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FORMATION OF A UNIFORM ION BEAM BASED ON NONLINEAR FOCUSING AND ITS APPLICATIONS AT THE JAEA TIARA CYCLOTRON

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Abstract

A formation/irradiation technique of large-area uniform ion beams based on nonlinear focusing of multipole magnets has been developed toward advanced research and efficient industrial applications at the TIARA AVF cyclotron facility of Japan Atomic Energy Agency. The formation procedure of the uniform beam has been established as follows: An ion beam extracted from the cyclotron is multiply scattered with a thin foil so that the transverse beam intensity distribution can be smoothed into a Gaussian-like one, prerequisite to the formation of a highly uniform beam. Then, the tail of the Gaussian-like distribution is folded into the inside by the nonlinear force of octupole magnets and eventually the distribution can be made uniform on a target. We have realized large-area uniform beams of ^{1}H, ^{12}C, ^{40}Ar, and ^{129}Xe typically over 100 cm^2 in area and below 10% in uniformity. Such uniform beams have enabled the suppression of local target heating and efficient low-fluence irradiation, and been applied to radiation degradation testing of space-use solar cells and a study on functional materials.

INTRODUCTION

The ion accelerator complex TIARA (Takasaki Ion Accelerators for Advanced Radiation Application) is an accelerator facility in Japan Atomic Energy Agency (JAEA), dedicatedly constructed for the advanced research and development (R&D) on material, biological and medical sciences and their applications [1]. The complex consists of four accelerators: An azimuthally-varying-field (AVF) cyclotron (*K* number of 110 MeV), a 3-MV tandem accelerator, a 3-MV single-ended accelerator and a 400-kV ion implanter.

A theoretical and experimental R&D study has been carried out on the formation of a large-area uniform beam with multipole magnets using ion beams from the AVF cyclotron for various applications [2-4]. The uniform-beam formation is based on the transformation of the transverse beam intensity distribution by means of the nonlinear focusing force produced mainly by octupole magnets [5]. It is possible to make the intensity distribution uniform by folding the tail of the Gaussian beam distribution with octupole magnets in a properly-designed beam transport line.

Recently, we have established the tuning procedure of the uniform-beam formation and then achieved the primary objective (to form a uniform region 100-cm^2 in area with a uniformity below 10%) using several species of ion beams from the cyclotron. In these proceedings, the latest R&D results and application examples of the uniform beam are reported.

BEAM TUNING PROCEDURE IN THE BEAM TRANSPORT SYSTEM

The schematic view of the cyclotron facility in TIARA is illustrated in Fig. 1. The main elements for the uniform-beam formation are a thin scattering foil for conditioning the prerequisite beam, octupole magnets for beam tail folding and a target station for beam measurement and utilization. The tuning procedure in the beam transport system for the efficient uniform-beam formation has been determined as follows through the beam optics design, tracking simulation, and repeated experiments.

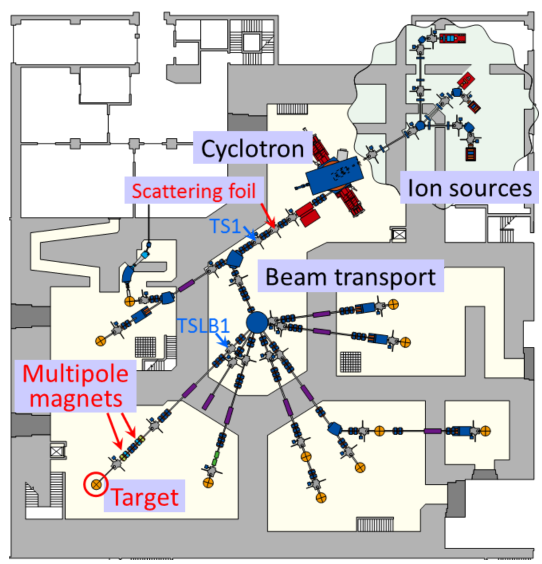

Figure 1: Schematic view of the JAEA AVF cyclotron facility. There are four ion sources, which can generate various ions from proton to osmium. A scattering foil is mounted at the first straight section after the cyclotron. The gray squares on the beam lines correspond to the beam diagnostic stations (labelled as TS1 and TSLB1) equipped with a silt, a wire profile monitor, a phosphor screen, and a Faraday cup. Multipole (sextupole and octupole) magnets have been installed in one of the beam lines for the formation of a uniform beam.

First, the transverse beam size and position are adjusted to the diameter (30 mm) of the scattering foil and the beam waist is formed at the diagnostic station TS1 using

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the triplet quadrupole and steering magnets after the cyclotron.

Table 1: Main Specifications of the Scattering Foils

Foil material	Al	Cu	Ta
Thickness [μm]	1, 1.5	2	1
Density [g/cm^3]	2.7	9.0	16.7
Radiation length [cm]	8.9	1.4	0.43

Then, the foil is inserted onto the beam axis. An ion beam extracted from the cyclotron is multiply scattered by passing through the foil so that the transverse intensity distribution of the beam becomes a Gaussian-like one, which is prerequisite to the uniform-beam formation [2]. (We actually confirmed that a sufficiently uniform beam was not formed from a "raw" cyclotron beam that had a complicated intensity distribution.) The Twiss parameters at the scattering foil and the betatron phase advance from the foil to the target have been properly chosen in order to enhance the scattering effect [3,6]. The scattering angle of 0.7~2 mrad is necessary for smoothing out the raw beam with a complicated profile. Therefore, one of the following foils, Al, Cu, and Ta, is chosen, depending on the ion species and its kinetic energy. The main specifications of the foils are summarized in Table 1. We have found that a thinner foil of a higher density is effective for the reduction of the kinetic energy loss due to multiple scattering as much as possible.

The charge state of the beam is changed and widely distributed by multiple scattering unless the ions are fully stripped and the kinetic energy of the beam is high enough. The beam with a specific charge state is, therefore, transported down to the final straight section through two bending magnets (see Fig. 1). The rms emittance of the scattered beam is increased to about 10 πmm·mrad.

The gradients of 22 quadrupole magnets after the scattering foil are usually fixed at designed values so that the number of tuning parameters is reduced. It is verified, using a wire profile monitor, that the waist beam profile similar to that at TS1 is reproduced at TSLB1.

Finally, the uniform intensity distribution is tuned mainly using two octupole and two quadrupole magnets nearby before the target (see Fig. 2). Undesirable horizontal-vertical coupling due to the nonlinear focusing force must be suppressed because it prevents the uniform-beam formation. Therefore, one transverse (horizontal or vertical) beam size must be set at much larger than the other at the locations of the octupole magnets, as shown in Fig. 2. For this purpose, the horizontally-elongated profile of the beam is checked with a profile monitor right after the first octupole magnet.

A target chamber equipped with lots of flange ports has been settled at the end of the beam line for different configurations of beam measurement and irradiation. The on-target beam profile is monitored in real time with a large-area phosphor screen. We have found that the misalignment of the beam orbit at the octupole magnets affects the cross-sectional shape and uniformity of the beam. Therefore, the beam orbit is aligned using steering dipole magnets. The beam shape is tailored by inserting slits in the beam line.

A series of the beam tuning procedure above usually finishes in about one hour.

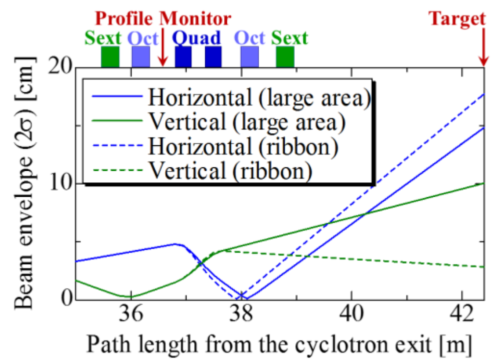

Figure 2: Transverse beam envelope around the multipole magnets and the target. The blue and green lines are, respectively, the horizontal and vertical envelopes when no multipole force is applied. The solid lines correspond to the case of a two-dimensional large-area beam, and the dashed lines correspond to the case of a horizontally-elongated ribbon beam. An rms emittance of 10 πmm·mrad has been assumed.

UNIFORM-BEAM MEASUREMENT

A large-area uniform beam formed by the procedure mentioned above was analysed using a radiochromic film. For this purpose, a precise, handy measurement technique of the transverse beam intensity distribution was developed [7]. The use of Gafchromic films (Ashland Inc.) and a general-purpose scanner enables us to measure and evaluate the intensity distribution with a high spatial resolution at a large size. We have confirmed that the increment of the optical density, induced by beam irradiation, is approximately proportional to the fluence of the beam in a low fluence region for several ion species such as H, Ar, and Xe. Therefore, the relative intensity distribution can be easily obtained, which makes it possible to evaluate the beam size and uniformity.

A measurement example of the relative beam intensity distribution is shown in Fig. 3. The uniform-intensity region over 100 cm^2 was formed while it was surrounded by the higher-intensity "wall" generated by the overshot tail of the Gaussian-like distribution. The rms uniformity of the central region is 9% in the 12-cm×11-cm area. The undesirable wall can be removed by slits installed in the beam transport line so that the entire profile of the beam can be made almost uniform. The use of dodecapole magnets is also useful to preventing the higher-intensity region as theoretically predicted in Ref. [2, 4].

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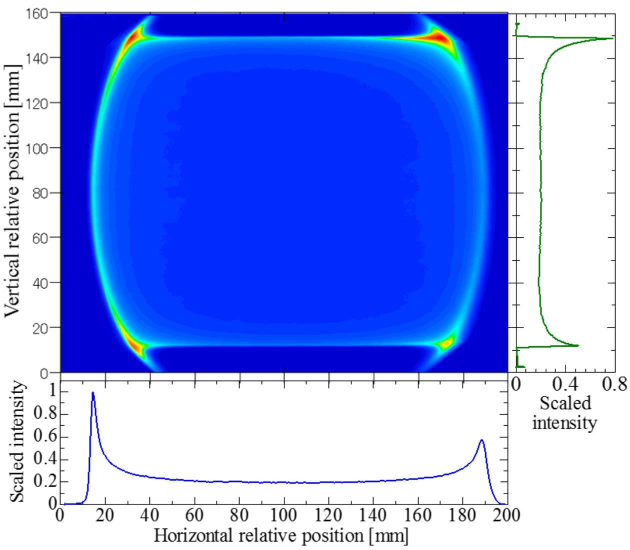

Figure 3: Relative transverse intensity distribution obtained from the optical density distribution of a Gafchromic film, HD-V2. The film was irradiated with a 4.1-MeV/u Xe beam of a few nA for 10 s. The horizontal and vertical axial distributions are shown in the lower and right sides, respectively.

Moreover, we have attained a horizontally-elongated "ribbon" uniform beam by adjusting the beam optics as shown in Fig. 2. The aspect ratio of the profile more than 15 was attained and the uniformity was 4% in Fig. 4. The ribbon uniform beam is suitable for efficient (fast) roll-to-roll irradiation of a thin long sample such as polymer films, which is useful for industrial applications. For a beam scanning irradiation method, a high scanning frequency, which makes the irradiation system large-scale, is necessary for uniform irradiation of the sample transported at a high roll-to-roll speed.

APPLICATION

Large-area uniform ion beams formed in the system have been applied to R&D studies in space and materials science in place of slow (~1 Hz) raster scanning irradiation in the TIARA cyclotron.

Proton uniform beams are utilized for the study on the radiation degradation of space-use solar cells conducted by Japan Aerospace Exploration Agency [8]. The degree of the performance degradation can be affected by local heating of the cell when the beam current density is high in the scanning irradiation method. On the other hand, the uniform beam can irradiate the whole sample continuously at a constant fluence rate (except for the 10-20 MHz repetition frequency of the cyclotron). Therefore, local heating of the sample can be suppressed. In addition, the experimental time has been reduced since the irradiation time in the low-fluence region is shortened as compared to the scanning irradiation in which short-time uniform irradiation is difficult. The irradiation technique of the uniform beam, which achieves the fluence rate up to 2×10^{11} ions/s/cm^2 for a 10-MeV proton beam, is a new testing means of solar cells.

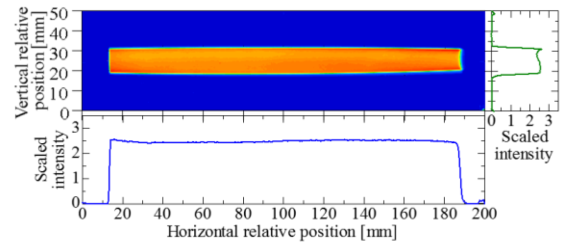

Figure 4: Relative transverse intensity distribution obtained from the optical density distribution of a Gafchromic film, HD-810. The film was irradiated with a 4.1-MeV/u Xe beam of 1.7 nA for 5 s. The horizontal and vertical axial distributions are shown in the lower and right sides, respectively.

A study on the innovative chemical modification of polymer films is explored using in-air and/or short-time uniform irradiation with heavy-ion uniform beams of Ar and Xe. Uniform irradiation at atmospheric pressure is available since a beam with a kinetic energy over about 10 MeV/u can be extracted to the air through a large-area thin-foil window instead of using the vacuum target chamber. Ultralow-fluence irradiation, for example, on the order of 10^6 ions/cm^2, is performed efficiently in a short time much less than one second by fast electrostatic beam chopping. The available beam intensity strongly depends on the ion species and its kinetic energy because of the performance of the ECR ion source and the charge-state distribution after multiple scattering. For example, the maximum fluence rate is currently on the order of 10^9 ions/s/cm^2 for a 9.3-MeV/u Ar beam and 10^7 ions/s/cm^2 for a 4.1-MeV/u Xe beam.

CONCLUSION

We developed the uniform-beam formation system using multipole magnets at the JAEA AVF cyclotron facility. An efficient procedure of the beam tuning was established. Large-area proton and heavy-ion beams has been realized at a uniformity of less than 10% and are applied to R&D experiments for space and materials science as a new useful tool instead of existing scanning irradiation.

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