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First Muon RF Acceleration for the Muon g-2 Experiment at J-PARC

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Muons have been accelerated by using a radio frequency accelerator for the first time. Negative muonium atoms (Mu^-), which are bound states of positive muons (μ^+) and two electrons, are generated from μ^+'s through the electron capture process in an aluminum degrader. The generated Mu^-'s are initially electrostatically accelerated and injected into a radio frequency quadrupole linac (RFQ). In the RFQ, the Mu^-'s are accelerated to 89 keV. The accelerated Mu^-'s are identified by momentum measurement and time of flight. This first muon acceleration is one of big milestones for realizing new muon g-2 experiment at J-PARC.

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1. Introduction

Muon acceleration using radio-frequency (RF) accelerator has been discussed for its potential advantages. For example, in muon collider and neutrino factory studies [1], it is proposed that the large transverse emittance of the muon beam can be reduced through ionisation energy loss and subsequent acceleration [2]. In material and life sciences, one promising application of muon acceleration is in the construction of a transmission muon microscope. If the muons can be cooled to the thermal temperature (ultraslow muon, USM) and subsequently re-accelerated, transmission muon microscopes will be realized [3].

Another application of USM acceleration is precise measurement of the muon anomalous magnetic moment $a_\mu = (g-2)_\mu/2$ and electric dipole moment (EDM) at J-PARC [4]. Muon acceleration is essential to realize these applications; however, it has not been demonstrated except for simple electrostatic acceleration. In October 2017, we successfully demonstrated the first negative muonium ions (Mu^-'s) [5], which will be reported in this paper.

2. Muon g-2 Experiment at J-PARC

Though the discovery of Higgs at LHC completed a list of the particles predicted in Standard Model (SM) of elementary particle physics, some observations such as possible existence of dark matter indicate new physics beyond SM at some energy or interaction scale. One of the clues for new physics is the muon anomalous magnetic moment a_μ ; it has been measured to 0.54 ppm [6] and a discrepancy of more than 3 standard deviations between measurement and the SM prediction was observed. This anomaly stimulated theorists to performing challenging calculations of corrections and uncertainties in the SM prediction of a_μ . After many years of scrutiny, the discrepancy remains unexplained [7]. Along with the theoretical efforts, new experiments should address this anomaly.

The previous experiment at Brookhaven National Laboratory (BNL), E821, used the technique so called magic momentum. Because the muon beam generated from the secondary pions has large emittance, strong electric focusing in addition to the magnetic field is necessary in a storage ring. The difference of the cyclotron motion frequency ($\vec{\omega}_c$) and the muon spin precession frequency ($\vec{\omega}_s$) is given by

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2-1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\vec{\beta}\times\vec{B} + \frac{\vec{E}}{c}\right)\right], \tag{2.1}$$

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 using a new method will verify the a_μ anomaly.

The J-PARC E34 experiment [4] aims to measure a_μ with a precision of 0.1 ppm and search for EDM with a sensitivity of about 10^{-21} e·cm by utilizing USM. Figure 1 shows the experimental setup. The experiment utilizes the proton beam from the 3 GeV synchrotron ring to Material and Life Science Experiment Facility (MLF). The proton beam is injected to the graphite target. The generated surface muons are extracted to one of the muon beamline, H-line. The surface muons stop in the silica aerogel and approximately half of the stopped muons form thermal muoniums (μ^+e^-). The paired electron in the muonium is knocked out by a 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 a silicon strip tracker and the spin precession frequency is obtained from variation of counting rate of the decay positron. Thanks to the ultracold 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. 2.1 becomes

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} + \frac{\eta}{2}(\vec{\beta}\times\vec{B})\right]. \tag{2.2}$$

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

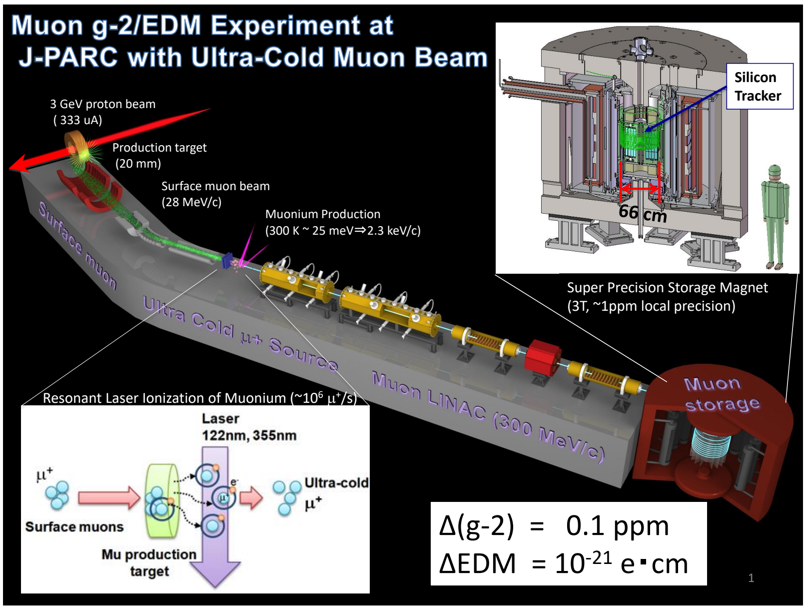

Figure 1: Overview of the J-PARC E34 experiment.

One of milestones for the experiment is demonstration of muon acceleration using a RF accelerator, which had been realized in the world.

3. Setup of the Muon Acceleration Experiment

Figure 2 shows the setup of the muon acceleration experiment. The J-PARC muon science facility (MUSE) [8] provides a pulsed surface muon (μ^+) beam with the 25-Hz repetition rate. The surface muons are decelerated by an aluminum degrader, and some portions form the negative muonium (Mu$^-$, $\mu^+ e^- e^-$). The Mu$^-$'s are extracted and accelerated to 5.6 keV by an electrostatic lens [9]. They are then injected to an RFQ and accelerated to 89 keV. The accelerated Mu$^-$'s are detected by a beam profile monitor (BPM) after a diagnostic beamline. The diagnostic beamline consists of a magnetic quadrupole pair (QM1 and QM2) and a bending magnet.

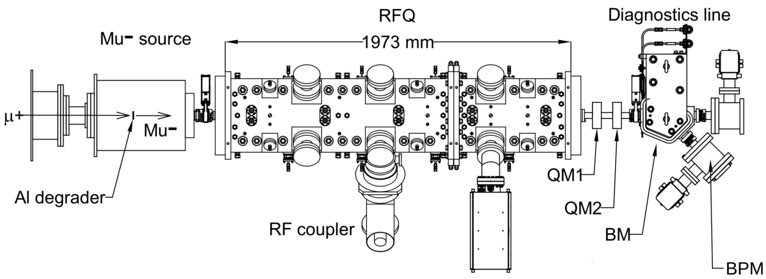

Figure 2: Schematic drawing of the experimental setup [5].

The diagnostic beamline was commissioned prior to the experiment using a H^- source [10]: The H^-'s are generated by exposing an Al foil surface to ultraviolet light. The extracted kinetic energy of the H^-'s is set to 10 keV so that the momentum of the H^-'s is the same as that of the accelerated Mu^-'s.

4. Result

Because the energy spectrum of simply degraded μ^+'s is very broad, some of those penetrate the RFQ without acceleration. The beam diagnostics system was verified using this penetrating μ^+ at the beginning of the muon acceleration experiment. Figure 3(A) is a scatter plot of pulse height vs. time of flight (TOF) for the observed μ^+ with the MCP. The muon arrival time at the Al degrader was measured with a set of scintillating counters located at the side of the Al degrader. Figure 3(B) is a projection to the pulse-height axis. The main background of the muon measurement is decay positrons from the μ^+. They penetrate the MCP, and thus are easily eliminated by applying a pulse-height cut. Figure 3(C) shows the TOF distribution after the pulse-height cut was applied. Because the distance between the Al degrader and the MCP is 3.4 m, the TOF of the 89 keV μ^+ is 270 ns. The observed TOF peak is consistent with this calculation.

Finally, the polarities of the magnets were flipped to the negative-charge configuration. Figure 4 shows the TOF spectrum with and without the RF operation after the pulse-height cut was applied. With the RF operation, a clear peak was observed at 830 ± 11 ns. The number of cells of this 324-MHz RFQ is 297, and thus it takes $\frac{297}{2\times324\times10^6} = 458$ ns to fully accelerate the particles through the 324 MHz RFQ. Therefore, the arrival time of the accelerated Mu^- is later than that of the penetrated μ^+. The TOF spectrum was confirmed with a series of simulations. The simulation of the Soa lens was conducted using GEANT4. The three-dimensional electric field was calculated with OPERA3D [11] and implemented in the simulation. The transit time through the Soa lens was estimated with this simulation to be 307 ns and the acceptance was estimated to be 4%. PARMTEQM [12] was employed for the RFQ simulation, and the transmission was estimated to be 5%. Almost all losses occurred at the RFQ entrance, because of much larger emittances than the acceptance of the RFQ. TRACE3D [13] and PARMILA [14] were utilized for the diagnostics line simulation. The transport efficiency to the MCP was evaluated to be 87%. The length of the diagnostics line is 0.91 m, and thus the transit time of the 89 keV Mu^- is 72 ns. The total flight time of the accelerated Mu^- from the Al degrader to the MCP was calculated to be

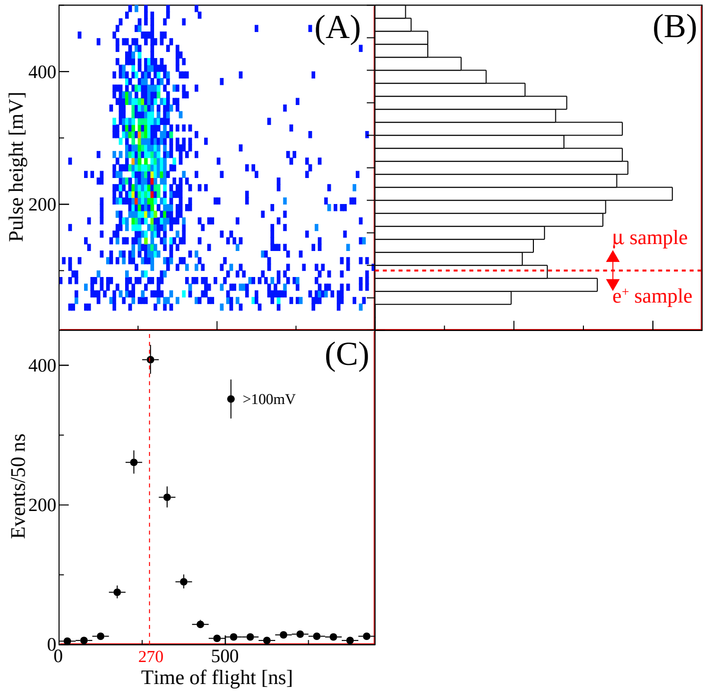

Figure 3: Distribution of the MCP pulse height and the TOF of the penetrating μ^+ [5]. (A) Scatter plot of the pulse height vs TOF. (B) Pulse height of the MCP signal. The events above 100 mV were regarded as μ^+. (C) TOF spectrum after the pulse-height cut was applied. The peak corresponds to the μ^+'s injected into the RFQ with an energy of 89 keV.

$t_{\mathrm{tran.}} = 307 + 458 + 72 = 837$ ns, which is consistent with the measurement. The hatched histogram in Fig. 4 represents the simulated TOF spectrum of the accelerated Mu$^-$. The number of simulation events was normalized to 4×10^{11} incident μ^+'s. The 46 ns rms width of the TOF spectrum is consistent with that from the timing distribution of the primary μ^+ at the Al degrader.

From these experimental results, it is concluded that the observed TOF peak is due to the Mu$^-$'s accelerated by the RFQ to 89 keV. The event rate in the 780 to 980 ns TOF range was estimated to be $(5 \pm 1) \times 10^{-4}$/s by subtracting the decay-positron events estimated from the timing region outside the signal range.

5. Summary

In summary, muons have been accelerated by RF acceleration for the first time. Slow Mu$^-$'s were generated through the electron capture process of the degraded μ^+'s in the D2 area of J-PARC MUSE, and accelerated with the RFQ up to 89 keV. The intensity of the accelerated Mu$^-$in this experiment is limited by the very low conversion efficiency of $\mu^+$to Mu$^-$. With the construction of the new H line and the laser-dissociation ultraslow muon source, the intensity is expected to be 10^6/s, The result presented in this letter is the first step toward making the low-emittance muon beam available as a powerful tool for application in material and life sciences and fundamental physics research.

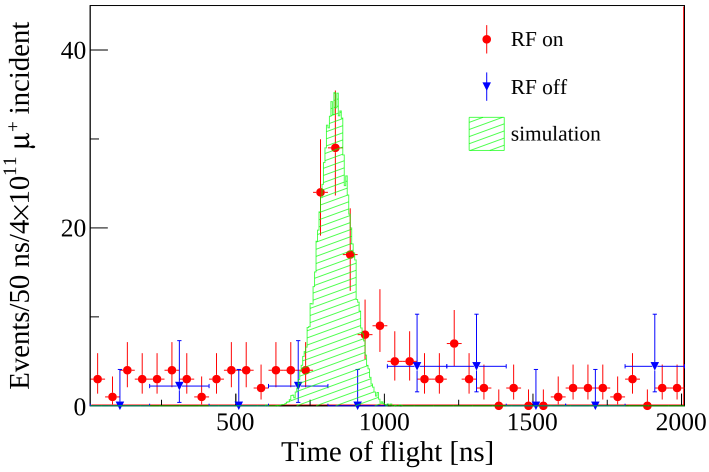

Figure 4: TOF spectra of the negative-charge configuration with RF on and off [5]. The clear peak of the RF on spectrum at 830 ns corresponds to the accelerated Mu^-'s. The error bars are statistical. A simulated TOF spectrum of the accelerated Mu^-'s is also plotted.

6. Acknowledgement

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