PROCEEDINGS OF SCIENCE

J-PARC muon facility

Takayuki Yamazaki[a,b,*] **on behalf of muon science section MLF J-PARC**

[a] *Materials and Life Science Division, Japan Proton Accelerator Research Complex (J-PARC), Tokai, Ibaraki 319-1195, Japan*

[b] *Institute of Materials Structure Science, High Energy Accelerator Research Organization (KEK), Tokai, Ibaraki 319-1106, Japan*

E-mail: takayuki@post.kek.jp

The J-PARC muon facility is a pulsed muon beam facility located in the Materials and Life Science Experimental Facility. It has four muon beamlines and seven experimental areas in operation, and a new beamline (H-line) and two new experimental areas (H1 and S2 areas) started operation in January 2022. They are used for fundamental physics experiments, such as precise measurements of muoniums, and a search for μ-e conversion. Further extension of the H-line is ongoing to develop a novel low emittance muon beam for a muon $g-2$/EDM experiment and a muon transmission microscope. For more future planning, the conceptual design of a new target station, which allows for over 50 times more intense muons, is underway.

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1. Overview

At the Japan Proton Accelerator Research Complex (J-PARC), various secondary particle beams are produced from the high-power proton beams and used in various scientific fields. High intense muon and neutron beams are produced by nuclear reactions of a 3-GeV proton beam (25 Hz, ~840 kW stable operation at present) from the Rapid Cycling Synchrotron (RCS) in target materials at the Materials and Life Science Experimental Facility (MLF), The muon target is made of 20 mm-thick graphite and located about 30 m upstream of the neutron target. About 5 % of proton beams are lost at the muon target and used to produce charged pions, and pions decay into muons. Muons are captured and transported using electromagnets to four muon beamlines and seven experimental areas in the J-PARC muon facility MUSE: Muon Science Establishment as shown in Fig. 1. Although most of the muon beamlines and experimental areas were intended for material sciences such as μSR (muon spin rotation/relaxation) and elemental analysis using muonic X-ray, a new beamline (H-line) and two new experimental areas (H1 and S2 areas) for fundamental physics experiments started operation in January 2022.

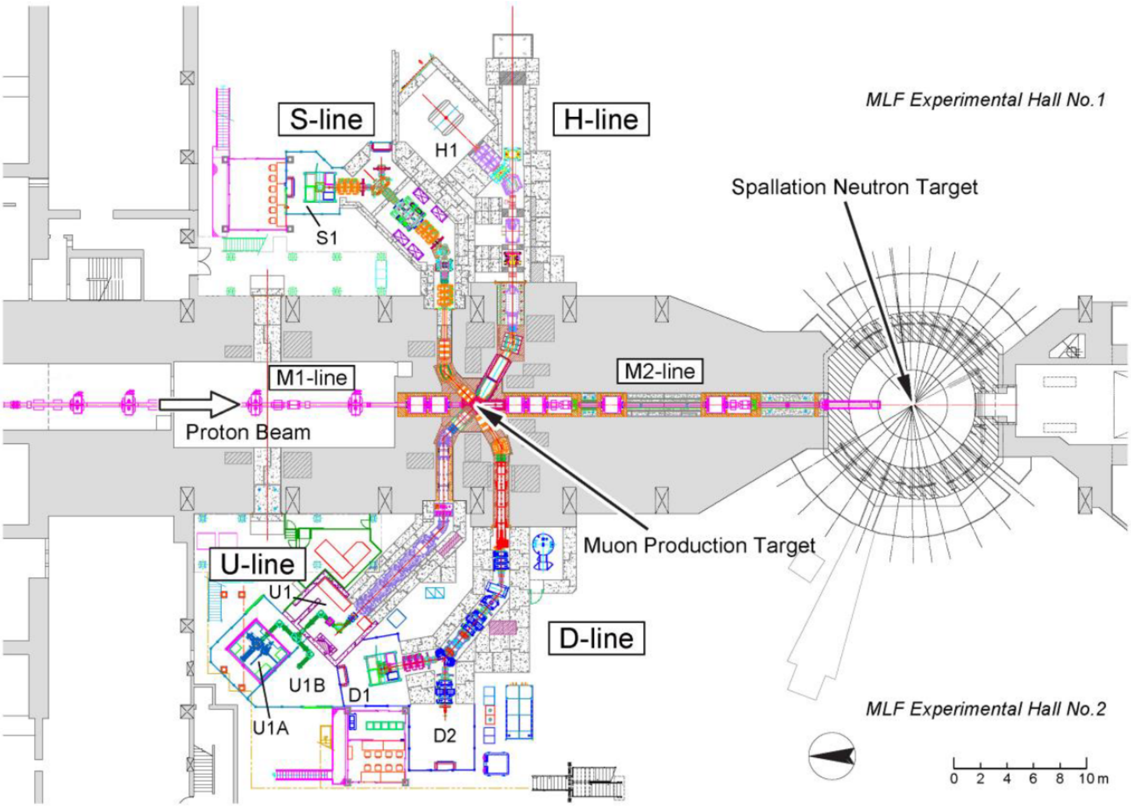

Figure 1: J-PARC muon facility in the MLF

2. New beamline and experimental areas for fundamental physics

The S2 area is the second branch of the S-line, where a muonium 1S-2S spectroscopy to precisely determine the mass of muonium state is underway. Besides the S2 area, a laser room to produce 244 and 355 nm wavelength lasers is equipped. Muonium atoms produced in the S2 area are transitioned from 1S to 2S by the interaction with two 244 nm wavelength lasers and then ionized by using a 355 nm wavelength laser. After the ionization, ultra-slow muons [1] with kinetic energies of about 30 meV are re-accelerated up to 30 keV and detected by a micro-channel plate as 1S-2S transition signals of muonium atoms.

The H1 area is the first branch of the H-line. The H-line is a high-intensity muon beamline that can generate both positive and negative muons [2]. Its capture solenoid has a large acceptance (108 mSr) of pions and muons, and the design intensity of surface muons, which originate from positive pions stopping and decaying in the surface of the muon production target, reaches 10^8 muons/s at a proton beam power of 1 MW. Muon beams at the H1 area were commissioned and the intensity and profile of the beams were measured. A DC separator (or Wien filter) [3] to reduce positron/electron backgrounds by filtering particle velocity using crossed electric and magnetic fields was not installed at the time of the beam commissioning. The intensity of surface muons was measured to be $5 \sim 9 \times 10^7$ muons/s at a proton beam power of 1 MW from the number of decay positrons from a muon-stopping target. This is a preliminary result, but it is not very different from the expected value of 10^8 muons/s. Figure 2 shows a typical beam profile of surface muons at the H1 area. It was measured by a beam profile monitor developed by T. U. Ito, *et al.* [4].

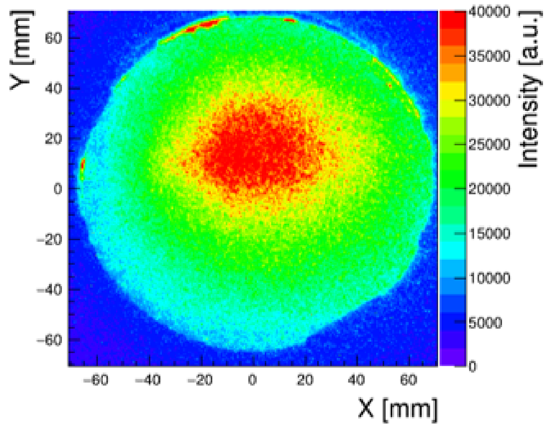

Figure 2: A beam profile of surface muons measured with a beam profile monitor at the H1 area

The commissioning of negative muon beams was also conducted. The intensities were measured by counting decay electrons from an alminium target as a function of the beam momentum. The result is summarized in Fig. 3. The black circles show measured intensities and the red squares are obtained with the simulation by Geant4 [5] and G4beamline. They are in good agreement. The plateau observed over 50 MeV/c is due to the failure of the power supplies of the capture solenoid. Their maximum currents were limited to less than half of their rated currents so that the efficiency of capturing high momentum particles was not as high as expected. The failure was fixed in April 2023 and new measurements will be conducted in JFY2023.

At the H1 area, data taking for the search for μ-e conversion (DeeMe experiment [6]) is ongoing, and a precise measurement of the hyperfine structure of muoniums (MuSEUM experiment [7]) is scheduled to be conducted in JFY2023.

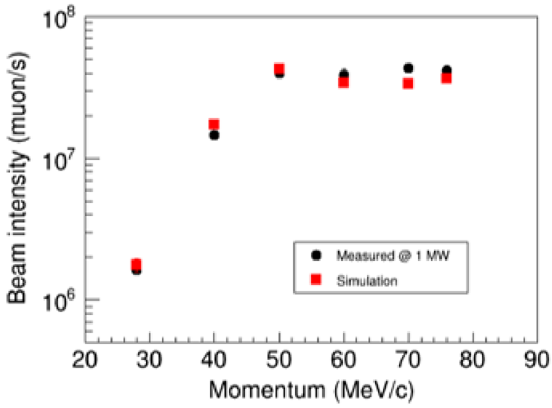

Figure 3: Negative muon yields measured with several momentum settings. The black circles are measured intensities and the red squares are the results of simulation.

3. Extension of H-line

The H-line is planned to be extended to develop a novel low-emittance muon beamline. Low emittance beam is very important for the muon $g-2$/EDM experiment at J-PARC [8] because it enables electric-field-free storage of muons in a compact storage ring. Moreover, it opens up a novel microscopic imaging technique: transmission muon microscopy (TμM). The advantage of TμM is its high transmissivity, therefore it enables the observation of thick samples nondestructively.

The second branch of the H-line (H2 area), which is under construction in the MLF, is planned to be extended further in a new building (H-line experimental building) to be constructed on the east side of the MLF as shown in Fig. 4. Ultra-slow muons are produced and re-accelerated up to 4 MeV using a radio-frequency quadrupole linac (RFQ) and an inter-digital H-mode drift-tube linac (IH-DTL) at the H2 area. At the H-line experimental building, muons are accelerated up to 212 MeV using a disk-and-washer (DAW)-type coupled cell linac and four disk-loaded structures (DLS). The 212 MeV muon beam is stored in a compact storage ring and the anomalous magnetic moment of muon is measured precisely. For the transmission muon microscope, muon beams with kinetic energy of 40 MeV are used.

The construction of the H2 area made progress in JFY2022. Radiation shields were fabricated and assembled, and a safety interlock system to protect users from radiation was implemented. Focusing magnets for the H2 area are not installed yet, but low-intensity surface muons are scheduled to be delivered to the H2 area in JFY2023 by connecting vacuum ducts. Full power beam will be available in JFY2024 after the focusing magnets have been manufactured and installed.

The design of the new building by an architectural design office is scheduled to be completed in JFY2023. Preparatory works, such as geotechnical investigation, survey, the relocation of existing equipment, and research of buried cultural properties at the construction site, have been already finished.

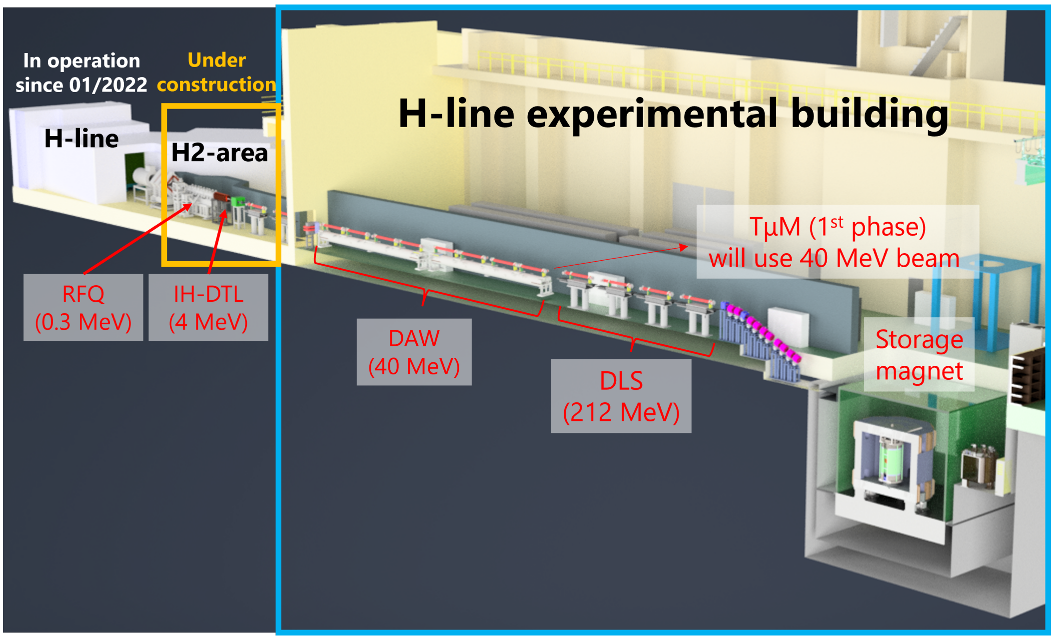

Figure 4: A 3D drawing of the extension plan of the H-line.

4. Second target station

Conceptual design of a new target station (TS2: second target station) is underway as a future plan for the next 10-20 years. TS2 is proposed to be constructed on the west side of the MLF as shown in Fig. 5. The beam power of protons will be increased to 1.5 MW, of which 1 MW will be delivered to TS2. A target is used to produce both muons and neutrons at TS2, therefore ten times more pions and muons are produced in TS2 than in the tandem target of the MLF. By placing a large-bore superconducting solenoid in the vicinity to the target, the efficiency of capturing pions and muons is increased approximately 5-fold. In total, the number of muons reaches about 50 times or more than the MLF.

5. Summary

The J-PARC muon facility can provide the world's most intense pulsed muon beam and promotes a variety of sciences in its four beamlines and seven experimental areas. The H1 and S2 areas started operation in January 2022 and are used for fundamental physics like precision measurements of muonium and a search for μ-e conversion. The high-intensity muon beamline is being further extended to produce a novel low-emittance muon beam by re-accelerating ultra-slow muons up to 212 MeV with linear accelerators. The low-emittance muon beam is planned to be used in the muon $g-2$/EDM experiment and transmission muon microscopy. Concurrently, the conceptual design of the second target station is underway as a future plan. In the next decade, various experimental results using the upgraded facility are expected.

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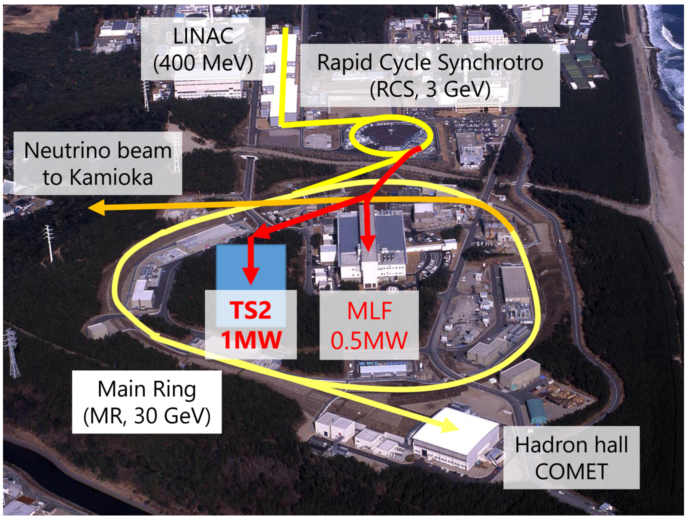

Figure 5: The proposed site of the second target station (TS2)

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