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ON WAKEFIELD ACCELERATION IN INHOMOGENEOUS PLASMA

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In laser-plasma wakefield acceleration, an actual and widely studied issue is the obtaining small self-injected bunches and enhancement of their energy and accelerating gradient by variation the parameters of laser pulses and plasma. In particular, using the special plasma profiles has a significant effect. Earlier it has been shown that with a longitudinal linearly increasing plasma density profile, due to compression of the wakefield bubble, synchronism of the maximum accelerating field at the rear wall of the wakefield bubble and the self-injected bunch is achieved. In this work, the wakefield acceleration in a non-monotonically inhomogeneous plasma was investigated by numerical simulation using the OSIRIS code. In the first short section, the plasma density decreases, which ensures controlled self-injection of the electron bunch even at a low intensity of the laser pulse. Then, in a long section, the plasma density increases in order to prolong the time of movement of the self-injected bunch in the wakefield acceleration phase and increase the energy of the bunch. The article shows an increase in the effect of energy growth and an increase in the bunch charge compared to the previously obtained results. In addition, the effects of the formation of self-injected bunches with their subsequent retention for lasers of lower amplitude than in previous studies have been demonstrated, which expands the experimental possibilities.

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INTRODUCTION

The study of fields and self-injected bunches in high-density plasmas by high-power lasers has long been regarded as a promising area of research in which extremely large amplitudes of acceleration fields can be achieved [1–3]. The development of wakefield acceleration methods, especially in high-density plasma, is facilitated by the development of physical technologies, in particular, the creation of powerful laser pulses [4, 5].

Wakefield methods allow the formation, acceleration and focusing of relativistic, high-energy electron bunches [6–26].

It was previously shown that in an inhomogeneous plasma, including when using profiling, retention of a self-injected bunch in the acceleration phase of the wakefield is observed. The longitudinal inhomogeneity of the plasma was considered [27, 28].

Inhomogeneous plasma is a pressing issue in modern research. In particular, it is considered as a negative effect of plasma inhomogeneity [29]. These early studies became the forerunner to further developments in the use of plasma density gradients. In particular, at the Relativistic Laser Science Centre in the Republic of Korea, an experiment on wakefield laser acceleration by a high-power pulse was conducted. The setup involved generating various gas density profiles by adjusting the tilt angle of the gas nozzle from 0 to 30°. Additionally, changes in the inlet pressure and the interaction position above the nozzle were made to stabilize the electron beam in terms of pointing, charge, and divergence. Computational fluid dynamics simulations were used to obtain the density profiles. The experimental method allowed for the generation of multiple plasma density profiles with varying ramp slopes and shapes [30]. Authors of [31] explore the effects of spatially uniform initial density and linear density ramps on the energy of ions accelerated by high-intensity laser pulses. By varying the plasma density profile, the authors analyze the resulting ion acceleration dynamics and observe the generation of high-energy ions, with energies reaching up to 1 GeV under optimal conditions. These studies are based on simulations and theoretical models to understand how different plasma density profiles influence the acceleration by lasers.

In [32] inhomogeneous plasma profiles related to the diffusion of plasma through an aperture in a diverging magnetic field were studied. Authors focused on observing the evolution of plasma density and potential under these conditions.

The article [33] investigates the significant impact of external focusing on the plasma density and diameter of femtosecond Ti-sapphire laser filaments generated in air. The study highlights how plasma density notably increases from 10^{15} to $2\cdot10^{18}$ cm^{-3} as the focal length of the lens decreases from 380 to 10 cm. This change accompanies variations in the diameter of the plasma column from 30 to 90 μm, indicating that external focusing parameters crucially influence plasma characteristics. These findings are corroborated by both experimental results and numerical simulations.

In presented paper, the authors considered wakefield acceleration by a laser pulse in a high-density plasma. The scheme of sequential change of density gradients from decreasing gradient to increasing gradient is realized. Due to this it is possible to improve the quality of self-injected bunches. The study was carried out using 2.5-dimensional numerical simulation. A modern OSIRIS code [34] was used.

STATEMENT OF THE PROBLEM

The article proposes to consider the excitation of the wakefield by a laser pulse in an inhomogeneous plasma. In this case, it is proposed to consider the formation of a self-injected bunch in a high-density plasma by a laser pulse, the amplitude of which is initially insufficient to ensure self-injection of electrons from the background plasma. It is proposed to solve this problem by initially reducing the density (exponentially with rate −0.233251) by 65.64%. The parameters are selected using numerical simulation to demonstrate the effect. Further, according to the scheme of holding a self-injected bunch in the acceleration phase, a linear increase in density was ensured. The result was an increase in the energy of the self-injected bunch. The density profile is shown in more detail in Fig. 1. The OSIRIS code, which was used for numerical simulation of the excitation of the wakefield in the plasma by a laser pulse, is validated and used at a professional scientific level for simulation of wakefield excitation by laser pulse in plasma [35, 37, 38]. It combines a number of important advantages [36] that have been used by the authors to achieve the results: Fully Relativistic Electro-Magnetic Particle-In-Cell code, High-order particle interpolation, Advanced filtering schemes for currents and EM fields, Parallel using MPI, Customized plasma and laser profiles are full available.

The code also allows observe the formation of self-injected bunches and study their dynamics. All units of length in the code were normalized to c/ω_{pe}, all time in ω_{pe}^{-1}, electric fields: E' [real un.]=$e/(\omega_{pe}m_ec)$E [arb. un.], e is the electron charge, c – speed of light, m_e – electron mass, ω_{pe} – plasma frequency. Momenta normalized on m_ec, energy – on m_ec^2. Plasma electron density n_e normalized (arb. un.) on $1.74\cdot10^{19}$ cm^{-3}. The dimensions of the area are from $x_{min}=20c/\omega_{pe}$ to $x_{max}=65c/\omega_{pe}$ in the longitudinal direction and $y_{min}=0$, $y_{max}=20c/\omega_{pe}$ in the transverse direction. Cartesian coordinates (x, y) were considered. In the figures x1 corresponds to x and x2 corresponds to y. The simulation step in dimensional units is $2.8\omega_{pe}^{-1}$, the conversion factor to normalized units is ω_{pe}^{-1}=4.25 fs. Laser pulse parameters: amplitude is 1.5, FWHM is 4.0, w0 (waist) is 2.5. The laser pulse waist is the location along the beam where the cross-sectional area is the smallest and the intensity of the beam is the highest (Fig. 2). The longitudinal and transverse distribution of laser pulse intensity corresponding to the Gaussian law is considered. Intensity of laser pulse further from the center than 3σ is 0.

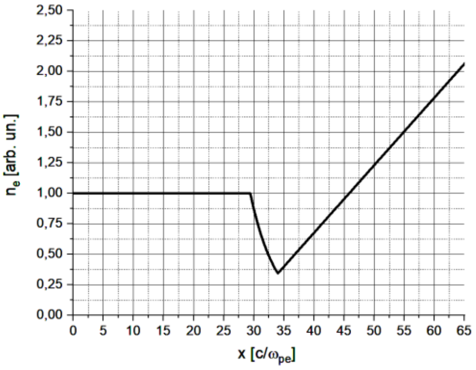

Fig. 1. Plasma electron density longitudinal profile $n_e(x)$

Laser wavelength λ_l=800 nm, $\omega_{las}=10\omega_{pe}$. $\omega_{pe}=2.353\cdot10^{14}$ s^{-1}. The total simulation time is $44.8\omega_{pe}^{-1}$ (190.4 fs). Thus, the parameters correspond to general trends in the wakefield experiments [35].

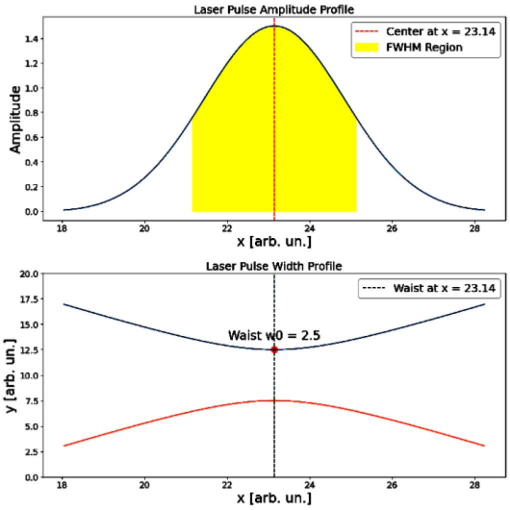

Fig. 2. Laser pulse shape illustration

RESULTS OF SIMULATION

Fig. 3 shows the excitation of the wakefield by the laser pulse. The plasma electron density is homogeneous and equal to 1 in normalized units. Otherwise, the parameters correspond to those given above. It can be verified that there is no observed self-injection phenomenon. The reason for this is the insufficient amplitude of the laser pulse. The solution to this problem has already been announced in the statement of the problem of this article. The authors used the combined plasma density profile shown in Fig. 1 (inhomogeneous plasma).

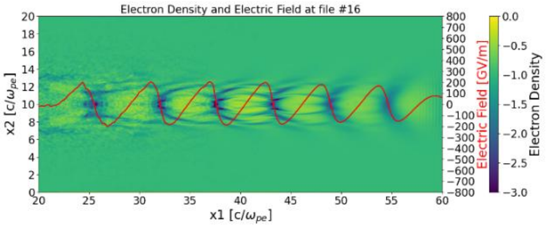

Fig. 3. Plasma electron density
and longitudinal electric field $E_x(x)$, t=190.4 fs.
Uniform plasma. Self-injection absence

Fig. 4 shows the moment of formation of a self-injected bunch. A comparison of Figs. 1 and 4 shows that the formation of a self-injected bunch is observed in the region of an exponential decrease in plasma density, which confirms the assumption that self-injection can be achieved on a descending density gradient. Figs. 5, 6 shows the intermediate moment: retention of a self-injected bunch in the accelerating field region. The synchronization of the self-injected bunch and the accelerating phase of the wakefield is observed due to an increasing density gradient.

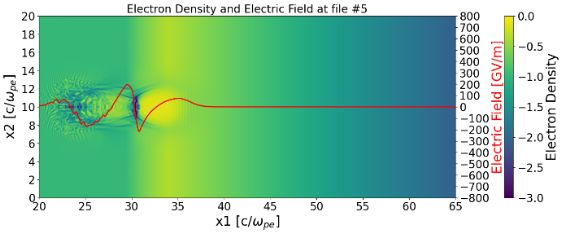

Fig. 4. Plasma electron density and
longitudinal electric field $E_x(x)$, t=59.5 fs

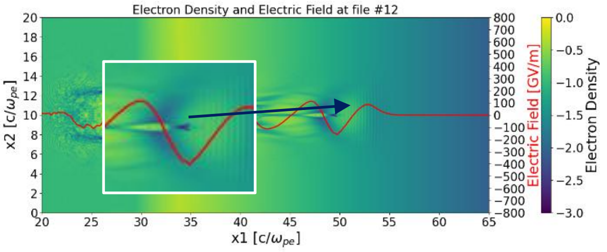

Fig. 5. Plasma electron density (full distribution), longitudinal electric field $E_x(x)$, t=142.8 fs

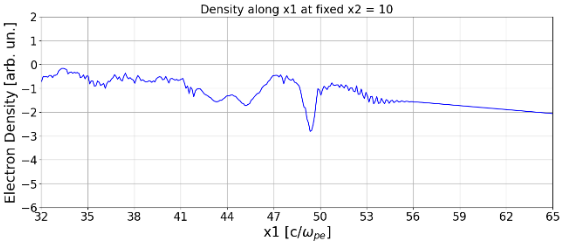

Fig. 6. Plasma electron density (top is full distribution and bottom is when $y=y_{max}/2$), longitudinal electric field $E_x(x)$, t=142.8 fs

In Fig. 7 one can see last step demonstrated in this simulation. The self-injected bunch is in the acceleration phase towards the end of the proposed simulation area.

Thus, the considered plasma density profile led to the formation and retention of a self-injected bunch in the accelerating phase at its initial absence in the homogeneous plasma.

The charge of the bunch did not undergo significant changes as the bunch moved and is equal to 20 pC.

By the time t=190.4 fs the spatial size of the bunch is of about 2×0.5 c/ω_{pe}.

From the moment of self-injection, the bunch does not exceed this size, does not significantly oscillate along the radius and does not decay.

Comparing the results of the current study with previous studies [27, 28], it can be concluded that the current study provides the process of formation and subsequent retention of a self-injected bunch at laser amplitudes 2.0 [27] and 3.33 [28] times smaller, which brings the research topics closer to experimental realization. In the current study, a 10^4 times lower plasma density is considered.

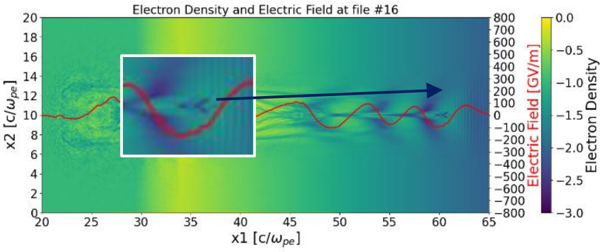

Fig. 7. Plasma electron density and longitudinal electric field $E_x(x)$, t=190.4 fs

In addition, in the current study, compared to [27, 28] an increase in the bunch charge from 0.56 to 20 pC (by a factor of 35.7) is observed. Also, an energy increase of 7.67 times compared to 3.67 times [28] for the observed time intervals is observed.

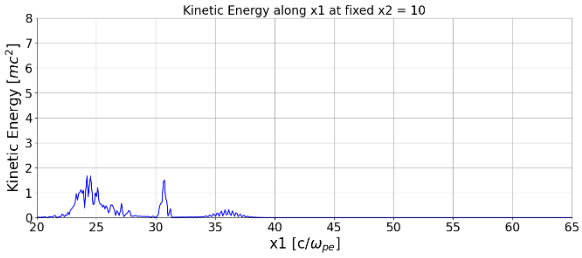

Fig. 8. Kinetic energy when $y=y_{max}/2$, t=59.5 fs

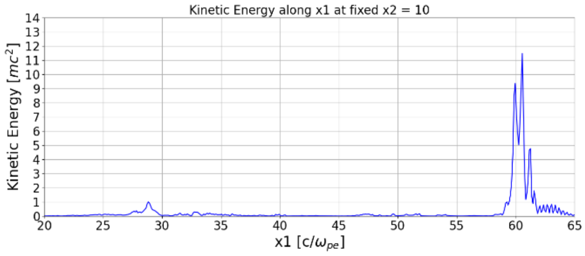

Fig. 9. Kinetic energy when $y=y_{max}/2$, t=190.4 fs

Comparison of Figs. 8, 9 allows us to conclude that the proposed method allows increasing the energy of the bunch. In particular, by the time t=190.4 fs a value of kinetic energy (in normalized units) 11.5 is reached, which exceeds the formation energy by 7.67 times.

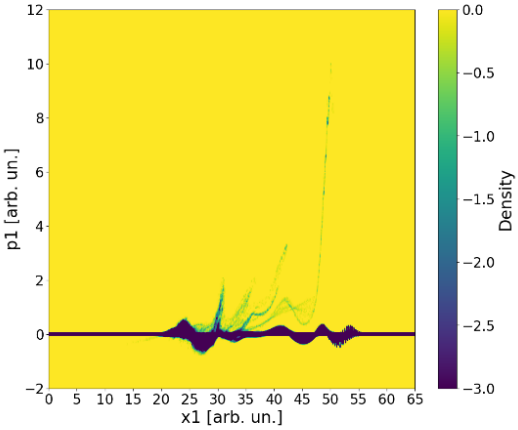

Fig. 10. Longitudinal component p_1 of momentum along x, t=142.8 fs

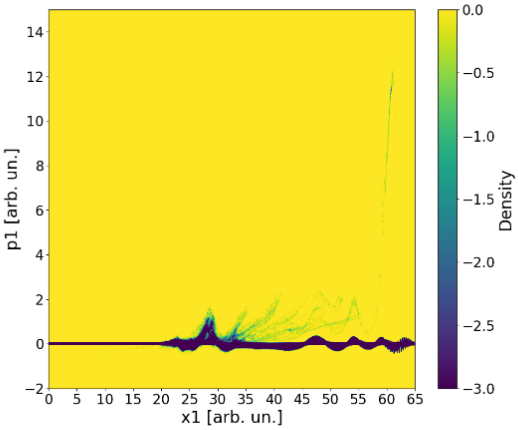

Fig. 11. Longitudinal component p_1 of momentum along x, t=190.4 fs

In Figs. 10, 11 show the distribution of the longitudinal component of the momentum at $y=y_{max}/2$ depending on the longitudinal coordinate.

The momentum distribution allows us to state that by the final moment of the simulation, there is both an increase in energy and a maximum increase in the maximum value of the longitudinal momentum, which reaches $p1=p_x=12.3\ m_ec$ at the moment of time t=190.4 fs.

CONCLUSIONS

In this paper, using a fully relativistic PIC 2.5D numerical simulation code OSIRIS, a study was performed on a method for providing self-injection, holding a self-injected bunch in the acceleration phase in order to increase the energy of the self-injected bunch.

A complex plasma profile was considered: first, a region of decreasing density, due to which the formation of a self-injection bunch occurred, then a region of increasing density, due to which, according to previous studies, the synchronization of the self-injected bunch and the accelerating phase of the wakefield is observed. As a result, the energy value increases.

By time t=190.4 fs, there was an increase in the energy of the self-injected bunch by 7.67 times, as well as an increase to 11.5 in normalized units of the longitudinal momentum of the bunches.

Compared to previous studies, the process of self-injection and bunch retention observed at a lower laser amplitude (at least by a factor of 2). A lower plasma density (10^4 times) was considered. At the same time, a significant increase in the bunch charge and 2 times increase in the energy increasing for the observed time were investigated.

REFERENCES

1. T. Tajima, J.M. Dawson. Laser Electron Accelerator // *Phys. Rev. Lett*. 1979, v. 43, N 4, p. 267-270; doi: 10.1103/PhysRevLett.43.267

2. T. Tajima, G. Mourou. Zettawatt-exawatt lasers and their applications in ultrastrong-field physics // *Phys. Rev. ST Accel. Beams*. 2002, v. 5, p. 031301; doi: 10.1103/physrevstab.5.031301

3. W. Leemans, E. Esarey. Laser-driven plasma-wave electron accelerators // *Phys. Today*. 2009, v. 62, N 3, p. 44-49; doi: 10.1063/1.3099645

4. C. Danson, D. Hillier, N.W. Hopps, D. Neely. Peta-watt class lasers worldwid // *High Power Laser Science and Engineering*. 2015, v. 3; doi: 10.1017/hpl.2014.52

5. M.W. Guetg, A.A. Lutman, Y. Ding, T.J. Maxwell, F.-J. Decker, U. Bergmann, Z. Huang. Generation of High-Power High-Intensity Short X-Ray Free-Electron-Laser Pulses // *Phys. Rev. Lett*. 2018, v. 120, p. 014801; doi: 10.1103/PhysRevLett.120.014801

6. S.M. Hooker. Developments in laser-driven plasma accelerators // *Nat. Photonics*. 2013, v. 7, p. 775; doi: 10.1038/nphoton.2013.234

7. W. Lu et al. Generating multi-GeV electron bunches using single stage laser wakefield acceleration in a 3D nonlinear regime // *Physical Review Special Topics – Accelerators and Beams*. 2007, v. 10, N 6, p. 061301.

8. Wim Leemans, Bob Nagler, A.J. Gonsalves, Cs. Toth, Kei Nakamura, C.G.R. Geddes, E. Esarey, C.B. Schroeder, S.M. Hooker. GeV electron beams from a centimetre-scale accelerator // *Nature Physics*. 2006, v. 2, p. 696-699; doi: 10.1038/nphys418

9. 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.

10. 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.

11. 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.

12. 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.

13. 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.

14. 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.

15. 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.

16. 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. 2*015, N 4, p. 120-123.

17. 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.

18. 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, v. 6, p. 156-159.

19. V.I. Maslov, R.T. Ovsiannikov, 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.

20. 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.

21. V.I. Maslov, D.S. Bondar, V. Grigorenko, 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.

22. 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(134), p. 70-73; doi: 10.46813/2021-134-070

23. 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.

24. 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, N 2, p. 64-68.

25. 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; doi: 10.46813/2023-148-065

26. 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;
doi: 10.46813/2023-145-108

27. V.I. Maslov, D.S. Bondar, I.N. Onishchenko. Investi-gation of the Way of Phase Synchronization of a Self-Injected Bunch and an Accelerating Wakefield in Solid-State Plasma // *Photonics*. 2022, v. 9, N 3, p. 174; doi: 10.3390/photonics9030174

28. D.S. Bondar, V.I. Maslov, I.N. Onishchenko. Amethod for maintaining the acceleration rate and increasing the energy of self-injected bunch due to the use of inhomogeneous plasma // *Problems of Atomic Science and Technology*. 2023, N 4(146), p. 67-70; doi: 10.46813/2023-146-067

29. S.J. Kim, J.J. Lee, Y.S. Lee, D.W. Kim, S.J. You. Effect of an inhomogeneous electron density profile on the transmission microwave frequency spectrum of the cutoff probe // *Plasma Sources Sci. Technol.* 2020, v. 29, N 12, p. 125014;
doi: 10.1088/1361-6595/abc816

30. C. Aniculaesei et al. Electron energy increase in a laser wakefield accelerator using up-ramp plasma density profiles // *Sci. Rep*. 2019, v. 9, p. 11249;
doi: 10.1038/s41598-019-47677-5

31. A.R. Holkundkar, N.K. Gupta. Effect of initial plasma density on laser induced ion acceleration // *Phys. Plasmas*. 2008, v. 15, N 12, p. 123104;
doi: 10.1063/1.3037264

32. S.K. Saha et al. Plasma density accumulation on a conical surface for diffusion along a diverging magnetic field // *Phys. Plasmas*. 2014, v. 21, N 4, p. 043502; doi: 10.1063/1.4870758

33. F. Théberge, W. Liu, P.T.R. Simard, A. Becker, S.L. Chin. Plasma density inside a femtosecond laser filament in air: Strong dependence on external focusing *// Phys. Rev. E*. 2006, v. 74, N 3, p. 036406;
doi: 10.1103/PhysRevE.74.036406

34. R. Fonseca et al. Exploiting multi-scale parallelism for large scale numerical modelling of laser wakefield accelerators // *Plasma Phys. Control. Fusion*. 2013, v. 55, p. 124011;
doi: 10.1088/0741-3335/55/12/124011

35. X. Xu et al. Generation of ultrabright and low energy spread electron beams in laser wakefield acceleration in a uniform plasma // *Phys. Rev. Accel. Beams*. 2023, v. 26, p. 111302;
doi: 10.1103/PhysRevAccelBeams.26.111302

36. Інформаційна сторінка репозиторію коду OSIRIS; https://osiris-code.github.io/ (дата звернення 19.04.2024 р.).

37. H. Ding et al. Nonlinear plasma wavelength scalings in a laser wakefield accelerator // *Phys. Rev. E*. 2020, v. 101, p. 023209;
doi: 10.1103/PhysRevE.101.023209

38. S.J. Yoon, J.P. Palastro, H.M. Milchberg. Quasi-Phase-Matched Laser Wakefield Acceleration // *Phys. Rev. Lett.* 2014, v. 112, p. 134803;
doi: 10.1103/PhysRevLett.112.134803

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ДО КІЛЬВАТЕРНОГО ПРИСКОРЕННЯ У НЕОДНОРІДНІЙ ПЛАЗМІ

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

У лазерно-плазмовому кільватерному прискоренні актуальним і широко досліджуваним питанням є отримання малих самоінжектованих згустків і підвищення їхньої енергії та швидкості прискорення шляхом варіації параметрів лазерних імпульсів і плазми. Зокрема, значний ефект дає використання спеціальних профілів плазми. Раніше було показано, що при поздовжньому лінійно зростаючому профілі густини плазми за рахунок стиснення кільватерної бульбашки досягається синхронність максимального прискорювального поля на задній стінці кільватерної бульбашки та самоінжектованого згустка. Шляхом числового моделювання з використанням коду OSIRIS досліджено кільватерне прискорення у немонотонно неоднорідній плазмі. У першій короткій ділянці густина плазми зменшується, що забезпечує контрольовану самоінжекцію електронного згустка навіть при малій інтенсивності лазерного імпульсу. Потім у довгій ділянці густина плазми збільшується з метою подовження часу руху самоінжектованого згустка у фазі прискорення кільватерного поля і збільшення енергії згустка. Показано збільшення ефекту зростання енергії та збільшення заряду згустка порівняно з раніше отриманими результатами. Крім того, продемонстровані ефекти утворення самоінжектованих згустків з подальшим їх утриманням для лазерів меншої амплітуди, ніж у попередніх дослідженнях, що розширює експериментальні можливості.