Large-Area Uniform Ion Beam Formed by the Nonlinear Beam Optics at the JAEA TIARA Cyclotron

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Abstract

A uniform ion-beam formation/irradiation system has been developed at the accelerator complex TIARA in Japan Atomic Energy Agency (JAEA). In this system, a large-area beam with a uniform intensity distribution can be formed on the target by the nonlinear beam optics including octupole magnets. Therefore, the whole of a large-area sample can be irradiated uniformly at a constant fluence rate unlike a conventional scanning method and, thus, this uniform beam is suitable for short-time, low-fluence and/or low-fluence-rate irradiations. Recently, a versatile target chamber has been installed in order to conduct various beam studies and users' experiments efficiently. The ion-irradiation response of Gafchromic radiochromic films has been investigated for the evaluation of the transverse intensity distribution of the uniform beams. For several species of heavy ions, beam characteristics are explored toward realization of a heavy-ion uniform beam. We have, so far, obtained the uniform intensity distribution of 9 cm square with an rms uniformity of 5% for a 10-MeV proton beam. Such a large-area uniform beam has been used for the radiation degradation test of space solar cells.

1. Introduction

Large-area uniform irradiation is an indispensable accelerator technique for bringing about a homogeneous irradiation effect in various quantum-beam-applied researches such as radiation effect studies on space-use electronic devices. A new uniform-beam formation system has been developed at the JAEA TIARA azimuthally-varying-field (AVF) cyclotron for materials and biological sciences. The principle of the system is based on the nonlinear focusing method (NFM): The tail of the Gaussian transverse intensity distribution is folded into the inside by the nonlinear focusing force of multipole magnets so that the intensity distribution can be made uniform [1, 2]. Therefore, the particle fluence rate can be made constant anywhere on a large-area sample. This characteristic of the method is suitable for uniform irradiation in a short time, at a low fluence and/or at a low fluence rate. It is, thus, anticipated that NFM can compensate shortcomings of conventional irradiation methods (a beam scanning method and a beam scattering method) and is helpful in advanced applications [3].

In these proceedings, the recent progress is summarized related to the uniform beam formation. In Sec. 2, a brief overview is given on the system of the uniform beam formation and irradiation including a versatile target chamber installed recently. The transverse intensity distribution of the uniform beam is evaluated using Gafchromic radiochromic films. The ion-irradiation response of the films is investigated in Sec. 3. Commissioning toward the formation of heavy-ion uniform beams is explored in Sec. 4. Finally, the present status is summarized in Sec. 5.

2. Overview of the uniform-beam formation system

The schematic view of the JAEA AVF cyclotron [4] and its beam lines is shown in Fig. 1. One of the high-energy beam transport lines has been improved dedicatedly for uniform beam formation and irradiation. The beam line has been equipped with two couples of sextupole and octupole magnets and a target chamber. The total length of the beam line is 42 m from the exit of the cyclotron to the target.

2.1 Procedure of the uniform beam formation

The uniform beam is formed and provided for irradiation by following the procedure below: The initial intensity distribution of the beam should be Gaussian (or parabolic) as a prerequisite for uniform beam formation. However, the profile of the ion beam extracted from the cyclotron is not Gaussian but usually asymmetric, which is a severe obstacle to forming a uniform beam. The ion beam is, therefore, multiply-scattered through a thin foil so that a Gaussian-like distribution can be obtained. The installation location of the foil and the beam optics is optimized for efficient multiple Coulomb scattering [3, 5]. Then, the Gaussian-like beam is focused by the multipole magnets installed near the target. Octupole magnets are mainly employed to form a uniform distribution. Sextupole magnets can be also utilized since they have different effects on the distribution transformation [2, 3, 6]. A dedicated beam optics has been realized for the prevention of betatron coupling due to multipole magnets [3]. During beam tuning, the on-target intensity distribution of the beam is monitored using a fluorescent screen such as DRZ-high (Mitsubishi Chemical) and AF995R (Desmarquest) [7].

For irradiation with the uniform beam, the particle fluence can be adjusted using a beam attenuator [8] and/or an electrostatic beam chopper [9]. The attenuator, composed of metallic foils with pores, can reduce the spatial intensity of the beam widely. The chopper can change the time-average intensity by adjusting the duty of the beam injected into the cyclotron. The irradiation time of the beam can be controlled also by the chopper.

2.2 Target chamber

A target chamber was installed at the end of the beam line in 2011 for efficient beam studies and users' experiments. The chamber consists of two parts as shown in Fig. 2: One is a main target chamber on the beam axis, equipped with several flanges designed for different types of beam measurement and sample irradiation. For example, a viewport, which can be seen in Fig. 2, is available for a solar simulator required in a degradation test of space-use solar cells. The other is a small side chamber that can keep 22 sheet samples (up to 21 cm square in size), which enables us to replace the samples readily without affecting a vacuum pressure in the main chamber. A sample on the target position can be exchanged within two minutes by a motor-driven changer. A vacuum pressure of the order of 10^{-4} Pa, which is required for beam transport, can be attained in about one hour if samples are sufficiently pre-degassed.

To meet the need in some experiments, the uniform beam irradiation can be performed also in air by changing the chamber setup. The beam of more than about 10 MeV/u can be extracted into the air through a 30-μm-thick titanium foil window.

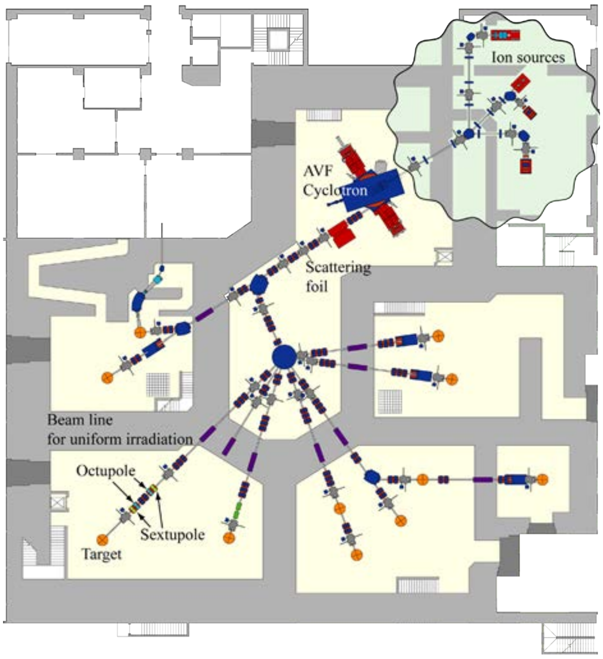

Fig. 1: Schematic layout of the JAEA AVF cyclotron (K number of 110 MeV) facility. There are four ion sources in the basement, which can produce proton and various heavy ions up to osmium. The beam attenuator and the electrostatic chopper are installed in the low-energy injection line. The scattering foil can be inserted at the first straight section after the cyclotron. A uniform beam is formed at the LB beam line equipped with multipole magnets.

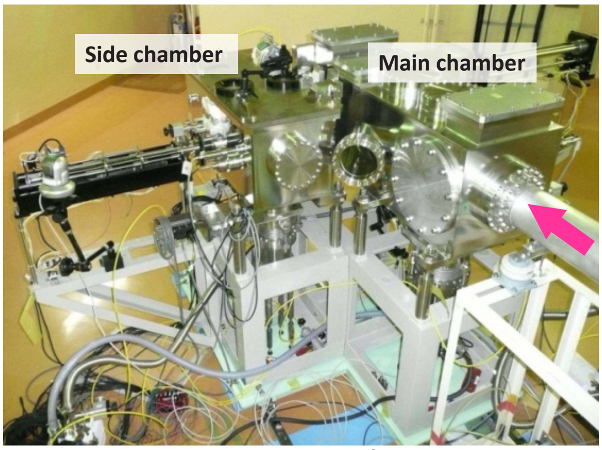

Fig. 2: Versatile target chamber for experiments using large-area uniform beams. The beam comes from the direction of the pink arrow in the picture. The whole of the chamber is settled on a linear motion guide for the quick arrangement of the target setup.

3. Intensity distribution measurement using Gafchromic films

Gafchromic radiochromic films (Ashland Inc.), whose color turns blue due to radiation exposure, are used for the measurement of the two-dimensional (2D) intensity distribution of the beam on the target. Various characteristics of the film, such as high spatial resolution, large area, relatively low-dose range, and easy handling, are appropriate as a handy measurement technique of a large-area beam. The coloring response of ion-irradiated films has been investigated as a change in the optical density using general-purpose scanners for precise analysis [10]. 10-MeV ^{1}H and 520-MeV ^{40}Ar ion beams have been used for the investigation.

3.1 Film calibration

Two types of Gafchromic films have been chosen for the present study: One is HD-810, whose active layer (6.5 μm thick) is behind a 0.75-μm-thick surface layer and coated on a 97-μm-thick polyester substrate. The other is EBT2, whose active layer (30 μm thick) is put between 80-μm and 175-μm polyester layers. According to the manufacturer, the available photon dose ranges of the films are 10~400 Gy and 0.01~10 Gy, respectively.

The following procedure was taken for film calibration: First of all, the films were irradiated uniformly with the ion beam. The beam current was measured by a Faraday cup near the target. The irradiation time was controlled by the electrostatic chopper between 10^{-3} and 10^{1} s, depending on the fluence, intensity of the beam, and the film type. Then, irradiated films were read by general-purpose scanners to digitize them into TIFF images with 16-bit RGB color intensity values. Two different kinds of flat-bed scanners were employed: Canon LiDE50 (reflection type) and Epson ES-10000G (reflection/transmission type). The irradiated films were scanned in more than one day after irradiation to prevent the color variation right after irradiation. Finally, the optical density d_X was determined for each X of RGB color values by the equation: $d_X = \log_{10}\left(2^{16} - 1/X\right)$.

Figure 3 shows the fluence response of HD-810 films irradiated with the 10-MeV H beam and scanned by LiDE50. The optical densities of all three color intensities increase linearly with the particle fluence in the low fluence range and then are saturated in the high one. The optical density obtained from the red color component is the largest in the linear-response range. On the other hand, the blue component is the least sensitive. This reflects the characteristic that the absorption of the irradiated film is the highest in the wavelength between 650 and 700 nm. Thus, the fluence of the 10-MeV H beam can be measured from 1×10^{9} to 2×10^{11} cm^{-2} with a moderate S/N ratio by choosing an appropriate color component of HD-810. When the films were scanned by ES-10000G with a transmission mode, the optical densities were slightly smaller than that in Fig. 3 although a similar linear response of the optical density was observed in almost the same fluence range.

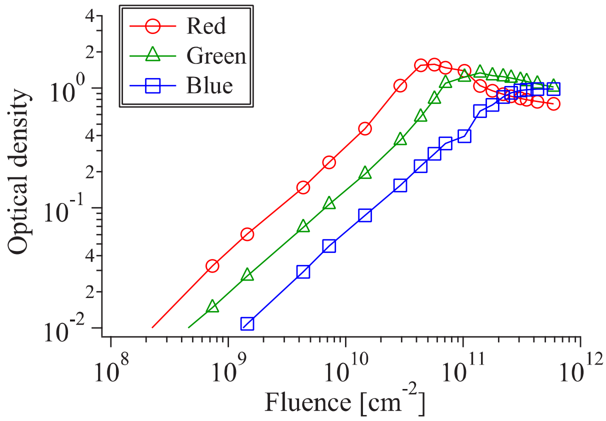

Fig. 3: Optical density of Gafchromic film HD-810 as a function of the 10-MeV H beam fluence. LiDE50 was used for film scanning. The background value (i.e., the optical density of a non-irradiated film) of about 0.04 has been subtracted from each optical density.

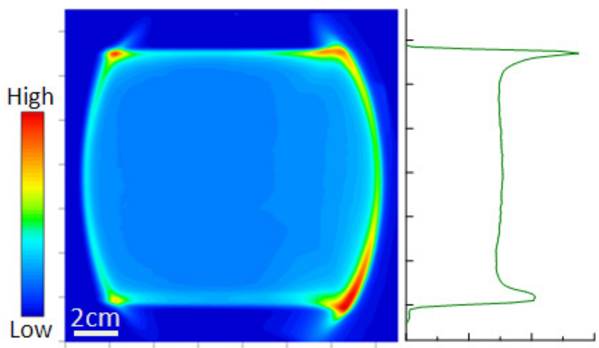

Fig. 4: Relative transverse intensity distribution of an octupole-focused uniform beam measured with a Gafchromic film. The HD-810 film was irradiated with 10-MeV H beam of a few nA for 90 s. The left and right panels show the 2D distribution and the vertical distribution along the beam central axis, respectively.

The fluence response of EBT2 to proton irradiation behaves very differently from Fig. 3. The optical density from the blue color is always high and less sensitive to beam irradiation due to the yellow fundamental color of the film. Only the optical density from the green component is approximately proportional to the fluence in the low fluence range. As expected, the available fluence (from 1×10^{8} to 3×10^{9} cm^{-2}) of EBT2 was lower as compared to HD-810, but the practical range was not as wide as the specification.

Similarly, we have found that, for 520-MeV Ar, the linear-response ranges of HD-810 and EBT2 are 1×10^{7} ~ 2×10^{9} cm^{-2} and 1×10^{6} ~ 2×10^{7} cm^{-2}, respectively.

3.2 Uniform-beam measurement

The measurement technique above is applied to the evaluation of a large-area uniform beam formed by the nonlinear beam optics. Note that the fluence evaluated from the optical density does not always guarantee the absolute value since it is not easy to control film's external conditions strictly, such as the fluence rate, elapsed time from irradiation to film reading, and environmental temperature and humidity, as well as lot-to-lot variation of the film. However, we have confirmed, by repeated experiments, that the response curve is reproducible within a tolerable level and that there always exists the linear regime of the fluence response as long as the optical density is below unity, as shown in Fig. 3. Employing this feature of the Gafchromic-film response, the relative transverse intensity distribution of the beam can be measured readily without considering various external conditions.

The relative transverse intensity distribution of the large-area uniform beam measured is shown in Fig. 4. The rms uniformity of the distribution is evaluated as 5% in the central region of 9 cm × 9 cm [11]. The uniformity is better in the inner area of the uniform region. Note that the circumferential peak, which is produced due to over-focusing of the Gaussian-like tail and unnecessary for uniform irradiation, can be flattened by removing the tail of the Gaussian beam at a specific location upstream of the octupole magnet and, thus, the nearly uniform profile can be formed [3].

4. Commissioning of heavy-ion beams

An experimental beam study with a few kinds of heavy ions has been conducted toward realization of a heavy-ion uniform beam. Generating a Gaussian-like beam by multiple Coulomb scattering is the first necessary step also for heavy-ion beams. Therefore, the kinetic-energy loss and the charge-state transformation due to multiple scattering of the heavy-ion beams were investigated in detail since they are pronounced as compared to proton beams and directly related to the beam quality.

Several different kinds of thin foils (Al, Ti Cu and Ta with 1~3 μm thicknesses) were tested for a 520 MeV $^{40}Ar^{14+}$ beam. For each foil, the loss ratio of the kinetic energy was estimated at 1~2% (5~10 MeV), which is much larger than that of the proton beam but is not significant. The charge state of the beam was also changed. It was confirmed, by analyzing with a dipole magnet, that the charge state of a large part of the Ar ions changed to 17. The equilibrium charge state and the charge distribution observed agreed with theoretical prediction [12, 13]. For a 450 MeV $^{129}Xe^{23+}$ beam, by a 3-μm-thick Al foil, the kinetic energy was reduced down to about 400 MeV and the charge state was widely distributed between 30 and 40. Only one charge state of the beam can be transported down to the target through bending magnets. We have confirmed that the heavy-ion beam intensity of the order of 10^8 s^{-1} is still available for irradiation and that a Gaussian-like beam distribution can be obtained on the target, although large reductions of kinetic energy and intensity are unavoidable in multiple scattering of low-energy heavy-ion beams.

5. Summary

We have developed the formation/irradiation system of proton and heavy-ion large-area uniform beams by means of NFM at TIARA as a new tool in the quantum-beam-based technology. The procedure of the uniform beam formation has been almost established. The 2D intensity distribution of the uniform beam can be evaluated handily using Gafchromic films. A uniform beam of 9 cm square with 5% uniformity has been achieved for a 10-MeV proton beam. The proton uniform beam has been already used for the radiation degradation test of space solar cells in collaboration with JAXA [14, 15]. For heavy-ion beams, R&D studies related to the production of functional polymer membranes have been started recently.

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