DEVELOPMENT OF A DATA ACQUISITION SYSTEM FOR THE MUON $g$-2 EXPERIMENT AT FERMILAB

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ABSTRACT. The Fermilab muon $g$-2 experiment (E989) aims to measure the muon anomalous magnetic moment ($a_{\mu}$) to 0.14 parts per million. Precision measurements of $a_{\mu}$ are sensitive to new physics at the TeV scale. The University of Kentucky is a founding member of the E989 collaboration and has committed to providing the data acquisition (DAQ) system required to process and analyze raw detector signals. This proposal requests $9246 to purchase equipment that will be used to prototype the interface between the DAQ system and the calorimeter detector electronics.
1. Plan of Project

1.1. Scientific Objectives. The muon is a fundamental particle with electric charge $e$, intrinsic angular momentum $\vec{S} = \frac{\hbar}{2}$, and a mass $m \sim 200$ times larger than that of the electron. This combination of charge and spin make the muon behave like a tiny magnet. The magnetic dipole moment ($\vec{M}$) characterizes the magnetic properties of a charged particle with half-integer spin:

$$\vec{M} = g \frac{e}{2mc} \vec{S}$$

where $c$ is the speed of light. The g-factor relates the particle’s spin and magnetic moment and can be decomposed into two terms: $g = 2(1 + a)$. Dirac predicted that all point-like spin $\frac{\hbar}{2}$ charged particles, such as the muon, would have a g-factor of precisely 2. However, due to interactions with virtual particle fluctuations in the vacuum, the muon magnetic moment deviates from this expectation and acquires a non-zero anomalous magnetic moment ($a_{\mu}$). This term, often rewritten as $a_{\mu} = \frac{(g-2)}{2}$, encapsulates the contributions to $M_{\mu}$ from the muon’s interaction with all fundamental particles that exist in our universe.

The muon’s anomalous moment is important because $a_{\mu}$ is calculable and measurable with extraordinary precision. A significant discrepancy between the measurement and the Standard Model prediction of $a_{\mu}$ would imply the existence of new particles and/or forces of nature. Indeed, recent experimental developments have lead the particle physics community to believe these contributions, generally referred to as Beyond the Standard Model (BSM) contributions, are real and may be deeply connected to the origin of dark matter and neutrino oscillations. The search for BSM signals was a primary motivation for building the Large Hadron Collider at CERN and remains one of the highest scientific priorities in particle physics today.

The new muon $g - 2$ experiment E989 proposes to measure the muon anomalous magnetic moment $a_{\mu} \equiv \frac{(g-2)}{2}$ to 0.14 parts per million (ppm), a level of precision expected to be sensitive to contributions from new fundamental particles. This experiment received Stage I approval from Fermi National Laboratory (FNAL) in January of 2011 and CD-0 status from the Department of Energy in September of 2012, allowing the construction of a new experimental hall, the relocation of the muon storage ring from Brookhaven National Laboratory (BNL) to FNAL and research and development on a muon beamline at FNAL to proceed. The P.I.’s, in collaboration with Cornell University, University of Washington, University of Virginia and James Madison University, have recently submitted a Major Research Instrumentation proposal to the NSF requesting funds for the construction of calorimeter detectors, electronics and data acquisition (DAQ) equipment. The timeline for E989 construction is aggressive, with first beam expected in 2016,
and the MRI funds (if awarded) will not be available for another fiscal year. Support from this grant will allow the P.I.’s to continue with essential research and development for the DAQ system, which in turn will provide justification for future requests of support from NSF.

1.2. Background. The $a_\mu$ was first measured in 1957 by Charpak et al. [1] and found to be consistent with zero. Since that time, four experiments have measured a nonzero $a_\mu$, each with an increasing level of precision. The most recent measurement by the E821[2] collaboration at BNL resulted in a 3.2 $\sigma$ discrepancy between data and SM theory (Fig. 1a): $\Delta a_\mu(Expt - SM) = (255 \pm 80) \times 10^{-11}$. While $\sim$2000 papers have cited this result as a possible indicator of new physics at the TeV scale (Fig.1b), it falls short of the necessary discovery level deviation of $> 5 \sigma$, providing a clear motivation for a higher precision measurement of $a_\mu$.

![Figure 1](image.png)

**Figure 1.** a) Comparison of two recent Standard Model evaluations (HLMNT [3], DHMZ [4]) and the earlier BNL-E821 $g-2$ experiment [2]. The narrow band represents the goal of Fermilab E989. b) Citations to the BNL $g-2$ experiment by year. c) Data (green points) and fit (blue line) of the anomalous precession frequency, $\omega_a$, from one of the BNL running years.

1.3. Significance. E988 aims to acquire 20x the statistics of the E821 BNL experiment, reducing the total error by four-fold. If the central value of $a_\mu$ in E989 remains the same, and the theoretical errors are reduced by the projected 40%, the data-theory difference would translate to a 7.5 $\sigma$ discrepancy, well above the discovery threshold. A deviation from the SM prediction at the observed level could be explained by several BSM scenarios. More importantly, the improved precision will significantly constrain key parameters in supersymmetry, one of the most widely discussed BSM models. The fact that current collider experiments have very limited sensitivity to these same SUSY parameters underscores the importance of the $g-2$ experiment in the search for new physics at the TeV scale.

1.4. Procedures. Polarized muons will be injected into a storage ring with a highly uniform magnetic field $B = 1.45$ T. The muons will circulate around the ring at the cyclotron frequency $\omega_c = -eB/m_\gamma$, where $\gamma = (1 - v^2/c^2)^{-\frac{1}{2}}$ is the relativistic gamma. The muon spins will couple to the magnetic field and precess.
with a frequency \( \omega_s = \frac{-geB}{2m} - (1 - \gamma) \frac{eB}{m\gamma} \). If the muon momentum is fixed at 3.1 GeV/c, then the anomalous precession frequency can be expressed simply as \( \omega_a = \omega_s - \omega_c = -a_\mu \frac{eB}{m} \), and \( a_\mu \) can be determined from a precision measurement of \( \omega_a \) and \( B \). The collaboration is split into two teams: one to measure \( \omega_a \) and the other \( \vec{B} \). The P.I.’s are members of the \( \omega_a \) team and the remainder of this document will address only the experimental procedures for measuring \( \omega_a \).

The anomalous precision frequency \( \omega_a \) is measured by detecting positrons, emitted in muon decay, with 24 electromagnetic calorimeters stationed symmetrically around the storage ring. The positrons are preferentially emitted in the direction of the muon spin, producing a signal that oscillates at the frequency \( \omega_a \) and steadily decreases over the course of the entire 700 \( \mu s \) fill. Figure 1c shows the positron signal for a single fill; note that time is permitted to wrap around on the x axis. The storage ring will be filled at 12 Hz and each fill, containing up to 15,000 stored muons, will produce analog signals in the calorimeters. These signals will be continuously recorded throughout the fill by custom waveform digitizers, resulting in more than 8 GB/s of data to be managed by the DAQ system.

The data acquisition for the \( \omega_a \) measurement will provide continuous readout, event building and data storage of the 12-bit, 500 MSPS digitizers instrumenting the 24×54 calorimeter segments. Onboard memories in the digitizers will buffer the raw data and allow its asynchronous readout over 10 Gbit ethernet, thus decoupling the DAQ event cycles from storage ring fill cycles. The frontend layer of multicore-CPUs with GPUs will process the digitized records of individual fills into several derived datasets, while a backend layer of multicore CPUs will handle the assembly and storage of the event fragments from the frontend layer. Each stored event will represent a complete record of the activity in the detector systems for each storage ring fill.

The DAQ will be implemented as a modular, distributed system on a parallel, layered array of networked, commodity PC’s running Scientific Linux (SL). The system will be based on the MIDAS data acquisition framework and the ROOT data analysis framework. The design will offer the flexibility to construct the \( T, Q \) and other datasets at the software level in the frontend CPU/GPU layer. The \( T \)-method data will be constructed by saving individual “islands” of above-threshold calorimeter signals and the \( Q \)-method data will be constructed by accumulating histograms of fully-digitized fills. This scheme will reduce the 8 GByte/s rate of continuous digitization to less than 100 MByte/s.

Our concepts for digitizer readout, data compression and event building have been demonstrated on an R&D platform operated at UKY. Our MIDAS-based DAQ
prototype incorporates 12-bit, 500 MHz Struck SIS3350 waveform digitizer modules with Ethernet readout, a frontend processor with two quad-core CPUs and a NVIDIA Tesla C1060 GPU for deriving $T^-, Q$-method datasets, and one backend processor for event building and data storage. The prototype has also been used for development work on the digitizer readout, data compression, event building and other tasks. An additional frontend is used to control a FPGA-based programmable pulser that generates timing signals to mimic the time structure of storage ring fills. The DAQ prototype and Struck digitizers have enabled R&D work on: high-rate processing of network packets using 10 Gbit Ethernet hardware, high-rate derivation of $T^-, Q$- method datasets via multi-threaded operations on a 1.3 GHz, 240-core, NVIDIA Tesla c1060 GPU, high-rate matching / assembly of fill-by-fill events from event fragments, and development and testing of the DAQ control and synchronization system.

1.5. **Justification.** The next step requires interfacing the DAQ prototype system with the custom built waveform digitizers (WFD) that will be used to read out the 54 electromagnetic calorimeter channels. The WFD will be implemented as eleven 5-channel Advanced mezzanine Cards (AMC’s) designed to reside in a single Vadatech VT892 µTCA crate. The crate is controlled via a µTCA Carrier Hub, while the interface between the crate and the AMC cards is handled by a custom AMC13 card. The AMC13 will allow parallel readout of the AMC cards at a rate of 5 Gbit/s, while also handing the precision clock distribution to each of the 11 AMC cards. The DAQ system will communicate with the WFD system via a standard 10-Gbit optical NIC. The AMC cards are currently being designed and prototyped and will be available for purchase in late spring of 2013. If funded, the equipment purchased with the this proposal will permit the development and testing of the software needed to communicate with the µTCA crate and the AMC-13 card. After communications are established and verified, development of the event builder code, necessary for matching and assembling a complete event from disparate detector systems, can begin. Finally, if these tests are carried out in a timely fashion they can provide feedback to the final design of the frontend calorimeter electronics.

1.6. **Budget Justification.** The P.I.’s request $9246 to purchase a µTCA crate, power supply, carrier hub and an AMC 13 card. This equipment is essential for the timely development of the DAQ system for the E989 g-2 experiment.
1.7. **Current and Pending Awards.** Only award 2) was submitted with a component dedicated to the g-2 E989 experiment. Awards 1) and 3) were submitted for alternate experimental programs and proposal 4) is unfunded to date. W. Gohn is supported as a postdoctoral associate from grant 2).

1) R. Fatemi has $480,000 of support from the National Science Foundation for experimental work on “Fundamental Studies of the Proton in QCD” at Brookhaven National Laboratory covering the funding period from May 2012 - 2015.

2) T. Gorringe has $510,000 of support from the National Science Foundation for experimental work on “Low Energy, High Precision Muon Experiments” at the Paul Scherrer Institute and Fermi National Laboratory covering the funding period from May 2012-2015.

3) T. Gorringe has $587,999 of support from the National Science Foundation for experimental work on “Studies of fundamental constants, interactions and symmetries via low-energy, high-precision muon experiments” covering the funding period from September 2009 - 2013.

4) R. Fatemi and T. Gorringe have submitted a MRI proposal for $205,055 of support from the National Science Foundation for experimental work on “Development of Instrumentation to Measure the Spin Precession Frequency in the Fermilab Muon g-2” covering the funding period from August 2013-2016.

**References**