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# MUON ACCELERATION TEST WITH THE RFQ TOWARDS THE DEVELOPMENT OF THE MUON LINAC

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*Abstract*

The muon linac is planned at the Japan Proton Accelerator Research Complex (J-PARC) for the precision measurement of the muon dipole moments. However, the muon acceleration with an radio-frequency (RF) accelerator was not carried out yet. Then, the first muon RF acceleration experiment using an radio-frequency quadrupole (RFQ) linac was carried out in the J-PARC. The incident positive muon was cooled using the production of the negative muonium ion ($Mu^-$) before the accelaration. Subsequently, the $Mu^-$ was accelerated to 89 keV with the RFQ. Thanks to the pulsed muon beam in the J-PARC, the accelerated $Mu^-$ was clearly identified with the Time-Of-Flight measurement after the momentum selection with the bending magnet. The measured event rate of the accelerated $Mu^-$ was consistent with the expectation using the simulation and the result of the $Mu^-$ production experiment as the preparatory experiment of the acceleration experiment. The first muon RF acceleration was successful.

## INTRODUCTION

A muon anomalous magnetic moment $(g-2)_\mu$ is one of the quantities theoretically predicted with the high precision. The E821 experiment at the Brookhaven National Laboratory (BNL) measured $(g-2)_\mu$ with the precision of the 0.54 ppm and reported a discrepancy of more than three standard deviations between the experimental value and the prediction with the standard model (SM) of the particle physics [1]. Since the $(g-2)_\mu$ includes contributions from the physics beyond the SM via quantum loop effects, this discrepancy may imply the evidence of the new physics (NP). As one possibility, the non-zero small muon electric dipole moment (EDM) may contribute the discrepancy of the $(g-2)_\mu$ [2] [3]. Therefore, a more precise and independent measurement of the $(g-2)_\mu$ and the muon EDM than the BNL E821 has been desired to search the NP.

The new precision measurement of the $(g-2)_\mu$ and the muon EDM, the E34 experiment is proposed at the Japan Proton Accelerator Research Complex (J-PARC) using the low-emittance muon beam [4]. Final goals of the J-PARC E34 are 0.1 ppm for the $(g-2)_\mu$ and $10^{-21}$ $e$·cm for the muon EDM, respectively. One of the key components is the low-emittance muon beam produced using the low-energy muon source and the muon linac [5]. However, the muon acceleration with the radio-frequency (RF) accelerator was not carried out yet. Therefore, the demonstration of the muon RF acceleration should be carried out to develop the method of the measurement for the accelerated muon beam towards the construction of the muon linac. The first muon RF acceleration using an radio-frequency quadrupole (RFQ) linac was demonstrated at the J-PARC Material and Life science experimental Facility (MLF) [6] [7]. This paper reports the result of the first muon RF acceleration in the world.

## PRODUCTION OF THE NEGATIVE MUONIUM ION

To accelerate muons using the RFQ, the muons should be cooled to match the input energy of 5.6 keV for the RFQ, because the kinetic energy of the high-intensity muon beam supplied at the J-PARC MLF is about 4 MeV. When the positive muon penetrates through a thin aluminum foil target (Al target), the negative muonium ion ($Mu^-$) is produced [8] [9]. The $Mu^-$ is in the bound state of a positive muon and two electrons. Since the mean initial kinetic energy of the $Mu^-$ is in vicinity of 0.2 keV, the $Mu^-$ production can be used as the cooling method for the muon RF acceleration.

The $Mu^-$ production was carried out to estimate the event rate of the accelerated $Mu^-$ in the muon acceleration experiment. Figure 1 shows the experimental setup of the $Mu^-$ production experiment as the preparatory experiment of the muon acceleration experiment [10].

Both of this $Mu^-$ production experiment and the muon acceleration experiment were carried out at the Muon D-

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line in the J-PARC MLF [11] [12]. The proton beam power was about 150 in the Mu⁻ production experiment and about 300 kW in the muon acceleration experiment, respectively. The repetition rate and the pulse mode of the proton beam were 25 Hz and single-bunch mode, respectively, for both experiments.

Incident positive muons with 3 MeV energy were decelerated with a SUS foil window, a Kapton degrader and the Al target. Then, the Mu⁻ is produced at the Al target. The produced Mu⁻ was extracted with an electrostatic accelerator, which is referred to as a "Soa lens" [13] and transported to the detector through the diagnostic beam line.

The diagnostic beam line consists of the an electrostatic deflector, a bending magnet and several electric quadrupoles. Since the Mu⁻ beam includes the backgrounds such as incident positive muons, decay positrons and low-energy electrons produced by the field emission at the Soa lens, the backgrounds can be suppressed by kinetic-energy and momentum selections using the electrostatic deflector and the bending magnet.

The Mu⁻ was detected with a micro-channel plate (MCP) detector [14] located at the end of the diagnostic beam line. The time difference between the collision time of the incident muons at the Al target and the detection time at the MCP is defined as a Time-Of-Flight (TOF). Thanks to the pulsed muon beam supplied from the J-PARC, the measurement of the TOF can be used to identify the Mu⁻. Figure 2 shows the measured TOF distribution using the MCP. The clear signal of the Mu⁻ was observed with the TOF measurement. Since the measured TOF was consistent with the expectation in the simulation, the Mu⁻ source for the muon acceleration experiment was developed.

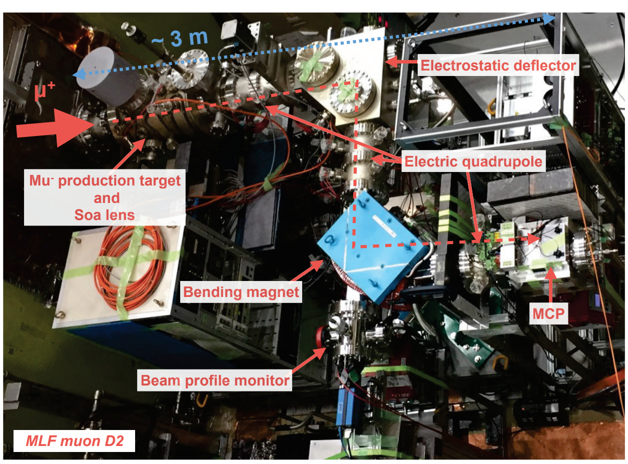


Figure 1: Experimental setup of the Mu⁻ production experiment.

## MUON ACCELERATION EXPERIMENT

Using the developed Mu⁻ source, the muon acceleration experiment with the RFQ [15] was carried out [16]. Figure 3 shows the experimental setup of the muon acceleration experiment. The produced Mu⁻ was extracted with the Soa lens and transported into the entrance of the RFQ. Then, the Mu⁻ was accelerated to 89 keV with the RFQ.

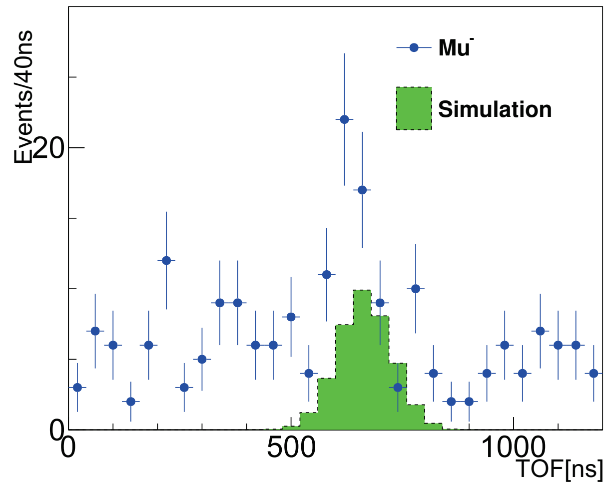


Figure 2: Measured TOF distribution in the Mu⁻ production experiment.

The accelerated Mu⁻ was transported to the MCP through the diagnostic beam line. This diagnostic beam line is composed of two magnetic quadrupoles (QM) and a bending magnet (BM). The accelerated Mu⁻ beam contains the backgrounds such as positive muons penetrating through the Al target and decay positrons from incident muons. Therefore, the accelerated Mu⁻ was identified with the TOF measurement as well as the momentum selection using the BM to suppress the backgrounds. The definition of the TOF is same as that in the Mu⁻ production experiment. The Soa lens and the diagnostic beam line were tested using a H⁻ beam before the acceleration experiment [17].

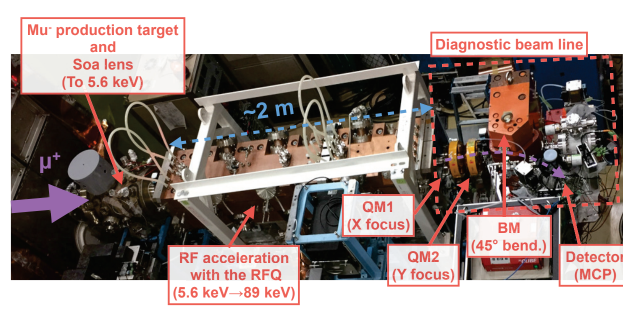


Figure 3: Experimental setup of the muon acceleration experiment.

## SIMULATION

The beam transport in the muon acceleration experiment was simulated using some simulation software. The in-

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cident muon beam was simulated using G4beamline [18]. At the $Mu^-$ production, the initial kinetic-energy distribution of the $Mu^-$ was generated using the data of the deceleration for the low-energy proton [19]. The electrostatic acceleration with the Soa lens was simulated using musrSim [20]. The muon acceleration in the RFQ was simulated with PARMTEQM [21] and GPT [22]. Finally, the beam transport in the diagnostic beam line was simulated using TRACE3D [23] and PARMILA [24]. Figure 4 shows simulated phase space distributions of the accelerated $Mu^-$ at the MCP. The accelerated $Mu^-$ beam was transported into the effective area of the MCP as shown in Fig. 4. The expected TOF of the accelerated $Mu^-$ in the muon acceleration experiment was evaluated using the simulation. The expected TOF's in the electrostatic acceleration, the RFQ and the diagnostic beam line are 289.3 ns, 460.6 ns and 63.2 ns, respectively. Therefore, the total TOF is 813.1 ns. The expected event rate was calculated from the transport efficiency estimated using the simulation and the result of the $Mu^-$ production experiment. The expected event rate of the accelerated $Mu^-$ is $(6.8 \pm 1.2) \times 10^{-4}$ /s.

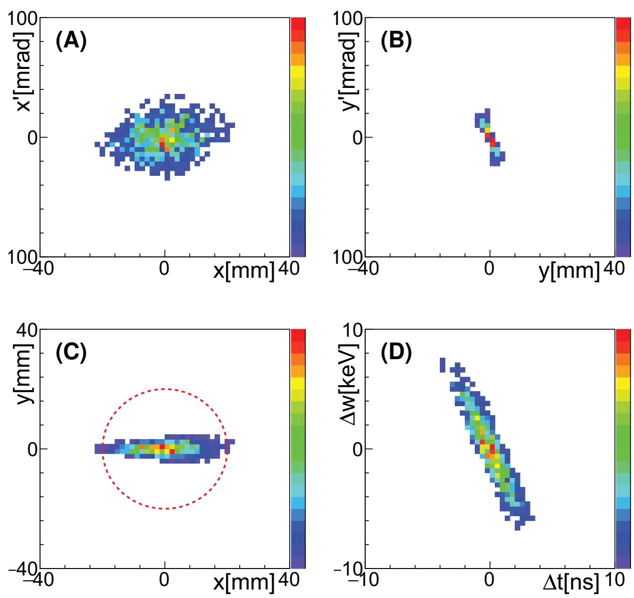


Figure 4: Simulated phase space distributions at the MCP. (A) the horizontal divergence angle x' vs the horizontal position x, (B) the vertical divergence angle y' vs vertical position y, (C) y vs x, and (D) the displacement from the mean kinetic energy ΔW vs the displacement from the mean kinetic energy Δw vs the displacement from the mean TOF Δt. Red dotted line shows the effective area of the MCP.

## RESULT

The clear signal of the accelerated $Mu^-$ was observed with the TOF measurement. Figure 5 shows the TOF distributions for the RF-on and RF-off data, and the simulation. When the RF power of the RFQ was tuned on, the signal peak of the accelerated $Mu^-$ was observed. The measured TOF was 827.8±8.8 ns and corresponded to the expectation in the simulation. On the other hand, no significant signal was observed when the RF power was tuned off.

The measured event rate of the accelerated $Mu^-$ was evaluated with the fitting in the TOF distribution and was $(5.1 \pm 0.8) \times 10^{-4}$ /s. Therefore, the measured event rate was consistent with the expectation. We concluded that the muon ($Mu^-$) was exactly accelerated with the RFQ.

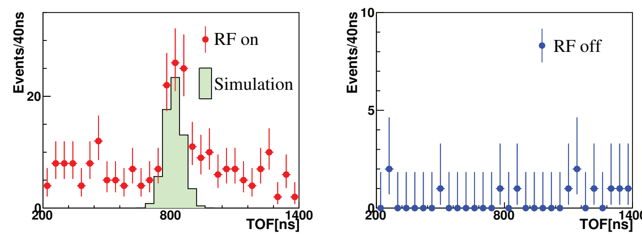


Figure 5: Measured TOF distributions between the RF-on and RF-off data, and simulation in the muon acceleration experiment. The numbers of triggers for RF-on and RF-off data are $4 \times 10^6$ and $4 \times 10^5$, respectively.

## SUMMARY

The J-PARC E34 experiment aims to measure the $(g-2)_\mu$ and the muon EDM precisely using the low-emittance muon beam. Although the muon linac is one of the key components to obtained the low-emittance muon beam, the muon RF acceleration was not demonstrated yet.

The $Mu^-$ source for the muon cooling before the acceleration was developed to demonstrate the muon RF acceleration using the RFQ. Then, using the developed $Mu^-$ source, the muon acceleration experiment was carried out. Thanks to the TOF measurement and the momentum selection, the clear signal of the accelerated $Mu^-$ was observed. This result is the first muon RF acceleration in the world and the important milestone to construct the muon linac.

## ACKNOWLEDGEMENT

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