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Investigation of the Way of Phase Synchronization of a Self-Injected Bunch and an Accelerating Wakefield in Solid-State Plasma

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Abstract: The electron acceleration, in a laser wakefield accelerator, controlled through plasma density inhomogeneity is studied on a basis of 2.5-dimensional particle-in-cell simulation. The acceleration requires a concordance of the density scale length and shift of the accelerated electron bunch relative to wake bubble during electron acceleration. This paper considers the excitation of a wakefield in plasma with a density equal to the density of free electrons in metals, solid-state plasma (the original idea of Prof. T. Tajima), in the context of studying the wakefield process. As is known in the wake process, as the wake bubble moves through the plasma, the self-injected electron bunch shifts along the wake bubble. Then, the self-injected bunch falls into the phase of deceleration of the wake wave. In this paper, support of the acceleration process by maintaining the position of the self-injected electron bunch using an inhomogeneous plasma is proposed. It is confirmed that the method of maintaining phase synchronization proposed in the article by using a nonuniform plasma leads to an increase in the accelerating gradient and energy of the accelerated electron bunch in comparison with the case of self-injection and acceleration in a homogeneous plasma.

Keywords: laser; wakefield; inhomogeneous plasma; acceleration; high energy

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1. Introduction

According to the general principles of wakefield acceleration, when a laser pulse is injected into a plasma, a charge separation is formed and a longitudinal accelerating field is excited. The formation of self-injected bunches in regions of increased electron density is also observed (see [1–6]). The plasma electrons are spontaneously injected into the wakefield due to a wave-breaking (see [4–6]). When a wakefield is excited in a solid-state density plasma by an X-ray laser pulse, both an increase in the accelerating gradient and an increase in the density of self-injected bunches are observed. Previously, the process of wakefield acceleration in high-density plasma by X-ray laser pulses was investigated [7,8]. It was shown that self-injected bunches are formed, and the amplitude of the longitudinal acceleration field reaches several teravolts per meter [9] in accordance with analytical estimates, obtained with the formula (see [10,11]). In this paper, the process of wakefield excitation in plasma is investigated by numerical simulation using the UMKA code [12]. Wake acceleration is a powerful tool for achieving high accelerating gradients, but often requires specific conditions—for example, significant acceleration rates are possible in a capillary at laser powers of 0.5 PW. Moreover, the excitation of the wakefield in capillaries was investigated [13,14]. It was shown that in a solid-state plasma, it is possible to excite fields whose amplitude reaches teravolts per centimeter [15]. It is possible to excite the wakefield in other environments, for example, by a beam in a dielectric, in which the accelerating gradient 13.8 GV/m is achieved [16]. To implement the wakefield acceleration method in a solid-density plasma, new types of lasers are required, which, in many respects, remain a promising idea [17,18]. The excitation of a wakefield in a dielectric was also previously investigated (see [19,20]). When the wakefield is excited by a beam driver, it is possible to effectively excite the wakefield even in the non-resonant case [21–23] and provide a high transformer ratio value, which can be approximately defined as the ratio of the maximum accelerating field after the driver to the maximum decelerating field inside the driver (see [24,25]). Thus, the wakefield excitation and acceleration bears great potential for the ability to customize the application for each specific case.

This paper deals with the support of the phase synchronization of the self-injected and accelerated electron bunch and the wake wave through the plasma density inhomogeneity. Two cases are considered. In the first case, the plasma is homogeneous. The wakefield is excited by a single laser pulse. The picture is standard for the wake process: the formation of a wake bubble and a self-injected bunch. The self-injected bunch moves along the wake bubble. At the beginning of its movement (Figure 1) the self-injected bunch is in the acceleration phase, moving to the opposite edge of the wake bubble (Figure 2). Thus, the phase synchronization of the self-injected bunch and the wake wave is violated, leading to the termination of acceleration and subsequent deceleration of the self-injected bunch. The main purpose of this work is to maintain phase synchronization as the self-injected bunch moves. The electron bunch acceleration is considered in solid-state plasma.

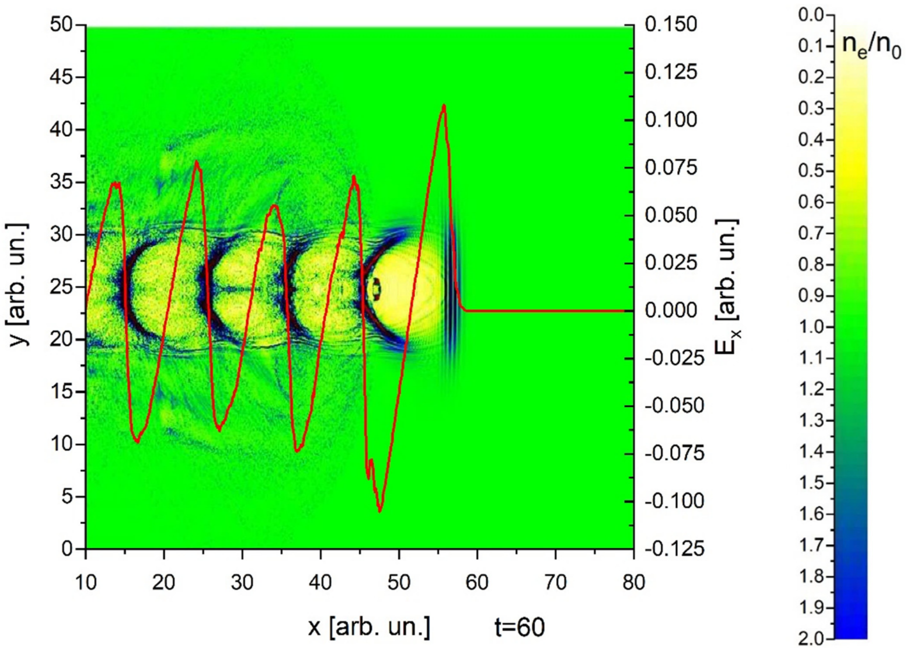

Figure 1. Excitation of a wakefield by a laser pulse in homogeneous plasma $t = 60T_0$. The self-injected bunch is close to the area of maximum accelerating gradient. Separate areas in which the ratio of electron densities reaches a value of 9 are highlighted in red. Plasma electron density and longitudinal accelerating field distributions. x, y are normalized to λ, E_x is normalized to $E_0 = m_e c\omega_\ell/2\pi e$.

At the moment the self-injected bunch reaches approximately middle of the wake bubble, the acceleration ceases. Now let us take into account that in a denser plasma the plasma wavelength is lower and that the leading edge of the wake bubble is associated with the driver. Then, if the driver moves into a denser plasma, the trailing edge of the wake bubble shifts towards the leading edge. Now let us take into account that the maximum accelerating gradient is on the trailing edge of the wake bubble. Then, with a certain choice of plasma density inhomogeneity, the trailing edge moves synchronously with the accelerated bunch, and the accelerated bunch during acceleration is in the area of maximum accelerating gradient. In [1] plasma density inhomogeneity was used to control electron injection into the wake wave. In [2] a negative density gradient with respect to the laser pulse propagation direction and in [3] a positive density gradient were employed at the electron injection into the wake wave. In this paper a density gradient is used to support a synchronization of accelerated electrons with the maximum wakefield phase. Thus, the acceleration requires a concordance of the density scale length and shift of accelerated bunch relative to the wake bubble during electron acceleration. By timely reducing the length of the wake bubble (the length of the wake bubble is equal to the length of the nonlinear plasma wave loaded by driver and witness) one will be able to maintain the self-injected bunch at the trailing edge of the wake bubble in the area of the highest accelerating gradient of the wake bubble. The reduction of the length of the wake bubble occurs owing to a reduction in the length of the plasma wave. This is possible in inhomogeneous plasma. Namely, the plasma density must be increased approximately by a factor of four during the time (at a distance) until the self-injected bunch reaches the middle of the wake bubble.

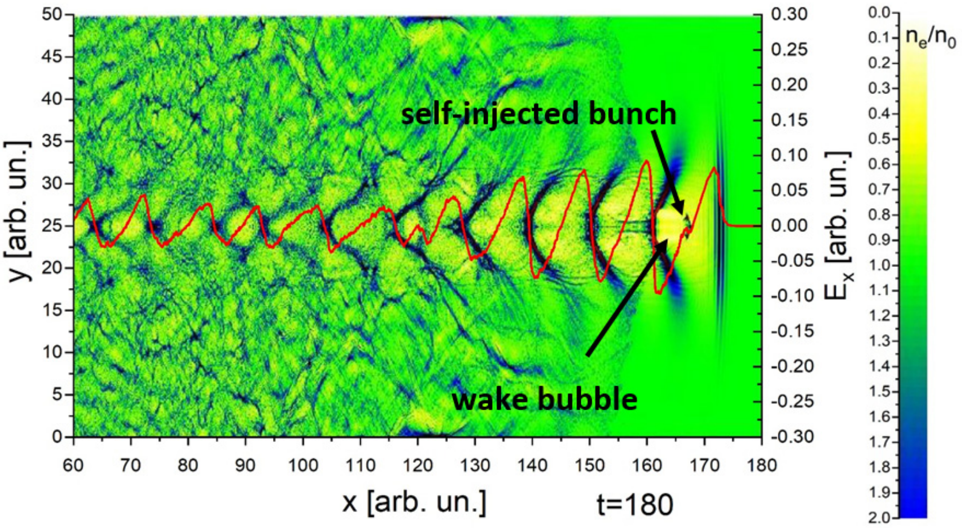

Figure 2. Excitation of a wakefield by a laser pulse in homogeneous plasma $t = 180T_0$. The self-injected bunch is close to the middle of the bubble. Separate areas in which the ratio of electron densities reaches a value of 9 are highlighted in red. Plasma electron density and longitudinal accelerating field distributions. x, y are normalized to λ, E_x is normalized to $E_0 = m_e c\omega_\ell/2\pi e$.

2. Results of Simulation

The study was carried out through numerical simulation using the UMKA code. The simulation was performed by the PIC method. The electron density of a homogeneous plasma was $n_0 = 10^{23}\ cm^{-3}$. All density values are normalized to n_0. The length of the system in the longitudinal direction is 300λ and the width of the system is 50λ in the transverse direction. All lengths and distances are normalized to the laser wavelength $\lambda = 10.65\ nm$. Laser period is $T_0 = c^{-1}\lambda = 35.3\ as$.

Wakefield amplitude $E = aE_0$ is normalized to $E_0 = m_e c\omega_\ell/2\pi e$ = 48.08 TV/m, ω_l represents the laser frequency. We use frequency ratio approximately equal $\omega_{pe}\omega_l^{-1} = 0.1008$. Excitation of the wakefield by a single laser pulse with an amplitude of $a = 3$ is considered. FLHM (full length at half maximum) of laser pulse equals 2λ and FWHM (full width at half maximum) equals 8λ. We consider a homogeneous plasma near the injection boundary of a laser pulse in the formation interval of self-injected bunch. When a self-injected bunch is formed, it, together with the driver and bubble, approaches the point of plasma density growth (Figure 3). Moving along the system in an inhomogeneous plasma with increasing density, the self-injected bunch is held in one position at the area of maximum accelerating gradient. As a result, the self-injected bunch is constantly under the action of the accelerating field, without entering the deceleration phase (Figure 4). In the considered homogeneous case, at the moment the self-injected bunch reaches the point $x_1 = 47\lambda$, the self-injected bunch detaches from the wake bubble trailing edge. The bunch reaches the middle of the wake bubble at point $x_2 = 167\lambda$. In the interval from $x_1 = 47\lambda$ to the bottom of the system $x = 300\lambda$, the plasma density is inhomogeneous and varies according to the longitudinal distribution $n_e = n_0((x - 47\lambda)/40\lambda + 1)$. Consequently, it is possible to reach the plasma density value $n_e = 4n_0$ at the point $x_2 = 167\lambda$. Due to this, it is possible to achieve at the point $x_2 = 167\lambda$ a two-fold decrease of the plasma wavelength. At the same time, a decrease in the wake bubble length to approximately 60% of the initial length is observed.

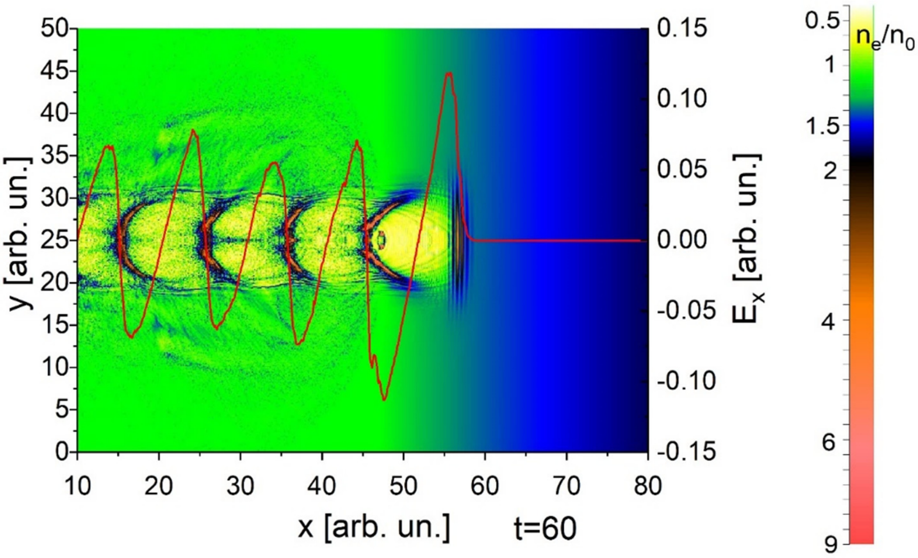

Figure 3. Excitation of a wakefield by a laser pulse in inhomogeneous plasma $t = 60T_0$. The self-injected bunch is close to the area of maximum accelerating gradient. Plasma electron density and longitudinal accelerating field distributions. x, y are normalized to λ, E_x is normalized to $E_0 = m_e c\omega_\ell/2\pi e$.

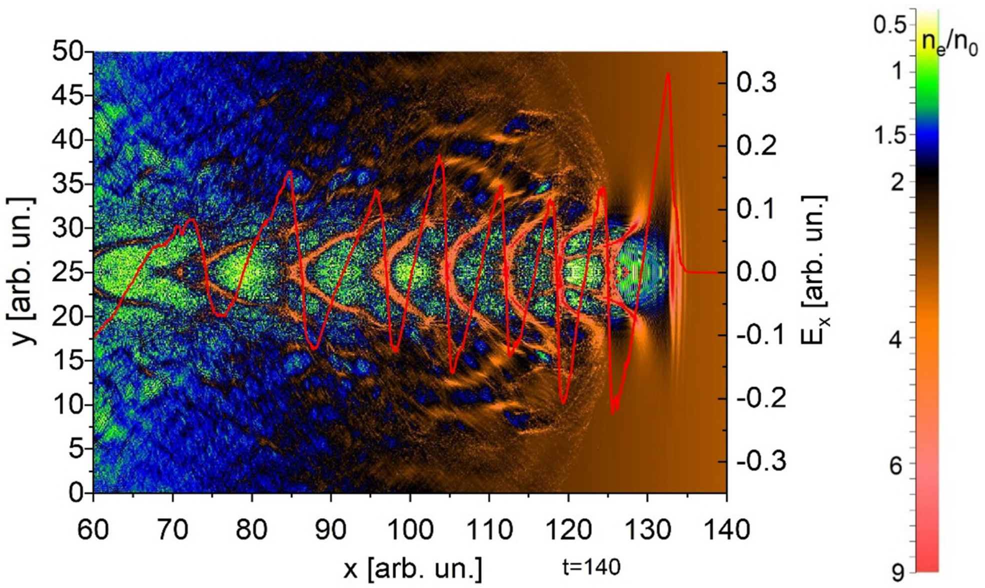

Figure 4. Excitation of a wakefield by a laser pulse in inhomogeneous plasma $t = 140T_0$. The self-injected bunch is close to the area of maximum accelerating gradient. Plasma electron density and longitudinal accelerating field distributions. x, y are normalized to λ, E_x is normalized to $E_0 = m_e c\omega_\ell/2\pi e$.

The deviation is explained by the fact that the bubble is nonlinear and its length is greater than the linear plasma wavelength. A comparison of Figures 2 and 5 shows that the amplitude of the accelerating wakefield in the case of an inhomogeneous plasma is 2 times higher than the amplitude in the case of a homogeneous one.

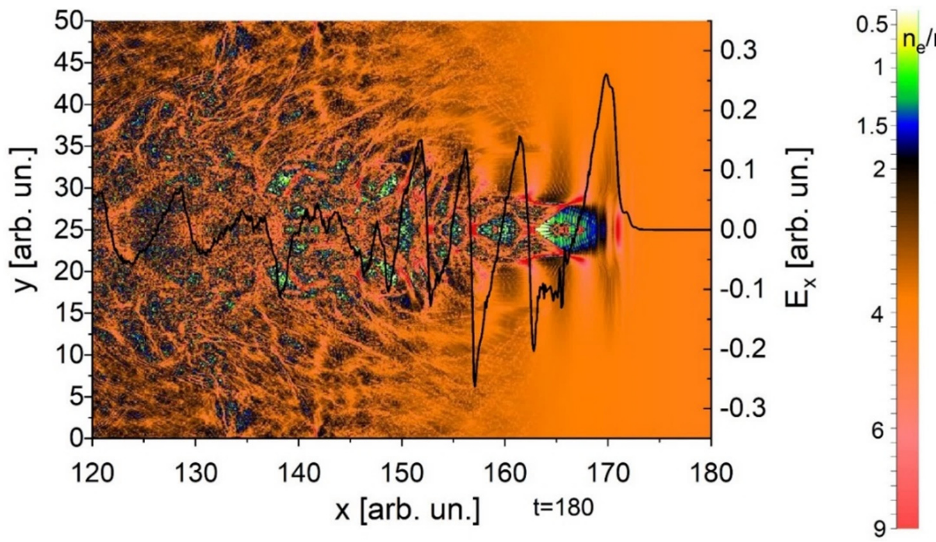

Figure 5. Excitation of a wakefield by a laser pulse in inhomogeneous plasma $t = 180T_0$. Plasma electron density distribution and longitudinal accelerating field. x, y are normalized to λ, E_x is normalized to $E_0 = m_e c\omega_\ell/2\pi e$.

In Figure 2, it can be seen that at the moment when the acceleration process of the self-injected bunch has ceased in the homogeneous case, in the inhomogeneous case (see Figure 5) a significant part of the bunch is accelerated by field of 0.1, which is equal to the initial acceleration field in the homogeneous case. The proposed method for restoring phase synchronization in a laboratory experiment can be implemented, for example, when using multilayer sputtering with different metals. Similar technologies have been widely researched [26].

In Figure 6, one can observe self-injected bunches after about 140 laser periods after the beginning of acceleration in inhomogeneous (a) and homogeneous (b) plasmas. The maximum energy of accelerated electrons in inhomogeneous plasma is 1.7 times higher than in homogeneous plasma. Comparison of Figure 6a,b shows the efficiency of phase synchronization and confinement of the self-injected bunch in the area of high accelerating gradient. Namely, the self-injected and accelerated electron bunch is in the area of high accelerating gradient and is of a higher energy in the case of phase synchronization.

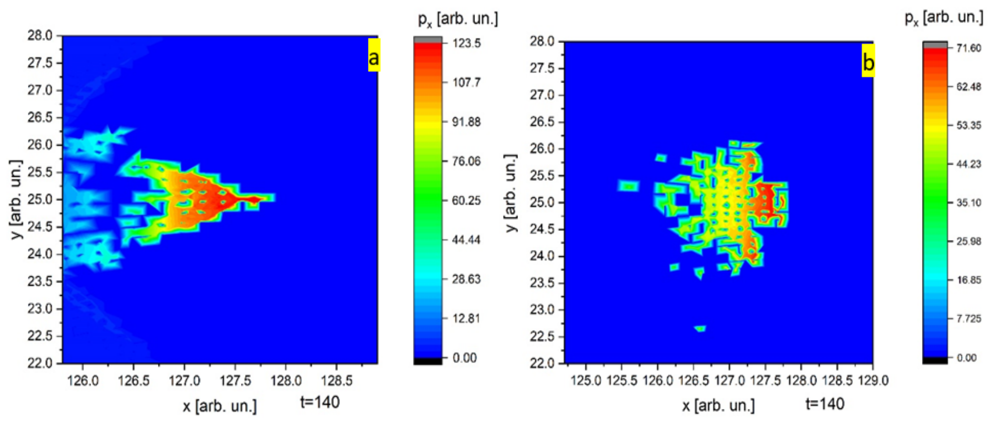

Figure 6. Distribution of the longitudinal momentum of self-injected bunch in inhomogeneous (**a**) and homogeneous (**b**) plasma $t = 140T_0$. p_x is normalized to $m_e c$.

3. Conclusions

During the study, it was shown that the use of a longitudinally inhomogeneous plasma renders it possible to provide phase synchronization of a self-injected bunch and an accelerating longitudinal wakefield, maintaining the self-injected bunch in the area of high accelerating gradient.

The longitudinal distribution according to which the plasma density changes must be developed with the condition, that at the distance that the self-injected bunch shifts, for example, to the middle of the wake bubble in the homogeneous plasma, in the inhomogeneous plasma, the plasma density should increase by a factor of 4.

The proposed method improves the efficiency of acceleration of the self-injected bunch and leads to an increase in the bunch electron energy.

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