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# IMPROVING STABILITY OF THE SELF-INJECTED BUNCH BY VARIATION OF A SEQUENCE OF TWO LASER PULSES PARAMETERS AT WAKEFIELD EXCITATION IN A METAL DENSITY PLASMA

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The variation of parameters of a sequence of two laser pulses exciting wakefield in a metal density plasma are considered as a way to improve the self-injected bunch stability: suppression of transverse bunch decay and increasing the existing time of a self-injected bunch in plasma are investigated. Two scenarios of parameter variation were considered. In the first scenario, the simultaneous variation of the parameters of both laser pulses was considered; in the second scenario, the set of parameters for one of the laser pulses after variation differed from the set of parameters for the other laser pulse (profiled sequence of 2 laser pulses) was considered.

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## INTRODUCTION

The field of laser-plasma acceleration has seen significant advancements over the past few decades. The concept of using ultra-high intensity laser pulses to achieve extreme material states in the laboratory has become almost routine with the development of petawatt and even zettawatt-exawatt class lasers [1 - 3]. These lasers have been constructed for specific research activities, including particle acceleration, inertial confinement fusion, and radiation therapy, and have been used to generate secondary sources such as x-rays, electrons, protons, neutrons, and ions [4, 5].

Wakefield in plasma provides the high accelerating gradients. Analytical studies, simulations, and many experiments have shown that wakefield in plasma can support gradients of 100 GeV/m [6 - 8]. The ability to produce high intensities with these lasers opens up new possibilities for the study of relativistic and even nuclear physics.

One of the problems at the wakefield excitation in a plasma of metallic density by exawatt laser pulse is obtaining self-injected bunches. This is particularly relevant in the context of laser-plasma accelerators, where the production of high-quality injected electron beams is a key goal. Production, trapping and acceleration of self-injected bunches at plasma wakefield excitation were studied in [9 - 12].

Synchronization of self-injected bunches with an accelerating field in a metal-density plasma was also studied [13, 14].

The use of laser-plasma acceleration, high-density plasma in the excitation of a wakefield, laser pulse sequences, and laser parameters variation method present a promising approach to saving the stability of self-injected bunches during excitation of a wakefield in plasma.

In this paper the issue of influence of exawatt laser pulses sequence parameters variation on the process of metallic density plasma wakefield excitation was investigated with a goal to improve the self-injected bunch stability: suppression of transverse bunch decay and increasing the existing time of a self-injected bunch in plasma are investigated.

## 1. STATEMENT OF THE PROBLEM

The process of using a laser pulse to excite a wakefield in a plasma is investigated by numerical simulation. The density of this plasma is approximately equal to the density of free electrons in metals. A sequence of laser pulses located at a distance of one plasma wavelength is considered. In addition, suppression of the transverse expansion (instability) of bunches by varying the parameters is demonstrated.

The main idea was to show the advantages of the parameter variation method for producing self-injected bunches with the suppression of transverse bunch decay and extending the time of motion (existing) of the bunch in plasma.

Main system parameters include: an unperturbed plasma electron density, normalized to $n_{0e}=10^{23}$ cm$^{-3}$, a ratio between the plasma frequency and laser frequency, $\omega_{pe}/\omega_0$, equating to 0.1 (where $\omega_0$ and $\omega_{pe}$ are the laser and plasma frequencies respectively). The laser wavelength was $\lambda_l$=10.6 nm, and all lengths, distances and coordinates were normalized to this laser wavelength, $\lambda_l$. The laser pulse was directed along the system's axis. The plasma wavelength is $\lambda_{pe}$=106 nm.

The dimensions of the simulation window were a length of 800 and width of 50. The laser amplitude, a, was normalized to the broken field $E_0=m_e c\omega_0/e$. Time normalized to the electromagnetic wave period $T_0$.

Sequences of two bunches were considered. It was shown that it is possible to improve the stability of self-injected bunches, prevent their decay and increase the existing time in two scenarios.

In the first scenario, parameter variation was considered under the condition that the parameters of the two lasers were varied simultaneously. That is, even after varying the parameters, the equivalent parameters were used for each of the two laser pulses. In this case, the amplitude of the lasers was maintained, and the shape of the pulses became more spherical.

In the second scenario, variation of the parameters of the sequence of two laser pulses was considered, provided that the parameters of the laser pulses after the variation were not equal to each other. The laser pulses had different intensities. Such sequence can be considered as a profiled sequence.

In both scenarios, self-injected bunch stability was achieved, transverse decay was prevented, and the existing time of the self-injected bunch was increased.

## 2. RESULTS OF SIMULATION

In both scenarios, a sequence with these parameters was considered as initial (before parameter variation): half-length 1, half-width 3, amplitude 5 (initial sequence).

In the first scenario, when the parameters of the laser pulses were varied simultaneously, the sequence considered as the result of parameter variation is length 1.5, half-width 2, amplitude 5 (scenario 1 sequence).

In the second scenario, the sequence was considered as the result of parameter variation: first laser pulse (half-length 2, half-width 1.5, amplitude 2), second laser pulse (half-length 1, half-width 3, amplitude 4), (scenario 2 sequence).

In both scenarios authors compared the sequence from scenarios 1 and 2 with the initial sequence.

### 2.1. THE FIRST SCENARIO OF PARAMETER VARIATION

In real studies, it is not uncommon to find situations when it is necessary that, even with parameter variation, the parameters of two bunches change simultaneously.

At the same time, it is required to suppress the transverse instability of electron bunches, in fact, the separation of the bunch into two parts, which scatter along the radius from the axis of the system.

The most difficult case is when, in the case of a sequence of two laser pulses, it is required to suppress the transverse expansion (instability) of only one bunch.

In this section, it is supposed to investigate the suppression of this instability using numerical simulation by the method of parameter variation.

Figs. 1, 2 show the simulation results for the initial, before parameters variation sequence. At first glance, the problem becomes obvious, the decay of the first self-injected bunch into three parts. Two parts of the bunch scatter along the axis and the bunch ceases to exist as a whole. The sequence considered as the result of parameter variation is length 1.5, half-width 2, amplitude 5 (scenario 1 sequence). That is, if compared to the original sequence, the laser pulses become more spherical after the parametric variation.

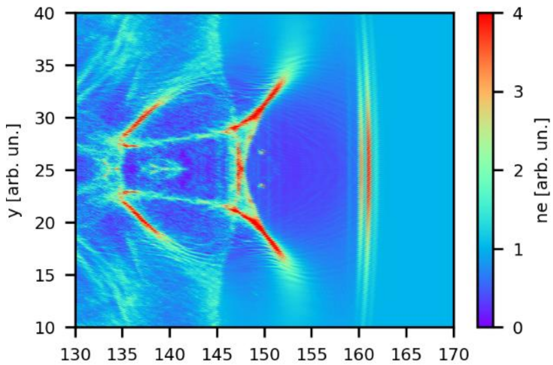


*Fig. 1. Plasma electron density distribution $n_e(x, y)$, $t=175T_0$. Initial sequence*

These parameters make it possible to suppress the transverse decay of the first self-injected bunch of the sequence while saving the second. Fig. 3 shows the distribution of the first self-injected bunch for this sequence, after applying the parameter variation method.

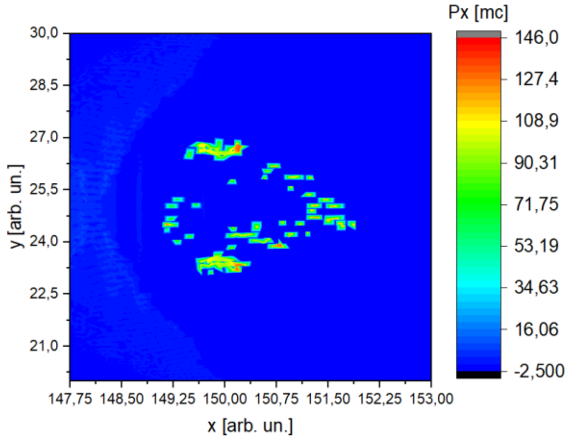


*Fig. 2. Longitudinal momentum distribution $P_x(x, y)$, $t=175T_0$. Initial sequence*

In Fig. 4 shown the distribution function of longitudinal momentum of bunch electron after varying the parameters (scenario 1 sequence).

In Fig. 5 shown the simulation result for sequence (half-length 1.5, half-width 2, amplitude 4.75) with lower (by 5%) amplitude. The results of the study for this sequence allow us to conclude that using the parameter variation method, even without changing the amplitude, it is possible to achieve the suppressing of the transverse decay of bunches, increasing stability of the bunch.

A comparison of Figs. 4, 9, 11 suggests that the variation of the parameters in both scenarios considered leads to improved self-injection due to an increase in the number of particles in the bunch. In case of the 1st scenario, the number of particles in the self-injected bunch increases by a factor of 3.4. In the case of the second scenario, the number of particles in the bunch increases by a factor of 12.9.

Comparison of Figs. 2 and 3 allows the authors to conclude the decrease of the bunch radius as a result of the parameter variation from 21.2 to 13.25 nm. A slight variation of the parameters leads to the formation of a distinguishable peak on the distribution function.

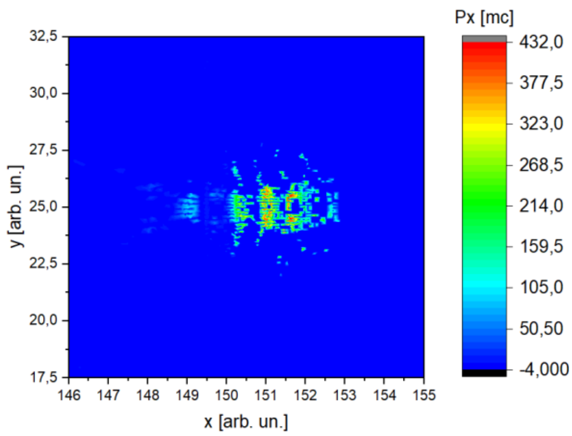


*Fig. 3. Longitudinal momentum distribution $P_x(x, y)$, $t=175T_0$. Scenario 1 sequence*

At the same time, a significant variation in the amplitude value leads to the disappearance of the bunch.

Thus, a comparison of laser pulse sequences before parameter variation and after variation indicates that the parameter variation method has clear advantages and its use promotes bunch saving.

In Fig. 3, it was observed the formation of a self-injected bunch, which splits into several electron bunches located sequentially close to each other. In fact, a single bunch structure is formed at suppression of the transverse decay of the bunch.

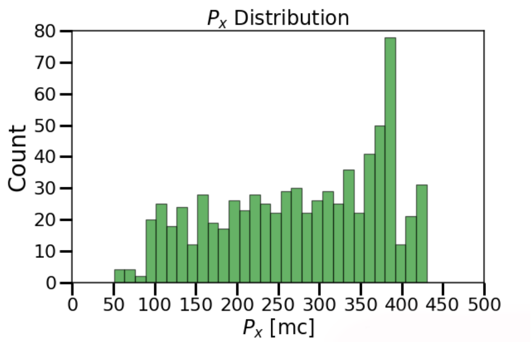


*Fig. 4. $P_x$ distribution function. $t=175T_0$. Scenario 1 sequence*

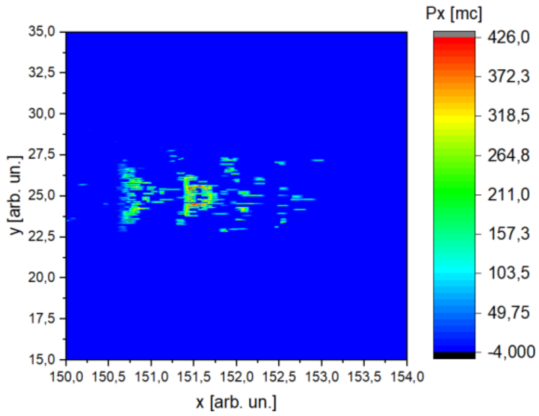


*Fig. 5. Longitudinal momentum distribution $P_x(x, y)$, $t=175T_0$. Scenario 1 sequence (with a -5% amplitude correction)*

## 2.2. THE SECOND SCENARIO OF PARAMETER VARIATION

The sequence after parameters variation: 1st pulse (half-length 2, half-width 1.5, amplitude 2); 2nd pulse (half-length 1, half-width 3, amplitude 4), (scenario 2 sequence). This case can be considered as a profiled sequence of 2 laser pulses for plasma wakefield excitation and self-injected bunch producing.

An initial sequence, without lasers parameters variation is the sequence with two identical laser pulses was considered: half-length 1, half-width 3, amplitude 5.

In Figs. 6, 7 shown the distribution of plasma and bunch electrons, as well as the distribution of longitudinal pulses.

In Fig. 8 shown a picture of the motion of a self-injected bunch at large time ($t=375T_0$).

Figs. 9, 10 shown longitudinal momentum distribution function of self-injected bunches. Time points $175T_0$ and $200T_0$ are shown in normalized units. At these moments, the self-injected bunch moves through wake bubble. The figures show the optimal moment of the wake process, when it is supposed to use a self-injected bunch in practice.

Figs. 9, 10 illustrate the distributions in the case of a sequence before parameters variation. Comparison of Figs. 3 and 4 allows us to show the dynamics at short times for the case of a sequence after parameters variation, leads to an increase in the number of electrons in the high energy region (by 30% at maximum).

Comparison of Figs. 2 and 7 allows us to conclude that the variation of parameters according to the second scenario allows preserving the self-injected bunch and prevents its destruction (transverse decay). This is the benefit of parameter variation sequence. The bunch save its structure, the head and the central part of the bunch do not decay.

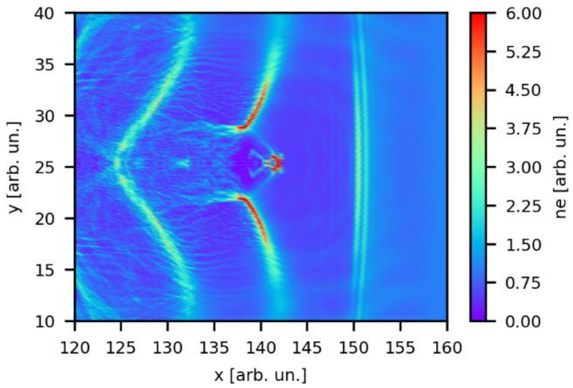


*Fig. 6. Plasma electron density distribution $n_e(x, y)$, $t=175T_0$. Scenario 2 sequence*

In the absence of parameter variation (see Fig. 2), the structure of the self-injected electron bunch in the plasma is lost. The bunch breaks into several pieces that move mainly in the transverse and partly in the longitudinal direction. This is a significant disadvantage. Therefore, the case of varying the parameters has an advantage in the context of saving the stability of the bunch.

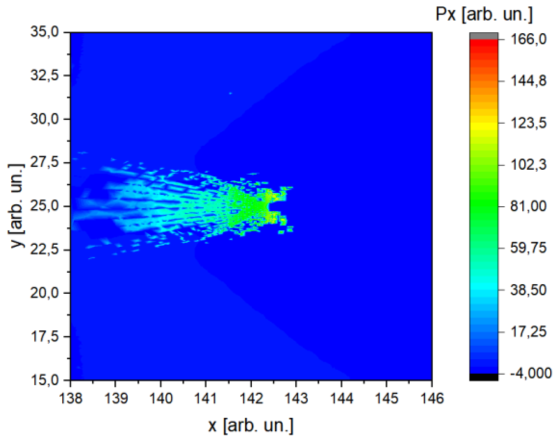


*Fig. 7. Longitudinal momentum distribution $P_x(x, y)$, $t=175T_0$. Scenario 2 sequence*

During research, the authors observed that, in a number of cases, self-injection is not observed at all. This circumstance, taking into account the characteristics of these laser sequences, explains the advantage of laser pulse parameters variation in cases where self-injection as such is absent without it. This also applies to minimum (less than 0.75 in normalized units) values of length width, and especially amplitude. In addition to considered earlier, the effect of saving a structure of self-injected bunch during its movement in plasma was observed for a longer time than in the initial case without parameters variation.

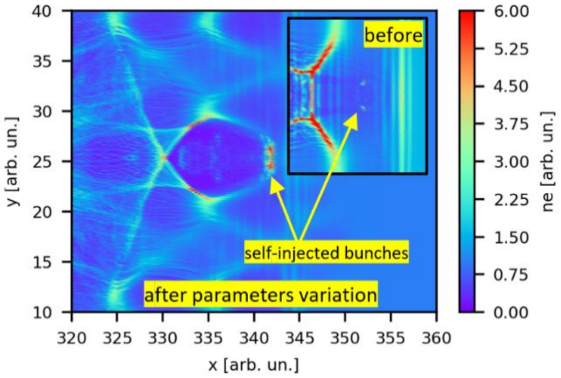


*Fig. 8. Plasma electron density distribution $n_e(x, y)$, $t=375T_0$. Scenario 2 sequence*

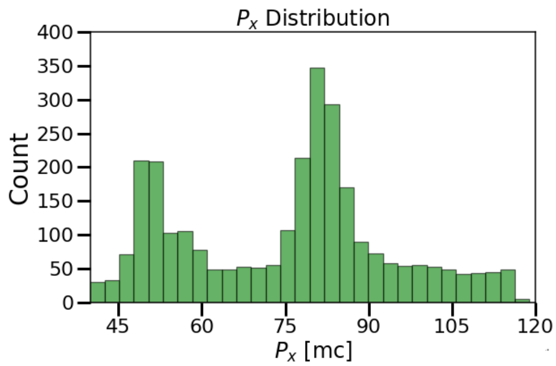


*Fig. 9. $P_x$ distribution function, $t=175T_0$. Scenario 2 sequence*

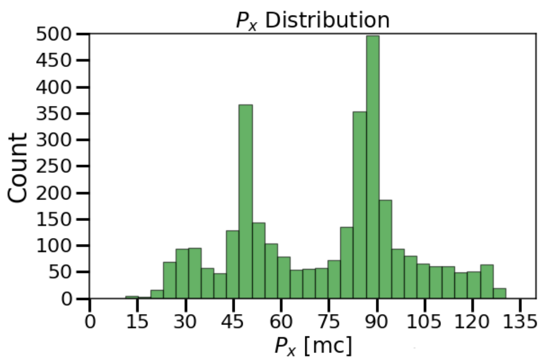


*Fig. 10. $P_x$ distribution function, $t=200T_0$. Scenario 2 sequence*

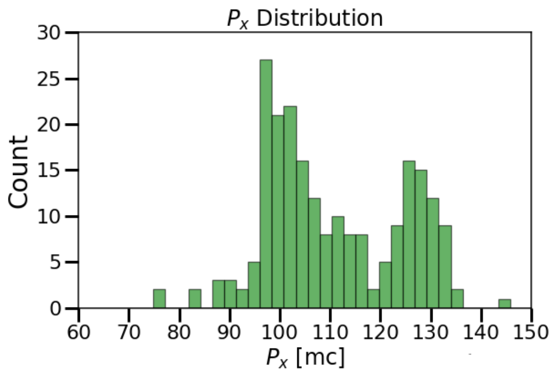


*Fig. 11. $P_x$ distribution function, $t=175T_0$. Scenario 1 sequence (related to Fig. 2)*

Namely, it was observed that at time $t=375T_0$ in the case of scenario 2 sequence after parameters variation the self-injected bunch structure was saved. At the same time, in the case of sequence before parameters variation, at the same moment the bunch is almost completely destroyed (see Fig. 8). Based on the results of the study, the advantages of the sequence after parameters variation are obvious. In the case of the second scenario of parameter variation, the existence of a self-injected bunch is observed until it reaches the edge of the wakefield bubble at $t=375T_0$. In the case of the initial sequence, before the parameter variation, the self-injected bunch decayed all time moments during motion.

## CONCLUSIONS

In this paper, the variation of parameters of a sequence of two laser pulses exciting wakefield in a metal density plasma was considered. The authors considered two scenarios of parameter variation. The first scenario assumed a simultaneous variation of the sequence parameters of the two laser pulses. The second scenario assumed that the parameters of each laser pulse of the sequence were different.

It has been shown that the stability of self-injected bunches is achieved using the parameter variation method, namely, the transverse bunch decay is overcome and the bunch existence time without disintegration is increased. In addition, a significant, up to 12.9 times increase in the number of particles in the self-injected bunch (in the second parameters variation scenario) was observed. In the first scenario, this value is 3.4.

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## ПІДВИЩЕННЯ СТАБІЛЬНОСТІ САМОІНЖЕКТОВАНОГО ЗГУСТКА ШЛЯХОМ ВАРІЮВАННЯ ПАРАМЕТРІВ ПОСЛІДОВНОСТІ ДВОХ ЛАЗЕРНИХ ІМПУЛЬСІВ ПРИ ЗБУДЖЕННІ КІЛЬВАТЕРНОГО ПОЛЯ В ПЛАЗМІ МЕТАЛЕВОЇ ГУСТИНИ

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

Розглянута варіація параметрів послідовності двох лазерних імпульсів, що збуджують кільватерне поле в плазмі металевої густини, як спосіб поліпшення стабільності самоінжектованого згустка: придушення поперечного розпаду згустка та збільшення часу існування самоінжектованого згустка в плазмі. Розглянуто два сценарії варіювання параметрів. У першому сценарії розглянуто одночасну зміну параметрів обох лазерних імпульсів; у другому сценарії набір параметрів для одного з лазерних імпульсів після варіювання відрізнявся від набору параметрів для іншого лазерного імпульсу (профільована послідовність двох лазерних імпульсів).