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# A METHOD FOR MAINTAINING THE ACCELERATION RATE AND INCREASING THE ENERGY OF SELF-INJECTED BUNCH DUE TO THE USE OF INHOMOGENEOUS PLASMA

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The paper considers the process of excitation of a wakefield in a plasma by a laser pulse. The plasma density corresponds to the density of free electrons in the metal. A method is demonstrated for keeping self-injected bunch in the accelerating phase of the wakefield as laser pulse and bunch move in plasma with an increasing density gradient. Thus, the rate of acceleration of self-injected bunch is maintained and enhanced.

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## INTRODUCTION

Wakefield acceleration has been a subject of intense research due to its potential to revolutionize particle acceleration technology. This method of particle acceleration utilizes the electric fields generated in the wake of a driving pulse, typically a laser or a particle beam, propagating through a plasma [1 - 5]. The advantages of wakefield acceleration are numerous and have been explored in various contexts, including solid-state plasmas and longitudinally inhomogeneous plasmas.

One of the primary advantages of wakefield acceleration is its ability to achieve extremely high accelerating gradients, several orders of magnitude higher than those achievable with conventional accelerator technology. This high gradient allows for the production of high-energy particles over short distances, potentially leading to more compact and cost-effective accelerators [6 - 8].

In the context of solid-state plasmas, wakefield acceleration can be particularly advantageous. Solid-state plasmas are dense electron plasmas in solid-state materials, such as metals, semiconductors etc. The high density of these plasmas allows for the generation of strong wakefield and, consequently, high accelerating gradients. Moreover, solid-state plasmas can be more easily manipulated and controlled than gaseous plasmas, allowing for more precise control over the acceleration process [9 - 11].

Wakefield acceleration in longitudinally inhomogeneous plasmas also presents unique advantages. Longitudinal inhomogeneity refers to variations in the plasma density along the direction of propagation of the driving pulse. These variations can be exploited to enhance the efficiency of energy transfer from the driving pulse to the wakefield, thereby increasing the accelerating gradient. Furthermore, by carefully designing the longitudinal density profile, it is possible to optimize the acceleration of particles [12, 13].

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In conclusion, wakefield acceleration offers a promising avenue for advancing particle acceleration technology. Its potential for achieving high accelerating gradients in a compact setup, coupled with its versatility and applicability in various contexts, makes it a compelling subject for further research and development.

The excitation of the wakefield and the motion of bunch in an inhomogeneous plasma were studied. The motion of bunch was considered at the beginning of the simulation process, not far from the injection point. In particular, the fields acting on the bunch and the longitudinal momentum of the bunch are investigated.

## 1. STATEMENT OF THE PROBLEM

With the help of numerical simulation, excitation by a laser pulse of a wakefield in a plasma is considered. The plasma density is considered, which is close to the density of free electrons in metals. Profiled pulse is considered. Profiling is achieved by using "semi-cosine" pulse with a cosine intensity distribution ranging from 0 to $\pi/2$.

The main parameters of the system were as follows: the plasma electron density (unperturbed), to which the density on the graph is normalized is $n_{0e}=10^{23}$ cm$^{-3}$, the ratio of the plasma frequency to the laser frequency is $\omega_{pe}/\omega_0=0.1008$, where $\omega_0$ is the laser frequency, $\omega_{pe}$ is the plasma frequency. The laser wavelength was $\lambda_l=10.6$ nm. All lengths, distances and coordinates were normalized to the laser wavelength $\lambda_l$. The laser pulse propagated along the axis of the system. The length of the simulation window was 800, the width 50. The laser amplitude $a=EE_0^{-1}$ was normalized to the overturning field $E_0=m_e c\omega_0(2\pi e)^{-1}$. Force normalization, respectively, $F_0=m_e c\omega_0/2\pi$. The mass ratio of ions and electrons was 1836. Time was normalized to the period of the electromagnetic wave $T_0$. A laser pulse with the following parameters is considered: amplitude a=5, half-length equal to 3, half-width at half-height equal to 4. The spatial dimensions are indicated for a cosine pulse, for a half-cosine pulse it is half as much. It is known that a self-injected bunch, moving along the wake bubble, enters the deceleration phase of the wake wave. The process begins after the self-injected bunch reaches the middle of the wake bubble. This leads to the stop of the acceleration process and the loss of energy by the self-injected bunch. The main idea of inhomogeneity is that during the time until the self-injected bunch from the injection point reaches the middle of the wake bubble in homogeneous case, the plasma density will increase by 4 times. This will lead to a twofold decrease in the plasma wave length and, as a consequence, to stabilization of the position of the self-injected bunch in the region of the accelerating phase of the wakefield.

## 2. RESULTS OF SIMULATION

At first, let us consider how the bunch energy changes in the inhomogeneous case. The condition for the Cherenkov resonance of a laser pulse with a wake plasma wave:

$$KV_g=\omega_{pe} \quad (1)$$

or

$$V_g=v_{ph}=\omega_{pe}/K, \quad (2)$$

$K=2\pi/\lambda$; $v_{ph}$ – wave vector and phase velocity of the Langmuir wave. $V_g$, $\omega$, k – group velocity, frequency and wave vector of the laser pulse.

$$\omega=(\omega_{pe}^2+c^2k^2)^{1/2}, \quad (3)$$

$$k=(\omega^2-\omega_{pe}^2)^{1/2}/c. \quad (4)$$

From (3) it can be obtained:

$$V_g=d\omega/dk=c^2k/(\omega_{pe}^2+c^2k^2)^{1/2}=c^2k/\omega=$$
$$=c(1-\omega_{pe}^2/\omega^2)^{1/2}\approx c(1-\omega_{pe}^2/2\omega^2). \quad (5)$$

From (2) it can be obtained:

$$\lambda=2\pi V_g/\omega_{pe}=2\pi(c/\omega_{pe})(1-\omega_{pe}^2/\omega^2)^{1/2}\approx$$
$$\approx 2\pi(c/\omega_{pe})(1-\omega_{pe}^2/2\omega^2). \quad (6)$$

Both factors $c/\omega_{pe}$ and $(1-\omega_{pe}^2/2\omega^2)$ decrease $\lambda$ as $n_e(x)$ increases. But the 1st multiplier reduces more.

In order for the accelerated bunch to stay in the region of the maximum accelerating field all the time, the bunch shear rate relative to the bubble $V_b(t)-V_g(x)$ should be equal to the plasma wave length contraction rate $d\lambda/dt$.

$$V_b(t)-V_g(x)=d\lambda/dt=(d\lambda/dz)(dz/dt), \quad (7)$$
$$dz/dt=V_g.$$

In the ultrarelativistic bunch approximation $V_b\approx c$. And neglecting the change in $V_g$ in an inhomogeneous plasma, we obtain:

$$c/V_g-1=d\lambda/dz. \quad (8)$$

At times $\tau(c-V_g)=\lambda/2$ shift by $\tau(c-V_g)=\lambda/2$ in the case of a homogeneous plasma and in the approximation that in an inhomogeneous plasma the bunch accelerates to $E_{xmax}$ and in the approximation that $E_x$ is distributed $E_x=E_{xmax}(1-2x/\lambda)$ in the case of a homogeneous plasma the bunch accelerates to

$$d\varepsilon_b/dt=eEv, \quad (9)$$

$$\varepsilon_b=ec\int E_x dx/(c-V_g)=$$
$$=ecE_{xmax}(\lambda/4)(1-2x/\lambda)^2/(c-V_g)|_0^{\lambda/2}=$$
$$=ecE_{xmax}(\lambda/4)/(c-V_g). \quad (10)$$

In an inhomogeneous plasma with a constant $E_{xmax}$ and with acceleration over an interval of almost 2 times greater, since it accelerates until the bubble almost completely collapses.

$$\varepsilon_b=ecE_{xmax}(\lambda/2)2/(c-V_g)=$$
$$=ecE_{xmax}\lambda/(c-V_g). \quad (11)$$

In the inhomogeneous case, the energy acquired by a self-injected bunch is theoretically 4 times higher than the energy in the homogeneous case. In fact in the inhomogeneous case the accelerating wakefield grows and the energy of accelerated electrons increases even more. Let us perform numerical simulation to verify the efficiency of using inhomogeneous plasma.

Obviously, when simulating a real case, taking into account all factors, including the nonlinearity and location of the bunch relative to the accelerating phase of the wake wave, we will observe a smaller value of the energy increase but, nevertheless, an increase in energy will be observed.

Fig. 1 shows a graph of the density during the process of excitation of the wakefield in the plasma by a laser pulse. The pattern of simulation in the homogeneous and inhomogeneous cases is the same. One can observe a self-injected bunch, which has just formed and begins its movement along the wake bubble ($t=60T_0$).

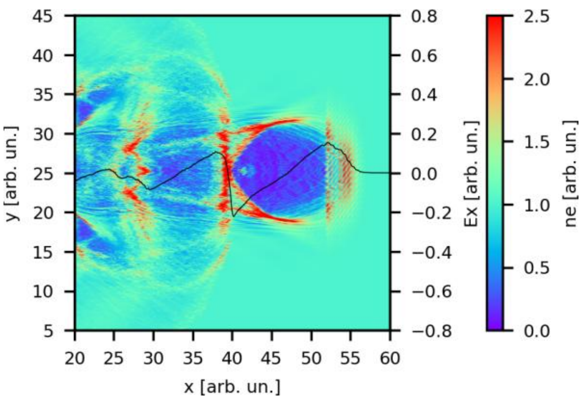


*Fig. 1. Plasma electron density distribution $n_e(x, y)$ and longitudinal accelerating field $E_x(x)$, $t=60T_0$. Semi-cosine distribution of laser pulse both in the homogeneous and inhomogeneous case*

Fig. 2 characterizes the simulation pattern in the homogeneous case at the moment when the self-injected bunch approaches the point when the accelerating wakefield $E_x=0$.

Comparison of Figs. 2 and 3, homogeneous and inhomogeneous cases at the same time points, indicates that due to the use of longitudinally inhomogeneous plasma, it is possible to keep the self-injected bunch in the acceleration phase, almost at the injection point.

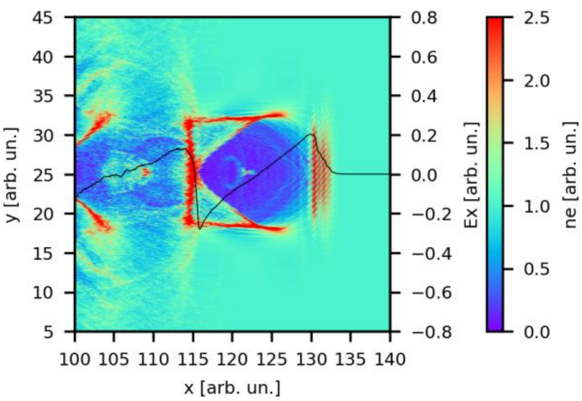


*Fig. 2. Plasma electron density distribution $n_e(x, y)$ and longitudinal accelerating field $E_x(x)$, $t=140T_0$. Semi-cosine distribution in the homogeneous case*

At the same time, when the self-injected bunch hits zero field in the homogeneous case, and later in the deceleration phase of the wake wave.

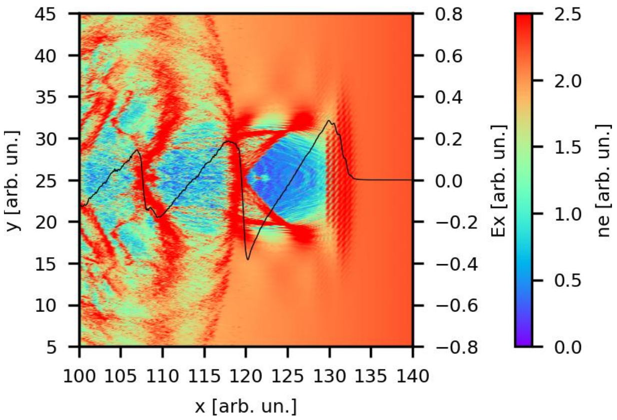


*Fig. 3. Plasma electron density distribution $n_e(x, y)$ and longitudinal accelerating field $E_x(x)$, $t=140T_0$. Semi-cosine distribution in the inhomogeneous case*

Fig. 4 shows the case of a full cosine laser intensity distribution (non-profiled case). Obviously, the advantage of using profiling, due to which stabilization of bunches is observed, their transverse expansion is reduced.

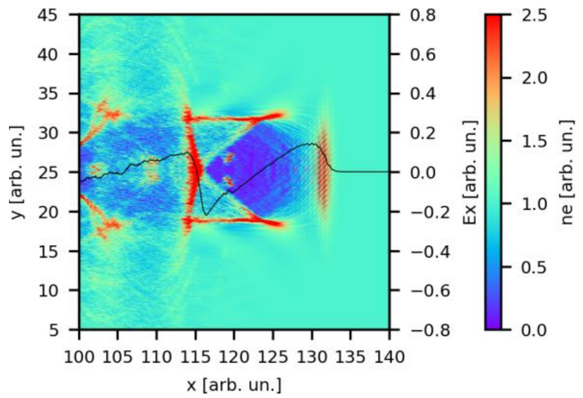


*Fig. 4. Plasma electron density distribution $n_e(x, y)$ and longitudinal accelerating field $E_x(x)$, $t=140T_0$. Full-cosine distribution in the homogeneous case*

Fig. 5 shows the distribution of the longitudinal component of the pulse of a self-injected bunch simultaneously in the homogeneous and inhomogeneous cases, when the effect of inhomogeneity is not yet felt in the case of a half-cosine laser. A stable bunch can be observed, but small momentum values.

Comparing Figs. 5 and 6, we can conclude that in the inhomogeneous case, when the self-injected bunch reaches the middle of the wake bubble, there is an increase in the longitudinal momentum by a factor of 2.2 if we compare the bunch momenta at moments $t=60T_0$ and $t=140T_0$. The average momentum in the main region of the bunch was taken as the momentum based on the graphic dependences. It has been studied that the increase in energy in the inhomogeneous case as compared to the homogeneous case reaches 3. In the homogeneous case, due to the motion of the self-injected bunch along the wake bubble, at the moment 140 the longitudinal field in the bunch region in normalized units reaches approximately 0.0354. In the inhomogeneous case, due to the confinement of the bunch near the injection point, at the same time in the bunch region, the value of the longitudinal acceleration field is 0.2681. Thus, an increase in the bunch acceleration field by a factor of approximately 7.6 is observed due to the use of plasma inhomogeneity.

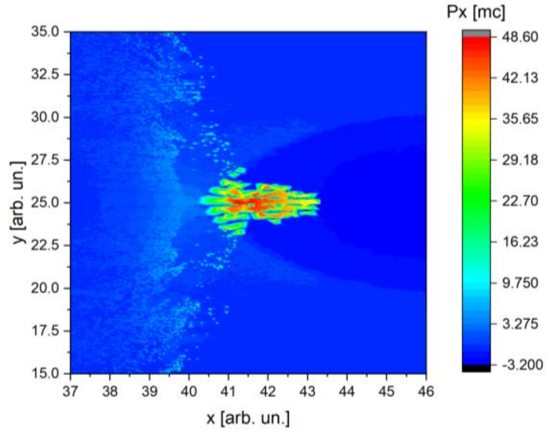


*Fig. 5. Distribution of the longitudinal component of the momentum $P_x(x, y)$ in the electrons of a self-injected bunch, $t=60T_0$. Semi-cosine distribution both in the homogeneous and inhomogeneous case*

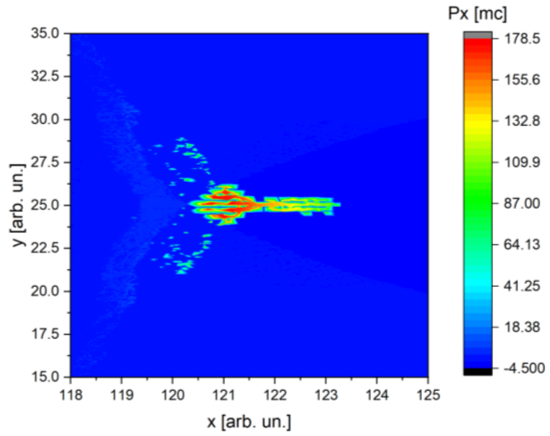


*Fig. 6. Distribution of the longitudinal component of the momentum $P_x(x, y)$ in the electrons of a self-injected bunch, $t=140T_0$. Semi-cosine distribution both in the inhomogeneous case*

In the case of a semi-cosine intensity distribution, when the plasma is inhomogeneous, at time $t=140T_0$, the formation of self-injected bunches with a minimum spatial distribution in the transverse direction is observed. This contrasts with the homogeneous case of an unshaped laser pulse. In this case, the decay of the self-injected bunch into 3 parts is observed, the transverse size of the bunch is much larger than the bunch in the case when the driver is semi-cosine and the plasma is inhomogeneous.

## CONCLUSIONS

In the course of the study, the use of inhomogeneous plasma was considered in the study of self-injected bunches, which were formed when the wake field was excited by a profiled laser pulse.

It was shown that the use of profiled pulse and inhomogeneous plasma has a positive effect on the quality of self-injected bunch and leads to the retention of bunch in the acceleration field, which contributes to an increase in the energy gain and an increase in the longitudinal acceleration field in the bunch region.

In addition, the advantage of using shaped pulse in an inhomogeneous case is the increased longitudinal momentum of the bunch, which provides more efficient acceleration.


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## СПОСІБ ПІДТРИМАННЯ ТЕМПУ ПРИСКОРЕННЯ ТА ЗБІЛЬШЕННЯ ЕНЕРГІЇ САМОІНЖЕКТОВАНОГО ЗГУСТКА ШЛЯХОМ ВИКОРИСТАННЯ НЕОДНОРІДНОЇ ПЛАЗМИ


***Д.С. Бондар, В.І. Маслов, І.М. Оніщенко***



Розглянуто процес збудження кільватерного поля в плазмі лазерним імпульсом. Густина плазми відповідає густині вільних електронів у металі. Продемонстровано метод утримання самоінжектованого згустка у фазі прискорення кільватерного поля, коли лазерний імпульс і згусток рухаються в плазмі зі зростаючим градієнтом щільності. Таким чином, темп прискорення самоінжектованого згустка зберігається.