ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB318

UNIFORMIZATION OF THE TRANSVERSE BEAM PROFILE WITH NONLINEAR MAGNET*

Y. Li[1,2], S. X. Zheng[1,2†], H. J. Yao[1,2‡], Y. Yang[1,2], W. B. Ye[1,2], X. Y. Liu[1,2], Q. Z. Xing[1,2], X. W. Wang[1,2], X. L. Guan[1,2], Key Laboratory of Particle & Radiation Imaging (Tsinghua University), Ministry of Education, Beijing, China
[1]also at Laboratory for Advanced Radiation Sources and Application, Tsinghua University, Beijing, China
[2]also at Department of Engineering Physics, Tsinghua University, Beijing, China

Abstract

The beam generated after slow extraction of the synchrotron is always not uniform and asymmetrical in transverse distribution. In practice, radiation therapy or radiation irradiation requires a high degree of uniformity of beam spot. Therefore, it is necessary to adjust the beam distribution with nonlinear magnet and other elements on the transport line from synchrotron ring to beam target station. Nonlinear magnet has high requirements on beam quality. Before passing through the nonlinear magnet field, the beam center can be adjusted by taking advantage of the gradient change distribution of nonlinear magnet's transverse field map to achieve uniform distribution at the target station. As an example, we use the parameters of heavy ions of XiPAF (Xi'an 200 MeV Proton Application Facility) to simulate the beam transport from synchrotron ring to beam target station.

INTRODUCTION

In many applications of charged-particle beam, the uniformization of beam transverse profile is an important index, especially in radiotherapy which is used more and more widely [1]. Synchrotron is widely used in producing charged-particle beam. After the beam is extracted from the synchrotron ring by slow extraction, the beam is transmitted through the ring to target beam transport (RTBT) line, and finally the transverse homogenized beam is obtained at the target station. The nonlinear magnet has a better homogenization effect on the beam with Gaussian distribution, but the beam extracted from the synchrotron is asymmetrical in the horizontal direction. So the homogenization effect in the horizontal direction after passing through the nonlinear magnet is limited. In this paper, a method is introduced to further optimize the uniformization of beam transverse profile at target station based on the characteristics of the magnetic field distribution of nonlinear magnets. As an example, we use the parameters of heavy ions of XiPAF (Xi'an 200 MeV Proton Application Facility) to simulate the beam transport from the synchrotron ring to beam target station.

* Project 12075131 supported by NSFC.
† zhengsx@tsinghua.edu.cn
‡ yaohongjuan@tsinghua.edu.cn

NONLINEAR MAGNET AND BEAM UNIFORMIZATION

The field distribution of the nonlinear magnet adjusting the horizontal beam distribution is shown in the Fig. 1. The magnetic field intensity is limited in the middle region, while the magnetic field in the edge region is strong. When the beam passes through the field, the particles in the middle region are not affected by the magnetic field or are nearly not affected by the magnetic field, while the particles in the edge region are affected by the magnetic field. If a proper phase shift is adjusted between the nonlinear magnet and the target, the edge particles can be superimposed into the beam nucleus and the beam distribution can be improved [2]. A nearly uniform square distribution beam on the target can be obtained by applying the nonlinear magnet in both horizontal and vertical directions. The beam derived from the synchrotron is consistent with the Gaussian distribution in the vertical direction, and is symmetric about the center. It does not need additional processing and can be uniformly distributed through the nonlinear magnet. But the beam in the horizontal direction is not symmetrical about the center. So we need to pay attention to the field of the nonlinear magnet that adjusts the beam distribution in the horizontal direction.

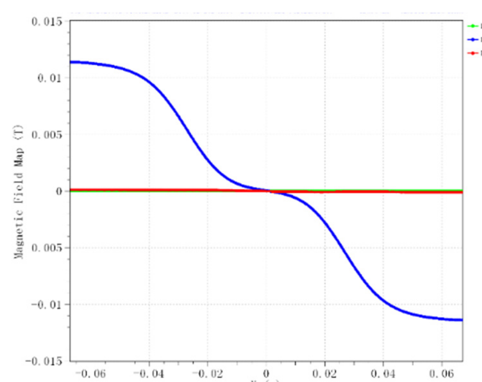

Figure 1: The field distribution of the nonlinear magnet adjusting the horizontal beam distribution.

Figure 2 shows the nonlinear magnet for regulating the horizontal beam distribution. The beam pipe is long at horizontal direction and narrow at vertical direction.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB318

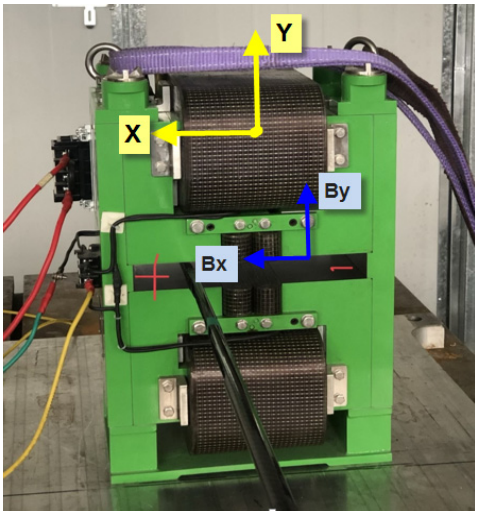

Figure 2: Nonlinear magnet adjusting the horizontal beam distribution.

For the beam that is asymmetric about the center, passing through the nonlinear magnet directly cannot adjust the symmetry of the beam, because it cannot use the field of the nonlinear magnet to superimpose the edge particles into the middle area and then the overall distribution is a square uniform beam. If we make full use of the field distribution characteristics of nonlinear magnet, let the beam use the correction magnet to make a deviation of the beam center before entering the entrance of the nonlinear magnet, so that the side with higher particle density will have a smaller field strength on the nonlinear magnet. The side with the smaller particle density is more in the edge area where the field is strong, so that when the beam passes through the nonlinear magnet, the particles in the dense area are basically unaffected, and the particles in the low density area are superimposed to the beam nucleus after being transmitted for a certain distance. To the central area of the beam, it will eventually produce a square beam, that is, a uniform beam.

Two pictures of Fig. 3 are the phase space distribution of the beam at the entrance of the horizontal nonlinear magnet with or without the correction magnet. The beam is long in the horizontal direction, occupying about a 30 mm's district, and narrow in the vertical direction, occupying only about a 4 mm's district.

In order to measure the uniformity of the beam spot at the target station, we divide the target district into several small grids, the coordinates of each grid are determined by the subscripts i, j, and the number of particles in each grid is N_{ij}, i, j = 1, ... n. The formula for calculating the inhomogeneity is defined as:

$$u = \pm \frac{\overline{\left| N_{ij} - \overline{N_{ij}} \right|}}{\overline{N_{ij}}}. \qquad (1)$$

The greater the value of the inhomogeneity, the less uniform of the beam spot.

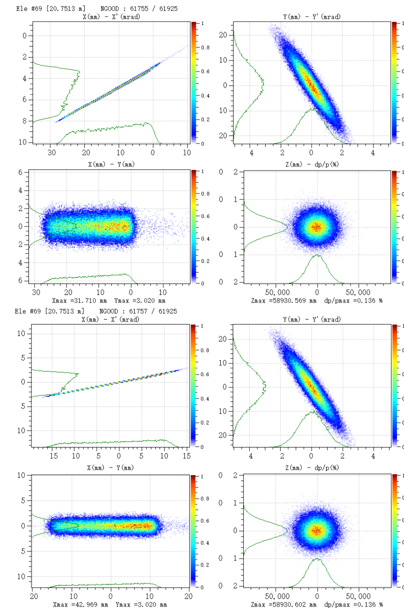

Figure 3: The phase space distribution of the beam before the horizontal nonlinear magnet with (4 above) or without (4 below) the correction magnet.

SIMULATION RESULTS

As an example, we used a designed RTBT to simulate the above process in TraceWin. The initial beam is the beam extracted from the synchrotron ring by slow extraction. As the Fig. 4 shows, the distribution at horizontal direction is asymmetric about the beam center, and is Gaussian at the vertical direction.

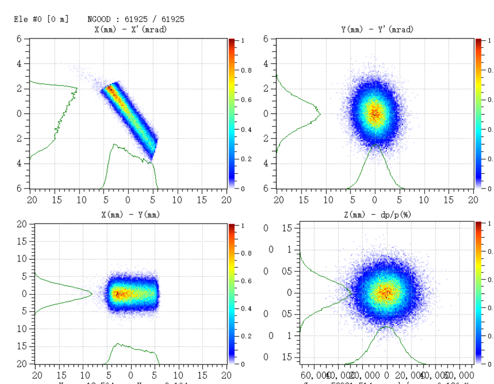

Figure 4: The phase space distribution of the beam at the entrance of RTBT.

Figure 5 shows the distribution of the beam at the target station without changing the center trajectory of the beam during transport. Take out the 50 mm × 50 mm district of the central area in the transverse phase space and divide it into a grid of 2.5 mm × 2.5 mm, that is, 20 × 20 grids, count the number of particles in each grid, and draw the particle number distribution diagram as Fig. 6 shows. Among them, the larger the area of the circle, the more particles in the grid. It can be seen that the particle number distribution presents an obvious phenomenon that there are more particles on the left side of the center and fewer particles on the right side. Select the middle 5 to 16 grids,

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB318

that is, the middle 30 mm × 30 mm area. According to the inhomogeneity formula, the value of inhomogeneity is calculated to be ±14.69%.

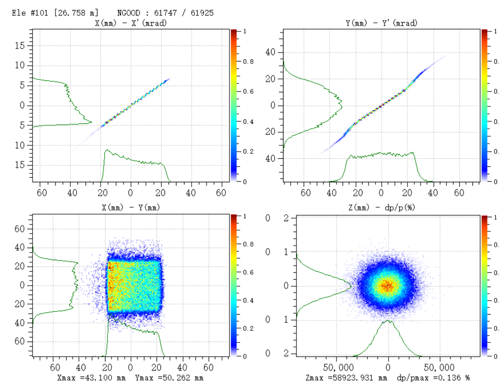

Figure 5: The phase space distribution of the beam at the target station.

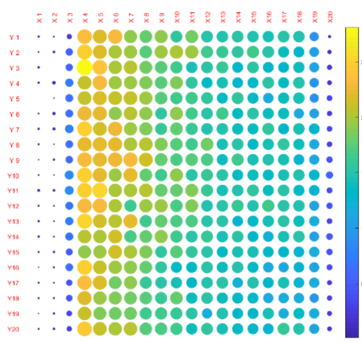

Figure 6: The particle number distribution diagram.

At this situation, the beam center trajectory and envelope during transmission are shown in the Fig. 7. The purple line represents the beam center trajectory. FM1 and FM2 are the nonlinear magnets that adjust the beam distribution in the horizontal and vertical directions. The blue lines are the beam envelope during transmission.

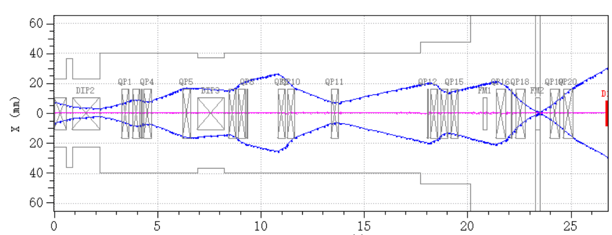

Figure 7: The beam center trajectory and envelope during transmission.

The correction magnet on the RTBT is used to produce an offset in the beam center at the entrance of FM1 area. After passing through FM1, another correction magnet is used to adjust the horizontal center of the beam back to the center of the pipe. The beam center trajectory and envelope of the adjusted beam during transmission process are shown in the Fig. 8. FM1 is the nonlinear magnet that adjusts the horizontal beam current. There is an offset of about 10 mm at the entrance of the FM1. After the correction magnet between FM1 and FM2, the beam center is adjusted back to the center of the pipe before the beam passes through the FM2.

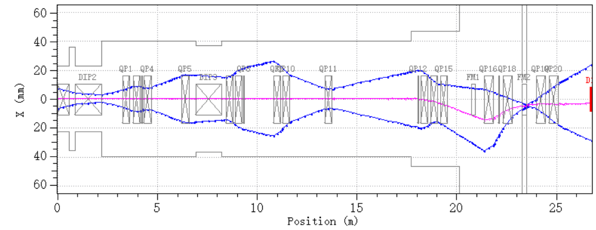

Figure 8: The beam center trajectory and envelope during transmission.

Figures 9 and 10 show the distribution of the beam at the target station.

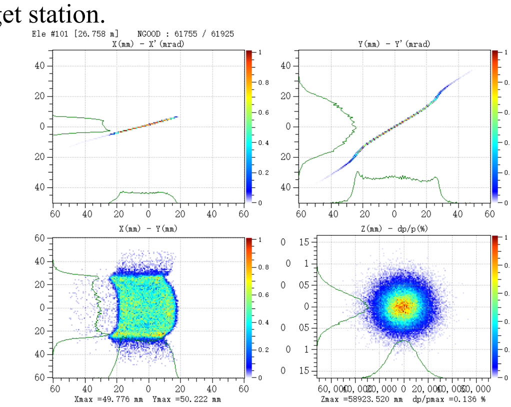

Figure 9: The phase space distribution of the beam at the target station.

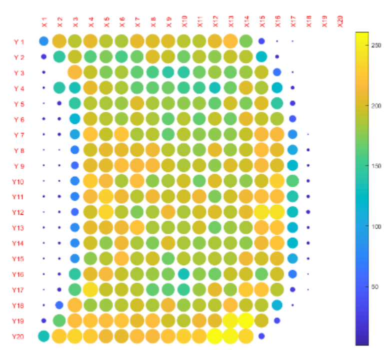

Figure 10: The particle number distribution diagram.

The value of inhomogeneity is ±7.31% when the grid is divided into 2.5 mm × 2.5 mm in the center of 30 mm × 30 mm. If the overall horizontal shift is 3 mm, the value of inhomogeneity is ±6.31%. Compared with the inhomogeneity of the target station before adjusting the beam center, the value of inhomogeneity is only half than before, and the uniformity is further improved.

CONCLUSION

To make the beam distribution at the target station more uniform, nonlinear magnet can be used. Due to the nonlinear magnetic field map, better uniformization of transverse asymmetrical beam can be achieved by using the corrector magnet so that the beam center is somewhat offset in front of the nonlinear magnetic. The simulation results correspond with expectations.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-THPAB318

REFERENCES

[1] G. Gu and W. B. Liu, "Uniformization of the Transverse Beam Profile by a New Type Nonlinear Magnet", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 272-274. doi:10.18429/JACoW-IPAC2015-MOPWA065

[2] Y. Yuri, N. Miyawaki, T. Kamiya, W. Yokota, K. Arakawa, and M. Fukuda, "Uniformization of the transverse beam profile by means of nonlinear focusing method", *Physical Review Special Topics - Accelerators and Beams*, vol. 10, p. 104001, 2007. doi:10.1103/physrevstab.10.104001