Optical and Quantum Electronics (2021) 53:617
https://doi.org/10.1007/s11082-021-03241-y

Laser wakefield and direct laser acceleration of electron in plasma bubble regime with circularly polarized laser pulse

Amrit Kumar[1] · Niti Kant[1] · Harjit Singh Ghotra[1,2]

Received: 1 December 2020 / Accepted: 3 September 2021 / Published online: 13 October 2021

Abstract

With a circularly polarized (CP) Gaussian laser pulse, we examine theoretically the acceleration of electrons due to a combined effect of laser wakefield (LW) and direct laser (DL) in the plasma bubble regime. The CP laser pulse is ideal for DLA, since it allows for better electron trapping in the plasma bubble regime than a linearly polarized (LP) laser pulse. As a result of a CP laser pulse propagation in z direction, the electrons are accelerated in longitudinal direction by the accelerating field (W_z) and focused in the transverse direction by the focusing fields (W_x, W_y). The density of plasma medium is about $\sim 1.8 \times 10^{18}\mathrm{cm}^{-3}$ which is from a 99.9% He / 0.1% N_2 neutral mix, laser pulse duration is 30fs and wavelength $0.8\mu m$. A bubble radius of over $20\mu m$ is achieved with a CP laser pulse at an intensity on the order of $a_0 = 7$ ($\sim 2.14 \times 10^{20} W/\mathrm{cm}^2$), although the same can be achieved with an LP laser at a significantly higher intensity. The electron energy gain with a CP laser pulse appears to be above 3GeV at this intensity. CP laser pulse appeared with a lower transverse emittance and a higher energy gain than an LP laser pulse of the same intensity. In comparison to LP laser pulse, CP laser pulse appears to have a more effective acceleration mechanism for LWFA with DLA in the plasma-bubble regime.

Keywords Circularly polarized laser pulse · Laser wakefield acceleration · Direct laser acceleration · Bubble regime · Dephasing length

1 Introduction

Laser driven plasma acceleration is a fascinating area of research during last few decades as it paves the way for particle acceleration to relativistic energy over extremely small distances (Malka et al. 1997; Geddes et al. 2004; Nemeth et al. 2008; Wong et al. 2017). Two important phenomena namely Direct Laser Acceleration (DLA) (Arefiev et al. 2016; Joshi 2017; Li et al. 2011; Ghotra and Kant 2016; Ghotra et al. 2018) and Laser Wakefield

✉ Harjit Singh Ghotra
harjit.ghotra@yahoo.com

1 Department of Physics, Lovely Professional University, G. T. Road, Phagwara, Punjab 144411, India

2 Advanced Study Hub (ASH) – Theoretical and Computational Research Form (TCRF), Near GT Road Jalandhar, Punjab 144001, India

Acceleration (LWFA) (Sprangle et al. 1989; Amiranoff et al. 1998; Antonsen and Mora 1992) are most widely studied for electron acceleration. When a high intensity relativistic laser is incident on plasma for the time period longer than that of electron response time, a steady state channel with transverse and longitudinal field is formed in plasma which further expels out the electrons to achieve high acceleration gradient within a distance of few cm (Arefiev et al. 2016). The laser pulse exerts a longitudinal, radiation-driven "ponderomotive force" on the plasma electrons pushing them forward and backward from regions of high to low laser intensity (Joshi 2017). Thus, with an ultra-intense and short-pulsed laser of the intensity $\sim 10^{20}\mathrm{W/cm^2}$, the electrons can be accelerated to $\sim$ 3GeV of energy through DLA mechanism in plasma with effective acceleration gradient $\sim 10\mathrm{GeV/cm}$ (Li et al. 2011). Multi-GeV electron energy gain was observed by using Gaussian laser pulse under DLA mechanism (Ghotra and Kant 2016; Ghotra et al. 2018). LWFA takes place when an ultra-short high-power laser interacts with plasma. It provides both radial and axial ponderomotive forces to the plasma electrons (Sprangle et al. 1989; Amiranoff et al. 1998). As the plasma electrons flow around the laser pulse, large amplitude plasma waves are generated, the electrons get trapped in such generated wake and gets excited. The excitation of the electron plasma wave is maximum when the laser pulse duration is of the order of $1/\omega_p$, where ω_p is the plasma frequency (Amiranoff et al. 1998). When a laser acts on high density plasma it breaks into short pulses at $1/\omega_p$ through Raman scattering instability, due to which a high electric field is generated by plasma waves in radial direction which traps the plasma electrons and accelerate them in the longitudinal direction to higher energies (Antonsen and Mora 1992). An external magnetic field is offered for enhanced acceleration during laser plasma interaction (Varaki 2018, 2019), where the electron energy obtained is larger in the presence of a helical magnetostatic wiggler than in the absence of the wiggler field. In a strong nonlinear regime of LWFA, a complete blow out of the plasma electrons from the laser's path can generate high monoenergetic electron beam that have recently reached *GeV* scale energy (Ferri et al. 2016). The ultra-relativistic laser pulses of short (or comparable to plasma) wavelength are intense enough to break and expel out the electrons from an under dense plasma from the axial region of the laser propagation. This forms a nonlinear wake with ion cavity free from electrons which represents a 'plasma-bubble' or 'blowout regime' (Ferri et al. 2016; Mohammed et al. 2017; Wang et al. 2019). Such regime can trap electrons and move with relativistic velocity. Shock ion acceleration (Fiuza et al. 2012; Kim et al. 2015; Macchi et al. 2012) has recently been observed as an alternative way for high-quality ion beams. When an intense (~ 2.14 X 10^{20} W / cm^2) laser pulse irradiates an over-dense target, the ions are compressed to produce a density spike, which causes electrostatic shocks (Denavit 1992; Forslund and Shonk 1970). As the shock Mach number exceeds the threshold value (> 1.5), these shocks can reflect upstream ions and produce monoenergetic ion beams. Another shock acceleration approach is based on the nonlinear threshold phenomena of ion reflection from the front of a laser pulse, which can be used to produce high-density quasi-monoenergetic protons by focusing two counterpropagating laser pulses (Avetissian et al. 2011). 1-MeV protons with a 4% energy spread was observed with a flux of 4×10^{11} protons/MeV/sr utilizing the circularly polarized (CP) laser (Palmer et al. 2011), where the hole-boring acceleration (HBA) dominates and the shock is driven by the radiation pressure. In an experiment, the electrostatic collision-less shock acceleration was observed as a result of the near-critical-density (NCD) plasma being pushed by a femtosecond PW laser. Because high plasma density permits efficient and targeted laser absorption and a larger pileup of helium ions on the channel wall to augment the shock potential, shock acceleration is observed at higher densities, leading to the creation of a shock by helium plasma and the acceleration of protons as a result (Singh et al. 2020). High-speed imaging and intensity measurements of the shockwave system produced at breakdown are used to investigate the structure of the breakdown plasma and the resulting bubble dynamics. It is observed that the system's parameters can be tuned to improve repeatability and sphericity (Sinibaldi et al. 2019). Another method involved using laser induced breakdown spectroscopy to analyze laser generated cavitation with the heavy elements in water with high sensitivity where the plasma was generated by an 8 ns Q-switched fundamental Nd:YAG laser pulse of energy 180 mJ with 10 Hz repetition rate (Sawaf and Tawfik 2014). Their laser intensity was optimized to avoid the ambient air breakdown, which may influence the manganese plasma emission lines.

The benefit of working in the ion bubble regime is that it leads to quasi-monoenergetic electron beams (Pukhov et al. 2004). Besides the advantages, DLA and LWFA have their own limitations also. To prevail over, the model of synergistically DLA and LWFA was suggested in the bubble regime for electron accelerator (Zhang et al. 2015). In their hybrid accelerator a significant improvement has been suggested by combining the energy gains of both laser and wake field without compromising with the narrow energy spread. By using LP laser pulse of wavelength $\lambda_p = 0.8\mu m$ an accelerating gradient of $2\mathrm{GeV/cm}$ is observed. Accordingly, DLA enlarges the de-phasing length which enforces the LWFA energy gain to rise. The phase space bifurcation of electrons into high energy DLA and low energy non-DLA group has been observed (Zhang et al. 2015). It is demonstrated that ultrashort radially polarized pulses produce super-ponderomotive electrons more efficiently than pulses of the linear and circular polarization when considering electron acceleration in direct laser-solid interactions much beyond the ponderomotive limit (Wen et al. 2020). The polarization aspects of laser pulse show that the motion of electron under CP laser is more effective than that of LP laser (Ghotra and Kant 2018). The CP laser pulse not only transfers momentum to the electrons in the direction of propagation it also transfers a transverse momentum resulting the electrons to rotate around the axis of propagation of laser pulse which provides better collimation and stability to the ultra-relativistic electrons. The CP laser pulse has a helical motion so the interaction time of electrons with the laser field is comparatively more. Thus, for synergistic DL and LWF acceleration the possibility of energetic electrons is comparatively high with CP laser pulse than that with LP laser. To the best of our knowledge the synergistic DLA and LWFA in bubble regime with a CP laser pulse was never investigated earlier for higher energy gain by electron in plasma.

In this work we present a bubble regime acceleration of electron with combine DL and LWF acceleration using CP Gaussian laser pulse and observe high energy gain with low emittance. The azimuthal current is absent while using LP laser pulse, therefore the electrons oscillate up and down in the direction of polarization and the current gets filament and distorted whereas with CP laser, more symmetric trajectory of electron is possible, paving for better collimation of electron. The electrons are accelerated in the longitudinal direction by the accelerating field and focused in the transverse direction by the focusing fields when a CP laser pulse propagates in an evenly density plasma. CP laser pulse is also optimum for DLA and can support self-injection of electrons in the plasma bubble. The self-injection of electrons is shown to be improved with optimum bubble size. In such case self-injected electrons of less energy are also gets accelerated as they slowly drift backwards in bubble regime. Moreover, CP laser pulse provide a better focusing field in bubble regime, makes bubble less asymmetric and more suitable for electron acceleration than that with LP laser pulse. With an appropriate selection of intensity parameter and bubble size one can obtain the electron energy gain under the non-linear effects of combine LW and DL acceleration, which appearing more efficiently with CP than LP laser pulse. In the plasma bubble regime, we investigate the effects of numerous parameters on electron acceleration by a laser pulse and the associated electron energy gain. Specifically, we consider the role played by: (1) CP laser pulse in comparison with the LP laser pulse, (2) laser pulse Intensity parameters, (3) bubble size, (4) accelerating field and focusing field, and (5) combining LW and DL acceleration. All of these characteristics are found to result in a significant increase in electron energy under specific situations. In contrast with LP laser pulse the CP laser pulse appeared with substantial energy to the electron with same set of intensity in plasma bubble regime. In section II, the electron dynamics and field equations originated from laser profile has been defined. In section III, obtained results have been discussed and the outcome of the presented work has concluded in section IV.

2 Electron dynamics and field equations

Inside the bubble monoenergetic electrons are generated during laser plasma interaction. For a CP laser pulse propagating in z-direction the transverse components of electric field under paraxial approximation can be written as (Zhang 2010):

$$\mathrm{E_X(r,z,t)} = \frac{\mathrm{E_0 r_0}}{\mathrm{w(z)}} \exp(\mathrm{i}\varphi) \exp\left(-\frac{\mathrm{r}^2}{\mathrm{w}^2(\mathrm{z})}\right) \mathrm{f(t')} \tag{1}$$

$$\mathrm{E_y(r,z,t)} = \frac{\mathrm{E_0 r_0}}{\mathrm{w(z)}} \exp\left[\mathrm{i}\left(\varphi + \frac{\pi}{2}\right)\right] \exp\left(-\frac{\mathrm{r}^2}{\mathrm{w}^2(\mathrm{z})}\right) \mathrm{f(t')} \tag{2}$$

where the parameters $\mathrm{E_0}$ is the electric field amplitude, φ is the Gaussian beam phase, $f(t') = \exp\left\{-\left[\mathrm{t} - \frac{(\mathrm{z-z_L})}{\mathrm{v_{ph}}}\right]^2 / \tau^2\right\}$ is the pulse envelope, τ is the pulse duration, $\mathrm{z_L}$ is initial position of the laser pulse peak, $\mathrm{v_{ph}} = c\sqrt{1 - \omega_p^2/\omega_L^2}$, $r^2 = x^2 + y^2$, r_0 is the minimum laser spot size, $\mathrm{w(z)} = r_0\sqrt{1+\xi^2}$ is beam radius, $\xi = z/Z_R$ is the normalized propagation distance, $Z_R = kr_0^2/2$ is the Rayleigh length, k is the laser wave number, $\varphi = \omega_L t - kz + \tan^{-1}\xi - \frac{zr^2}{Z_R r_0^2 f^2} + \varphi_0$, φ_0 is the initial phase, ω_L. is the laser frequency and $\tan^{-1}\xi$ is the Guoy phase. For the more accurate observations the longitudinal electric and magnetic field components can be expressed as:

$$\mathrm{E_z(r,z,t)} = -\frac{i}{\mathrm{k}}\left(\frac{\partial E_x}{\partial x} + \frac{\partial E_y}{\partial y}\right), \tag{3}$$

$$\boldsymbol{B} = \frac{ic}{\omega_L}(\nabla \times \boldsymbol{E}), \tag{4}$$

where $\boldsymbol{E}$ represents the laser's electric field and $\boldsymbol{B}$ represents the magnetic field for the incident laser pulse. The pulse envelop term $\mathrm{f}(t')$ in paraxial approximated field component Eqs. (1)–(2) violate the Maxwell's equation. In order to satisfy the Maxwell's equation, we consider: (a) The pulse envelop term $\mathrm{f}(t')$ is under slowly varying envelop approximation (SVEA) (Fortin et al. 2009). Accordingly, the second or higher order derivative terms can be neglected with respect to envelop. The laser pulse duration is about 30fs making $f(t')$ under SVEA. (b) The waist radius which is about $20\mu m$ is much larger than the wavelength $(1\mu m)$ such that the longitudinal component of the ectric field can be neglected (Nesterov and Niziev 2000).

We consider the plasma with a uniform density of about $n = 1.8 \times 10^{18} cm^{-3}$, laser wavelength $\lambda_L = 0.8 \mu m$, angular frequency of laser as $\omega_L = 2.355 \times 10^{15} rad/s$, and angular frequency of plasma as $\omega_p = 0.7536 \times 10^{14} rad/s$. The plasma medium is from a 99.9% He / 0.1% N_2 neutral mix. Our calculated ratio of the plasma and laser frequency $\omega_p/\omega_L = 0.032$, is in equivalence with the plasma parameters used in ref. (Zhang et al. 2015) and is consistent with the plasma density making the phase velocity of the lowest laser mode supported by the plasma where $v_{ph} = 0.9985c$. To achieve an effective LW-DL acceleration of electrons in the bubble regime, two conditions must be met: (1) an influential overlap between the laser field and injected electron for effective DLA, and (2) the initial energy of injected electrons into the bubble must be sufficient transversely to overcome the deceleration caused by the longitudinal bubble field. The CP laser pulse helps to meet the conditions for trapping and acceleration inside the bubble for a longer period of time. The self-injection of background plasma electrons into the bubble is offered as a way to realize the second criterion. The power required to excite the nonlinear wakes or generates a plasma-bubble in its wake is so-called critical power $\approx P_{cr}$ for relativistic self-focusing and is given by Sun et al. (1987): $P_{cr} \approx 17\left(\frac{\omega_L}{\omega_p}\right)^2$ (GW) $\approx$ 16.6 TW. The self-focusing occurs as a result of the ponderomotive expulsion of electrons which causes the electron density to decrease in that region, behind the leading laser pulse. The laser beam power, P must be greater than the critical power, P_{cr} for this to happen, i.e. $P > P_{cr}$. In that region, the effect is so strong that all electrons are expelled from a self-focused laser light channel's core radial region, which we name as plasma-bubble.

Figure 1 shows a schematic representing the (i) formation of bubble when a high intensity laser is interacted with plasma, (ii) generation of electron cloud around the bubble and (iii) self-injection of electrons at the rear of the bubble. A short laser pulse with a duration of $\tau \sim (1/\omega_p)$ can form a plasma bubble, which is a blow-out nonlinear plasma structure comparable to an ion channel (Pukhov and Meyer-ter-Vehn 2002; Kostyukov et al. 2004). As the pulse penetrates the plasma, which 99.9% He / 0.1% N_2 neutral mix making a density of about $n = 1.8 \times 10^{18} cm^{-3}$, its ponderomotive force begins to expel some of the electrons out of the path of laser pulse in the transverse direction resulting in a plasma-bubble.

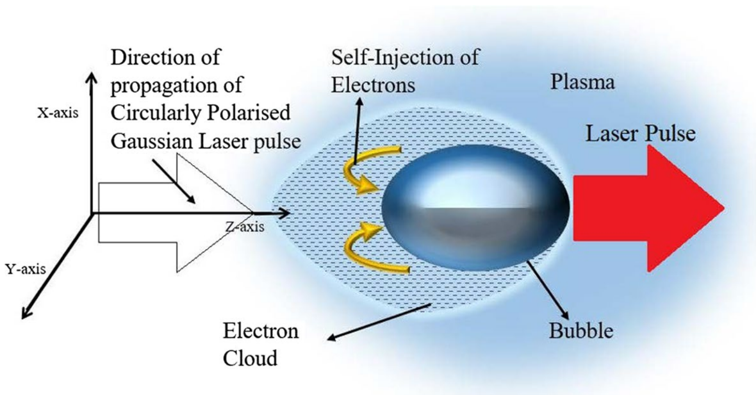

Fig. 1 Schematic representing the (i) Formation of bubble when a high intensity laser in introduced on plasma, (ii) Generation of electron cloud around the bubble and (iii) Self-injection of electrons at the rear of the bubble

This plasma-bubble, which is a propagating region in which plasma electrons are evacuated by the ponderomotive force caused by a strong laser pulse, enables both focusing and accelerating electromagnetic fields. Inside the bubble, due to a CP laser pulse propagation in z direction, the electrons are accelerated in longitudinal direction by the accelerating field (say W_z) and focused in the transverse direction by the focusing fields (say W_x and W_y). Thus, both transversely focusing and longitudinally accelerating fields are generated inside the bubble, which presents important factor for high quality electron acceleration. These fields are symmetric with respect to the center of the bubble. For symmetry consider a spherical bubble of radius r_b moving with the relativistic velocity $v_b \approx c\left(1 - \frac{1}{2\gamma_b^2}\right)$ where γ_b is the relativistic factor. The wake fields inside the spherical bubble are defined as (Phuoc et al. 2008):

$W_z = \frac{m\omega_p^2(z - r_b - v_b t)}{2e}$ as longitudinal accelerating field,

$$W_x = \frac{m\omega_p^2 x}{2e} \text{ and } W_y = \frac{m\omega_p^2 y}{2e} \text{ as transverse focusing fields} \tag{5}$$

where $\omega_p^2 = 4\pi e^2 n/m_e$. The equations of electron motion include the dependence of focusing wakes inside a spherical bubble of radius r_b propagating with relativistic velocity v_b (Phuoc et al. 2008). With a CP laser pulse, the focusing wakes as per Eqs. (5) controls the de-phasing of accelerated electron inside the bubble for a longer duration as compared to that with a LP laser pulse. The electron momentum and energy can be written in terms of following equations:

$$\frac{dp_x}{dt} = -eE_x + e\beta_z B_y - e\beta_y B_z - eW_x \tag{6}$$

$$\frac{dp_y}{dt} = -eE_y + e\beta_x B_z - e\beta_z B_x - eW_y \tag{7}$$

$$\frac{dp_z}{dt} = -eE_z + e\beta_y B_x - e\beta_x B_y - eW_z \tag{8}$$

where the momentum of the electron is $\mathbf{p}$ and $\left(p_x, p_y, p_z\right)$ are the (x, y, z) coordinates, the normalized velocity of electron is $\boldsymbol{\beta}$ and $\left(\beta_x, \beta_y, \beta_z\right)$ are the (x, y, z) components, $\gamma = 1 + \left(\frac{p^2}{m_0^2c^2}\right)^{\frac{1}{2}}$ is the Lorentz's factor, $-e$ and m_0 are the charge and rest mass of the electron respectively. The other normalized dimensionless quantities are expressed as: $a_0 \to eE_0/m_0\omega_L c$, $\tau' \to \omega_L t$, $z' \to z\omega_L/c$, $x' \to x\omega_L/c$, $y' \to y\omega_L/c$, $r_b' \to r_b\omega_L/c$, $p_x' \to p_x/m_0c$, $p_y' \to p_y/m_0c$, $p_z' \to p_z/m_0c$, $\beta_x \to v_x/c$, $\beta_y \to v_y/c$, and $\beta_z \to v_z/c$.

3 Results and discussion

For calculations we set the numerical values of various parameters as follow: the normalized laser intensity parameter $a_0 = 2.5$, 5 and 10 corresponding to the intensity values, $1.34 \times 10^{19} W/cm^2$, $5.35 \times 10^{19} W/cm^2$ and $2.14 \times 10^{20} W/cm^2$ respectively for a LP laser pulse; the normalized laser spot size $r_0' = 157$ corresponds to laser spot size $r_0 = 20\mu m$; laser pulse duration is $\tau' = 71$ corresponding to 30fs. Considering initial position of pulse peak $z_L = 0$, initial pulse electron position $\left(x_0', y_0', z_0'\right) = (0, 0, 0)$, initial phase of laser $\varphi_0 = 0$. The bubble radii $r_b^{'} = 55$, 83 and 166 corresponds to $r_b = 7.04\mu m$, 10.58 μm and 21.16 μm respectively. The laser pulse peak power is about 84TW, 360TW and 1.4PW for $a_0 = 2.5$, 5 and 10 respectively with $r_0' = 157$ for LP laser pulse. In present scenario, the laser pulse with peak power in the range of PW is feasible and presented experimentally (Gales et al. 2018; Dabu 2017). The organization of the high amplification 2×10PW femtosecond laser system of the Extreme Light Infrastructure Nuclear Physics (ELI-NP) facility is explained (Dabu 2017). LW-DL acceleration in bubble regime is influenced by two conditions: (1) overlapping of laser field with electron to support injection, and (2) enough transverse momentum of injected electron to control deceleration due to longitudinal bubble field. Two laser pulses were employed to satisfy first condition (Zhang et al. 2018). The second condition is proposed to realize by devising the self-injection of the background plasma electrons into the bubble (Zhang et al. 2015). Here, the CP laser pulse is prioritized to present the better acceleration than LP laser pulse. The injected electron appears with energy and momentum values as (a) minimum, for non-direct laser acceleration (DLA) to (b) maximum for DLA group of electrons. As a result, injected electrons are bifurcated into two separate groups: high-energy DLA and lower-energy non-DLA. A single particle dynamic is investigated for combine LW and DL fields for DLA as well as non-DLA group of electrons.

Figure 2 shows the electron trajectories of a typical non-DLA and DLA group of electrons with $a_0 = 2.5$ for LP and $a_0 = 2.5/\sqrt{2}$ for CP laser pulse with $r_0^{'} = 157$. Figure 2a and b are showing the trajectories for non-DLA group of electrons (with blue lines) with LP and CP laser pulse. Comparatively larger transverse trajectories are appearing for DLA group of electrons (with red lines).

Figure 3 represents the variation of electron energy gain for typical DLA (blue lines) and non-DLA (red lines) under collective LW-DL fields with respect to the normalized propagation distance with distinct intensity values as $a_0 = 2.5$, 5 and $a_0 = 2.5/\sqrt{2}$, $a_0 = 5/\sqrt{2}$ for LP and CP laser pulse respectively. The bubble size varies according to the relation $k_p r_b = 1.12\sqrt{a_0}$ for 1-D case which is related for LP and $k_p r_b = 2\sqrt{a_0}$ for 2-D case related for CP laser pulse, where $k_p = \omega_p/c$ is the plasma wave number (Chang et al. 2017). The energy gain with CP laser pulse is much higher than that with LP laser pulse due to the bigger bubble size in case of CP laser pulse for the same intensity value.

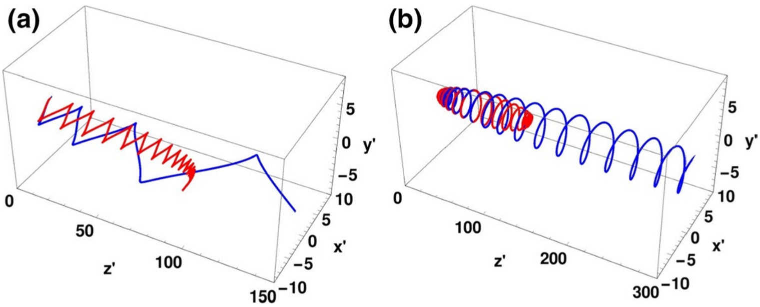

Fig. 2 Trajectory of electron in 3D plane under combined LW-DL fields for two typical electron as non-DLA (red lines) and DLA (blue lines) with **a** LP (for a_0=2.5 and r_b'=55) and **b** CP (for a_0=2.5/$\sqrt{2}$ and r_b'=83). The other parameters are: λ=800nm, τ=30fs, r_0'=157, v_{ph}=0.9985c, x_i'=0, y_i'=0, z_i'=0, z_L'=0 and φ_0=0

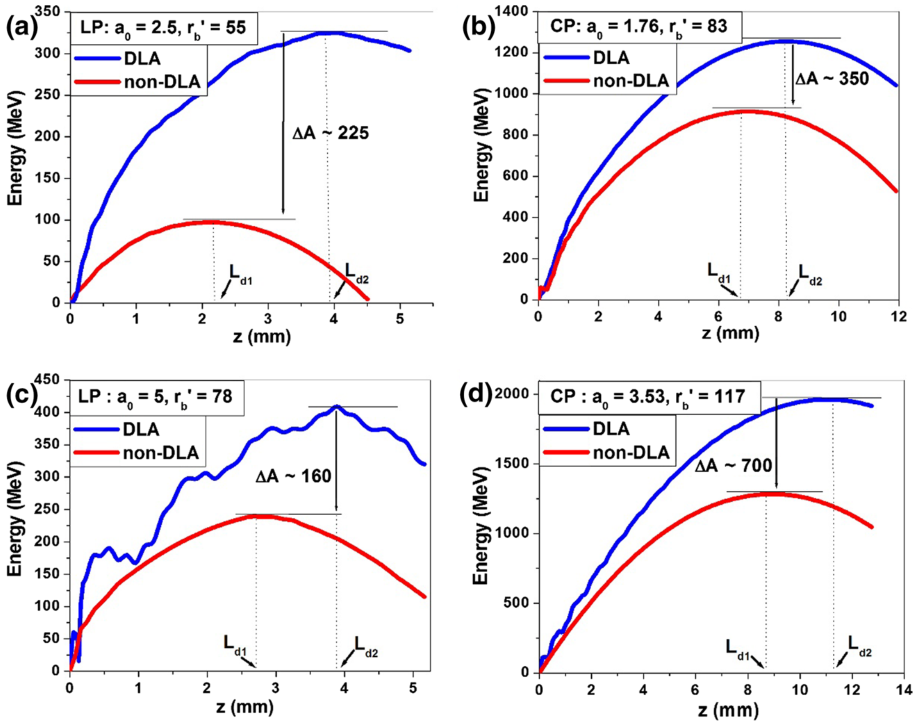

Fig. 3 Electron energy gain in variation with normalized propagation distance for non-DLA (red line) and DLA (blue line) group of electrons under collective LW-DL fields. **a** LP, a_0=2.5, r_b'=55, **b** CP, a_0=2.5/$\sqrt{2}$, r_b'=83, **c** LP, a_0=5, r_b'=78, and **d** CP, a_0=5/$\sqrt{2}$, r_b'=117. Other supportive parameters are same as in Fig 2

As appearing from Fig. 3a, for $a_0 = 2.5$, the electron energy gain is about 325 MeV for LP laser pulse with normalized bubble radius $r_b^{'} = 55$ ($\sim 7.04\mu m$) for DLA electron and from Fig. 3b, for $a_0 = 2.5/\sqrt{2}$, the electron energy gain is about is above 1200 MeV for a CP laser pulse with normalized bubble radius 83($\sim 10.6\mu m$) for DLA electron. The energy gain by electron in bubble regime under combine LW and DL fields is the sum total of energy gain from wakefield ($A_W = -e \int W_z v_z dt$) and direct laser field ($A_L = -e \int E^L v dt$) (Arefiev et al. 2016). Thus, $\Delta A = \Delta A_W + \Delta A_L$ is the energy gain by DLA electron with respect to non-DLA electron as reflecting in Fig. 3. On increasing the intensity of laser pulse, the bubble radius increases. One can observe dephasing (from Fig. 3) where the energy starts to decrease. The propagation distance up to which the energy is still increasing represents the dephasing length for electron acceleration. So, as long as the plasma density and plasma wavelength are uniform, the dephasing time and propagation length of the accelerated electron are not affected with the laser parameters even if the intensity or the radius of the bubble is increased. However, in the bubble regime, the processes like laser self-focusing, etching-compression or filamentation, depend on the laser power and intensity and thus affect strongly the propagation and acceleration.

Figure 4 represents the electron energy gain and ejection angle for DLA electron as a function of normalized propagation distance for under collective LW- DL fields for $a_0 = 10$ with LP and $a_0 = 10/\sqrt{2}$ with CP laser pulse. Analysis shows, 3 times higher energy gain, 4-time longer dephasing length, 1.7 times bigger bubble size and less than half of energy

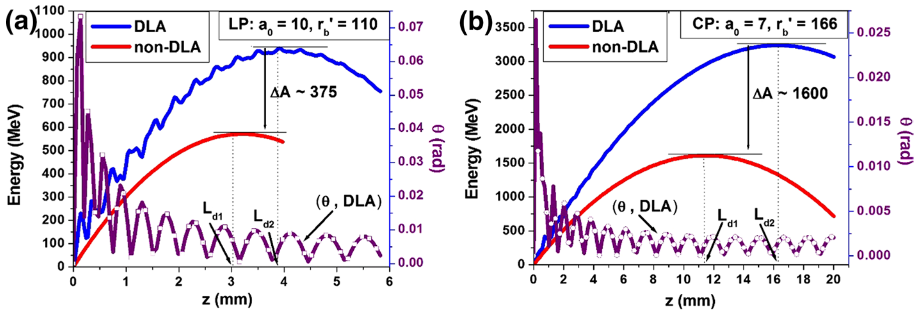

Fig. 4 Variation of electron energy gain and ejection angle for typical DLA group electron as a function of accelerating distance under collective LW-DL fields for **a** LP (with a_0=10, r_b'=110) and **b** CP (with a_0=10/$\sqrt{2}$, r_b'=166). Other supportive parameters are same as in Fig. 2

spread with CP than that with LP laser pulse. Thus, with an appropriate selection of intensity parameter and bubble size one can obtain the electron energy gain under the non-linear effects of combine LW and DL acceleration more efficiently. Secondly, using a CP laser pulse in comparison with LP laser pulse an efficient electron energy gain can be obtained in bubble regime. Numerous studies reported that the plasma electrons oscillate around the propagation direction of laser pulse during interaction of CP laser pulse with plasma and this give rise to azimuthal current and hence azimuthal magnetic field, which generates axial magnetic field (Naseri et al. 2010). Such field is helpful in self- injection of electron in bubble regime. Thus, the CP laser pulse also supports the self-Injection of electron in bubble regime whereas for LP laser pulse self-injection phenomena are vague. For self-injection, the rear end electrons of the blowout regime must be able to catch up with the wake. The necessary physical condition to support this is that the blowout radius should be large enough so that, when the particles reach the rear of the bubble, they move predominately in the forward direction with the speed close to the speed of light (Lu et al. 2007). As depicted above in case of a CP laser pulse at the intensity parameter of $a_0 = 10/\sqrt{2}$, where the corresponding bubble radius $r_b > 20\mu m$ is large enough, such that the self-injection is effectively achieved with electron energy gain above 3 GeV in bubble regime.

4 Conclusion

We theoretically explored electron acceleration in the bubble regime using a CP Gaussian laser pulse under a combined LW and DL acceleration mechanism, and contrasted the significant enhancement in electron acceleration with an LP laser pulse. The total energy gain from the wakefield and direct laser field is used to calculate the energy gain by electron in the bubble regime under combined LW and DL fields. The injected electrons are separated into two groups: high-energy DLA and lower-energy non-DLA, based on their initial energy and momentum values. The CP laser pulse entrails a delayed dephasing, better self-injection of electron in bubble regime and higher energy gain by electron. For a CP laser pulse, a bubble radius over $20\mu m$ can be achieved at intensity of the order of $a_0 = 7(\sim 2.14 \times 10^{20} W/cm^2)$, where the same with LP laser is possible at much higher intensity which is approximately ten time higher than the intensity with CP laser pulse. At this intensity the electron energy gain with CP laser pulse is appear to be above 3 GeV. A comparatively low transverse emittance and high energy gain is observed with a CP laser than that with LP laser pulse of same intensity. Hence, in comparison to LP laser pulse, CP laser pulse appears to have a more effective acceleration mechanism for LWFA with DLA in the bubble regime. The results mark a significant step toward future developments in compact laser plasma electron accelerators.

Funding No funding.

Availability of data and material Data available on request from the authors: The data that support the findings of this study are available from the corresponding author upon reasonable request.

Decalarations

Conflict of interest The authors declare that they have no conflict of interest.

References

Amiranoff, F., Baton, S., Bernard, D., Cros, B., Descamps, D., Dorchies, F., Jacquet, F., Malka, V., Marquès, J.R., Matthieussent, G., Mine, P., Modena, A., Mora, P., Morillo, J., Najmudin, Z.: Observation of Laser Wakefield Acceleration of Electrons. Phys. Rev. Lett. **81**(5), 995–998 (1998)

Antonsen, T.M., Mora, P.: Self-focusing and Raman scattering of laser pulses in tenuous plasmas. Phys. Rev. Lett. **69**, 2204–2207 (1992)

Arefiev, A.V., Khudik, V.N., Robinson, A.P.L., Shvets, G., Willingale, L., Schollmeier, M.: Beyond the ponderomotive limit: direct laser acceleration of relativistic electrons in sub-critical plasmas. Phys. Plasmas **23**, 056704 (2016)

Avetissian, H.K., Avetissian, A.K., Mkrtchian, G.F., Sedrakian, K.V.: Production of fast ion and nuclei bunches of solid densities from nanolayers by ultrarelativistic laser pulses. Phys. Rev. ST Accel Beams **14**, 101301 (2011)

Chang, H.X., Qiao, B., Huang, T.W., Xu, Z., Zhou, C.T., Gy, Y.Q., Yan, X.Q., Zepf, M., He, X.T.: Brilliant petawatt gamma-ray pulse generation in quantum electrodynamic laser-plasma interaction. Sci. Rep. **7**, 45031 (2017)

Dabu, R.: High power, high contrast hybrid femtosecond laser system. AIP Conf. Proc. **1852**, 070001 (2017)

Denavit, J.: Absorption of high-intensity subpicosecond lasers on solid density targets. Phys. Rev. Lett. **69**, 3052–3055 (1992)

Ferri, J., Davoine, X., Kalmykov, S.Y., Lifschitz, A.: Electron acceleration and generation of high-brilliance x-ray radiation in kilojoule, subpicosecond laser-plasma interactions. Phys. Rev. Accel. Beams **19**, 101301 (2016)

Fiuza, F., Stockem, A., Boella, E., Fonseca, R.A., Silva, L.O., Haberberger, D., Tochitsky, S., Gong, C., Mori, W.B., Joshi, C.: Laser-driven shock acceleration of monoenergetic ion beams. Phys. Rev. Lett. **109**, 215001 (2012)

Forslund, D.W., Shonk, C.R.: Formation and structure of electrostatic collisionless shocks. Phys. Rev. Lett. **25**, 1699–1702 (1970)

Fortin, P.L., Piche, M., Varin, C.: Direct-field electron acceleration with ultrafast radially polarized laser beams: scaling laws and optimization. J. Phys. b: at. Mol. Opt. Phys. **43**(2), 025401 (2009)

Gales, S., Tanaka, K.A., Balabanski, D.L., Negoita, F., Stutman, D., Tesileanu, O., Ur, C.A., Ursescu, D., Andrei, I., Ataman, S., Cernaianu, M.O., D'Alessi, L., Dancus, I., Diaconescu, B., Djourelov, N., Filipescu, D., Ghenuche, P., Ghita, D.G., Matei, C., Seto, K., Zeng, M., Zamfir, N.V.: The extreme light infrastructure—nuclear physics (ELI-NP) facility: new horizons in physics with 10 PW ultra-intense lasers and 20 MeV brilliant gamma beams. Rep. Progr. Phys. **81**(9), 094301 (2018)

Geddes, C.G.R., Toth, C., Tilborg, J.V., Esarey, E., Schroeder, C.B., Bruhwiler, D., Nieter, C., Cary, J., Leemans, W.P.: High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding. Nature **431**, 538–541 (2004)

Ghotra, H.S., Kant, N.: Electron injection for direct acceleration to multi-GeV energy by a Gaussian laser field under the influence of axial magnetic field. Phys. Plasmas **23**, 053115 (2016)

Ghotra, H.S., Kant, N.: Effects of laser-polarization and wiggler magnetic fields on electron acceleration in laser-cluster interaction. Laser Phys. Lett. **15**, 066001 (2018)

Ghotra, H.S., Jaroszynski, D., Ersfeld, B., Saini, N.S., Yoffe, S., Kant, N.: Transverse electromagnetic Hermite-Gaussian mode-driven direct laser acceleration of electron under the influence of axial magnetic field. Laser Part. Beams **36**, 154–161 (2018)

Joshi, C.: Laser-driven plasma accelerators operating in the self-guided blowout regime. IEEE Trans. Plasma Sci. **45**(12), 3134–3146 (2017)

Kim, Y.K., Cho, M.H., Song, H.S., Kang, T., Park, H.J., Jung, M.Y., Hur, M.S.: Shock ion acceleration by an ultrashort circularly polarized laser pulse via relativistic transparency in an exploded target. Phys. Rev. E **92**, 043102 (2015)

Kostyukov, I., Pukhov, A., Kiselev, S.: Phenomenological theory of laser-plasma interaction in bubble regime. Phys. Plasmas **11**(11), 5256–5264 (2004)

Li, Y.Y., Gu, Y.J., Zhu, Z., Li, X.F., Ban, H.Y., Kong, Q., Kawata, S.: Direct laser acceleration of electron by an ultra intense and short-pulsed laser in under-dense plasma. Phys. Plasmas **18**, 053104 (2011)

Lu, W., Tzoufras, M., Joshi, C., Tsung, F.S., Mori, W.B., Vieira, J., Fonseca, R.A., Silva, L.O.: Generating multi-GeV electron bunches using single stage laser wakefield acceleration in a 3D nonlinear regime. Phys. Rev. ST Accel. Beams **10**, 061301 (2007)

Macchi, A., Nindrayog, A.S., Pegoraro, F.: Solitary versus shock wave acceleration in laser-plasma interactions. Phys. Rev. E **85**, 046402 (2012)

Malka, G., Lefebvre, E., Miquel, J.L.: Experimental observation of electrons accelerated in vacuum to relativistic energies by a high-intensity laser. Phys. Rev. Lett. **78**, 3314–3317 (1997)

Mohammed, J., Ghotra, H.S., Kaur, R., Hafeez, H.Y., Kant, N.: Electron Acceleration in Bubble Regime. AIP Conf. Proc. **1860**, 020013 (2017)

Naseri, N., Bychenkov, V.Y., Rozmus, W.: Axial magnetic field generation by intense circularly polarized laser pulses in underdense plasmas. Phys. Plasmas **17**, 083109 (2010)

Nemeth, K., Shen, B., Li, Y., Shang, H., Crowell, R., Harkay, K.C., Cary, J.R.: Laser-driven coherent betatron oscillation in a laser-wakefield cavity. Phys. Rev. Lett. **100**, 095002 (2008)

Nesterov, A.V., Niziev, V.G.: Laser beams with axially symmetric polarization. J. Phys. D: Appl. Phys. **33**, 1817–1822 (2000)

Palmer, C.A.J., Dover, N.P., Pogorelsky, I., Babzien, M., Dudnikov, G.I., Ispiriyan, M., Polyanskiy, M.N., Schreiber, J., Shkolnikov, P., Yakimenko, V., Najmudin, Z.: Monoenergetic proton beams accelerated by a radiation pressure driven shock. Phys. Rev. Lett. **106**, 014801 (2011)

Phuoc, K.T., Corde, S., Fitour, R., Shah, R., Albert, F., Rousseau, J.-P., Burgy, F., Rousse, A., Seredov, V., Pukhov, A.: Analysis of wakefield electron orbits in plasma wiggler. Phys. Plasmas **15**, 073106 (2008)

Pukhov, A., Meyer-ter-Vehn, J.: Laser wake field acceleration: the highly non-linear broken-wave regime. Appl. Phys. B **74**, 355–361 (2002)

Pukhov, A., Gordienko, S., Kiselev, S., Kostyukov, I.: The bubble regime of laser-plasma acceleration: monoenergetic electrons and the scalability. Plasma Phys. Control. Fusion **46**, B179–B186 (2004)

Sawaf, S., Tawfik, W.: Analysis of heavy elements in water with high sensitivity using laser induced breakdown spectroscopy. Optoelectron. Adv. Mater. **8**, 414–417 (2014)

Singh, P.K., Pathak, V.B., Shin, J.H., Choi, I.W., Nakajima, K., Lee, S.K., Sung, J.H., Lee, H.W., Rhee, Y.J., Aniculaesei, C., Kim, C.M., Pae, K.H., Cho, M.H., Hojbota, C., Lee, S.G., Mollica, F., Malka, V., Ryu, C.M., Kim, H.T., Nam, C.H.: Electrostatic shock acceleration of ions in near-critical-density plasma driven by a femtosecond petawatt laser. Sci. Rep. **10**, 18452 (2020)

Sinibaldi, G., Occhicone, A., Pereira, F.A., Caprini, D., Marino, L., Michelotti, F., Casciola, C.M.: Laser induced cavitation: plasma generation and breakdown shockwave. Phys. Fluids **31**, 103302 (2019)

Sprangle, P., Esarey, E., Ting, T., Joyce, G.: Laser wakefield acceleration and relativistic optical guiding. AIP Conf. Proc. **193**, 376–387 (1989)

Sun, G.Z., Ott, E., Lee, Y.C., Guzdar, P.: Self-focusing of short intense pulses in plasmas. The Phys. of Fluids **30**, 526–532 (1987)

Varaki, M.A.: Electron acceleration by a circularly polarized electromagnetic wave publishing in plasma with a periodic magnetic field and an axial guide magnetic field. Modern Phys. Lett. B **32**(20), 1850225 (2018)

Varaki, M.A.: Electron acceleration of a surface wave propagating in wiggler-assisted plasma. Modern Phys. Lett. B **33**(23), 1950267 (2019)

Wang, T., Khudik, V., Arefiev, A., Shvets, G.: Direct laser acceleration of electrons in the plasma bubble by tightly focused laser pulses. Phys. Plasmas **26**, 083101 (2019)

Wen, M., Salamin, Y.I., Keitel, C.H.: Electron acceleration in direct laser-solid interaction far beyond the ponderomotive limit. Phys. Rev. Applied **13**, 034001 (2020)

Wong, L.J., Hong, K.H., Carbajo, S., Fallahi, A., Iot, P., Soljacic, M., Joannopoulos, J.D., Kartner, F.X., Kaminer, I.: Laser-induced linear-field particle acceleration in free space. Nature **7**, 11159 (2017)
Zhang, S.Y.: Accurate correction field of circularly polarized laser and its acceleration effect. J. at. Mol. Sci. **1**(4), 308–317 (2010)
Zhang, X., Khudik, V.N., Shvets, G.: Synergistics Laser-Wakefield and Direct-Laser Acceleration in the Plasma-Bubble Regime. Phys. Rev. Lett. **114**, 184801 (2015)
Zhang, X., Wang, T., Khudik, V.N., Bernstein, A.C., Downer, M.C., Shvets, G.: Effects of laser polarization and wavelength on hybrid laser wakefield and direct acceleration. Plasma Phys. Control. Fusion **60**, 105002 (2018)