A simulation study of muon transport in the Ultra-Slow Muon beamline at J-PARC

N Teshima[1,2], S Kanda[1,2], T Adachi[3], Y Ikedo[1,2], Y Miyake[1,2], Y Nagatani[1,2], Y Oishi[1,2], K Shimomura[1,2] and P Strasser[1,2]

[1] Muon Science Laboratory, Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK), 203-1 Shirakata, Tokai, Naka District, Ibaraki 319-1106, Japan
[2] Muon Science Section, Materials and Life Science Division, J-PARC Center, 2-4 Shirane Shirakata, Tokai-mura, Naka-gun, Ibaraki 319-1195, Japan
[3] Nishina Center for Accelerator-Based Science, RIKEN, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

E-mail: nteshima@post.kek.jp

Abstract. The Super-Omega beamline at J-PARC Materials and Life Science Experimental Facility provides an intense pulsed slow positive muon beam. Combined with a muonium production target and laser light for muonium ionization, the pulsed ultra-slow muon facility has been developed. At the facility, a spectrometer for muon spin rotation measurements using ultra-slow muons is under commissioning. In this paper, we will report on the current status of the beam optics optimization of slow muon transport and ultra-slow muon extraction to improve the intensity and quality of the ultra-slow muon beam.

1. Introduction

1.1. Muon Science

The fundamental properties of muons themselves are the subject of study. On the other hand, in materials science, the muon spin rotation, relaxation and resonance (μSR) method, which uses the muon spin as a probe, has been used in a variety of studies. This method reveals various physical properties in a sample by injecting spin-polarized muons into the sample and measuring the distribution of positrons emitted by the decay after they were affected by the local magnetic field inside the sample. The slow muons conventionally used, called surface muons, have a positive charge, a kinetic energy of approximately 4 MeV, a large emittance, and a large energy spread. In surface science research, ultra-slow muon beams with small emittance are in demand to investigate small samples.

In addition, a new three-dimensional imaging technique called "ultra-slow muon microscopy", which uses a muon microbeam re-accelerated from ultra-slow muons with extremely small energy dispersion as a wave, is expected to be applied to the study of various physical properties in a sample [1].

1.2. Ultra-slow muon source
Slow muon beams are moderated by passing through a thin cryogenic solid layer of argon and nitrogen, and low-energy DC muon beams with energies of a few keV have been successfully produced at Paul Scherrer Institute (PSI) [2]. Meanwhile, J-PARC Materials and Life Science Experimental Facility (MLF) MUon Science Establishment (MUSE) has employed the method started at RIKEN-RAL [3, 4] shown in Fig. 1. When slow muons are stopped in a hot tungsten foil heated to 2000 K, muons near the surface of the foil capture conduction electrons and muoniums evaporate. Muoniums are resonance-ionized by a pulsed laser to produce ultra-slow muons with thermal energy of 0.2 eV.

Figure 2 shows the ultra-slow muon source at J-PARC MLF MUSE. 3 GeV, 800–900 kW (as of early 2022) proton beam from the Rapid Cycling Synchrotron (RCS) is transported to a 2 cm-thick muon production target made of carbon. The proton beam from the RCS has a double pulse structure with a width of 100 ns, an interval of 600 ns, and a repetition rate of 25 Hz, and the muons produced have the same time structure.

The Super-Omega beamline consists of three main parts: a normal conducting capture solenoid, a superconducting curved transport solenoid, and an axial focusing solenoid. Slow (positive) muons are produced when positive pions stop and decay at the surface of the muon production target, while cloud (positive and negative) muons come from positive and negative pions that decay-in-flight outside the target. The Super-Omega beamline captures surface (slow) muons and cloud muons at a large solid angle of 400 msr and extracts them at an angle

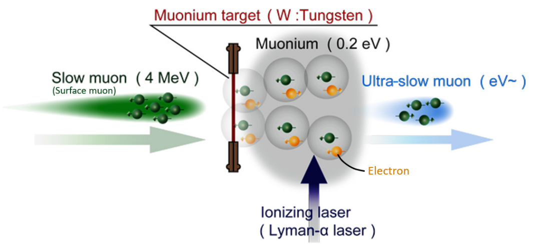

Figure 1. Method for generation of ultra-slow muons. Slow muons are injected to a muonium target to obtain muonium, that is a pair of a positive muon and an electron. The electrons are then stripped from the muoniums by laser light.

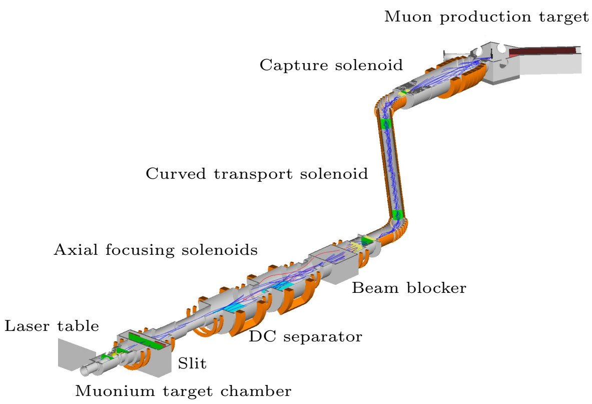

Figure 2. Simulation model of the Super-Omega beamline. The trajectory length from the muon production target to the muonium production target is approximately 20 m.

Figure 3. Photo of the U-Line at J-PARC. The area covered with dark pink concrete is called the U1 area, where slow muons are transported by the Super-Omega beamline and combined with a muonium target and laser. Downstream are areas called U1A and U1B for the use of ultra-slow muons.

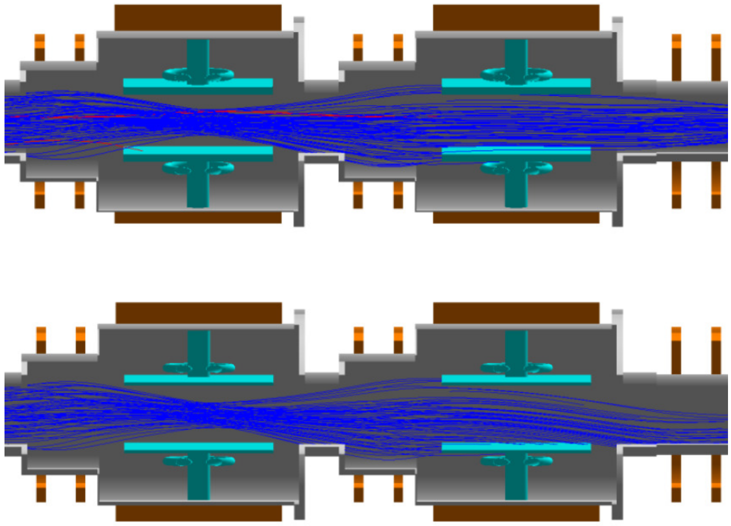

Figure 4. Beam envelopes of the DC separator section simulated by G4beamline [10]. Muons pass through (top) and positrons do not (bottom).

of 45 degrees backward. The captured muons are transported to the superconducting curved transport solenoid. After the first 45-degree curved section, the positive (negative) muons move parallel to the ceiling (ground). The muon charge is selected by two vertical dipole coils in the straight section of the curved transport solenoid. In the second 45-degree curved section, the vertical shift of the muons is restored. In the axial focusing solenoid section, the muon beam is focused toward the muonium production target while particle selection is performed by the DC separator. At the muonium production target, the muon beam size is approximately 40 mm (standard deviation), the beam momentum width is about 10%, and the beam intensity is on the order of 10^8 μ^+/s [5–7]. High intensity surface muons are injected into the tungsten foil installed in the muonium chamber. Muonium atoms evaporate into the vacuum, and pulsed lasers, for a sequence of muonium transitions of 1s-2p-unbound states, are injected just behind the tungsten foil parallel to the target surface to obtain ultra-slow muons [8].

Construction of the U-Line has been completed as shown in Fig. 3, and commissioning for material science studies is underway [9].

2. Simulation studies

2.1. DC separator

The DC separator in the Super-Omega beamline eliminates positrons and electrons from the muon beam. A side view of the DC separators is shown in Fig. 4, where the beam passes from left to right. The size of the electrodes generating the electrostatic field is 500 mm wide in the horizontal direction, and 750 mm long in the beam direction. The distance between the upper and lower electrodes is 300 mm. Currently, +270 kV is applied to the positive electrode and −280 kV to the negative electrode due to empirical evidence of reduced electrode discharge. The vertical electric field gradient is approximately 1.8 MV/m as shown in Fig. 5. Rectangular 120-turn coils placed on a cylindrical beam duct create a magnetic field perpendicular to the beam direction and the direction of the electric field. To allow only muons with a momentum of $\simeq$ 28 MeV/c to pass through, we need the strength of transverse magnetic field of

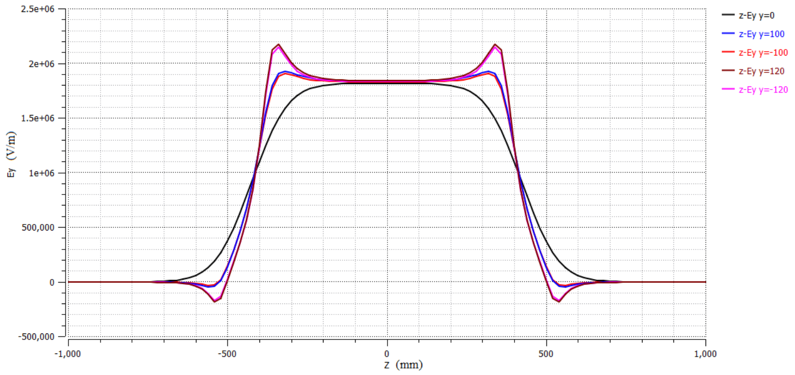

Figure 5. Plot of E_y, the electric field vertical component in the DC separator, versus z, beam axis direction, calculated using Opera-3D [11]. Due to the asymmetry of the voltage applied to the positive and negative electrodes, the strength of the electric field for $y > 0$ (ceiling side) and $y < 0$ (ground side) is also slightly asymmetric.

$$\begin{aligned} |\mathbf{B}| &= |\mathbf{E}|/|\mathbf{v}| \\ &\simeq (1.8 \times 10^6 \text{ V/m})/(7.7 \times 10^7 \text{ m/s}) \\ &\simeq 2.3 \times 10^{-2} \text{ T}, \end{aligned}$$

where $|\mathbf{E}|$ is the strength of the vertical electric field, and $|\mathbf{v}|$ is the absolute value of the velocity of the particles passing through.

2.2. Optimization of the current in the DC separator coil

In the U-Line commissioning in the spring of 2022, the yield and profile of ultra-slow muons was measured with a microchannel plate (MCP) using different settings for the axial focusing solenoid currents, DC separator current, hot tungsten target or silica aerogel target for muonium production, target voltage, laser frequency and timing, electric quadrupoles, magnetic bends.

Figure 6 shows an example of the measured number of ultra-slow muons extracted to the entrance of U1A/U1B area as a function of the current in the coil of the DC separator. The detector was placed about 7 m downstream from the DC separator. In the experiment, +270 kV and −280 kV were applied to the electrodes of the DC separator, and the coil current was lowered in 5 A steps from its original setting of 200 A. The lower the coil current, the more ultra-slow muons we obtained. However, when the current reaches 175 A, the electrodes discharge and the system does not operate stably.

A simulation model was assembled in which the magnetic field maps for each solenoid were placed in G4beamline [10], and a muon beam with a Gaussian distribution of mean momentum of 28 MeV/c and standard deviation of 2.8 MeV/c was passed through. The currents in each solenoid were as follows: capture solenoid 1 and 2 were 925 A and 570 A (central magnetic field is 0.27 T); the curved transport solenoid and z-correction were 52.25 A and 15.25 A (central magnetic field is 1.3 T); the twelve focusing solenoids were 24.5 A, 19.6 A, 25.0 A, 25.6 A, 11.2 A, 29.0 A, 30.0 A, 0.5 A, 10.9 A, 2.0 A, 7.1 A, and 26.3 A (the maximum is approximately 0.3 T).

The number of positive muons passing through the DC separator and the average position of the beam are simulated as shown in Figs. 7 and 8, respectively. According to these results, at the original setting of 200 A, the beam does not pass through the center of the beam duct. Lowering the coil current seems to increase the muon number as the beam moves closer to the center of the beam duct.

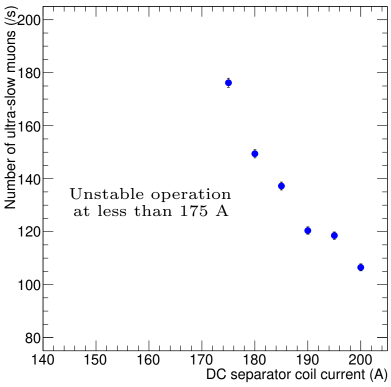

Figure 6. An example of actual measurements of the number of ultra-slow muons extracted to entrance of the U1A/U1B area versus the current in the DC separator coil.

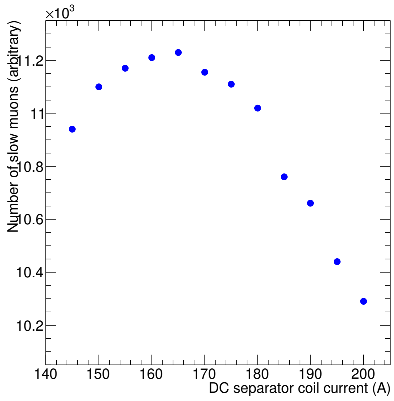

Figure 7. Simulated number of slow muons downstream of the DC separator versus the current in the DC separator coil.

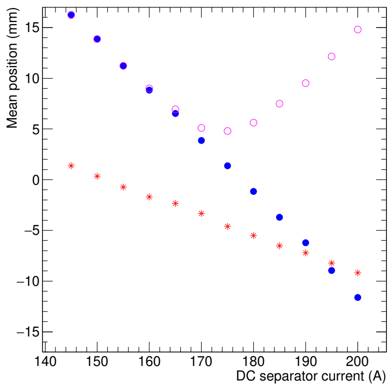

Figure 8. Simulated mean horizontal (x-axis) position (red star), mean vertical (y-axis) position (circle filled with blue), and square root of x-mean squared plus y-mean squared (pink line circle) as a function of the current in the DC separator coil.

2.3. Counting of decay particles by a detector placed above the muonium target chamber

As shown in Fig. 9, we simulated transporting 5×10^6 positive muons to the muonium production target and counting the decay particles with a detector placed on the top flange of the muonium target chamber. On the lower face of the flange with $\simeq 2 \times 10^{-1}$ sr, 4.4×10^5 decay particles are reduced to 5.2×10^2 (electrons, photons, positrons) after being absorbed by the 2 cm-thick stainless steel flange. A detector with an active area of 14 mm $\times$ 14 mm placed 400 mm from the target has a solid angle of $\simeq 1/100$ of that of the flange surface. Therefore, the number of particles to be detected will be 100 times smaller.

3. Summary and future prospects

The ultra-slow muon beamline at J-PARC is under commissioning for user experiments that will contribute to materials science. A simulation study of the Super-Omega beamline, that is part

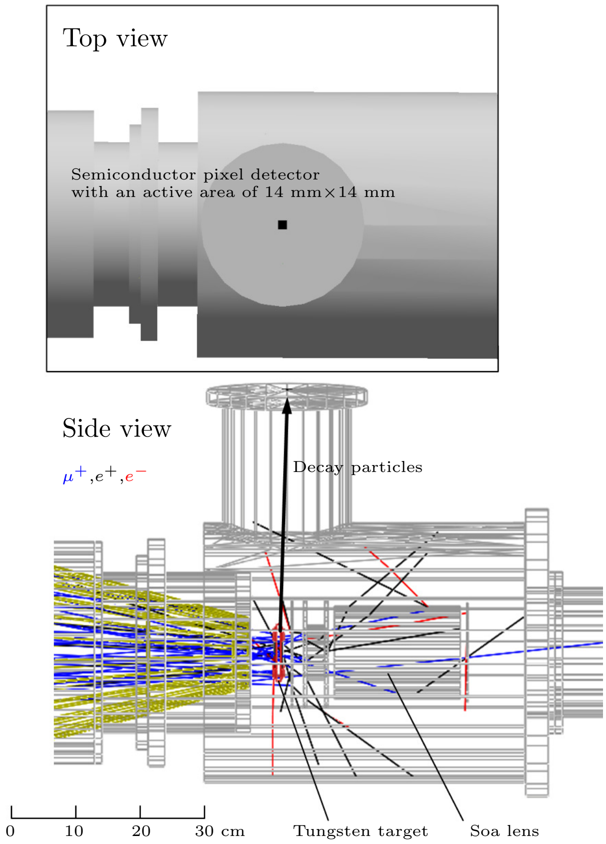

Figure 9. Simulation model of the muonium production target chamber downstream of the Super-Omega beamline. The red object is the muonium production target (tungsten) and its holder. Downstream of it are several electrodes called Soa lens to extract ultra-slow muons.

of the ultra-slow muon beamline, was performed. For the DC separator, it may be possible to lower the voltage applied to the electrodes so that the positive muons pass through the center of the beam duct. In this case, the efficiency of positron removal at the reduced voltage needs to be studied. Measurements of the muon beam rate were made with a semiconductor pixel detector placed above the muonium production target chamber. There is a plan to synchronise two semiconductor pixel detectors to measure the muon beam profile, and preparations are in progress.

References

[1] Miyake Y *et al.* 2014 *JPS. Conf. Proc.* **2** 010101
[2] PSI *Low-Energy Muon Facility (LEM)* 2022 `https://www.psi.ch/en/smus/lem`
[3] Bakule P *et al.* 2008 *Nucl. Instrum. and Methods Phys. Res. Sect. B* **266** 335
[4] Matsuda Y *et al.* 2003 *Physica B* **326** 217
[5] Nakahara K *et al.* 2009 *Nucl. Instrum. and Methods Phys. Res. Sect. A* **600** 132
[6] Ikedo Y *et al.* 2012 *Physics Procedia* **30** 34
[7] Strasser P *et al.* 2013 *Nucl. Instrum. and Methods Phys. Res. Sect. B* **317** 361
[8] Saito N *et al.* 2016 *Optics Express* **24** (7) 7566
[9] Kanda S *et al.* 2021 "Commissioning of the μSR Spectrometer at U1A" *J-PARC MLF Annual Report 2020* `https://mlfinfo.jp/_src/resource/PEPngy9XwF/MLF_AR_2020.pdf`
[10] Muons, Inc. *G4beamline* 2019 `http://www.muonsinternal.com/muons3/G4beamline`
[11] Dassault Systèmes S.E. *Opera* 2022 `https://www.3ds.com/products-services/simulia/products/opera/`