RESEARCH AND DEVELOPMENT OF HIGH INTENSITY BEAM TRANSPORT TO THE TARGET FACILITIES AT J-PARC

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ABSTRACT

Since 2008, the Japanese Spallation Neutron Source (JSNS) of J-PARC has produced a high-power proton beam of 300 kW. In order to operate with high intensity beam such as 1 MW, a reliable profile monitor system is required. Since pitting erosion was found at the vessel of the spallation neutron target at other facility of SNS, the beam current density at the target should be kept as low as possible. In order to decrease the beam density, a beam flattering system based on a non-linear optics with octupole magnets was developed. It was found that the beam profile at the target obtained with the Multi Wire Profile Monitor (MWPM) showed flat distribution and showed good agreement with the design calculation. Furthermore, the present status of the development of the profile monitor is also described.

KEYWORDS
Spallation neutron source, 3GeV Beam Transport Facility, Beam monitor, Nonlinear beam optics

1. INTRODUCTION

In the Japan Proton Accelerator Research Complex (JPARC)[1], a MW-class pulsed neutron source, the Japan Spallation Neutron Source (JSNS) [2], and the Muon Science facility (MUSE) [3] were installed in the Materials and Life Science Experimental Facility (MLF) shown in Fig. 1. Since 2008, this source has produced a high-power proton beam of 300 kW. In 2015, we successfully ramped up beam power to 500 kW and delivered the 1-MW beam to the targets. To produce a neutron source, a 3 GeV proton beam collides with a mercury target, and to produce a muon source, the 3 GeV proton beam collides with a 2-cm-thick carbon graphite target. To efficiently use the proton beam for particle production, both targets are aligned in a cascade scheme, with the graphite target placed 33 m upstream of the neutron target. For both sources, the 3 GeV proton beam is delivered from a rapid cycling synchrotron (RCS) to the targets by the 3NBT (3 GeV RCS to Neutron facility Beam Transport) [4-6]. Before injection into the RCS, the proton beam is accelerated up to 0.4 GeV by a LINAC. The beam is accumulated in two short bunches and accelerated up to 3 GeV in the RCS. The extracted 3 GeV proton beam, with a 150 ns bunch width and a spacing of 600 ns, is transferred to the muon production target and the spallation neutron source.

Since early stage of the JSNS design, pitting damage became evident in the mercury target container[7], by the similar circumstance of the JSNS and the extent of the damage is proportional to the fourth power of the peak current density of the proton beam. After operating the beam at high power, significant
Pitting damage was observed at the spent mercury target vessel at JSNS and at the Spallation Neutron Source in Oak Ridge National Laboratory [8, 9]. Using linear optics (i.e., quadrupole magnets) for beam transport, the peak current density can be reduced by expanding the beam at the target. However, beam expansion increases heat in the vicinity of the target, where shielding and the neutron reflector are located. Therefore, the peak current density is limited by the heat induced at the vicinity of the target such as reflector and shielding blocks. At the JSNS, the minimum peak current density is expected to be 9 $\mu$A/cm$^2$, which gives a thermal energy density at the target of 14 J/cm$^3$/pulse [10]. Because the pitting damage goes as the fourth power of the peak density, scanning the beam with a deflecting magnetic field will not mitigate the pitting damage. To obtain flat shape of the beam by deflecting magnet, the pulse magnet for the present short pulse having length such as ~1 ms is required very high frequency such as THz, which is impossible in the present technology.

Beam profile monitoring plays an important role in comprehending the damage to the target. Therefore it is very important to watch continuously the status of the beam at the target at the JSNS especially for the peak current density. We have developed a reliable beam profile monitor for the target by using Multi Wire Profile Monitor (MWPM). In order to watch the two dimensional profile on the target, we have also developed the profile monitor based on the imaging of radiation of the target vessel after beam irradiation. In this paper, the present status of the beam commissioning at the spallation neutron source is described.

![Figure 1. Plan of rapid cycling synchrotron (RCS) at the Materials and Life Science Experimental Facility (MLF) at J-PARC.](image)

2. BEAM MONITOR SYSTEM AT BEAM TRANSPORT TO TARGET

2.1. Silicon Carbide Sensor Wire

In order to obtain the characteristics of the proton beam, diagnostic system based on a Multi Wire Profile Monitor (MWPM) was developed. Principle of the MWPM is simple to observe the amount of the electron emission by the interaction of the beam at the wire. As a material of sensitive wire, usually tungsten wire is selected due to large emission amount of the electron and having high temperature melting point. In the present system, silicon carbide (SiC) was chosen due to the high resistance of the radiation [11], which can survive for 80 DPA. Due to the interaction, the beam loss is caused, which is one of issues of the high intensity proton accelerator and the optimization of the beam loss is important. The angular differential cross section of Rutherford scattering is proportional to square of atomic number of wire materi-
al. Therefore wire material with low atomic number has advantage for beam loss. Here, we compare property between tungsten and SiC. Since the average atomic number of SiC is 10, the differential cross section of SiC becomes 1/55 times of the cross section of tungsten. In order to obtain the angular distribution after scattered by the wire is calculated with revised DECAY-TURTLE [12] by Paul Scherrer Institute (PSI) [13]. Thus, SiC was chosen as wire of a standard model of the profile monitor at the 3NBT.

![Image](image_url)

**Figure 2.** Movable MWPM placed at the beam transport line. (top: MWPM and frame inside the vacuum chamber. bottom: MWPM and chamber placed in the beam transport line).

### 2.2. Multi Wire Profile Monitor

The view of MWPM is shown in Fig. 2. Along the beam transport line, 15 sets of movable MWPMs are placed to measure the beam profile. The MWPM frame has 31 wires of SiC with the spacing pitch of 6 mm for each horizontal and vertical direction. We employed the SiC wire having diameter of 0.1 mm, which has a tungsten core of 0.01 mm and is coated with 1 μm of pyrolytic carbon. The wire frame made of aluminum oxide with purity more than 95% is selected due to the high radiation resistance. In order to sustain with the fixed tension, wires are kept by the holder with spring, which gives the unique tension of 0.6 N to the wire. The frame of wires is placed in the vacuum chamber made of titanium, which is selected by the following reason, good vacuum characteristics and low activation. In order to avoid unnecessary irradiation of the wires, the frame can retract and moves like the pendulum motion. During the profile measurement, the beam loss monitors observe the loss due to the scattering at wires. For the practical aspect, beam loss cased at the MWPM can be utilized to calibrate the beam loss monitors. For the actual high intensity beam tuning, it is important to know the beam parameter. The intrinsic parameters of the beam transport were confirmed by observing response of beam position for the kick angle of the steering magnet. By the observation of the beam width by the MWPMs, the Twiss parameter and the beam emittance can be acquired.
2.3. Monitors Placed at Proton Beam Window

Continuously observing the characteristics of the proton beam introduced to the spallation target is very important. Due to the high activations caused by the neutron produced at the target, remote handling technique is necessary to exchange the beam monitor for the target. In order to decrease the radiation produced at the spallation neutron target, shielding above the monitor was required. To decrease the difficulties of the exchange work and decrease of the shielding, we combined the beam monitors with a Proton Beam Window (PBW) for separation between the vacuum region of the accelerator and the helium region around the neutron target. The PBW is better to be placed closer to the target where distance between the target and the PBW is 1.8 m, which gives reliable profile at the target. In Fig. 3, the MWPM placed at the center of vacuum chamber of the PBW is shown. In order to avoid excessive heat load at target vicinities, beam halo monitors are placed as well. The chamber of the PBW has inflatable vacuum seal called pillow seal. Due to the pillow seal, the monitors can be changed by the remote handling technique. In order to calibrate sensitivity of each wire, the signal was observed by the scanning the position with narrow width beam. It was found that the difference of individual sensitivity was 6% at most.

Figure 3. MWPM and beam halo monitors placed at the Proton Beam Window (PBW) having outer diameter of 60 cm

It should be noted that the estimation of the lifetime of the PBW is important for the high power beam operation, which may be determined by the hydrogen and helium gas production at the window. In order to measure gas production rate of aluminum alloy utilized at the PBW, the gas production rate is planned to be measured using beam dump line placing thin aluminum foil at the entrance of the beam dump.

4. DEVELOPMENT OF BEAM FLATTERING SYSTEM USING NON-LINEAR BEAM OPTICS

Distribution of the beam extracted from the RCS can be described well by a simple Gaussian [6]. With an ordinary beam optics, which is linear optics, the beam shape becomes a Gaussian at all place. By using non-linear optics, the beam particles located at the edge is bent to the center so that the distribution can become flat. In order to obtain flat shape for each horizontal and vertical direction, two octupole magnets are required. These octupole magnets can be placed at anywhere upstream of the target except the place where the phase advance between the magnet and the mercury target is an integer multiple of $\pi$. Since the proton beam had irradiated the targets for 5 years, the radiation dose around the targets is too high to place magnet. Therefore, two octupole magnets (OCT1, OCT2) are placed at upstream of the muon target as shown in Fig. 4. In briefly, the fundamental of the beam flattering is based on the edge folding by the
high order magnet of octupole magnet. By choosing appropriate octupole magnetic field, a flat beam distribution can be obtained.

4.2. Octupole Magnets

Based on the optics design, two pieces of the octupole magnet were fabricated, which had field gradient is 800 T/m³ for 700 A with a bore diameter of 0.3 m and 0.6 m in length of pole. Using a hall prove, the field gradient was measured. It was confirmed that the magnetic field were in good agreement with the design calculation. In an actual beam operation, the beam centering at the octupole is important to avoid peak at the edge. To perform centering, beam position monitor was installed in each octupole magnet.

Figure 4. Plan of octupole magnets for beam flattening system, which is to be placed upstream of muon production target shown in right side.

Figure 5. Beam profile obtained with calculations (line) compared with result by the MWPM (dots) supplying current of (a) 0 A and (b) 698 A to octupole magnet. Upper and bottom figure represents for horizontal and vertical directions, respectively.
4.3. Beam Profile with Nonlinear Optics

Beam Profile with nonlinear Optics In order to obtain the beam profile at the neutron source, SAD code is utilized, which provide beam information by fitting the result given by the MWPM placed at upstream of the octupole magnet. Also revised DECAY-TURTLE by PSI [13] is utilized to simulate multiple scattering at the muon target. Figure 5 shows results of beam profile for 800 kW beam with and without excitation of the octupole magnets. The beam profile shown in Fig. 5 was observed by the MWPM placed at the PBW. It can be found that considerable flat distribution can be obtained by the non-linear optics. The halo monitor observed decrease of the halo intensity by the non-linear optic. The calculation results with and without excitation are also shown in Fig 5. The calculation results show good agree with the experiment ones with and without octupole magnetic field. It is also confirmed that the calculated beam profile by using the muon target showed good agreement with the experiment for both cases with and without octupole magnetic field. By the calculation result, the peak density can be thought to be reduced by 30% compared with the linear optics.

5. SUMMARY

For reliable beam operation at the JSNS in J-PARC, beam monitor system with the MWPM and the halo monitor was developed. By using the MWPM, beam parameter such as the emittance and Twiss parameter can be obtained by several shots of the beam. In order to reduce peak density of the beam current at the target, nonlinear beam optics with the octupole magnets was developed. By the present system, it was found that the flat shape could be obtained. The calculation simulation shows good agreement with the result obtained with the present profile monitor, which implies that the beam flattening can be achieved by the design of optics having large $\pi$ function at the octupole magnet and an appropriate phase advance between the octupole and the mercury target. By the calculation including with the beam scattering on the muon production target, it is shown that the peak current density can be reduced about 30% of the peak density without the non-linear beam optics.

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