ION AND NEUTRAL BEAM GENERATION BY 1 TW, 50 fs LASER IRRADIATION OF THIN FOILS

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Abstract

Thin (< 10 μm) plastic and metal foils were irradiated by a 1 TW, 50 fs laser pulses. The foil surface was located at $\pi/4$ to the laser injection. Particle beams were obtained on both sides of the foil with respect to the laser injection. The laser intensity under 10^{17} W cm^{-2} produced only neutral particle beams on the rear side of the laser illumination, flowing to the direction perpendicular to the foil surface with small ($\sim 15°$) divergence. The laser intensity over 10^{17} W cm^{-2} produced also ion beams with larger ($> 45°$) divergence. The components of the neutrals and ions were contaminants of the foil surface. To the contrary, mainly ions were observed on the laser-illuminated side, which were components of the target foils. The most energetic particles were protons on both sides, whose energy was about 550 keV.

INTRODUCTION

In recent years, interaction between high-intensity laser and matter has been actively studied. Especially, the generation of multi-MeV ions produced by the interaction between a short (< 1 ps) and high-power (> 10 TW) laser pulse and thin foils is a rapidly growing research area [1–9]. If this phenomenon is reproduced by a T^3 laser, it will enable construction of a compact ion source of an accelerator. Although Zhidkov *et al.*[10] have shown the possibility of MeV proton generation using a laser with 10^{17} W cm^{-2} intensity, few experiments have been carried out so far using lasers with intensity below 10^{18} W cm^{-2}, except the work of Badziak *et al.*[11] who obtained the 300 keV proton energy with a double-layer foil target using a 1 ps laser with 10^{17} W cm^{-2} intensity.

This paper reports experiments to irradiate thinner ($< 10\mu$m) plastic and metal foils by a laser with smaller power (1 TW) and shorter pulse width (50 fs) than the hitherto experiments. We define the laser-illuminated side and the other side by "backward" and "forward", respectively. It was found that the intensity threshold of the ion generation was 10^{17} W cm^{-2} on the forward side. Under the threshold, neutral beams with small divergence are generated. However, there were no definite thresholds on the backward side. The most energetic particles were protons on both sides, whose energy was about 550 keV.

In the next section, we describe the experimental apparatus and in the third section, we describe the experimental results and their discussions. The final section gives summary.

EXPERIMENTAL APPARATUS

The experiments were performed with a Ti:Sapphire laser, 50 mJ in pulse energy, 50 fs in pulse width (1 TW in pulse power), 800 nm in wavelength and 10 Hz in pulse frequency. A main pulse was accompanied with a pre-pulse in the ns range, whose total power was $\sim$ 1/2,000 of the main. The surface of the target foil was located at $\pi/4$ to the laser injection. An f=120 mm lens located inside of a vacuum chamber focused the laser to a target in the chamber. The delivered energy to the interaction point was about 38 mJ. A single shot autocorrelator tells that typical pulse duration was $\sim$ 40fs in FWHM before the laser pulse goes through the window and the lens, which give the laser intensity on the target as about 2×10^{17} W cm^{-2}. Two types of materials were tried as the target foils; mylar $(C_{10}H_8O_4)_n$ and aluminum (Al). Their thickness was mostly less than 10 μm. Typical vacuum in the chamber was $\sim 10^{-3}$ Pa.

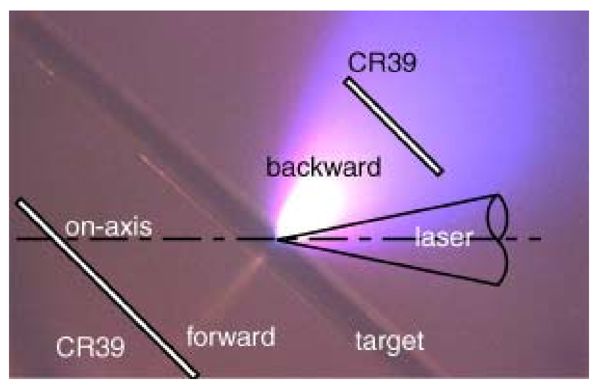

Figure 1: Picture of the interaction between the laser with intensity of $\sim 4 \times 10^{16}$ W cm^{-2} and 3 μm-thick Al target foil with schematic of the experimental setup. Definitions of "backward" and "forward" sides are also given.

Figure 1 shows a picture taken at the moment of the laser irradiation, from the direction parallel to the laser axis and perpendicular to the foil surface, Al in 3 μm-thick in this case. It shows a fine but bright trace to the forward direction, besides the backward laser refection. A CR39 and a Thomson parabola spectrometer were used to detect generated particles. The CR39 is a track detector sensitive only to ion (and neutron generated by recoil protons or carbons) [12]. The Thomson parabola spectrometer consists of an aperture (0.5 mm ϕ) and a pair of dipole magnets (0.48 T). The pair magnets have also the role of electrodes $(2.9 \times 10^5$

V m^{-1}). The computer code MAFIA [1] was used to calculate the field distributions, and particle tracking code was used to estimate the deflection of the charged particles.

RESULTS AND DISCUSSIONS

In order to measure particle distributions, we placed the CR39 plates on both forward and backward sides across the target, and also in the direction on the laser axis as shown in Fig. 1. Each CR39 plate is located with distance of 30 mm away from the interaction point. Figure 2(a) and (b) show photographs of CR39 tracks at the forward direction obtained by an Al target in 3 μm-thick in case that the laser intensities are 2.1×10^{17} W cm^{-2} and 1.1×10^{17} W cm^{-2}, respectively. They show that particles concentrate in the direction normal to the target surface and that few particles are observed on the laser axis. In Fig. 2(a), the particle distribution has two components; one is narrow ($\sim 15°$ in FWHM), another is wide ($> 45°$). In Fig. 2(b), the distribution has only the narrow component. The narrow component consists of neutrals, while the wide component consists of ions as described in the following.

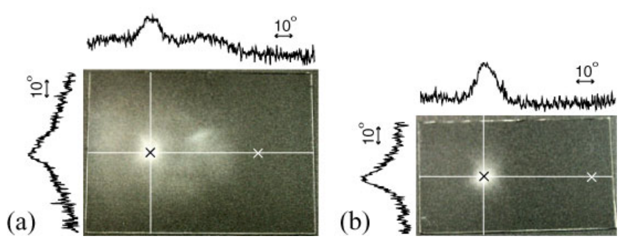

Figure 2: Typical CR39 images of generated particles in the forward direction. Target was Al in 3μm-thick. Black cross indicates the direction normal to the target surface and white cross indicates on-axis direction. Curves show distributions of etch pits along the path indicated in white lines. Laser intensities were (a): 2.1×10^{17} W cm^{-2} and (b): 1.1×10^{17} W cm^{-2}.

Figure 3 shows the result of Thomson parabola measurement on the forward side obtained by an Al target in 3 μm-thick. The spectra in (a) and (b) are results of sum of 60 laser shots in the forward direction in case that the laser intensity is 2.0×10^{17} W cm^{-2} and 5.8×10^{16} W cm^{-2}, respectively. Lines are results of calculation by MAFIA. Neutral particles are concentrated on the $E = B = 0$ point in both figures. The darkest curve is in fine agreement with the theoretical proton parabola. Figure 3(c) shows three energy spectra of protons; two were given by the 3 μm-thick Al target at two laser intensities over 10^{17} W cm^{-2}, and one was given by a 5.7μm-thick mylar target at the laser intensity of 2.1×10^{17} W cm^{-2}. Maximum proton energy was about 550 keV in the mylar target, and 150 keV in the Al target. Figure 3(d) shows the dependence of the number of particles on the laser intensity. Both ions and neutrals were detected above 10^{17} W cm^{-2}, but few ions were detected below 10^{17} W cm^{-2}. We therefore conclude that the threshold intensity of the ion generation is around 10^{17} W cm^{-2}.

[1] See http://www.cst.de

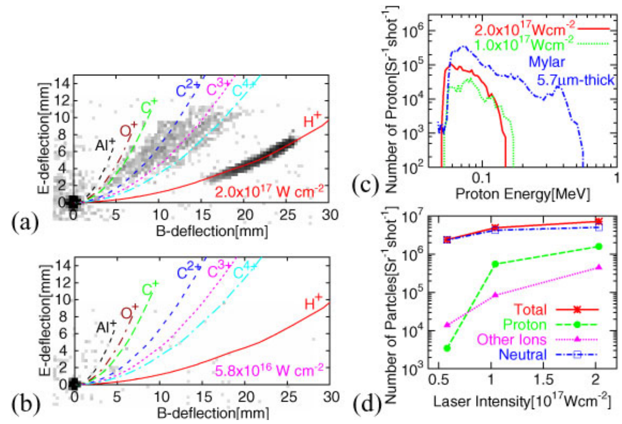

Figure 3: (a) and (b) Thomson parabola spectra from Al 3 μm-thick targets in the forward direction. (c) Proton spectra obtained at laser intensities above 10^{17} W cm^{-2} from the Al targets. A dot-dash line shows the case of mylar in 5.7μm-thick with 2.1×10^{17} W cm^{-2} laser intensity. (d) Dependence of the number of particles on the laser intensity.

On the backward side, particles distribute between the laser axis and the direction normal to the target surface, with an angle of $> 45°$. Figure 4 shows the Thomson parabola spectra on this side. Figure 4(a) and (b) show these given mylar target in 8.7 μm-thick. The laser intensities were 2.1×10^{17} W cm^{-2} and 5.9×10^{16} W cm^{-2}, respectively. Even the laser intensity under 10^{17} W cm^{-2} produced ions but few neutrals. Figure 4(c) shows the spectra of the Al target in 3 μm-thick at 2.1×10^{17} W cm^{-2} laser intensity. The main components of particles are Al ions and few protons and neutrals are found. Figure 4(d) shows the proton spectra and (e) shows dependence of the number of particles on the laser intensity. Maximum proton energy was about 550 keV in mylar target.

Let us compare the Thomson parabola spectra of Al, Fig. 3(a)-(b) measured on the forward side and Fig. 4(c) on the backward side. The superior particles in the forward direction are neutrals. Protons and carbon ions were not found below the threshold of 10^{17} W cm^{-2}. Note that no Al ions were obtained on this side. The protons must be originated from water vapor and/or hydrocarbons contaminating the target surface as indicated in the hitherto experiments [1–6]. Both sides of the mylar targets generate similar species, but we can deduce that the protons on the backward side are components of the targets while those on the forward side are contaminants, because Al targets do not generate protons on the backward side.

Spectra of visible radiation emitted at the interaction were measured by an asymmetric Czerny-Turner type poly-

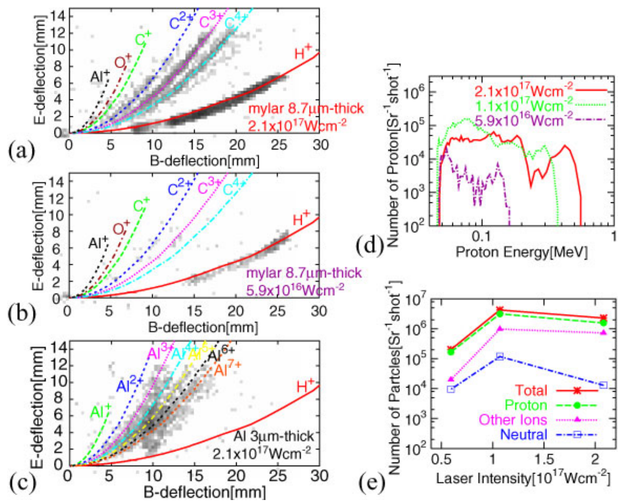

Figure 4: (a)-(c) Thomson parabola spectra in the backward direction. (a) and (b) from 8.7 μm-thick mylar target with laser intensities of 2.1×10^{17} W cm^{-2} and 5.9×10^{16} W cm^{-2}, respectively. (c) from 3 μm-thick Al target with laser intensity of 2.1×10^{17} W cm^{-2}. (d) Proton energy spectra obtained from 8.7 μm-thick mylar target. (e) Dependence of the number of particles on the laser intensity.

chrometer. Two lenses transferred image of the radiation at a specific position to the polychrometer slit outside of the vacuum chamber with resolution of 1 mm. The range between 413 and 928 nm was detectable with the resolution of 0.07 nm. We identified the observed spectral lines with NIST Spectra Line Database [2]. The measurement found different species between Al and mylar targets on the backward side. The Al targets gave lines of Al, H, C, O atoms and $Al^{1+,2+,3+}$, C^{1+}, O^{1+} ions, while the mylar targets gave those of H, C, O atoms and $C^{1+,2+,3+,4+}$, $O^{1+,2+}$ ions. This also supports the assumption that the particles on the forward side are originated from contaminants and those on the backward side are mainly components of the targets.

Previous works have not reported the generation of neutral particles explicitly, including the paper of Gitomer *et al.*[14] whose laser intensity was under 10^{17} W cm^{-2} in most cases. This is probably because the mechanism caused by their long ($\sim$ ns) laser pulse is different from that caused by our short ($\sim$ 50 fs) laser pulse. The CR39 measurements of the neutral particles generated at the laser intensity around 4×10^{16} W cm^{-2} have been previously described in detail [13].

The number of particles generated was estimated to be under 10^7 [Sr^{-1} shot^{-1}] in all cases. This value is lower than the interpolation based on the previous experiments obtained using the laser intensity around 10^{18} W cm^{-2} with longer pulse width [1–6]. This is because our laser energy is small; it is not the laser power but the laser energy that is more closely related to the particle generation. Though the energies could be useful, the number of particles obtained by our T^3 laser is too small and their emittance is too large for practical use as an accelerator ion source. Appropriate shaping or conditioning of the target will improve the situation [4, 5, 7, 11]. The neutral beams with high energy and small emittance will be able to find their own applications.

[2] The NIST Spectra Line Database is available at http://physics.nist.gov/cgi-bin/AtData/main_asd

SUMMARY

In summary, we have detected neutral particles and ions in the interaction between a T^3 laser and thin foils. The neutral particles with a small divergence were detected on the forward side with the laser intensity under 10^{17} W cm^{-2}, and ions, mainly protons, were also detected with the laser intensity over 10^{17} W cm^{-2}. In this direction, the generated particles originate from contaminants of the target surface. On the backward side, ions characteristic to the target materials were obtained but no neutrals were stably detected. The maximum proton energy was 550 keV in mylar targets on both sides.

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REFERENCES

[1] E. L. Clark *et al.*, Phys. Rev. Lett. **84** (2000) 670.

[2] A. Maksimchuk *et al.*, Phys. Rev. Lett. **84** (2000) 4108.

[3] R. A. Snavely *et al.*, Phys. Rev. Lett. **85** (2000) 2945.

[4] M. Roth *et al.*, Phys. Rev. ST Accel. Beams **5** (2002) 061301.

[5] M. Hegelich *et al.*, Phys. Rev. Lett. **89** (2002) 085002.

[6] P. McKenna *et al.*, Rev. Sci. Intrum. **73** (2002) 4176.

[7] S. C. Wilks *et al.*, Phys. Plasmas **8** (2001) 542.

[8] A. Pukhov, Phys. Rev. Lett. **86** (2001) 3562.

[9] T. Nakamura and S. Kawata, Phys. Rev. E **67** (2003) 026403.

[10] A. Zhidkov *et al.*, Phys. Rev. E **61** (2000) R2224.

[11] J. Badziak *et al.*, Phys. Rev. Lett. **87** (2001) 215001.

[12] B. G. Cartwright *et al.*, Nucl. Instr. and Meth. **153** (1978) 457.

[13] Y. Wada, T. Kubota and A. Ogata, AIP Conf. Proc. **634** (2002) 329.

[14] S. J. Gitomer *et al.*, Phys. Fluids **29** (1986) 2679.