CHIN.PHYS.LETT. Vol. 18, No. 12 (2001) 1628

Particle Simulation Research on the Detailed Process of Bubble Generation *

MA Yan-Yun(马燕云), CHANG Wen-Wei(常文蔚), YIN Yan(银燕),
CAO Li-Hua(曹莉华), YUE Zong-Wu(岳宗五)
Department of Applied Physics, National University of Defense Technology, Changsha 410073

(Received 10 June 2001)

The detailed process of bubble generation in laser–plasma interaction has been studied by particle simulation. During the interaction between laser and plasma, a strong electrostatic field caused by charge separation is observed, whose structure looks like a potential well. Electrons are accelerated to 10 MeV within some tens of femtoseconds when the laser intensity is $5\times10^{18}\,W/cm^2$. After many electrons escape from the potential-well-like structure, electron cavitons are generated. Because of laser filamentation, the intensity of the laser becomes very asymmetric, the caviton structure is squeezed and deformed, and then electron bubbles are generated, which finally results in ion bubble formation. It is the electron caviton and laser beam filamentation that cause bubble generation. The 10 MeV superthermal electron generation accompanied by the electron caviton is attributed to $\boldsymbol{E}\nabla\cdot\boldsymbol{E}$ heating, which is a locally oscillating electron heating mechanism.

PACS: 52. 35. Mw, 52. 40. Nk, 52. 65. Rr

Laser pulses with some 100 fs duration and energy up to kilojoules[1] result in numerous abnormal phenomena.[2−4] Ultra-high laser pulses make it significant to explore the phenomena occurring during the interaction between such lasers and plasma. Particle simulation is a very effective method for exploring such ultra-fast process. By using particle simulation, many new phenomena[4] have been found. A 2.5D particle-in-cell (PIC) code is used to simulate the interaction between the ultra-high laser pulse and plasma. In this letter, we give the detailed process of bubble generation. The key results are that a 10^9 V/cm electrostatic field is found, whose structure is potential-well-like, and electrons oscillate in this structure. Electrons are accelerated to a very high speed and escape from this structure, and then electron cavitons are formed. Once the incident laser becomes filamentary, the intensity of the laser becomes very asymmetric, the caviton structure is squeezed and deformed, and then electron bubbles are generated. It is believed that the main heating mechanism is the $\boldsymbol{E}\nabla\cdot\boldsymbol{E}$ heating mechanism. These results are new, in contrast with the results obtained by other authors.[5,6]

We use a 2.5D electromagnetic, relativistic, collisional[7] particle-in-cell code to study this process. We begin with a simulation which focuses on the interaction of high-intensity laser light with a pre-formed plasma. Laser light with wavelength $\lambda_0 = 1.06\,\mu$m and a Gaussian intensity profile (in the y-direction) is introduced at the left boundary and propagates (in the x-direction) through a region of vacuum onto a slope of plasma. The system is $8\,\lambda_0$ long in the x-direction and $8\lambda_0$ wide in the y-direction. With $3.5\lambda_0$ of vacuum preceded, the plasma density is ramped from 0 to $3n_c$, (where n_c is the critical density) over a distance of $4\lambda_0$, then there is a plasma plateau which is $0.5\lambda_0$ in length and $3n_c$ in density. The initial electron temperature T_e is 4 keV, and the ion temperature T_i is one third of T_e. The electron–ion mass ratio is 1/1836. The incident wave is turned on over $72\omega_0^{-1}$ and has a Gaussian transverse intensity profile with the half width of $1\lambda_0$, and a peak intensity of $I = 5\times10^{18}\,\mathrm{W/cm^2}$. The incident laser is s-polarized.

The intense, s-polarized laser beam irradiates the plasma ramp normally and is reflected near n_c. Then the standing wave is generated in the underdense plasma. Electrons are pushed towards the nodes of the standing wave just by the gradient of the wave field,[8] but ions do not move because the process is too fast for ions to catch up with the motion of electrons. The electron density changes greatly and two cavitons are formed, but ion does not change on the whole, as shown in Fig. 1. The charge separation results in the generation of a strong electrostatic field, whose structure is just like some potential wells. The distribution of the field along the x-direction is shown in Fig. 2. In order to study the origin of the electrostatic field further, Fig. 3 presents the evolution of the oscillating current and the electrostatic field at the spot $(4.9\,\lambda_0, 5.5\,\lambda_0)$. From Fig. 3 we can see the relation between the electrostatic field and the oscillating current. The electrostatic field changes with the oscillating current. The electron density at that spot becomes smaller and smaller, while the current becomes larger and larger, so electrons at that spot must be accelerated. From Fig. 4 we can see that there are two groups of high-energy electrons, and they are accelerated within a very small region. In this region, the structure of the electrostatic field is just like a potential well. Electrons are confined in the potential-well-like structure

*Supported by the Hi-Tech ICF Committee of China and the National Natural Science Foundation of China under Grant Nos. 10085002 and 19885008.

©2001 Chinese Physical Society and IOP Publishing Ltd

at first, but during the oscillation and acceleration some of them have such high speed that they can escape from this structure. When they escape from this region, they lose their energy and their energy becomes the electrostatic energy. During the process, charge separation becomes larger and larger because more and more electrons escape from the structure, and the field becomes stronger and stronger until this structure is broken. When the potential-well-like structure is broken, the energy of the electrostatic field transforms into electron energy. With more and more electrons escaping from this structure, electron cavitons are formed. In order to show this more clearly, we change the width of the computational region from $8\lambda_0$ to $4\lambda_0$ in the y-direction and obtain the caviton figure shown in Figs. 5. From Figs. 1 and 5, we can clearly see that two cavitons are formed.

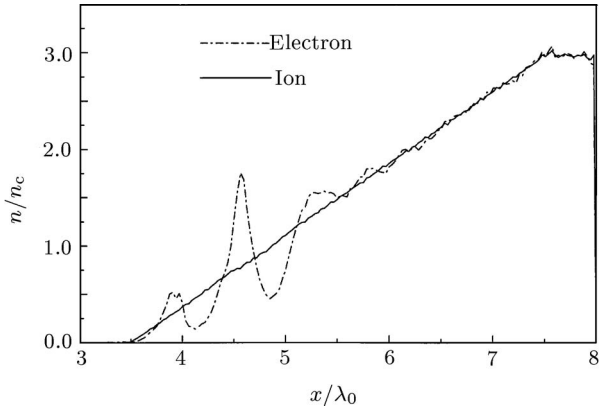

Fig. 1. Plasma density distribution along the x-direction at time $\omega_0 t = 67.6$.

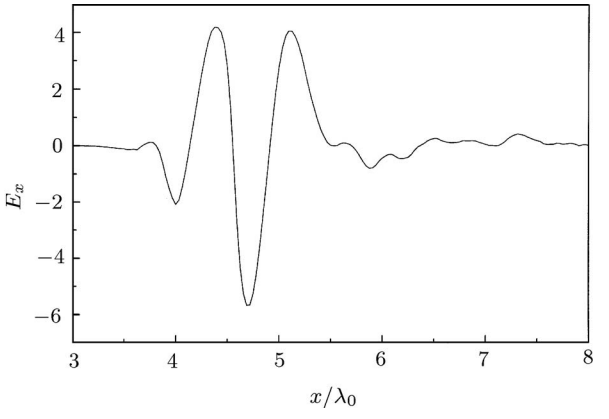

Fig. 2. Electrostatic field distribution along the x-direction at time $\omega_0 t = 60.8$.

During the process, the oscillating character of electron acceleration is different from abnormal-skin-heating,[9,10] vacuum heating,[11] $\boldsymbol{J} \times \boldsymbol{B}$ heating[12] and so on. It is also different from the electron acceleration mechanism during the hole boring when an ultra-intense laser impinges onto overdense plasma.[13] In that case, electrons are accelerated and move forward, which also causes ions to move forward. Electrons do not oscillate and there is not as strong an electrostatic field by contrast with this case. Thus it must be a kind of new heating mechanism, which we call the locally oscillating electron heating mechanism. This is much more effective than $\boldsymbol{J}\times\boldsymbol{B}$ heating partly because electrons are accelerated many times during the oscillation process.

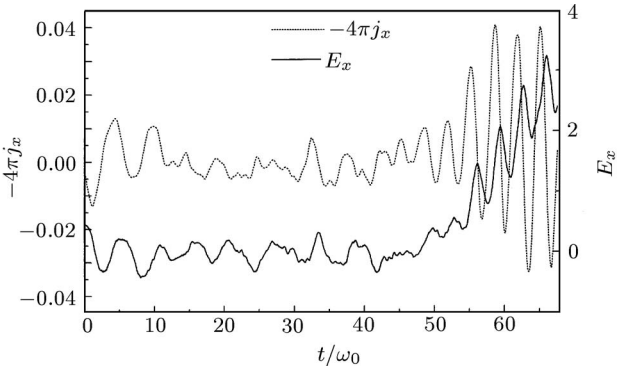

Fig. 3. Evolution of electrostatic field and current at the spot (4.9λ,5.5λ).

Generally speaking, cavitons (or ripples) are caused by nonlinear force. Nonlinear force (sometime called ponderomotive force) includes several terms. In this process, the $\boldsymbol{J} \times \boldsymbol{B}$ term may play the role of a drive source. The $\boldsymbol{E}\nabla\cdot\boldsymbol{E}$ term plays an important role in the electron heating process. If merely $\boldsymbol{J}\times\boldsymbol{B}$ heating exists, electrons cannot be accelerated to such a high speed that their energy can reach to 10 MeV.

Though our results are mainly based on single-particle simulation, we should mention an interesting relation to the macroscopic two-fluid plasma equations. The force density equation in a plasma is (Eq. (8.3) in Ref. [14])

$$\boldsymbol{f}_{\mathrm{NL}} = \frac{1}{c}\boldsymbol{J}\times\boldsymbol{B} + \frac{1}{4\pi}\boldsymbol{E}\nabla\cdot\boldsymbol{E} + \cdots, \qquad (1)$$

where we only consider the first two terms because the other terms are smaller. In our simulations the electrostatic field E_x is very large and the divergence of $\boldsymbol{E}$ is also very large, so the product of them is still larger. This mechanism is more effective than $\boldsymbol{J}\times\boldsymbol{B}$. The electrostatic field E_x or the divergence of $\boldsymbol{E}$ may be positive in some places and negative in other places, so the electron heating is a localized oscillating acceleration process.

We also note that the caviton field E_{cx} of a few 10^9 V/cm can be compared with the laser field amplitude in vacuum of about 10^{10} V/cm. There is a similarity to the general numerical results from the genuine two-fluid model[14–17] that the laser-driven longitudinal oscillations have an amplitude of about one tenth of the laser field amplitude in vacuum.

With time passing, we can see the filamentation and self-focusing of the laser. Laser filaments in the

underdense plasma and self-focusing in the overdense plasma are shown in Fig. 6. Filamentation makes the intensity of the laser become very asymmetric and the electron caviton structure is squeezed and deformed. In some places, the intensity of the laser is so great that electrons are pushed into the cavitons, whereas in other places electrons cannot be pushed into the cavitons because of the smaller laser intensity, and then electron bubbles are generated (Fig. 7). Some small electron bubbles are generated initially, then they are combined to form bigger bubbles. At last, ion bubbles are generated (Fig. 8). We can conclude that the formation of cavitons and laser filamentation is critical to the generation of bubbles. There are no bubbles under the condition that one of them is absent. When the p-polarized laser irradiates, similar phenomena are observed.

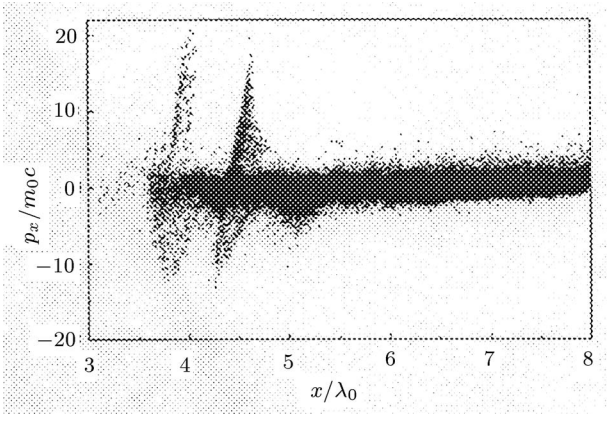

Fig. 4. Snapshot of electron phase space ($\boldsymbol{p}_x$ versus $\boldsymbol{x}$) at time $\omega_0 t = 60.8$.

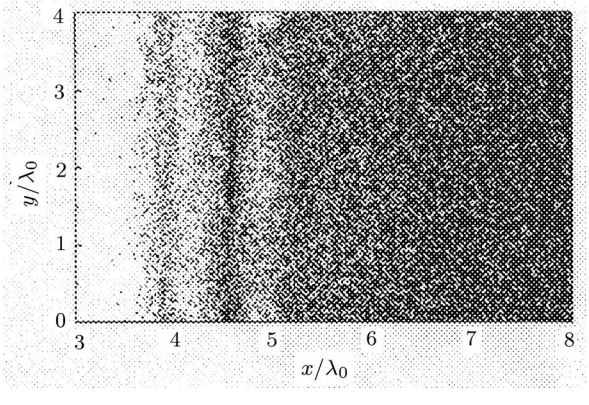

Fig. 5. Electron density in real space at time $\omega_0 t = 67.6$.

Estabrook[6] first studied the plasma bubbles, and later some other people studied the phenomena. Though our work is similar to their work, there are a lot of differences between our work and theirs. Firstly, Estabrook found the ion caviton at the critical density, but in our simulations the process is so fast that ions seldom move and only electron cavitons are formed. Secondly, the ion caviton was found by Estabrook only at the critical density, but in our simulations, electron cavitons are found not only at the critical density but also near $0.5n_c$. In fact, the place and number of cavitons are related to the scale length of the plasma. In other words, they are directly related to the number of nodes of the standing wave in plasma. In our simulations, we changed the scale length from $4\lambda_0$ to $12\lambda_0$, and found more cavitons. Our work is more similar to the work of Wilks[4], but he did not give the detailed process of the generation of bubbles. The absorption in our simulation is much more effective than the purely $\boldsymbol{J}\times\boldsymbol{B}$ mechanism. In Wilks' simulation, when the laser intensity is $10^{19}\,\mathrm{W/cm^2}$, the momentum p_x/m_0c (dimensionless quantity) of the hot electron is not more than 6 at $\omega_0 t = 180$. But, in our simulations, the momentum p_x/m_0c can reach 20 at $\omega_0 t = 60$ when the laser intensity is 5×10^{18} W/cm^2. Lastly, Estabrook thinks that it is the sausage-type instability that causes the bubbles, but we find that it is attributed to the formation of electron caviton and laser filamentation. We must point out that the condition of our work is different from Estabrook's though the results are similar. Under his conditions, we cannot find these phenomena within such a short time. Maybe these phenomena only occur when nonlinear effects are obvious.

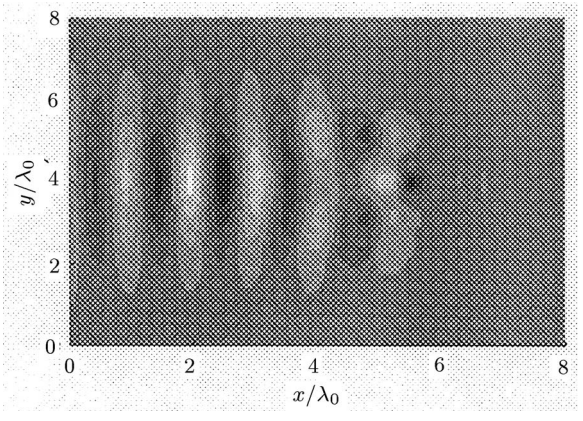

Fig. 6. Spatial contours of the laser field (magnetic field B_y) at time $\omega_0 t = 81.1$.

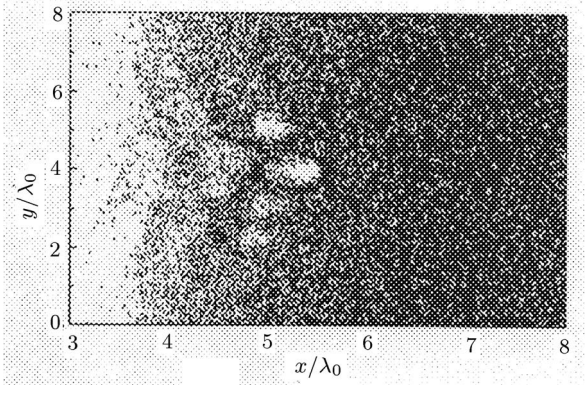

Fig. 7. Electron density in real space at time $\omega_0 t = 81.1$.

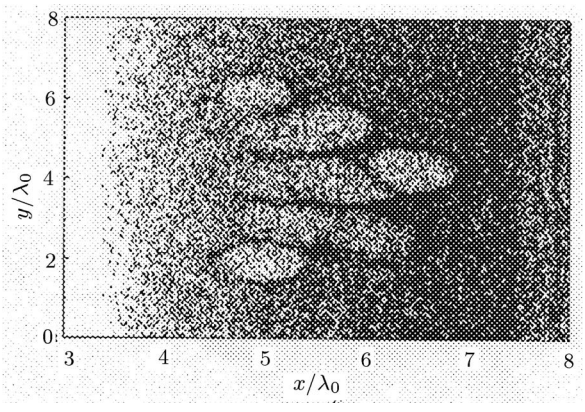

Fig. 8. Ion density in real space at time $\omega_0 t$=202.8.

This process is very important to the fast ignition concept[18] because it involves superthermal electron generation and hole boring, which are critical to fast ignition. Its effect on ignition deserves further study.

In summary, we study the formation of bubbles by particle simulation. During the interaction between laser and plasma, electron cavitons are produced by nonlinear force, and a strong electrostatic field is formed by charge separation, whose structure is just like potential wells. Electrons are accelerated to a very high speed and escape from this structure, and then charge separation becomes larger and larger until this structure is broken. It is believed that the main heating mechanism is the $\boldsymbol{E}\nabla\cdot\boldsymbol{E}$ heating mechanism. Because of laser filamentation, the intensity of the laser becomes very asymmetric, the caviton structure is squeezed and deformed, and then the electron bubbles are generated. The formation of cavitons and laser filamentation is critical to the generation of bubbles. The process is important to the realization of fast ignition.

We thank Professor Heinrich Hora of the University of New South Wales, Australia, for valuable scientific discussion.

References

[1] Perry M and Mourow G 1994 *Science* **91** 264
[2] Liu S B et al 2000 *Chin. Phys. Lett.* **17** 120
[3] Zheng C Y et al 2000 *Chin. Phys. Lett.* **17** 746
[4] Wilks S C et al 1992 *Phys. Rev. Lett.* **69** 1383
[5] Valeo E J and Estabrook K G 1975 *Phys. Rev. Lett.* **34** 1008
[6] Estabrook K 1976 *Phys. Fluids* **19** 1733
[7] Ma Y Y et al 2000 *Acta Phys. Sin.* **49** 1513 (in Chinese)
[8] Hora H 2000 *Plasmas at High Temperature and Density* (Regensburg: Roderer-Verlag)
[9] Hartemann F V et al 1998 *Phys. Rev.* E **58** 5001
[10] Wang J X et al 1998 *Phys. Rev.* E **58** 6575
[11] Brunel F 1987 *Phys. Rev. Lett.* **59** 52
[12] Kruer W L and Estabrook K 1985 *Phys. Fluids* **28** 430
[13] Ma Y Y et al 2000 *High Power Laser Part. Beams* **12** 589 (in Chinese)
[14] Hora H 2000 *Plasmas at High Temperature and Density* (Regensburg: Roderer-Verlag) p 134
[15] Hora H 2000 *Laser Plasmas Physics: Forces and the Nonlinearity Principle* (Bellingham, WA: PIE Books)
[16] Cicchhikelli L et al 1990 *Phys. Rev.* A **41** 3727
[17] Hora H, Llouris P and Eliezer S 1984 *Phys. Rev. Lett.* **53** 1650
[18] Tabak M et al 1994 *Phys. Plasmas* **1** 1623