Propagation of a relativistic ultrashort laser pulse in a near-critical-density plasma layer

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Two-dimensional characteristics of propagation of a relativistic ultrashort laser pulse in a thin plasma layer with near-critical density have been studied. Although the critical density increases due to the relativistic effect, the incident laser pulse does not penetrate into overdense plasma because a high-density wall of electrons is generated in front of the laser pulse. It was found that the thin plasma layer is useful for reducing the pulse length of the incident laser as a nonlinear optical material. [S1063-651X(98)02110-2]

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Recent progress in laser technology has made possible the generation of ultrashort laser pulses, of which peak power exceeds 10 TW. These high-power lasers allow us to investigate laser-matter interaction with intensities exceeding 10^{19} W/cm^2. In such an intense laser field, the matter is instantly transformed to plasma and the electrons oscillate with relativistic quivering energy. Since the electron mass increases due to the relativistic effect, the critical density of the plasma increases with increasing laser intensity. At the same time, the electrons are moved by very strong ponderomotive and $\mathbf{v}\times\mathbf{B}$ forces. But, electrons cannot move freely in high-density plasmas because of a strong electrostatic restoring force. Therefore the interaction of an intense laser pulse with high-density plasma is very complicated, and many studies have reported on propagation and absorption of intense laser pulses in underdense [1–5] or near-critical-density plasmas [6–10].

In the nonrelativistic limit, an electromagnetic wave cannot propagate in plasma where the electron density is higher than the critical density, which is defined as $n_{\mathrm{cr}} = m_e \epsilon_0 \omega_0^2 / e^2$ where ω_0 is the angular frequency of the wave. However, for the relativistic intensity of $a_0 > 1$, where $a_0 = eE_0 / m_e \omega_0 c$ is the normalized field amplitude and E_0 the electric field of the incident wave, the wave can propagate beyond the critical density due to the relativistic effect as discussed below. In the past few years, this relativistic transparency has been investigated by means of numerical simulations. Using one-dimensional particle-in-cell (PIC) simulations, the transition from a regime of wave reflection to one of penetration was observed with increasing laser intensity [7]. During the penetration of the laser pulse, a strong longitudinal electric field is generated and a substantial fraction of the incident laser energy is converted to the longitudinal kinetic energy of electrons [8]. More recently, two-dimensional simulations revealed that both longitudinal and transverse heatings are significant and result in highly energetic electrons up to several tens of MeV [10]. The propagation condition including the relativistic effect depends on wave polarization. For a circularly polarized wave, the condition is obtained as $\omega_0^2 > \omega_p^2 / \gamma$ [8], where $\gamma = (1 + a_0^2)^{1/2}$ is the relativistic factor of an electron quivering in the laser field and ω_p the plasma frequency for the rest electron mass. For a linearly polarized wave, the expression is more complicated [8]. In these analyses, the propagation condition was studied assuming constant electron density. In a real situation, the electron density is modified by the interaction with the laser pulse. In particular, for an intense ultrashort laser pulse, the ponderomotive force is strong in the longitudinal direction and pushes electrons forward. As a result, the electron density increases significantly in front of the laser pulse. This high-density region interrupts the laser propagating forward. Therefore, even if the initial electron density is in a transparent regime, the density may be increased locally over the threshold value above which the laser pulse cannot propagate.

The purpose of the present study is to investigate propagation of a relativistic ultrashort laser pulse in near-critical-density plasma, taking into account the plasma dynamics. This study has been carried out using a two-dimensional PIC simulation code. The numerical procedure used in the code is similar to that in Ref. [11]. The laser pulse was normally incident on a thin plasma layer and had a wavelength $\lambda_0 = 800$ nm, a pulse length $\tau_{\mathrm{pulse}} = 16$ fs, a peak intensity $I_0 = 10^{19}$–10^{20} W/cm^2, and a linear polarization. The pulse shape was assumed to be Gaussian in both longitudinal and transverse directions. We used a simulation box of $40\lambda_0$ in the x (longitudinal) direction and $20\lambda_0$ in the y (transverse) direction. The size of the spatial mesh was $0.1\lambda_0$. The laser pulse propagated from the left to the right in the x direction and was focused at the center $(x=0)$. The plasma consisted of electrons and ions with the ion mass of $m_i = 1836 m_e$. Initially, the particles were placed in the central region of the x direction uniformly. A typical width of the plasma layer was $4\lambda_0$ and there were about 50 particles per cell in the plasma region.

Here, it is noted that there are several constraints in a real situation. The laser pulse shape is not ideal, having some pedestal or prepulse. It may disturb the laser pulse to interact with the uniform initial plasma and change the propagation of the main pulse. It is difficult to make an ideal plasma layer with the low density and the thin dimension. The plasma layer can be made from the thin foil or foam. When the thin foil is heated by the other short laser pulse with low intensity, the solid density plasma is produced initially and the density decreases in the following expansion period. The plastic foil with a few tens of nanometers is suitable for making the above mentioned plasma layer, but the plasma has a nonuniform density profile.

First, two-dimensional characteristics of propagation were examined for the laser pulse, which was focused on the

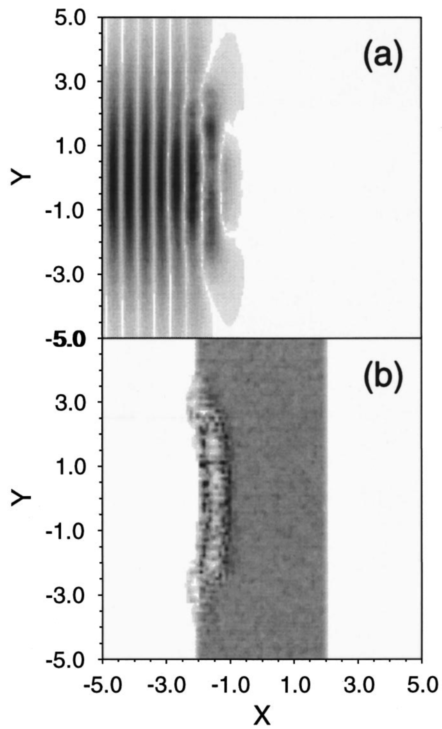

FIG. 1. Contours of an absolute value of the laser field, E_z (a) and the electron density (b) at $t=9\lambda_0/c$. The laser has a wavelength $\lambda_0=800$ nm, a pulse length $\tau_{\rm pulse}=16$ fs, a focal radius $r_0=3\lambda_0$, a peak intensity $I_0=10^{20}$ W/cm^2, and s polarization. The plasma has an initial electron density equal to the critical density.

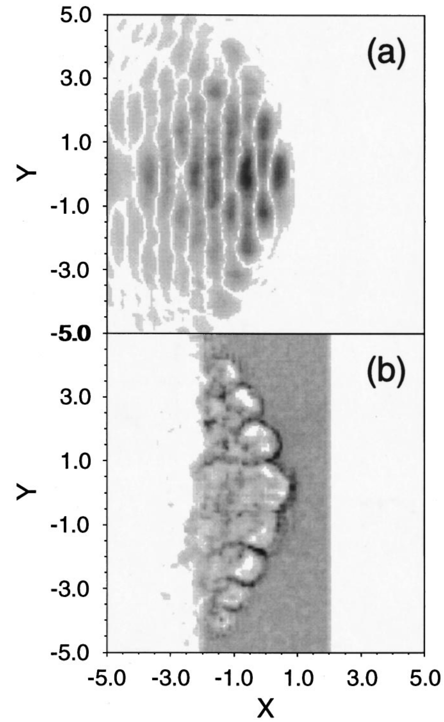

FIG. 2. Contours of an absolute value of the laser field, E_z (a) and the electron density (b) at $t=12.5\lambda_0/c$. The other parameters are the same as those in Fig. 1.

plasma layer having a uniform initial electron density equal to the critical density. The focal spot diameter was $6\lambda_0$, which was defined as a full width at e^{-1} of the electric field. The laser pulse was s polarized, the electric field being in the direction perpendicular to the x-y plane. (The p-polarized wave has the electric field in the x-y plane.) Initially, at $t=0$, the peak of the envelope of the laser field was located at $x=-12\lambda_0$ and $y=0$. When the laser pulse penetrates into the plasma, electrons are pushed forward by the strong longitudinal ponderomotive force. Figure 1 shows contours of the laser electric field and electron density at $t=9\lambda_0/c$ [an absolute value of the electric field in the z direction is shown in Fig. 1(a)]. As can be seen in Fig. 1(b), the electron density increases in front of the laser pulse. This high-density region forms a wall of electrons having a density of several times the critical density. Such a wall of electrons apparently influences the relativistic transparency. Then, the high-density wall is broken from the peripheral region and the structure of the electron density is changed from a wall-like to a bubblelike one. Figure 2 shows contours of the laser field and electron density at $t=12.5\lambda_0/c$ when the laser pulse penetrates deeply into the plasma layer. The bubblelike structure of the electron density is observed in Fig. 2(b) and a typical scale of the bubble is $1\lambda_0$–$1.5\lambda_0$. This phenomenon is similar to the corrugated plasma surface found in Ref. [6], which is the structure of the ion density in the ramped density region in front of the overdense plasma. In the present study, no similar structure was observed in the ion density as the laser pulse is too short for ion motion to occur. As can be seen in Fig. 2(a), the structure of the laser field is also distorted significantly and the laser pulse is broken into small pieces. It was observed that the distribution of the distorted laser field is consistent with the distribution of the electron density bubble. The laser field was intense in the low-density region ($n_e/n_{\rm cr}=0.1$–0.5) and weak in the high-density region ($n_e/n_{\rm cr}=2$–3). The electron density had a stochastic structure after the passage of the laser pulse.

It is thought that the transverse distribution of the laser pulse influences the formation of the bubblelike structure. So, we examined how the structure depends on the laser focal size. Figure 3 shows two contours of the electron density at $t=14\lambda_0/c$; (a) is the case with an infinite focal size (a plane wave) and (b) is the case with a focal spot diameter of $6\lambda_0$. Figure 3(a) shows clear filamentation with an average transverse size of $1.7\lambda_0$. This phenomenon is essentially equal to that found in Ref. [10], where the average size of $1.9\lambda_0$ is observed in the initial phase and it increases with time. These results suggest that the initial growth rate is large in the short wavelength region. We consider the filamentation as follows: if the laser pulse is perturbed transversely, the transverse ponderomotive force expels electrons into the lower-intensity region where, as a result, the electron density increases. It enhances the perturbation of the laser intensity and the filamentation instability grows. As an electromagnetic wave cannot be broken into pieces smaller than the wavelength, this instability grows abruptly once the scale of the perturbation becomes larger than the wavelength.

The formation of bubble or filamentation of the electron density induces the accompanied electrostatic field. In the case of a bubble, the electric field has longitudinal and transverse components irregularly and it results in stochastic heating of electrons. Absorption of the laser pulse incident on the plasma layer with near-critical density has been examined by several authors. They studied one-dimensional cases [7,8] or

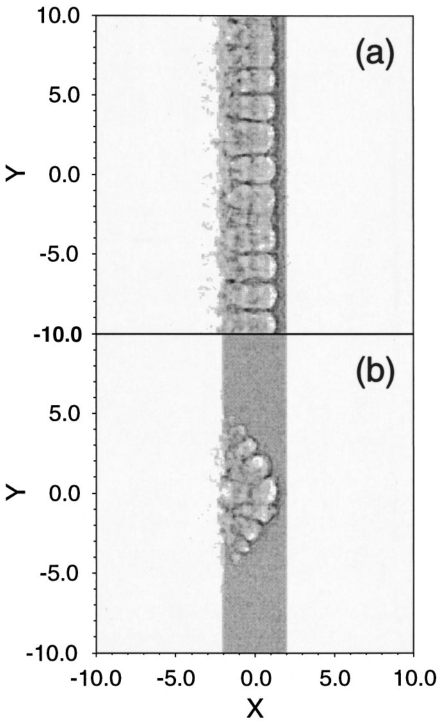

FIG. 3. Contours of the electron density at $t=14\lambda_0/c$; (a) is the case with an infinite focal size and (b) is the case with a focal spot diameter of $6\lambda_0$. The other parameters are the same as those in Fig. 1.

two-dimensional cases, mainly using a plane wave [10]. Here, we have examined absorption, reflection, and transparency of the incident laser pulse with a finite focal size. Figure 4 shows reflectivity, transparency, and kinetic energies of electrons and ions as a function of the electron density. The reflectivity and transparency were determined from electromagnetic wave energies in the left and right vacuum regions, respectively. The kinetic energy of electrons increases by a factor of 50 with increasing the density from $n_e/n_{cr}=0.1$ to 1. It means that the absorption is enhanced near the critical density. The kinetic energy of electrons is larger than that of ions by a factor of 10 at the critical density. The difference increases in a lower-density range. In the case shown with the peak intensity of 10^{20} W/cm^2 ($a_0=6.8$), the kinetic energy of electrons is maximum at $n_e/n_{cr}=2$, while it is maximum at $n_e/n_{cr}=0.8-1$ in a case with a lower peak intensity of 10^{19} W/cm^2 ($a_0=2.2$). Although the density which gives maximum absorption depends on the laser intensity, the maximum value was about 30% independent of the intensity in the range of $10^{19}-10^{20}$ W/cm^2. On the other hand, the reflectivity increases with increasing electron density and is equal to the transparency at $n_e/n_{cr}=1.3$ in the case of 10^{20} W/cm^2, while it is equal to the transparency at $n_e/n_{cr}=0.7$ in the case of 10^{19} W/cm^2. Although the relativistic factor is considerably higher than one, the transition from reflection to penetration occurs at a low electron density near the critical value. This is due to the high-density wall of electrons generated in front of the laser pulse.

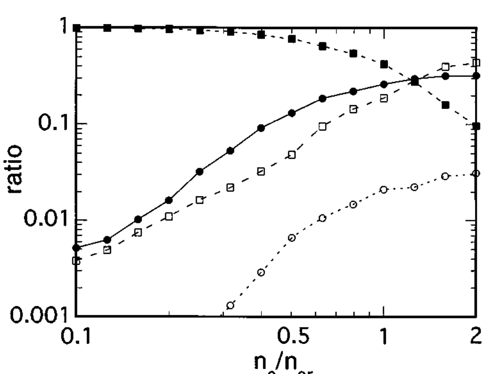

FIG. 4. Reflectivity (the open square), transparency (the solid square), kinetic energies of electrons (the solid circle), and ions (the open circle) as a function of the electron density. The other parameters are the same as those in Fig. 1.

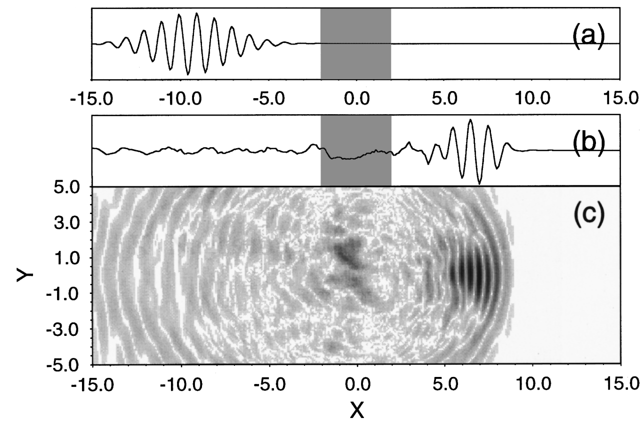

FIG. 5. Two shapes of the electric field, E_z; (a) is the case at $t=3\lambda_0/c$ before penetrating into the plasma layer and (b) is the case at $t=21.5\lambda_0/c$ after passing the plasma layer. The shaded region is the plasma layer which has an initial electron density equal to the critical density. A contour of an absolute value of the electric field at $t=21.5\lambda_0/c$ is also shown in (c). The other parameters are the same as those in Fig. 1.

The absorption, reflectivity, and transparency were examined by changing a focal spot size of the incident pulse and no clear dependence on the focal size was found. The dependence on polarization of the incident pulse was also examined. The kinetic energy of electrons for the p-polarized wave was 30–50 % higher than that for the s-polarized wave in a density range of $n_e/n_{cr}\geqslant 1$. It is thought that the difference is due to resonance absorption and/or vacuum heating for oblique incidence [12]. On the other hand, the reflectivity of the p-polarized wave was about 40% lower than that of the s-polarized wave in the entire density range of $n_e/n_{cr}=0.1-2$.

Next, the thin plasma layer was examined as a nonlinear optical material. In marginally overdense plasma, a high-intensity portion of the laser pulse can propagate due to the relativistic effect, but a low-intensity portion cannot propagate. Therefore it is thought that the thin plasma layer works as a nonlinear optical material which reduces the pulse length. In a real situation, as mentioned previously, the electron density is increased in front of the laser pulse. So, if the initial electron density is marginally below the critical density, some degree of reduction of the pulse length can be expected. On the other hand, in highly overdense plasma, transparency of the incident pulse decreases significantly as shown in Fig. 4. So, it is not suitable for use as an optical material. In a case with the peak intensity 10^{20} W/cm^2 and the pulse length 16 fs, the best condition for reducing the pulse length without the significant decrease of the laser power could be obtained as the initial electron density of $n_e/n_{\rm cr}\approx 1$. Figure 5 shows two shapes of the laser electric field, E_z, before penetrating into the plasma layer (a) and after passing the plasma layer (b). The shaded region shows the plasma layer, which has a width of $4\lambda_0$ and an initial electron density equal to the critical density. It is found that the pulse length is reduced by a factor of about 2.

Figure 5(c) shows a contour of an absolute value of the electric field. It is observed that the focal size is significantly reduced in the region of $5\lambda_0 \leqslant x \leqslant 8\lambda_0$. This is caused by the relativistic focusing in the plasma layer. In this case, the plasma layer is thinner than the focal length and works as an optical convex lens. In the case shown, the focal size decreased dramatically and the laser pulse was diffracted away immediately. When the focal size of the initial laser pulse was larger with the same peak intensity, the effect of diffraction was weaker without influencing the pulse length reduction.

In summary, we have studied two-dimensional characteristics of propagation of a relativistic ultrashort laser pulse in a thin plasma layer. When the electron density is nearly equal to the critical density, the structure of the electron density changes from a wall-like to a bubblelike one, as the laser pulse penetrates the plasma layer. Even if the laser intensity is highly relativistic, the transition from reflection to penetration occurs at $n_e/n_{\rm cr}\approx 1$ because of the high-density wall of electrons generated in front of the laser pulse. The energy of the electromagnetic wave is substantially converted to the kinetic energy of electrons near the critical density. Moreover, we have examined the thin plasma layer as a nonlinear optical material. It was found that this plasma layer is useful for reducing the pulse length of the incident laser and also for a focusing lens.

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