Development of Beam Flattening System Using Non-Linear Beam Optics at J-PARC

Shin-ichiro Meigo[1], **Hiroshi Fujimori**[2], **Shinichi Sakamoto**[1],
and Masatoshi Futakawa[1]

[1] J-PARC Center, JAEA, 2-4 Shirakata Shirane, Tokai, Ibaraki 319-1195 Japan

[2] J-PARC Center, KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801 Japan

E-mail: meigo.shinichiro@jaea.go.jp

Abstract. As increasing in the beam power, the damage of the target becomes serious. Especially for a high power short pulse spallation neutron source, the damage due to the proton beam on the target vessel for liquid metal target such as mercury is reported to be proportional of 4th power of the peak intensity of the proton beam. To reduce peak intensity, a beam transport system by using non-linear beam optics with the octupole magnets was studied. Beam flattering technique with high order magnet is based on the folding of the beam at the edge. We try to find the solution by placing two octupole magnets at about 50 m upstream from the targets, where the radiation does is low. Simulation result shows that the beam flattening can be achieved by the beam optics having large beta function at the octupole magnet and an appropriate phase advance between the octupole and the mercury target. By the simulation including beam scattering on the muon production target, it is confirmed that the peak intensity can be reduced about 30 % due to the present beam flattening system.

1. Introduction

In the Japan Proton Accelerator Research Complex (J-PARC)[1], a MW-class pulsed neutron source, the Japan Spallation Neutron Source (JSNS) [2], and the Muon Science facility (MUSE) [3] will be installed in the materials and life science facility (MLF) shown in Fig. 1. A 3GeV proton beam is introduced to the mercury target for a neutron source and to a carbon graphite target of 20 mm 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 located 33m upstream of the neutron target. For both sources the 3-GeV proton beam is delivered from a rapid cycling synchrotron (RCS) to the targets. Before injection to the RCS, the proton beam is accelerated up to 181MeV by a LINAC. The beam is accumulated in short bunches of less than 100 ns duration and accelerated up to 3 GeV in the RCS. After extraction, the 3-GeV proton beam is transferred to the muon production target and the spallation neutron source. The maximum beam power extracted from the RCS is 0.4 MW. In 2013, 400 MeV LINAC and new RFQ will be installed so that 1 MW operation will begin.

As increasing in the beam power, the damage of the target becomes serious. Especially for a high power short pulse spallation neutron source, the damage due to the proton beam on the target vessel for liquid metal target such as mercury is reported to be proportional of 4th power of the peak intensity of the proton beam [4, 5]. Reduction of the peak intensity is quite important for the beam injection system of the spallation neutron source using the mercury as the target material. At the JSNS, beam profile can be described well by the Gaussian [6]. With the linear optics and completely Gaussian distribution of the beam, the minimum peak density in the unit of the heat density produced at the target can be predicted as 14 J/cc/pulse[7] in the unit of heat density, which is determined by the heat density at target vicinities less than 1 W/cc. As for the practical beam operation, it is better to keep the peak as small as possible to reduce the waste of the targets and the proton beam window. To reduce peak density, a beam transport system by using non-linear beam optics has been developed.

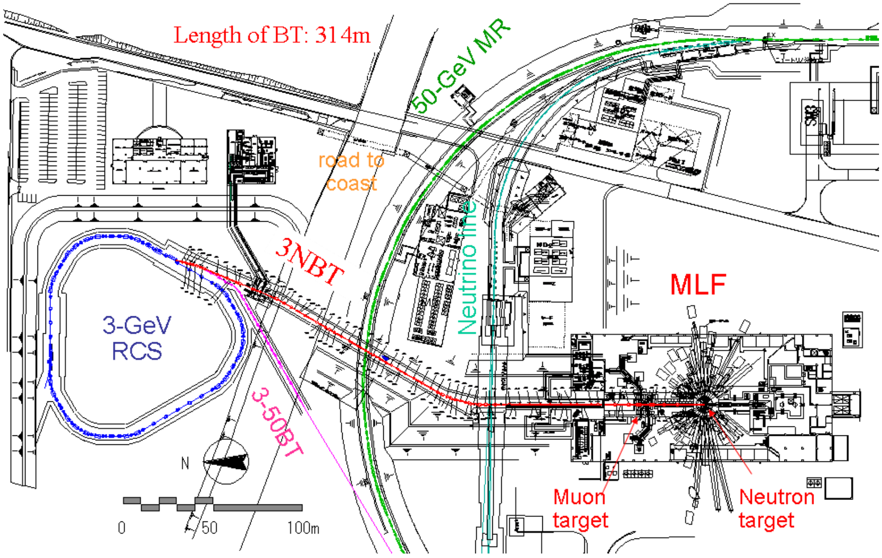


Figure 1 Layout of JSNS and MUSE at J-PARC. The beam transport line (3NBT) introduces the beam to both facilities located in the MLF building.

2. Design of the non-linear optics

Beam flattering technique with non-linear optics is based on the folding of the beam at the edge. For the beam having Gaussian distribution in phase space, the distribution in the real space is kept to be Gaussian at all place. By using non-linear optics, the beam at the edge is fold to the center so that the uniform beam is shaped. At each octupole magnets, the beam is expanded in horizontal and vertical directions, respectively, to maximize the effect of the non-linear force on the beam. In ideal beam optics, octupole magnets can be arbitrary placed. It is known that the beam offsets at the transport system, on the contrary, enhances the peaks edge [8]. To understand the allowance of the alignment and the beam stabilities, we performed simulations described in the next section.

It should note that, in the early beam optics design [8], a conceptual design already made by using non-linear optics. However, it can be anticipated that the instability of the beam due to lack of experience of the beam extraction control so that we hesitated to install the octupole magnet. Regardless of our conscious, the beam position showed good stability at the extraction channel of the RCS and the target so that we decided to install the non-linear magnets.

3. Beam optics design for beam

3.1. Field strength of the octupole magnet

According to Ref [9], in order to obtain flat beam at the target for the Gaussian beam by the non-linear optics, the octupole of field gradient is represented by the following equation,

$$KL = (\varepsilon\beta^2\tan\phi)^{-1} \tag{1}$$

where K, L, ε, β and ϕ is the field strength of octupole magnet(m^{-2}), the length of the octupole magnet(m), root mean square of the beam emittance (π mm mrad), beta function at the octupole magnet (m), and phase advance between the octupole magnet and the target, respectively. It is shown that large beta function and the strength of the octupole are necessary for the beam flattening. In ideally beam optics, octupole magnets can be placed at an arbitrary position. Since the beam halo is increased by the non-linear optics, it seems to be better to be placed near the target position. As cascaded scheme the muon production target placing at the upstream of the mercury target, the octupole magnets seem to be better to be placed in front of the neutron target for the sake of simplification to eliminate the beam scattering on the muon target. Due to the beam operation so far, the radiation dose at M2, where around at the muon and neutron production targets, was extremely high does around the targets so that installation of the new magnet is difficult. Recently our experience [7] showed that the beam should be kept smaller in M2 to avoid beam loss, which implies to avoid placing the octupole magnets in M2. Therefore we try to find the solution by placing two Octupole magnets at about 50 m upstream from the targets, where the radiation does is low.

It should note that equation (1) is for the combination of higher order magnets such as dodecapole. Appling only octupole magnets as higher order magnet, the beam density at the edge becomes larger than the density at the center[9]. To suppress the edge density, we adjusted the strength of the octupole. Smaller strength compared with the equation (1) gives good distribution.

3.2. Beam optics for flattening system

In order to obtain beam with the realistic octupole strength, large beta is required at the octupole magnets. Figure 2 shows the beam optics along the whole beam line. In the basic design using linear optics, the largest beta function in the beam line is about 40 m. The beta function for non-linear optics is increased to 100 m, where the octupole is located.

Since large beta is required, the beam acceptance at the octupole magnets is important. In the original design of the beam optics, the acceptance of 324 π mm mrad is given by the aperture of the collimator located at the RCS. Recent simulation result of the extraction beam shows that the acceptable can be decreased to 250 π mm mrad on the condition that beam loss is smaller than 1 W/m.

3.3. Calculation of the beam profile

In order to obtain beam profile at the mercury target of the JSNS, calculations were performed by the DECAY-TURTLE[10] code developed at PSI[11], which can trace the beam including the high order magnetic fields and the effect of the beam scattering at the muon production target. The initial beam distribution was given by the calculation of the RCS team.

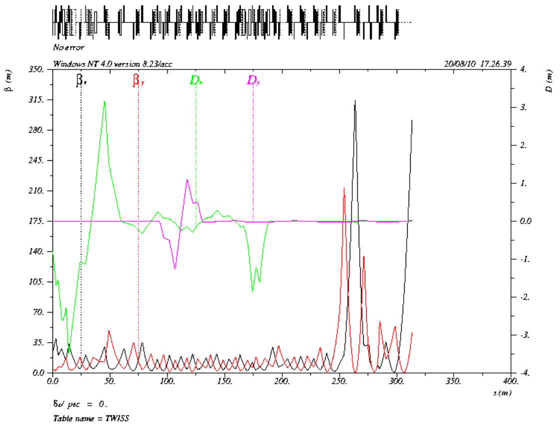


Figure 2 Beam optics for flattering system using octupole magnets located at large beta

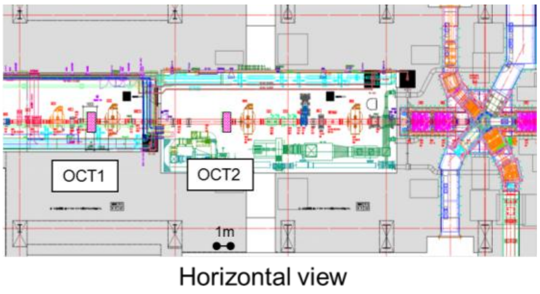
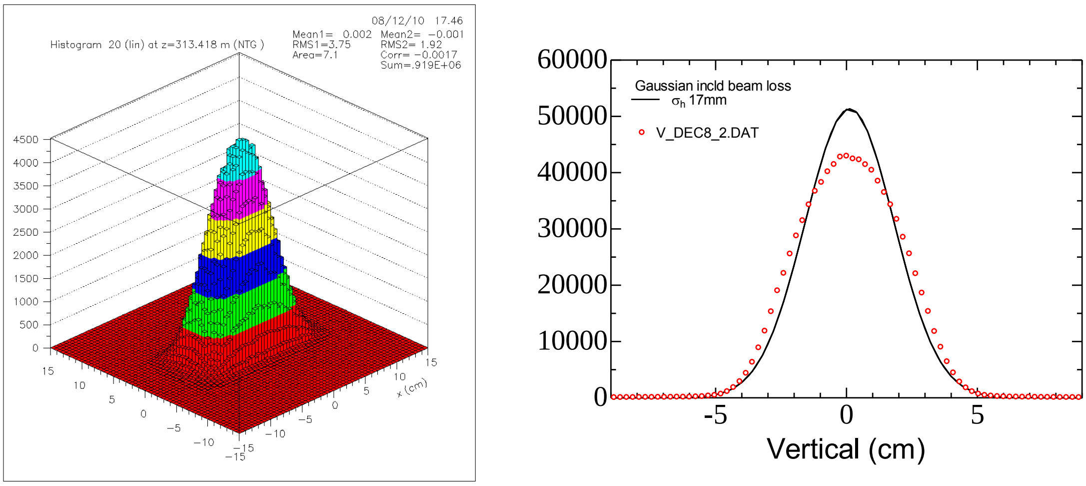


Figure 3 Schematic view of the beam flattening system around at octupole magnets

4. Result and discussions

4.1. Beam profile at the target

Figure 4 shows the profile at the target. It is shown that the peak density, which gives heat density as 11 J/cc/pulse, can be reduced about 30 % of the Gaussian. In the calculation, the beam acceptance has larger than 250 π mm mrad. Other calculation results show that peak reduction of 40 % is achievable in the case of that the beam acceptance decreases to 100 π mm mrad, which implies that the peak can be reduces more if beam halo grows can kept be small.



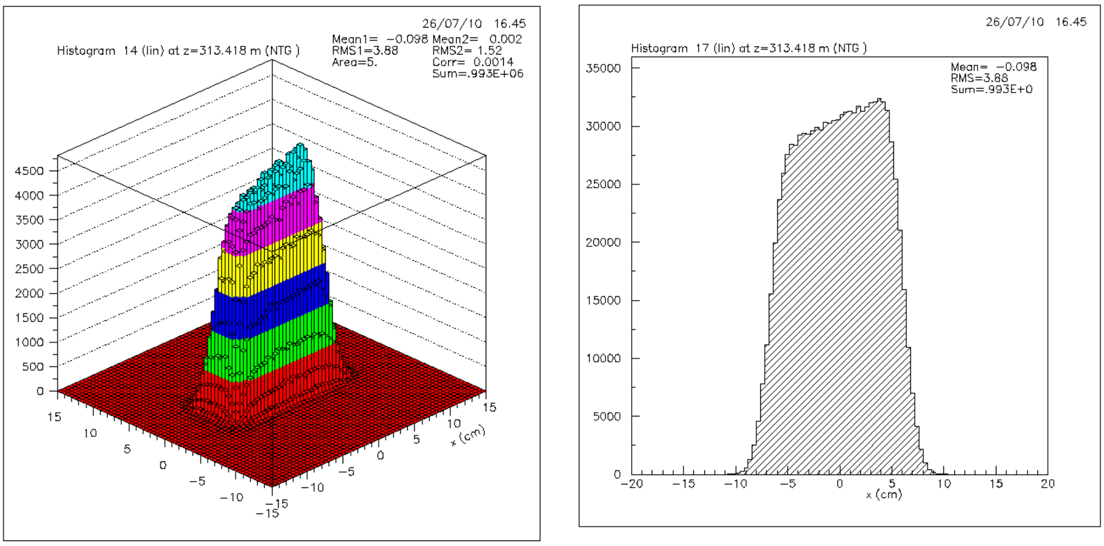
(a) (b)

Figure 4 Beam profile by the beam flattering system (a): 2D beam profile at the target, (b): beam profile in vertical direction compared with the Gaussian case without flattering system.

4.2. Allowance of the alignment of magnets

In practical beam operation, the beam offset will be caused due to the miss alignment, uneven settlement and instability of the beam positions. Eventually beam offset makes the increase of the density at the edge. For the understanding of the tolerance of error such as the beam offset and the alignment, the beam profile was calculated by including the error of the alignment.

In figure 5, the profile is shown for the case of having horizontal 2 mm shift of beam at the octupole magnet. In order to be simple, the muon target is ignored in the calculation and the required the acceptance at the beam line. Without the error of the beam position, the beam profile can be shaped significant flat. It is found that the density at the edge increases 8 %. From the result, we decided the allowable error for the octupole magnet to be 1 mm, which will increase only 4 % even in the ideal flat case. Another calculation was made for tilting of the octupole magnet. It is found that allowable tilting of the octupole magnet is about 0.5 mrad, which has less sensitivity than the beam positions. We also calculated the miss-alignment effect of the magnet located at the downstream of the octupole magnets. Although the beam position is oscillated due to the beta-tron motion, the beam can be kept flat shape without appearing the peak at the edge. Actually at M2 where locates at downstream of the octupole magnet, re-alignment of the magnets is impossible. This result is great advantage for the cascade target scheme.

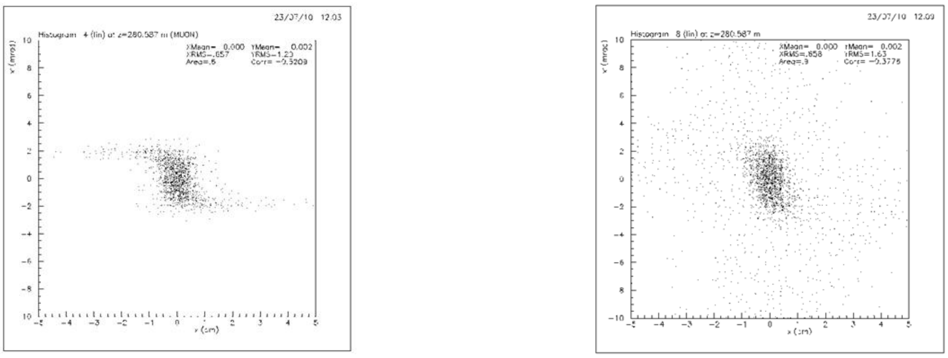


(a) (b)

Figure 5 Beam profile with the beam offset of 2 mm in horizontal at the octupole magnet. (a): 2D profile at the target, (b): beam profile in the horizontal direction

4.3. Effect of the muon production target

At the present system, the proton beam is scattered at the muon production target. In order to recognize the scattering effect on the flattening system, the phase space distribution at the muon production target is calculated which is shown in figure 6. Before enter the muon production target, it is found that arm shaped band is produced by the magnet field of the octupole. This arm band fold makes the shape as flat by folding the edge to the centre at the target. However, it is found that the band blurs after penetration of the target. Due to the scattering effect, the distribution blurs along the beam divergence direction, which is vertical axis in figure 6. Thus, the scattering effect introduces the beam shape to be formed Gaussian again. In order to minimize the scattering effect, the beam should be focused on the target as possible as smaller. By the focusing, the divergence of the beam is increased so that the arm shaped band is conserved.



(a) (b)

Figure 6 Beam scattering effect in the phase space distribution (a): In front of the muon production target, (b): After penetration the muon production target.

5. Octupole magnet

Following the requirement of the beam optics, design of the octupole magnet was performed. Already the octupole magnets were fabricated. Figure 7 shows the view of the octupole magnet, which has field gradient of 800 T/m^3. In the summer 2013, the octupole magnets will be installed during long shut down period when the energy of the LINAC will increase to 0.4 GeV. In order to ensure the beam centering, the beam position monitors will be installed in the octupole magnets. Additional steering magnets will be also installed.

Figure 7 Octupole fabricated for the beam flattering system

6. Conclusion

In order to reduce peak intensity, a beam transport system by using non-linear beam optics with the octupole magnets was developed. Simulation result shows 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.

It is well known that the peak at the edge target appears in case of the beam offset at the magnet. We studied the tolerance of the beam offset at the magnets. It is found that the allowable beam offset is recognized about 1 mm at octupole magnets, which is feasible because the beam position is stable for long duration in beam operation so far. In order to recognize the beam status at the octupole, we will place the beam position monitor in the octupole. It is shown from the simulation result that the beam distribution does not change due to the alignment error of magnets located downstream of the octupole magnets. In order to reduce the effect of the beam scattering at the muon production target, the beam is well focused on the muon production target. By the simulation including beam scattering on the muon production target, it is recognized that the peak intensity can be reduced about 30 %.

References

[1] The Joint Project Team of JAERI and KEK, JAERI-Tech 99-56, 1999.
[2] Y.Ikeda, Nucl. Instrum. Meth. A600, (2009) 1.
[3] Y.Miyake, et al., Physica B404 (2009) 957.
[4] M. Futakawa, et al., J. Nucl. Sci. Technol.40 (2004) 895.
[5] M. Futakawa, et al., J. Nucl. Matter.343 (2005) 70.
[6] S. Meigo, et al., Nucl. Instrum. Meth. A562, (2006) 569
[7] S. Meigo, et al., ICANS-19 as presented as 314
[8] S. Meigo, JAERI-Tech 2000-088 (2001).
[9] Y. Yuri, et al., Phys. Rev.ST Accel. Beams 10, 104001 (2007)
[10] PSI Graphic Turtle Framework by U. Rohrer based on a CERN-SLAC-FERMILAB version
[11] K.L. Brown, Ch. Iselin, D.C. Carey: Decay Turtle, CERN 74-2 (1974)