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بررسی اثر فرکانس چیرپ در شتاب‌دهی الکترون با دو موج لیزر تخت متقاطع

زینب مشیری، بهروز مراغه‌چی و حسین صابری

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چکیده – در این پژوهش شتاب‌دهی الکترون در خلأ با استفاده از دو پرتو لیزر تخت قطبیده خطی متقاطع مورد مطالعه قرار گرفته است و تاثیر فرکانس چیرپ شده لیزر در شتاب‌دهی الکترون بررسی شده است. محل برخورد الکترون و لیزرها در نقطه تقاطع دو پرتو لیزر می‌باشد. با بکاربردن چیرپ مناسب الکترون انرژی بیشتری در برهمکنش با نیم سیکل لیزر بدست می‌آورد. علاوه بر این نشان داده شده که با بکار بردن لیزرهای با توان بیشتر و الکترون‌های با سرعت اولیه، در انتهای برهم‌کنش الکترون‌های پرانرژی‌تری بدست می‌آید.

کلید واژه- پرتوهای لیزر متقاطع، چیرپ فرکانس، شتاب‌دهی الکترون .

Effect Of Frequency Chirping On Subcycle Electron Acceleration With Two Crossing Plane-Wave Laser Beams

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Abstract- Vacuum electron acceleration by using two linearly polarized plane-wave laser beams, crossing at arbitary angles, has been studied. The effect of frequency chirping of laser beams on the electron acceleration has been investigated. The electron interacts with the laser beams at the crossing point of the two beams. With a proper chirp parameter, the electron could achieve higher energies by interaction on a half-cycle of the laser beams. Ferthermore, it is shown that with stronger laser beams and by using a preaccelerated electron, even more energetic electron at the end of the interaction length could be obtained.

Keywords: electron acceleration, frequency chirping , two crossed laser beams.

1 Introduction

According to the Lawson-Woodward (LW) [1] theorem an electron can not extract energy from an electromagnetic plane wave in an infinite vacuum. Due to the symmetry of the plane-wave, an electron obtains energy in one half cycle of the wave and then loses it in the subsequent half cycle and finally the electron gains no net energy. However, if the conditions of LW theorem could be violated, the symmetry in the plane-wave will be removed and the electron could be accelerated to high energies [2- 8]. It is shown that by using external electric and magnetic fields [2- 5], using two crossing laser beams [6] and a frequency-chirped laser beam [7,8], the electron can gain energy from plane-wave laser beams.

In this paper, we reconsider the mechanism proposed by Salamin and Keitel [6] to investigate the effect of frequency chirping of two crossing plane-wave laser beams on the electron acceleration. We will show that by using a proper chirp parameter, the electron acceleration could be improved compared to unchirped laser beams. We also investigate the effect of lasers intensity and preaccelerated electrons.

2 The Acceleration Equations

The geometry of the electron acceleration is assumed to be the same as that of references [6].. Two linearly polarized, frequency-chirped plane-wave laser beams with propagation angles $\pm\theta$ interact with an electron at the crossing point in the origin. We introduce a linear chirp to the frequency of laser beams and investigate its effect on the electron acceleration mechanism. Therefore, the frequencies become $\omega_1 = \omega(1-\alpha\eta_1)$ and $\omega_2 = \omega(1-\alpha\eta_2)$, where ω and α are the laser frequency and the chirp parameter, respectively. The laser beams are assumed to have identical intensities, frequencies and chirp parameters.

In common plane-wave fields, the phases are $\eta_1 = \omega t - \mathbf{k_1}\cdot\mathbf{r} = \eta - \xi$ and $\eta_2 = \omega t - \mathbf{k_2}\cdot\mathbf{r} = \eta + \xi$, in which we define η and ξ as $\eta = \omega\left(t - \frac{z}{c}\cos\theta\right)$ and $\xi = \omega x \sin\theta / c$. Here $\mathbf{k_1} = \omega(\sin\theta\,\hat{\mathrm{e}}_\mathrm{x} + \cos\theta\,\hat{\mathrm{e}}_\mathrm{z})/c$ and $\mathbf{k_2} = \omega(-\sin\theta\,\hat{\mathrm{e}}_\mathrm{x} + \cos\theta\,\hat{\mathrm{e}}_\mathrm{z})/c$ are propagation vectors. However, by assuming a linear chirp, the two phases will change to $(\eta_1 - \alpha\eta_1^2)$ and $(\eta_2 - \alpha\eta_2^2)$, respectively. So, the electric and magnetic components of the two laser beams are given by:

$$\mathbf{E_1} = E_0 \sin(\eta_1 - \alpha\eta_1^2)(\cos\theta\,\hat{\mathrm{e}}_\mathrm{x} - \sin\theta\,\hat{\mathrm{e}}_\mathrm{z}) \tag{1}$$

$$\mathbf{E_2} = -E_0 \sin(\eta_2 - \alpha\eta_2^2)(\cos\theta\,\hat{\mathrm{e}}_\mathrm{x} + \sin\theta\,\hat{\mathrm{e}}_\mathrm{z}) \tag{2}$$

$$\mathbf{B_1} = E_0 \sin(\eta_1 - \alpha\eta_1^2)\hat{\mathrm{e}}_\mathrm{y} \tag{3}$$

$$\mathbf{B_2} = -E_0 \sin(\eta_2 - \alpha\eta_2^2)\hat{\mathrm{e}}_\mathrm{y} \tag{4}$$

Because of the symmetric interaction of the laser beams, transverse components of the fields cancell each other and the longitudinal components will add up. Therefore, the resultant electric and magnetic field components of the beams will become

$$\begin{aligned}\mathbf{E} = &-\left(2E_0\cos(\eta - \alpha\eta^2)\sin(\xi - \alpha\xi^2)\cos\theta\right)\hat{\mathrm{e}}_\mathrm{x} \\ &- \left(2\mathrm{E}\ \sin(\eta - \alpha\eta^2)\cos(\xi - \alpha\xi^2)\sin\theta\right)\hat{\mathrm{e}}_\mathrm{k}\ ,\end{aligned} \tag{5}$$

$$\mathbf{B} = -\left(2E_0\cos(\eta - \alpha\eta^2)\sin(\xi - \alpha\xi^2)\right)\hat{\mathrm{e}}_\mathrm{y} \tag{6}$$

The magnetic field vanishes at all points on the z-axis , however, the electric field has only a nonzero longitudinal component that is given by

$$E_z(0,0,z) = -2E_0\sin\theta\sin(\eta - \alpha\eta^2) \tag{7}$$

The interaction of lasers with the electron is assumed to be at the origin, so, the only resultant field that affects the electron motion is the longitudinal electric field and the electron will be accelerated along the z- axis. The electron motion in electromagnetic fields is governed by the relativistic Lorentz equation

$$\frac{d\mathbf{P}}{dt} = -e\left(\mathbf{E} + \frac{\mathbf{V}}{c}\times\mathbf{B}\right) \tag{8}$$

and the energy gain equation

$$\frac{d\varepsilon}{dt} = -e\,c\,\boldsymbol{\beta}.\mathbf{E} \tag{9}$$

Where $\mathbf{P} = \gamma m_e c\boldsymbol{\beta}$ is the electron relativistic momentum, m_e and e are the mass and charge of the electron, c is the speed of light in vacuum. $\gamma = 1/\sqrt{1-\beta^2}$ is the Lorentz factor where $\boldsymbol{\beta} = \frac{\mathbf{V}}{c}$ is the normalized velocity and $\varepsilon = \gamma m_e c^2$ is the electron relativistic energy. The electron moves along the z- axis and it does not have any motion in the x- and y- direction. Therefore, equations describing the electron motion become

$$\frac{d(\gamma\beta_z)}{dt} = 2a_0\omega\sin\theta\sin(\eta - \alpha\eta^2) \tag{10}$$

$$\frac{d\gamma}{dt} = 2a_0\omega \sin\theta \sin\left(\eta - \alpha\eta^2\right)\beta_z \qquad (11)$$

Where $a_0 = eE_0 / m_e c\omega$ is the dimentionless intensity parameter. The electron energy gain will be defined as $w(\eta) \equiv mc^2(\gamma(\eta) - \gamma_0)$, where γ_0 is the electron initial energy.

Similar to the analysis in reference [6] , we investigate the electron motion by studying the phases of fields. The main difference in our calculation is that we have used frequency-chirped plane-wave laser beams. By using $d\eta / dt = \omega(1 - \beta\cos\theta)$, we can rearrange Equation (11) to obtain

$$\frac{\omega(1-\beta\cos\theta)}{\left(1-\beta^2\right)^{\frac{3}{2}}} d\beta = 2a_0 \sin\theta \sin\left(\eta - \alpha\eta^2\right) d\eta \qquad (12)$$

Then, by integrating of Equation (12) , and after some straightforward algebra we obtain

$$\gamma \times (\beta - \cos\theta) = \gamma_0 \times (\beta_0 - \cos\theta) + 2a_0 \sin\theta \left(\sqrt{\frac{\pi}{2\alpha}}\right) \times \begin{pmatrix} -\cos\left(\frac{1}{4\alpha}\right) S\left(\frac{2\alpha\eta - 1}{\sqrt{2\pi\alpha}}\right) + \\ \sin\left(\frac{1}{4\alpha}\right) C\left(\frac{2\alpha\eta - 1}{\sqrt{2\pi\alpha}}\right) \end{pmatrix} = f(\eta) \qquad (13)$$

where we assumed $\eta(t = 0) = 0$. Here, C(x) and S(x) are cosine and sine Fresnel integrals. Whit solving Equation (13) for β and γ we obtain

$$\beta(\eta) = \frac{\cos\theta + f(\eta)\sqrt{(f(\eta))^2 + \sin^2\theta}}{1 + (f(\eta))^2} \qquad (14)$$

$$\gamma(\eta) = \frac{f(\eta)\cos\theta + \sqrt{(f(\eta))^2 + \sin^2\theta}}{\sin^2\theta}$$

(15) The longitudinal electron coordinate is easily given by

$$\frac{dz}{d\eta} = \frac{dz}{dt}\frac{dt}{d\eta} = \frac{c}{\omega}\frac{\beta(\eta)}{(1 - \beta(\eta)\cos\theta)} \; . \qquad (16)$$

In this calculation $\beta(\eta)$ and $\gamma(\eta)$ are given analytically by Equations (14) – (15), but Equation (16) is solved numerically by a fourth-order Runge-Kutta method.

3 Numerical Simulation And Results

We investigate the effect of frequency chirping, laser amplitudes and electron initial velocity through Figures 1, 2. The two plane-wave lasers are assumed to have identical wavelengths, amplitudes and chirp parameters.

In reference [6], the electron acceleration is restricted to one half cycle of the laser fields to avoid phase slippage of the electron in the subsequent half cycle. In other words, in one laser cycle the electron could never gain energy. However, as shown in Figure 1, with the proper chirp parameter $\alpha = 0.05$, the symmetry in the resultant laser field will be removed and the electron energy gain in a cycle will be nonzero.

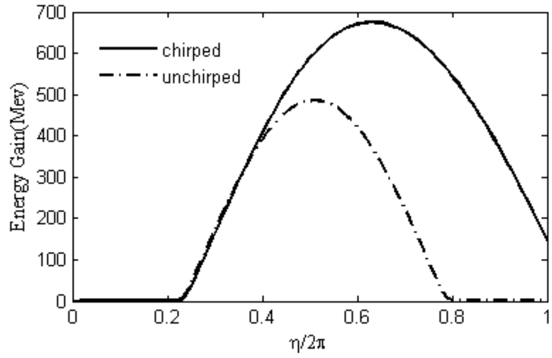

Figure 1: Electron energy gain vs $\eta / 2\pi$ for chirped and unchirped frequencies in one laser cycle. Laser parameters are $\alpha = 0.05, \theta = 0.06, \lambda = 1\mu$m. The electron is assumed to be initially at rest at the origin.

Figures 2(a) - 2(c) show the electron energy gain vs electron distance on the z- axis. As can be seen in Figure 2(a), by increasing the intensity parameter a_0, electron achieves higher energies. In Figures 2(b)-2(c) we can see that with a higher chirp parameter and with a more energetic preaccelerated electron, the electron gains more energy.

4 Conclusions

In this paper, we have investigated the effect of frequency chirping on the electron acceleration by using two crossing plane-wave laser beams. In this mechanism the symmetry of laser beams will be removed and the LW conditions are no longer held. Using a proper chirp parameter, the electron gains more energy. Furthermore, with the use of more intense beams as well as a preaccelerated electron, acceleration could be improved and the electron could gain more energy.

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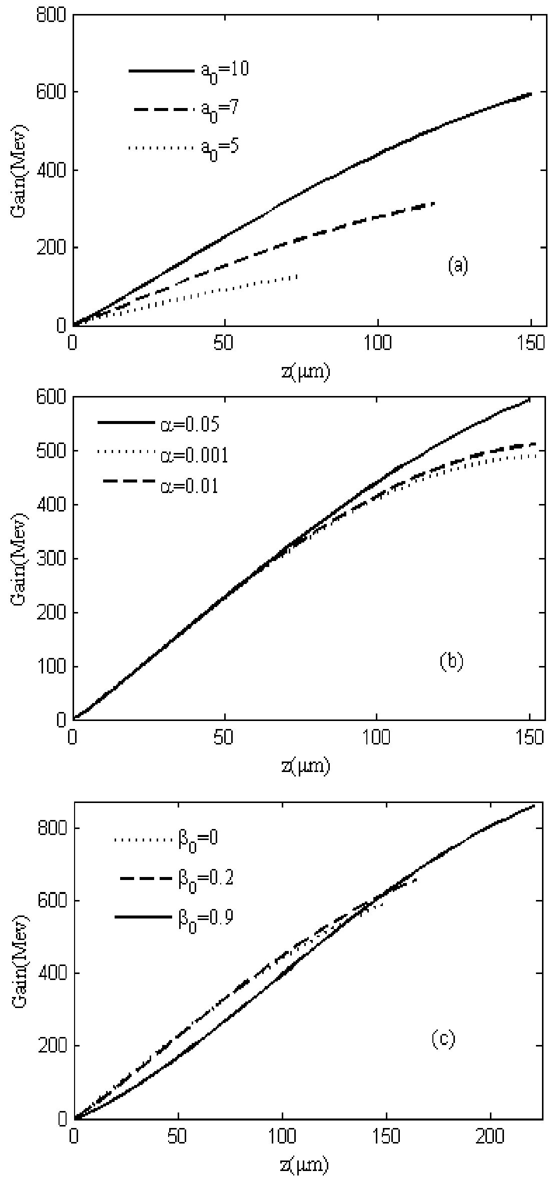

Figure 2: Electron energy gain vs electron distance on the z-axis. The effect of laser intensity (a), chirp parameter (b), and preaccelerated electron (c) is shown. The parameters are the same as in Figure1.