Relativistic electron drift in overdense plasma produced by a superintense femtosecond laser pulse

V. S. Rastunkov and V. P. Krainov
Moscow Institute of Physics and Technology, 141700 Dolgoprudny, Moscow Region, Russia
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The general peculiarities of electron motion in the skin layer at the irradiation of overdense plasma by a superintense linearly polarized laser pulse of femtosecond duration are considered. The quiver electron energy is assumed to be a relativistic quantity. Relativistic electron drift along the propagation of laser radiation produced by a magnetic part of a laser field remains after the end of the laser pulse, unlike the relativistic drift of a free electron in underdense plasma. As a result, the penetration depth is much larger than the classical skin depth. The conclusion has been made that the drift velocity is a nonrelativistic quantity even at the peak laser intensity of 10^{21} W/cm^2. The time at which an electron penetrates into field-free matter from the skin layer is much less than the pulse duration.

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A laser beam propagating in *underdense* plasma with a plasma frequency ω_p smaller than the laser frequency ω undergoes relativistic self-focusing as soon as its total power exceeds the critical value [1]. This has been established both theoretically [2] and experimentally [3]. The self-focusing is due to the relativistic mass increase of plasma electrons and the ponderomotive expulsion of electrons from the pulse region. Both effects lead to a local decrease of plasma frequency and an increase in refractive index. The medium then acts as a positive lens. In the case of the relativistic intensity of a laser pulse, the laser radiation drives strong currents of relativistic electrons in the direction of light propagation [4]. They generate superstrong vortex magnetic fields and strongly influence light propagation. Relativistic self-channeling of a picosecond laser pulse in a plasma near the critical density has been observed experimentally [5]. A temperature of a few hundred keV was reported for the fast-electron population from superintense laser pulse interactions with solid targets [6].

A laser beam propagates in *overdense* plasma with a plasma frequency ω_p greater than the laser frequency ω in the skin layer having a depth $\sim c/\omega_p$. The goal of this work is to consider the relativistic motion of free electrons induced by the superintense laser field inside the skin layer. We assume the femtosecond duration of a laser pulse in order to exclude the electron drift produced by the ponderomotive force due to spatial distribution of the laser field in the focal volume (the electron drift in the latter case of a long laser pulse was observed experimentally in [7,8]). In practice, this ponderomotive drift is significant only when the duration of a laser pulse exceeds picoseconds [9]. The eightfold motion of a free electron in underdense plasma, or in vacuum produced by the plane electromagnetic wave, is well known [10]. The electron trajectories are described by simple analytic expressions. But the analogous electron motion in overdense plasma cannot be described analytically and is unknown.

For the sake of simplicity, we assume that the *linearly* polarized laser beam propagates perpendicular to the plane surface of a dense matter. Let us direct the axis X along the propagation of the laser pulse, the axis Y along the electric-field strength, and the axis Z along the magnetic-field strength. We do not consider here how free electrons are produced inside the skin layer due to multiple ionization at the leading edge of the laser pulse. The relativistic plasma frequency is $\omega_p=\sqrt{4\pi n_e/\gamma}$, where n_e is the number density of free electrons in the skin layer (the relativistic system of units $m_e=e=c=1$ is used throughout the paper). Here the relativistic factor is $\gamma=\sqrt{1+(F^{\text{in}}/\omega)^2}>1$ and F^{in} is the electric-field amplitude inside the plasma [11]. We assume that $\omega_p \gg \omega$, which is usually fulfilled at the irradiation of solids by a superintense laser pulse due to multiple ionization. Then inside the skin layer the electric field is small compared to the magnetic field, and we can use the nonrelativistic plasma frequency ($\gamma\approx 1$) up to the laser intensity of 10^{19} W/cm^2.

The boundary conditions for the electric and magnetic fields on the surface vacuum–overdense plasma are of the well-known form

$$F^{\text{in}}=\frac{2}{1+\sqrt{\varepsilon}}F(t)\approx\frac{2}{\sqrt{\varepsilon}}F(t),$$

$$B^{\text{in}}=\frac{2\sqrt{\varepsilon}}{1+\sqrt{\varepsilon}}F(t)\approx 2F(t).$$

Here $F(t)$ is the amplitude of the electric- (magnetic-) field strength of the laser electromagnetic wave with the frequency ω outside the plasma, and

$$\varepsilon=1-\frac{\omega_p^2}{\omega^2}\approx-\frac{\omega_p^2}{\omega^2}$$

is the dielectric constant of plasma produced by free electrons ($|\varepsilon|\gg 1$). The laser pulse is turned on and off adiabatically, i.e.,

$$F(t)=F\exp(-t^2/\tau^2),$$

where τ is the duration of a laser pulse, and $\omega\tau\gg 1$.

The Newton classical equations for the relativistic electron momenta p_x and p_y inside the skin layer ($x>0$) are of the form

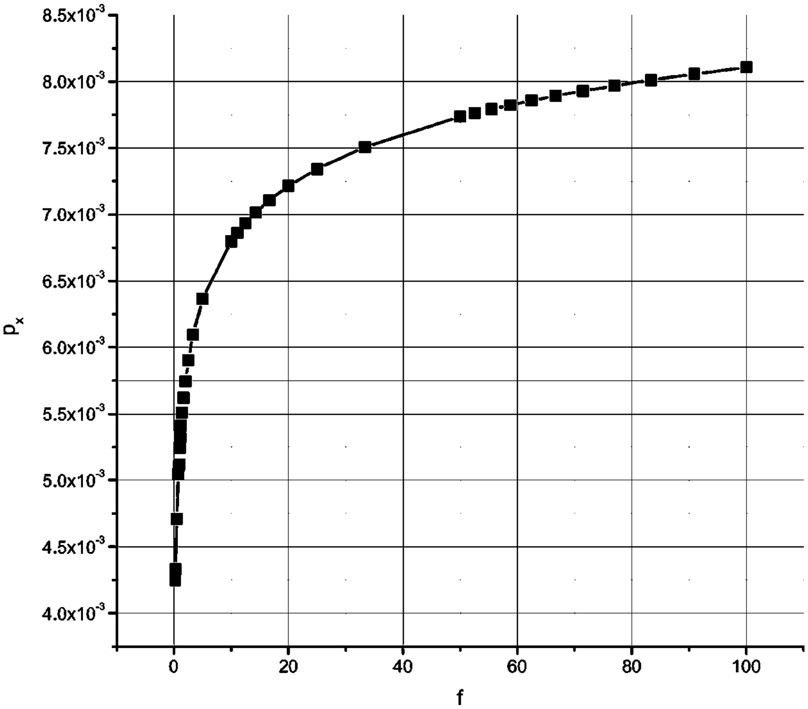

FIG. 1. The dependence of the dimensionless final electron drift momentum p_x (in units of the speed of light mc) along the propagation of a laser pulse inside the skin layer on the dimensionless relativistic field parameter $f=2F/\omega$.

$$\frac{dp_x}{dt}=2v_yF(t)\exp(-x/\delta)\sin(\omega t), \tag{1}$$

$$\frac{dp_y}{dt}=2\frac{\omega}{\omega_p}F(t)\exp(-x/\delta)\cos(\omega t) -2v_xF(t)\exp(-x/\delta)\sin(\omega t). \tag{2}$$

$\delta=1/\omega_p$ is the depth of the skin layer; v_x and v_y are the electron velocities, i.e.,

$$v_x=\frac{p_x}{\sqrt{1+p_x^2+p_y^2}}, \quad v_y=\frac{p_y}{\sqrt{1+p_x^2+p_y^2}}. \tag{3}$$

$x=0$ is the surface of the target. We assume also that there is no electron motion along the magnetic-field strength, the axis Z. There is no dependence of results on the initial laser phase because of its adiabaticity.

It is very important that the phases of electric and magnetic fields inside the skin layer are shifted to each other by 90° under the condition $\omega_p>\omega$. Therefore, the relativistic drift force along the axis X of laser propagation according to Eqs. (1) and (2) is proportional to $\sin^2(\omega t)$. Indeed, the second term on the right-hand side of Eq. (2) is small compared to the first term due to nonrelativistic values of the drift velocity (see below). Hence, this force results in the nonzero final electron drift velocity along the propagation of the laser pulse (always directed inside the skin layer). Oppositely, electric and magnetic fields are of the same phase in underdense plasma (or vacuum), and the electron relativistic drift disappears after the end of the laser pulse (an electron is shifted and stopped at the same distance from the initial position along the X axis) [12,13].

Collisions of electrons are neglected in our consideration because of relatively high drift electron velocities in the case of superintense laser pulses. Thus, these equations can be solved with the initial conditions that at the time instance $t=-\infty$ an electron is at rest when $x=y=0$. Of course, the average electron velocity along the Y axis (parallel to the surface of the target) is zero. After the end of a laser pulse, an electron has zero velocity in the Y direction and nonzero velocity in the X direction.

The electron motion is determined only by two dimensionless parameters $f=2F/\omega$ and ω_p/ω. The value $f=1$ corresponds to the peak laser intensity of 5×10^{17} W/cm^2 (at the laser photon energy $\hbar\omega=1.5$ eV). We fixed the value $\omega_p/\omega=7$ and $\omega\tau/2\pi=30$ in our numerical derivations of the electron motion according to Eqs. (1)–(3). These parameters correspond to the pulse duration $\tau=83$ fs and the electron number density $n_e=8\times10^{22}$ cm^{-3}.

In Fig. 1, the dependence of the dimensionless drift electron momentum p_x (in units of mc) after the end of the laser pulse has been presented as a function of the dimensionless relativistic field parameter $0<f<100$. This momentum increases with the laser intensity, but it is a nonrelativistic quantity ($p_x\ll$mc) even at the relativistic peak laser intensity of 10^{21} W/cm^2. The qualitative reason is the small electric-field strength inside the skin layer due to the strong reflection of a laser pulse from plasma. Besides this, an electron leaves the skin layer into field-free matter far before the maximum of the laser pulse.

Figure 2 demonstrates the electron momenta $p_x(t)$ and $p_y(t)$ (in units of mc) at the leading edge of the laser pulse for the typical value of the relativistic field parameter $f=10$ (the peak laser intensity is 5×10^{19} W/cm^2). It is seen that (i) an electron goes from the skin layer inside field-free matter before the laser pulse reaches its maximum, and (ii)

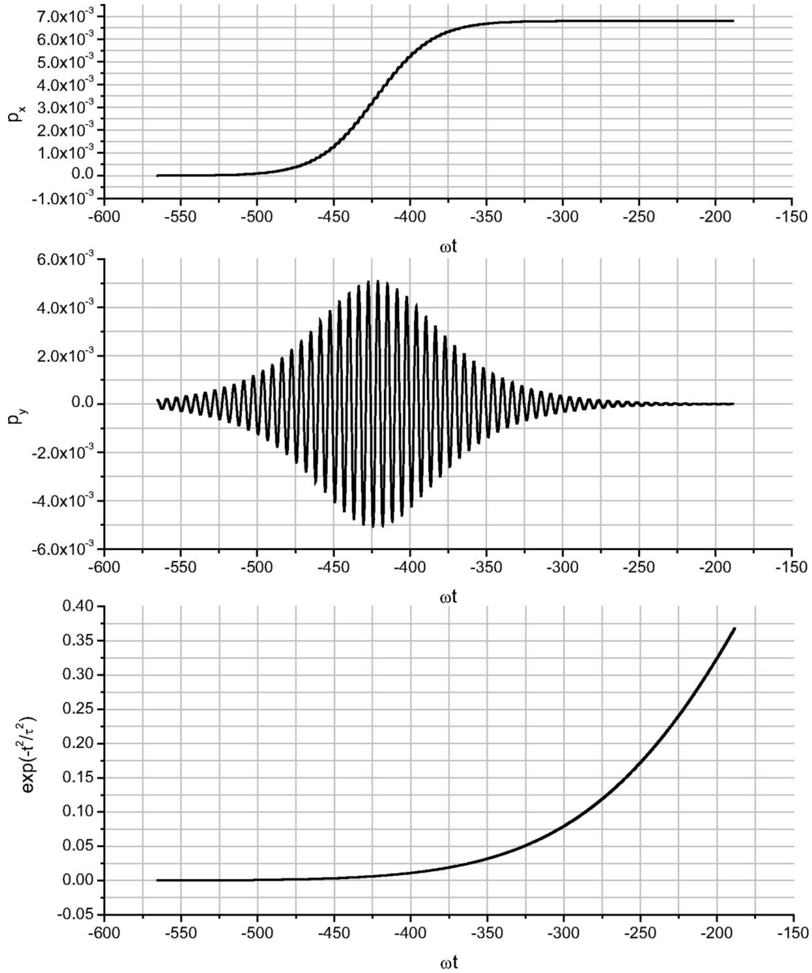

FIG. 2. The dependences of the dimensionless electron momenta p_x and p_y (in units of the speed of light mc) on the phase ωt at the leading edge of the laser pulse for the value of the relativistic field parameter $f=2F/\omega=10$. The lower curve demonstrates the dependence of the field strength envelope on the phase ωt at the leading edge of a laser pulse.

$p_y \rightarrow 0$ when an electron leaves the skin layer. The qualitative reason for the first result is the small depth of the skin layer: an electron stops acceleration on the rear border of the skin layer. The reason for the second result is the adiabaticity of the laser pulse.

Finally, in Fig. 3 the electron trajectory is presented (also for $f=10$). The dimensionless electron coordinates x and y are given in units of the skin depth δ. It is seen that the amplitude of electron oscillations in the transverse direction Y is much less than its drift motion in the direction of laser pulse propagation (the X axis). It is concluded that an electron penetrates many skin depths into field-free matter even before the laser pulse reaches its maximum.

These results can be explained qualitatively. It follows from Eqs. (1) and (2) that the velocity of the electron drift has the estimate

$$v_x \sim C\left(\frac{F}{\omega_p c}\right)^2 c. \tag{4}$$

Here C is the numerical factor. $C \ll 1$ since the electric field is depleted quickly in the skin layer. It follows from Fig. 2 that $C=0.014$. Hence, the time t_p for penetration of the skin layer having the depth $\delta=c/\omega_p$ is approximately

$$t_p \approx \frac{\delta}{v_x} \sim \frac{\omega_p c^2}{CF^2}. \tag{5}$$

In the case of the peak laser intensity 5×10^{19} W/cm^2 and $\hbar\omega_p=10.5$ eV, one obtains, according to Fig. 2 or Eqs. (4) and (5), that $v_x=2\times10^8$ cm/c and $\delta=2\times10^{-6}$ cm. Hence, $t_p \sim 10$ fs$\ll\tau$. Thus, an electron goes quickly from the skin layer into field-free matter.

Of course, there are also other mechanisms for deep penetration of superintense laser radiation into dense plasma [14]. Hole boring by the laser beam is one of the features of laser-solid interaction [15,16]. The ponderomotive force of a laser can excite a longitudinal electron plasma wave with a phase velocity close to the speed of light. The acceleration of electrons injected in a plasma wave generated by the laser wakefield mechanism was observed in [17]. Deep penetration of electrons can be produced also at the irradiation by inclined p-polarized laser pulses due to the vacuum heating effect [18].

The relativistic electron drift current produces the steady vortex magnetic field, which can achieve giant values for the superintense laser pulses [19]. The variable part of the nonlinear electron motion can produce harmonics of incident laser radiation at the electron-ion collisions [20].

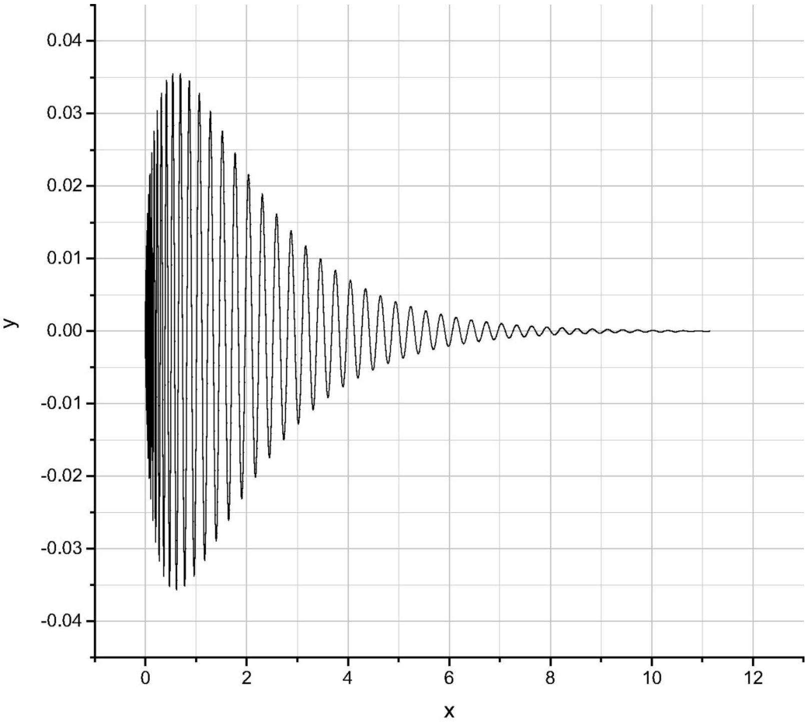

FIG. 3. The electron trajectory in the plane (X,Y) for the value of the relativistic field parameter $f=2F/\omega=10$. The dimensionless electron coordinates are given in units of the skin layer depth δ.

Thus, the relativistic electron drift in overdense plasma along the propagation of laser radiation produced by a magnetic part of a laser field remains after the end of the laser pulse, unlike the relativistic drift of free electrons in underdense plasma. The conclusion has been made that the electron drift velocity in the skin layer is a nonrelativistic quantity even at the peak laser intensity of 10^{21} W/cm^2. We found also that the time at which an electron penetrates into field-free matter from the skin layer is much less than the pulse duration τ. This penetration occurs at the leading edge of the laser pulse. The following deep penetration of electrons into field-free matter takes place until their collisions stop this motion.

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