UNIFORM BEAM DISTRIBUTION BY NONLINEAR FOCUSING FORCES

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Abstract

To achieve large-area uniform irradiation of ion beams for advanced applications in the fields of materials science and biology, a uniform-beam irradiation system equipped with multipole magnets has been developed at the Japan Atomic Energy Agency cyclotron facility. The system consists of a beam attenuator for the wide-range intensity control, an electrostatic beam chopper for the control of irradiation time, scattering foils for conditioning of the initial beam distribution, octupole magnets for transverse tail-folding, sextupole magnets for the correction of the beam misalignment, and the diagnostic station of the two-dimensional beam profile. In this paper, recent experimental results are described on the formation of a beam with a uniform transverse distribution in combination with the sextupole and octupole magnets. We have also confirmed that uniform irradiation can be carried out at an ultralow fluence rate or at an ultralow fluence using the beam attenuator and the beam chopper.

INTRODUCTION

In the charged-particle beam applications, such as materials science and biology, uniform irradiation is often required to obtain a uniform dose on an irradiation sample. Conventionally, a *raster scanning method* and a *multiple scattering method* have been widely used. Recently, a *nonlinear focusing method* is developed where the transverse beam profile is made uniform by the nonlinear focusing forces of multipole magnets [1, 2]. At Japan Atomic Energy Agency (JAEA), a uniform irradiation system, called MuPUS (multipole-magnet beam profile uniformization system), has been developed. Both sextupole and octupole magnets have been installed for more elaborate uniform-beam irradiation [2]. The feature of this method is simultaneous uniform irradiation of a large-area sample, namely, uniform irradiation at a constant particle fluence rate in any position of the sample. Therefore, the shortening of the irradiation time can be expected since the achievable uniformity of the dose distribution is independent of the irradiation time unlike the raster scanning method, which requires a long irradiation time for sufficient uniformity [3]. In this paper, we report the recent experimental results of several uniform distributions using multipole magnets.

EXPERIMENT

System Layout

Figure 1 shows the layout of the azimuthally-varying-field (AVF) cyclotron facility [4] of JAEA, where MuPUS has been installed. The main components for uniform-beam formation and irradiation are as follows:

- Beam attenuator for the wide-range control of the beam intensity.
- Electrostatic beam chopper for the control of irradiation time.
- Scattering foil for conditioning the initial distribution of the beam extracted from the cyclotron.
- Octupole magnets for folding the transverse tail of the conditioned beam, and then making the beam profile uniform.
- Sextupole magnets for the correction of the beam misalignment at the octupole magnet [2].
- Diagnostic station of the beam current and the two-dimensional (2D) beam profile near the target.

The multipole magnets are installed before the target in the high energy beam transport (HEBT) line. The beta function around the multipole magnets is shown in Fig. 2. To reduce the horizontal-vertical coupling of motion due to the multipole magnets, the cross-section of the beam is elongated in one direction, namely, the horizontal beta function is larger than the vertical one for folding the

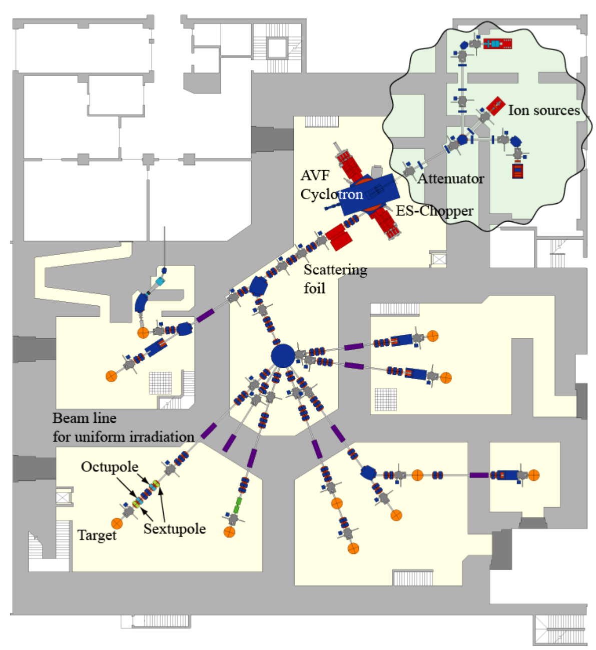

Figure 1: Schematic layout of the JAEA AVF cyclotron facility. There are four ion sources for the cyclotron (one of them is not shown in this figure). The beam attenuator and the electrostatic chopper are installed in the injection line. A scattering foil for beam conditioning is installed in the first straight section of HEBT for charge separation of a scattered (heavy-ion) beam.

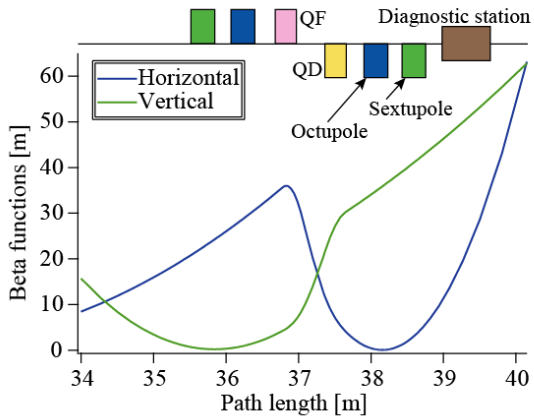

Figure 2: Layout of the magnets and the beta functions around the end of the beam line for uniform-beam formation. The origin of the path length is set at the exit of the cyclotron QF (QD) denotes the horizontally focusing (defocusing) quadrupole magnet.

horizontal beam tail, and vice versa [2]. At present, the beam is extracted into air through a 30-μm-thick titanium foil window and transported several centimeters in air for the diagnostics of the 2D beam profile and the trial use of sample irradiation.

Ion Species

Among a wide choice of ion species accelerated by the cyclotron, we have adopted a proton of 10 MeV as a R&D target ion species for the following reasons; it has sufficiently high kinetic energy to pass through the conditioning foil, the titanium window, air of several centimeters, and then a radiochromic film dosimeter (explained later) on the target. The beam optics does not have to be changed since the energy loss is very small and the charge state does not change when the beam passes through the foil.

2D Beam Profile Measurement

The most important characteristics in the process of the uniform-beam formation are the uniformity and the cross-sectional area of the beam. Therefore, the 2D beam distribution on the target is measured with Gafchromic films [5] and the characteristics are evaluated by the coloration of the irradiated film [6]. The linearity of the coloration against the particle fluence has been confirmed.

Beam Conditioning

To form a highly uniform beam, the distribution of a beam extracted from the cyclotron is required to be transformed to the Gaussian one approximately before the beam is nonlinearly focused. We have, therefore, adopted the use of a multiple scattering foil for beam conditioning. The emittance increase by multiple scattering is helpful also for forming a large-area beam. The effectiveness of the beam conditioning by multiple scattering was optimized. It is desirable to use a thicker foil for obtaining a nearly Gaussian distribution. However, too thick a foil

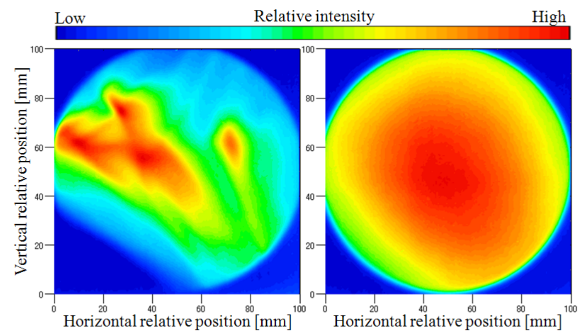

Figure 3: 2D relative intensity distributions of the 10-MeV proton beam without (left picture) and with (right picture) conditioning using a 1.5- μm-thick aluminium foil. Note that the beam size is currently limited by the 100-mm-diameter titanium vacuum window.

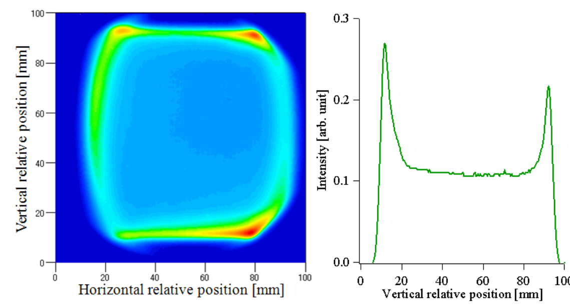

Figure 4: 2D and 1D relative intensity distributions of the beam where two octupole magnets are turned on.

results in increasing the transverse emittance of the beam beyond the acceptance of the beam line. The beam line shown in Fig. 2 can accept a beam of about 10π mm.mrad. We have confirmed that the degree of the effectiveness of multiple scattering depends on the installation location of the foil, namely, the phase-space distribution of the beam. It has been found that, as shown in Fig. 3, an aluminium foil of 1.5-μm thickness is suitable for 10-MeV proton beams whose root-mean-squared (rms) emittance before scattering is typically 1π mm.mrad in the present case.

Uniform-Beam Formation

The transverse tail of the Gaussian-like beam conditioned by multiple scattering is folded by the two octupole magnets so that the beam distribution is made uniform. The distribution is shown in Fig. 4. The cross-section of the beam is rectangular where the uniform region is surrounded by the higher intensity region. The rms uniformity of the beam is 5% in the area of 50 mm x 50 mm. The uniformity is better in the inner area of the uniform region. The achievable size of the uniform beam is currently limited by the size of the vacuum window. A target chamber will be installed for formation of a larger-area beam and several applications.

The circumferential peak (green or red region in the left picture in Fig. 4) can be removed by chopping the tail of the Gaussian beam at a specific location upstream of the octupole magnet and, thus, the nearly uniform profile can be formed.

Fluence Control

In some applications, low-fluence-rate and/or low-fluence uniform irradiation is requested. To reduce the fluence rate, i.e., beam current without affecting the beam dynamics both in the cyclotron and in HEBT, a beam attenuator can be used. It consists of 10 thin copper mesh plates, each of which has an opening ratio of 0.5, 0.1, 0.01, or 0.001. The beam current can be reduced by inserting one (or more) of the meshes onto the beam line. Recently, the specifications of the meshes were improved so that the beam intensity can be reduced more precisely with less impact to the beam profile [7]. We have confirmed that the relative profile and uniformity of the beam are less sensitive to the use of the combination of the meshes.

Another possible way to control the particle fluence is the control of irradiation time. However, a normal beam shutter is not suitable to precise control of the short irradiation time since it takes 0.1~1 s to open or close. To demonstrate the short-time irradiation of the uniform beam, a beam chopper of the electrostatic field (voltage amplitude: 1 kV) was used. We have also confirmed that it is possible to carry out uniform irradiation of a short time width (~1 ms) and of an ultralow fluence (~10^6 cm^{-2}).

Beam Misalignment

If the beam is misaligned against the magnetic center of octupole magnets, the uniform beam profile on the target is deformed [1, 2]. On the other hand, it is theoretically shown that the deformed profile can be corrected by adding sextupole focusing (instead of using dipole steering magnets) since the second-order sextupole force has an effect analogous to the dipole force that can steer the beam [2]. This was explored experimentally. When the beam passes through the center of the octupole magnet, the distribution on the target can be made uniform (blue solid curve in Fig. 5. See also the right picture in Fig. 4). If the beam centroid is deviated from the magnetic center, the final distribution is deformed (green dotted curve in Fig. 5), dependent on the magnitude of the deviation, which results in the deterioration of the uniformity. Additional sextupole focusing can correct the tilted profile to the flattop one (pink dashed curve in Fig. 5). We have also confirmed that the size of the distribution corrected by the sextupole field becomes larger than that of the original centered distribution as predicted in Ref. [2].

SUMMARY

We have studied the formation of a uniform beam by means of the nonlinear focusing method. The beam conditioning by multiple scattering is indispensable for realizing a highly uniform beam. The effect of sextupole and octupole focusing on the uniform beam profile has been explored. It has been shown that the sextupole force can compensate for the deformed distribution due to the beam misalignment.

For materials science and biology applications, we have demonstrated a high potential of this method (ultra-short-time and ultra-low-fluence irradiation). As an example, a uniform proton beam has now been applied to the radiation test of space-use solar cells [8]. This irradiation method can provide a uniform irradiation field closer to the actual space environment.

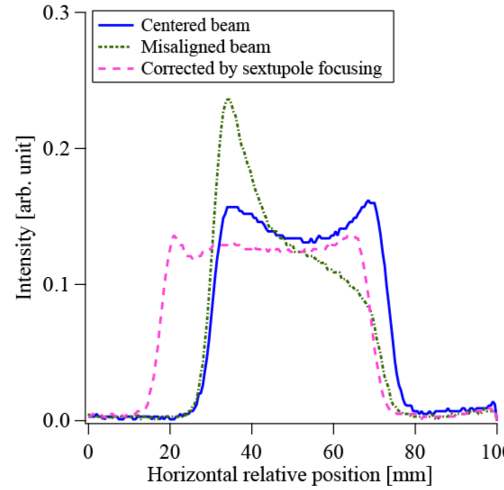

Figure 5: 1D relative distributions on the target for three different cases (see text).

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