PROCEEDINGS OF SCIENCE

Muon $g-2$/EDM Experiment at J-PARC

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The muon anomalous magnetic moment $(g-2)_\mu$ and electric dipole moment are sensitive to new physics beyond Standard Model (SM). There is a discrepancy between the $(g-2)_\mu$ measured by E821 collaboration at Brookhaven National Laboratory (BNL) and the SM prediction at more than 3σ level. Our goal is to measure $(g-2)_\mu$ with a precision of 0.1 parts per million and search for electric dipole moment with a sensitivity of $10^{-21}e\cdot$cm, respectively. To achieve unprecedented precision, we utilize high intensity proton beam at J-PARC and newly developed technique of ultra-cold muon beam from muonium, which is completely different and independent from methods used at BNL and Fermi National Accelerator Laboratory. We report our experimental approaches and current status of each component of our experiment.

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1. Introduction

In the presence of static electric and magnetic fields, the rate at which the spin turns relative to the momentum is written by

$$\vec{\omega} = -\frac{e}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right], \tag{1.1}$$

where $\vec{B}$ and $\vec{E}$ are the magnetic and electric field strengths, e is elementary charge, m_μ is muon mass, $a_\mu = (g-2)_\mu/2$ is muon anomalous magnetic moment, $\gamma = 1/\sqrt{1-v^2}$ is the relativistic Lorentz Factor, β is the ratio of particle velocity to the speed of light c, and η is electric dipole moment (EDM). In the experiment, ω_a and B are measured to determine a_μ. At Brookhaven National Laboratory(BNL)-E821, the muon momentum is chosen to be "magic momentum" of 3.094 GeV/C such that $a_\mu - 1/(\gamma^2-1) = 0$. There is a discrepancy between the $(g-2)_\mu$ measured by BNL-E821 [1] and the SM prediction at more than 3σ level. To verify the $(g-2)_\mu$ anomaly, two new experiments are progressing. One is the experiment by E989 collaboration at Fermi National Accelerator Laboratory (FNAL) [2]. They will reduce the combined statistical and systematic error of the BNL experiment by a factor of 4.

The other is the experiment by our E34 collaboration at J-PARC. We eliminate second term by choose the electric field be null. The spin precession equation is simplified:

$$\vec{\omega} = -\frac{e}{m_\mu}\left[a_\mu \vec{B} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B}\right)\right]. \tag{1.2}$$

Since the rotation axes of anomalous magnetic moment and electric dipole moment are orthogonal each other, we can separate signals due to the anomalous magnetic moment and electric dipole moment. In order to achieve our goal, we will utilize the high intensity proton beam at J-PARC and newly developed novel technique of the ultra-cold muon beam. The muon beam can be stored without requiring an electric focusing field, because the ultra-cold muon beam has an extremely small transverse momentum. Figure 1 shows the overview of E34 experiment. A proton beam is transported from the 3 GeV Synchrotron ring to Materials and Life Science facility (MLF), and injected to the graphite target. The generated surface muons are transported to one of the muon beam line of H-line. The ultra-cold muon is generated from thermal muonium production by the silica aerogel followed by the laser ionization, and then accelerated up to 300 MeV/c at a linac. The muon is injected to the super-conducting storage magnet supplying 3 T field by newly developed three dimensional injection scheme and the decay positron is detected by the silicon strip detector. We aim to measure $(g-2)_\mu$ with a precision of 0.1 parts per million (ppm) and search for EDM with a sensitivity of $10^{-21}e\cdot$cm, respectively.

2. Current status

2.1 Muonium Production Target

The muonium emission rate is essential from the view point of statistics. We use silica aerogel as the muonium production target. A room temperature target such as silica is suitable for E34

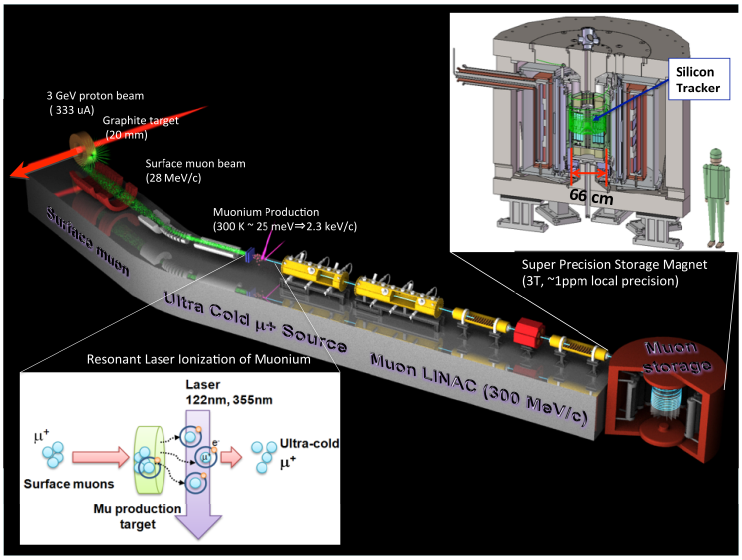

Figure 1: Overview of E34 experiment.

experiment because the resultant muonium has a smaller emittance. However, the muonium production rate was lower than our requirement. The muonium production rate from the standard silica aerogel is limited because the muonium diffusion distances($\sim 30\mu$m) is smaller than the scale of the muon stopping and muonium formation distribution ($\sim$a few mm). To increase surface area of silica aerogel, we introduced many cylindrical holes created by laser ablation as shown in Figure 2. The muonium production rate from the laser ablated aerogel was measured at the TRIUMF M15 beamline [3]. Figure 3 shows the timing distribution of the reconstructed decay positrons downstream of the laser ablated aerogel with equal spacing of 300 μm with comparison to that from the silica aerogel without laser ablation. We have succeeded in enhancement of the muonium production rate from silica aerogel by introducing laser ablation. The emission rate for the ablated aerogel with holes is at least eight times higher than that without the laser ablation. We can achieve the statistical precision of 0.4 ppm for $(g-2)_\mu$ in 10^7 s of data taking time by using this target. We expect further improvement by optimization of parameters such as hole diameter, pitch, and depth.

2.2 Muon Linac

The ultra-slow muons must be accelerated to a momentum of 300 MeV/c to suppress muon decay loss during the acceleration. Furthermore, the transverse emittance growth in the linac should be suppressed to as small a value as possible. In accelerating the muons, the β increases rapidly with the kinetic energy. To realize sufficiently effective acceleration over wide β region, we adopt several types of RF cavities; radio-frequency; RFQ, IH-DTL [4], DAQ CCL and DLS. An Radio-Frequency Quadrupole (RFQ) is the first RF accelerator in the muon LINAC in order to bunch the muons and accelerate them. Inter-digital H-mode drift tube linac (IH-DTL) for low $\beta(\beta < 0.27)$, disk and washer (DAW) for middle $\beta(0.27 < \beta < 0.7)$, and disk loaded structure for high $\beta(0.7 < \beta)$. The particle tracking for the all sections in the muon linac was simulated based on

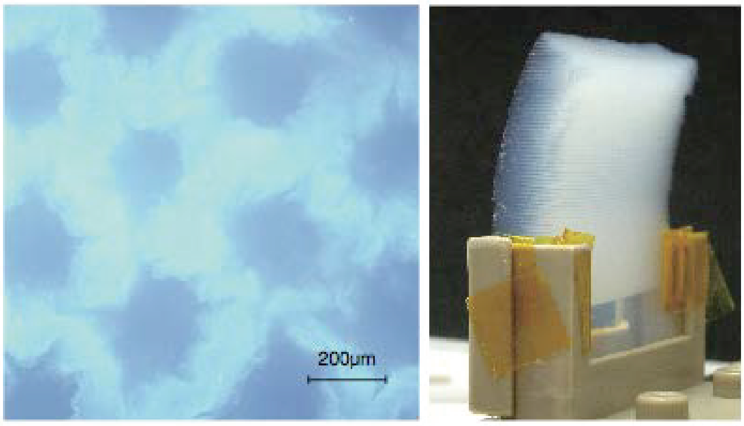

Figure 2: Muonium production target. (left) Photo of surface on the laser ablated aerogel sample. (right) Photo of the laser ablated aerogel installed on a target holder.

the each cavity design. The emittance growth in designed muon linac satisfied the experimental requirement. We are planning the demonstration of muon acceleration with RFQ. which would be the first time in the world and one of the milestone for our experiment.

2.3 Injection

The radius of our storage ring is 66 cm, which is about 20 times smaller than that at BNL and FNAL. To inject our compact storage ring, it is impossible to adopt the procedures used at BNL and FNAL. We have designed new injection scheme, so called spiral injection scheme [5]. Figure 4 shows the concept of the spiral injection scheme. The muon beam is injected into the injection volume in an oblique direction. The spiral motion of muon beam is compressed by a radial magnetic field, which will be arisen as radial fringe field. The pulser magnetic kicker is used to guide the spiral muon beam into a stable orbit at the center of the storage region. The spiral injection scheme is being demonstrated with electron gun. We successfully injected the electron beam into the storage chamber and observed its trajectory. Commissioning work for stable injection is ongoing.

2.4 Magnet and Detector

To detect positron from muon decays, we locate high granular and fast response silicon strip detector in the storage magnet, which provide a magnetic field of 3 T with locally uniformity of 1 ppm. The silicon strip detector are radially placed in the detection volume to efficiently detect the circular track of the positrons as shown in Figure 5.

The design of silicon strip sensor was determined based on the study of the prototype silicon strip sensor and the simulation [6]. The silicon strip sensor have 1024 readout strips at a constant 190-μm. The active area is 97.28 mm $\times$ 97.28 mm and thickness is 320 μm, The real silicon strip sensor has been fabricated as shown in Figure 6. Basic characteristics such as the full depletion voltage, the bulk capacitance, and the inter-strip capacitance were measured. We estimated the detector capacitance to be 17 pF per strip and found no serious problem.

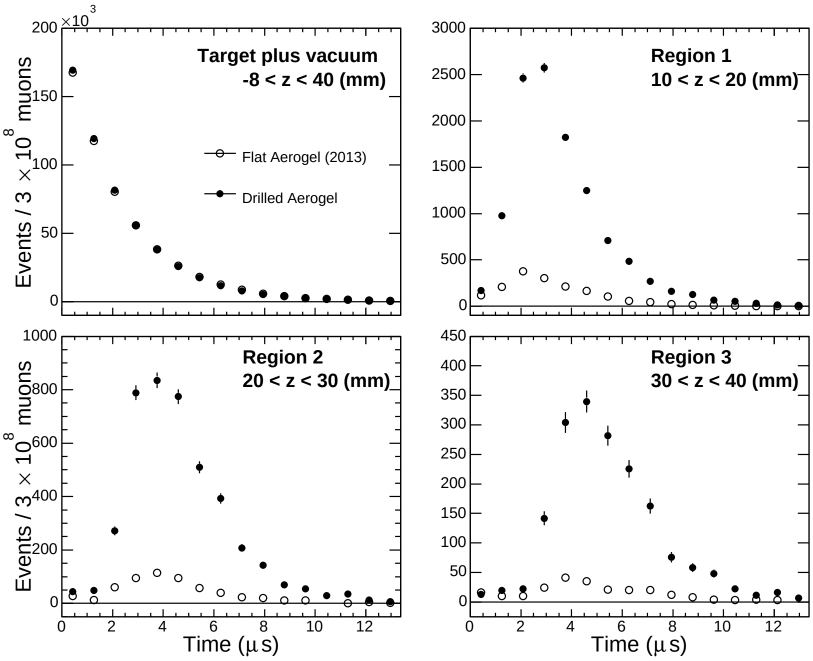

Figure 3: Time distributions of positrons in the entire region and in each of three vacuum regions, for aerogel without laser ablation (open circles) and aerogel with laser ablation (closed circles).

The front-end ASIC is required to tolerate high hit-rate ($\sim$ a few MHz) and the change of hit-rate by a factor of $e^{-5} = 1/150$. We have been fabricated three versions of prototype ASICs [7]. The latest prototype front-end ASIC ("SliT128A") is fabricated by Silterra 0.18 μm CMOS technologies, and have 128 channels as shown in Figure 6. We designed a board for the performance test and SliT128A was mounted on the board by wire-bonding. As a result of the performance test, we confirmed to satisfy almost all of the requirements. An equivalent noise charge is estimated to be 800 electrons assuming the detector capacitance is 23.4 pF. We injected ten consecutive test pulses of 3.84 fC, which corresponds to expected charges by a minimum ionizing particle, with 4 MHz intervals and then observed separate ten output signals. Therefore, we confirm to meet the requirement of hit rate tolerance. After the performance test of "SliT128A" we connected the SliT128A with real silicon strip sensor by wire-bonding and succeeded in observing signals from radiation source (Sr90). We will check the performance of this module at beam test.

3. Summary

E34 experiment at J-PARC aims to measure $(g-2)_\mu$ with a precision of 0.1 ppm and search for electric dipole moment with a sensitivity of $10^{-21} e\cdot$cm. To achieve our goal, we utilize high intensity proton beam at J-PARC and newly developed technique of ultra-cold muon beam from muonium. We are developing all the components: beam line, ultra-cold muon source, muon linac, injection, storage magnet and detector.

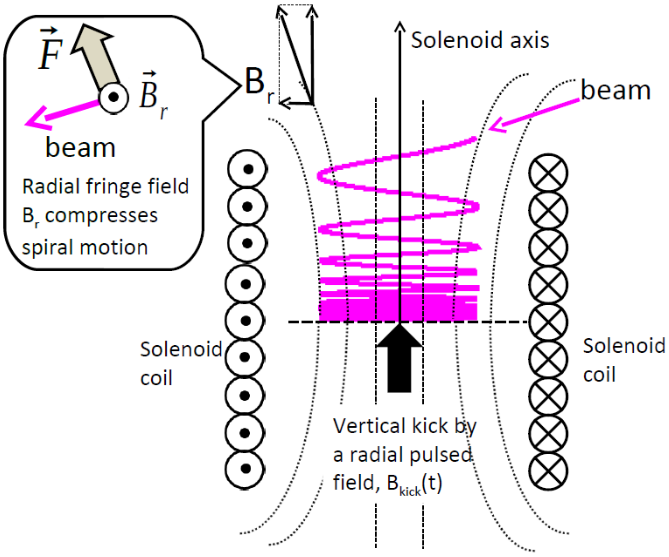

Figure 4: Spiral injection scheme. The muon beam momentum is deflected vertically by a radial magnetic field, which will be built into the solenoid fringe field (B_r).

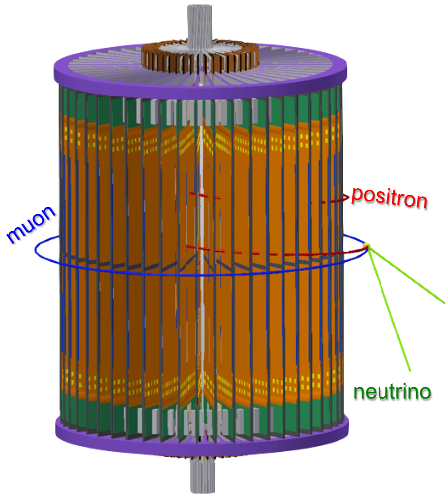

Figure 5: Overview of detector.

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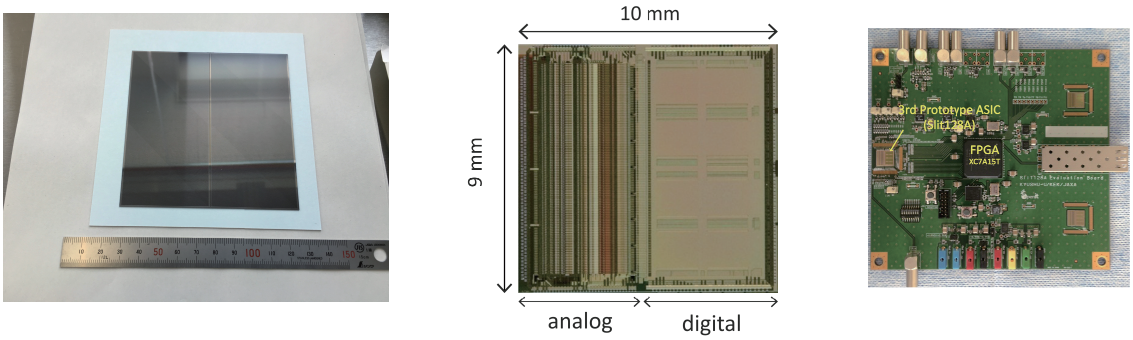

Figure 6: Real silicon strip sensor (left), the latest prototype front-end ASIC "SliT128A" (center), and the board for the performance test of SliT128A (right).

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