Development of the fast muon kicker for the muon g-2 experiment at Fermilab

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Muon g-2 collaboration

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Outline

An introduction of Muon g-2 experiment at Fermilab (E989)

An introduction of the kicker system

The design and development of the kicker system at Cornell

Faraday magnetometer to measure the kicker pulse

Modeling the kicker system

Conclusion
Muon g-2 experiment at Fermilab (E989)

\[ \mu = g \frac{e}{2m} \rightarrow = (1 + \frac{g - 2}{2}) \frac{e}{m} \rightarrow = a (\text{anomalous magnetic moment}) \]

The precision measurement of \( a \) has been a channel leading to the discovery of the new physics.

Muon is a good tool to study \( a \) because \( a \) arises from all the coupling virtual particles and their contribution scales as \( \left( \frac{m_{\text{muon}}}{m_X} \right)^2 \) as well as its simplicity and good lifetime.

The latest measurement of \( a_\mu \) at BNL (E821) shows tension between the standard model prediction and the measurement.

\[ a_{\mu}^{E821} = (116 592 089 \pm 63) \times 10^{-11}, \quad a_{\mu}^{SM} = (116 591 802 \pm 49) \times 10^{-11} \]

\[ \Rightarrow \Delta a_{\mu} (E821-\text{SM}) = (286 \pm 80) \times 10^{-11} \sim 3.6 \sigma \text{ discrepancy} \]

E989 is the follow-up experiment of the BNL experiment.
Muon g-2 experiment at Fermilab (E989)

Storage ring

=> Built for the BNL exp (E821)
=> superferric “C” shaped magnet excited by superconducting coil
=> orbit radius : 7.112 m, storage region diameter = 90 mm
=> $B = 1.451 \, \text{T}$
Measuring $\omega_a$

$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C$

$$\tilde{\omega}_a = -\frac{q}{m} \left[ a_\mu \vec{B} - \left( a_\mu - \frac{1}{\gamma^2 - 1} \right) \frac{\vec{\beta} \times \vec{E}}{c} \right]$$

vanishing when $\gamma = 29.3$

(magic momentum, 3.09 GeV/c)

$$\omega_a = a_\mu \frac{eB}{m_\mu} = \frac{g_\mu - 2}{2} \frac{eB}{m_\mu}$$
Measuring $\omega_a$

$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$

P violation prefers the positron emitted in the direction of the muon spin.

The variation of the positron counting rate above an energy threshold due to $\omega_a$ for about 10 muon lifetime
The trajectory of the muons intersects the ideal orbit at an angle of $\theta_0 = 10.8 \text{ mrad}$.

The kicker is a pulsed magnet to provide a transverse kick to compensate the crossing angle.

The kicker is comprised of three independent 1.7 m long magnets, each with dedicated pulse forming network.

The muons are delivered to the storage ring in pulses with transverse emittance near $40\pi \text{ mm-mrad}$, pulse length of about 120 ns and at a repetition rate of up to 100Hz.

10 - 14 mrad kick requires an integrated vertical field of 1.02-1.4 kG-m.
The kicker system

The ideal kicker field maintains a flat top at about 220-280 Gauss, for the full 120 ns, and then returns to zero before the muons complete a single revolution and re-enter the kicker aperture 149 ns later.

The kicker hardware cannot contain magnetic elements such as ferrites, since they will spoil the uniform magnetic field.

Any eddy currents produced in the vacuum chamber, or in the kicker electrodes, must be negligible by 10 to 20 us after injection, or must be well known and corrected for in the measurement.
Determination of the “right kick”

Maximize the muon capture efficiency

Beam dynamics point of view
=> Minimize the coherent betatron oscillation (CBO) to reduce the systematic error

![Graph showing muon capture efficiency vs kicker B-field](image1)

![Graph showing CBO amplitude of stored muons vs kicker B-field](image2)
The kicker design at Cornell

Using the double transmission line (Blumlein) for the pulse forming network

=> The pulse duration (D) is decided by the travel time of the EM wave through the transmission line.

\[ D = \frac{2 \times l}{c} \]  

(length of transmission line) / (the speed of EM wave) \( \sim 120 \) ns

=> Using triaxial line

The kicker system

=> Blumlein pulse forming network + kicker magnet (plates)
6.5 m long blumlein filled with the silicon oil $Z_0 = 25$ ohm
The HV coaxial cable connecting between the blumlein & the kicker magnet => two 50 ohm cables in parallel
25 ohm, high voltage, low inductive load resistance mounted before the kicker magnet
The prototype kicker magnet and vacuum chamber
New geometry of the kicker plates

In the E821 kicker, the field strength is very large at the edge of the plates. So, given the current, the field strength is weaker in the center between the plates.
Thyratron

A gas discharge device working as a high power electrical switch and the controlled rectifier

<table>
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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>Peak Voltage [kV]</td>
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<tr>
<td>Peak Current [kA]</td>
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</tr>
<tr>
<td>(dl/dt) [kA/us]</td>
<td>&gt;300</td>
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<tr>
<td>Repetition rate [Hz]</td>
<td>2000</td>
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<td>Grids</td>
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10.8 mrad kick corresponds to 3.5kA.

=> For 25 Ω load resistance, \(V = 87.5\) kV

=> Considering 12.5 Ω impedance blumlein pulse forming network ...

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Test of the prototype kicker with the Faraday Magnetometer

Measuring kicker magnetic field with Faraday Magnetometer

$\Rightarrow$ Magnetometer using the Faraday Effect

$\Rightarrow$ Optical method to measure the magnetic field

No effect on the eddy current generation

$\Rightarrow$ Fast time response

2-3 ns rise and falling time, limited by the electronics

The schematic diagram of FM
Faraday Magnetometer System
to measure the magnetic pulse generated by the kicker

Laser: 60 mW, Green Laser (532 nm), GAR035, Laserglow technologies

Muon Kicker Chamber

Enclosed box for laser detectors

Polarizer

TGG, 1.1 cm

Half-wave plate

Wollaston prism

Neutral Filter

two photodiodes

=> PDA10A, 2.3 ns rise time, Thorlabs
Preliminary measurement of the kicker field with FM

For 100G field,
$\Delta V/V = 0.046$

So,
ch 1: $0.087V/3.33V = 0.0261 \Rightarrow 56.7 \text{ G}$
ch 2: $0.088V/3.385V = 0.0260 \Rightarrow 56.5 \text{ G}$

Oscilloscope BW limit setting : 25MHz

~160 ns width
Modeling kicker magnet with Microwave Studio (MWS)

kicker length : 1.7 m
width btw two plates : 8.42 cm
plates height : ~ 5 cm
thickness of plates : 1.6 mm
B field to current ratio : 1 kA => 65G  
(E821: 35G)  

3.5 kA for 230G !
Modeling the kicker system with MWS

=> Blumlein pulse forming network + load resistance + kicker magnet

=> Understanding and reproducing the measurement

=> Design and optimization of the system

6.5 m blumlein + 1.7m kicker magnet
Conclusion

The prototype kicker system for the g-2 experiment has been built and tested.

The optimization of the system is underway.
=> the increase of the field strength, the length of the kicker plates better impedance matching, etc...

The kicker system will be ready by early 2016.

The experimental hall completed in May, 2014
### Big Picture Schedule - Project/Ops/Analysis

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<tr>
<th>FY14</th>
<th>FY15</th>
<th>FY16</th>
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**Construction (Project & Muon Campus):**
- MC-1 (GPP)
- g-2 Cryo Plant (AIP)
- Ring Assembly 🟠 Ring cold ready for operations
- Shim Field
- Prep Chambers/Install
- Construct/Install Sub-systems 🟠 Experiment ready for operations
- Accelerator Modifications 🟠 Accelerator ready for operations

**Operations (Laboratory):**
- Ring Cold
- Detector/DAQ Commission
- Beam Tune-up 🟠 Full Running Intensity
- Physics Production Running

**Analysis (Collaboration):**
- Analysis Tools Development
- Mock Data
- 1st Results 🟠 1-2 x BNL statistics
- ~5-10 x BNL
- 2nd Results 🟠 2 x BNL
- 21 x BNL
- Final Results 🟠