Generation of a large amount of energetic electrons in complex-structure bubble

Jiancai Xu¹, Baifei Shen¹,³, Xiaomei Zhang¹, Meng Wen¹, Liangliang Ji¹, Wenpeng Wang¹, Yahong Yu¹ and Kazuhisa Nakajima²

¹ State Key Laboratory of High Field Laser Physics, Shanghai Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, PO Box 800-211, Shanghai 201800, People’s Republic of China
² High Energy Accelerator Research Organization, KEK 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan
E-mail: bfshen@mail.shcnc.ac.cn

Abstract. By means of particle-in-cell (PIC) simulations, we found that when the focus size of a laser pulse is much larger than the plasma wavelength and when the laser power is hundreds of times larger than the critical power required for relativistic self-focusing, a large complex bubble is formed. The transversal size of the bubble depends on the laser spot size. Owing to the large bubble size, a bunch of electrons with the total charge in the range of a few tens of nano-Coulombs is trapped and accelerated in the bubble. When the plasma density is $2 \times 10^{19}$ cm$^{-3}$, the charge of the energetic electron bunch with energy above 5 MeV exceeds 45 nC with a laser spot size of 60 µm. Electrons continuously self-injected into such a complex bubble serve as an effective source of high-charge electron bunches.
1. Introduction

Remarkable experimental progress in the field of electron acceleration with relativistic laser pulses has been seen in the past several years. In 2004, mono-energetic electron bunches were observed with laser–gas interaction [1]–[3]. The energy of a monoenergetic electron bunch has been up to GeV [4, 5] at present. The stability and control of the electron bunch have been partly solved by using another injecting laser pulse [6, 7] or other methods [8]–[10]. A laser-plasma accelerator may serve as an efficient accelerator with wide applications. However, there remains another important problem: the total charge of the energetic electron bunch. According to the present experimental and simulation results, the total charge is usually from several tens pC to 1 nC, while much larger charge is required for many applications, such as high-energy physics, femtosecond-timescale measurement, fast ignition for laser fusion, beam-driven inertial fusion and ultrahigh intense x-ray or γ-ray radiation sources from Betatron radiation and/or Thomson radiation [11, 12].

The bunch charge is limited by the injection method together with laser and plasma parameters [13, 14]. In the bubble regime [15], the maximum charge number is usually limited by evacuated electrons that is determined by plasma density and bubble size [16, 17]. A bubble can be roughly regarded as a sphere with the diameter of the plasma wavelength scaling with \( n_e^{-1/2} \); hence, the evacuated electron number \( N = \frac{1}{3} \pi (\frac{\lambda_p}{2})^3 n_e \) scales with \( n_e^{-1/2} \). This means that larger charge number can be obtained with smaller plasma density. However, smaller plasma density requires higher laser intensity, so that a bubble can be formed and electrons can be trapped and accelerated. In addition, smaller plasma density is more optimal for generating high-energy electron bunches.

In order to generate electron bunches with large charge number but relatively small electron energy, we propose a new method by which a laser pulse with focus size much larger than the plasma wavelength is employed to form a large bubble with complex structure. Due to the large bubble size, a bunch of electrons with the total charge in the range of a few tens of nano-Coulombs is trapped and accelerated in the bubble.

2. Formation of a large complex bubble with self-injected electrons

2.1. Three-dimensional (3D) simulation results

We first use the particle-in-cell (PIC) simulation code VORPAL [18] to study the self-injection and acceleration of electrons in the bubble regime. In the 3D PIC simulation, a
140 TW, 30 fs, 800 nm linearly polarized Gaussian laser pulse with a focus size of 35 μm full-width at half-maximum (FWHM) propagates through a uniform plasma with electron density \( n_e = 2 \times 10^{19} \text{ cm}^{-3} \), i.e. the corresponding plasma wavelength of 7.38 μm. It should be mentioned that the chosen plasma density is larger than that normally required to obtain a quasi-monoenergetic electron bunch [3]. This is because the higher density can provide many more electrons and make the laser pulse focused more easily. The plasma occupies a region of \((5–950 \mu\text{m}) \times (-70–70 \mu\text{m}) \times (-70–70 \mu\text{m})\) in \(x, y\) and \(z\), respectively, and the laser pulse propagates in the \(x\)-direction.

Figure 1 shows the contours of the charge density \( \rho \) at \( t = 2.133 \) ps where a typical complex bubble structure is displayed. The longitudinal size of the structure matches the plasma wavelength roughly, while the transverse size (\( \sim 40 \mu\text{m} \)) is much larger than the plasma wavelength. With such a complex bubble structure, the number of evacuated electrons is much larger than that with a small laser spot size (for comparison, a normal bubble excited by a laser pulse with a small spot size will also be shown in section 3). In this complex-structure bubble scheme, the transverse size of the bubble is no longer determined by the plasma wavelength, but instead by the laser focus size. Therefore, for a given laser intensity, the evacuated electron number scales with \( N = n_e (\pi L_P w_L^2) \propto \sqrt{n_e w_L^2} \), where \( w_L \) is the laser focus size and \( L_P \) is the longitudinal size (\( \sim 1/\sqrt{n_e} \)). This means that the number of evacuated electrons increases with the plasma density and the laser focus size. In this context we may obtain a high-charge electron bunch with relatively low electron energy by using high-density plasma. In this simulation, electrons of about 11.67 nC with energies above 5 MeV have been obtained from such a complex bubble structure.

In the normal bubble regime, the electrons are expelled mainly in the transverse direction to form a narrow sheath just around the bubble radius [19, 20]. But in this complex bubble regime, part of the expelled electrons also form another ‘electron sheath’ inside the bubble, shown as a small circle in the \( y–z \) plane in figure 1(b). In other words, the orbits of the expelled electrons are not only in the boundary of the bubble, but also inside the bubble, as shown in figure 1(a). Such a bubble with a complex structure in the transverse direction appears after the laser pulse has been focused to its minimum. The bubble shape is determined mainly by the ponderomotive potential of the laser pulse [21]. We shall study in detail the laser pulse evolution after it reaches a focus.
2.2. Analysis of complex bubble formation

The laser evolution of the transverse laser field is shown in figure 2. Since the laser power in our simulation is much larger than the critical power \( P_{cr} = \frac{17n_{c}/n_{e}}{GW} = 1.46 \text{TW} \) required for relativistic self-focusing, the spot size of the laser pulse reduces quickly and reaches its minimum, 4.5 \( \mu \text{m} \), at \( \sim 1.4 \text{ps} \). At that time, a normal bubble has already been formed and many electrons have been self-injected into the acceleration phase. After the laser pulse begins to defocus, it induces a complex bubble structure as shown in figure 1.

The distribution of a laser field at three different times is shown in figure 3. At the focus point of the laser pulse as shown in figures 3(a)–(c), there is only a single laser field peak in the transverse direction. After the laser spot size reaches its minimum, its profile is no longer Gaussian and the spherical aberrations occur as shown in figures 3(d)–(f). Consequently, a multi-peak structure of the laser pulse in the transverse direction appears due to strong relativistic self-focusing, and each peak undergoes individual self-focusing as shown in figures 3(g)–(i).

In laser–plasma interaction, electrons can be redistributed by the ponderomotive force \( F_p \propto \nabla I \), where \( I \) is the laser intensity. When the laser field has only one peak in the transverse direction, electrons are expelled in the transverse direction and form a sheath around the electron plasma cavity, i.e. the bubble. However, after the laser pulse is focused to its minimum, because of the induced transversal multi-peak structure of the laser pulse, a great number of electrons congregate between peaks of the laser intensity, escape from the laser pulse and quickly flow toward the bubble base to form a new ‘electron sheath’ inside the first bubble, as shown in figure 1(a). Compared with a normal bubble, the transverse bubble size increases accordingly. Moreover, we find that the longitudinal size also increases due to both the continuous electron injection and the large laser amplitude. Hence, many more electrons can be taken along by the bubble as more freight on a bigger boat.
Figure 3. Spatial distribution of the y component of the electron field ($E_y$) in the plasma at (a) 1.467 ps, (d) 1.733 ps and (g) 2.133 ps showing the transverse distribution evolution of the laser pulse at $z = 0$, respectively. Here, the vertical lineout of $E_y$ is shown in (b), (e) and (h), respectively, and the horizontal profile is shown in (c), (f) and (i), respectively.

Figure 4. The energy spectrum of the electron bunch driven by a 140 TW, 30 fs laser pulse with 35 µm FWHM focus size in the plasma density of $n_e = 2 \times 10^{19}$ cm$^{-3}$.

It can also be seen in figure 1(a) that the length of the electron bunch is more than 10 µm. Such a long bunch is generated because the electron self-injection starts before the laser pulse is focused and continues during pulse diffraction. The electrons at different positions within the same bunch are accelerated at different rates. The large charge-separation field due to the large charge number also makes the electrons pushed by additional non-uniform electrostatic force. Therefore, the bunch has a broad energy spread as shown in figure 4. The maximum energy of the bunch is about 450 MeV, much larger than the energy gain estimated by the linear or slightly nonlinear wakefield theory for the same plasma density [22], since the laser power for this simulation is high enough to accelerate a large amount of electrons up to high energies. When the energetic bunch leaves from the plasma, it contains the electron charge of 11.67 nC with energy higher than 5 MeV. This means that the wakefield is loaded with approximately 30% of the expelled electron charge of 36 nC.
Figure 5. The contours of the charge density $\rho$ are given in the $x$–$y$ plane at $z = 0$ with the initial laser spot size of (a) $w_L = 8 \, \mu m$, (b) $w_L = 35 \, \mu m$, (c) $w_L = 50 \, \mu m$, respectively, and the transverse profile in the $y$–$z$ plane at (d) $x = 0.42 \, mm$ for $w_L = 8 \, \mu m$, (e) $x = 0.62 \, mm$ for $w_L = 35 \, \mu m$ and (f) $x = 0.74 \, mm$ for $w_L = 50 \, \mu m$, respectively, where $\rho$ is normalized to $en_e$, and the window size shows only a fraction of the simulation box.

3. Effect of the laser spot size on the complex bubble size

In order to find out whether an even larger-size bubble exists, we perform a series of simulations with the laser spot sizes increasing from 8 to 70 $\mu m$, keeping the peak laser amplitude of $a_0 = 3.62$ and a uniform plasma density of $n_e = 2 \times 10^{19} \, cm^{-3}$.

Figure 5 displays the results with various laser spot sizes. In figure 5(a), with an initial laser spot size of 8 $\mu m$, a normal bubble is excited. The bubble radius is approximately equal to the plasma wavelength, so the evacuated electron charge is only 5 nC. With the same initial laser intensity $a_0$ and a much larger initial laser spot size of 35 $\mu m$, however, a complex bubble is excited to the transverse size of 40 $\mu m$, as shown in figure 5(b), thus corresponding to seven times larger evacuated electron charge of 36 nC than that of the former. Moreover, if the laser spot size increases further to 50 $\mu m$, the complex bubble structure becomes more complicated as shown in figures 5(c) and (f). In the $x$–$y$ plane, the bubble has been divided into several parts by the small ‘electron sheaths’ displayed as concentric circles with different radii in the $y$–$z$ plane. More detailed and comprehensive simulation results are listed in table 1.

According to table 1, the electron charge $Q_1$ with energy above 5 MeV increases with the laser spot size, and an increase of the accelerated electron number is consistent with that of the total expelled electron number when the laser spot size increases from 8 to 50 $\mu m$. Therefore, the ratio of beam-loading is relatively constant over such a range of the laser spot size. It is noted that the charge of the electron bunch with $w_L = 70 \, \mu m$ is smaller than that with $w_L = 60 \, \mu m$. This means that it is not always efficient to increase the accelerated electron...
Table 1. The simulation results with various laser spot sizes, where \( w_L \) is the initial laser spot size, \( Q_1 \) is the charge of the energetic bunch, \( L_b \) is the electron bunch length, \( I_{\text{peak}} \) is the peak current of the electron bunch, \( \langle E \rangle \) is the average energy of the bunch with energy over 5 MeV, \( I_A \) is the Alfven limit and \( \eta \) is the conversion efficiency of energy from the laser pulse to the electron bunch, respectively.

| \( w_L \) (\( \mu m \)) | \( P/p_{\text{cr}} \) | \( Q_1 \) (nC) \( (E > 5 \text{ MeV}) \) | \( L_b \) (\( \mu m \)) | \( I_{\text{peak}} \) (kA) | \( \langle E \rangle \) (MeV) | \( I_A \) (kA) | \( \eta \) (%) |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------|
| 8              | 7.3            | 1.64           | 8              | 61.5           | 38.71          | 1304           | 15.2     |
| 35             | 140            | 11.67          | 15             | 233.4          | 125.79         | 4201           | 18.3     |
| 50             | 280            | 30.57          | 18             | 509.5          | 106.20         | 3550           | 20.1     |
| 60             | 410            | 46.40          | 20             | 696            | 97.74          | 3268           | 19.7     |
| 70             | 560            | 45.84          | 20             | 687.6          | 94.68          | 3166           | 13.56    |

number by increasing the laser spot size and that there is an optimum spot size for high-charge electron acceleration.

With the electron bunch length and charge, this gives a peak current \( I_{\text{peak}} \). It can be seen in table 1 that the peak current of the bunch is much larger than that of the conventional accelerator but is still less than the Alfven limit given by \( I_A = 17\beta\gamma \) (kA), where \( \beta \) is the ratio of the average velocity of the electron bunch to the speed of light and \( \gamma \) is the Lorentz factor.

The conversion efficiency of energy from the laser pulse to the electron bunch reaches its maximum at \( w_L = 50 \mu m \). The average energy of the energetic bunch (>5 MeV) decreases as the laser spot size increases, because the complicated bubble structure may affect the acceleration field.

In general, the laser spot size determines the transverse bubble size and the evacuated electron number. With a large laser spot size, a large complex bubble is generated, leading to a large amount of self-injected and accelerated electrons. With an optimum spot size \( w_L = 60 \mu m \), the total charge of electrons with energy above 5 MeV reaches almost 45 nC in our simulation as shown in table 1. Such a high-charge electron bunch, with a large energy spread, has very important applications. For example, the electron beam from a laser-plasma accelerator can be converted into a \( \gamma \)-ray source using bremsstrahlung radiation in a dense material. Using such a \( \gamma \)-ray source, radiography of complex and dense objects with sub-millimetre resolution can be performed [12].

4. Discussions and conclusions

A complex structure bubble results from 3D effects. Two-dimensional (2D) simulations have been made with the same laser and plasma parameters as those for the 3D simulations. They show that although the structure of several peaks of the laser field in the transverse direction also appears, it results in several separate bubbles in the transverse direction eventually, instead of a bubble with the complex structure discussed above.

When the focus size of a laser pulse is much larger than the plasma wavelength, and the laser power is hundreds of times larger than the critical power for relativistic self-focusing,
the evacuated electron number scales with $n_1^{1/2}$. This indicates that higher plasma density would provide a higher number of evacuated electrons. In very-high-density plasma, the laser pulse focuses/defocuses very quickly. Correspondingly, the bubble complex structure also disperses and disappears very fast, so that there would be no time for many background electrons to be injected into the bubble. In order to further increase the total charge of the energetic electron bunch, further research is required to find a solution for overcoming the quick dispersion.

In conclusion, by 3D PIC simulation, we have studied the interaction of underdense plasma with an ultra-intense laser pulse with large spot size, the power of which is hundreds of times larger than the critical power required for self-focusing. A multi-peak structure of the laser field in the transverse direction occurs, to form a large bubble with a complicated structure because of the relativistic self-focusing after the laser pulse reaches a focus. As a result, a large amount of background electrons is continuously self-injected and accelerated in the bubble.

The complex bubble becomes larger and more complicated as the laser spot size increases. Simultaneously, the beam-loading efficiency is relatively stable. But it is not always effective to increase the laser spot size and there is an optimal spot size for a high-charge electron accelerator. In the plasma density of $2 \times 10^{19}$ cm$^{-3}$, the energetic electron bunch charge with energy above 5 MeV reaches 45 nC with a laser spot size of 60 $\mu$m.

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References

[1] Mangles S P D et al 2004 Nature 431 535
[2] Geddes C G R, Toth C, Tiborg J V, Esarey E, Schroeder C B, Bruhwilder D, Nieter C, Cary J and Leemans W P 2004 Nature 431 538
[3] Faure J, Glinec Y, Pukhov A, Kiselev S, Gordienko S, Lefebvre E, Rousseau J P, Burgy F and Malka V 2004 Nature 431 541
[4] Hafz N A M et al 2008 Nat. Photon. 2 571
[5] Leemans W P, Nagler B, Gonsalves A J, Toth C, Nakamura K, Geddes C G R, Esarey E, Schroeder C B and Hooker S M 2006 Nat. Phys. 2 696
[6] Rechatin C et al 2009 Phys. Rev. Lett. 102 164801
[7] Faure J, Rechatin C, Norlin A, Lifschitz A, Glinec Y and Nalka V 2006 Nature 444 737
[8] Osterhoff J et al 2006 Phys. Rev. Lett. 101 085002
[9] Shen B F et al 2007 Phys. Plasmas 14 053115
[10] Geddes C G R et al 2008 Phys. Rev. Lett. 100 215004
[11] Schlenvoigt H-P et al 2008 Nat. Phys. 4 130
[12] Glinec Y et al 2005 Phys. Rev. Lett. 94 025003
[13] Zhidkov A, Fujii T and Nemoto K 2008 Phys. Rev. E 78 036406
[14] Hosokai T, Kinoshita K, Zhidkov A, Maekawa A, Yamazaki A and Uesaka M 2006 Phys. Rev. Lett. 97 075004
[15] Geissler M, Schreiber J and Meyer-ter-vehn J 2006 New J. Phys. 8 186
[16] Lu W, Tzoufras M, Joshi C, Tsung F S, Mori W B, Vieira J, Fonseca R A and Silva L O 2007 Phys. Rev. Sel. Top. Accel. Beams 10 061301
[17] Gordienko S and Pukhov A 2005 Phys. Plasmas 12 043109
[18] Nieter C and Cary J R 2004 J. Comput. Phys. 196 448
[19] Lu W, Huang C, Zhou M, Mori W B and Katsouleas T 2006 Phys. Rev. Lett. 96 165002
[20] Lu W, Huang C, Zhou M, Tzoufras M, Tsung F S and Mori W B 2006 Phys. Plasmas 13 056709
[21] Kostyukov I, Pukhov A and Kiselev S 2004 Phys. Plasmas 11 5256
[22] Cormier-Michel E, Geddes C G R, Esarey E, Schroeder C B, Bruhwiler D L and Cowan P K 2009 AIP Conf. Proc. 1086 297