ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB167

WAKEFIELD EXCITATION IN PLASMA OF METALLIC DENSITY BY A LASER PULSE*

D. S. Bondar[1, †], V. I. Maslov[1], I. N. Onishchenko, Kharkiv Institute of Physics and Technology, Kharkiv, Ukraine
[1]also at V. N. Karazin Kharkiv National University, Kharkiv, Ukraine

Abstract

Recently the proposal to use X-ray Exawatt pulse for particle acceleration in a crystal has been declared. Short X-ray high-power pulse excites wakefield in electron plasma of metallic density which can be used for high gradient acceleration of charged particles. This wakefield is suited for laser wakefield acceleration.

In this paper there are simulated with PIC code UMKA: excitation of the large wakefield amplitude up to several TV/m in electron plasma of metallic density by a powerful X-ray laser pulse; laser plasma wakefield acceleration of self-injected electron bunch in such setup; combined acceleration by plasma wakefield driven by laser pulse (LPWA) and by self-injected electron bunch (PWFA).

INTRODUCTION

The maximal accelerating field can be achieved in conventional accelerators is limited 100 MV/m because of breakdown at higher amplitudes. For plasma wakefield accelerators this limit reaches up to 100 GV/m. Laser plasma wakefield accelerators can produce short electron bunches of high energy and high accelerating gradients [1-3]. High accelerating gradients allows reducing dimensions and cost of the accelerators, based on plasma wakefield methods of acceleration. It is so difficult for us to excite wakefield resonantly by the long sequences of electron bunches, to focus them, and to obtain large transformer ratio because of nonstationarity of laboratory plasma [4, 5]. It was founded [5] and studied [6, 7] mechanism of electron bunches sequences focusing.

A lot of experiments on laser plasma wakefield acceleration are devoted to elaboration of plasma-based accelerators [8, 9]. Great accelerating gradients help to diminish geometrical parameters of the accelerators and the estimated cost. The electron bunches formed at intense laser-plasma interactions has a small energy spread [10]. Electron self-injection generated by intense laser pulse in the wake bubble at underdense plasma was investigated by numerical simulation in [11]. In [12] the researches have been considered and experimentally studied phenomena of electron acceleration and self-injection. The occurrence of the slingshot effect at the impact of a very short and intense laser pulse onto a diluted plasma has been studied in [13].

During the process of exciting the wakefield, the laser pulse is destroyed (for reasons of nonlinear processes, expansion of the wake bubble and so on).

It can be solved by using capillary for laser pulse instead of waveguide or by passing energy to accelerated bunch and transforming it into driver-bunch for wakefield excitation.

The transition from laser plasma wakefield acceleration to acceleration by plasma wakefield driven with electron bunch was considered in [14].

PARAMETERS OF SIMULATION

PIC simulation completed by UMKA 2D3V code [15]. A computational region (x, y) is rectangular. Distances are normalized to the laser wavelength $\lambda = 8$ nm (X-Ray). The time interval of simulation is $\tau = 0.05$, the number of particles per cell is 8 and the total number of cells of about 15.6 M. The simulation time is 800 laser periods. Time units t are normalized on laser pulse period $T_0 = 2\pi\omega_0^{-1}$. The $\omega_0 = 7.5 \cdot 10^{16}$ rad/s is a laser frequency. The s-polarized laser pulse enters inside uniform plasma. Free boundary conditions are taken for fields along x axis and periodical ones for fields along y axis. Nonlinear case is considered.

The initial plasma density is $n_0 = 1.8 \cdot 10^{23}$ cm^{-3}. This density equals the density of free electrons in metals. Nonlinear case was considered. Laser pulse has profile like $(\cos A)^2$. 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. 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 $\vec{E}_z \uparrow\uparrow \vec{z}$. For all laser pulses electric field amplitude $E_z = 3E_0$, $a = 3$. When $a = 1$ the intensity of laser pulse is 10^{18} W/cm^2. Accelerating wakefield amplitude is E_x. The two cases were considered. The first case: 2 laser pulses sequence with length at half maximum (LHM) equals 2 for the first laser and 4 for the second laser. The width at half maximum (WHM) equals 10 for the first and 6 for the second laser. The second case: laser pulses sequence with LHM equals 4 for the first laser pulse and 6 for the second laser. WHM equals 8 and 4. Coordinates x and y, are given in dimensionless form in units of λ. For laser pulse LHM equals 4 corresponds to 0.34 fs duration.

RESULTS OF SIMULATION

Three stages of wakefield excitation by a sequence of laser pulses in a plasma are investigated. In Figs. 1 and 2 two of them are shown.

Figure 1 shows that at $t = 60$ as a result of the wake process, two selfinjected bunches are formed: both after the

*The study is supported by the National Research Foundation of Ukraine under the program "Leading and Young Scientists Research Support" (project # 2020.02/0299).
†E-mail: bondard12@gmail.com

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB167

first and after the second laser pulses. Then self-injected bunches move through wake bubble and fall into the accelerating phase of the wakefield. They have a small spatial size (their sizes 7 times lower than sizes of the wake bubble). At the same time, they have relatively low energy (illustrated by momentum graphs in Figs. 3(a) and 3(b). The average energy twice lower than in the case when self-injected bunches in the middle of accelerating phase in Figs. 3(c) and 3(d)). Figure 3(a) corresponds to the first self-injected bunch in Figs. 1 and 3(b) corresponds to the self-injected bunch after the second laser pulse in Fig. 1. In Figs. 1, 2, and 4 longitudinal wakefields E_x are shown by red lines. Maximal accelerating field value reaches 7 TV/m.

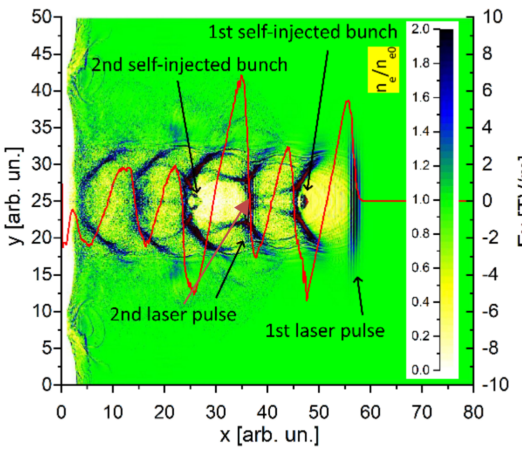

Figure 1: Wakefield excitation in plasma by the sequence of 2 laser pulses (1st case). $t = 60$. Longitudinal wakefield amplitude E_x is shown by red line.

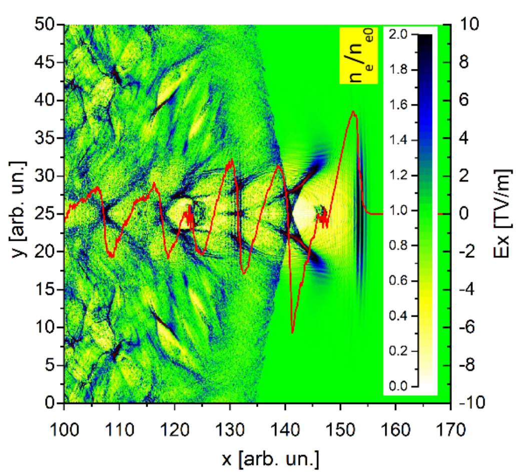

Figure 2: Wakefield excitation in plasma by the sequence of 2 laser pulses (1st case). $t = 160$. Longitudinal wakefield amplitude E_x is shown by red line.

Figures 2, 3(c), and 3(d) at $t = 160$ show that after the self-injected bunch passed the accelerating phase and begin to enter the wakefield deceleration phase, its spatial size increases, the energy spread is almost saved and the electron energy of the bunches increases.

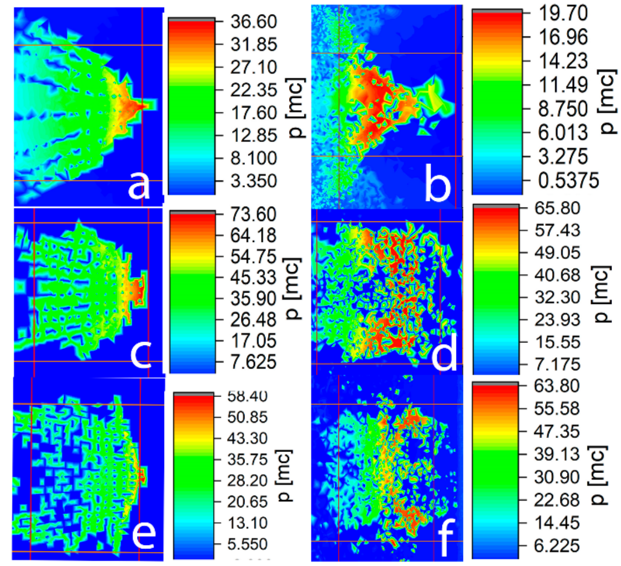

Figure 3: Detailed view of self-injected bunches. Distribution of longitudinal momentum. Normalized on $[m_e c]$ where m_e is the electron mass and c is the light speed. Figure's relations: Fig. 1 (a-first, b-second) means that in Fig. 3(a) one can see the first selfinjected electron bunch after first laser pulse from Fig. 1 and in Fig. 3(b) is the second bunch. Similarly: Fig. 2 (c-first, d-second), Fig. 4 (e-first, f-second).

This means that due to the action of the wakefield, self-injected bunches acquire additional energy without significant defocusing. This is an important stage in combined laser-plasma acceleration.

Finally, Figs. 3(e), 3(f), and 4, at $t = 260$ show that self-injected bunches fall into the decelerating phase of the wake wave. This leads to an increase in their spatial size and energy dispersion and to a decrease of self-injected bunches energy. The bunches are substantially defocused and destroyed. The reason for this may be relativistic defocusing due to a decrease in the gamma factor of bunches electrons.

The energy is transferred to the wave. As a result, as we can see from the comparison of Figs. 1 and 4, in the case of self-injected bunches, both after the first and after the second laser pulses, the energy transfer from the bunches to the wave leads to an increase in the accelerating wakefield by about 28%. The accelerating gradient of the accelerating field at this moment reaches a value of 8 TV/m. Such rates of acceleration are possible due to the high density of the plasma and high-power X-Ray laser pulses. To implement such a regime, very powerful X-ray lasers are needed. A promising technology will make it possible to create compact and powerful charged particle accelerators. The mechanism of the formation of self-injected bunches makes it possible to obtain focused bunches of high energies (see Fig. 3(b)), but it requires careful control of the parameters of the system.

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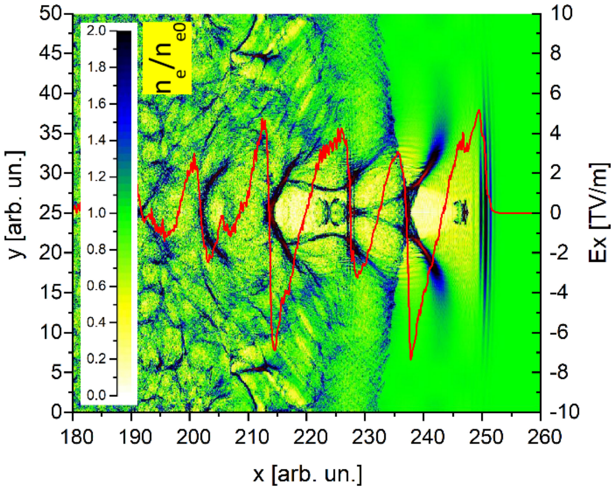

Figure 4: Wakefield excitation in plasma by the sequence of 2 laser pulses (1st case). $t = 260$. Longitudinal wakefield amplitude E_x is shown by red line.

When considering the second case with LHM equals 4 for the first laser pulse and 6 for the second laser. WHM equals 8 and 4, we can observe a similar picture: the effect of the combined laser-plasma acceleration leads to an increase of the accelerating wakefield amplitude.

And thanks to the use of high dense plasma ($n_0 = 1.8 \cdot 10^{23}$ cm^{-3}) and a high-power (of about 10^{18} W/cm^2) low duration (of about 0.34 fs) X-ray (of about $\lambda = 8$ nm) laser pulse, one can obtain accelerating gradients reaching several teravolts per meter. New self-injected bunches will be accelerated by the energy of the laser pulse and the previous self-injected bunches. We call this process the combined laser-plasma acceleration mode. Combined laser-plasma acceleration is considered as a process that will provide a significant acceleration rate of bunches of charged particles both during self-injection and for injection from outside.

CONCLUSION

In this paper, the excitation of the wakefield by a sequence of high-power low-duration X-ray laser pulses in high density plasma is considered. It was shown that the excitation of the wakefield under such conditions is accompanied by the formation of self-injected bunches. It is investigated that the dynamics of these bunches affects the magnitude of the accelerating wakefield and leads to the origin of a combined laser-plasma acceleration regime, in which new self-injected bunches are accelerated due to the energy of the laser field and previous selfinjected bunches. The shown above scheme of excitation of the wakefield by a laser makes it possible to achieve accelerating gradients of several teravolts per meter.

ACKNOWLEDGEMENTS

The study is supported by the National Research Foundation of Ukraine under the program “Leading and Young Scientists Research Support” (project #2020.02/0299).

REFERENCES

[1] T. Tajima, “Laser Acceleration in Novel Media”, *Eur. Phys. J. Spec. Top.*, vol. 223, pp. 1037–44, 2014. doi:10.1140/epjst/e2014-02154-6

[2] A. J. Gonsalves *et al.*, “Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide”, *Phys. Rev. Lett.*, vol. 122, p. 084801, 2019. doi:10.1103/PhysRevLett.122.084801

[3] I. Blumenfeld *et al.*, “Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator”, *Nature,* vol. 445, pp. 741-744, 2007. doi:10.1038/nature05538

[4] V. I. Maslov, D. S. Bondar, I. P. Levchuk, I. N. Onishchenko, “Homogeneous focusing field for short relativistic electron bunches in plasma”, *Problems of Atomic Science & Technology*, vol. 3-127, pp. 68-72, 2020.

[5] K. V. Lotov, V. I. Maslov, I. N. Onishchenko, E. N. Svistun, “Resonant excitation of plasma wakefield by a nonresonant train of short electron bunches”, *Plasma Phys. Cont. Fus.*, vol. 52, p. 065009, 2010. doi:10.1088/0741-3335/52/6/065009

[6] K. V. Lotov, V. I. Maslov, N. I. Onishchenko, E. N. Svistun, “2.5D simulation of plasma wakefield excitation by a nonresonant chain of relativistic electron bunches”, *Problems of Atomic Science & Technology*, vol. 2, pp. 122-24, 2010.

[7] G.V. Sotnikov, P. I. Markov, I. N. Onishchenko, “Focusing of Drive and Test Bunches in a Dielectric Waveguide Filled with Inhomogeneous Plasma”, *JINST*, vol. 15, p. C09001, 2020. doi:10.1088/1748-0221/15/09/C09001

[8] Z. Huang *et al.*, “Compact X-ray Free-Electron Laser from a Laser-Plasma Accelerator Using a Transverse-Gradient Undulator”, *Phys. Rev. Lett.*, vol. 109, p. 204801, 2012. doi:10.1103/PhysRevLett.109.204801

[9] S. Shiraishi *et al.*, “Laser red shifting based characterization of wakefield excitation in a laser-plasma accelerator”, *Phys. Plas.*, vol. 20, p. 063103, 2013. doi:10.1063/1.4810802

[10] S. P. D. Mangles *et al.*, “Monoenergetic beams of relativistic electrons from intense laser–plasma interactions”, *Nature*, vol. 431, pp. 535-538, 2004. doi:10.1038/nature02939

[11] C. Benedetti *et al.*, “Numerical investigation of electron self-injection in the nonlinear bubble regime”, *Phys. Plasmas.*, vol. 20, p. 103108, 2013. doi:10.1063/1.4824811

[12] O. Lundh, C. Rechatin, J. Lim, V. Malka, J. Faure, “Experimental Measurements of Electron-Bunch Trains in a Laser-Plasma Accelerator”, *PRL*, vol. 110, p. 065005, 2013. doi:10.1103/PhysRevLett.110.065005

[13] 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

[14] G. Mourou *et al.*, “Single Cycle Thin Film Compressor Opening the Door to Zeptosecond-Exawatt Physics”, *EPJ*, vol. 223, pp. 1181-88, 2014. doi:10.1140/epjst/e2014-02171-5

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