Transformation of the Beam Intensity Distribution and Formation of a Uniform Ion Beam by Means of Nonlinear Focusing*)

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Avoiding undesirable thermal stress or damage of a target vessel is an essential subject in high-intensity beam irradiation for accelerator-driven neutron production. A promising method to tailor the transverse beam intensity distribution for uniform beam irradiation on the target is the use of multipole magnets. We, therefore, study the transformation and uniformization of the transverse intensity distribution by means of nonlinear focusing induced from multipole magnets. It is theoretically described how the intensity distribution is transformed and made uniform by the nonlinear focusing force. Large-area uniform proton and heavy-ion beams are experimentally formed using octupole magnets at the azimuthally-varying-field cyclotron in Japan Atomic Energy Agency.

Keywords: multipole magnet, octupole magnet, uniform irradiation, ion beam, beam transport system, beam intensity distribution

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1. Introduction

Large-area uniform irradiation with a charged-particle beam is widely used for bringing about a homogeneous irradiation effect on a sample in various applications such as materials science, biotechnology, and medicine. In accelerator-based neutron facilities, uniform beam irradiation is required in order to avoid undesirable thermal stress or damage of a target vessel. For this purpose, a high-intensity driver beam such as protons, deuterons and electrons, is usually defocused by quadrupole magnets or scanned by ac dipole magnets on the target, depending on an irradiation condition. These are, however, not always sufficient for uniform irradiation and thus for the reduction of local target heating.

The use of multipole magnets is feasible as another beam-formation method for uniform irradiation. The transverse intensity distribution of the beam can be transformed into a uniform one through the nonlinear focusing force produced with multipole magnets (mainly, octupole magnets) in the nonlinear focusing method [1, 2]. Actually, the uniform beam formation has been realized in several facilities using octupole [3–5] and sextupole magnets [6]. The nonlinear focusing method is attracting attention as a new technique for uniform irradiation with high-intensity beams in accelerator-driven neutron facilities: The use of multipole magnets is developed or planned in many high-power neutron facilities now in operation or under construction [7–11].

The requirement of the nonlinear force for the uniformization and the width of the resultant uniform distribution were already studied theoretically [2]. In the present paper, the transformation of the transverse beam intensity distribution by nonlinear focusing is explored systematically. Understanding such a basic dynamical behavior of the beam is still practically important for more efficient application as a promising uniform irradiation method. First, how the intensity distribution is transformed by octupole focusing is investigated theoretically from the viewpoint of the root-mean-square (rms) radius of the on-target beam. It is analytically derived as a function of the octupole strength from the second-order moment and verified by a particle tracking simulation. Then, the effect of the dodecapole force on more uniform distribution is studied in addition to octupole focusing. These results should be helpful for the design and operation of the accelerator and irradiation system. Finally, the experimental results on the nonlinear focusing are described. We demonstrate that large-area uniform ion beams can be formed using octupole magnets at the azimuthally-varying-field (AVF) cyclotron in Japan Atomic Energy Agency (JAEA).

2. Theoretical Analysis

Assume that a charged-particle beam with a Gaussian transverse intensity distribution travels along a linear beam transport line composed of an octupole magnet with an

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integrated strength of K_8 and following quadrupole magnets of an arbitrary configuration. We here consider only one transverse direction of motion in order to eliminate the complexity of the analysis. According to Ref. [2], the on-target spatial distribution ρ_t of the beam focused by the octupole magnet can be determined analytically. It is given as follows:

$$\rho_t = \rho_0 \Bigg/ \left| \left[\sqrt{\frac{\beta_t}{\beta_0}} \cos\phi - \frac{1}{2}\sqrt{\beta_0\beta_t}(\sin\phi) K_8 x_0^2 \right] \right|, \quad (1)$$

where β_0 and β_t are, respectively, the beta functions at the octupole magnet and at the target, ϕ is the betatron phase advance from the octupole magnet to the target, and x_0 is the particle's coordinate at the octupole magnet. ρ_0 is the initial Gaussian distribution $\rho_0 = 1/\sqrt{2\pi\varepsilon\beta_0}\exp[-x_0^2/(2\varepsilon\beta_0)]$ at the octupole magnet, with the rms emittance ε of the beam.

The transverse beam radius on the target can be derived from the following first-order and second-order moments of the on-target distribution Eq. (1):

$$\langle x_t \rangle = \int x_t \rho_t dx_t = 0, \quad (2)$$

$$\left\langle (x_t - \langle x_t \rangle)^2 \right\rangle = \int (x_t - \langle x_t \rangle)^2 \rho_t dx_t, \quad (3)$$

where x_t is the particle's coordinate at the target. The moments can be analytically integrated if the initial distribution is Gaussian. We thus have the rms beam radius σ on the target, which is the square root of the second-order moment:

$$\begin{aligned}\sigma &\equiv \sqrt{\left\langle x_t^2 \right\rangle} \\ &= \sqrt{\varepsilon\beta_t}\sqrt{1 - \varepsilon\beta_0^2 K_8 \tan\phi + \frac{5}{12}(\varepsilon\beta_0^2 K_8 \tan\phi)^2} |\cos\phi|. \end{aligned} \quad (4)$$

The beam radius can be reduced by focusing the beam with an octupole magnet of a proper field polarity, and then minimized to $\sigma_{min} = \sqrt{2/5}\sqrt{\varepsilon\beta_t}|\cos\phi|$ at a octupole strength of $K_8 = 6/(5\varepsilon\beta_0^2 \tan\phi)$. With a higher strength, σ is increased due to over-focusing.

Similarly, the dependence of σ on the multipole strength can be obtained for multipole focusing of any order. The sextupole-focusing case has been obtained in Ref. [6]. The beam centroid, which can be obtained from the first-order moment in Eq. (2), is always zero as long as the initial beam is on-axis and the order of the multipole force is odd such as octupole, dodecapole.

3. Numerical Simulation

A systematic tracking simulation was performed to confirm the analytical result in the previous section. We considered an actual layout of the beam transport system at the JAEA AVF cyclotron, equipped with octupole magnets whose axial length is 0.30 m [2]. Only the horizontal degree of freedom of the beam motion was considered here so that numerical results could be compared with the analytical results. As an initial condition of the beam, Gaussian intensity distribution and rms emittance ε of 10π mm mrad were assumed.

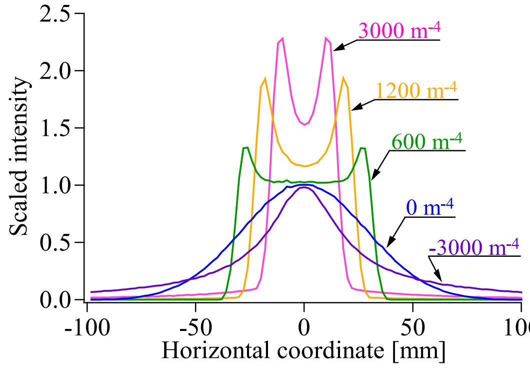

Fig. 1 On-target real-space distributions of the beam focused by an octupole magnet with several different strengths.

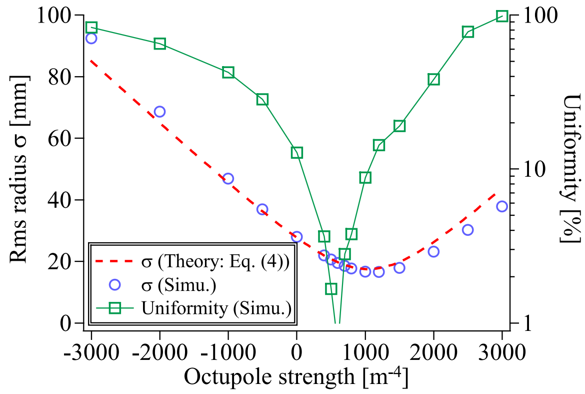

Fig. 2 Rms radius and uniformity of the beam as a function of the octupole strength. The uniformity of the beam has been evaluated within the rms radius of the beam.

Figure 1 shows the on-target spatial distributions of the beams focused with several different octupole strengths. With the positive polarity of the magnet in the present case, the tail of the Gaussian beam is folded, and thus the resultant distribution has a steep edge. The central part of the distribution is made uniform at a gradient of $600\,\mathrm{m}^{-4}$. This strength is about 30% weaker than in the case of perfect uniformization using an ideal multipole force [2]. The uniform region is surrounded by higher-intensity peaks induced through folding the Gaussian tail. A hollow beam profile is thus formed with a stronger octupole force. The beam radius σ on the target and the uniformity of the beam are obtained from the tracking result. As shown in Fig. 2, the dependence of σ on the octupole strength agrees well with the analytical result Eq. (4). The highly uniform distribution (with a uniformity below 10%) can be formed before the rms beam radius is minimized. Note that, according to the simulation result, the full width

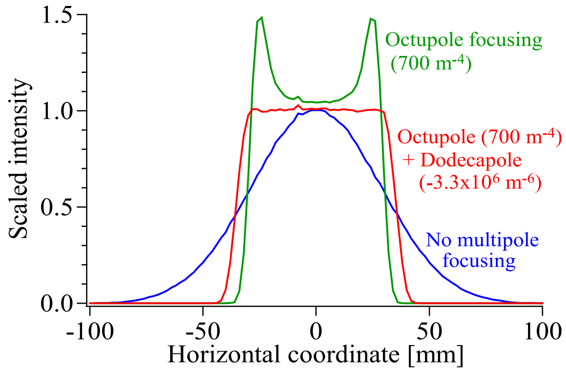

Fig. 3 On-target real-space distributions of the beam focused by octupole and dodecapole magnets with three different strengths. The blue curve is the same as in Fig. 1.

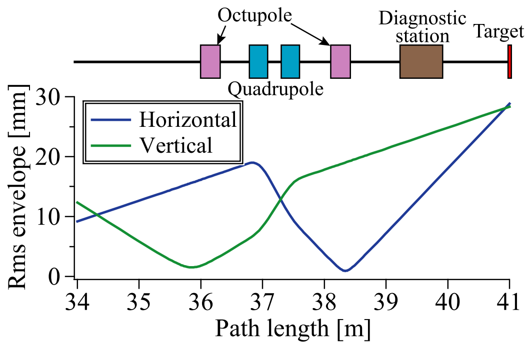

Fig. 4 Schematic layout and beam envelope around the end of the beam line at the JAEA AVF cyclotron. The path length indicates the distance from the cyclotron. The axial length of the octupole magnets is 0.30 m. The beam-optical parameter has been adjusted so that the horizontal (vertical) beam size is much larger than the other at the first (second) octupole magnet.

at half maximum is reduced with the octupole focusing force.

The high-intensity peaks at the edge may not be desirable for the application of high-intensity beam irradiation. The effect of the higher-order multipole force is, therefore, investigated for more uniform intensity distribution. As demonstrated in Fig. 3, a flattop uniform distribution without the high-intensity peaks can be formed by focusing the beam additionally with a dodecapole magnet of -3.3×10^6 m^{-6}. The width of the uniform region has been expanded to 7 cm, which agrees with the theoretical prediction [2]. Thus, the uniformity has been also improved as a whole beam. The present dodecapole gradient corresponds to the magnetic field on the order of 0.1 T at a bore radius of 100 mm for a beam with a rigidity of 1.5 Tm, which is technically well attainable.

4. Experiment

The transformation of the transverse intensity distribution into a uniform one was experimentally investigated using octupole magnets at the JAEA AVF cyclotron.

A beam with a two-dimensionally uniform intensity distribution was formed in the following procedure: The beam extracted from the cyclotron, which often had a rather asymmetric intensity distribution, was first smoothed into a Gaussian-like transverse distribution through multiple Coulomb scattering of a thin metallic foil of 1 ∼ 2 µm thick. For MeV-class heavy-ion beams, the energy loss due to multiple scattering is significant. The foil is, therefore, placed in the location where the beam envelope is not a local minimum and the betatron phase from the scattering foil to the target was optimized in order to enhance the scattering effect with the energy loss as low as possible [5, 12]. The scattering angle, energy, and charge-state distribution of the scattered beam agreed well with the theory [13, 14] and SRIM simulation [15]. Note that it may not be necessary to multiply-scatter the beam if the initial beam distribution can be regarded well as a Gaussian one. Then, the Gaussian-like beam was focused by two octupole magnets. In order to suppress betatron coupling induced inevitably by octupole magnets, a practical beam-optical setting was introduced as shown in Fig. 4: The beam size in one transverse direction is made larger than the other at the octupole magnet. Thus, two octupole magnets are required for the formation of a two-dimensionally uniform beam, which enables us to tune the octupole-focusing effect independently in the two transverse directions.

The on-target intensity distribution of the beam was adjusted using fluorescent screens in a real time and measured using Gafchromic radiochromic films. With the help of the linear response of the film's optical density to ion irradiation, the relative 2D intensity distribution can be obtained and thus the size and uniformity of the beam can be easily evaluated [16]. The measurement result of the octupole-focused beam is shown in Fig. 5 where a rectangular uniform distribution is formed. The central uniform region is surrounded by the high-intensity edge, as explained in Sec. 3. The rms uniformity is 5% in the uniform region 10-cm square. By adjusting the beam optics with octupole magnets, the on-target profile can be changed diversely depending on utilization conditions. For example, a uniform "ribbon" beam is demonstrated in Fig. 6. An almost flattop uniform distribution was formed by tuning the final quadrupole doublet and collimating the tail of the Gaussian-like beam using a beam slit before the octupole magnets. The uniformity is 3%. We have also confirmed that uniform irradiation is performed in a short time much less than 1 s at an ultralow fluence of 10^6 cm^{-2}.

5. Summary

We explored the effect of nonlinear focusing on the transverse beam intensity distribution through theoretical analysis, numerical simulations and experiments. The changes in the rms beam radius due to octupole focusing were confirmed theoretically. The dependence of the

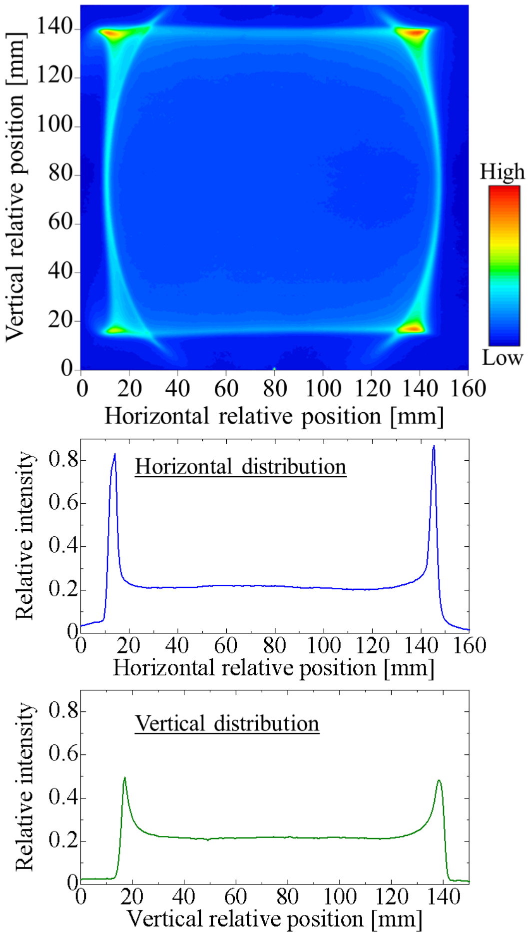

Fig. 5 Spatial intensity distributions of the 10-MeV proton beam focused by octupole magnets. The upper picture is the 2D relative distribution. The middle and lower are the cross-sectional distributions along the horizontal and vertical central axis, respectively. A Gafchromic film HD-810 was irradiated with the beam of 4 nA for 60 s. The average fluence was estimated as 7×10^9 cm^{-2} in the central uniform region.

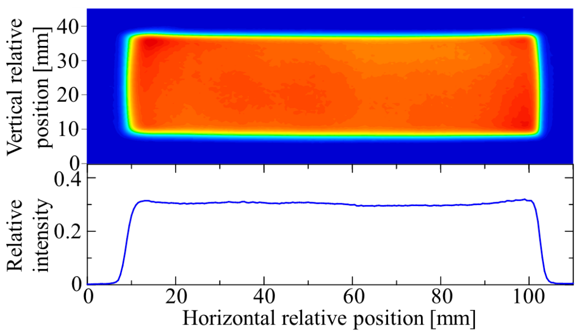

Fig. 6 Spatial intensity distributions of the 520-MeV argon beam focused by octupole magnets. The upper picture is the 2D relative distribution and the lower one is the cross-sectional distribution along the horizontal central axis, respectively. An HD-810 film was irradiated in air with the 3-nA beam extracted through a thin-foil window for 3 s. The average fluence was 1×10^8 cm^{-2}.

beam uniformity on the octupole force was also revealed. The additional dodecapole force is useful for more precise tuning of the uniform distribution. The present results are practically helpful for the design and operation of a uniform-beam irradiation system using multipole magnets. In the experimental study at the JAEA AVF cyclotron, 2D uniform beams were formed using two octupole magnets. Such an ion beam with a specific transverse distribution tailored by the nonlinear focusing force has been already employed for the beam application in space [17] and materials sciences in JAEA, and will be a useful tool also for neutron production using high-intensity beams.

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