Fast Electron Production by Irradiation of Ultrashort Laser Pulses on Copper

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Abstract. Fast electrons were produced by laser irradiation of 43-fs, 2.7×10^{18} W/cm^2 on a 30 μm thick copper target. The energy spectra of the electrons were directly measured using a magnetic spectrometer with an imaging plate. The typical temperature was 350 keV for 15° irradiation and was found to be close to the ponderomotive potential at the intensity 2.7×10^{18} W/cm^2. The energy spectra of high-energy photons, which are expected to be produced from the electrons, were also calculated.

INTRODUCTION

The chirped pulse amplification technique opened new fields of laser interaction physics including high energy particle generation such as electrons, x-ray photons, ions, neutrons, and positrons[1]. Among them, the electron generation is the most basic phenomena because other particles are generated by the interaction of electrons with matters. Although relativistic electrons are obtained using a subpicosecond pulse laser, when shorter pulses are used, a smaller energy laser can obtain the intensity which is necessary for production of relativistic electrons. The result is that laser systems become compact and high repetition rate irradiation is possible.

Recently, several groups reported the generation of fast electrons using pulse durations of several ten femtoseconds. Gahn et al.[2] estimated 0.9 MeV as the temperature of electrons which were produced by a 130-fs pulse of intensity higher than 10^{18} W/cm^2 when an artificial prepulse of an order of 10^{16} W/cm^2 was combined. Without an artificial prepulse, Schworer et al.[3] measured the angular variation of the hard x-ray spectrum at 5×10^{18} W/cm^2 using a 60-fs laser, and estimated an electron temperature of 0.7 MeV in the specular direction and 0.3 MeV in the laser forward direction. However, the electron temperatures of these experiments using shorter pulses were not directly estimated, but estimated from photon spectra.
Here, we report on results of direct measurements of fast electrons penetrating through copper film targets using 43 fs, 90 mJ pulse without an artificial prepulse [4]. The energy spectra of electrons were measured using a magnetic spectrometer with an imaging plate (IP), which is used for electron microscopy and x-ray imaging. In addition, spectra of high-energy photons originating from the electrons were simulated by GEANT4 [5].

**EXPERIMENTAL SETUP**

The diagram of the experimental setup is shown in Fig.1. The experiments were performed using a 4 TW Ti:Sapphire laser at the Materials and Structures Lab. in Tokyo Institute of Technology [6], which is based on Chirped Pulse Amplification technique and able to deliver up to 200 mJ, 43 fs pulse duration at the wavelength of 780nm with a repetition rate of 10 Hz. The contrast ratio of the main pulse to the undesirable small prepulse that precedes it by 8 ns is grater than $10^6$. In this study, the delivered energy to the vacuum chamber was between 85 and 100 mJ. The p-polarized laser beam was incident at 15 and 45 ° to the normal of the target and focused down to a spot size of $5 \mu m \times 20 \mu m$ in FWHM, with an f/3 ($f_{\text{effective}}=152.4 \text{ mm}$) off-axis parabolic mirror. Therefore, the maximum intensity was estimated to be $\sim 2.7 \times 10^{18} \text{ W/cm}^2$. Tape-like targets (30 $\mu m$ thick) made of copper were irradiated and its surface was translated for every shot. The surface displacements of the target caused by tape movement was measured to be less than ±10 $\mu m$ which was small enough compared with the collimated range of 90 $\mu m$. The copper target was chosen because this was the well-known material in the previous experiments for X-ray generation. The energy of electron with the projectile range of 30 $\mu m$ is 120 keV, therefore, electrons higher than 120 keV was expected to be able to penetrate through the copper target from laser irradiation side to backside and to be captured by an electron detector.
The electron energy spectrum was measured with a magnetic electron spectrometer located 13 cm from the backside surface of the target. The energy of electron deflected by 180° was derived from the two dimensional calculation of electrons trajectories using a map of the measured magnetic field, which was about 1.3 kG. Because of mechanical structure of a tape drive equipment, only electrons emitted to the target normal direction were detected by the spectrometer. The slit width of the spectrometer entrance was 5 mm, so an energy resolution is calculated to be about ±50 keV. The IP [Fuji Film FDL-UR-V] were used to monitor the electron flux and were covered with 15 μm thick aluminum film as a light shield. A lead block was used to shield the imaging plates from X-ray generated by laser produced plasma. The electron flux was calibrated using the sensitivity data provided by the manufacturer in the energy range between 50 keV and 1 MeV. For the range higher than 1 MeV, the electron flux was corrected by a linear extrapolation of the sensitivity data. The IP sensitivity has a maximum value at 150 keV and gradually decreases to about 0.18 of the maximum value at 1 MeV.

We obtained very close signal intensities per one shot with 100 times different shot numbers, therefore, the response of an imaging plate was linear enough and the deviation of imaging plates did not cause any significant errors to the temperature measurements. The background noise obtained by reversing the magnetic field was negligible.

RESULTS AND DISCUSSIONS

Figure 2 shows an example of an electron image recorded on the IP. Regions where electrons reached are dark. From this figure, it is evident that relativistic electrons with energies more than 1.0 MeV were generated. The energy spectra of electrons for laser irradiation at 15° and 45° are shown in Fig. 3. These spectra were obtained with 20 shots in both cases.

FIGURE 2. Electron trajectories and electron image recorded on the imaging plate attached to spectrometer.
FIGURE 3. Spectra of fast electrons penetrate the 30 μm thick copper target measured at normal direction to the target surface for laser irradiation at 15° and 45°. The Broken line shows ponderomotive scaling.

The electron temperatures were estimated from fitting to the Boltzmann distribution in the range between 500 keV and 1 MeV because in the low energy region around 200 keV, the sensitivity of the IP changes significantly. The estimated temperatures were 350 keV for the irradiation at 15° and 300 keV for the irradiation at 45°. The broken line shows ponderomotive scaling described by

\[ k_B T_e = m_e c^2 \left( 1 + \frac{I}{E_0} \right)^{1/2} \left( 1.38 \times 10^{18} - 1 \right) \]  

[7]. Although the laser intensities of these experiments were on the border of the relativistic region where the ponderomotive force is dominant, the obtained electron temperatures were close to the ponderomotive potential of 250 keV. We observed fast electrons for the irradiation at 15°, which was not expected to cause significant resonance absorption. Therefore, the main acceleration mechanism should be due to the ponderomotive force. Figure 4 shows the relation between laser intensities and electron temperatures. Our result is marked as an asterisk, which is almost on the curve of the ponderomotive scaling.

These fast electrons can produce high-energy photons by bremsstrahlung, and the estimation of photon energy and yield is important for photon applications. The photon spectrum for the 30 μm thick copper target was calculated using a simulation program GEANT4 and the results are shown in Fig. 5. In this calculation, x-rays were generated by electrons which were assumed to be accelerated to a high temperature of 350 keV in the direction normal to the target surface and the cut-off electron energy was assumed to be 3 MeV. The estimated temperature of the x-ray spectrum was 260 keV. In Schwoere’s experiments, a laser pulse at an intensity of 5.0 \times 10^{18} W/cm² with 60 fs duration was irradiated on a 1 mm thick tantalum target and x-ray temperature was estimated at 200 keV. We also calculated a photon spectrum for a 1 mm thick tantalum target, by which efficient x-ray production can be expected. The calculated temperature was 250 keV, which was close to the results of Schwoerer et al.
[3] and the estimated intensity of photons was ten times larger than that for 30 μm thick copper target, as indicated in Fig. 5.

![Figure 4](image-url)

**Figure 4.** Relation between laser intensities and electron temperatures. Our result is marked as an asterisk.

![Figure 5](image-url)

**Figure 5.** Calculated energy spectra of photons which are generated by the interaction of electrons with 30 μm thick copper target and 1 mm thick tantalum target.

**SUMMARY**

In summary, fast electrons were produced by laser irradiation of 43-fs, $2.7 \times 10^{18}$ W/cm$^2$ on a 30 μm thick copper target and the energy spectra were directly measured.
using a magnetic spectrometer with an imaging plate. The typical temperature was 350 keV for 15° irradiation and was found to be close to the ponderomotive potential at the intensity $2.7 \times 10^{18}$ W/cm². With ultrashort pulses, particles with energy corresponding to the ponderomotive potential can be produced by a small laser. Higher temperatures may be possible with an artificial prepulse, and a small and high-repetition ultrashort laser can be used for studies of high-energy particle generation.

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REFERENCES


