Magnetic Field Perturbations Due to a MicroTCA Crate

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Abstract

The Muon g-2 experiment at Fermi National Accelerator Laboratory intends to test the completeness of the Standard Model. The E821 experiment at Brookhaven National Laboratory measured the anomalous magnetic moment of the muon in a constant magnetic field and found a 3.6σ standard deviation from the theoretically predicted value. Fermilab′s experiment aims to increase the precision of their experiment to determine if there is a 5σ standard deviation. If so, this would lead to the conclusion that the Standard Model is incomplete. In order to ensure this precision, the electronics near the experiment were tested to check how high the magnetic field perturbations were when put near a calibration magnet.

1 Introduction

Leptons (electrons, muons, and taons) have a magnetic moment along their spin, described by:

$$\vec{\mu}_\ell = g_\ell \frac{q}{2m_\ell} \vec{S} \tag{1}$$

where q is the charge of the lepton and m_ℓ is the mass of the lepton. Here, g_ℓ, the gyromagnetic ratio, is the value that the experiment at Brookhaven and Fermilab have and will measure. Dirac predicted that g should equal two for all leptons, but the actual experimental value deviates from this. This deviation is known as the anomalous magnetic moment, described by:

$$a_\ell = \frac{g_\ell - 2}{2} \tag{2}$$

This equation then gives us a way to measure that deviation from Dirac′s theory.

Theory predicts that the anomalous magnetic moment for the muon is created by three separate factors:

$$a_{SM} = a_{QED} + a_{EW} + a_{had} \tag{3}$$

These three loop contributions are quantum electrodynamics, electroweak interactions, and hadronic interactions. From all of these three contributions, the expected Standard Model prediction for the anomalous magnetic moment for the muon is found to be:[1]

$$a_{SM} = .00116591803(1)(42)(26) \tag{4}$$

Here, the errors result from the electroweak, the lowest-order hadronic, and the higher-order hadronic loop contributions, in that order. At Brookhaven National Laboratory, the E821 experiment found that the anomalous magnetic moment for the muon was:

$$a_{SM} = .00116592081(54)(33) \tag{5}$$

The first error here is statistical while the second error is systematic. The experiment found that there was a 3.6σ deviation between theory and experiment, suggesting that there may be some new physics not accounted for in the theory′s prediction.[2]

The Muon g-2 experiment at Fermilab intends to replicate the same experiment. However, the experiment will be precise enough to see a 5σ discrepancy if it exists. If we find our data to have this large discrepancy, then that would be enough evidence to conclude the existence of new physics. In this experiment, as with Brookhaven, μ^+ and μ^- will be accelerated to a high intensity and then moved into a 50 foot in diameter superconducting coil that will act as a storage ring for the muons. The setup for g-2 with the superconducting coil is found in Figure 1.

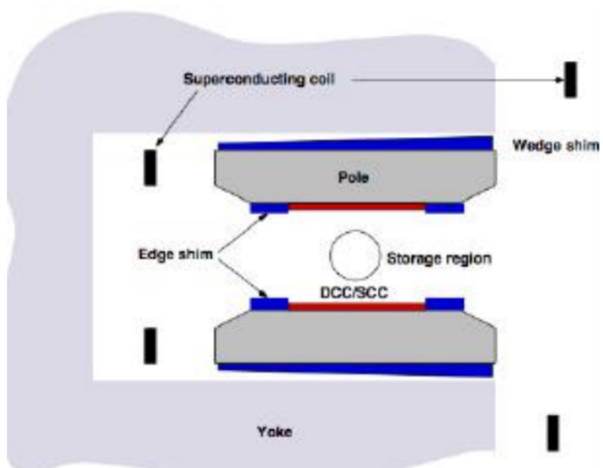


Figure 1: Cross-Section of Superconducting Coil and Magnet Poles in g-2 experiment.[3]

For this experiment, the 1.45 T magnetic field must be highly uniform to allow the measurement to be as precise as possible. In the calculation of the anomalous magnetic moment, the value of the magnetic field is included. Thus, the more uniform the field and the lower the uncertainty on it, the more precise our measurement will be, meaning a better chance at finding new physics. For the E821 experiment at Brookhaven, the static magnetic field moved by about 40 ppm, while the transient field had an uncertainty of 30 ppb.[4] In the g-2 experiment, the uncertainty will be decreased on both of these values to make the field more uniform and thus more precise. We intend to get the static magnet field down to an uncertainty of 10 ppm by better controlling the temperature and to get the transient field down to an uncertainty of about 10 ppb.[4] Furthermore, the magnetic field inside the rings will only deviate from the average value by at most 1.5 ppm. A contour plot of these deviations can be found in Figure 2. In order to accomplish this task, we have to ensure that no electronics with current or other machines around the superconducting magnets will perturb the field.

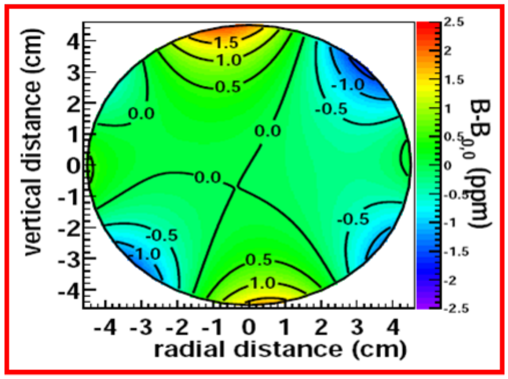
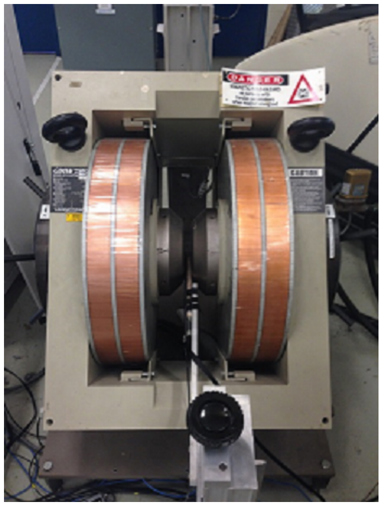


Figure 2: Magnetic Field Contour Map showing the ppm deviations from the average magnetic field inside of the storage ring.[2]

2 Materials and Methods

For the g-2 experiment, many electronics will be placed inside of the superconducting ring. In order to make sure that the magnetic field remains highly uniform, we needed to test the magnetic properties of the electronics that will be placed around the ring. The test entailed measuring the magnetic field perturbations created by a MicroTCA crate and its subsequent parts and determining whether the perturbations they created in the field were high enough to cause nonuniformity of the magnetic field in the experiment. In other words, we were testing how much the magnetic field was offset by the electronics. If the perturbations were above 1 ppm, then they were concerning enough to possibly be replaced. This experiment was to be completed using a calibration magnet with an NMR probe.

The magnet was a GMW 3474 calibration magnet, seen in Figure 3a, with 150 mm tapered pole caps attached to it, separated by 20 mm. We took the NMR probe and placed it in the center of the magnet using a movable arm. A Teslameter then received the data from the NMR probe, which read off the field strength in tesla. A power supply supplied the current through the magnet and allowed us to keep the current at a constant, consistent value for all of our tests. Each test had the field kept at around 2.019 T in the center of the magnet. This created a radial fringe field of 0.1150 T at 20 cm, 0.0560 T at 25 cm, and 0.0260 T at 30 cm, where most of the tests in our experiment were done. In the g-2 experiment, the fringe field at the electronics will be at about 0.01 T, smaller than any of the fields we experienced here. However, the reason for testing at these field values was to check and see if any of the parts were ferromagnetic. Furthermore, the 30 cm fringe field



(a) GMW 3474 magnet with NMR probe in center.

(b) MicroTCA crate with power module cable.

Figure 3: Pictures of equipment used in experiment.

is a little over twice as high as the actual fringe field in the experiment so dividing by two gives us a rough estimate of the actual perturbations in the experiment. Two separate tests checked to see if the crate and its parts had the same perturbations when the power was off as when the power was on, checking to make sure a current did not perturb the field more. For most of our tests, due to the size of the MicroTCA crate and the small gap between the poles, the experiment was carried out 30 cm away from the center of the magnet. However, after running tests, as can be seen in the results below, we determined that the MicroTCA crate had field perturbations that were too high to be ignored. Therefore, we took the crate apart and tested each of its separate parts at distances of 30, 25, and 20 cm away from the center of the magnet. After doing this, we could conclude what parts needed to be replaced so that they would not affect the uniformity of the magnetic field in our experiment.

Initially, we tested three separate parts, the power module, the power cable, and the MicroTCA crate itself. By observing what materials each part was made of, it was easy to make conclusions about the results of our experiment. The crate was a special aluminum chassis which was expected to cut down on the magnetic field perturbations. Much of the power module appeared to be nonmagnetic, other than a thin metal bar that protruded from its socket. The power cable seemed like it would be an issue as the hoods covering the sockets and plug appeared to be made of iron, meaning it would be ferromagnetic. The three separate pieces are shown connected to each other in Figure 3b.

For the first tests, we took each part and held it 30 cm away from the NMR probe. An initial field value was written down and then the part was introduced to the field, creating perturbations. The perturbations were measured three different times for each part and then an average was taken of the results. For the module, we initially had the plug facing the magnet and then turned the socket towards it, getting perturbations for each. This was similar to the method by which we tested the crate where the left side and then the right side were made to face the magnet. Then, we connected the power module and cable to the crate and ran tests again, turning the left side and then right side to the magnet. However, this time we ran tests with the power off and then the power on for the MicroTCA crate, trying to determine if a current changed the perturbations by more than 1 ppm. As before, an average was taken of the results and then compared to the initial field value taken to find the perturbations.

After these first tests, the perturbations created by the MicroTCA crate were too high to be ignored so we took apart the crate and tested each part inside of it separately. The parts were introduced to the field at 30, 25, and 20 cm away from the center of the magnet, if they could fit, and an average was taken of the three different results.

3 Results

3.1 Experiments with Three Parts Separate and Together

The results for the first tests where the parts were tested separately are shown in Table 1. Each side of the crate is listed, along with both the socket and plug of the power module, remembering that the socket of the power module is the side that contained the metal bar. For each part, there is an uncertainty of ± 2 ppm on the perturbations.

Part	Field Perturbation (ppm)
Power Cable	2.0
Socket of Power Module	1.6
Plug of Power Module	0.6
MicroTCA Crate (Left)	50.3
MicroTCA Crate (Right)	50.5

The first thing to notice from the results is that the socket of the power module, where the metal bar was, had a larger perturbation than the plug of the power module. Furthermore, the power cable also had a perturbation of about the same magnitude as the socket, both of which we expected initially. However, the aspect of the results that stands out the most is the how large the perturbations of the crate are compared to everything else, already a concerning factor for the experiment, especially since the crate's exterior is made entirely out of aluminum.

Next, the table below shows the results from the second part of the first tests where the crate and subsequent parts were put together. For the left side and the right side of the chassis, we took data with the power on and the power off for the crate. It is important to note here before the results are viewed that the left side of the chassis was the side on which the power module and power cable were found. Because these parts are on this side, their perturbations should add to the perturbations on that side from the crate itself, rather than the right side, which should have the same perturbations as before. As in the first test, there is an uncertainty of ± 2 ppm on the values here.

Side, Power	Field Perturbations (ppm)
Left Side, Power Off	57.2
Left Side, Power On	56.5
Right Side, Power Off	50.2
Right Side, Power On	50.7

The left side had higher perturbations as is to be expected in these tests. Furthermore, current running through the crate had little to no effect on the perturbations of the field which bodes well for the experiment, as that is one less problem we have to correct for in the magnetic field. However, the results from both of the tests indicated that the MicroTCA crate, even though it was made entirely out of aluminum, had some parts inside of it that were magnetic and causing those high perturbations. Therefore, we decided that we needed to take the crate apart and run further tests on what was found inside of it.

3.2 Experiments on Parts of Crate

The first thing we noticed on the crate was the fact that the screws on the crate were made out of stainless steel, instead of aluminum, a problem viewable without opening up any part of the crate. After we removed as much as we could from the crate, there ended up being eight separate parts that could be tested: the sides and bottom of the crate, the top and back of the crate, two cooling fans, two divider holders, the back panel of the crate, and the metal power box. The only two parts not put at 20, 25 and 30 cm were the sides and bottom of the crate and the top and back of the crate as they did not fit past 30 cm away from the center of the magnet. The results from these tests can be found in the table below. As before, three different results gave an average value, which was then used to calculate the field perturbations. Again, an uncertainty of ± 2 ppm should be applied to all of these values.

Part	20 cm (ppm)	25 cm(ppm)	30 cm (ppm)
Sides and Bottom of Crate	-	-	0.1
Top and Back of Crate	-	-	6.3
Top Cooling Fan	21.0	6.8	3.1
Bottom Cooling Fan	20.4	6.5	3.3
Top Divider Holder	50.7	15.8	5.1
Bottom Divider Holder	44.0	14.3	5.9
Back Panel	0.7	0.7	0.5
Power Box	55.2	23.1	11.6

The power box by far had the largest perturbations out of all the parts, which made sense, as the outside covering was almost entirely made out of stainless steel. The top and back of the crate had some smaller power boxes and cables attached to it that I would attribute to its large perturbations at 30 cm. We were unconcerned about the divider holders until they were 20 cm away from the magnet at which point their perturbations rose dramatically, possibly due to the fact that they contain ferromagnetic metals. Otherwise, many of the parts did not create perturbations in the field large enough to be concerned about their effects on the g-2 experiment.

4 Conclusions

After running the tests on each part of the crate, we were finally able to conclude what parts needed to replaced before they are used in the actual experiment. The power cable will be replaced due to its metal hood causing large perturbations. Furthermore, the metal bar on the power module will be removed to cut down on its perturbations. For the MicroTCA crate, the screws, power box, divider holders, and some of the parts on the back of crate need to be replaced. If these parts are replaced, then we should be able to guarantee negligible perturbations of the 1.45 T field due to any of the electronics around the storage ring in the experiment. Improvements on these results could be made, however. A larger magnet will allow us to test further the parts that could not fit past 30 cm. These results seem conclusive, but the same tests done in a larger setting could help us to get a better idea of the field perturbations caused by each of the parts used in this experiment.

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