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TRANSVERSE PROFILE SHAPING OF A CHARGED-PARTICLE BEAM USING MULTIPOLE MAGNETS - FORMATION OF HOLLOW BEAMS -

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Abstract

The use of multipole magnets enables us to transform the transverse profile of a charged-particle beam into various ones that can never be formed through linear beam optics. To date, the formation of a large-area beam with a uniform transverse intensity distribution has been realized using octupole magnets for uniform beam irradiation. Here, we report the first demonstration of the hollow-beam formation using multipole magnets in a beam transport line. Results of beam-formation experiments and tracking simulations are shown. The hollow beam has a steep peak at the edge of the beam and thus has a high contrast between the edge peak and the intensity near the beam center.

INTRODUCTION

It is essential to properly manipulate the transverse intensity distribution or irradiation field of a charged-particle beam extracted from a high-energy accelerator for the utilization of the beam. Various types of magnets and/or other apparatuses such as collimators and scatterers can be employed to shape a beam profile and irradiate a target sample according to user demands. Especially, the use of a nonlinear force enables us to shape unique transverse beam profiles that can never be realized through linear beam optics. A typical example is the formation of a uniform beam using multipole (mainly, octupole) magnets in a beam transport line, which has been practically applied to uniform beam irradiation in several accelerator facilities [1-4].

It should be generally possible to form not only uniform distributions but also various shapes and distributions by designing the nonlinear beam optics properly. We have, therefore, investigated the further feasibility of nonlinear beam shaping and recently demonstrated the formation of a hollow transverse profile using octupole and sextupole magnets in a beam transport line [5]. Here, the hollow beam can be defined as a beam with a higher intensity in the peripheral (radially outer) part than that in the central (inner) part of a transverse beam cross-section, which is qualitatively different from wobbling irradiation using a spot beam in that the beam itself has a hollow intensity distribution. In this paper, we report this novel beam-profile manipulation, and introduce a possible application of the hollow beam.

Prior to our study, the formation of hollow beams was investigated with a few methods [6-8]. To the best of our knowledge, the only method that can be applied to high-energy ion beams is probably the use of a plasma lens, in which a strong nonlinear magnetic field is generated. A hollow circular profile of a high-energy (a few 100 MeV/u) pulsed heavy-ion beam was formed for the study of high energy density physics and heavy-ion inertial confinement fusion [7]. In contrast to the existing methods, our present method is simple and thus has higher applicability and controllability because the source of the nonlinear force is the magnetostatic field produced by multipole magnets.

NONLINEAR BEAM OPTICS

When the nonlinear force is applied to the beam, the phase-space distribution of the beam is distorted. This is well-known as the filamentation of the phase space [9]. The present method makes positive use of this phenomenon induced by multipole magnets in a beam transport line. In fact, the transverse phase-space shape of the beam focused with octupole magnets can be strongly deformed into an "S"-shape. Therefore, a distinct edge of the beam is generated. See Refs. [5, 10] for details of the beam behavior under the nonlinear focusing force of octupole magnets.

The beam-formation experiment was conducted at the azimuthally varying field cyclotron (with a *K*-number of 110 MeV) of the Takasaki Advanced Radiation Research Institute, National Institutes for Quantum and Radiological Science and Technology [11]. Two octupole and two sextupole magnets were installed together with some quadrupole magnets near the end of the high-energy beam transport line, as shown in Fig. 1. The detailed parameters of the beam line and multipole magnets are summarized in Ref. [3]. The ion species chosen for the experiment was a 10-MeV proton (magnetic rigidity of 0.46 Tm).

Figure 1 shows a typical design of the linear beam envelope near the target for hollow-beam formation. The beam size at the target has been designed to become relatively

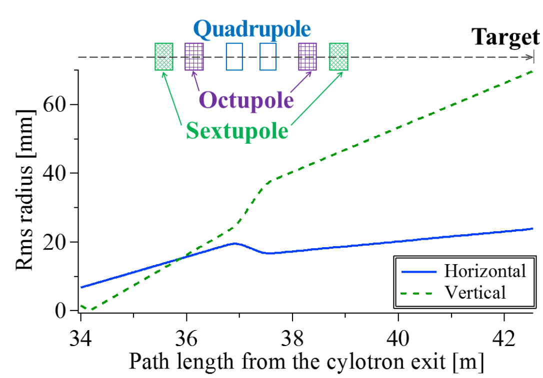

Figure 1: Schematic layout of magnets and transverse beam envelope calculation near the hollow-beam formation target. The root-mean-square (rms) emittance assumed is 2π mm·mrad in the horizontal direction and 1π mm·mrad in the vertical direction. Two sets of sextupole and octupole magnets have been installed beside the finial quadrupole doublet.

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large (5–10 cm) to conduct the tuning and measurement of the cross-sectional profile more readily. The major difference between the present beam optics for hollow-beam and uniform-beam formations is the existence of the betatron oscillation's horizontal–vertical coupling at the multipole magnets in the former. The betatron coupling is crucial for the formation of a hollow beam with various cross-sectional shapes, as will be explained later. The space-charge effect is negligible in this study because the beam current is reduced to the order of 1 nA.

EXPERIMENT

Figure 2 shows on-target real-space intensity distributions of a beam focused using octupole magnets to show the effect of the third-order nonlinear force on the beam profile. These were measured using radiochromic films [12]. When one octupole magnet was turned on with other quadrupole magnets, the tail of the original beam profile was folded toward the inside on (and near) the horizontal and vertical axes owing to the focusing effect based on the polarity of the octupole magnetic field, as shown in Fig. 2(a). A steep peak was already generated at the edge of the beam. In the oblique directions, on the other hand, particles were defocused, and the four tips at which the particle density was locally high were generated owing to betatron coupling.

When two octupole magnets were turned on, the tips were focused inward to form an elliptical cross-section, as shown in Fig. 2(b). The steep high-intensity peak surrounding the central low-intensity part of the beam was generated in the periphery of the beam. Thus, the hollow beam naturally has a distinct edge. In Fig. 2(b), the eight "streaks" grew from the four peaks slightly inside the edge on the axes, due to a strong nonlinear kick of ions with large betatron amplitude at the octupole magnets. We have confirmed that the streaks are not generated when the tail of the original beam is removed using horizontal and vertical beam-defining slits located 2.2 m before the first octupole magnet. Following this beam collimation, the resultant cross-sectional shape of the hollow beam was nearly circular, as shown in Fig. 2(c).

Furthermore, the cross-sectional shape of the hollow beam could be changed into other shapes, such as a rounded rectangle and rhombus, by simply adjusting the strengths of the two octupole magnets (with the linear beam optics kept the same). This measurement result of the change in the cross-sectional shape suggests that the cross-sectional shape of the hollow beam depends on the degree of nonlinear betatron coupling, while the cross-sectional shape is usually somewhat rectangular in the case of the uniform-beam formation in the optics where the betatron coupling is sufficiently suppressed.

The contrast, defined here as the ratio of the peak intensity to the intensity around the beam center, and the width of the edge peak were evaluated for the characterization of the hollow beam. The peak height was not even along the edge but was maximized near the horizontal and vertical axes. The maximum contrast is 14 in Figs. 2(b) and 2(c). The width of the peripheral peak is 1–2 mm for the full width at half maximum (FWHM). Here, while the beam size is much larger, the observed contrast and peak width of the edge are, respectively, higher and smaller than those of the hollow beams generated using the plasma lens [7].

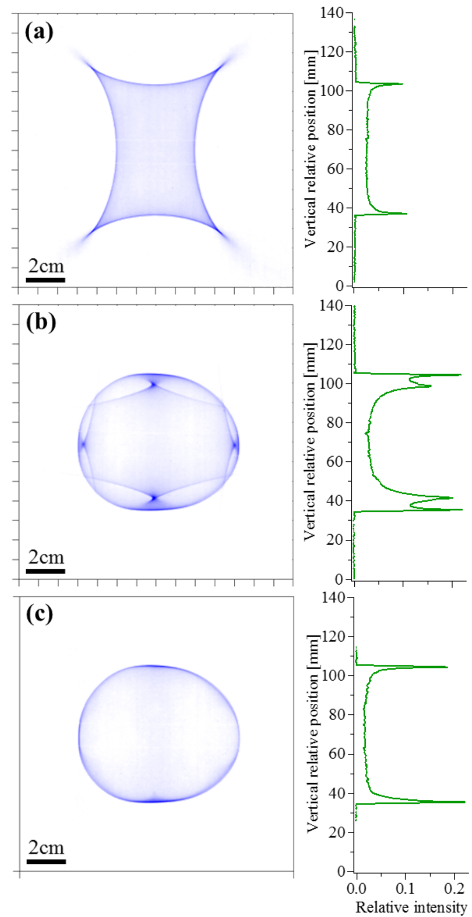

Figure 2: Spatial intensity distributions of the 10-MeV proton beam focused with one or two octupole magnets. The strengths (K_{OCT1}, K_{OCT2}) of the two octupole magnets are (a) (0 m^{-4}, 3100 m^{-4}), (b) and (c) (−10500 m^{-4}, 3100 m^{-4}). In (c), the beam tail has been collimated. The left and right panels are the cross-sectional and vertical axial distributions of the beams, respectively.

TRACKING SIMULATION

Numerical simulations were performed to confirm the measurement results above. In the simulation, a particle-tracking code that can consider the ideal nonlinear magnetic fields produced by multipole magnets (up to dodecapole) was employed [10]. The beam optics, the same as in Fig. 1, was incorporated. As an initial condition, the transverse intensity distribution of the beam was assumed to be Gaussian, and the un-normalized rms emittance ε was set as 2π mm·mrad in the horizontal direction and 1π mm·mrad in the vertical direction, according to past measurements [3].

Figure 3 presents the on-target beam profiles, where the beam-optical parameters including the two octupole magnets are the same as those in Fig. 2(b). As can be seen, an elliptical hollow beam similar to the profile in Fig. 2(b) has

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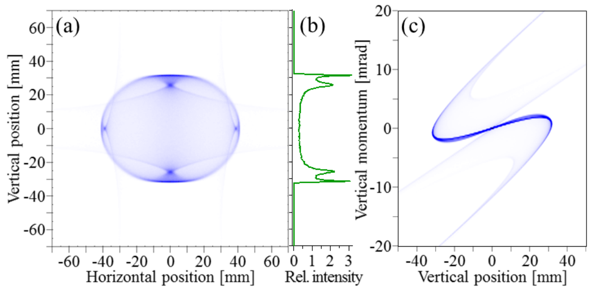

Figure 3: Tracking simulation result of the 10-MeV proton beam focused using two octupole magnets. The beam-line parameters are the same as those in Fig. 2(b). (a) Relative intensity distribution of the beam cross-section. (b) One-dimensional relative intensity distribution along the vertical axis in (a). (c) Phase-space distribution in the vertical direction.

been formed. The maximum contrast is 11 and the peak width of the beam is 1 mm (FWHM). We have also confirmed that more than 50% of the constituent particles in the beam are concentrated in the edge peak region for the present beam optics. The transverse phase-space distribution has been bent into an S-shape due to the third-order focusing force, as shown in Fig. 3(c).

APPLICATION OF A HOLLOW BEAM

A possible application of the hollow beam is briefly introduced here. A muon experimental facility was recently developed for diverse muon sciences at the Research Center for Nuclear Physics, Osaka University. Currently, a high-energy proton beam (392 MeV, 1 μA) from a ring cyclotron is focused using quadrupole magnets and centered on a front face of a cylindrical graphite target (20 cm in length, 4 cm in diameter) for pion and muon production [13]. In order to produce low-energy (surface) muons efficiently, more low-energy pions must be generated close to the surface in the target. For this purpose, injecting a hollow beam along the side surface of the cylindrical target is a new irradiation scheme. (Beam wobbling is not preferable because local heating of the target and the periodic time fluctuation of muons should be avoided.)

The design study of the beam line is ongoing for the hollow beam formation using multipole magnets. As a first step, the effect of multiple Coulomb scattering of a round hollow beam passing through the graphite target is investigated numerically. Figure 4 shows the cross-sectional profiles of the hollow beam at the front and rear of the target. Not surprisingly, the height and sharpness of the edge peak are reduced due to multiple scattering. On the other hand, it is found that the hollow structure of the beam is roughly maintained even at the rear and that the increase of the beam size is not very significant in the present beam optics.

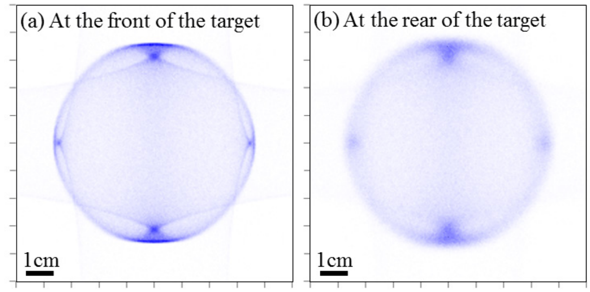

Figure 4: Cross-sectional profiles of the hollow beam at the front and rear of the target. The on-target shape of the beam has been transformed from an ellipse (Fig. 3) into a circle by adjusting the beam optics. For simplicity, particles in the hollow beam are kicked randomly at the front of the target with an average angle of 8 mrad, which corresponds to the multiple-scattering angle of a 392 MeV proton beam in a 20-cm-long graphite (2.3 g/cm^3).

CONCLUSION

The formations of various hollow ion beams using multipole magnets in a beam transport line have been demonstrated experimentally and numerically. The hollow beams have a distinct edge with a high contrast and a narrow width. The cross-sectional shape of the beam can be easily changed through the strength of the applied multipole magnets together with the linear beam optics. The proposed beam-manipulation method, based on existing accelerator technologies, is applicable to various charged-particle beams of different parameters such as the particle species, kinetic energy, and time structure.

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REFERENCES

[1] N. Tsoupas *et al.*, Phys. Rev. ST Accel. Beams 10, 024701 (2007).

[2] A. Bogdanov *et al.*, in *Proc. 2007 Particle Accelerator Conf.*, Albuquerque, USA (2007) p. 1748.

[3] Y. Yuri *et al.*, Nucl. Instrum. Meth. Phys. Res. A 642, 10 (2011).

[4] S. Meigo *et al.*, in *Proc. 5th Int. Particle Accelerator Conf.*, Dresden, Germany (2014) p. 896.

[5] Y. Yuri, M. Fukuda, and T. Yuyama, Prog. Theor. Exp. Phys. 2019, 053G01 (2019).

[6] J. W. Stetson *et al.*, in *Proc. 17th Int. Conf. on Cyclotrons and Their Applications*, Tokyo, Japan (2004) p. 483.

[7] U. Neuner *et al.*, *Phys. Rev. Lett.* 85, 4518 (2000).

[8] G. Stancari *et al.*, *Phys. Rev. Lett.* 107, 084802 (2011).

[9] M. Reiser, Theory and Design of Charged Particle Beams, Wiley-VCH, 2008.

[10] Y. Yuri *et al.*, *Phys. Rev. ST Accel. Beams* 10, 104001 (2007).

[11] K. Arakawa *et al.*, in *Proc. 13th Int. Cyclotron Conf. and Their Applications*, Vancouver, Canada (1992) p. 119.

[12] Y. Yuri *et al.*, *Nucl. Instrum. Meth. Phys.* Res. B 406, 221 (2017).

[13] D. Tomono *et al.*, JPS Conf. Proc., 011057 (2018).