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CONFERENCE PROCEEDING

Pulsed muon facility of J-PARC MUSE

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Abstract
J-PARC Muon Facility: MUSE (Muon Science Establishment) is responsible for the inter-university user program and the operation, maintenance, and construction of the muon beamlines, namely D-line, S-line, U-line, and H-line, along with the muon source at J-PARC Materials and Life Science Facility (MLF). In this paper, recent developments are briefly presented.

Keywords Muon · μSR · Non-destructive element analysis · Exotic atom · Particle physics

1 Introduction

The Japan Proton Accelerator Research Complex (J-PARC) has operated smoothly since 2008. The average operating time of the Muon Science Establishment (MUSE) during this period was 160 days per year. The beam power has increased by 100 kW yearly for the

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past few years and was stable at about 900 kW in the first half of 2023. If no unexpected problems occur, the beam power is expected to reach its design value of 1 MW in about two years. The layout of MUSE [1] in the Materials and Life Science Facility (MLF) featuring the four muon beamlines arranged around the muon target is shown in Fig. 1. The D-line comprises a conventional superconducting solenoid, the U-line uses a curved solenoid and an axial-focusing system to transport muons with a large solid angle to produce ultra-slow muons, the S-line is a beamline specialized in μSR studies, and the H-line is mainly dedicated to high-statistics fundamental physics experiments. More than 80% of the D-line and S-line beamtime is used for inter-university user 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 the MLF started operation in September 2008, fixed graphite targets have been used for muon and pion production at MUSE. The lifetime of a fixed target is less than 1 year at 1 MW proton beam operation due to the proton-irradiation damage of graphite. In 2014, a new rotating target was installed to avoid frequent replacement of the fixed target. It was fabricated referring to the rotating carbon target initially developed at PSI that had been smoothly operating for more than ten years [2]. 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. During regular maintenance in the summer shutdown, one of the two flexible couplings connecting the rotating shaft to the rotary feedthrough in the vacuum was found damaged due to inadequate machining. The broken coupling was replaced immediately, while the other one, still in working condition, couldn't be exchanged because of uneasy access, high residual radiation dose, and high tritium contamination. Replacing the whole rotating target assembly with the spare one before the restart of the beam operation was also challenging. The existing target continued to be utilized until the summer of 2019 after sufficient safety measures were taken to monitor carefully any transmission loss. In the summer of 2019, it was replaced with the second rotating target assembly, and regular operations returned to normal. A third target assembly is being built and expected to be completed in FY2023. A new monitoring system for the muon-rotating target using an infrared camera is also currently being developed.

3 Secondary beamlines

3.1 D-line

The D-line is a beamline that includes a superconducting solenoid and can supply both positive or negative decay muons and surface (positive) muons to two experimental areas D1 and D2 (Fig. 2). The proton beam from the J-PARC RCS has a higher energy of 3 GeV than other muon facilities, resulting in a particularly high yield of negative muons. Taking advantage of this feature, nondestructive elemental analysis and μSR research using negative muons have recently been actively conducted. Examples include nondestructive elemental analysis of samples brought back by Hayabusa2 from the asteroid Ryugu [3], and

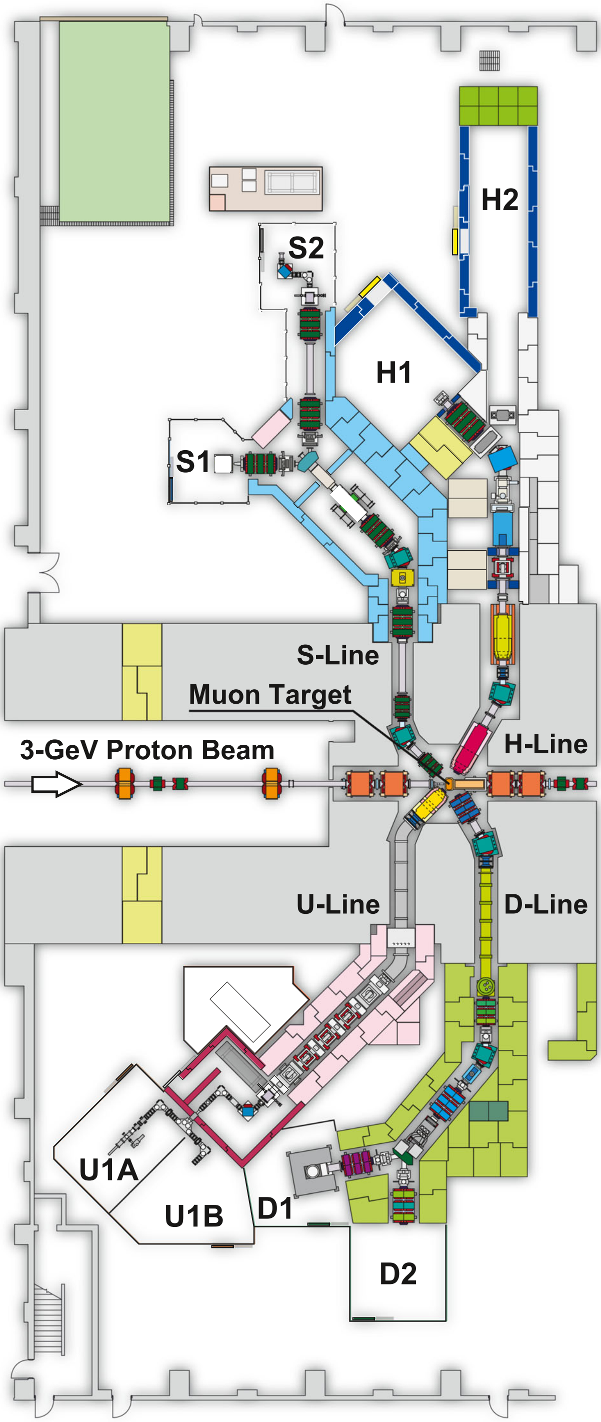

Fig. 1 Layout of the MUSE facility designed with four beamlines arranged around the muon target

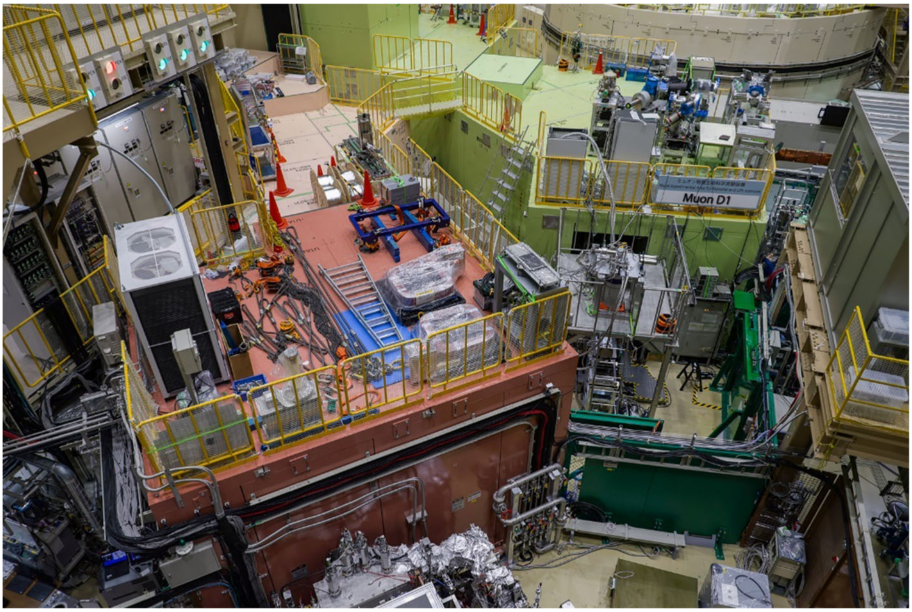

Fig. 2 Picture of the MUSE facility in the MLF experimental hall No. 2 showing the U-line (left) and D-line (right) with the D1 area

identification of the contents of a medicine bottle owned by Ogata Koan, a Japanese doctor in the Edo period [4]. Integration of arts and sciences research is currently being actively conducted and has yielded results such as research on the manufacturing method of koban (small gold coins) from the Edo period. Analysis of trace carbon in Japanese swords was also initiated using a newly developed negative muon lifetime measurement method. In addition, precision spectroscopy of exotic atoms, including negative muons, has been actively studied. For example, precision X-ray spectroscopy of muonic neon atoms using a Transition Edge Sensor (TES) was conducted to precisely verify quantum electrodynamics [5], and microwave precision spectroscopy of the hyperfine structure of muonic helium atoms was performed [6].

3.2 U-line

The U-line is a beamline that focuses on low-energy muon production obtained by laser ionization of thermal muonium for various experiments, providing ultra-low velocity muons of 50 eV – 30 keV to two experimental areas U1A and U1B (Fig. 2). The ultra-slow muons are obtained by stopping intense surface muons on high-temperature tungsten or silica aerogel and resonantly ionizing the thermal muonium drifting out into the vacuum with a Lyman-α laser system. In the U1A area, surface and interface science research will be carried out using these ultra-low velocity muons. Measurements of thin-film superconductors have recently been performed. In the U1B area, an attempt to realize a transmission muon microscope is underway by re-accelerating the ultra-slow muons to 5 MeV using a cyclotron and connecting

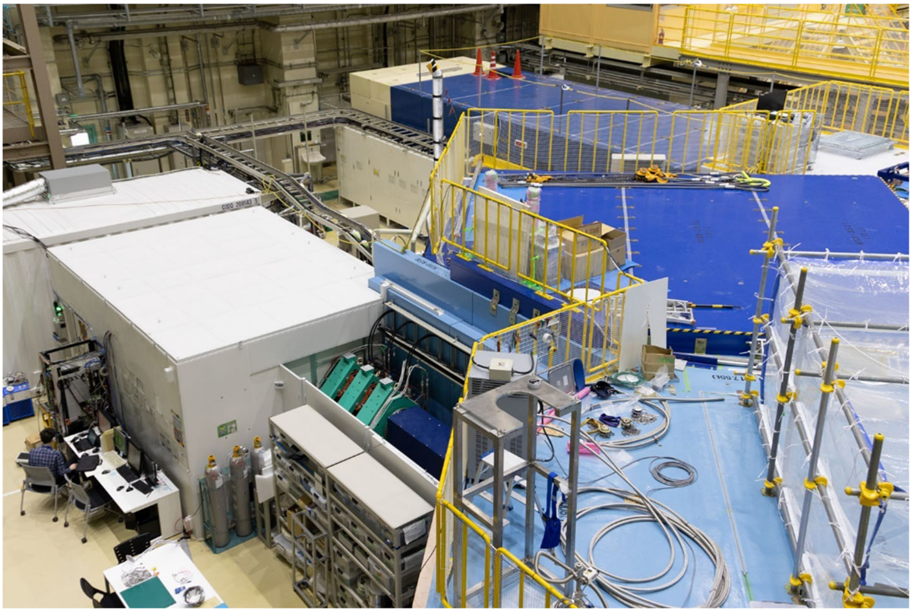

Fig. 3 Picture of the MUSE facility in the MLF experimental hall No. 1 showing the S-line (bottom) with the S2 area and the H-line (top) with the H1 and H2 areas

a microscopy instrument behind the cyclotron. The installation of the cyclotron has been completed and acceleration tests are scheduled to start in FY2023.

3.3 S-line

The S line is a dedicated beamline for surface muon extraction and will eventually have four experimental areas. Currently, two experimental areas are in operation: the S1 area is equipped with an μSR spectrometer, and various condensed matter experiments under inter-university user programs are being carried out; the S2 area (Fig. 3) is used for the high-precision laser spectroscopy of the energy splitting between $1s$ and $2s$ levels in muonium. These areas are supplied with muon beams simultaneously using an electric kicker system. Recent advances include the operation of a 5 T high field spectrometer and the development of a new data acquisition method called transient μSR [7].

3.4 H-line

The H line is designed with solenoids instead of quadrupole magnets to increase the efficiency of muon beam transport. This beamline has two experimental areas (Fig. 3). In the H1 area, muon-electron conversion process search and precision measurements of muonium hyperfine structure are being performed. The H2 area is scheduled to start supplying beams in FY2024 and will be used for muon $g-2$ measurements and transmission muon microscopy. These facilities will be installed in a new building that will be an extension of the current MLF experimental hall No. 1.

4 Conclusion

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.

Author Contributions K.S. wrote the main manuscript text and prepared Figs. 2 and 3. P.S. prepared Fig. 1. All authors reviewed the manuscript.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

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