31st EPS Conference on Plasma Phys. London, 28 June - 2 July 2004 ECA Vol.**28G**, P-4.023 (2004)

Phase dependence of relativistic electron dynamics and emission spectra in the superposition of a ultraintense laser field and a strong uniform magnetic field

Xinkui He, Ruxin Li, Bin Shuai, Xiaochun Ge, and Z. Z. Xu

Laboratory for High Intensity Optics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, Shanghai 201800, China

Abstract. The phase dependence of the dynamics and emission spectra of a fully relativistic electron in the superposition of a ultra-intense plane wave laser field and a strong uniform magnetic field has been investigated. For circular polarization only the axis of the helical trajectory is changed with the variation of the initial laser field phase. However, for linear polarization, the effect of changing initial phase is contrary in the two parameter regions divided by the resonance condition. Phase dependence of the electron's energy and velocity components was also studied. Some beat structure is found when the initial laser phase is zero and this structure is absent when the initial laser phase is a quarter of a period.

1. INTRODUCTION

The development of ultra-intense lasers has led to much interest in laser-matter interaction because of the new possibility to study high-field and ultra-high-field physics and new method to generate efficient sources of x-ray and high-energy particles [1]. An important model for electron acceleration and x-ray emission is the interaction of free-electrons with ultra-intense laser, such as nonlinear Thomson scattering [2,3].

In this letter, we investigate the interaction of a relativistic free-electron and the ultra-intense laser with an added uniform magnetic field parallel to the laser propagation direction. This problem is important for the understanding of laser plasma interaction and the related problems of high-energy electron emission [4,5], as well as for the study of inertial confined fusion using fast ignition concept [6]. In recent papers [7,8], Salamin presented the exact analytic solution of the problem. He found that, there is a very important parameter r which affects the behavior of the system critically. Here r stands for the frequency ratio

$$r = \frac{\omega_c}{\omega_l}\sqrt{(1+\beta_0)/(1-\beta_0)} \tag{1}$$

where $\beta_0 = v_0 / c$ is the initial electron speed normalized by c, and $\omega_c = eB_s / mc$ is the cyclotron frequency of the electron moving in the magnetic field B_s, ω_l is the frequency of laser field. When $r = 1$, the electron can gain maximum energy from the laser field, so $r = 1$ is called the resonance condition [8]. When $r \neq 1$, for observation along the same direction of laser propagation and the magnetic field, light at frequency of the laser and another frequency Ω_0 is scattered, and Ω_0 dependent on the electron initial velocity, the intensity and frequency of the laser and the strength of the magnetic field, which is called magnetic peak [7].

Because of the ultrahigh intensity of the laser field and the ultrashort duration of the laser pulse, the phase at which the electron experience the laser pulse will be important. All of the previous work of this model considered that the initial laser phase is zero. In this letter, we investigate the influence of the initial laser phase on the dynamics of the relativistic electron and its emission spectra. In the problem of free electrons interacting with intense laser field, different electron will enter the laser field at different time or different position, so in the initial position different electron will see different laser field phase. In this work we suppose that the initial position of the electrons is the same point (0,0,0), but the electrons enter the laser field at different time.

2. FORMULATION

Considering a relativistic electron with mass m and charge -e, in the simultaneous presence of an intense plane-wave laser field and a strong uniform magnetic field. The vector potential of the fields can be represented by

$$\mathbf{A} = \mathbf{A}_l\left[\hat{\mathbf{i}}\delta\cos\eta + \hat{\mathbf{j}}\sqrt{1-\delta^2}\sin\eta\right] - \frac{\mathbf{B}_s}{2}\left(\hat{\mathbf{i}}y - \hat{\mathbf{j}}x\right) \qquad (2)$$

The first term in Eq. (2) represents a linearly polarized plane-wave with field strength A_l, where $\eta = \omega_l t - \mathbf{k}\bullet\mathbf{r} + {}_0$ is the phase of the laser field with frequency ω_l, η_0 is the initial laser field phase at $t = 0$, and k is the wave vector of the laser field, pointing in the positive z direction. The second term represents the uniform magnetic field in the same direction. The electric field and magnetic field can be derived from equations

$$\mathbf{E} = -\frac{1}{c}\frac{\partial\mathbf{A}}{\partial t}, \qquad \mathbf{B} = \nabla\times\mathbf{A}\,. \qquad (3)$$

The behaviors of the election in the superposed fields is governed by equation

$$\frac{d\mathbf{P}}{dt} = -e(\mathbf{E}+\boldsymbol{\beta}\times\mathbf{B}) \qquad \frac{d\varepsilon}{dt} = -ec\boldsymbol{\beta}\bullet\mathbf{E}\,, \qquad (4)$$

where $\varepsilon = \gamma mc^2$, $\mathbf{P} = \gamma mc\boldsymbol{\beta}$, $\boldsymbol{\beta}$ is the electron velocity normalized by c, the speed of light, and $\gamma = \left(1-\beta^2\right)^{-1/2}$.

3. PHASE DEPENDENCE OF THE ELECTRON'S DYNAMICS

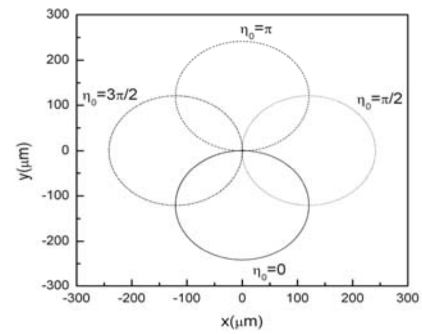

Figure 1. Projection of the electron trajectory of different initial laser field phase η_0 on the xy plate for circular polarization. It is plot over 450 field cycles with $\beta_0 = 0$. $q = 3$ and $\lambda = 0.8\mu m$, the magnetic field $B_s = 30T$.

The trajectory equation and the normalized components of velocity of the relativistic electron with arbitrary initial laser field phase can be derived from Eq. (4). Following, we give numerical results of the electron dynamics graphically.

That can be learned from Salamin's work [7], the electron will follow a wiggly helical path whose axis is parallel to common direction of $\mathbf{B}_s$ and $\mathbf{k}$. So we just present the projection of the trajectory on the plane perpendicular to the laser propagation. In the case of circular

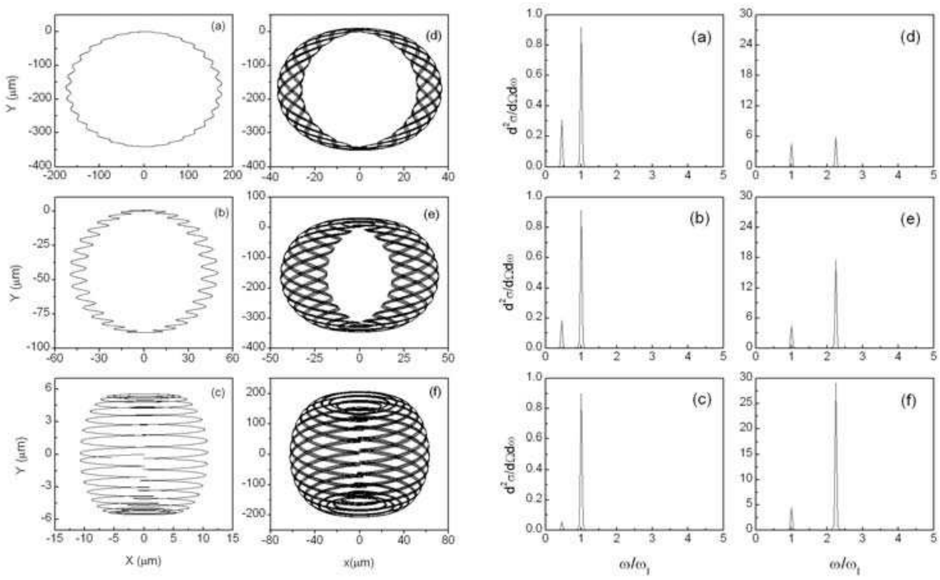

Figure 2. Projection of the electron trajectory on the xy plate (left: The trajectory is plot over 32 field cycles) and the corresponding spectra (right) for linear polarization. Left: (a)-(c) for r=0.0316 with β_0 =0.99, and (d)-(f) for r=1.4173 with β_0=0.999995, (a) (d) η_0=0, (b) η_0=π/2.4, (e) η_0=π/8, (c) (f) η_0=π/2. Right: (a)-(c) r=0.4482, (d)-(f) r=2.2409. (a) (d) η_0=0, (b) (e) η_0=π/4, (c) (f) η_0=π/2.

polarization, we can see from Fig.1 ($q = eA_l / mc^2$ is the dimensionless intensity parameter), for different initial laser phase the axis of the helical trajectory is different. It also can be found that, other physical characteristics will not change with the initial laser field phase for the case of circular polarization. For linear polarization case, from Figure 2 one can see that, for $r < 1$, when the initial laser phase change from 0 to $\pi/2$, the radius of the helical trajectory is decreased, with a minimum value at $\pi/2$. Note that the amplitude of the wiggles does not change, so it seems that the wiggles looks more violent. When $r > 1$, the radius of the helical trajectory is increased with the increase of the laser field phase from 0 to $\pi/2$, and the amplitude of the wiggles is increased too. We found that the helical axis also changes with the initial laser phase.

In Figure 3 (left) we show the velocity components $\beta_x, \beta_x, \beta_x$ as a function of the laser phase for the initial laser field phase 0 and $\pi/2$. Figure 3 (right) shows the energy as a function of the laser phase at the same parameters. The figures clearly show that β_x, β_x and γ exhibit beat structures as $\eta_0 = 0$, and β_x also exhibit some periodical structure, but all these structures absent when $\eta_0 = \pi/2$, instead the curves exhibit oscillation almost at the uniform amplitude (except for β_x). We also found that the maximum value of β_x and the average value of γ is obviously smaller at $\eta_0 = \pi/2$ than that at $\eta_0 = 0$. It seems that the electron exchanges less energy with the laser field when the initial laser field phase is $\pi/2$ than it does when $\eta_0 = 0$

4. RADIATION SPECTRA

The spectrum that would be observed along the laser propagation direction is shown in Figure 2 (right), Consistent with Salamin's work, there are only two peaks in the spectrum, the Thomson peak and the magnetic peak. When $r < 1$, we can find that, the height of the magnetic peak decreases with the increase of the laser field initial phase from 0 to $\pi/2$. The contrary result is found when $r > 1$. This also indicates that the magnetic peak is decided by the helical trajectory of the electron's movement.

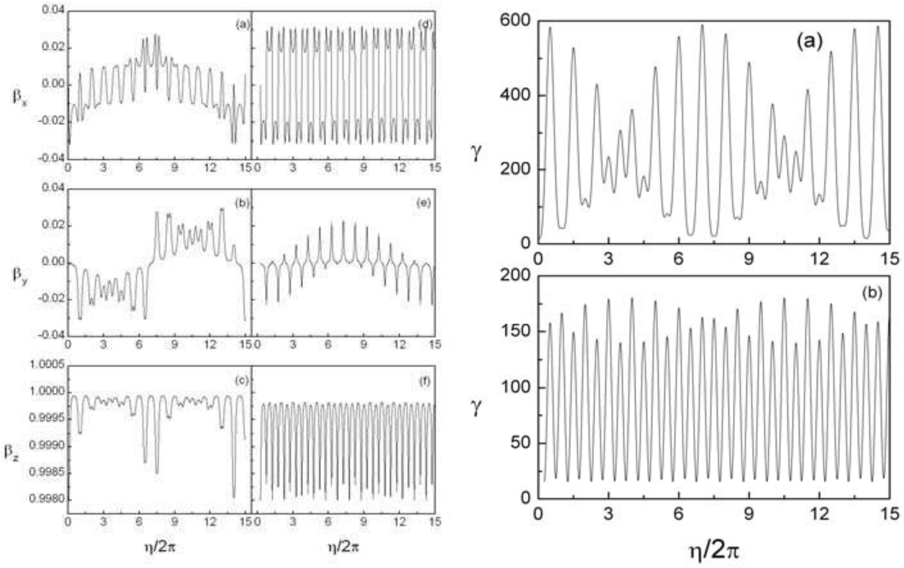

Figure 3. Components of the scaled velocity vector (left) and the scaled energy (right) of the electron is shown over 15 field cycles. $\beta_0 = 0.998$. The parameter of laser field and uniform magnetic field is the same as Figure 1. (a)-(c) $\eta_0 = 0$, (d)-(f) $\eta_0 = \pi/2$.

5. SUMMARY

we have shown that, the dynamic behaviors of the relativistic electron and the emission spectrum vary dramatically with different initial laser field phase. For linear polarization, the effect of changing initial phase is contrary in the two parameter regions divided by the resonance condition $r = 1$ for both the radius of electron's helical trajectory and the height of magnetic peak. This indicates that the magnetic peak is decided by the helical trajectory of the electron's movement. We also studied the phase dependent of the electron's energy and velocity components, and found they show some beat structure when $\eta_0 = 0$ and this structure absent when $\eta_0 = \pi/2$.

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