Electron injection by a nanowire in the bubble regime

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The triggering of wave-breaking in a three-dimensional laser plasma wake (bubble) is investigated. The Coulomb potential from a nanowire is used to disturb the wake field to initialize the wave-breaking. The electron acceleration becomes more stable and the laser power needed for self-trapping is lowered. Three-dimensional particle-in-cell simulations were performed. Electrons with a charge of about 100 pC can be accelerated stably to energy about 170 MeV with a laser energy of 460 mJ. The first step towards tailoring the electron beam properties such as the energy, energy spread, and charge is discussed. © *2007 American Institute of Physics*.
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I. INTRODUCTION

Electron acceleration in laser-driven plasmas has drawn wide attention due to the potential for making small-scale high-energy accelerators.[1–3] The recent development of the "bubble" regime[4–10] has demonstrated the capability of generating high-quality electron beams with beam energy up to 1 GeV,[10] and relatively small energy spread and emittance approaching that from a conventional accelerator. Driven by an intense electron beam, an energy gain of 2 GeV is obtained over a distance of 10 cm.[11]

A "bubble" is a three-dimensional (3D) plasma wave formed when the electrons are pushed away by an intense laser pulse, leaving a cavity behind. The return current of the electrons come back and form the cavity's shell. The maximum electric field in the bubble, given by $eE_{\max}/mc\omega_p = \sqrt{2}(P/P_c)^{1/6}$, has a very weak dependence on the laser power P,[12] where m is the electron mass, c is the light velocity, and ω_p is the plasma frequency. The critical laser power for relativistic self-focusing is $P_c = 17 n_c/n_e$ GW, where n_e and n_c are plasma density and critical density, respectively.[13] As electron flows collide at the base of the bubble, transverse wave-breaking may occur when the local electric field is large enough or when the electron energy distribution has a long tail to the high-energy side.[14,15] In this case, a dense electron bunch is injected and trapped into the plasma wave and is violently accelerated. The bunch of the injected electrons produces a Coulomb field that terminates the injection abruptly until the next time the wave-breaking threshold is reached (which may not happen). This process, termed beam loading, usually results in spatially and temporally localized injection and thus the formation of a quasimonoenergetic electron beam.[15]

The "bubbles" tend to be easily formed when the laser power satisfies $P > [\tau(\mathrm{fs})/\lambda(\mu\mathrm{m})]^2 \times 30$ GW.[16] Here τ and λ are duration and wavelength of the drive laser, respectively. The plasma density must be large enough for the laser pulse to self-focus and small enough so that the plasma wavelength is comparable to that of the laser pulse duration. In a recent experiment, it was demonstrated that longer laser pulses can also form bubbles via self-modulation and compression.[9]

While a bubble can be relatively easily formed over a broad range of laser and plasma parameters, the parameters for wave-breaking are more precise. In one dimension, wave-breaking occurs when the electric field is larger than $E_{\mathrm{WB}} = \sqrt{2}(\gamma_{\mathrm{p}}-1)^{1/2}E_0$ for a cold plasma in the nonlinear regime, where $\gamma_p = (1-v_p^2/c^2)^{-1/2}$ is the relativistic factor associated with the phase velocity v_p of the plasma wave and $E_0[\mathrm{V/cm}] \approx 0.96 n_e^{1/2}[\mathrm{cm}^{-3}]$ is the nonrelativistic wave-breaking field.[17–19] For three dimensions, a similar situation exists. In general, it is very difficult to control the breaking of the wave due to the highly nonlinear behavior of the wake, which in turn directly impacts the amount of trapped electrons and their acceleration.

In this sense, the scheme of external injection of electrons into a wake field or induced self-injection by additional laser pulses or density disturbance are both still viable solutions. Several injection schemes have been proposed. One method utilizes the ponderomotive force of an additional laser field, such as a crossing laser pulse,[20] the beat wave of two colliding pulses,[21] or a counterpropagating pulse.[22,23] Another scheme introduces a plasma density disturbance such as a sharp density drop.[24–28]

In this paper, we analyze the wave-breaking triggering mechanism and propose to control the breaking by using a trigger disturbance to the wake field supplied by a nanowire in the plasma. The scheme is demonstrated in a series of 3D particle-in-cell (PIC) simulations using the code VORPAL.[29]

II. THEORY

While the bubble is a special 3D structure of a wake, the field structure is still similar to a one-dimensional wake.[3] Therefore, we begin with a one-dimensional analysis of the bubble field. Considering a circularly polarized, plane-wave laser pulse of amplitude $a=eA/mc^2$ propagating in the x direction, leaving a bubble behind it with a wake field of scalar potential $\phi(\xi)=\phi(\xi)/mc^2$, the phase velocity $\beta_{\mathrm{ph}}=v_{\mathrm{ph}}/c$ of the wake equals the group velocity of the laser pulse. Here $\xi=x-v_{\mathrm{ph}}t$. We have[3]

$$\sqrt{1+p_x^2+a^2(\xi)}-\phi(\xi)-\beta_{\mathrm{ph}}p_x=h_0, \tag{1}$$

where the integral constant h_0 depends on the initial velocity of the electron. For electrons in front of the laser pulse, $h_0=\sqrt{1+p_x^2}-\beta_{\mathrm{ph}}p_x$. The momentum of the electron is given by

$$p_x=\frac{\beta_{\mathrm{ph}}(\phi+h_0)\pm\sqrt{(\phi+h_0)^2-(1-\beta_{\mathrm{ph}}^2)(1+a^2)}}{1-\beta_{\mathrm{ph}}^2}. \tag{2}$$

For $\beta_{\mathrm{ph}}\to 1$, we have[18]

$$k_p^{-2}\frac{\partial^2\phi}{\partial\xi^2}=\frac{1+a^2}{2(1+\phi)^2}-\frac{1}{2}. \tag{3}$$

As an example, we consider a laser pulse of wavelength 0.8 μm, a peak amplitude $a=2$, and a duration of 30 fs. The plasma density is 6×10^{18} cm^{-3} with a corresponding plasma wavelength of 13.6 μm. Using Eqs. (1)–(3), the vector potential of the driving laser pulse and the generated scalar potential of the wake in Fig. 1(a) are obtained. The field minimum corresponds to the base of the bubble. Under this field, the electrons initially in front of the laser pulse move along the trajectory in the phase space in Fig. 1(b). At the base of the bubble, the electron reaches its momentum maximum. For an electron with zero initial momentum, the change is normally not large enough to place it in the accelerating phase or to be "trapped" in the bubble; hence it falls behind the bubble. There are two ways to put an electron into an accelerating trajectory. The first is to give the electron a big enough positive initial momentum, and the other is to modify the scalar potential (field) at the bubble base. Both are demonstrated in Fig. 1(b). Electrons of initial momentum 0.26 mc (compared to the longitudinal momentum in the laser pulse of $a^2/2=2$) are found to be trapped, while a minor perturbation of the field (about 10% of the peak vector potential of the laser) at the bubble base kicks an electron with zero initial momentum into the accelerating trajectory. Here the field perturbation is added artificially and is shown in Fig. 1(a). In the 1D limit, the threshold for the trapping is $\phi_{\min}=(1/\gamma_p-h_0)$.

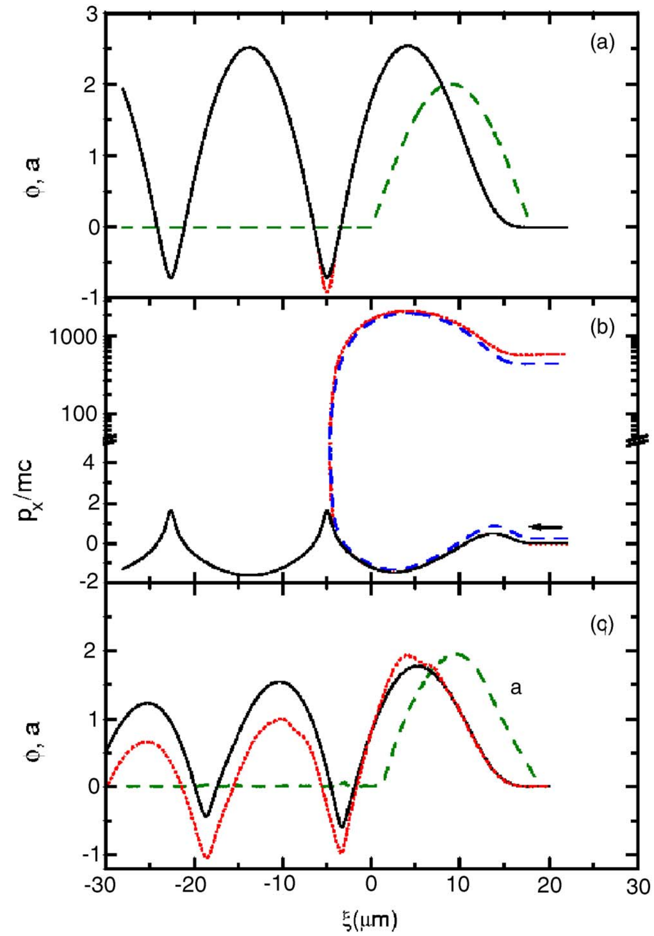

FIG. 1. (Color online) (a) Analytical calculation for the vector potential of the laser pulse (dashed line) and scalar potential with (dotted) and without (solid) a 10% perturbation for a 1D wake in a plasma of density 6×10^{18} cm^{-3} driven by a circularly polarized laser pulse of peak amplitude $a=2$ and duration 30 fs; (b) trajectories of electrons under different conditions from (a): zero initial momentum with (dotted) and without (solid) the 10% field perturbation, and 0.26 mc initial momentum without field perturbation (dashed); (c) 3D PIC simulation for the same plasma conditions with laser peak amplitude $a=1.414$ and a transverse FWHM of 12 μm. The solid (dotted) line shows the vector potential of the wake before (after) the bubble base hits the wire. The dashed line is the vector potential of the laser pulse. The arrow in (b) indicates the direction in which the electron is moving.

It should be mentioned that in this model, the electrons are supplied as test particles. In reality they are also the electrons from the wake wave, therefore the trapping indicates the breaking of the wake wave.

To initiate a disturbance to the scalar potential, we propose to use a nanometer-sized wire inside the bubble. As the laser hits the wire, some of the electrons are stripped off by the ponderomotive force, leaving the ions, which need more time to move. When the base of the bubble hits these ions, the Coulomb field of the ions and the Langmuir wave that is excited cause a significant disturbance to the scalar potential, resulting in breaking of the wave and trapping of the electrons.

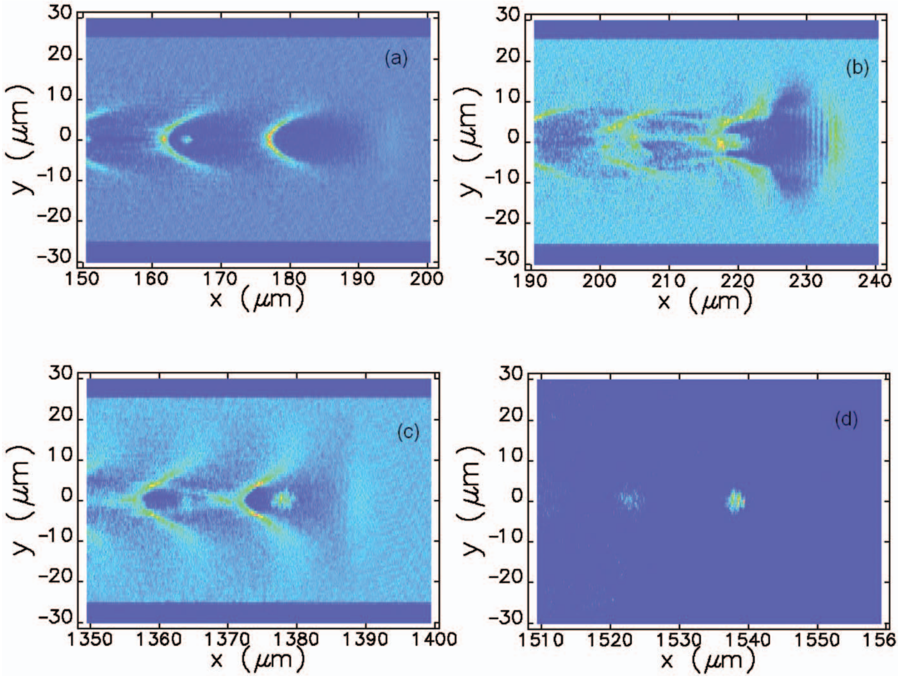

FIG. 2. (Color) Electron density contour plots at different times. The plasma density is 6×10^{18} cm^{-3} and the peak laser amplitude is 1.414. The wire is at $x=200$ μm and $z=6.35$ μm. (a) $t=0.67$ ps, just before the laser pulse meets the wire; (b) $t=0.8$ ps, right after the first bubble goes through the wire; (c) $t=4.67$ ps, when the trapped beam is still in the plasma; (d) at $t=5.2$ ps, after the electron bunch breaks into vacuum. The time is relative to when the laser enters the simulation box.

III. SIMULATIONS

To demonstrate the scheme, we carried out 3D PIC simulations using the code VORPAL.[29] In the simulation, the plasma has a density of 6×10^{18} cm^{-3} with sharp edges on both sides along the laser propagation direction (x). The circularly polarized laser pulse has a peak amplitude $a=1.414$, a transverse Gaussian distribution with a FWHM of 12 μm, and a longitudinal sinusoidal wave form with a duration of 30 fs, the same as the one used in the analytical calculation. The total laser energy is about 460 mJ. The plasma layer is from $x=5$ μm to $x=1500$ μm. With these parameters, all electrons are pushed away by the pondermotive force and bubble formation is observed, as shown in Fig. 2(a).[7] Without the trigger wire, we see wave-breaking and electrons trapped in the second bubble perhaps due to the sharp boundary of the plasma,[24] but no electrons are found to be trapped in the first bubble immediately following the laser pulse, similar to simulations of Faure *et al.* with the same parameters.[7] The vector and scalar potentials for this simulation are given in Fig. 1(c). Note that the peak laser strength is larger than that of the input pulse due to self-focusing in the plasma. Comparing it with the analytical field Fig. 1(a), the similarity in the field structure is obvious. From Eq. (2), one finds that at wave-breaking $\phi_{\min}=1/\gamma_p-1$, which is not met; hence no wave-breaking occurs.

The trigger wire changes the scenario dramatically. The wire, which is 0.7×0.7 μm^2 in cross section with an equal electron and ion density of 1.2×10^{21}/cm^3, is placed at $x=200$ μm in the x-y plane. To account for potential experiment error in placing the wire and to demonstrate the robustness of the scheme, we intentionally place the wire 6.35 μm off the laser axis in the z direction. As the laser pulse passes the wire, some electrons are stripped off by the pondermotive force, thus establishing a static Coulomb potential with amplitude up to that of the laser ponderomotive potential [Fig. 2(b)]. When the base of the bubble encounters the wire, a disturbance to the scalar wave potential with a frequency equal to the reciprocal of the wire size is initiated. This in turn changes the momentum of the electrons in the wake and drives some of them into an accelerating trajectory [Figs. 1(b) and 1(c)]. As the bubble moves forward, the distortion disappears, the field oscillation dumps, and the wave-breaking terminates. This process is depicted in the electron density contour plots at different times in Fig. 2. In Fig. 2(a),

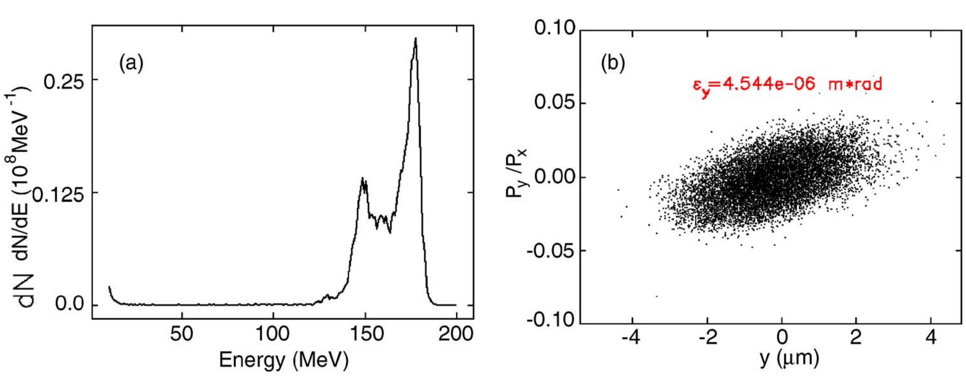

FIG. 3. Energy spectrum and emittance of the electron bunch accelerated in the first bubble after exiting the plasma at 1.5 mm.

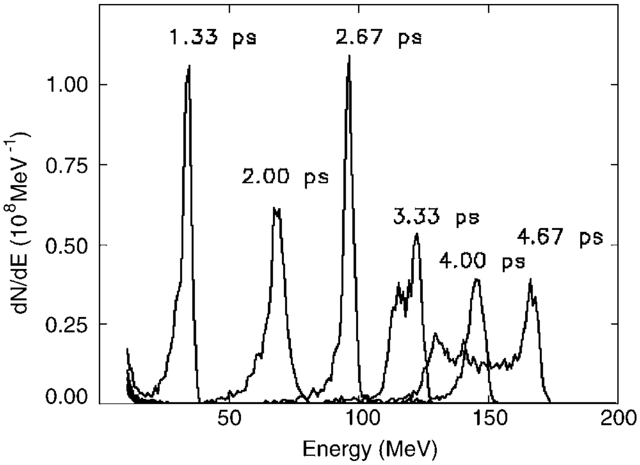

FIG. 4. Energy spectrum of the electron bunch at different times.

before the bubble meets the wire, no electrons are trapped in the first bubble, but some are in the second bubble. Trapping in the second bubble is the result of the sharp plasma boundary in the simulation, which displaces the phase of the background electrons due to the sudden density change.[24–28] Just after the first bubble goes through the wire, apparent wave-breaking occurs in it, while the second bubble is almost completely destroyed, as shown in Fig. 2(b). Afterwards, the structure of the bubble is partially restored; however, no further wave-breaking occurs [Figs. 2(c) and 2(d)]. The large amplitude modulation of the scalar field in Fig. 1(c) and the wave structure suggest a wave-breaking.

The energy spectrum and normalized emittance of the accelerated beam are given in Fig. 3. The peak energy is about 170 MeV, and the total charge is about 92 pC. With a bunch length of 6 μm, this gives a peak current of 4.5 kA. While there is a sharp edge at the high-energy side, the energy spread is relatively large at 10%, and the normalized emittance is 4.5 mm mrad. We believe the energy spread is dominated by space-charge-induced spreading, which eventually leads to a longitudinal energy chirp. The electrostatic field of the bubble is roughly linear but much steeper near the base of the bubble. The electrostatic field of the electron bunch itself has an opposite gradient to the field of the bubble. The sum of these two fields makes the energy spread change with time. The details are under investigation. This is seen in Fig. 4, where we find that the energy spectrum is narrow before $t=2.67$ ps when the peak energy is about 100 MeV; it becomes broader at later times, as has been observed by Gordienko *et al.*[16] This space-charge effect may prevent us from obtaining a high-energy, small-energy spread and a high charge at the same time.

To evaluate the robustness of the triggering scheme, additional simulations were performed. The trapped charge is apparently dependent on the transverse position of the wire. By moving the wire from $z_0=6.35$ μm to $z_0=2.15$ μm off the laser axis, the charge increases from 92 pC to 140 pC. The energy spectrum and normalized emittance for $z_0=2.15$ μm are given in Fig. 5. This is consistent with a wave-breaking scenario in which the total charge injected is proportional to the local background electron density. From the present simulations, the charge is estimated to be proportional to $n_e(r_b^2-z_0^2)$, where n_e is the background electron density, and r_b is the radius of the bubble. The energy spectra are very similar with smaller peak energy of 150 MeV. The spectrum broadens at earlier times, which are consistent with the beam-loading effect and space-charge-induced energy spread. This demonstrates the robustness of the scheme with respect to the transverse position of the wire. On the other hand, wire location also provides a means of finely controlling the beam parameters. The peak energy can be changed by modifying the longitudinal position of the wire, which controls the time of wave-breaking and hence the total acceleration. We also found that the scheme is not sensitive to wire cross section changes from 0.49 μm^2 to 1 μm^2.

IV. CONCLUSION

In summary, we have demonstrated that the wave-breaking process can be triggered by an abrupt disturbance of the wake field in the bubble regime by placing a nanowire into the bubble-forming plasma. By triggering the wave-breaking, we reduce the pump energy required for beam injection through wave-breaking by a factor of 2. The triggering also results in an electron bunch size smaller than 10 μm, and a charge of 140 pC can be accelerated to more than 170 MeV with a current of several kA. In an experiment, the wire may also be replaced by nanometer-sized particles or clusters in the gas jet.

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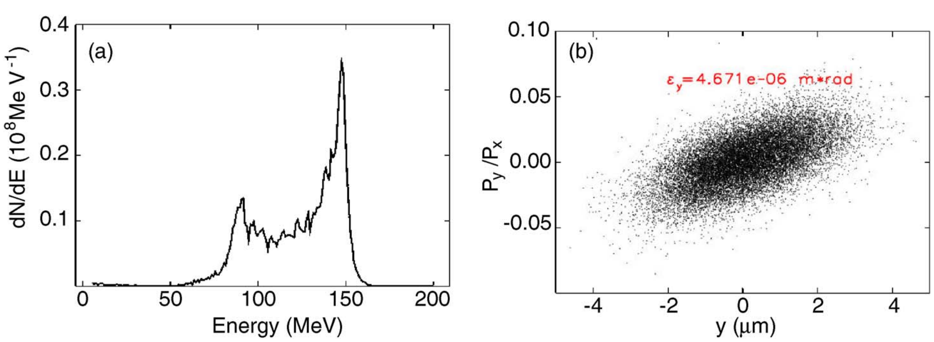

FIG. 5. The plasma and laser parameters are the same as for Fig. 2. The wire is at $x=200$ μm and $z=2.15$ μm.

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