FERMILAB-CONF-18-167-E

NEW FAST KICKER RESULTS FROM THE MUON g-2 E-989 EXPERIMENT AT FERMILAB

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Abstract

We describe the installation, commissioning, and characterization of the injection kicker system for the E-989 experiment at Fermilab for a precision measurement of the muon anomalous magnetic moment. Control and monitoring systems have been implemented to acquire and record the waveforms of each kicker pulse, and measurements of various kicker system observables were recorded in the presence of the 1.45 T g-2 storage ring magnetic field. These monitoring systems are necessary to understand the systematic contribution to the measurement of the precession frequency. We examine the dependence of muon capture to kicker field predictions.

OVERVIEW

The E-989 experiment (Muon g-2) at Fermilab will measure the muon magnetic anomaly (a_μ) to a target precision of 0.14 ppm [1]. E-989 is the successor to the E-821 experiment, described in [2-4], which was performed at BNL and measured a_μ to a precision of 0.54 ppm. Both experiments use the same 1.45 T magnetic storage ring.

Polarized muons in the E-989 experiment are delivered to the storage ring through a network of Fermilab accelerators that make use of proton beams, interactions with a nickel-based target, and pion decays. Muons arising from these decays are fed into the storage volume through an inflector magnet [5], which is tangentially aligned to the ring and has its interior aperture displaced 77 mm from the central radius of the storage region.

The trajectory of the injected muons is shifted from the 7.11 m design orbit radius due to the aforementioned displacement. A series of three 1.27-meter long kicker magnets located ¼ turn downstream from the inflector steers the muon beam onto the closed orbit needed to meet the experiment's physics goals.

Beam arrives from the accelerator in 120-ns long bunch trains at a peak rate of 100 Hz. It is injected into the storage ring, which has a revolution period of 149 ns. These features establish the timing constraints of the kicker system, as it needs to support the 16-pulse train, the kicker field ideally affects the entire time profile of the injected muons, and the current must shut off before the particles complete one revolution. A Blumlein pulser was selected to meet these specifications. The design of the kicker system and its requirements are described in [6-8].

In these proceedings, we focus on the implementation of monitoring resources, the information obtained from specific waveforms, and simulations that studied the impact of the kickers on beam dynamics.

MONITORING TOOLS

One of the major developments during the 2017 commissioning period was the implementation of monitoring hardware and software. Various electrical waveforms are collected that serve both operational and analytical purposes, and additional measurements are taken to ensure the safe operation of the kicker system. A summary list is included in Table 1.

Table 1: Monitored Information and Function

Monitor	Source	Function
Blumlein charging voltage	Transformer	Strength calibration Timing information
dB/dt coil voltage	Coil	Pulse measurements Spark monitor
Castor oil level and flow	On/Off Switches	Blumlein health
Castor oil temperature	Sensor	
Fluorinert temperature	Sensor	HV feedthrough health
Software	Code	Ensures monitor data collection

The Blumlein charging and dB/dt coil monitors facilitate additional analyses that demonstrate important connections between fundamental system observables and the physics objectives of the experiment. Specifically, the performance of the kickers is directly correlated to the efficiency of muon storage and the impact of coherent betatron oscillation (CBO), a stroboscopic effect driven by betatron oscillation and detector sampling that affects the number of events observed in the detectors.

Blumlein Charging Voltage

Transformers supply each of the Blumlein pulsers, and the voltage on the secondary winding is read out via a 5000:1 capacitive divider. During the 2017 commissioning run, these waveforms were recorded using BS10 BitScopes and a custom-built code framework. Currently,

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This document was prepared by [Muon G-2 Collaboration] using the resources of the Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359.

we are deploying a new data acquisition scheme that will replace the scopes with electronics that are integrated with Muon g-2's MIDAS-based DAQ.

An example charging waveform is shown in Fig. 1. Here, the Kicker 2 transformer begins receiving current at around 140 µs, and the thyratron initiates the discharge at roughly 760 µs. A derivative-based method is applied to these waveforms to determine the kick strength based upon the magnitude of the abrupt voltage drop. The red horizontal lines in Fig. 1 display the calculated voltages. The nominal operational voltage is 55 kV, independently calibrated using a Tektronix TBS2104 oscilloscope.

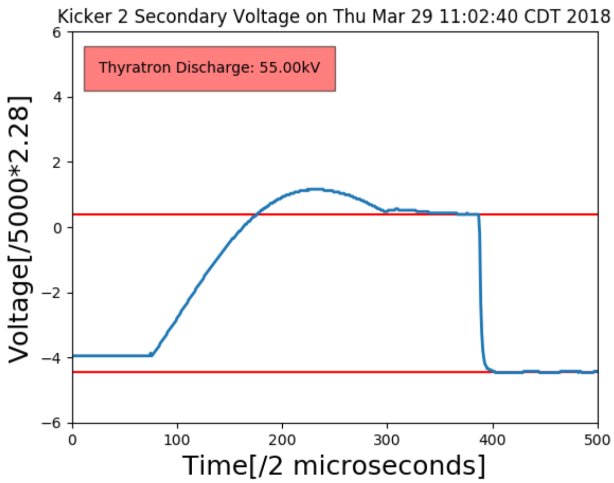

Figure 1: Blumlein charging voltage as read from the Kicker 2 transformer. Each clock tick corresponds to 2 µs. The numbers displayed in the vertical axis label designate the overall calibration constant applied to compensate for added cable capacitance in the DAQ system.

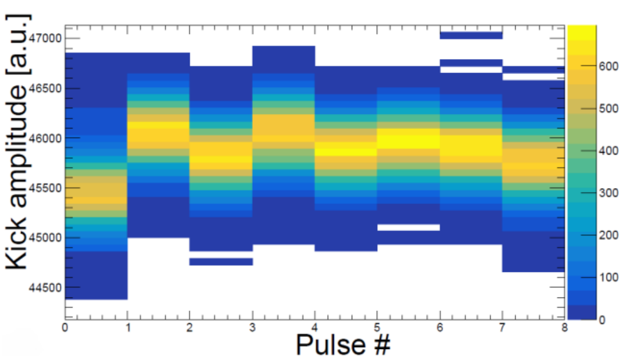

Figure 2: Amplitude of the kick strength in arbitrary units for eight pulses in a 100 Hz train.

With increased statistics, a time profile of the kicker strength can be assembled. An example of this is shown in Fig. 2, where the measured amplitudes were binned according to the pulse position in the train. In this data sample, we observe that the kicker strength is stable to within a few percent. Here, we verify that the charging system is capable of kicking multiple pulses in the accelerator train and provide an analytical tool that maps muon data to the kicker pulse information. In particular, these data are important to CBO studies, and as such, demonstrating the function of the DAQ setup at Fermilab was an important milestone.

dB/dt Coil Voltage

A coil is placed near each of the three kicker plates that facilitates measurements of the change in the magnetic field as current is delivered. These waveforms are recorded for every pulse by both the Muon g-2 DAQ and a DRS4 Evaluation Board oscilloscope.

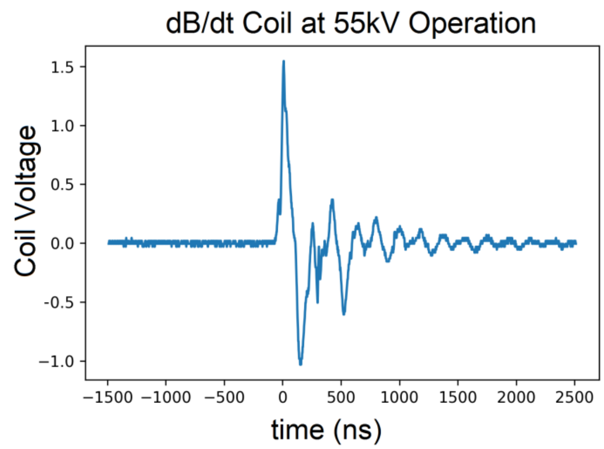

Figure 3: A voltage vs. time waveform recorded using Kicker 3's dB/dt coil.

The dB/dt coil waveforms, an example of which is shown in Fig. 3, serve several important operational functions. For example, we use the coils to verify that current is being delivered to the kicker plates. In addition, in the event of an anomalous discharge (e.g. one due to sparking), high-amplitude, high-frequency noise is observed. A veto system that relies on these waveforms is presently deployed to protect equipment if an atypical trace is recorded.

Ongoing investigations involving the system impedance and grounding are being performed to improve our understanding of the tail structure seen at $t > 250$ ns in Fig. 3.

BEAM DYNAMICS

The injection kicker is a fundamental component of the Muon g-2 storage ring. Performance has a direct impact on the number of muons that are stored per accelerator fill, making system optimization a crucial consideration for the experiment. Likewise, the amplitude of the kick is a driving factor in reducing the effects of CBO, which arises as a significant systematic in the precession measurement.

Muon Storage

Muon storage depends upon both the timing and strength of the kicker pulse. The timing controls are integrated into the Muon g-2 DAQ, and the pulse can be triggered at assigned placements with a granularity of 1.25 ns. The experiment will occasionally run timing scans to confirm that the thyratron discharge triggers are optimally set.

The waveform shown in Fig. 3 was integrated to produce a B-field function. This function is used in several simulations to estimate the muon storage and impact on CBO amplitude, which can then be compared to measurement. A result is shown in Fig. 4, where the storage is evaluated with respect to the kicker magnetic field given four beam injection conditions. As an example, the simulation below predicts optimal storage at roughly 225 G.

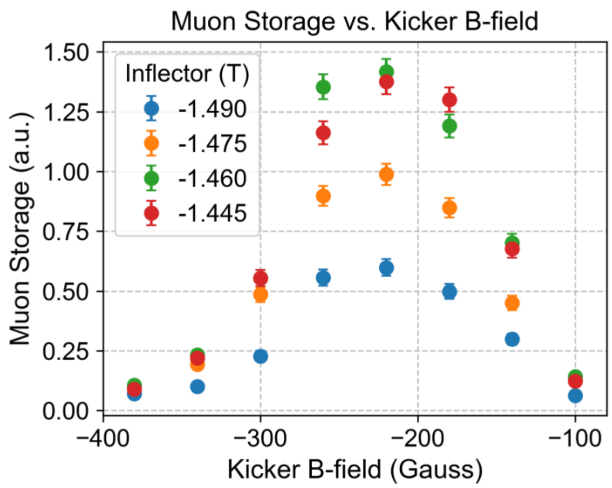

Figure 4: Simulated muon storage in arbitrary units vs. kicker magnetic field for different inflector currents.

These same simulations have also guided our efforts to optimize the number of stored muons in the ring. Over the first two months of 2018, various efforts have led to an 8x improvement since the start of the run.

Coherent Betatron Oscillation

Additional simulation using the integrated waveform in Fig. 3 assessed the CBO amplitude as a function of the kicker field.

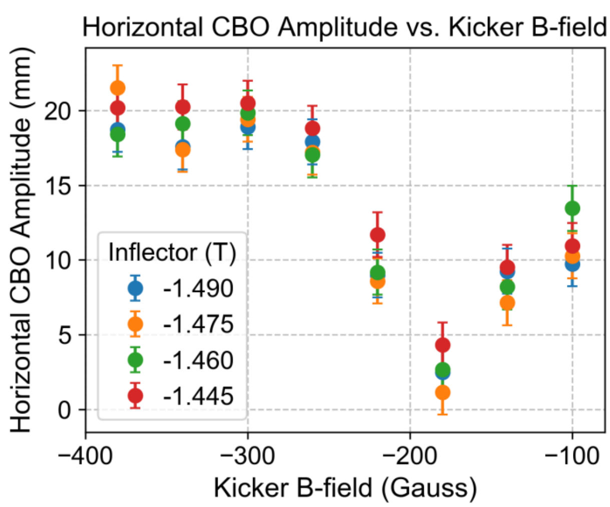

Figure 5: CBO amplitude vs. kicker magnetic field for different inflector currents.

Understanding this systematic is particularly important because it relates to the interplay between detector sampling and betatron oscillation. Muon g-2 is a counting experiment that relies upon extracting a frequency at high precision. Therefore, any systematic that can generate a time-dependent variation in the event rate could bias that extraction.

In Fig. 5, we show that the amplitude of the CBO effect is dependent upon the strength of the kickers. Again, with this example, this specific simulation predicts that the CBO impact is minimized when the kicker field strength is roughly 175 G, given the sampled injection conditions.

This finding motivates further optimization work to overcome the tension exhibited between the muon storage and CBO simulations, Figs. 4 and 5. In addition, this is indicative that CBO vs. kicker strength monitoring will be an important diagnostic to demonstrate that we understand the operation and simulation of our experiment.

CONCLUSION

The implementation of kicker system monitoring tools has greatly aided the Muon g-2 experiment. We have now taken data with a muon beam and have observed decay positrons, evidence that the injection kickers are functioning. In addition, the experiment now has the means to acquire and save relevant waveforms for analysis use.

Future work will focus on measurements of the magnetic field using a Faraday magnetometer, improvements that correct the observed tail structure in the dB/dt coil data, and explorations that further increase beam storage. We are on pace to surpass the statistics collected by the E-821 BNL experiment and aim to make significant advancements in the coming months. With these improvements, we seek the best precision a_μ measurement.

ACKNOWLEDGMENT

We thank our E-989 collaborators and Fermi National Accelerator Laboratory (Fermilab), a U.S. Department of Energy, Office of Science, HEP User Facility for the resources provided. Fermilab is managed by the Fermi Research Alliance (FRA), acting under Contract No. DE-AC02-07CH11359. The authors are supported by the DOE-OHEP and the UK NSF under separate grants.

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