ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THAN2

BEAM PROFILE MEASUREMENT OF THE ULTRA-SLOW MUON FOR THE TRANSMISSION MUON MICROSCOPE

Y. Nakazawa*, T. Adachi, J. Ohnishi, RIKEN Nishina Center, Saitama, Japan
T. Adachi, A. Goto, Y. Ikedo, S. Kanda, Y. Miyake, Y. Nagatani, Y. Oishi, K. Shimomura, P. Strasser, N. Teshima, T. Yamazaki, T. Yuasa, KEK, Ibaraki, Japan
S. Nakamura, K. Umeda, T. Umezawa, Ibaraki University, Ibaraki, Japan

Abstract

We have performed a beam profile measurement of the ultra-slow muon for the transmission muon microscope, which is being developed at the Japan Proton Accelerator Research Complex (J-PARC). A laser ionization of thermal muonium generates the ultra-slow muon. The generated ultra-slow muon is extracted by an electrostatic lens and transported to the beam profile monitor, which consists of a micro-channel plate and delay-line anode. In this paper, the results of profile measurements and the beam commissioning status of the ultra-low muon beamline are reported.

INTRODUCTION

At the J-PARC Materials and Life Science Experimental Facility MUSE (Muon Science Establishment), we are developing a transmission muon microscope [1] as a new quantum imaging technique using a low-emittance muon beam. Muon has a mass about 200 times greater than electrons and exhibits a smaller interaction in matter at higher energies than protons and electrons, giving them superior transmissivity through matter. The transmission muon microscope will enable transmission observations with observable thicknesses on the order of several hundred m, for example, three-dimensional imaging of cellular activities from synapses to neurons. The observable thickness depends on the muon beam energy, and the imaging resolution depends on the emittance and energy spread of the muon beam. For example, a muon beam with an energy of 5 MeV and an emittance of 1 mm mrad is required for transmission observations with an observable thickness of the order of several m.

A surface muon beam is generated from pion decay at rest near the surface of a muon production target. It has a larger emittance compared to typical electron and proton beams. To achieve the low-emittance muon beam, a laser resonant ionization of the thermal muonium has been developed [2]. A surface muon (μ^+) is decelerated in a hot tungsten target of 2000 K; then, the μ^+ captures an electron to become the muonium (Mu; μ^+, e^-). The Mu is thermally emitted from the target into the vacuum. Then, the pulsed laser lights with wavelengths of 122 nm and 355 nm are exposed to resonantly excite and ionize the Mu. Using this method, μ^+ with a kinetic energy of 0.2 eV can be obtained, assuming a Maxwell-Boltzmann distribution, so-called ultra-slow muons (USMs).

The USMs are accelerated up to 5 MeV using an azimuthally varying field (AVF) cyclotron with a flat-top rf cavity. Table 1 shows the specifications of the AVF cyclotron. The design, fabrication, low-power, and high-power tests have already been completed [3–7]. The Output emittance and energy dispersion after cyclotron exit depends on the phase-space distribution of the input beam [7], so accurate beam diagnostics and beam matching of the USMs are required for beam commissioning. In this paper, the result of the beam profile measurement in the x-y direction of the USMs is described.

EXPERIMENTAL APPARATUS

Figure 1 shows the experimental apparatus at the J-PARC MUSE ultra-slow muon beamline. The ultra-slow muon beamline consists of the Super-Omega beamline (U-line) for surface muon [8, 9], muonium production target, all-solid-state light source for the ionization laser, electrostatic extractor, and transport line. The USMs are transported to two experimental areas, U1A (USM-μSR [10]) and U1B (transmission muon microscopy), respectively.

The Super-omega beamline transports surface muons with a large aperture superconducting solenoid, which enables us to extract high intensity muons at a large solid angle. The surface muon beam has a double-pulse structure with a bunch width of 100 ns, spacing of 600 ns, and repetition rate of 25 Hz. The total flux of the surface muon beam is on the order of 10^{8} $^+$/s.

A tungsten foil heated up to 2000 K was used as a muonium emitter. The epi-thermal muonium in the ground state $1S$ is excited to the $2P$ state by a 122.09 nm (Lyman-α) light and ionized by a 355 nm light. The pulse energy of Lyman-α light reaching the muonium target was approx-

Table 1: Basic Parameters of the AVF Cyclotron for the Transmission Muon Microscope

Beam species	μ^+
Repetition rate	25 Hz
Operating frequency	108 MHz
Acceleration harmonics	2
Average magnetic field	0.4 T
Extraction radius	0.26 m
Injection: energy	30 keV
Injection: transverse emittance (rms)	1 mm mrad
Extraction: energy	5.2 MeV

* yuga.nakazawa@riken.jp

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THAN2

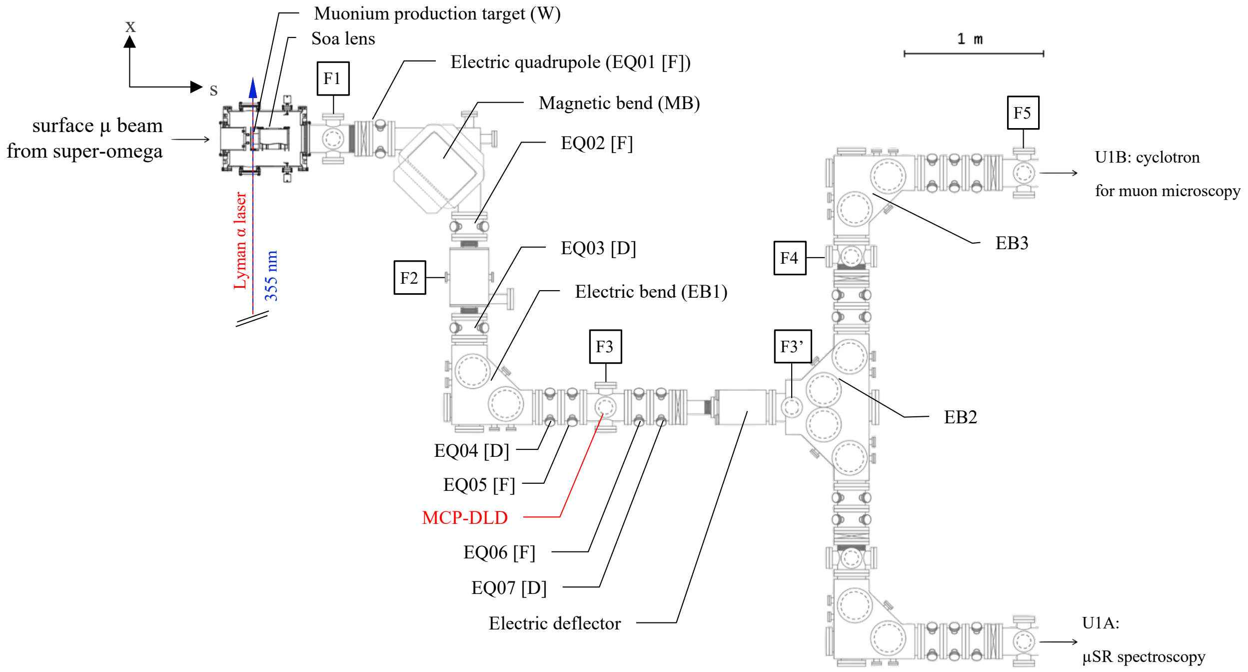

Figure 1: Experimental apparatus at the J-PARC MUSE ultra-slow muon beamline.

imately 10 J [11]. The total width of the laser beam was 8.7 mm and 2 mm in the vertical and horizontal directions, respectively. Laser positions, angles, and injection timing were optimized to maximize the USM yield.

USMs were electrostatically extracted and accelerated to 30 keV by a Soa lens [12] composed of cylindrical electrodes. USMs were then transported by a transport beamline consisting of electric quadrupoles (EQs), a magnetic bend, electric bends, an electric deflector, and detectors. A microchannel plate with delay line anodes (MCP-DLD: Roentdek, DLD40 [13]) was used for the beam position monitor. A sensitive region of the MCP-DLD has a diameter of ϕ 40 mm. The time-to-digital converter [14] with a timestamp of 1 ns was used for data acquisition. The beam profile was measured at the third detection position (F3) because of high background events derived mainly from decay positrons at the first (F1) and second (F2) detection positions.

SIMULATION

Beam dynamics of the transport beamline were simulated using musrSim [15]. The electrostatic and magnetic field maps on the transport beamlines were calculated using OPERA-3D (TOSCA) [16] and implemented in the musrSim code. The initial particle distribution of the USMs in the simulations was assumed to be similar to the overlapping volume of muonium emitted in vacuum and Lyman–α and 355 nm light. The beam width of 1σ in the x, y, and z directions was defined as 17.0 mm, 2.1 mm, and 1.0 mm, respectively. Assuming a Maxwell-Boltzmann distribution

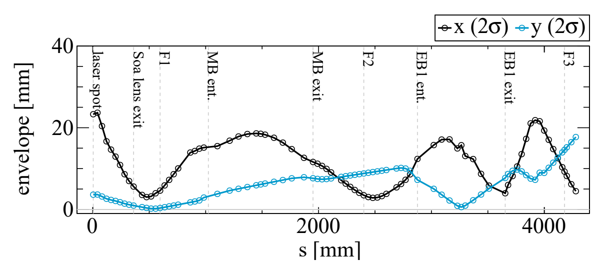

Figure 2: Simulated beam envelope of 2σ in the x- and y-direction.

at a typical temperature of 2000 K, the initial kinetic energy was defined as 0.2 eV.

Figure 2 shows the simulated beam envelope from the USM production point to F3. The optics of the transport beamline were optimized to maximize the event of USMs at F3. The kinetic energy is 30.2 keV, and the transmission efficiency to F3 is 97%. The flight time from the USM production point to the F3 was 640 ns, and the total transmission efficiency, including muon decay losses, was 73%.

PROFILE MEASUREMENT

At the J-PARC MUSE ultra-slow muon beamline, the USM beam profile measurement at F3 was conducted. Figure 3 shows the measured beam profile in the x-y direction, with the circle denoting the MCP-DLD sensitive region of ϕ 40 mm. The USM signal was identified by a time-of-flight measurement [10]. The multi-hit signals caused by the simul-

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THAN2

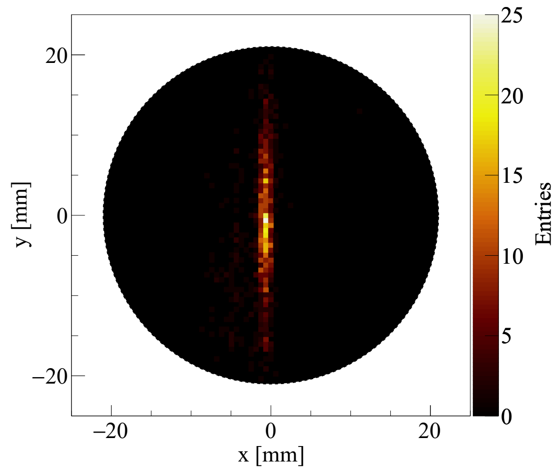

Figure 3: Measured beam profile of the USMs at F3. The aperture of MCP-DLD is 40 mm in diameter. The beam width is focused in the *x*-direction by EQ05.

taneous propagation of multiple pairs of pulses with different starting points were excluded by taking the coincidence of all signals in the anode wires for the x and y coordinates of the MCP-DLD. The USM rate was limited to approximately 20 cps (count per second) by adjusting the laser intensity to prevent the pileup of the MCP-DLD.

After observing USMs at F3, quadrupole scan measurements were conducted using EQ04 (D) and EQ05 (F) upstream of F3 to scan the beam width. Figure 4 shows the measured and simulated beam width of 1σ at the F3. The horizontal axis of (a) and (b) indicates the applied voltage of the EQ05 and EQ04, respectively. The vertical axis of (a) and (b) indicates the beam width in the *x*- and *y*-direction. The beam width of 1σ was evaluated by taking the Gaussian fitting from the beam profile distribution. The measured beam width while scanning the strength of the EQ was in good agreement with the simulation result, confirming that the measured data are quantitatively comparable with the simulation result.

CONCLUSION

At the J-PARC MUSE ultra-slow muon beamline, the beam commissioning of USMs for the transmission muon microscope is underway. The profile measurement of the USMs using the MCP-DLD was carried out at F3 as a preliminary measurement for the beam injection into the AVF cyclotron. The measured beam profiles agree well with the simulation results, verifying the soundness of the simulation code. The next step is to evaluate the Twiss parameters and emittance at F5 just before cyclotron injection for beam matching to the cyclotron.

ACKNOWLEDGEMENTS

This work was supported by JSPS KAKENHI grant numbers JP17H06126, JP23KJ2176 . The muon experiment at the Materials and Life Science Experimental Facility of the J-PARC was performed under instrument program.

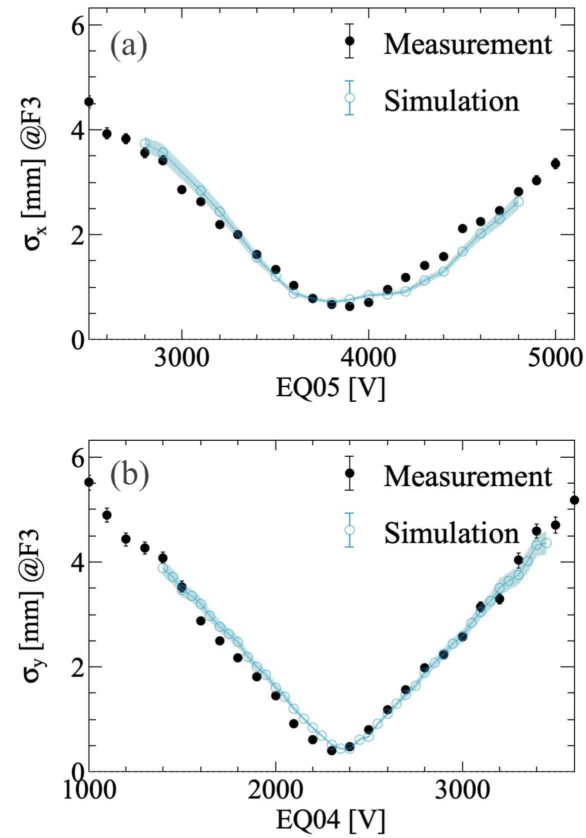

Figure 4: The measured and simulated beam width (1σ) of the USMs at F3. (a) the beam width in the *x*-direction when scanning the EQ05. (b) the beam width in the *y*-direction when scanning the EQ04. The black and blue data indicate the measurement and simulation, respectively.

REFERENCES

[1] Y. Miyake*et al.*, "Ultra Slow Muon Project at J-PARC MUSE", in *JPS Conf. Proc.*, 2014, 2, 010101. doi:10.7566/JPSCP.2.010101

[2] K. Nagamine *et al.*, *Phys. Rev. Lett.*, 74 4811, 1995.

[3] J. Ohnishi *et al.*, in *Proc. 16th Annual Meeting of Particle Accelerator Society of Japan (PASJ2019)*, Kyoto, Japan, Jul.-Aug. 2019, pp. 121–125.

[4] J. Ohnishi *et al.*, in *Proc. 17th Annual Meeting of Particle Accelerator Society of Japan (PASJ2020)*, Online, Sep. 2020, pp. 669–673.

[5] T. Yamazaki *et al.*, in *Proc. 17th Annual Meeting of Particle Accelerator Society of Japan (PASJ2020)*, Online, Sep. 2020, pp. 885–887.

[6] J. Ohnishi *et al.*, in *Proc. 18th Annual Meeting of Particle Accelerator Society of Japan (PASJ2021)*, Online, Aug. 2021, pp. 845–849.

[7] J. Ohnishi *et al.*, in *Proc. 19th Annual Meeting of Particle Accelerator Society of Japan (PASJ2022)*, Online, Oct. 2022, pp. 906–910.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THAN2

[8] Y. Ikedo *et al.*, “Positron separators in Superomega muon beamline at J-PARC”, *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 317, pp. 365–368, 2013. doi:10.1016/j.nimb.2013.07.060

[9] P. Strasser *et al.*, “Superconducting curved transport solenoid with dipole coils for charge selection of the muon beam”, *Nucl. Instrum. Methods Phys. Res., Sect. B*, vol. 317, pp. 361–364, 2013. doi.org/10.1016/j.nimb.2013.07.046

[10] S. Kanda *et al.*, “The Ultra-Slow Muon beamline at J-PARC: present status and future prospects”, *J. Phys.: Conf. Ser.*, 2462, 012030, 2023. doi:10.1088/1742-6596/2462/1/012030

[11] Y. Oishi *et al.*, “Intense Lyman-alpha light source for ultra-slow muon generation”, *J. Phys.: Conf. Ser.*, 2462, 012026, 2023. doi:10.1088/1742-6596/2462/1/012026

[12] P. Strasser *et al.*, “Design and construction of the ultra-slow muon beamline at J-PARC/MUSE”, *J. Phys.: Conf. Ser.*, 551, 012065, 2014.

[13] O. Jagutzki *et al.*, “A broad-application microchannel-plate detector system for advanced particle or photon detection tasks: large area imaging, precise multi-hit timing information and high detection rate”, *Nucl. Instrum. Methods Phys. Res., Sect. A*, 477, 244–249, 2002.

[14] K. M. Kojima *et al.*, “New μSR spectrometer at J-PARC MUSE based on Kalliope detectors”, *J. Phys.: Conf. Ser.*, 551, 012063, 2014. doi:10.1088/1742-6596/551/1/012063

[15] K. Sedlak *et al.*, *Manual of musrSim*, http://lmu.web.psi.ch/simulation/index.html

[16] A. D. Pant *et al.*, “Characterization and optimization of ultra slow muon beam at J-PARC/MUSE: A simulation study”, *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 929, pp. 129–133, 2019. doi:10.1016/j.nima.2019.02.065