USE OF GAFCHROMIC FILMS TO MEASURE THE TRANSVERSE INTENSITY DISTRIBUTION OF A LARGE-AREA ION BEAM

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Abstract

A technique of forming a large-area uniform ion beam by multipole magnets is developed at the TIARA cyclotron facility of Japan Atomic Energy Agency. The quality of the uniform ion beam is described by the cross-sectional area and uniformity. A technique has, therefore, been developed to measure the two-dimensional transverse intensity distribution of the ion beam using Gafchromic radiochromic films, which are widely used for dose distribution evaluation in radiation therapy. The coloring response of Gafchromic films irradiated with ion beams is investigated as a change in the optical density of the film. It has been found that the optical density increases linearly with the ion-beam fluence and that, thus, the relative transverse intensity distribution of ion beams can be measured using the film at practical fluence ranges for materials and biological research. Furthermore, it is confirmed, by evaluating the microscopic pore area-density distribution in a track-etched polymer film, that the uniform intensity distribution of the multipole-focused beam is realized microscopically, too.

INTRODUCTION

A research and development (R&D) study is in progress on formation and irradiation of a large-area uniform beam using multipole magnets at the ion accelerator facility, TIARA, of Japan Atomic Energy Agency (JAEA) [1]. It is necessary to evaluate the quality of the uniform beam both precisely and handily. As a possible technique, we have, thus, employed Gafchromic radiochromic films (Ashland Inc.) [2] for the evaluation of the cross-sectional area and uniformity of the large-area uniform ion beams. The film, whose color turns blue due to radiation exposure, was originally produced for dose evaluation in X-ray or gamma-ray radiotherapy, but can be also applied to the intensity distribution measurement for different kinds of beams. The use of the film is suitable for the present purpose since the film has various characteristics such as high spatial resolution, large area, relatively low-dose range, and easy handling.

Therefore, ion-beam irradiation experiments for the film calibration were performed at the TIARA azimuthally-varying-field (AVF) cyclotron [3] to investigate the coloring response. For precise and handy evaluation, general-purpose scanners were employed to analyze a change in the optical density of irradiated films, instead of using a dedicated two-dimensional spectrophotometer.

Furthermore, the beam intensity distribution determined by the Gafchromic film was compared with the microscopic area-density distribution of track-etched pores in a polyethylene terephthalate (PET) film [4].

CALIBRATION OF GAFCHROMIC FILMS

Procedure

Two types of Gafchromic films have been chosen for the present study [2]: 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 [2], 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 10-MeV ^{1}H and 520-MeV ^{40}Ar beams from the AVF cyclotron in TIARA. The beam current was measured by a Faraday cup near the target. The irradiation time was controlled by an electrostatic beam deflector from 10^{-3} to 10^{1} s, depending on the fluence, intensity of the beam and the film type. Then, the irradiated film was read by general-purpose scanners to digitize into a TIFF image with 16-bit RGB color intensity values. Two different kinds of flat-bed scanners were employed for film reading: 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: $d_X = \log_{10}\left(2^{16} - 1/X\right)$.

Results

Figure 1 shows the fluence response of HD-810 films irradiated with 10-MeV H beams and scanned by LiDE50. The optical densities of all three color intensities increase linearly with the particle fluence at a low fluence and then are saturated at a high fluence. The optical density obtained from the red color component is the largest in the linear-response region. On the other hand, the blue component is the least sensitive. This reflects the fact that the absorption of the irradiated film is the highest in the wavelength between 650 and 700 nm [2]. Thus, the fluence of 10-MeV H beams 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

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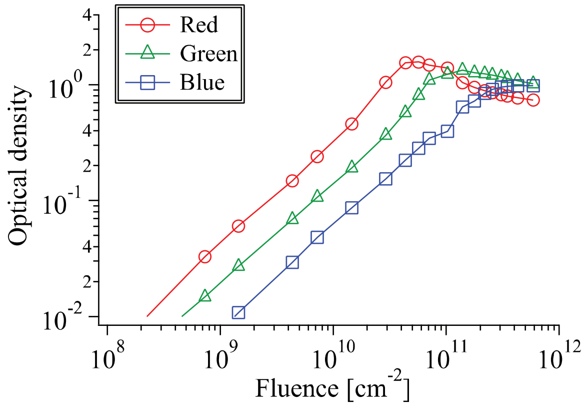

Figure 1: Optical density of Gafchromic film HD-810 as a function of the 10-MeV H beam fluence. LiDE50 was used for film scanning. The background value (i. e., the optical density of a non-irradiated film) of about 0. 04 has been subtracted from each optical density.

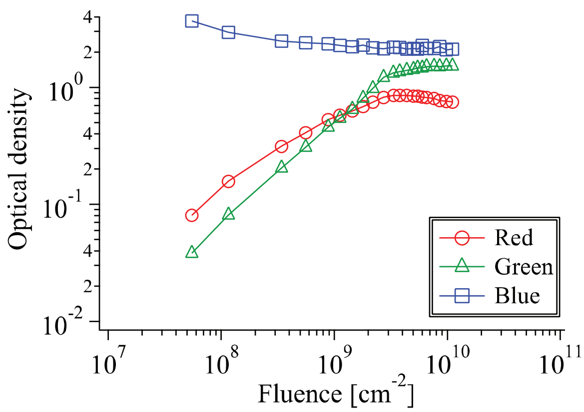

Figure 2: Optical density of Gafchromic film EBT2 as a function of the 10-MeV H beam fluence. LiDE50 was used for film scanning. The background levels of 0.15 and 0.20 have been subtracted from the optical densities of red and green components, respectively. For the blue component, the background level has not been subtracted since the optical densities at finite fluences are smaller than that of a non-irradiated film.

smaller than in Fig. 1 although a similar linear response of the optical density was observed in almost the same fluence region.

As shown in Fig. 2, the fluence response of EBT2 to the H irradiation behaves very differently from Fig. 1. 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 at a low fluence. As expected, the available fluence range (from 10^8 to 3×10^9 cm^{-2}) of EBT2 is about two orders of magnitude lower as compared to HD-810.

Similarly, it has been found that, for 520-MeV Ar, the response of HD810 is linear in the fluence on the orders of $10^7 \sim 10^9$ cm^{-2}.

In this calibration experiment, film's external conditions were not strictly controlled, such as the fluence rate, elapsed time from irradiation to film reading, and

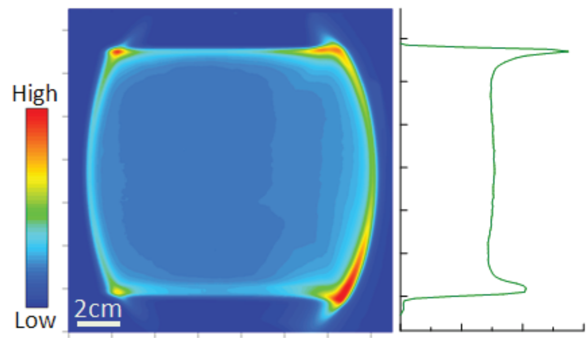

Figure 3: Relative transverse intensity distribution of an octupole-focused uniform beam measured with a Gafchromic film. The HD-810 film was irradiated with 10-MeV H beam of a few nA for 90 s. The left and right panels show the two-dimensional (2D) distribution and the vertical distribution along the beam central axis, respectively.

environmental temperature and humidity. Therefore, the response curve obtained here does not always guarantee the absolute calibration of the films. However, we have confirmed, by repeated experiments, that there always exists the linear regime of the fluence response as long as the optical density is below unity, as shown in Fig. 1. Employing this feature of the Gafchromic-film response, the relative transverse intensity distribution of the beam can be measured handily without caring about various external conditions.

MEASUREMENT OF THE TRANSVERSE INTENSITY DITRIBUTION

We apply the above measurement technique to the evaluation of the uniform beam formation using multipole magnets at the TIARA cyclotron [1].

An ion beam extracted from the cyclotron, which often has an asymmetric intensity distribution, is firstly smoothed to a sufficiently Gaussian-like transverse distribution by multiple Coulomb scattering of a thin foil. Then, the tail of the Gaussian-like beam is folded into the inside by octupole magnets so that the transverse distribution is made uniform on the target. In a series of these processes of the uniform beam formation, various relative distributions have been measured using Gafchromic films. As an example, the relative intensity distribution of the uniform beam measured is shown in Fig. 3. The rms uniformity of the distribution is 5% in the central region of 9 cm × 9 cm.

COMPARISON WITH THE TRACK-ETCHED PORE DISTRIBUTION

Another different method of the distribution measurement has been performed in order to verify the reliability of the above technique [4]. We here employ a track-etching technique, which involves irradiation of a polymer film with heavy-ion beams and chemical etching of resultant tracks in the film. Microscopic pores, each of which corresponds to an incident ion to the film, can be

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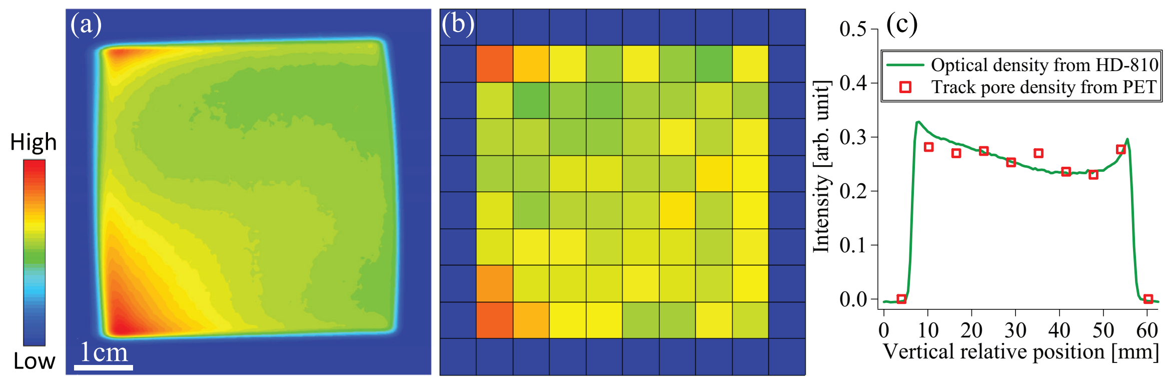

Figure 4: Relative transverse intensity distributions of the Ar uniform beam obtained from HD-810 and PET films. (a) The 2D distribution from the HD-810 film. The spatial resolution of the scanned film is 50.8 dpi. (b) The 2D distribution obtained from the track-pore density of the PET film. The area density of the pore was counted at 64 square-grid points, each of which has an area of 200 μm^2. (c) The 1D distributions along the vertical direction, extracted from (a) and (b).

formed on the film. The pore distribution should correspond to the transverse beam intensity distribution.

Procedure

Both HD-810 and PET films were irradiated with the octupole-focused 520-MeV Ar beam under the same condition: The cross-sectional size and fluence of the beam were adjusted to 5-cm square and 1×10^8 cm^{-2}, respectively. For the HD-810 film, the beam uniformity was determined from the relative intensity distribution through the optical density. On the other hand, the PET film was etched with an alkaline solution to form track pores on the film. 64 square-grid points with a microscopic area (~200 μm^2 each) on the film were observed using a scanning electron microscope. Then, the relative standard deviation (RSD) of the pore area-density distribution was evaluated as a measure of the beam uniformity.

Results

The beam intensity distribution is compared between the two films in Fig. 4. Figure 4(a) is the 2D relative intensity distribution given by the HD-810 optical density. Figure 4(b) shows the 2D relative intensity distribution obtained from the microscopic track-pore density of the PET film, which is composed of 64 data points. The two distributions do not coincide exactly, but a similar tendency can be seen as shown in Fig. 4(c) where the 1D distributions extracted from Figs. 4(a) and 4(b) are plotted. We have actually confirmed that the RSD (12%) of the 64 data points in Fig. 4(b) is equal to the uniformity of the distribution in Fig. 4(a).

In the case where the uniform distribution was deformed purposely using a steering magnet [1], the beam uniformity determined from the optical density distribution was deteriorated to 22%, which, again, agreed with the RSD of the track-pore density distribution. Thus, the present evaluation of the microscopic distribution using 64 data points is adequate in a statistical sense.

We can conclude that the technique of measuring the beam intensity distribution through the optical density of Gafchromic films reflects an actual beam intensity distribution and that the uniform intensity distribution formed by multipole magnets is realized microscopically.

SUMMARY

We explored the adaptability of Gafchromic radiochromic films HD-810 and EBT2 for measuring the transverse beam intensity distribution of energetic ion beams. For this purpose, the beam irradiation experiment was performed at the TIARA AVF cyclotron. The fluence response of the films' optical density was investigated using flat-bed scanners. It has been found that the optical density increases linearly with the ion-beam fluence at a low fluence. The available fluence ranges of the films are overlapped with those often required for materials and biological research using ion beams.

The Gafchromic-film technique of measuring the relative transverse intensity distribution is useful in the beam evaluation although it is difficult to determine the absolute fluence distribution. Using the technique, we have actually confirmed that an ion beam with a large-area uniform transverse distribution is formed by multipole magnets, and evaluated the cross-sectional area and uniformity. The relative intensity density distribution determined by the Gafchromic film was verified with the help of the track-etching technique. It has been demonstrated that the uniform intensity distribution formed by multipole magnets is realized also in a microscopic viewpoint.

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