論文の内容の要旨

Demonstration of the muon acceleration with Radio-Frequency Quadrupole linac (RFQ 線形加速器を用いたミューオン加速の実証実験)

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Since a conventional muon beam is produced from a proton beam through pion decays, this conventional muon beam has a large transverse RMS emittance of about 1000π mm mrad. In contrast, a low-emittance muon beam has the normalized rms transverse emttance of less than a few π mm mrad and is expected to provide many attractive applications in various scientific fields. In the condensed matter physics and the chemistry, for example, the low-emittance muon beam is expected to be used in studies of the magnetic systems around the surface boundary with the method of the muon spin rotation, relaxation and resonance (μSR). As for the muon tomogramphy, the low-emittance muon beam is expected to be useful to explore inner-structures of large objects.

In the particle physics, a precision measurement of the muon dipole moments and a muon collider are expected to be realized using the low-emittance muon beam. Particularly, this precision measurement of the muon dipole moments is expected to play an important role to explore a new physics beyond the standard model. The E821 experiment at the Brookhaven

National Laboratory (BNL) measured a muon anomalous magnetic moment $(g\text{-}2)_\mu$ with the precision of 0.54 ppm and reported the discrepancy of more than three standard deviations between the experimental value and the prediction with the standard model. On the other hand, the muon electric dipole moment (EDM) is expected to be one of the sources of the CP violation to explain the matter-antimatter asymmetry of the universe. The BNL E821 reported a current limit of 1.8×10^{-19} e・cm for the muon EDM. However, since the result of the BNL E821 did not directly exclude the possibility that a nonzero muon EDM contributed to the discrepancy of the $(g\text{-}2)_\mu$, the sufficiently precision measurement of both $(g\text{-}2)_\mu$ and EDM has strongly been desired. Therefore, the new precision measurement of the muon dipole moments using the low-emittance muon beam is proposed.

The E34 experiment at the Japan Proton Accelerator Research Complex (J-PARC) aims to precisely measure the $(g\text{-}2)_\mu$ with the precision of 0.46 ppm and the muon EDM with the sensitivity of 1.5×10^{-21} e・cm, respectively, using the muon beam with the 100 % transverse emittance of less than 1.5π mm mrad. If the conventional muon beam is once cooled and then rapidly re-accelerated with the linear accelerator because the muon decays with the mean life time of about 2.2 μs, such the low-emittance muon beam is obtained. To accelerate the muon almost at rest, an radio-frequency quadrupole (RFQ) linac is used as the initial radio-frequency (RF) accelerator. However, since the intensity of the accelerated muon beam is quite lower than that of the ordinary electron or proton beam, the method of the measurement for the accelerated muon beam should be developed. Therefore, the demonstration of the muon RF acceleration must be carried out in a timely manner to develop the low-emittance muon beam.

The production of a negative muonium ion (Mu^-, $\mu^+ e^- e^-$) is used for the muon cooling in the demonstration of the muon RF acceleration. When the positive muon hits the thin aluminum foil target (Al target), the Mu^- is produced.

Since the mean initial kinetic energy of the Mu^- is in vicinity of 0.2 keV, the Mu^- beam extracted with the electrostatic acceleration can match the input energy acceptance of the RFQ.

To use the production of the Mu^- as the cooling method in the muon RF acceleration experiment, the production yield of the Mu^- should be measured to estimate the event rate of the accelerated Mu^- with the RFQ. Therefore, the production yield of the Mu^- from the Al target was measured. However, the signal-to-noise ratio of the Mu^- beam is so small that a measurement system should be developed to identify the Mu^- beam. Then, a new measurement system has been developed using a Time-Of-Flight (TOF) measurement, considering the feature of the pulsed muon beam supplied from the J-PARC. The TOF measurement can suppress many backgrounds such as incident positive muons, decay positrons and low-energy electrons from the field emission. This measurement system consists of the Al target, an electrostatic accelerator, an electric deflector and a bending magnet to reduce the backgrounds and a micro-channel plate (MCP) to detect the Mu^-. The time difference between the collision time of the incident muon at the Al target and the detection time at the MCP is defined as the TOF. With this measurement system, the clear signal of the Mu^- was obtained and the production yield of the Mu^- was measured. The measured event rate of the Mu^- was $(1.7\pm0.3)\times10^{-3}$ /s. From these results, the well-defined Mu^- source was developed towards the demonstration of the muon acceleration with the RFQ.

The demonstration of the muon RF acceleration was carried out using this developed Mu^- source. Figure 1 shows an experimental setup of the muon acceleration experiment. In this experiment, the Mu^- source including the electrostatic accelerator was connected to the RFQ. The Mu^- extracted from

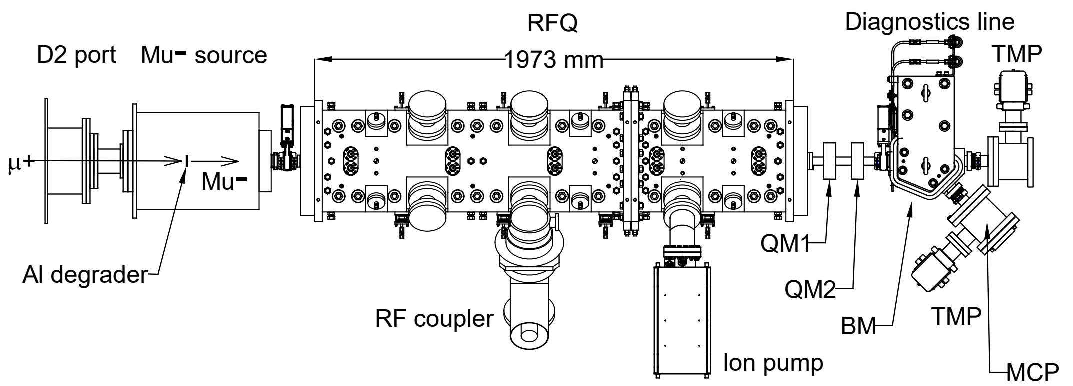

Figure 1. Schematic drawing of the muon acceleration experiment.

the Al target is accelerated with the RFQ. Since the accelerated Mu^- contains the backgrounds such as incident positive muons and decay positrons, this accelerated Mu^- is identified with the TOF measurement as well as the momentum selection using the bending magnet to suppress the backgrounds. Figure 2 shows TOF distributions of the RF-on and RF-off data for the RFQ. The clear signal of the accelerated Mu^- was observed with the TOF measurement, when the RF power of the RFQ was turned on. On the other hand, no significant signal was observed, when the RF power was turned off. The measured event rate of the accelerated Mu^- was $(5.1\pm0.8)\times10^{-4}$ /s, while the expected event rate was $(6.8\pm1.2)\times10^{-4}$ /s from the result of the Mu^- production experiment. The measured event rate was consistent with the expectation. Therefore, we concluded that the Mu^- was exactly accelerated with the RFQ. This is the first result muon RF acceleration in the world.
This method of the TOF measurement is used to identify the accelerated Mu^- in the future commissioning of the muon linac for the J-PARC E34. The successful demonstration of the muon RF acceleration is expected to greatly advance the realization of the low-emittance muon beam and the precision measurement of the muon dipole moments. This result opens the door for various interesting applications using the low-emitatance muon beam to develop the new scientific fields.

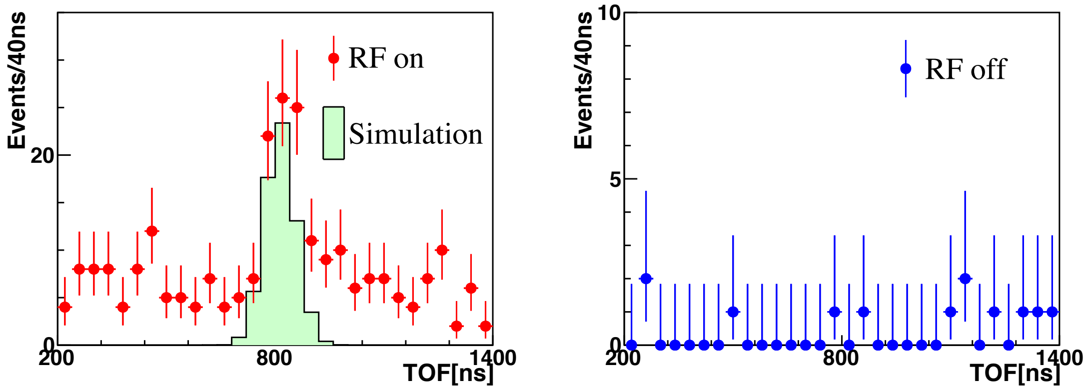

Figure 2. TOF distributions of the RF-on (left) and RF-off (right) data for the RFQ. A simulated histogram is also shown as a hatched histogram.