«Wakefield Excitation by a Sequence of Laser Pulses in Plasma*»

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INTRODUCTION

As we well know, the scale of energies encountered by physicists in their research has increased significantly recently. And now, energies of about several TeV are being reached at the Large Hadron Collider. An increase to the needed energies requires new approaches and new principles of acceleration.

Large Hadron Collider

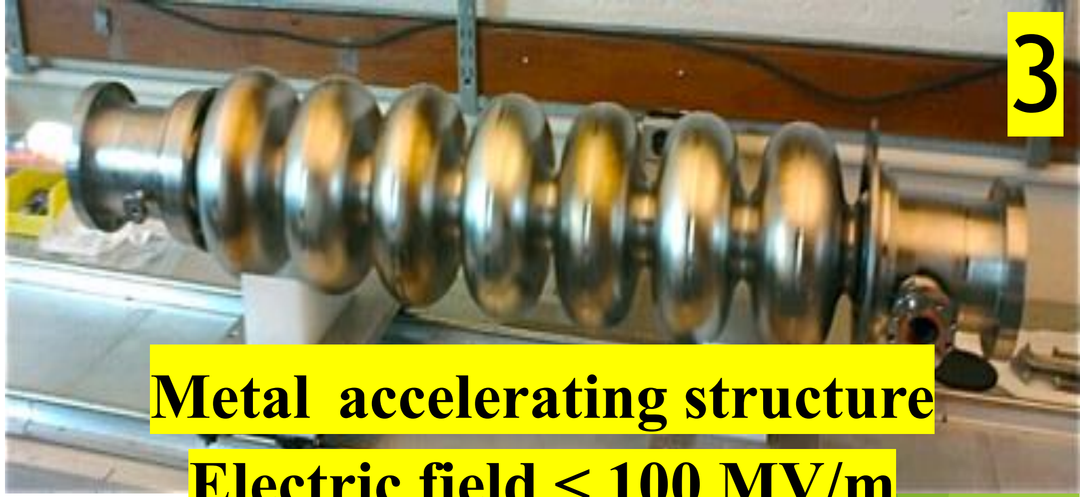
https://home.cern/

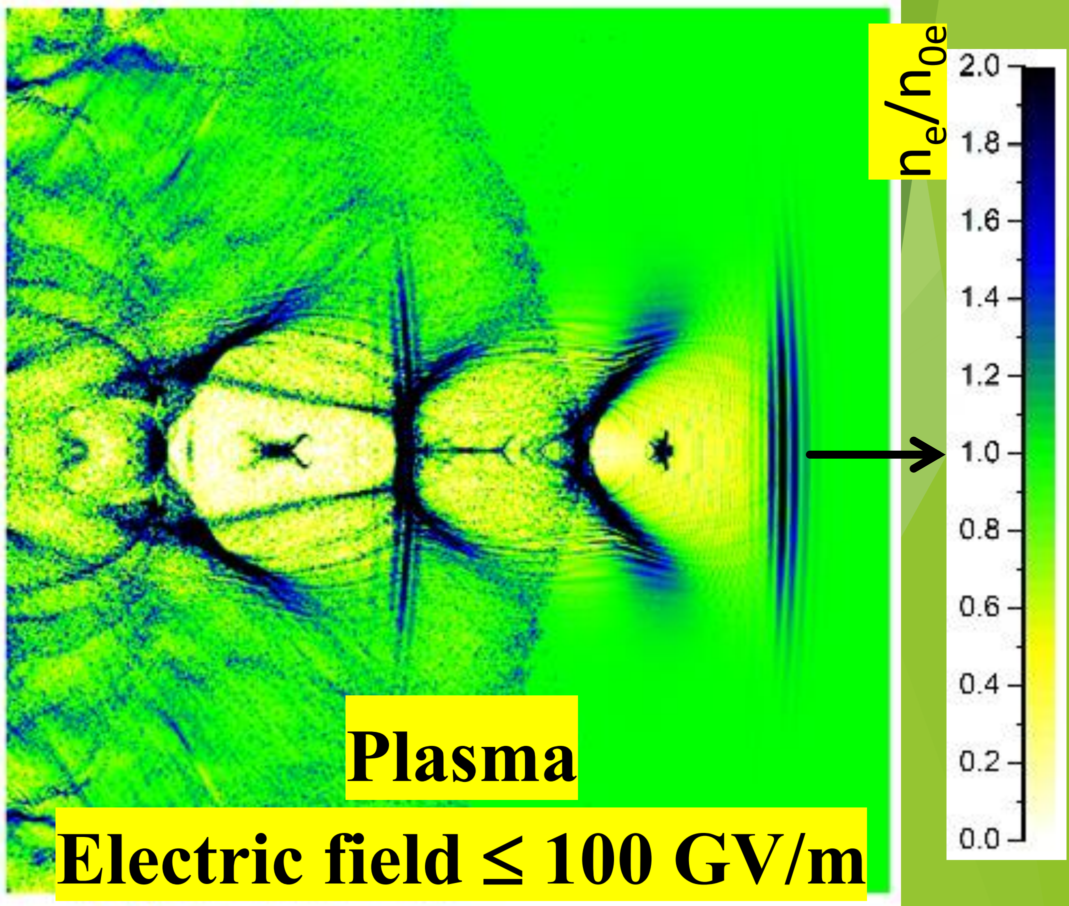
One of the approaches is the using of the so-called wakefield acceleration method. The wakefield acceleration method contains several key advantages: this method removes the issue of limiting the maximum acceleration gradient to the value at which breakdown occurs - in many structures it is hundreds of MV per meter or a little more. In addition, wakefield methods make it possible to achieve fields exceeding several hundred GV/m and even TV/m with relatively small accelerators.

A large number of studies confirm the fact that by exciting the wakefield using laser pulses it is possible to obtain acceleration gradients of the order of several TV/m [1, 2]. An important role in studies of the excitation of a wakefield is played by the question of the coherence of laser pulses [3]. Coherent addition avoids suppression of the accelerating wakefield by the laser field.

In this article the coherent addition of accelerating wakefields after laser pulses, using PIC modeling (UMKA code 2.5D [4]), was performed. Due to the increasing scale of energies required by scientists, wake plasma accelerators are very relevant. With their help, it is possible to avoid the limitation of 100 MV per meter in conventional accelerators [5-8]. The scientists have previously investigated issues related to wake acceleration. In particular, related to the combined laser-plasma acceleration. One way or another, in the non-linear case, at a sufficiently large amplitude, self-injected bunches are formed, due to which it is possible to implement a scheme of combined laser-plasma acceleration [9-14].

Previously, the excitation of a wakefield in a plasma by a short and intense laser pulse was studied (see [15]).





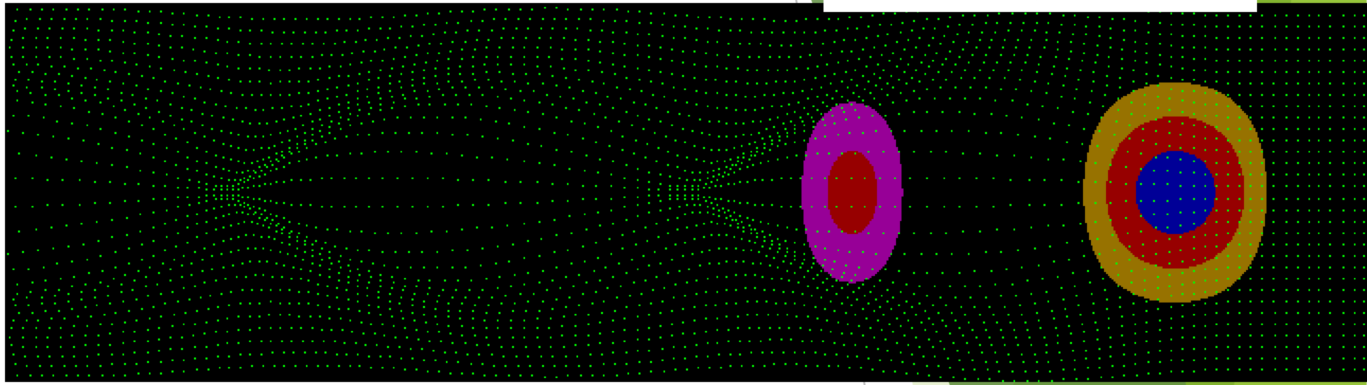
Wakefield acceleration

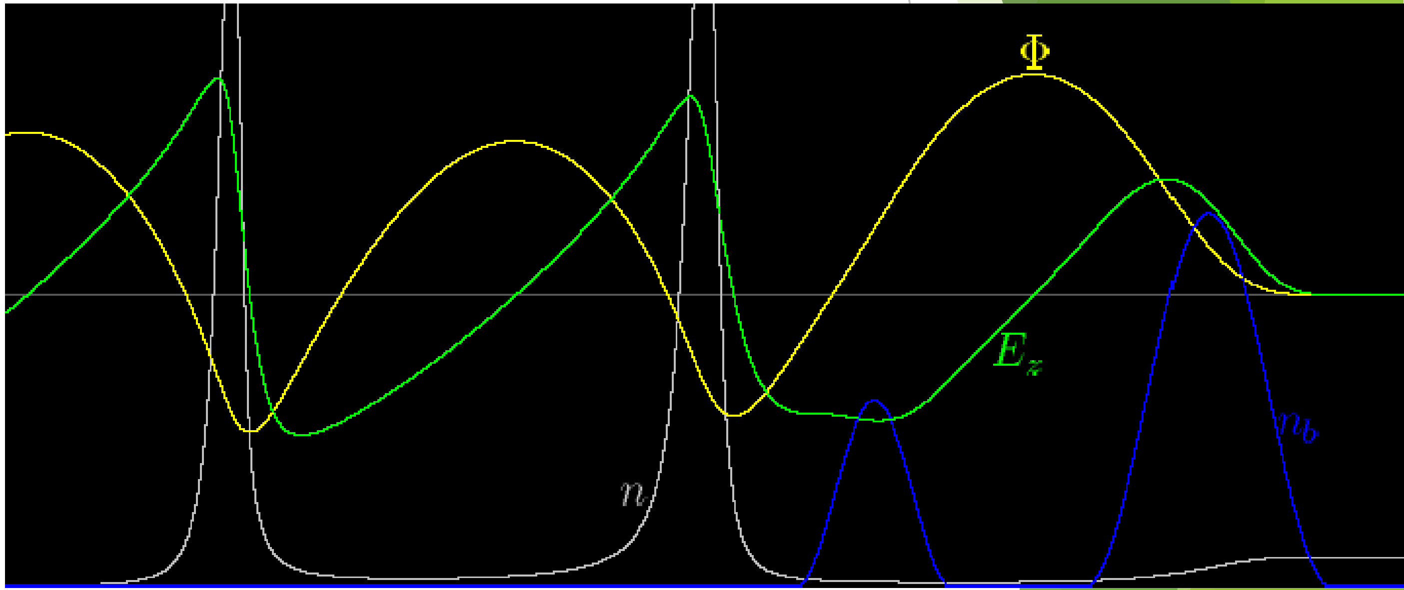
I.Yu.Kostyukov

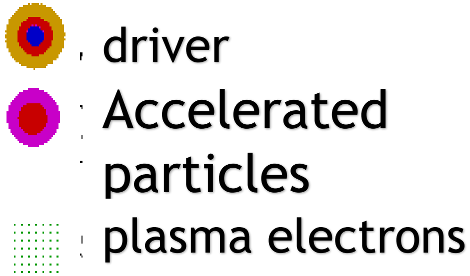
In the right Figure one can see the wakefield principle illustration. Driver (in our case) - a laser pulse moving through the plasma pushes electrons apart.

This is due to the action on the electrons of the so-called pondemotor i.e. Millar force. As a result, it is possible to separate the charges, creating an excess of negative electrons in one region. Heavy ions remain inactive.

Thus, it is possible to create fields of the order of 100GV/m in plasma and TV/m in plasma of metal density with the possibility of their subsequent use to accelerate charged particles.







Problem statement

- Investigate the features of coherent addition of wakefields from a chain of laser pulses. Consider parameter variation.
- Consider nonlinear cases.
- Consider additional effects that were identified during the study.

Simulation

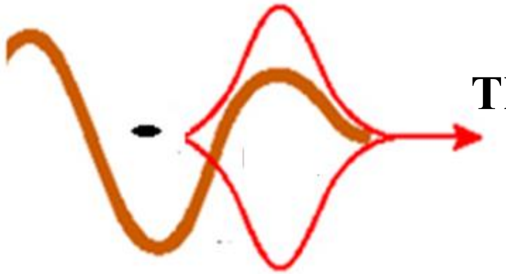
In the course of the study performed, a sequence of three identical laser pulses was studied. The coherent addition of accelerating fields from laser pulses was investigated. The amplitude varied from a weakly nonlinear to a highly nonlinear case. In the course of the study, additional effects were studied that accompanied the picture of coherent addition of the laser fields.

The case of a plasma was considered, the density of which is approximately equal to the density of free electrons in metals at a low (X-ray) laser wavelength. This choice is due to the fact that under the proposed conditions, significant (on the order of teravolts per meter) amplitude accelerating fields are formed. You can see on this slide the main and most important parameters of the system that was considered during the study. The study was carried out using numerical simulation using the UMKA code by the Particles-in-Cells method with the number of particles not less than 5,960,000 for the specified area. Further on the graphs, the normalized units will be indicated, considering the information that you can see.

Next slide illustrates the main parameters of simulation.

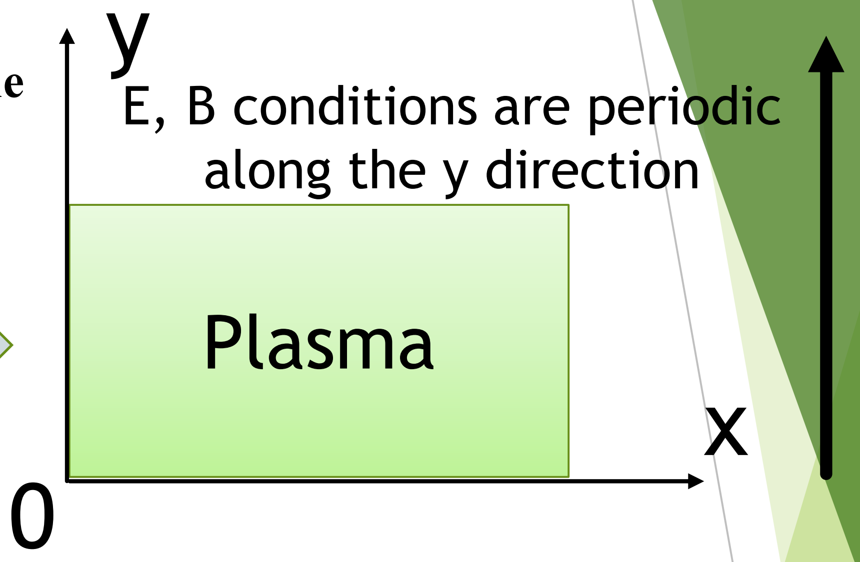
Investigation of the features of laser pulses chain fields coherent addition

UMKA code 2d3v code



The pulse profile corresponds to the dependence «$\cos^2 A$»

S-polarised laser (3 pulses)



Parameter	Value
Plasma density	$n_{pe} = 1.8 \cdot 10^{22}\ cm^{-3}$
Laser pulses wavelength	$\lambda = 25\ nm$
Simulation window length	800λ
Simulation window width	50λ
Laser wave field amplitude	$E_0 = 30.45\ TV/m\ (a_0 = 1)$
Laser pulse period	$t_0 = {}^{2\pi c}/_{\omega_0} = 0.08\ fs$
Length and width of laser pulse	$2\ \lambda$

Simulation

When a wakefield is excited in plasma in a nonlinear case, the behavior of plasma structures and laser pulses is far from obvious and simple. For example, it is difficult to predict the expansion of the plasma wake bubble. Even with the help of approximate calculations, it is impossible to consider all the details and processes at the same time. This means that in real (laboratory) experiments it will be necessary to spend a lot of time and resources in order to achieve the desired parameters. This can be avoided using numerical simulation.

In this paper, we consider the coherent addition of the wakefields of a chain of three laser pulses in the nonlinear case. In Fig. 1(a) (slide 9), we see that when the amplitude of the laser pulses is small and the case is weakly nonlinear (almost linear), the coherent addition occurs according to the well-known rule: the amplitudes of the accelerating fields after laser pulses relate to each other approximately as 1:2:3.

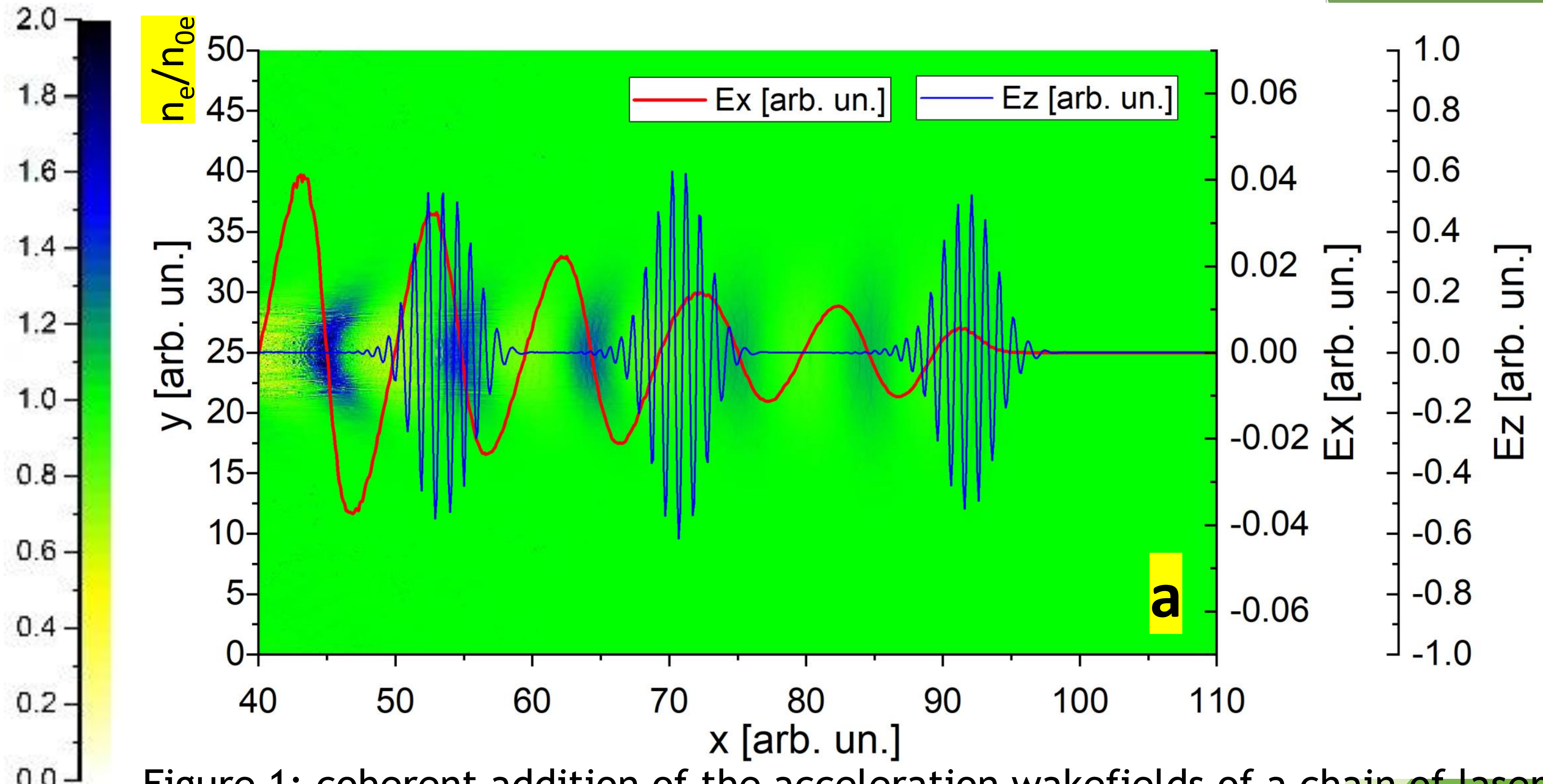
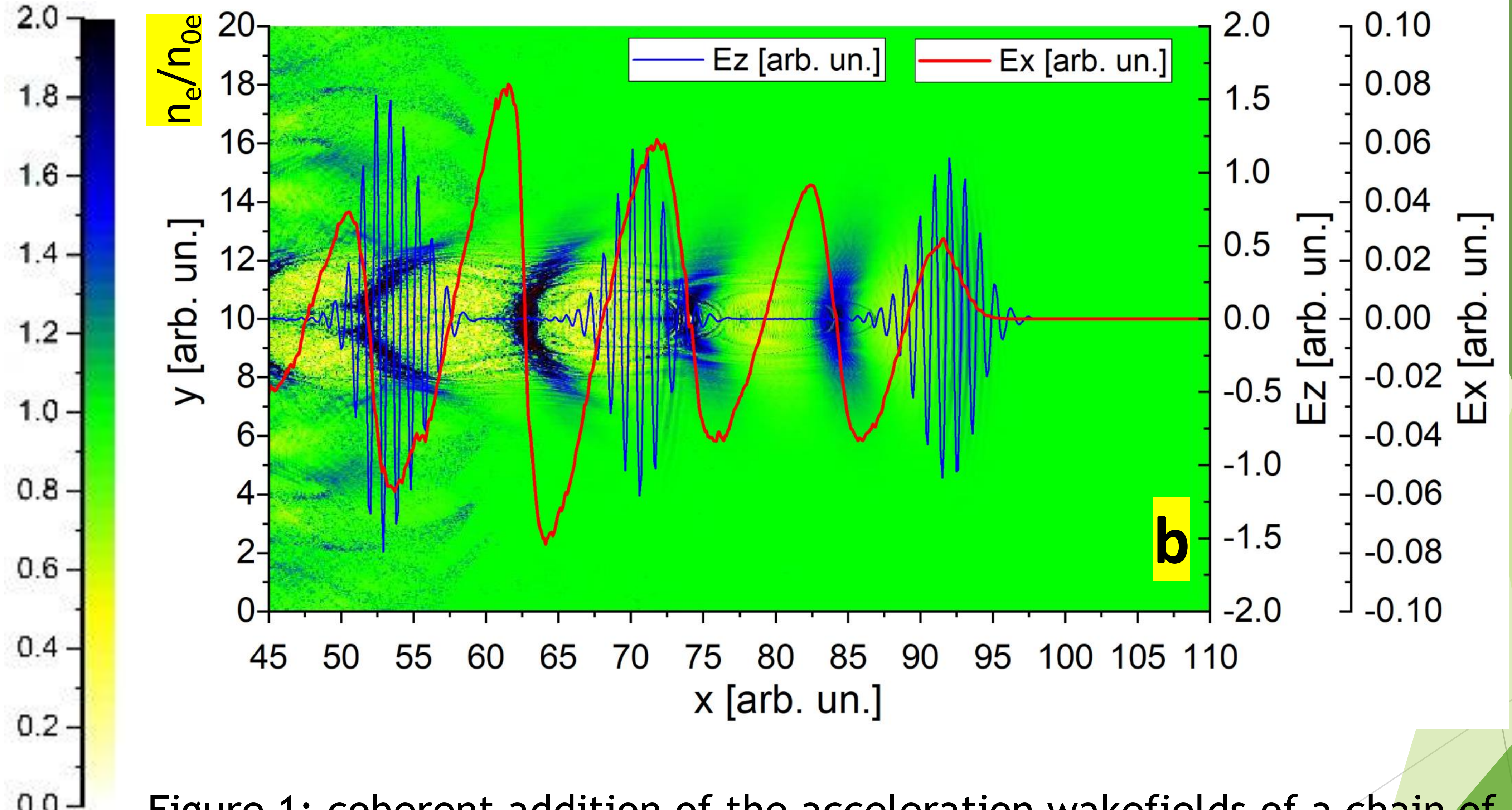


Figure 1: coherent addition of the acceleration wakefields of a chain of laser pulses. Nonlinear case $t = 100T_0$. Half width at half maximum equals 2, amplitude equals 1 for (a) and 2 for (b), (c). (c) illustrates “adjustment”. Color scale in Fig 1(a) works for all pictures

Simulation

Fig. 1(b) (slide 11) illustrates a completely different situation. In the nonlinear case, the wake bubble expands. This leads to a phase shift of the laser pulse relative to the wake wave, as a result of which the laser pulse enters the acceleration phase of the wakefield and suppress it. This figure shows that the presence of the laser pulse (third) in anti-phase to the first and second laser pulses leads to a violation of the coherent addition process, a decrease in the accelerating field and a significant drop in the acceleration efficiency.



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Simulation

The authors propose to solve this problem in the following way: it is necessary to change the distance be-tween the second and third laser pulse so that 3rd pulse will fall into the decelerating phase of the wakefield. Moreover, if we change the initial location of the laser pulses (moment $t = 0$) according to the data at moment $t = 100T_0$, then with a new, verification simulation, we will get the expected right result that third laser pulse falls into the deceleration phase of the wake wave (see Fig. 1(c) (slide 13)).

The authors called this method “adjustment”.

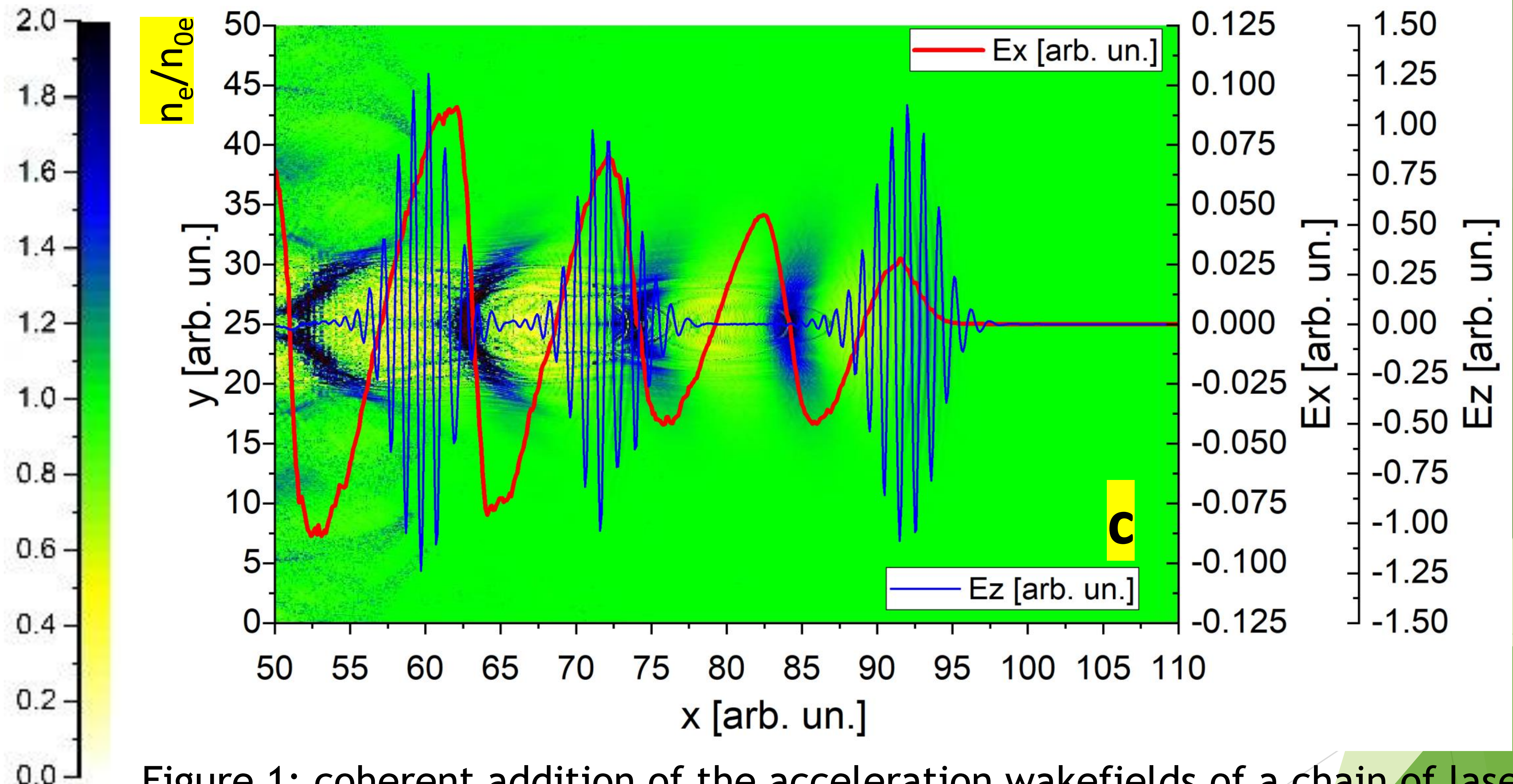


Figure 1: coherent addition of the acceleration wakefields of a chain of laser pulses. Nonlinear case $t = 100T_0$. Half width at half maximum equals 2, amplitude equals 1 for (a) and 2 for (b), (c). (c) illustrates “adjustment”. Color scale in Fig 1(a) works for all pictures

Simulation

In Fig. 2 (slide 15), the effect of an increase in the amplitude of the accelerating field can be observed in the region far after the third laser pulse up to the injection boundary. The formation of special plasma structures can be considered as the cause of this phenomenon. It can be seen that the shape of the plasma structures changes along the axis from the first laser pulse to the injection axis. The further, the more tapered they become. A change in the geometry of the electrons oscillations is observed and, as a consequence, an increase in the amplitude of the accelerating field.

Excitation of the wakefield by the X-ray laser pulse leads to the fact that the amplitude of the accelerating field reaches enormous values. For example, about 1.8 TV/m at maximum in Fig. 2 (slide 15, slide 16).

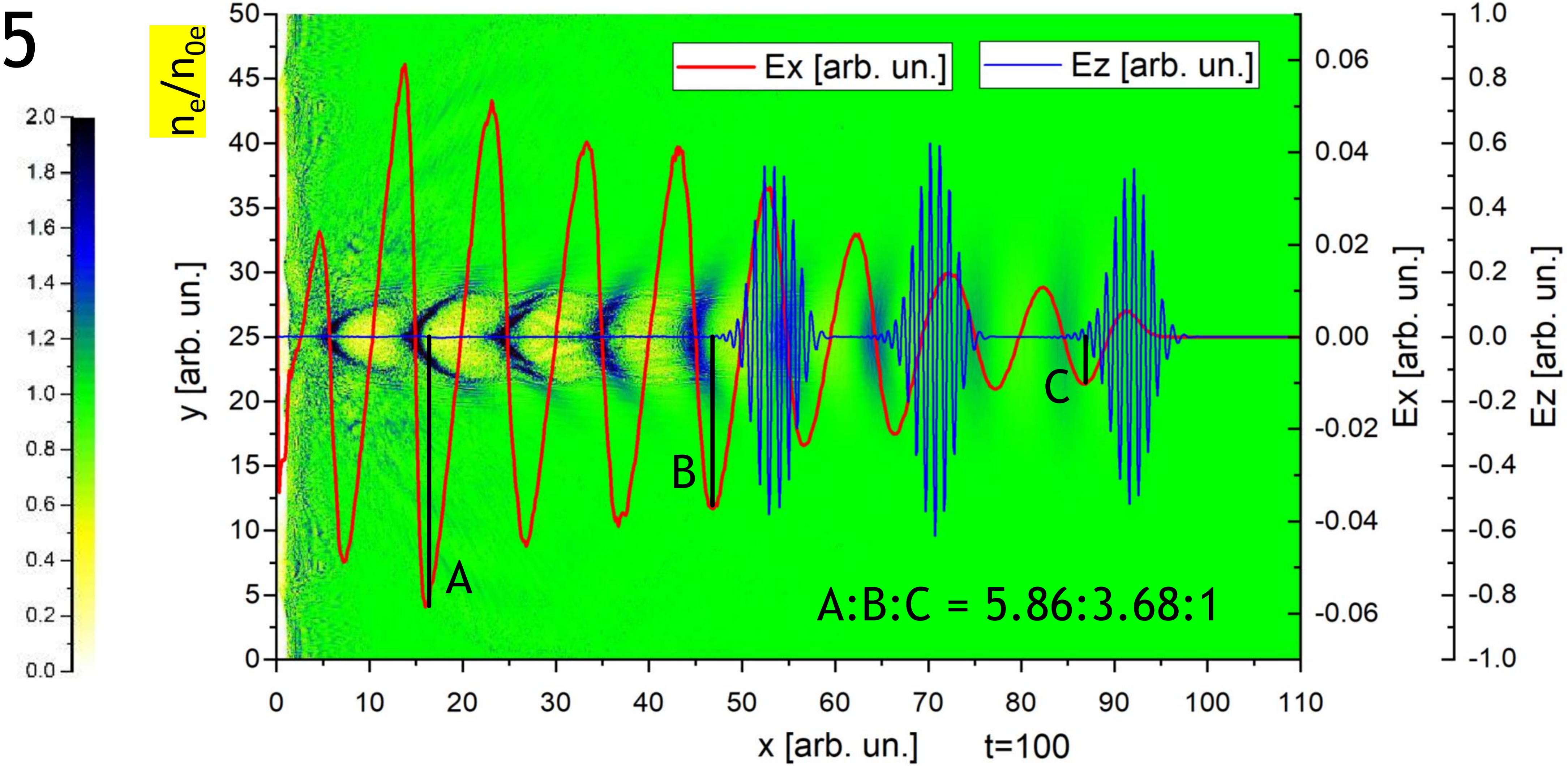
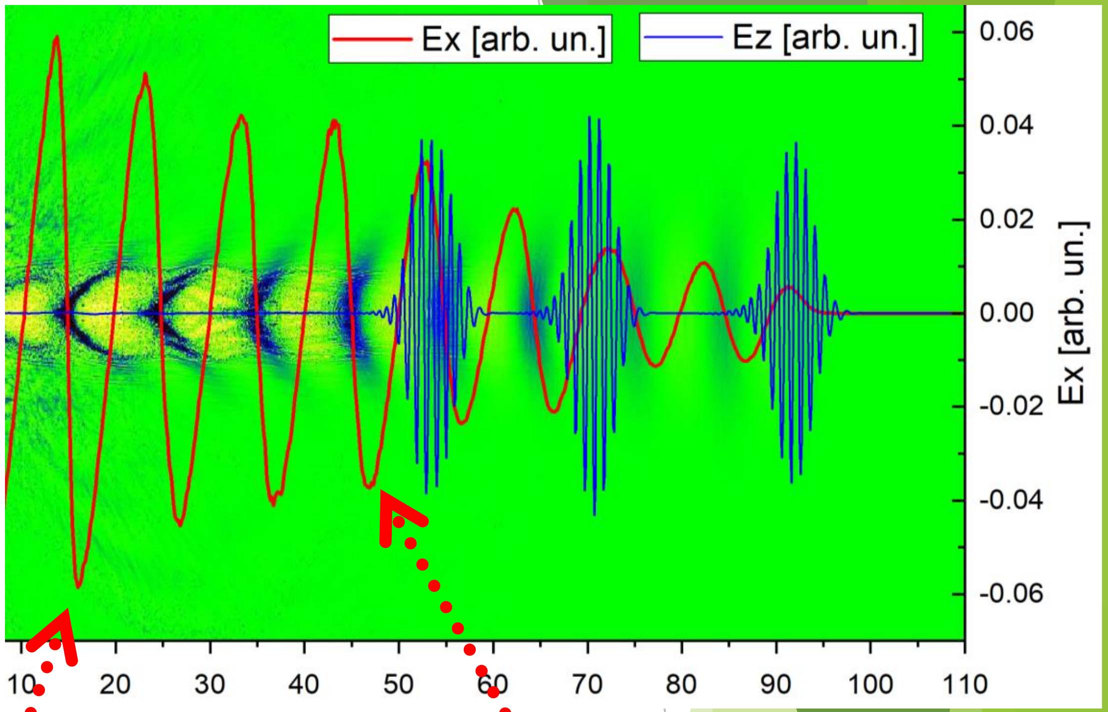


Figure 2: The effect of increasing the amplitude of the accelerating wakefield after laser pulses and before the start of the system.
The figure shows at the time t = 100

Wakefield acceleration in plasma with density that close to density electrons in metal

$$n_e = 1.8 \cdot 10^{22}\ cm^{-3}$$

$E_x^{V/m} \sim 1.2 - 1.8\ \mathrm{TV/m}$ >>**100 GV/m**



MAXIMAL

ACCELERATING FIELD

of about 1.8 TV/m

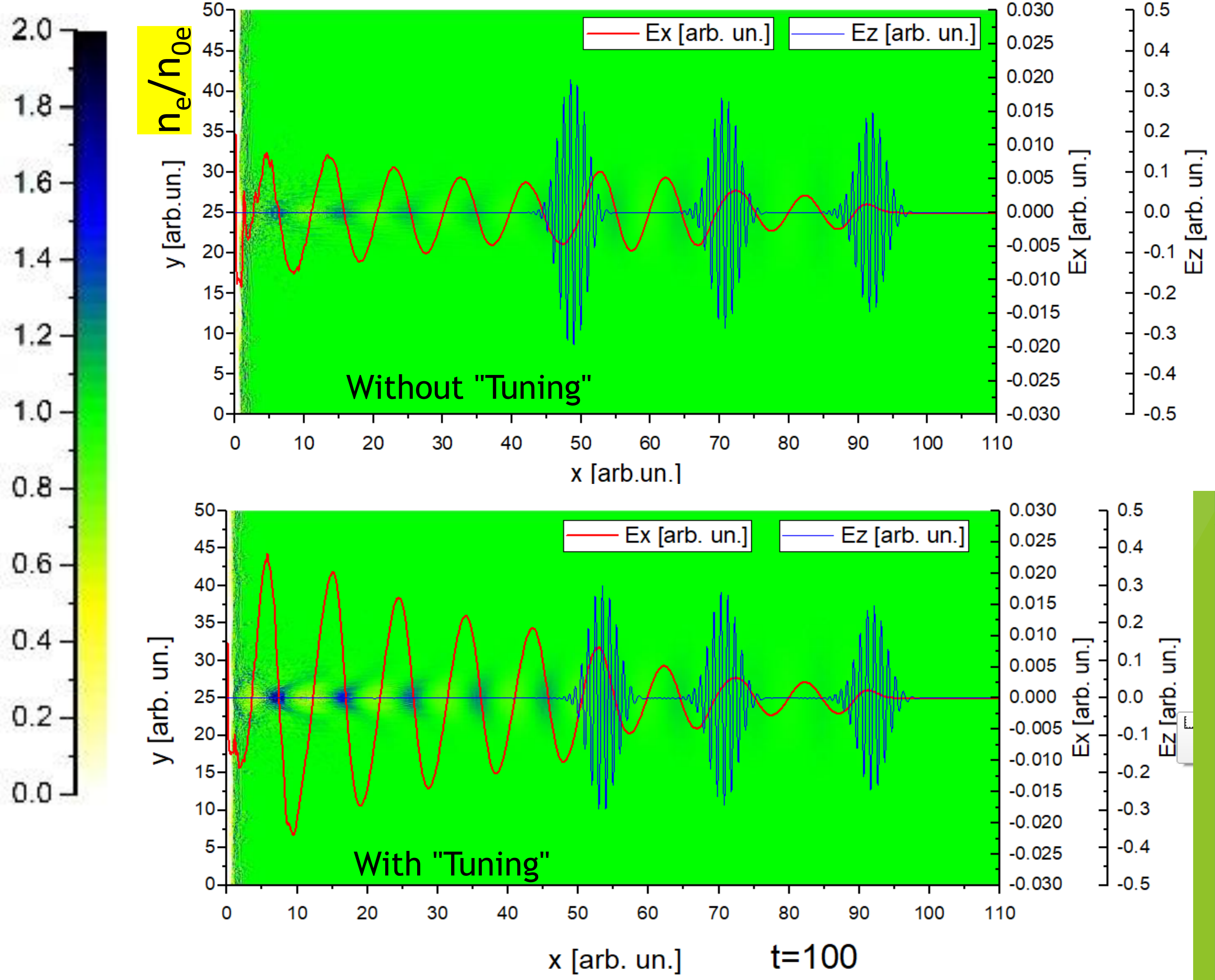
Accel. field ~ 1.2 TV/m

Simulation

“Adjustment” method works well in both the nonlinear (Fig. 1 (slides 9, 11, 13)) and linear (Fig. 3 (slide 18)) cases. As it can be seen from Fig. 1,3, the accuracy of the method is sufficient to restore the process of coherent addition and to ensure an increase in the amplitude of the accelerating field after the third laser pulse.

Coherent addition of the wakefields of the laser pulses was considered for the cases of laser pulses with different widths. In Fig. 4 (slide 19) one can see a graph of the ratios of the accelerating field amplitudes versus the amplitudes of the laser pulses. Obviously, coherent addition is not observed in nonlinear cases. This creates the need to use “adjustment”. A similar result was obtained in cases of laser pulse widths 1 and 3.

Figure 3: coherent addition of the acceleration wakefields of a chain of laser pulses. The weakly nonlinear case $t = 100T_0$. Half width at half maximum equals 1, amplitude equals 0.5. Fig. 3(a) without "adjustment" and (b) with adjustment.



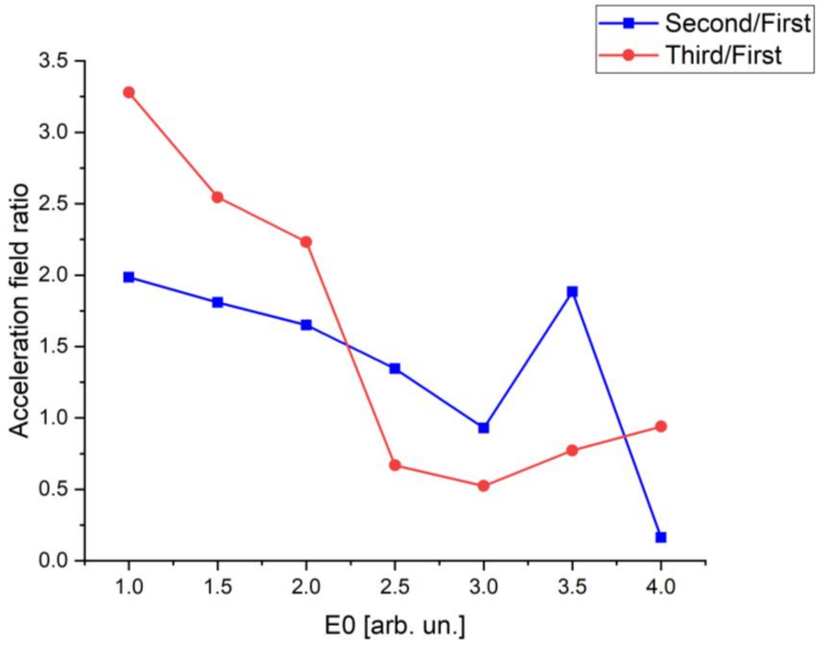
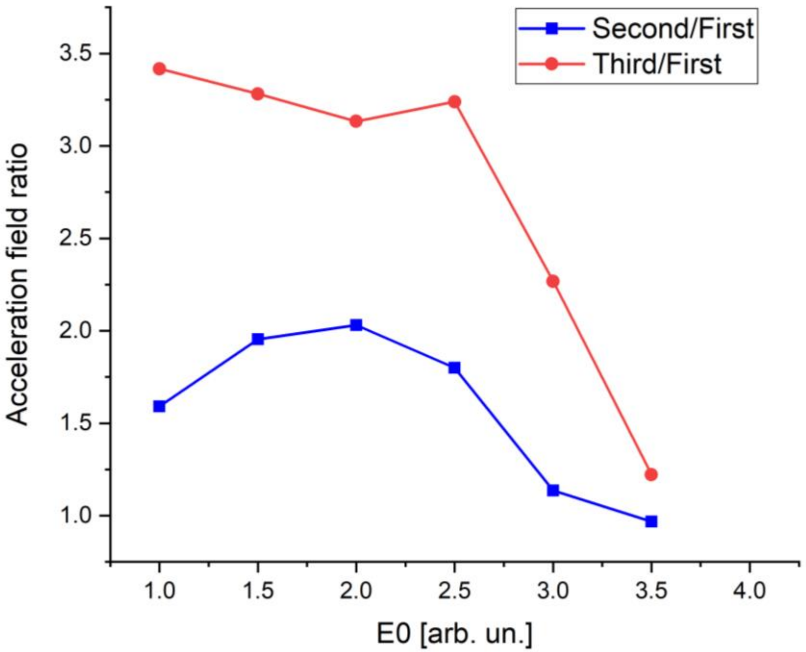
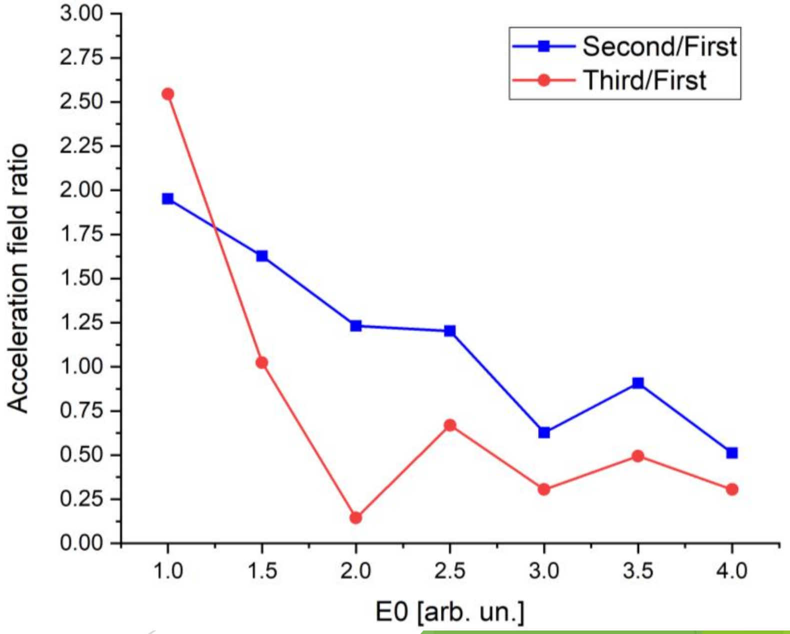


Figure 4: dependence of the ratio of the accelerating wakefields after the second and third bunches to the fields after the first pulse on the amplitude of laser pulses. The abscissa is the amplitude of the laser pulses, and the ordinate is the ratio of the accelerating wakefields.

The ratio of the wakefields after the second pulse to the after first and after the third to the after first laser pulse for various parameters depending on the amplitude. The parameters of all pulses are changed simultaneously.



Half-width at half-height is 1



Half-width at half-height is 3

CONCLUSION

- The excitation of a wakefield in plasma by a chain of three laser pulses was investigated.
- It was observed that a laser pulse hit to the wakefield accelerating phases and suppress the accelerating field because of the well-known effect of increasing of length of the wake bubble in the nonlinear case.
- The mechanism of «adjustment» the location of laser pulses was investigated, which made it possible to reduce the negative effect of laser pulses hitting the accelerating phases.
- The effect of an amplitude increasing of the accelerating wakefield in the region after laser pulses was observed due to the formation of special plasma structures that enhance the accelerating wakefield.
- The value of the accelerating wakefield amplitude was obtained.

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