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Precision Magnetic Field Calibration for the Muon g-2 Experiment at Fermilab

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The Muon $g-2$ Experiment at Fermilab (E989) has been designed to determine the muon anomalous magnetic moment to a precision of 140 parts per billion (ppb), a four-fold improvement over the Brookhaven E821 measurement. Key to this precision goal is the absolute determination of the magnetic field of the experiment's muon storage ring to better than 70 ppb. The magnetic field will be measured and monitored by nuclear magnetic resonance (NMR) probes, which are mounted on a trolley and pulled through the muon storage region when muons are not being stored. These trolley probes will be calibrated in terms of the free-proton Larmor precession frequency ω_p by a specially-constructed NMR absolute calibration probe. In E821, the uncertainty in the field measurement was 170 ppb, of which 50 ppb was due to the absolute probe. In E989, these uncertainties will be reduced to 70 ppb and 35 ppb, respectively. To meet these stringent requirements, a new calibration probe has been designed and is currently under construction, along with a so-called plunging probe. This plunging probe will be used to transfer the calibration to the trolley probes. This poster will present the design, fabrication, and testing of the absolute and plunging probes, along with the calibration procedure.

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1. Introduction

1.1 The Anomalous Magnetic Moment

The spin g factor of a particle relates its magnetic dipole moment to its spin angular momentum via:

$$\vec{\mu} = g\frac{e}{2m}\vec{s}, \tag{1.1}$$

where $\vec{\mu}$ denotes the magnetic moment, $\vec{s}$ the spin, m the mass, and e the electric charge of the particle. From Dirac's relativistic theory [1, 2] $g = 2$ for particles like the muon and electron. However in 1947, hyperfine structure experiments on hydrogen [3, 4, 5] yielded splittings larger than expected from theory; motivated by this, Schwinger showed that such a discrepancy can be resolved by including radiative corrections to the Dirac magnetic moment [6, 7]. This additional term is the *anomalous* magnetic moment, written in terms of g:

$$a = \frac{g-2}{2}. \tag{1.2}$$

The anomalous magnetic moment for the muon, a_μ, has contributions from the quantum electrodynamics, electroweak, and quantum chromodynamics sectors, and has been calculated to a precision of ~ 0.4 parts per million (ppm) [8]. Experimentally, a_μ has been determined most recently with a precision of 0.54 ppm at Brookhaven National Laboratory (BNL) [9, 10]. The BNL result differs with the theoretical calculation by about 3.5σ, which has sparked extensive research from investigating missing systematic effects to looking for new physics beyond the Standard Model to account for the discrepancy. On the theoretical side, in addition to investigating physics beyond the Standard Model, work is ongoing [8, 11, 12, 13] to improve the uncertainty on the Standard Model calculations. On the experimental side, a new experiment is being constructed at Fermi National Accelerator Laboratory (FNAL) [8] to address the discrepancy, and intends to measure the anomalous magnetic moment to a precision of 140 ppb—a four-fold improvement on the BNL result.

1.2 Measuring the Anomalous Magnetic Moment of the Muon

Like the experiment before it at BNL, the new experiment at FNAL will inject positively-charged muons into a superconducting magnetic storage ring with a vertical magnetic field of 1.4513 T in magnitude, shimmed to be uniform at the ppm level. Vertical focusing of the muon beam is accomplished by electrostatic quadrupoles. Two frequencies will be measured: the rate at which the muon spin (polarization) rotates relative to its momentum, ω_a, and the magnetic field $\vec{B}$ in terms of the free proton Larmor precession frequency, ω_p. These frequencies are related to one another via:

$$\vec{\omega}_a = \vec{\omega}_S - \vec{\omega}_C = -\left(\frac{g-2}{2}\right)\frac{e}{m}\vec{B} = -a_\mu\frac{e}{m}\vec{B}, \tag{1.3}$$

where $\vec{\omega}_S$ denotes the rate of precession of the muon's spin, and the cyclotron frequency of the muons is denoted by $\vec{\omega}_C$. To extract the anomalous magnetic moment, B is expressed in terms of ω_p and Eq. 1.3 is rewritten as [8]:

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$$a_\mu = \frac{\omega_a}{\omega_p}\frac{\mu_p}{\mu_e}\frac{m_\mu}{m_e}\frac{g_e}{2}, \tag{1.4}$$

where the ratios come from experimental measurements [14]: $\mu_e/\mu_p = -658.210\,6866(20)$, $m_\mu/m_e = 206.768\,2826(46)$, and $g_e/2 = 1.001\,159\,652\,180\,91(26)$.

To measure ω_a, the parity-violating decay process $\mu^+ \to e^+\bar{\nu}_\mu \nu_e$ is exploited. In this process, the highest-energy positrons are emitted preferentially along the direction of the muon's polarization. Therefore, there will be a modulation in the arrival time of the highest-energy positrons, detected by electromagnetic calorimeters; this allows the extraction of ω_a. For more details, see Refs. [8, 10].

2. Measuring and Calibrating the Magnetic Field

The magnetic field measurement calls for extracting $\vec{B}$ in terms of the free-proton Larmor precession frequency, ω_p. This is accomplished by conducting pulsed NMR measurements on proton-rich samples, since free proton samples are not readily available. NMR samples filled with petroleum jelly are used in the NMR probes for the measurements. These probes will be arranged on a lattice called the NMR trolley, and is pulled through the muon storage region during specialized runs when muons are not being stored. Since the chemical properties of petroleum jelly are not well known, the measurements from the trolley probes will be calibrated against a specialized "plunging probe" that uses a water sample, whose diamagnetic shielding properties have been measured to high precision [15]. In principle, an NMR measurement yields a field measurement different from the field a free proton would see since the probe materials and NMR sample perturb the field. Such effects are accounted for by conducting a careful study of the magnetic properties of the materials used in constructing the plunging probe. Once these perturbations have been quantified, the free-proton precession frequency ω_p may be extracted from plunging probe NMR measurements. This in turn allows a calibration of the NMR trolley probe measurements.

The calibration work is currently underway at Argonne National Laboratory, where a medical MRI solenoid magnet has been acquired for this effort. This magnet allows for quantifying the effects that the components of the plunging probe may have on the magnetic field, and testing the fully constructed probe. We have shimmed this magnet to a uniformity of 13 ppm peak-to-peak over a 50-cm diameter spherical volume, with measured gradients at the level of $\sim$ 10–20 ppb/mm. Work is ongoing to improve this uniformity to the 1 ppb/mm level.

For recording the NMR data, we have designed and built a high-precision data acquistion system, which has a bandwidth of $\pm$50 kHz ($\pm$833 ppm) centered on the free-proton Larmor frequency of 61.79 MHz[1]. The system has a resolution of better than 1 ppb relative to 61.79 MHz. The system consists of a mechanical switch, a radio frequency (RF) microelectromechanical switch, preamplifiers and low-pass filters resulting in high signal-to-noise levels of 1000:1 with signal amplitudes of 1 V at the start of acquiring the data and RMS noise levels of $\sim$ 1 mV. The setup also includes a 16-bit analog-to-digital converter for digitization of the data and two frequency synthesizers where the internal clock for the each of these components is stabilized by a rubidium clock. Also included

[1] For a magnetic field of $B = 1.4513$ T.

in the system is a field-programmable gate array which controls the timing sequences of the system when running.

Currently under development is the absolute calibration plunging probe, which will feature a cylindrical sample[2]. For the resonant circuit used to deliver $\pi/2$ pulses to the NMR sample and receive the free-induction decay signals, we use nominally non-magnetic variable capacitors and an RF coil. We have measured the capacitors to have a perturbation at the level of 3 ppb. The coil, which is an aluminum wire inside a copper tube—chosen because the magnetic susceptibilities of aluminum and copper roughly cancel—has been measured to have a perturbation of 4 ppb. Going forward, the plunging probe will be constructed and testing will be done to investigate how large of a perturbation this probe has on the field. Additionally, studies will be carried out to understand how gradients in the magnetic field coupled to positional uncertainties affect our measurements; temperature effects and field drift over time will also be studied. The end goal of this work is to quantify all of these effects at high precision (< 35 ppb).

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[2]A cylindrical sample is easier to machine compared to a spherical sample. The level of construction quality and asymmetry of the NMR sample perturbs the magnetic field.

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