Fast heating of wire target attached on entrant hollow cone with ultra-intense laser up to keV order

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Abstract. We demonstrated efficient fast heating of a solid wire target attached on a hollow entrant cone target with an ultra-intense laser. The heating temperatures were 1.2-2.1 keV and the heated temperatures were independent of the wire length, implying strong collimation of high energy density electrons produced in an interaction of the ultra-intense laser light with the cone-wire target along the wire. The high energy density electrons propagated along the wire target with maintaining the high energy density of electrons.

1. Introduction

High energy density electron beams produced in an interaction of ultra-intense laser with a solid target have energy of MeV order and density of several 100 TA/cm² [1]. The high energy electron beams can instantaneously heat solid materials and high density plasmas with a temperature of keV order. The fast heating takes place on the time scale of the laser pulse duration (from several 100 fs to a few ps). The time scale is shorter than that of the plasma expansions and compressions. As a consequence, the effect of expansion and compression could be ignored, and the volume of the heated plasmas is constant during the fast heating. Namely the heating is regarded as isochoric process. There is also an opportunity to create extremely high-pressure materials (more than 1 Gbar) by fast heating of solid density materials with a temperature of keV order and to measure the equation of state [2] and opacity under conditions relevant to astrophysics [3]. Especially, using a cone geometry target, energetic electrons are more efficiently generated from the cone by irradiation of the ultra-intense laser. The energy coupling efficiency from the laser to energetic electrons could be enhanced in the cone
geometry by factor of 2-3 as compared with the open geometry. A part out of encircled area of the focused laser pulse would be reflected on the side wall of the cone and efficiently guided into a tip of the cone and, eventually most of the laser energy was deposited into the tip of the cone [4]. These results must be due to the plasma mirror effects at the side wall.

Recently, we demonstrated guiding and collimation of the energetic electrons with a carbon wire target attached on an entrant hollow cone [5]. Particle in cell simulation shows the propagation of high energy density electrons are guided and collimated with a strong azimuthal magnetic field and a strong radial electrostatic field surrounding the wire. The energetic electrons are pushed outside the wire by the magnetic field and are pulled back to the wire by the electric field. If the electric force and the magnetic force are balanced, the energetic electrons can propagate along the wire. The wire was instantaneously heated by the propagation of the energetic electrons and became wire plasma. The plasma expansion in the direction perpendicular to the wire axis indicated the wire was heated to a temperature of 2-4 keV by observing time-resolved two-dimensional optical emissions from the wire plasma. However, we have not directly measured the heating temperature of the wire target.

In this report, we demonstrated efficient fast heating of a solid wire target attached on a hollow entrant cone target with an ultra-intense laser and directly diagnosed the heating temperature of the wire target by measuring neutron spectra.

2. Experiments and simulation

Experiments were carried out using a PW laser at Osaka University [6]. The energy was 120 J, the wavelength 1.053 µm and the pulse duration between 0.7 and 1.1 ps. The laser pulse was focused by an f/7 off axis parabolic mirror onto the cone tip. The spot size was between 40 and 60 µm. A peak intensity of approximately $10^{19}$ W/cm$^2$ was obtained at the target. The amplified spontaneous emission was about 10$^{-7}$. A plastic (CD) wire target attached on the tip of a gold cone was used. A thickness of the cone was 10 µm, the open angle 30 deg., and the tip diameter 30 µm. And the diameter of the wire was 20 µm.

We diagnosed a heating temperature of a wire target by measuring neutron spectra. Neutrons were generated by fusions of two deuterium nuclei to a $^3$He nucleus (d(d,n)$^3$He) in the wire plasma, and provided a precise measurement of the plasma ion temperature. The plasma ion temperature was estimated by a relation $T_i$(keV) = ($\Delta E_{\text{FWHM}}$(keV)/c)$^2$, where $\Delta E_{\text{FWHM}}$ was the energy spread of the

![Fig. 1: A thermal neutron spectrum. The thermal neutron yields were $1 \times 10^6$. The line is a gaussian fit to the data points, indicating a spectral width of 130 keV. Taking account of the energy resolution of the detector, this spectral width is corresponding to 1.5 keV for a plasma ion temperature.](image-url)
thermal neutrons and $c = 82.48$ for a deuterium-deuterium fusion reaction [7]. The neutron energy spectra were obtained using a multi-channel wave coincidence method to suppress an influence of gamma-ray signals and beam like fusion neutron signals [8]. Peaks at an energy of 2.45MeV were observed, corresponding to neutrons from a thermonuclear $d(d,n)^3He$ reaction. The neutron time-of-flight spectrum in Fig. 1 shows a signal corresponding to thermonuclear neutron yields of $1 \times 10^6$ neutrons. The line is a gaussian fit to the data points, indicating a spectral width of 130 keV. Taking account of the energy resolution of the detector, this spectral width is corresponding to 1.5 keV for the plasma ion temperature. We observed the ion temperature of 1.2-2.1 keV in several shots. These temperatures were lower than prospective temperature for the carbon wire [5] since the diameter of the CD wire was 20 µm, which was larger than that of carbon wire 5 µm.

Figure 2 shows a plot of the observed neutron yields and the plasma ion temperature vs the plasma ion temperature, where solid and empty circles represent the neutron yields with 300 µm and 700 µm length wire, respectively. Lines in Fig. 2 represent the calculated neutron yields using the ILESTA-1D hydrodynamic simulation code [9], where solid and dashed lines represent the neutron yields with 300 µm and 700 µm length wire, respectively. The heated temperatures were 1.2-1.5 keV with 100 µm length wire, 1.2-2.1 keV with 300 µm length wire, and 1.3-1.7 keV with 700 µm length wire. These results indicated that the heated temperature were independent of the length of the wire because of the guiding and the collimation of the high energy density electrons. The high energy density electrons propagated along the wire target with maintaining the high energy density of electrons.

We observed time-resolved two-dimensional optical emissions from the wire plasma with a two-dimensional (2D) spatially resolved optical high-speed sampling camera (HISAC) [10]. Figure 3(a) shows a configuration of a cone wire target. The rectangular area represents a measurement area of an optical emission with HISAC. Figures 3(b) and 3(c) show the optical emission 40 ps and 100 ps after an interaction of the PW laser with the cone wire target, respectively. The wire plasmas in the two images were created along the wire. The images of the optical emission also indicated the guiding of the energetic electrons along the wire target. The plasma expansions in the direction perpendicular to the wire axis, which happens long after propagation of the energetic electrons, were observed. The peak flux of the emission and the expansion in the direction perpendicular were independent of the length of the wire, indicating the heated temperature were independent of the length of the wire. The point of the peak flux of the optical emission was located on the tip of the wire. These locations indicated the energetic electrons through the wire forward were reflected back again from the vacuum region because of negative space charge in the vacuum.
Fig. 3 (a) A configuration of cone wire target. And a rectangular area represents a measurement area of the optical emission from the wire with HISAC. The observed optical emission from the wire plasma (b) 40 ps after an interaction of the PW laser with the cone wire target and (c) 100 ps.

3. Summary

We demonstrated efficient fast heating of a solid wire target attached on a hollow entrant cone target with an ultra-intense laser. The heating temperatures were 1.2-2.1 keV. The heated temperatures were independent of the wire length. The high energy density electrons propagated along the wire target with maintaining the high energy density.

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