PROCEEDINGS OF SCIENCE

Muon cooling at J-PARC

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Muon cooling is an important technology for novel muon experiments involving muon acceleration such as the J-PARC muon g-2/EDM experiment, a muon microscope, and a muon collider. At J-PARC, the ultra-slow muon source, generated by laser ionization of thermal muonium in the vacuum, is under development. The emittance of the muon beam can be reduced by three orders of magnitude compared to the conventional muon beam through the re-acceleration of the ultra-slow muon. At the H2 area, one of the branches of the high-intensity pulsed muon beamline (H-line) at J-PARC, the designed flux of the ultra-slow muon source is an order of 10^5 1/s, with completion projected for FY 2026. This paper provides the current status of muon cooling at J-PARC and its future prospects.

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1. Introduction

A muon beam plays an important role in particle physics and material science experiments. In accelerator-based experiments, the muon beam is produced by the decay of charged pions generated in the production target irradiated by a proton beam. Recently, a high-intensity muon beam with a flux of more than 10^8 1/s has been produced at high-intensity proton beam facilities. Although the conventional muon beam is successfully used for various muon experiments, there is a need for a muon beam with lower beam emittance. Various muon cooling techniques have been proposed to reduce the emittance of the conventional muon beam [1–3]. At J-PARC MLF MUSE, the development of the ultra-slow muon (USM) source is underway. The USM is a thermal energy muon generated by the laser ionization of thermal muonium [4]. A low emittance muon beam produced through the acceleration of the USM is utilized for the new muon g-2/EDM experiment at J-PARC [5] and transmission muon microscope. In addition, the use of the USM is also considered in the recently proposed $\mu^+\mu^+$ and μ^+e^- colliders [6].

2. The ultra-slow muon source

Figure 1 shows a schematic of the experimental configuration of the ultra-slow moun source. Initially, the conventional muon beam, known as a surface muon beam, is directed onto a muonium production target. Muonium is a bound state of a muon and an electron. Although various materials such as hot tungsten can be used as muonium targets, we will focus on a silica aerogel target. A fraction of the muon stopped inside the target forms muonium. The muonium diffuses inside the target and is emitted into the vacuum.

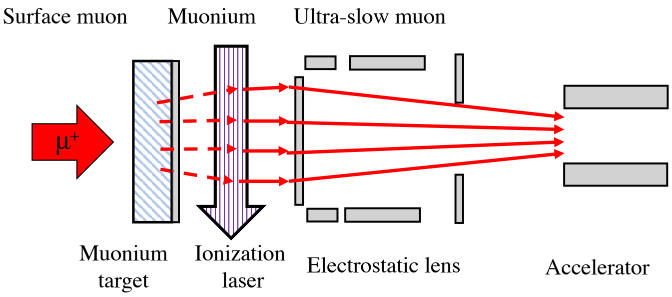

Figure 1: Schematic view of the ultra-slow muon source

The muonium emitted into the vacuum is ionized by irradiation of pulsed lasers. The ionization process involves the resonant excitation of muonium from its ground state to an intermediate state by an excitation laser, followed by ionization from this excited state by an ionization laser. Two ionization schemes are feasible. The first scheme employs the 2P state as the intermediate state (1S-2P-unbound scheme). In this approach, a light source at $\lambda = 122$ nm is used for the excitation to the 2P state, and a light source at $\lambda = 355$ nm is used for the ionization from the 2P state. This approach benefits from the large absorption cross section of the 1S-2P transition, resulting in a relatively low energy requirement for the excitation light source. However, it should be noted that the development of a VUV light source is technically challenging. Another approach is the ionization through the 2S state using a pulsed laser at 244 nm (1S-2S-unbound scheme). Since this excitation is a two-photon absorption process, a high-intensity pulse is required. However, a light source at this wavelength is technically more established than a VUV light source. No additional laser is required to ionize the excited muonium. In the case of the 1S-2P-unbound scheme, the required pulse energy is 100 μJ for the 122 nm light source, and 300 mJ for the 355 nm light source. The pulse duration of the lasers is 2 ns. For the 244 nm light source, the required pulse energy is 60 mJ with multiple reflections by mirrors to enhance the spatial overlap. The optimal pulse duration is around 50 ns. The spin polarization of USM is reduced to 50 % by the electron-muon spin exchange. The efficiency of generating the USM per surface muon is on the order of 10^{-3}. The USM is extracted by using a pair of electrostatic lenses and transported to the subsequent accelerators. The transverse normalized RMS emittance of the USM is 0.3 π mm·mrad, which is about three orders of magnitude smaller than that of the surface muon.

Table. 1 summarizes the designed performance of the ultra-slow muon source after the ionization at the H2 area in the MLF. Fig. 2 shows the expected phase space distribution of the ultra-slow muon before the extraction at the H2 area.

Parameters	Surface muon	Ultra-slow muon
Flux	1.6×10^8	3.5×10^5
Energy	4 MeV	25 meV
Transverse normalized emittance	$\sim$1000 π mm·mrad	1.5 π mm·mrad
Spin polarization	100%	50%
Pulse duration	$\sim$100 ns	2 ns

Table 1: Designed performance of the surface muon and the ultra-slow muon source at the H2 area

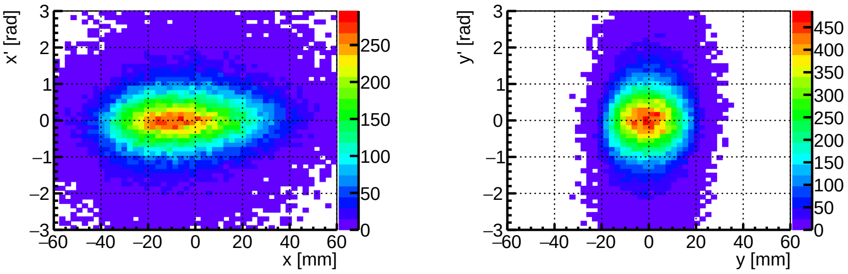

Figure 2: Expected phase-space distribution of the USM at the H2 area. The kinetic energy is around 25 meV, corresponding to $\beta \sim 2.2 \times 10^{-5}$.

3. Current status of the muon cooling at J-PARC

3.1 Surface muon beamline

Among the four muon beamlines in the MLF, two beamlines providing intense surface muon beams are used as the primary beams for ultra-slow muon sources. The U-line delivers a flux of

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pulsed surface muons on the order of 10^8 Hz. The beamline has two branches, the U1A for μSR and the U1B for transmission muon microscope [7]. The H2 area is also dedicated to the production of the ultra-slow muon. The H2 area is one of the branches of the H-line and is currently under construction. The designed flux of the surface muon at the H2 area is 1.6×10^8 Hz. A linac for accelerating the ultra-slow muon to 210 MeV will be constructed for the J-PARC muon g-2/EDM experiment [5] and the transmission muon microscope.

3.2 Muonium production target

A laser-ablated silica aerogel target is devised as a muonium target [8]. A tenfold increase in the muonium emission rate is achieved by ablating the surface of a conventional aerogel target. Muonium diffusion is modeled by a 3-D random walk in an isotropic material. The probability of muonium formation is measured to be 0.52. The temperature of the target is evaluated to be 320 K and its diffusion constant is evaluated to be 570 cm^2/s. A mesh electrode is attached to the target for the extraction. The muonium emission efficiency per surface muon at the H2 area is estimated to be 0.014 by simulation. About 27% of the muonium emitted into the vacuum overlaps with the laser pulse in space and time. In contrast, a hot tungsten target at 2000 K is used as the muonium target at the U-line, and the commissioning of the ultra-slow muon beamline is in progress [7].

3.3 Laser

The common requirement for light sources is long-term operation at 25 Hz. Consequently, all lasers have employed all-solid-state amplifiers. For example, the lifetime of the diode-pumped solid-state laser is more than 10^9 shots, corresponding to over a year of operation at 25 Hz.

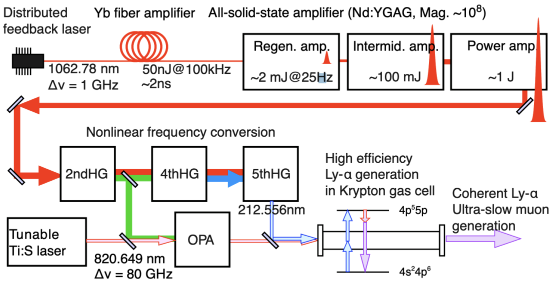

Figure 3: Schematic of the 122 nm light source [9].

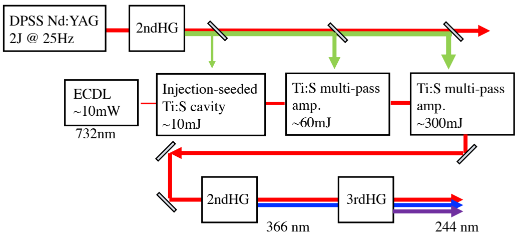

Figure 4: Schematic of the 244 nm light source.

Fig. 3 shows a schematic of the 122 nm light source [9]. The pulsed radiation at 122 nm is generated by the resonant four-wave mixing (FWM) inside Kr-Ar gas of 212.5 nm and 820 nm radiation pulses. The pulse light at 212.5 nm is generated by the 5th harmonic generation of the 1062.78-nm radiation from an all-solid-state laser system. A tunable Ti:sapphire laser is introduced as a seed laser for the 820 nm pulse. The linewidth is tuned to 80 GHz to encompass the Doppler width of the muonium. A pulse energy of 1.6 mJ at 212 nm and a pulse energy of 2.1 mJ at 820-nm are used for the FWM in a 1 m long gas cell. The pulse energy at 122 nm at the muonium emission region is 5 μJ, and the pulse duration is 2 ns. The laser system is in operation at the U-line, and the USM flux of 300 Hz is delivered stably [7]. A power amplifier for 1062.78 nm using a Nd:YSAG ceramic is under demonstration to double the pulse energy.

A Light source at λ=355 nm to ionize the excited muonium is also required. Currently, the third harmonic of the 1062.78 nm pulse is used for ionization from the 2P state. Using the remaining energy of the 1062.78 nm light source, pulse energy up to 8 mJ at 355 nm is produced and in operation at the U-line. For higher pulse energy up to 300 mJ with a pulse duration of 2 ns, a diode-pumped solid-state Nd:YAG laser is being demonstrated. The Nd:YAG laser currently produces pulses of 1.7 J at 1064 nm at 5 Hz, and the pulse duration is 10 ns. Preparations for third harmonic generation, 25 Hz operation, and short pulse operation are underway.

Finally, a high energy 244 nm light source for the 1S-2S-unbound scheme is under demonstration. Fig. 3 shows a schematic view of the laser. The required wavelength is generated by frequency tripling of pulsed light from a Ti:S laser operating at 732 nm. The Ti:S laser consists of an injection-seeded Ti:S cavity and Ti:S multi-pass amplifiers. The second harmonic of the Nd:YAG laser described above is utilized as the pump laser for the Ti:S. Currently, the Nd:YAG laser produces pulses of 1 J at 532 nm. The pulse energy at 732 nm is 54 mJ using 300 mJ of the pump energy. An additional Ti:S amplifier will be installed to utilize the remaining pump energy.

3.4 Extraction and initial beam transport

The ultra-slow muon is collected by an electrostatic immersion lens originally developed for positron optics. A new USM chamber including the immersion lens and electrostatic deflector is designed for operation at the H2 area. The extraction energy is 5.7 keV to match the input energy of an RFQ. A pair of three-axis coils is also installed to control the spin orientation of the USM.

4. Demonstration experiment

From FY 2022, a demonstration experiment of the muon cooling and the re-acceleration is underway at the S2 area of the MLF. The experimental setup is shown in Fig. 5. The USM chamber for the H2 area is located at the exit of the surface muon beamline. Another 244 nm pulsed laser for the muonium spectroscopy experiment is used for the ionization [10]. A slow muon beam transport (SMBL) is connected to the USM chamber. The energy and momentum of the extracted particle are filtered by electrostatic and magnetic bends (EB and MB). Electrostatic quadrupole (EQ) lenses are arranged for beam focusing. The USM signal is detected by an MCP located at the exit of the SMBL. An MCP-based beam profile monitor is also utilized to measure the beam profile of the USM [11]. After completing the evaluation of the phase space distribution of the USM, the acceleration of the USM to 80 keV using an RFQ will be performed in FY 2023.

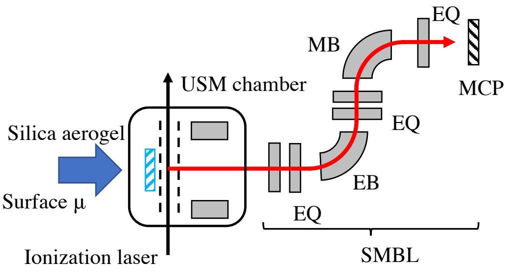

Figure 5: Schematic view of the experimental setup of the muon cooling demonstration at the S2 area.

5. Future prospect

The commissioning of the USM source at the H2 area will be performed in FY 2024. The acceleration of the USM to 4 MeV will be performed at the H2 area in FY2025. The design flux will be achieved in FY 2026 after the completion of the laser development at the H2 area including an installation of a longer gas cell for higher FWM efficiency.

A new layout of the muonium emission target is proposed to increase the intensity of ultra-slow muon [12]. Multiple pieces of the aerogel targets are employed to increase the fraction of muonium emitted into the vacuum. Using six pieces of the targets and five times more laser energy, the USM flux increases three times more. Optical pumping of muonium is also proposed to increase the spin polarization of the USM [13]. It is calculated that the spin polarization can be as high as 80% after optical pumping using a pulse train of circularly polarized light at 122 nm.

6. Summary

The muon cooling technology is necessary to realize new experiments that involve a low emittance muon beam. The ultra-slow muon is one of the promising approaches in muon cooling. The emittance of the muon beam is reduced to 0.3 π mm·mrad by the acceleration of the ultra-slow muon. Demonstration of muon cooling using the silica aerogel target is underway. The construction of the H2 area for a high-intensity ultra-slow muon source will be completed in FY 2024, and the target flux of order of 10^5 Hz will be achieved in FY 2026.

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