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Ion Production Enhancement by Prepulse in Ultrashort-Pulse Laser Interaction with Foil Targets

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We report on ion generation in the interaction between a 1 TW, 50 fs laser and thin foils. Ions and neutral particles were obtained on both sides of the target. Henceforth, we define "forward" as the laser penetration side, and "backward" as the laser reflection side. It was found that ion production in ultrashort-pulse laser interaction with foil targets has an optimum target position when the main laser pulse is accompanied by prepulses that evaporate the target.

We used a commercial Ti:Sapphire laser system (B. M. Industries, α-Line series) based on the chirped pulse amplification technique generating up to 50 mJ, 50 fs (1 TW) pulses. The wavelength of the laser is 800 nm and the repetition rate is 10 Hz. The laser system is not equipped with a pulse cleaner, so each main pulse was accompanied by prepulses. According to observations by a photodiode detector, there is a train of prepulses 5 ns, 8.5 ns, 17 ns, 26 ns, and 34.5 ns before the main pulse and their energies are 10^{-3} to 10^{-4} that of the main pulse.

Our experiments were carried out in a cylindrical vacuum chamber 400 mm in radius and 200 mm in depth under a typical pressure of $\sim 5 \times 10^{-3}$ Pa. An f = 300 mm off-axis parabola mirror (OAP) focused a p-polarized laser on a target in the chamber with an angle of incidence of $\sim \pi/6$. The laser intensity on the target was up to 1.6×10^{17} W cm^{-2}. The measured spot size (w_0) was 11 μm in half width at e^{-2} of maximum and the Rayleigh length (Z_R) was 0.44 mm. We used Mylar $(C_{10}H_8O_4)_n$ with a thickness of 2.5 μm as the target foil.

First, we measured the size of a hole bored by a laser pulse on a foil target, changing the distance between the OAP and the target in order to determine the waist position. The measured hole sizes are shown in Fig. 1(a) as a function of the distance from the assumed focal point. The sizes of the holes were large near the vacuum waist with either two maxima or one maximum and one inflection, when the laser energy was large. However, they simply had one minimum when the energy was small. We regard the position of the minimum as the focal point.

We varied the distance from the OAP to the target, irradiated the target, and measured the energies of generated particles. Two Thomson parabolas, each having an aperture of 0.5mm in diameter with a CR39 detector, were set in the direction normal to the target in the forward and backward directions, respectively, 100 mm from the irradiation point. The present paper mainly reports the results obtained on the forward side. The maximum proton energies observed are shown as a function of the target positions in Fig. 1(b) for various laser energies.

The target positions giving the maximum proton energies did not coincide with the laser waist. Instead, two positions existed that gave the local maxima: one 0.5 to 1.5 mm before the waist, and the other 0 to 1 mm behind the waist. As the laser energy became smaller, the target position giving the maximum proton energy became closer to the laser waist. The positions before the waist gave larger energies to the protons than those behind the waist. The same tendency was obtained in the backward direction.

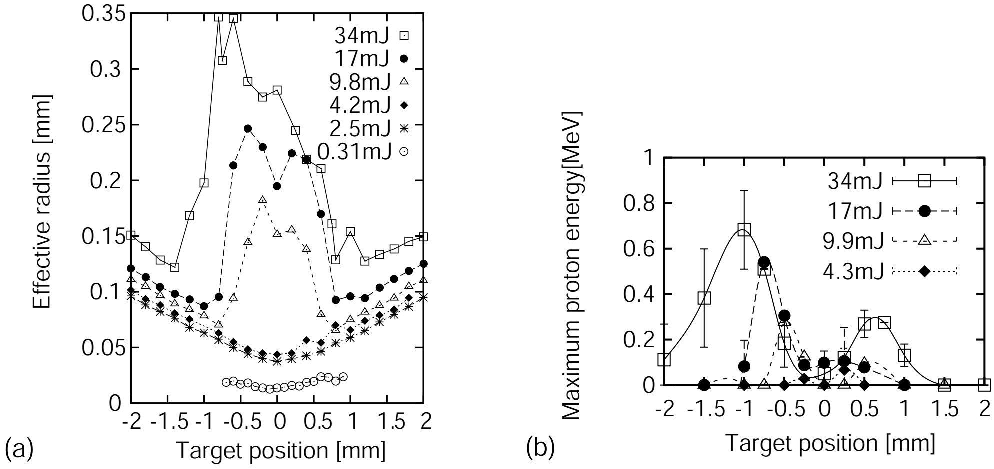

Figure 1: (a) Measured hole sizes as a function of the target positions at various laser energies. The vertical axis shows the effective radius defined by $\sqrt{A/\pi}$, where A is the measured area of a hole. The laser with an energy of 0.31 mJ penetrated the target only at a distance between -0.7 mm and 0.9 mm. (b) Dependence of maximum proton energies on target positions relative to the focal point observed on the forward side.

Figure 2(a) shows typical parabola images obtained in the forward direction. The laser energy was 34 mJ and the target position was -1.0 mm. Protons, other ions, and neutral particles were detected.

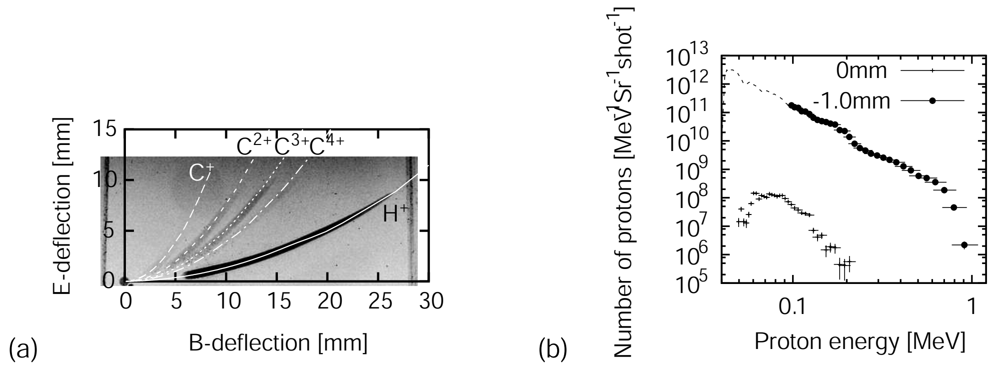

Figure 2: (a) Typical CR39 images of the Thomson parabola. The field strengths of the Thomson parabola were 2.9×10^5 V m^{-1} electrically and 0.45 T magnetically. The laser energy was 34 mJ and the target position was -1.0 mm. The lines were calculated by MAFIA. Neutral particles were detected at the origin. (b) Energy spectra of protons at two target positions.

Figure 2(b) shows the proton energy spectra at two target positions. The maximum proton energy was 900 keV at -1.0 mm, which was about five times as large as that at 0 mm. The number of ions at -1.0 mm was four orders of magnitude larger than that at 0 mm. A recent study shows that the maximum proton energies should be scaled not by the laser intensities but by the fluences in an ultra-short pulse regime such as several tens of femto-seconds [1]. It shows that the laser fluence of more than 10^5 J cm^{-2} is necessary to generate MeV protons, but the fluence of 0.8×10^4 J cm^{-2} generated 900 keV protons in the present experiment.

It was found that the intensity of the prepulses strongly influences the proton energies, as shown in Fig. 3(a). A larger prepulse resulted in smaller proton energy. Although we cannot decrease the intensity of the prepulses further, there should be an optimum intensity. Maksimchuk *et al.* [2] reported the existence of optimum intensity and timing of the prepulse, although their experimental conditions were different from ours.

Figure 3(b) shows the relation between the laser intensity at the beam waist and the optimum target position for proton generation (open symbols), and maximum proton energy (filled symbols). The triangles are the same data as in Fig. 1(b), while the circles are the data obtained in a different setup using an f = 150 mm OAP-focused laser with an angle of incidence of $\pi/4$, $w_0 = 7.5\mu$m, and $Z_R = 0.17$ mm. The laser intensity on the target was up to 2.5×10^{17} W cm^{-2}. Even with different setups, the same tendency was obtained. We can estimate the optimum target position for proton generation (Z_o) for the laser intensity at the beam waist using this target material and the energy of the prepulses from the following empirical formula: $Z_o/Z_R = 0.74\ln(I[\mathrm{W\,cm^{-2}}]) - 27.2$.

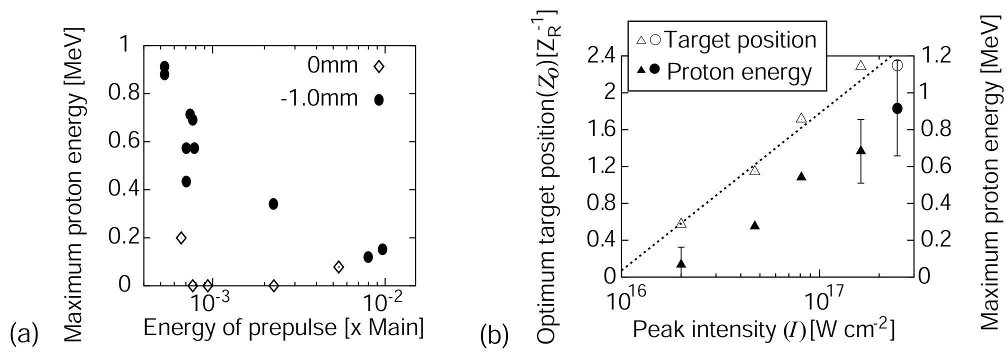

Figure 3: (a) Dependence of the maximum proton energy on the prepulse intensities at two target positions on the forward side. The horizontal scale shows the amplitude of the prepulse. The amplitude of the main pulse is kept constant. (b) Dependence of the maximum proton energy (filled symbols) and optimum target position (open symbols) on the laser intensity at the beam waist. The triangles are the same data as in Fig. 1(b), while the circles show the results obtained using f = 150 mm OAP, $w_0 = 7.5$ μm, and $Z_R = 0.17$ mm. The broken line shows an empirical formula for the optimum target position: $Z_o/Z_R = 0.74\ln(I[\mathrm{W\,cm^{-2}}]) - 27.2$.

Next we discuss our experimental results. Our interests are why the position dependencies of the hole sizes have two maxima in high-energy cases (exceeding 9.9 mJ), and why the energy of generated ions is not highest at the beam waist.

Regarding the former, low-fluence lasers have only an optical effect and the hole size created by them has a minimum on the waist and no maxima. When the fluence exceeds a certain threshold, the ablation process is accompanied by a thermomechanical effect, which enlarges the hole size. The hole size or the cross section that exceeds this threshold is smallest at the waist, and increases temporally as it leaves the waist. As the target becomes more distant from the waist, the hole size is reduced to that caused only by the optical effect. The threshold fluence of the thermomechanical effect on Cu plate is between 250 J cm^{-2} and 3600 J cm^{-2} [3], so it must be around 1000 J cm^{-2} in Mylar.

The second interest is why the energy of generated ions is not highest at the beam waist. We introduce a model to explain these experimental results. In our model, a prepulse first evaporates or ablates the surface of the target to create a neutral gas layer in front of the target. The nonlinear refractive index proportional to the intensity of the main pulse guides the main pulse itself. The main pulse with a smaller radius than in a vacuum thus interacts with the target, enabling more efficient ion generation. If the target position coincides with the waist, the prepulse intensity is, however, too high to create neutral gas. The prepulse creates plasma instead. The plasma density distribution is highest on the laser axis, which diffracts the main pulse.

Moreover, a blueshift of $\sim$ 15 nm or $\sim$ 1.88 % in the main pulse was observed in the present experiment. This supports the creation of neutral gas by the prepulses, because the blueshift is caused by the difference of refraction experienced by the main pulse; i.e., the head of the main pulse is refracted by the neutral gas left by the prepulses, while the tail is refracted by the plasma created by its own head [4].

We calculated the equation of the propagation of the laser spot size in neutral gas numerically. When 20% of the prepulse energy makes the neutral gases, the positions of the minimum spot size are -1.0 mm and 1.1 mm. This is consistent with the results of our experiment. Furthermore, the calculation successfully reproduces the tendency that the smaller the laser energy, the nearer the position of the minimum spot size to the beam waist.

In summary, we detected the ions and neutral particles in the interaction between a 1 TW, 50 fs, and 10^{-3} contrast laser and thin foils. The main component of the generated ions was protons and the maximum energy was 900 keV on both sides of the target. The ion production in ultrashort-pulse laser interaction with foil targets has an optimum target position, if the main laser pulse is accompanied by prepulses that evaporate the target. Although it has been thought up to now that a laser fluence of more than 10^5 J cm^{-2} is necessary to generate MeV protons, this experiment suggests the possibility that the fluence of less than 10^4 J cm^{-2} can generate them.

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