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Optimizing the electron acceleration in vacuum by chirped ultrashort laser pulse using particle swarm method

Mohammad Rezaei-Pandari, Fazel Jahangiri and Ali Reza Niknam

Laser and Plasma Research Institute, Shahid Beheshti University, Tehran, Iran

Research Article

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Author for correspondence:
Fazel Jahangiri, Laser and Plasma Research Institute, Shahid Beheshti University, Tehran, Iran, E-mail: f_jahangiri@sbu.ac.ir

Abstract

Efficient electron acceleration by a linearly chirped ultrashort laser pulse in vacuum is investigated using the particle swarm optimization method. By applying this method for optimizing the initial parameters of the laser pulse, a pronounced increase in final energy gain of the electron is obtained compared to that expected from the successive optimization method. Our results also suggest that the value of the optimal chirp parameter is independent of laser polarization and the energy gain could be insensitive to the sign of this parameter when the initial phase is optimally adjusted. In addition, utilizing the chirped laser pulse with optimized conditions for acceleration of an electron bunch reveals that the energy spectrum is shifted to considerably higher energies and the spatial distribution is significantly improved in a polarization-dependent manner.

Introduction

Charged particle acceleration by intense laser pulses has remained in the focus of the theoretical and experimental researches due to the expanding applications in medical science, high field physics, intense radiation generation, etc. (Faenov *et al*., 2016; Hu *et al*., 2016; Huang *et al*., 2016). It has been demonstrated that several application requirements are possible with the use of laser-accelerated electrons including radio-isotope production (Leemans *et al*., 2001), coherent terahertz radiation (Leemans *et al*., 2005; Malik and Malik 2011, 2012, 2013; Malik 2013, 2014, 2015; Singh and Malik 2014; Niknam *et al*., 2016; Annenkov *et al*., 2018), and femtosecond x-ray pulses (Corde *et al*., 2013). Several approaches have been proposed for enhancing the laser acceleration effect in vacuum and plasma medium (Hora *et al*., 1978, 2000; Scheid and Hora 1989; Khachatryan *et al*., 2005; Gupta and Suk 2006; Singh and Malik 2008; Li *et al*., 2014; Mirzanejhad *et al*., 2015; Ghotra and Kant 2016*b*, 2017, 2018; Singh *et al*., 2016; Rezaei-Pandari *et al*., 2017, 2018). Among them, electron acceleration using chirped frequency laser pulses in vacuum [firstly introduced by Khachatryan *et al*. (2005)] has been well developed by many groups and the influence of different contributing parameters has been investigated (Singh 2005; Gupta *et al*., 2007; Kumar and Yoon 2008; Sohbatzadeh *et al*., 2009; Li *et al*., 2010; Sohbatzadeh and Aku 2011; Wu *et al*., 2012; Akhyani *et al*., 2015; Ghotra and Kant 2016*a*; Singh *et al*., 2016). Sohbatzadeh *et al*. have shown that electron bunch acceleration becomes more effective by using circularly polarized chirped laser pulses, while a linearly polarized chirped laser pulse is more efficient for single electron acceleration (Sohbatzadeh *et al*., 2009; Sohbatzadeh and Aku 2011). Gupta *et al*. revealed that the energy gain could be higher when circularly polarized laser pulses are employed (Gupta *et al*., 2007). Singh *et al*., have studied the ability of circularly polarized chirped intense laser pulses for generating quasi-monoenergetic accelerated electrons (Singh *et al*., 2009). It has been also suggested that the optimum chirp parameter would depend on laser polarization (Sohbatzadeh *et al*., 2010). A range of positive linear chirp parameter has been presented by Afhami and Eslami for which the electron energy gain could be maximized in the field of the linearly polarized laser pulse (Afhami and Eslami 2014). Kumar and Yoon have shown that the acceleration energy increases by negatively chirping the frequency of a circularly polarized laser pulse (Kumar and Yoon 2008).

Meanwhile, several studies have focused on determining how the frequency chirping influences the acceleration effect. Sohbatzadeh *et al*. have revealed that the negative chirp causes the phase variations to slow down in a specific stage of the acceleration and leads to the phase synchronization between the axial force and the accelerated electron (Sohbatzadeh *et al*., 2009). Singh has attributed the electron acceleration to the pulse segment with an asymmetric wave oscillation due to a negative chirp (Singh 2005). Considering the fact that the electron acceleration by a chirped laser pulse can be explained by the temporal variations of the electric field (Akhyani *et al*., 2015), it would be useful to study how the polarization influences the energy gain evolution in such field. Moreover, since the acceleration effect has appeared to be highly sensitive to the magnitude, sign, and non-linearity of the chirp parameter (Afhami and Eslami 2014; Akhyani *et al*., 2015; Akou 2018), it is interesting to know how this sensitivity depends on laser polarization. In this work, we present a comprehensive investigation on the laser ellipticity dependence of the electron energy gain in the field of a linearly chirped laser pulse by assuming a general polarization form for the laser pulse that is adjustable at any arbitrary state.

On the other hand, optimizing the electron dynamics in the field of chirped laser pulses have been the subject of many works. However, the optimum values of the parameters required for maximizing the energy gain have been calculated in general by utilizing a sequential optimization process. The drawback of such an approach is that each parameter is individually optimized by assuming that the other parameters are fixed. Therefore, depending on which sequence the optimization is performed, different optimal values for the effective parameters could be predicted and thus incompatible electron dynamics would be corresponded. Moreover, the initial phase of the laser field cannot be assumed fixed in such calculations because the instantaneous phase of such a field is determined not only by the initial phase, but also by the chirp parameter as well as the polarization state. This is particularly important because it has been consistently confirmed that the instantaneous phase of a chirped laser pulse could dramatically alter the final energy gain of the electron (Kumar and Yoon 2008; Sohbatzadeh and Aku 2011; Akhyani *et al*., 2015). To overcome this issue, we have employed a powerful global computational optimization technique in which all the parameters are optimized simultaneously (Poli *et al*., 2007; Xu *et al*., 2017). A powerful computational technique for this purpose is the particle swarm optimization (PSO) method (Parsopoulos and Vrahatis 2002). The robust algorithmic simplicity of PSO method has made it suited for a variety of applications including the electromagnetic waves engineering (Robinson and Rahmat-Samii 2004), light scattering (Qi *et al*., 2011), pulsed laser milling (Teixidor *et al*., 2013), transient-conduction radiation (Qi *et al*., 2015), radiative heat transfer and phase transition in semitransparent media (Zhang *et al*., 2015), laser-induced molecular quantum state excitations (Sharma *et al*., 2010), mixed-variable laser peening process (Singh *et al*., 2010), and analyzing the inverse transient radiation in non-homogeneous slabs (Qi *et al*., 2011).

Our numerical results show that employing the PSO method can improve the final energy gain of the electron as well as the features of the electron bunch in the field of a chirped laser pulse. We report a pronounced increase in final energy gain of the electron, in comparison with that expected from successive optimization methods. It is also revealed that the energy gain of the electron could be independent of the sign of the chirp parameter, when the initial phase is adjusted at its optimal value. Moreover, by studying the contribution of the laser polarization to the acceleration effect, it is implied that the value of the optimal chirp parameter could be independent of the laser polarization state. In addition, it is shown that the electron bunch acceleration by a chirped laser pulse significantly depends on laser polarization state and the optimal parameters obtained by PSO method could improve the average energy gain as well as the spatial distribution.

This paper is organized into four sections. Section "Theoretical model and assumptions", includes the theoretical model and assumptions in terms of the basic equations describing the electron acceleration in vacuum by a chirped laser pulse. The numerical results are presented and discussed in section "Optimal single electron acceleration". Finally, the conclusion is presented in section "Electron bunch acceleration".

Theoretical model and assumptions

We consider the interaction of a polarized Gaussian laser pulse, which propagates in the z-direction, with an electron in vacuum. The transverse electric field components of the laser pulse are described as follows:

$$E_x(\eta) = a_0\left(\frac{1+\alpha}{2}\right)^{0.5}\exp\left(-\frac{\eta^2}{\tau^2}\right)\cos\,(\eta + b\eta^2 + \phi_0), \quad (1)$$

$$E_y(\eta) = a_0\left(\frac{1-\alpha}{2}\right)^{0.5}\exp\left(-\frac{\eta^2}{\tau^2}\right)\cos\,(\eta + b\eta^2 + \phi_0 + \delta), \quad (2)$$

where $a_0 = eE_0/m_0c\omega$ is the normalized amplitude of the electrical field E_0, c is the speed of light in vacuum, e is the electric charge, τ is the temporal pulse duration that is normalized to the carrier frequency ω, ϕ_0 is the initial phase, b is the linear chirp parameter, and $\eta = \omega t - kz$, where k is the wavenumber. The ellipse of polarization of the laser field is determined by a couple of parameters (α, δ); for example, $\alpha = \pm 1$ shows the linear polarization and ($\alpha = 0$, $\delta = \pi/2$) denotes the circular polarization. Since the interaction region is considered to be temporally confined to the assumed Gaussian envelope, our results could be extended to the cases with definite spatial profiles, in which the final energy gain of the electron would not be significantly different (Yousef *et al*., 2015). The electron is injected into the laser field at an initial velocity given by $\vec{\beta} = \beta_x\hat{i} + \beta_y\hat{j} + \beta_z\hat{k}$, in which β_x, β_y, and β_z are Cartesian components of the velocity vector that are normalized to c and makes the polar angle of θ and azimuthal angle of ϕ with respect to the propagation axis. The electron dynamics is generally described by

$$\frac{d\vec{P}}{dt} = -e[\vec{E} + \vec{\beta}\times\vec{B}] \quad (3)$$

and

$$\frac{d\varepsilon}{dt} = -ec\vec{\beta}.\vec{E}, \quad (4)$$

where, $\vec{P} = \gamma mc\vec{\beta}$ and ε are the momentum and energy, respectively, and $\gamma = (1-\beta^2)^{-1/2}$ is the relativistic factor. Taking into consideration Eqs. (1)–(4), the equations of the momentum and energy evolution could be rewritten as

$$\frac{d\beta_x}{d\eta} = \frac{E_x(\beta_x^2 - \beta_z - 1) + E_y\beta_x\beta_y}{\gamma(1-\beta_z)}, \quad (5)$$

$$\frac{d\beta_y}{d\eta} = \frac{E_x\beta_x\beta_y + E_y(\beta_y^2 - \beta_z - 1)}{\gamma(1-\beta_z)}, \quad (6)$$

$$\frac{d\beta_z}{d\eta} = \frac{E_x(\beta_x\beta_z - \beta_x) + E_y(\beta_z\beta_y - \beta_y)}{\gamma(1-\beta_z)}, \quad (7)$$

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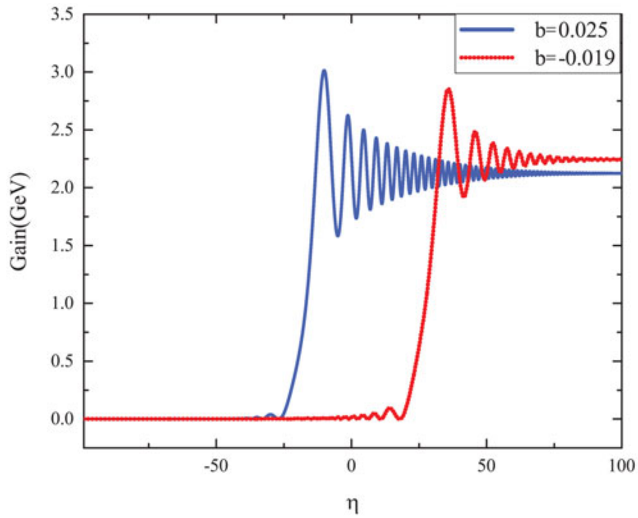

Fig. 1. The comparison of energy gain evolutions of an electron in the fields of a linearly chirped laser pulse with the initial phases and chirp parameters that are adjusted at optimal values obtained by sequential optimization method (blue) and PSO method (red). It has been assumed that the electron with an initial velocity of 0.99*c* is axially injected into the laser pulse with a normalized duration of 50, normalized electric field amplitude of 2.15, and the central wavelength of 800 nm.

$$\frac{d\gamma}{d\eta} = \frac{E_x\beta_x + E_y\beta_y}{(1-\beta_z)}. \quad (8)$$

The above equations are numerically solved by the fourth order RungeKutta method and then the electron dynamics and its final energy are optimized by using the particle swarm algorithm. This algorithm is initialized with a group of random solutions and then searches for optima by updating generations. The three main steps of such algorithm consist of fitness evaluation of each optimum, updating the individual and global bests and updating of each optimum. Such steps are repeated until the stopping conditions according to the required accuracy are reached (Poli *et al.*, 2007; Xu *et al.*, 2017). In addition, by considering a Gaussian velocity distribution for the input electron bunch, the momentum-space evolution, as well as the output energy spectrum in interaction with such optimized laser field, is studied. As the main parameters of the accelerated bunch, we take into consideration the trajectories of the electrons during the interaction with the laser pulse. This could be stated by using the divergence angle of

$$\theta_f = \tan^{-1}\left(\frac{(P_x^2 + P_y^2)^{1/2}}{P_z}\right), \quad (9)$$

which describes the direction of the motion for each electron with respect to the laser propagation axis in terms of its final momentum components. By calculating this angle for every electron among the electron bunch, the spatial distribution of the accelerated bunch is numerically determined.

Optimal single electron acceleration

Now we present the numerical results of electron acceleration in vacuum induced by a chirped laser pulse that is optimized by

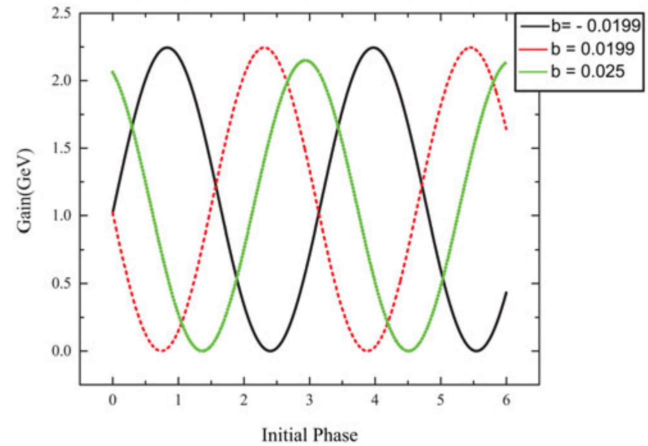

Fig. 2. Variations of the final energy gain of an electron versus the initial phase of laser pulses with optimal chirp parameters of 0.025 and ±0.0199 that are obtained by using the sequential method (green) and PSO method (red/black), respectively. The initial parameters are the same as those in Figure 1.

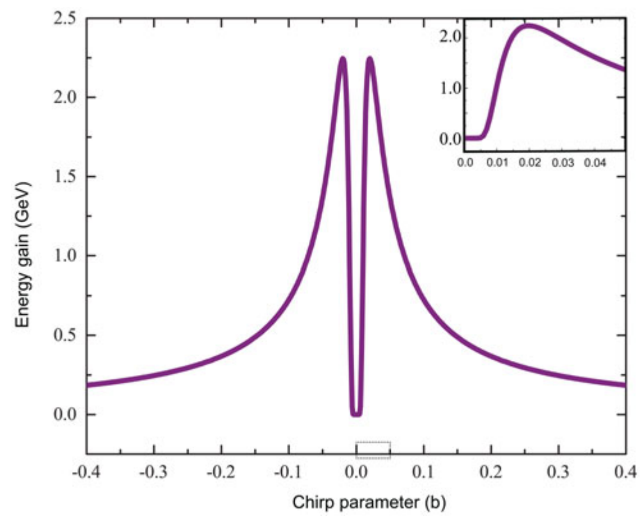

Fig. 3. Variation of the final energy gain of an electron versus the chirp parameter in the field of a linearly chirped laser pulse. The inset shows a magnified view around the maximum at 0.019 indicated by a dashed line. The initial parameters are the same as those in Figure 1.

the PSO method. In these calculations, the laser pulse is assumed to be linearly chirped with a normalized duration of 50, the normalized amplitude of 2.15, and a central wavelength of 800 nm. The electron is injected into the laser field through an axial direction and with an initial normalized velocity of 0.99. By comparing the results obtained by the PSO method with those by sequential optimization method, it is found that these two methods yield two different optimum values for the chirp parameter, which lead to different maximum energies. Figure 1 illustrates the energy gain evolution of the electron in the field of the chirped laser pulse that is calculated through the two above mentioned optimization processes. It can be seen that a higher final energy gain is obtained by PSO method (red) with an optimum chirp value at −0.019, when compared with that by the sequential method (blue) with an optimum chirp value at 0.025. In order to interpret the observed increase in the energy, we have compared the dependence of the final energy gain on laser initial phase at these

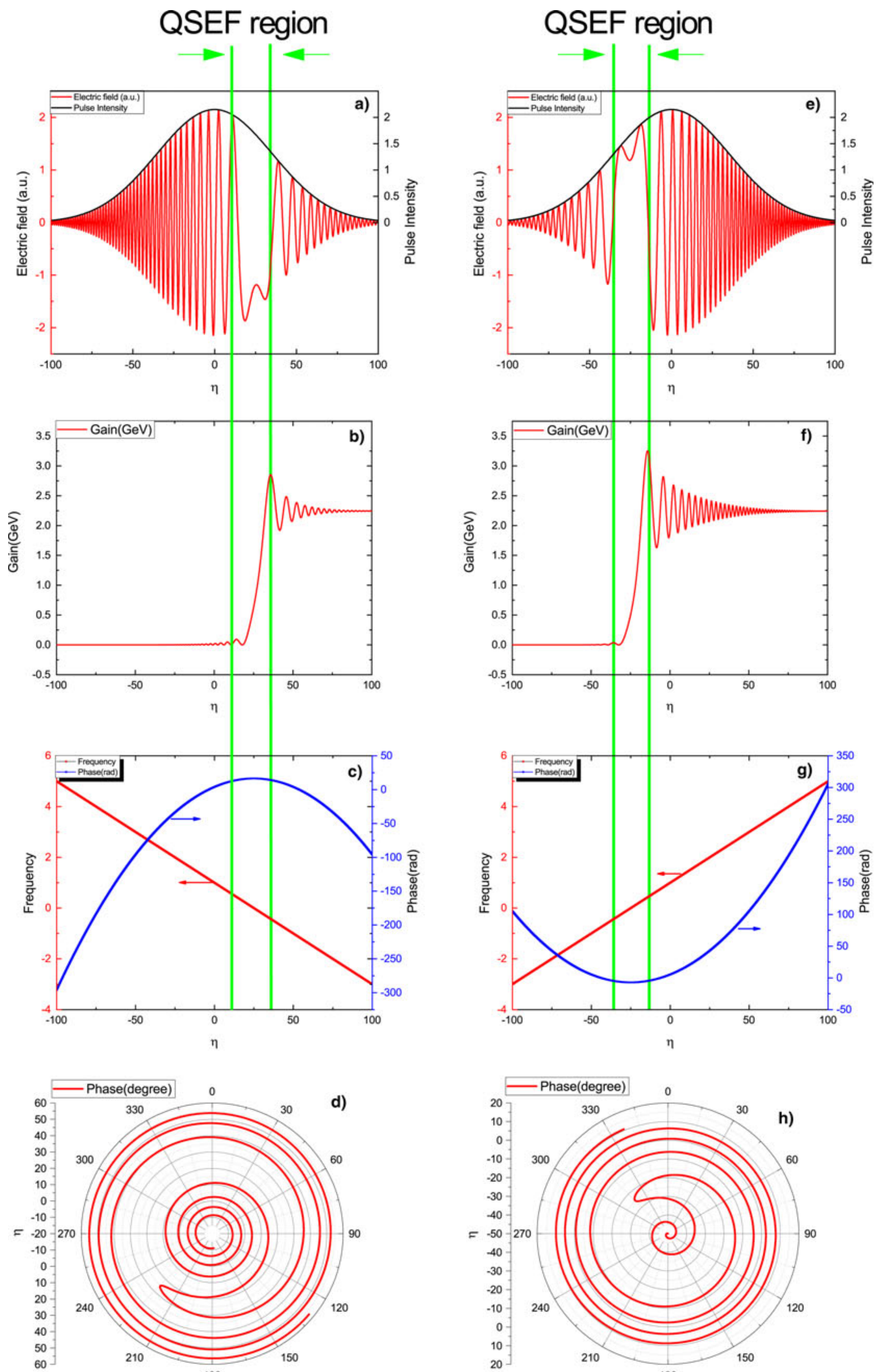

Fig. 4. Temporal shape of the electric field of the linearly chirped laser pulse, the energy gain evolutions of the electron in this field, the corresponding variation of the central frequency, and the instantaneous phase evolution when the chirp parameter is adjusted at optimal values of +0.0199 (a–d) and −0.0199 (e–f), respectively. The other parameters are the same as those in Figure 1.

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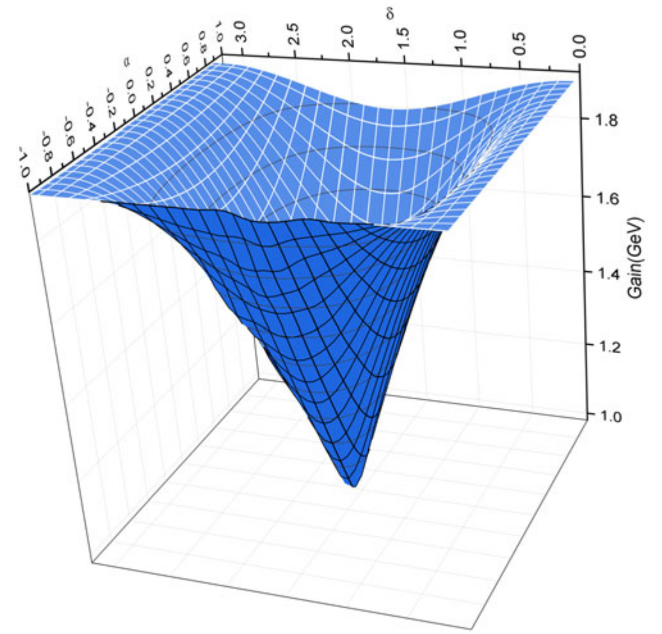

Fig. 5. The maximum energy gain of the electron in the field of linearly chirped laser pulse with various polarizations, when the other effective parameters are optimized accordingly.

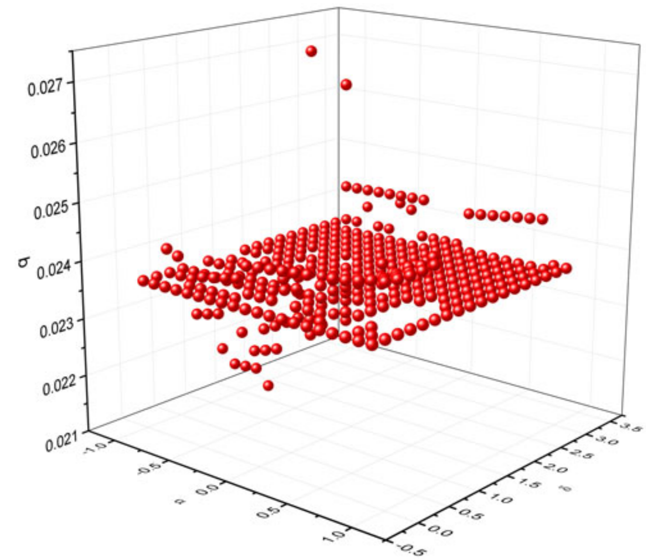

Fig. 6. The optimum chirp parameter required for maximum energy gain of the electron in the field of linearly chirped laser pulse with various polarizations, when the other effective parameters are optimized accordingly.

different conditions. Figure 2 illustrates the variation of the final energy gain versus the initial phase of the laser pulse with different optimum values of chirp parameter obtained by sequential and PSO method. It is observed that the initial phase at which the gain is maximized is not unique and depends on the value of the chirp parameter. Therefore, the pronounced increase of the energy gain observed in Figure 1 can be attributed to the different values of the corresponding initial phases that are provided by two optimization methods. In fact, in the sequential optimization procedure, the chirp parameter is optimized by assuming that other parameters, especially the initial phase, are fixed at values which are not necessarily optimal. However, in the PSO method, all effective parameters are explored dependently through their individual available ranges to get the best-fulfilled optimal conditions, simultaneously.

It is also interesting to observe in Figure 2 that the maximum energy gain is identical for both values of chirp parameter (± 0.0199), regardless of its negative or positive sign. This is because the maximum energy gain is obtained at initial phases which are differently determined according to the sign of the optimum chirp parameter. This could be guaranteed by employing the PSO method which provides the appropriate initial phase relevant to the sign and value of the chirp parameter. For further investigating the gain behavior versus the chirp parameter, we have calculated the variation of the final energy gain versus chirp parameter, as shown in Figure 3. It is evident in this figure that the final energy gain is independent of the sign of the chirp parameter. In fact, the sign of the chirp parameter cannot affect the net force experienced by the electron in a linearly chirped laser pulse.

To elaborate it further, we have compared the temporal shapes of two identical chirped laser pulses with chirp parameters equal to the optimum value obtained in our calculations but at opposite signs (i.e. ± 0.0199). It can be observed in Figure 4a and 4e that the rapid fluctuations of the laser electric field become asymmetric in a region that is called quasi-static-electric-field (QSEF) region (Akhyani *et al.*, 2015). Moreover, the surge in the energy gain of the electron occurs exactly when the electron interacts with such region (Fig. 4b and 4f). Since the total net electric field and consequently the net force that is experienced by the electron are identical, the total energy gain would be the same in both cases. In other words, changing the sign of the chirp parameter can just shift the time moment at which the energy surge occurs without altering the value of the final energy gain.

In order to emphasize the role of the QSEF region, we have also illustrated the evolution of instantaneous phase for both the above laser pulses in Figure 4c and 4g. It is shown that QSEF region in both the cases involves the slowest variation of laser instantaneous phase, which could provide the phase synchronization between the axial force and the accelerated electron (Sohbatzadeh *et al.*, 2009).

In addition, it is worthy to note that applying PSO method for achieving efficient conditions of the acceleration process would be more crucial when the number of the effective parameters, as well as their adjustable ranges, is extended. This would happen by taking into account the polarization state, for instance, or in the case of non-linearly chirped laser pulses. It can be simply expected, according to Eqs. (1) and (2), that the polarization state of the laser pulse will affect the instantaneous phase and, consequently, the optimum conditions of the interaction. In the following, we investigate the influence of polarization state on the acceleration effect in the field of linearly chirped laser pulses. Here the calculations are not only limited to the comparison between circular and linear polarization, but we take into consideration all possible (elliptical) polarization states in order to study the polarization dependence thoroughly. The optimum value of final energy gain for each polarization state (α, δ) has been illustrated in Figure 5. It can be seen that the final energy gain is maximized in the case of linear polarization, then it gradually decreases for the cases with elliptical polarization and the minimum value is obtained when the circularly polarized laser pulse is employed. For each polarization state in the above calculations, the other

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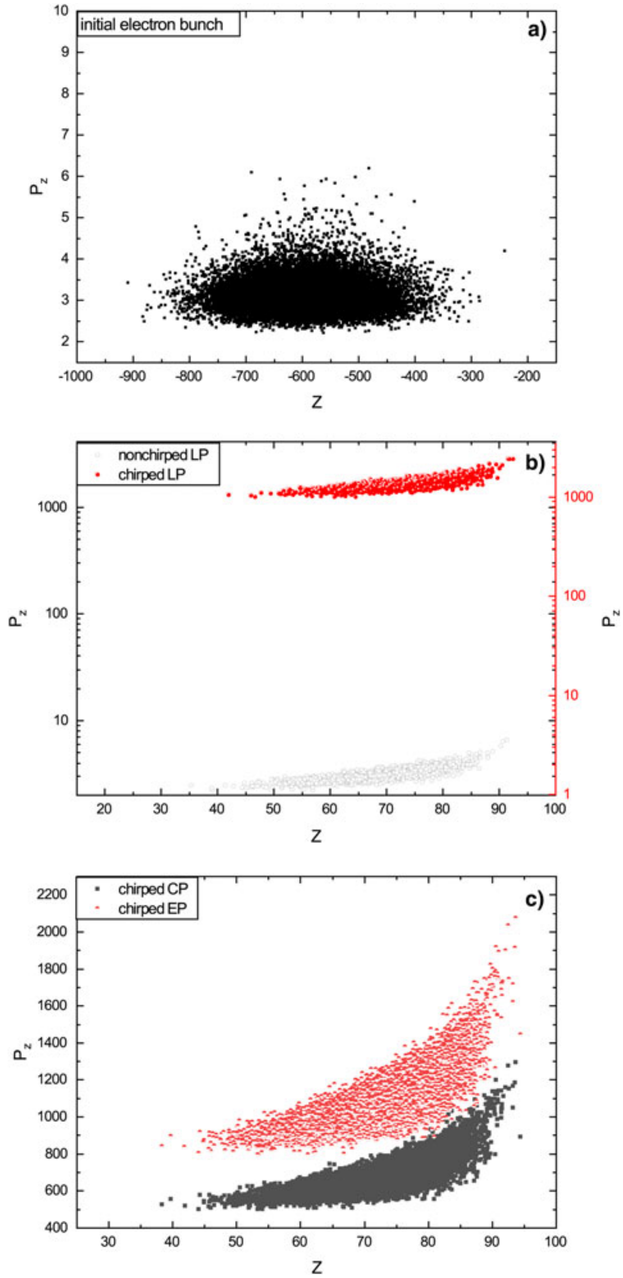

Fig. 7. Momentum-space distribution of input electron bunch (a) and those accelerated by non-chirped (black) and chirped (red) laser pulses with linear polarization (b). (c) Electron bunch accelerated by elliptically ($\alpha = 0.3$; $\delta = 0.1$) and circularly polarized chirped laser pulses (red and black, respectively).

parameters including the chirp parameter have been optimized simultaneously by using the PSO method to maximize the energy gain. By plotting the values of the optimum chirp parameter that is calculated for each polarization state (Fig. 6), it can be found that the optimum chirp parameter is independent of laser polarization. Instead of keeping the initial phase fixed at a value which may not be necessarily optimal for all polarization states, the appropriate initial phase for each polarization state is individually calculated by the PSO method. Thus, the instantaneous phase is properly adjusted in a manner that retains the final energy gain at its maximum possible value. In other words, our calculations suggest a unique optimal value for the chirp parameter, provided by a properly attributed initial phase, which is applicable to all polarization states for obtaining the maximum energy gain.

Electron bunch acceleration

By employing the optimum values of the laser parameters obtained in the previous section, different features of the electron bunch accelerated in such a laser field are numerically calculated. The simulation results are achieved based on the standard model in which the electron–electron interaction is neglected (Sohbatzadeh and Aku 2011; Akou and Hamedi 2015). It is assumed that the initial electron bunch is composed of $N_0 = 10^5$ electrons that have a Gaussian velocity distribution according to the Box Muller transform algorithm (Box and Muller 1958). The spatial distribution is considered to center around (0, 0, −590) with a normalized FWHM beam-width of (30, 30, 80) in x, y, and z directions, respectively. The initial electron velocity is also assumed to center around $(\beta_x, \beta_y, \beta_z) = (0, 0, 0.95)$ with an FWHM width of (0.03, 0.03, 0.01), respectively. Figure 7a illustrates the momentum-space distribution of the input electron bunch. As presented in Figure 7b, our simulation reveals that the accelerated electron bunch is spatially compressed (in z direction) in the field of both chirped and non-chirped laser pulses. However, the momentum enhancement of the electron bunch in the field of a linearly polarized chirped laser pulse is three orders of magnitude higher than that in the field of the linearly polarized non-chirped laser pulse. Our further investigations imply that utilizing chirped laser pulses with elliptical and circular polarizations lead to less momentum improvement (Fig. 7c). This is consistent with the results presented in the case of single electron acceleration.

A more comprehensive comparison of electron bunch acceleration features in such optimized laser field would be obtained by taking into consideration the evolutions of particle energies as well as their spatial trajectories. Thus, we present the simulation results for energy distributions of the electrons in a bunch before and after acceleration. By considering a Gaussian distribution for the velocity of the electrons, the energy distribution of input electron bunch is obtained as in Figure 8a, accordingly. Our simulations reveal that the energy distribution of the electron bunch in the field of a non-chirped laser pulse remains identical to that of the input bunch (Fig. 8b). This is consistent with that could be expected from the well-known Lawson–Woodward theorem. However, in the field of the chirped laser pulse (Fig. 8c and 8d), the energy distribution is significantly broadened and shifts to much higher energies. Moreover, it can be found in these figures that linear polarization causes a larger shifting and broadening in comparison to that by circular and elliptical polarizations. In fact, the energy shift that is experienced by high (low) energy tail of the bunch's energy spectrum is much higher (lower) than that by electrons in the spectrum's peak. Such energy broadening occurs in a velocity and polarization manner and could be attributed to the non-linear variation of the energy gain versus the initial electron velocity, which differs depending on laser polarization (Fig. 8e).

Finally, in order to determine the spatial evolution of the accelerated bunch, the distribution of electron directions with respect to the laser propagation axis is simulated. Figure 9a presents the divergence angle distribution of the input electron bunch that is calculated according to Eq. (9). The results of similar calculations for the electrons accelerated by chirped and

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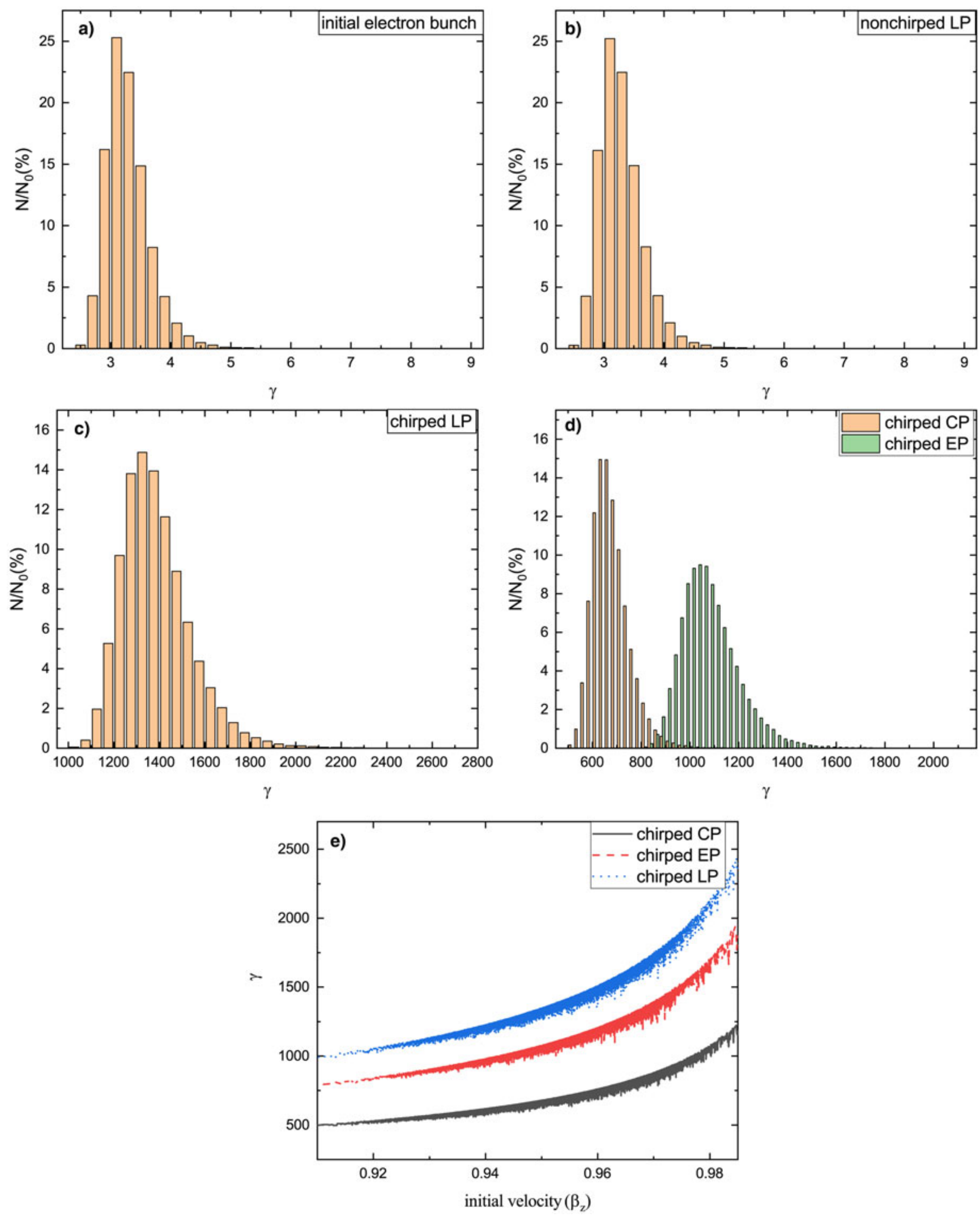

Fig. 8. The energy spectrum of the electrons in the bunch before (a) and after interaction with a linearly polarized non-chirped (b) and chirped (c) laser pulses in comparison to that with elliptically and circularly polarized chirped laser pulses (d). The electron numbers in the vertical axis are normalized to their total number (in percent). (e) Non-linear dependence of final energy gain of the electrons on their initial axial velocity in the field of chirped laser pulses with different polarizations.

non-chirped laser pulses are compared in Figure 9b. It is clear that the spatial distribution of the bunch remains almost identical in the field of a non-chirped laser pulse. However, the electron bunch is converged during the acceleration by a chirped laser pulse. This is consistent with that is expected for the acceleration of an electron bunch by a Gaussian chirped laser pulse in magnetized plasma (Ahmadian 2014). Our results also imply that the amount of the converging angle, as well as the dominant divergence angel after the acceleration process, depends on the polarization state of the laser pulse, as presented in Figure 9c. For a better quantitative comparison of the bunch features, we summarize the obtained results in Table 1.

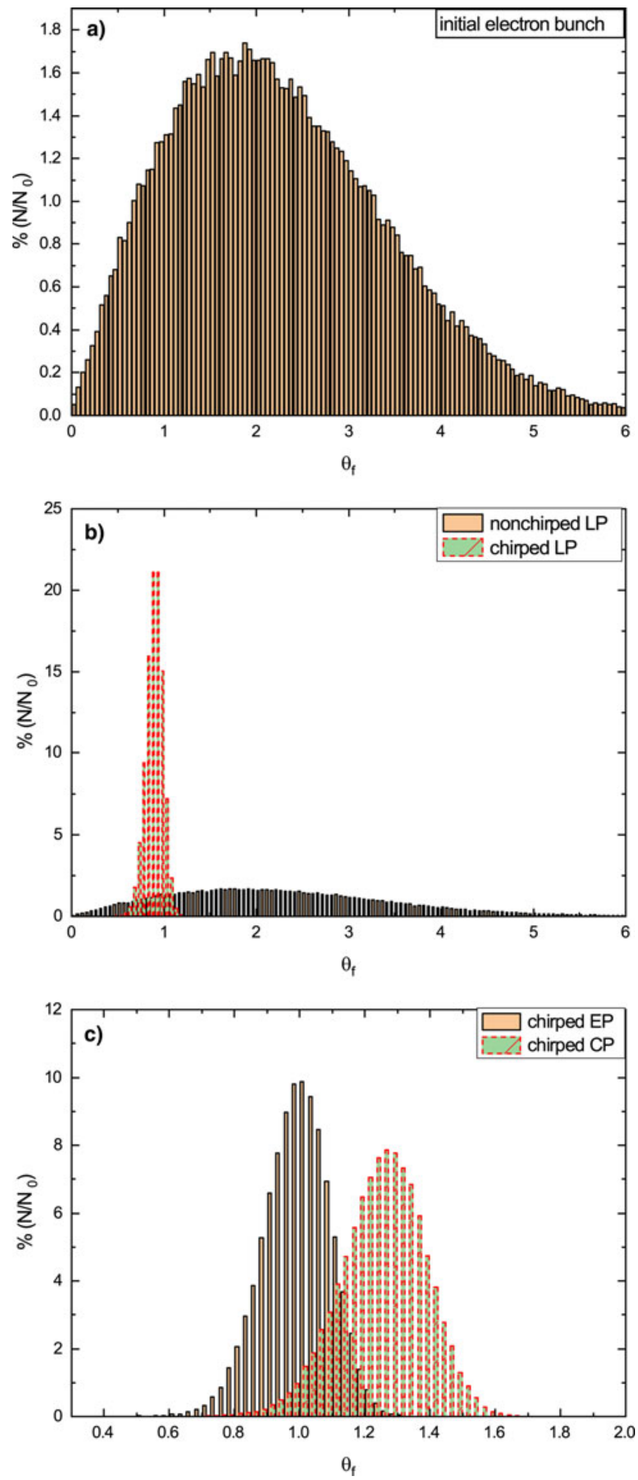

Fig. 9. Spatial distribution of the electron bunch in terms of the divergence angle with respect to the laser propagation axis before (a) and after interaction with linearly polarized chirped and non-chirped laser pulses (b), in comparison to that with elliptically and circularly polarized chirped laser pulses (c). The electron numbers in the vertical axis are normalized to their total number.

Summary and conclusion

We have shown that optimizing the laser initial parameters by using the PSO method could improve the final energy gain of the electron as well as the features of the electron bunch in the field of a chirped laser pulse. It has been shown that the optimum chirp parameter is identical for all polarization states and the final energy gain of an electron pronouncedly increases in such a field independently from the sign of chirp parameter. It has been also revealed that optimized values obtained for the initial phase, chirp parameter, and field polarization of the laser pulse could enhance the electron bunch acceleration effect. It has been revealed that the energy spectrum of the bunch is shifted to considerably higher energies and its divergence angle is decreased to the extent that is significantly influenced by laser polarization state. These findings could be considered useful in practically choosing the optimal parameters and theoretically explaining the acceleration mechanism in interactions involving more extensive effective parameters such as plasma and wakefield parameters (Malik 2004, 2008; Golian and Dorranian 2017), pulse shape effect (Ahmadian 2014; Mahmoodi-Darian *et al.*, 2016), external magnetic field (Ahmadian 2014; Mahmoodi-Darian *et al.*, 2016), and non-linear chirping.

Table 1. Average energy gain (γ_m) and divergence angle (θ_f^m) with their standard deviations calculated for the electron bunch before and after interaction with non-chirped laser pulse in comparison with those in chirped laser pulses with linear, circular and elliptical polarization

	γ_m	St.Dev. γ_m	θ_f^m	St.Dev. θ_f^m
Initial electron bunch	3.28	0.36	2.26	1.18
Non-chirped	3.28	0.36	2.28	1.19
LP chirped	1353.54	150.73	0.89	0.09
CP chirped	678.64	75.83	1.25	0.12
EP chirped	1081.28	120.47	0.99	0.10

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