https://doi.org/10.46813/2024-151-067

PASSIVE PLASMA LENS, REDUCING ENERGY SPREAD OF GAUSSIAN-KIND BUNCHES

I.V. Demydenko[1,2]*, V.I. Maslov*[1,2,3]
[1]*V.N. Karazin Kharkiv National University, Kharkiv, Ukraine;*
[2]*NSC "Kharkov Institute of Physics and Technology", Kharkiv, Ukraine;*
[3]*DESY, Hamburg, Germany*
E-mail: demydenko2021tya11@student.karazin.ua; vmaslov@kipt.kharkov.ua

Acceleration by the wakefield in the plasma can provide compact sources of relativistic electron beams of high brightness. Free electron lasers and particle colliders, using plasma wakefield accelerators, require high efficiency and beams with low energy spread. In this paper, we investigated by numerical simulation the focusing of Gaussian-kind bunches by a passive plasma lens depending on their length. We have shown that for a homogeneous focusing field and to prevent loss of energy from bunches, the presence of an electron bunch-precursor is necessary. This plasma lens decreases the energy spread of bunches, since the first front of the bunch, which is of more energy, is in decelerating field, and its back front, which is of smaller energy, is in accelerating field. In addition, we investigated the evolution of the bunches with time to visually demonstrate the effect of the plasma lens in the wakefield accelerator.

PACS: 29.17.+w; 41.75.Lx

INTRODUCTION

Advanced plasma wakefield accelerators can support accelerating gradients to 100 GV⁄m [1–3]. Traditional conventional accelerators can support accelerating gradient no more than 100 MV⁄m [4]. Advanced plasma wakefield experiments [1–3] have demonstrated perspective of this method of electron acceleration to many GeV energy. This is why the plasma wakefield are developed (see [5–33]).

But characteristics of accelerated electron beam in plasma wakefield are not sufficiently applicable. Therefore, advanced way to essentially improve the accelerated electron bunch quality is the usage of electron bunches, produced by traditional well-developed RF accelerators.

The bunch focusing is especially important in multi-cell plasma accelerators and after accelerating cell before the transport channel [34–42]. The investigation of this process is important especially for the bunch of the finite length and inhomogeneous charge profile and for a sequence of bunches with any distance between bunches. We investigate by numerical simulation wakefield plasma lens for focusing of bunches and train of Gaussian bunches with bunch-precursor depending on their lengths, gaps, charges for stable electron beam propagation in a plasma. We demonstrate that bunch-precursor is needed for more uniform focusing and so that the witness does not loss energy creating a plasma lens. The plasma lens reduces the energy spread of bunches, since the head of the bunch, which has more energy, loses energy, and its tail, which has less energy, accelerates. We demonstrate that in the linear case it is possible to ensure focusing of bunches with a length greater than the wavelength, while in the blowout case only short bunches whose length is less than the length of the bubble can be used.

We present results of numerical simulation of plasma wakefield excitation. The numerical simulation has performed with 2.5D code LCODE, which considers the beam electrons as ensembles of macroparticles. We demonstrate influence of currents and spatial distribution of bunches and influence of plasma parameters on wakefield excitation in a plasma lens with wakefield excited by electron bunches injected from the RF accelerator with high quality.

We consider the bunch, where electrons are distributed according to Gaussian in the transverse direction. We use the cylindrical coordinate system (r, z) and draw longitudinal and transversal electric fields at some z as a function of the dimensionless time $\tau=\omega_p t$ and $\xi=V_b t-z$, where V_b is the bunch velocity. Time is normalized on electron plasma frequency ω_{pe}^{-1}, distance – on c/ω_{pe}, bunch current I_b – on $I_{cr}=\pi mc^3/4e$, fields – on $mc\omega_{pe}/e$. e, m are the charge and mass of the electron, c is the light velocity.

1. PLASMA PASSIVE LENS EXCITATION IN LINEAR REGIME

Let us consider the case of injection of rather rare bunches, when the bunch repetition rate is much less than the electron plasma frequency $\omega_b \ll \omega_{pe}$. In this case, as one of the options, we consider the case when the plasma is not renewed between two main bunches.

Let us first consider bunches-homogeneous-cylinders. Consider both short (their length ℓ_b is less than half wavelength) $\ell_b<\lambda/2$, also intermediate length of bunches $\ell_b=\lambda/2$ and long bunches $\ell_b>\lambda/2$ ($\ell_b=2\lambda$, 3λ) with one precursor-bunch. The length of the precursor-bunch is equal to half wavelength $\ell_{bp}=\lambda/2$, and half particle density relative to the main bunch $n_{bp}=n_b/2$. We note right away that the precursor-bunch can be replaced similar to the replacement of the spent driver-bunch, since the precursor-bunch, unlike the main bunch, loses energy and focuses inhomogeneously. Thus, without plasma renewal, uniform focusing of the main bunch(es) (chain bunches) takes place without energy loss. In this case, the precursor-bunch loses energy to create a focusing field and is inhomogeneously focused. Therefore, as noted earlier, the precursor-bunch can be replaced similar to the replacement of the used driver-bunch. And this is not a disadvantage, but rather an advantage compared to using a plasma lens in blowout regime without a precursor-bunch. This advantage is determined by the fact that:

1) when the bunch itself forms a plasma lens in the blowout regime without a precursor bunch, the main bunch loses an energy (inhomogeneously) to create a plasma lens, and also;

2) in this case, the leading edge of the main bunch is focused inhomogeneously. Then the energy spread of the bunch increases. In the plasma lens considered here, two advantages are realized in the linear regime. The minimum possible energy is spent not by the main bunch itself, but by the precursor-bunch, which can then be removed from the system similar to the spent driver-bunch. The precursor-bunch is for focusing main bunch. Moreover, after the main bunch, one can place a follower-bunch that will take back energy and after it is removed from the system, together with the precursor-bunch and driver-bunch, this energy can be recovered from the follower-bunch.

Let us consider first short bunches. For example, we consider first the case of using rare bunches-thin-needles with a length of each of them equal to a quarter of the wavelength $\ell_b=\lambda/4$ with one bunch-precursor and without plasma renewal. From figure one can see that a fairly uniform focusing field is formed for bunches.

For uniform focusing of the second main bunch, it must be placed in a small accelerating field (Fig. 1).

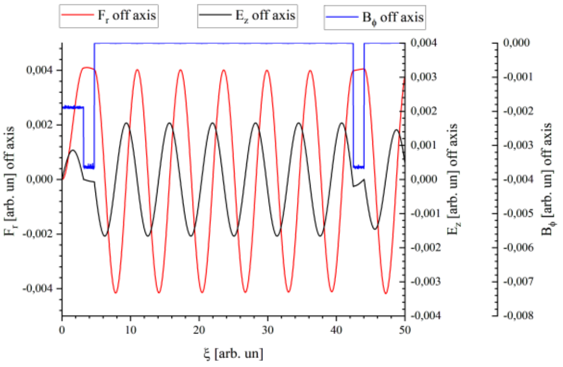

Fig. 1. $E_z(\xi)$, $F_r(\xi)$, $B_\varphi(\xi)$, ξ =ct-z, the homogeneous precursor-bunch (of length $\ell_{pr}=\lambda/2$ and density $n_{pr}=n_b/2$, n_b is the density of the main bunches) and two rare main bunches, the length of each of them equals to a quarter wavelength $\ell_b=\lambda/4$, move in plasma from right to left. The density of bunches decreases along the radius according to Gaussian dependence. The radius of bunches is equal to 0.1. The current of bunch equals $0.3\cdot 10^{-3}$. The relativistic factor of bunches is equal to 1000

In the case of bunches-thin-needles at $\ell_b=\lambda/2$ with one precursor-bunch and without plasma renewal, a rather uniform focusing field is formed for the bunches (see Fig. 1). In this case, the first main bunch is at $E_z=0$ (Fig. 2). I.e., it only focuses and does not exchange energy with the plasma. However, in order to form a uniform focusing field for the second far-lagging bunch, it has to be placed in such a phase that its leading edge enters a small accelerating field and its trailing edge enters a small decelerating field (see Fig. 2).

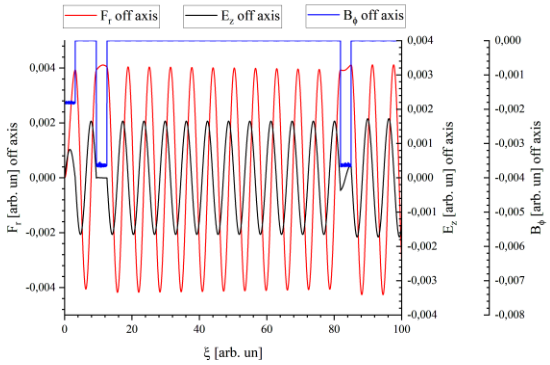

Fig. 2. $E_z(\xi)$, $F_r(\xi)$, $B_\varphi(\xi)$, the homogeneous precursor-bunch (of length $\ell_{pr}=\lambda/2$ and density $n_{pr}=n_b/2$, n_b is the density of the main bunches) and two rare main bunches, the length of each of them equals to a half wavelength $\ell_b=\lambda/2$, move in plasma from right to left. The density of bunches decreases along the radius according to Gaussian dependence. Parameters of bunches are identical to Fig. 1

Now we consider a long main bunch with a precursor-bunch (Fig. 3). The precursor-bunch can be separated from the main bunch. But for now, we consider the case when the main bunch touches the precursor-bunch. In the case of a long main bunch-thin-needle at $\ell_b=2\lambda$ with a precursor-bunch, a fairly uniform focusing field is formed for the main bunch (see Fig. 3). The precursor-bunch loses energy to create a focusing field and is inhomogeneously focused. The main bunch is in $E_z=0$ (see Fig. 3). I.e., it only focuses and does not exchange energy with the plasma.

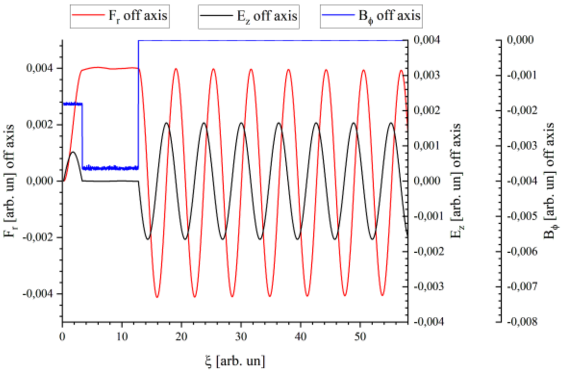

Fig. 3. $E_z(\xi)$, $F_r(\xi)$, $B_\varphi(\xi)$, the homogeneous precursor-bunch (of length $\ell_{pr}=\lambda/2$ and density $n_{pr}=n_b/2$, n_b is the density of the main bunches) and two rare main bunches, the length of main bunch equals to two wavelengths $\ell_b=2\lambda$, move in plasma from right to left. The density of bunches decreases along the radius according to Gaussian dependence. Parameters of bunches are identical to Fig. 1

Now we consider Gaussian-like bunches. In the case of rare Gaussian-like bunches-thin-needles with their lengths $\ell_b=\lambda$ (at the base of the bunch) with one precursor-bunch (Fig. 4) and without plasma renewal, a focusing field is formed for the bunches, for the first main bunch, a focusing field flat top (see Fig. 4). In this case, the central parts of the main bunches are in E_z=0. I.e., the central parts of the main bunches are only focused and do not exchange energy with the plasma. However, the fronts of the main bunches exchange energy with the wakefield. Namely, the leading edges of the main bunches lose energy, and their trailing edges accelerate. With a certain selection of parameters, this will lead to a decrease in the energy spread of the main bunches. Therefore, there is no need for other ways to reduce the energy spread of bunches.

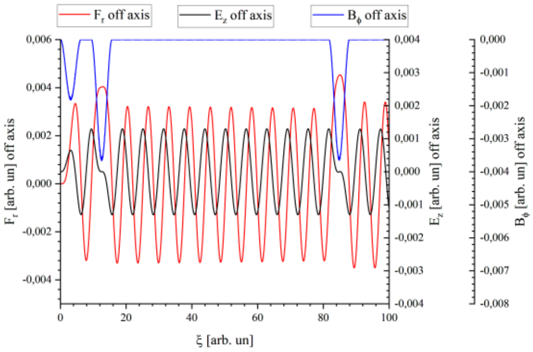

Fig. 4. $E_z(\xi)$, $F_r(\xi)$, $B_\varphi(\xi)$, the Gaussian precursor-bunch (of length $\ell_{pr}=\lambda$ at the base of the precursor and density $n_{pr}=n_b/2$, n_b is the density of the main bunches) and two rare main Gaussian (in all directions) bunches, the length of each of them equals to a wavelength (at the base of the bunch) $\ell_b=\lambda$, move in plasma from right to left. Parameters of bunches are identical to Fig. 1

Let us show that this method of reducing the energy spread of the main bunches can be controlled. For example, we consider the main bunches in view of homogeneous cylinders of length λ with semi-Gaussian fronts of length λ/2 (Fig. 5). One can see that one can control the decelerating wakefield on the first front of main bunch and one can control the accelerating wakefield on the back front of main bunch.

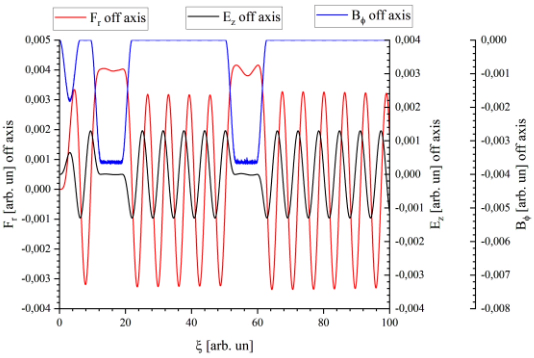

Fig. 5. $E_z(\xi)$, $F_r(\xi)$, $B_\varphi(\xi)$, the Gaussian precursor-bunch (of length $\ell_{pr}=\lambda$ at the base of the precursor and density $n_{pr}=n_b/2$, n_b is the density of the main bunches) and two rare main inhomogeneous Gaussian-kind bunches, the length of each of them equals to two wavelengths (at the base of the bunch) $\ell_b=2\lambda$, move in plasma from right to left. Each front of the main is semi-Gaussian of length λ/2. The main part of the main bunch is homogeneous of length λ. Parameters of bunches are identical to Fig. 1

Also, to demonstrate the adjustment of the energy spread of the main bunch, we consider the main bunch in view of homogeneous cylinders of length 2λ with semi-Gaussian fronts of length λ/2 (Fig. 6).

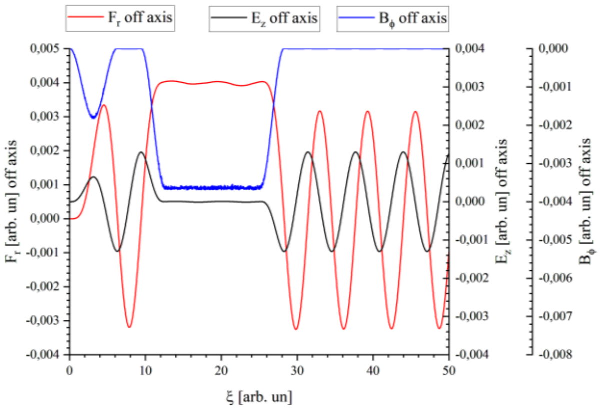

Fig. 6. $E_z(\xi)$, $F_r(\xi)$, $B_\varphi(\xi)$, the Gaussian precursor-bunch (of length $\ell_{pr}=\lambda$ at the base of the precursor and density $n_{pr}=n_b/2$, n_b is the density of the main bunches) and two rare main inhomogeneous Gaussian-kind bunches the length of each of them equals to three wavelengths (at the base of the bunch) $\ell_b=3\lambda$, move in plasma from right to left. Each front of the main is semi-Gaussian of length λ/2. The main part of the main bunch is homogeneous of length 2λ. Parameters of bunches are identical to Fig. 1

2. EVOLUTION OF BUNCHES WITH TIME

Now let us briefly discuss the action of passive plasma lens. In this section we will show the evolution of bunches in time (Figs. 7–12).

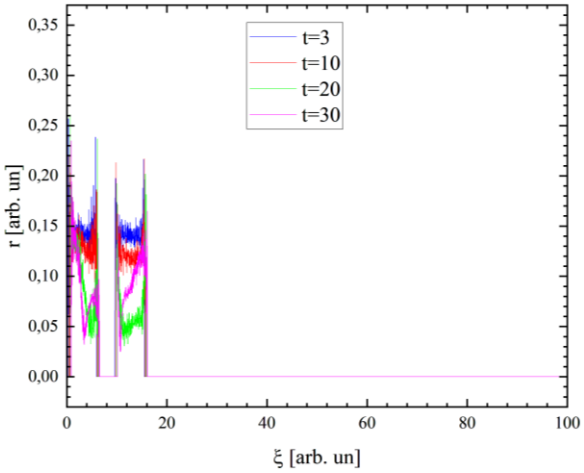

Fig. 7. Radius evolution of cosine Gaussian-kind bunches with time. Density of the second bunch in two times bigger than the density of the first one. The length of each of them equals to one wavelength (at the base of the bunch) $\ell_b=\lambda$. Bunches move in plasma from right to left. The radius of bunches is equal to 0.1. The current of bunch equals $0.3\cdot10^{-3}$. The relativistic factor of bunches is equal to 5

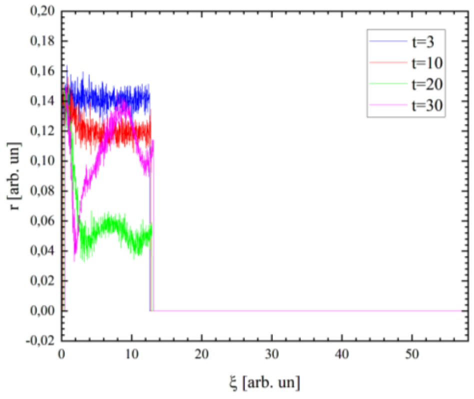

Fig. 8. Radius evolution of unitary precursor and unitary main bunches with time. Density of the precursor-bunch with $\ell_{pr}=\lambda/2$ is $n_{pr}=n_b/2$, n_b is the density of the main bunch. The length of main bunch is $\ell_b=3\lambda/2$. Bunches move in plasma from right to left. Parameters of bunches are identical to Fig. 7

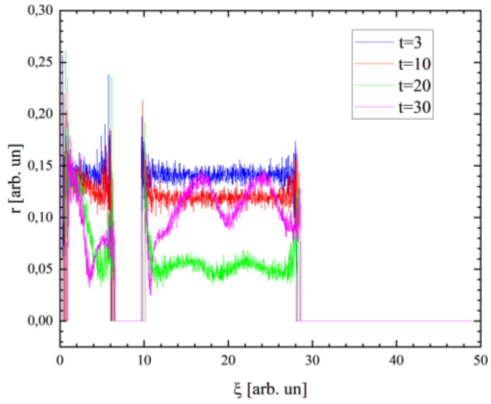

Fig. 9. Radius evolution of cosine Gaussian-kind precursor (of length $\ell_{pr}=\lambda$ at the base of the precursor and density $n_{pr}=n_b/2$, n_b is the density of the main bunch) and main semi cosine-kind bunch with time. The length of main bunch is 4λ (at the base). Central part is unitary with length 3λ, each front is semi cosine-kind with length λ/2. Bunches move in plasma from right to left. Parameters of bunches are identical to Fig. 7

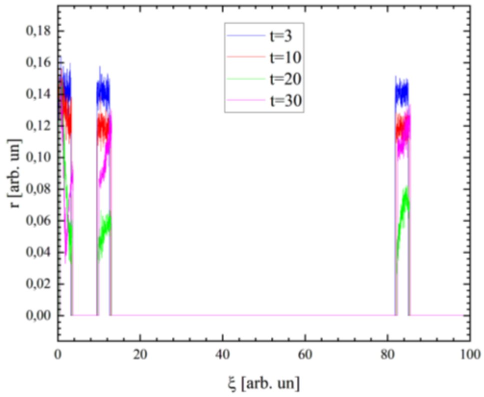

Fig. 10. Radius evolution of unitary precursor and two rare main unitary bunches. Bunches move in plasma from right to left. Density of the precursor bunch with $\ell_{pr}=\lambda/2$ is $n_{pr}=n_b/2$, n_b is the density of the main bunch. The length of main bunches is $\ell_b=\lambda/2$. Parameters of bunches are identical to Fig. 7

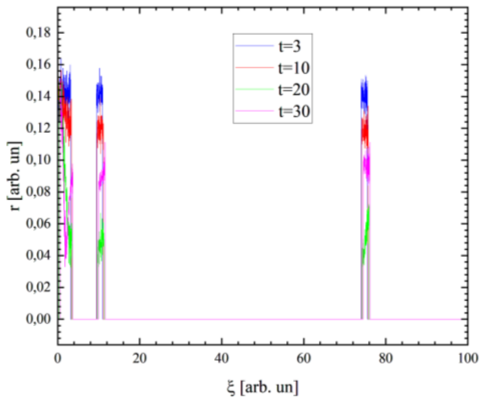

Fig. 11. Radius evolution of unitary precursor and two rare main unitary bunches. Bunches move in plasma from right to left. Density of the precursor bunch with $\ell_{pr}=\lambda/2$ is $n_{pr}=n_b/2$, n_b is the density of the main bunch. The length of main bunches is $\ell_b=\lambda/4$. Parameters of bunches are identical to Fig. 7

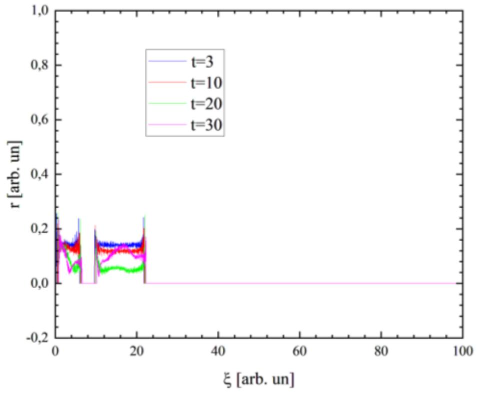

Fig. 12. Radius evolution of cosine-kind precursor (of length $\ell_{pr}=\lambda$ at the base of the precursor and density $n_{pr}=n_b/2$, n_b is the density of the main bunch) and main semi cosine-kind bunch with time. The length of main bunch is 2λ (at the base). Central part is unitary with length λ, each front is semi cosine-kind with length λ/2. Bunches move in plasma from right to left. Parameters of bunches are identical to Fig. 7

From Figs. 7–12 one can see that between $\tau=20$ and $\tau=30$ bunches start to defocusing. From this follows that for maximal efficiency of wakefield accelerator we have to create a capillary discharge with length that equals to length of passive plasma lens (that is determined by focusing time of the bunch).

CONCLUSIONS

So, we demonstrated that precursor-bunch is needed for more uniform focusing and so that the witness does not loss energy to create a plasma lens. The plasma lens reduces the energy spread of bunches, since the head of the bunch, which has more energy, loses energy, and its tail, which has less energy, accelerates. We demonstrate that in the linear case it is possible to ensure focusing of bunches with a length greater than the wavelength.

REFERENCES

1. W.P. Leemans, A.J. Gonsalves, H.-S. Mao, et al. Multi-GeV Electron Beams from Capillary-Discharge-

Guided Subpetawatt Laser Pulses in the Self-Trapping Regime // *Phys. Rev. Lett*. 2014, v. 113. p. 245002.

2. A.J. Gonsalves, K. Nakamura, J. Daniels, et al. Petawatt Laser Guiding and Electron Beam Acceleration to 8 GeV in a Laser-Heated Capillary Discharge Waveguide // *Phys. Rev. Lett*. 2019, v. 122, p. 084801.

3. I. Blumenfeld, C.E. Clayton, F.-J. Decker, et al. Energy doubling of 42 GeV electrons in a metre-scale plasma wakefield accelerator // *Nature, Letters*. 2007, v. 445, p. 741-744.

4. E. Esarey, C.B. Schroeder, W.P. Leemans. Physics of laser-driven plasma-based electron accelerators // *Rev. Mod. Phys*. 2009, v. 81, p. 1229-1285.

5. V.I. Maslov, I.N. Onishchenko, I.P. Yarovaya. Transformation ratio at excitation of nonlinear wake field in plasma by shaped sequence of electron bunches with linear growth of charge // *Problems of Atomic Science and Technology*. 2012, N 4, p. 126-128.

6. V.I. Maslov, I.N. Onishchenko. Transformation ratio at wakefield excitation in dielectric resonator accelerator by shaped sequence of electron bunches with linear growth of current // *Problems of Atomic Science and Technology*. 2013, N 4, p. 69-72.

7. V.I. Maslov, O.M. Svystun, I.N. Onishchenko, et al. Joint wakefield acceleration by laser pulse and by self-injected electron bunches // *Problems of Atomic Science and Technology*. 2016, N 6, p. 144-147.

8. V.A. Balakirev, V.I. Maslov, I.N. Onishchenko. Instability of cylindrical relativistic electron beam, propagating in plasma // *Problems of Atomic Science and Technology.* 2011, N 3, p. 92-95.

9. D.S. Bondar, I.P. Levchuk, V.I. Maslov, et al. Dynamics of self-injected electron bunches at their acceleration by laser pulse in plasma // *Problems of Atomic Science and Technology*. 2017, N 6, p. 76-79.

10. I.P. Levchuk, V.I. Maslov, I.N. Onishchenko. Transformation ratio at wakefield excitation in dissipative media by sequence of electron bunches // *Problems of Atomic Science and Technology*. 2017, N 6, p. 43-46.

11. I.P. Levchuk, V.I. Maslov, I.N. Onishchenko. Focusing by wakefield and plasma focusing of relativistic electrons in dependence on parameters of experiments // *Problems of Atomic Science and Technology*. 2016, N 3, p. 62-65.

12. V.I. Maslov, I.P. Levchuk, I.N. Onishchenko. Focusing of relativistic electron bunches by nonresonant wakefield excited in plasma // *Problems of Atomic Science and Technology*. 2015, N 4, p. 120-123.

13. V.I. Maslov, I.N. Onishchenko. Transformation ratio at wakefield excitation in dielectric resonator by sequence of rectangular electron bunches with linear growth of charge // *Problems of Atomic Science and Technology*. 2014, N 3, p. 95-98.

14. D.S. Bondar, V.I. Maslov, I.P. Levchuk, I.N. Onishchenko. Excitation of wakefield by a laser pulse in a metallic-density electron plasma // *Problems of Atomic Science and Technology*. 2018, N 6, p. 156-159.

15. V.I. Maslov, D.S. Bondar, I.N. Onishchenko. Investigation of the Way of Phase Synchronization of a Self-Injected Bunch and an Accelerating Wakefield in Solid-State Plasma // *Photonics*. 2022, N 3, p. 174.

16. V.I. Maslov, R.T. Ovsiannikov, N. Delerue, et al. Numerical simulation of plateau formation by an electron bunch on the distribution of an accelerating wakefield in a plasma // *Problems of Atomic Science and Technology*. 2020, N 6, p. 47-49.

17. R. Assmann, E. Gschwendtner, K. Cassou, et al. High-gradient plasma and laser accelerators // *CERN Yellow Reports:* Monographs 1. 2022, p. 91.

18. S. Diederichs, C. Benedetti, M. Thévenet, E. Esarey, J. Osterhoff, et al. Self-stabilizing positron acceleration in a plasma column // *arXiv preprint* arXiv:2206. 2022. 11967.

19. S. Diederichs, C. Benedetti, E. Esarey, M. Thévenet, J. Osterhoff, et al. Stable electron beam propagation in a plasma column // *Physics of Plasmas*. 2022, v. 29 (4), p. 043101.

20. C. Benedetti, S.S. Bulanov, E. Esarey, et al. Linear collider based on laser-plasma accelerators // *arXiv preprint* arXiv:2203.08366. 2022.

21. T. Tajima, J.M. Dawson. Laser Electron Accelerator // *Phys. Rev. Lett*. 1979, v. 43, p. 267.

22. T. Tajima. Laser Acceleration in Novel Media // *Eur. Phys. J. Spec. Top*. 2014, v. 223, p. 1037.

23. T. Tajima, K. Nakajima, G. Mourou. Laser Acceleration // *Rivista del Nuovo Cimento* 2017, v. 40, p. 33.

24. T. Tajima. Laser acceleration and its future // *Proc. Jpn. Acad. Ser. B.* 2010, v. 86, p. 147.

25. V. Maslov, D. Bondar, I. Levchuk, et al. Uniform focusing of sequence of relativistic positron bunches in plasma // *East European Journal of Physics*. 2019, N 2, p. 69-74.

26. N.I. Ayzatsky, A.N. Dovbnya, V.A. Kushnir, et al. Electron resonant high-current accelerator for research of collective acceleration methods // *Plasma Phys*. 1994, v. 20, N 7,8, p. 671-673.

27. V.I. Maslov, D.S. Bondar, V. Grigorencko, et al. Control of characteristics of self-injected and accelerated electron bunch in plasma by laser pulse shaping on radius, intensity and shape // *Problems of Atomic Science and Technology.* 2019, N 6, p. 39-42.

28. S. Romeo, M. Ferrario, A.R. Rossi. Beam loading assisted matching scheme for high quality plasma acceleration in linear regime // *Phys. Rev. Accel. Beams*. 2020, v. 23, p. 071301.

29. T. Katsouleas, S. Wilks, P. Chen, T.J.M. Dawson, J.J. Su. Beam Loading in Plasma Accelerators // *Particle Accelerators.* 1987, v. 22, p. 81-99.

30. V.M. Tsakanov On collinear wakefield acceleration with high transformer ratio // *Nucl. Instr. and Meth. in Phys. Res. A.* 1999, v. 432, p. 202-213.

31. E. Esarey, S. Sprangle, J. Krall, A. Ting. Overview of Plasma-Based Accelerator Concepts // *IEEE Trans. Plasma Sci.* 1996, v. PS-24(2), p. 252.

32. A. Picksley, A. Alejo, J. Cowley, et al. Guiding of high-intensity laser pulses in 100-mm-long

hydrodynamic optical-field-ionized plasma channels // *Phys. Rev. Accel. Beams*. 2020, v. 23, p. 081303.

33. J. Cowley, C. Thornton, C. Arran, et al. Excitation and Control of Plasma Wakefields by Multiple Laser Pulses // *Phys. Rev. Lett*. 2017, v. 119, p. 044802.

34. J.S.T. Ng, P. Chen, H. Baldis, et al. Observation of Plasma Focusing of a 28.5 GeV Positron Beam // *Phys. Rev. Lett*. 2001, v. 87, p. 244801.

35. C.E. Clayton, B.E. Blue, E.S. Dodd, et al. Transverse Envelope Dynamics of a 28.5-GeV Electron Beam in a Long Plasma // *Phys. Rev. Lett*. 2002, v. 88, p. 154801.

36. D.S. Bondar, V.I. Maslov, I.N. Onishchenko, R.T. Ovsiannikov. Plasma lens for electron and positron beams // *Problems of Atomic Science and Technology*. 2021, N 4, p. 70-73.

37. M.C. Thompson et al. Observations of low-aberration plasma lens focusing of relativistic electron bunches at the underdense threshold // *Phys. Plasmas*. 2010, v. 17, p. 073105.

38. G.P. Berezina, A.F. Linnik, V.I. Maslov, et al. Transformation ratio increase at wakefields excitation in the dielectric structure by a shaped sequence of relativistic electron bunches // *Problems of Atomic Science and Technology*. 2016, N 3, p. 69-73.

39. V. Maslov, D. Bondar, I. Levchuk, I. Onishchenko. Improvement of properties of self-injected and accelerated electron bunch by laser pulse in plasma, using pulse precursor // *East European Journal of Physics*. 2019, v. 2, p. 64-68.

40. G. Hairapetian et al. Transverse dynamic of a short relativistic electrons bunch in a plasma lens // *Phys. Plasma*. 1995, v. 2, p. 2555.

41. D.O. Shendryk, R.T. Ovsiannikov, V.I. Maslov, et al. Simulation of the identical plateaus formation on plasma wakefield for long driver-bunch and witness-bunches // *Problems of Atomic Science and Technology*. 2023, N 6, p. 67-70.

42. I.V. Demydenko, V.I. Maslov. Identical decelerating wakefields for driver-bunches and identical accelerating wakefields for witness-bunches for their periodic sequence // *Problems of Atomic Science and Technology*. 2023, N 3, p. 108-111.

Article received 30.04.2024

ПАСИВНА ПЛАЗМОВА ЛІНЗА, ЩО ЗМЕНШУЄ ЕНЕРГЕТИЧНИЙ РОЗКИД ГАУССОПОДІБНИХ ЗГУСТКІВ

І.В. Демиденко, В.І. Маслов

Прискорення кільватерним полем у плазмі може забезпечити компактні джерела релятивістських електронних пучків високої яскравості. Лазери на вільних електронах та колайдери частинок, де використовуються плазмові кільватерні прискорювачі, вимагають високої ефективності і пучків з низьким розкидом за енергією. У цій роботі ми числовим моделюванням дослідили фокусування пасивною плазмовою лінзою гауссоподібних згустків у залежності від їх довжини. Ми показали, що для формування однорідного фокусуючого поля і щоб запобігти втраті енергії згустками є необхідною наявність електронного згустка-передвісника. Ця плазмова лінза зменшує енергетичний розкид згустків, оскільки перший фронт згустка, який має більшу енергію, знаходиться у гальмівному полі, а його задній фронт, який має меншу енергію, знаходиться у прискорювальному полі. Окрім цього, ми дослідили еволюцію згустків з часом для наочної демонстрації дії плазмової лінзи у кільватерному прискорювачі.