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Response of HD-V2 radiochromic film to argon ions*

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A two-dimensional dose detector for ion beam is required in many high energy density physics experiments. As a solid detector, the GAFChromic film offers a good spatial resolution and dosimetric accuracy. For an absolute dose measurement, the relative effectiveness, which represents the darkening efficiency of the film to a radiation source, needs to be taken into consideration. In this contribution, the dose-response of HD-V2 to argon ions is presented for the first time. The calibration was taken over the dose range of 65 Gy–660 Gy with 8-keV argon ions. The response of net optical density is from 0.01 to 0.05. Triple-color dose-response functions are derived. The relative effectiveness for the argon ion beams is about 5%, much lower than that of protons and carbon ions. To explain this effect, the inactivation probability based on track theory of ion bombardment is proposed. Furthermore, a theoretical prediction of the relative effectiveness for single ion is presented, showing the dependence of the darkening efficiency on the atomic number and the incident energy of ions.

Keywords: radiochromic film, dosimetry, ion bombardment, relative effectiveness

PACS: 07.77.Ka **DOI:** 10.1088/1674-1056/ac077f

1. Introduction

In the process of laser plasma interaction, there are several mechanisms to produce ion beams, such as target normal sheath acceleration,[1,2] radiation pressure acceleration,[3] breakout afterburner acceleration,[4] and collisionless shock acceleration.[5] Measuring these ion beams requires a detector with good dosimetric accuracy. Besides, in the experiments of laser inertial confinement fusion and laboratory astrophysics,[6,7] a high-resolution detector is required to record the two-dimensional distribution of the ion beam, which is usually used as a probe to revive the electromagnetic field.

There are several candidates for the detection of ion beams, such as radiochromic film (RCF),[7] imaging plate,[8] microchannel plate with phosphor,[9] scintillator, and dially glycol carbonate.[10–12] As a self-developing film, RCF requires no secondary-exposure or chemicals to dispose of, and has less restrictions on experimental conditions. With various types supported (HD-V2, MD-V3, and EBT3), it is capable to measure the radiation in a wide range of dose. The ion energy spectrum and intensity spatial distribution can be measured by stacking.[13,14] Besides, the incorporation of a yellow marker dye, which enables the benefits of multi-channel dosimetry and improves the dosimetric accuracy, makes it a suitable candidate for the ion detection.[15,16]

The relative effectiveness (RE) is a term to quantify the efficiency of response (darkening efficiency for RCFs), defined as the ratio of the absolute dose of photon relative to that of ion to achieve the same change of color. Previous studies have found that RCFs have different REs to different radiation sources. For example, Xu *et al.*[17] have found that for HD-V2 and MD-V3, the response to proton is 30% lower than that of the photon, and the response to carbon ions shows a significantly different trend for incident energy of 10 MeV, 20 MeV, and 30 MeV. The dependence of response on radiation sources has also been found in the earlier type of RCF. For example, Martišíková *et al.*[18] have found that the RE of EBT film is about 1.0 for protons of 50 MeV and 200 MeV, and about 0.68 for carbon ions for the accelerator energy of 100 MeV/u and 0.76 for 400 MeV/u. However, there are few studies explain these differences clearly.

In this contribution, a calibration of HD-V2 for 8 keV argon ions is presented for the first time. Multichannel dose-response functions are derived. The dependence of darkening efficiency on atomic number and energy of the incident ions is discussed. Theoretical method for RE calculation of HD-V2 to single ion is established.

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2. Methods

2.1. Experimental setup

Argon ion beams were produced by the electron beam ion trap (EBIT) facility in the National Astronomical Observatories, Chinese Academy of Sciences. The device is a commercial product from DREEBIT. Schematic diagram of EBIT is shown in Fig. 1(a).[19,20] Hot electrons are emitted by a cathode and accelerated into an ion trap. The ion trap is composed of a set of drift tubes and a pair of permanent magnets. The magnetic field is mainly to constrain the electron beams. The first and the third voltage stage of the drift tubes are higher than the second one, and a negative potential region is formed in the middle of the tubes. Argon ions of multiple charge states are generated by the continuous collision between the injected argon atoms and the electron beams. The spatial distribution of the electron beam confines the ions in the radial direction, and the potential trap in the axial direction. The longer the ion is trapped, the higher the charge state is. However, the total energy (sum of ionization energy and kinetic energy) the ions obtained from the trap is constant.

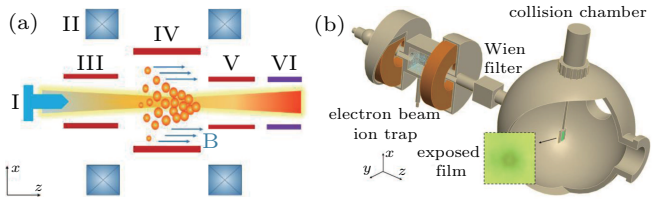


Fig. 1. Experimental setup: (a) schematic diagram of the ion generator EBIT, composed of: I a cathode (in blue) emits hot electrons, II a pair of permanent magnets, and III, IV, V a set of drift tubes forms an ion trap. The voltages of III the first and V the third stages of the drift tubes are higher than IV the second one. The end of the EBIT is IV an electron collector (in purple). (b) Main structure of the experimental platform, composed of an EBIT and a collision chamber, equipped with an ion selection system. Argon ions generated from the EBIT hit a piece of RCF in the chamber. An exposed film shows a darken area in the green background.

The main structure of the experimental platform is shown in Fig. 1(b). In this case, the vlotage of the cathode was set to −3 kV, and the current of the ejected electron beam was about 80 mA. The electron beam was accelerated by the voltage difference between the cathode and the drift tube, reaching about 12 keV. After passing through the drift tubes, the electrons were decelerated and finally collected by the electron collector as shown in Fig. 1(a). The ion current was about 200 pA. Available charge states mainly included Ar^{+} to Ar^{16+} (measured by a Faraday cup), and argon ions accelerated into the chamber were 8 keV in all these states. A piece of RCF was cut into a square of 8 mm × 15 mm, inserted on a rotatable stage in the chamber. Radiation spot was focused to 3 mm of diameter on the film.

The exposed films were stored in a dark box for more than 40 hours to eliminate the effect of post-exposure density growth.[15,21] Although the film can be handled in room light, the influence of stray lights on it was minimized during calibration and digitalization. Then, the films were scanned by an EPSON V850 scanner at 6400 dpi in transmission mode. Images were digitized in 48-bit RBG channel and saved in TIFF format.

2.2. Dose calculation

The dose of the incident ions deposited in the RCF is calculated as follows:

$$D = \frac{\varphi}{\rho} \cdot \frac{\Delta E}{L}, \tag{1}$$

where φ is the ion flux, ρ is the density of the film, L is the depth of the active layer, and ΔE is the deposited energy of the ion in the active layer.[17]

Figure 2 shows the dose for single argon ion deposited in the active layer with different energies, assuming that the ion is incident from the side of the active layer. The ΔE is calculated by a Monte Carlo program SRIM (The Stopping and Range of Ions in Matter).[22,23] In the simulation, the target model follows the structure of HD-V2, composed of an active layer (thickness of 8 μm, density of 1.2 g/cm^3) on a 97-μm thick polyester substrate.[15] The calculation shows that argon ion of 50 MeV has the highest dose. The stopping range of ion of 15 MeV overlaps with the depth of the active layer. Therefore, for the ion with energy less than 15 MeV, the absorbed dose is proportional to the energy.

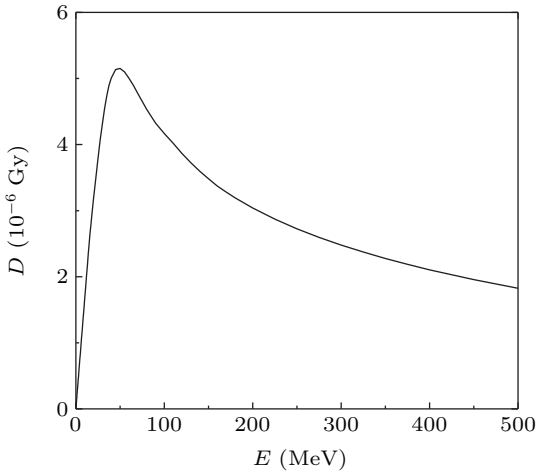


Fig. 2. Dose deposition of single argon ion in the active layer of HD-V2 RCF.

3. Results

The net optical density (OD_{net}) is used to quantify the darkening of the film. Equation (2) is an empirical formula for the conversion from the pixel value to the OD_{net}, which makes the expression of the film darkening independent of the color resolution of the scanner.[24]

$$OD_{\text{net}} = OD_{\text{exp}} - OD_{\text{unexp}} = \log_{10} \frac{PV_{\text{unexp}} - PV_{\text{bckg}}}{PV_{\text{exp}} - PV_{\text{bckg}}}, \tag{2}$$

where PV_{unexp}, PV_{exp}, and PV_{bckg} are the measured pixel values of unexposed, exposed film, and black opaque cardboard, respectively.

The dose-responses of HD-V2 to the argon ions in multi-channel are shown in Fig. 3. When the active component in the film is exposed to radiation, it reacts to form a blue colored polymer with the absorption maximum at approximately 670 nm.[15,25] Therefore, the red channel of response has the best contrast. In this range of dose, the red channel is preferable to the other two channels when adopted in single channel measurement. The dependence of the dose on optical density is fitted by Eq. (3).[26] The values of coefficients a, b, and n are listed in Table 1.

$$D = aOD_{\text{net}} + bOD_{\text{net}}^{n}. \tag{3}$$

Table 1. Coefficients and errors of multi-channel calibration fitting functions for response of HD-V2 to argon ions.

Color channel	a	b	n	RMSE	R-square
Red	5.6×10^{3}	2.7×10^{6}	3.0	1.813	9.998×10^{-1}
Green	8.0×10^{3}	3.5×10^{7}	3.5	29.212	9.797×10^{-1}
Blue	8.2×10^{3}	6.5×10^{8}	4.0	45.268	9.512×10^{-1}

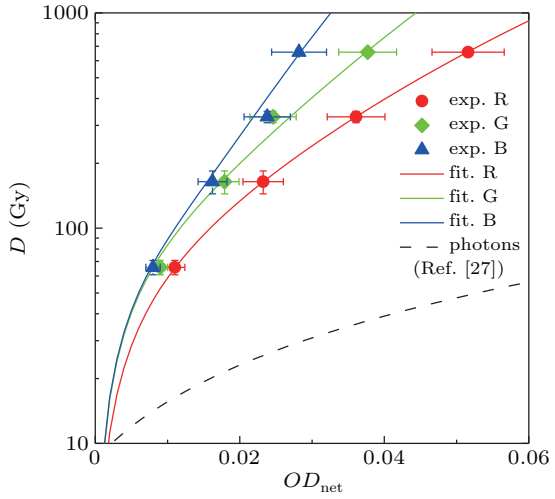


Fig. 3. Optical density response of HD-V2 RCF to 8-keV argon ions. Both experimental and fitting response are presented in RGB three channels respectively. The response of HD-V2 to 10-MeV photons (scanned in grayscale channel) is shown for comparisons.[27]

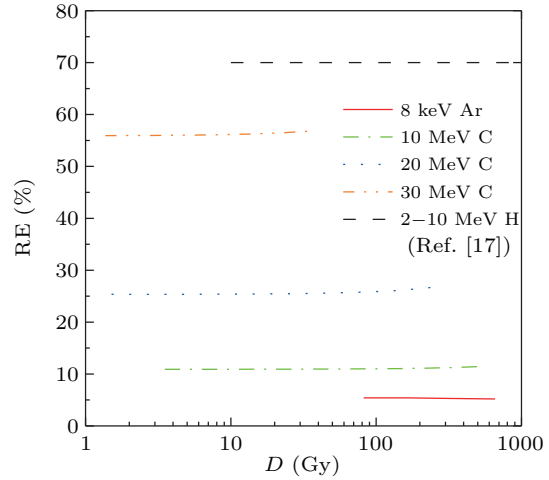


Fig. 4. Relative effectiveness of HD-V2 RCF to 8-keV argon ions. The RE curves of protons with incident energy of 2 MeV–10 MeV and carbon ions with incident energy of 10 MeV, 20 MeV, and 30 MeV are shown for comparisons.[17]

4. Discussion

Based on the photon calibration for HD-V2 (performed by Chen *et al.*[27]), RE (defined as $\frac{D_{\text{photon}}}{D_{\text{ion}}}\Big|OD_{\text{net}}$) of the argon ions is derived, as shown in Fig. 4. In the dose range of 65 Gy–660 Gy, the RE is about 5%. The REs of protons and carbon ions are derived from the calibration of dose-response performed by Xu *et al.*[17]

Obviously, RE of the argon ions is much lower than those of protons and carbon ions. The track theory based on the δ-ray model (developed by Katz *et al.*[28]) allows for the prediction of the relative biological effectiveness for heavy ion bombardment of dry enzymes and viruses, as well as the dose response of a physical detector exposed to ions.[29,30] The detector is assumed to consist of sensitive elements (dye molecules in this case) which have a given response to γ ray dose. The inactivation probability for a dye molecule is a function of radial distance from the ion's path, and then integrated over all space to derive the inactivation cross section (S), described by the following equation:

$$S = 2\pi\int_0^R \left\{1-\exp\left[-\frac{CZ^{*2}}{2\pi r\beta^2 D_\gamma^{37}}\left(\frac{1}{r}-\frac{1}{R}\right)\right]\right\} r\mathrm{d}r, \tag{4}$$

where r is the radial distance, and R is the upper limit, which is derived from kinematic considerations in a head-on collision.[28] C is a material constant (1.36×10^{-7} erg/cm (1 erg $=10^{-7}$ J) for water). D_γ^{37} is the γ ray dose for 37% survival. Z^* is the number of effective charge for an ion of atomic number Z at speed βc,[31]

$$Z^* = Z[1-\exp(-125\beta Z^{-2/3})]. \tag{5}$$

There is an explanation that the RE is dependent on the linear energy transfer (LET) and the LET quenching effect accounts for the decrease of RE.[32–34] LET is the energy loss per unit length of a charged particle traveling through the target, which is essentially equivalent to the stopping power of the target material. We show the relationship between LET and S in Fig. 5. For the same LET, the ions of lower Z have higher S, which indicates that heavier ions have lower efficiency of dyeing. Due to inhomogeneous dose distribution of δ-ray around the ion track, local saturation effect will affect the overall response efficiency. With the increase of LET, S tends to be saturated, which corresponds to the LET quenching effect.

However, it is inadequate to derive the quantitative response of RCF through the LET. Because only a small part of LET can convert into the energy of secondary electrons (δ-ray), which trigger the bond-breaking of dye molecules in the active layer.[35] In other words, the polymerization process depends on the energy of the δ-ray, not the total stopping power. Therefore, it is possible to predict the response of RCF to an ion by calculating the energy of the δ-ray.

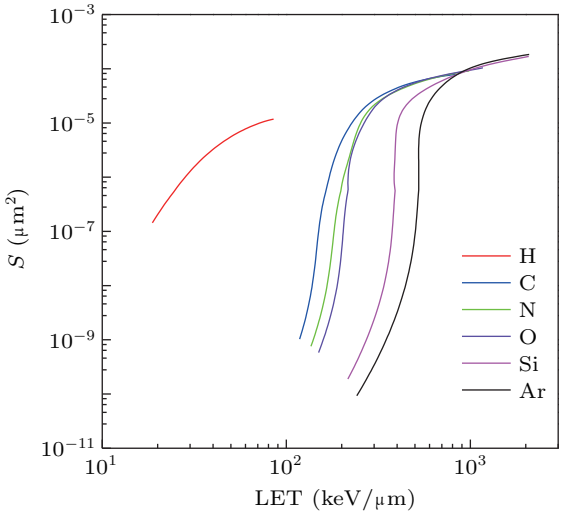


Fig. 5. Calculation of inactivation cross section for ion bombardment of RCF active layer.

As ions travel through the film, the change of color is an accumulation of all inactivated dye molecules in the cylinder with the path as axis. Assuming that the dye molecules in the active layer are uniformly distributed with density n_0 (in unit cm^{-3}), the total number of molecules inactivated by the incident ion $N_{\rm dye}$ can be derived by integration over the path as

$$N_{\rm dye} = n_0 \int_0^L S {\rm d}x. \tag{6}$$

For single ion, whose range covers the depth of the active layer, its relative effectiveness η can be defined as Eq. (7). Figure 6 shows the theoretical trends of η for different ions. Here, D_γ^{37} is taken as 2×10^7 erg/cm^3 (based on the photon calibration[27]) and this value mainly determines at what dose the response begins to saturate.

$$\eta = \frac{D_{\rm photon}}{D_{\rm ion}}\bigg|_{N_{\rm dye}}. \tag{7}$$

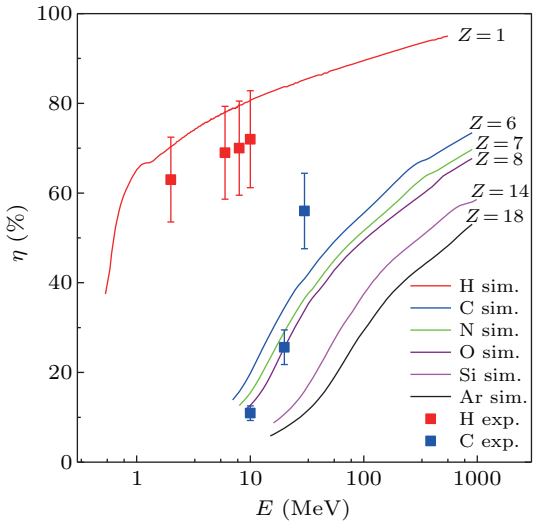


Fig. 6. Theoretical prediction of relative effectiveness of HD-V2 RCF to single ion with different incident energies. The experimental RE results of proton and carbon ion beams are shown for comparisons.[17]

Note that the η is not equivalent to RE, for it only represents the response ability of RCF to single ion. If the average separation between ion tracks is smaller than twice the average maximal δ-ray travel, over-lapping dose will affect the distribution of the inactivation probability.[29] This in turn degrades the quality of the predictions. As the theoretical calculation only considers the ions whose range reaches the depth of the active layer, here we only cite the experimental results of protons and carbon ions, as shown in Fig. 6. Generally, the experimental RE is lower than the predicted η within 15% and shares a common growth trend. With the increase of incident energy, the η of protons exceeds 90% and gradually approaches that of photons (100%), which is consistent with the experimental results of Martišíková *et al.*[18]

5. Conclusion

The dose response of GAFChromic HD-V2 film to 8-keV argon ion beams is presented in this work. The film's response was measured over the dose range of 65 Gy–660 Gy, which corresponds to the net optical density ranging from 0.01 to 0.05. Triple-color calibration functions are derived. The RE for the argon ions is about 5%. Theoretical interpretation based on track theory was made about the difference of darkening efficiency. Furthermore, the prediction of RE for single ion is presented, demonstrating the dependence of darkening efficiency on the atomic number and incident energy of the ions. These results may be used as a reference for response of RCF to ions bombardment in other physical experiments.

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