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# Cyclotron resonance effects on electron acceleration by two lasers of different wavelengths

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## Abstract

Cyclotron resonance effects on electron acceleration by two lasers of different wavelengths in the presence of a magnetic field have been investigated. Beating of two high-intensity lasers of different wavelengths, propagating in opposite direction to each other, can produce a high accelerating field gradient. An electron can be accelerated by such accelerating field to a sufficiently higher energy level. Additional energy gain has been observed due to the applied magnetic field. The magnetic field turns down the electrons to the acceleration region to extract more energy from the accelerating field produced by the beating of the lasers. At resonance, when the Larmor frequency is comparable to the laser frequency, this effect becomes more pronounced. Using some reasonable experimental parameters, we estimate the electron energy gain for this mechanism.

**Keywords:** Cyclotron resonance; Electron acceleration; High-intensity lasers

## 1. INTRODUCTION

Particle accelerations have emerged as a frontier research area in the last few decades. The development of high-power laser system (Strickland & Mourou, 1985) has renewed this area due to its potential application in electron and ion accelerations (Umstadter, 2001, 2003; Kitagawa *et al.*, 2004; Modena *et al.*, 1995; Esarey *et al.*, 1996; Hoffmann *et al.*, 2005; Gibbon, 2005; Roth *et al.*, 2005; Glinec *et al.*, 2005; Giulietti *et al.*, 2005; Lifschitz *et al.*, 2006; Yin *et al.*, 2006; Hoffmann *et al.*, 2007). Electron can be accelerated in vacuum easily by a laser field (Evans, 1988; Hauser *et al*, 1994; Sprangle *et al.*, 1996; Hartemann *et al.*, 1998; Hora *et al.*, 2000; Cheng & Xu, 1999; Singh, 2005; Liu *et al.*, 2006; Gupta & Ryu, 2005; Gupta & Suk, 2006*a*, 2006*b*; Nishida, 2009; Smorenburg *et al.*, 2010). An electron, having the velocity comparable to the speed of light in vacuum, can extract energy from the laser field. Lawson-Woodward theorem shows the limitations of vacuum electron acceleration (Esarey *et al.*, 1995).

Electron accelerated in vacuum is basically a kick-off process in which the longitudinal electric field of the electromagnetic wave scatters the electrons beyond the interaction region. This acceleration is also due to the fact that the Lorentz force is associated with the laser field interaction. The polarization of electromagnetic field is also very important in this process. In the case of a linearly polarized laser pulse, the parameters of the laser pulse interaction with an electron depend upon the direction of polarization, and resonance absorption possesses an inhomogeneous distribution, which reduces the efficiency of acceleration process (Gupta *et al.*, 2007*a*; Niu *et al.*, 2008; Singh *et al.*, 2009). In the case of a circularly polarized laser pulse, resonance absorption possesses axial symmetry, which confines the electron near the axis. Other than this, the other laser parameters such as the laser spot size, position of the peak of pulse, initial electron energy gain play an important role in electron acceleration in vacuum. The momentum of electron increases with the magnitude of the electric field. For a small focal spot size, the transverse amplitude is dominant, thus, the electrons escapes in the transverse direction (Hartemann *et al.*, 1998; Kawata *et al.*, 2005; Xu *et al.*, 2007*a*, 2007*b*; Gupta *et al.*, 2009). For more accurate electron dynamics, the longitudinal component of the field should be taken into consideration (Cicchitelli *et al.*, 1990). In that case, the acceleration is possible almost symmetrically around the laser propagation direction (Malka *et al.*, 1997; Mora & Quesnel, 1998). GeV class

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electron acceleration can be obtained using the lowest order axicon fields (with small spot size) of a high power laser beam (Salamin, 2006). The electrons produced due to the above-threshold ionization of high-$Z$ atoms can also be accelerated to GeV level energies (Karmakar & Pukhov, 2007).

Usually, electron cannot retain most of its acceleration energy due to the deceleration by the training part of the pulse. The magnetic field may play a crucial role in reducing the energy loss during the deceleration cycle (Singh *et al.*, 2009). There are two factors that affect the vacuum electron acceleration in the presence of the magnetic field. One is the electron motion and the other is the enhancement in the strength of ponderomotive force ($\vec{\upsilon}\times\vec{B}$) to the electrons. The applied magnetic field bends the interacting electron to the interaction region and the enhanced ponderomotive force accelerates it further. At resonance, the electron not only accelerates to a higher energy level but also retains it even after passing of the laser pulse in the form of betatron oscillations. Recently, we have proposed some vacuum electron acceleration mechanism and observed the effect of applied magnetic field (Gupta *et al.*, 2005, 2006*a*, 2006*b*). The electron accelerations have been studied in a combined circularly polarized laser pulse fields with strong axial magnetic fields, and found that energy gain depends on the ratio of Larmor frequency and laser frequency along with laser intensity.

In fact, the electron energy gain during laser acceleration in a vacuum strongly depends on the laser intensity as the longitudinal momentum of the electron is proportional to the square of the laser intensity amplitude. Two lasers have some advantages over single laser for electron acceleration in a vacuum. If the frequencies, amplitudes, and polarizations of both lasers are considered such that only axial field survives, then the theoretical analysis can be considered linear. Two crossed lasers having the same amplitude and frequency are responsible for interference in a vacuum (Maher & Hall, 1976; Hora, 1988; Salamin & Keitel, 2000; Gupta & Suk, 2007*b*; Singh *et al.*, 2008). Due to the constructive interference, the resultant field amplitude enhances and improves the electron energy gain compared to the cases of single lasers. Also, due to the beating effect of the electromagnetic waves, the electron can gain additional energy (Gupta *et al.*, 2007*c*). We revisit the previous work by including the effect of an applied magnetic field and find some additional results. Two high-intensity lasers with different wavelengths (propagating in opposite direction to each other) cause modulation of the fields. However, the resultant field accelerates the electron, but the magnetic field plays an important role to enhance the electron energy during this mechanism. We find the cyclotron resonance effect on the estimation of electron energy gain. We examine the dynamics of an electron in the presence of a magnetic field in vacuum, where two lasers have been used for acceleration. The electron energy gain has been estimated by solving the resultant coupled differential equations using a single particle code. The simulation results have been discussed and a discussion of the results is given.

## 2. LINEAR ANALYSIS

The laser-driven electron dynamics can be analyzed using the equation of motion and the energy equation. To understand this, let us consider the linear approximation analysis. We consider two lasers propagate in vacuum in opposite directions to each other such that their focal points intersect at origin to interact with an electron. The vector potential of both lasers can be given by $\vec{A}_j = \hat{x}A_{0j}\cos(\omega_j t - k_j z)$, where $A_j$ is the laser amplitude, $\omega_j$ is the laser frequency, $k_j$ is the wave number, and $j =$ 1, 2. Note that the field of the second laser can be written by replacing $k_{0j}$ by $-k_{0j}$ in all expressions. The scalar potential of the laser can be written as $\phi_j = \alpha_j \cos(\omega_j t - k_j z)$, where $\alpha_j$ is the undetermined function and can be calculated by Lorentz gauge $\nabla.\vec{A}_j + (k_j^2/\omega_j^2)\partial\phi_j/\partial t$. The electric and magnetic field corresponding to the vector and scalar potential of the laser can be given by $\vec{E}_j = -\partial A_j/\partial t - \nabla\phi_j$ and $\vec{B}_j = \nabla\times\vec{A}_j$, respectively. There also exists an applied transverse magnetic field, i.e., $B_s = (\hat{x}+\hat{y})B_0$, where $B_0$ is the amplitude of the magnitude field. The equations governing electron momentum and energy are

$$\frac{d\vec{p}}{dt} = -e\left(\vec{E}_j + \vec{\upsilon}\times(\vec{B}_j + \vec{B}_s)\right), \quad (1)$$

$$\frac{d(mc^2\gamma)}{dt} = -e\vec{\upsilon}\cdot\vec{E}_j, \quad (2)$$

where $\vec{p} = \gamma m\vec{\upsilon}$ is the electron momentum, $\gamma = (1 - \upsilon^2/c^2)^{-1/2}$ is the Lorentz factor, $\vec{\upsilon}$ is the electron velocity, $c$ is the speed of light, and $-e$ and $m$ are the electron's charge and rest mass, respectively.

We solve the momentum and energy equations, i.e., Eqs. (1) and (2) using a relativistic single-particle code. The electron energy $\gamma mc^2$ as a function of the propagation distance is obtained for different parameters by assuming the initial electron energy $\gamma_0 mc^2$, where $\gamma_0 = (1 - \upsilon_0^2/c^2)^{-1/2}$ and $\vec{\upsilon}_0$ is the initial electron velocity. Throughout this calculation, time and length are normalized by $1/\omega_{01}$ and $c/\omega_{01}$, respectively. Velocity, momentum and energy are normalized by $c$, $mc$, and $mc^2$, respectively. The laser intensity parameter is normalized as $a_{0j} = eA_{0j}/m\omega_j c$. In this calculation, we use parameters, $a_{0j} = 1$ (corresponding to laser intensity $I_j \sim 1.37\times10^{18}\ W/cm^2$, $a_{0j} = 3$ (corresponding to laser intensity $I_j \sim 1.25\times10^{19}\ W/cm^2$), $a_{0j} = 5$ (corresponding to laser intensity $I_j \sim 3.46\times10^{19}\ W/cm^2$), the considered laser wavelengths are $\lambda_{0j} \sim 1,\ 5,\ 10\,\mu$m, and $\gamma_0 mc^2 =$ 5, 7, 10 MeV. The used magnetic field strength parameter is $b_0 = eB_0/mc = 0.05,\ 0.1$.

We solve Eqs. (1) and (2) to find out the electron energy and the results are given as follows. Figure 1a shows the electron energy ($\gamma mc^2$, in MeV) as a function of the propagation distance ($z\omega_{01}/c$) at different magnetic field strengths ($b_0 =$ 0.05, 0.1) for $a_{0j} = 3$ and $\gamma_0 mc^2 = 5$ MeV. Due to the beating of two lasers of different wavelengths (short and long wavelength), the test electron trapped and further accelerated to gain energy. The results show that the applied magnetic

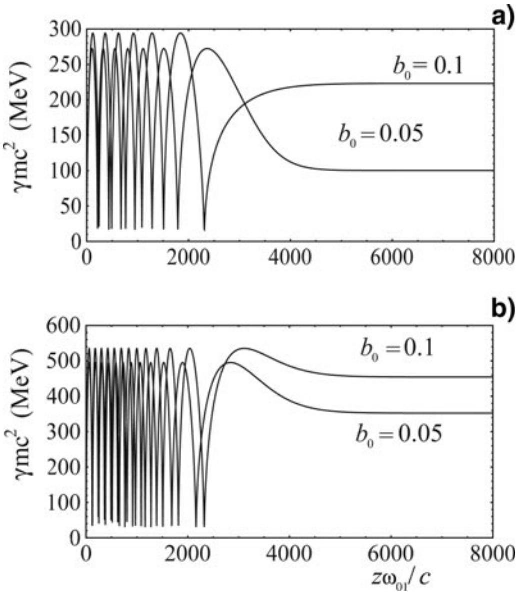

**Fig. 1.** Electron energy ($\gamma mc^2$, in MeV) as a function of the propagation distance ($z\omega_{01}/c$) with two lasers in the presence of magnetic fields $b_0 = 0..05$, 0.1 for (**a**) $\lambda_{01} \sim 1$ µm, $\lambda_{02} \sim 5$µm and (**b**) $\lambda_{01} \sim 1$µm, $\lambda_{02} \sim 8$µm. Other simulation parameters are $a_{0j} = 3$, and $\gamma_0\, mc^2 = 5$ MeV.

field is very important in this acceleration mechanism. Initially, the electron moves around the propagation axis. As the gyration frequency of electron increases, the magnetic field turns the electron in interaction region. In this way, the electron stays in the interaction region longer and gains more energy during the acceleration. If the magnetic field is absent in this mechanism, however, then the electron can be accelerated to get such an amount of energy but will lose it during deceleration. Figure 1b shows the same for large wavelength difference of the lasers. The electron energy gain increase as the difference of wavelengths of both lasers wave increased. Our results show about two-fold electron energy gain compare to the former case for $\Delta\lambda_0 \sim 7$ µm. The large wavelength difference may allow the interacting electron in the interaction region for long time, consequently, if the electron gains more energy. From these simple calculations, it may be shown that both the cyclotron resonance effect and the laser wavelength modulation lead to a significant energy transfer to an electron. Now, we extend this analysis using the actual laser fields to simulate the electron energy gain during acceleration.

## 3. NONLINEAR ANALYSIS

Let us consider again the electron dynamics under two laser pulses propagates in opposite direction to each there. The actual electric and magnetic field can be approximated as (Esarey *et al.*, 1995; Cicchitelli *et al.*, 1990)

$$E_{xj} = A_{0j}\cos(\phi_j)\exp\left(-\frac{r^2}{r_{0j}^2 f_j^2}\right) g_j(z,t), \tag{3}$$

$$\begin{aligned} E_{zj} = -\frac{A_{0j}}{f_j}\Bigg[ & \frac{2x}{k_j^2 r_{0j}^2 f_j^2}\sin(\phi_j) \\ & + \frac{x}{z[1+(R_{dj}/z)^2]}\cos(\phi_j)\Bigg]\exp\left(-\frac{r^2}{r_{0j}^2 f_j^2}\right) g_j(z,t), \end{aligned} \tag{4}$$

where $g_j = \exp[-(z-ct)^2/c^2\tau_{0j}^2]$, $\phi_j = \omega_{0j} - k_{0j} + \tan^{-1}(z/R_{dj}) - k_{0j}r^2/2z[1+(R_{dj}/z)^2]$, $f_j = 1 + (z/R_{dj})^2$, $k_0 = \omega_0/c$, $R_{dj} = k_{0j}^2 r_{0j}^2/2$ is the Rayleigh length, $r_{0j}$ is the minimum spot size of the laser, and $\tau_{0j}$ is the laser-pulse duration.

Following the previous procedure, using Eqs. (3) and (4), we again solve Eqs. (1) and (2) for electron dynamics and energy gain. We again use test particle calculations to study the electron dynamics in the fields of two lasers and the magnetic field. The numerical parameters are also the same as those of earlier study. The electron trajectory in the *x-z* plane can be seen in Figure 2a for different magnetic field strengths ($b_0 = 0..05$, 0.1). The corresponding electron energy gain ($\gamma mc^2$, in MeV) as a function of the propagation distance ($z\omega_{01}$/c) is shown in Figure 2b. The laser beam-waist size is equal to $r_{0j} = 10\lambda_{0j}$ and the laser pulse length is $c\tau_{0j} = 7.5\lambda_{0j}$. The initial position of the laser pulse peak is chosen at origin and the optimum position of test electron is adopted as good magnetic field effects on energy gain. As we can imagine, the field intensity distribution is quite important for vacuum electron acceleration. The intense

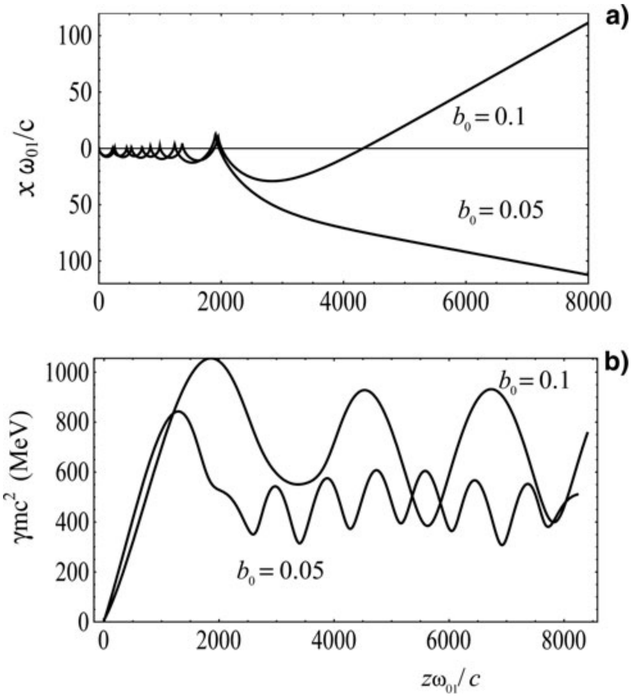

**Fig. 2.** (**a**) Electron trajectory in *x* - *z* plane and (**b**) corresponding electron energy ($\gamma mc^2$, in MeV) as a function of the propagation distance ($z\omega_{01}/c$) for different magnetic fields ($b_0 = 0..05$, 0.1). Other simulation parameters are $\lambda_{01} \sim 1$ µm, $\lambda_{02} \sim 5$ µm $a_{0j} = 5$, and $\gamma_0 mc^2 = 10$ MeV.

ponderomotive force driven by the long wavelength laser pushes the electrons in the forward direction, so the electron can be accelerated to an energy level. Furthermore, the second laser of short wavelength can accelerate this electron to further energy gain. Due to this trapping and acceleration process finally, the electron gain a significant energy.

The test electron experiences a ponderomotive force due to the laser pulses in the presence of the magnetic field. The external magnetic field is employed so that it can affect the electron dynamics efficiently. Due to the combined effect of the magnetic field and the resultant field of the lasers, the electron rotates around the propagation direction of the laser pulse. The external magnetic field enhances the strength of ponderomotive force to the electron. At resonance, electron gyration frequency is comparable to the laser frequency, the maximum energy can be transferred to the test electron and the electron can gain maximum energy. From the results, we see that after passing the laser pulse, betatron oscillations set up between the electron and the resultant electric field of the laser pulses, and the electron also retains the maximum energy due to the effect of the magnetic field.

Specific role of the applied magnetic field can be observed from Figure 3. To observe the cyclotron resonance effect, the maximum electron energy gain ($\gamma_m mc^2$) during the acceleration by two laser pulses has been depicted with the electron cyclotron frequency ($\omega_c/\omega_{01}$) for different laser intensity amplitudes ($a_{0j} = 1, 3, 5$) as shown in Figure 3a and different initial electron energies ($\gamma_0 mc^2 = 5, 7, 10$ MeV) as shown in Figure 3b. The magnetic field enhances the oscillatory velocity of the electron due to cyclotron resonance that leads to enhancement of the ponderomotive force. Also, the magnetic field deflects and keeps the electron in the accelerating phase. Hence, electron gains significant energy via resonant electron acceleration under the resultant field of the lasers and the magnetic field. At cyclotron resonance, when the Larmor frequency is comparable to the field frequency, the electron energy gain maximizes due to the efficient energy transfer process. The electron energy gain also increases due to the high amplitude of laser intensity. We find that a less magnetic field is required to get the higher electron energy for a high intensity laser. At high-intensity of the laser, the quiver electron velocity exceeds the laser spot size, which allows it to escape from the laser pulse around the focus with enough electron energy. If high-intensity laser is used for electron acceleration in vacuum, then the electrons closer to the propagation axis can be accelerated in laser propagation direction. The electron energy gain in this scheme strongly depends on the initial electron energy. A pre-accelerated electron moves to the interaction region soon and then accelerates to higher energy.

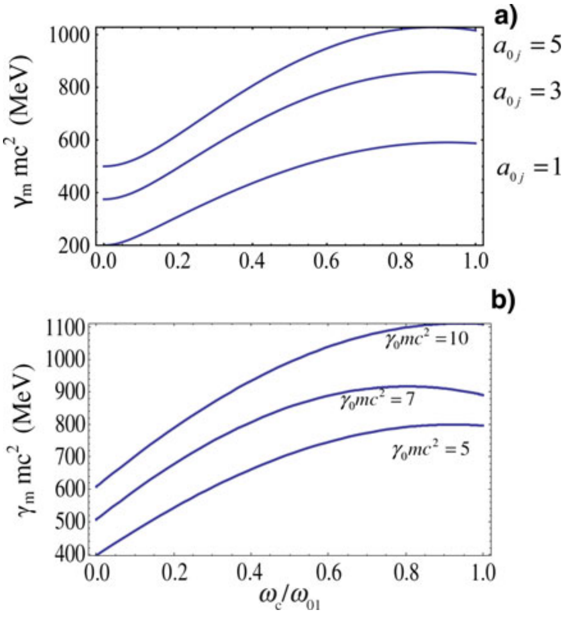

**Fig. 3.** Maximum electron energy ($\gamma_m mc^2$ 5 MeV) with ($\omega_c/\omega_{01}$) for (**a**) different laser intensity parameters ($a_{0j} = 1, 3, 5$), where $\gamma_0 mc^2 = 1$ MeV is considered and (**b**) different initial electron energies ($\gamma_0 mc^2 = 5, 7, 10$ MeV), where $a_{0j} = 5$ is considered. Other simulation parameters are same as discussed previously.

## 4. CONCLUSIONS

Cyclotron resonance effects on electron accelerations by two lasers of different wavelength have been analyzed. The beating of two lasers produces a higher resultant field that can accelerate the test electron to a significant energy level. The wavelength difference of the lasers traps and further accelerates the electrons. The applied magnetic field in this scheme is not only important to enhance the electron energy gain but also crucial to retains it in the form of betatron oscillations. The electron motion under magnetic field is influenced by the cyclotron frequency. In the beginning, when the electron has modest velocity, the cyclotron resonance plays an important role and after getting enough velocity, the electron gains energy from the laser field via Cerenkov resonance. The results show that the electron energy gain increases when the magnetic field strength increases and the electron energy is maximizes at a certain value of magnetic field sue to the cyclotron resonance.

Recent experimental results (Malka *et al.*, 1997) have been reported on the MeV electron acceleration by a high-intensity laser in vacuum. A laser of peak intensity on the order of $10^{19}$ $W/cm^2$ with wavelength of 1.056 μm and spot diameter of 10 μm has been employed to accelerate an electron in vacuum. The electrons with initial energies of 10 KeV are accelerated up to 1 MeV in this experiment. In our work, we have used two lasers of different wavelengths in place of a single laser. However, the electron energy gain is much higher in our case as the initial electron kinetic energy of the electrons is very high and compare to the reported experiment. Also, it is evident from our calculations that certain specific values of the magnetic field allow attaining maximum energy by the electron for a particular intensity of the lasers. The efficiency of energy transfer in the presence of a magnetic field enhances with the laser intensity amplitude and the initial electron energy. If high-intensity lasers are applied then one may utilize a weak magnetic field for sufficient electron energy gain in this mechanism. Similarly, higher electron energy has been expected with higher initial electron energy.

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