https://doi.org/10.46813/2026-165-077

DEPENDENCE OF SELF-INJECTED BUNCH PARAMETERS ON THE PLASMA DENSITY GRADIENT AND LASER PULSE AMPLITUDE AT LWFA IN A CONICAL PLASMA CHANNEL

D.S. Bondar[1], V.I. Maslov[1,2], I.N. Onishchenko[1]
[1]National Science Center "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine;
[2]Deutsches Elektronen-Synchrotron DESY, Hamburg, Germany
E-mail: bondar.ds@yahoo.com

Laser wakefield acceleration (LWFA) is an advanced method of high gradient acceleration of charged particles with wakefield excited in plasma by laser pulse. A distinctive feature of this method is the ability to create and accelerate so-called self-injected bunches with unique parameters – charge, energy, emittance, and geometric dimensions – without the need for an external injector of the required bunches for their subsequent acceleration to higher energies. Self-injected bunches emerge due to the plasma electrons trapping by the excited wakefield (self-injection phenomenon). For many applications, self-injected bunches can be used directly in relevant experiments. The dependence of the self-injected bunch parameters on the laser pulse amplitude and longitudinal gradient of plasma density in tapered plasma channel is investigated using numerical simulation with the WarpX code. At the laser amplitude $a_0=E_0(m_ec\omega/e)^{-1}=3.6$ in a conical channel with the radius decreasing from 4.0 to 2.16 c/ω_{pe} and with the plasma density increasing linearly from $n_e=2.61\cdot10^{19}$ cm^{-3} at the channel entrance to $3n_e$ at the exit, a self-injected bunch is obtained with the charge $3.21\cdot10^4$ nC/m, the mean longitudinal momentum 111.9 m_ec, the length 5.10 μm, the area 5.3 μm^2, the transverse emittance $1.6\cdot10^{-2}$ mm·mrad.

PACS: 29.17.+w; 41.75.Lx

INTRODUCTION

Laser wakefield acceleration (LWFA) is a promising method for generating and accelerating relativistic electron bunches, and to obtain the high accelerating gradients in plasma [1–5]. Experiments have demonstrated quasi-monoenergetic GeV electron beams from compact setups [6–9].

Formation and dynamics of self-injected bunches was previously studied for dense plasma in [10–12] and in [13, 14] for plasma channel obtained by discharge in a capillary used for increasing the acceleration length. Self-injected bunches can be formed in the plasma-dielectric structures at wakefield excitation by electron bunches instead of the laser pulse [15–17].

Joint acceleration by a laser pulse and self-injected bunches as well as hybrid schemes has been considered in [18–21]. A key feature of LWFA is internal injection (so-called self-injection) when background electrons are trapped directly by the wakefield and accelerated without an external injector. The parameters of a self-injected bunch are highly sensitive to the laser and plasma parameters and can be controlled by changing laser driver parameters, using plasma density gradients, laser amplitude, channel profile. In [22–26] shaped plasma density profiles are used to control parameters of self-injected bunches.

Control of the self-injected bunch parameters by laser pulse profile shaping was investigated in [27], and its phase synchronization with the accelerating wakefield in high density plasma in [28–35].

However, in these studies the set of parameters was not considered and the limiting configurations and optimal parameters were not investigated. There are several studies of the generation of high-quality bunches in high density plasma [36], the control of the self-injection threshold by the laser pulse parameters [37, 38].

In this paper some problems are considered that were not investigated before. In particular, it is considered the limit of the inhomogeneity gradient at which the effect of longitudinal momentum increase is offset by strong deformation of the wake bubble and subsequent destroying of the self-injected bunch.

Furthermore, in this paper the dependence of self-injected bunch parameters on laser amplitude is studied and the optimal range within which wake bubble deformation does not lead to the destroying of part of the bunch at the rear wall is to be found. The combined influence of amplitude changes, density gradient and conical channel effect on the shape and size of the wake bubble and, as a consequence, on the self-injected bunch is to be investigated.

The dependence of the self-injected bunch parameters on the laser pulse amplitude a_0, channel profile, plasma gradient is investigated, by numerical simulation with the WarpX code [39, 40, 41] in a conical plasma channel for different longitudinally increasing plasma density gradients.

Finding the optimal combination of the density gradient and the laser amplitude is important for obtaining self-injected bunches with needed parameters.

STATEMENT OF THE PROBLEM

The aim of the study is to determine how the longitudinal plasma density gradient and the laser pulse amplitude influence the parameters of a self-injected electron bunch in a conical plasma channel.

It is needed to show the limits of the parameters within which the deformation of the wake bubble keeps the bunch in the accelerating phase without the destroying of part of the bunch at the bubble rear wall, to find the limiting (too high) density gradient, and to determine the laser amplitude effect for each gradient.

Since the transverse size of the plasma channel affects the dimensions of the forming and accelerating bubble, we use a conical plasma channel to maintain the accelerated bunch within the accelerating wakefield region.

The simulations have been carried out with the fully relativistic particle-in-cell (PIC) code WarpX [39] in 2D3V plane geometry. All lengths are normalized to c/ω_{pe} (1.27 μm), time t is normalized to $1/\omega_{pe}$ (4.25 fs), where $\omega_{pe}=(4\pi n_{pe}e^2/m_e)^{1/2}$ is the electron plasma frequency at n_{pe}. In this paper, the ω_{pe} used for normalization is calculated at the reference density $n_{pe}=0.667n_e$, where $n_e=2.61\cdot10^{19}$ cm^{-3} is the plasma density of the homogeneous section of the channel.

The longitudinal field E_z is normalized to $m_ec\omega_{pe}/e$, the laser energy density to $n_{pe}m_ec^2$, the mean electron longitudinal momentum $<p_z>$ to m_ec. The linear charge of self-injected bunch Q_{bunch} is normalized to $en_{pe}(c/\omega_{pe})^2=4.52\cdot10^3$ nC/m. The simulation domain is $0\le z\le120$, $|x|\le7.5$. It is considered 4096×512 cells ($\Delta z=\Delta x=0.029$). It is used Yee scheme with the time step $\Delta t=0.021$ (CFL is 1). t=82.9, 4000 steps. Number of macroparticles per cell is 25.

A conical plasma channel with a decreasing radius and a longitudinally increasing plasma density will be considered (Fig. 1). Channel radius is $r_{CH}=4$ up to z=25 (channel of constant radius), decreases linearly to $r_{ch}=2.16$ at z=85 (cone). Four configurations will be studied: a homogeneous case n_e and three linear longitudinally increasing gradients with max. values $2n_e$, $3n_e$ and $4n_e$ at the channel exit (see Fig. 1).

For each configuration the amplitude is chosen as $a_0=2,\ 2.4,\ 2.8,\ 3.2,\ 3.6,\ 4.0$. $a_0=E_0(m_ec\omega/e)^{-1}$ is the normalized laser amplitude, where E_0 is the peak laser electric field and ω is the laser frequency. The laser wavelength is λ=800 nm, the waist $w_0=3.9$ and the duration τ=5.11 (21.7 fs). Both the longitudinal and transverse laser pulse profiles are Gaussian.

The self-injected bunch parameters are analyzed at time t=82.9, when the wake bubble head reaches the channel exit on a z=76…90.

RESULTS OF SIMULATION

Fig. 1 shows the initial configuration. There are considered cone with homogeneous density n_e or with density gradients rising longitudinally along the cone from n_e up to $2n_e$, $3n_e$, and $4n_e$. Laser pulse and the wake bubble propagate from left to right in the conical channel.

Inside the conical channel laser pulse moves with a radial compression, which increases of laser energy density on the axis of the system that leads to an increase in the efficiency of wake acceleration (see [33]).

It is observed that the maximum laser pulse energy density (Fig. 2) at the system axis is 2.1 times higher (up to $1.98\cdot10^3$) in the case of the considered conical channel (see Fig. 1) compared to the same channel in which the cone is replaced by a channel of the constant radius 4.

Both channels are compared under the same conditions, at $a_0=4$, the homogeneous density n_e and the same time t=82.9, so that only the channel geometry differs. The maximum is reached at the axis at z=86, near the channel exit (laser pulse energy is $0.95\cdot10^3$ in the channel of the constant radius and $1.98\cdot10^3$ in the cone).

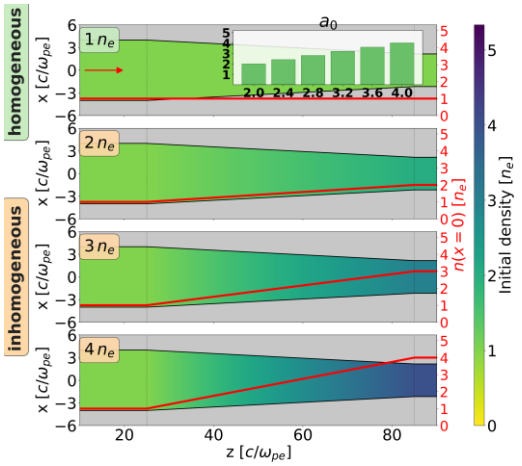


Fig. 1. Initial electron density (color, in n_e) of the converging-cone target in the z-x plane (c/ω_{pe}). Four cases differ in the density ramp along the cone (red line, right axis): homogeneous n_e and inhomogeneous up to $2n_e$, $3n_e$, $4n_e$ at the cone exit (yellow labels). The red arrow marks laser injection. Considered laser amplitudes a_0 =2.0…4.0 (step 0.4); t=82.9

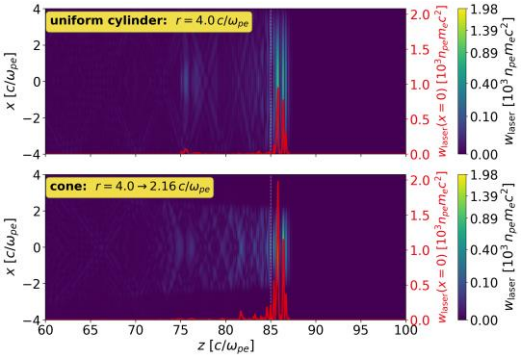


Fig. 2. Laser pulse energy density w_{laser} in the z-x plane and its value at x=0 for a channel of the constant radius (top) and for the cone (bottom); t=82.9

Obtained results of simulation the longitudinal field E_z and electron density $n_e(z,x)$ are shown in Figs. 3a, 3b for the a_0 = 2.0, 2.4, 2.8 (see Fig. 3a) and the a_0 = 3.2, 3.6, 4.0 (see Fig. 3b). Fig. 3a and Fig. 3b present only a fragment near the channel exit, with a length of about the plasma wavelength (z=76…90).

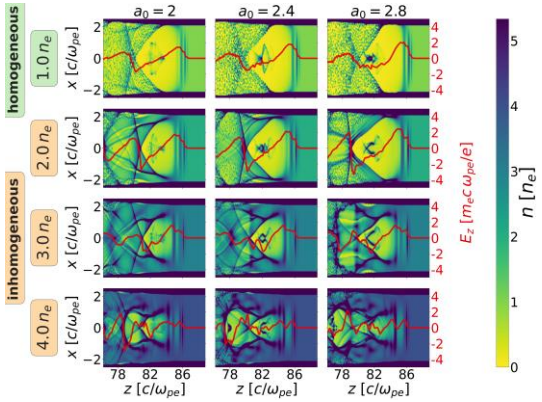


Fig. 3a. Longitudinal field E_z (red line) and electron density n_e (z, x) for laser amplitudes a_0 = 2, 2.4, 2.8 (columns) and tapered channel densities: homogeneous n_e, inhomogeneous $2n_e$, $3n_e$, $4n_e$ (rows); t=82.9

The wake bubble is formed behind the laser pulse. To be effectively accelerated the self-injected bunch should be located near the wake bubble tail, where the accelerating field is largest. The accelerating field E_z is about 3.2 (see Figs. 3a, 3b, see red curves).

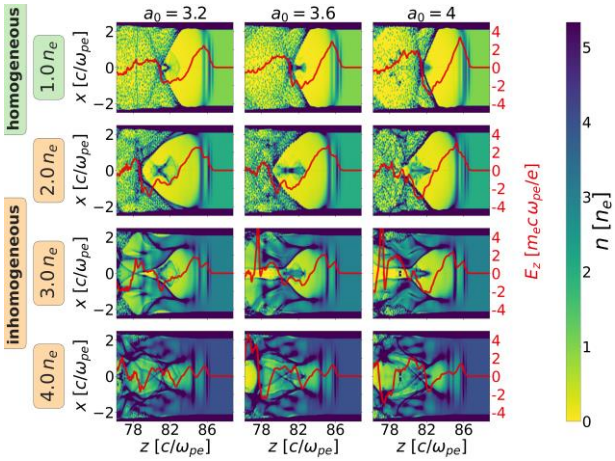


Fig. 3b. Longitudinal field E_z (red curve) and electron density $n_e(z, x)$(colour scale, right) for laser pulse amplitudes a_0 = 3.2, 3.6, 4.0 (columns) and tapered channel filled with plasma densities: homogeneous n_e, inhomogeneous $2n_e$, $3n_e$, $4n_e$ (rows); t=82.9

The rough theoretical estimation of bubble size can be taken from [42] $R_b \approx 2\sqrt{a_0}$ $[c/\omega_{pe}]$. For a_0=2.0…4.0 it gives bubble radius R_b=2.8…4.0, which already exceeds the channel radius 2.16 at the cone exit. In the considered geometry the bubble is touched by the channel walls in the homogeneous case.

In Figs. 3a, 3b, in the homogeneous conical channel, the wake bubble is seen to shorten as the amplitude increases. The effect is that, with growing amplitude, the bubble would tend to expand, but the channel walls limit it, so that only the front of the wake bubble is formed and the rear side of the wake bubble is lost. A larger amplitude gives a larger loss and a stronger shortening of the wake bubble along z.

In this case, when a longitudinal gradient of inhomogeneity is used, a decreasing in the plasma wavelength is observed that leads to the decreasing in the wake bubble size. In the inhomogeneous cases the bubble is smaller than the channel (the ratios of the channel radius to the bubble radius obtained at the channel exit are 1.13, 1.59 and 2.83 for $2n_e$, $3n_e$ and $4n_e$, they vary only weakly with the amplitude, Fig. 4).

Laser pulse amplitude increasing effect. As seen in Figs. 6, 7, and 8, the bunch length, charge and area grow with a_0 up to a_0=2.8 and then fall in the homogeneous case and at inhomogeneous $4n_e$. This fall indicates the destroying of part of the bunch. At $2n_e$, $3n_e$ these parameters continue increasing with a_0, and the length is largest at a_0=3.6. As seen in Fig. 5, p_z grows with a_0 in all cases. At $3n_e$ p_z rises from 78 at a_0=2.0 to 126.5 at a_0=4.0. In the homogeneous channel p_z reaches 96.7 at a_0=4.0. At inhomogeneous $4n_e$ the gain of p_z with a_0 is smaller than at $3n_e$. The length, charge and area grow with a_0 at $2n_e$, $3n_e$ and decrease after a_0=2.8 in the homogeneous case and at inhomogeneous $4n_e$, while p_z keeps growing up to a_0=4.0.

Longitudinal density increasing effect. The longitudinal increase of density shortens the plasma wavelength λ_p, and the bubble becomes smaller than the channel. At $2n_e$, $3n_e$ the bubble does not touch the channel walls, and the bunch stays in the accelerating phase. This is seen at a_0=2.8…3.6. At inhomogeneous $4n_e$ the bubble contracts too strongly and part of the bunch is lost at the rear wall. At $3n_e$ and a_0=3.6…4.0 a small plasma channel of length 3.92 and width 0.67 forms at the bubble tail due to beam loading (see Figs. 3b, 4). At fixed a_0 the gradient raises p_z up to $3n_e$. At a_0=4.0 p_z reaches 126.5. At a_0=2.0 p_z reaches 78. At inhomogeneous $4n_e$ the gain in p_z is smaller. A moderate gradient at $2n_e$, $3n_e$ keeps the bunch in the accelerating phase, while inhomogeneous $4n_e$ is excessive and leads to a fall of p_z.

The formation of this small channel in the tail region of the wake bubble leads to the deformation of the wakefield bubble structure. Compared with the $2n_e$ case, where no such channel forms, the maximum field E_z at $3n_e$ is lower by 19% at a_0=3.6 and by 27% at a_0=4.0.

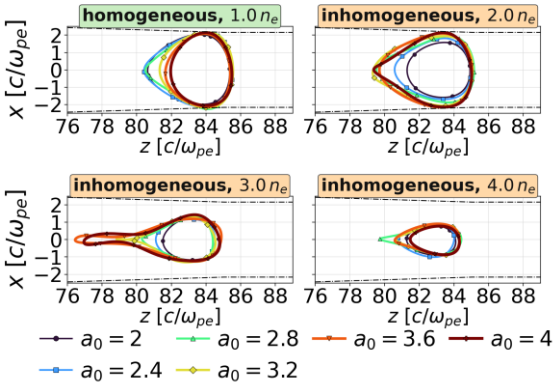


Fig. 4. Plasma-bubble, one panel per channel density (homogeneous n_e, inhomogeneous $2n_e$, $3n_e$, $4n_e$), with one contour per laser amplitude a_0 = 2.0…4.0 (step 0.4, line thickness grows with a_0). Black dash lines show the tapered channel walls; t=82.9

Fig. 5 shows a graph of longitudinal momentum p_z. In the homogeneous case n_e and in the case of inhomogeneous plasma an increase in the average longitudinal momentum p_z is observed with an increase in the laser amplitude a_0. In the homogeneous case n_e, the maximum value (a_0=4.0) of p_z is 96.7. In the inhomogeneous case $2n_e$ p_z increases to 118.4. In the inhomogeneous case $3n_e$ p_z increases to 126.5.

At the same time, in the case $4n_e$, compared to the homogeneous case, p_z increases to 123. Thus, for $4n_e$, the effect of the p_z increase is even smaller than for $3n_e$.

From Fig. 5 it can be concluded that a case of inhomogeneous plasma with density value of $4n_e$ is too high and leads only to a contraction of the wake bubble, the destroying of part of the self-injected bunch and a decrease in the mean longitudinal momentum p_z. This effect is observed for all laser pulse amplitudes. It is important to note that for a fixed amplitude a_0, the use of inhomogeneous plasma with density gradient up to $3n_e$, leads to p_z of 126.5 at a_0=4.0 and 78 at a_0=2.0 (see Fig. 5).

A further increase in the plasma density to $4n_e$ does not lead to an increase in longitudinal momentum p_z, due to the previously discussed reason for the significant decrease in the wake bubble size.

In Figs. 6–8 it is presented the main parameters of the bunch length, area and charge. The bunch length (see Fig. 6) shows the same threshold behavior as the charge (see Fig. 7). In the homogeneous case n_e length grows from 2.34 at a_0=2.0 to 2.98 at a_0=2.8…3.2 and then falls to 1.66 at a_0=4.0.

At $4n_e$ bunch length reaches 2.53 at a_0=2.8 and falls to 1.59 at a_0=4.0, which indicates the destroying of part of the bunch at the rear wake bubble wall.

For the moderate gradients $2n_e$, $3n_e$ the length continues increasing with the amplitude growth and reaches 3.87 at $2n_e$ and 4.01 at $3n_e$ (a_0=3.6).

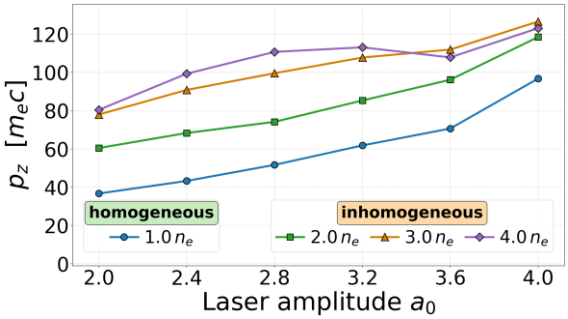


Fig. 5. Mean longitudinal electron momentum p_z (in m_ec) dependence from laser amplitude a_0, for the four channel densities (homogeneous n_e, inhomogeneous $2n_e$, $3n_e$, $4n_e$); t=82.9

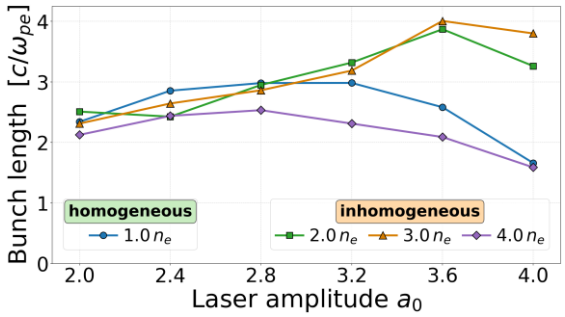


Fig. 6. Electron bunch length dependence on laser amplitude a_0, for the four plasma densities in the channel (homogeneous n_e, inhomogeneous $2n_e$, $3n_e$, $4n_e$); t=82.9

Both in the homogeneous case n_e, and in the inhomogeneous case with density $4n_e$, a decrease in the charge of the self-injected bunch is observed when reaching high amplitude a_0=4.0 (see Fig. 7).

In homogeneous case n_e charge changes to 3.0 at a_0=4.0 when initial value at a_0=2.0 is the 2.2, maximum value at a_0=2.8 is the 5.0.

At $4n_e$, a change from 1.7 to 3.1 when changing from a_0=2.0 to a_0=4.0 is observed (maximum value at a_0=2.8 is the 4.5). In other cases, for $2n_e$ and $3n_e$, an increase in the charge of the bunch is observed by 2.84 times and 3.13 times respectively when comparing cases a_0=4.0 and a_0=2.0. Thus, the use of inhomogeneous plasma leads to an increase in the charge of the self-injected bunch Q_{bunch}. This increase shows threshold behavior. In the homogeneous case (n_e) or with extreme inhomogeneity ($4n_e$), the charge reaches a maximum and then falls. In the cases of inhomogeneous increasing densities up to $2n_e$ and $3n_e$, an increase in charge of up to 2.31 times is observed compared to the homogeneous case and the gradient with maximum value $4n_e$.

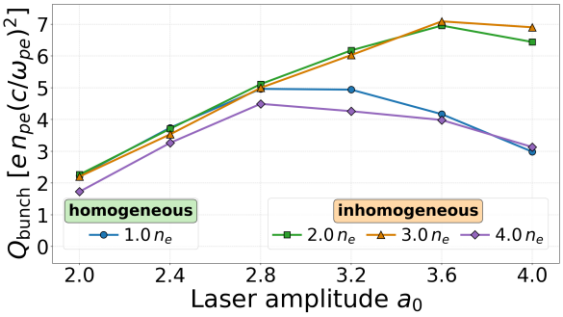


Fig. 7. Bunch charge Q_{bunch} dependence on normalized laser amplitude a_0 for the four plasma densities in the channel (homogeneous n_e, inhomogeneous $2n_e$, $3n_e$, $4n_e$); t=82.9

The dynamic of the self-injected bunch area (see Fig. 8) is similar to the charge trend. An increase of the bunch area is observed in the cases $2n_e$, $3n_e$ when amplitude a_0 is increasing.

It is observed that in the homogeneous case, as well as in the case of too high inhomogeneous gradient $4n_e$, with an increase in amplitude, the area of the bunch decreases, which indicates the destroying of part of the bunch.

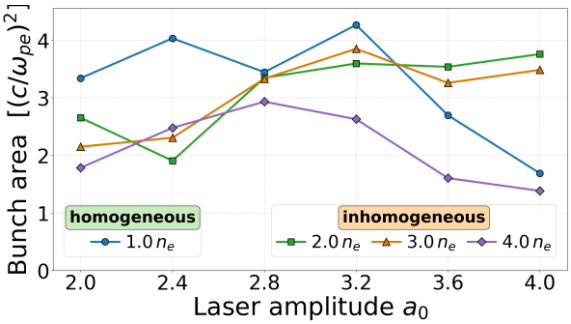


Fig. 8. Electron bunch area dependence on laser amplitude a_0, for the four channel densities (homogeneous n_e, inhomogeneous $2n_e$, $3n_e$, $4n_e$); t=82.9

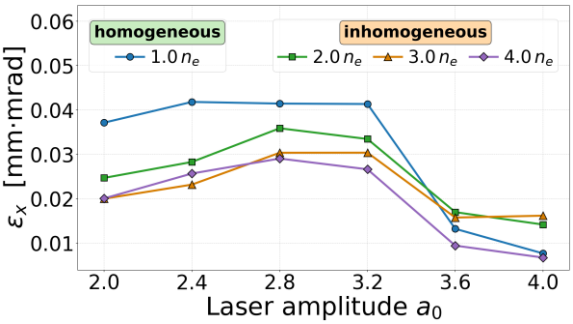


Fig. 9. Electron bunch transverse emittance ε_x dependence on laser amplitude a_0, for the four channel densities (homogeneous n_e, inhomogeneous $2n_e$, $3n_e$, $4n_e$); t=82.9

Fig. 9 shows the emittance graph. The emittance ε_x (transverse RMS) does not exceed $4.2\cdot10^{-2}$ mm·mrad.

Using an inhomogeneous plasma in a conical plasma channel led to an increase in longitudinal momentum p_z with increasing gradient value until the limiting density is reached ($4n_e$). The effect was observed for all fixed amplitudes. For a_0=4.0 p_z reaches 126.5 at $3n_e$. For a_0=2.0 p_z reaches 78 at $3n_e$.

Thus, it has been demonstrated that when the gradient

of the plasma density is fixed, an increase in the value of the longitudinal momentum is observed until the wake bubble contracts so strongly that part of the bunch is destroyed.

The obtained results agree with the available experimental data. In [26], an up-ramp plasma density profile increased the mean electron peak energy by more than 50%, agreed with the growth of p_z obtained here for gradients up to $3n_e$, by 31% at $a_0=4$ and up to a factor of 2.1 at lower amplitudes.

Controlled injection in channel-guided accelerators has also been considered and improved by shaping plasma channel [43]. A conical can be formed experimentally in a gas jet by the expansion driven by a laser a preceding laser pulse [44].

CONCLUSIONS

In this paper the influence of the laser amplitude a_0 and the longitudinal plasma density gradient on a self-injected bunch in a conical plasma channel was studied by 2D3V WarpX simulations, for a homogeneous channel n_e and three linear longitudinally increasing plasma densities with maximum values $2n_e$, $3n_e$, and $4n_e$.

Inside the conical channel laser pulse moves with a radial compression, which increases of laser energy density on the axis of the system. At the channel exit the peak laser energy density 2.1 times higher than in a channel of constant radius 4.

The longitudinal density gradient using leads to the mean longitudinal momentum of the self-injected bunch increasing to 126.5 at $3n_e$ and $a_0=4.0$ compared with 96.7 in the homogeneous case, while the emittance stays below $4.2\cdot10^{-2}$ mm·mrad. With a gradient increase the wake bubble becomes smaller than the channel with the shortening of the plasma wavelength, so the gradient and the amplitude compensate each other and the bunch is kept in the accelerating phase, its charge exceeding the homogeneous case by up to 2.31 times. The density $4n_e$ is the limit because the bubble contracts too strongly and the momentum reaches only 123 m_ec.

Changing the amplitude of the laser pulse a_0 affects the longitudinal momentum p_z of the self-injected bunch. With growing a_0 at $3n_e$, p_z rises from 78 at $a_0=2$ to 126.5 at $a_0=4$, and over the same amplitude range the bunch charge grows 3.13 times. At $2n_e$ and $3n_e$ length and area of the bunch grow with the amplitude, but in the homogeneous channel and at $4n_e$ these parameters pass through a maximum and then fall, which indicates the destroying of part of the bunch. The working range is $a_0=2.8$-3.6 with densities $2n_e$, $3n_e$. At large amplitudes close to $a_0=4$ absorption of the bunch tail and falling of p_z were observed in the homogeneous case.

The optimal obtained bunch ($a_0=3.6$, $3n_e$) has the charge 7.1 ($3.21\cdot10^4$ nC/m), $p_z=111.9$ m_ec, the length 4.01 (5.10 μm), the area 3.26 (5.3 μm^2) and $\varepsilon_x=1.6\cdot10^{-2}$ mm·mrad.

ACKNOWLEDGEMENTS

The study is supported by the National Research Foundation of Ukraine under the program "Excellent Science in Ukraine" (project # 2023.03/0182).

The work was inspired by discussions with Professor Dr. W.P. Leemans (DESY). We are grateful to Dr. Maxence Thèvenet for the useful discussion and recommendations for improving the text of the article.

REFERENCES

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

2. E. Esarey, C.B. Schroeder, W.P. Leemans. Physics of laser-driven plasma-based accelerators // *Reviews of Modern Physics*. 2009, v. 81, N 3, p. 1229-1285; doi: 10.1103/RevModPhys.81.1229

3. A.C. Ting. Ultra-high gradient acceleration of electrons by laser wakefield plasma waves // *Proc. 26th IEEE International Conference on Plasma Science*. 1999, p. 153; doi: 10.1109/PLASMA.1999.829398

4. I.N. Onishchenko. Wakefield acceleration based on high power pulsed lasers and electron beams (overview) // *Problems of Atomic Science and Technology*. 2006, N 2(46), p. 17-24.

5. S.M. Hooker. Developments in laser-driven plasma accelerators // *Nature Photonics*. 2013, v. 7, p. 775-782; doi: 10.1038/nphoton.2013.234

6. W.P. Leemans, B. Nagler, A.J. Gonsalves, C. Toth, K. 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

7. S.P.D. Mangles et al. Monoenergetic beams of relativistic electrons from intense laser-plasma interactions // *Nature.* 2004, v. 431, p. 535-538; doi: 10.1038/nature02939

8. C.G.R. Geddes et al. High-quality electron beams from a laser wakefield accelerator using plasma-channel guiding // *Nature.* 2004, v. 431, p. 538-541; doi: 10.1038/nature02900

9. 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, p. 061301; doi: 10.1103/PhysRevSTAB.10.061301

10. V.I. Maslov, O.M. Svystun, I.N. Onishchenko, V.I. Tkachenko. Dynamics of electron bunches at the laser-plasma interaction in the bubble regime // *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*. 2016, v. 829, p. 422-425; doi: 10.1016/j.nima.2016.04.018

11. D.S. Bondar, I.P. Levchuk, V.I. Maslov, S. Nikonova, I.N. Onishchenko. Dynamics of self-injected electron bunches at their acceleration by laser pulse in plasma // *Problems of Atomic Science and Technology.* 2017, N 6(112), p. 76-79.

12. 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(118), p. 156-159.

13. A. Butler, D.J. Spence, S.M. Hooker. Guiding of high-intensity laser pulses with a hydrogen-filled capillary discharge waveguide // *Physical Review Letters.* 2002, v. 89, N 18, p. 185003; doi: 10.1103/PhysRevLett.89.185003

14. C.G.R. Geddes, C. Toth, J. Van Tilborg, E. Esarey, C.B. Schroeder, D. Bruhwiler, C. Nieter,

J. Cary, W.P. Leemans. Guiding of relativistic laser pulses by preformed plasma channels // *Physical Review Letters.* 2005, v. 95, N 14, p. 145002;
doi: 10.1103/PhysRevLett.95.145002

15. G.V. Sotnikov, R.R. Kniaziev, O.V. Manuilenko, P.I. Markov, I.N. Onishchenko. Analytical and numerical studies of underdense and overdense regimes in plasma-dielectric wakefield accelerator // *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*. 2014, v. 740, p. 124-129;
doi: 10.1016/j.nima.2013.10.087

16. I.V. Demydenko, V.I. Maslov, I.N. Onishchenko. Suppression of bunch destruction under resonant excitation of the plasma wakefield // *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*. 2026, Article 170851;
doi: 10.1016/j.nima.2025.170851

17. I.V. Demydenko, V.I. Maslov. Electron acceleration by a wakefield excited in plasma by a profiled train of bunches under conditions of their greatest stability and a plateau on the wakefield // *IEEE Transactions on Plasma Science*. 2026, v. 54, N 1, p. 117-120; doi: 10.1109/TPS.2025.3636828

18. V.I. Maslov, O.M. Svystun, I.N. Onishchenko, A.M. Yegorov. Joint wakefield acceleration by laser pulse and by self-injected electron bunches // *Problems of Atomic Science and Technology.* 2016, N 6(106), p. 144-147.

19. S. Steinke et al. Multistage coupling of independent laser-plasma accelerators // *Nature.* 2016, v. 530, p. 190-193; doi: 10.1038/nature16525

20. T. Kurz, T. Heinemann, M.F. Gilljohann, et al. Demonstration of a compact plasma accelerator powered by laser-accelerated electron beams // *Nature Communications.* 2021, v. 12, p. 2895;
doi: 10.1038/s41467-021-23000-7

21. M. Litos et al. High-efficiency acceleration of an electron beam in a plasma wakefield accelerator // *Nature*. 2014, v. 515, p. 92-95;
doi: 10.1038/nature13882

22. Z-H. He et al. High repetition-rate wakefield electron source generated by few-millijoule, 30 fs laser pulses on a density downramp // *New Journal of Physics*. 2013, v. 15, p. 053016;
doi: 10.1088/1367-2630/15/5/053016

23. M.P. Tooley et al. Towards attosecond high-energy electron bunches: Controlling self-injection in laser-wakefield accelerators through plasma-density modulation // *Physical Review Letters*. 2017, v. 119, p. 044801; doi: 10.1103/PhysRevLett.119.044801

24. P. Lee et al. Dynamics of electron injection and acceleration driven by laser wakefield in tailored density profiles // *Physical Review Accelerators and Beams*. 2016, v. 19, N 11, p. 112802;
doi: 10.1103/PhysRevAccelBeams.19.112802

25. C.G.R. Geddes et al. Plasma-Density-Gradient Injection of Low Absolute-Momentum-Spread Electron Bunches // *Physical Review Letters*. 2008, v. 100, p. 215004; doi: 10.1103/PhysRevLett.100.215004

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

27. D.S. Bondar, V.I. Maslov, I.N. Onishchenko. Wakefield Acceleration Driven by the Laser Pulse with a Steep Front in Various Plasma Channels // *Ukrainian Journal of Physical Optics.* 2026, v. 27, issue 3, p. 03069-03082;
doi: 10.3116/16091833/Ukr.J.Phys.Opt.2026.03069

28. 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, v. 9, p. 174;
doi: 10.3390/photonics9030174

29. D.S. Bondar, V.I. Maslov, I.N. Onishchenko. A method 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

30. D.S. Bondar, V.I. Maslov, I.N. Onishchenko. Improving stability of the self-injected bunch by variation of a sequence of two laser pulses parameters at wakefield excitation in a metal density plasma // *Problems of Atomic Science and Technology*. 2023, N 6(148), p. 69-73; doi: 10.46813/2023-148-069

31. D.S. Bondar, V.I. Maslov, I.N. Onishchenko. On Wakefield Acceleration in Inhomogeneous Plasma // *Problems of Atomic Science and Technology*. 2024, N 3(151), p. 55-59; doi: 10.46813/2024-151-055

32. D.S. Bondar, V.I. Maslov, I.N. Onishchenko. Electron Source Based on Emergence of Self-Injected Electron Bunch at Plasma Wakefield Excitation by a TW Laser Pulse // *Problems of Atomic Science and Technology.* 2024, N 5(153), p. 59-65;
doi: 10.46813/2024-153-059

33. D.S. Bondar, W. Leemans, V.I. Maslov, I.N. Onishchenko. Laser-Plasma Acceleration in a Conical Plasma Channel with Longitudinally Inhomogeneous Plasma Profile // *Problems of Atomic Science and Technology.* 2025, N 4(158), p. 56-60;
doi: 10.46813/2025-158-056

34. D.S. Bondar, W. Leemans, V.I. Maslov, I.N. Onishchenko. Wakefield Acceleration of Self-Injected Bunch in a Conical Plasma Channels // *Problems of Atomic Science and Technology*. 2025, N 6(160), p. 26-30; doi: 10.46813/2025-160-026

35. F. Tsung, R. Narang, W.B. Mori, C. Joshi, R.A. Fonseca, L.O. Silva. Near-GeV-energy laser-wakefield acceleration of self-injected electrons in a centimeter-scale plasma channel // *Physical Review Letters.* 2004, v. 93, N 18, p. 185002;
doi: 10.1103/PhysRevLett.93.185002

36. B.S. Rao, A. Moorti, R. Rathore, J.A. Chakera, P.A. Naik, P.D. Gupta. High-quality stable electron beams from laser wakefield acceleration in high density plasma // *Physical Review Special Topics – Accelerators and Beams.* 2014, v. 17, N 1, p. 011301;
doi: 10.1103/PhysRevSTAB.17.011301

37. S. Kuschel, M.B. Schwab, M. Yeung, D. Hollatz, A. Seidel, W. Ziegler, M. Zepf. Controlling the self-injection threshold in laser wakefield accelerators //

Physical Review Letters. 2018, v. 121, N 15, p. 154801; doi: 10.1103/PhysRevLett.121.154801

38. A. Döpp, E. Guillaume, C. Thaury, A. Lifschitz, K. Ta Phuoc, V. Malka. Energy boost in laser wakefield accelerators using sharp density transitions // *Physics of Plasmas.* 2016, v. 23, N 5, p. 056702.

39. L. Fedeli et al. Pushing the Frontier in the Design of Laser-Based Electron Accelerators with Groundbreaking Mesh-Refined Particle-In-Cell Simulations on Exascale-Class Supercomputers // *SC22: International Conference for High Performance Computing*, Networking, Storage and Analysis, Dallas, TX, USA, 2022, p. 25-36;
doi: 10.1109/SC41404.2022.00008

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

41. R. Sandberg et al. Synthesizing Particle-In-Cell Simulations through Learning and GPU Computing for Hybrid Particle Accelerator Beamlines // *Proc. Platform for Advanced Scientific Computing Conference (PASC'24).* 2024, Article N 23, p. 1-11;
doi: 10.1145/3659914.3659937

42. W. Lu et al. Nonlinear theory for relativistic plasma wakefields in the blowout regime // *Physical Review Letters*. 2006, v. 96, p. 165002;
doi: 10.1103/PhysRevLett.96.165002

43. R.J. Shalloo et al. Controlled Injection in a Laser Plasma Accelerator via an Optically Generated Waveguide Constriction // arXiv preprint. 2024. arXiv:2410.15937.

44. M. Vranic, R.A. Fonseca, L.O. Silva. Extremely intense laser-based electron acceleration in a plasma channel // *Plasma Physics and Controlled Fusion*. 2018, v. 60, N 3, p. 034002; doi: 10.1088/1361-6587/aaa36c

Article received 07.09.2026

ЗАЛЕЖНІСТЬ ПАРАМЕТРІВ САМОІНЖЕКТОВАНОГО ЗГУСТКА ВІД ГРАДІЄНТА ГУСТИНИ ПЛАЗМИ ТА АМПЛІТУДИ ЛАЗЕРНОГО ІМПУЛЬСУ В ЛАЗЕРНОМУ КІЛЬВАТЕРНОМУ ПРИСКОРЕННІ В КОНІЧНОМУ ПЛАЗМОВОМУ КАНАЛІ

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

Лазерне кільватерне прискорення (LWFA) є передовим методом високоградієнтного прискорення заряджених частинок кільватерним полем, збудженим у плазмі лазерним імпульсом. Особливістю цього методу є можливість створювати та прискорювати так звані самоінжектовані згустки з унікальними параметрами – зарядом, енергією, емітансом і геометричними розмірами – без потреби у зовнішньому інжекторі згустків для їх подальшого прискорення до більш високих енергій. Самоінжектовані згустки виникають унаслідок захоплення електронів плазми збудженим кільватерним полем (явище самоінжекції). Для багатьох застосувань самоінжектовані згустки можуть використовуватися безпосередньо у відповідних експериментах. За допомогою чисельного моделювання з використанням коду WarpX досліджено залежність параметрів самоінжектованого згустка від амплітуди лазерного імпульсу та поздовжнього градієнта густини плазми в конічному плазмовому каналі. За амплітуди лазерного імпульсу $a_0=E_0(m_ec\omega/e)^{-1}=3,6$ у конічному каналі з радіусом, що спадає від 4,0 c/ω_{pe} до 2,16 c/ω_{pe}, та з густиною плазми, що лінійно зростає від $n_e=2,61\cdot10^{19}$ см$^{-3}$ на вході каналу до $3n_e$ на виході, отримано самоінжектований згусток із зарядом $3,21\cdot10^4$ нКл/м, середнім поздовжнім імпульсом 111,9 m_ec, довжиною 5,10 мкм, площею 5,3 мкм^2 та поперечним емітансом $1,6\cdot10^{-2}$ мм·мрад.