Current status of the J-PARC muon facility, MUSE

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Abstract. The muon science facility (MUSE), along with the neutron, hadron, and neutrino facilities, is one of the experimental areas of the J-PARC project. The MUSE facility is located in the Materials and Life Science Facility (MLF), which is a building integrated to include both neutron and muon science programs. Since the autumn of 2008, users operation is effective and making use of the pulsed muon beam particularly at the D-Line. Unfortunately, MUSE suffered severe damages from the earthquake on March 11, 2011, the so-called “Higashi-Nippon Dai-Shinsai”. We managed to have a stable operation of the superconducting solenoid magnet with use of the on-line refrigerator on December, 2012, although we had to overcome a lot of difficulties against components not working properly. But we had to stop again the whole operations on May 2013, because of the radioactive materials leakage accident at the Hadron Hall Experimental Facility. Finally we restarted the users’ runs on February 2014.

1. J-PARC MUSE

The muon science facility (MUSE), along with the neutron, hadron, and neutrino facilities, is one of the experimental areas of the J-PARC project. The MUSE is located in the Materials and Life Science Facility (MLF), which is a building integrated to include both neutron and muon science programs [1]. The 3 GeV proton beam from the 3 GeV proton synchrotron ring (RCS) is focused on the 1st graphite target with 20 mm thickness. For phase 1, MUSE is designed to extract efficiently either pions or muons from a muon production graphite target to the four muon beam lines, the so-called D-Line, U-Line, S-Line and H-Line, enabling a variety of muon related experiments, at the ten experimental areas (D1, D2, U1A, U1B, S1, S2, S3, S4, H1 and H2) utilizing unique features of the pulsed muon beams. Figure 1 shows a layout of the MUSE facility. The repetition rate of the 3 GeV synchrotron is 25 Hz, with a pulse-separation of 40
ms. Therefore always pulsed muons are delivered to the any experimental area, consisting of two bunches separated by 600 ns with a full width of 100-150 ns.

A superconducting decay/surface beam line, the so-called D-Line, was constructed as the first muon beam line and has been used as a general use muon beam line since September 2008. It has a modest-acceptance pion injector of about 45 mSr, where either surface muons, or decay muons (5-120 MeV/c, \(\mu^+\) or \(\mu^-\)) can be extracted that are obtained through the in-flight decay of \(\pi^+/\pi^-\) confined by a strong longitudinal magnetic field of several tesla from a superconducting decay solenoid magnet. In November 2009, the surface muon extraction rate was significantly increased up to \(1.8 \times 10^6\) pulses/s with a 120 kW proton beam from the RCS [2]. One of the sales point of the D-Line is its intense \(\mu^-\) yield, since the cross section of \(\pi^-\) at a 3 GeV proton beam is larger than that at the other meson factories [3]. Therefore, the yields of the decay \(\mu^+\) and the decay \(\mu^-\) are equivalent for the same momentum. In particular, decay \(\mu^-\) as low as 5 MeV/c, which has an implantation depth of 1 \(\mu\)m in the case of gold, can be extracted with an intensity of one \(\mu^-\)/pulse.

2. Damages by the earthquake Higashi-Nippon Dai-Shinsai

The D-Line as well as the other MUSE facility suffered severe damages from the earthquake on March 11, 2011, the so-called Higashi-Nippon Dai-Shinsai. In particular, damages on the boundaries of the building structure were serious, since severe ground settlements occurred due to the Higashi-Nippon Dai-Shinsai. In the following, we specify the major damages.

- The helium ducts, control cables, power cables, compressed air piping for the superconducting magnet, and support stand for the D-line on-line refrigeration system were damaged, due to ground settlements, about 10 cm to 1.5 m at the boundaries of the MLF building, as is shown in Figure 2. Also a buffer tank for the He gas was tilted by 2-3 degrees. Because of the high-pressure gas regulation, we had to replace all the helium ducts at the boundary. Therefore we fixed all the ducts element as well as a support for the ducts and had a high pressure gas inspection on September, 2011.

- The M1 and M2 air circulation systems for the proton beam tunnels in the vicinity of the muon target were damaged. In particular, water ducts and control cables were found necessary to be removed and re-built, since the wall where they have been fixed was about to fall down located at an expansion joint between MLF and the proton beam transport line from the 3-GeV RCS (3NBT). Finally, the wall and water ducts etc. in the vicinity of the expansion joint were fixed by November, 2011, which enabled us to run a stable operation of the air circulation systems. Figure 3 is showing a picture of the damaged wall which was about to fall down at the expansion joint between 3NBT and MLF, as if water ducts for the M1 and M2 air circulation systems, were supporting the wall.

- The M2 tunnel consists of a target chamber, six quadrupole magnets, four steering magnets, two sets of profile monitor assemblies, 29 sets of pillow-seal assemblies, and seven sets of duct assemblies. When electricity was recovered in a month after the earthquake, it turned out that the M2 line primary beam duct was vented. We suspected something wrong with the pillow-seals caused some leakage in vacuum. By undergoing vacuum leak check for all the pillow-seals, it turned out that the pillow-seals themselves were not damaged, but tightness of a metal gate valve was not appropriate.

- We have been adopting an edge-cooled non-rotating graphite target, a so-called fixed target because of its ease of handling during maintenance. In this target, graphite is indirectly cooled by a copper frame, which surrounds the graphite. In order to reduce stress, a titanium buffer layer of 2 mm is placed between the graphite disk and the copper frame. In order to inspect the soundness of the graphite target, just in case damages were caused by the earthquake, the graphite target assembly was transported to the hot cell. There we
Figure 1. A layout of the J-PARC MUSE facility. The D-Line and the U-Line are located in the west wing in the MLF experimental hall No. 2. The S-Line and the H-Line are located in the east wing of the MLF experimental hall No. 1.
investigated not only dimensional changes but also heat conductivity by remote handling techniques. Consequently, it turned out the graphite target was alive and can be operated at least for another year.

- It was surprising that a lot of anchor bolts (M24) were ripped out from the concrete shielding blocks due to slipping off by the strong quake. Therefore several concrete shielding blocks were broken or cracked. All the damaged blocks were temporarily repaired by a concrete maker until November 2011.

- Moreover, the slipping off the concrete blocks by several tens of cm gave us more serious damages to the beam line components. In particular, an air-sealing hatch to prevent activated air in the tunnel from leaking into the user area, was smashed, causing deterioration in the air tightness. It had to be re-fabricated and re-installed because of the radiation safety. Also cable racks in the M2 tunnel struck by a heavy concrete block were found to be pushed away from the wall.

![Damaged helium ducts for the D-Line on-line refrigerator at the boundary of the MLF building.](image)

**Figure 2.** Damaged helium ducts for the D-Line on-line refrigerator at the boundary of the MLF building.

### 3. D-Line, recent developments and current status

Although MUSE suffered severe damages from the earthquake on March 11, 2011, consequently, we managed to re-operate the D-line by recovering from almost all the damages by the end of December, 2011. It was our great pleasure to report we could deliver again, surface and decay muons up to 60 MeV/c beam towards D1 and D2 during the commissioning beam time held on January 17, 2012, with an equivalent intensity as before 2011. The regular users runs were restarted from February 2, 2012.

Utilizing a beam-off period, we managed to install a switch yard, a kicker and a septum magnets to allow a single bunched muon beam up to 60 MeV/c towards D1 and D2 area in the D-line. It worked successfully to deliver a single pulse towards the D1 area. We have a plan to install a new $\mu$SR spectrometer at the D2 area in future.

A new $\mu$SR spectrometer was installed at the D1 area. It consists of 1280 scintillators (640 telescopes) with their scintillation light detected by pixeled avalanche photo diodes (MPPCs), covering a total solid angle of 23.4 %, which is 3.3 times larger [4] than the conventional D1 spectrometer, DΩ1. The spectrometer is equipped with a Helmholtz coil of 4 kG with a gap of 135 mm, which can be rotated by 90 degree, allowing us to apply either transverse or longitudinal
magnetic field. It is also designed to be connected with a fly path chamber with a diameter of 410 mm. During the commissioning, it was demonstrated that 200 M of coincidence positron events per hour were collected for a sample specimen of $15 \times 15 \text{ mm}^2$ with a 20 mm collimator. The event rate is 2-3 times higher than that in RIKEN-RAL [3], due to the stronger pulsed muon beam intensity of J-PARC.

4. U-Line

In addition to the D-Line, the U-line was constructed as the second muon beam line just beside of the D-Line in the MLF building No. 2. The U-line consists of a large acceptance solenoid made of mineral insulation cables (MIC), a superconducting curved transport solenoid magnet and a superconducting axial focusing magnets system. There, it allows to collect surface muons with a large acceptance solid angle of 400 mSr [5]. Compared to the conventional beam lines such as the D-line, the large acceptance of the front-end solenoid enables to capture more than ten times higher intensity pulsed surface muons of $5 \times 10^8$/s (proton beam intensity of 1MW operation). The U-line components of the superconducting curved and axial focusing magnets were already fabricated and installed in the end of September of 2012. In the commissioning works held in October, 2012, it turned out that the surface muon intensity achieved at the U-line exceeded the intensities at the D-line by one order of magnitude. Finally, it was succeeded to extract the world’s highest intensity pulsed muons, 2,500,000 muons per pulse ($6.4 \times 10^7$/s at 212 kW, corresponding to $3 \times 10^8$/s at 1MW) to the U1 experimental area. Another important feature of the U-Line adopting all the axial focusing transport system, was that we could extract not only positive muons, but also negative muons with a yield of 1/10 of the surface muons. Simultaneous extraction of positive and negative muons enables us to generate an exotic atom $\mu^+\mu^-$, although those can be easily separated by a pair of the dipole magnets equipped with the superconducting curved transport solenoid [6].

As a next step, it is planned to stop such intense pulsed muons into a hot tungsten target for generating an intense ultra slow muon beams in order to realize ultraslow muon microscopes [7]h that will enable us not only for a variety of surface, and nano-science, but also 3D imaging. Installation of a slow ion optics [8] as well as a $\mu$SR spectrometer dedicated to the ultra slow muons were completed [9]. When the production of intense ultra slow muon is realized, the use of its short-range penetration depth (e.g., 1 nm resolution at a penetration of 1 nm, and 10 nm

**Figure 3.** The damaged wall was about to fall down at the expansion joint between 3NBT and MLF, as if water ducts for the M1 and M2 air circulation systems, were supporting the wall.
at a penetration of 6 nm in Gold) will allow muon science to be expanded towards a variety of new scientific fields [10] such as,

- Surface/boundary magnetism utilizing its spin polarization and unique time-window,
- Sub-Surface chemistry, utilizing a feature of a light isotope of hydrogen,
- Precise fundamental physics such as QED, and
- Ion sources towards $\mu^+\mu^-$ collider experiments in high-energy physics.

5. S-Line
We are constructing a new surface muon beam line dedicated to the material sciences, the so-called S-Line. Although we are planning to construct four experimental areas, S1, S2, S3, and S4 areas finally, we are constructing the beam line up to the S1 area now. It consists of large acceptance quadrupole triplets made of MIC as a front-end in the vicinity of the muon target, four sets of normal quadrupole triplet magnets, three sets of bending magnets and an electrical kicker system, associated with a set of 250 kV DC separator [11]. Recently, we managed to complete the installation of a power supply yard with four floors, two users cabins, a dedicated catswalk, and beam line shielding blocks. We are planning to complete the installation of the key components of the S-Line, for the beam commissioning in the coming summer of 2014.

6. H-Line
The fourth muon beam line, the so-called H-line, was designed to extract muons or positrons (electrons) up to 120 MeV/c, for fundamental physics such as experiments on the precise Mu hyperfine measurement, muon-electron conversion experiment, or g-2/EDM experiment. Its front-end components such as large acceptance solenoid magnets, HS1 and HS2 made of MIC, and a bending magnet HB1 were installed in the vicinity of the muon target, where radiation is very high in the order of several mSv/h to Sv/h [12].

7. Summary
Although the whole J-PARC MUSE operation had to be shut down due to not only the Higashi-Nippon Dai-Shinsai but also the radioactive materials leakage accident at the Hadron Hall Experimental Facility, finally we restarted users run at the D-Line on February, 2014.

We completed the installation of the U-line, which consists of a large acceptance solenoid made of mineral insulation cables (MIC) and a superconducting curved transport solenoid and 6 sets of superconducting axial focusing magnets. There, we managed to extract the world’s highest intensity pulsed muons, 2,500,000 muons per pulse ($6.4 \times 10^7$/s) at 212 kW, for the intense ultra slow muon source.

We are planning to complete the installation of the key components of the S-Line, for the beam commissioning in the coming summer of 2014.

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