ACTIVE COMPENSATION COILS IN THE FERMILAB G-2 EXPERIMENT

K. E. Badgley†, B. Kiburg, *on behalf of the Muon g-2 Collaboration*, Fermilab, Batavia IL, USA
M. Smith, University of Washington, Seattle WA, USA

Abstract

The Fermilab muon g-2 experiment is aiming to determine the anomalous magnetic moment of the muon to 140 ppb. A uniform storage ring magnetic field is required to achieve this level of precision, where the magnetic field seen by the muon must be known to within a fraction of a ppm. In addition to the mechanical adjustments made to the magnet pole tips, a set of 200 compensation coils were added to the ring. These coils form concentric rings with a 100 each on the top and bottom poles. Measurements of the remaining integrated field errors were made using NMR probes. The use of these coils to reduce the remaining higher order field errors will be discussed.

INTRODUCTION

The Fermilab muon g-2 experiment [1] aims to measure the muon anomalous magnetic moment, α_μ to the unprecedented precision of 140 parts per billion. A 3.1 GeV polarized positive muon beam will be injected into a storage ring that has a uniform magnetic field. The muon spins will precess in the storage ring magnetic field. Muons decay via the parity violating Weak interaction, which leads to a correlation between the decay positron direction and muon spin. The anomalous magnetic moment is proportional to the anomalous precession frequency and inversely proportional to the storage ring magnetic field. Hence, both the magnetic field uniformity along with a detailed knowledge of the magnetic field are important.

Main Dipole

The main 1.45 T dipole field of the g-2 ring is formed by a C-shaped iron magnet excited with superconducting coils. A cross section of the magnet is shown in Fig. 1.

Shimming Results

Once the main mechanical knobs had been adjusted, further field smoothing was accomplished through a massive shimming campaign. Over 8280 foils on sheets of G10 were added to the upper and lower pole faces to reduce the field to less that 10ppm [2]. During the field adjustment process, and periodically throughout the g-2 experiment, a trolley with an array of NMR probes is used to measure the magnetic field [1]. The average remaining field and higher order multipoles measured with the trolley NMR probe array are reported in table 1. During the g-2 experiment, the trolley will periodically measure the field, and corrective adjustments can be made with the compensation coils.

†kbadgley@fnal.gov

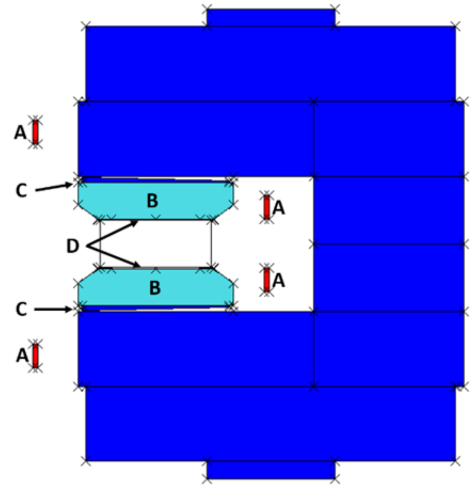

Figure 1: OPERA model of the main ring showing the superconducting coils (A), iron pole faces (B), iron adjustment wedges (C), and the compensation coils (D).

Table 1: Azimuthally Averaged Higher Order Multipole Coefficients

Multipole (ppm)	Normal	Skew
n=1	0.02	-0.56
n=2	-0.71	-3.77
n=3	0.75	0.62
n=4	0.44	1.61

COMPENSATION COILS

A set of 200 coils were added to the surface of the magnet poles, 100 each on top and bottom, as an adjustment knob for correcting the remaining higher order multipoles around the ring. These coils form concentric rings with a positive current defined as producing an upward field in the ring center. The coils are located on the pole faces and sit on top of the G10 sheets and shims.

Setup

The coils are formed as traces on printed circuit boards, where there are 36 boards for both the upper and lower pole faces. Each board makes up 10° of the main ring and has a 3.33° taper with an inner radius of 6.954 m and outer radius 7.269 m. The 70 mil (1.778 mm) traces have a 100 mil (2.54 mm) spacing and form continuous rings through connectors on both ends of each board. At the connection region, the current is brought 2.5 mm above the main coil plane for 14-14.5 mm. All 200 coils can be individually controlled up to +/- 2.5 A.

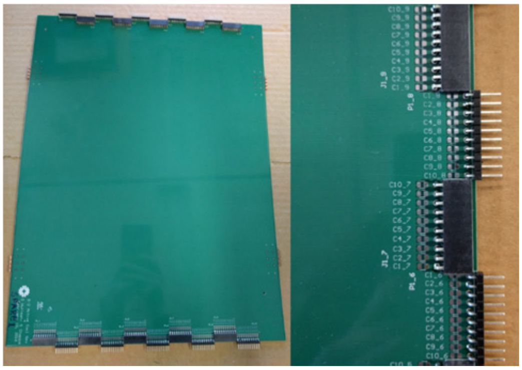

Figure 2: One of the spare correction coil boards(left). A close up of the alternating male and female connector pins on the sides(right).

Modeling

The 200 coils were modeled using OPERA 2D FEA simulation software [3]. The iron and coils of the main dipole magnet and the iron poles and wedges were included in the model. The shimming foils were not included as they vary in azimuth around the ring. Figure 1 shows the magnetic model and location of the compensation coils. The multipoles were calculated according to eqns. 1-3 around a reference radius (r_0) of 4.5 cm. The normal multipole ($b_n = r_0^n B_n/B_0$) and skew multipole ($a_n = r_0^n A_n/B_0$) coefficients are with respect to the main $B_0 = 1.45\ T$ dipole field of the g-2 ring.

$$B_y(r,\theta) = \sum_{n=0}^{\infty} (B_n \cos(n\theta) - A_n \sin(n\theta)) r_0^n \quad (1)$$

$$B_0 = \frac{1}{2\pi} \int_0^{2\pi} B_y(r,\theta) d\theta \quad (2)$$

$$r_0^n B_n = \frac{1}{\pi} \int_0^{2\pi} B_y(r,\theta) \cos(n\theta)\, d\theta \quad (3)$$

The currents required to produce the multipoles are listed in table 2. These currents were based on previous work [4,5], with some modification and an expansion to include the n=5 multipole. The resulting magnetic field, with overlaid potential lines for the normal and skew multipoles, is shown in Fig. 3 and 5 respectively. Table 3 gives the calculated multipole for each of these current configurations. The distributions were scaled to ensure the max current for any coil was 2.5A. Due to the asymmetry from the iron wedges, these ideal current distributions for the normal multipoles will need further adjustment. Figure 4 shows the result of adjustment on the normal quadrupole (Fig. 3a).

Once the model and the actual response from the coils agree, a full simulation sweep through each coils contribution to the normal and skew components will be made. The results will be put in a matrix which can be optimized to quickly determine the required currents on each wire to cancel out the multipoles. This procedure will be repeated after the periodic trolley runs.

The average magnetic field will also depend on the contribution from the coil trace connection regions, which sit in a plane 2.5 mm above the main coils. This connection region makes up 7 % of the coil length and will be added to the average based on a simulation performed by shifting the coils 2.5 mm toward the center.

Table 2: Current Distributions to Produce the Listed Higher Order Multipole. For the Normal Components, the Top and Bottom Current are the Same. For the Skew, the Top and Bottom Currents have Opposite Sign. For Both, the Top Currents are Listed and h is the Half Magnet Gap Length.

Multipole	**Normal**	**Skew**
Dipole	-	1
Quadrupole	h	x
Sextupole	$h^2 - x^2$	$x^2 - h^2$
Octupole	$h^3 - 3hx^2$	$x^3 - 3h^2x$
Decapole	$h^4 - 6h^2x^2 + x^4$	$4hx(h^2 - x^2)$

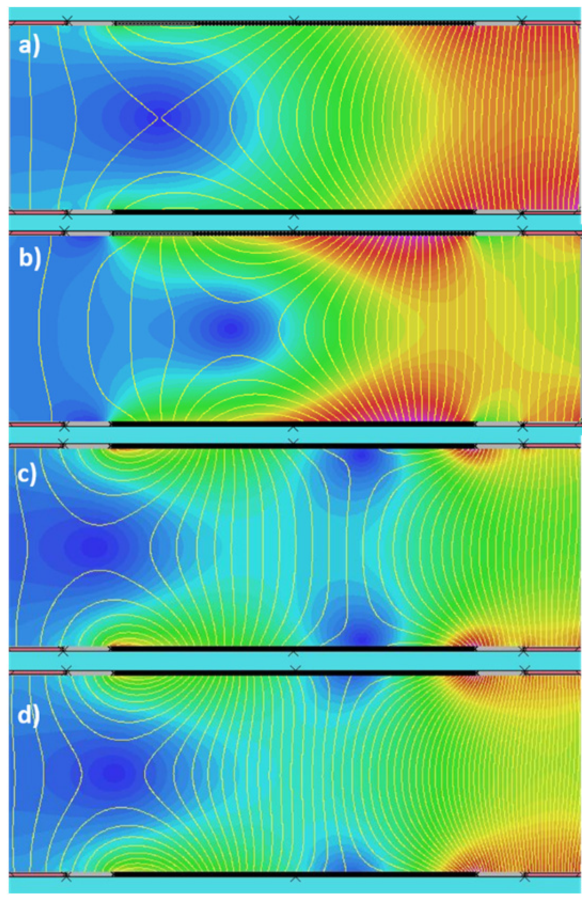

Figure 3: Normal higher order multipoles produced by the current distributions listed in table 2 for the a) quadrupole, b) sextupole, c) octupole, and d) decapole. Color scale is arbitrary, with max current for each distribution set to 2.5 A.

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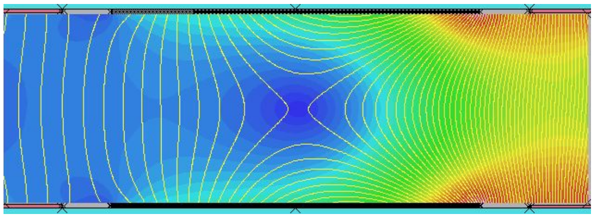

Figure 4: Normal quadrupole with tilted current density compared with Fig 3a.

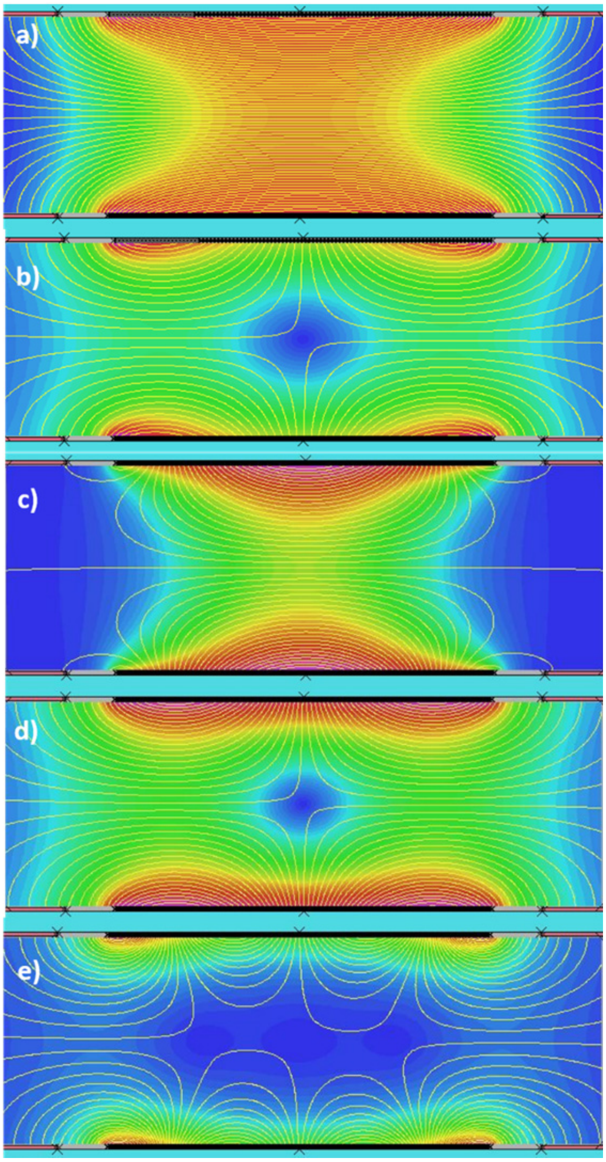

Figure 5: Skew higher order multipoles produced by the current distributions listed in table 2 for the a) dipole, b) quadrupole, c) sextupole, d) octupole, and e) decapole. Color scale is arbitrary, with max current for each distribution set to 2.5 A.

Comparison to experiment

The installation of the compensation coils is ongoing, but a measurement was made with the NMR trolley using 12 of the coils while the main dipole field was on. The coils are numbered 1-100 for the top and bottom, with 1 being closest to the inside of the ring. For this setup, top coils 1-8 and bottom coils 1-4 were set to 2A. Bottom coils 91-94 were set to -2A. The resulting change in the dipole and other higher order multipoles, with the coils on and off, is being used to adjust the vertical location of the correction coils in the model. The difference in the field produced by these coils is shown in Fig. 6 and the measured ppm change is in table 3. Further testing with more activated coils will be performed in the near future.

Table 3: PPM Change in the Field Due to 16 Activated Currents.

Multipole	ppm change in field
Dipole	-46.8
Normal Quad	-1.5
Normal Sext	3.2
Normal Oct	-0.6
Normal Dec	0.49
Skew Quad	0.49
Skew Sext	3.1
Skew Oct	-
Skew Dec	-0.15

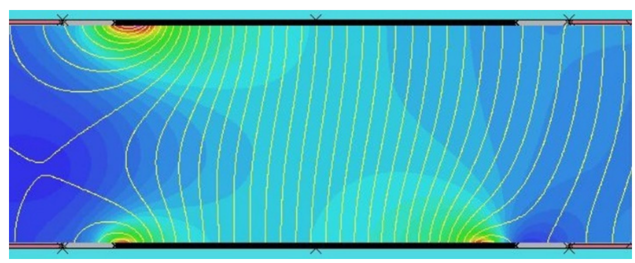

Figure 6: Simulation of 16 activated coils to compare to experiment.

CONCLUSION

The Fermilab muon g-2 experiment aims to produce a sub 1ppm uniform magnetic field. The last knob to fine tune the field is the compensation coils which can be used to dynamically cancel out the remaining higher order multipoles. Once the coils have been fully connected, further work will be needed to match simulation to the experimental setup.

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