New Detection Device for Thomson Parabola Spectrometer for Diagnosis of the Laser-Plasma Ion Beam

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A new detection device for evaluating the ion energy distributions of a laser-plasma ion source is demonstrated. The Imaging Plate (IP) with no protective layer as ion detector device for the Thomson Parabola spectrometer is used. The Imaging Plate Thomson Parabola spectrometer (IPTPS) is applicable for the analysis of the energy distribution of the laser-driven ion beam using an opto-electric digitizing technique.

Keywords: laser-driven ion source, Thomson parabola spectrometer, imaging plate, T^3 laser

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1. Introduction

Much interest has been focused to fast ions emitted from a solid target irradiated by an intense laser [1,2]. Different ion species with wide range of energy distributions have been observed in the energetic ions produced by a laser-plasma ion source [2]. Thus, it is important for the application of laser-plasma ion source to obtain the energy distributions of different ion species separately. The Thomson Parabola spectrometer using a combination of electrostatic and magnetic fields has been successfully applied in laser-plasma interaction studies. In order to obtain quantitative information corresponding to the number of ions, a solid-state nuclear track detector (SSNTD) such as the CR-39 has been frequently used [3]. In addition, the Thomson Parabola spectrometer coupled with a microchannel plate (MCP), two-dimensional position sensitive anode [4], or streak camera [5] has also been developed. Recently, the imaging plate (IP) has been used for obtaining the electron energy spectrum in laser-plasma interaction research [6]. The IP that makes use of the photo-stimulated luminescence effect is a time-integrated type radiation detector (therefore, many-shot-integrated operation is available) and can be recorded as a digital data by using IP reader coupled with a PC. This data can be directly processed by a PC. The advantages of IP are high dynamic range ($\sim 10^5$) and high sensitivity (~100 times higher than a normal x-ray film) [7]. Moreover, the IP is sensitive not only to electrons but also to ions [8, 9]. However, the IP is also sensitive to x-rays, Ultraviolet radiations, and neutrals. Therefore, the spatial-resolved type spectrometer (i.e. Thomson Parabola spectrometer) is necessary to diagnose ion beam from laser-plasma interaction by using the IP. In this work, we tried to confirm the applicability of the IP as an ion detector for the Thomson Parabola spectrometer for diagnosing the laser-plasma ion source.

2. Experimental Setup

Figure 1 shows a schematic of the experimental setup for IP characterization employing a laser-plasma ion beam source. The JLITE-X Ti:Sapphire laser system [10] with 1 TW operating mode is used, generating 250 mJ and 220 fs pulse duration in full width half maximum. The laser is focused onto a 5 μm thick Ti foil target using an

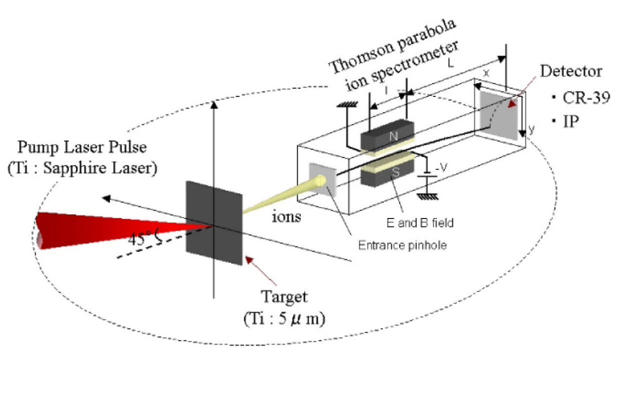

Fig. 1 Schematic of the principle of the Thomson Parabola spectrometer and experimental setup for IP characterization.

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f/13 off axis parabolic mirror. The focal spot is 25 μm in e^{-2} of the peak intensity with an energy concentration of 60%. The focused peak intensity is estimated to be 2×10^{17} W/cm^2. The Ti foil target is positioned at 45 degrees relative to the axis of laser propagation for p-polarization. The Ti foil surface is naturally contaminated by hydrocarbon. This contamination is important role as ion beam source [11]. The Thomson Parabola spectrometer is placed at a distance of 1750 mm from the target. At the Thomson Parabola spectrometer, assuming the collinear homogeneous electric field E and magnetic field B, for the deflection of a charged particle with given Z/A and velocity v on a screen at the distance L, the deflections due to the electric and magnetic fields ($eZB/(Am_p) \ll v/l$ is assumed) are

$$x = \frac{eZBlL}{Am_p v}\left(1 - \frac{l}{2L}\right), \quad y = \frac{eZElL}{Am_p v^2}\left(1 - \frac{l}{2L}\right). \quad (1)$$

Here, e is the electron charge, m_p is the proton mass, and l is the length of the region filled by the E and B fields. This allows ions having equal charge-to-mass ratios Z/A make parabola-shaped traces on the detector plane in such a way that the distance to origin corresponds to a particular velocity. In our Thomson Parabola spectrometer, l = 50 mm, L = 100 mm, $E = 4.0 \times 10^5$ V/m and B = 0.16 T is used. Moreover, an entrance collimator pinhole with a diameter of 300 μm is used. In order to estimate the sensitivity of the IP, we compare the absolute energy distribution from the CR-39 with the PSL value from the IP at the Thomson Parabola spectrometer. We take five data sets; each set corresponds to 100 accumulated shots for exposing the IP. In order to prevent the ion beam from stopping at the protective layer, an IP without a protective layer (Fuji-film BAS-TR) is used. The BAS-TR is composed of 50 μm phosphor, 250 μm support, and 160 μm magnetic layers. The exposed radiation image is taken by using a Fuji-film BAS-1800II imaging plate reader. It has been previously pointed out that the fading effect cannot be ignored to determine the radiation dose or number of nuclear particles [6]. In Ref. [8], the fading effect's dependence on alpha, beta, and gamma ray radiation and their energies was measured on a BAS-TR type IP. Short half-life (2-3 hours at 30 °C) which did not depend on the nuclear species was obtained. In order to ensure stable and accurate readout process, we set the readout time at 120 min after ion irradiation to the IP.

3. Results and Discussions

Figures 2 and 3 shows typical Thomson Parabola spectrometer on the CR-39 and the IP. The CR-39 and the IP show similar images. Lower left spot (Or_1) is the origin. The CR-39 is sensitive not only to ions but also to neutrals, therefore this spot is from neutrals. On the IP, this spot is owing not only to neutrals but also to x-rays and Ultraviolet light from plasma due to the IP's sensitivity to both these sources. The bright trace by protons (p^+) on the CR-39 and the IP are observed. This is a Thomson Parabola trace having a charge-to-mass ratio that is estimated to be Z/A = 0.98. That is in close agreement with that of the theoretical value of the ionized proton trace (i.e. Z/A = 1.00). On a high contrast image on the IP, two weak intensity traces and a line directed from the lower left to the right upper side (Or_2) are observed (see Fig. 3 (b)). This trace is also observed by the CR-39 with utilization of a microscope. However, this image obtained by the CR-39 cannot be observed clearly via an imaging scanner because the scanner's resolution (8 bit) is lower than that of an IP reader (16 bit). The weak intensity traces have parabolic

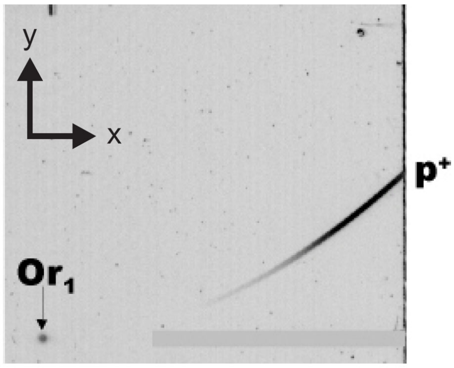

Fig. 2 Thomson Parabola image on the CR-39. The x and y-axes correspond to x and y-axes of the detector shown in Fig. 1, respectively.

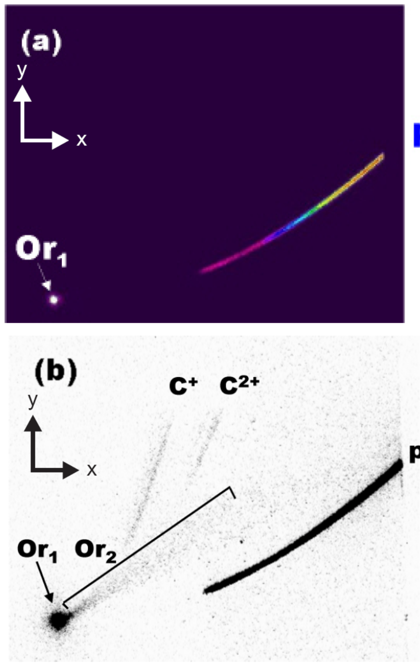

Fig. 3 (a) Thomson Parabola image on the IP with low contrast. (b) Thomson Parabola image on the IP with high contrast. The x and y-axes correspond to x and y-axes of detector on Fig. 1, respectively.

shapes and the charge-to-mass ratio Z/A of the two components are estimated to be 0.082 and 0.16, respectively. These values are in agreement with the theoretical value of $C^{+}(Z/A = 0.083)$ and $C^{2+}(Z/A = 0.17)$. A straight line from the lower left to the right upper side (Or_2) is observed. A similar result has been previously reported in a charge-and mass-resolved time of flight ion spectrometer [12]. They reported it resulted from charge exchange in a relatively poor vacuum condition. In our result, we observed that the direction of this image is inverted in the y-direction due to inversion of the electric field of the Thomson Parabola spectrometer. We believe that the Or_2 image is from plus charged particle which resulted by the charge exchange effect. From Eq. (1), the particle energy $\epsilon \simeq mv^2$ can be roughly evaluated by using $v = (E/B)(x/y)$. Assuming that the particles that created the Or_2 image are protons, the particle energies are estimated to be mainly < 100 keV. This feature will disappear after improving the vacuum condition.

Figure 4 (a) shows the absolute distribution of energetic protons detected by the CR-39 and the PSL distribution on the IP. The high energy cut-off ~700 keV and shoulder from 350 keV to 600 keV are observed on both the CR-39 and the IP. The ratio between PSL and N_{CR-39} is increased with increasing proton energy. This result suggests that the sensitivity of the imaging plate as a function of proton energy is not constant, but that it depends on proton energy. Figure 4 (b) shows the sensitivity of the IP to protons. In the energy range from 250 keV to 700 keV, it seems that the sensitivity of the IP is proportional to the proton energy ϵ. This linearity implies that the quantum efficiency of the IP to PSL from incident ions is roughly constant for such proton energies. In Ref. [9], the sensitivity of different imaging plates ranging from 3 MeV to 12 MeV protons was measured. They found that the sensitivity depends on the energy loss at the phosphor layer of energies of less than 6 MeV which is higher than the stopping power of the phosphor layer. In our case, the stopping power of the proton at the IP's phosphor layer (which is composed of BaFBrI:Eu^{2+} phosphor and urethane resin) is estimated to be 15 μm. Thus, all protons are stopped in the phosphor layer (50 μm) and the energy is transferred to the PSL. If we consider the stopping power of the proton at the phosphor layer, this linearity will be applicable to ~1.5 MeV at most. Moreover, the typical average background of the IP is 0.01 PSL/shot/50^2 μm^2. In order to evaluate the sensitivity, we subtracted this background from the raw data. The noise level is thus from the fluctuation of the background. This fluctuation is 10 times smaller than the background level (i.e. 0.001 PSL/shot/50^2 μm^2). Therefore, the SN ratio at 700 keV is almost 8. On the other hand, we think this sensitivity cannot be applicable to another species. In Ref. [13], the sensitivities of the IP for heavy ion beams were evaluated. PSL excitation spectra for Ne, O, Ar, and Kr were measured. The PSL excitation spectra changed with each species. This difference was considered to be due to the "*LET effect*". We think the experimental evaluation of sensitivity of IP is necessary for each species. We note that this sensitivity of the IP is only applicable to the reading interval of 120 minutes which is from the irradiation to the reading process. If the interval is changed, this sensitivity will be changed by the fading effect.

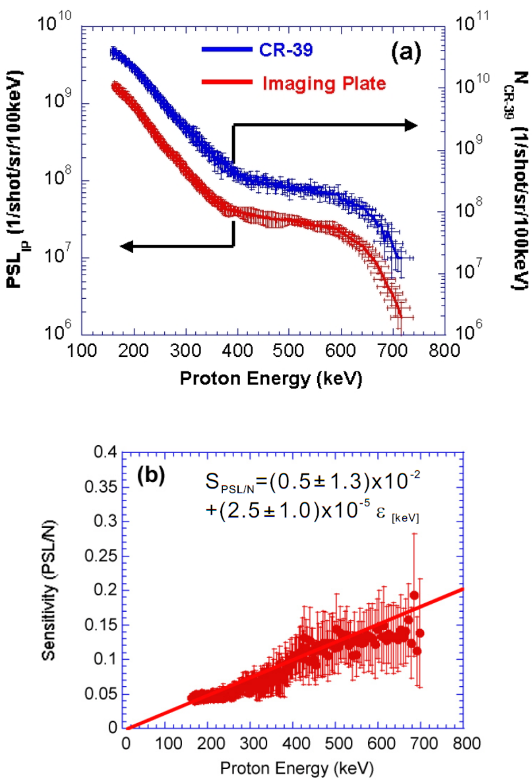

Fig. 4 (a) Energy spectra of fast protons on the CR-39 (blue line) and the IP (red line). (b) Sensitivity of the imaging plate as a function of proton energy.

4. Summary

In summary, the utility of the Thomson Parabola ion spectrometer equipped with an imaging plate (IP) rather than a solid-state nuclear track detector (SSNTD) was confirmed. The ion sensitivity of the imaging plate utilized by the Thomson Parabola ion spectrometer was measured using laser-driven ion beam. The Imaging Plate Thomson Parabola spectrometer (IPTPS) proved to be a useful tool for the energy analysis of the ion beam generated by laser-plasma interaction.

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