Motion and acceleration of electrons in high-intensity laser standing waves*

Zhang Qiu-Ju(张秋菊)[a)†], Yu Wei(余 玮)[b)], Luan Shi-Xia(栾仕霞)[b)], and Ma Guang-Jin(马光金)[b)]

[a)] College of Physics and Electronics, Shandong Normal University, Jinan 250014, China

[b)] Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

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The motion and the energy of electrons driven by the ponderomotive force in linearly polarized high-intensity laser standing wave fields are considered. The results show that there exists a threshold laser intensity, above which the motion of electrons incident parallel to the electric field of the laser standing waves undergoes a transition from regulation to chaos. We propose that the huge energy exchange between the electrons and the strong laser standing waves is triggered by inelastic scattering, which is related to the chaos patterns. It is shown that an electron's energy gain of tens of MeV can be realized for a laser intensity of 10^{20} W/cm^2.

Keywords: electron motion, inelastic scattering, laser standing wave, energy exchange

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1. Introduction

An electron's motion in high-intensity fields and the mechanism leading to significant acceleration of electrons have stimulated a great deal of research over the past years.[1−6] The research includes the study of the ponderomotive acceleration with the assistance of additional fields, such as the counter-propagating laser fields.[7] When two laser pulses propagate, counter, and overlap, a laser standing wave (SW) field comes into being. The interaction characteristics of atoms as well as electrons with laser SW fields have triggered much interest.[8−10] The electron's motion in laser SW fields is related mostly to the regular non-relativistic laser–electron interaction, such as the Kapitzar–Dirac effects,[11−13] the sign reversion of the ponderomotive force,[14−15] and the sorting and separating of electrons by the laser SW.[16−19] In recent works, the non-elastic scattering and the acceleration of electrons in the SW with large field gradients are investigated.[20] However, the motion and the energy of relativistic electrons launched into the high-intensity laser SW and their characteristic difference from those of the weak field cases have not been discussed comprehensively yet.

This work is devoted to an extended investigation of the interaction of relativistic electrons with the laser SW. We will study the electron's motion, the electron's energy, and the transition from regular mode to chaos in the high-intensity laser SW. The paper is organized as follows. The model for the motion of a relativistic electron in a laser SW is given in Section 2. In Section 3, we calculate the electron's trajectory, the energy gain, and the dependence of the electron's velocity on time in the laser SW. Some chaos patterns and the related huge net energy gain in the non-elastic scattering are presented in Section 4. Conclusion and discussion are given in Section 5.

2. Model of relativistic electron motion in laser standing wave

We consider two Gaussian linearly polarized laser pulses focused in the x–y plane counter-propagating along the z axis with the vector potential expressed as

$$\boldsymbol{a} = a_0 \exp(-\rho^2/b_0^2)\left[\cos(z-t)\hat{\boldsymbol{x}} + \cos(z+t)\hat{\boldsymbol{x}}\right], \quad (1)$$

where $\rho^2 = x^2 + y^2$, a_0 is the peak amplitude of one laser beam normalized by mc^2/e, m and e are the electron's mass and charge, respectively, c is the speed of light in vacuum, and b_0 is the beam waist width. In

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†Corresponding author. E-mail: qjzhang@sdnu.edu.cn

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the above definitions, the space and the time coordinates are normalized by k_0^{-1} and ω_0^{-1}, respectively, where ω_0 and k_0 are the laser frequency and the wave number, respectively. The standing wave formed in the z axis by these two laser pulses is

$$\boldsymbol{a} = 2a_0 \exp(-\rho^2/b_0^2) \cos z \cos t\hat{\boldsymbol{x}}. \tag{2}$$

The configuration of an electron launching into the counter-propagating laser SW field is shown in Fig. 1. We assume that an electron initially near the focal plane is launched along the transverse $+x$ axis, which is parallel to the electric field of the laser SW.

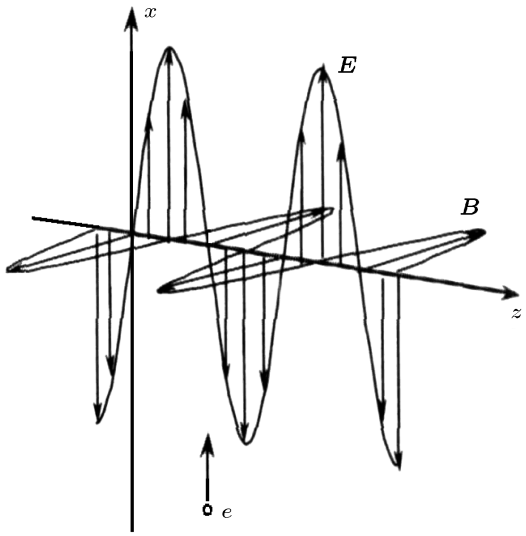


Fig. 1. Schematic geometry of an electron launched into a linear polarized laser SW.

The motion of the electron in the electromagnetic wave is described by the Lorentz equation[21]

$$\mathrm{d}_t\,(\boldsymbol{p} - \boldsymbol{a}) = -\nabla_{\boldsymbol{a}}(\boldsymbol{u} \cdot \boldsymbol{a}) \tag{3}$$

together with the energy equation

$$\mathrm{d}_t\gamma = \boldsymbol{u} \cdot \partial_t \boldsymbol{a}, \tag{4}$$

where $\boldsymbol{u}$ is the velocity normalized by c, $\boldsymbol{p} = \gamma\boldsymbol{u}$ is the electron momentum normalized by mc, $\gamma = \left(1 - u^2\right)^{-1/2}$ is the relativistic factor or the electron energy normalized by mc^2, and $\nabla_{\boldsymbol{a}}$ acts on $\boldsymbol{a}$ only. Substituting Eq. (2) into Eqs. (3) and (4), we find

$$\gamma \mathrm{d}_t u_x = (1 - u_x^2)\partial_t a + u_y \partial_y a_x + u_z \partial_z a_x, \tag{5}$$

$$\gamma \mathrm{d}_t u_y = -u_x \partial_y a - u_x u_y \partial_t a, \tag{6}$$

$$\gamma \mathrm{d}_t u_z = -u_x \partial_z a - u_x u_z \partial_t a, \tag{7}$$

$$\mathrm{d}_t \gamma = u_x \partial_t a, \tag{8}$$

where u_x, u_y, and u_z are the components of the electron's velocity in x, y, and z directions, respectively. Solving Eqs. (5)–(8) with the electron's initial position x_0, z_0 and initial energy $\gamma_0 = 0$, we can obtain the electron's trajectory and energy in any time during the interaction. For convenience, we have set $y_0 = 0$, as the motion of the electron is limited in the x–z plane.

3. Regular motion of electron and transition to chaos in laser SW

At a weak laser intensity, the interaction between electrons and the SW is an elastic process, the motion of electrons in the SW is regular and without net energy gain no matter how electrons are launched.

When the incident electron is launched in the anti-node $z_0 = n\pi$, $(n = 0, 1, 2, \ldots)$ SW plane, where $\boldsymbol{E}$ field peaks and $\boldsymbol{B}$ field vanishes, the interaction between the electron and the SW is also elastic even with a relativistic laser intensity. Figures 2 and 3 show the case of the incident electron launched in the anti-node with $x_0 = -3b_0$ (used all through the following text), $z_0 = n\pi$, $b_0 = 10\pi$ (i.e., 5λ, λ is the laser wavelength), and $a_0 = 5$, the velocity of the electron is along the x direction, and the trajectory is along the x axis. Figures 2(a) and 2(b) show the energy and the velocity of the electron reflected by the SW, where the electron's

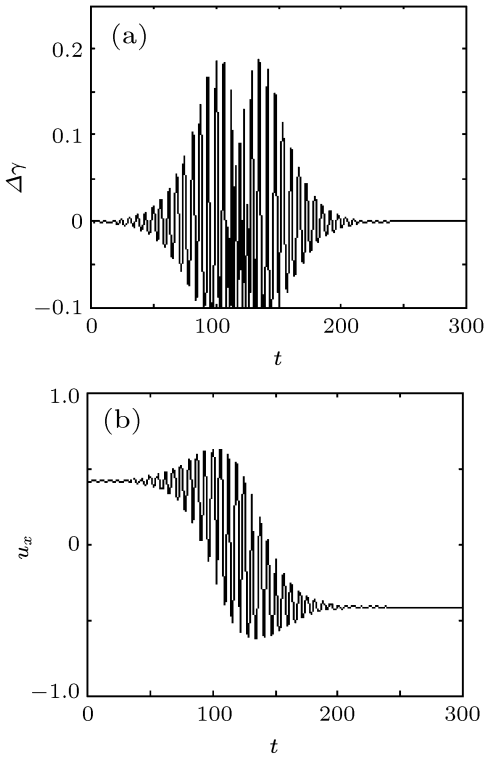


Fig. 2. (a) Electron energy gain and (b) velocity during the interaction for an electron launched in anti-node into a linearly polarized laser SW with $b_0 = 5\lambda$, $a_0 = 5$, and $\gamma_0 = 1.1$.

initial energy is $\gamma_0 = 1.1$. Figures 3(a) and 3(b) show the velocity and energy of the electron with critical electron energy $\gamma_0 = 6.5$. The critical energy is the energy, in excess of which the electron goes through the anti-node of the SW. Results show that the critical electron energy increases with the increase of field intensity. Faster oscillations are found for the later case.

For the incidence from node plane $z_0 = (2n + 1)\pi/2$, $(n = 0, 1, 2, \ldots)$, the results show that there exists a threshold intensity for the laser SW, above which the motion of electrons undergoes a transition from regular to chaotic. A conversion from the elastic to the inelastic interaction also occurs. Figure 4 shows the regular motion mode of electrons driven by the Lorentz field. The electron oscillates in the z direction and moves towards the positive x direction. Even with very small initial energy, the electron can pass through the relativistic SW field after oscillating, gaining and losing energy in front and behind the standing wave centre, respectively. The final energy remains unchanged.

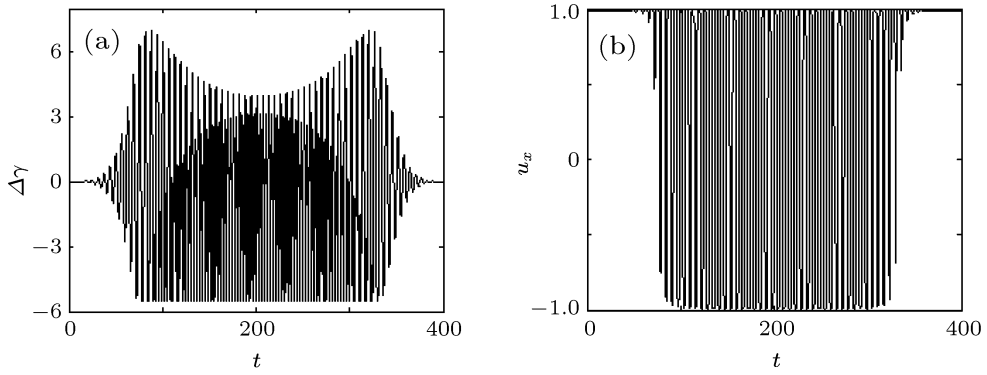


Fig. 3. (a) Electron energy gain and (b) velocity during the interaction, which are obtained for an electron launched in anti-node into a linearly polarized laser SW with $b_0 = 5\lambda$, $a_0 = 5$, and $\gamma_0 = 6.5$.

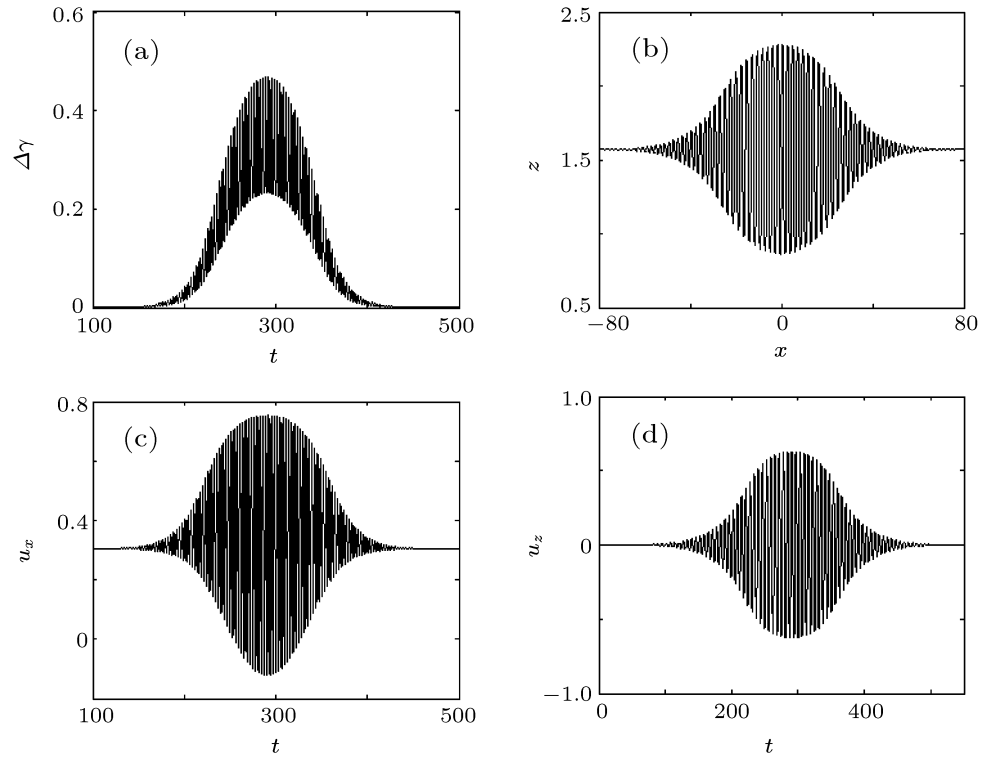


Fig. 4. (a) Electron energy gain, (b) electron trajectory, and dependence of x-component (c) and z-component (d) velocities on time during the interaction with the node of a linearly polarized laser SW at $a_0 = 1$, $b_0 = 5\lambda$, and $\gamma_0 = 1.05$.

With the increase of the intensity of the laser SW, the average electron velocity in the x direction gets

smaller. Figure 5 shows that the intensity of the laser SW comes to its maximum $a_0 = 1.977$ for the regular electron motion with $\gamma_0 = 1.2$, where the mean of u_x approaches to around zero in Fig. 5(c).

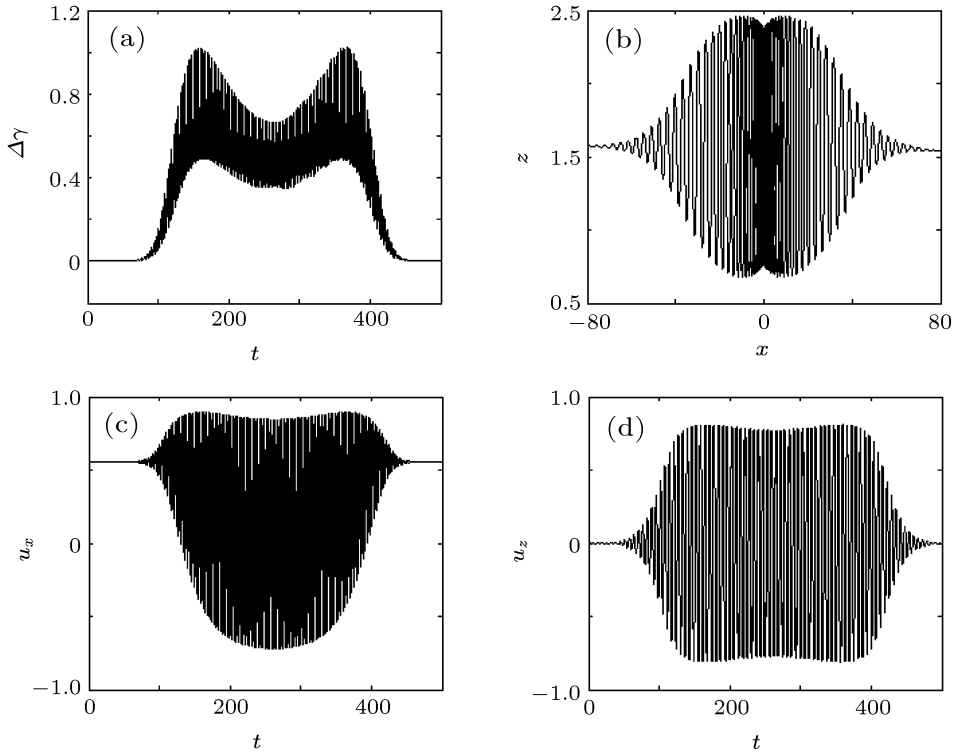


Fig. 5. (a) Electron energy gain, (b) electron trajectory, the dependence of x-component (c) and z-component (d) velocities on time during the interaction with the node of a linearly polarized laser SW at $a_0 = 1.977$, $b_0 = 5\lambda$, and $\gamma_0 = 1.2$.

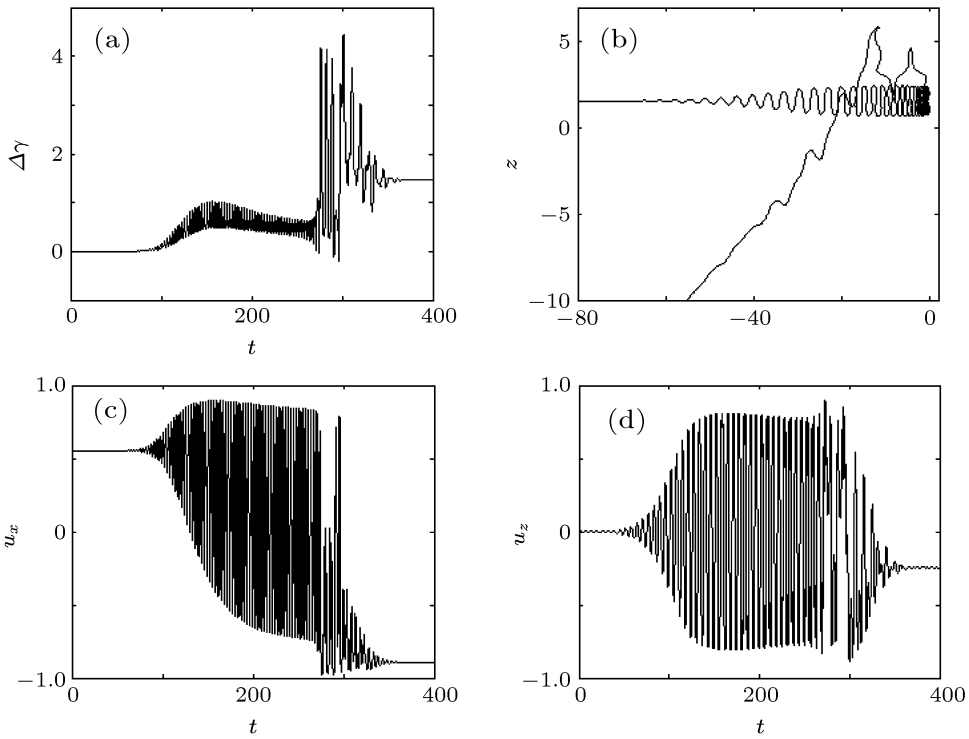


Fig. 6. (a) Electron energy gain, (b) electron trajectory, the dependence of x-component (c) and z-component (d) velocity on time during the interaction with the node of a linearly polarized laser SW for $a_0 = 1.978$, $b_0 = 5\lambda$ and $\gamma_0 = 1.2$.

In Fig. 6, an anomaly of the electron motion appears abruptly in the latter-half interaction as the intensity of the laser SW exceeds its ceiling for the regular electron motion. The transition proves the existence of the intensity threshold and the mutuality between chaos and inelastic events with a possible energy exchange. We also find the threshold value of the laser intensity ascends with electron initial energy γ_0, for example, $a_0 = 1.395$ corresponding to $\gamma_0 = 1.05$, and $a_0 = 1.978$ corresponding to $\gamma_0 = 1.2$.

4. Chaos patterns and huge net energy gain in non-elastic scattering

For the case of incidence in the node plane, we study the dependence of chaos patterns on the electron energy. Results show that there are three levels of interactions of electrons with the SW determined by the election initial energy: reflection level, overpass level, and the intervenient level, i.e., both-handed level. In the both-handed level, which is between $\gamma_0 = 3.12$ and $\gamma_0 = 5.1$ for the case of $a_0 = 5$ and $b_0 = 5\lambda$, the modes of the reflection and the overpass are intercurrent. When falling into the chaos state, which is characterized by different trajectories induced by little changes in the initial conditions, the motion of electron presents considerable abundant patterns. Figures 7(a) and 7(b) show distinct chaos patterns, in which the electron is thrown back by the SW or overpasses the SW, respectively.

Now we show that there may be huge energy exchanges between electrons and SW fields in the case of extremely tight laser focusing, such as $b_0 = \lambda$ and $a_0 = 10$. Figures 8 and 9 display the cases of electrons launched from node $z_0 = \pi/2$ and arbitrary plane $z_0 = \pi/4$, respectively. The inelastic scattering of electrons in the high-intensity laser SW is related to the chaos patterns, in which an electron energy gain of up to 20 MeV can be realized.

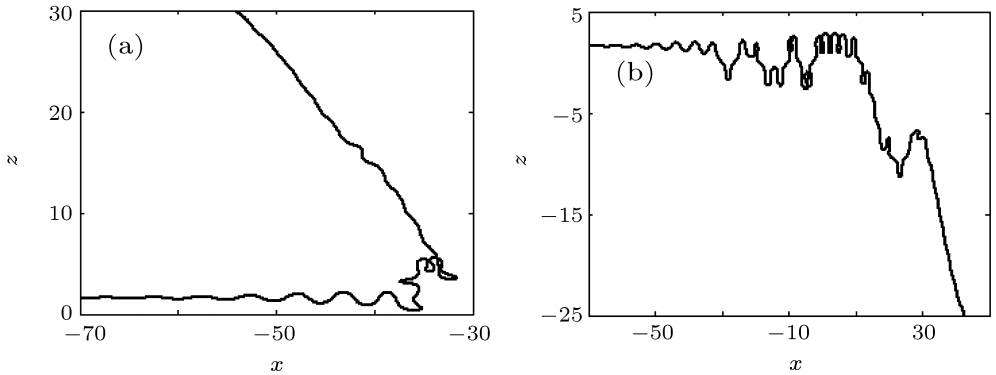


Fig. 7. Electron trajectories for (a) $\gamma_0 = 1.6$ and (b) $\gamma_0 = 3.22$ during the interaction with a linearly polarized laser SW for $a_0 = 5$, $b_0 = 5\lambda$.

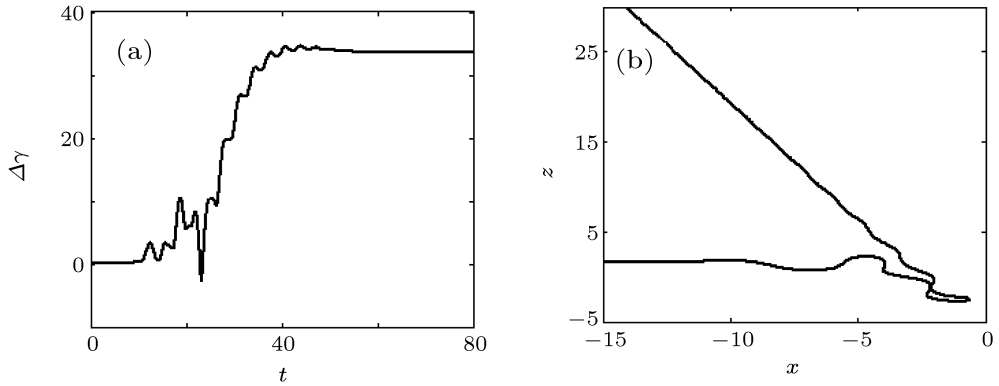


Fig. 8. (a) Electron energy gain and (b) electron trajectory during the interaction with a linearly polarized laser SW for $a_0 = 10$, $b_0 = \lambda$, $z_0 = \pi/2$, and $\gamma_0 = 5.0$.

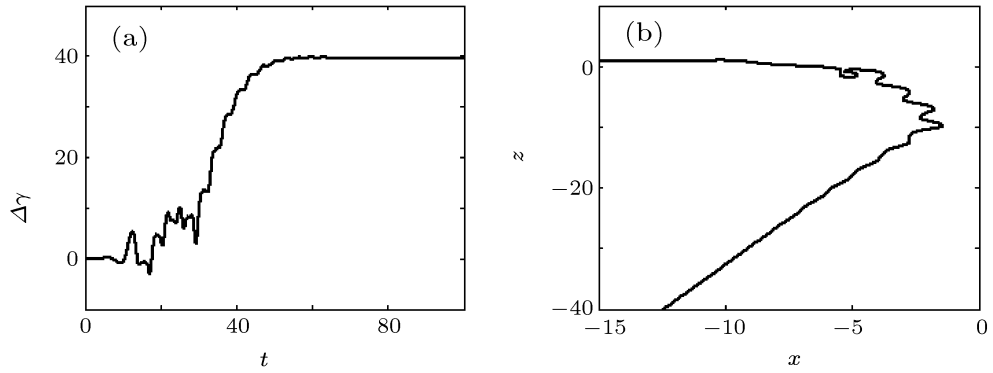


Fig. 9. (a) Electron energy gain and (b) electron trajectory during the interaction with a linearly polarized laser SW for $a_0 = 10$, $b_0 = \lambda$, $z_0 = \pi/4$, and $\gamma_0 = 4.4$.

5. Conclusion

In this work, we have investigated the interaction of relativistic electrons with a linearly polarized high-intensity laser SW. The motion and the energy of the electrons in laser SW fields are calculated with the relativistic Lorentz equation. The results show that there exists a threshold intensity, above which the motion of the electrons incident in the node plane parallel to the electric field undergoes a transition from regulation to chaos. The inelastic scattering of electrons in strong laser standing waves is related to the chaos and may induce a huge energy exchange. When the initial energy of electrons overruns the limit of the intensity threshold of the laser, the motion relapses to the regular one similar to that in the case of weak fields.

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