Long-Scale Jet Formation with Specularly Reflected Light in Ultraintense Laser-Plasma Interactions

R. Kodama,[1] K. A. Tanaka,[1,2] Y. Sentoku,[1] T. Matsushita,[1] K. Takahashi,[1] H. Fujita,[1] Y. Kitagawa,[1] Y. Kato,[1] T. Yamanaka,[1] and K. Mima[1]

[1]*Institute of Laser Engineering, Osaka University, Yamada Oka 2-6 Suita, Yamada Oka, Osaka 565-0871, Japan*
[2]*Department of Electromagnetic Energy Engineering, Osaka University, Yamada Oka 2-1 Suita, Osaka 565-0871, Japan*
(Received 18 June 1999)

Long-scale jetlike x-ray emission was observed in a 100-TW laser-plasma interaction. The jet was well collimated with a divergence of 30–40 mrad and continued from the target surface into underdense regions for a distance over 4 mm in the specular direction of the laser light. A two-dimensional particle-in-cell simulation shows an electron acceleration with the specularly reflected laser light and collimation of the electron stream by a self-generated magnetic field, resulting in the electron jet to the direction of the specularly reflected light.

PACS numbers: 52.40.Nk, 52.25.Nr, 52.70.La

Ultraintense laser light interactions with long scale-length plasmas open a new horizon for basic physics in a relativistic regime and potentially attractive applications such as a fast ignitor concept in inertial confinement fusion, laser application, and x-ray lasers using short pulse laser light [1–3]. The fast ignitor concept, especially, requires understanding of laser-plasma interactions at relativistic laser intensities in an inhomogeneous plasma with a long-scale length. Numerous theoretical and experimental works have been devoted to investigate the interactions of the relativistic laser light with long scale-length underdense plasmas. A well-known formula for the critical power given by $P_{\mathrm{cr}} = 17 n_c/n_e$ [GW], where n_c is the critical density and n_e the electron density, determines a laser power necessary for relativistic self-focusing in underdense homogeneous plasmas [4].

Most studies of such ultraintense laser interactions have been made at laser powers less than a few tens of TW, higher than the critical power. In these cases, only incident laser light have been considered in the interactions. However, at laser powers exceeding 100 TW, the strong laser field of reflected light from the target could do much for the interactions as well as those with the incident laser light. The power of the specularly reflected light could still exceed the critical power in long scale-length plasmas, which might generate a stable channel in underdense plasmas from the higher to lower density regions. Recent experiments [5] and numerical investigations [6,7] of the formation of the collimated electron ejection into the underdense plasmas indicate an important role of the reflected light as well as the Brunel absorption of the p-polarized laser light. For oblique incidence of s-polarized laser light, the Brunel absorption [8] is minimized. In this case, the interaction of electromagnetic fields of the reflected light with the long scale-length plasma will dominate and will be easier to study.

We have studied specularly reflected light effects on the interactions of 100 TW laser light with long scale-length plasmas. Jetlike x-ray (1–30 keV) emission with a few mm length with directly observed in the specular direction of the s-polarized reflected laser light from the target surface for the first time. A two-dimensional particle-in-cell code was used to understand the formation of electron jets to the specular direction with an s-polarized laser beam.

The experiments have been carried out with a 100 TW short pulse laser system [9] at ILE, Osaka University, which delivers a 0.5–1 ps pulse with energies up to 50 J on targets. By using an $f/3.6$ on-axis parabola mirror, the short pulse was focused onto a plasma created on a CH target (preformed plasma) with the three beams of the GEKKO XII long pulse laser light. The vacuum incident angle of the short pulse was normal to the target. The spot diameter of the short pulse at the best focus position was 20–30 μm in vacuum giving peak intensities of $(0.5–1) \times 10^{19}$ W/cm^2. The focus position of the short pulse in the preformed plasma was set at 250–300 μm from the target surface, corresponding to geometrical spot diameters of 70–80 μm on the target surface. The preformed plasma was created at 0.8–1 ns before the short pulse by a 0.53-μm double pulse (100 ps) with a time separation of 400 ps at intensities of 10^{14}–10^{15} W/cm^2 with a spot diameter of 350 μm.

X-ray images were obtained with two different pinhole cameras coupled to x-ray charge-coupled device (CCD) cameras: one is aimed for a high spatial resolution (about 13 μm on the target) and another for a high sensitivity. The high-sensitivity pinhole cameras had aperture sizes of 250 μm for viewing the target rear and of 280 μm for the side. The sensitivity of the large aperture pinhole cameras was 350 times higher than those of the small pinhole cameras. These large aperture pinhole cameras also worked as penumbral imaging systems for small sources with a size of less than the aperture size. Both types of the pinhole cameras had a 40-μm-thick Be filter, resulting in the spectral sensitivities of 1 to 30 keV and an effective peak of the spectral response at about 5 keV.

 0031-9007/00/84(4)/674(4)$15.00

Figure 1 shows the intensity contour plots of x-ray images of a 100 TW laser interaction from both front and side views taken with the high-resolution pinhole cameras for the preformed plasma created at 10^{14} W/cm^2. An intense hot spot with a diameter of 40–50 μm appeared on the target surface [Fig. 1(a)], and its size was smaller than the geometrical focus spot in vacuum (70–80 μm) on the target surface. The hot spot could result from a part of the laser light self-focused in the preformed plasma and channeled into an overdense region, which was similar to the x-ray images as mentioned in Ref. [10]. Such hot spots were scattered only upward or downward or sometimes split to two ways (up and downward) from shot to shot. These scattered directions of the hot spot were approximately perpendicular to the laser polarization plane. The side view image [Fig. 1(b)] shows the hot spot emission starts almost from the target surface and extends toward the underdense plasma, which appears as a plasma jet in the specular direction of the laser light. This jetlike emission appeared always when the intense hot spot was observed on the target surface. We had also shots showing jetlike emission to the target normal at a different prepulse condition. Figure 2 shows intensity contour plots of x-ray images from both front and side views for the preformed plasma created at 10^{15} W/cm^2. This shot resulted in the jet normal to the target surface, namely without bending the laser propagation. Intense hot spots appeared on the target surface, and their positions were near the center axis of the laser beam. The hot spot size was again smaller than the original focal spot as shown in Fig. 2(a). The jetlike emission started from the hot spot on the target surface in the direction to the target normal when the hot spot appeared at the beam axis as shown in Fig. 2(b). When the hot spot was above the center axis on the target surface, the jetlike emission was directed upward, and when the hot spot was below the center axis, a downward jet was observed. All of the x-ray images showing the jetlike emission indicate that the jets are along the direction of specular reflection of the laser light. In order to check the correlation of the direction between the jetlike emission and the specularly reflected laser light, we also measured relative fluence of the backscattered light collected by the focus mirror. When the jetlike emission directed to the target normal on the beam axis, the reflectivity of the laser light to the focus mirror was about 6% of the input laser energy. However, the reflectivity of less than 2% was obtained for the observation of the jetlike emission with its direction upward and/or downward, when the reflected light was out of the collection angle with the focus mirror. The absolute values of the reflectivity might have some errors but are correct in a relative scale. Therefore, the results indicate correlation between the specularly reflected light and the jetlike emission.

The jetlike emission was also observed with the high-sensitive pinhole cameras. Figure 3(a) shows a typical jetlike emission from the target rear side taken at the shot same as shown in Fig. 1. Long-scale jetlike emission is clearly seen for a distance over 4 mm to the specular

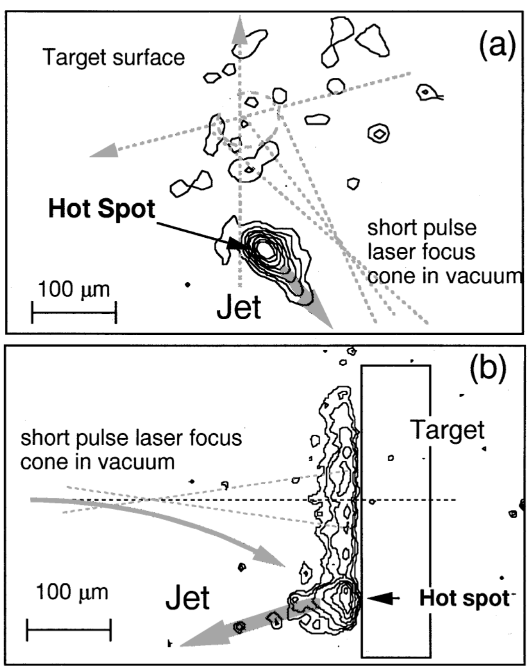

FIG. 1. Intensity contour plots of x-ray images (1–30 keV) of a 100 TW laser interaction with the preformed plasmas created at a laser intensity $I_L = 10^{14}$ W/cm^2 from (a) front and (b) side views taken with the high-resolution pinhole cameras. The focus cone and focal spot of the 100 TW laser light in vacuum are shown as dotted lines.

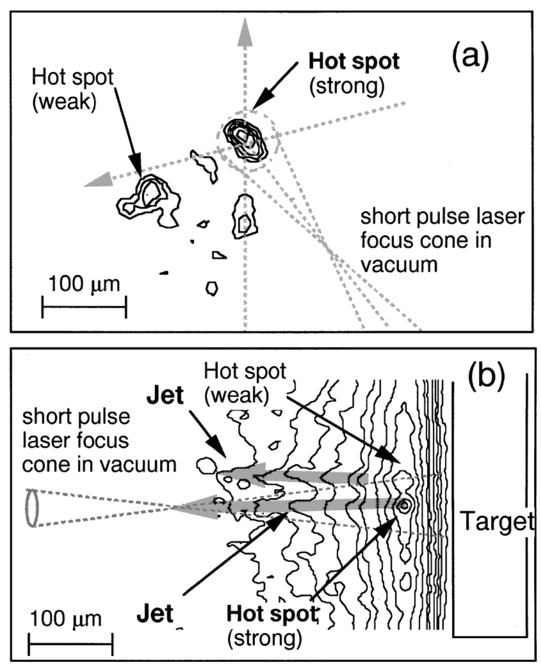

FIG. 2. Intensity contour plots of x-ray images from (a) front and (b) side views taken with the high-resolution pinhole cameras for the preformed plasma created at $I_L = 10^{15}$ W/cm^2. The images show no significant bending of the beam in the preformed plasma and jets to the target normal.

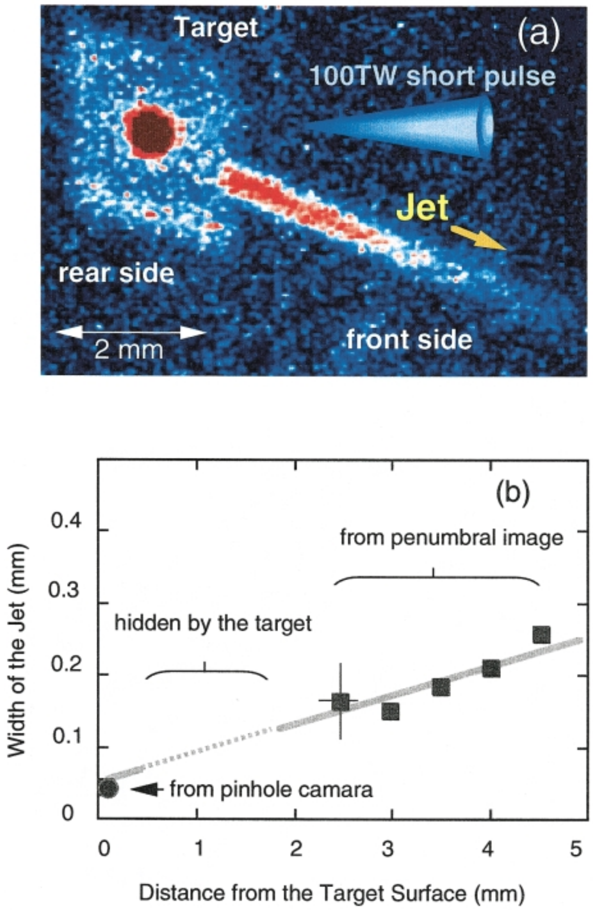

FIG. 3 (color). (a) X-ray image from the target rear side with the large aperture pinhole camera at the same shot as shown in Fig. 1. The jet observed in Fig. 1 is elongated over a few mm. (b) The width (FWHM of the emission) of the jet obtained with the pinhole cameras. The width at a few mm from the target surface was evaluated by one-dimensional reconstruction of a penumbral image obtained with the large aperture.

direction, which is consistent with the direction of the jet on Fig. 1. By using the high-resolution cameras, the extensions of the jetlike emission were only a few 100 μm because of its low sensitivity. However, the large aperture cameras had a sensitivity to collect a weaker signal, resulting in the observation of the jet with a few mm length. The direction of the jets obtained with the high-resolution cameras was exactly the same as that of the jets with high-sensitive cameras. The emission close to the target surface observed in Fig. 1 is hidden by the target on Fig. 3, since the observation was made from the target rear. The collimation of the jet is represented by the estimation of the emission width perpendicular to the direction of the jetlike emission as shown in Fig. 3(b). The widths of the jet were evaluated by one-dimensional image reconstruction as a penumbral image obtained with the large aperture. The jet width close to the target surface is estimated from the high resolution camera as shown in Fig. 1, which is reasonably connected to the widths from the penumbral image reconstructions. The divergence of the jet is 30–40 mrad at 4 mm from the images, indicating a significant collimation of the jet. All of the jetlike emissions were elongated over a few mm with collimation as shown in Fig. 3 for the other shots.

A two-dimensional particle-in-cell (PIC) code has been carried out to investigate the jet formation from the target surface to the specular direction. In the simulation code, the deuteron plasmas are fully ionized and its geometry has an oblique surface to the laser axis set in the middle of a simulation box (23 μm square). The density profile from $4n_c$ as a maximum density to $0.1n_c$ has a steep exponential shape with a scale length of 0.2 μm. The corona plasma with a constant density of $0.1n_c$ is set at the front of the laser irradiation side over 10 μm in the simulation box. The laser pulse has a rise time of 25 fs and keeps the peak intensity of 2×10^{18} W/cm^2 during the simulation within a 7 μm spot diameter. Taking account of the plasma size in the experiments, the peak intensity of 2×10^{18} W/cm^2 is used for a coupling efficiency of 20%–50% of the laser light [11]. The same s-polarized laser beam is used as the experiments. The laser beam bent in the plasma to the direction perpendicular to the polarization in the experiment, which means the laser light is s polarized when it interacts with the target surface. The incident angle of the laser light is 29° to the target normal. More details of the code and p-polarization cases are described in Ref. [6].

Figures 4(a) and 4(b) show the electron energy density contours overlapped with the instantaneous laser intensity map and the quasistatic magnetic fields at 200 fs from the simulations, respectively. A few MeV high energy electrons are ejected from the high density region in the direction of the specularly reflected light and are collimated as a jet started from the target surface as shown in Fig. 4(a). For an oblique incidence, the absorption of s-polarized light is expected to be less than the p-polarized light case because of poor Brunel absorption of the s-polarized light. The absorption of the s-polarized light is only 7.8%, whereas there is 26% absorption for the p-polarized light. Then the significant effect is expected on the plasma interaction with the strong reflected light for the s polarization. The direction of the electron jet for the s-polarized light is exactly the same as the specular direction while the p-polarized light has some discrepancy between them due to the high energy electrons directed to the target normal created by the Brunel absorption [6]. A large amount of the specularly reflected light is temporally modulated at near the critical point in the plasma with a steep density gradient as shown in Fig. 4(a). The intensity of the reflected light increases due to the self-focusing of the reflected light via the surface deformation with a strong ponderomotive force of the incident light and the relativistic effects of the reflected light [12]. High density electrons ejected from the target surface ($4n_c$) are trapped in these reflected modulation pulses and accelerated over MeV energy into coronal plasmas. The electron acceleration in the field of the specularly reflected light increases the self-generated magnetic field with a distance from the target surface as shown in

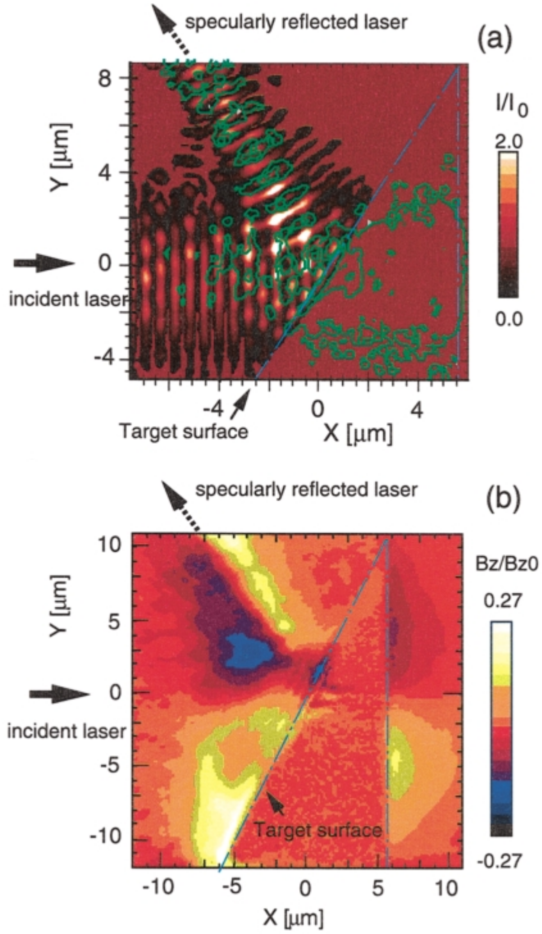

FIG. 4 (color). PIC simulation results of (a) the electron energy density $(\gamma - 1)n_e/0.1n_c$ contours (green line) overplotted with the instantaneous laser intensity map normalized with the incident laser intensity I_0 and (b) the quasistatic magnetic fields normalized with a field of the incident laser light B_{z0} at 200 fs. Electrons ejected from the target surface are accelerated by the specularly reflected light and are collimated with self-magnetic fields, resulting in the high energy density electron jets to the specular directions emitting x rays.

Fig. 4(b). Magnetic fields of 20–30 MG are created by the electron jet. The collimation of the electron jet is explained by this self-generated magnetic field induced by the electron stream. The current in the jet is 30 kA with an average electron energy of about 600 keV. This current is higher than the Alfvén limit, which is a critical value to change the electron motion by pinch forces [13], for electrons with energies of less than about 1 MeV. Therefore, the magnetic force could pinch and collimate the electron stream to create high aspect jets with high densities. These high energy density electrons could emit strong x rays, resulting in jetlike emission in the specular direction. The 2D PIC simulation results show the electron jets with high energy densities due to the s-polarized specularly reflected light, the direction and the collimation of which are consistent with the observed jets as shown in Figs. 1 and 2.

Besides this process, the longer scale jetlike emission as shown in Fig. 3 might need an additional physical process in the long-scale plasma; e.g., the specularly reflected light could be channeled in the long scale-length plasmas into underdense regions because its power is still high enough to create a relativistic channel. From the reflectivity of the laser light to the specular direction, the power of the reflected specular light would be expected still to be a few TW (1–5 TW). The analogy of a critical power to create a stable channel in a homogeneous plasma implies that this power of the reflected light is much higher than P_c to create a stable relativistic channel at electron densities above $(0.4-2) \times 10^{19}$ cm^{-3}. Such density plasmas could exist even at a few mm from the target surface based on our hydrodynamic simulation.

We have observed mm-scale jetlike x-ray emission in the direction of the specularly reflected light at 100 TW laser-plasma interactions. The jet grown from the hot spot appeared on the target surface in the specular direction with a high degree of collimation for a few mm. Our two-dimensional PIC code results indicate electrons with a few MeV energy accelerated by the s-polarized specularly reflected light. Such a jet formation with the reflected laser light from overcritical densities to the coronal region may be introduced to a novel scheme of a significantly collimated electron accelerator with a high density source. The observed high aspect jets may be important also from a viewpoint of highly collimated astrophysical jets [14] caused by high Mach number outflows from young stars.

We acknowledge all the technical supports of the engineering staffs at Institute of Laser Engineering for the laser system operation, target fabrication, and data acquisition. We especially thank Dr. T. Norimatsu, Dr. K. Nagai, Dr. H. Yoshida, Dr. T. Kawasaki, and Dr. S. Matsuo for their invaluable support.

[1] M. Tabak *et al.*, Phys. Plasmas **1**, 1626 (1994).
[2] T. Tajima and J.M. Dawson, Phys. Rev. Lett. **43**, 267 (1979); K. Nakajima *et al.*, Phys. Rev. Lett. **74**, 4428 (1995).
[3] P.V. Nickles *et al.*, Phys. Rev. Lett. **78**, 2748 (1997).
[4] A.B. Borisov *et al.*, Phys. Rev. Lett. **68**, 2309 (1992); A.B. Borisov *et al.*, Phys. Rev. A **45**, 5830 (1992).
[5] S. Bastiani *et al.*, Phys. Rev. E **56**, 7179 (1997).
[6] Y. Sentoku *et al.*, Phys. Plasmas **6**, 2855 (1999).
[7] H. Ruhl *et al.*, Phys. Rev. Lett. **82**, 743 (1999).
[8] F. Brunel, Phys. Fluids **31**, 2714 (1998); Phys. Rev. Lett. **59**, 52 (1987).
[9] Y. Kato *et al.*, Plasma Phys. Controlled Fusion **39**, A145 (1997).
[10] R. Kodama *et al.*, Phys. Rev. Lett. **77**, 4906 (1996).
[11] We have also tested at 10^{19} W/cm^2 and no significant difference is observed on the jet formation with s-polarized beam.
[12] V.A. Vshivkov *et al.*, Phys. Plasmas **5**, 2727 (1998).
[13] H. Alfven, Phys. Rev. **55**, 425 (1934); J.D. Lawson, J. Electron. Control **5**, 146 (1958).
[14] C.J. Burrows *et al.*, Astrophys. J. **473**, 437 (1996); T. Buhrke *et al.*, Astron. Astrophys. **200**, 99 (1988).