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Enhancement of high energy proton yield with a polystyrene-coated metal target driven by a high-intensity femtosecond laser

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ABSTRACT We present experimental results on protons accelerated up to 950 keV from a 3-μm thick tantalum foil with a 133-nm thick polystyrene layer on its rear surface, irradiated with a laser pulse having the duration of 70 fs and the intensity of 2.7×10^{18} W/cm^2. The energy distribution of fast protons was measured simultaneously with that of the hot-electrons from the rear surface. The proton yield from the polystyrene-coated target is about 10 times as high as that from the uncoated metal target. This enhancement of the proton yield is roughly proportional to the increase of hydrogen atoms given by the 133-nm thick polystyrene layer, assuming a contaminant layer of ∼ 10-nm thickness is on the metal surface without coating. This result shows that the polystyrene layer contributes to the yield enhancement.

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1 Introduction

The study of the interaction between a high-intensity laser and solid materials provides new research fields of science and technology including the emission of hard x-rays, electrons, neutrons and high-energy ions. Especially, MeV-energy protons are generated [1–6] from thin foils irradiated with short-pulse lasers, which can deliver intensities exceeding 10^{18} W/cm^2. Allen et al. [5] experimentally observed that the higher-energy protons originate from rear-surface contaminants.

Recently, several experimental studies [7–11] were performed with a double-layer target having a metal layer as a source of fast electrons and an additional layer on the rear surface as a source of fast ions. Hegelich et al. [7] obtained the first conclusive evidence that the fast ions are accelerated from the target rear-surface. Fuchs et al. [8] confirmed that rear-surface acceleration generates particle beams of higher quality than front-surface acceleration. On the other hand, a hydrocarbon layer of a few μm thickness coated on a metal foil [9, 10] provided higher proton yield than that of an uncoated metal foil. However, it is rather difficult to compare precisely the proton yield between coated and uncoated targets because as in [9, 10] an additional hydrocarbon layer as thick as the metal layer may change not only the target thickness itself but also the acceleration potential on the rear surface. Roth et al. [11] successfully observed an increase in the conversion efficiency of laser energy into fast-proton energy by using a sufficiently thin hydrocarbon layer whose thickness was varied from 5 to 100 nm.

In order to clarify the mechanism of proton acceleration in the double-layer targets, a sufficiently thin hydrogen-rich layer should be coated. The total ion charge generated in the additional hydrogen-rich layer should also be much smaller than that of the metal layer. Also, we have to evaluate the effect of the additional layer on the acceleration field at the rear surface. In this paper, we report systematic measurements of fast protons emitted from a double-layer target coupled with measurements of the energy distributions of the hot electrons. The proton energy distribution is measured for a double-layer target with the rear surface coated by a polystyrene layer of 133-nm thickness and for an uncoated metal target. The temperature of the hot-electrons is deduced from energy spectra of the hot-electrons emitted from the rear side of the two targets. We also obtain the conversion efficiency of laser energy into fast-proton energy.

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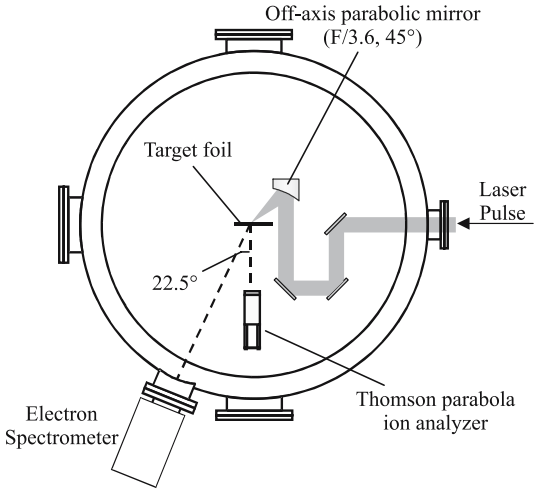

FIGURE 1 Experimental setup for the ion acceleration

2 Experiment

The experiments were performed using the Ti:sapphire laser system at the Central Research Institute of Electric Power Industry. The experimental setup [12–16] is shown in Fig. 1. The *p*-polarized laser pulse of $\lambda = 800\,\text{nm}$ was delivered to the target chamber with the energy of 250 mJ and the duration of 70 fs (FWHM). The laser pulse was focused by an off-axis parabolic mirror with the *F*-number of 3.6 under the incidence angle of 45° relative to the target normal surface, giving the peak intensity of $2.7 \times 10^{18}\,\text{W/cm}^2$ at the focal spot. This intensity corresponds to the dimensionless amplitude of $a_0 = 1.1$. The intensity ratio between the main pulse and the strongest prepulse was $\sim 10^{-5}$. The target foils were mounted on a motorized stage and moved for each laser shot. The energy distributions of the accelerated protons were measured by a Thomson parabola coupled to a track detector (CR-39) placed in the normal direction of the target rear surface. The energy of the electrons from the rear surface was recorded simultaneously with the proton detection, by using an electron spectrometer (ESM) placed at 22.5° with respect to the normal of the target rear surface.

The double-layer target was prepared by the spin-coating method [17]. The rear surface of the 3-μm thick tantalum foil was coated by a polystyrene layer, as depicted in Fig. 2. The thickness of the polystyrene layer was 133 nm. It is noted that our hydrogen-rich layer is much thinner than those of the previous works of [9, 10], and rather thicker than those used by Roth et al. [11].

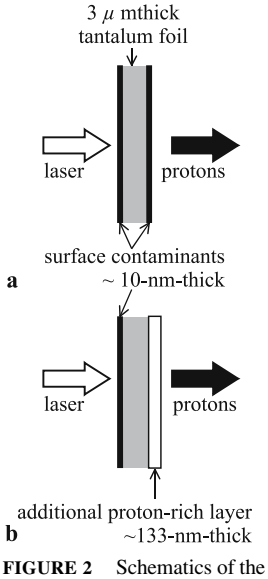

FIGURE 2 Schematics of the target foils: (**a**) the uncoated metal foil and (**b**) the double-layer target used in this work

3 Results and discussion

Figure 3 shows electron energy spectra obtained for the polystyrene-coated tantalum (PS-Ta) foil and the tantalum-only foil. In this figure, the electron energy distributions are well fitted by Maxwellian functions in the range of 500–1000 keV with the temperature of $T_e \sim 420\,\text{keV}$ for both types of foils. According to the sheath acceleration model [18], the acceleration field is expressed as a function of the hot-electron temperature, T_e. Therefore, this experimental result implies that the magnitude of the acceleration potential generated on the rear surface of the PS-Ta foil is comparable with that of the Ta-only foil. Hence, the polystyrene layer is sufficiently thin to make no drastic change on the acceleration potential.

Figure 4 shows energy spectra of protons emitted from the two foils. Clearly, the proton yield due to the PS-Ta foil is higher than that due to the Ta-only foil. The yield of 3.5×10^4 protons/shot/msr/100 keV is obtained at 530 keV for the Ta-only foil, while the PS-Ta foil shows the yield of 4.8×10^5 protons/shot/msr/100 keV, which is an order of magnitude larger. In the case of the Ta-only foil, the fast protons originate from the rear-surface contaminants embedded in a layer of $\sim 10\,\text{nm}$ thickness [4, 20], as shown in Fig. 2. Hence, the number of hydrogen atoms in the 133-nm thick polystyrene layer is about 10 times as large as that in the contaminant layer. This increase of protons emitted from the rear surface is in agreement with the fact that an order of magnitude enhancement of the fast-proton yield was found as mentioned above. This fact indicates that protons of the polystyrene layer are

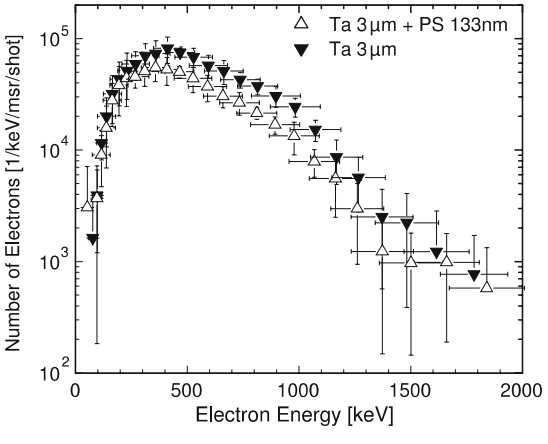

FIGURE 3 Electron energy distributions measured at 22.5° with respect to the target surface normal, as shown in Fig. 2. The spectra were obtained for the polystyrene-coated tantalum foil (*open triangles*) and the tantalum-only foil (*closed triangles*)

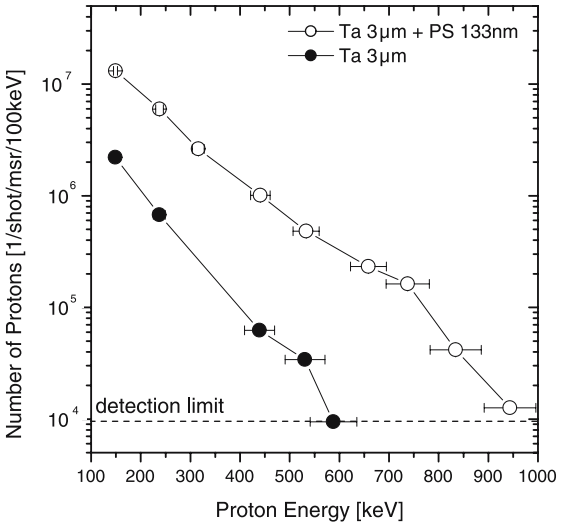

FIGURE 4 Energy distributions of protons accelerated from the rear surface of the polystyrene-coated tantalum foil (*open circles*) and the tantalum-only foil (*closed circles*)

efficiently accelerated by the potential induced by the hot-electrons.

Assuming that the protons are collimated to the half-angle of 10° [15], we obtain the conversion efficiency of laser energy into fast-proton energy ($\geq$ 150 keV) of 0.02% for the PS-Ta foil and 0.003% for the Ta-only foil. On the other hand, the estimated conversion efficiency of laser energy into hot-electron energy is $\sim$ 16% [19], which is significantly larger than that of protons. This result also indicates that the additional protons emitted from the PS-Ta foil can be treated as test particles in the acceleration potential. As long as the additional protons satisfy the test particle approximation, the proton yield will increase further if the thickness of the polystyrene layer increases. However, too thick a polystyrene layer may decrease the maximum energy of protons. Further studies are necessary to prove the dependence of the proton yield and maximum energy upon the thickness of the additional layer.

4 Summary

We measured the energy spectrum of protons generated from 3-μm-thick tantalum foils coated with a 133-nm-thick polystyrene layer on their rear surface. The electron energy spectra, obtained simultaneously with protons, indicate that the energy distributions of hot-electrons are almost the same both for the PS-Ta foil and the Ta-only foil. This result implies that the polystyrene layer is sufficiently thin to make no drastic change on the acceleration potential. The PS-Ta foil generates the proton yield of 4.8×10^5 protons/shot/msr/100 keV at 530 keV, which is about 10 times as high as that of the Ta-only foil without coating. This yield enhancement is in agreement with the increase of protons on the rear surface, indicating that the additional layer directly contributes to the enhancement of the proton yield.

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