Protons and electrons generated from a 5- μm thick copper tape target irradiated by *s*-, circularly-, and *p*-polarized 55-fs laser pulses

Z. Li,^{1,2*} H. Daido,¹ A. Fukumi,^{1,2†} S. V. Bulanov,^{1‡} A. Sagisaka,¹ K. Ogura,¹ A. Yogo,¹ M. Nishiuchi,¹ S. Orimo,¹ M. Mori,¹ Y. Oishi,³ T. Nayuki,³ T. Fujii,³ K. Nemoto,³ S. Nakamura,⁴ A. Noda,⁴ I. W. Choi,⁵ J. H. Sung,⁵ D.-K. Ko,⁵ and J. Lee⁵

1 Advanced Photon Research Center, Japan Atomic Energy Agency, Umeimidai 8-1, Kizu, Kyoto 619-0215, Japan

2 National Institute of Radiological Sciences, Anagawa 4-9-1, Inage, Chiba 263-8555, Japan

3 Central Research Institute of Electric Power Industry, Nagasaka 2-6-1, Yokosuka, Kanagawa 240-0196, Japan

4 Institute of Chemical Research, Kyoto University, Gokasho, Uji, Kyoto 611-0011, Japan

5 Advanced Photonics Research Institute, Gwangju Institute of Science and Technology, Gwangju 500-712, Republic of Korea

Abstract: The angular distribution and energy spectra of energetic protons emitted from a 5- μm thick copper tape target irradiated by *p*-, circularly-, and *s*-polarized 55-fs laser pulses with intensity of $8\text{-}9 \times 10^{18} \text{ W/cm}^2$ are measured. The protons are found in the rear target normal direction while the hot electrons are found in the laser propagation direction. The maximum energy of protons is equal to 1.34 MeV for *p*-polarized irradiation. The energy spectrum of protons depends strongly on the total amount of electrons but it does not so strongly depend on the electron angular distribution under our experiment conditions. Two dimensional particle in cell

* Present Address: Shanghai Institute of Applied Physics, Shanghai 201800, China. E-Mail: lizhong@sinap.ac.cn

† Present Address: Okayama University, Tsushima-naka 3-1-1, Japan Okayama 700-8530, Japan

‡ Also at: A. M. Prokhorov Institute of General Physics, RAS, Moscow, 119991, Russia

simulations also show the maximal proton acceleration for the p-polarized pulse, less efficient acceleration for the circular polarization, and lower acceleration efficiency in the case of the s-polarization, which is related to the electron acceleration efficiency at the front side of the target.

Key Words: femtosecond laser pulses, proton, electron, foil, polarization

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The energetic ion generation driven by laser pulses is a new charged particle acceleration mechanism with the development of ultra-short intense laser pulses equipped with chirped pulse amplification (CPA) technique [1]. Up to now, the protons with energy up to 58 MeV have been reported [2]. The laser driven ion beam provides a lot of potential applications in material sciences, biology, hadron therapy in oncology, and so on. A number of models were proposed to interpret the acceleration mechanism [1, 3-6].

The electron motion in a laser field can be characterized by the laser strength:

$$a = eE / m\omega_0 c = 0.85 \left(I_{18} \lambda_{\mu m}^2 \right)^{1/2}, \quad (1)$$

where e is the charge of electron, E the laser electric field amplitude, m the electron mass, ω_0 the angular frequency of laser, c the light speed, I_{18} the laser intensity in 10^{18} W/cm², and $\lambda_{\mu m}$ the wavelength of laser in micron. While $a > 1$, the electron motion is relativistic. The temperature of the hot electrons can be scaled by: [7, 11, 12]

$$kT_h = 511 \left[\left(1 + \frac{I_{18} \lambda_{\mu m}^2}{1.37} \right)^{1/2} - 1 \right] (keV), \quad (2)$$

The acceleration of the hot electrons is dominated by the ponderomotive force and the hot electrons are driven to the laser propagation direction.

The movement of hot electron can induce a quasi-electrostatic field due to the charge separation. The protons are accelerated by the electrostatic field: [4, 13-15]

$$|E| \propto \frac{kT_h}{e\lambda_D} \quad (3)$$

where λ_D is the Debye length of hot electrons. The maximum energy of a proton gained in the electrostatic field is:

$$\varepsilon_{\max} = e|E|\lambda_D. \quad (4)$$

Allen *et al* [15] reported the electron and proton energy spectral measurements. They found that the protons in the target normal direction have the highest maximum energy. Maksimchuk *et al* [16] and Fukumi *et al* [5] studied the dependence of maximum proton energy on the irradiation polarizations. Fukumi *et al* [5] and Nishiuchi *et al* [4] pointed out that maximum energy and energy spectrum of protons can be explained by the energy spectrum of hot electrons. Li *et al* [17] found a sharp hot electron flow appeared in the target normal direction for *p*-polarized irradiation and they also found a broadened angular distribution of hot electrons at the target rear side for *s*-polarized irradiation at laser intensity of $a=1$ which is approximately 10^{18} W/cm^2 . They pointed out that the *p*-polarized irradiation provides better proton acceleration at oblique incidence than the *s*-polarized.

In this letter, we report our measured angular distributions and energy spectra of electrons and protons at a laser intensity around $8 \times 10^{18} \text{ W/cm}^2$ ($a=2$). We discuss the dependence of proton acceleration on the electron heating and laser radiation

polarization.

The experiment is performed with a 20 TW Ti:sapphire laser system at Central Research Institute of Electric Power Industry of Japan. The laser works at the central wavelength of 800 nm. It delivers a *p*-polarized pulse with an energy of 750 mJ in a full-width-at-half-maximum (FWHM) pulse duration of 55 fs on the target. The intensity contrast ratio of a pre-pulse at 5 ns ahead the main pulse versus the main pulse is less than 10^{-5} . It is monitored by a PIN diode in nanosecond scale for each shot. Figure 1 shows the experimental setup. The rear target normal direction is defined as 0° . The incident angle of the focused laser beam onto the target is 45° . The chamber was kept at 10^{-5} torr in experiment. The laser beam with a diameter of 50 mm is focused with an F/3.6 off-axis parabolic mirror. The focal length of the off-axis parabolic mirror is 179 mm. The focus spot is $9.6\mu\text{m} \times 5.7\mu\text{m}$ (FWHM). Within the focus spot 22% of laser energy is included which is measured with a charge coupled device (CCD). The peak intensity on the target is $8.8 \times 10^{18} \text{ W/cm}^2$. The polarization is changed with the wave-plates placed before the off-axis parabolic mirror. The *p*-, circularly, and *s*-polarizations are tested in our experiment. The transmission of the half-wave plate for *s*-polarization and the quarter-wave plate for circular- polarization are 80.6% and 85.3%, respectively. The copper tape target with a thickness of 5- μm and width of 5-mm is used

[18]. The angular distribution of the protons is measured with CR-39 track detectors covered with a 5 μ m-thick aluminum filter whose lowest penetration energy of protons is 500 keV. The CR-39 track detectors are placed in the rear target normal, the laser propagation, the target surface and the specular directions. Instead of CR-39 track detectors, a Thomson parabola ion analyzer is placed in the rear target normal direction with a distance of 280 mm away from the target to distinguish the emitted ion and measure the energy spectra of the ions [3]. The Thomson parabola ion analyzer is calibrated with proton and helium ions generated from an electrostatic accelerator at the Institute of Chemical Research of Kyoto University and Nara Women University. A magnetic electron energy spectrometer is placed at 7° off the rear target normal direction to measure the energy spectrum of the emitted electrons. The electron spectrometer is calibrated with a beam source [19]. To measure the wide range of angular distribution of the electrons, a belt type imaging plate is fixed on the inner wall of the chamber placed at 10° of latitude above the horizontal plane [17]. The imaging plate is covered with a 12- μ m thick aluminum filter. The lowest penetration energies of the 12- μ m thick aluminum filter are 36 keV for electrons and 900 keV for protons.

Figure 2(a) shows the angular distribution of electrons above 36 keV measured by the imaging plates. The figure shows that the electron yield starts to increase at around

45° for all the polarizations. Then the imaging plate is getting saturated at around 90°. We find that the features are different from the ones in the case of $a=1$, [17]. Firstly, the angular distributions for p - and s -polarized irradianations are different in the case of $a=1$. Here, the angular distributions for all the polarizations show similar features but the total yield of escaped hot electrons are different. The yield for p - is the largest, then that of circular- and finally that of s -polarizations. Secondly, the peak in the target normal direction for p -polarized irradiation in the case of $a=1$ [17] disappears. This means that the electron acceleration mechanism changes. In the case of $a=1$, the hot electrons are accelerated towards the target normal direction via mainly the resonant absorption for p -polarized irradiation. In the case of $a=2$, the significant part of hot electrons are accelerated towards the laser propagation direction for all polarizations. The result suggests that the ponderomotive acceleration may play a significant role. It is noted that a few tens of micron scale preformed plasma in the target front side is measured with the two color interferometer, while no preformed plasma is found in the rear side within the accuracy of measurement [20].

Figure 2(b) shows the transverse proton beam intensity profiles recorded on CR-39 track detectors with 25 shots accumulation for p -, circularly-, and s -polarized irradiation pulses. The white part on the image is caused by the pits. The dark arc lines on the

images indicate the 5 and 10 degree positions. Although the detector in the target normal direction is saturated, the beam divergence is roughly 10° . We find the protons in the target normal direction but no protons are detected in the laser propagation direction and specular reflection direction of the incident laser in the target front side. The cases for p - and s -polarized irradiations show same result showing that the protons are predominately accelerated in the rear target normal direction although the hot electrons are accelerated in the wider range of angles. The energetic protons are accelerated by the field which is formed perpendicular to the target surface.

Figure 3(a) shows the energy spectra of hot electrons at 7° measured by the electron spectrometer with 25 shots accumulation. The drop below 100 keV is caused by the anisotropy of the potential or self-generated magnetic field. [17, 21] The high energy component can be fitted with quasi-Maxwellian distribution. [17] The temperatures are 175keV, 202keV and 242keV for s -, circularly-, and p -polarized irradiations, respectively. They are much lower than the value estimated by the Eq.2 of $kT_h=644\text{keV}$. The polarization dependency of electrons is similar to that in the case of $a=1$. The maximum energy and the total yield in the spectrum for s -polarized irradiation are lower than those for p -polarized irradiation. While those for circularly-polarized irradiation shows intermediate between those for s - and p -polarized irradiations. [17]

The measured result given by the Thomson parabola ion analyzer indicates that the emitted energetic ions are almost protons. Figure 3(b) is the energy spectra of the protons measured with the Thomson parabola ion analyzer with 5 shots accumulation. The energy spectrum has a low energy component, a high energy component, and a cut-off. The maximum proton energies at cut-off are 1050keV, 1180keV, and 1340keV for *s*-, circularly-, and *p*-polarized irradiations, respectively. The maximum energies of protons are concurrent with the experimental results in the literatures. [16, 22, 23] For *p*-polarization case, the conversion efficiency from laser energy to the proton energy whose energy is above 330 keV is 0.03%. The temperatures which fit the experimental results of the high energy components are 175keV, 213keV, and 214keV for *s*-, circularly-, and *p*-polarized irradiations, respectively. They are close to the temperatures obtained by the hot electron measurements described previously but again far from the predicted values [4, 24].

By comparing the polarization dependencies of hot electrons and protons in Fig. 3, we find that the maximum energy and total yield of protons simply depend on the total yield of electrons regardless to the electron angular distributions. Figure 3c is the simulated energy spectra of protons for *p*-, circularly-, and *s*-polarizations. The simulations are performed with the 2D PIC relativistic electromagnetic code REMP. [25]

The laser intensity is $a=2$. The target is 5- μm -thick copper ($Z=4$) foil with a density of $n=4n_{cr}$ and a 0.5- μm -thick proton layer with a density of $n=n_{cr}$, where the n_{cr} is the critical density. The laser irradiates the target obliquely with an incident angle of 45° . We find the dependence of proton energy spectrum on polarization given by the simulations is in acceptable agreement with our experimental results. This dependence is a consequence of the electron acceleration efficiency at the front side of the target. The electron acceleration is more efficient for the p -polarized radiation, when the electrons are accelerated in the process of “vacuum heating” [8]. It is less efficient for the circular polarized pulse, which can be regarded as a superposition of the p - and s -polarized electromagnetic waves. The electron acceleration has lower efficiency in the case of the s -polarization than in the cases of the p - and s -polarized electromagnetic pulses.

In summary, we measured the angular distributions and energy spectra for both electrons and protons emitted from a thin copper tape target irradiated by p -, circularly-, and s -polarized femtosecond laser pulses with a laser intensity of $a=2$. The significant part of the hot electrons is accelerated towards the laser propagation direction. The protons are measured in the target normal direction in the rear side. The dependencies of energy spectrum on polarization indicate that the acceleration of protons depends

simply on the total amount of hot electrons regardless to their angular distributions in our experimental conditions, such as $a=2$, target with a small preformed plasma.

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Figure captures:

FIG. 1 Experiment setup, where TPIA stands for the Thomson parabola ion analyzer, ESM the electron spectrometer, and IP the imaging plate.

Fig. 2 (a) Angular distribution of electrons measured with a filtered imaging plate for p -(triangles), s -(squares), and circular-(circles) polarizations. (b) Transverse proton beam intensity profiles recoded with CR-39 track detectors for proton angular distribution measurement in the target normal direction of 0° (left), laser propagation direction of 45° (middle), and specular direction of 135° (right) for p -(top), circularly-(middle), and s -(bottom) polarized irradiations. The white regions correspond to the proton etch pits.

Fig. 3 (a) Energy spectra of electrons measured at 7° . Dashed-dot lines are the Maxwellian fits. (b) Energy spectra of protons measured at the target normal direction in the rear side. (c) Simulated energy spectra of protons. The symbols of squares, circles, and triangles represent the results for s -, circularly-, and p -polarized irradiations, respectively.

Figure 1

Figure 2

Figure 3