Building IBMS Detectors for Muon g-2

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Abstract. The purpose for the Muon *g*-2 experiment at Fermi National Accelerator Laboratory is to measure the anomalous magnetic moment of the muon to unprecedented precision in the hopes of providing evidence for physics Beyond the Standard Model. This research involves injecting a beam of muons into a magnetic storage ring, and observing how these particles interact with the field. The Inflector Beam Monitoring System (IBMS) will be used to understand how the beam enters the ring in order to facilitate storage of the muons, ultimately increasing data acquisition and experimental precision of the project as a whole. The IBMS consists of three detectors, which will be built, tested and calibrated at CENPA. These detectors will be installed at different positions in the upstream region of the magnetic storage ring.

Keywords: Brookhaven, Fermilab, gyromagnetic ratio, magnet, muon, neutral density filter, scintillating fiber, silicon photomultiplier, Standard Model.

1 Introduction

E989 is a research project funded by the Department of Energy, which is taking place at Fermi National Acceleratory Laboratory (Fermilab). E989 will be carried out by the Muon *g*-2 collaboration, which currently consists of involvement from eight countries and 33 institutions. The motivation for Muon *g*-2 is it hopes to give evidence for Beyond the Standard Model (BSM). The Standard Model has proven to be an extremely robust and consistent theory describing our current comprehension of elementary particle physics. However, there are still holes in our understanding that leave big questions unanswered, for instance does a quantized theory of gravity exist, or are there viable dark matter particles? It's not an overstatement to say that Muon *g*-2 is at the forefront of particle physics research, and most in the field are watching closely to see what the project finds.

Muon *g*-2 aims to measure the gyromagnetic ratio or "*g*" of the muon, which is the ratio of a muon's magnetic moment to its angular momentum and a value that ought to be particularly sensitive to particles or interactions BSM.[1] Quantum Mechanics and the Standard Model predict *g* to be equal to 2 for spin ½ particles like the muon. However, experiment E821 that occurred at Brookhaven National Lab (Brookhaven) in 2001 measured *g* to be over this expected value for the muon. Brookhaven found a 3.5 sigma level discrepancy between the theoretical calculation and the experimental value of *g* for the muon.[2] Fermilab aims to repeat a similar experiment, but one that is more precise hopefully reaching or surpassing a discrepancy level of 5 sigma in order to confirm the data from E821 is not merely a statistical fluctuation. If Fermilab shows Brookhaven's discrepancy to be false, then the results will further support the standard model. On the other hand, if a 5-sigma level discrepancy is achieved, the new *g*-2 measurement would indicate physics BSM.

Muons are used because they carry a fundamental spin property, which makes the particles act like gyroscopes or a tiny tops spinning about an axis. When placed in a magnetic field, a muon will spin about an axis that revolves perpendicularly to the magnetic field, and the rate of revolution can be used to find *g*. It is thought that "virtual" particles that continually pop in and out of existence are disturbing the muon's interaction with the magnetic field, causing the *g*-2 anomaly. Although another lepton generation could be used to perform the experiment, muons are best suited because they are roughly 40,000 times more sensitive to new physics than electrons and tau are simply too short lived to be handled experimentally.[3] Although the rest muon lifetime is only 2.2 microseconds, muons in the experiment live an average of 64.4 microseconds because they are moving very close to the speed of (velocity=0.9994c, $\gamma = 29.3$).

2 Experimental Design

In order to experimentally determine *g*, a beam of polarized muons must be introduced into a magnetic field. The muon beam for the experiment is made by allowing protons hit a target creating quark antiquark pairs called pions.[4] These pions eventually decay into muons, which are then injected into a uniform, azimuthally symmetric magnetic field generated by a C-shaped magnet causing the beam of muons to travel in a circle (Figure 1). After orbiting the ring many times, a muon will spontaneously decay into a positron and two neutrinos via the weak force.[5] Because of momentum conservation, the positron has a smaller momentum than the muon, and, as a result, crawls towards the center of the storage ring, where calorimeter detectors are positioned. Due to a correlation between the muon spin and the decay positron direction, *g*-2 can be calculated.[6]

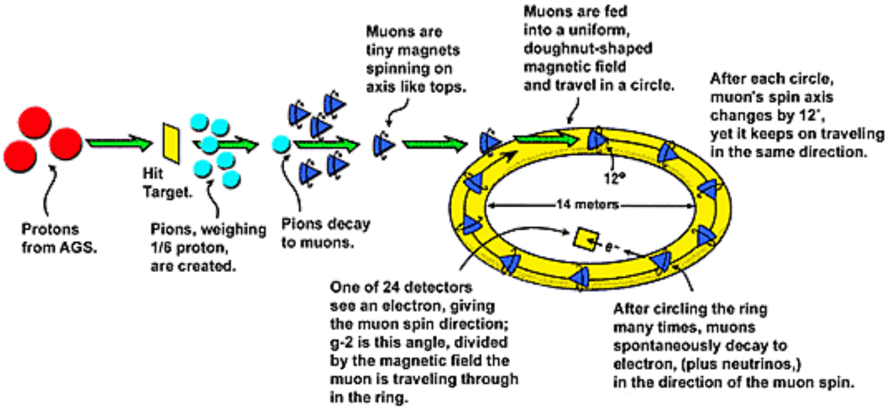

Figure 1. Diagram showing the generation of the muon beam, and its path as it is introduced into the magnetic storage ring. Source: https://www.bnl.gov/bnlweb/pubaf/pr/2001/g-2_backgrounder.htm (accessed August 25, 2016).[7]

3 IBMS Overview

IBMS stands for "inflector beam monitoring system". IBMS is responsible for observing how muons are injected into the *g*-2 magnetic storage ring. Besides the storage ring, there exists another magnet called the inflector, which facilitates the injection of the muons into the ring. The inflector is positioned where the beam of muons initially enters the storage ring, and its role is to cancel out the main magnetic field of the storage ring, so the muons experience a field-free region during injection. Ideally the muon beam would exhibit no lateral motion during injection, however the changing magnetic field results in less muons being stored due the beam scraping against small spatial apertures. The beam's swimming ultimately introduces subtle systematic effects that are troublesome for a precision experiment. IBMS will measure the x y profiles of the muons in order to optimize the injection of the beam into the storage ring and minimize systematic errors due to these "coherent betatron oscillations". IBMS detectors will allow us to understand how the injection tune is correlated with muon storage and beam dynamics.

4 Building IBMS Detector Prototype

My work at CENPA has focused on developing and testing the IBMS detectors. The detectors are made up of scintillating fibers (Figure 2a) read out by silicon photo-multipliers (SiPMs, Figure 2b). When charged particles pass through the scintillating fibers, energy is deposited, which is converted to light, causing the fibers to fluoresce blue. The light travelling out of the end of the fibers is translated into an electrical pulse by the SiPMs, i.e. small chips consisting of 10,000 pixels used specifically for detecting photons of the wavelength produced by the scintillating fibers.

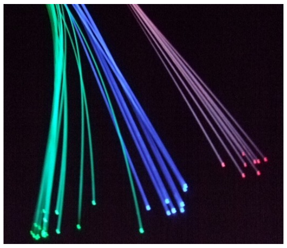

Figure 2a. Example of scintillating fibers

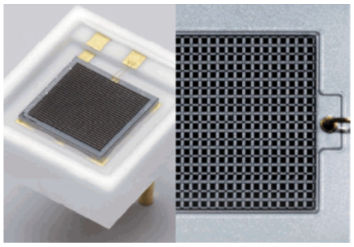

Figure 2b. Example of a SiPM

The electrical pulse can then be observed using an oscilloscope, and data can be acquired via a computer. To build an IBMS detector, I started by inspecting a spool of scintillating fiber under a high-resolution microscope, and only used clean sections (Figure 3).

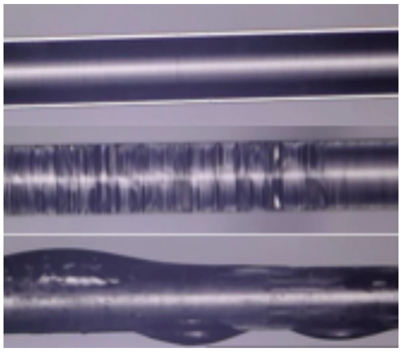

Figure 3. Top image shows a clean fiber, middle image shows a fiber with damage to the cladding, bottom image shows fiber with epoxy dried on exterior

Good sections of fiber were then threaded through drilled holes in an aluminum frame, and one side of the frame was glued with epoxy. After the first side was cured, the second side was glued in the same fashion and weights were hung as the fibers dried in order to ensure they would dry straight (Figure 4).

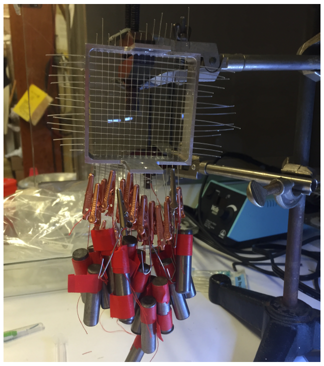

Figure 4. Prototype detector being built. Weights hung on end of fibers recently glued with epoxy.

After the fibers were secured to the frame, the ends were cut and polished with 1200-grit emery paper in order to achieve a smooth and clean polished fiber end (Figure 5a). Beforehand, I had experimented with different grit size emery papers on scrap pieces of aluminum. As it turns out, polishing the frame first with the 1200-grit emery paper, followed by the 30-micron optical polishing film, and finally the 3-micron film produced deep scratches in the ends of the fibers (Figure 5b). In addition, polishing with 1200-grit emery paper followed by 3-micron optical polishing film caused chips of aluminum from the frame to become embedded within the ends of the fibers (Figure 5c). Damage to the end of the fibers may cause problems with the effectiveness and efficiency of our dectectors, as it could alter the amount of light readout by the SiPMs.

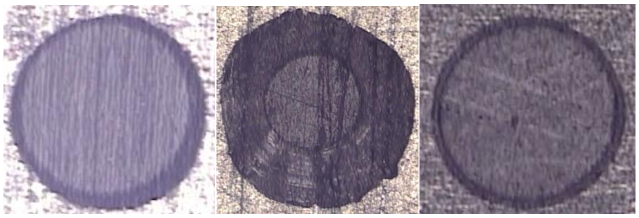

Figure 5 a,b,c. Pictures of the ends of fibers under a high-resolution microscope.

5 Testing IBMS Detector Prototype

To test a prototype detector, the detector must be located in a dark box to cut out ambient noise from the light in the room in order for the SiPMs to readout the light from the fibers. IBMS detectors can be calibrated using an LED to produce light in the fibers in place of using muons to generate internal scintillation. For this a blue LED was coupled directly to a fiber end opposite a SiPM. We used neutral density filters positioned between the LED and the fiber in order to decrease the intensity of the light hitting the SiPM (Figure 6).

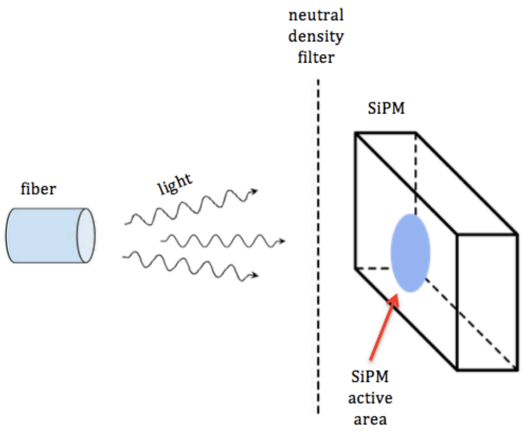

Figure 6. Diagram of experimental setup to callibrate an IBMS detector

This allowed us to determine if the SiPM was being saturated with light or if it was in the linear regime. It was determined with seven filters in place, every additional filter there after cuts down the signal by the same fractional amount, which indicates we are in the linear regime of the SiPM, in other words the SiPM was not being saturated with light. This is represented by exponential decay of the voltage read out by the SiPM with increasing number of filters (Figure 7). In addition, different behavior was found for when less than seven filter were in place indicating the SiPM was saturated with light. This is represented by linear decay of the voltage read out by the SiPM with increasing number of filters (Figure 7).

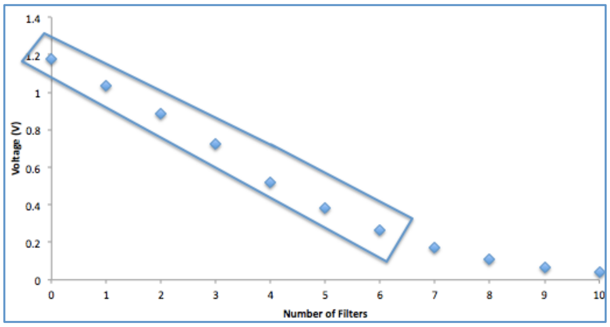

Figure 7. Plot of voltage decreasing woth increasing the number of filters

In order to optimize SiPM signal, we also experimented with changing the distance between the SiPM and the end of the fiber in order to optimize the amount of light the hitting the SiPM, therefore maximizing the number of pixels firing (Figure 8). It was found that a distance of roughly 1.2 mm between the fiber end and SiPM maximized the surface area light hits the SiPM without cutting down intensity.

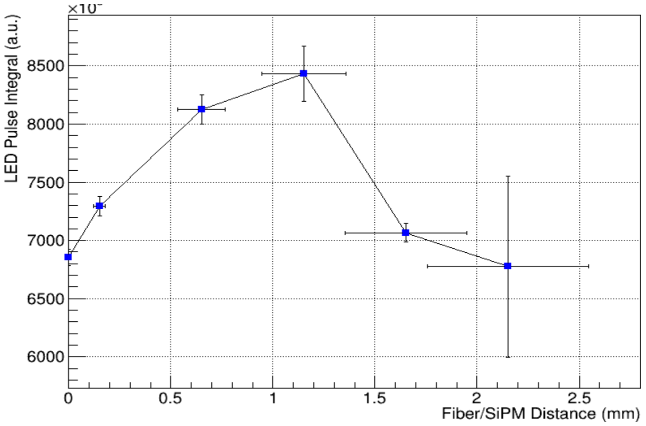

Figure 8. Plot of the LED pulse signal versus distance between fiber and SiPM

7 Muon g-2 Going Forward

IBMS prototype detectors will be tested with the Van Der Grauff accelerator on campus. This is to ensure the detectors remain functional after being bombarded by protons, and do not as a result melt or experience radiation damage rendering them ineffective for further measurements. Assuming the prototypes remain effective, new detectors will be built at CENPA using the same design and materials, and be shipped to Fermilab for installation. As for the rest of the experiment, the hope it that most Muon g-2 collaborators will move onsite to Fermilab this September, the downstream calorimeter detectors will be installed in the ring in October, our IBMS detectors will be installed early 2017, and the first beam of muons launched in the spring of next year.

Acknowledgments

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