ION-IRRADIATION RESPONSE OF GAFCHROMIC FILMS AND THEIR APPLICATION TO THE MEASUREMENT OF THE TRANSVERSE BEAM INTENSITY DISTRIBUTION

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Abstract

The response of radiochromic films, Gafchromic HD-810 and EBT2, was investigated using MeV/u-class proton and heavy-ion beams to apply the films to a measurement technique of the transverse beam intensity distribution at an azimuthally-varying-field cyclotron of Japan Atomic Energy Agency. The optical density of the irradiated films increased linearly with the particle fluence of the beam in a low-fluence region. The linear-response range of the fluence strongly depended on ion species as well as on the film type. By analyzing the film response to absorbed dose, it was found that the sensitivity of the film decreased for a beam with higher linear energy transfer. Based on the linear response of the Gafchromic film, we measured the relative intensity distribution of a large-area ion beam focused with multipole magnets. It was demonstrated that the present technique was useful for evaluation of the size and uniformity of the ion beam.

INTRODUCTION

Precise, handy evaluation of the transverse intensity distribution of a large-area ion beam with various ion species is required for materials and biological researches at the accelerator facility TIARA of Japan Atomic Energy Agency (JAEA). Radiochromic films, Gafchromic HD-810 and EBT2 (Ashland Inc.) [1], were, therefore, adopted as a possible measurement technique of the transverse beam intensity distribution. Various properties of the film, such as high spatial resolution (below 1 mm), large size (over 100 cm^2), thinness (for the penetration of a low-energy ion beam), and easy handling, are advantageous to the present purpose.

A beam irradiation experiment was carried out systematically in order to determine the applicability of Gafchromic films to various ion beams at the azimuthally-varying-field (AVF) cyclotron in TIARA [2]. Their response characteristics were investigated in a wide fluence range. Furthermore, the optical-density response of the films was analyzed in terms of linear energy transfer (LET) and dose [3]. Based on the linear-response characteristics of the films, we measured the relative intensity distribution of a large-area beam focused with multipole magnets [4] and evaluated the size and uniformity of the beam.

FLUENCE RESPONSE

HD-810 and EBT2 films were irradiated uniformly with 10-MeV ^{1}H, 13-MeV/u ^{40}Ar, and 3.5-MeV/u ^{129}Xe beams from the AVF cyclotron. The irradiated films were read at a resolution of 127 dpi with a general-purpose flat-bed scanner, LiDE50 (Canon Inc.), to digitize them into TIFF-formatted images with 16-bit RGB color intensity values. The film scanning was performed in more than one day after irradiation to prevent short-term color variation after irradiation. The optical density d_X in each color channel X (red, green, or blue) was determined from the equation: $d_X = \log_{10}((2^{16}-1)/I_X)$, where I_X is the 16-bit intensity value.

The response of HD-810 films irradiated with the ion beams is shown as a function of the fluence in Fig. 1. The increment of the optical density depends on the color channels for each ion species. The optical density obtained from the red channel is the largest at a given fluence in the linear-response region, while that from the blue channel is the least sensitive. This reflects that the film absorption sensitivity is higher in the longer wavelength region. Thus, the intensity distribution of the beam can be measured in a wide fluence range with a moderate signal-to-noise ratio by choosing an appropriate color channel of the scanned image. The range of the response curves shifted drastically toward a lower-fluence region for heavier-ion beams, as clearly seen in Fig. 1.

For EBT2, the optical density only of the green channel exhibited the linear response in a low-fluence range. The linear-response range is one order of magnitude lower than that of HD-810.

DOSE RESPONSE

The strong dependence of the film response on ion species, as shown in Fig. 1, is probably due to the difference of the LET in the active layer of the film. To see this, the particle fluence F is transformed into the dose D using the following relation: $D = c\,(LET/\rho)\,F$, where ρ is the density of the active layer of the film and c is a constant. The LETs of the beams at each layer of the films can be determined using SRIM code [5]. For example, the average LETs in the active layer (ρ = 1.08 g/cm^3) of HD-810 are 5.0×10^{0}, 1.2×10^{3}, and 1.1×10^{4} keV/μm for the H, Ar, and Xe ion beams in the present case, respectively.

The response curves of the three ion species are replotted as a function of the average dose in the active layer of HD-810 in Fig. 2. For the proton beam, the linear response in Fig. 2(a) is similar to those observed in previous studies in spite of the differences in proton energy and scanners [6-8]. Although the linear-response dose range has been partially overlapped with the manufacturer's specifications (10~400 Gy) of the film in

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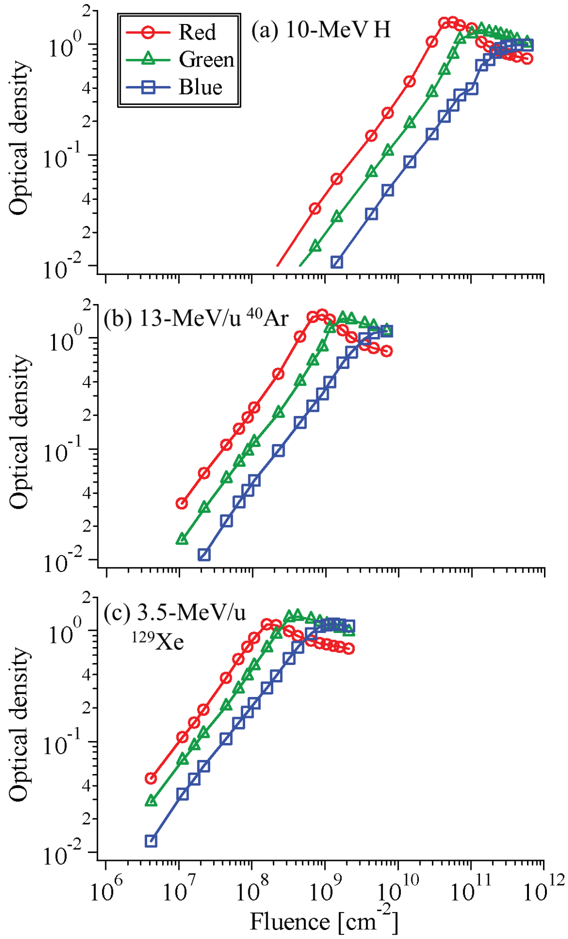

Figure 1: Response curves of the Gafchromic film HD-810 for three different ion beams as a function of the particle fluence.

all three ion species, the dose-response curves shift slightly to the right for heavier-ion beams and the film response seems still dependent on ion species. Therefore, the sensitivity of the film, defined here as a gradient of the linear-response region with respect to the dose, is evaluated for the three ion species and summarized as a function of LET in Fig. 3. The sensitivities of the EBT2 green channel for H and Ar beams are also plotted in Fig. 3. (The EBT2 film is not applicable to the 3.5-MeV/u Xe beam because the kinetic energy is too low for the beam to reach the active layer of the film.) It is clearly reconfirmed that the sensitivity is lower for heavier-ion beams and higher for EBT2. The sensitivity reduction for heavier-ion beams is probably because, for a heavy ion with a higher LET, the local dose along the ion's trajectory is very high and the coloration in the microscopic region becomes saturated: a large part of the deposited dose does not contribute to the film coloration. This tendency agrees well with previous studies [6, 9]. Similar sensitivity reduction of radiochromic films in a Bragg peak (where LET is large) is known as a quenching effect [10].

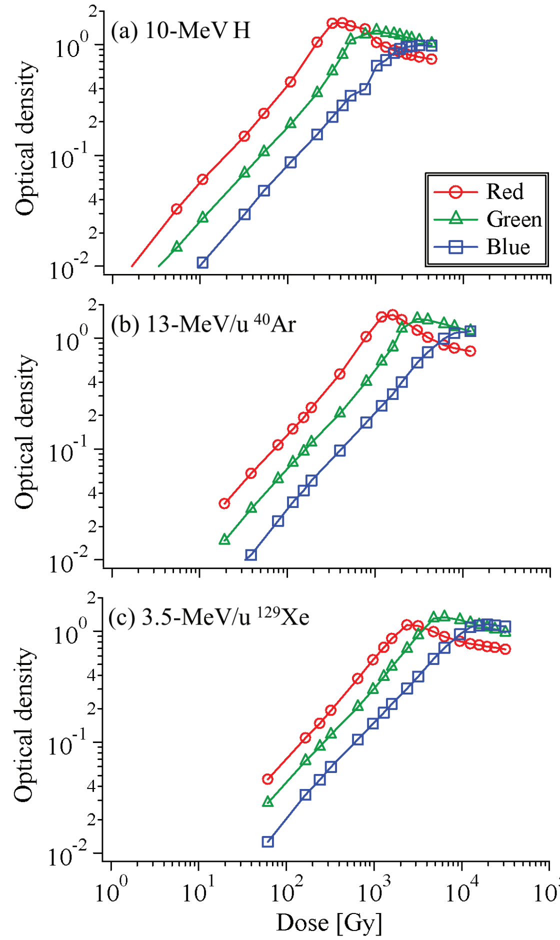

Figure 2: Response curves of the Gafchromic film HD-810 for three different ion beams as a function of the dose in the active layer of the film. The experimental data is the same as in Fig. 1.

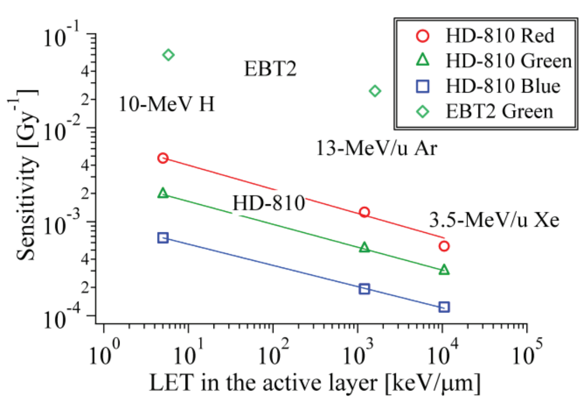

Figure 3: Sensitivity of the HD-810 and EBT2 films as a function of LET. For HD-810, the sensitivities of the red, green, and blue channels are fitted by power functions of $(\mathrm{LET})^{-0.26}$, $(\mathrm{LET})^{-0.24}$, and $(\mathrm{LET})^{-0.21}$ in the present case, respectively. For EBT2, the sensitivity of the green channel where the response is linear is plotted.

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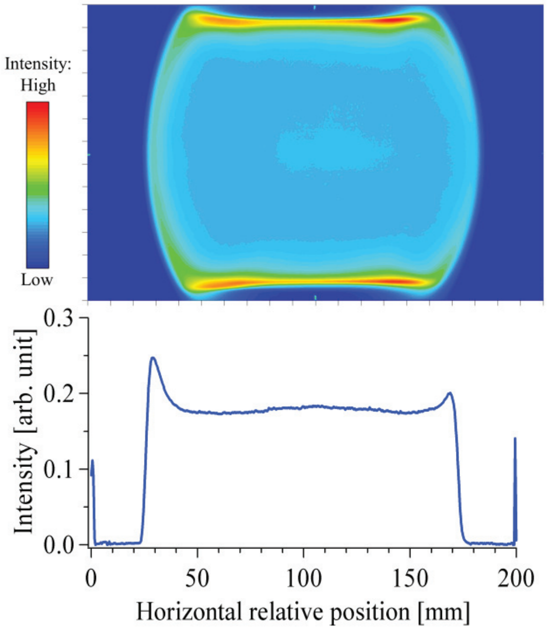

Figure 4: Relative transverse intensity distribution obtained from the optical density distribution of an HD-810 film. The film was irradiated with a 13-MeV/u Ar beam of 0.1 µA for 0.5 s, and scanned with the LiDE50 at a spatial resolution of 127 dpi. The 2D cross-sectional distribution is shown in the upper panel. In the lower panel, the 1D distribution is shown along the horizontal axis. The peaks appearing at both ends in the lower panel correspond to marks put on the film for indicating the central axial position.

INTENSITY DISTRIBUTION MEASUREMENT USING THE FILMS

As can be seen from Figs. 1 and 2, the response of the film is always linear in a low-fluence (low-dose) region where the optical density is well below unity. It is, thus, not always necessary to obtain the response curve in every experiment. This feature gives us a handy technique to measure the relative intensity distribution of the beam directly from the optical density. The relative distribution suffices for the evaluation of the size and uniformity.

Figure 4 shows the measurement result of the relative intensity distribution of a large-area ion beam, obtained from the optical density distribution of HD-810. As can be seen in the figure, the uniform intensity region is formed in the inner part of the profile. Such a beam was formed as follows: The ion beam from the cyclotron was first multiply-scattered with a thin foil to smooth the initial distribution into a Gaussian-like distribution and then focused by octupole magnets so that the intensity distribution could be made uniform on the target [11]. In this uniform-beam formation method, the intensity in the peripheral part of the beam can be very high due to overshooting the tail of the Gaussian-like beam focused by octupole magnets and thus the optical density of the high-intensity region may go beyond the available linear-response range of the Gafchromic film. Even in such a situation, the uniformity of the inner central region can be evaluated if the optical density in the uniform region is well below unity. In Fig. 4, the root-mean-square uniformity is evaluated as 7% in the 120-cm^2 flat-top region surrounded by a high-intensity peak. The uniformity is better (4%) in the inner 9-cm-square central region around the beam center, as predicted theoretically [4].

It is worthwhile to note that the beam uniformity, determined from the optical density of the Gafchromic film, is equal to that of the track-pore density distribution observed more microscopically through a track-etching technique [2, 12].

SUMMARY

The applicability of Gafchromic films HD-810 and EBT2 to proton and heavy-ion beams was investigated for the measurement and evaluation of large-area beam intensity distributions at the JAEA AVF cyclotron. The available fluence range was strongly dependent on ion species as well as on the film type. The sensitivity of the film was lower for a beam with higher LET.

Paying attention to the linear response of Gafchromic films, we developed a handy technique for obtaining the relative transverse intensity distribution of the beam. Using the technique, we confirmed that an ion beam with a uniform intensity distribution was formed by multipole magnets, and the size and uniformity of the beam was evaluated. Large-area proton and heavy-ion beams over 100 cm^2 can be realized at a uniformity of less than 10% and are applied to experiments for space [13] and materials science at TIARA.

REFERENCES

[1] http://gafchromic.com/
[2] Y. Yuri, T. Ishizaka, T. Yuyama, I. Ishibori, S. Okumura, A. Kitamura (Ogawa), T. Yamaki, and S. Sawada, Proc. 1st International Beam Instrumentation Conference, Tsukuba, Japan, 2012, p. 531.
[3] Y. Yuri, T. Ishizaka, T. Yuyama, I. Ishibori, and S. Okumura, Nucl. Instrum. Methods Phys. Res. Sect. A **727** (2013) 40.
[4] Y. Yuri, N. Miyawaki, T. Kamiya, W. Yokota, K. Arakawa, and M. Fukuda, Phys. Rev. ST Accel. Beams **10** (2007) 104001.
[5] http://www.srim.org/
[6] A. E. Buenfil et al., Nucl. Instrum. Methods Phys. Res. Sect. B **197** (2002) 317.
[7] D. S. Hey et al., Rev. Sci. Instrum. **79** (2008) 053501.
[8] F. Nürnberg et al., Rev. Sci. Instrum. **80** (2009) 033301.
[9] T. Kojima et al., Rad. Phys. Chem. **68** (2003) 975.
[10] D. Kirby et al., Phys. Med. Biol. **55** (2010) 417.
[11] Y. Yuri, T. Ishizaka, T. Yuyama, I. Ishibori, S. Okumura, and K. Yoshida, Nucl. Instrum. Methods Phys. Res. Sect. A **642** (2011) 10.
[12] A. Kitamura (Ogawa), T. Yamaki, Y. Yuri, S. Sawada, and T. Yuyama, to be published in Nucl. Instrum. Methods Phys. Res. Sect. B.
[13] M. Imaizumi, Y. Yuri, P. R. Bolton, S. Sato, and T. Ohshima, Proc. 38th IEEE Photovoltaic Specialists Conference (2012) 2831.