A BUNCH STRUCTURE MEASUREMENT OF MUONS ACCELERATED BY RFQ USING A LONGITUDINAL BEAM-PROFILE MONITOR WITH HIGH TIME RESOLUTION

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Abstract

The result of bunch size measurement of muon accelerated by RFQ up to 89 keV is presented in this paper. A four-stage muon linac for precise measurement of muon property is under construction in the J-PARC. The demonstration of the first muon RF acceleration with an RFQ linac was conducted and the transverse profile of the accelerated muons was measured in 2017. As one of the remaining issues for the beam-diagnostic system, the longitudinal beam profile after the RFQ should be measured to match the profile to the designed acceptance of the subsequent accelerator. For this purpose, the new longitudinal beam monitor using the micro-channel plate is under development. The time resolution of the monitor aims to be around 30 to 40 ps corresponding to 1% of a period of an operating frequency of the accelerator, which is 324 MHz. On November 2018, the bunch size of accelerated negative muonium ion ($\mu^+e^-e^-$) of 89 keV with the RFQ was measured using this monitor at the J-PARC MLF. The measured bunch width is σ=0.54±0.13 ns, which is consistent with the simulation.

INTRODUCTION

Anomalous magnetic moment ($g-2$) is one of the most precisely measured physical quantity. It is reported that the discrepancy between the measurement value and the theoretical prediction of Standard Model reached more than 3σ [1]. J-PARC E34 experiment [2] aims to measure muon's $g-2$ and electric dipole moment with high precision by a different way from the previous experiments [3] and the successor experiment [4]. In this experiment, a low-emittance muon beam is provided using epithermal energy muons and a four-stage linac. Demonstration of the first muon RF acceleration with an Radio-Frequency Quadrupole (RFQ) linac was conducted [5] and the transverse profile of the accel-

erated muons was measured last year [6]. As one of the remaining issues for the beam-diagnostic system, the longitudinal beam profile of low-beta muons should be measured for beam matching to a subsequent accelerator. For this purpose, a new longitudinal beam monitor using micro-channel plates is under development. Time resolution of the monitor aims to be around several ten ps corresponding to 1% of a period of an operating frequency of the accelerator which is 324 MHz.

In this paper, the experimental setup of muon bunch size by using the beam monitor with high-time precision and the result are presented.

EXPERIMENTAL SETUP

The beam test was conducted at the Muon Facility D2 area in the J-PARC Materials and Life Science Facility (MLF). Figure 1 shows an experimental setup in the D2 beam area. Positive muons (μ^+) whose kinetic energy is about 2.9 MeV are provided from D2 port. Because the RCS is operated in double-bunch mode, the μ^+ bunches come at intervals of 598 ns. And the bunch size of μ^+ is around σ=50 ns. During the measurement, the proton beam power of the RCS, which is the Synchrotron providing proton to MLF for production of muon, is 305 and 509 kW. Estimated μ^+ intensity are 2.5×10^6 and 4.0×10^6 [μ^+/s]. These μ^+ are degraded by a target which consists of kapton and aluminum foil. A part of μ^+ forms negative muonium ion (Mu$^-$, $\mu^+e^-e^-$), whose kinetic energy is about 25 meV, at the surface of target and diffuse out of that [7]. The production efficiency of Mu$^-$ is estimated to be 8×10^{-7} [8]. Mu$^-$s are accelerated up to 5.6 keV by the electro-static lens system, which is Soa len [9], and are injected into the RFQ. This linac which is the prototype RFQ [10] of J-PARC can accelerate the Mu$^-$ up to 89 keV [5].

In a diagnostic beam line at the downstream, the Mu$^-$s are transferred by a couple of quadrupole magnets (QM1
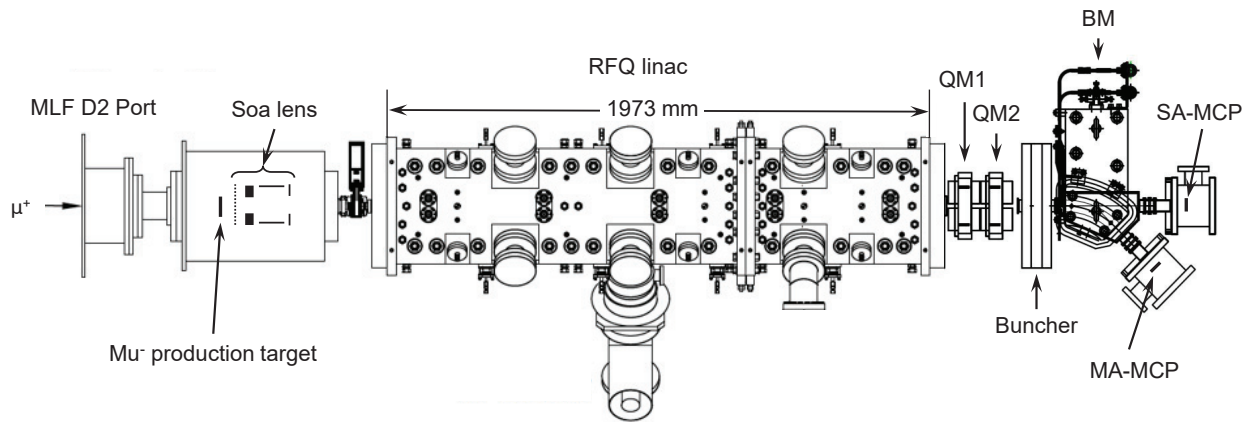
Figure 1: The figure of experimental setup introduced in J-PARC MLF D2 area.

and QM2) and a buncher. The gradients of QMs are 200 and -180[G/cm], which are X-focus and Y-focus respectively. The buncher is a 324 MHz cavity of Drift-Tube-Linac type, and the total maximum effective gap voltage is estimated to be 5.3 keV through two gaps in CST studio simulation. The Mu^-s that have the kinetic energy of 89 keV are bent at 45 degrees by a bending magnet. A couple of MCP detectors are located in a straight section and a deflected section. A single-anode MCP detector in the straight section can be used to detect multipacting electrons emitted from a buncher, which are background events. A multi-anode MCP detector in the deflected section is a longitudinal beam monitor described in next section.

The RF power applied to the RFQ and the buncher are respectively 2345 W and 356 W. The RF power and relative phase of the RFQ and the buncher are monitored and adjusted not to deviate more than 60 W and 3 degrees during the data taking. An on-phase, which is relative phase to bunch Mu^- properly, is determined from the calculation of Time-Of-Flight of Mu^- and monitored value.

MONITOR

The longitudinal beam profile monitor aims to measure bunch size by measuring the time when a muon hit on the surface of MCP and reference time with high time resolution. The monitor is composed of two-stage MCP (Hamamatsu Photonics F1217-011G [11]) and a readout system. The MCP can detect one muon. The signal timing is determined by a constant-fraction discriminator [12], which can reduce pulse-height dependency. The reference timing which synchronizes the phase of the RF applied the RFQ is also obtained. The time information acquired by TDC (CAEN V1290A [13]), whose time resolution of each channels is σ =35 ps. In addition, the signal shape of MCP is acquired by Flash-ADC (CAEN V1720 [14]). Figure 2 shows the result of time resolution using photo-electrons. This monitor including the readout system achieves the time

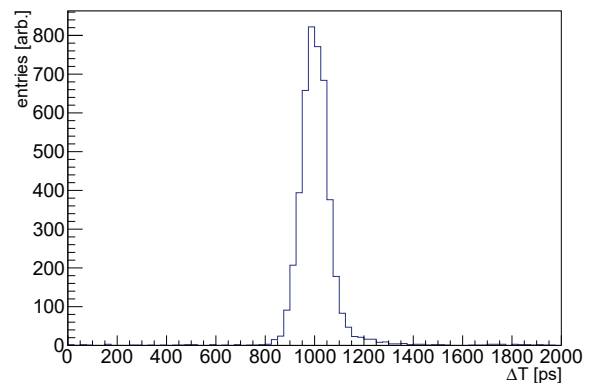resolution of less than 70 ps in an offline test using electron.

Figure 2: The result of offline test using electrons. The X axis is the time difference between the electron detection and the reference signal.

RESULTS

The signal events are extracted by Time-Of-Flight (TOF) and pulse height of the signal. Figure 3 shows the time and pulse-height distribution. A main source of backgrounds is electrons emitted by muon decay. The TOF of accelerated Mu^- can be calculated to be 839 ns. The signal timing is indicated as red area in the figure. Figure 4 is comparing the signal region and a background region drawn as a blue area in Fig. 3. It can be seen that the signal events have higher pulse height, then the signal whose pulse-height is more than 800 mV is used. The quantities of background in the signal region are estimated by fitting to the background region. As a result of the selection, around 69 Mu^- accelerated with on-phase are accumulated by about 4×10^5 incident μ^+.

Figure 5 shows the result of the bunch size measurement. The bunch width is σ=0.54±0.13 ps. The main source of error is statistic error, and systematic error coming from the
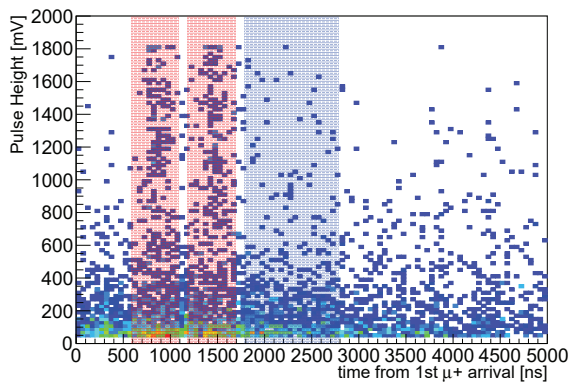
Figure 3: The TOF and pulse heigh distribution. X-axis is time of MCP signal from μ^+ arriving at target. Y-axis is pulse height of the signal.

Figure 4: The conmparison of pulse-height distribution. Red dots are signal region (ON-TIME) and Blue squares are background region (OFF-TIME). Two data are normalized by the number of events less than 600 mV.

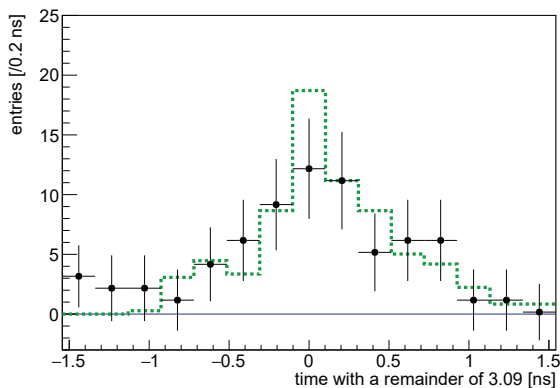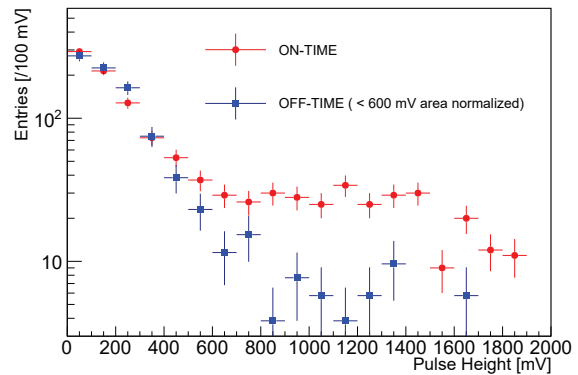time resolution of the monitor is negligibly small. The data is consistent with the simulation which based on Geant4, PARMTEQ and PARMILA.

Figure 5: The result of bunch size measuremnt. The range of X-axis correspond to one period of 324 MHz. The black dots are data and the broken line is the simulation.

CONCLUSION

The muon linear accelerator is under development at the J-PARC for the precise measurement of muon $g - 2$. The longitudinal beam profile monitor for low-beta muon with MCP is designed and developed. The measurement of bunch size of Mu^- accelerated up to 89 keV is conducted. The bunch width is $\sigma=0.54\pm0.13$ ps, which is consistent with the simulation. This result means effectiveness of the method to measure the bunch size of low-beta and low-intensity muon beam. Further studies are needed in order to improve the resolution of the monitor.

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