptance of forward going particles (50% acceptance at 5 degrees from the beam axis)**
- **Maximum current is at 3770 A with the full field at 3.58 T**

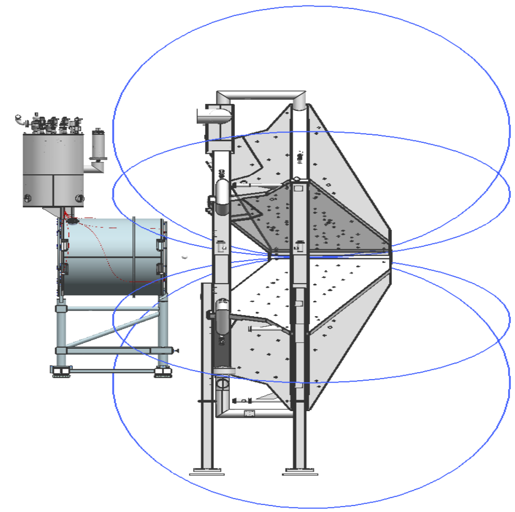


Fig. 1. Schematic of TORUS magnet and direction of the field lines

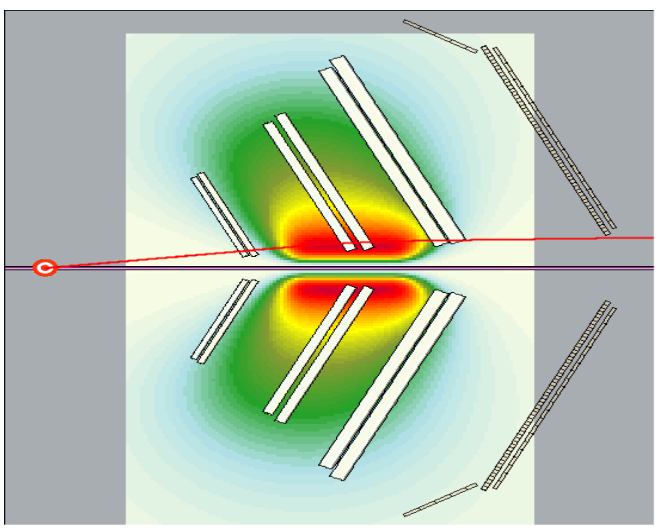
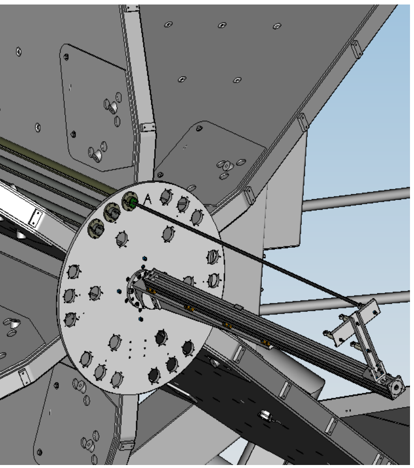


Fig. 2. In-bending track in the presence of the TORUS nominal field configuration

- Must understand the deviations of the coil positions and angular orientations due to manufacturing and installation process

TORUS Measurement and Fitting Procedure

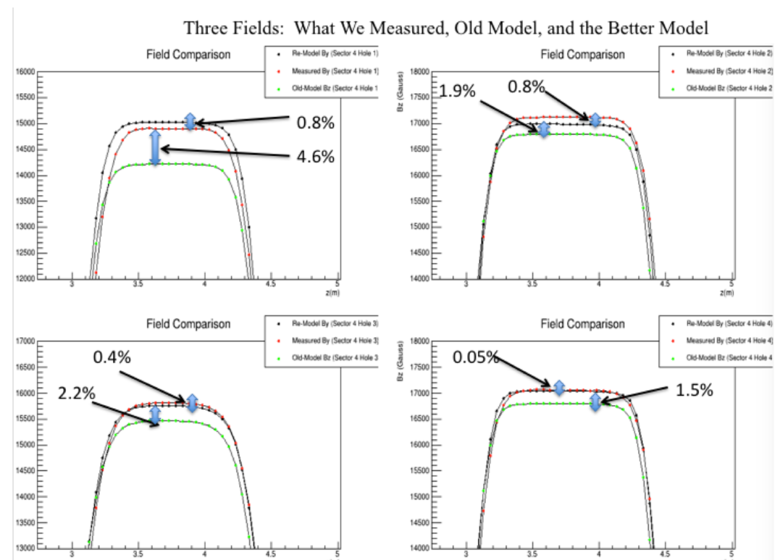
- Measure all components of the TORUS field at 24 positions in the XY plane along 40 positions along the z-axis and calculate the "distortion field"
- Minimize a chi-squared function that compares the measured and modeled "distortion fields" caused by the anticipated movements of the six coils



Visual model of the Hall probe being pushed by a motor along the beam axis inside a non-magnetic Carbon tube

$$\chi^2 = \sum_{pts=1}^{24} \sum_{dim=1}^{3} \left(\frac{\Delta B_{meas}(dim, pts) - \Delta B_{calc}(dim, pts)}{\delta B(dim)} \right)^2$$

- Measured data was compared to pre-calculated fields where coils were intentionally moved by a unit distance laterally offset, downstream, and radially outward from the bore.
- Using MINUIT, the coil movements from the designed position are determined by calculating the unit coefficients within the chi-squared function



Improvement of new field map (January 2018) compared to original map

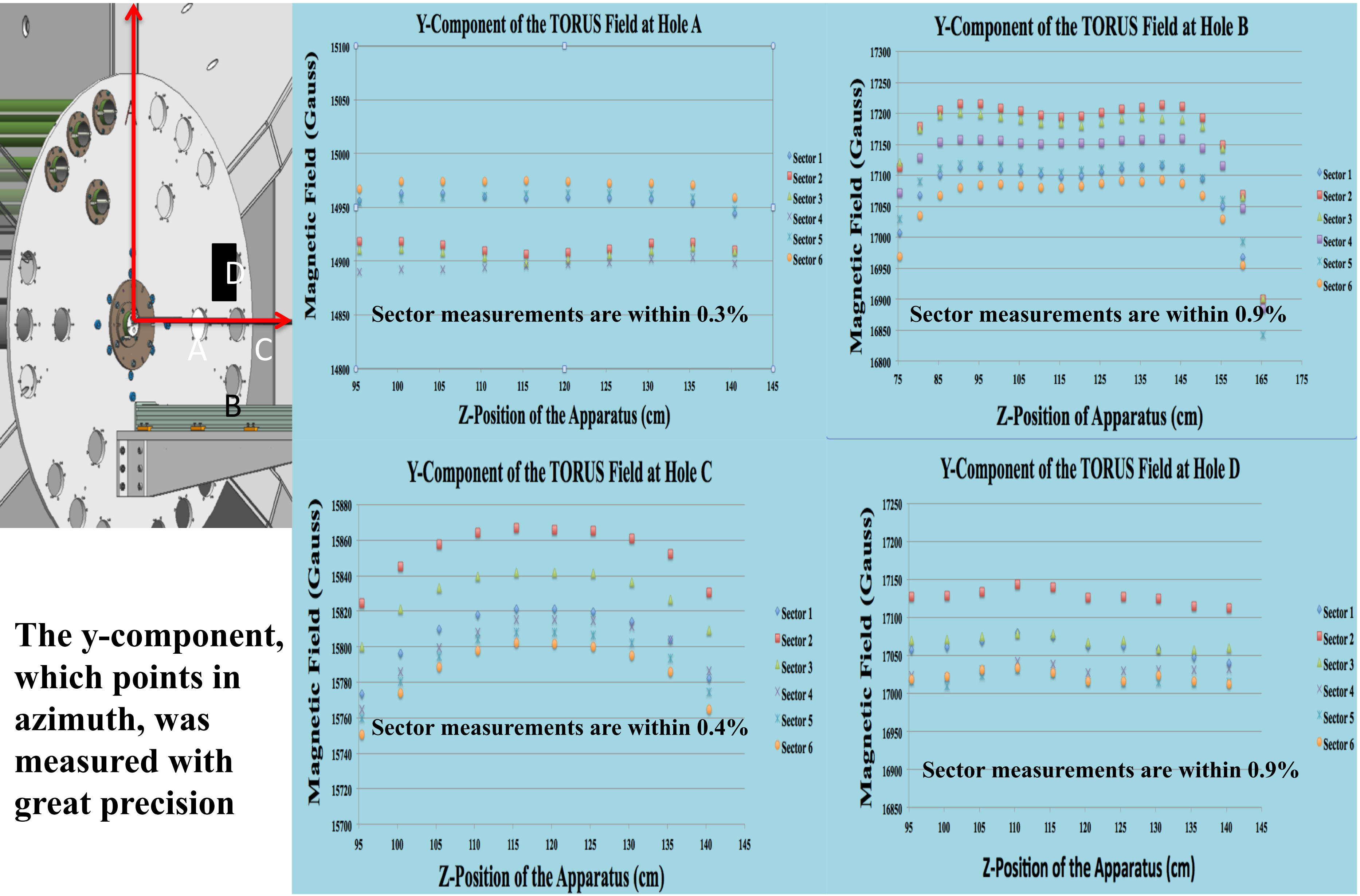
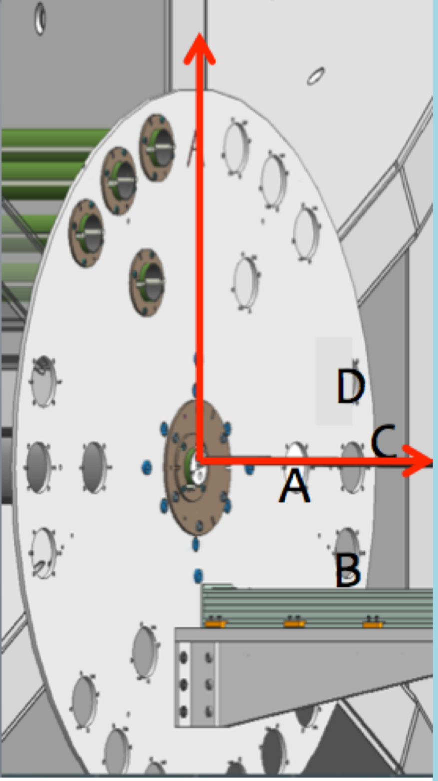
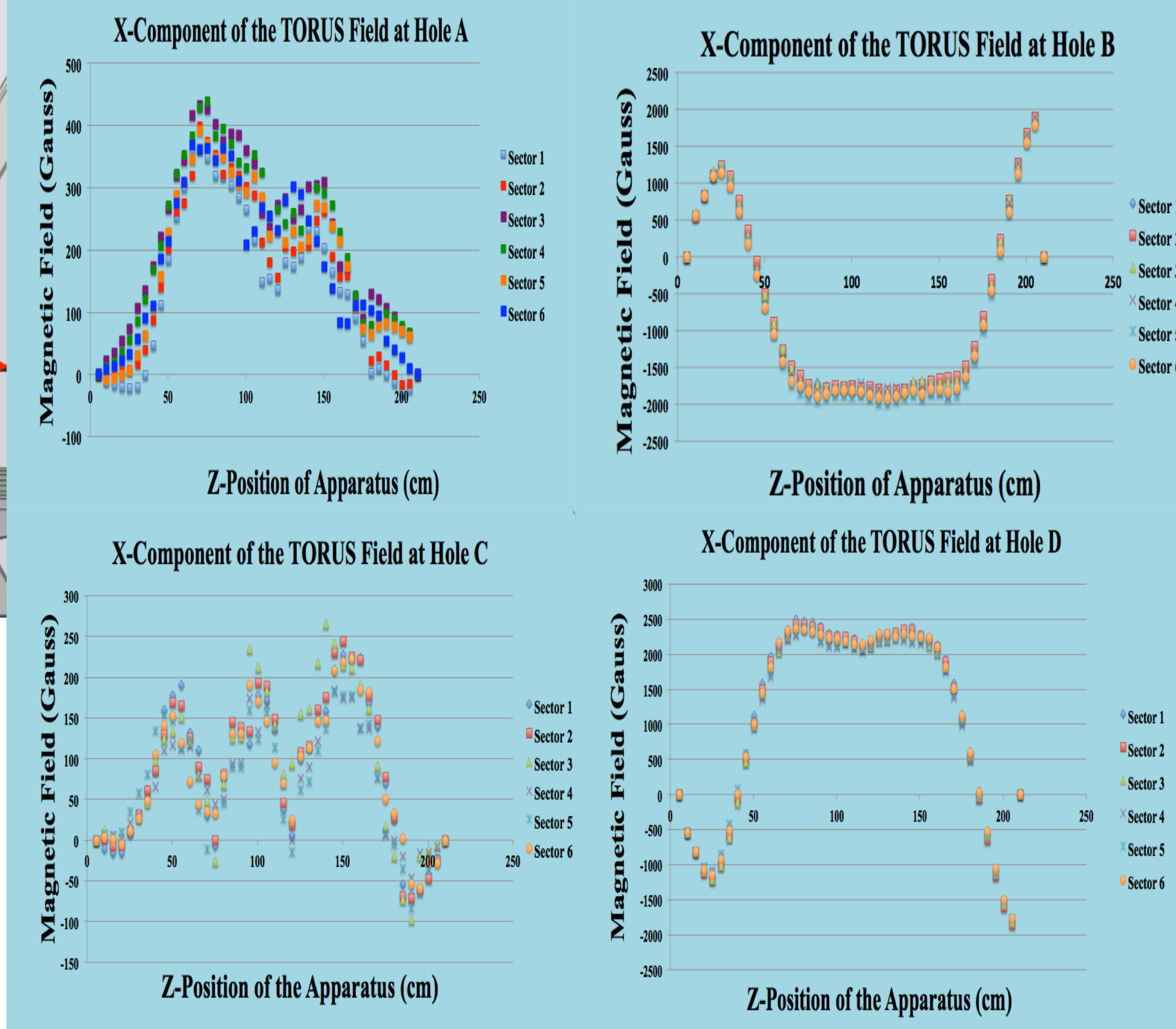


Fig. 4. Large component of the TORUS field at Holes A-D as measured in all six sectors.





The x-component, especially at Holes A and C, are viable ways of checking for systematic errors

Fig. 5. X-component of the TORUS field at Holes A-D in Sectors 1-6.

Production of TORUS Models

- Software -> Opera
- Produced By -> Dr. Probir Ghoshal
- Measured Data
- Nominal Model
- Field Map For Unit Distortion #1
- Field Map For Unit Distortion #2
- Field Map For Unit Distortion #3

$$\chi^2 = \sum_{pts=1}^{24} \sum_{dim=1}^{3} \left(\frac{\mathbf{\Delta B_{meas}(dim, pts) - \Delta B_{calc}(dim, pts)}}{\delta B(dim)}\right)^2$$

$$\Delta \mathrm{B}_{meas}(dim, pts) = [\mathrm{B}_{meas}(dim, pts) - \mathrm{B}_{ideal}(dim, pts)]$$

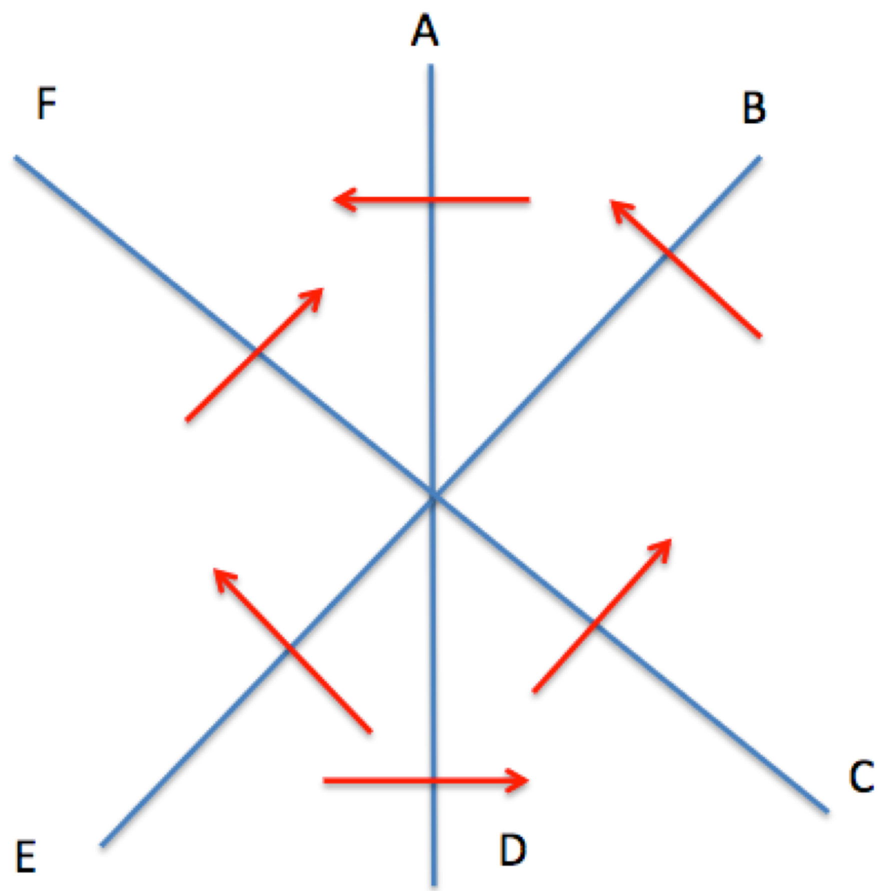
$$\Delta \mathbf{B_{calc}(dim, pts)} = \sum_{icoil=1}^{6} \sum_{mode=1}^{3} \alpha_{mode,icoil}(\mathbf{B_{ideal}(dim, pts)}$$

$$-\mathbf{B_{distortion}(dim, pts, icoil, mode)})$$

*ROOT/C++ script attempts to minimize chi-squared function which depends on the comparison of measured data's deviation from nominal with pre-produced data from nominal

Preliminary Results For Selected Z-Positions

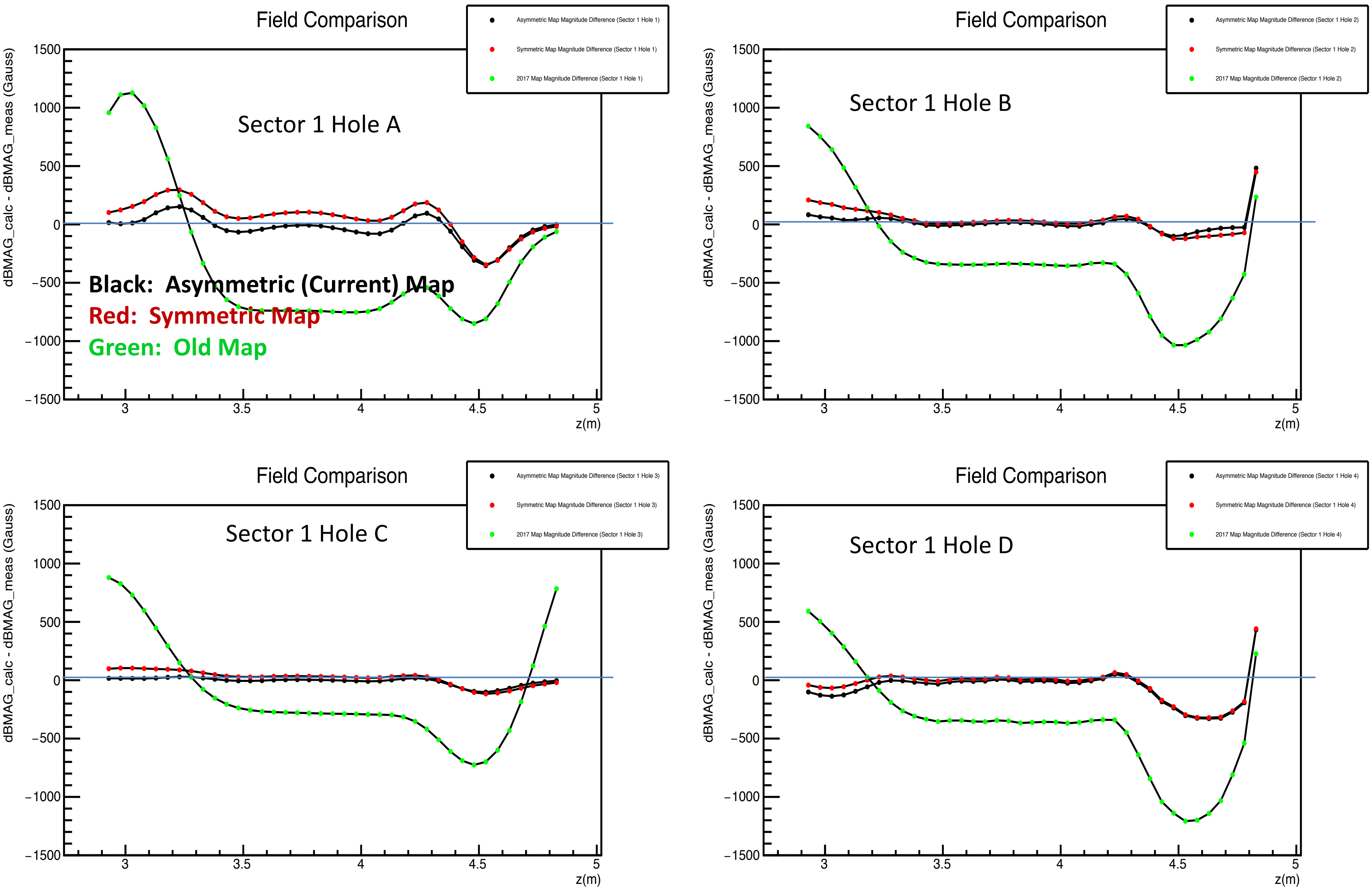
Coil 1 Radial Shift in mm	0.36185
Coil 2 Radial Shift in mm	-0.311987
Coil 3 Radial Shift in mm	-0.458769
Coil 4 Radial Shift in mm	-0.519575
Coil 5 Radial Shift in mm	2.21523
Coil 6 Radial Shift in mm	1.68347
Coil 1 Downstream Shift in mm	-0.217562
Coil 2 Downstream Shift in mm	1.67751
Coil 3 Downstream Shift in mm	3.04286
Coil 4 Downstream Shift in mm	4.36706
Coil 5 Downstream Shift in mm	2.51131
Coil 6 Downstream Shift in mm	0.23668
Coil 1 Azimuthal Shift in mm	-0.250904
Coil 2 Azimuthal Shift in mm	-0.40883
Coil 3 Azimuthal Shift in mm	-0.728354
Coil 4 Azimuthal Shift in mm	0.606732
Coil 5 Azimuthal Shift in mm	0.0660279
Coil 6 Azimuthal Shift in mm	0.0198553

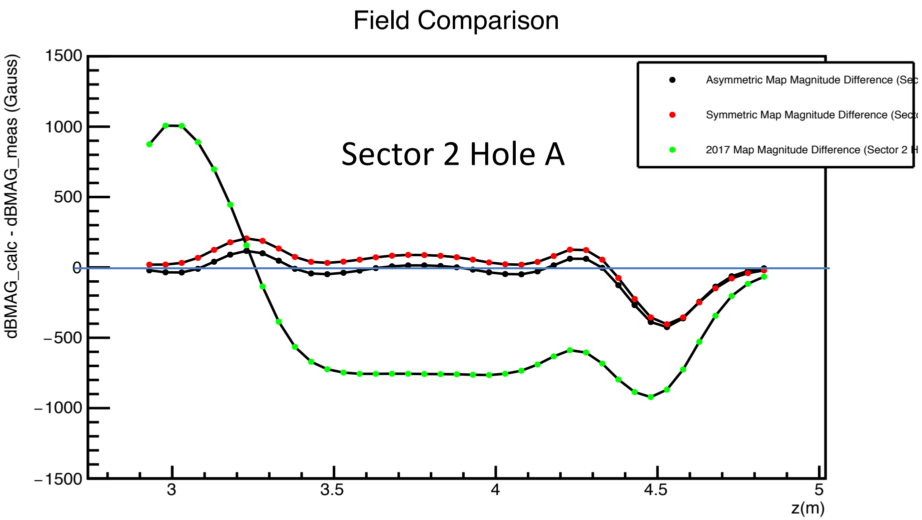


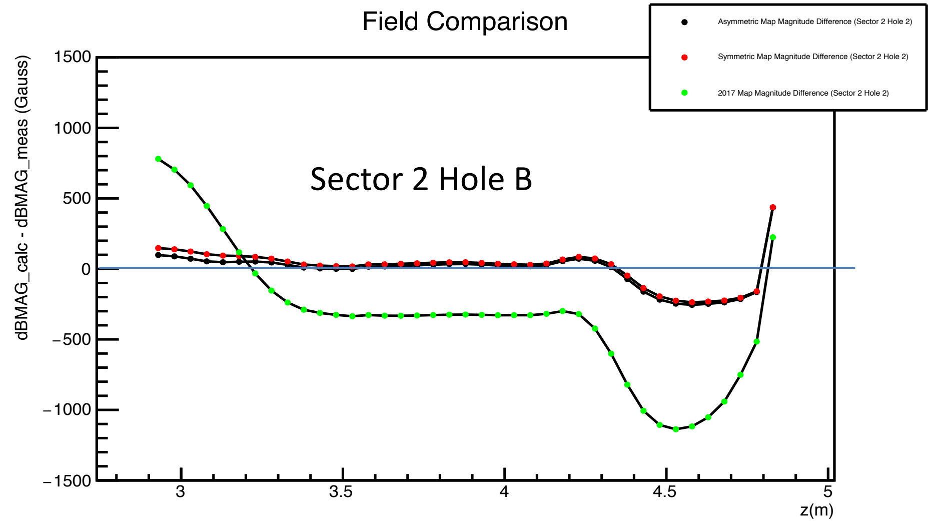
With shifts in azimuth, the entire coil moves translationally. There is no rotation.

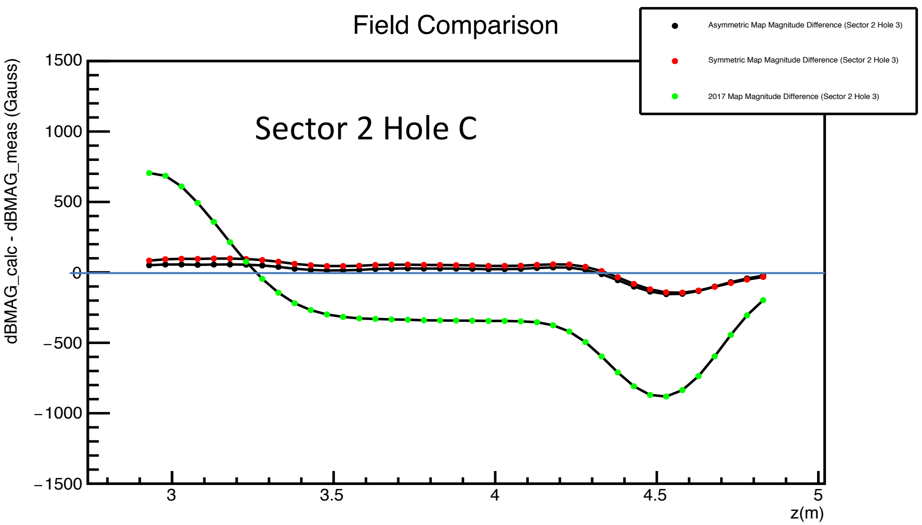
Evolution of the Field Map

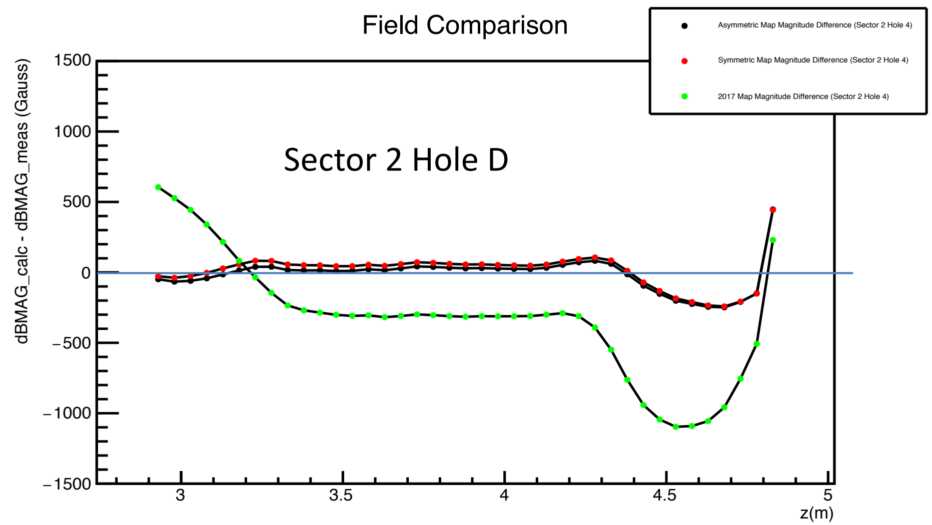
- Before January 2018: Symmetric Field Map With Relatively Simplistic Coil Shape Compared To Refined Coil Shape
- January 2018: Asymmetric Field Map With Coils Moved Inward With The Original Coil Shapes
- April 2018: Symmetric Field Map With Refined Coil Shapes
- May 2018: Asymmetric Field Map With The Refined Coil Shapes Taking Into Account The Calculated Coil Positions

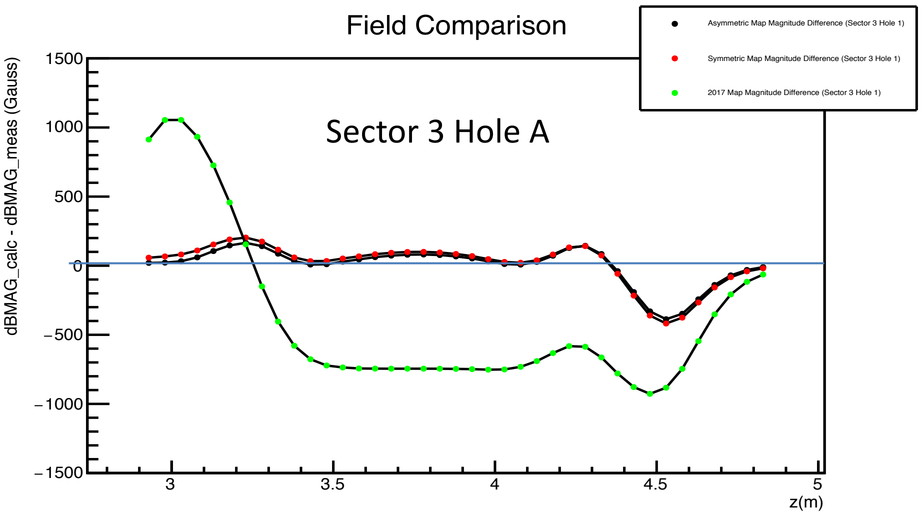

Field Comparison
Asymmetric Map Magnitude Difference (Sector 1 Hole 1)
Symmetric Map Magnitude Difference (Sector 1 Hole 1)
2017 Map Magnitude Difference (Sector 1 Hole 1)
Sector 1 Hole A
Black: Asymmetric (Current) Map
Red: Symmetric Map
Green: Old Map
dBMAG_calc - dBMAG_meas (Gauss)
z(m)
Field Comparison
Asymmetric Map Magnitude Difference (Sector 1 Hole 2)
Symmetric Map Magnitude Difference (Sector 1 Hole 2)
2017 Map Magnitude Difference (Sector 1 Hole 2)
Sector 1 Hole B
dBMAG_calc - dBMAG_meas (Gauss)
z(m)
Field Comparison
Asymmetric Map Magnitude Difference (Sector 1 Hole 3)
Symmetric Map Magnitude Difference (Sector 1 Hole 3)
2017 Map Magnitude Difference (Sector 1 Hole 3)
Sector 1 Hole C
dBMAG_calc - dBMAG_meas (Gauss)
z(m)
Field Comparison
Asymmetric Map Magnitude Difference (Sector 1 Hole 4)
Symmetric Map Magnitude Difference (Sector 1 Hole 4)
2017 Map Magnitude Difference (Sector 1 Hole 4)
Sector 1 Hole D
dBMAG_calc - dBMAG_meas (Gauss)
z(m)


Field Comparison
Asymmetric Map Magnitude Difference (Sec
Symmetric Map Magnitude Difference (Sec
2017 Map Magnitude Difference (Sector 2 H
Sector 2 Hole A
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)

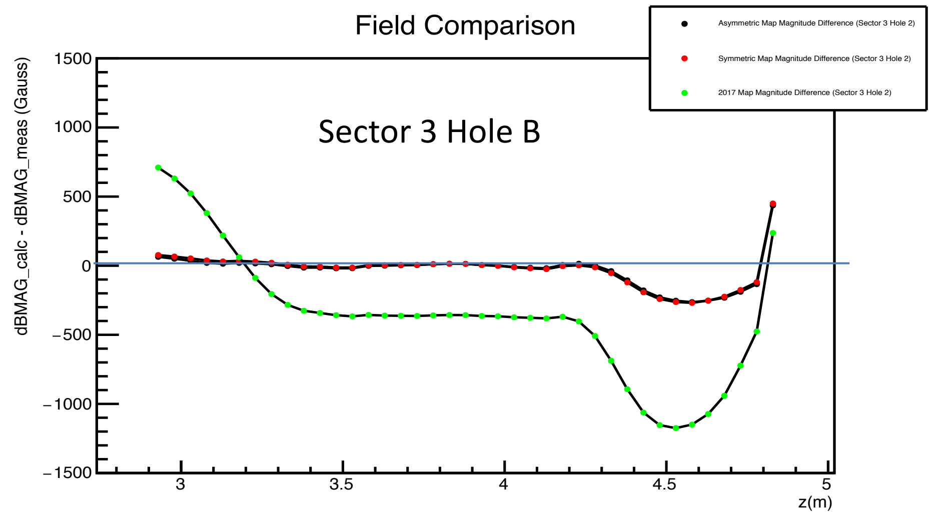

Field Comparison
Asymmetric Map Magnitude Difference (Sector 2 Hole 2)
Symmetric Map Magnitude Difference (Sector 2 Hole 2)
2017 Map Magnitude Difference (Sector 2 Hole 2)
Sector 2 Hole B
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)


Field Comparison
Asymmetric Map Magnitude Difference (Sector 2 Hole 3)
Symmetric Map Magnitude Difference (Sector 2 Hole 3)
2017 Map Magnitude Difference (Sector 2 Hole 3)
Sector 2 Hole C
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)

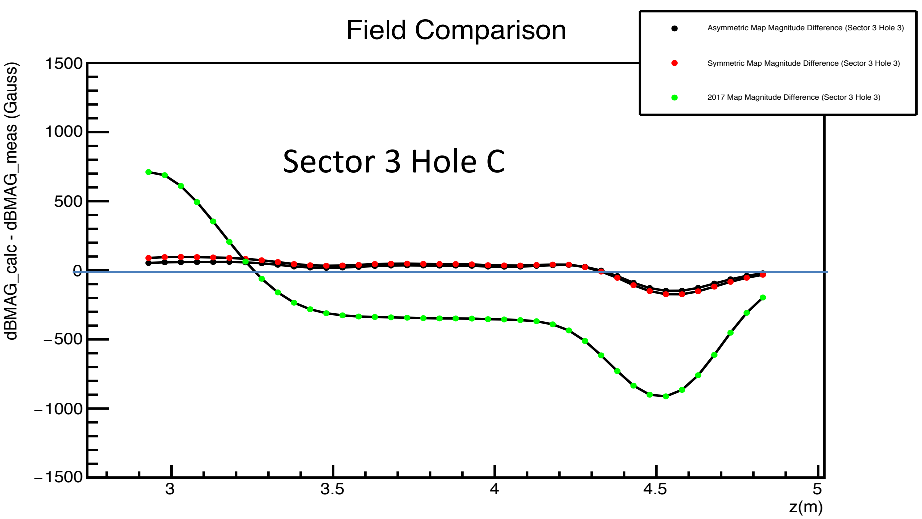

Field Comparison
Asymmetric Map Magnitude Difference (Sector 2 Hole 4)
Symmetric Map Magnitude Difference (Sector 2 Hole 4)
2017 Map Magnitude Difference (Sector 2 Hole 4)
Sector 2 Hole D
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)



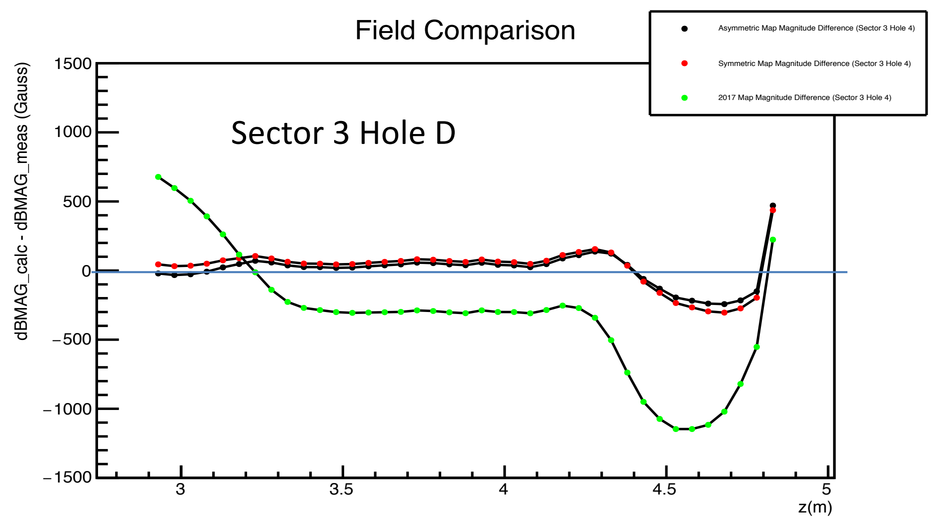
Field Comparison
Asymmetric Map Magnitude Difference (Sector 3 Hole 1)
Symmetric Map Magnitude Difference (Sector 3 Hole 1)
2017 Map Magnitude Difference (Sector 3 Hole 1)
Sector 3 Hole A
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)



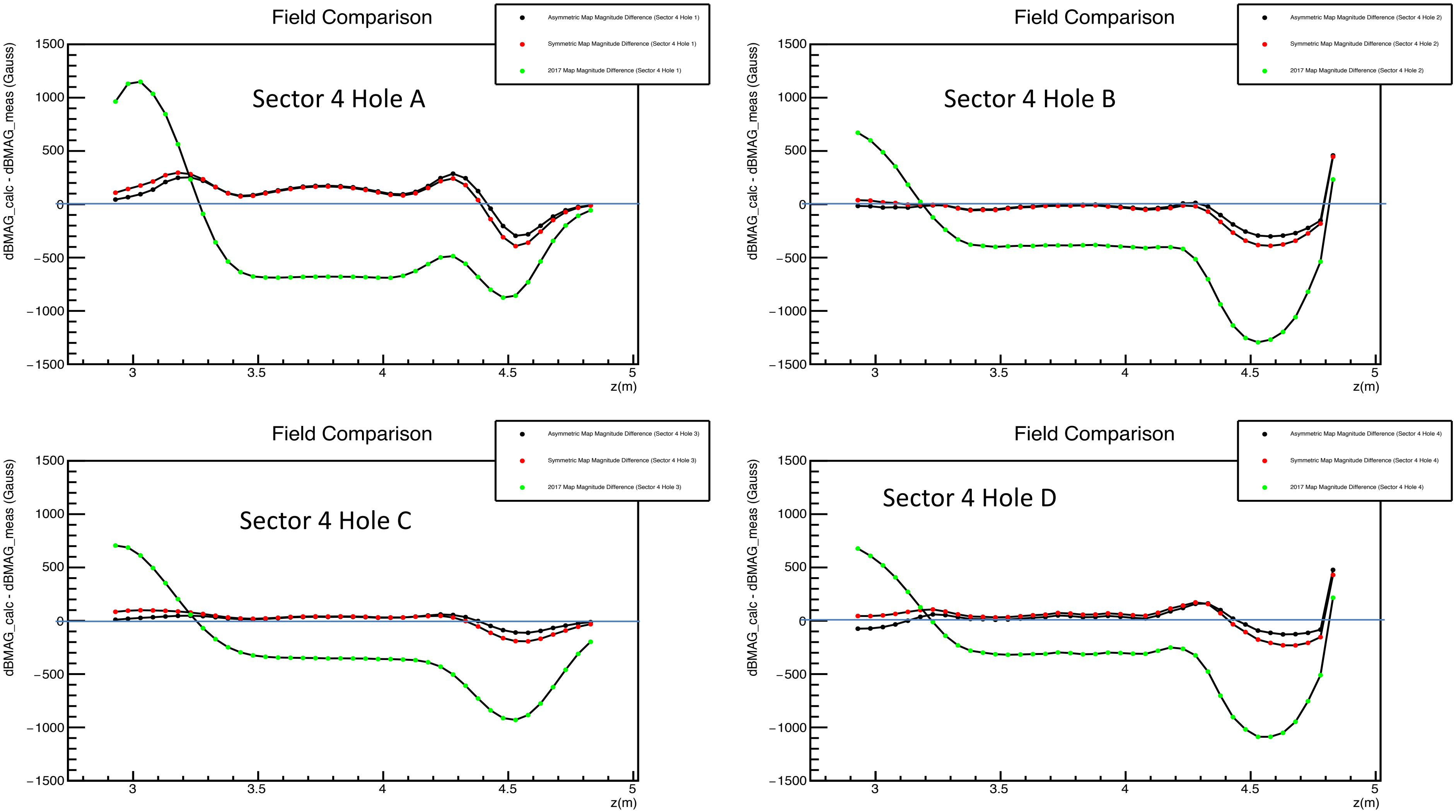
Field Comparison
Asymmetric Map Magnitude Difference (Sector 3 Hole 2)
Symmetric Map Magnitude Difference (Sector 3 Hole 2)
2017 Map Magnitude Difference (Sector 3 Hole 2)
Sector 3 Hole B
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)

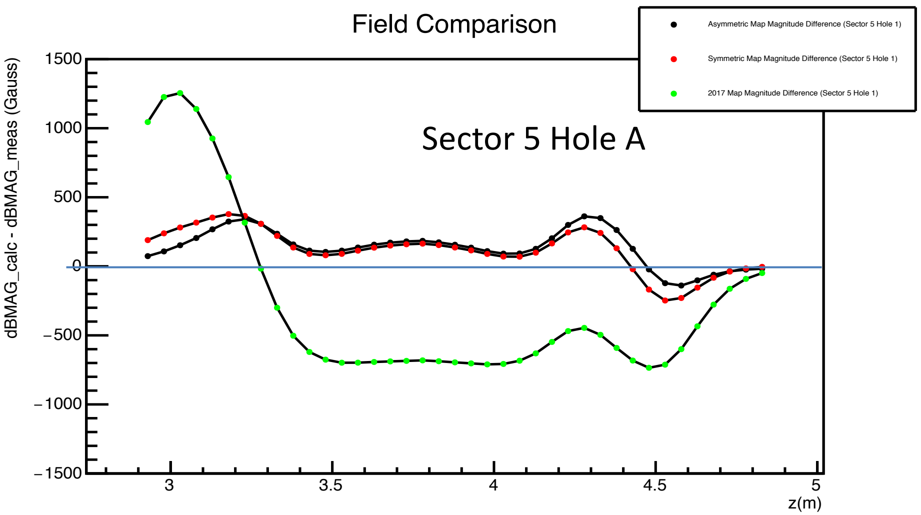


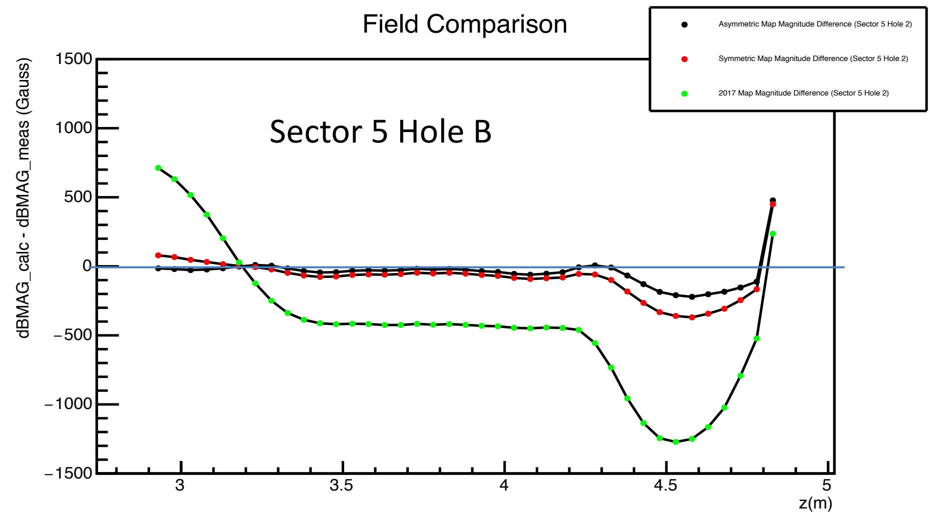
Field Comparison
Asymmetric Map Magnitude Difference (Sector 3 Hole 3)
Symmetric Map Magnitude Difference (Sector 3 Hole 3)
2017 Map Magnitude Difference (Sector 3 Hole 3)
Sector 3 Hole C
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)

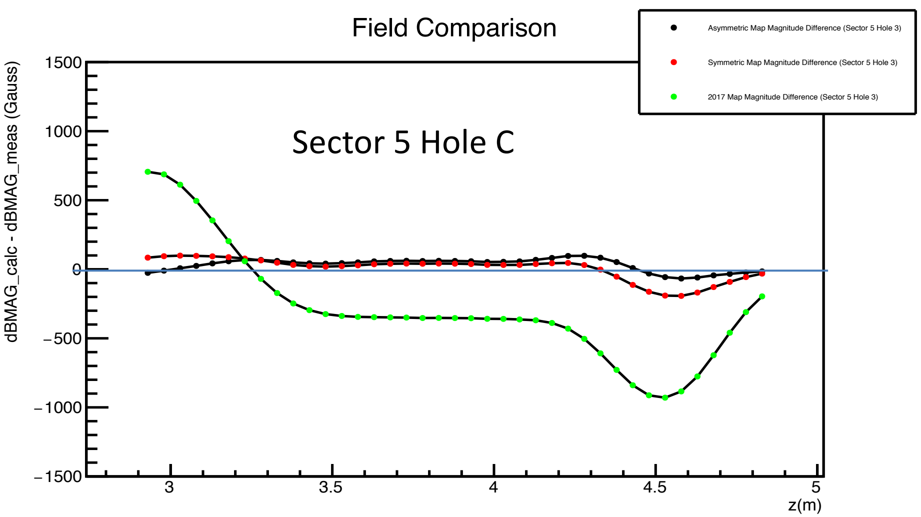


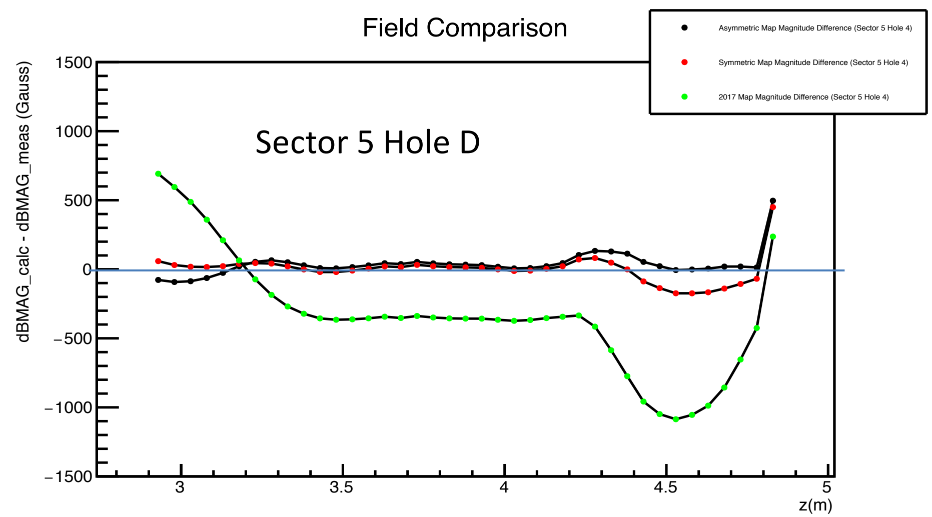
Field Comparison
Asymmetric Map Magnitude Difference (Sector 3 Hole 4)
Symmetric Map Magnitude Difference (Sector 3 Hole 4)
2017 Map Magnitude Difference (Sector 3 Hole 4)
Sector 3 Hole D
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)

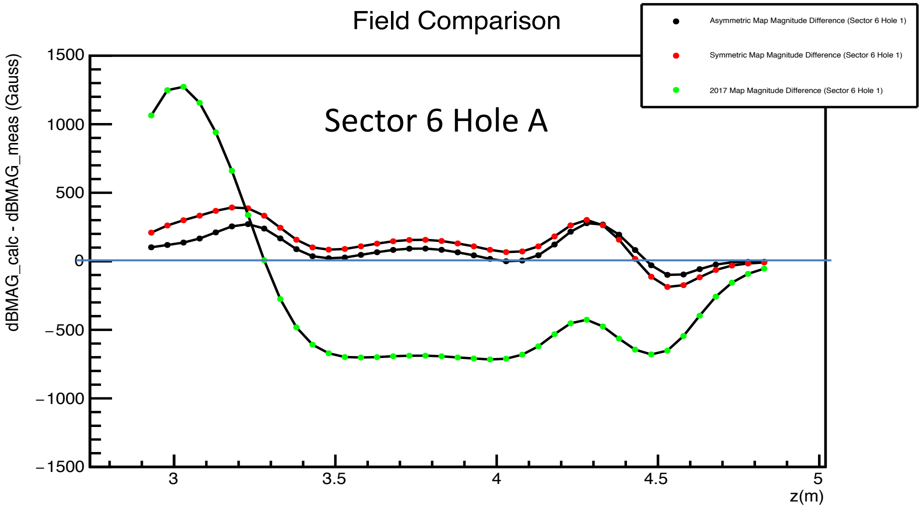

Field Comparison
Asymmetric Map Magnitude Difference (Sector 4 Hole 1)
Symmetric Map Magnitude Difference (Sector 4 Hole 1)
2017 Map Magnitude Difference (Sector 4 Hole 1)
Sector 4 Hole A
dBMAG_calc - dBMAG_meas (Gauss)
z(m)
Field Comparison
Asymmetric Map Magnitude Difference (Sector 4 Hole 2)
Symmetric Map Magnitude Difference (Sector 4 Hole 2)
2017 Map Magnitude Difference (Sector 4 Hole 2)
Sector 4 Hole B
dBMAG_calc - dBMAG_meas (Gauss)
z(m)
Field Comparison
Asymmetric Map Magnitude Difference (Sector 4 Hole 3)
Symmetric Map Magnitude Difference (Sector 4 Hole 3)
2017 Map Magnitude Difference (Sector 4 Hole 3)
Sector 4 Hole C
dBMAG_calc - dBMAG_meas (Gauss)
z(m)
Field Comparison
Asymmetric Map Magnitude Difference (Sector 4 Hole 4)
Symmetric Map Magnitude Difference (Sector 4 Hole 4)
2017 Map Magnitude Difference (Sector 4 Hole 4)
Sector 4 Hole D
dBMAG_calc - dBMAG_meas (Gauss)
z(m)

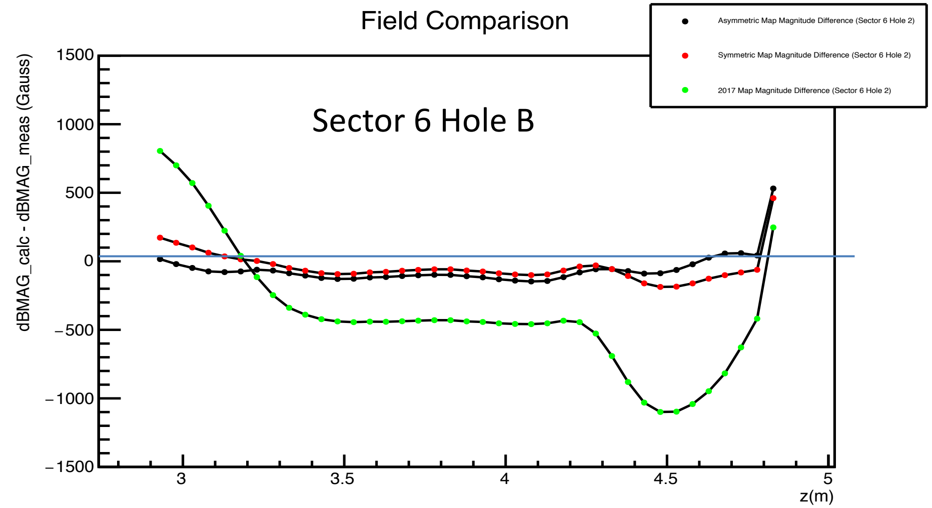

Field Comparison
Asymmetric Map Magnitude Difference (Sector 5 Hole 1)
Symmetric Map Magnitude Difference (Sector 5 Hole 1)
2017 Map Magnitude Difference (Sector 5 Hole 1)
Sector 5 Hole A
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)

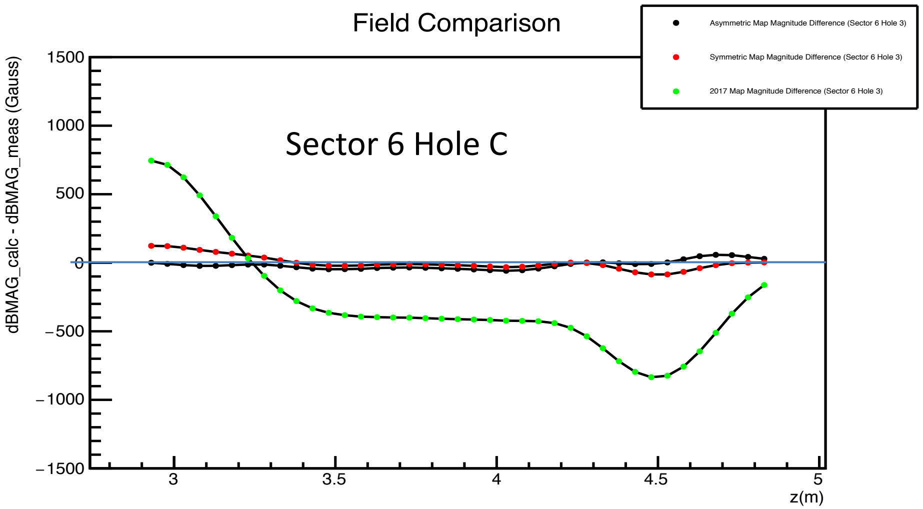

Field Comparison
Asymmetric Map Magnitude Difference (Sector 5 Hole 2)
Symmetric Map Magnitude Difference (Sector 5 Hole 2)
2017 Map Magnitude Difference (Sector 5 Hole 2)
Sector 5 Hole B
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)

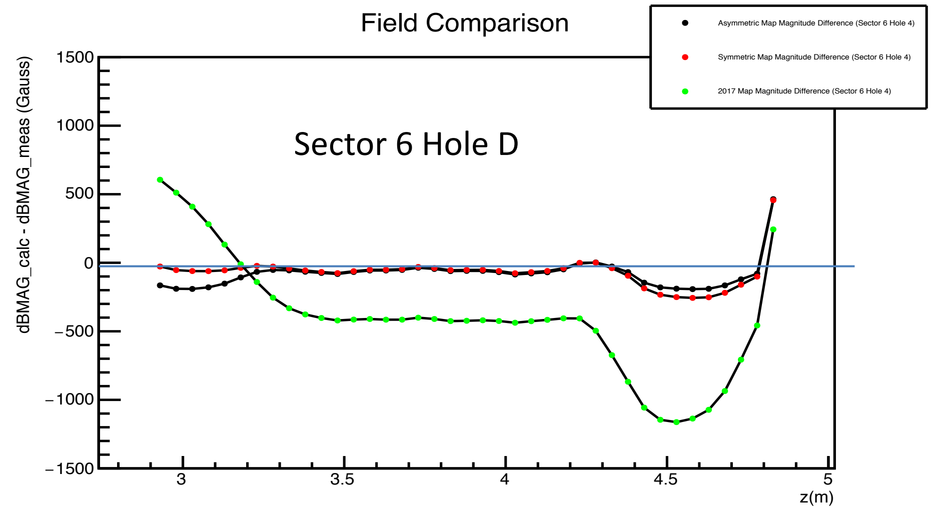

Field Comparison
Asymmetric Map Magnitude Difference (Sector 5 Hole 3)
Symmetric Map Magnitude Difference (Sector 5 Hole 3)
2017 Map Magnitude Difference (Sector 5 Hole 3)
Sector 5 Hole C
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)


Field Comparison
Asymmetric Map Magnitude Difference (Sector 5 Hole 4)
Symmetric Map Magnitude Difference (Sector 5 Hole 4)
2017 Map Magnitude Difference (Sector 5 Hole 4)
Sector 5 Hole D
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)


Field Comparison
Asymmetric Map Magnitude Difference (Sector 6 Hole 1)
Symmetric Map Magnitude Difference (Sector 6 Hole 1)
2017 Map Magnitude Difference (Sector 6 Hole 1)
Sector 6 Hole A
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)


Field Comparison
Asymmetric Map Magnitude Difference (Sector 6 Hole 2)
Symmetric Map Magnitude Difference (Sector 6 Hole 2)
2017 Map Magnitude Difference (Sector 6 Hole 2)
Sector 6 Hole B
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)


Field Comparison
Asymmetric Map Magnitude Difference (Sector 6 Hole 3)
Symmetric Map Magnitude Difference (Sector 6 Hole 3)
2017 Map Magnitude Difference (Sector 6 Hole 3)
Sector 6 Hole C
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)


Field Comparison
Asymmetric Map Magnitude Difference (Sector 6 Hole 4)
Symmetric Map Magnitude Difference (Sector 6 Hole 4)
2017 Map Magnitude Difference (Sector 6 Hole 4)
Sector 6 Hole D
dBMAG_calc - dBMAG_meas (Gauss)
1500
1000
500
0
−500
−1000
−1500
3
3.5
4
4.5
5
z(m)

Ongoing Studies and Improvement of Fit

- Interpretation of the bore data
- Testing the effect of different weighted constants for different measurement values
- Using more robust fitting algorithms and strategies with MINUIT

Conclusions

*Inner (30 cm) measurements indicate approximately a 0.5% deviation from the measured data
*Outer (46.5 cm) measurements indicate approximately a 0.05% deviation from the measured data
*Fluctuations in the inner measurement deviations are consistent with the effect of a 1.5 mm change to the outer radius of the coil shape

Acknowledgements

- Thanks to our project managers: Mac Mestayer and Renuka Rajput-Ghoshal
- Thanks to our data analyst: Joseph Newton
- Thanks to our field model producer: Probir Ghoshal
- Thanks for the work on improving Torus coil representation in model: Dave Kashy
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- Thanks to all of our shift workers from the CLAS collaboration: Harut Avagyan, Dan Carman, Jixie Zhang, Olga Cortes Beccera, Eugene Pasyuk, Stepan Stepanyan, Maurizio Ungaro, Victoria Lagerquist