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H line; a beam line for fundamental physics study

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Abstract. The muon facility, J-PARC (Muon Science Establishment; MUSE), has been operating since the first beam in 2008. Starting with a 200 kW proton beam, a beam intensity of 3×10^6 muons/s was reached in 2009 which was the most intense pulsed muon beam in the world. From the 2 cm thick graphite target, four secondary muon beam lines are designed to be extracted. Three beam lines currently exist, the first being operational and the other two undergoing commissioning. The fourth and the last beam line, the H line, is planned to be constructed. This new beam line is designed to have a large acceptance, provides the ability to tune the momentum, and use a kicker magnet and/or a Wien filter. The H line is designed to provide an intense beam of 10^8 surface muons/s for fundamental physics studies to observe new physics beyond the standard model. Such studies require high statistics and they need to occupy the experimental areas for a relatively long period.

1. Introduction

The Japan Proton Accelerator Research Complex (J-PARC) project was proposed jointly by Japan Atomic Energy Agency (JAEA) and High Energy Accelerator Research Organization (KEK) [1]. J-PARC consists of a 400 MeV linac, 3 GeV and 50 GeV synchrotron rings, which provide an intense proton beam to pursue particle and nuclear physics, materials and life science and nuclear technology. A 1 MW proton beam is transported from the 3 GeV synchrotron ring to Materials and Life Science Facility (MLF) which consists of the muon and the spallation neutron facilities, MUSE and JSNS. As shown in Fig. 1 and 2, the proton-beam-line tunnel runs through the center of MLF building from the north to the south. The east and the west wings are experimental halls where neutron and muon beam lines are constructed. In order to avoid the diffusion of radioactive contamination generated around the muon target chamber and along the proton beam transport tunnel, the proton-beam transport tunnel is isolated from the experimental halls dividing the MLF building into east and west wings. This building structure achieved its purpose to confine the contamination and contributed to making the radiation-shield structure simple. However, the severe geometrical constraint which was put on the design of the secondary beam required the number and the directions of muon beam lines to be fixed at the primary stage of the building design.

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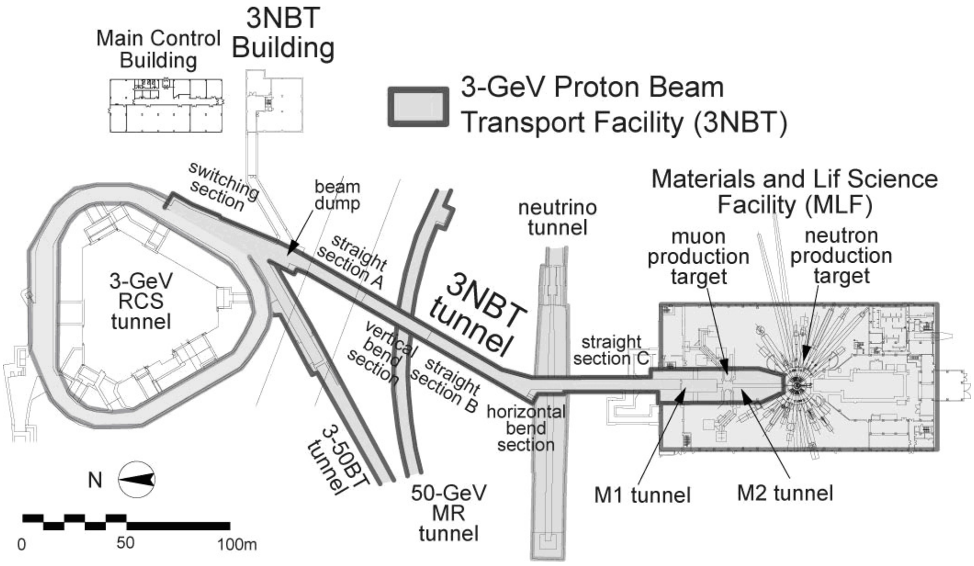

Figure 1. A schematic drawing from 3 GeV rapid cycling synchrotron (RCS) to MLF.

The muon-production target is inserted at about 30 m upstream of the neutron target in the proton beam line. From the muon target, we decided to extract four muon beam lines. Each of them provides the intense pulsed muon beam with an individual design concept to be used for a variety of muon science experiments. Two of the secondary beam lines are extracted at the angle of 60 degrees to the proton beam line, and the others are at 135 degrees [2].

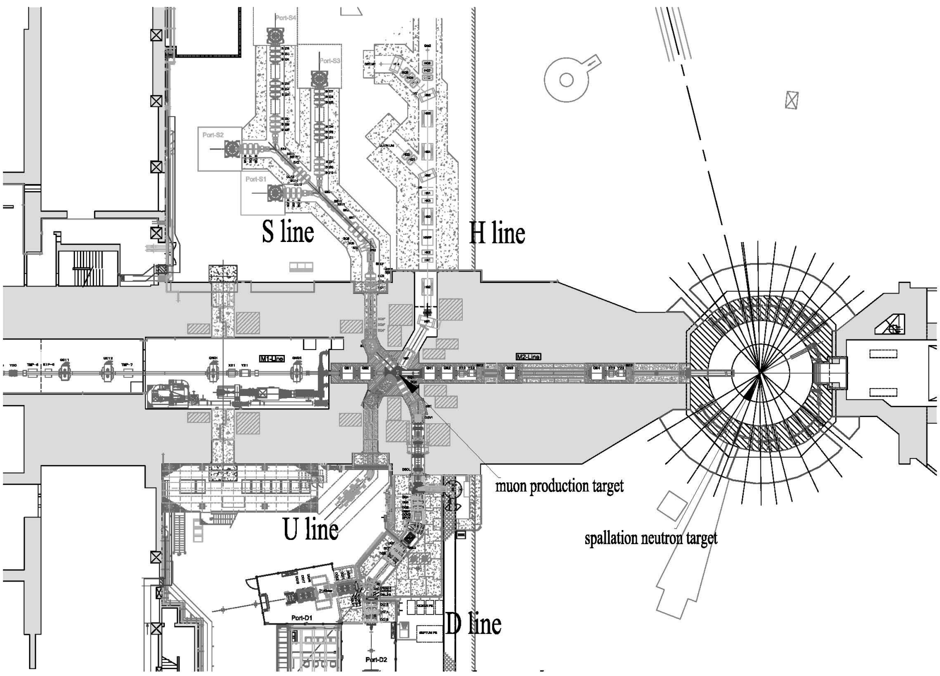

Figure 2. The layout plan of MUSE.

The decay muon beam line (D line) was constructed first, and this is the only beam line under operation. The D line extracts both negative and positive decay muons up to a momentum of 120 MeV/c, as well as 30-MeV/c surface and cloud muons [3]. The ability of wide-range momentum-tuning answers a variety of user's programs. The second beam line, the U line, provides the most intense surface-muon beam among the four secondary lines [4] and will be used to generate an ultra-slow muon beam by the laser resonant ionization method [5]. It is currently under commissioning. The remaining two beam lines, the S and the H line, are located in the east experimental hall. The S line, dedicated to μSR spectroscopy, is designed to distribute the surface muon pulses to several experimental areas simultaneously by using kicker devices. The first beam is planned to be delivered in 2014.

A typical period of an experiment in the field of material science is a few days to obtain enough statistics for μSR spectrum of sample materials. Therefore, a study requiring much higher statistics [6, 7, 8] does not match the design of the existing S, D and U lines. The fourth beam line, the H line, aims to answer the demands for these fundamental physics studies that need high statistics, *i.e.* the use of a high intensity beam for a long periods, typically more than one year.

2. Muon Source

The intense pulsed muon beam is produced by a 3-GeV proton beam injected to the target made of 20 mm thick isotropic graphite [9]. About 5% of proton beam is consumed at the target to produce pions. A surface muon is produced when a positive pion is stopped near the surface inside the production target and a muon, whereas a decay beam is produced when positive or negative pions decay in flight along the beamline.

The surface muon intensity can be estimated from the number of pions stopped near the surface. Calculation was performed utilizing the measured data on pion production cross sections [10] followed by tracking of the pions with GEANT 3.21. By integrating the generator equation for various angles and for pion energies, the total cross section for pion production is about 90 mb, generating about 0.016 per a 3-GeV proton passing through the 2-cm (3.6 g/cm^2) graphite target. Thus, 3.2×10^{13} pions/s are estimated to be generated from 1 MW (333μA) proton beam. Taking into account the emitting angle and energy distribution of the pions, 7.4×10^9 pions/s are simulated to be stopped in 0.1 mm from the target surface and in a diameter of 24 mm which corresponds with the proton beam spot size on the target.

The details of the H line is described in the sections below. Starting from a source distribution of 24 mm in diameter, about 90% of the beam transmission efficiency is able to be achieved for the muons plunging into the H line of which solid angle is about 120 mstr. This transmission efficiency is almost constant for the beam with the momentum range of $\pm 5\%$ from the central momentum so that a beam in the range 27.0 to 29.8 MeV/c, can be transported with the efficiency of 90%. The momentum spread of the surface muon reflects the generated depth from the target surface of the pion stopping position. A muon generated at 0.2 mm in depth has 27.0 MeV/c. Taking into account the effective depth to the H line extracted at 60 degrees 15×10^9 pions/s contribute to generate the surface muons. The overall beam intensity in the H line is then evaluated to be $15 \times 10^9 \times 120 \times 10^{-3}/4\pi \times 0.9 = 1.2 \times 10^8$ muons/s. Assuming that the efficiency of the final focusing part is 80%, 1×10^8 muons can be available in the experimental area.

3. Beam line optics

The intended experiments in H line require high statistics, *i.e.* high intensity beam. Momentum tune-ability is also needed. Both features will be important for potential experiments in future. The design work on H line is performed along these two concepts. The basic idea of the beam line optics was proposed to use a large-aperture muon-capture solenoid, a wide-gap bending magnet and a pair of two solenoid magnets which have opposite-direction field each other [11]. Conventional matrix calculation is not applicable because the near-axis approximation is not good in a large-aperture solenoid. Thus, G4BEAMLINE [12] is applied to optimize the parameters of the beam line magnets.

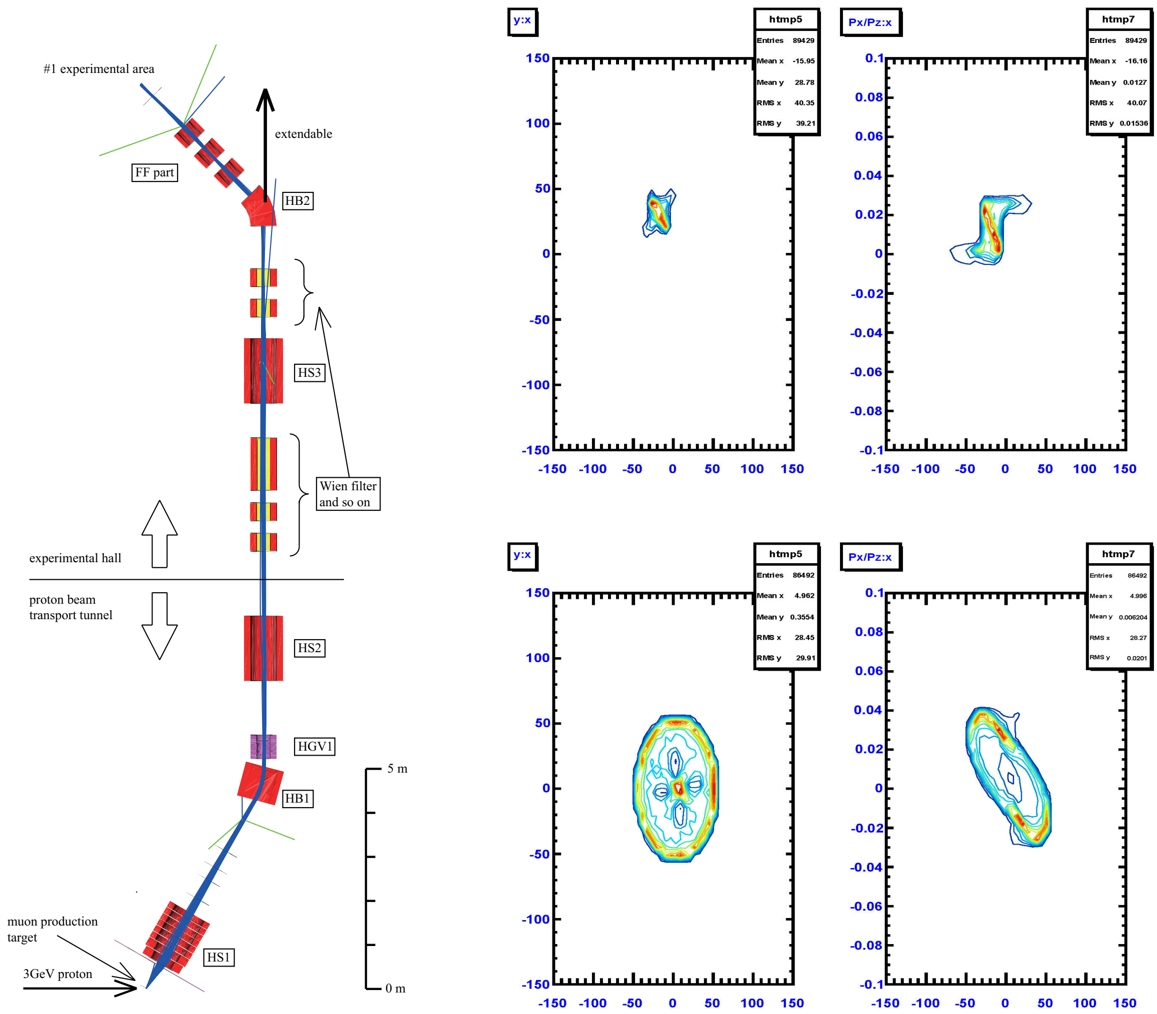

Figure 3. A typical result of G4BEAMLINE calculation. The blue lines are beam trajectories (left). The surface muon beam from a point source is transported to the first experimental area through three solenoid magnets and two bending magnets. The wien filter and the kicker magnets are also shown, but they are not in use in this transmission. The beam profile at the exit of HS2 and HS3 are shown (right).

The front-end capture solenoid magnet (HS1) consists of 8 coils, and three kinds of currents are supplied to the first, the second and the remaining coils, respectively. The first and the second coils make the main capture field, and by tuning the rest, the beam profile is minimized at around the first bending magnet (HB1) and the gate valve (HGV1) necessary for beam line maintenance. The second solenoid magnet (HS2) generates a weak field to produce a parallel or slightly-focusing beam. The third solenoid magnet (HS3) makes an opposite-direction field to cancel the beam-profile rotation caused by HS2. This canceling function doesn't depend on the momentum, and thus beam loss due to momentum dispersion at the second bending magnet (HB2) is reduced. The distance between HS2 and HS3 can be extended to about 5 m, and HB2 which determines the position of the experimental area can be placed where the area doesn't interfere the neighboring S line. In addition, one can install a Wien filter, a kicker magnet and other devices like vacuum components in this 5 m gap. Depending on the intended experiment, installed devices in this gap are selected. For instance, a Wien filter is installed to eliminate electrons/positrons from the beam [6, 7], and the second Wien filter is necessary to obtain full polarization rotation. Kicker magnets are considered to be installed instead of a Wien filter to protect detectors from the prompt burst of muons and electrons right after the proton pulse injection and to detect delayed electrons from μ-e conversion generated in the muon production target [8], although the detector which is tolerant of the burst is under development not to use kicker magnets.

Figure 3 shows a typical transport calculation, and the beam is delivered to the first experimental area which is the nearest to the muon source. Turning off HB2, the beam goes straight and is transported to the extended beam line by adopting another pair of opposite-field solenoid magnets. Namely, H line can provide the intense beam to a few experiments which use different apparatuses and cannot share the experimental area.

In the other high intensity beam line in MUSE, the U line, we adopted only axial focusing magnets to obtain high transmission efficiency [4]. In contrast the H line uses bending magnets, whose non-axial focusing makes beam losses higher. To maintain high transmission efficiency, large aperture magnets and other devices are adopted in the H line. A typical size of the aperture is 600 mm in diameter.

4. Construction status

At the primary stage of Muon Facility construction, only the magnets in the D line and the frontend magnets in the S line were installed, and then the frontend magnets in the U line were installed in 2009. In the H line, temporary radiation-shield blocks were placed. J-PARC has been operated since 2008, and thus the activation around the muon production target and the shield in the H line becomes serious year by year. According to the evaluation by a Monte-Carlo code, the dose rate beside the target chamber was estimated to be close to 1 Sv/h, and the summer shutdown in 2012 would be the actual time limit to install the frontend magnets in the H line. Thus, installation of the frontend devices, *i.e.* the muon-capture solenoid, HS1, the first bending magnet, HB1, and the vacuum components took precedence in 2012.

The magnets and other devices in the downstream are under designing. These devices are placed in the experimental hall, and thus they have many design options regarding material selection, geometrical size and position and so on. In order to provide the satisfactory muon beam to all the planed experiments in the H line, designing work is performed.

The designing work of the radiation shield is also in progress according to the same manner in the other beam lines [13]. Along the beam line a few meter thick concrete shield will be necessary to enclose the streaming neutrons and other radiation sources. Because the H line adopts large aperture devices, the effect of the streaming neutrons are more serious than the other beam lines. The evaluation of the streaming neutron is important not only for the radiation safety but also to check its effect on the detectors and other devices in the experimental area.

5. Summary

The H line is designed to be dedicated to fundamental physics studies to observe a new physics beyond the standard model, and they require high intensity beam and need to occupy an experimental area for a long period of more than a year.

The beam optics calculation predicts high transmission efficiency, and more than 80% of the captured muons can be transported. The detailed design work of the magnets and the other beam-line components is in progress, and the result will be fed back to the optics calculation. In total, 1×10^8 surface muons/s us calculated to be available.

The muon facility has been under operation since 2008. The temporary radiation shields had been placed in H line, and they have been activated. The radiation dose from the residual activities was expected to reach the order of 1 Sv/h in 2012. Thus HS1, HB1 and the other front-end devices were needed to be installed as early as possible, and their installation work was successfully completed. The devices in the downstream are under designing at present.

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