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Construction and Commisioning of the Beam delivery, storage ring and g-2 detectors at FNAL

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The muon anomaly $a_\mu = (g-2)/2$ has been measured to 0.54 parts per million by E821 experiment at Brookhaven, and at present there is a 3 to 4-standard deviations difference between the Standard Model prediction and the experimental value. A new muon *g-2* experiment, E989, is starting at Fermilab with the aim to improve the experimental error by a factor of four to clarify this difference. Some details of the beam delivery, storage ring and new experimental detector system of the *g-2* experiment will be presented.

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1. Introduction

The muon anomaly $a_\mu = (g-2)/2$ is a low-energy observable, which can be both measured and computed to high precision [1, 2]. It provides an important test of the Standard Model (SM) and it is a sensitive search for new physics [3]. The result obtained from the precision measurement of a_μ by the E821 experiment at BNL [4], showed a discrepancy between its experimental value and the SM prediction. The major contribution to the uncertainty in the theoretical calculation are mainly due to the strong interaction effects which cannot be computed perturbatively at low energies. The experimental error achieved by the E821 experiment is $\delta a_\mu^{\text{EXP}} = 6.3 \times 10^{-10}$ ($0.54 ppm$) [5]. The new experiment E989 at Fermilab aims to improve a fourfold factor with respect to the E821 experiment, reducing the systematic errors with the implementation of a more refined detector system and electronic together with an improvement of a factor 20 in statistics thanks to the Fermilab accelerator complex.

2. Principle of the Muon g-2 experiment

A beam of highly polarized muons of $3.1 GeV$ is injected into the *g-2* storage ring where a strong (1.45T) magnetic fields both traps the μ's and causes their spin to precess. Muons momentum turns at the cyclotron frequency $\omega_c = \frac{eB}{\gamma m}$ while the spin rotates due to the combination of Larmor and Thomas precession $\omega_s = \frac{geB}{2m} + (1-\gamma)\frac{eB}{\gamma m}$.
Working at the precise muon momentum $p_\mu = 3.1 GeV$ causes that the difference of these frequencies to be independent of γ and proportional to the anomalous magnetic moment $\omega_a = \omega_s - \omega_c = \frac{a_\mu eB}{m}$.
The quantity a_μ, is obtained by measuring the frequency ω_a and the magnetic field B, which can be tied to the precession frequency of free protons ω_p. The ω_a measurement is performed by detecting the high energy decay positrons emitted in the muon weak decay in the 24 calorimeter stations placed around the storage ring. This is made possible thanks to the parity-violating nature of the weak decay of the muon which leads to a strong correlation between the muon spin and the high energy positron emitted. At the same time precise knowledge of the magnetic field is obtained by Nuclear Magnetic Resonance (NMR) probes that relates the proton precession frequency ω_p to the absolute field experienced by muons.

3. Ring and beam

The 14 meters BNL storage ring of the E821 experiment was relocated to Fermilab in 2013. It permits to store muons in a high uniform magnetic field. Critical issue for the experiment was the reinstallation of the storage ring. This procedure started immediately once the new MC-1 building was ready. The magnet is fully operational and shimmed at $\pm 25 ppm$ and all the detectors are installed and operational. Another important point are the upgrades of the Fermilab accelerator complex. One of this upgrades is related to the conversion of the antiproton complex to a muon source capable to delivery a high-purity $3.1 GeV$ muon beam to the Muon *g-2* experiment. Commissioning started in 2017 and the first beam arrived in June.

4. Detectors

4.1 Calorimeter

The new calorimeters of the E989 consist of 24 stations placed around the ring. Each calorimeter is an 9×6 array of pure PbF_2 Cerenkov crystals readout by SiPM. The higly segmentation allow for a better spatial resolution of pileup events while the fast nature of Cerenkov radiation improves time resolution [6]. SiPMs are suitable for the application inside high magnetic field with no interference and a stable voltage distribution is necessary to maintain gain stability together with a dedicated Laser Calibration System, in order to improve the systematic errors due to gain fluctuations. All the calorimeters are installed around the ring and succesfully tested during the June test run[1], see Fig.1.

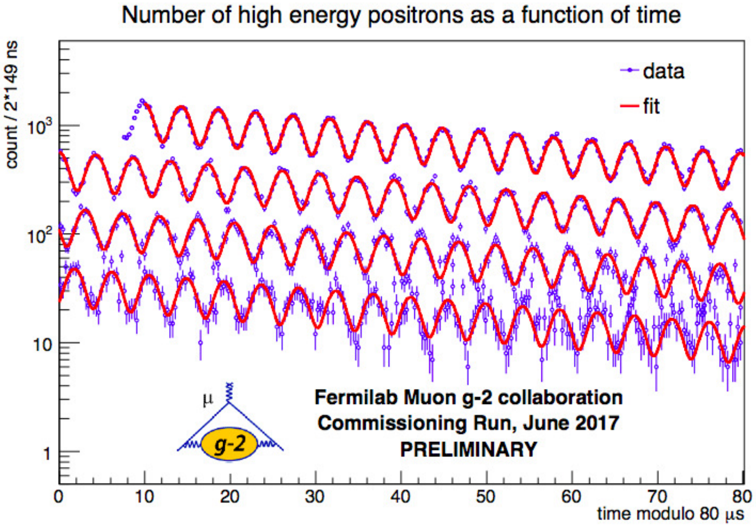

Figure 1: The figure was accumulated from two weeks of data accumulated in June 2017 and has approximately 700k positrons. The number of wiggles is somewhere between that achieved by CERN-II and CERN-III.

4.2 Tracking system

A tracking system has been developed to reduce systematic error due to beam dynamics inside the storage ring. Three detectors will be installed along the ring. Each detector is composed by 8 modules of mylar straw fibers and dedicated electronic [7].
Laboratory test confirmed high level efficiency of 99.2% for a single module.
All the 8 modules of the first tracker detector have been installed and commissioned during the test run.

4.3 Laser Calibration System

A high performance calibration system is required for the on-line monitoring of the output stability of each individual tower in all calorimeter stations. It is estimated that the detector re-

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[1] The test run took place from June 1 to July 7.

sponse must be calibrated with relative accuracy at sub-per mil level to achieve the goal of the E989 experiment to keep systematics contributions to the accuracy on ω_a at $0.02 ppm$ level. This is a challenge for the design of the calibration system because the desired accuracy is at least one order of magnitude higher than that of all other existing, or adopted in the past, calibration systems for calorimetry in particle physics.

As almost 1300 channels must be kept calibrated during data taking, the proposed solution is based on the method of sending simultaneous light calibration pulses onto the readout photodetector through the crystals of the calorimeter. Light pulses should be stable in intensity and timing in order to correct for systematic effects due to drifts in the response of the crystal readout devices. A suitable photo-detector system must be included in the calibration architecture to monitor any fluctuation of the light. The guidelines given by the experiment to define in the correct way the architecture of the entire system can be found in [8]. Several test beam were performed to test all the performance of the system. The final design of the Laser Calibration System installed at Fermilab is shown in Fig.2. The system has been heavily used during the test run.

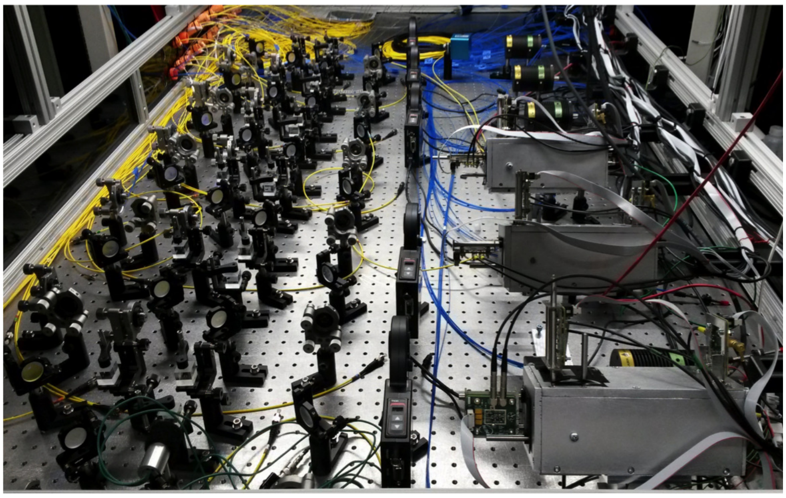

Figure 2: The Laser Calibration System optica table.

5. Conclusion

A five weeks commissioning run has been completed successfully in July and the first commissioning data analysis has started. The next run is scheduled for mid of October 2017. The goal is to reach the BNL level precision with the data taken in early 2018, and the final $0.14 ppm$ result measurement in 2020. This will require a total of $1.5x10^{11}$ collected events.

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