DEVELOPMENT OF MUON LINAC FOR THE MUON G-2/EDM EXPERIMENT AT J-PARC

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Abstract

Muon acceleration is beyond our experiences. It enables us to measure the muon anomalous magnetic moment with an accuracy of 0.1 ppm and search for electric dipole moment with a sensitivity of 10^{-21}e · cm to explore beyond Standard Model of elementary particle physics. We are developing a linac dedicated to the muon acceleration and planning to try the muon acceleration by utilizing slow negative muonium production. This paper described status of these developments.

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

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

where e is elementary charge, m is muon mass, a_μ is anomalous magnetic moment, γ is the Lorentz Factor, β is the ratio of particle velocity to the speed of light c, and η 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 1.9×10^{-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

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

Because the anomalous magnetic moment and EDM are perpendicular each other, these can be measured simultaneously.

One of the milestones for the experiment is verification of the muon acceleration from thermal energy to 212 MeV, which is the first case in the world. This paper describes status of developments of the muon accelerator and the first experimental verification of the muon acceleration. Other developments can be found elsewhere [5–7].

DEVELOPMENTS FOR THE MUON LINEAR ACCELERATOR

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

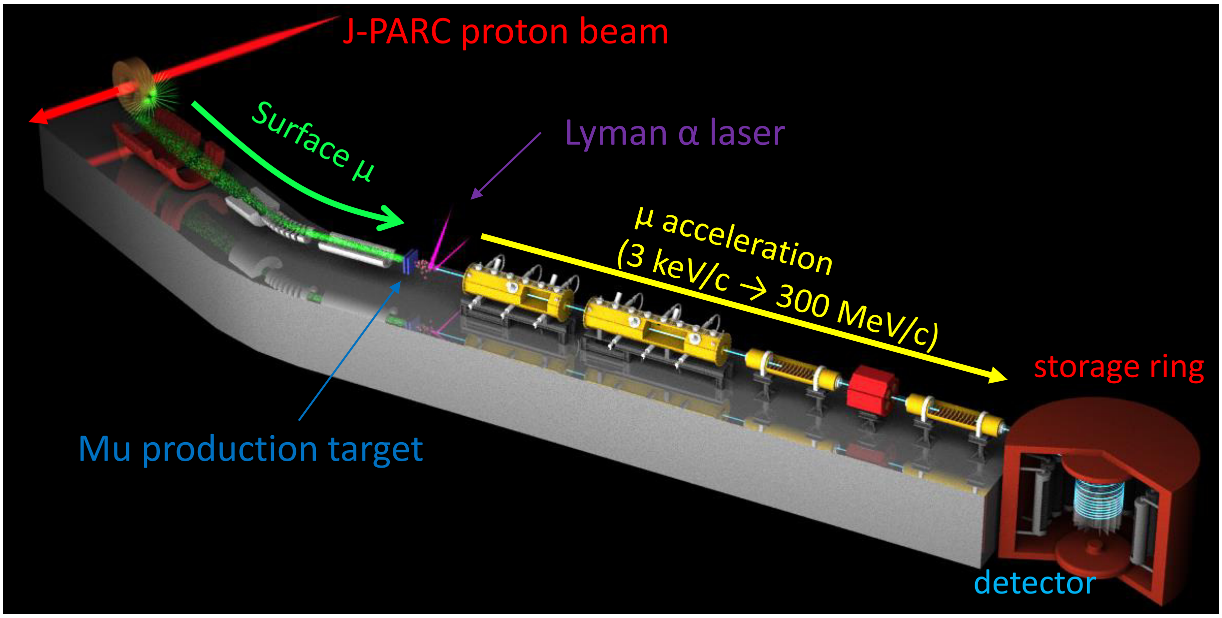

Figure 1: Schematic view of E34.

Initial acceleration will be performed with electro-static lens and RFQ. The electro-static lens consists of the target holder and four electrodes accelerating charged particles emitted from the target region. The transport efficiency is estimated to be about 70% including decay loss with electric-field calculated by OPERA and the particle tracking by the GEANT4 simulation. A spare RFQ of the J-PARC linac (RFQ II) will be used for the muon linac. RFQ II is originally designed to accelerate H^-, the mass of which is nine times larger than that of muon. To accelerate muons using RFQ II, it can be operated with 1/80 of the design power. Details for the muon RFQ are described in [8].

After bunching and acceleration by RFQ, muons will be accelerated by the IH mode cavity. The IH employs APF (Alternative Phase Focusing) to realize the fast acceleration and efficient power consumption. According to the electromagnetic calculation by CST MICROWAVE studio and particle tracking by GPT, first prototype of the IH module was manufactured. Resonant frequency is measured to be consistent with designed value and further measurements are being scheduled.

In the middle beta section, DAW cavity will be employed. It has high effective shut impedance and high degree of coupling between adjacent RF cavities. In order to solve the mode overlapping problem, a bi-periodic L-support structure is employed [9]. By using the electromagnetic calculator of SUPERFISH for two dimensional model and CST MICROWAVE studio for three dimensional model (Fig. 2), the cavity parameters are optimized so that the shunt impedance is maximized in each length of cavity. Figure 3 shows calculated shunt impedance along β [10]. Because the klystron power and experimental space are limited, the shunt impedance is required to be more than 32 MΩ/m. Optimized model satisfies the requirement in average.

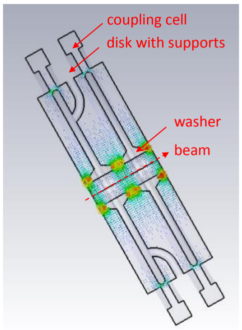

Figure 2: Cross-section of the three dimensional DAW model in the CST MICROWAVE studio.

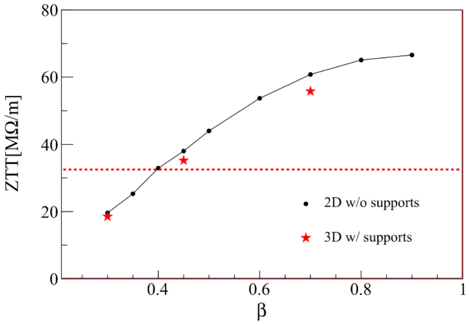

Figure 3: Calculated effective shunt impedance with the optimized DAW cavity. These are calculated by SUPERFISH for two dimensional model without supports and CST MICROWAVE studio for three dimensional model with supports.

VERIFICATION OF THE MUON ACCELERATION WITH SLOW NEGATIVE MUONIUM

In order to perform experimental verification of the muon acceleration, slow muon source is being developed. One of the promising candidates is negative muonium ($\mu^+e^-e^-$, Mu^-) emission by injecting the surface muon beam to a thin metal foil. Previous experiment observed Mu^- emission from an Al foil [11] and the average energy was measured to be 0.2 ± 0.1 keV, which can be applied to the RFQ II acceleration whose injection energy is 5.6 keV.

The measurement of the Mu^- emission efficiency and its kinematics was proposed and approved in J-PARC MLF MUSE. Figure 4 shows experimental setup of the measurement. Surface muons are injected into the Mu^- production target. The emitted Mu^- is accelerated and focused by the electro-static lens and transported to the detector chamber by following electro-static quadrupoles and electro-static deflector. The Micro-Channel-Plate (MCP) is used for counting and timing measurement of Mu^- and surrounding plastic scintillators for the decay-positron detection.

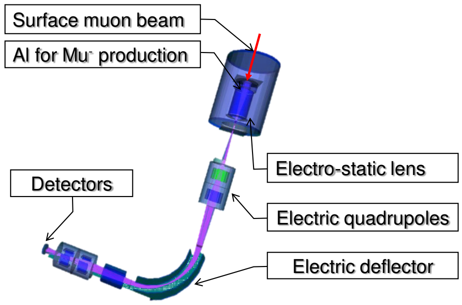

Figure 4: Experimental setup for the Mu^- emission measurement at the J-PARC MLF muon beamline.

Figure 5 shows expected MCP timing distribution estimated by the GEANT4 simulation. In the simulation, the Mu^- signals are generated at the Mu^- target with kinetic energy of 0.2 keV and beam related backgrounds are estimated by injecting the beam muons towards the target. Background events mainly consist of decay-positron from beam muon stopped around the target and the deflector, which can be reduced effectively by lead shield around the target chamber and the collimator located on downstream of the deflector. The signal to background ratio is more than ten and clear separation between these can be achieved by observed timing as shown in Fig. 5.

The beamline for the Mu^- transportation is being assembled in J-PARC MLF. It was originally developed and operated in RIKEN-RAL port-3 [12]. It successfully demonstrated transportation of the slow muon beam. After shutdown of the beamline, some of the beamline components were moved to J-PARC for the Mu^- measurement in summer 2014. Figure 6 shows current status of the beamline. The beamline is being commissioned and the beamline will be ready in the end of May 2015. The Mu^- measurement is scheduled within 2015.

SUMMARY

The E34 experiment aims to measure muon anomalous magnetic moment with a precision of 0.1 ppm and search for electric dipole moment with a sensitivity to $10^{-21}\text{e}\cdot\text{cm}$. One of the milestones of the experiment is experimental verification of the muon acceleration, which will be the first case in the world. To realize the fast acceleration, a linac dedicated to the muon is being developed. It consists electro-static lens, RFQ, and following three types of RF cavities. First prototype of IH for acceleration in the low β section was manufactured and being tested now. The cavity design of the DAW cavity, which will be used for the middle *beta* section, is being designed by the simulation. The slow negative muonium source is being developed towards verification of the muon acceleration by the RFQ. The beamline for a negative muonium transportation is being assembled in J-PARC MLF and will be ready in May 2015. The measurement of the negative muonium emission is performed within 2015, after which the acceleration test is surveyed.

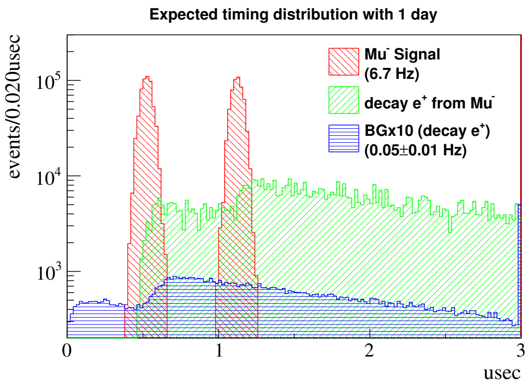

Figure 5: Expected timing distribution estimated by the GEANT4 simulation.

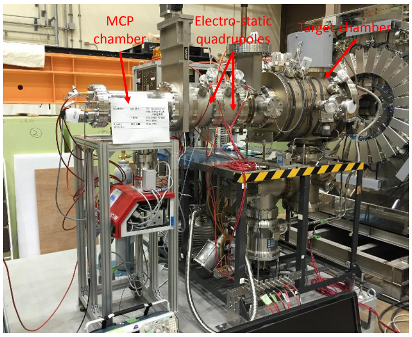

Figure 6: Current status of the Mu^- beamline assembly.

ACKNOWLEDGMENT

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