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Particle simulation on electron acceleration process by the laser ponderomotive force in inhomogeneous underdense plasma layers*

Cao Li-Hua(曹莉华)[a)†], Yu Wei(余 玮)[b)], Xu Han(徐 涵)[b)],
Liu Zhan-Jun(刘占军)[a)], Zheng Chun-Yang(郑春阳)[a)], and Li Bin(李 斌)[a)]

[a)] *Institute of Applied Physics and Computational Mathematics, Beijing* 100088, *China*

[b)] *Shanghai Institute of Optics and Fine Mechanics, Shanghai* 201800, *China*

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The mechanism of electron ponderomotive acceleration due to increasing group velocity of laser pulse in inhomogeneous underdense plasma layers is studied by two-dimensional relativistic parallel particle-in-cell code. The electrons within the laser pulse move with it and can be strongly accelerated ponderomotively when the duration of laser pulse is much shorter than the duration of optimum condition for acceleration in the wake. The extra energy gain can be attributed to the change of laser group velocity. More high energy electrons are generated in the plasma layer with descending density profile than that with ascending density profile. The process and character of electron acceleration in three kinds of underdense plasma layers are presented and compared.

Keywords: ponderomotive force, particle simulation, electron acceleration, inhomogeneous underdense plasma layers

PACC: 5260, 5240, 5235

1. Introduction

The generation and transport of energetic electrons by high intensity laser pulse have been of particular interest and much progress has been achieved in laser–solid interactions. They have a wide range of potential applications, such as the x-ray lasers,[1] fast ignition in laser fusion,[2] laser–plasma accelerator[3,4] and generation of fast ions.[5−7] But the laser on plasma dynamics is not fully understood and the underlying physics is strongly nonlinear. The particle-in-cell (PIC) method can provide very detailed kinetic descriptions of plasmas by following the motions of particles in the self-consistent electromagnetic field and has already become a useful tools in studies of laser plasma interaction,[8] and much progress has been reported.[9−12]

The propagation of laser pulse in underdense plasma has attracted much interest. Direct ponderomotive acceleration in a uniform preplasma was investigated,[13−15] and it was found that there is strong electron acceleration inside the pulse with sufficiently short duration and strong intensity. In uniform preplasmas, the laser pulse propagates with constant group velocity; the momentum and density distribution of the accelerated electrons remain unchanged. In real situations, a low density plasma is always set up at the front of a solid target with a naturally present or deliberately created repulse so that the preplasma has an inhomogeneous density profile in which the laser propagates with variable group velocity. The increasing group velocity of the laser pulse will result in a stronger electron acceleration in an inhomogeneous underdense plasma than in a uniform low density plasma layer. The electron acceleration process is respectively studied and compared in a uniform and two kinds of inhomogeneous underdense plasma layers with linearly ascending and descending density profiles by a fully relativistic 2d3v PIC code (PPICC) under a distributed-memory parallel environment,[16,17] which works more efficiently than the code used in our previous work.[18−20]

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†E-mail: lihua@iapcm.ac.cn

2. Description of mechanism

In this paper, we discuss the scheme of electron acceleration by the ponderomotive force associated with the laser pulse. It is instructive to first review and discuss the theoretical model.[21] The motion of a particle with charge q and mass m in a circular polarized laser field satisfies $\left(\frac{1}{v_g^2}-1\right)u_{||}^2-\frac{2u_{||}}{v_g}+\frac{u_\perp^2}{v_g^2}=0$, where v_g is the group velocity of laser pulse normalized by c, the speed of light in vacuum, so $v_g<1$, $u_{||}$ and $u_\perp$ are respectively the transversal and longitudinal momenta normalized by mc; it is assumed that the particle is initially at rest. The formula describes an ellipse which is symmetrical to the longitudinal momentum. Fig.1(a) plots its half part for positive transverse momentum. The particle moves from point A toward point B, where $u_{||}=v_g$, $u_\perp=(1+v_g^2)^{1/2}v_g$. If the electron has acquired a transverse momentum $u_\perp$ greater than $(1+v_g^2)^{1/2}v_g$ before the peak of the pulse, it will continue to go toward C, which corresponds to the leading edge of the pulse. Eventually, it reaches the point C, where $u_\perp$=0, $u_{||}=2v_g/(1-v_g^2)$; its energy gain will be $\delta\gamma=2v_g^2/(1-v_g^2)$ as shown in Fig.1(b). Apparently, the electron will obtain higher energy in a more tenuous underdense plasma where the laser pulse propagates with larger group velocity if the laser field is intense enough so that the electron can get across the point B.

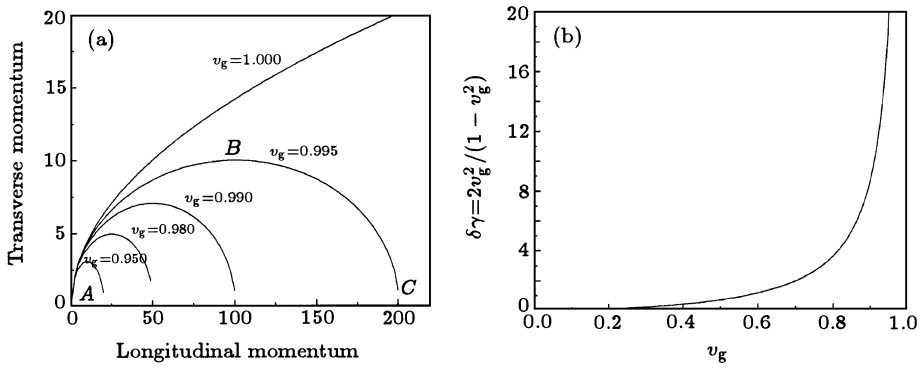


Fig.1. Diagram of the relation between longitudinal and transverse momentum for different laser group velocity (a) and the kinetic energy of electron at point C versus laser group velocity (b).

The above model is evidently simple although it can expound in principle the effect of laser group velocity. Some physical quantities such as longitudinal momentum $u_{||}$ and energy gain $\delta\gamma$ at point C would be infinite if v_g=1. Practically, the electron energy within the laser pulse would be depressed greatly if the effect of background electrons was considered. In Fig.4 of Ref.[13], the maximum electron energy does not exceed $100mc^2$ for tenuous plasmas with density $10^{-4}n_c$ or $10^{-3}n_c$ even for normalized laser intensity $a\sim$15, where n_c is the critical density and $a=0.85\times10^{-9}\lambda I^{1/2}$ is the laser strength parameter: I is in W/cm^2 and λ is the wavelength in μm. This seems more reasonable. Another useful tool is PIC simulation that can investigate more efficiently the laser propagation in nonuniform low-density plasma.

3. Simulations and discussions

A circularly polarized, Gaussian shape laser pulse with peak intensity 5×10^{19}W/cm^2, wavelength λ=1μm and pulse duration $5T$, corresponding to a cycle time of $T\sim$3fs, is launched normally on the plasma layers from the left-hand boundary and propagates in the x direction. The $v\times B$ effect can be minimized for a circularly polarized laser, and the density is set much less than the critical density to avoid instabilities and strong electrostatic field. Initial velocities for both electrons and ions have Maxwellian distributions with temperatures of 1keV for electrons and 1/3keV for ions. We use a spatial mesh of 512×512 cells with 10^6 electrons and the same for the ions; they are initially filled in the simulation box to form a definite density profile and move in the x–y plane. Three initial configurations of underdense plasma layers with length of 20λ are assumed as follows: (1) homogeneous plasma with density $10^{-3}n_c$; (2) linearly ascending density profile from 0 to $10^{-3}n_c$ and (3) linearly descending density profile from $10^{-3}n_c$ to 0. Two vacuum gaps with length 10λ are assigned at both the left and right boundaries of the simulation box which is 40λ long and 30λ in width. The nonreflecting boundary is chosen at the right boundary of the box for electromagnetic fields and the calculation is continued until the peak of the laser pulse arrives at the right edge of the plasma

layer. The ions are protons with mass M=1836m and Z=1. Anywhere below, the spatial coordinate, time, momentum and energy are given in λ, T, mc and mc^2.

Figure 2 illustrates the longitudinal electron momenta at different moments t=22,31 and 40. A group of electrons are accelerated ponderomotively and synchronized with the laser pulse with so short a duration and so great an intensity that the pulse traps the electrons inside it and carries them as a soliton-like system; a similar character has been described in uniform underdense plasmas in Refs.[13,14]. The pulse moves up the density gradient with first rising and then falling peak electron momentum in the ascending density plasma layer as shown in Figs.2(a)–(c), but the maximum electron momentum keeps rising when the pulse passes through the plasma layer with linearly dropping density as shown in Figs.2(d)–(f); the greater space-charge field created by the electron bunching results in a larger relativistic return current behind the pulse between $10 < x/\lambda < 20$ (Fig.2(f)) than in the descending density plasma layer (Fig.2(c)).

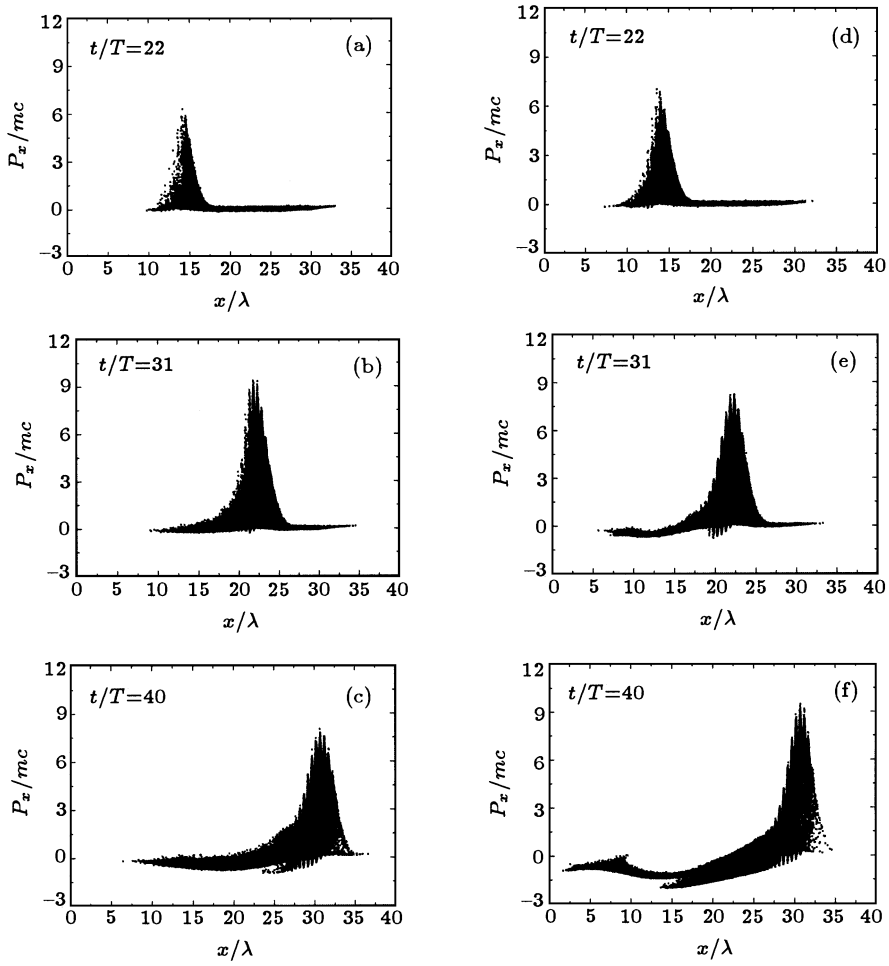


Fig.2. Electrons in phase space (x, P_x) at t=22, 31, 40 in ascending (a)–(c) and descending (d)–(f) density plasma layers.

A narrow spike-shaped electron density profile is excited by the tremendous laser ponderomotive force and continually pushed in front of the laser pulse. Fig.3 shows three snapshots of density profiles averaged in the y direction as they evolve from the initial linear profile. The peak density of the ponderomotively accelerated electrons increases with time in the ascending density plasma layer, but decreases with time in the descending density plasma layer. The laser group velocity is close to the speed of light in such subtle plasmas so that it is difficult to diagnose it directly in the simulation. But it can be estimated roughly without considering the relativistic effect. The dispersion relation for light wave in

a plasma is $\omega^2 = \omega_{pe}^2 + k^2c^2$; its group velocity is $v_g = d\omega/dk = c\sqrt{1-\frac{\omega_{pe}^2}{\omega^2}} = c\sqrt{1-\frac{n_e}{n_c}}$, where c and n_e is the electron density of plasma. The peak densities are respectively $4.65\times10^{-4}n_c$, $1.43\times10^{-3}n_c$, 1.85×10^{-3} n_c in Fig.3(a) at times t=22,31 and 40; correspondingly, the group velocities of pulse can be estimated to be $0.9998c$, $0.9993c$ and $0.9991c$, which indicates quantitatively that the laser pulse propagates with nonlinear decreasing group velocity in such an ascending density plasma layer. The peak densities are respectively $2.14\times10^{-3}n_c$,$1.63\times10^{-3}n_c$,7.88×10^{-4} n_c in Fig.3(b); the laser group velocities can be estimated to be $0.9989c$, $0.9992c$ and $0.9996c$, which increase with the laser pulse propagating down the gradient density.

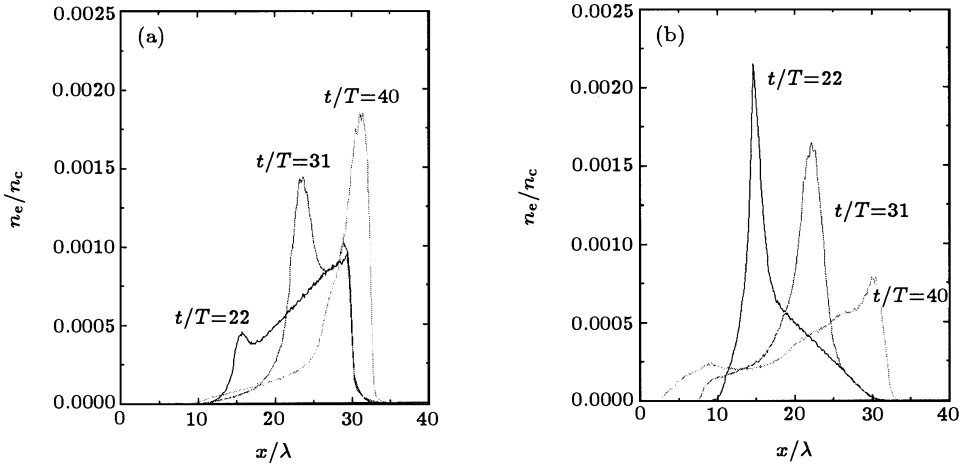


Fig.3. Snapshots of electron density profiles averaged in the y direction at t=22, 31, 40 in ascending (a) and descending (b) density plasma layers.

Figure 4 is the time evolution of electron maximum kinetic energy in three kinds of plasma layers before the laser peak touches the right plasma boundary, where γ is the relativistic factor. In the homogeneous plasma layer (Fig.4(a)), the maximum electron kinetic energy is kept constant at 8.4. In the ramping density plasma layer (Fig.4(b)), it rises to 10.3 firstly after the laser pulse propagates in the plasma and then begins to fall; there is a turning point at time 28 when the laser peak locates at $x \sim$20. In the underdense plasma layer with descending density profile (Fig.4(c)), the maximum electron kinetic energy keeps increasing as the laser pulse propagates down the plasma density gradient with increasing group velocity; it can approach to 10.5 when the laser peak reaches the right plasma boundary. For circular polarized laser with peak intensity 5×10^{19}W/cm^2, the normalized laser intensity is $a \approx$4.2. The Lorentz factor of an electron can be written as $\gamma = \sqrt{1+P_\perp^2+P_{||}^2}$ with $P_y \sim a$, $P_z \sim a$, $P\perp^2 = P_y^2 + P_z^2 \sim 2a^2$ and $P_{||} \sim a^2/2$, so $\gamma - 1 = \sqrt{1+P_\perp^2+P_{||}^2} - 1 \approx \sqrt{1+2a^2+a^4/4} - 1 \sim 9.7$. For higher intensity laser with larger a, $\gamma - 1 \sim a^2/2 \sim 8.82$. The extra energy gain in inhomogeneous plasma layers can be attributed to the nonlinear increase in the group velocity of intense pulse,[21,22] which is variable in nonuniform underdense plasma.

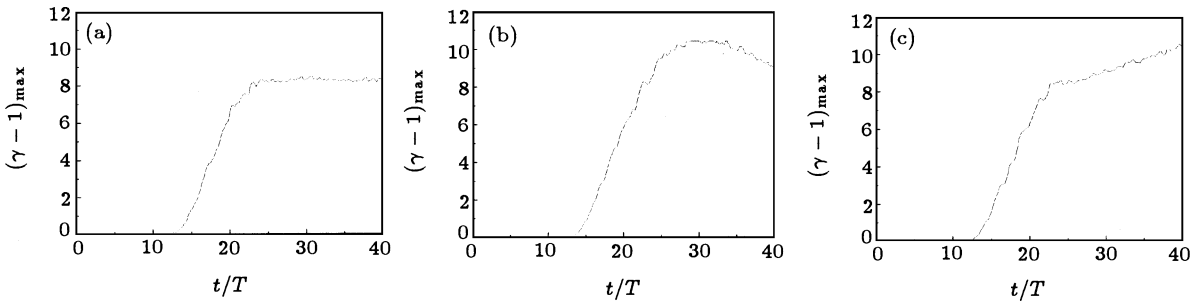


Fig.4. Time dependences of maximum kinetic energy of electrons in uniform (a), ascending (b) and descending (c) density plasma layers.

The time dependence of number and average kinetic energy of energetic electrons with $\gamma - 1$ greater than 8 are also diagnosed in the simulations. Few electrons with such high energies are produced in uniform plasma with electron density $10^{-3}n_c$ except in the plasma layers with density gradients. Their number and average kinetic energy rise and fall with time in the rising density plasma as shown Figs.5(a) and 5(b); it should be noticed that the time for them to approach the maximum values are different. The number of this kind of fast electrons culminates at time 34 but their average energy is highest at time 29 which is close to the turning point described in Fig.4(b). There are still more and more electrons with kinetic energies greater than 8 being created unceasingly as shown in Fig.5(a) between the two peak values, but their energies are not so high due to the decrease in laser group velocity, so their average energy starts to decline before the number of energetic electrons begins to fall, and there exists a time delay between them. This differs considerably in the ascending plasma layer, where the laser group velocity keeps increasing during its propagation down the density gradient; more and more electrons are trapped to higher energies. Both their number and average energy increase with time as shown in Figs.5(c) and 5(d). Meanwhile, there are many more electrons with such high energies than in the ramping density underdense plasma.

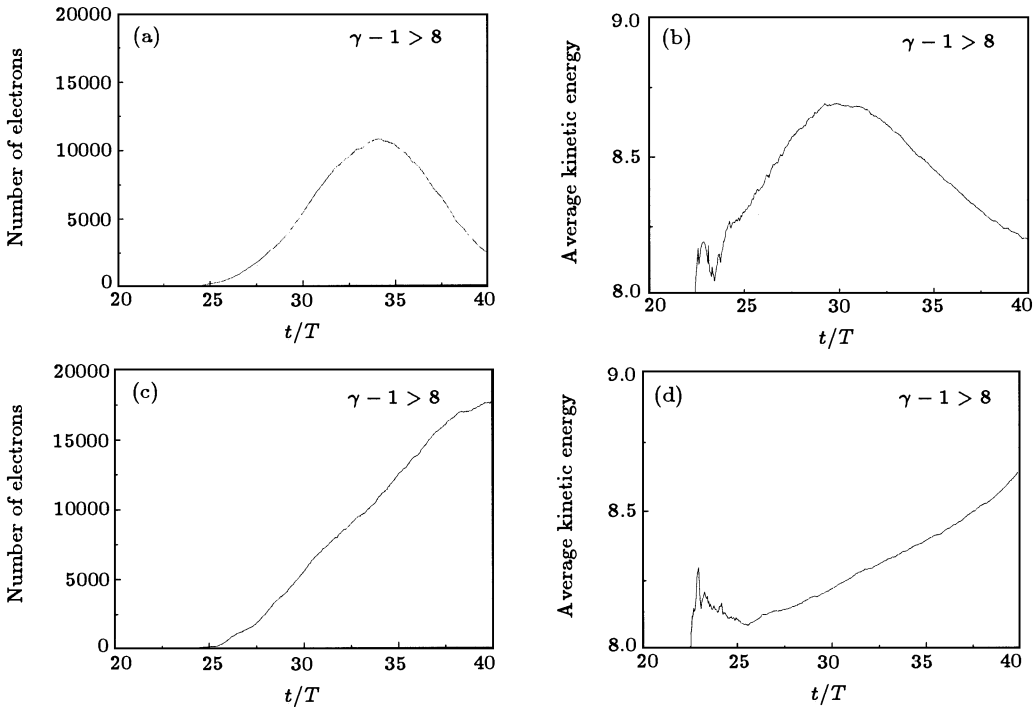


Fig.5. Time evolution of the number and average kinetic energy for electrons with $\gamma - 1$ greater than 8 in ascending (a,b) and descending (c,d) density plasma layers.

It is known that an electron is driven forward in the ascending front of laser pulse and backwards in its descending front; it can be accelerated ponderomotively continuously to higher energy if it is always ahead of the laser pulse.[15] In order to gain more insight into the process of electron acceleration, we track the most energetic electrons during the simulations. The time dependences of their longitudinal positions are exhibited in Fig.6 and the locations of laser peaks are also overlapped because the spatial relation between them is crucial to electron acceleration. Figure 6 shows clearly the pursuing process between the laser pulse and the fastest electron. Meanwhile, the trajectories of longitudinal and transversal momenta and the mean values are also displayed in Fig.7. Both the transverse and longitudinal momenta show regular oscillations in the two tenuous plasma layers. The electrons driven by the huge ponderomotive force forwards produce a positive charge separation electrostatic field within the laser pulse, which acts as a deceleration force for the electrons behind the laser pulse front. In the ascending plasma layer, the fastest electron initially situated near the vacuum–plasma interface ($x \sim 10$) can be pushed forward by the huge pon-

deromotive force and goes ahead of the pulse, whose group velocity is less than c since it enters into the plasma layer, and the electron can gain energy continuously from the pulse until it is overtaken by the pulse near the turning point (t ~28) which agrees with Fig.4(b), and then it lags behind the pulse as shown in Fig.6(a). Correspondingly, its average longitudinal momentum rises and begins to fall after the turning point as shown in Fig.7(a), but its average still keeps positive as a whole and is about 4.6 during time 18–40. Initially, the electron is not at the centre of the laser spot and locates in real space (10.7,14.3). It experiences a transversal ponderomotive force below the middle line (y=20) and comes to (26.4,7.8) at time 40. So it has larger negative amplitude of transversal momentum than the positive one; its mean value is near –1.7 in the period 18–40.

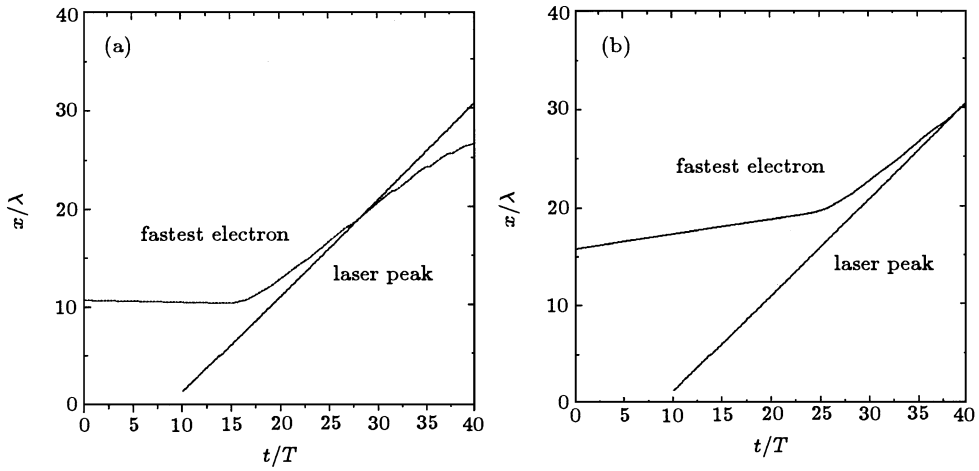


Fig.6. Time evolution of longitudinal position of the fastest electrons and laser peaks in ascending (a) and descending (b) density plasma layers.

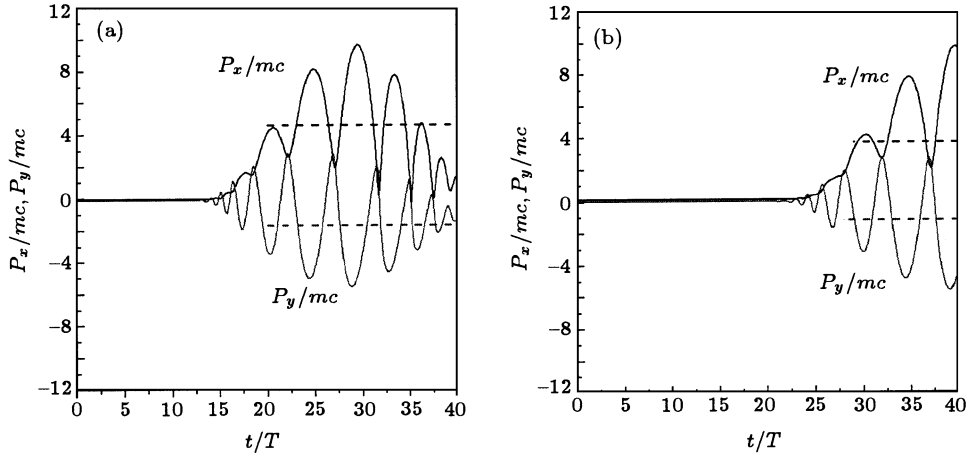


Fig.7. Time evolution of the transverse and longitudinal momenta of the fastest electrons in ascending (a) and descending (b) density plasma layers, dashed lines are the mean values during time 18–40 (a) and 22–40 (b).

It differs entirely in the descending density plasma layer; the fastest electron goes ahead of the pulse all the time and gains energy continuously although the pulse keeps chasing after it with increasing group velocity; the distance between them keeps shortening gradually until the electron is exceeded by the pulse which enters into the right vacuum gap where its group velocity is close to the speed of light in vacuum (Figs.6(b) and 7(b)); the average of longitudinal momentum grows continuously and is approximately 3.7 between t ~22 and t ~40. The electron is driven from (15.8,12.1) initially to (30.3,10.4) at t ~40. Its

transversal shift is weaker than the electron described in Figs.6(a) and 7(a); the mean transversal momentum is about –1.1 in the period of 22–40.

4. Conclusions

In conclusion, the electrons within the laser pulse can move with it and be accelerated ponderomotively when the duration of laser pulse is much shorter than the duration of optimum condition for acceleration in the wake. The extra electron acceleration due to the increasing group velocity of laser pulse in inhomogeneous underdense plasma layers has been presented and compared in three kinds of underdense plasma layers. The peak momentum and electron density almost keep constant with time in uniform plasma, they differ in inhomogeneous plasma layers. Compared with uniform plasma, a nonuniform tenuous plasma with linearly descending density profile enables the laser ponderomotive acceleration as the pulse propagates down the density gradient with increasing group velocity; a bunch of energetic electrons moving with the pulse can be strongly accelerated to high energies. The number and average energy of accelerated electrons increase with time. If the propagating laser pulse is abruptly stopped at the solid target, the highly energized electrons will continue to move forward inertially and escape from the pulse as well as the target without much energy loss if their stopping distance is much larger than the laser skin depth and the target thickness. In the real situation, a low-density plasma is always set up at the front of a solid target with a naturally present or deliberately created repulse. The incident laser travels up the density gradient with decreasing group velocity, but the reflected light propagates down the density gradient with increasing group velocity so that some energetic electrons are generated ponderomotively. We will discuss this problem elsewhere.

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