# Present status of J-PARC MUSE

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**Abstract.** At J-PARC MUSE, since the $\mu$SR2017 conference and up to FY2022, there have been several new developments at the facility, including the completion of a new experimental area S2 at the surface muon beamline S-line and the first muon beam extraction to the H1 area in the H-line, mainly to carry out high-statistics fundamental physics experiments. Several new studies are also underway, such as applying negative muon non-destructive elemental analysis to the analysis of samples returned from the asteroid Ryugu in the D2 area of the D-line. This paper reports on the latest status of MUSE.

## 1. Operational status of J-PARC MUSE

The Japan Proton Accelerator Research Complex (J-PARC) generally operated smoothly from 2017 to 2021, although there have been a few small time losses, such as reduced beamtime due to extended maintenance periods and outages due to COVID19. The average operating time of the Muon Science Establishment (MUSE) during this period was 160 days per year. However, in FY2022, due to a significant increase in electricity costs, the beamtime is expected to be only around 110 days. Securing additional funds for future electricity expenditure and extending beamtime are becoming the most critical issues for next year and beyond. The beam power has increased by 100 kW yearly for the past few years and was stable at about 800 kW in the first half of 2022. If no unexpected problems occur, the beam power is expected to reach its design value of 1 MW in about two years.

In particular, more than 80% of the D-line and S-line is used for inter-university experiments. In total, 50–60 general-use proposals per beam cycle (twice a year) are carried out on both beamlines, and the ratio of adopted proposals to the total number of submitted proposals is about half.

## 2. Muon target

Since September 2008, when the facility started operation, fixed graphite targets have been used safely and stably for the muon and pion production at J-PARC MUSE. However, the lifetime of a fixed target will be less than 1 year due to the proton-irradiation damage of graphite at 1 MW proton beam operation. In 2014, to free the fixed target from frequent replacement, it was replaced by a new rotating target, which was fabricated referring to the rotating carbon target initially developed at PSI that had been operating successfully for over ten years [1]. In a rotating target, the radiation damage is distributed to a wider area to increase its lifetime, but regular maintenance is required to replace the rotary feedthrough. The first rotating target operated successfully until the summer of 2018 when, during regular maintenance in the summer shutdown, it was discovered that the flexible coupling connecting the rotating shaft to the rotary feedthrough in the vacuum was damaged. The damage originated from inadequate drawing instructions for the machining of the coupling. The inappropriate couplings were employed in two places of the rotation mechanism. While the broken coupling was replaced with the appropriate one immediately, the other one couldn't be replaced before the restart of the beam operation because of uneasy access, high residual radiation dose, and high tritium contamination. It was also difficult to replace the whole rotating target assembly with the spare one during this shutdown period. Consequently, we decided to keep on utilizing the existing target until the summer of 2019 after sufficient safety measures were taken to carefully monitor for any loss of transmission due to the remaining inappropriate coupling. In the summer of 2019, it was replaced with the second rotating target assembly, and regular operation was resumed. As there are no more spares for the muon rotating target, a third target assembly is currently being built, which is expected to be completed in 2023. S. Matoba reports further details in [2] of these proceedings with the development of a new monitoring system for the muon rotating target using an infrared camera.

## 3. Secondary beamlines

MUSE is designed with four beamlines arranged around the muon target (see Fig. 1). The D-line has a superconducting solenoid, the U-line uses an axial-focusing system and can transport muons with large solid angles to produce ultra-slow muons, the S-line is a beamline specialized in $\mu$SR studies, and the H-line is mainly used for high-statistics fundamental physics experiments.

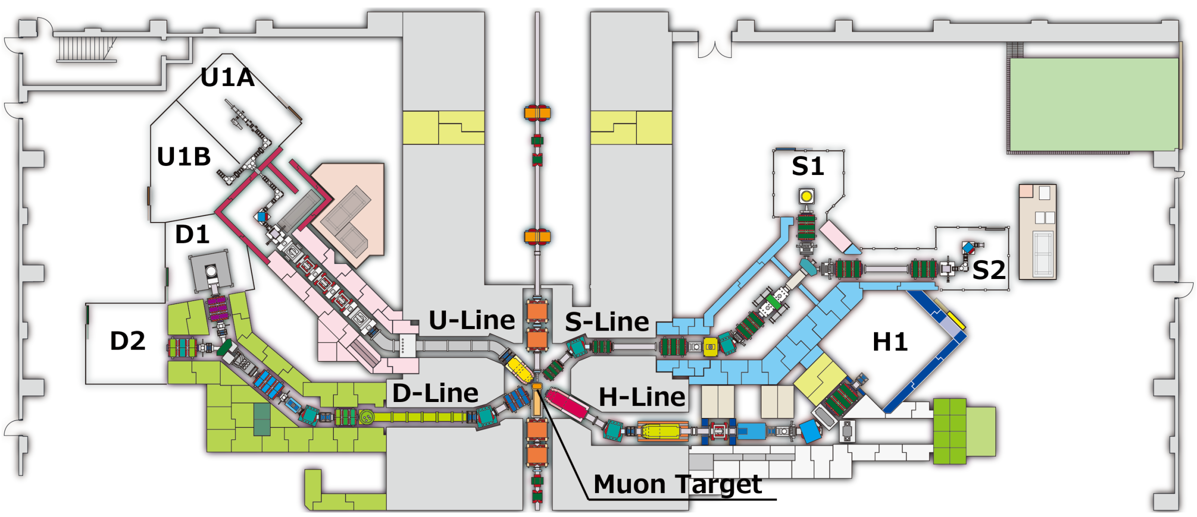


**Figure 1.** The layout of the MUSE facility at J-PARC.

### *3.1. D-Line*

The D-line has a superconducting solenoid to efficiently capture and transport muons generated by the decay of pions in flight. Conventional superconducting transport solenoids are usually cold-bore systems that require thin aluminum beam windows as a thermal shield at the entrance and exit of the solenoid, thus limiting the extraction of extremely low-energy decay backward muons. For this reason, in 2015, the old cold-bore solenoid was replaced by a warm-bore superconducting solenoid without any beam windows. Since then, efforts have been made to optimize the beam transport and as a result, low-energy negative muons of around 100 keV can now be extracted at intensities of nearly 1000 $\mu^-$/sec, which can be used in practical experiments. One application is the study of the Ag/Au concentration on the surface of old Japanese gold coins by varying the muon penetration depth. A thinner surface with a high Au concentration can tell about the expertise of the unique minting process for gold coins in the Edo era. This technique allowed them to reduce the amount of gold in the coin while keeping its golden shine, and elemental analysis using low-energy negative muons can enlighten how they improved their minting process over time. Further details are reported by M. Tampo [3] in these proceedings.

This has led to research into historical samples, such as analysis of the contents of sealed medicine bottles used by the physician Ogata Koan in the Japanese Edo period [4]. Among many other experiments, element analysis of samples from the carbonaceous asteroid Ryugu that were brought back to Earth by the Hayabusa2 spacecraft was carried out. The Japanese mission Hayabusa2 was designed to collect samples directly from the surface of this asteroid, which is thought to have preserved the elemental composition of the solar system in its primordial state, and return them to Earth for laboratory analysis [5]. Identification of metalized ions deposited in lithium batteries [6], and muon pioneer work in various atomic and molecular research fields, such as precise X-ray spectroscopy of negative muon capture and deexcitation reactions in rare-gas nuclei using Transition Edge Sensor (TES) [7], were also performed. All the above studies are mainly carried out in the D2 area, where researchers can freely set up their own experimental equipment.

In the D1 area, a general-purpose $\mu$SR spectrometer is equipped (see [8] section 4.1), where experiments using dilution refrigeration and $\mu$SR measurements with negative muons are mainly carried out.

### *3.2. U-Line*

The U-line consists of a normal-conducting capture solenoid made of radiation-resistant mineral insulation cables (MIC), a superconducting curved transport solenoid, and a superconducting axial focusing magnet system, which can capture pulsed muons with a large solid angle of 400 mSr [9]. Its primary purpose is to produce an intense surface muon source with an intensity ten times higher than that of conventional beamlines such as the D-line which will be used to produce ultra-slow muons (USMs). This beamline is directly connected to the USM beamline in the area U1 [10]. Surface muons are stopped in a tungsten foil heated to 2000°C [11, 12], or silica aerogel at room temperature [13], to produce thermal muonium in an ultra-high vacuum. Muonium atoms are then ionized using high-intensity lasers to generate ultra-slow muons that are reaccelerated up to 30 keV using an electrostatic immersion lens and directed to two experimental areas, U1A (for USM-$\mu$SR) and U1B (for further re-acceleration, microbeam $\mu$SR, muon transmission microscopy, etc.) [8, 14].

The 1s–2p–unbound transition is adopted as the resonance ionization scheme of muonium. In particular, the development of a 122-nm (Lyman-alpha) vacuum ultraviolet (VUV) laser for the 1s–2p transition required time for the fabrication of the final stage amplifier. We are currently overcoming this difficulty by employing new crystals. Details are given in Y. Oishi's report [15] of these proceedings. Recent developments include the remote tuning of the laser using a CMOS camera as feedback (beam locking) to keep the laser beam trajectory constant and optimize the overlap between Lyman-alpha and 355-nm (2p–unbound transition) lights. Beamline commissioning, measurement system, and sample environment are now in progress, and $\mu$SR measurements using ultra-slow muons will soon be available in the U1A area, where the $\mu$SR spectrometer (see [8] section 4.2) is being upgraded for the start of the inter-university user program. In particular, the detector performance that was affected by the heat generated from the longitudinal coil (LC) magnet is being improved by installing a copper thermal shield and cooling water piping to stabilize the temperature of the silicon photomultipliers (SiPM). A lead wall was also placed in front of the spectrometer to suppress the positron background from upstream. The $\mu$SR spectrometer is located on a 30-kV high-voltage stage, and the muon penetration depth into the sample can be controlled by changing the muon energy from sub-keV to 30 keV. The latest developments can be found in the contributions by S. Kanda [16] and N. Teshima [17] of this issue.

In the U1B area, a project is currently underway to re-accelerate ultra-slow muons up to 5 MeV using a muon cyclotron to realize the first transmission microscope using muons. If successful, it will offer unique capabilities to visualize nanoscale structures and function with ~10-$\mu$m-thick specimens due to the muon high penetrability.

### *3.3. S-Line*
The surface muon beamline S-Line dedicated to materials science was constructed in 2016 and became available for general-use experiments in late 2017. The beamline will eventually have four experimental areas S1, S2, S3, and S4. In the S1 area, a general purpose $\mu$SR spectrometer assembled with Kalliope detectors is installed (similar to the spectrometer in the D1 area). Almost all $\mu$SR experiments, except those using a dilution refrigerator and negative muons that need to be performed at D1, are presently carried out here.

Recent developments include the commissioning of a new 5-T high-field $\mu$SR instrument as well as the elaboration of a new transient $\mu$SR method. With the conventional $\mu$SR method, the measurement has to be interrupted when the sample environment, such as temperature or magnetic field, is changed to keep the measurement condition constant resulting in sacrificing the measurement time or ruining the data. This new measurement approach will integrate and analyze external parameters (temperature, magnetic field, etc.) and $\mu$SR data pulse by pulse, allowing the sample environment to be changed even while the measurement is being performed, which will enable us to study transient processes while making effective use of the high-intensity muon beam at J-PARC MUSE.

A group at Okayama University received a sizeable external grant (Japanese Grant-in-Aid for Scientific Research) from the Japan Society for the Promotion of Science (JSPS) for the project “Precision test of electroweak theory and search for new physics beyond the standard model by laser spectroscopy of purely leptonic atoms”. A new experimental area, S2, was constructed in FY2020 (see Fig. 1) to realize this project and perform high-precision laser spectroscopy of the energy splitting between 1s and 2s levels in muonium. The first muon beam extraction was successfully carried out in the S2 area in July 2021. Currently, a 244-nm laser and an instrumentation system are installed for the muonium 1s–2s spectroscopy. Resonance signals were successfully observed in early 2022, and efforts are currently being made to reduce systematic errors. Details are reported by S. Yamamoto [18] in these proceedings.

### *3.4. H-Line*
The H-line is a high-intensity muon beamline that has been in preparation and construction for nearly ten years. The beamline will be used to realize high-statistics fundamental physics experiments such as 1) precise measurements of muonium hyperfine structure (MuSEUM) [19, 20], 2) muon-electron ($\mu$–e) conversion process search (DeeMe) [21], 3) precision measurements of muon anomalous magnetic moment (g–2/EDM) [22], and new materials and life science

tools such as a transmission muon microscope. In early 2022, the muon beam was successfully transported to the H1 area, although the DC separator was not yet ready. At present, $\mu$–e conversion measurements, which do not require a DC separator, are being carried out first, and precision measurements of muonium hyperfine structure will start in 2023. Construction of the H2 area for precision measurements of muon anomalous magnetic moment and transmission muon microscope partly started this year.

## 4. Summary

As illustrated above, J-PARC MUSE promotes a wide range of fields such as materials and life science, industrial application research, integration of arts and sciences research, muon atomic physics, and muon particle physics in a well-balanced manner. In the future, steady progress is expected toward further upgrading of the facility and the creation of new results.

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