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WAKEFIELD EXCITATION BY A SEQUENCE OF LASER PULSES IN PLASMA

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Abstract

PIC simulation by means of 2.5D UMKA code of the wakefield excitation by a sequence of three Gaussian laser pulses in plasma was carried out. The dependence of excited wakefield intensity on power and width of laser pulses was investigated.

It was shown the coherent addition of wakefield, excited by each laser pulse of the sequence, for linear case, while for the nonlinear case the coherency was destroyed. The profiled sequence of laser pulses was also considered.

The possibility to obtain the same total wakefield excited by the profiled sequence of laser pulses with decreasing intensity, as for the uniform sequence was studied.

INTRODUCTION

A large number of studies confirm the fact that by exciting the wakefield using laser pulses it is possible to obtain accelerating gradients of the order of about TV/m [1, 2]. The question of the coherence of laser pulses plays an important role in studies of the excitation of a wakefield [3]. In this article the coherent addition of accelerating wakefields after laser pulses was performed by 2.5D simulation with PIC code UMKA [4].

Plasma wakefield accelerators are appropriate to avoid the limitation of 100 MV/m for accelerating gradient in conventional accelerators [5-8]. The scientists have previously investigated issues related to wake acceleration. In the nonlinear case, at a sufficiently large amplitude of the wakefield, self-injected bunches are formed, that makes possible to implement the 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]).

PARAMETERS OF SIMULATION

Plasma shape was rectangular of about 800λ long and 50λ wide. λ is the laser wavelength. Plasma model is hydrodynamic. Ions are immobile. Distances are normalized to the laser wavelength $\lambda = 25$ nm (X-Ray). Timestep equals $\tau = 0.05$. There are 8 particles per one cell and also 15.6 M as total amount. The simulation time is $800T_0$, where $T_0 = 2\pi\omega_0^{-1}$ is the laser period. Laser frequency is $\omega_0 = 7.5 \cdot 10^{16}$ rad/s. Laser wave s polarization and plasma region is initially uniform with density $n_0 = 1.8 \times 10^{22}$ cm^{-3}. Free boundary conditions are taken for fields along x axis and periodical ones for fields along y axis. Nonlinear case is considered. The density in the figures is normalized to the unperturbed plasma density. Black areas correspond to the density increase by 2 times. Laser pulse has profile like $\cos^2 A$. In all cases, three laser pulses of equal amplitude, duration, and width were injected into the plasma. The half-length at half maximum of all pulses in all cases is 2. All laser pulses duration is 0.34 fs.

Electric field amplitude E is normalized on $EE_0^{-1} = a$, where $E_0 = m_e c\omega_0(2\pi e)^{-1}$ for all cases. Arbitrary units in graphs correspond to the dimensionless quantity a.

RESULTS OF SIMULATION

When 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 experiments one need a lot of efforts to obtain the desired result. This can be avoided using numerical simulation. In this paper, we consider the coherent addition of the wakefields of a sequence of three laser pulses in the nonlinear case.

Figure 1 shows the plane of simulation (x, y), plasma density distribution (shown by color), accelerating wakefield E_x and laser pulse E_z field amplitudes. The process of the wakefield excitation is considered in a (x, y) plane, but the system is homogeneous and endless in the perpendicular direction z. Laser field amplitude vector $\vec{E}_z \uparrow\uparrow \vec{z}$.

In Fig. 1(a), 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 E_x after laser pulses relate to each other approximately as 1:2:3.

Figure 1(b) illustrates a completely different situation. In the nonlinear case, the wake bubble occurs which is expanding. This leads to the phase shift of the laser pulse relatively to the wake wave. As a result, the laser pulse enters in the accelerating phase of the wakefield and suppress it. Figure 1(b) shows that the location of the third laser pulse in wakefield antiphase to that of the first and second laser pulses leads to the violation of the coherent addition process, decrease in the accelerating field and a significant drop in the acceleration efficiency. The authors propose to solve this problem in the following way: it is necessary to change the distance between 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

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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)). The authors called this method “adjustment”.

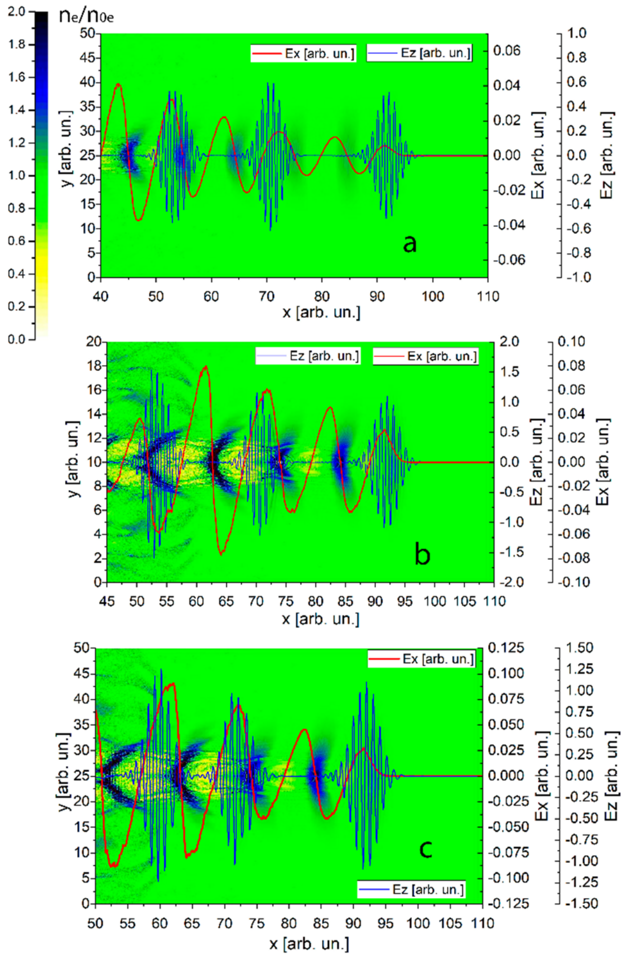

Figure 1: Coherent addition of the accelerating wakefields of a sequence of laser pulses at $t = 100T_0$. Half width at half maximum equals 2, amplitude equals 1 for (a) (weakly nonlinear case) and 2 for (b), (c) (nonlinear case). (c) illustrates “adjustment”. Color scale in Fig. 1(a) refers to all pictures.

This method works well in both the nonlinear (Fig. 1) and linear (Fig. 2) cases. Proposed method allows to restore the process of coherent addition in nonlinear (Fig. 1) and linear (Fig. 2) cases. This leads to 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. 3 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.

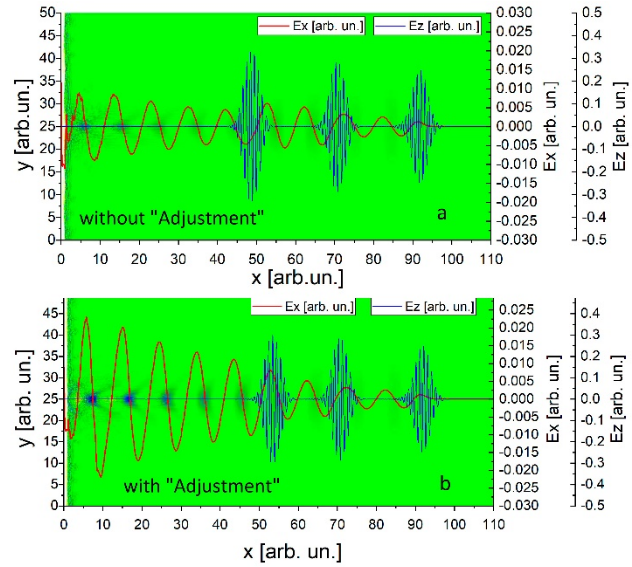

Figure 2: Coherent addition of the accelerating wakefields of a sequence of laser pulses at $t = 100T_0$. The weakly nonlinear case with amplitude equals 0.5. Half width at half maximum equals 1. Figure (a) without “adjustment” and (b) with adjustment.

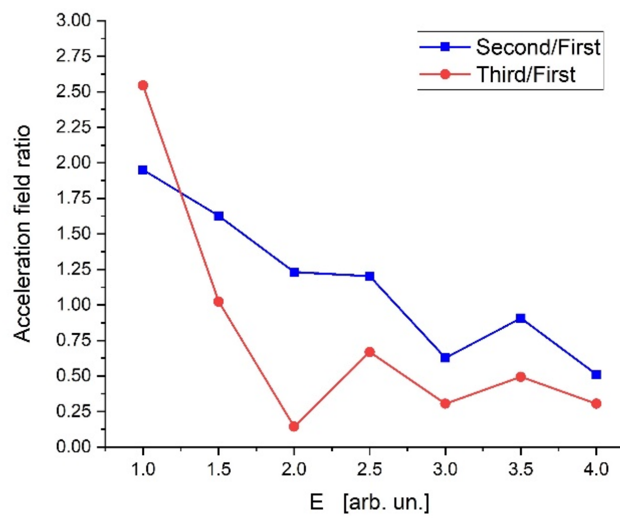

Figure 3: Dependence of the ratio of the accelerating wakefields after the second and third laser pulses to the fields after the first pulse upon the amplitude of laser pulses.

In Fig. 4, 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 plasma structure of electron seals can be considered as the cause of this phenomenon.

It can be seen that the shape of the plasma electron seals changes along the axis from the first laser pulse to the injection boundary. Near the injection boundary, the angle at the top of the seals decreases. A change in the characteristics of the electrons oscillations is observed and, as a consequence, the amplitude of the accelerating field increases. This question needs additional investigations.

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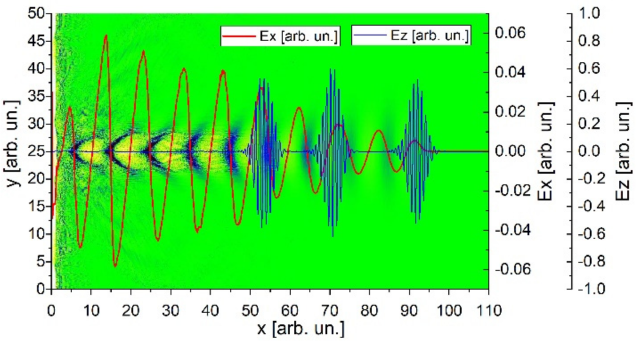

Figure 4: Effect of increasing the amplitude of the accelerating wakefield after laser pulses and before the start of the system. $t = 100T_0$.

Excitation of the wakefield by the high power (10^{18} W/cm^2) X-ray ($\lambda = 25$ nm) short duration (0.17 fs) laser pulse in high density plasma ($n_0 = 1.8 \times 10^{22}$ cm^{-3}) leads to the fact that the amplitude of the accelerating field reaches enormous values. For example, about 1 TV/m at maximum in Fig. 3.

CONCLUSION

In this paper, the coherent addition of the accelerating fields was considered when wakefield is existed by the sequence of three identical laser pulses. It was found that in weakly nonlinear case coherent addition is observed (Fig. 1(a)). It was also found that in the non-linear case, due to the hit of the laser pulse in the accelerating phase of the wakefield, the effect of coherent addition is destroyed.

This problem can be corrected using the so-called "adjustment" – changing of the initial position of the laser pulses. Due to the formation of special plasma structures, an increase of the accelerating field amplitude is observed. When a wakefield was excited in a high-density plasma by an X-ray Exawatt laser pulse of short duration, accelerating field with an amplitude of about several teravolts per meter was observed.

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REFERENCES

[1] Z. Xiaomei *et al.*, "Particle-in-cell simulation of x-ray wakefield acceleration and betatron radiation in nanotubes", *Phys. Rev. Accel. Beams*, vol. 19, p. 101004, 2016. doi:10.1103/PhysRevAccelBeams.19.101004

[2] T. Tajima, "Laser Acceleration in Novel Media", *Eur. Phys. J. Spec. Top.*, vol. 223, p. 1037–1044, 2014. doi:10.1140/epjst/e2014-02154-6

[3] T. Tajima, X. Q. Yan, and T. Ebisuzaki, "Wakefield acceleration", *Reviews of Modern Plasma Physics*, vol. 4, no. 4, 2020. doi:10.1007/s41614-020-0043-z

[4] I. Dudnikova, T. V. Liseykina, and V. Yu. Bychenkov, "Parallel algorithms for numerical simulation of propagation of an electromagnetic radiation in plasma", *Comp. Techn.*, vol. 10, p. 37, 2005.

[5] J. van Tilborg *et al.*, "Measurement of the laser-pulse group velocity in plasma waveguides", *Phys. Rev. E*, vol. 89, p. 063103, 2014. doi:10.1103/PhysRevE.89.063103

[6] H. T. Kim *et al.*, "Enhancement of Electron Energy to the Multi-GeV Regime by a Dual-Stage Laser-Wakefield Accelerator Pumped by Petawatt Laser Pulses", *Phys. Rev. Lett*, vol. 111, p. 165002, 2013. doi:10.1103/PhysRevLett.111.165002

[7] A. J. Gonsalves *et al.*, "Tunable laser plasma accelerator based on longitudinal density tailoring", *Nature Physics*, vol. 7, pp. 862–866, 2011. doi:10.1038/nphys2071

[8] X. Wang *et al.*, "Quasi-monoenergetic laser-plasma acceleration of electrons to 2 GeV", *Nature Communications*, vol. 4, p. 1988, 2013. doi:10.1038/ncomms2988

[9] K. H. Pae, I. W. Choi, and J. Leea, "Self-mode-transition from laser wakefield accelerator to plasma wakefield accelerator of laser-driven plasma-based electron acceleration", *Physics of Plasmas*, vol. 17, p. 123104, 2010. doi:10.1063/1.3522757

[10] B. Hidding *et al.*, "Monoenergetic Energy Doubling in a Hybrid Laser-Plasma Wakefield Accelerator", *Phys. Rev. Lett.*, vol. 104, p. 195002, 2010. doi:10.1103/PhysRevLett.104.195002

[11] W. P. Leemans *et al.*, "Multi-GeV electron beams from capillary-discharge-guided subpetawatt laser pulses in the self-trapping regime", *Phys. Rev. Lett.*, vol. 113, p. 245002, 2014. doi:10.1103/PhysRevLett.113.245002

[12] S. Corde *et al.*, "Mapping X-Ray Emission Region in a Laser-Plasma Accelerator", *Physical Review Letters*, vol. 107, p. 215004, 2011. doi:10.1103/PhysRevLett.107.215004

[13] V. I. Maslov, O. M. Svystun, I. N. Onishchenko, and V. I. Tkachenko, "Dynamics of Electron Bunches at the Laser-Plasma Interaction in the Bubble Regime", *Nuclear Instruments and Methods in Physics Research A.*, vol. 829, pp. 422–425, 2016. doi: 10.1016/j.nima.2016.04.018

[14] D. S. Bondar, I. P. Levchuk, V. I. Maslov, S. Nikonova, and I. N. Onishchenko, "Dynamics of Self-Injected Electron Bunches at their Acceleration by Laser Pulse in Plasma", *Problems of Atomic Science & Technology*, vol. 6, pp. 76–79, 2017.

[15] G. Fiore *et al.*, "On cold diluted plasmas hit by short laser pulses", *Nucl. Instr. & Meth. in Phys. Res. A*, vol. 909, pp. 41–45, 2018. doi:10.1016/j.nima.2018.03.038