BEAM UNIFORMIZATION USING MULTIPOLE MAGNETS AT THE JAEA AVF CYCLOTRON

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Abstract

It has been known that uniformization of a beam with a Gaussian profile is possible utilizing odd-order nonlinear forces [1]. Applying this mehcanism to beam irradiation, we can perform high-uniformity irradiation at a constant particle fluence rate over the whole area of a large target. Theoretical and experimental studies of uniform beam formation by means of the *nonlinear focusing method* are now in progress at the Japan Atomic Energy Agency (JAEA) azimuthally varying field (AVF) cyclotron facility. In this paper, we theoretically investigate uniformization of the transverse beam profile using nonlinear-focusing forces produced by multipole magnets, and numerically design a new beam line equipped with multipole magnets. The experimental results are also presented on uniformization of the beam extracted from the cyclotron.

INTRODUCTION

In recent years, nonlinear beam focusing using a multipole magnet has been widely utilized as an alternative technique for uniformization and tail reduction of the beam profile [2]. At the JAEA AVF cyclotron facility [3], we have been developing the multipole magnet beam profile uniformization system (MuPUS) for advanced ion-beam applications in the field of material sciences. This technique enables us to perform high-uniformity irradiation at a constant particle fluence rate over the whole area of a large target, and is superior to currently available uniform irradiation methods, i.e., the *beam scanning method* using time-varying dipole magnetic fields and the *beam expansion method* using scatterers.

In the present paper, we describe the summary of the theoretical development on beam uniformization [4], the beam optics based on the developed formulas, tracking results, and recent experimetal results of uniform beam formation at the cyclotron facility.

THEORETICAL DEVELOPMENT

In order to explore the effect of both odd- and even-order nonlinear magnetic fields on the beam profile, we have advanced the previous theoretical studies that revealed the possibility of beam uniformization using odd-order fields [5-7].

Uniformization Using the Odd-Order Fields

A Gaussian profile of an initial beam is assumed to be transformed to a uniform one in the beam transport system containing a thin multipole magnet which can generate an ideal nonlinear field expanded into a power series of the coordinate. The final beam intensity distribution at a target is expressed using the initial distribution and well-known Twiss parameters that define the beam optics between the multipole magnet and the target. In order to produce a uniform beam at the target, all the odd-order multipole magnetic components are required. The first two odd-order integrated strengths (octupole and dodecapole) are as follows [4]:

$$K_{\mathrm{OCT}} = \frac{1}{\varepsilon \beta_0^2 \tan\phi},\ K_{\mathrm{DODECA}} = -\frac{3}{\varepsilon^2 \beta_0^3 \tan\phi}, \tag{1}$$

where ε is the rms emittance of the beam, β_0 is the beta function at the multipole magnet, and ϕ is the betatron phase advance between the multipole magnet and the target. The resultant full width $2w$ of the uniform region is expressed by

$$2w = \sqrt{2\pi}\sqrt{\varepsilon\beta_{\mathrm{t}}}\,\left|\cos\phi\right|, \tag{2}$$

where β_{t} is the beta function at the target.

Systematic tracking simulations have been carried out to demonstrate the validity of the above formula. A uniform region surrounded by steep peaks is formed only with the octupole force, as shown in Fig. 1. By superimposing the dodecapole force predicted in Eq. (1), we can eliminate the peaks of the edges and expand the uniform region in the final profile. The full width of the uniform region is approximately equal to the theoretical value (0.19 m) in Eq. (2).

Uniformization of an Off-Axis Beam

An asymmetric beam is also possible to be transformed to a uniform beam by a combination of the even and odd-order fields. In the case of a misaligned Gaussian beam, all the orders of the multipole magnetic fields are required for uniformization. The first two nonlinear strengths

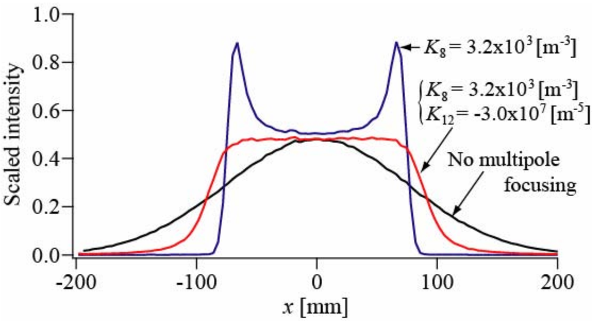

Figure 1: Final beam intensity distribution at the target for three different nonlinear strengths. When the nonlinear force is absent, the final distribution at the target is also Gaussian since the initial distribution is Gaussian. The tail of the Gaussian distribution is folded into the inside by the odd-order multipole field.

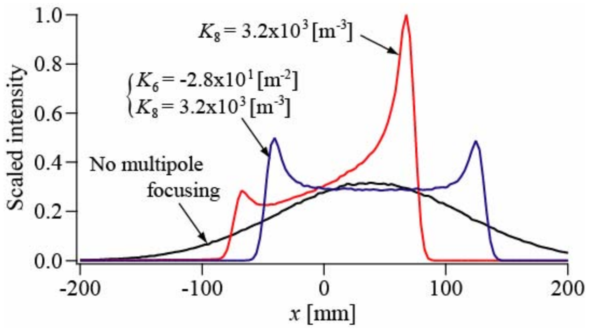

Figure 2: Final beam intensity distribution at the target for three different nonlinear strengths in the case of a misaligned Gaussian beam. Initial beam conditions are the same as those in Fig.1 except for the misalignment δx. When the nonlinear force is absent, the final distribution at the target is also off-axis Gaussian. By adding sextupole focusing to octupole focusing, the non-uniform profile caused by the misalignment can be modified into a uniform distribution, although the profile is still off-axis. Note that the final uniform beam size is larger than that in the case of δx=0 (Fig. 1) by the factor of $\exp\left[\delta x^2/2\sigma_1^2\right] \approx 1.13$.

(sextupole and octupole) are as follows:

$$K_{\mathrm{SXT}} = -\frac{1}{\beta_0 \tan\phi}\frac{\delta x}{\sigma_1^2},\quad K_{\mathrm{OCT}} = \frac{1}{\sigma_1^2 \beta_0 \tan\phi}\left(1-\frac{\delta x^2}{\sigma_1^2}\right), \tag{3}$$

where δx is the position deviation of the beam centroid and σ_1 is the rms radius of the misaligned Gaussian beam at the multipole magnet. The resultant extent of the uniform region is expressed by

$$2w = \sqrt{2\pi}\sqrt{\varepsilon\beta_{\mathrm{t}}}\,|\cos\phi|\exp\left[\delta x^2/2\sigma_1^2\right]. \tag{4}$$

As shown in Fig. 2, an approximately uniform beam can be practically produced with the sextupole and octupole fields, although higher-order multipole fields are theoretically required for perfect beam uniformization.

Uniformization Using the Even-Order Fields

Since the pioneering work done by Meads [1], it has been considered that an odd-order multipole field such as an octupole field are necessary to uniformize a Gaussian distribution [5-7]. The odd-order field can simultaneously fold both tails of the Gaussian beam profile, because the direction of the force depends on the sign of the betatron oscillation amplitude. On the other hand, an even-order field, such as a sextupole field, can fold only one side of the beam tail because the direction of the force does not depend on the sign. A combination of two even-order nonlinear magnets can, however, lead to beam uniformization by folding the two tails separately. Transformation of a Gaussian beam into an approximately uniform beam is, therefore, possible with two sextupole magnets [4].

DESIGN OF THE BEAM LINE

In the above, we have considered only one dimension in the transverse directions. In fact, the nonlinear force produced by a multipole magnet inevitably couples the horizontal and vertical motion. Such a coupling complicates the particle motion and is not practically preferable for individual adjustment of multipole focusing in each of two directions for uniformization. Multipole magnets should be, therefore, located at separate positions, each where the cross section of the beam is flat, to make the coupling as weak as possible. In other words, the multipole magnet for horizontal uniformization is located at the position where the horizontal envelope is sufficiently larger than the vertical one, and vice versa.

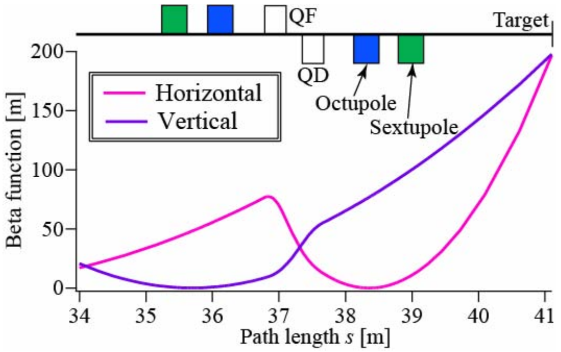

Figure 3: Beam optics for uniform beam formation at the JAEA AVF cyclotron facility. QF (QD) indicates the horizontally focusing (defocusing) quadrupole magnet. The origin of the abscissa is the exit of the AVF cyclotron. Two pairs of sextupole (axial length: 0.30 m, maximum gradient: 3.0×10^2 T/m^2) and octupole magnets (axial length: 0.30 m, maximum gradient: 1.3×10^4 T/m^3) are located where the beam cross section is flat to reduce the betatron coupling.

We have newly designed the beam line at the cyclotron facility for formation of a two-dimensionally uniform beam with multipole magnets; two octupole magnets for two-dimensional (2D) uniformization, and two sextupole magnets for correction of beam misalignment as well as uniformization without using the octupole field. A typical beam optics is shown in Fig. 3.

SIMULATION RESULT

Single-particle tracking simulations were carried out on formation of 2D uniform beams at the beam transport system (Fig. 3) of the JAEA AVF cyclotron. The initial intensity distribution is assumed to be Gaussian at the exit of the cyclotron in each transverse phase space. The final intensity distributions are shown in Fig. 4 when the strengths of the octupole magnets have been optimized so as to transform the Gaussian profile into a uniform one at the target. A uniform area 10 cm × 10 cm is achieved. The uniform area is surrounded by an overshot “wall” where the beam intensity is higher, similarly in Fig. 1.

The beam line in Fig. 3, including two bending magnets upstream, is not achromatic but has finite momentum dispersion. We have confirmed that, despite of the existence of the dispersion, the quality of the uniform beam is not affected by the energy spread on the order of 0.1 %, which is a typical value of the beams extracted from the cyclotron [8]. Note that the required multipole

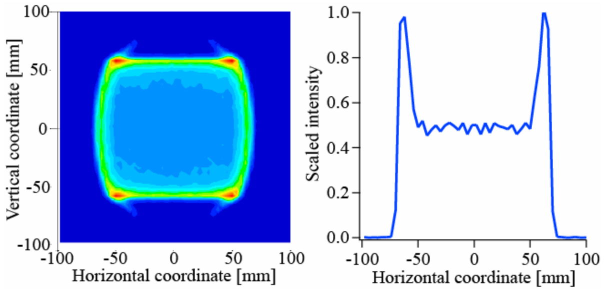

Figure 4: 2D and 1D beam intensity distributions at the target obtained by a single-particle tracking simulation based on the beam optics in Fig. 3. The optimized strengths of the two octupole magnets are -1.0×10^3 m^{-3} and 1.2×10^3 m^{-3}, respectively. The irradiation density is 5×10^3 cm^{-2} and the rms uniformity of the uniform region 8 cm square is about 5 %.

force can be lowered since the beam size at the multipole magnet becomes larger due to the dispersion and energy spread.

EXPERIMETAL RESULT

We now show recent experimental results of uniform beam formation using sextupole and octupole magnets.

The Gaussian profile of the beam is required to form a highly uniform beam as a precondition [4]. A thin aluminium foil was, therefore, set onto the beam line to produce a Gaussian beam through the multiple scattering in the foil [9].

The transverse profile at the target was tuned using two types of fluorescent screens, Cr-doped Al_2O_3 (AF995R, Desmarquest) and Tb-doped Gd_2O_2S (DRZ-PLUS, Kasei Optonix). DRZ-PLUS is suitable for real-time beam tuning since the optical decay time of DRZ-PLUS is much shorter than that of AF995R. It is worthy to note that less beam intensity is required for light emission of DRZ-PLUS by beam irradiation.

A uniform beam was formed, adjusting the strength of the multipole magnets. Coloration of a radio-chromic film was used for more precise measurement of 2D distribution. It is possible to readily measure the relative 2D dose distribution using a GAFCHROMIC film (HD-810, International Specialty Products) and a general-purpose image scanner [10]. A typical measurement result of the relative intensity distribution of the beam at the target is shown in Fig. 5. A uniform area 3 cm× 6 cm was achieved. The rms uniformity of the central part of the uniform region is about 2 %, calculated from the optical density of the irradiated film.

Alignment of the beam extracted from the cyclotron all along the beam transport line is practically impossible. There may exist misalignment in the transport process even if the beam centroid is adjusted on the target. When the beam is significantly misaligned at the octupole magnet, the resultant beam profile at the target is not uniform. In such a case, we have confirmed that it is possible to modify the non-uniform profile additionally exciting the sextupole magnet.

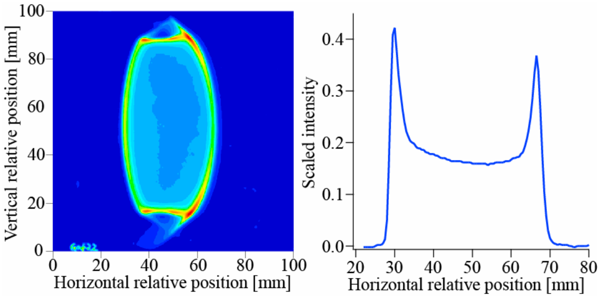

Figure 5: 2D and 1D beam intensity distributions of the beam at the target measured using a GAFCHROMIC film, which was irradiated by a 10-MeV proton beam extracted into air through a titanium foil window. Two octupole magnets were turned on. The right picture is a cross-section of the left one along the vertical relative position 50 mm. Note that the beam size was smaller than that in Fig. 4 since the film was put forward from the target position designed in Fig. 3.

SUMMARY

At the JAEA AVF cyclotron facility, sextupole and octupole magnets were installed for precise uniform beam formation, based on the developed formulas that predict both the strengths of the nonlinear magnetic fields required for beam uniformization and the resultant extent of a uniform region. We have experimentally achieved 2D uniform beams by means of the nonlinear focusing method. The deformation of a uniform profile due to beam misalignment can be compensated by a sextupole focusing field.

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