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A RELATIVISTIC QUASI-STATIC MODEL FOR ELECTRONS IN INTENSE LASER FIELDS*

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A relativistic quasi-static model for the motion of the electrons in relativistic laser fields is proposed. Using the model, the recent experimental results about the generation of the hot electrons in relativistic laser fields can be fit quite well and the important role of the rescattering can be shown clearly.

Keywords: relativistic quasi-static model, relativistic laser fields, hot electrons, rescattering
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I. INTRODUCTION

Corkum pointed out that an atom that undergoes photoionization would not immediately become a well-separated electron and ion. Rather, there is a significant probability of finding the electron in the vicinity of the ion for one or more laser periods. At the same time, he pointed out that the quasi-static model could describe the electron motion under the above-mentioned situations.[1] The quasi-static model suggested by Corkum is non-relativistic. When the laser intensity $I\lambda^2 > 10^{18}\mathrm{W\cdot cm^{-2}}\cdot\mu\mathrm{m}^2$, the relativistic effects become important. Therefore, a quasi-static model with the relativistic effects taken into account is needed. In this paper, we make a try to propose a relativistic quasi-static model.

II. BASIC EQUATIONS OF THE ELECTRONS IN INTENSE LASER FIELD

Because the laser field is so intense that as the zero-order approximation the basic equations of the electrons in the laser-plasma interaction can read as:

$$\dot{p}(t) = e\varepsilon \sin\omega t. \tag{1}$$

The integration of Eq.(1) gives

$$p(t) = -\frac{e\varepsilon}{\omega}\cos\omega t + C_1. \tag{2}$$

Assume

$$p(t_0) = 0, \tag{3}$$

we get

$$C_1 \frac{e\varepsilon}{\omega}\cos\omega t_0. \tag{4}$$

Using Eqs.(3) and (4), we get

$$p(t) = -\frac{e\omega}{\omega}(\cos\omega t - \cos\omega t_0). \tag{5}$$

By means of relativistic mass-energy relation, the total energy of the electron can be expressed as

$$\begin{aligned} E^2_{\mathrm{total}}(t) &= c^2p^2(t) + m^2c^4 \\ &= \frac{c^2e^2\varepsilon^2}{\omega^2}(\cos\omega t - \cos\omega t_0)^2 + m^2c^4. \end{aligned} \tag{6}$$

Introducing a symbol $a = \dfrac{e\varepsilon}{mc\omega} = 8.53\times10^{-10}(I\lambda^2)^{0.5}$ and averaging Eq.(6) with respect to t and t_0, we get an expression of the total average energy of the electron

$$\overline{E}_{\mathrm{total}} = \sqrt{1+a^2}mc^2. \tag{7}$$

Using Eq.(7), the average kinetic energy of the electron can be expressed as:

$$\overline{E}_d = (\sqrt{1+a^2} - 1)mc^2. \tag{8}$$

Based on the particle-in-cell simulation of laser-plasma interaction, Wilks *et al.*[2] pointed out that the temperature of the super-thermal electrons could be expressed as $T_h = (\sqrt{1+a^2} - 1)mc^2$, and the energy distribution $f(E_k) \propto \exp[-E_k/T_h]$. Obviously, Eq.(8) is the same as the formula given by Wilks *et al.* From

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physical viewpoint the identity means that the super-thermal electron temperature is nothing else but the average kinetic energy of electrons in the laser field. The reason why the electrons can gain a higher energy than the temperature is still not very clear.

Below we propose a mechanism which can make the kinetic energy of the electron much larger than the average kinetic energy of electrons given by Eq.(8).

Ⅲ. RESCATTERING EFFECT

Assuming that the electron is scattered elastically at time t_1 Eq.(7) becomes[3]

$$p_x(t) = -\frac{e\varepsilon}{\omega}(\cos\omega t - \cos\omega t_1) + \cos\theta\left[-\frac{e\varepsilon}{\omega}(\cos\omega t_1 - \cos\omega t_0)\right], \quad (9)$$

$$p_y(t) = \left[-\frac{e\varepsilon}{\omega}(\cos\omega t_1 - \cos\omega t_0)\right]\sin\theta. \quad (10)$$

Using the same procedure to get Eq.(6), the total energy of the electron can be presented as

$$\begin{aligned} E^2_{\rm total}(t) &= c^2p^2(t) + m^2c^4 \\ &= \frac{c^2e^2\varepsilon^2}{\omega^2}[(\cos\omega t - \cos\omega t_1)^2 \\ &\quad + (\cos\omega t_1 - \cos\omega t_0)^2 \\ &\quad + 2\cos\theta(\cos\omega t - \cos\omega t_1) \\ &\quad \cdot(\cos\omega t_1 - \cos\omega t_0)] + m^2c^4. \end{aligned} \quad (11)$$

It is easy to show that when $\cos\theta = -1, \cos\omega t_1 = 1, \cos\omega t = \cos\omega t_0 = -1$, formula (11) obtains its maximum value

$$E^{2,\max}_{\rm total} = (16a^2 + 1)m^2c^4. \quad (12)$$

Using Eq.(12), the maximum value of the kinetic energy of the electrons in a laser field can be expressed as

$$E_d^{\max} = (\sqrt{16a^2 + 1} - 1)mc^2. \quad (13)$$

Ⅳ. RESULTS AND DISCUSSION

Recently, Malka *et al.*[4] reported their experimental results about the super-thermal electron generation by an ultra-relativistic laser pulse. The results can be summarized as follows: for a relativistic laser pulse ($\lambda = 1.06\mu$m, $I = 3.0 \times 10^{18}$W·cm^{-2}), $T_h = 420.0$keV, $E_d^{\max} = 2.8$MeV.

Using the above-mentioned laser parameters, we get the following numerical results of the super-thermal electrons: $a = 1.6$, $\overline{E}_d$=440.0keV, $E_d^{\max}$=2.7MeV.

This means that the present model can explain the super-thermal electron temperature and its maximum kinetic energy observed in the experiment of Malka *et al.*

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