# g-2 J-PARC (E34)*

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## Abstract

The muon anomalous magnetic moment $(g-2)_\mu$ and electric dipole moment (EDM) are sensitive to new physics beyond Standard Model of elementary particle physics. The E34 experiment aims to measure $(g-2)_\mu$ and EDM with a precision of 0.1 ppm and a sensitivity to $10^{-21}$ e·cm, respectively, whereas current precision is 0.54 ppm and upper limit is $10^{-19}$ e·cm. We achieve the goal with high intensity proton beam at J-PARC and newly developed novel technique of the ultra-cold muon beam. The ultra-cold muon is generated from the thermal muonium production by the silica aerogel followed by the laser ionization, and then accelerated up to 300 MeV/c. The muon is injected to the super-conducting storage magnet supplying 3 T field and the decay positron is detected by the silicon detector. This paper reports current status of the each experimental component.


## INTRODUCTION

Though the discovery of Higgs at LHC completed the particles predicted in Standard Model (SM) of elementary particle physics, some observations such as dark matter existence indicate new physics beyond SM at some energy scale or interaction scale. One of the clues for new physics is anomaly of the muon anomalous magnetic moment $(g-2)_\mu$ ; There is a $\sim 3\,\sigma$ discrepancy between the SM prediction and the experimental value measured by E821 with a precision of 0.54 ppm [1]. Measurement with higher precision (0.1 ppm) is necessary to confirm this anomaly.

It should be also mentioned that measurements up to now rely on the technique of the magic momentum. Because the muon beam generated from the secondary pions in flight has large emittance, focusing with electric field in addition to the magnetic field is necessary in storage ring. The anomalous spin precision vector of muon is written by

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

where $e$ is elementary charge, $m$ is muon mass, $a_\mu$ is anomalous magnetic moment, $\gamma$ is the Lorentz Factor, $\beta$ is the ratio of particle velocity to the speed of light $c$, and $\eta$ is electric dipole moment. The second term depending on the electric field is eliminated when the muon momentum is 3.094 GeV/c, so called magic momentum. Measurement with a new method should be surveyed for verification of the $(g-2)_\mu$ anomaly.

The muon electric dipole moment (EDM) is also sensitive to new physics because it is strongly suppressed in SM ($10^{-38}$ e·cm), and violates CP symmetry assuming the CPT theorem. In addition to that, there is a possibility that anomaly of $(g-2)_\mu$ can be explained by finite EDM with an order of $10^{-20}$ e·cm [2], whereas current direct limit is $1.9\times10^{-19}$ e·cm [3].

The E34 experiment [4] aims to measure $(g-2)_\mu$ with a precision of 0.1 ppm and search for EDM with a sensitivity to $10^{-21}$ e·cm by utilizing high intensity proton beam at J-PARC and newly developed novel technique of the ultra-cold muon beam. Figure 1 shows the experimental setup. The experiment utilizes the proton beam from the 3 GeV Synchrotron ring to Materials and Life Science facility (MLF). The proton beam is injected to the graphite target. The generated surface muons are extracted to one of the muon beamline of H-line. Surface muons stop in the muonium ($\mu^+e^-$, Mu) production target of the silica aerogel and then form thermal muoniums. The paired electron in the muonium is knocked out by laser and thermal muon (3 keV/c) is generated. Then the muon is accelerated up to 300 MeV/c and injected to the storage ring supplying 3 T. The decay positron is detected by the silicon strip tracker and the spin precession frequency is obtained from variation of counting rate of the decay positron. Thanks to the ultra-cold beam ($\sigma_{pT}/p = 10^{-5}$) where $p_T$ is the transverse momentum of the beam particles, the electric focusing is not necessary anymore. Eq. 1 becomes

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

The anomalous magnetic moment and EDM are perpendicular each other. Therefore these can be measured simultaneously.

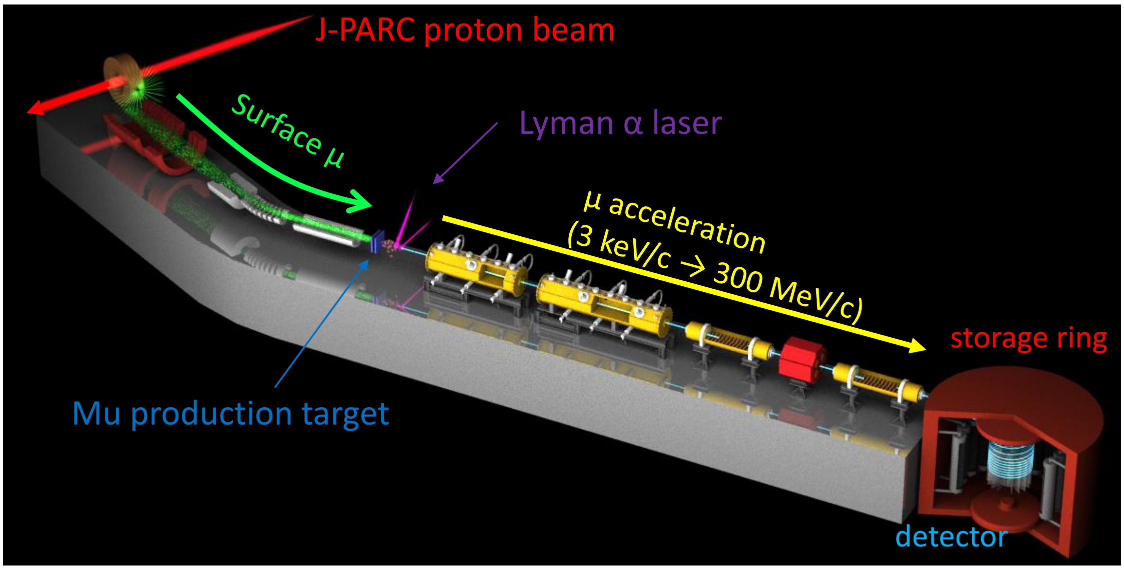


FIG. 1: Schematic view of E34

We are planning to start the experiment in 2019 and developing each experimental component. This paper reports current status of the each component.

## MUONIUM PRODUCTION TARGET

Hot tungsten foil is widely used and developed as a muonium production target [5, 6]. It has a high production efficiency but the generated muon has a high energy due to the high temperature of the tungsten (2100 K). The silica aerogel is also known as a Mu production target [7]. The aerogel can be used in the room temperature and energy of the generated muons satisfies our requirement (p=3 keV/c). The production efficiency, however, was smaller than our requirement.

Our previous measurement with silica aerogel [7] reveals that the diffusion length of muonium in the silica aerogel is 30 $\mu$m which is much shorter than the muon stopping distribution of several millimeters. It indicates that the aerogel with a sub-millimeter structure can emit muoniums to outside the target more easily.

According to this indication, the silica aerogel with sub-millimeter structure was fabricated by using femto-meter laser. The surface area was covered by a triangular pattern of holes of the 270 $\mu$m diameter with equal spacing of 300 $\mu$m, 400 $\mu$m (Fig. 2) and 500 $\mu$m. Measurement of the muonium emission from the laser ablated aerogel was performed at the TRIUMF M15 beamline in 2013 [8, 9]. Figure 3 shows the timing distribution of the reconstructed decay positrons downstream of the laser ablated aerogel with equal spacing of 300 $\mu$m with comparison to that from the silica aerogel without ablation. It is obvious that more emission rate is achieved with laser ablated aerogel, at leaset eight times higher than the one without the laser ablation. We can achieve the statistical precision of 0.36 ppm for $(g-2)_\mu$ in $2 \times 10^7$ s of data taking time by using this target. We are planning to perform further developments towards higher efficiency at the J-PARC muon beamline.

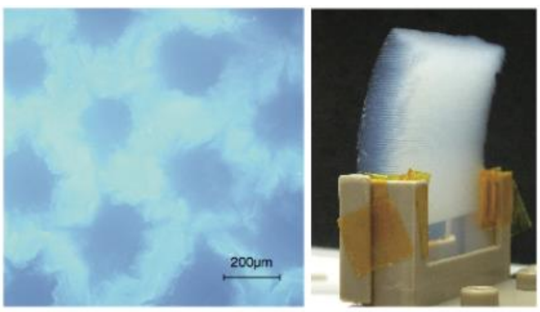


FIG. 2: (Left) Photo of surface on the laser ablated aerogel target. (Right) Whole picture of the target. The muon beam incidents from left and Mu is exiting from right surface. Ref. [8]

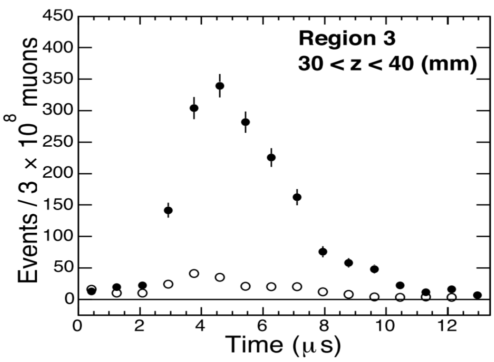


FIG. 3: Time distribution of positrons in near the target surface for flat aerogel (open circles) and laser ablated aerogel (close circles). No background has been subtracted. Ref. [8].

## IONIZATION LASER

Emitted thermal muonium is ionized by the two wavelengths of laser: 122 nm to excite a muonium from 1S ground state to 2P state and 355 nm to ionize from 2P. The latter is generated as a third harmonic of 1062.78 nm and the former is generated using a four-wave mixing technique in Kr gas (Lyman-$\alpha$). Figure 4 shows the schematic diagram of the laser system. The system has been developed in the J-PARC U-line and the Lyman-$\alpha$ laser was succeeded to be fired on August 2014 (Fig. 5). Now the development towards higher power is on-going. More detail discussions can be found elsewhere [10].

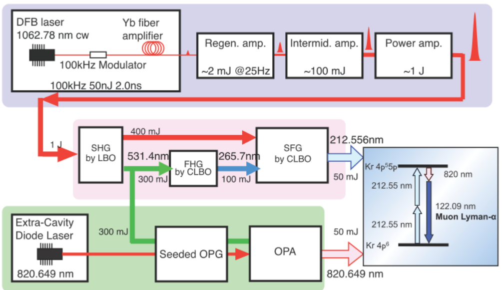


FIG. 4: Schematic diagram of the laser system.

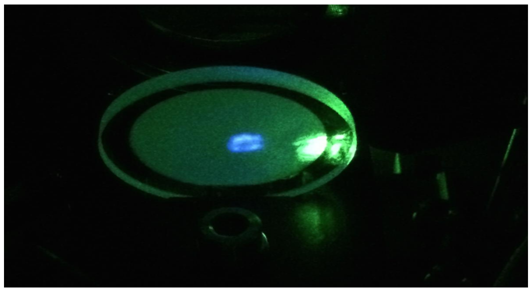

FIG. 5: Demonstration of the Lyman-$\alpha$ generation at the J-PARC MUSE U-line.

In addition to developments in J-PARC, ultra-slow muon production with the laser ablated silica aerogel will be investigated in RIKEN-RAL port3. Beam commissioning has been conducted from September 2015.

## MUON ACCELERATION

Because muon has a finite lifetime, the muon should be accelerated in a sufficiently short period of time to suppress the decay loss. To realize fast acceleration, a muon LINAC dedicated for our experiment is being developed (Fig. 6). Since velocity ($\beta$) of a muon largely varies during acceleration, several types of RF cavities should be adopted to realize sufficiently effective acceleration along with $\beta$. Three types of cavities are adopted after RFQ: inter-digital H-mode (IH) for low $\beta$ ($< 0.27$), disk and washer (DAW) for middle $\beta$ ($0.27 < \beta < 0.7$), and disk loaded structure for high $\beta$ ($0.7 > \beta$) section.

It is planned to utilize the spare RFQ structure from J-PARC proton LINAC (Fig. 7). The electric field of the RFQ is proportional to the mass of the particle to be handled and the RFQ can be operated with $\sim 1/9$ of the field strength for the J-PARC proton LINAC operation in principle. The transmission efficiency is estimated to be 76.8% including decay

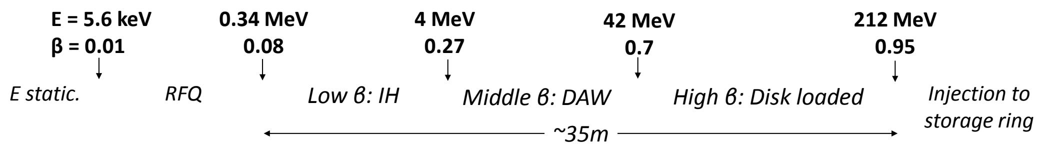


FIG. 6: Overview of the muon LINAC.

loss (19%) and the normalized rms transverse emittance for x (y) is estimated to be 0.294 (0.166) $\pi$ mm mrad with PARMTEQ [11]. The offline test of the RFQ was performed at J-PARC in July 2015. The RFQ was successfully operated with nominal power of 4.2 kW. The Micro Channel Plate detector for the accelerated muon detection was connected to the RFQ and measured background. It was shown that there is no background related to the RF operation [12].

The muon acceleration test with RFQ is under planning in 2016 in the actual experimental area. The equipments for the test such as electrostatic lens were transported from RIKEN-RAL port3 [6] to the J-PARC MLF experimental hall. All the equipments were re-assembled as shown in Fig. 8, with which measurement of the slow muon production is scheduled in 2016. Other studies towards the acceleration test such as the H-line design can be found elsewhere [13].

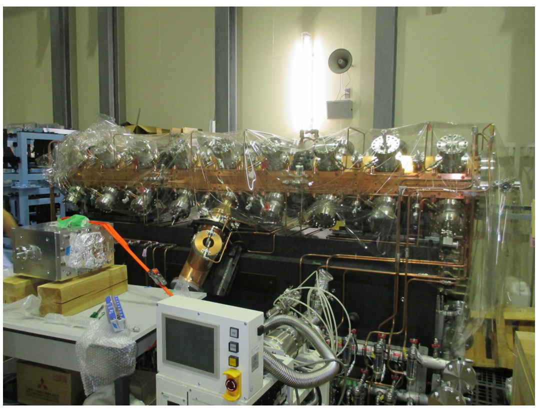

FIG. 7: Photo of the RFQ for muon acceleration.

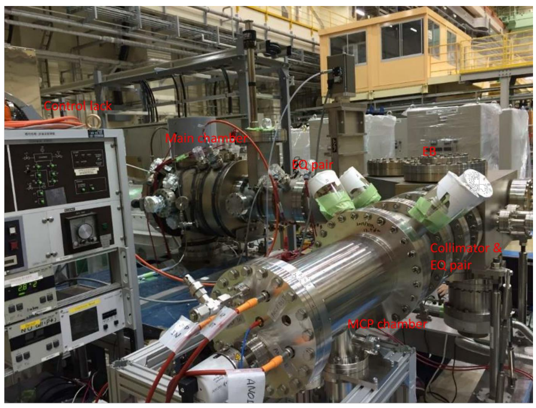

FIG. 8: Photo of slow muon beamline assembled in J-PARC MLF.

The IH cavity consists of a cylindrical cavity and two ridges that are mounted on the top and bottom of cavity. To operate it as an accelerator with the TE111 mode, drift tubes are mounted alternately on the top and bottom ridges via stems. To realize fast acceleration, Alternative Phase Focusing (APF) method is adopted. According to the simulation study, the prototype of the IH cavity was fabricated (Fig. 9). The resonant frequency is measured to be 323.48 MHz which is consistent to the designed value. Further optimization of the cavity design is in progress based on the prototype result.

DAW is one of coupled-cavity linacs. It has highly effective shunt impedance and strong coupling between acceleration and coupling mode. The optimization of the cell design was performed (Fig. 10) and can be found elsewhere [12, 14, 15].

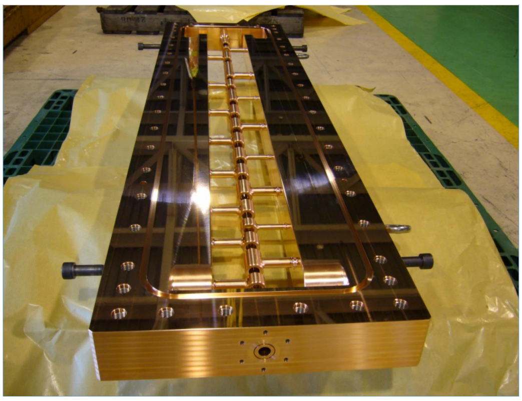

FIG. 9: Photo of the IH prototype in Tokyo Institute of Technology.

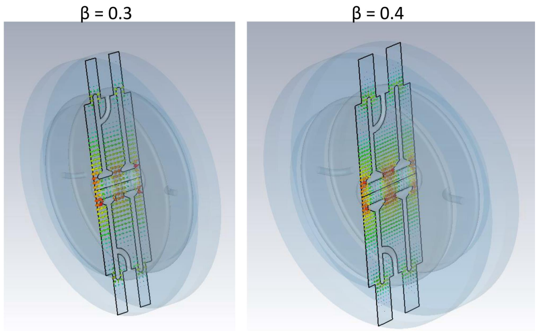


FIG. 10: Three dimensional model and calculated field of the acceleration mode of the DAW cavity in CST MW Studio.

### Injection and storage magnet

Because the radius of the beam orbit in the storage magnet is only 33.3 cm, the same apparatus as previous experiment, a devise called an inflector and kicker, can not be used in our experiment. That's why a three dimensional spiral injection scheme is adopted. In order to match the acceptance of the spiral injection estimated by the simulation, the transport beamline was designed. According to this design, small-scale beamline and solenoid magnet was constructed to demonstrate the injection and storage with electrons. All the apparatuses were assembled (Fig. 11) and the measurement with electrons is being performed.

The storage magnet consists of four super-conducting coils supplying injection field, focusing field and main field of 3 T with local uniformity of 1 ppm. The solenoid magnet is being designed in collaboration with a private company. In order to achieve high homogeneity of the magnetic field below 1 ppm, the error field is corrected by shimming with iron pieces inside the magnet bore and superconducting shim coils. The correction scheme with iron pieces was demonstrated with the magnet for the MuSEUM experiment [16] which supplies 1.7 T in this demonstration. Figure 12 shows the field residual after shimming. It was succeeded to get local uniformity with less than 1 ppm.

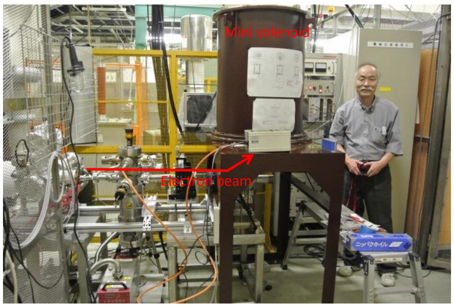

FIG. 11: Small-scale beamline and solenoid magnet to demonstrate the three dimensional spiral injection and storage.

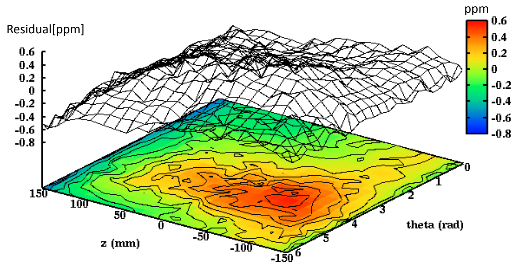


FIG. 12: Field residual after the shimming with iron pieces. Uniformity below 1 ppm in required region is successfully achieved.

**Detector**

The decay positron detector is required to be highly segmented and operated in 3 T. To satisfy these requirements, the silicon strip detectors are radially placed in the detection volume to efficiently detect the circular track of the positrons. The prototypes of the single silicon detector were produced (Fig. 13) according to the simulation study; the effective area is 102 mm $\times$ 72 mm and strip pitch (width) is 100 $\mu$m (27 $\mu$m) for axial direction and 188 $\mu$m (50 $\mu$m) for radial direction on p-side. Basic parameters such as the inter-strip capacitance and the full depletion voltage satisfy our requirement [17].

Because the mean hit rate per silicon strip is very high due to the high intensity pulsed beam, the readout electronics should be capable to record data stably up to several MHz. The analog part of ASICs (SlitA) is being developed with a electronics simulation and some prototypes were produced (Fig. 14). The basic performances were measured with the 200 MeV/c positron beam at Tohoku University and decay positron from muon beam at J-PARC [18].

## SUMMARY

Precise measurement of $(g-2)_\mu$ is one of the promising paths to establish new physics beyond SM and muon EDM is sensitive to new physics because it is very suppressed in SM.

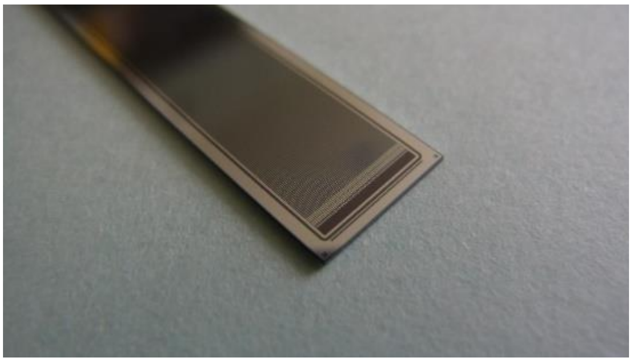

FIG. 13: Photo of the prototype of the silicon detector.

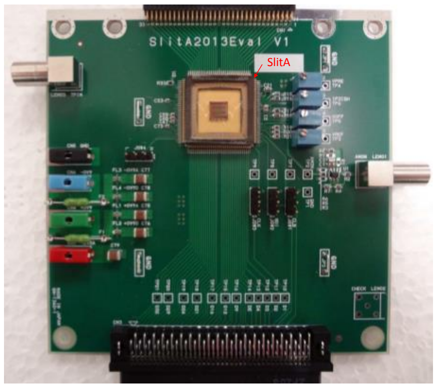


FIG. 14: Photo of the prototype of SlitA on an evaluation board.

E34 aims to measure $(g-2)_\mu$ and EDM with high precision and sensitivity with newly developed novel method of the ultra-cold muon beam. We successfully developed the muonium production target with higher production efficiency by utilizing laser ablated technique. The laser system has been developed in the J-PARC U-line and the Lyman-$\alpha$ laser was succeeded to be fired. The RFQ for initial acceleration and bunching of the cold muons is ready and following RF cavities are being designed. The prototypes of the silicon detector and readout electronics were produced and tested.

We submitted the Technical Design Report to the Program Advisory Committee (PAC) for Nuclear and Particle Physics Experiments at J-PARC and PAC for KEK IMSS MUSE to the aim of starting the experiment in 2019.

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