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Spectral and angular radiation characteristics of a charged particle in the plane monochromatic electromagnetic wave

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Abstract

Relying upon the solution of the relativistic equation of charged-particle motion that was obtained by Rukhadze et al., the spectral and angular characteristics of ultra-relativistic intensive radiation of a relativistic charged particle have been studied, the particle being linearly accelerated by a superpower laser pulse. The case where the particle propagates in vacuum without brake light was examined. The interaction of the charged particle with the large-amplitude ultra-short laser pulse was analyzed in details using the relativistic consideration. Formulae for the average radiated power of the relativistic charged particle, depending on the initial conditions, the electromagnetic-wave amplitude, intensity and polarization were obtained. For the case where the laser pulse can be represented by a monochromatic plane wave, analytical expressions for the radiation characteristics were put forward and the phase-angular distributions of relativistic radiated power and intensity were found. The Fourier transform of the electric-intensity radiation field of the charged particle and the particle's spectral density radiation in the field of a plane monochromatic wave for different types of polarization (linear and circular ones) were determined.

Keywords: Plane electromagnetic wave; Radiated power; Radiation intensity; Ultrashort laser pulse.

1. Introduction

The present work discusses the interaction between a charged particle and an ultrashort laser pulse with an intensity $I = 10^7$ TW·cm^{-2} in vacuum, without the bremsstrahlung taken into account. Based on the Newton equation and applying the Lorentz force, a number of studies [1–4] analyze the motion of a charged particle in the field of an ultrashort laser pulse. The wavefront is considered to be plane, and in the first approximation it corresponds to a plane monochromatic electromagnetic wave.

Refs. [2–4] introduce calculations for the average energy and kinetic characteristics of a charged particle for various polarizations. Ref. [1] demonstrated that the oscillation period of a particle differs from that of a plane wave field, and performed an averaging over the particle oscillation period. In this connection, it would be of interest to calculate the spectral and angular radiation characteristics and to average them over the oscillation period of a particle. The characteristics in question are the mean power, the total power and radiation intensity of a charged particle, the

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angular and the phase angular distributions of the radiation intensity. The Fourier transform of the strength of the electric field of the particle's radiation should be calculated for this purpose, with the magnitude of its spectral density estimated for different polarizations (the linear and the spectral).

2. Problem setting

Let us assume that the high-frequency Lorentz force acts on a charged particle q with the mass m; then the equation for the particle motion takes the form

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

where $\boldsymbol{p}$ is the momentum of the particle; $\boldsymbol{E}$ and $\boldsymbol{H}$ are the electric and the magnetic strengths of the laser field; q is the charge of the particle.

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

$$\boldsymbol{V}(0) = \boldsymbol{V}_0, \quad \boldsymbol{r}(0) = \boldsymbol{r}_0. \tag{2}$$

The relativistic factor γ is connected to the electromagnetic field intensity I by the following relation:

$$\gamma = \sqrt{1 + I/I_{rel}},$$

where the relativistic intensity I_{rel} (in $\mathrm{W \cdot cm^{-2}}$) is determined by the expression [5]:

$$I_{rel} = m^2c^3\omega^2/8\pi q^2 = 1.37 \cdot 10^{18}\lambda^{-2}. \tag{3}$$

Here λ (μm) is the wavelength, and ω ($\mathrm{s^{-1}}$) is the frequency of high-power ultrashort laser raditation (the carrier wave frequency).

Let us choose a system of coordinates so that the laser pulse propagates along the z-axis. We are going regard its phase front as plane, and the surface of the constant phase as perpendicular to the z-axis. In this case the components of the electric (**E**) and the magnetic (**H**) fields for a plane monochromatic electromagnetic wave are determined by the expressions [6]:

$$\begin{cases} E_x = H_y = b_x \cos\Phi, \\ E_y = -H_x = f b_y \sin\Phi, \\ E_z = H_z = 0, \end{cases} \tag{4}$$

where the x and the y axes coincide with the direction of the semi-axes of the wave polarization ellipse b_x and b_y, and

$$b_x \geq b_y \geq 0;\ \Phi = \omega\xi;\ \xi = t - z/c;$$

ω is the carrier wave frequency; $f = \pm 1$ is the polarization parameter: the upper sign for E_y corresponds to the right polarization, and the lower sign to the left one [7,8].

2.1. *Radiation intensity of the charged particle in the field of a plane monochromatic electromagnetic wave*

By multiplying Eq. (1) vectorially by the vector $\boldsymbol{H}$, we obtain the Umov–Poynting vector in the following form:

$$\boldsymbol{S} = \frac{c}{4\pi}[\boldsymbol{E} \times \boldsymbol{H}] = \frac{c}{4\pi q}[\boldsymbol{F} \times \boldsymbol{H}] - \frac{1}{4\pi}[[\boldsymbol{V} \times \boldsymbol{H}] \times \boldsymbol{H}], \tag{5}$$

where $\boldsymbol{F} = \frac{d\boldsymbol{p}}{dt}$.

The component-wise form of the vector (5) is

$$S_x(t) = -\frac{c}{4\pi q}H_yF_z + \frac{1}{4\pi}H_y\left(V_xH_y - V_yH_x\right), \tag{6}$$

$$S_y(t) = \frac{c}{4\pi q}H_xF_z + \frac{1}{4\pi}H_x\left(V_yH_x - V_xH_y\right), \tag{7}$$

$$S_z(t) = \frac{c}{4\pi q}\left(E_xF_x + E_yF_y\right) + \frac{1}{4\pi}V_z\left(H_x^2 + H_y^2\right). \tag{8}$$

The Lorentz force acting on the particle, has the following component-wise form [1]:

$$F_x = \frac{qb_x}{(1+g)}\cos\Phi', \tag{9}$$

$$F_y = \frac{fqb_y}{(1+g)}\sin\Phi', \tag{10}$$

$$F_z = \frac{\omega\gamma}{(1+g)}\left(\frac{q}{\gamma^2\omega}\left(\chi_xb_x\cos\Phi' + f\chi_yb_y\sin\Phi'\right) + \frac{q^2}{2\gamma^2\omega^2}\left(b_x^2 - b_y^2\right)\sin\left(2\Phi'\right)\right). \tag{11}$$

Since it follows from the Expression (11) that in the field of a plane monochromatic wave in the initial moment of time $t = 0$ the transverse component of the momentum $p_\parallel = const$ (i.e. without the bremsstrahlung taken into account the particle does not accelerate or decelerate), the Lawson–Woodward theorem is fulfilled in this case.

By substituting the Expressions (9) – (11) and the velocity values from Ref. [1] into Eqs. (6)–(8), we obtain the Umov–Poynting vector components in the following form:

$$S_x = 0,$$
$$S_y = 0,$$
$$S_z(t) = \frac{c}{4\pi}\left(b_x^2\cos^2\Phi' + b_y^2\sin^2\Phi'\right). \tag{12}$$