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J-PARC Muon Facility, MUSE

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Abstract. The muon science facility (MUSE, abbreviation of MUon Science Establishment), along with the neutron, hadron, and neutrino facilities, is one of the experimental areas of the J-PARC project, which was approved for construction in a period from 2001 to 2008. 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. Construction of the MLF building was started in the beginning of 2004, and was completed at the end of the 2006 fiscal year. For Phase 1, we managed to install one super-conducting decay/surface muon channel with a modest-acceptance (about 45 mSr) pion injector in the summer of 2008. Finally, on September 19th, 2008, the 20 mm thick edge-cooled, non-rotating graphite target, which is surrounded by a copper frame, was, for the first time, placed into the 3GeV proton beam obtained from the rapid cycling synchrotron (RCS). The nuclear reactions between the 3 GeV proton beam and the nucleus of carbon produce both positively (π^+) and negatively (π^-) charged pions. On September 26th, 2008, we finally succeeded to extract "surface muons (μ^+)", which are obtained from the decay of π^+ near the surface of the pion production target in the proton beam line. First, we commissioned the secondary muon beam line optics by tuning the superconducting magnet, the quadrupole and bending magnets, and the DC separator in order to optimize the transport of the surface muon beam and to eliminate the e^+ contamination. Then, on December 25th, 2008, we also succeeded in the extraction of the "decay muons (μ^+/μ^-)", which are obtained through the in-flight decay of π^+/π^-.

1. Introduction

The J-PARC (Japan Proton Accelerator Research Complex) has been constructed in the south part of the Tokai-JAEA (Japan Atomic Energy Agency) site, and consists of a 181 MeV LINAC

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(400 MeV in future), as well as a 3 GeV and a 50 GeV proton synchrotron rings. About 90% of the 3 GeV, 333 μA (1 MW) beam is sent to the MLF for the production of intense pulsed neutron and muon beams, while the remaining 10% will be sent to the 50 GeV ring for further acceleration for the kaon and neutrino physics programs [1].

2. Structure of the MLF Building and the NM tunnel

The MLF consists of the proton beamline tunnel (so called NM tunnel), and two wings for the experimental halls (east wing; Experimental hall No.1, west wing; Experimental hall No.2). The tunnel structure is designed to keep radioactive materials inside the tunnel, considering the safety of operations during maintenance work on the neutron target or muon target. The height of the building is 31 m for the tunnel and 21 m for the experimental halls. The width of the tunnel is 13.5 m, and the east and west wings are 24.5 m and 32 m wide, respectively. The proton beam height is 1.6 m from the floor level. The muon science facility is 30 m long along the proton beamline, and is located upstream of the neutron facility. Figure 1 shows a schematic drawing of the first floor of the MLF building. The proton beamline in the MLF building consists of the M1 line and M2 line regions. The M1 line is located upstream of the muon target, where no significant beam loss occurs. On the other hand, the M2 line is in the vicinity of the muon target where severe beam loss occurs due to the surrounding beamline components. Since a certain fraction of the primary 3 GeV proton beam is scattered preferentially downstream toward the neutron target, two sets of scrapers are installed to prevent severe damage to the beamline components such as quadrupole magnets, beam ducts etc. Although some of the scattered beam is deposited on the scrapers, the various beamline components such as the quadrupole magnets, target chamber, scraper chamber, pillow-seal, vacuum ducts etc. located along both the primary and secondary beamline will suffer not only from tremendously high radiation, but also from corrosion induced by NO_x in irradiated air. Therefore, in the M2 beamline, all of the maintenance work, including power and water connections, is intended to be done remotely from the top of the maintenance area, which is at a level of 4 m from the floor, following the lessons learned from PSI which has been dealing with a 1 MW-class proton beam [4]. Construction of the MLF building was started in the beginning of 2004, and was completed in the end of the 2006 fiscal year[2, 3].

3. Installation of the M2 line beam line components

In the M2 beamline, all beam line components must be installed via remote handling from the maintenance area above (FL 4 m). For that purpose, we installed baseplates with a precision of XY $\pm$ 0.5 mm on the floor of 0.5 m FL, and then we placed the alignment plates matching to the individual beam line components with a precision of XY $\pm$ 0.1 mm, Z $\pm$ 0.1 mm. Iron guide shields equipped with a guiding rail structure were aligned by placing knock pins on the alignment plates. The target chamber, the various beamline magnets (M2 primary line; six quadrupole magnets QM1, QM2, QN1, QN2, QN3, QN4 and four steering magnets, X22, Y22, X23, and Y23 and secondary line; DQ-1-3 , SQ 1-3 triplet magnets, DB1 and SB1 bending magnets), two sets of profile monitor assemblies, 20 sets of pillowseal assemblies, a gate valve assembly and seven sets of duct assemblies were also installed on the alignment plates equipped with the knock pins, which allow precise positioning, guided by the guide shields. The power and control cables are then connected between the magnets on the M2 line and the corresponding power supplies. Finally, a successful test was performed on the magnets on the M2 line by running them continuously for 12 hours. In addition, after completion of the vacuum connection, the ultimate vacuum achieved was as low as 3×10^{-5} Pa. All the beam line components in the M2 tunnel were successfully demonstrated to function properly, delivering the 3 GeV proton beam from the muon target to the neutron source as expected during the period from first proton beam injected into MLF on May 30th, 2008, to the following commissioning period.

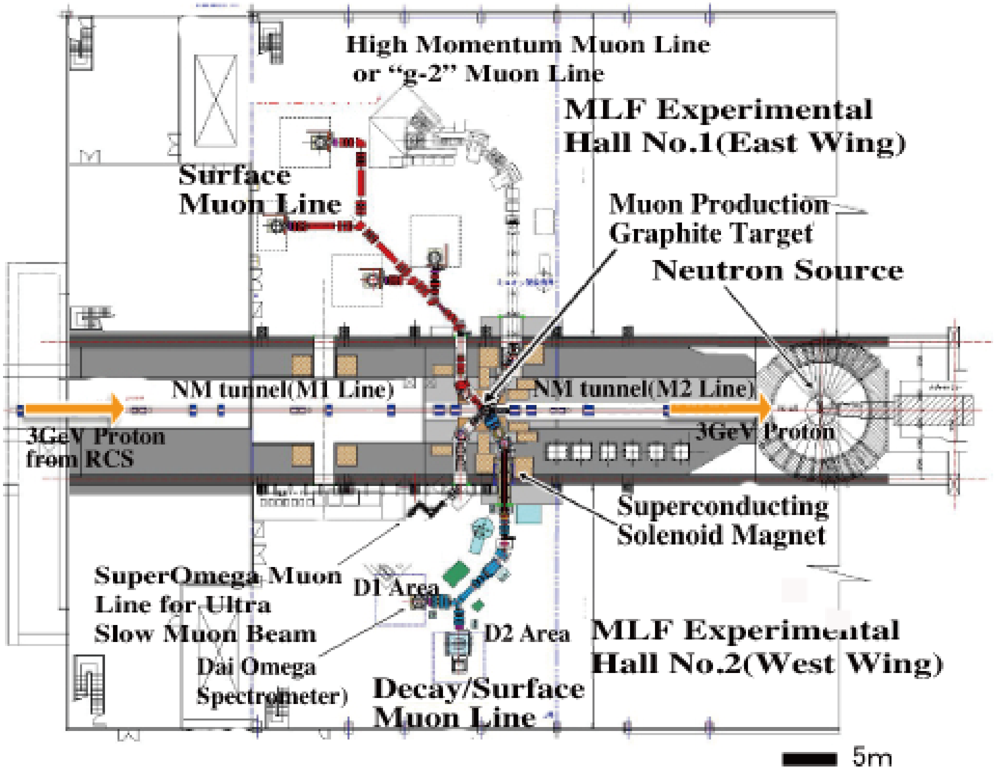

Figure 1. A schematic drawing of the MUSE facility located on the first floor of the MLF building.

4. The Muon Science facility with tandem-type production graphite target

The 3 GeV, 1 MW, 25 Hz proton beam from the RCS synchrotron is transported through the beam transport line (so called 3NBT line) over a distance of about 300 m and focused onto the 24 mm diameter muon target with a spot size that is as small as possible.

First of all, we had to make an important decision whether we should adopt having either a tandem-type target like PSI or RAL, or having a dedicated facility with our own beam dump like KEK-MSL. Finally, in order to stay within the total budget of the project utilizing the common use of the utilities and to avoid the severe beam dump construction costs associated with a tritium water handling facility with high concentration, and also from the viewpoint of the beam sharing with the neutron facility, we decided to construct the muon facility with the tandem-target configuration. The next important issue was how thick a graphite target could be installed in the proton beamline located upstream of the neutron source, causing a beam loss to some extent. After a long discussion and negotiation with the neutron science group, we reached an agreement that the total beam loss induced by the muon production targets should be no more than 10 %. Consequently, we made a basic design of MUSE, consisting of 10 mm and 20 mm thick graphite targets, corresponding to a beam loss of 3.5 % and 6.5 %, respectively, for the pion and muon production upstream of the neutron target, rather than constructing a separate building with our own proton (1 MW) beam dump.

For phase 1, we installed one graphite target with a thickness of 20 mm, from which four sets of the secondary lines can be expected to be built in the experimental hall. It is possible that one line will be used for the decay muon channel, one for high momentum muon channel and two for surface muon channels. In order to satisfy the requirements for the inlet and outlet of the primary 3 GeV line and 4 sets of the secondary lines, we fabricated a specialized target and scraper chamber. In our design concept, taking into account the ease of remote handling during maintenance work, the two sets of scrapers and muon production target are contained in one large vacuum chamber. All the water and cable connections are done at the top in the maintenance area. Consideration was given to the means of mounting the target, how to move and insert the target with the required precision, cooling, monitoring, and changing the target in the hot-cell.

5. Phase 1 of the MUSE

For Phase 1, we installed one super-conducting decay/surface muon channel with a modest-acceptance (about 45 mSr) pion injector. Details of the super-conducting decay/surface muon channel are reported by Strasser et al.[5] in this proceedings.

On September 19th, the 20 mm thick edge-cooled non-rotating graphite target, which is surrounded by a copper frame, was, for the first time, placed into the 3 GeV proton beam from the rapid cycling synchrotron (RCS). The nuclear reactions between the 3 GeV proton beam and the nucleus of carbon produce both positively (π^+) and negatively (π^-) charged pions.

5.1. Beam tuning

At first, we tried to extract a surface muon beam (positive muons) into the D1 area. In order to detect muons, we used two kinds of muon counters. The thinner counter (0.5 mm thick) was placed upstream to detect not only muons, but also positrons having the same momentum as the muons. The thicker (6 mm) counter was placed downstream, where surface muons did not pass through the first counter. Fig.2 shows the first observation of the timing signals in the oscilloscope. The earlier peak corresponds to positrons having the same momentum as the surface muons (having almost the light speed), and the delayed peak corresponds to the surface muons (having 1/4 of the light speed). By optimizing the DC separator, which is a static E $\times$ B filter, the positron contamination was removed. Practically, beam tuning has been done with use of a beam profiler, which is a two dimensional scintillator array (15 $\times$ 15). With use of the beam profiler, optimization of the beam size, timing, slits, and backgrounds, as well as the settings of the magnets along the secondary beam line, has been performed. These magnets include the pion injection magnets, the superconducting magnet, and the muon extraction magnets.

After the beam tuning, we are able to extract, at present, a surface muon (μ^+) rate of 1.1 $\times$ 10^7/s and a decay μ^+ rate of 2 $\times$ 10^6/s at 40 MeV/c and up to 10^7/s at 90 MeV/c, with a beam size of 50 mm in diameter. These rates are normalized to the intensity of the future 1 MW proton beam intensity, although the current intensity is only about 20 kW. These intensities, at the future 1 MW operation, will correspond to more than ten times those at the RIKEN/RAL Muon facility [6].

5.2. μSR experiments at the D1 area

A μSR spectrometer called DAI-OMEGA was placed at the D1 area. It consists of 64 $\times$ 2 forward and 64 $\times$ 2 backward scintillation counters, and is equipped with TF coils (up to 200 G), LF coils (up to 1.5 kG), and correction coils. Programming and adjustment of the DAQ (Data AcQuisition) system were done, as well as adjustment of the coincident timing between telescopes.

In front of a live audience, we demonstrated a μSR asymmetry measurement under a weak transverse magnetic field, adopting an aluminum plate as a sample, with use of the DAI-OMEGA spectrometer. Fig. 3 shows the first μSR asymmetry spectrum witnessed by the audience of about one hundred people. Afterwards, together with the audience, we celebrated the extraction

Figure 2. The first muon timing signals obtained in the oscilloscope.

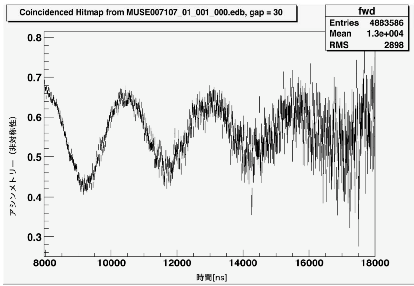

Figure 3. The first μ SR asymmetry spectrum of the aluminum target.

of the first muon beam. Fig. 4 shows a picture celebrating the first muon beam production at J-PARC MUSE.

We have already had more than ten users' runs. Among them, it is our great honor that Takeshita et al. already published a paper demonstrating the presence of a macroscopic phase separation between the superconducting and magnetic phases in Co-doped Iron Pnictide $CaFe_{1_x}Co_xAsF$, utilizing the MUSE facility[7].

5.3. Decay Muon Beam Extraction

On December 25th, 2008, we also succeeded in the extraction of the decay muons which are obtained through the in-flight decay of π^+/π^-, confined by a strong longitudinal field, which can be obtained by the superconducting magnet excited with a full specification of 600 A, corresponding to 6 tesla. As a demonstration of extracting a negatively charged muon beam, we did a trial of the non-destructive analysis of the Tempo-Koban (gold coin in Edo period), by measuring the characteristic muonic X-rays from Au and Ag. Details are shown by Ninomiya et al. in this proceedings [8].

6. Phase 2 of the MUSE

In addition to Phase 1, we are planning to install one surface muon channel with a modest-acceptance (about 50 mSr) and either a high momentum muon beam channel or a dedicated muon channel for the "g-2" experiment in the MLF experimental hall No. 1, and one super omega muon channel with a large acceptance of 400 mSr for the study of thin film magnetism or negative muon physics in the MLF experimental hall No. 2. In the case of the surface muon channel, we can expect a total of 1.6×10^7 surface μ^+/s with the 1 MW proton beam. By installing a kicker and beam slicer, we are planning to place four experimental ports. In the case of the super omega beam channel, we are going to install a large acceptance solenoid made of mineral insulation cables (MIC) and a superconducting curved transport solenoid. We can collect either surface or cloud muons with a large acceptance of 400 mSr. Finally, we are expecting 4×10^8 surface μ^+/s and 10^7 cloud μ^-/s in the MLF experimental hall No. 2 [9]. Although many of these studies can be performed using either surface or decay muons, at the super omega channel we are aiming to create a new type of muon source: an intense ultra-slow muon source. Slow muons are generated through resonant ionization of muonium (Mu). Mu

Figure 4. A picture celebrating the first muon beam production at J-PARC MUSE.

is formed by stopping an intense surface muon beam on the rear surface of a hot W foil. At the RIKEN/RAL muon facility, 20 slow μ^+/s are obtained out of 1.2 $\times$ 10^6 surface muons/s [10]. Taking into account the repetition rate of the pulsed laser system and the proton beam, as well as the surface muon ratio between RIKEN-RAL and J-PARC MUSE, we can expect 1.3 $\times$ 10^4 slow μ^+/s without any additional laser development. A rate of 1.3 $\times$ 10^6 slow μ^+/s can be achieved with additional laser development, such as the tripling of 366 nm photons with pico second pulse width to match the Doppler broadening of the Mu at 2000 K. When the production of this intense ultra-slow muon beam is realized, the use of its short-range penetration depth will allow muon science to be expanded towards a variety of new scientific fields, such as:

(i) Surface/boundary magnetism utilizing its spin polarization and unique time-window,
(ii) Surface chemistry, utilizing a feature of a light isotope of hydrogen; such as catalysis reactions,
(iii) Precise atomic physics such as QED (Quantum Electro Dynamics) and
(iv) Low emittance ion sources and further acceleration towards μ^+ μ^- collider experiments in high-energy physics.

7. Summary

Construction of the MLF building, as well as the fabrication and installation of various proton beam line components such as magnets, the muon target, scrapers, shields, monitors, and vacuum components, were completed in 2007, as scheduled. Finally, we succeeded in the extraction of a "surface muon (μ^+)" beam on September 26th, 2008. We also succeeded in the extraction of a "decay muon (μ^+/μ^-)" beam, which is obtained through the in-flight decay of π^+/π^-, on December 25th, 2008.

We have been accepting user's programs open to the world since January, 2009.

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