J-PARC Decay Muon Channel Construction Status

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Abstract. The new Muon Science Facility (MUSE) that is now under construction at J-PARC in the Materials and Life Science Facility (MLF) building will comprise four types of muon channels. In the first stage, a conventional superconducting decay muon channel (D-Line) was constructed, which can extract surface (positive) muons with an expected muon yield of $10^7$/s and decay positive/negative muons up to 120 MeV/c, with an expected muon yield of a few $10^6$/s at 60 MeV/c for both positive and negative muons. This channel will be used for various kinds of muon experiments like $\mu$SR, muon catalyzed fusion and nondestructive elements analysis.

1. Introduction
The new Muon Science Facility (MUSE) \cite{1} is now under construction at J-PARC (Japan Proton Accelerator Research Complex) at the Tokai campus of JAEA (Japan Atomic Energy Agency) in the Materials and Life Science Facility (MLF) building under the collaboration between KEK and JAEA. In the J-PARC project, the 3-GeV $333-\mu$A-proton beam from the rapid cycling synchrotron (RCS) will be transported from the RCS ring to the neutron source situated in the MLF building. There, in the M2 primary proton beamline (M2 tunnel), just 33 m upstream of the neutron source, the muon target made of a 2-cm-thick graphite disc for the production of intense pulsed pion and muon beams is located. To make use of the full potential of this new facility, four dedicated muon channels will be constructed. In the MLF building, the...

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experimental area is divided into two parts across the primary proton beamline, namely the experimental hall No. 1 (East) and the experimental hall No. 2 (West). The four secondary muon channels that are originating from the muon target in the M2 tunnel are the surface muon channel (S-line) and the high-momentum muon channel (H-line) in the experimental hall No. 1, and the superconducting decay muon channel (D-line) and the ultra-slow muon channel (U-line) in the experimental hall No. 2. At present, only the D-Line is under construction. The other three secondary muon channels were temporarily closed with iron shields and concrete blocks.

This report gives a brief overview of the D-line design and construction, including the superconducting solenoid, the vacuum system, the interlock system and the experimental areas. A previous report was published in [2]. The new muon profile monitor used in the beam commissioning and tuning is also described.

2. Superconducting Decay Muon Channel

The layout of the D-Line in the experimental hall No. 2 of the MLF building is shown in Fig. 1. It consists of three parts: (1) a pion injection, (2) a superconducting decay solenoid, and (3) a muon extraction. Two experimental areas are planned for simultaneous use. This conventional superconducting decay muon channel can extract surface (positive) muons with an expected muon yield of a few $10^7$/s and decay positive/negative muons up to 120 MeV/c, with an expected muon yield of a few $10^6$/s at 60 MeV/c for both positive and negative muons. The overall transport efficiency is estimated by TURTLE. This channel will be used for various kinds of muon experiments like $\mu$SR, muon catalyzed fusion and nondestructive elements analysis.

(1) Pion injection: A quadrupole triplet (DQ1-2-3) is placed at a position of 65 cm from the graphite target, which can accept pions in a solid angle of 65 msr. The following bending magnet (DB1) transports pions to the solenoid up to 250 MeV/c at maximum. Therefore kaon decay muon from the target can also be extracted by upgrading the muon extraction to 250 MeV/c. The coils of the quadrupole triplet and the bending magnet are made by MIC for the hard radiation environment. The magnets are directly installed in the M2 primary proton beamline.

(2) Superconducting decay solenoid: To obtain a high intensity decay muon beam, a superconducting solenoid magnet (DSOL) is employed for the pion to muon decay section. The basic design is similar to those used in the muon beamlines at KEK-MSL, TRIUMF and RIKEN-RAL. The decay solenoid consists of twelve units of superconducting coils with 6 cm in bore radius and 50 cm in length. The applied magnetic field is 5 T. The pions and muons are confined within a radius of 5 cm and therefore transported without any significant loss. The old solenoid that was used at KEK-MSL has been modified for this purpose. The magnet coil is forced-indirectly cooled by a supercritical helium gas supplied from an on-line helium refrigeration system. To achieve the muon extraction at low momentum, this cold bore magnet is directly connected to the muon beamline using only thin thermal insulating aluminum foils of 12.5 $\mu$m thick at the entrance and exit of the superconducting solenoid magnet, respectively. An insertion device has been developed for the installation of the superconducting solenoid, because it is set between the M2 tunnel and the experimental hall, as shown in Fig. 1. Two sets of linear guide were adopted for the horizontal transport motion to keep good reproducibility. Six iron blocks, with a total weight of about 50 tons, are also set on the insertion device for the radiation protection from the M2 primary beamline.

(3) Muon extraction: The extraction can transport muons up to 120 MeV/c. A magnetic kicker will be installed in a near future for single-pulse experiments and simultaneous use by the two experimental areas. The major components of the old decay muon channel at KEK-MSL, such as the bending magnets, the quadrupole magnets and the DC separator are being re-used. Three Q-triplets (DQ4-5-6, DQ7-8-9 and DQ13-14-15) and two bending magnets (DB2 and DB3) are used to transport the muon beam to the experimental area D2. The D1-leg at the downstream of DB3 that leads to the experimental area D1, which is equipped with two
Figure 1. Layout of the decay muon channel in the experimental hall No. 2 of the MLF building (left) and a picture showing the D-Line under construction (right).

Q-triplets (DQ10-11-12 and DQ16-17-18) and a beam-slicing kicker, is constructed by JAEA [3]. All of the magnets in the experimental hall, except those prepared by JAEA, were formerly used at KEK-MSL in Tsukuba. After refurbishment and modification, the magnets are now successfully installed on the D-line. The magnetic poles of both DB2 and DB3, which are made of SS400, were newly fabricated. In particular, the magnetic pole of DB3 was designed so that replacement with a septum magnet in a near future can be easily conducted. The field mapping of both bending magnets was examined after reassembling, resulting that the uniformity of BL integration is less than 2% for DB2 and 5% for DB3, respectively. The assembled Q-triplet, which shares a common star-shaped beam duct, was designed in view of handling by crane operation. The magnets are settled on a common support and placed on a pre-aligned base plate, so that the assemblies can be remotely installed and uninstalled. When placing the triplet magnets, they are guided and precisely positioned using pivots, which are secured on the base plate, in a similar manner to that of the M2 primary beamline magnets.

3. Superconducting Solenoid Refrigeration System

The solenoid magnet coil is forced-indirectly cooled by a supercritical He gas (4.8K at 1.0 MPa) supplied from an on-line helium refrigeration system (TCF 50) for the long-term stable operation. A 80 K copper thermal shield is positioned between the 6 K shield tube and the warm iron cryostat vessel. The 6 K and 80 K thermal shields are supported by insulation rods extending from the cryostat wall. The 80 K shield is cooled by the He gas taken from the intermediate heat exchanger in the cold box.

The helium refrigeration system consists principally of the followings: (1) a He buffer tank (20 m³, 0.95 MPaG), (2) a cooling tower and a water cooling pump, (3) a helium gas screw compressor (Kaeser), (4) an after cooler, (5) an oil separator, (6) load, unload and bypass
valves, (7) a cold box, (8) a VME based digital control device, (9) a PC system for control and data logging, and (10) a cryo panel for safety interlock control.

The screw compressor supplies high-pressure He gas (0.85 MPa) to the cold box. The cold box is designed to supply various types of He requested to the superconducting solenoid. Before the cooling down procedure from the room temperature is commenced, the oxygen concentration of the circulating He gas is reduced to be less than 50 ppm by the operating He gas purifier.

The cooling power is 35 W at 4.5K and 200W at 80K, and it can produce 8 l/h of liquid He. The whole system is monitored and controlled by a VME controller combined with a personal computer with dedicated software based on the LabVIEW system, and cools down automatically. The typical cooling period from the room temperature to the operating temperature (∼4 K) is about 4 days. The long-term (3 months) operation is established under quite stable condition.

To protect against any serious damage to the superconducting coils and the He refrigeration system, a VME based interlock system is installed. The system can detect any anomaly in the voltage of the superconducting solenoid, the power lead temperature and the trip signal from the He refrigeration system. Once any emergency status is detected, the electric power supply immediately stops the current supply and the refrigeration system changes to self-operation mode. This system can also record the temperatures and pressures of the superconducting coils, the cryostat and the power leads.

4. Vacuum System
The block diagram of the vacuum system of the decay muon channel is shown in Fig. 2. The vacuum system of the secondary beam channel is isolated from the primary proton beamline by an all-metal gate valve (DGV1: VAT 48146) with a 50 μm-thick Kapton beam window protected

Figure 2. Vacuum system diagram of the decay muon channel.

Figure 3. Area entry system diagram (top), and view of the area entry door (bottom).
a bypass. The beam channel is divided into four sections, separated by three gate valves (DGV2, DGV3-1, and DGV3-2; VAT 12150). Each of the sections is separately operated by using turbo molecular pumps with a pumping speed of 0.5 m³/s. It is noted that the section including the superconducting solenoid should have a separate vacuum system from a viewpoint of operation of the cryogenic system. Particularly, in the event of a quench of superconductivity, tritium gas absorbed through the bypass during the beam time is released due to the temperature raise. Therefore, the exhaust must be led to a vent stack without passing through the other pumping stations. The achieved pressure of the beam channel has been typically $\sim 1 \times 10^{-4}$ Pa. At the moment, the vacuum chamber of the DC separator (DSEP) is directly connected to the beamline. However, in order to prevent the high-voltage gap from vacuum discharging, it is designed to control pressure independently by inserting beam foils at both sides of the chamber.

A fast closing valve (DFCV; VAT 75046) is installed at the downstream of DGV2 to protect the vacuum of the primary beamline in the event of a sudden vacuum loss. Two FV-type pressure sensors are attached on each side of two beam legs, which respond in 1 ms to close DFCV. If closing of DFCV is detected, DGV2 is also automatically closed. In the case that either of the two experimental areas is in a maintenance condition, the corresponding pressure sensor is turned off depending on the states of DGV3-1 or DGV3-2. At both ends of the beamlines, there are beam foil windows made of Mylar or Kapton with a thickness of 100 µm. The pressure readouts and the open/close status of the gate valves are monitored at the MLF control room through the MELSEC network.

![Figure 4. The D-line experimental areas and the cabin in the experimental hall No.2 of the MLF building (top left). Detailed view of the experimental area D1 (top right), the area D2 (bottom left), and the counting room inside the cabin (bottom right).]
5. Interlock System

To ensure a safe operation of the facility, a number of safety systems have been incorporated into the interlock system. For example, to prevent users from being exposed to excess dosage of radiation, the entry to experimental areas is strictly controlled. In addition, proper and safe operation of the machines is also necessary. To ensure this, all the muon experimental instruments are controlled by means of the Muon Control System. Its purpose is to control and monitor the safe operation of all the muon instruments. In particular, the personal protection system (PPS) is in place to prevent personnel from being exposed to high levels of radiation, and is the highest priority interlock system at J-PARC. The Muon Control System is related to the operation of the muon target, the D-line and the D1, respectively D2, experimental area entry system. In particular, the experimental area entry system is categorized in the PPS system. All these components worked successfully on Day 1.

The experimental area entry system diagram is shown in Fig. 3 (top). In this system, several status of the PPS related components are being watched. For example, the status of the beam blockers are monitored, which is important to ensure the safety of the personnel. When the muon blocker is opened or the DB3 magnet, which acts as a switching magnet, is turned on, the PPS controller does not allow the area entry door to be opened. This logic guarantees the safety operation for the experimenter. Figure 3 (bottom) shows a view of the area entry door with the muon blocker controller (up) and the door controller (down). The blocker controller has five keys. Four keys are used as personal keys. If all the keys are not back to the muon blocker controller, one cannot lock the experimental area door. The operation of the muon blocker can be performed from this muon blocker controller. This system is common with the neutron shutter control system. The following procedure is necessary to enter an experimental area. An experimenter needs first to turn off the switching magnet and close the muon blocker. Then he moves a key from the blocker controller to the door controller and unlock the door. The area entry door can now be opened.

6. Experimental Areas and Cabin

The decay muon channel is divided into two legs after the bending magnet DB3 (see Fig. 1), each leg leading to an experimental area, D1 and D2, respectively. Between the two experimental areas, a cabin was installed to house the electronics room and the counting room. Pictures representing the two experimental areas and the cabin including detailed views of the experimental area D1, the experimental area D2 and the interior of the cabin are shown in Fig. 4. The experimental area D1 is occupied with a beam slicer with slits, a quadrupole magnet triplet and a $\mu$SR spectrometer for $\mu$SR experiments. A more detailed description of this $\mu$SR experimental apparatus is reported in these proceedings [3]. The experimental area D2 is presently used for commissioning and beam optics tuning. Each experimental area is equipped with electrical power outlets (AC 100V, 200V and 420V) and cooling water supply. In the future pressurized air, helium recovery line and exhaust line will also be installed. The cabin is divided into two parts, the electronics room and the counting room, respectively. The electronics room is air-conditioned and equipped with five 19-inch rack for the electronics modules of the data taking system. This cabin will be used by users who perform experiments at either one of the experimental areas.

7. Beam Tuning

A new muon beam profile monitor (MBPM) was constructed for the commissioning of the decay muon channel and the beam optics tuning. The objective for the design of this new beam profile monitor was similar to that developed at RIKEN-RAL with Dr. K. Ishida [4], that is to be able to obtain both horizontal and vertical beam profiles simultaneously using surface muons ($\mu^+$), which have a momentum of only 27 MeV/c. At this energy, the range of a muon in a
scintillator (NE-102) is only about 1 mm. This profile monitor should also be able to operate with pulsed beams and reject positron or electron contamination in the muon beam. Finally, it should work with high-intensity surface muon beams as well as with low-intensity backward decay muon ($\mu^+$/µ$^-$) beams.
The schematic view of the beam profile monitor is shown in Fig. 5. Each axis comprises fifteen (15) scintillators (4-mm wide and 0.5-mm thick, with 10-mm steps) mounted on a light guide and connected each with seven φ1-mm optical fibers to a multianode (4x4) photomultiplier (Hamamatsu type H6568-200-10MOD). Each scintillator is wrapped with two layers of 6-µm-thick Aluminum-Mylar. In addition, the front and the back of the central area are also covered with an additional layer. This proved to be sufficient to reduce light leaks to an acceptable level without significantly slowing down the incoming muons. Each photomultiplier output was sent to a charge ADC (LeCroy model 2249W) with a time gate of 200 ns to be digitized. The same data acquisition program used at RIKEN-RAL that is based on EXP2K and modified by Dr. K. Ishida for the use of the MBPM was used to process the data and fill the histograms. A picture of the new muon beam profile monitor is shown in Fig. 6.

As an example of the performance of this beam profile monitor, the horizontal and vertical muon beam profiles obtained with surface muons at the experimental area D1 for different DB3 bending magnet settings are shown in Fig. 7. Each profile can be obtained with just 1000 spills or about 40 seconds at 25Hz beam operation. Figure 8 shows the different beam profile parameters that are generated automatically after each profile is completed. This graphical interface was found to be very useful in rapid visualization of the response of the beam to each magnet and for optimization of the beamline parameters.

In the future, the three slit box that are used along the D-line to select the muon beam momentum and control the muon beam size will also have a compact muon beam profile monitor just behind the slits for beam optics tuning purposes. Until now, the muon beam tuning has only been performed at the end of a muon channel by looking at the total muon intensity or by measuring the muon beam profile. A vacuum version of this new MBPM using multianode PMT’s and optical fibers is now under consideration.

8. Concluding Remarks
At the end of the commissioning beam time of the experimental area D1 in December 2008, the muon beam profile shown in Fig. 9 was obtained. The figure on the left represents the beam profile measured with the new muon beam profile monitor, and the one on the right the profile measured with an imaging plate. The beam tuning is still not completely optimized yet, and the intensity is somewhat lower than expected. Further beam tuning is scheduled to optimize the beam transport efficiency as the beam power of the primary proton beam is gradually increased.

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