Laser and Particle Beams

cambridge.org/lpb

Research Article

**Cite this article:** Kargarian A, Hajisharifi K (2020). Self-magnetic field effects on laser-driven wakefield electron acceleration in axially magnetized ion channel. *Laser and Particle Beams* **38**, 222–228. https://doi.org/10.1017/S0263034620000324

Received: 7 July 2020
Revised: 25 August 2020
Accepted: 26 August 2020
First published online: 5 October 2020

**Key words:**
Axially magnetized channel; energy optimization; initial kinetic energy; self-magnetic field; wakefield acceleration

**Author for correspondence**: A. Kargarian, Plasma and Nuclear Fusion Research School, Nuclear Science and Technology Research Institute, Tehran 14399-51113, Iran. E-mail: akargarian@aeoi.org.ir



CAMBRIDGE
UNIVERSITY PRESS

# Self-magnetic field effects on laser-driven wakefield electron acceleration in axially magnetized ion channel

A. Kargarian[1] and K. Hajisharifi[2]

[1]Plasma and Nuclear Fusion Research School, Nuclear Science and Technology Research Institute, Tehran 14399-51113, Iran and [2]Department of Physics and Institute for Plasma Research, Kharazmi University, 49 Dr. Mofatteh Avenue, Tehran 15719-14911, Iran

## Abstract

In this paper, we have investigated the relativistic electron acceleration by plasma wave in an axially magnetized plasma by considering the self-magnetic field effects. We show that the optimum value of an external axial magnetic field could increase the electron energy gain more than 40% than that obtained in the absence of the magnetic field. Moreover, results demonstrate that the self-magnetic field produced by the electric current of the energetic electrons plays a significant role in the plasma wakefield acceleration of electron. In this regard, it will be shown that taking into account the self-magnetic field can increase the electron energy gain up to 36% for the case with self-magnetic field amplitude $\Omega_s = 0.3$ and even up to higher energies for the systems containing stronger self-magnetic field. The effects of plasma wave amplitude and phase, the ion channel field magnitude, and the electron initial kinetic energy on the acceleration of relativistic electron have also been investigated. A scaling law for the optimization of the electron energy is eventually proposed.

## Introduction

There are many acceleration schemes based on the large-amplitude plasma wave production such as plasma wakefield acceleration, plasma beat-wave acceleration, laser wakefield acceleration, resonant laser plasma acceleration, and self-modulated laser wakefield acceleration. Among them, the laser wakefield acceleration is one of the promising approaches for the future compact accelerators (Litos *et al*., 2014; Corde *et al*., 2015). In this scheme, a short high-power laser is used to create plasma waves with high-gradient fields. These fields can accelerate the injected electrons to high-level energies and the electron motion in these fields becomes relativistic. For a sufficiently intense laser pulse, the propagation of the laser pulse into the plasma can also create an ion channel (Tsung *et al*., 2004; Lu *et al*., 2006). In this case, expelling the electrons from the axial region by the radial component of the laser ponderomotive force results in creation an alternative focusing and guiding device for confining the electrons (Arefiev *et al*., 2014; Khudik *et al*., 2016). The ion channel can significantly affect the dynamics of electrons and causes the electrons to be further accelerated by the plasma wave.

Tajima and Dawson (1979) for the first time proposed that the ponderomotive force of the laser field excites a plasma wakefield propagating with the velocity close to the light speed. Recently, many theoretical and experimental models have been proposed to investigate the electron acceleration in plasmas. Shvets *et al.* (2002) studied the excitation of plasma waves using counter-propagating laser beams. A relativistic PIC model of particle energization by the nonlinear plasma wave in a finite-size multispecies plasma was developed by Kargarian *et al.* (2016). Clayton *et al.* (1994) observed the increasing of the electron energy gain by the plasma wave excited by beating of two laser beams in hydrogen plasma. Moreover, the acceleration of the injected electrons in plasma wakefields excited by colliding laser pulses was investigated by Faure *et al.* (2006). In addition to the theoretical works, Gahn *et al.* (1999) experimentally measured the Multi-MeV electrons in a dense plasma using the femtosecond laser pulse. They verified their results by a three-dimensional (3D) PIC simulation method. Leemans and Esarey (2009) also experimentally observed the high-quality electron bunches in a plasma channel.

Recently, it is demonstrated that imposing of the magnetic fields to the plasma environments has a significant role on the electron acceleration in the laser-plasma interaction systems. This can be attributed to the stabilizing and focusing of the electrons motion in the accelerating zone and also to the appearance of the effective force components in the propagation direction. Chauhan *et al.* (2015) studied the effects of a static magnetic field on the electron acceleration during the resonant interaction of electrons with surface plasma wave. The acceleration of electrons by a laser pulse in the presence of a magnetic wiggler in vacuum and plasma was investigated by Singh and Tripathi (2004). It was indicated that the magnetic wiggler causes the electron to be sustained in the resonance condition for longer time resulting in increasing the interaction time. A model based on the wakefield electron acceleration in the presence of a sheared magnetic field was proposed (Singh and Tripathi, 2004) that illustrate the increment of electron energy gain. Furthermore, it was concluded by Mehdian *et al.* (2015*a*, 2015*b*) that the electron energy gain increases by applying an oblique magnetic field in the ion channel. Kumar and Yoon (2008) also investigated the influences of a wiggler magnetic field on the electron acceleration by a chirped laser pulse with the circularly polarization. Moreover, Mehdian *et al.* (2015*a*, 2015*b*) studied the breaking of plasma waves excited by a high-power laser in the presence of an inhomogeneous magnetic field using the PIC simulation. Meanwhile, the interaction of a short intense laser pulse with a primarily carbon-based plasma was investigated by Hajisharifi *et al.* (2017). Furthermore, Kargarian *et al.* 2018 studied the laser-driven acceleration of the electron in a hydrogen pair-ion plasma with electron impurities.

In this paper, for the first time, we investigate the relativistic electron acceleration by a high-gradient plasma wave in a new configuration. In this regard, we consider the influences of the self-magnetic field in the presence of an external guiding magnetic field. The external axial magnetic field is applied to collimate electron and overcome the acceleration gradient reduction. The electrostatic force due to the ion channel assists to confine the electrons and injects them into the accelerating field for further energy gain. The self-magnetic field causes the large-amplitude plasma wave to resonantly accelerate the electrons to the high-level energies. It also prevents escaping of the accelerated electrons from the accelerating region. Our results show that taking into account the self-magnetic field can increase the electron energy gain up to 36% for the systems with self-magnetic field amplitude $\Omega_s =\ 0.3$ and even up to higher energies for stronger fields. Moreover, it will be shown that to attain a considerable electron energy gain in this configuration, the optimization of the external axial magnetic field could be so effective.

The paper is organized as follows: In the "Electron dynamic in externally magnetized ion channel by considering self-magnetic field effects" section, it is analytically investigated the electron dynamics using 3D Lorentz equations. A 3D single-particle simulation code with the Ronge–Kutta algorithm is used to validate the theoretical model. In the "Numerical results and discussion" section, the effects of the various parameters such as external- and self-magnetic fields' amplitude, plasma wave, the ion channel potential, as well as the initial electron energy on the relativistic electron acceleration have been discussed. These parameters are also optimized to overcome the resonance mismatch and dephasing restrictions to obtain an appropriate electron energy gain. Finally, the summary and conclusion are given in the "Conclusion" section.

## Electron dynamic in externally magnetized ion channel by considering self-magnetic field effects

In the scenario of the high-power laser-plasma interaction, a large-amplitude plasma wave is driven while the duration of the laser pulse is comparable to the plasma wave period. On the other hand, an ion channel can be created when the electrons are expelled from the high-intensity region making a density depression on the laser axis. Furthermore, during the laser pulse propagation through the plasma, a large self-magnetic field can be generated by the produced energetic electrons which carry an electric current (Tatarakis *et al.*, 2002*a*, 2002*b*; Gopal *et al.*, 2016). This self-magnetic field could have an important role on the electron acceleration mechanism in these systems. In this study, the electron acceleration in the laser-plasma interaction system is investigated in the presence of an external axial guiding magnetic field by taking into account the self-magnetic field effects in the calculations. We consider the self-magnetic field generated in the wake of the laser as follows (Singh *et al.*, 2003; Gupta *et al.*, 2016):

$$B_s = (B_s/r_0)e^{-x^2/2r_0^2}(-x\frown y), \tag{1}$$

where $B_s$ and $r_0$ represent to the self-magnetic field amplitude and the spot size of laser pulse, respectively. Also, we assume an external axial magnetic field with the amplitude $B_0$ as follows:

$$B_z = B_0\frown z. \tag{2}$$

In this system, it is considered a nonlinear profile for the generated plasma wave as follows (Yadav *et al.*, 2018):

$$\begin{aligned} E =&\hat{x}A_p\exp\left(\frac{-x^2}{r_p^2}\right)\frac{2x}{kr_p^2}\sin(\omega t - kz + \theta_0) \\ &+\frown zA_p\exp\left(\frac{-x^2}{r_p^2}\right)\cos(\omega t - kz + \theta_0), \end{aligned} \tag{3}$$

where $A_p$ is the electron wave amplitude, $r_p$ is the wakefield radius, and $\theta_0$ is the initial wave phase. An electron density depleted ion channel with a radial electric field affecting the dynamics of the injected electrons is also considered. The electrostatic force generated by the performed ion channel can be written as follows:

$$E_r = \nabla\varphi = \nabla\left[\varphi_0\frac{(1-r^2)}{r_0^2}\right] = -2\varphi_0\frac{r}{r_0^2}\frown r, \tag{4}$$

where $\varphi_0$ is the ion channel potential amplitude.

The energy and momentum equations for the relativistic electron are given by

$$\frac{dP}{dt} = -e(E + E_r) + \frac{V\times B}{c}, \tag{5}$$

$$\frac{d\gamma}{dt} = \frac{-e}{m_0c^2}(E + E_r)\cdot V, \tag{6}$$

where $B = B_s + B_z$ and $P = \gamma mv$ with $\gamma = 1 + ((p_x^2 + p_y^2 + p_z^2)/m^2c^2)$ is the momentum of the electron. Substituting the plasma wave field, ion channel potential, the external- and the self-magnetic fields from Eqs. (1)–(4) in momentum and energy equations and then by rewriting them into components, we have

$$\begin{aligned} \frac{dp_x}{dt} =& -eA_p\exp\left(\frac{-x^2}{r_p^2}\right)\frac{2x}{kr_p^2}\sin(\omega t - kz + \theta_0) \\ &-e\varphi_0\frac{2x}{r_0^2} - \frac{eV_yB_0}{c} - x\frac{eV_zB_s\exp(-x^2/2r_0^2)}{r_0c}, \end{aligned} \tag{7}$$

https://doi.org/10.1017/S0263034620000324 Published online by Cambridge University Press

$$\frac{dp_y}{dt} = -e\varphi_0 \frac{2y}{r_0^2} + \frac{eV_x B_0}{c}, \tag{8}$$

$$\frac{dp_z}{dt} = -eA_p \exp\left(\frac{-x^2}{r_p^2}\right)\cos(\omega t - kz + \theta_0) + x\frac{eV_X B_s \exp(-x^2/2r_0^2)}{r_0 c}, \tag{9}$$

$$\frac{d\gamma}{dt} = \frac{-eA_p v_z}{m_0 c^2}\exp\left(\frac{-x^2}{r_p^2}\right)\cos(\omega t - kz + \theta_0) - \frac{eA_p v_x}{m_0 c^2}\exp\left(\frac{-x^2}{r_p^2}\right)\frac{2x}{kr_p^2}\sin(\omega t - kz + \theta_0) - e\varphi_0 \frac{2xv_x}{m_0 c^2 r_0^2} - e\varphi_0 \frac{2yv_y}{m_0 c^2 r_0^2}. \tag{10}$$

We normalize Eqs. (7)–(10) using the dimensionless physical quantities as: $x' \to kx$, $t' \to \omega t$, $P' \to P/mc$, $k' \to kc/\omega$, $a_p \to eA_p/m_0\omega c$, $z' \to kz$, $r_1^2 \to k^2 r_0^2$, $r_2^2 \to k^2 r_p^2$, $\varphi_0 \to e\varphi_0/m_0 c^2$, $\Omega_\iota \to eB_0/m_0\omega$, $\Omega_s \to eB_s/m_0\omega$.

Thus, Eqs. (7)–(10) can be written as follows:

$$\frac{dp'_x}{dt'} = -a_p \exp\left(\frac{-x'^2}{r_2^2}\right)\frac{2x'}{kr_2^2}\sin(t' - z' + \theta_0) - k'\varphi_0 \frac{2x'}{r_1^2} - \frac{ep'_y\Omega_\iota}{\gamma} + \frac{ep'_z\Omega_s x' \exp(-x'^2/2r_1^2)}{r_1\gamma}, \tag{11}$$

$$\frac{dp'_y}{dt'} = -k'\varphi_0 \frac{2y'}{r_1^2} + \frac{ep'_x\Omega_\iota}{\gamma}, \tag{12}$$

$$\frac{dp'_z}{dt'} = -a_p \exp\left(\frac{-x'^2}{r_2^2}\right)\cos(t' - z' + \theta_0) - \frac{ep'_x\Omega_s x' \exp(-x'^2/2r_1^2)}{r_1\gamma}, \tag{13}$$

$$\frac{d\gamma}{dt'} = \frac{-a_p p'_z}{\gamma}\exp\left(\frac{-x'^2}{r_2^2}\right)\frac{2x'}{kr_2^2}\cos(t' - z' + \theta_0) - \frac{a_p}{\gamma}p'_x \exp\left(\frac{-x'^2}{r_2^2}\right)\sin(t' - z' + \theta_0) - \frac{a_p}{\gamma}p'_y \exp\left(\frac{-x'^2}{r_2^2}\right)\sin(t' - z' + \theta_0) - k'\varphi_0\frac{2p'_x x'}{\gamma r_1^2} - k'\varphi_0\frac{2p'_y y'}{\gamma r_1^2}. \tag{14}$$

Equations (11)–(14) are the coupled differential equations that describe the dynamics of the relativistic electron in an axial magnetized ion channel by considering the self-magnetic field effects. These equations are solved numerically using a relativistic 3D single-particle code with a fourth-order Runge–Kutta algorithm.

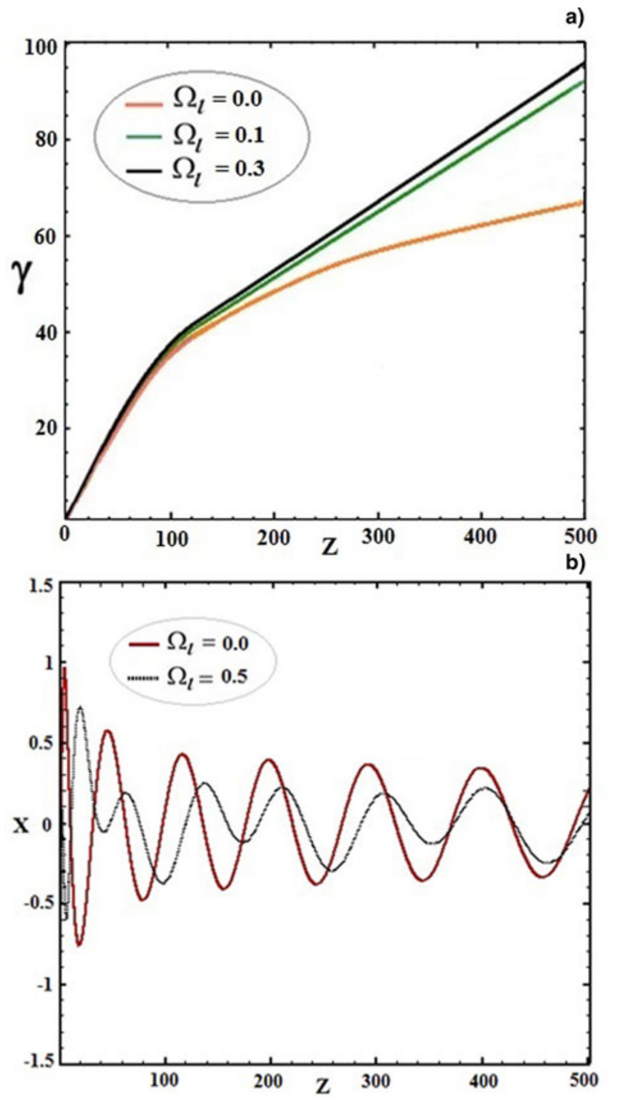


**Fig. 1.** (a) Electron energy gain γ versus the normalized distance (z) for different axial guiding magnetic field amplitudes $\Omega_\iota = 0.0$, 0.1, 0.3 and (b) the trajectory of electron in the absence ($\Omega_\iota = 0.0$) and presence of the external magnetic field ($\Omega_\iota = 0.5$). Other parameters are $a_p = 0.5$, $k = 1.01$, $\theta_0 = \pi/2$, $r_1 = 2$, $r_2 = 4$, $X_0 = 0.5$, $Y_0 = 0.0$, $Z_0 = 0.0$, $V_{x0} = 0.3$, $V_{y0} = 0.1$, $V_{z0} = 0.8$, and $\varphi_0 = 0.6$.

## Numerical results and discussion

A numerical model is proposed to describe the relativistic electron dynamics in an ion channel. In this system, the electron is affected by the radial field of the channel in the presence of the plasma wave and an external axial guiding magnetic field by taking into account the influence of the self-magnetic field. The self-magnetic field is produced by energetic electrons carrying an electric current. We have numerically solved the relativistic equations of motion and the energy equation using a 3D single-particle simulation code containing the fourth-order Runge–Kutta algorithm. The electron energy gain has been estimated for different parameters of the plasma wave, ion channel, external magnetic field, as well as the self-magnetic field. These parameters are also optimized to obtain the most appropriate system for the best electron energy gain. For calculations, we use the initial dimensionless parameters as $k = 1.01$, $\theta_0 = \pi/2$, $r_1 = 4$, $r_2 = 2$, $X_0 = 0.5$, $Y_0 = 0.0$, $Z_0 = 0.0$, $V_{x0} = 0.3$, $V_{y0} = 0.1$, $V_{z0} = 0.8$. The effects of the axial

https://doi.org/10.1017/S0263034620000324 Published online by Cambridge University Press

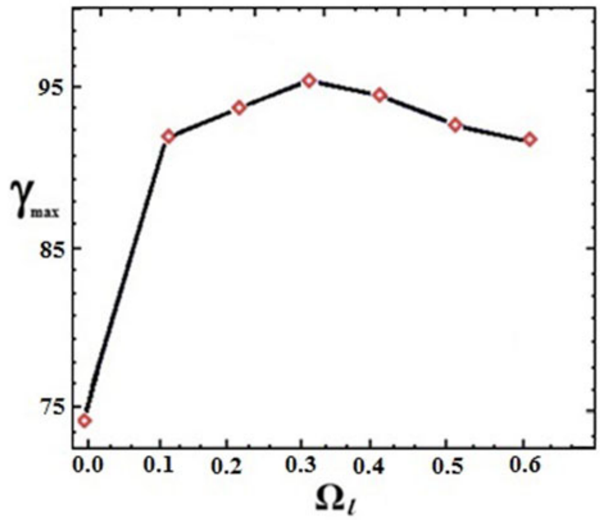


**Fig. 2.** The maximum of the electron energy gain $\gamma_{max}$ versus the axial guiding magnetic field amplitude ($\Omega_\iota$). Other parameters are the same as in Fig. 1.

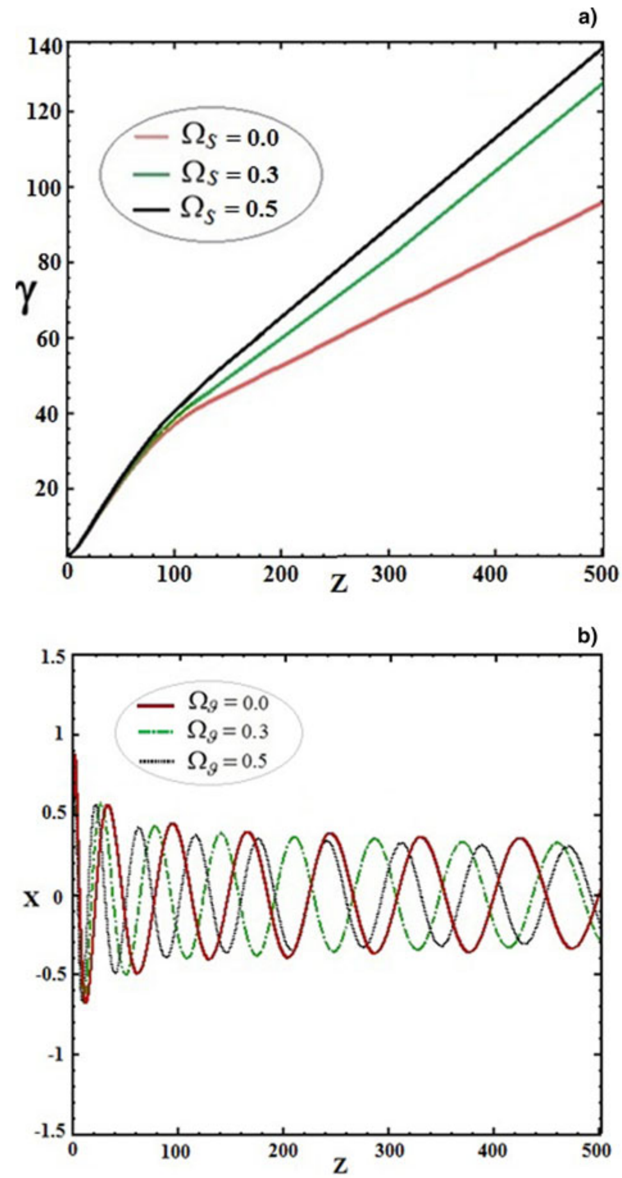


**Fig. 3.** (a) Electron energy gain $\gamma$ and (b) the trajectory of electron versus the normalized distance ($z$) for different self-magnetic field amplitude $\Omega_s = 0.0$, 0.3, 0.5 for $\Omega_\iota = 0.25$.

guiding magnetic field on the electron acceleration and its trajectory in the ion channel have been indicated in Figures 1a and 1b. An additional axial guiding magnetic field can modify the acceleration gradient by confining the electrons motion. In an electron acceleration process, a number of electrons escape from the interaction zone quickly and do not receive enough energy from the plasma wave. In order to confine the energetic electrons in the accelerating zone, we applied an external axial field along with the wave propagation direction. Figure 1a shows the variation of the electron energy $\gamma$ with the normalized distance $z$ for different axial guiding magnetic field amplitudes $\Omega_s = 0.0$, 0.3, 0.5 for $a_p = 0.5$, $\varphi_0 = 0.6$, and $\Omega_\iota = 0.0$. As shown in the figure, $\gamma$ increases with increasing the amplitude of the magnetic field. The guiding magnetic field causes the electrons to rotate with the cyclotron frequency about the force lines. In other words, this applied guiding magnetic field helps electron to be maintained in the propagation direction of the plasma wave which can resonantly accelerate the electrons to high-level energies. To show this convergence role of externally applied magnetic field, the electron trajectory in the $x$–$z$ plane in the both absence ($\Omega_\iota = 0.0$) and presence of the external magnetic field ($\Omega_\iota = 0.5$) has been illustrated in Figure 1b. As clearly seen in the figure, the axial guiding magnetic field converges the electron trajectory in the perpendicular direction ($x$-direction). The same scenario will be taken for the electron trajectory in another perpendicular direction ($y$-direction).

One may note that there is a limitation for the electron energy gain in the high amplitudes of magnetic field because of resonance mismatch. Therefore, it can be found that there is an optimum value of the external axial magnetic field strength for maximizing the electron energy gain. We have illustrated the maximum electron energy $\gamma_{max}$ as a function of the axial guiding magnetic field amplitude $\Omega_\iota$ in Figure 2. As seen in the figure, the maximum of the electron energy gain increases with magnetic field amplitude until an optimum strength of the magnetic field and beyond it, the energy gain starts to be reduced.

In the mechanism of the electron acceleration by the plasma wave, a major limitation of this scheme arises from the wave-particle dephasing. It is shown that this limitation can be overcome by considering the influence of the self-magnetic field which is perpendicular to the wave propagation direction. This field can considerably affect the electron acceleration during the interaction with the plasma wave. Thus, here, we investigate the role of the self-magnetic field [as shown in Eq. (1)] on the electron energy gain. Figure 3a illustrates the variation of the energy gain of electron with the normalized distance $z$ for different self-magnetic field amplitudes $\Omega_s = 0.0$, 0.3, 0.5. The figure has been plotted for the optimum amplitude of the external axial guiding magnetic field $\Omega_\iota = 0.25$ and other parameters are as kept in Figure 1. It is observed that the electron energy gain increases from $\gamma = 95$ to $\gamma = 131$ for the self-magnetic field with amplitude $\Omega_s = 0.3$. In this case, energy gain has increased more than 36% than one obtained in the absence of self-magnetic field amplitude. It is turns out that $\gamma$ increases significantly in systems containing stronger self-magnetic field. This can be attributed to the enhancement of the electron momentum due to the $v \times B$ force

https://doi.org/10.1017/S0263034620000324 Published online by Cambridge University Press

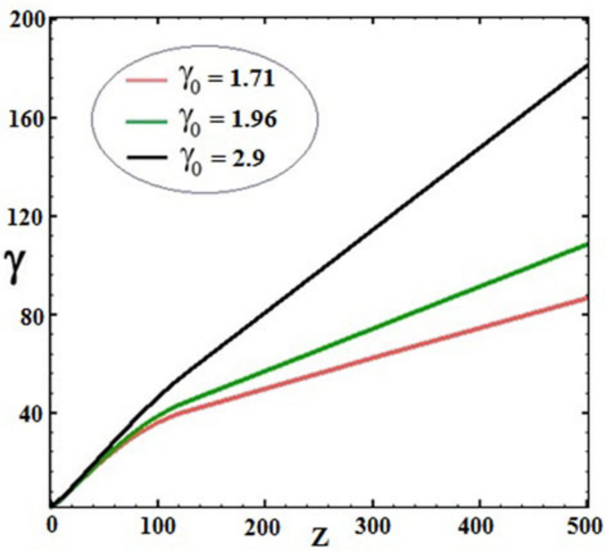


**Fig. 4.** Electron energy gain γ versus the normalized distance ($z$) for different initial kinetic energy of electron $\gamma_0 = 1.71$, 1.96, 2.6 for $\Omega_s = 0.3$, $\Omega_{\iota} = 0.25$, and $\theta_0 = \pi/2$.

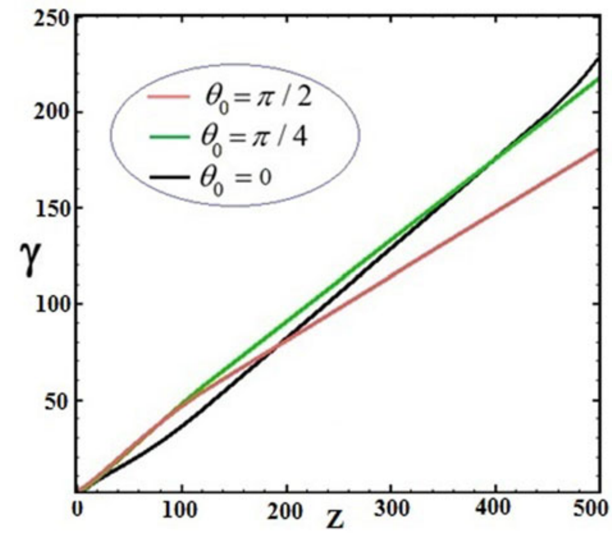


**Fig. 6.** Electron energy gain γ versus the normalized distance ($z$) for different the plasma wave phases $\theta_0 = 0$, $\pi/4$, $\pi/2$ for $\gamma_0 = 2.6$, $a_p = 5$, $\Omega_{\iota} = 0.25$, and $\Omega_s = 0.3$.

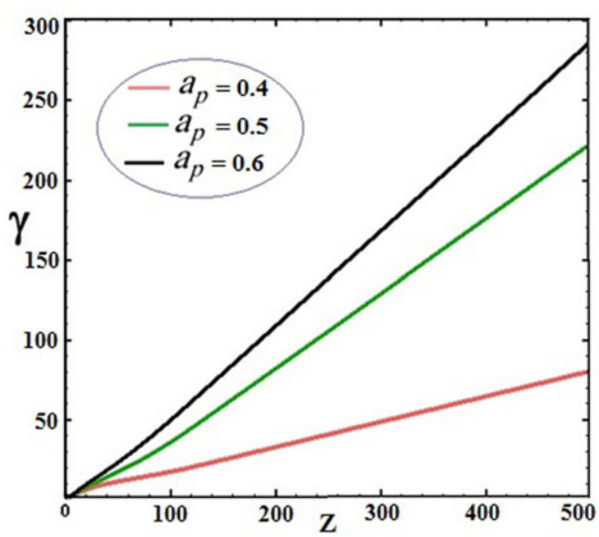


**Fig. 5.** Electron energy gain γ versus the normalized distance ($z$) for different plasma wave amplitudes $a_p = 0.4$, 0.5, 0.6 for $\gamma_0 = 2.6$, $\Omega_{\iota} = 0.25$, $\theta_0 = \pi/2$, and $\Omega_s = 0.3$.

appeared in the propagation direction of the plasma wave which can resonantly accelerate the electrons. On the other hand, as the self-magnetic field increases, the electron trajectory is stabilized as it moves further along the propagation direction and so the electron energy gain is improved with stronger magnetic field. One can clearly see that considering the self-magnetic field has a more significant role on the enhancement of the electron energy gain in an axially magnetized plasma. The presence of the external axial magnetic field causes the saturation of the energy gain to occur at the longer distances [compare the curve $\Omega_{\iota} = 0.0$ with other curves in Fig. 1(a)]. In other words, in such systems the gradient of electron energy gain increases as compared to the systems that considered the effect of the self-magnetic field in the absence of axial magnetic field (Singh *et al.*, 2003; Gupta *et al.*, 2016). Figure 3b indicates the electron trajectory in the $x$–$z$ plane for the same parameters in Figure 3a. As illustrated in the figure, the self-magnetic field not only can affect the electron trajectory in the perpendicular direction (a weak convergence in the $x$-direction) but also it significantly changes the electron trajectory in the longitudinal direction (a strong convergence in the $z$-direction). As clearly seen, by increasing the strength of the self-magnetic field the electrons return to the $z$-axis more frequently and so can gain more energy from the plasma wave.

In the following, we investigate the effect of the initial kinetic energy $\gamma_0$ on the electron energy gain during the acceleration by the plasma wave. For this purpose, the electron energy gain γ with the distance $z$ for different initial kinetic energy ($\gamma_0 = 1.71, 1.96, 2.6$) has indicated in Figure 4. As seen in the figure, the preaccelerated electron gains more energy as compared to the electron with low initial energy. It is observed that for the preaccelerated electrons with initial energy $\gamma_0 = 2.6$, the electron energy gain has increased to $\gamma = 180$, while for electron initial energy $\gamma_0 = 1.71$, it has increased to $\gamma = 84$. This is because the electron with higher initial energy can interact with the plasma wave for longer time because of the less scattering. In other words, by reduction of the ponderomotive scattering the electron remains confined in the ion channel for longer distances and consequently gains more energy from the plasma wave.

As in the plasma wakefield electron acceleration mechanism, the plasma wave is one of the major sources, the plasma wave phase $\theta_0$ and amplitude $a_p$, are the key parameters in this scenario. We have investigated the effects of these factors on the electron energy gain. Figure 5 indicates the variation of the electron energy γ with the normalized distance $z$ for different plasma wave amplitudes. As clearly seen in the figure, by increasing the plasma wave amplitude the electron energy gain increases significantly. In this case, the electrons trapped in high-intensity plasma waves can experience a stronger longitudinal force and consequently be accelerated to high-energy levels due to the dominant ponderomotive effects. The figure shows that in this configuration, the electron energy gain increases more than three times (from $\gamma = 80$ to $\gamma = 285$) by increasing the plasma wave amplitude from $a_p = 0.4$ to $a_p = 0.6$. However, for very high plasma wave

https://doi.org/10.1017/S0263034620000324 Published online by Cambridge University Press

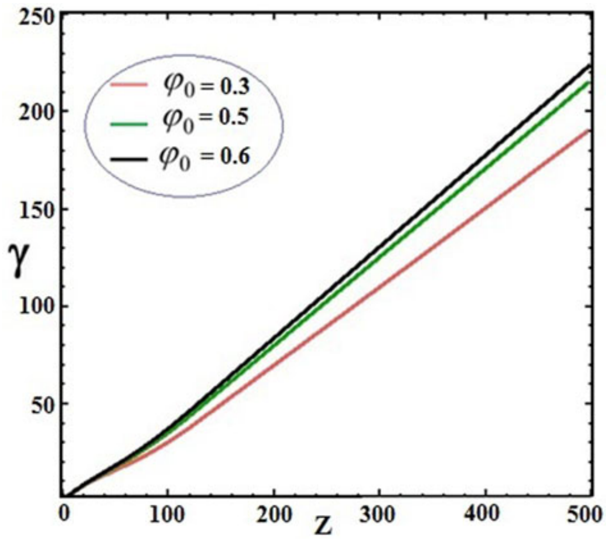


**Fig. 7.** Electron energy gain γ versus the normalized distance (*z*) for different ion channel potential amplitudes $\varphi_0 = 0.3$, 0.5, 0.6 for $\gamma_0 = 2.6$, $a_p = 5$, $\Omega_\iota = 0.25$, and $\Omega_s = 0.3$.

amplitudes the electron acceleration is limited due to the wave-breaking phenomenon related to the nonlinearity.

The electron can gain energy when it is trapped in the accelerating phase of the plasma wave. By deviation of the plasma wave phase, the electron goes into the defocusing and decelerating region and thereby it loses its energy. The variation of the electron energy γ with the normalized distance *z* for different plasma wave phases $\theta_0$ has shown in Figure 6. The figure illustrates that the electron can gain higher energy from the plasma wave for smaller phases. This is because the electron is in the plasma wave accelerating phase in smaller initial wave phases and, so, it can gain more energy from the plasma wave. This results show that there is an optimum value for the initial phase of plasma wave for maximizing the electron energy gain.

It is worth mentioning the role of the ion channel field as a substantial factor on the electron dynamics in this configuration. The radial electric field of the electron density depleted ion channel can significantly affect the acceleration of the injected electrons. It can confine the electron to propagate for longer distances along the longitudinal direction. To study the effect of the ion channel field, the electron energy γ with distance *z* has illustrated in Figure 7 for different normalized potential amplitudes of the ion channel. As illustrated in the figure, the electron energy gain mainly increases in the presence of the ion channel. In this state, the electron energy gain is improved during the acceleration by the plasma wave because the space-charge field stabilizes and focuses the electron motion in the acceleration region. A combined effect of the longitudinal electric field of the plasma wave and the transverse electric field of the ion channel can produce the energetic electrons. It may note that in the systems containing an ion channel with much stronger field the energy gain may be reduced due to the strong restoring force corresponding to the large space-charge fields.

At last but not least, it should be noted that although our results show that in most cases, the electron energy gain linearly increases by channel length, but in the long distances, where the nonlinear phenomena such as electron dephasing and resonance mismatch are important, the gradient of the electron energy gain decreases and finally becomes saturated.

## Conclusion

In summary, in this paper, the electron acceleration by plasma wave in the presence of an external axial guiding magnetic field and ion channel radial field has been investigated by taking into account the influence of the self-magnetic field. In the laser-plasma interaction system, the self-magnetic field is produced by energetic electrons carrying electric current. In this study, the effect of different parameters on the electron energy gain is numerically studied utilizing a 3D single-particle simulation method. The results indicate that there is an optimum value of the external axial magnetic field strength for maximizing the electron energy gain. It is found that at the optimum value of the external axial magnetic field amplitude, the electron energy gain can be increased more than 40% in comparison with the unmagnetized case. Moreover, it turns out that in this configuration, the electron energy gain increases significantly by considering the effect of the self-magnetic field that can compensate the electron dephasing. It is concluded that there is an increase about 36% in the calculated electron energy gain for a system containing the self-magnetic field with amplitude $\Omega_s = 0.3$. The electron energy gain can be increased even up to higher energies if there is a stronger self-magnetic field. Also, our calculations show that in this configuration, the electron with higher initial energy can interact with the plasma wave for longer time resulting in gaining much more energy. It is observed that for the preaccelerated electrons with initial energy $\gamma_0 = 1.71$, the electron energy gain increases to $\gamma = 84$, while for initial energy$\gamma_0 = 2.6$, it increases to $\gamma = 180$. Furthermore, one can see that there is an optimum values for the amplitude and initial phase of the plasma wave for maximizing the electron energy gain in such systems.

## References

**Arefiev AV, Khudik VN and Schollmeier M** (2014) Enhancement of laser-driven electron acceleration in an ion channel. *Physics of Plasmas* **21**, 033104.

**Chauhan P, Varshney DA and Sajal V** (2015) Electron acceleration by surface plasma waves in the presence of static magnetic field. *Laser and Particle Beams* **33**, 109.

**Clayton CE, Everett MJ, Lal A, Gordon D, Marsh KA and Joshi C** (1994) Acceleration and scattering of injected electrons in plasma beat wave accelerator experiments. *Physics of Plasmas* **1**, 1753–1760.

**Corde S, Adli E, Allen JM, An W, Clarke CI, Clayton CE, Delahaye JP, Frederico J, Gessner S, Green SZ and Hogan MJ** (2015) Multi-gigaelectronvolt acceleration of positrons in a self-loaded plasma wakefield. *Nature* **524**, 442–445.

**Faure J, Rechatin C, Norlin A, Lifschitz A, Glinec Y and Malka V** (2006) Controlled injection and acceleration of electrons in plasma wakefields by colliding laser pulses. *Nature* **444**, 737–739.

**Gahn C, Tsakiris GD, Pukhov A, Meyer-ter-Vehn J, Pretzler G, Thirolf P, Habs D and Witte KJ** (1999) Multi-MeV electron beam generation by direct laser acceleration in high-density plasma channels. *Physical Review Letters* **83**, 4772.

**Gopal K, Gupta DN, Kim YK, Hur MS and Suk H** (2016) Large-scale magnetic field generation by asymmetric laser-pulse interactions with a plasma in low-intensity regime. *Journal of Applied Physiology* **119**, 123101.

**Gupta DN, Kaur M, Gopal K and Suk H** (2016) Space-charge field assisted electron acceleration by plasma wave in magnetic plasma channel. *IEEE Transactions on Plasma Science* **44**, 2867–2873.

**Hajisharifi K, Kargarian A and Mehdian H** (2017) Transition between laser absorption dominated regimes in carbon-based plasma. *AIP Advances* **7**, 095106.

**Kargarian A, Hajisharifi K and Mehdian H** (2016) Nonlinear absorption of short intense laser pulse in multispecies plasma. *Physics of Plasmas* **23**, 082116.

https://doi.org/10.1017/S0263034620000324 Published online by Cambridge University Press

**Kargarian A, Hajisharifi K and Mehdian H** (2018) Laser-driven electron acceleration in hydrogen pair-ion plasma containing electron impurities. *Laser and Particle Beams* **36**, 203–209.

**Khudik V, Arefiev A, Zhang X and Shvets G** (2016) Universal scalings for laser acceleration of electrons in ion channels. *Physics of Plasmas* **23**, 103108.

**Kumar S and Yoon M** (2008) Electron acceleration by a chirped circularly polarized laser pulse in vacuum in the presence of a planar magnetic wiggler. *Physica Scripta* **77**, 025404.

**Leemans W and Esarey E** (2009) Laser-driven plasma-wave electron accelerators. *Physics Today* **62**, 44–49.

**Litos M, Adli E, An W, Clarke CI, Clayton CE, Corde S, Delahaye JP, England RJ, Fisher AS, Frederico J and Gessner S** (2014) High-efficiency acceleration of an electron beam in a plasma wakefield accelerator. *Nature* **515**, 92–95.

**Lu W, Huang C, Zhou M, Mori WB and Katsouleas T** (2006) Nonlinear theory for relativistic plasma wakefields in the blowout regime. *Physical Review Letters* **96**, 165002.

**Mehdian H, Kargarian A and Hajisharifi K** (2015a) Kinetic (particle-in-cell) simulation of nonlinear laser absorption in a finite-size plasma with a background inhomogeneous magnetic field. *Physics of Plasmas* **22**, 063102.

**Mehdian H, Kargarian A and Hasanbeigi A** (2015b) Numerical study of electron acceleration by plasma wave in an ion channel under obliquely applied magnetic field. *Optik* **126**, 3299–3302.

**Shvets G, Fisch NJ and Pukhov A** (2002) Excitation of accelerating plasma waves by counter-propagating laser beams. *Physics of Plasmas* **9**, 2383–2392.

**Singh KP and Tripathi VK** (2004) Laser induced electron acceleration in a tapered magnetic wiggler. *Physics of Plasmas* **11**, 743–746.

**Singh KP, Gupta VL, Bhasin L and Tripathi VK** (2003) Electron acceleration by a plasma wave in a sheared magnetic field. *Physics of Plasmas* **10**, 1493–1499.

**Tajima T and Dawson JM** (1979) Laser electron accelerator. *Physical Review Letters* **43**, 267.

**Tatarakis M, Gopal A, Watts I, Beg FN, Dangor AE, Krushelnick K, Wagner U, Norreys PA, Clark EL, Zepf M and Evans RG** (2002a) Measurements of ultrastrong magnetic fields during relativistic laser–plasma interactions. *Physics of Plasmas* **9**, 2244–2250.

**Tatarakis M, Watts I, Beg FN, Clark EL, Dangor AE, Gopal A, Haines PA, Norreys PA, Wagner U, Wei MS, Zepf M and Krushelnick K** (2002b) Laser technology: measuring huge magnetic field. *Nature* **415**, 280.

**Tsung FS, Narang R, Mori WB, Joshi C, Fonseca RA and Silva LO** (2004) Near-GeV-energy laser-wakefield acceleration of self-injected electrons in a centimeter-scale plasma channel. *Physical Review Letters* **93**, 185002.

**Yadav M, Sharma SC and Gupta DN** (2018) Electron acceleration by a relativistic electron plasma wave in inverse-free-electron laser mechanism. *IEEE Transactions on Plasma Science* **46**, 2521–2527.