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Electron Acceleration in the Bubble Regime with Dense-Plasma Wall Driven by an Ultraintense Laser Pulse *

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An optimizing scheme for electron acceleration in the wake bubble with dense-plasma wall driven by an ultraintense laser pulse is presented and investigated by particle-in-cell simulation. The wall has an inner diameter matching the expected lateral bubble size. The bubble shape can be transversely controlled and longitudinally shrunk. The accelerated electrons as a bunch have a high quality because the electrons almost stay close to the bottom of the bubble and are accelerated to much high energy with narrow energy spread.

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Driven by a short laser pulse or particle beam propagating in a tenuous plasma, a wake wave would be excited strongly that can be used to accelerate a charged particle due to its high acceleration gradient. The laser wakefield acceleration[1,2] and plasma wakefield acceleration[3] are promising to be substituted for traditional accelerators with greater acceleration rates and more compact facilities. Recent experiments have extended accelerated electron energy from around 100 MeV[4] to GeV or higher[5] in the wakefield acceleration regime. The other involving acceleration schemes are also proposed, e.g., proton driven acceleration[6] and comparable results are given for electrons and positrons accelerations.[7] Theoretically these wakefield electron acceleration experiments can be reasonably described in the blowout[8] or bubble[9] regime, in which the bulk plasma electrons are expelled by laser pulse and form an electron cavity which contains strong and almost linear[10−12] space-charge field. Certainly these accelerated electrons are trapped and self-injected at the bottom of the bubble due to wave breaking.[13,14] There have been many schemes proposed to improve the electron self-injection in wakefield acceleration, including optical injection,[15] downward plasma density transition,[16] parabolic plasma density profile,[17] tightly focused intense laser beam,[18] nanowire,[19] but few are presented for optimizing the acceleration process in the bubble regime. To obtain higher electron energy, we usually use lower plasma density and longer acceleration distance.[20] However continuous electron self-injection would result in poor quality of electron beams than single self-injection because of the beam loading.[21]

In this Letter, we present a way to optimize the electron acceleration in the wake bubble by adding a dense-plasma wall in the tenuous plasma. This wall has an inner diameter matching the expected lateral bubble size and forms the wall of a rarefied-plasma channel along the path of the driving source. The electron accelerations in the laser-plasma wake bubble with and without the wall are compared in the two-dimensional (2D) particle-in-cell (PIC) simulation.[22] We find that with the wall, the self-injected electron bunch is accelerated to much higher energy with narrower energy spread, and the rear part of the continuous self-injected electron bunch does good to enhance the acceleration field and to increase the energy of accelerated electrons.

We perform our investigation by using the 2D3V PIC simulation.[22] In order to carry out continuous electron self-injection, we use the simulation parameters similar to the previous investigation.[23] The incident laser pulse, propagating along the x-axis, has a Gaussian envelope $a \sim A_0 \exp[-0.5(y/R_L)^2 - 0.5(t/T_L)^2]$, where $R_L = 6.72\,\mu\text{m}$, $cT_L = 3.2\,\mu\text{m}$, and the laser wavelength is $\lambda = 800\,\text{nm}$. The laser amplitude is $a_0 = eA_0/mc^2 = 20$ (with the corresponding intensity $I = 8.6 \times 10^{20}\,\text{W/cm}^2$), where $-e$ and m are the electron charge and mass respectively, and c is the speed of light in vacuum. The simulation cell is constituted by longitudinal grid scale with 1/32 laser wavelength and transverse grid scale with 1/64 plasma wavelength. In addition, 8 particles are placed in each cell for background plasma and 800 particles for high-density wall region. The pulse enters a 1 mm long plasma slab with the density $n_0 = 0.01n_c$, where n_0 is the bulk plasma density, $n_c = m\omega^2/4\pi e^2$ is the critical density, ω is the laser frequency. The left vacuum is initially about 24 μm, and the preformed tenuous plasma has a density rising linearly from 0 to n_0 in a distance of 8 μm. To study how the dense-plasma wall affects the electron self-injection and acceleration, we carry out the simulations with and without the

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wall with the plasma density $n_w = n_c$, wall thickness $d_w = 2.4\,\mu$m and inner radius R_w close to the expected lateral bubble radius in the uniform tenuous plasmas. It should be noted that because of laser skin depth for wall is about $a\lambda_{p,wall}/\sqrt{2} < d_w$ and moreover the laser focus size is smaller than R_w, the longitudinal propagating laser is hardly transparent transversely to the wall.

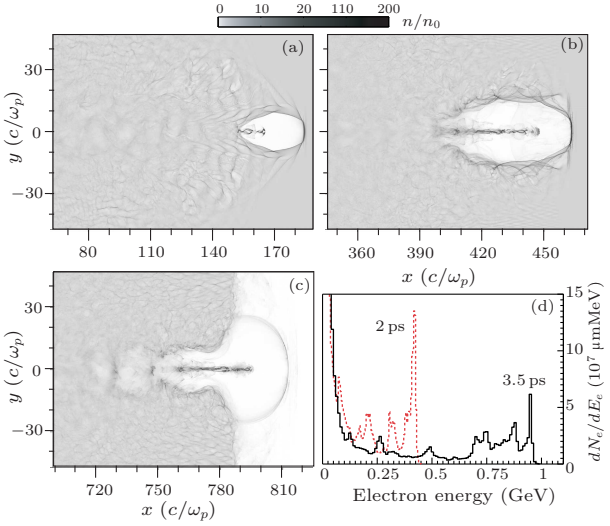


Fig. 1. (Color online) The simulation with a Z-LP laser pulse in uniform tenuous plasmas. Electron density distribution at (a) $t = 0.8$ ps, (b) $t = 2$ ps, and (c) $t = 3.5$ ps. (d) Electron energy spectrum at $t = 2$, 3.5 ps.

To approach the real three-dimensional (3D) situation, we also demonstrate the investigation with different laser polarizations: y-directionally linear-polarized (Y-LP), z-directionally linear-polarized (Z-LP) and circular-polarized (CP) in $y - z$ plane. For convenience, the dimensionless time, length, velocity, and momentum are given by $\omega_p t$, $\omega_p x/c$, v/c, and p/mc, respectively, where ω_p is the plasma frequency. The dimensionless electron density and electric field are given by n/n_0 and $eE/mc\omega_p$, respectively. In addition, because our simulations are 2D spatial, when we count the electron numbers, we assume that the length along z-direction is 1 μm, and the electron numbers will be given with an unit of 1/μm.

In Fig. 1, we demonstrate the continuous electron self-injection in the bubble regime with a Z-LP laser pulse propagating in an uniform tenuous plasmas with the parameters mentioned above. In our investigation, $a_0^2/2 \gg 8/R_L^2$ or $P \gg P_c$, where P is the peak power of the pulse and P_c is the critical power for relativistic self-focusing,[24] the pulse will be self-guided. In Fig. 1(a) at $t = 0.8$ ps, the pulse has been self-focused to an smaller spot size. The injected bunch has a length of about $14c/\omega_p$, and contains about 3×10^9 self-injected electrons, where $c/\omega_p \approx 1.27\,\mu$m. Then the pulse propagates another length of about Z_R at $t = 2$ ps in Fig. 1(b), where $Z_R = 2\pi R_L^2/\lambda \approx 353.8\,\mu$m is the Rayleigh length, i.e. ~ 278.6 normalized distance in units of $c/\omega_p \approx 1.27$. The pulse is compressed along the propagation direction, since the rear part of the pulse propagates faster than the front part. Even part of the rear part of the pulse overtakes the front part, and is diffracted to lateral sides of the bubble front since it is not guided in the ion channel. This leads to two small electron cavities beside the bubble front, or a ring in real 3D space, as can be seen in Fig. 1(b). The self-injections have occurred continuously, and the injected bunch has a length of about 48 with about 10^{10} injected electrons. Finally, after another $1.2\,Z_R$ distance, we obtain a $40c/\omega_p$ long accelerated bunch with about 10^{10} electrons, shown in Fig. 1(c). As we can see from Fig. 1(d), the energy spread of the electron bunch is broad and the energy spectrum is multi-peak, since the accelerated electrons are spread in broad space in the continuous self-injection, some have passed the bubble center after $t = 2$ ps and the large amount of self-injected electrons significantly impair the acceleration field.

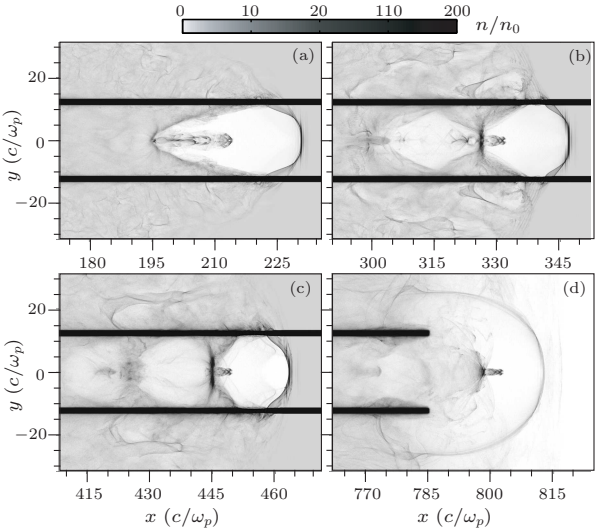


Fig. 2. (Color online) The simulation with the Z-LP laser pulse and a dense-plasma wall with inner radius $R_w = 11.31$. Electron density distribution at (a) $t = 1$ ps, (b) $t = 1.5$ ps, (c) $t = 2$ ps, and (d) $t = 3.5$ ps.

We can estimate the 2D lateral bubble size by comparing the potential energy of the expelled electrons at the bubble edge with the ponderomotive potential,[10,12,25] $\frac{1}{4}y_b^2 - \sigma y_b \sim \frac{\delta a}{\sqrt{2}}$, where y_b is the lateral radius of the bubble, $\sigma = \int_0^{y_0} n_b dy$ is due to the electrostatic force from the injected bunch, y_0 and n_b are the lateral radius and density of the injected bunch respectively, δa is the real-time pulse amplitude varying with time. In Fig. 1(a) at $t = 0.8$ ps, we take $\delta a = \sqrt{2}a_0$ as the pulse is self-focused more intensely, and take $\sigma = 0$ since the injected bunch is not so long or close to the bubble center to affect the lateral bubble size significantly. Then we obtain the estimated lateral bubble radius at $t = 0.8$ ps to be 8.94, which is close to the PIC data 9.1. In Fig. 1(b) at $t = 2$ ps, we take $\delta a = 2a_0$ due to the effects of self-focus and longitudinal compression, and take $\sigma = 2.18$, which

is half the average value of the injected bunch since the bunch occupies nearly half of the front half of the bubble. Then we estimate the lateral bubble radius at $t = 2$ ps to be 15.85, which is close to the PIC data of 15.4.

If we place a dense-plasma wall with an inner diameter smaller than the maximum lateral size of the bubble along the path of the laser pulse, we can expect that it would prevent the expansion of the bubble. In Fig. 2, we run the simulation by adding the wall with an inner radius $R_w = 11.31$ to form a channel along x-axis, where R_w is larger (smaller) than the minimum (maximum) lateral radius of the bubble in Fig. 1. We can see from Fig. 2 that there are roughly three stages of the electron acceleration: (i) the continuous self-injection stage, (ii) the stage of clipping the injected electron bunch, (iii) the quasi phase-stable acceleration stage.

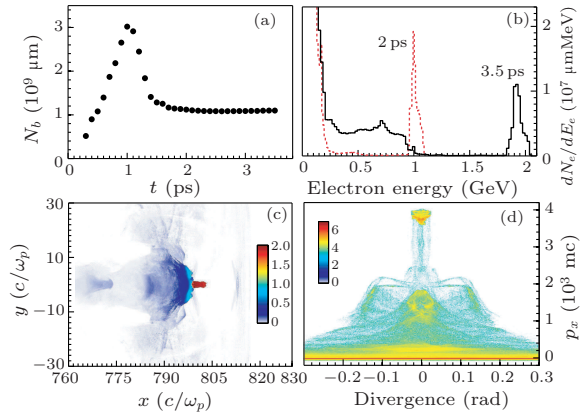


Fig. 3. (Color online) The properties of the electrons in Fig. 2. (a) The electron numbers of the accelerated bunch at different times. (b) Electron energy spectrum at $t = 2, 3.5$ ps. (c) Average energy distribution and (d) angular divergence of the electrons at $t = 3.5$ ps, where N'_e is the number of electrons per unit momentum (mc) per unit mrad.

In the continuous self-injection stage, i.e. before $t = 1$ ps, see Fig. 2(a), the lateral bubble size is smaller than the inner diameter of the wall, the bubble evolves as in the uniform tenuous plasmas previously, the self-injection occurs continuously.

The clipping stage of the injected bunch lasts from $t = 1$ ps to $t = 2$ ps, as can be seen from Figs. 2(a), 2(b) and 2(c). At the beginning of this stage, the bubble grows up to meet the dense-plasma wall, the latter shields the fields from the ion channel and injected bunch quickly, and prevents the expansion of the bubble. Meanwhile, the dense plasma electrons in the wall are expelled outward slightly. This causes a dense positive-charged thin layer at the lateral bubble edge. This dense positive-charged layer enhances the longitudinal acceleration field and leads to the shrink of the rear electron sheath of the bubble, then the rear part of the injected bunch is clipped behind the bottom of the first bubble, see Fig. 2(b). The clipped bunch is damped but pushes the electrons in front of it and drives the second bubble, so that the bottom electron sheath of the first bubble is made to be denser to further enhance the longitudinal acceleration field. We can see from Fig. 3(a) that, in the clipping stage, the electron numbers of the accelerated bunch keep decreasing from $t = 1$ ps to $t = 2$ ps, but tend to a constant after $t = 2$ ps. Finally, the shrink of the rear sheath of the first bubble becomes very slow, and the clipping of the injected bunch is stop, it comes to the quasi phase-stable acceleration stage.

The slowdown of the shrink of the bubble may be due to the three reasons: (i) the bubble may shrink to a certain size with the wall of a certain inner size, (ii) the decrease of the accelerated bunch and the depletion of the pulse lead to smaller lateral expansion;, (iii) the clipped bunch, which can push the bottom of the first bubble and can enhance the longitudinal acceleration field, is depleted gradually.

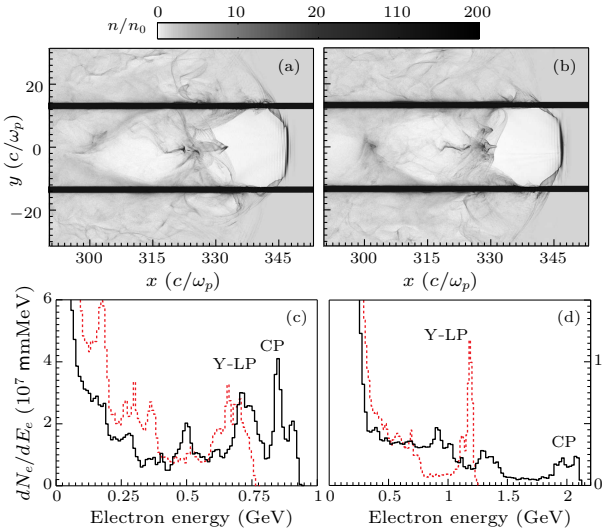


Fig. 4. (Color online) The simulations with the Y-LP/CP laser pulse and with/without a dense-plasma wall with inner radius $R_w = 12.25$. [(a) and (b)] Electron density distributions at $t = 1.5$ ps with the wall, where (a) with Y-LP laser (b) with CP laser. [(c) and (d)] Electron energy spectrums at $t = 3.5$ ps, where (c) without the wall, (d) with the wall.

In the quasi phase-stable acceleration stage, with the benefits of the push from the clipped bunch and the enhancement of the longitudinal acceleration field, a part of the electrons at the bottom of the first bubble goes forward with the accelerated bunch. We can see in Fig. 2(d) and 3(b), 3(c) and 3(d) at $t = 3.5$ ps, when the accelerated bunch run out of the plasma slab, a part of the electrons from the bubble bottom follows it with the longitudinal momentum of about 1–$2 \times 10^3 mc$. The divergence of the longitudinal speed between the accelerated bunch and the bottom of the bubble is quite smaller than that between the accelerated bunch and the front of the bubble. The accelerated bunch almost always stays close to the bottom of the bubble, and is quasi phase-stable accelerated forward, see Fig. 2(c) and 2(d). The slope of the lon-

gitudinal electric field at $t = 2$ ps is about 1.7, which is quite larger than 0.5,[10,12] because of the longitudinal shrink of the bubble and the enhancements from the dense positive-charged thin layer and the dense-electron bottom of the bubble. On the other hand, the weakening of the acceleration field from beam-loading is significantly reduced, therefore the acceleration field is quite larger than that in the uniform tenuous plasmas, and the accelerated bunch almost always stays close to the bottom of the bubble and feels the largest acceleration field so that it is accelerated to a much higher energy with a narrower energy spread and smaller angular divergence. For example, as shown in Figs. 3(b) and 3(d) at $t = 3.5$ ps, the injected bunch is accelerated to nearly 2 GeV with 4% energy spread within ± 25 mrad angular divergence, in comparison with that without the dense-plasma wall where the maximum energy is about 1 GeV and the energy spectrum is multi-peak, see Fig. 1(d).

If we make the inner diameter of the dense-plasma wall larger, the bubble size would be larger, the continuous self-injection stage would last longer, more electrons would be self-injected, but the clipping and quasi phase-stable acceleration stages would start later, and the remain accelerated bunch would be longer. This would lead to more accelerated electron numbers while lower electron energy and even multi electron energy peaks. On the other hand, if we make the inner diameter of the wall smaller, we would obtain smaller bubble, larger electron energy and narrower energy spread but fewer accelerated electrons. When the wall is too narrow, the injected bunch would be clipped at all.

When we use Y-LP or/and CP laser pulse in the $y-z$ plane to perform 2D PIC simulation, there is laser field in y-direction, and we can see from Figs. 4 that the bubbles become asymmetric because of the effect of the laser pulse carrier-envelop phase.[26] Because of this asymmetry, if we take the same size of the wall as in the Z-LP laser case, the injected bunch is clipped so much. Thus we use a wider wall with the inner radius $R_w = 12.25$. The laser power is kept equally, i.e., $a_y = 20$ in the Y-LP laser case, $a_y = a_z = 20/\sqrt{2}$ in the CP laser case. This means lager laser field in y-direction in the Y-LP laser case, and leads to lager asymmetry.[26] Because of this, lower accelerated electron energy is gained in the Y-LP laser case. Like the Z-LP laser case, the injected electron are accelerated to higher energy with the wall, see Figs. 4(c) and 4(d). With the wall, the injected bunch is accelerated to about 1.2 GeV with 4.4% energy spread in the Y-LP laser case at $t = 3.5$ ps, while it is 2 GeV with 10% energy spread in the CP laser case. The electron numbers of the finally gained accelerated bunches in both Y-LP and CP laser cases are about 0.5×10^9, which is half of that in the Z-LP laser case.

In summary, optimizing electron acceleration in the wake bubble is proposed by placing a dense-plasma wall. With the wall, the electron acceleration process could be roughly considered as three stages: (i) the continuous self-injection stage, (ii) the stage of clipping the injected bunch, and (iii) the quasi phase-stable acceleration stage. The dense plasma electrons in the wall are expelled outward slightly to cause a dense positive-charged thin layer at the lateral bubble edge, which significantly enhances the longitudinal acceleration field. The shrink of the bubble and the clipped bunch further enhance the acceleration field. Certainly because of the presence of high-density wall, the surface magnetic field by density jump would play a significant role[27] on modification of bubble shape and evolution. In addition, it also affects the bubble core fields that lead to enhancement of acceleration of electrons in the bubble. However, the detailed analysis is beyond the scope of present study and needs to study theoretically as well PIC numerically in future.

The computation was carried out at the HSCC of the Beijing Normal University.

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