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# Effects of laser pulse shape and carrier envelope phase on pair production

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ABSTRACT

For different fields of supercycle and subcycle laser pulses, the effects of laser pulse shape and carrier envelope phase on pair production are investigated by solving quantum Vlasov equation. By changing the pulse width and shape, the nonlinear behaviors of momentum distribution function and number density of created electron–positron pairs are obtained. It is found that there exist the multiphoton processes and stabilization phenomenon in pair production for supercycle situation. Our study may shed a light on optimizing the form of applied laser field to enhance the created pairs number, for example, when other conditions are fixed, the flat-top super-Gaussian laser pulse has advantage on pairs production.

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## 1. Introduction

When an external strong background electric field is applied, the quantum electrodynamics (QED) vacuum is unstable and decays to electron–positron pairs [1]. This process is usually called as Schwinger effect for pair production [2]. The corresponding Schwinger critical field strength is $E_{cr} = m_e^2c^3/e\hbar \sim 1.3 \times 10^{16}$ V/cm. It is difficult to reach this critical value in the laboratory at present, while by using X-ray free electron laser (XFEL) facilities we can get a strong field at about $E = 0.1E_{cr} = 1.3 \times 10^{15}$ V/cm.

Some theoretical analysis and numerical calculations have been performed for different forms of laser pulse, for example, the sinusoid form [3–5], the hyperbolic sinusoid form [7–9] and the combination form of sinusoid with exponential pulse [10,6] and so on. Some disadvantages and advantages of various combinational field have been discussed and an optimal combinational field has been proposed in our recent work [10].

In this Letter, we shall further examine carefully the Schwinger effect of different laser pulse shape, e.g. Gaussian and super-Gaussian. Both of supercycle and subcycle laser pulses are considered. We also examine the influence of carrier envelop phase (CEP) on the pair production. We will reveal some novel features of the studied problem, especially the remarkable nonlinear dependence of pair number density on laser pulse parameters.

In our study we employ a quantum kinetic approach. We assume that there exists a sub-critical electric field, i.e. $E < E_{cr}$, and there is no any magnetic field. As the pair production region is very small compared to the laser wavelength the background field can be regard as a time-dependent electric field only. For simplicity, through this Letter, we fix the field strength as $E = 0.1E_{cr}$ so that the back reaction can be neglected (refer to [11,12]). An electric field expression is $\mathbf{E}(t) = (0, 0, E(t))$ with

$$E(t) = E_0 \sin(\omega t + \varphi)e^{-(t/\tau)^{2m}}, \tag{1}$$

where $E_0$ is the field amplitude, $\omega$ and $\varphi$ are the laser frequency and phase, respectively, $\tau$ is the laser pulse duration and $m$ is an integer to denote a Gaussian or super-Gaussian character.

We use the electron quantities as the normalized units, i.e., length $\lambda_c = \hbar/m_ec = 3.862 \times 10^{-13}$ m, momentum $m_ec = 0.511$ MeV/$c$, time $\tau_e = \lambda_c/c = 1.288 \times 10^{-21}$ s. In our study some typical parameters are given, for example, the laser frequency is chosen as $\omega = 8.266 \times 10^3$ eV which corresponds to the laser wavelength $\lambda = 1.5 \times 10^{-10}$ m. It is easy to see that the normalized laser wavelength and normalized laser frequency are $\bar{\lambda} = \lambda/\lambda_c \approx 388.4$ and $\omega = 2\pi\lambda_c/\lambda \approx 0.0162$, respectively.

## 2. Theoretical formalism based on quantum Vlasov equation

The source term of pair production, $s(\mathbf{p}, t)$, obviously depends on the applied external field as well as the electron/positron

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kinetic property. From $df(\mathbf{p},t)/dt = s(\mathbf{p},t)$, where $f(\mathbf{p},t)$ is the momentum distribution of the created pairs, we get the quantum Vlasov equation (QVE) in the following integro-differential equation form

$$\frac{df(\mathbf{p},t)}{dt} = \frac{eE(t)\varepsilon_\perp^2}{2\omega^2(\mathbf{p},t)} \int_{t_0}^{t} dt' \frac{eE(t')[1-2f(\mathbf{p},t')]}{\omega^2(\mathbf{p},t')} \times \cos\left[2\int_{t'}^{t} d\tau\, \omega(\mathbf{p},\tau)\right], \tag{2}$$

where the quantities are the electron/positron momentum $\mathbf{p} = (\mathbf{p}_\perp, p_\parallel)$, transverse energy-squared $\varepsilon_\perp^2 = m_e^2 + p_\perp^2$, the total energy-squared $\omega^2(\mathbf{p},t) = \varepsilon_\perp^2 + p_\parallel^2$, and the longitudinal momentum $p_\parallel = P_3 - eA(t)$. If we define $q(\mathbf{p},t) = eE(t)\varepsilon_\perp/\omega^2(\mathbf{p},t)$ and $\Theta(\mathbf{p},t',t) = \int_{t'}^{t} \omega(\mathbf{p},\tau)\,d\tau$ then Eq. (2) becomes

$$\frac{df(\mathbf{p},t)}{dt} = \frac{1}{2}q(\mathbf{p},t)\int_{t_0}^{t} dt'\, q(\mathbf{p},t')\left[1-2f(\mathbf{p},t')\right] \times \cos\left[2\Theta(\mathbf{p},t',t)\right]. \tag{3}$$

Moreover when the integral part is represented by $g(\mathbf{p},t)$ in Eq. (3), the equation can be expressed as a set of first order ordinary differential equations (ODEs) [6]

$$\dot{f}(\mathbf{p},t) = \frac{1}{2}q(\mathbf{p},t)g(\mathbf{p},t), \tag{4}$$

$$\dot{g}(\mathbf{p},t) = q(\mathbf{p},t)\left[1-2f(\mathbf{p},t)\right] - 2\omega(\mathbf{p},t)w(\mathbf{p},t), \tag{5}$$

$$\dot{w}(\mathbf{p},t) = 2\omega(\mathbf{p},t)g(\mathbf{p},t). \tag{6}$$

For convenience and simplicity we denote the derivative of a physical quantity with respect to time by a symbol dot above this quantity. It should be emphasized that the change from the original integral-differential equation to a set of ODEs not only makes the numerical treatment simpler but also makes the involved physical quantities or/and terms clearer. For example the term $g(\mathbf{p},t)$, i.e. the integral part of Eq. (3), constitutes an important contribution to the source of pair production. In fact this term reveals also the quantum statistics character through the term $[1-2f(\mathbf{p},t)]$ due to the Pauli exclusive principle. On the other hand, $w(\mathbf{p},t)$ denotes a countering term to pair production, which is associated to the pair annihilation in pair created process to some extent. Obviously the last one of ODEs means that the more pairs are created, the more pairs are annihilated probably in pair created process. Thus combining all factors aforementioned will conclude that the studied system exhibits a typical non-Markovian character.

The initial condition of Eq. (3) can be given as $f(\mathbf{p},t_0)$, $g(\mathbf{p},t_0)$ and $w(\mathbf{p},t_0)$ in terms of concrete physical problem. Integrating the distribution function to momentum we can get the time-dependent $e^-e^+$ pair number density as

$$n(t) = 2\int \frac{d^3\mathbf{p}}{(2\pi)^3} f(\mathbf{p},t), \tag{7}$$

which will be very useful in the following study on pair creation enhancement. Since the applied laser field becomes zero when $t \to \infty$, therefore, what we are interested in are the stationary distribution function $f = f(\mathbf{p}, t \to \infty)$ as well as the number density $n = n(t \to \infty)$.

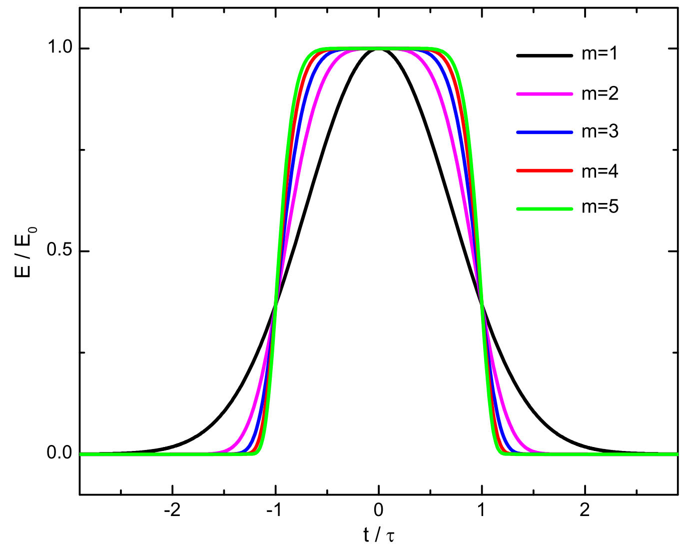


**Fig. 1.** (Color online.) Laser pulse envelop shape of field $E/E_0 = e^{-(t/\tau)^{2m}}$ for different $m$.

## 3. Numerical results of momentum distribution and pair number density

The laser pulse shape can be given by

$$E(t) = E_0 e^{-(t/\tau)^{2m}} \tag{8}$$

where $E_0 = 0.1$ and $m$ is an integer, for example, $m = 1, 2, 3, 4, 5$ in our studied cases, which denotes the Gaussian envelop ($m = 1$) or/and the degree of super-Gaussian envelop. In Fig. 1 we plot the time dependence of the normalized electric field envelop. It can be seen that as $m$ increases the electric field strength changes more rapidly and the top becomes flatter.

Now we will focus our attentions on two typical cases of $m = 1$ and $m = 5$ because the case of $m = 1$ corresponds to usual Gaussian envelop and the case of $m = 5$ is a typical super-Gaussian envelop with a flat top. The studies are performed for the supercycle and the subcycle laser pulse, respectively.

### 3.1. Supercycle laser pulse

We choose a typical supercycle laser pulse field as

$$E_1(t) = E_0 \sin(b\omega t + \varphi)e^{-(t/\tau)^{2m}}. \tag{9}$$

For simplicity the pulse duration $\tau = 1/\omega$ is fixed, where $\omega = 0.0162$, and $b \gg 1$ is an adjustable parameter which meets $1/b\omega \ll \tau$. Let us see the effects of laser pulse shape and the CEP on the pair production.

1. *Laser pulse shape*. By keeping $\varphi = 0$ but changing the $m$ we examine the effects of laser pulse shape on electric field strength, momentum distribution function and pair number density.

First, the time dependence of the laser electric fields are shown in Fig. 2 (a) for $m = 1$ and (b) for $m = 5$ (black solid lines), respectively, at given cycle parameter $b = 10$. When $m = 5$, the electric field changes more rapidly and the top is flatter, while the number of the oscillation cycle within the envelope is reduced compared to $m = 1$.

Second, the momentum distribution function of created electrons are shown in Fig. 3 (a) for $m = 1$ and (d) for $m = 5$. From them one can see clearly that there are many oscillations of the momentum distribution. In fact, the oscillatory phenomenon has been quantitatively studied by Dumlu and Dunne using the phase

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