New beamlines and future prospects of the J-PARC muon facility

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Abstract. At the J-PARC muon facility (MUSE), new beamlines started operation recently. H-line is a high-intensity pulsed muon beamline for fundamental physics experiments. The first beam of the H-line was delivered to its first branch (H1 area) in January 2022, where a precise measurement of the muonium hyperfine structure and a search for μ-e conversion will be conducted. Further extension of the second branch of the H-line for a muon g-2/EDM experiment and a transmission muon microscope project is also ongoing. In addition, the second branch of the surface muon beamline (S2 area of the S-line) was opened for a muonium 1S-2S spectroscopy experiment in FY2021. In this paper, the recent upgrade and present status of the J-PARC muon facility and its prospects are presented.

1 Introduction

The J-PARC muon facility (MUSE) is a pulsed muon beam facility in the Material and Life Science Facility (MLF) of the J-PARC. The 3 GeV proton beam from the RCS hits a rotating graphite target and produces charged pions via proton-nucleon reactions. Muons produced by the decay of charged pions are captured and delivered to experimental areas using electromagnets. There are four muon beamlines and seven experimental areas at MUSE. Recently, one new beamline (H-line) and two new experimental areas (H1 and S2 area) for fundamental physics programs started operation.

2 New beamlines for fundamental physics

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2.1 H-line

H-line is a muon beamline in the east #1 experimental hall of MLF. It is a general-purpose beamline [1] that can generate both positive and negative muons. The capture electromagnet of the H-line has a large acceptance of 108 mSr, which enables us to deliver high-intense muon beams. The design intensity of surface muons at the H-line is 10^8 muons/s with a proton beam power of 1 MW. An experimental area at the first branch of the H-line named H1 area started operation in January 2022, where the hyperfine splitting measurement of muonium (MuSEUM experiment [2]) and the search for a cLFV (charged Lepton Flavour Violation) process (DeeMe experiment [3]) are planned. Further extension of the second branch of the H-line is ongoing, at which a low emittance muon beam will be produced by re-accelerating ultra-slow muons to be used for the muon g-2/EDM experiment at J-PARC [4] and a transmission muon microscope (TμM) project.

2.1.1 Beam commissioning at H1 area

Beam commissioning of the H-line was conducted at the H1 area. Because a DC separator (Wien filter) as a velocity selector is not installed in the H-line yet, a large positron/electron background existed during the beam commissioning. It made the beam commissioning difficult, but we managed to measure the beam intensity, profile, and momentum of surface muons and the beam intensities of negative muons at several momenta. Installation of a DC separator is scheduled within JFY2022.

Figure 1 shows the setup to measure the intensity of surface muons. Decay positrons from the muon-stopping target are measured using a pair of plastic scintillators. The number of detected positrons was obtained by fitting the time spectrum of decay positrons shown in Fig. 2. To estimate the muon beam intensity in the H-line, we estimated the detector acceptance and the transmission efficiency of the Kapton window using a Geant4-based simulation [5] and measured the detection efficiency of the plastic scintillator pair. As a preliminary result, the surface muon beam intensity was estimated to be $(9.9\pm1.0)\times10^7$ muon/s for 1 MW proton beam.

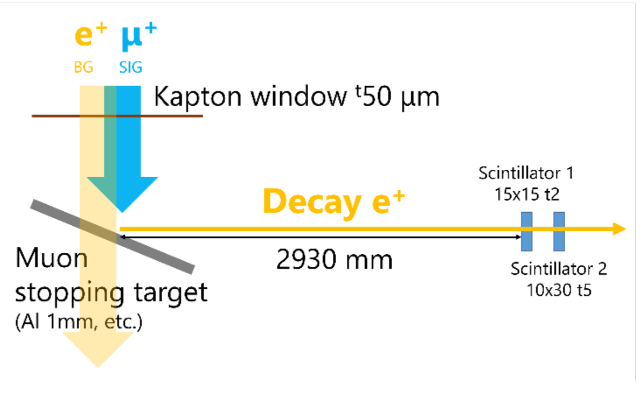

Fig. 1. Experimental setup to measure the intensity of surface muons

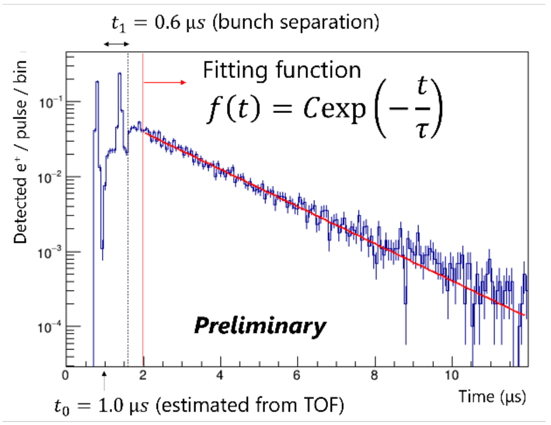

Fig. 2. Time spectrum of decay positrons in the intensity measurement of surface muons

The momentum of surface muons was also measured with almost the same setup as the intensity measurement, but a magnetic field of 23.85 G was applied to an Aluminium target of various thicknesses. Due to the muon spin rotation in a magnetic field, the time spectrum of decay positrons showed a wiggled structure. In Fig. 3, the beat amplitudes are plotted as a function of the thickness of Al targets. The range of surface muons in Al was obtained by fitting this plot with an error function, and then we estimated the beam momentum to be 28.0 MeV/c (RMS 1.2 MeV/c) as expected.

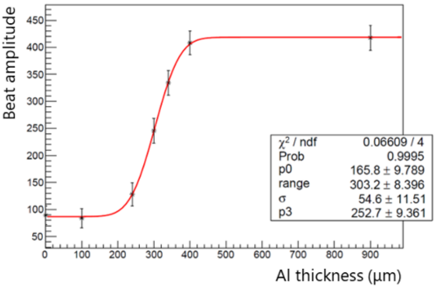

Fig. 3. Range measurement of surface muons to estimate their momenta

The beam profile of surface muons at the H1 area was measured using a beam profile monitor which is developed by T. U. Ito, *et al*. [6]. A typical beam profile is shown in Fig. 4, whose horizontal and vertical sizes are σ_x = 44 mm and σ_y = 24 mm, respectively.

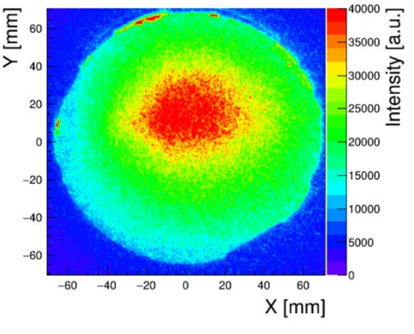

Fig. 4. Typical beam profile of surface muons at the H1 area

As the commissioning of negative muons, beam intensities with several momentum setups were measured. The measured intensities have good agreement with a Geant4-based simulation as shown in Fig. 5. Due to the failure of the power supplies of the muon/pion capture solenoid of the H-line, a plateau is observed above 50 MeV/c. The power supplies are going to be fixed within JFY2022, and then we will be able to deliver more negative muons with higher momentum at the H1 area.

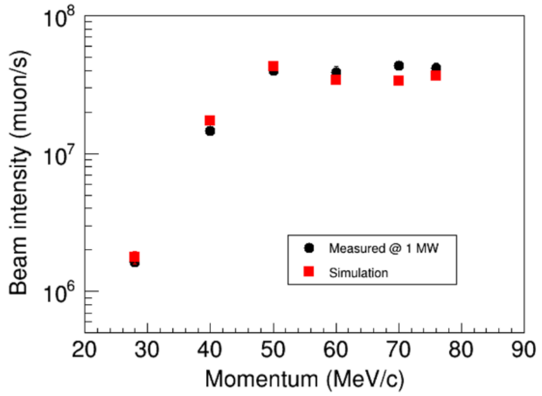

Fig. 5. Intensity of negative muons as a function of momentum of muons

2.1.2 Extension of the H-line

The extension of the second branch of the H-line is ongoing. The second experimental area named H2 area is under construction inside the MLF, where ultra-slow muons are produced and re-accelerated up to 4.5 MeV as a first stage to produce a low emittance muon beam. Radiation shields of the H2 area were already fabricated and installed, and the first beam at the H2 area is scheduled within JFY2022.

Further extension is planned in a new building named H-line experimental building as shown in Fig.6. A low-emittance muon beam accelerated up to 212 MeV will be utilized to precisely measure the muon *g-2*/EDM. In the H-line experimental building, a transmission muon microscope (TμM) is also planned to be installed, which enables non-destructive observation of thick samples. Preparatory work before starting construction of the new building, such as geotechnical investigation, a survey of the construction site, the relocation of existing cables, and so on, is ongoing.

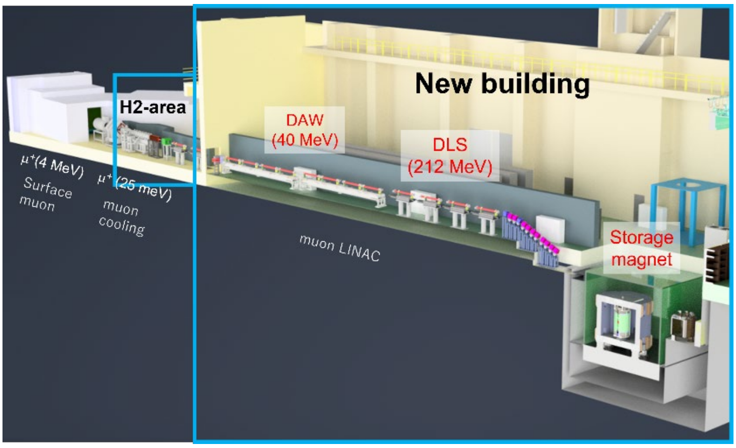

Fig. 6. Extension plan of the H-line.

2.2 S2 area of S-line

The S-line is a surface muon beamline that has two branches named S1 and S2 area. By using a kicker device installed in the S-line, the S1 and S2 areas can be operated simultaneously. The S2 area started its operation in 2021, where the spectroscopy of the 1S-2S interval of muonium is underway to determine the muonium mass precisely.

3 Second target station

A new target station (second target station, "TS2") to produce muons and neutrons is under consideration as one of the future programs of J-PARC MLF. The proposed construction site is on the west side of the MLF. At TS2, a common target is utilized to produce both muons and neutrons. Compared to the current muon production target in the MLF, which is in tandem with the neutron target, ten times more muons are produced in the target of TS2. In addition, the extraction efficiency of muons will be about 5 times better by placing a large-bore capture solenoid in the vicinity of the target. Therefore, more than a 50-fold increase in muon beam intensity is expected.

4 Summary

A new beamline (H-line) and two new experimental areas (H1 and S2 area) began operation recently. H-line is a high-intense muon beamline and surface muons of about 10^8 muons/s are obtained at the H1 area. The momentum and profile of surface muons were also measured and are consistent with our expectations. Negative muon yields at high momentum are not as high as expected because the pion/muon capture solenoid of the H-line cannot be fully excited due to the failure of its power supplies. They are scheduled to be repaired within JFY2022.

Further extension of the H-line is underway to produce a novel low-emittance muon beam by re-accelerating ultra-slow muons. H2 area in the MLF is being constructed with the aim of starting operation within JFY2022. Preparatory work to build a new building for the muon *g-2*/EDM experiment and the transmission muon microscope is underway.

The S2 area in the second branch of the S-line started operation in 2021 and a precise measurement of the mass of muonium is ongoing at the S2 area.

The conceptual design of the second target station (TS2) is in progress. Its greatest advantage is the increase in the muon beam intensity. In TS2, neutrons and muons are produced in the same target and a muon/pion capture solenoid will be placed in the vicinity of the target. These characteristics enable a more than 50-fold increase in muon yields.

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