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Plasma Wave Acceleration of Electron in Bubble Regime in Presence of a Planar Wiggler

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Abstract

The plasma wave acceleration of electron in the bubble regime is investigated in a new configuration containing a planar wiggler. The space-charge field of the laser-created ion channel can focuse and stabilize the electron trajectory to guide it toward the acceleration region. The high-gradient plasma wave field can resonantly accelerate the trapped electron to higher energies in the presence of a planar wiggler compensating the electron dephasing. The results show that in the lower plasma wave amplitudes the planar wiggler plays a more significant role on the electron energy enhancement. The increment of the electron energy in this configuration is validated using a three-dimension single-particle code. The energy gain of electron dependency on the planar wiggler, ion channel field, plasma wave angle and amplitude as well as the initial energy of electron has been investigated. The results of paper will be of importance in the optimization of electron energy and improving the quality of the accelerated electrons in the plasma wakefield accelerators.

Keywords: Plasma wave; Planar wiggler; Bubble regime; Energy gain.

Introduction

The high-amplitude plasma wakefields are known as the new potential sources for the accelerating the charged particles. There are two main schemes for the acceleration of particles by plasma wakefield: particle beam-driven wakefield acceleration (PWFA) and laser-driven wakefield acceleration (LWFA). In PWFA, the plasma wave is driven by the high energetic bunchs of particles, while, in LWFA, the driver is an intense laser pulse. The generated plasma wave can trap the electrons, either from the background of plasma or injected from the outside, and accelerates them to high energy levels. The electron acceleration by plasma wave in the bubble regime [1-3], where the axial field in the moving bubble is due to the excited plasma wave and the radial field is basically due to the ion space-charge, is one of the most interesting areas of research in the recent years. In LWFA, a high-intensity laser can drive a large-amplitude plasma wave (wakefield) due to the ponderomotive force. If $\langle a^2 \rangle << 1$, where a is the normalized amplitude of the laser and has relation with the intensity by $I = 1.37 \frac{a^2}{\lambda_L{}^2} \times 10^{18} W / cm^2 \mu m^2$, the excited wakefield is weakly driven, and it is treated as

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the small perturbation of plasma with a quiescent background, known as linear regime. In the linear regime, the electron density in the generated wakefield is just weakly perturbed and it may be written as $n_e = n_0 + \delta n$, where $|\delta n| << n_0$ [4-5]. However, this cannot be more true when $a^2 \geq 1$. In fact, if $a^2 \geq 1$, the transverse component of the ponderomotive force is extremely strong that drastically acts as a snowplow for sweeping the electron density, and creates an ion cavity named ion channel [6-7]. This regime has been known as the bubble (or blow-out) regime [8]. In this regime, the plasma wakefield can accelerate the electrons to high-level energies [9] while the created ion channel acts as an alternative guiding and focusing device which confines the electrons and can significantly influence on the dynamics of the electrons and causes the electrons to be further accelerated by the plasma wave [10-11].

In the few past decades, the electron acceleration mechanism by plasma wave has been investigated both theoretically and experimentally.The scheme in which the ponderomotive force of the laser field excites a plasma wave propagating with the velocity close to the light speed was proposed by Tajima and Dawson [12] in 1979 for the first time. In 1994, Everett et al. [13] observed the electron energy enhancement by the plasma wave derived using two laser beams beated in a hydrogen plasma. In 1999, the Multi-MeV electrons in plasma using a femtosecond laser pulse were experimentally observed and verified by three-dimension PIC simulation method [14]. In 2002, Shvets et al. [15] studied the plasma wave excitation using counter-propagating beams. Moreover, in 2003, Singh and Gupta [16] proposed a model based on the wake-field electron acceleration in the presence of an azimuthally magnetic field illustrating the electron energy increment. Also, the acceleration of electrons by a laser pulse in presence of a magnetic wiggler in vacuum and plasma was investigated by Singh and Tripathi [17] in 2004. In 2006, Faure et al. [18] investigated the acceleration of the injected electrons in plasma wave excited by the colliding laser pulses. Also, in 2009, Leemans et al. [19] experimentally observed the high-quality electron bunches in the presence of an ion channel. The more completed investigation on the laser-created ion channel was done by Arefiev et al. [20] in 2014. They indicated that the radial component of the ponderomotive force of laser expels the plasma electrons from the axial region resulting in creation an alternative guiding and focusing device to confine the electrons. In 2015, it was shown by Mehdian et al. [21] that the energy gain of electron in an ion channel increases by applying an oblique magnetic field. In addition, in 2016, Gupta et al. [22] proposed a model based on the electron acceleration by the plasma wave in an azimuthally magnetized ion channel that illustrates that the energy gain of electron increases in the magnetized ion channel. In 2017, Kaur and Gupta [23] studied the enhancement of the acceleration of electron using a laser pulse with the radial polarization in presence of an ion channel. Yadave et al. [24] also studied the increment of the electron acceleration by the plasma wave in the presence of an imposed magnetic field in absence of the ion channel field. Furthermore, in 2018, Kargarian et al. [25] studied the laser-driven wakefield acceleration in an ion channel created in the hydrogen pair-ion plasma using PIC simulation.

In this paper, we investigate the relativistic electron energy enhancement by a high-gradient plasma wakefield in the bubble regime in the precence of a planar wiggler. The radial force of the ion channel confines the electrons and injects them towards the acceleration region for gaining more energy. In the presence of a planar wiggler the large-amplitude plasma wave can resonantly accelerate the electrons to the high-energy levels. The planar wiggler magnetic field also causes the electron to sustain in the resonance conditions for more time resulting in increasing the interaction time with the plasma wave. In other words, it reduces the electron dephasing which limits the energy gain of the electron. It is demonstrated that, in the presence of the wiggler, to transfer the more energy to the electrons, the resonance condition can be written by $\lambda_L \approx (1+\beta_\omega^2)\lambda_\omega / 2\gamma^2$, where λ_L is wavelength of the laser , λ_ω is wavelength of the wiggler, β_ω is amplitude of the wiggler, and γ is the Lorentz factor [26]. In this configuration, it is necessary the optimization of the planar wiggler amplitude for attaining an appropriate energy gain of electron because the detour of the resonance condition restricts the energy gain of the electron. We emphasize that the electron acceleration by the plasma wave can replace the mechanisms of the electron acceleration by laser pulse to overcome the crucial limitations related to the lasers such as laser diffraction and particle dephasing.

The paper is organized as follows: In section 2, the electron dynamics using three-dimension Lorentz equations is analytically investigated. A three-dimension single-particle simulation code containing the Ronge-Kutta numerical algorithm is used to validate our theoretical model. In section 3, the effects of the various parameters such as wiggler magnetic field amplitude, plasma wave's amplitude and phase, the ion channel field, and the initial electron energy on the acceleration of relativistic electron has been investigated. Finally, the summary and conclusion is given in section 4.

The Relativistic Analysis

Here, we investigate the acceleration of the relativistic electron affected by the plasma wave in a laser-created ion channel in the presence of a planar wiggler. In our configuration, the approach in which the plasma wave is excited and accelerates the electron is LWFA. In this approach, by passing a short-pulse high-power laser (with amplitude $a \geq 1$) in a plasma, the laser axial ponderomotive force can bunch the electrons and generate a plasma wavkfield behind the laser pulse. Furthermore, in this mechanism, an ion channel can be created by pushing the electrons in radial direction via the action of the radial component of the ponderomotive force of the high-intensity laser (bubble regime) [27].

We consider a laser-created ion channel with a radial field affecting the dynamics of the electron, hence, the electrostatic force generated by the performed ion channel can be written as [28]

$$E_c = \nabla\varphi = \nabla[\varphi_0(1-r^2)/r_0^2)] = -2\varphi_0 \frac{r}{r_0^2}\hat{r} \qquad (1)$$

where φ_0 is the ion channel potential amplitude and r_0 is the channel radius. The generated plasma wave could have a nonlinear profile as [22-23, 29],

$$\mathbf{E} = \hat{x}A_p \frac{2x}{kr_p^2}\exp(-x^2/r_p^2)\sin(\omega t - kz + \theta_0) + \hat{z}A_p \exp(-x^2/r_p^2)\cos(\omega t - kz + \theta_0) \qquad (2)$$

where A_p is the plasma wave amplitude, r_p is the wakefield radius and θ_0 is the initial wave phase. The acceleration of the electrons in this ion channel is investigated in presence of a planar wiggler as

$$\mathbf{B}_p = \beta_p \sin(k_p z)\hat{x} \qquad (3)$$

where β_p is the planer wiggler amplitude and k_p is the wavenumber of the planar wiggler. The value of the parameter, k_p, has been optimized by the resonance condition which indicates a unique relation between the wavelength of the wiggler, the amplitude of the wiggler, the wavelength of laser, and the energy gain of the electron. Therefore, the energy gain of the electron is intensively limited due to the detour of the the resonance condition.

In this configuration, the governing equations for electron momentum and energy are given by

$$\frac{d\mathbf{p}}{dt} = -e(\mathbf{E} + E_c) + \frac{\mathbf{V}\times\mathbf{B}}{c} \qquad (4)$$

$$\frac{d\gamma}{dt} = \frac{-e}{m_0c^2}(\mathbf{E} + E_c).\mathbf{V} \qquad (5)$$

where $\mathbf{B} = \mathbf{B}_p$ and $\mathrm{P} = \gamma m\mathrm{V}$ with $\gamma = 1 + ((p_x^2 + p_y^2 + p_z^2)/m^2c^2)$ is the electron momentum. Substituting the electric field of the plasma wave, ion channel field, and the wiggler field from equations (1) - (3) in equations of momentum and energy and writing them in three components, we have

$$\frac{dp_x}{dt} = -eA_p \frac{2x}{kr_p^2}\exp(-x^2/r_p^2)\sin(\omega t - kz + \theta_0) - \frac{2e\varphi_0 x}{r_0^2} \qquad (6)$$

$$\frac{dp_y}{dt} = -\frac{eV_z\beta_p}{c}\sin(2\pi z/\lambda_p) - \frac{2e\varphi_0 y}{r_0^2} \qquad (7)$$

$$\frac{dp_z}{dt} = -eA_p \exp(-x^2/r_p^2)\cos(\omega t - kz + \theta_0) + \frac{eV_y\beta_p}{c}\sin(2\pi z/\lambda_p) \qquad (8)$$

$$\frac{d\gamma}{dt} = -\frac{eA_p}{m_0c^2}\left(\frac{2xv_x}{kr_p^2}\exp(-x^2/r_p^2)\sin(\omega t - kz + \theta_0) + \mathrm{v}_z \exp(-x^2/r_p^2)\cos(\omega t - kz + \theta_0)\right) - e\varphi_0 \frac{2xv_x}{m_0c^2r_0^2} - e\varphi_0 \frac{2yv_y}{m_0c^2r_0^2} \qquad (9).$$

We normalize these equations using the dimensionless physical quantities as follows: $a_p \to eA_p/m_0\omega c$, $\varphi_0 \to e\varphi_0/m_0c^2$, $\mathbf{p'} \to \mathbf{p}/mc$, $\mathrm{k'} \to \mathrm{k}c/\omega$, $z' \to kz$, $x' \to k\mathrm{x}$, $r_2^2 \to k^2r_p^2$, $r_1^2 \to k^2r_0^2$, $\mathrm{t'} \to \omega\mathrm{t}$, $\Omega_p \to e\beta_p/m_0\omega$, $\kappa_p \to k_p/k$.

Thus, the equations (7)–(9) can be written as follows

$$\frac{dp_x'}{dt'} = -a_p \frac{2x'}{kr_2^2}\exp(-x'^2/r_2^2)\sin(t' - z' + \theta_0) - 2k'\frac{\varphi_0 x'}{r_1^2} \qquad (10)$$

$$\frac{dp_y'}{dt'} = -2k'\frac{\varphi_0 y'}{r_1^2} - \frac{ep'_z\,\Omega_p}{\gamma}\sin(\kappa_p z') \qquad (11)$$

$$\frac{dp_z'}{dt'} = -a_p \exp(-x'^2/r_2^2)\cos(t' - z' + \theta_0) + \frac{ep'_y\,\Omega_p}{\gamma}\sin(\kappa_p z') \qquad (12)$$

$$\frac{d\gamma}{dt'} = p'_z \frac{-a_p}{\gamma}\frac{2x'}{kr_2^2}\exp(-x'^2/r_2^2)\cos(t'-z'+\theta_0)$$
$$-p'_x\frac{a_p}{\gamma}\exp(-x'^2/r_2^2)\sin(t'-z'+\theta_0)-p'_y\frac{a_p}{\gamma}$$
$$\exp(-x'^2/r_2^2)\sin(t'-z'+\theta_0)-k'\frac{2\varphi_0 p'_x x'}{\gamma r_1^2}-k'\frac{2\varphi_0 p'_y y'}{\gamma r_1^2} \quad (13).$$

These normalized equations are coupled differential equations that can describe the dynamics of a relativistic electron in an ion channel. We numerically solve the equations (10)–(13) using a relativistic three-dimension single-particle code containing the forth-order Runge-Kutta scheme [16-17, 22-23, 28].

Results And Discussion

A numerical model of the relativistic electron acceleration by plasma wakefield in the presence of the radial field of the ion channel and a planar wiggler is presented. In this configuration, increasing or decreasing of the energy gain of electron, during its motion in the ion channel, by changing the parameters of the plasma wave, the ion channel, and the wiggler clearly shows when the electron moves in the acceleration and focusing phase of the plasma wave or when it is in the deceleration and defocusing region [8, 30-31]. For calculations, the initial conditions in our configuration are considred as $k = 1.01$, $r_1 = 4$, $r_2 = 2$, $X_0 = 0.5$, $Y_0 = 0.0$, $Z_0 = 0.0$, $V_{x0} = 0.3$, $V_{y0} = 0.1$, $V_{z0} = 0.7$. At the first step, we investigate the role of the ion channel as a substantial factor on the electron dynamics in this configuration. The radial electric field of ion channel can considerably affect the acceleration of the electrons. To investigate the effect of the ion channel field, the electron energy γ with distance z has depicted in Figure 1 for different normalized potential amplitudes of the ion channel. Other parameters are $a_p = 0.5$, $\theta_0 = 0$, and $\Omega_p = 0$. As illustrated in this figure, the energy gain of the electron increases by increment of the ion channel field. As clearly seen, the energy gain of electron in case of $\varphi_0 = 0.6$ is clearly more than two times than the value obtained in the case of $\varphi_0 = 0.4$. The space-charge field of the channel can concentrate and stabilize the electron motion in the acceleration zone. A combined influence of the transverse ion channel field and the longitudinal plasma wave electric field provides the optimum conditions for the electron energy enhancement. One may note that the further increasing of the ion channel field can reduce the energy gain of electron due to the restoring force corresponding to the large ion channel fields.

The electron with adequate initial kinetic energy moving in the ion channel may be accelerated to higher energies. Thus, here, we investigate the role of the initial kinetic energy of the electron on the energy gain of electron during the accelerating process. For this purpose, the energy gain of electron γ with the

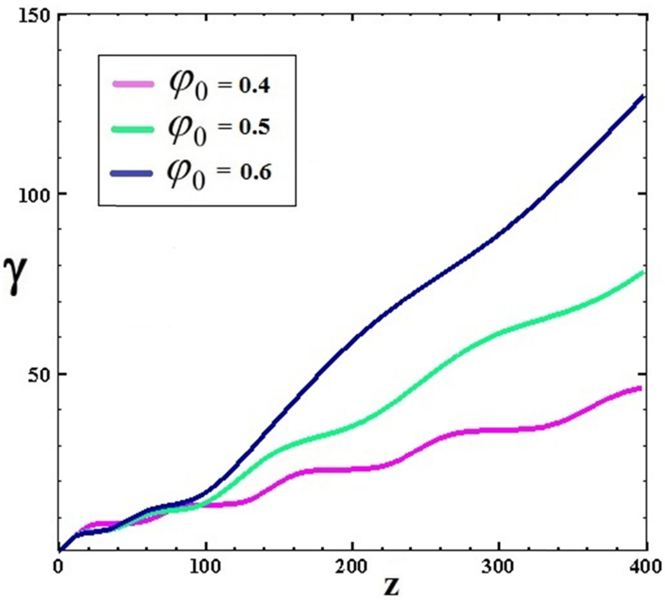

Figure 1. Energy gain of the electron (γ) versus the normalized longitudinal distance (z) for different ion channel normalized potential amplitudes $\varphi_0 = 0.4, 0.5, 0.6$, $a_p = 5$, $\theta_0 = 0$, and $\Omega_p = 0$.

distance z for different initial kinetic energy (γ_0) has illustrated in Figure 2. As indicated in this figure, the electron with high initial energy can gain more energy as compared to the electron with low initial energy. For instance, by increasing the initial energy of electron from $\gamma_0 = 1.56$ to $\gamma_0 = 1.93$ the energy gain of electron enhances from $\gamma = 78$ to $\gamma = 180$. This is because the electron with high initial energy can interact with the plasma wave for longer times because of the less scattering. In other words, by increasing the initial energy of the electron, the scattering can significantly reduce and consequently the electron can remain confined in the channel for longer longitudinal distances resulting in more energy gain.

In the plasma wake-field electron acceleration scheme, the plasma wakefield is one of the main sources for the enhancement of the energy gain of the electron. Thus, the wakefield phase and amplitude are the critical parameters in this scenario. Here, we investigate the effects of these parameters on the energy gain. Figure 3 shows the variation of the electron energy γ versus the

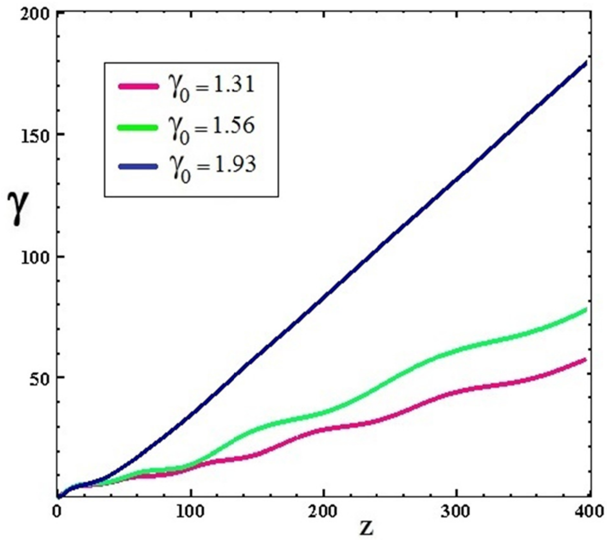

Figure 2. Energy gain of the electron (γ) versus the normalized longitudinal distance (z) for different initial kinetic energy of electron $\gamma_0 = 1.31,\ 1.56,\ 1.93$. Other parameters are as in Figure 1.

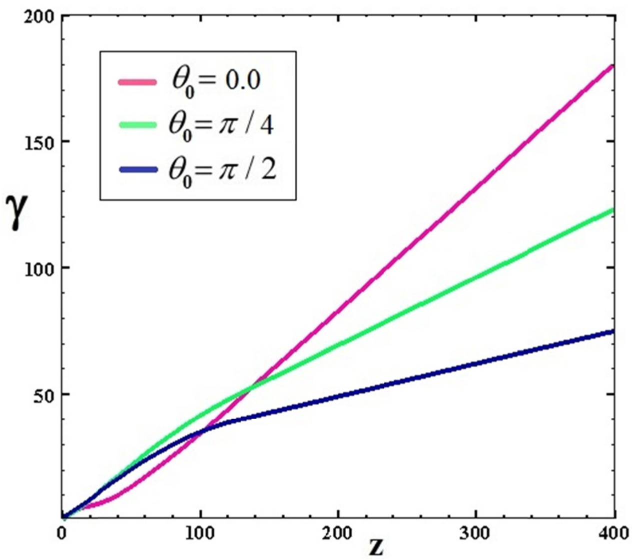

Figure 3. Energy gain of the electron (γ) versus the normalized longitudinal distance (z) for different plasma wave phases $\theta_0 = 0, \pi/4, \pi/2$.

normalized longitudinal distance z for different plasma wave phases $\theta_0 = 0, \pi/4, \pi/2$. The electron attains energy when it is trapped in the focusing and accelerating phase of the plasma wave. By deviation of the plasma wave phase the electron goes into the defocusing and decelerating phase and therefore it loses the energy. This figure illustrates that the electron can gain higher energy from the plasma wave for smaller phases. Because, in smaller initial phases the electron is in the plasma wave accelerating phase and therefore it can gain more energy from the wave. As shown in this figure, the energy gain of electron in case of $\theta_0 = 0$ has increased more than two times as compared to the case of $\theta_0 = \pi/2$. The variation of the electron energy γ with the normalized distance z for different plasma wave amplitudes a_p for $\theta_0 = 0$ has been indicated in Figure 4. As clearly seen in this figure, the

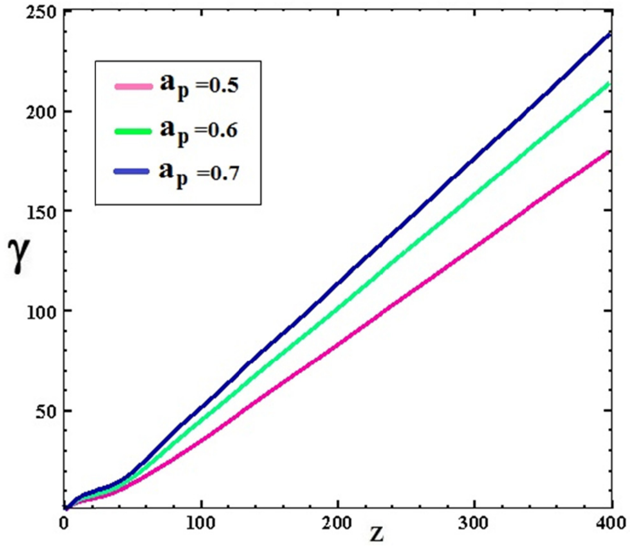

Figure 4. Energy gain of the electron (γ) versus the normalized longitudinal distance (z) for different plasma wave amplitudes $a_p = 0.4, 0.5, 0.6$.

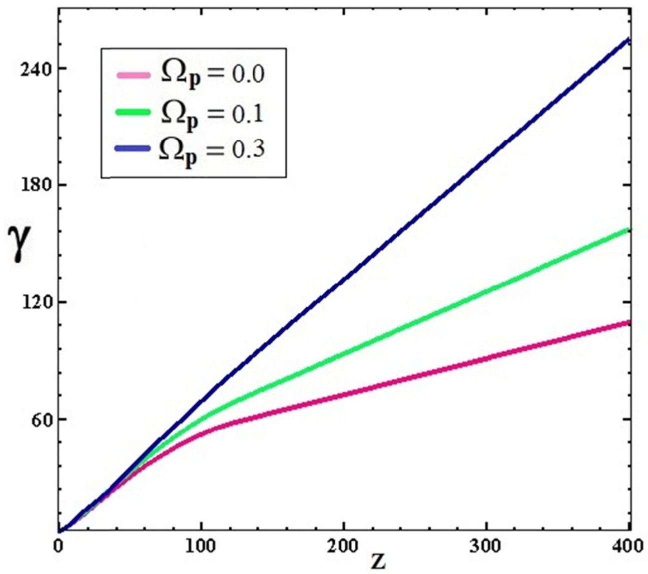

Figure 5. Energy gain of the electron (γ) versus the normalized longitudinal distance (z) for different amplitudes of the wiggler $\Omega_p = 0, 0.1, 0.3$.

energy gain significantly increases by increasing the plasma wave amplitude. Because, the electron which is trapped in a high-amplitude plasma wave can experience a powerful longitudinal force and consequently accelerates to higher energies because of the dominant ponderomotive influences. As this figure shows the energy gain of the electron increases about 35% by increasing the plasma wave amplitude from $a_p = 0.5$ to $a_p = 0.7$.

It is demonstrated that a planar wiggler can play a crucial role in the electron energy enhancement due to the reduction of the electron dephasing which is a limiting factor in the scheme of the plasma wave electron acceleration. Moreover, the results illustrate that the planar wiggler can considerably affect the energy gain of electron in low amplitudes of the plasma wave. We have plotted the energy gain γ versus the normalized longitudinal distance z in Figure 5 for different amplitudes of the wiggler, $\Omega_p = 0, 0.1, 0.3$, and for the plasma wave with amplitude $a_p = 0.4$ and phase $\theta = 0$. Other parameters are as in Figure 1. As clearly seen in this figure, the planar wiggler significantly affects the energy gain of the electron. The wiggler causes the electron to remain in the resonance condition for more time resulting in the interaction time enhancement. The figure shows that by increasing the amplitude of the planar wiggler the γ increases. It is observed that the energy gain of electron increases from $\gamma = 108$ to $\gamma = 156$ by imposing a planar wiggler with amplitude $\Omega_p = 0.1$ and also it increases to $\gamma = 251$ for $\Omega_p = 0.3$. In case of $\Omega_p = 0.1$ energy enhances 45% and in case of $\Omega_p = 0.3$ energy gain is more than two times than one attained in the absence of the planar wiggler. This is because in the presence of the planar wiggler the electron can remain in the accelerating phase for more time. In fact, the wiggler focuses the electron motion to maintain it in the accelerating region and so can gain more energy during the interaction with the plasma wakefield. Moreover, in the presence of the planar wiggler the electron longitudinal momentum increases due to the force component appeared in the propagation direction of the plasma wave which can resonantly accelerate the electron. However, one may expect by increasing the amplitude of the planar wiggler the energy gain of electron start to to be reduced because of the resonance mismatch. To investigate this scenario, the maximum of the energy gain of electron γ_{max} as a function of the planar wiggler amplitude has been depicted in Figure 6. As indicated in this figure, by increasing the amplitude of the planar wiggler, the maximum energy gain increases with the wiggler amplitude and after reaching a peak energy it starts to reduce. Figure 6 shows that the energy gain of the electron grows with the planar wiggler until an optimum value of the magnetic field strength and beyond it the energy gain of electron is reduced because of the resonance mismatch. In other words, the wiggler can maximize the energy gain of the electron in the accelerating region at a specific amplitude.

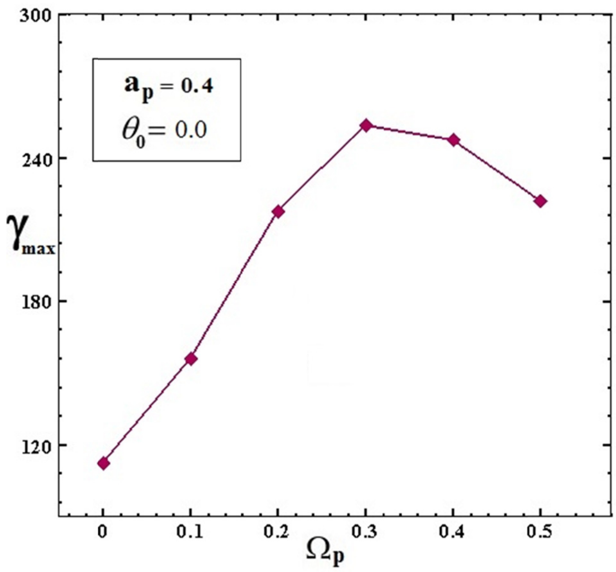

Figure 6. The maximum of energy gain of electron (γ_{max}) versus the planar wiggler amplitude (Ω_p) for $a_p = 0.4$ and $\theta = 0$.

Conclusion

In summary, we studied the electron acceleration by a high-amplitude plasma wave in bubble regime with a new configuration containing a planar wiggler. The effects of ion channel space-charge field, the plasma wave, the planar wiggler and the electron initial kinetic energy on electron energy enhancement is numerically investigated using a three-dimension simulation code. The radial field of the ion channel significantly affects the energy gain of electron. In presence of the ion channel, the energy gain of electron is improved because the space-charge field stabilizes and concentrates the electron motion and causes the electron to maintain in the accelerating region. A combined influence of the ion channel electric field and the plasma wave field provides the electron energy enhancement. In this configuration, the can gain energy while confined in the the plasma wave accelerating phase. The results show that the energy gain of the electron increases for the smaller plasma wave initial phases. Furthermore, the energy gain of the electron increases by increasing the plasma wave amplitude because of the scattering reduction and also the electrons trapped in the high-amplitude plasma wave can experience a more strong longitudinal force. It is demonstrated that the electrons are more accelerated by the additional resonance which is provided by a planar wiggler that decreases the electron dephasing. In the presence of the wiggler the electron longitudinal momentum increases due to the force component appeared in the propagation direction of the plasma wave which can resonantly accelerate the electrons. As results show the planar wiggler have a significant role on the regime of the electron acceleration by low-amplitude plasma waves. However, there is an optimum strength of the planar wiggler for attaining the

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