ISSN 1547-4771, Physics of Particles and Nuclei Letters, 2018, Vol. 15, No. 7, pp. 728–731. © Pleiades Publishing, Ltd., 2018.
Original Russian Text © S.V. Kuznetsov, 2018, published in Pis'ma v Zhurnal Fizika Elementarnykh Chastits i Atomnogo Yadra, 2018.

HIGH ENERGY ACCELERATORS AND COLLIDERS

Trapping and Acceleration of Electron Bunches Generated by a Laser Pulse Moving through the Sharp Plasma Boundary

S. V. Kuznetsov*

Joint Institute for High Temperatures, Russian Academy of Sciences, Moscow, 125412 Russia

**e-mail: svk-IVTAN@yandex.ru*

Received November 1, 2017

Abstract—The formation and acceleration of electron bunches resulting from the self-injection of electrons into the wake wave from the laser pulse moving through a sharp plasma boundary are investigated in one-dimensional geometry. It is shown that electron trapping in the accelerating wakefield is governed by the electron energy and has a threshold character. The acceleration of the trapped bunch is numerically simulated.

DOI: 10.1134/S1547477118070476

INTRODUCTION

Successful experiments on the laser—plasma acceleration of electron bunches performed at a number of laboratories (see for example [1]) have demonstrated the acceleration of electrons to the energy of a few GeV over the length of ~10 cm and showed perspectives for developing a new class of small, inexpensive electron accelerators. Now the main objective is to improve the quality of the accelerated electron bunch, which depends to a large extent on the method used to inject electrons in the accelerating wakefield of the laser pulse.

One of the methods being extensively investigated is the insertion of electrons into the accelerating laser—plasma system based on the self-injection of electrons as the laser pulse moves through the plasma inhomogeneity [2]. One promising way to inject electrons of the plasma with increasing the density gradient was proposed in [3], where it was shown by numeric simulation that, under particular conditions in almost one-dimensional geometry, the interaction of a laser pulse with plasma results in the generation of electron bunches in a localized space region near the transition to the plateau in the plasma density profile. A theoretical analysis of this phenomenon [4–6] showed that the injection of electrons by this method [3] requires a laser pulse of very high intensity with the dimensionless vector potential $a_0 = |e| A_0 / mc^2 \sim 10$. On the other hand, a similar process of electron bunch generation under similar conditions was also studied by numeric simulation in [7], where a much lower laser pulse amplitude $a_0 \sim 1$ was enough to initiate the self-injection of electrons in the wakefield of the laser pulse passing through the sharp plasma boundary and their subsequent trapping and acceleration in it.

In this work, features of the physical mechanism for the generation of electron bunches at relatively low laser-pulse intensities are clarified and the necessary conditions for the self-injection and trapping of electrons in the wakefield for subsequent acceleration are found.

PHYSICOMATHEMATICAL MODEL

Let us consider a semibounded plasma, which we describe using the model of cold plasma in which only electrons are mobile while ions make up a fixed homogeneous positively charged background. A laser pulse is incident on the plasma boundary (considered sharp for simplicity) along the z axis normal to the plasma surface with its origin coinciding with the plasma boundary. The wave frequency of the incident pulse is much higher than the plasma frequency, which allows the plasma to be considered rarified.

In one-dimensional geometry, equations of motion of plasma electrons affected by the circularly polarized laser pulse have the form

$$\frac{dP}{dt} = |e|\frac{\partial \varphi}{\partial z} - mc^2 \frac{\frac{\partial}{\partial z}\left(\frac{eA}{mc^2}\right)^2}{2\sqrt{1 + \frac{P^2}{m^2c^2} + \left(\frac{eA}{mc^2}\right)^2}},$$
$$\frac{dz}{dt} = u = \frac{P/m}{\sqrt{1 + \frac{P^2}{m^2c^2} + \left(\frac{eA}{mc^2}\right)^2}}, \quad (1)$$

where $A(z,t)$ is the envelope amplitude of the vector potential of the laser pulse, $\varphi(z,t)$ is the scalar poten-

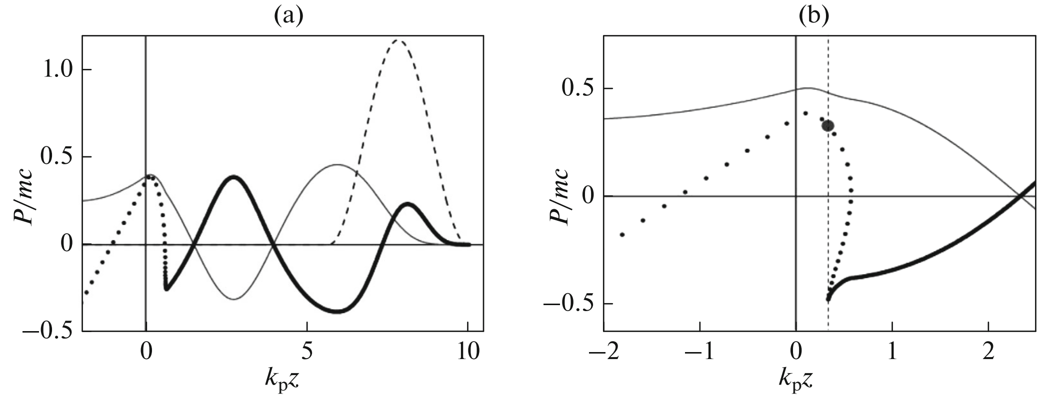

Fig. 1. Distribution of plasma electrons in the z, P phase plane at different instants of time: (a) beginning of the electron mixing; (b) self-injection of electrons in the wake field.

tial of the charge separation field, P and u are the electron momentum and velocity, and $-|e|$ and m are the electron charge and mass. The charge separation field arises from the effect of the laser pulse on the electron, which results in the electron being shifted from its initial equilibrium position z_0. Therefore, Eqs. (1) are closed for completeness by the Poisson equation $d^2\varphi/dz^2 = 4\pi|e|(n - n_0)$, where n and n_0 are the electron and the ion background densities.

According to [7], the laser-pulse profile can be considered invariable; therefore, the effect of the pulse on various plasma electrons differs only by the temporal shift $\Delta z_0/V_{gr}$, where Δz_0 is the initial distance between the electrons before their being affected by the laser pulse and V_{gr} is its group velocity. Upon the completion of the interaction between the laser pulse and the electron, its further motion in the region $z > 0$ is only under the effect of the charge separation field in plasma E_z, which, under the condition that the electron order is retained, depends on the shift of the electron with respect to its initial position z_0 and is defined by the formula $E_z = 4\pi|e|n_0(z - z_0)$. As a result, each of the electrons is a relativistic oscillator with the integral of the equation of motion

$$\sqrt{m^2c^4 + P^2c^2} + 2\pi e^2 n_0 (z - z_0)^2 = E_{os}, \qquad (2)$$

where E_{os} is the total oscillator energy. Thus, the effect of the laser pulse on the plasma is reduced to the excitation of a system of plasma oscillators with identical energy E_{os}.

Relation (2) holds for any plasma electron until it goes beyond the ion background, i.e., until it crosses the boundary of the unperturbed plasma. Under this condition the oscillator motion paths of all plasma electrons are similar, with a constant phase shift between them. The situation is different when electrons go beyond the ion background into the vacuum region $z < 0$. In this region, at the unchanged electron order, the force returning the electron to its oscillation center does not depend on its shift any longer. Therefore, the coherence of paths between the electrons returning from vacuum and between them and the electrons that do not leave for the region $z < 0$ is broken, which leads to their mixing and eventually to self-injection in the wakefield of the laser pulse.

NUMERIC SIMULATION

The numeric simulation of electron self-injection in the wakefield was performed for a laser pulse with an envelope that depended on time at the plasma boundary $(z = 0)$ as $a = a_0 \cos^2(t/\tau_L) \times \mathrm{sgn}(\pi\tau_L/2 - |t|)$, where $a_0 = |e|A_0/mc^2 = 0.827$ is the dimensionless amplitude of the vector potential and τ_L is the duration of the laser pulse corresponding to its duration at half-maximum $\tau_{FWHM} = 1.143\tau_L = 25$ fs. The group velocity V_{gr} of the laser pulse propagation in the plasma is taken to correspond to the gamma factor $\gamma_{ph} = 1/\sqrt{1 - V_{gr}^2/c^2} = 30$. The plasma density is determined from the relation $k_0/k_p = \gamma_{ph}$, where k_0 is the wave vector of the laser-pulse RF filling corresponding to the wavelength $\lambda_0 = 1$ μm and $k_p = \sqrt{4\pi e^2 n_0/(mc^2)}$.

Figure 1a shows the distribution of electrons in the z, P phase plane at the time when mixing of electrons begins after their return from the vacuum. Electrons in the z, P phase plane are shown by dots, and electrons that did not leave for the vacuum merge into a thick solid line. The laser pulse (dotted line) and the wake potential (thin solid line) are also schematically shown in the figure.

The simulation of the electron trapping by the accelerating wakefield showed that it was completely determined by electron oscillation energy E_{os} and had a threshold character. To reveal its features, the above-

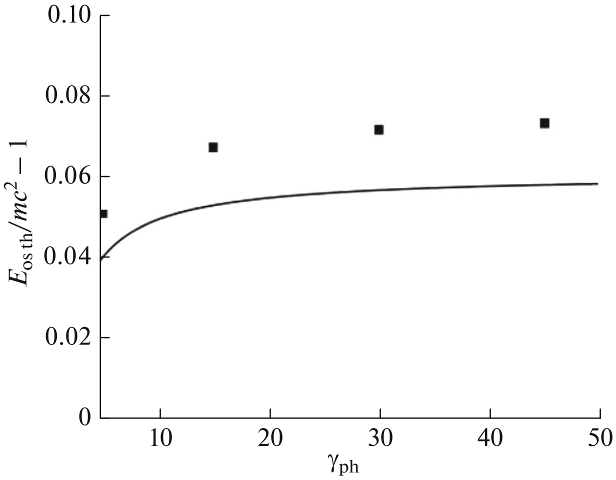

Fig. 2. Gamma factor dependence of the threshold energy of electron self-injection and trapping in the wake wave. Squares are simulation, and the solid line is the estimation by formula (3).

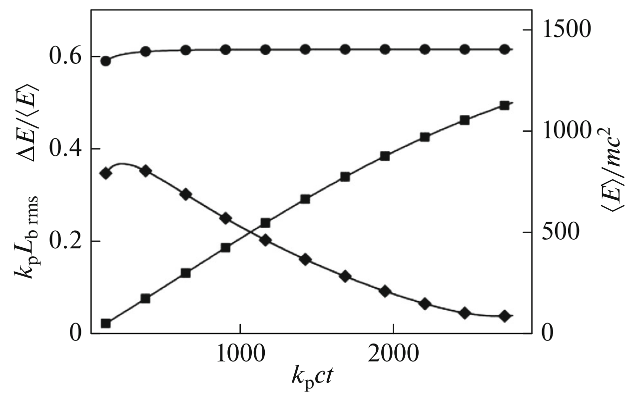

Fig. 3. Temporal variation in the electron-bunch length $L_{b\ rms}$ (circles), relative bunch electron energy spread $\Delta E/\langle E\rangle$ (diamonds), and average electron energy $\langle E\rangle$ (squares) during acceleration.

mentioned laser pulse parameters were chosen so that the energy of the excited plasma oscillators was equal to the threshold value $E_{os\ th}$ at which only one electron is trapped in the wakefield. This electron is shown in Fig. 1b by a large circle.

It is evident from Figs. 1a and 1b that the coherence breaking of oscillatory motion of electrons causes their mixing near the plasma boundary in a region much smaller in size than the plasma wavelength. Electrons from the vacuum approach the mixing region with a nearly maximum velocity in the positive direction of the z axis, and electrons from the plasma approach that region with the maximum velocity in the opposite direction, thus turning out to be in antiphase to a fraction of the electrons from the vacuum. This counterflow results in the intense mixing of the electrons and their self-injection in the wake wave, which may end with the trapping of a number of injected electrons for subsequent acceleration.

The electron that has the maximum velocity at self-injection—i.e., it is near its oscillation center and simultaneously enters the wake-wave phase corresponding to the maximum of its potential—is under the most favorable conditions for trapping in the wake wave. Replacing the nonstationary wake potential in the mixing region with the corresponding stationary potential excited in the plasma by the laser pulse with the same characteristics, one can estimate the threshold energy of plasma oscillators $E_{os\ th}$. For the stationary potential, the phase of its maximum is shown in Fig. 1b by the vertical dashed line.

The potential difference in the stationary wake wave is expressed in terms of the plasma oscillator energy $|e|\Delta\varphi/mc^2 = 2\sqrt{1-\gamma_{ph}^{-2}}\sqrt{E_{os}^2/m^2c^4 - 1}$. At the injection energy $E_{inj} = E_{os}$ the electron can be trapped in the wake wave only if its velocity in the region of the phase of the minimum wake potential becomes equal to the phase velocity of the wake wave. It gives us a formula for estimating the threshold energy for self-injection and trapping of electrons in the wake wave, which is shown in Fig. 2 as a function of γ_{ph} in comparison to the simulation results,

$$E_{os\ th} = mc^2\left(-\gamma_{ph} + \sqrt{72}(\gamma_{ph}^2 - 1)\right)\Big/(8\gamma_{ph}^2 - 9). \quad (3)$$

If the laser-pulse amplitude is such that the energy of plasma oscillators is higher than the threshold, it is not a single electron but rather an electron bunch that is trapped in the wake wave and subsequently accelerated by its wake potential. Figure 3 shows the results of simulating the self-injection, trapping, and acceleration of electrons under the effect produced on the plasma by a laser pulse with the amplitude $a_0 = 1.06$, which at $\gamma_{ph} = 30$ excites plasma oscillators with the energy $E_{os} = 1.16\ mc^2 > E_{os\ th} \approx 1.072\ mc^2$ and generates a rather short electron bunch suitable for monoenergetic acceleration.

CONCLUSIONS

A physical mechanism for the generation of electron bunches by a laser pulse with a moderate intensity $a_0 \sim 1$ crossing the sharp plasma boundary is considered. It is shown that this phenomenon can ensure the injection of plasma electrons in the laser-pulse wake wave with their subsequent trapping and acceleration in the form of short electron bunches (~10 fs long) to an energy close to 1 GeV with a relative energy spread of a few percent.

REFERENCES

1. W. P. Leemans et al., "Multi-GeV electron beams from capillary-discharge-guided subpetawatt laser pulses in the self-trapping regime," Phys. Rev. Lett. **113**, 245002 (2014).
2. S. Bulanov et al., "Particle injection into the wave acceleration phase due to nonlinear wake wave breaking," Phys. Rev. E **58**, R5257–R5260 (1998).
3. F. Y. Li et al., "Dense attosecond electron sheets from laser wakefields using an up-ramp density transition," Phys. Rev. Lett. **110**, 135002 (2013).
4. S. V. Kuznetsov, "Laser-pulse-induced generation of attosecond electron bunches on crossing the vacuum–plasma boundary," Tech. Phys. Lett. **42**, 740 (2016).
5. S. V. Kuznetsov, "Generation of short electron bunches by a laser pulse crossing a sharp boundary of inhomogeneous plasma," J. Exp. Theor. Phys. **123**, 169 (2016).
6. S. V. Kuznetsov, "Generation of attosecond electron bunches upon laser pulse propagation through a sharp plasma boundary," Quantum Electron. **47**, 87–96 (2017).
7. S. B. Bulanov et al., "The excitation of a relativistic wakefield wave and electron acceleration upon the action of an electromagnetic pulse on a collisionless plasma," Sov. J. Plasma Phys. **16**, 444 (1990).

Translated by M. Potapov