TRANSVERSE INTENSITY DISTRIBUTION MEASUREMENT OF ION BEAMS USING GAFCHROMIC FILMS

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Abstract

A possible method of measuring the transverse spatial distribution of energetic ion beams is developed at Takasaki Advanced Radiation Research Institute, National Institutes for Quantum and Radiological Science and Technology (formerly, Japan Atomic Energy Agency). For this purpose, a radiochromic film, Gafchromic film (Ashland Inc.), is employed since it enables us to easily measure a large-area irradiation field distribution at a high spatial resolution. Gafchromic EBT3 and HD-V2 films are irradiated with ion beams of various species and kinetic energies extracted from a cyclotron and electrostatic accelerators at QST/Takasaki. Then, the coloration response of the films is analyzed in terms of the optical density. It is demonstrated that EBT3 and HD-V2 films are useful for the beam profile measurement at low fluence and at low energy, respectively.

INTRODUCTION

Various kinds of ion beams with different kinetic energies ranging from 0.1 keV/u to 10 MeV/u are widely used for radiation science research related to materials science and biotechnology in Takasaki Ion Accelerators for Advanced Radiation Application (TIARA), National Institutes for Quantum and Radiological Science and Technology (QST) [1]. It is necessary to measure the transverse spatial intensity distribution and fluence distribution of the ion beams for the utilization. To measure such a two-dimensional (2D) beam profile, we here employ a Gafchromic radiochromic film [2, 3] (Ashland Inc.), which is well-known as a useful dosimetry tool in ion-beam cancer therapy as well as in radiation therapy using photon beams. The combined use of the films and a general-purpose flatbed scanner enables us to easily measure the transverse intensity distribution of a large-area (over 100 cm^2) beam with a high spatial resolution (below 1 mm). We actually developed the technique of measuring and evaluating the beam profile for previous models of Gafchromic films, EBT2 and HD-810 [4, 5].

In this study, the irradiation responses of successor models, EBT3 and HD-V2, to various ion beams in TIARA, QST are investigated experimentally for the beam profile measurement at low fluence and at low energy, respectively.

GAFCHROMIC FILMS

The structure of EBT3 film is as follows [2]: The active layer (nominally, 28 μm in thickness and 1.35 g/cm^3 in density) is sandwiched by two polyester films of 125 μm in thickness. On the other hand, HD-V2 film is composed of an active layer (nominally, 12 μm in thickness and 1.2 g/cm^3 in density) and a 100-μm-thick polyester base. There are two major differences in the two models. One is the dose range. According to the manufacturer, it is 0.01–40 Gy for EBT3 and 10–1000 Gy for HD-V2. Thus, the profile measurement at low fluence is expected using EBT3. The other is the existence or nonexistence of a surface layer. For EBT3, the kinetic energy of an incident ion beam must be higher than, for example, 3 MeV for H, 6 MeV/u for C, and 8 MeV/u for Ar so that the beam can reach the active layer through the 125-μm-thick surface film. In contrast, HD-V2 might be applied to lower-energy ion beams since the active layer is uncovered.

The coloration of the films due to ion irradiation is quantified as optical density (OD). Films were read at the transmission mode with a general-purpose flatbed scanner ES-10000G (EPSON) according to a procedure recommended by the manufacturer [6]. Then, the image obtained was digitized into 48-bit (3×16-bit) red-green-blue (RGB) color values at a spatial resolution of 127 dpi. The OD was obtained from the RGB color value using the following equation: $OD_X = \log_{10}(65535/I_X)$, where I_X is the 16-bit color value in a red, green, or blue color channel.

ION IRRADIATION

The ion irradiation was carried out in TIARA. EBT3 films were irradiated uniformly over a wide fluence range with three different species (10 MeV ^{1}H, 27 MeV/u ^{12}C, and 13 MeV/u ^{40}Ar) of ion beams accelerated in an azimuthally-varying-field (AVF) cyclotron with a *K*-number of 110 MeV [7]. These beams have sufficiently high energy to reach and penetrate the active layer of the film. The beam size and the current were adjusted to 30–50 cm^2 and to the order of 1–10 nA, respectively, depending on ion species.

HD-V2 films were irradiated with ^{12}C ion beams between 27 MeV/u and 1.5 keV/u from the AVF cyclotron, the 3-MV tandem accelerator, and the 400-kV implanter [8]. Note that the range of the beam is shorter than the thickness of the active layer when the kinetic energy of the incident C beam is lower than 0.9 MeV/u.

The OD averaged over the uniform irradiation area was obtained, whose root-mean-square (rms) uniformity was typically below 10%.

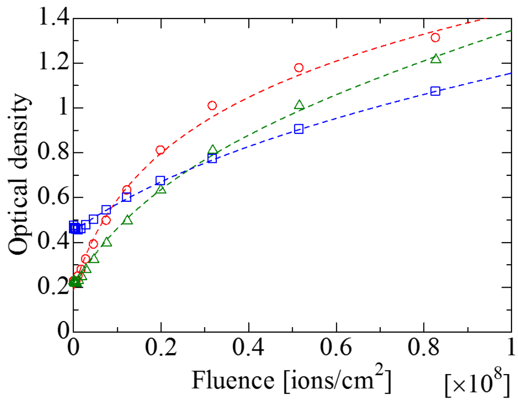

Figure 1: OD response of EBT3 films irradiated with the 13-MeV/u Ar beam. The ODs in all three color channels are plotted as a function of the fluence. Dashed lines are the response curves obtained using Eq. (1).

RESULT AND DISCUSSION

Irradiation Response of EBT3

The OD response of EBT3 to 13-MeV/u Ar ion irradiation is shown in Fig. 1. The ODs in the three (red, green, and blue) color channels are plotted as a function of the fluence. The visible blue coloration was observed from a very low fluence of the order of 10^5 ions/cm^2. The OD in the blue channel is the largest among the three ODs at low fluence because of the yellow original color of an unirradiated film. The red channel is the most sensitive, while the blue channel is the least. This behavior is very similar to that of the films irradiated with ^{60}Co gamma rays [9].

The net OD responses of EBT3 to the three species of ion beams are summarized in Fig. 2. In these logarithmic plots, the OD of the unirradiated film has been subtracted from each data to clearly recognize the range difference among ion species and the linearity of the OD increment. As seen in the figure, the fluence range is lower for a heavier ion species. This is because the linear energy transfer (LET) is higher for heavier ion species [5]. According to the SRIM calculation [10], the average LETs in the EBT3 active layer are 5.8 keV/μm for H, 97 keV/μm for C, and 1.7 MeV/μm for Ar in the present case. In a low fluence region, the increment of the OD is approximately linearly proportional to the fluence when OD < 0.1 for all the ion species in all three color channels. In this linear response range, the relative intensity distribution of the ion beam can be determined simply from the OD distribution.

2D Beam Profile Measurement

The 2D intensity distribution of the beam can be determined in a wide fluence range using an OD response curve including a nonlinear-response region. The response data is, therefore, fitted by the following rational function [6]:

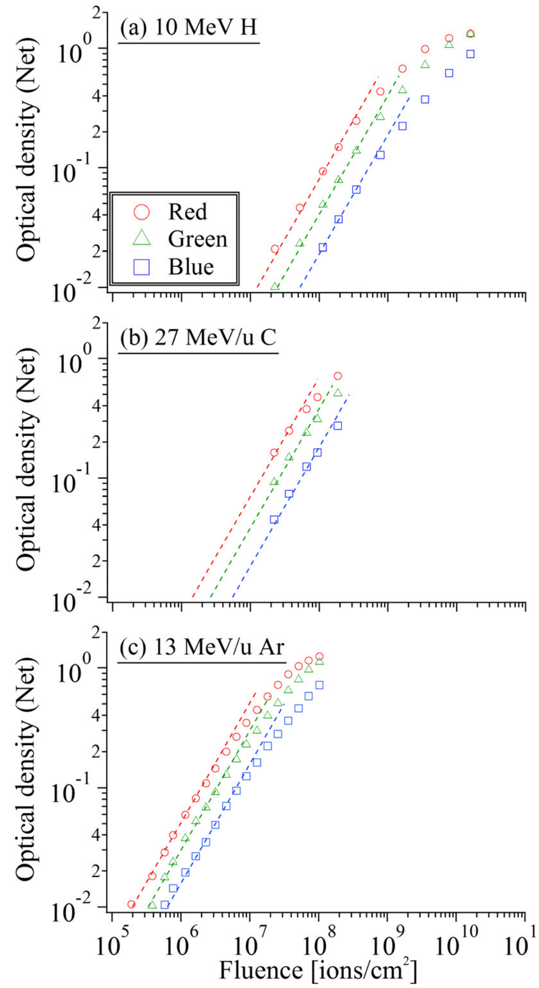

Figure 2: Net OD response of EBT3 to H, C, and Ar ion beams. The ODs in all three color channels are plotted as a function of the fluence. Dashed lines are the linear fitting results in a low fluence region.

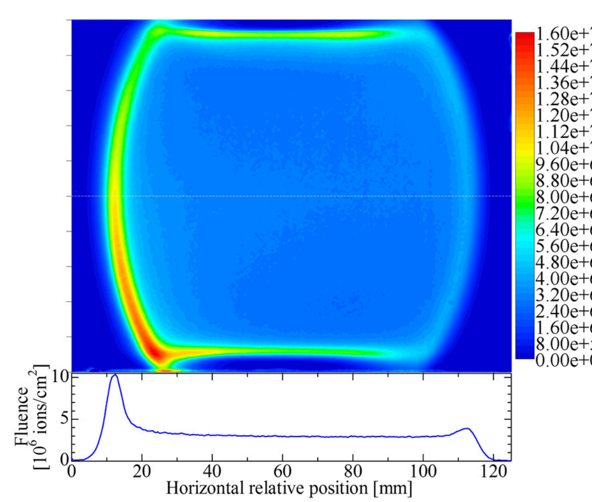

Figure 3: Fluence distribution of the 13-MeV/u Ar beam, obtained from the response curve of EBT3 films. The graph in the bottom shows the 1D intensity distribution along the central horizontal axis (dashed line).

 ISBN 978-3-95450-147-2

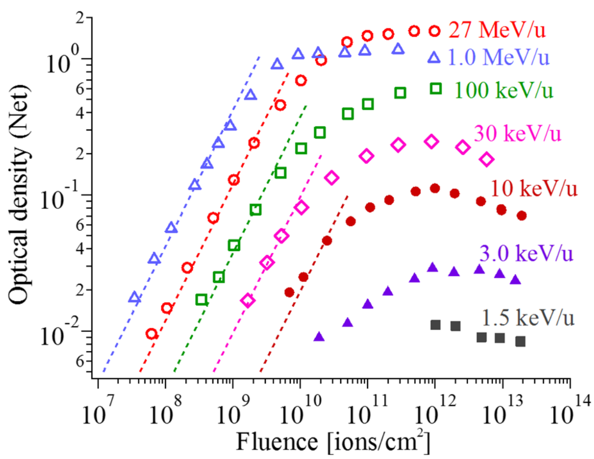

Figure 4: Net OD response of HD-V2 to C-ion irradiation at seven different kinetic energies. The net ODs in the red channel are plotted as a function of the fluence of the beam. Dashed lines are the linear fitting results in a low fluence region.

$$\mathrm{OD}_X(F) = -\log_{10}\left(\frac{a_X + b_X F}{c_X + F}\right), \quad (1)$$

where F is the fluence and a_X, b_X, and c_X are the fitting coefficients for a color channel X (red, green, or blue). For example, the three coefficients a_R, b_R, and c_R are 4.30×10^6 cm^{-2}, -2.98×10^{-3}, and 6.63×10^6 cm^{-2}, respectively, in the red channel for the 13-MeV/u Ar beam in Fig. 1. The response curves of the three channels are plotted in Fig. 1.

A measurement example of a 2D intensity distribution obtained using Eq. (1) is shown in Fig. 3. A large-area beam with a uniform central region surrounded by a high-intensity peak was generated by folding the tail of the Gaussian-like intensity distribution using octupole magnets [11]. The beam current was a few nA and the irradiation time was 0.3 s, which was controlled by an electrostatic chopper. It was found that the rms uniformity of the central 8-cm-square region in Fig. 3 was evaluated as 9%.

Low-Energy Ion Irradiation of HD-V2

As mentioned above, HD-V2 might be available to lower-energy ion beams because of no surface protection layer. We, therefore, investigated the kinetic-energy dependence of the HD-V2 response [12].

The irradiation result is summarized in Fig. 4. For simplicity, the net OD in the red channel has been plotted since it is the most sensitive among the three color channels, similarly to Fig. 2. From the figure, we can recognize that the linear-response OD range, the sensitivity, and the maximum OD depend strongly on the kinetic energy of the beam. The OD increment is well proportional to the fluence at low fluence when the kinetic energy of the incident beam is higher than 10 keV/u, as depicted by the dashed lines in Fig. 4. In contrast, the OD change was very small and entirely nonlinear with respect to the fluence below 10 keV/u. Moreover, we could not sufficiently avoid undesirable coloration of the films induced by the frequent electric discharge of the film in this low-energy range.

We have actually confirmed that the 2D fluence distribution like Fig. 3 can be obtained for ion beams of the orders of 10 keV/u by following the same procedure as described in the previous subsection. It can be concluded, from these results, that HD-V2 is practically available to low-energy ion beams down to approximately 10 keV/u, at which the linear response of the OD is observed without the undesirable coloration by the discharge.

CONCLUSION

In this study, the irradiation response of Gafchromic EBT3 and HD-V2 films to various ion beams was investigated experimentally for the application to the measurement and evaluation of the 2D beam profile. The characteristics of the film, such as the fluence range and the response linearity, were specified for various ion beams. EBT3 is useful for the 2D profile measurement of ion beams around 10 MeV/u at low fluence. We have also demonstrated that HD-V2 is available for ion beams with kinetic energies two or three orders of magnitude lower than that available for EBT3.

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