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Research Article

Radiation reaction induced spiral attractors in ultra-intense colliding laser beams

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Abstract

The radiation reaction effects on electron dynamics in counter-propagating circularly polarized laser beams are investigated through the linearization theorem and the results are in great agreement with numeric solutions. For the first time, the properties of fixed points in electron phase-space were analyzed with linear stability theory, showing that center nodes will become attractors if the classical radiation reaction is considered. Electron dynamics are significantly affected by the properties of the fixed points and the electron phase-space densities are found to be increasing exponentially near the attractors. The density growth rates are derived theoretically and further verified by particle-in-cell simulations, which can be detected in experiments to explore the effects of radiation reaction qualitatively. The attractor can also facilitate realizing a series of nanometer-scaled flying electron slices via adjusting the colliding laser frequencies.

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Keywords: Radiation reaction effect; Phase space dynamics; PIC simulation

1. Introduction

The interactions of ultra-short and ultra-intense laser pulses with various plasmas can generate brilliant sources of energetic electrons, ions, X/γ-rays, and positrons with proper laser plasma parameters [1−5]. Electrons are the most fundamental particles in laser plasma interaction as electrons can be easily accelerated to relativistic velocities with laser intensities higher than 10^{18} W/cm^2 [6−8]. The electron dynamics in laser fields has been investigated thoroughly under the framework of classical electrodynamics. However, with the advent of more powerful laser facilities, laser intensities are about to achieve 10^{23} W/cm^2 [9] and electron dynamics in such intense laser fields are substantially different since here the magnitude of radiation reaction (RR) force and Lorentz force are comparable [10]. The quantum electrodynamics (QED) based numeric method [11−15] provides an explicitly self-consistent description of electron discrete emission and the corresponding radiation recoil. Semi-classical description [16,17] of radiation reaction force provides a reliable theoretical method to estimate the continuous radiation effects, avoiding the well-known self-acceleration solutions of classical models [18]. Novel phenomena beyond the framework of classical electrodynamics are predicted by the semi-classical method and

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QED model such as the radiation trapping [19−21], phase space contraction [22,23], QED induced stochastic effect [15,24] and e^+e^- pair production [25].

Experimental detection of radiation reaction effect could be difficult as it is almost unaccessible to measure the microscopic quantities of a single electron motion. However, with proper experimental setup, the tiny differences in electron dynamics can lead to the changes of macroscopic quantities that can be measured with available techniques [26,27]. Detecting the angular distribution changing of the electron or its emitted photon in counter-propagating laser fields provides an optimal method to qualitatively explore the signatures of radiation reaction [28,29]. Recently, γ-ray generation and pair production in counter-propagating laser fields have been investigated widely [30−32], whereas the electron spatiotemporal evolution near the attractors in intense colliding laser beams still lacks a quantitative prediction. On the other hand, for laser radiation with 1 μm wavelength, the radiation friction force changes the scenario of the electromagnetic wave interaction with matters at the intensity of $I_R \approx 10^{23}$ W/cm^2. For the laser intensity close to I_R, the electron interaction with the electromagnetic field is principally determined by a counterplay between the radiation friction and quantum effects [5,33]. When the laser intensity is higher than $I_Q = 5.75 \times 10^{23}$ (1 μm/λ) W/cm^2, the QED effects weaken the electromagnetic emission [34] and the process of photon emission becomes stochastic [11]. Provided that the QED induced radiation is weakened and the stochastic effect is indifferent under the laser intensity lower than I_Q, the classical radiation reaction approach still gives us valid results. In this paper, we utilized the classical radiation reaction model to investigate the electron dynamics in counter-propagating laser fields. The presented electron spatiotemporal evolution was dominantly affected by the fixed points in electron phase-space and the analytical solutions of electron dynamics were obtained with linear stability theory [35]. It is found that the spiral attractors induced by radiation reaction can lead to exponential growth of in situ density and the analytic growth rates were given and compared with numeric solutions.

2. Theoretical analysis

For simplicity and generality, the counter propagating laser pulses are described by infinite plane wave vector potential, $\boldsymbol{A}_1 = a_0[\sin(t-x)\widehat{\boldsymbol{y}} + \cos(t-x)\widehat{\boldsymbol{z}}]$ and $\boldsymbol{A}_2 = a_0[\sin(t+x)\widehat{\boldsymbol{y}} + \cos(t+x)\widehat{\boldsymbol{z}}]$; $\widehat{\boldsymbol{y}}$(or $\widehat{\boldsymbol{z}}$) is the unit vector in y (or z) direction; a_0 is the normalized laser amplitude ($a_0 = eE_0/m_e c w_0$), where e and m_e are the electron charge and mass, E_0 and w_0 are the electric amplitude and frequency, c is the speed of light, respectively; x and t are normalized to c/w_0 and w_0, respectively. The electromagnetic standing wave (SW) field can be deduced as $\boldsymbol{E} = -\partial \boldsymbol{A}/\partial t = -2a_0\cos(x)\cos(t)\widehat{\boldsymbol{y}} + 2a_0\cos(x)\sin(t)\widehat{\boldsymbol{z}}$ and $\boldsymbol{B} = \nabla \times \boldsymbol{A} = 2a_0\sin(x)\cos(t)\widehat{\boldsymbol{y}} - 2a_0\sin(x)\sin(t)\widehat{\boldsymbol{z}}$ from the whole region vector potential $\boldsymbol{A} = \boldsymbol{A}_1 + \boldsymbol{A}_2$.

First of all, considering the condition without RR recoil, electron dynamics in phase-space x-p_x is determined by relativistic Lorentz force $\mathrm{d}\boldsymbol{p}/\mathrm{d}t = \partial \boldsymbol{A}/\partial t - \boldsymbol{v} \times (\nabla \times \boldsymbol{A})$. As SW field is independent of y and z, there are two invariant equations:

$$\frac{\mathrm{d}p_y}{\mathrm{d}t} = \frac{\partial A_y}{\partial t} + v_x\frac{\partial A_y}{\partial x} = \frac{\mathrm{d}A_y}{\mathrm{d}t}, \tag{1}$$

$$\frac{\mathrm{d}p_z}{\mathrm{d}t} = \frac{\partial A_z}{\partial t} + v_x\frac{\partial A_z}{\partial x} = \frac{\mathrm{d}A_z}{\mathrm{d}t}. \tag{2}$$

Assuming at initial time $p_y|_{t=0} = A_y|_{t=0}$ ($p_z|_{t=0} = A_z|_{t=0}$), the above conservative relations tell us that $p_z \equiv A_z = 2a_0\cos(x)\cos(t)$ ($p_y \equiv A_y = 2a_0\cos(x)\sin(t)$). For the relativistic factor $\gamma = \sqrt{1+p_x^2+4a_0^2\cos^2(x)}$, the nonlinear differential equation in x-p_x space is derived as:

$$\frac{\mathrm{d}x}{\mathrm{d}t} = \frac{p_x}{\gamma} = \frac{p_x}{\sqrt{1+p_x^2+4a_0^2\cos^2(x)}}, \tag{3}$$

$$\frac{\mathrm{d}p_x}{\mathrm{d}t} = -v_y B_z + v_z B_y = \frac{4a_0^2\cos(x)\sin(x)}{\sqrt{1+p_x^2+4a_0^2\cos^2(x)}}. \tag{4}$$

From the time-independent nonlinear relationship Eqs. (3) and (4) (i.e., autonomous nonlinear system in mathematics), we can exactly find that the relativistic factor is a conservative Hamiltonian:

$$H = \gamma = \sqrt{1+p_x^2+4a_0^2\cos^2(x)}, \tag{5}$$

since $\mathrm{d}H/\mathrm{d}t = \partial H/\partial t \equiv 0$ is validated from the corresponding canonical equation $\mathrm{d}x/\mathrm{d}t = \partial\gamma/\partial p_x = f(x, p_x)$ and $\mathrm{d}p_x/\mathrm{d}t = -\partial\gamma/\partial x = g(x, p_x)$, which are completely equivalent with Eqs. (3) and (4). The Hamiltonian H is symmetrical and periodic, and note that there are some special solutions of these differential equations when the initial value (x^*, p_x^*) satisfies $f(x^*, p_x^*) = 0$ and $g(x^*, p_x^*) = 0$. This is the constant solution $(x, p_x) \equiv (x^*, p_x^*)$. A constant solution such as this is called an equilibrium solution or equilibrium point for the equation [35]. Subsequently there are four equilibrium points (x^*, p_x^*) at electric nodes (π/2, 0), (3π/2, 0) and antinodes (0, 0), (π, 0) in a SW period, as shown in Fig. 1(a). The property of an equilibrium point in the nonlinear system can be classified via its linear approximation near the equilibrium point. The Jacobian matrix is a linearization method via calculating the first partial derivatives, which facilitates us to investigate the property of the equilibrium point [35,36]. To determine whether the equilibrium point is stable or not, by making the disturbance expansion near $(x - x^*, p_x - p_x^*)$ and dropping quadratic terms to linearize Eqs. (3) and (4), the characteristic Jacobian matrix **Ja** at the equilibrium point (x^*, p_x^*) is obtained:

$$\mathbf{Ja} = \begin{pmatrix} \dfrac{\partial f(x,p_x)}{\partial x} & \dfrac{\partial f(x,p_x)}{\partial p_x} \\ \dfrac{\partial g(x,p_x)}{\partial x} & \dfrac{\partial g(x,p_x)}{\partial p_x} \end{pmatrix}_{x^*,p_x^*} = \begin{pmatrix} 0 & \dfrac{1}{\gamma} \\ \dfrac{4a_0^2\cos(2x)}{\gamma} & 0 \end{pmatrix}_{x^*,p_x^*}. \tag{6}$$

For the electric node $x^* = \pi/2$ or $3\pi/2$, the trace and determinant of Jacobian matrix are $\mathrm{tr}(\mathbf{Ja}) = 0$ and