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The motion of a charged particle in the field of a frequency-modulated electromagnetic wave and in the constant magnetic field

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Abstract

In this article the problem on the motion of a charged particle in the field of frequency-modulated electromagnetic wave and in the external uniform static magnetic field has been analyzed; the exact solutions of the corresponding equations have been presented. This problem is of great importance to study the interaction of high-intensity laser pulses with solid targets and to develop practically multifrequency lasers and the laser-modulation emission technology.

The formulae for the mean kinetic energy of a relativistic charged particle as a function of initial conditions, electromagnetic wave amplitude, wave intensity and its polarization parameter were obtained. The different cases of initial conditions of a charged particle motion and of a wave polarization were investigated. The obtained results can be put to use when studying the high-temperature plasma formed on the surface of the target and when searching for new modes of laser- plasma interaction.

Keywords: Plane electromagnetic wave; Charged particle; Ultrashort laser pulse.

1. Introduction

The trailblazing study by Tajima and Dawson [1] has attracted a wide interest in laser-induced particle acceleration from researchers all over the world. Currently, the focus of theoretical and practical studies is on accelerating the motion of charged plasma particles by ultra-short laser pulses of high intensity [2–5]. The advances in laser technologies have allowed to create terawatt and petawatt laser pulses [6–10] that can be used to study the interaction between the strong fine-focused light pulses and the charged particles in plasma. The development of such areas of physics and engineering as plasma physics, astrophysics, powerful relativistic high-frequency electronics, and accelerating machines pave the way for studying the interaction of charged particles with frequency-modulated electromagnetic waves. Relativistic charged particles in strong electromagnetic fields play a special role in these interactions. Obtaining the energy characteristics of a charged particle in the field of a

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frequency-modulated electromagnetic wave is necessary for designing multi-frequency lasers that can be then used in practice and for developing various laser modulation techniques.

In the present paper we discuss the electron dynamics in an intense frequency-modulated electromagnetic field of elliptical polarization with a constant uniform magnetic field. Studying the interaction of charged particles with ultrashort femtosecond laser pulses with radiation intensities up to 10^{22} W/cm^2 is currently one of the main areas in laser physics.

The problem of a charged particle moving in the field of a plane frequency-modulated electromagnetic wave was formulated and solved for the cases of linear and circular polarization in Ref. [11]. However, the authors did not average the speed, the momentum, and the kinetic energy of the particle over the oscillation period in the field of the plane frequency-modulated electromagnetic wave in the presence of the constant uniform magnetic field, which is, without a doubt, is both of theoretical and practical interest.

The goal of this study is to analyze the motion of a charged particle in the external field of a randomly-polarized frequency-modulated electromagnetic wave of high intensity in the presence of a constant uniform magnetic field. In particular, the equations for the mean kinetic particle energy averaged over its oscillation period need to be formulated.

2. Problem statement

The equation for the motion of the charged particle with the mass m and the charge q in a high-frequency laser electromagnetic field in the presence of a constant uniform magnetic field $\boldsymbol{H}_0$ has the following form [9,12]:

$$\frac{d\boldsymbol{p}}{dt} = q\boldsymbol{E} + \frac{q}{c}[\boldsymbol{V} \times \boldsymbol{H}_\Sigma] \tag{1}$$

where $\boldsymbol{p}$ is the momentum of the charged particle; $\boldsymbol{E}$ is the strength of the electric laser field of radiation; $\boldsymbol{H}_\Sigma = \boldsymbol{H}_0 + \boldsymbol{H}$ is the strength of the combined magnetic field, including the uniform constant magnetic field $\boldsymbol{H}_0$ and the magnetic component of the laser field $\boldsymbol{H}$; q is the particle charge.

Eq. (1) is complemented by the initial conditions for the velocity and the position of the particle:

$$\boldsymbol{V}(0) = \boldsymbol{V}_0,\ \boldsymbol{r}(0) = \boldsymbol{r}_0$$

The particle momentum and its velocity are connected by the following equality [9]:

$$\boldsymbol{p} = \frac{m\boldsymbol{V}}{\sqrt{1 - \frac{V^2}{c^2}}}. \tag{2}$$

The change in the particle energy

$$\varepsilon = \frac{mc^2}{\sqrt{1 - \frac{V^2}{c^2}}} = \sqrt{m^2c^4 + p^2c^2} \tag{3}$$

is determined by the equation

$$\frac{d\varepsilon}{dt} = q\boldsymbol{E}\boldsymbol{V}. \tag{4}$$

The energy, the momentum, and the velocity of the particle are connected by the relationship

$$\boldsymbol{p} = \frac{\varepsilon \boldsymbol{V}}{c^2}. \tag{5}$$

It is assumed in this paper that the frequency of the electromagnetic wave is modulated by the harmonic law:

$$\varphi = \mu \sin\left(\omega'\xi + \psi\right),$$

where $\mu = \Delta\omega/\omega'$ is the modulation index equal to the ratio between the frequency deviation $\Delta\omega$ and the frequency of the modulating wave ω'; ψ is the constant phase;

$$\xi = t - z/c.$$

Let us assume that the plane frequency-modulated wave propagates along the z axis, while the strength $\boldsymbol{H}_0 = \boldsymbol{k}H_0$ of the constant uniform magnetic field is also directed along the z axis (**k** is the basis vector of the z axis). In this case the vector components of the electric ($\boldsymbol{E}$) and the magnetic ($\boldsymbol{H}$) fields for the plane frequency-modulated electromagnetic waves are determined by the expressions [11]:

$$\begin{cases} E_x = H_y = b_x \exp(-i(\omega\xi + \alpha + \mu \sin(\omega'\xi + \psi))); \\ E_y = -H_x = f b_y \exp(-i(\omega\xi + \alpha \\ \qquad\qquad + \mu \sin(\omega'\xi + \psi))); \\ E_z = H_z = 0, \end{cases} \tag{6}$$

where ω is carrier wave frequency; α is the constant phase; the x and the y axes coincide with the direction of the b_x and the b_y axes of the wave polarization ellipse, with $b_x \geq b_y \geq 0$; $f = \pm 1$ is the polarization parameter (the upper and the lower signs in the expression for E_y correspond to the right and the left polarization, respectively [14,15]).

If we apply the Jacobi–Anger expansion then the real part of the expressions (6) takes the form