# MUON ACCELERATION USING AN RFQ

Y. Kondo*, K. Hasegawa, JAEA, Tokai, Naka, Ibaraki, 319-1195, Japan
M. Otani, T. Mibe, Y. Fukao, N. Kawamura, Y. Miyake, K. Shimomura,
KEK, Oho, Tsukuba, Ibaraki, 305-0801, Japan
R. Kitamura, Univ. of Tokyo, Hongo, Tokyo, 113-8654, Japan
K. Ishida, Riken, Wako, Saitama, 351-0198, Japan
N. Saito, J-PARC Center, Tokai, Naka, Ibaraki, 319-1195, Japan

*Abstract*

A muon linac development for a new muon g-2 experiment is now going on at J-PARC muon science facility. In this experiment, room temperature muons (ultra-slow muons: USMs) are generated and accelerated to 212 MeV using a muon linac. As the first accelerating structure, a spare radio frequency quadruple (RFQ) linac of the J-PARC linac will be used. Prior to constructing the muon linac, we are planning to conduct the first acceleration experiment using this RFQ. For this experiment, a degraded muon beam will be used (slow-muon source), instead of the USM source. In this paper, the beam test of this slow-muon source and simulation studies of the muon acceleration using the RFQ are presented.

## INTRODUCTION

The muon anomalous magnetic moment $(g-2)_\mu$ is one of the most promising prove to explore the elementary particle physics beyond the standard model (SM). Currently, the most precise $(g-2)_\mu$ experiment is E821 of Brookhaven national laboratory [1]. The precision is 0.54 ppm and the measured value indicates approximately three standard deviations from the SM prediction. The J-PARC E34 experiment aims to measure the $(g-2)_\mu$ with a precision of 0.1 ppm. In addition, the electric dipole moment (EDM) also can be measured with a precision of $1\times10^{-21}e{\cdot}$cm [2]. The experimental method of E34 is completely different from that of the previous experiments. The previous experiments directory used decay muons from the secondary pions generated on the production target. The emittance of such muon beam is very large (typically, 1000 $\pi$ mm mrad); this is a source of uncertainty of the measurement. On the other hand, E34 will use a low emittance muon beam to improve the precision. The required transverse momentum spread $\Delta p_t/p$ is less than $10^{-5}$, and assumed transverse emittance is 1.5 $\pi$ mm mrad. To satisfy this requirement, we are planning to use ultra-slow muons (USMs) generated by laser-dissociation of thermal muoniums (Mu: $\mu^+e^-$) form a silica-aerogel target [3]. The room temperature USMs (25 meV) should be accelerated to 212 MeV to obtain the required $\Delta p_t/p$. A linac realizes rapid acceleration required to accelerate muons, whose lifetime is very short (2.2 $\mu$s). In Figure 1, the configuration of the muon linac [4] is shown.

* yasuhiro.kondo@j-parc.jp

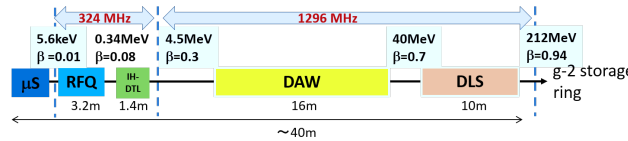


Figure 1: Configuration of the muon linac.

The muon linac will be constructed at the H line [5] of the J-PARC muon science facility (MUSE). The USMs are bunched and accelerated to 340 MeV by a radio frequency quadrupole linac (RFQ). Following the RFQ, an interdigital H-mode drift tube linac [6] is used to accelerate to 4.5 MeV. Then, muons are accelerated to 40 MeV through disk and washer coupled cavity linac section, and finally accelerated to 212 MeV by using disk loaded structure traveling-wave linac. As the first step, a spare RFQ of J-PARC linac (RFQ II [7]) will be used as a front-end accelerator. This RFQ is originally designed to accelerate negative hydrogens. However, by scaling the intervane voltage by the masses, it can be used for muon acceleration [8].

In this paper, present status of muon-acceleration experiment using this RFQ is described.

## MUON-ACCELERATION EXPERIMENT USING THE RFQ

Prior to constructing the muon linac, we are planning to conduct a muon-acceleration experiment using RFQ II at the H line. Figure 2 shows the experimental setup.

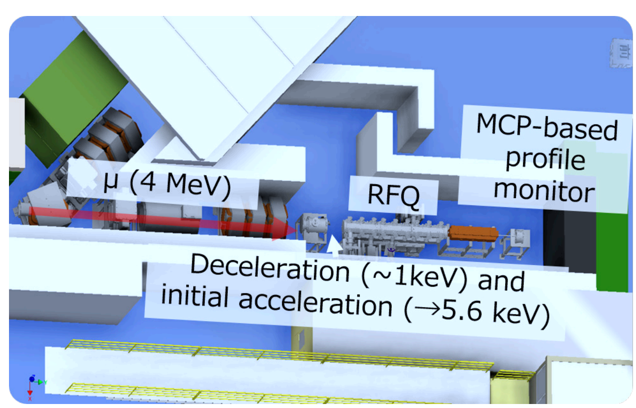


Figure 2: Experimental setup of the muon-acceleration experiment using the RFQ.

The USM source is assumed to be unavailable at the first stage of the muon-acceleration experiment. Instead, we are developing a slow-muon source utilizing a degrader made of a metal foil [9]. With this method, by degrading the surface muon beam though the metal foil, slow $\mu^+$'s or negative muoniums (Mu$^-$: $\mu^+e^-e^-$) with energy of less than 1 keV can be obtained. The production efficiency is much smaller than that of the laser-dissociation method. However, the device becomes very simple, and the cost can be drastically reduced: this feature is suitable for the R&D use. After the aluminum degrader, an SOA lens, which can accelerate and focus simultaneously, is used. We reuse the SOA lens used in the USM source system at RIKEN-RAL [10].

The efficiency of ordinary particle detectors such as scintillators is not sufficient for slow muons. While, micro channel plates (MCPs) has high gain for low-energy particles and the fast time response. Therefore, the profile of extracted muons are measured using a MCP based two-dimensional profile monitor (MPM). It was already confirmed that no significant background is not observed by the MCP attached just after the RFQ, even if the nominal RF power of 4.2 kW is applied [11].

## BEAM TEST OF THE SLOW-MUON SOURCE

To confirm the performance of the slow-muon source described in previous section, we performed a beam test at the MUSE D2 line in Feb. 2016. Figure 3 shows the experimental setup.

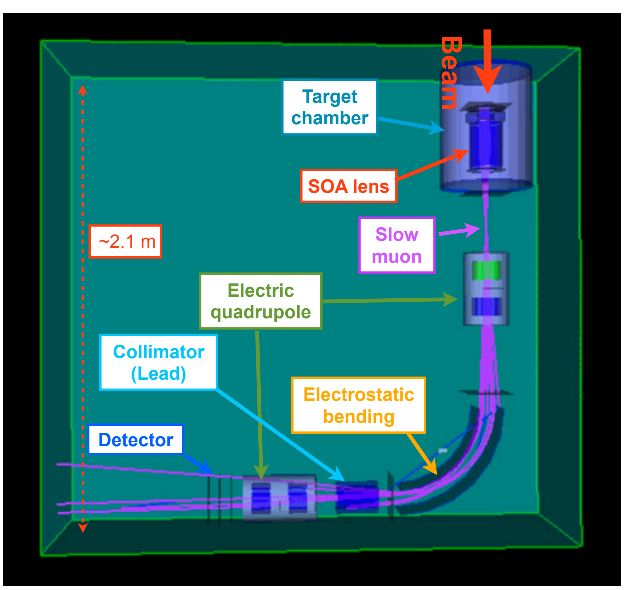


Figure 3: The schematic view of the slow-muon production experiment.

In this experiment, a surface muon beam with 3-MeV energy was exposed to the Al target. The muons were degraded to slow $\mu^+$ and accelerated to 7 keV using the SOA lens. The energy of the muons was separated by an electrostatic bend, subsequently, transmitted to a MCP. The intensity and time of light (TOF) were measured with the MCP. In addition, the MCP chamber was surrounded by scintillator plates to detect positrons from the muon decay (positron counters). The wavelength of the light from the scintillators are converted by wavelength shifting fibers, thus read by using multi pixel photon counters (MPPCs). The positron counters were located at the both sides and top of the MCP chamber, and each detector has two layers. The muons were identified by detecting the positrons using this positron counters.

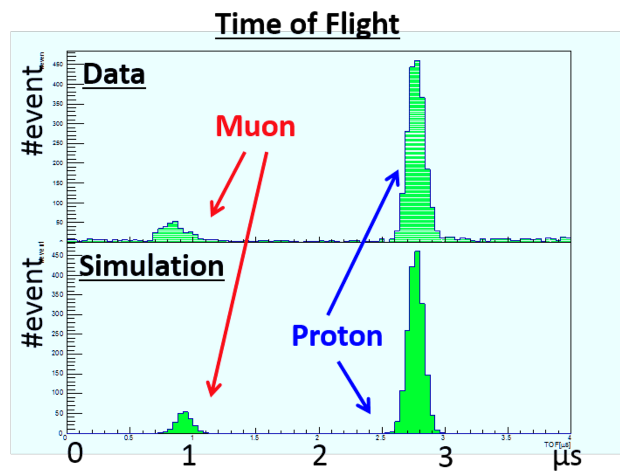


Figure 4: Measured TOF distribution of the slow-muon production experiment.

Figure 4 shows the TOF spectrum. The measured TOF spectrum of the slow $\mu^+$'s well agrees with that of the simulation. In estimating the muon intensity, the main background in the muon signal is from the decay positrons. This background was subtracted by fitting the exponential function of 2.2 $\mu$s decay constant. The measured intensity was $3 \times 10^{-2}$/s. The geometrical factor of the target, transmission efficiency, and the energy acceptance was estimated using GEANT4 [12] simulation. Taking these factors into account, the conversion efficiency from the surface muons to the slow $\mu^+$ measured in this experiment was consistent with that of the previous experiment [9].

## SIMULATION OF THE MUON ACCELERATION USING THE RFQ

Figure 5 shows the setup of the muon-acceleration experiment with the RFQ.

The slow muons generated on the Al foil are accelerated to 5.6 keV using the SOA lens and injected into the RFQ. The muons are accelerated to 340 keV using the RFQ, and then, transported through a sector bending magnet to the MPM at the downstream end. Background particles such as unaccelerated muons and electrons are swept by the bending magnet with a curvature radius of 263 mm and a bending angle of 45 degrees. The MPM consists of a MCP, a phosphor screen, and a CCD camera. The energy of the


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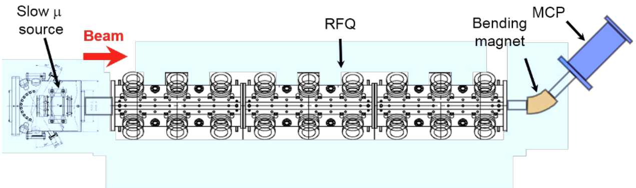


Figure 5: The setup of the muon-acceleration experiment using the RFQ.

accelerated muons are analyzed by using the bending magnet and the MPM. The transverse emittance is measured by changing the z position of the MPM.

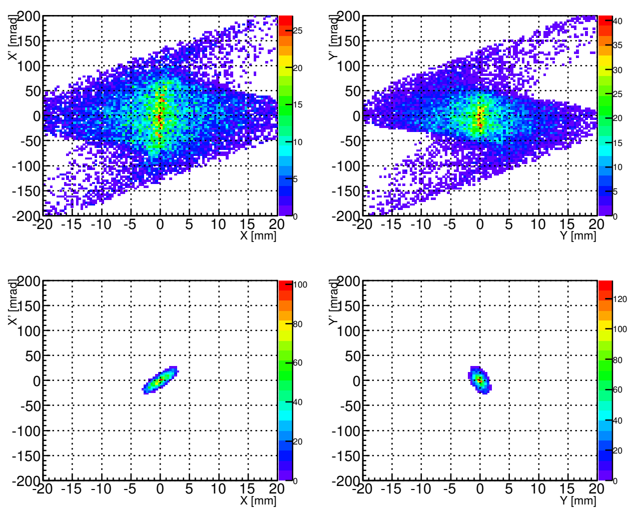

Figure 6: Simulated phase space distribution. Upper figures shows the distributions from the slow-muon source at the RFQ input. Lower figures represent the simulated phase space distribution at the RFQ exit.

Figures 6 represents the simulated particle distribution at the entrance and exit of the RFQ, respectively. The input distribution is obtained using GEANT4; the information from the beam experiment mentioned previous section is took into account. The RFQ simulation was conducted using PARMTEQM [13]. The emittance of the slow-muon source is rather large, but collimated by the RFQ. From the obtained efficiency of slow $\mu^+$ production, the yield at the RFQ exit is estimated. We assume to use the H line and 1-MW beam power on the surface muon target. The yield at the RFQ exit is estimated to be a few Hz. This is enough to measure the beam property.

Figure 7 represents the beam profiles in x direction at various z positions. The simulation after the RFQ exit through the bend is done using PARMILA [14]. The emittance can be measured by changing the z position with a step of ~10 cm. The fiducial area of the MCP is a 42 mm diameter circle, and the position resolution of the MPM is a few 100 $\mu$m. Therefore all these beam widths can be measured

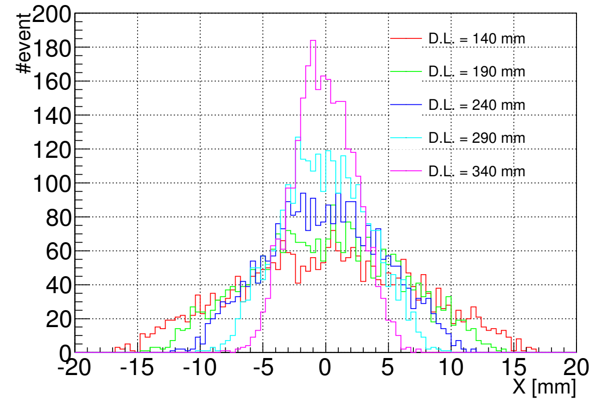


Figure 7: Simulated beam profile in the x direction (horizontal) at the MPM.

with sufficient accuracy, thus the emittance can be derived from this information.

## SUMMARY

We are preparing the world's first muon acceleration using an RFQ. A slow-muon source for this experiment was tested using the surface muon beam. The experimental data and simulation results are consistent each other. Simulation of the muon acceleration is also done and the estimated muon rate at the RFQ exit is a few Hz. It is shown that emittance measurement by changing the profile measurement position is feasible. All the components for the muon-acceleration experiment using the RFQ are almost ready, so the acceleration experiment can be started immediately if appropriate muon beam-line is available.

## ACKNOWLEDGMENT

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