FORMATION OF A UNIFORM ION BEAM USING MULTIPOLE MAGNETS

Y. Yuri, T. Ishizaka, T. Yuyama, S. Okumura, I. Ishibori, and W. Yokota,
Takasaki Advanced Radiation Research Institute, Japan Atomic Energy Agency,
1233 Watanuki-machi, Takasaki, Gunma 370-1292, Japan
S. Watanabe, S. Kubono, and Y. Ohshiro
Center for Nuclear Study, University of Tokyo, 2-1 Hirosawa, Wako, Saitama 351-0198, Japan

Abstract

It is possible to fold the tails of the transverse beam profile to the inside, or even to make the beam intensity distribution uniform in a beam transport system by means of a *nonlinear focusing method*. A two-dimensionally uniform beam has been formed using sextupole and octupole magnets at the azimuthally-varying-field (AVF) cyclotron facility of Japan Atomic Energy Agency (JAEA). Such a uniform beam exhibits a unique feature from the viewpoint of a uniform irradiation system for applications to materials science and biology; as compared to a raster scanning system, it enables one to perform uniform irradiation over the whole area of a large sample at a constant particle fluence rate. Uniformization of heavy-ion beams as well as proton beams has been realized. In order to reduce undesirable beam halos at the target, this technique has been studied for the beam transport line of the CNS RI beam separator (CRIB) of the Center for Nuclear Study (CNS), the University of Tokyo.

NONLINEAR FOCUSING METHOD

In the ion-beam application to materials science and biology, uniform irradiation is a very useful technique to control the total dose on a large-area sample or a number of samples to be simultaneously irradiated. Recently, uniform beam irradiation systems with octupole magnets have been planned, or developed, in several facilities as an alternative uniform irradiation method [1]. This uniform beam irradiation technique is based on the idea of beam uniformization by means of the third-order nonlinear force [2].

A research and development study was started for uniform irradiation at the JAEA AVF cyclotron (K = 110 MeV) facility [3]. This method enables us to perform high-uniformity irradiation at any point over a large-area field at a constant particle fluence rate, which compensates the shortcomings of well-known methods (beam expansion using a scattering material and beam scanning using a dipole magnetic field) [4].

The beam profile can be changed by applying a nonlinear force to the beam. A Gaussian transverse distribution can be transformed into a uniform one by a combination of all the odd-order multipole (octupole, dodecapole, and so on) magnetic fields [4]. In practice, an approximately uniform profile can be produced using an octupole magnet alone. The phase-space beam shape is deformed from an ellipse into an "S"-shape by the nonlinear force.

It is also possible to uniformize an asymmetric beam profile using all the orders of multipole (sextupole, octupole, decapole, and so on) fields [4]. An example of the asymmetry is a displacement of the beam centroid with respect to the reference orbit. The displacement at the octupole magnet inclines the flat distribution of the uniform region on the target, which results in deterioration of the beam uniformity. Actually, it is possible to make an off-center Gaussian beam approximately uniform only with sextupole and octupole magnets.

The nonlinear beam line for uniform irradiation has been developed at JAEA, based on the principle above. The beam line is equipped with not only octupole magnets but also sextupole magnets for correction of the beam centroid displacement [5].

In this paper, we report the recent experimental results of uniform-beam formation by the nonlinear focusing method, and discuss its feature as a uniform irradiation technique. As an application of the method, the tail-folding of spot (non-uniform) beams using octupole magnets is also investigated to reduce beam halos at the target for CRIB of the University of Tokyo, at the RIKEN AVF cyclotron (K = 78 MeV) facility [6].

EXPERIMENT

System Layout

A uniform-beam formation/irradiation system has been developed at one of the beam lines at the JAEA AVF cyclotron facility [5]. The length of the beam line is about 40 m from the exit of the cyclotron, and two couples of sextupole and octupole magnets were installed before and after the quadrupole doublet closest to the target for formation of two-dimensionally uniform beams. The beta functions have been set flat at the multipole magnet positions, as shown in Fig. 1. This optics is designed to reduce the undesirable coupling of motion between the horizontal and vertical directions due to the multipole magnet, and, thus, enables us to adjust the two directions separately.

The uniformity of the formed beam strongly depends on the original beam distribution, while the distribution of a beam extracted from the cyclotron is usually not Gaussian. To form a highly uniform beam, an initial distribution should be simple such as a Gaussian or

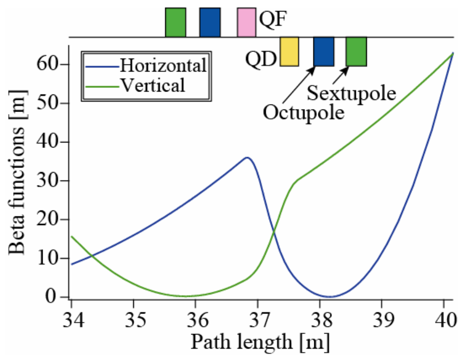

Figure 1: Layout of the magnets and beta functions around the end of the beam line for uniform-beam formation. The origin of the path length is set at the exit of the cyclotron. QF (QD) denotes the horizontally focusing (defocusing) quadrupole magnet. Two couples of sextupole (effective axial length: 33 cm, maximum gradient: 3.0×10^2 T/m^2) and octupole magnets (effective axial length: 33 cm, maximum gradient: 1.3×10^4 T/m^3) are located where the beam cross-section is flat ($\beta_x/\beta_y >> 1$ or $\beta_x/\beta_y << 1$).

parabolic distribution [4]. Thin aluminum foils (0.8 ~ 3 µm thick) are, therefore, inserted at two separate locations on the beam line to make the initial beam distribution approximately a Gaussian one. The horizontal and vertical phase advances from the first foil to the second have been set to be about 90*n* degrees (*n*: odd integer) so that the phase-space distribution becomes sufficiently Gaussian.

Uniform-Beam Formation

Figure 2 shows a typical example of a two-dimensional (2D) distribution of a beam focused by the octupole force. The distribution was measured using a radio-chromic film (GAFCHROMIC film, International Specialty Products Inc.). It is possible to readily measure the relative 2D dose distribution using an irradiated GAFCHROMIC film and a general-purpose image scanner [7]. The maximum area of the uniform beam is limited to about 6 cm × 6 cm due to the size of the beam pipe. The root-mean-squared (rms) uniformity of the central part of the uniform region is 2 %, as calculated from the optical density of the irradiated

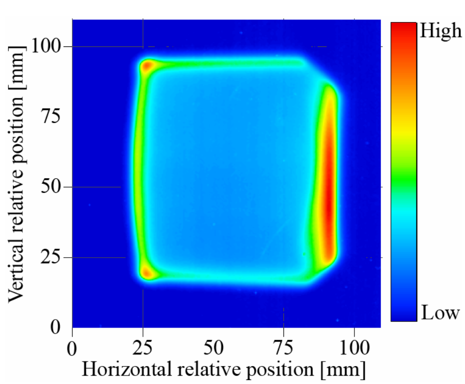

Figure 2: 2D intensity distribution of a 10 MeV proton beam on the target. The relative intensity of the beam is obtained from the optical density of the irradiated GAFCHROMIC film.

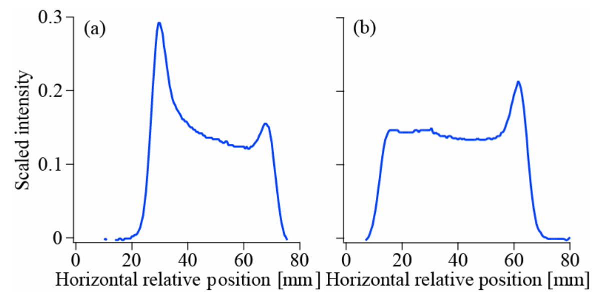

Figure 3: 1D intensity distributions measured on the target, indicating the effect of the beam centroid displacement (a) and sextupole field (b).

film. Note that the higher-intensity "wall" surrounding the uniform region is produced by overshot tail-folding through octupole focusing [4]. The intensity of the wall can be reduced by collimating the tail of the Gaussian distribution upstream of the multipole magnet.

We examined the effect of the transverse beam position on the uniform profile. The resultant profile is deformed as expected in Ref. [4] (Fig. 3(a)) when the beam centroid displacement is significant at the octupole magnet. The inclined distribution can be corrected into a uniform one by adding sextupole force as demonstrated in Fig. 3(b).

We also tried uniformization of heavy-ion beams using 13 MeV/u $^{20}Ne^{7+}$. The foil for obtaining a Gaussian distribution changes the charge state of ions and, thus, lowers the magnetic rigidity of the beam. In the present case, passing through the scattering foil, most part of the beam becomes fully stripped ($^{20}Ne^{10+}$). Adjusting the gradients of the magnets, we obtained a similar uniform profile on the target as shown in Fig. 2.

CHARACTERISTICS AS A UNIFORM IRRADIATION SYSTEM

In this section, we discuss the feature of the nonlinear focusing method as a uniform irradiation system, in comparison to the raster scanning method.

In the raster scanning method, the uniform irradiation field is achieved by sweeping a focused non-uniform beam two-dimensionally at different scanning frequencies for each direction (horizontally 50 Hz, and vertically 0.25 ~ 5 Hz in the case of the JAEA cyclotron facility). Namely, the *local* particle fluence rate on the target is not constant but periodically changes from zero to a very high value, depending on the two frequencies. This time-dependence of the fluence is undesirable, e.g., in the case where local target heating, induced by irradiation of a high-intensity beam, is intolerable.

On the other hand, in the nonlinear focusing method, the intensity distribution of the beam itself is uniform. The particle fluence rate is, therefore, constant at any point over the irradiation area. This feature is especially suitable to observe a transient phenomenon of the sample during irradiation. At JAEA, an irradiation test of the uniform beam has been started for the study of the radiation tolerance of solar cells for space use; a very high and time-dependent local fluence rate caused by the

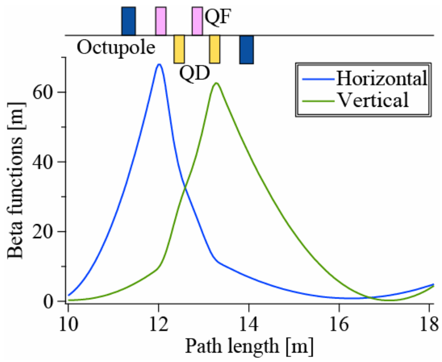

Figure 4: Layout of the magnets and the beta functions around the end of the CRIB beam line in the RIKEN AVF cyclotron facility, assumed for a beam-tail-folding simulation. We have considered two octupole magnets for tail-folding. The waist position is slightly shifted from the target so that the phase-space ellipse of the beam can be folded into an S-shape and thus the tail can be shortened on the target. The effect of the beam axis rotation, introduced to achromatically switch the beam for another experimental line [8], is ignored for brevity.

raster-scanned beam does not agree with the actual space environment and, thus, may affect the result.

Another merit of this method is to allow short-time irradiation. In raster scanning, the minimum irradiation time is limited by the scanning frequency and the tolerable uniformity. If the lower frequency is, for instance, 1 Hz, the irradiation time should be longer than 100 s to tolerate a dose error of 1 % caused by the difference of the number of scanning times. In order to lengthen the irradiation time, the beam current may be forced to be reduced. This procedure sometimes makes tuning of the beam spot size difficult. On the other hand, there is, in principle, no lower limit for the irradiation time in the nonlinear focusing method. As an example, even the irradiation time of much shorter than 1 ms is possible by chopping the beam using an electrostatic deflector. It is also possible to make the particle fluence rate very low using an attenuator mesh since the uniform beam profile is less sensitive to inserting the mesh. The dose rate during irradiation and/or the total dose can be widely changed by combining these techniques.

TAIL-FOLDING OF A SPOT BEAM

At the CNS, a smaller beam spot without halos is needed at the window-less gas target for nuclear physics experiments using high-intensity radioactive-isotope beams. The nonlinear focusing method is, therefore, applied to tail-folding of the beam spot. The effect of the tail-folding by octupole focusing has been numerically studied.

An example of the designed lattice function is shown in Fig. 4. To reduce the betatron coupling induced by the octupole force, the flat optics is again adopted at the octupole magnet positions. We have confirmed, by single-particle tracking simulations, that the tail of the beam with a Gaussian profile can be folded into the inside on the target (Fig. 5). The rms beam size is decreased by more than 20 %, and, thus, the peak intensity is increased by more than 20 % through octupole focusing. Further studies are in progress to verify the tail-folding of an actual beam with a halo, the effect of the beam axis rotation that induces the betatron coupling [8], etc.

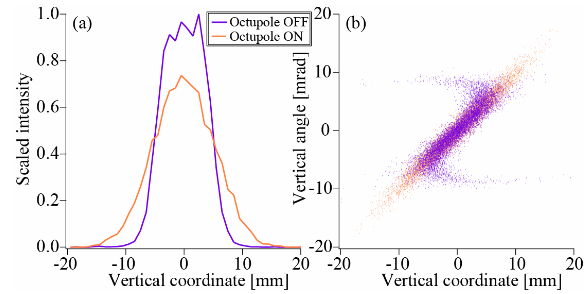

Figure 5: Real-space and phase-space distributions of the beam on the target obtained by single-particle tracking based on the beam optics in Fig. 4. The ion species is 6.4 MeV/u $^{14}N^{6+}$ with the rms emittance of 6π mm mrad.

SUMMARY

A nonlinear focusing method has been applied not only to achieve large-area uniform irradiation but also tail-folding of a spot beam. A large-area uniform transverse beam profile of protons and heavy-ions has been achieved using sextupole and octupole focusing at the JAEA AVF cyclotron facility. The beam provides a constant particle-fluence rate on the whole area of the sample, and allows extremely short-time uniform irradiation. A smaller beam spot can be obtained by tail-folding of octupole focusing on the CRIB target at the RIKEN AVF cyclotron facility.

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