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Direct electron acceleration with a linearly polarized laser beam in a two-dimensional magnetized plasma channel

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Research Article

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Abstract

We examine the electron acceleration induced by an ultra-relativistic intensity laser–plasma interaction in a two-dimensional plasma channel in the presence of a self-generated transverse magnetic field. We find that the electron dynamics is strongly affected by the laser pulse polarization angle, plasma density, and magnetic field strength. We investigate in detail, the dependencies of the electron acceleration in terms of different parameters and find excellent agreement with non-magnetized plasma in the absence of the magnetic field. The numerical results show that the self-generated magnetic field plays a constructive role in the electron acceleration process. It is shown that electron acceleration is more affected by self-generated magnetic field for the laser radiations with large polarization angles. The numerical results show the maximum enhancement for electron acceleration for a laser radiation with polarization angle $\theta = \pi/2$.

Introduction

A broad range of applications, such as GeV electrons sources (Wang *et al.*, 2013), multi-MeV protons, ion, and gamma ray sources (Fuchs *et al.*, 2006; Kneip *et al.*, 2008; Flippo *et al.*, 2010; Cipiccia *et al.*, 2011), have been employed in relativistic laser target interaction in a properly chosen experimental setup. These applications reveal the importance of investigation of the laser interaction with plasmas and matters (Wilks *et al.*, 1992; Brandl *et al.*, 2009; Arefiev *et al.*, 2012; Kemp and Divol, 2012; Breuer and Hommelhoff, 2013; Chen *et al.*, 2013; Liu *et al.*, 2013; Braenzel *et al.*, 2017; Cheng *et al.*, 2017). The most important question is how we can transfer the enormous fraction of laser energy into the generation of relativistic electrons. In the laser interaction with underdense plasma, the electron acceleration mechanism strongly depends on the laser pulse duration. In the wakefield acceleration, the laser pulse duration should be shorter or comparable to the plasma wave period (Esarey *et al.*, 2009), and this mechanism becomes less efficient by long laser pulses (Malka *et al.*, 2001; Mangles *et al.*, 2005).

For generation more energetic electrons by making use of a laser beam, different additional concept have been used, such as fast electron beams generation from plasma mirrors (Bocoum *et al.*, 2016), vacuum laser acceleration of relativistic electron (MeLikian, 2014; Thevenet *et al.*, 2016; Zhang *et al.*, 2017; Pandari *et al.*, 2019), relativistic electron mirrors from nanoscale foils (Kiefer *et al.*, 2013), boosted high harmonic pulse from a double-sided relativistic mirror (Esirkepov *et al.*, 2009), and electron acceleration by relativistic surface plasmons (Fedeli *et al.*, 2016).

We can avoid deceleration when the light field is reflected out of the electron trajectory (Singh, 2004; Mulser *et al.*, 2008; Wu *et al.*, 2010) and or by electron injection into the light field with a specific initial momentum (Dodin and Fisch, 2003; Andreev and Platonov, 2013; Bocoum *et al.*, 2016; Thevenet *et al.*, 2016). Moreover, the electron acceleration has already been enhanced by making use of an additional external electric field (Plettner *et al.*, 2005; Dimant and Oppenheim, 2010; He *et al.*, 2013; Cheng *et al.*, 2016).

It is well known that the non-linear plasma properties are intensified by magnetic field due to the Lorentz force, so it is reasonable the plasma dynamics affected by magnetic field. Therefore, generation of magnetic fields is one of the more interesting debatable topics among the scientists in laser–plasma interaction. This issue has a wide range of applications in fast ignition scheme for inertial confinement fusion (Tabak *et al.*, 1994), laboratory astrophysics (Ripin *et al.*, 1990), and particle acceleration (Schmitz and Kull, 2002; Yu *et al.*, 2003; Liu *et al.*, 2004; Qiao *et al.*, 2005). The experiments have been reported the magnetic field strength in the order of about tens of mega-gauss (MG) (Fuchs *et al.*, 1998; Najmudin *et al.*, 2001); however, the recent 3D particle-in-cell (PIC) simulation and analytical investigations predicted generation of the super strong magnetic field up to 100 MG in laser interaction with an overdense plasma channel (Pukhov and Meyer-ter-Vehn, 1996; Qiao *et al.*, 2006; Wang *et al.*, 2011; Stark *et al.*, 2016).

The ponderomotive force plays an important role in a long laser pulse interaction with plasma. In this case, the ponderomotive pressure repels the electrons away from the axis of the beam in the transverse direction, while the heavy ions remain at rest. As a result, an ion channel is created with a quasi-static transverse electric field due to the charge separation. The electron acceleration in an ion channel has been experimentally demonstrated in the past decades (Gahn *et al.*, 1999, 2002; Kitagawa *et al.*, 2004; Walton *et al.*, 2006; Kneip *et al.*, 2008, 2009); however, the test electron acceleration by strong laser field in an ion channel has already been studied theoretically by Arefiev *et al.* (2014).

In this paper, we will follow the method is used by Arefiev *et al.*, by taking into account the fact that the plasma channel should be magnetized (Pukhov and Meyer-ter-Vehn, 1996; Stark *et al.*, 2016). Therefore, we would like to examine the electron direct laser acceleration (DLA) in a two-dimensional magnetized plasma channel. We will focus our attention on the role played by the self-generated quasi-static magnetic field on the electron acceleration process.

The paper is organized in the following fashion. In the "Model description" section, a single electron model is formulated for an electron irradiated by an incoming laser pulse in a steady-state two-dimensional transversely magnetized ion channel. The purpose of this section is to justify the necessity of including the self-generated magnetic field during the plasma channel creation, to explain how such a plasma channel can be modeled. We try to explain the effect of the self-generated magnetic field on the dephasing rate in this section. In the "Numerical results and discussion" section, the closed set of electron motion of equations in the presence of the laser pulse and self-generated magnetic field is presented and solved with proper initial condition. Finally, the summary and conclusion are given in the last section.

Model description

In this section, we describe a single electron dynamics irradiated by a laser field in a homogenous transversely magnetized plasma channel. The origin of the self-generated magnetic field is the current induced in the channel. The PIC simulations show that the quasi-static magnetic field increases proportional at distance from axis and modulates in the direction of laser field propagation with spatial variation in the order of the laser wavelength λ (Stark *et al.*, 2016; Pukhov and Meyer-ter-Vehn, 1996).

It is well known in the interaction of high intensity laser field with a plasma, since the longitudinal momentum dominates the kinetic energy of electrons, we can assume that all of the electrons moving forward with relativistic velocity. However, a few number of electrons move under the angle with respect to the channel axis; therefore, if we assume the radius of channel is R, it is easy to show that the magnetic field for $y < R$ is given by $B_x = 2\pi J_z y/c$, where $J_z = en_e c$. On the other hand, if we include the magnetic field modulation in z direction, we can present the quasi-static magnetic field in the form as follows:

$$B_x/B_0 = (n_e/2n_c)(2\pi \mid y \mid /\lambda)\sin 2\pi z/\lambda, \tag{1}$$

where $B_0 = mc\omega/e$ and $n_c = \pi mc^2/(e\lambda)^2$ are the magnetic field of the laser field and critical density, respectively. Figure 1 depicts a two-dimensional spatial setup, with a Cartesian system of coordinates (x, y, z). The figure shows the channel is a slab of heavy immobile ions with density n_0. The static electric field $E_c = \mathbf{e}_y \omega_{pe}^2 m_e y/|e|$ induced due to the charge separation, where $\mathbf{e}_y$ is a unit vector in y direction and $\omega_{pe} = (4\pi n_0 e^2/m_e)^{1/2}$ refers to the plasma frequency (m_e and e are electron mass and charge). The laser field is linearly polarized by polarization angle θ and propagates in the z direction. In addition, the self-generated magnetic field is perpendicular to y–z plane.

It is worthwhile to note that the plasma channel generally is cylindrical; however, because of azimuthal symmetry and with no loss of generality, we can use a two-dimensional (2D) plasma channel. On the other hand, the 2D plasma channel has some advantages: first for simplicity and the second is that for a given laser amplitude, the amplitude of laser field that responsible to direct acceleration of betatron oscillation is changed by changing the polarization angle. Therefore, we can examine the interplay between the oscillating electric field and the electrostatic field of the channel.

At this stage, we consider a single electron dynamics placed in an ion channel (Fig. 1) irradiated by a laser field. We assume that the laser field has the same parameters with the laser which produced the channel. We introduced the laser field by normalized vector potential as follows:

$$\mathbf{a}(z, t) = a(\xi)[\mathbf{e}_x \cos\theta + \mathbf{e}_y \sin\theta], \tag{2}$$

where $\xi = \omega(t - z/c)$ is the wave phase in which ω is wave frequency and c is the speed of light. Also, t is the time in the channel frame of reference, and $\mathbf{e}_x$ is a unit vector in x direction. We consider pulse amplitude in the form of $a(\xi) = a_*(\xi)\sin\xi$, where $0 \le a_*(\xi) \le a_0$ is a given slowly varying envelope. The total electric and magnetic fields inside the plasma channel are as follows:

$$\mathbf{E} = \mathbf{E}_c + \mathbf{E}_L, \quad \mathbf{B} = \mathbf{B}_L + \mathbf{B}_x, \tag{3}$$

where $\mathbf{B}_x$ is the quasi-static self-generated magnetic field directed along the x-axis, and the electric and magnetic fields corresponding to the laser field can be expressed as follows:

$$\mathbf{E}_L = -\frac{m_e c}{|e|}\frac{\partial \mathbf{a}}{\partial t}, \quad \mathbf{B}_L = \frac{m_e c^2}{|e|}\nabla \times \mathbf{a}. \tag{4}$$

The equation of motion for an electron inside the plasma channel is given by the following equation:

$$\frac{d\mathbf{p}}{dt} = \frac{-|e|\mathbf{E}}{m_e c} - \frac{|e|}{\gamma m_e c}\mathbf{p} \times \mathbf{B}, \tag{5}$$

where $\mathbf{p}$ is the dimensionless electron momentum normalized to $m_e c$, and $\gamma = \sqrt{1 + \mathbf{p}^2}$ is the relativistic factor. By making use of Eqs (1)–(5), we obtain the closed set of equations to describe the electron dynamics in the plasma channel as follows:

$$\begin{aligned}
&\frac{d}{d\tau}[p_y - a\sin\theta] = -\gamma\frac{\omega_{pe}^2}{\omega^2}Y_B - \frac{\omega_{ce}}{\omega}p_z,\\
&\frac{dp_z}{d\tau} = p_x\left(\cos\theta\frac{\partial a}{\partial \xi}\right) + p_y\left(\sin\theta\frac{\partial a}{\partial \xi} + \frac{\omega_{ce}}{\omega}\right),\\
&\frac{d\xi}{d\tau} = \gamma - p_z,\\
&\frac{dY_B}{d\tau} = p_y,\\
&p_x = a\cos\theta,
\end{aligned} \tag{6}$$

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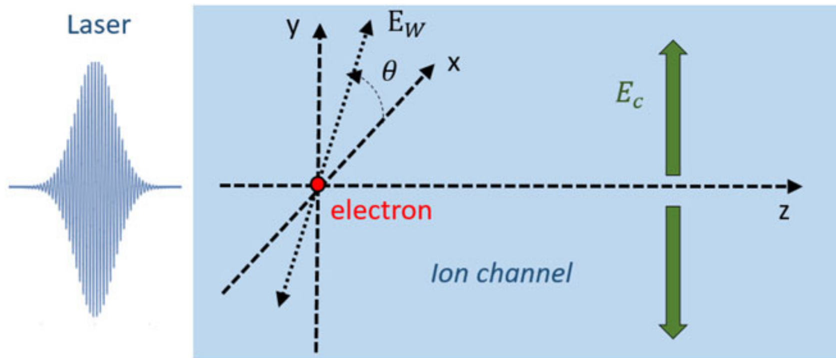

Fig. 1. Schematic setup of a single electron model in an ion channel.

where τ is a dimensionless proper time defined by the relation $d\tau/dt = \omega/\gamma$, and $Y_B = \omega y/c$ is dimensionless displacement across the channel. Moreover, $\omega_{ce} = eB_x/m_e c$ and $\omega_{pe} = (4\pi n_e^2/m_e)^{1/2}$ are electron cyclotron and plasma frequencies, where n_e shows the electron density. The third relation in Eq. (6) represents a dephasing rate and usually defines as $R_B = \gamma - p_z$. Using Eq. (6), we can show that

$$\frac{d}{d\tau}\left(\gamma - p_z + \frac{1}{2}\frac{\omega_{pe}^2}{\omega^2}Y_B^2 + Y_B\frac{\omega_{ce}}{\omega}\right) = 0. \tag{7}$$

Integrating Eq. (7), we get

$$R_B = \gamma - p_z = I_B - \frac{1}{2}\Omega_B^2 Y_B^2 - \Omega_{ce}Y_B, \tag{8}$$

where I_B is a constant and determined by initial conditions, and $\Omega_B = \omega_{pe}/\omega$ and $\Omega_{ce} = \omega_{ce}/\omega$ are normalized plasma and cyclotron frequencies, respectively. For example, if we assume the electron is initially at rest (i.e., $R \to 1$) and is placed on Y_{0B}, we can find I_B as follows:

$$I_B = 1 + \frac{1}{2}\Omega_B^2 Y_{0B}^2 + \Omega'_{ce}Y_{0B}, \tag{9}$$

where Ω'_{ce} refers to normalized cyclotron frequency at $Y = Y_{0B}$. It should be noted that the last term on the right-hand side of Eq. (8) shows the effect of the self-generated magnetic field on the dephasing rate. It is well known that the axial part of the electron momentum larger than the transverse part at ultra-relativistic wave amplitude ($a \gg 1$); therefore, we expect that $R_B \to 0$ when the electron efficiently accelerated by the laser field.

In order to determine the electron maximum displacement across to the channel, the dephasing rate should becomes small vanishingly in Eq. (8). Therefore, substituting $R_B = 0$ in Eq. (8), we get

$$Y_{B*} = \frac{-\Omega_{ce} \pm \sqrt{\Omega_{ce}^2 + 2I_B\Omega_B^2}}{\Omega_B^2}. \tag{10}$$

Equation (10) is in complete agreement with the previous knowledge (Arefiev *et al.*, 2014) in the limit of $\Omega_{ce} = 0$, for a non-magnetized plasma channel.

Numerical results and discussion

In this section, we investigate the electron dynamics in the plasma channel for a laser irradiated with polarization angle θ in the presence of the self-generated static magnetic field in the form of Eq. (1).

The electron dynamics is studied by the numerical solution of the coupled relations in Eq. (6) for a Gaussian profile pulse laser $a = a_*(\xi)\sin(\xi)$ is defined as follows:

$$a_*(\xi) = a_0 \exp\left[-\frac{(\xi - \xi_0)^2}{2\sigma^2}\right], \tag{11}$$

where $a_0 = 10$, $\xi_0 = 400$, and $\sigma = 100$. Here, a_0 is the normalized laser field amplitude, and parameters ξ_0 and σ characterize the laser beam initial position with respect to the electron and the beam duration. In the course of this paper, we consider the initial condition for electron at $\tau = 0$, with $p_y(0) = 0$, $p_z(0) = 0$, $Y_0 = 0.05$, and $\xi = 0$.

Figure 2 shows the variation of $\gamma_{max}/\gamma_{vac}$ (where γ_{max} is the maximum γ-factor and $\gamma_{vac} = 1 + a_0^2/2$) as a function of normalized plasma frequency in the magnetized and non-magnetized plasma channels. Figure 2a and 2b are plotted for polarization angles $\theta = \pi/2$ and $\theta = 0$, respectively. In addition, Figure 2c and 2d indicate the maximum strength of magnetic field would feel by the test electron for polarization angles $\theta = \pi/2$ and $\theta = 0$. The figure shows the strength of self-generated magnetic field rises as the plasma density increases. We find that the role of magnetic field is more effective in the enhancement of electron acceleration for polarization angle $\theta = \pi/2$.

Actually, the electron acceleration is affected by plasma density, laser field amplitude and polarization angle, and self-generated magnetic field strength. The previous investigation have been revealed the efficient electron acceleration by low density plasma channels and also the maximum enhancement when laser electric field and the field of the channel are collinear (Arefiev *et al.*, 2014). Figure 2 shows when the effect of self-generated magnetic field is included not only the maximum γ-factor increases but also the electron acceleration enhanced for a relatively high-density plasma channel.

The electron has two oscillating motions: (a) oscillation with laser field frequency in polarization plane and (b) betatron oscillating motion around magnetic field with frequency ω_c. Two oscillatory motions are in y–z plane for polarization angle $\theta = \pi/2$. Therefore, we expect the resonance takes place when the electron betatron oscillation closes to the laser field frequency. For example, the resonant absorption for polarization angle $\theta = \pi/2$ is clearly shown in Figure 2a and 2c for $\omega_{pe}/\omega = 0.356$ when the

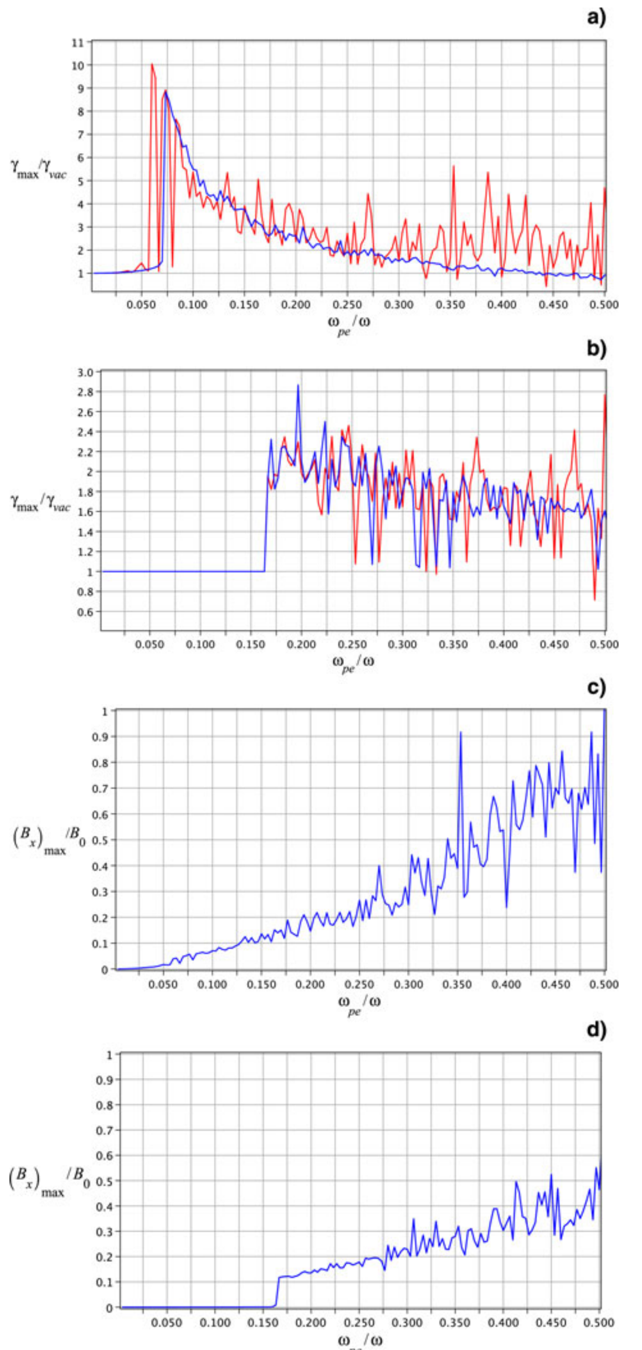

Fig. 2. Maximum normalized γ-factor as a function of ω_{pe}/ω for a magnetized (red line) and non-magnetized plasma channel. (a) Polarization angle $\theta = \pi/2$ and (b) polarization angle $\theta = 0$. (c,d) Indicate the normalized maximum self-generated magnetic field variation as a function of ω_{pe}/ω for polarization angles $\theta = \pi/2$ and $\theta = 0$, respectively.

$(B_x)_{max} \approx 0.9B_0$. This process is governed mechanism for the enhancement of electron acceleration for polarization angle in the vicinity of $\theta \approx \pi/2$.

Figure 3a and 3b demonstrate the normalized γ-factor variation as a function of $\xi/2\pi$ for polarization angle $\theta = \pi/2$ in the magnetized and non-magnetized plasma channels, respectively. The figure compares the electron acceleration in the presence of the plasma channel and vacuum. Thus, even for $\gamma < \gamma_{vac}$, the electron is accelerated ($\gamma_{vac} = 51$). It is understood from Figure 3a that $\gamma > \gamma_{vac}$ for wide range of $\xi/2\pi$, means that electron acceleration is enhanced in the presence of the magnetized plasma channel. This is not true for a non-magnetized plasma channel in Figure 3b. The maximum γ-factor for electron driven by laser beam is around $\gamma_{max}/\gamma_{vac} \approx 5.7$ which is in good agreement with Figure 2a.

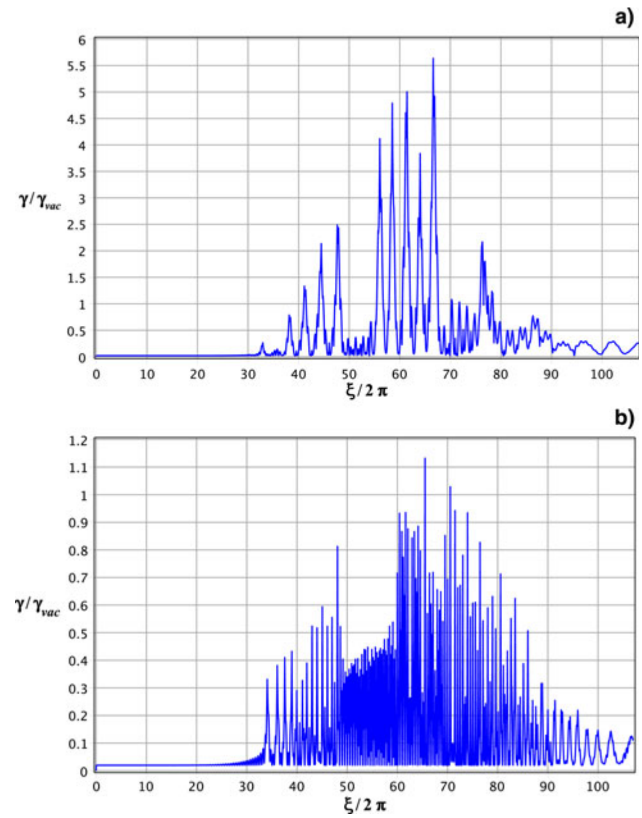

Fig. 3. Relative γ-factor at $\theta = \pi/2$ and $\omega_p/\omega = 0.353$ (a) for a magnetized and (b) for a non-magnetized plasma channel as a function of $\xi/2\pi$.

In order to determine simultaneous effects of the polarization angle and channel density, we plotted the variation of maximum γ-factor with respect to the θ and ω_{pe}/ω in Figures 4 and 5. In Fig. 4, the influence of self-generated magnetic field is included, while Fig. 5 are plotted for a non-magnetized plasma channel. It seems for a magnetized plasma channel and for polarization angles $0.39\pi \le \theta \le 0.5\pi$ electron acceleration enhanced up to $\gamma_{max} \approx 12\gamma_{vac}$ and the required threshold density for electron acceleration decreases to $n_e = 0.0036n_c$. While for non-magnetized plasma, the maximum acceleration for polarization angles $0.32\pi \le \theta \le 0.5\pi$ is around $\gamma_{max} \approx 8\gamma_{vac}$ for threshold density $n_e = 0.0064n_c$. Therefore, for polarization angles near to $\theta \approx \pi/2$, resonant absorption plays an important role in acceleration enhancement. As we mentioned, the enhancement occurs when the frequency of betatron oscillation closes to the laser field frequency. For a magnetized plasma channel, the resonance condition is satisfied for different plasma densities at different polarization angles in the range $0.39\pi \le \theta \le 0.5\pi$. Figure 4 indicates that the electron acceleration enhanced in magnetized plasma specially for the relatively dense plasma channel.

Summary and conclusion

In summary, we have analyzed the dynamics of an electron irradiated by a linearly polarized laser pulse in a two-dimensional

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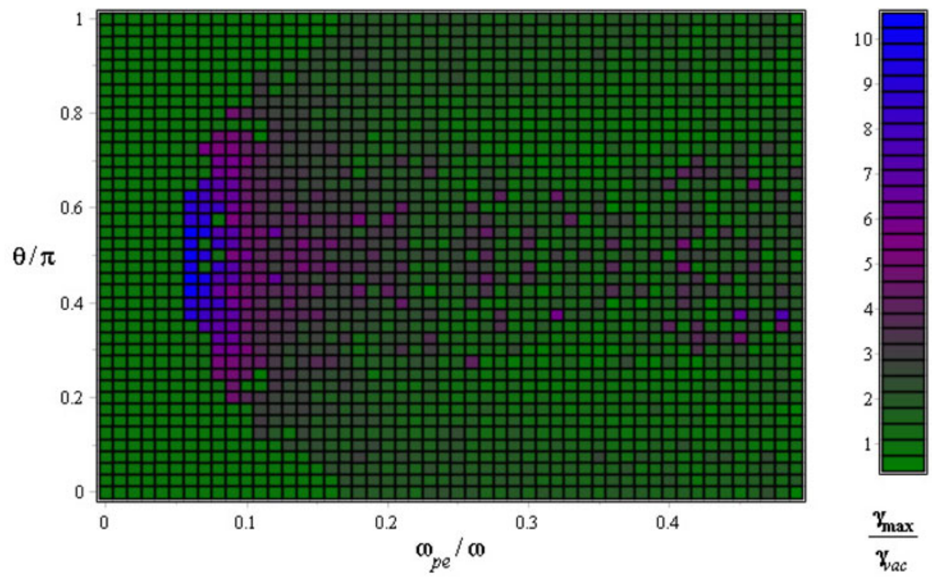

Fig. 4. Variation of maximum γ-factor as a function of ω_{pe}/ω and polarization angle θ for a magnetized plasma channel.

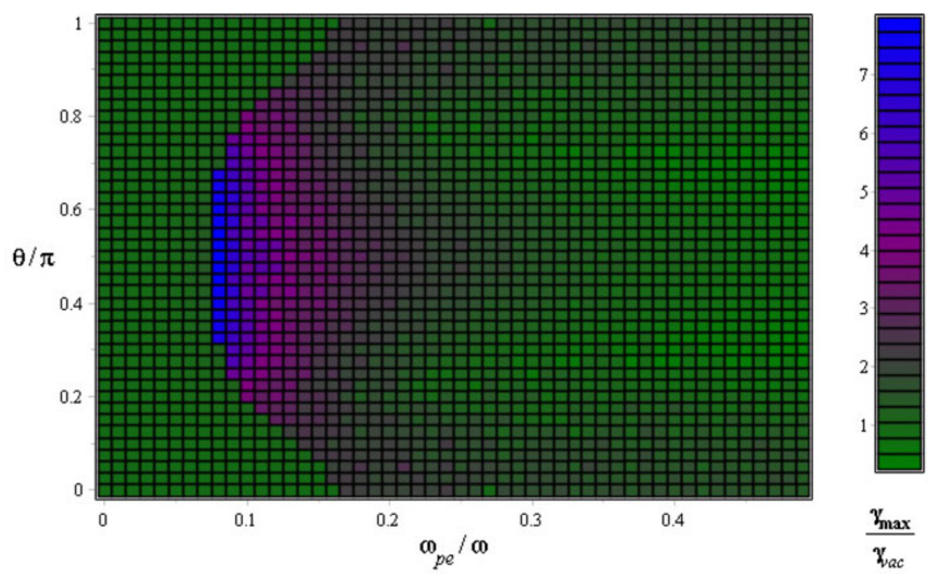

Fig. 5. Variation of maximum γ-factor as a function of ω_{pe}/ω and polarization angle θ for a non-magnetized plasma channel.

transversely magnetized ion channel. Taking into account that a real plasma channel is magnetized, we expect magnetic field makes affect the test electron acceleration through plasma channel. Therefore, the outcomes of the present paper help to the reader to study a real physical system. We supposed that the magnetic field is generated due the current induced inside the channel and presented a simple model for a magnetized plasma channel. The results revealed that the self-generated magnetic field sustains the electron acceleration for polarization angle near to $\theta = \pi/2$. For small polarization angle, the effect of magnetic field was no perceptible. It is shown that for polarization angle near to $\theta \approx \pi/2$, when the electron betatron oscillation frequency closes to the laser field frequency, the resonance condition is achieved and electron acceleration enhanced.

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