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Highly directional sub-MeV electron emission form long wires irradiated by intense laser pulses

高強度レーザー照射長尺ワイヤーから放射される高指向性sub-MeV電子ビーム

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We have experimentally demonstrated that fast electrons emitted from a metallic wire irradiated by a 5 × 10^{18} W/cm^2 laser pulse can be collimated along the wire, and that their intensity is significantly enhanced in the axial direction of the wire. As wire length is increased up to 30 mm from the laser focal spot, the angular divergence of the emitted electrons decreases to 65 mrad.

1. Introduction

Fast electron generation and transport via the interaction of relativistic-intensity laser pulses with solid-density targets have been extensively studied because of their potential applications, such as electron diffraction [1–3], particle acceleration [4], and fast ignition fusion [5]. Many efforts have been made to improve the intensity, directivity, and monochromaticity of electron beams.

Collimated beam generation has been demonstrated experimentally using various targets. A short thin wire attached to a cone-shape target irradiated with a 0.3 PW laser pulse has been used to guide and to collimate electrons in the MeV energy range [6]. A small metal target with a resistivity boundary has been used to collimate electrons by irradiation with a 10^{20} W/cm^2 laser pulse [7]. Using planar targets, collimated beam generation has also been demonstrated [8–11]. In studies on relativistic laser–solid interactions, such as the above-mentioned works, particle-in-cell (PIC) plasma simulations for a small space (hundreds of micrometers at most) near the laser irradiation spot have been successfully carried out to explain the experimental results. That is to say, such phenomena have been explained by effects in small-scale models.

Here, we experimentally demonstrate collimated electron-beam generation using long metallic wire targets with lengths of the order of centimeters. The characteristics of the electron emission strongly depend on the length of the wire: collimation becomes stronger with increasing wire length.

2. Experimental Setup

A Ti:sapphire chirped-pulse amplification system operating with a central wavelength of 800 nm and a pulse duration of 150 fs is used as the laser source. Laser pulses with a pulse energy of 140 mJ are focused with an *f* / 3.5 off-axis parabolic mirror to a spot size of 3 μm × 4 μm, resulting in a peak intensity of 5 × 10^{18} W/cm^2. Amplified spontaneous emission is measured to be less than 10^{-7} of the peak intensity of the laser pulse. The laser pulse is *p*-polarized and irradiates a tungsten wire with diameter of 300 μm at an incidence angle of 45°. Imaging plates (IPs) are used to detect fast electrons. The IPs have high sensitivity in the energy range from 40 to 1000 keV and are most sensitive at around 200 keV. The whole setup is placed in a vacuum chamber with pressure of 0.1 Pa.

Figure 1 shows the experimental setup for measuring the angular distribution of electron emission. Wire length L between the laser focal spot and the end of the wire is varied from 2.5 to 30 mm. Double-layer stacked IPs are placed at a distance of z = 150 mm from the laser focal spot and are covered with aluminum foil of 11 μm in thickness in order to prevent exposure of the IPs to light.

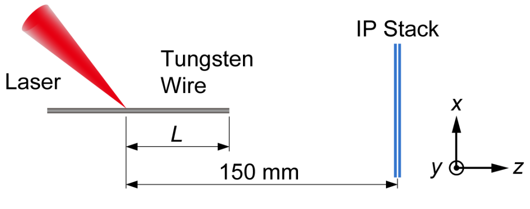

Fig. 1. Experimental setup [12].

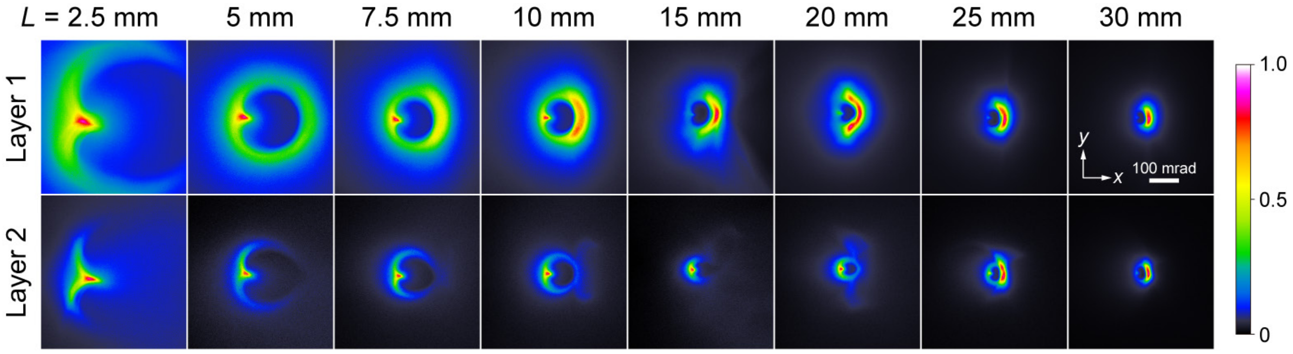

Fig. 2. Single-shot images detected by IPs for $L = 2.5, 5, 7.5, 10, 15, 20, 25$ and 30 mm. The color scale is set independently for each image for maximum contrast. The actual dimensions of the images are 75 mm × 80 mm. The center of each image roughly corresponds to the wire axis.

3. Results

Figure 2 shows typical single-shot images detected with the IPs for $L = 2.5$ to 30 mm. On the second-layer IP, electrons with energies greater than about 400 keV can be detected. The electrons form distinctive ring-shaped patterns on the IPs. The patterns for each wire length are highly reproducible; however, the center of the ring-shaped pattern shows slight shot-to-shot fluctuation within ±30 mrad because its position is sensitive to the axial direction of the wire. The overall size of the pattern is drastically reduced as the wire length L is increased. The size of the hole in the ring decreases from 65 to 6 mm in height as L is increased from 2.5 to 30 mm. The full angle at half-maximum of the electron emission in the horizontal and vertical direction is as narrow as 20 and 65 mrad, respectively, at $L = 30$ mm. In contrast, the IP signal intensity increases with increasing the wire length: the signal intensity at the brightest spot for $L = 30$ mm is 7-fold higher than that for $L = 2.5$ mm. Assuming a typical electron energy to be 300 keV, the total number of detected electrons is estimated to be of the order of 3×10^9 at $L = 30$ mm, resulting in laser-to-electron energy conversion efficiency as high as 0.1%.

4. Conclusion

We have demonstrated collimated fast electron emission through the interaction of intense femtosecond laser pulses with long metallic wire targets with lengths of the order of centimeters. Emission of electrons with high angular density of nearly 10^{12} sr^{-1} and energies of hundreds of keV was observed. From the viewpoint of potential applications, since the generated electron beam has a broad velocity distribution and is energy chirped in time, it would be particularly useful as a novel electron source for single-shot time-resolved measurements of ultrafast phenomena, for instance, an electron streak camera [1] or ultrafast electron diffraction with pulse compression [3]. In regard to another aspect of intense laser interactions, these experimental results proved that large regions of a metallic target can affect electron emission. It can be considered that the present phenomenon is strongly related not to the acceleration process, but rather to the target shape.

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