

BEAM FLATTENING SYSTEM BASED ON NON-LINEAR OPTICS FOR HIGH POWER SPALLATION NEUTRON TARGET AT J-PARC

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Abstract

In the Japanese Spallation Neutron Source (JSNS) of J-PARC, mercury is utilized as a target material. Since serious pitting erosion was found at the target vessel at SNS in ORNL and JSNS, a reduction of a peak current density is required. In order to decrease the peak, we have developed the beam optics based on a non-linear using an octupole magnets. In a design calculation, it is found that the peak current density of 30 % can be reduced by introducing the octupole magnets.

INTRODUCTION

In the Japan Proton Accelerator Research Complex (J-PARC) [1], a MW-class pulsed neutron source of 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) and had been operated with high power proton beam of 300 KW since 2008. The 3-GeV proton beam is introduced to the mercury target for a neutron source and to a carbon graphite target of 2 cm thickness for a muon source. In order to utilize the proton beam efficiently for particle productions, both targets are aligned in a cascade scheme, where the graphite target is placed at 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 [4–6]. Before injection to the RCS, the proton beam is accelerated up to 0.4 GeV by a LINAC. The beam is accumulated in short two bunches and accelerated up to 3 GeV in the RCS. The extracted 3-GeV proton beam having width about 150 ns for each bunch is transferred to the muon production target and the spallation neutron source. Recently it became evident that pitting damage appears in the target container of the mercury target [7]. It has been reported that the damage is proportional to the 4th power of the peak current density of the beam [8]. After high power beam operation, significant pitting damage were found at spent mercury target vessel of SNS and JSNS [9, 10]. For the beam transport with linear optics, the minimum peak heat density at the target can be expected as 14 J/cc/pulse [11], which is determined by the heat load at target vicinities. To reduce the peak density, we have developed the beam flattening system with a non-linear beam optics.

DESIGN OF 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 is 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 π . Since the targets had been irradiated by the beam for 5 years, the radiation dose around the targets is too high to place magnet. Therefore, two octupole magnets (OCT1, OCT2) should be placed at upstream of the muon target as shown in Fig. 1.

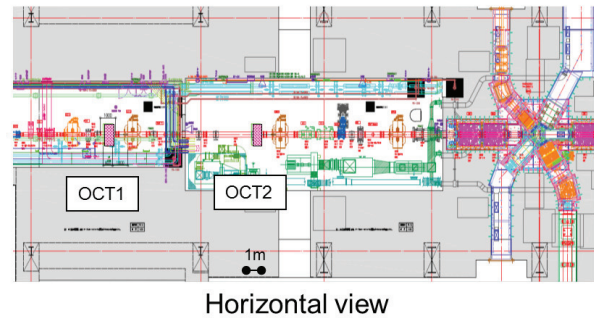


Figure 1: Position of the octupole magnets placed at upstream of the muon production target

Octupole Magnetic Field

In order to obtain flat distribution at the target, the multipole magnetic fields are given by the following equation [12] for the Gaussian distribution beam in the transverse phase space.

$$K'_{2n} L = \frac{(n-2)!}{(n/2-1)!} \frac{(-1)^{n/2}}{(2\epsilon\beta)^{n/2-1}} \frac{1}{\beta \tan \phi} \quad (n = 4, 6, 8, \dots) \quad (1)$$

Using Eq. (1), required octupole magnetic field is,

$$K'_8 L = (\epsilon\beta^2 \tan \phi)^{-1} \quad (2)$$

where K'_8 is the octupole magnetic field ($/m^3$), L is the length of the magnet (m), ϵ is the root-mean-squared (rms) beam emittance (π mm mrad), β is the beta function at the octupole magnet, and ϕ is the phase advance between the octupole magnet and the target.

In Eq. (1), higher order field than octupole is required to make flat distribution. Without a dodecapole field in Eq.

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(1) the beam distribution was reported not to be a flat and making peak at the edge [12, 13]. For low energy accelerator facilities, the edge peak can be removed by installation of the beam collimator. For a high power accelerator facility such as the JSNS, the edge peak can not be easily eliminated.

A principle of beam flattening system is bending beam from the edge to the center by the high order of the magnetic field. At the center of the target, the beam peak intensity does not change significantly by the excitation of the high order magnetic field. Because of bending of the beam to center region with the high order field, the intensity increases at the tail part. Therefore the intensity at the edge peak can reduce by a decrease of the high order field although the edge shape blurs.

Here let us consider that the transverse beam has a uniform distribution in the phase space. As for the uniform beam distribution in the phase space, the required field of octupole is given by the following equation [14].

$$K_8'' L = \cos^3 \phi / 12 \epsilon \beta^2 \sin \phi \quad (3)$$

K_8'' is the required octupole field for the beam with uniform distribution in phase space. In Eq. (3), the distribution in real space can not be flat. Here, one can expect to obtain flat with suppressing the edge peak in the intermediate of Eq. (2) and Eq. (3), which is described in Eq. (4).

$$K_8 = (K_8' + K_8'') / 2 \quad (4)$$

By setting octupole magnetic field given by Eq. (4), a flat beam distribution can be obtained as shown in Fig. 2. Although the distribution in Fig. 2 around the edge is not sharp shape comparing with the distribution by Eq. (2), the edge peak can be suppressed well.

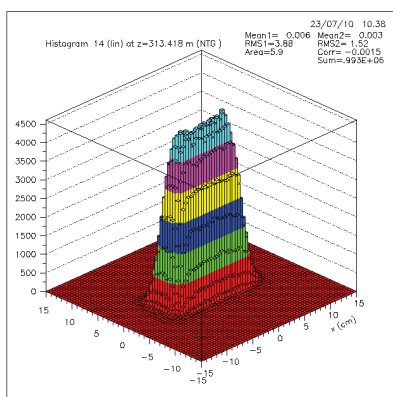


Figure 2: Beam profile by using two set of octupole magnets ignoring beam scattering effect at the muon production target.

Beam Flattering System at the JSNS

Beam optics for a whole beam transport line is shown in Fig. 3 showing beta functions from the RCS to the mercury target. In order to achieve flat distribution, the octupole field is proportional to the inverse square of the beta functions

described in Eqs. (2) and (3). Due to the high momentum of the present beam, achievement of a large octupole field of the K is difficult. To obtain the flat shape with the realistic K of the octupole, we expand the beam at the octupole magnet to have large beta function. Around the octupole magnet, since physical aperture of quadrupole magnets was fixed to 300 mm, we determined the physical aperture of the octupole magnet to 300 mm. In the linear beam optics, the admittance of the beam is designed to have 324π mm mrad, which is given by the beam collimator placed at the RCS. Recent study of the RCS [15] shows that the transverse emittance will become as small as 250π mm mrad. Therefore, the beam admittance at the octupole is determined to 250π mm mrad and the beta function at the octupole magnets is chosen to 200 m.

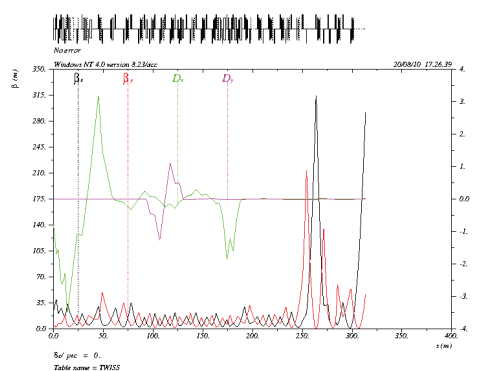


Figure 3: Twiss parameter for beam optics using octupole magnets for beam flattening

OCTUPOLE MAGNETS

Based on the optics design, two pieces of the octupole magnet shown in Fig. 4 were fabricated. The designed field gradient is 800 T/m^3 with a bore diameter of 0.3 m and 0.6 m in length of pole. Using a hall probe, the field gradient was measured. It was confirmed that The magnetic field were in good agreement with the design value. In an actual beam operation, the beam centering at the octupole is important. To perform centering, beam position monitor was installed in each magnet. The octupole magnets had already installed at the beam transport in 2013 autumn. By exception of the octupole magnet, the beam profile was measured in front of the mercury target.

RESULT AND DISCUSSION

Calculation of Beam Profile

In order to obtain the beam profile at the neutron source, DECAY-TURTLE [16] calculation code revised version by Paul Scherrer Institute (PSI) [17] is utilized. Because of the modification implemented by the PSI, the beam transport calculation can be performed with the octupole magnetic field and the beam scattering at the carbon target.

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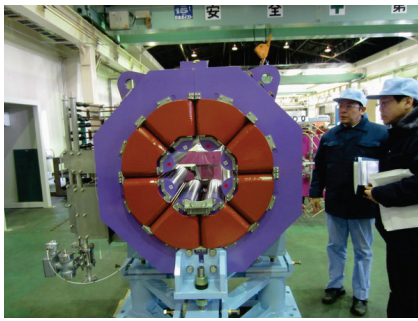


Figure 4: View of the octupole magnet at the manufacture factory

Comparison with Experimental Results

Figure 5 shows preliminary results of beam profile with and without excitation of the octupole magnets, which are presented as black and cyan dots respectively. Those results were obtained by the Multi Wire Profile Monitor (MWPM) beam profile placed at the proton beam window where is located at 1.8 m upstream of mercury target. For simplify, the muon production target is placed at out of beam position. The calculation results with and without excitation are also shown in Fig. 5, which are shown as lines. The calculation results shows good agree with the experiment ones with and without octupole magnets. In Fig. 5, the profile result with the muon target and the octupole field is also compared. It is found that the calculation becomes more likely Gaussian than the measurements, which might be caused by the over prediction of the scattering effect in the calculation. By taking account of this phenomena, it can be thought that the calculation gives conservative peak density.

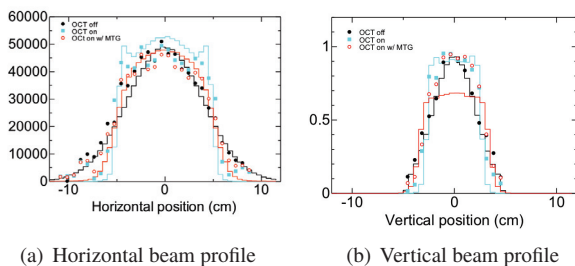
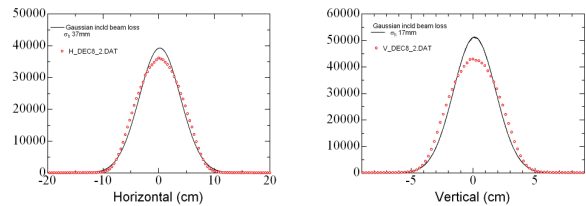


Figure 5: Beam profile obtained by the MWPM (dots) compared with the calculations of DECAY-TURTLE (lines) for the result without excitation of octupole (black), with excitation of octupole (cyan) and with excitation of octupole and irradiation on the muon production target (red).

Beam Profile at Neutron Production Target at 1 MW Operation

Beam profile at the neutron target including the beam scattering at muon target calculated with the DECAY-TURTLE are shown in Fig. 6, in which the peak heat density becomes 11 J/cc/pulse. From the comparison of the linear optics shown in Fig. 6, it is shown that the peak density can reduce by about 30 %.



(a) Horizontal beam profile (b) Vertical beam profile

Figure 6: Comparison of beam profile with linear optics (line) and with nonlinear optics with the octupole magnets (red circle)

CONCLUSION

In order to reduce peak density of the beam on the target, a beam transport system by using non-linear beam optics with the octupole magnets was developed. Simulation results show that the beam flattening can be achieved by the design of optics having large beta function at the octupole magnet and an appropriate phase advance between the octupole and the mercury target. By the calculation 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. It should note that the present non-linear beam optics system is the first attempt for a hadron accelerator with the beam power of MW class.

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