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PARAMETERS OF ELECTRON BUNCHES AT OFF-AXIS INJECTION INTO A THREE-ZONE RECTANGULAR DIELECTRIC-PLASMA ACCELERATING STRUCTURE

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The results of numerical three-dimensional PIC simulations of self-consistent dynamics of off-axis charged particles under the influence of the excited wake field in a three-zone rectangular dielectric-plasma accelerating structure are presented, which showed the possibility of simultaneous acceleration of the test electron bunch and its focusing, that made it possible to transport off-axis bunches. In a vacuum structure, bunch focusing is completely absent, but stable bunch transport over a finite length is also possible, although in a somewhat smaller range of transverse displacements. The limiting values of the permissible displacement of the test bunch are estimated, which allow bunches to be carried through a resonator of finite length without charge losses on dielectric or metal surfaces.

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INTRODUCTION

Recently, to improve the transfer of charged bunches in dielectric wake accelerators (DWA) it was proposed to use filling the vacuum channel with plasma [1]. The following more detailed studies (theoretical and experimental) showed that DWA with plasma filling (PDWA) make it possible to reduce the transverse size of accelerated bunches [2–5] and suppress the beam breakup instability [6].

Most of the studies on wake fields in dielectric structures have been performed for cylindrical configurations. Recently, the main interest has been found in planar [7–12] and rectangular forms of dielectric structures [13, 14]. This is due to a number of their advantages [16]. The study of the effect of plasma filling of rectangular dielectric structures on the transport of drive and test bunches has not yet been researched.

During the construction of DWA and PDWA, a good adjustment of the injector of charged bunches and the slow-wave structure is required. We decided to simulate the processes that occur during non-axial injection of bunches into the drift chamber and estimate possible tolerances for the shift of the injector axis relative to the axis of the structure. The equipment of the IPENMA NSC KIPT "Almaz-2" was used as an experimental prototype in the simulation, in which a regular sequence of electron bunches excites the wake field, the frequencies of the eigenwaves of which are equal to or multiples of the repetition rate of the bunches of 2.805 GHz [16–20]. Experiments on the injection of electron bunches into a rectangular dielectric resonator with plasma filling are performed on this equipment.

1. SETTING THE TASK

To obtain a rectangular three-zone dielectric-plasma waveguide, we used a metal waveguide with transverse dimensions $a \times b$ (where $a = 9$ cm and $b = 4.5$ cm) with two Teflon dielectric plates (with permeability $\varepsilon = 2.051$), which covered the opposite wide walls of the waveguide. The dimensions of the dielectric plates for a vacuum rectangular waveguide and a given energy of electron beams can be calculated using the excitation theory of multi-zone dielectric waveguides [15, 16, 21]. The eigenfrequencies of plasma-filled rectangular waveguides, and accordingly the dimensions of the dielectric plates with plasma filling of the bunch transport channel, can be found after a slight modification of the dispersion equations given in these works. The excitation theory of plasma-filled rectangular waveguides will be presented in a separate publication. In current studies the drift channel of the dielectric structure was filled with plasma of uniform density $n_p = 10^{10}$ cm^{-3}. For this plasma density, the thickness of the dielectric plates ensuring synchronism with the symmetric LSM wave mode was 8.182 mm. A sequence of 10 drive electron bunches with charges $Q = 2.6$ nC passed through the decelerating structure and excited the wake field.

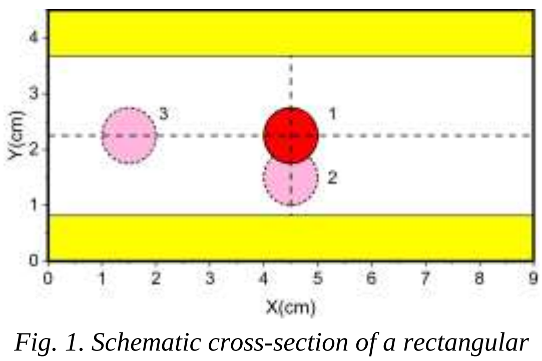

Fig. 1. Schematic cross-section of a rectangular dielectric waveguide. The yellow rectangles show the dielectric plates, the red circle 1 shows the electron bunch injected along the axis, pink circles 2 and 3 show bunches injected with a shift

After a certain time delay $t_{del} = 89.7$ ps, after the last drive bunch injection, a test electron bunch with a charge of 100 times smaller than has the drive bunch was injected into the system and was affected by the wake field created by the drive sequence. When the last drive bunch reached the output end of the structure (6.06 ns after the drive injection start), we stopped the calculations.

The initial bunches diameter was 1 cm, the pulse duration of the drive bunch was 44.83 ps, and that of the test bunch was twice longer. The pulse repetition period of the drive sequence was 0.3568 ns. The bunches energy was 4.5 MeV. The length of the system was 85.1 cm. We studied changes in the characteristics of both the driver sequence and the test bunch as a function of time when they were injected with a shift relative to the axis of the structure (Fig. 1). The initial displacement of both drive and test bunches was assumed to be the same. At that, the shift could be both in the direction perpendicular to the dielectric plate plane (see pink circle 2 in Fig. 1) and along the plate (see pink circle 3 in Fig. 1).

2. SIMULATION RESULTS USING 3D SELF-CONSISTENT PIC CODE

Fig. 2 shows the root-mean-square deviations of bunches particles (solid curve) from their average position (dashed line) during injection with a shift relative to the axis of the structure in the direction perpendicular to the plane of the dielectric plate (along the y coordinate) as a function of time. On the left of each row in Fig. 2, the coordinates of the initial bunches shift from the axis of the structure x_{shift} and y_{shift} are given. The left column of the graphs corresponds to the structure with plasma filling the drift channel. Right column correspond to the structure without plasma filling. The deviation of the test bunch is shown in red on the graphs. The deviations of the drive bunches are shown in other colors in accordance with the notations given to the left of the graphs. Dim colors show the regions that cover the particles of the drive bunch sequence and the test bunch during their motion. The upper row presents the case of axial injection $x_{shift} = 0$, $y_{shift} = 0$. The bottom row shows the case of the largest considered displacement of the bunches from the axis in the y-direction $x_{shift} = 0$, $y_{shift} = 0.75$ cm. Fig. 2 shows that the presence of plasma significantly affects the motion of bunches and leads to the focusing of the test bunches relative to the average position of its particles. Regarding bunches of the drive sequence, it should be noted that their defocusing is observed for most bunches in the presence of plasma, which even exceed the defocusing without plasma. But for some drive bunches, for example, for the 2nd and 6th, there is a tendency to focus. If for the test bunch the focusing effect was predictable due to a specially selected injection with a delay t_{del}, we did not pay attention to the focusing of the drive bunches sequence at small displacement values, because the drive bunches take on a pyriform shape: their front part is wider and the back is smaller than the original transverse size. At large shift value $y_{shift} = 0.75$ cm, the focusing of the bunches of the drive sequence becomes very asymmetric: a part of the defocusing bunches goes down to the dielectric plate and, in the end, the bunch particles begin to land on it, which is unacceptable.

In the absence of plasma in the drift channel, focusing of the test bunch is practically not observed. However, its defocus is also missing. In addition to this, the test bunch is shifted as a whole in the direction opposite to the initial shift, so there is a stabilization of the test bunch position relative to the axis. Bunches of the driver sequence are slightly defocused and additionally shifted as a whole in the direction of the initial shift. But this shift is small, and therefore, even with an unacceptable shift for a system filled with plasma ($y_{shift} = 0.75$ cm) in a vacuum system, the precipitation of drive bunch particles on the dielectric plates is not observed.

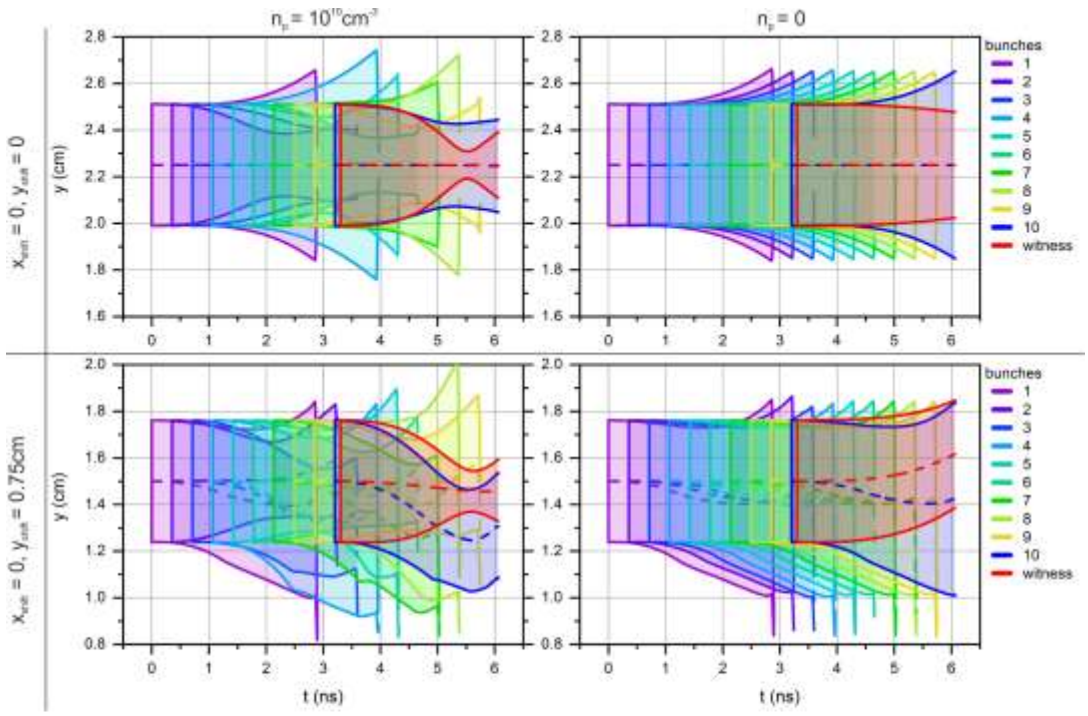

Fig. 2. Root-mean-square deviations of bunches particles from their mean position during off-axis injection in the direction perpendicular to the plane of the dielectric plate (along the y coordinate) as a function of time

Separately, it should be noted that the irregular peaks on the curves in Fig. 2, which correspond to the drive bunches sequence, are associated with the effects of the exit of deformed bunches from the system, that leads to sharp changes in the ordinates of the curves at shift values.

Fig. 3 shows the position of the test bunch electrons by red, and blue shows the position of the last drive bunch immediately before its exit from the waveguide when injected with a shift relative to the axis of the structure in the direction perpendicular to the plane of the dielectric plate in the YZ plane. The orange parallelepipeds show the position of the dielectric plate. Just as in Fig. 2, on the left for each row in Fig. 3 shows the coordinates of the initial displacement of the bunches from the axis of the structure.

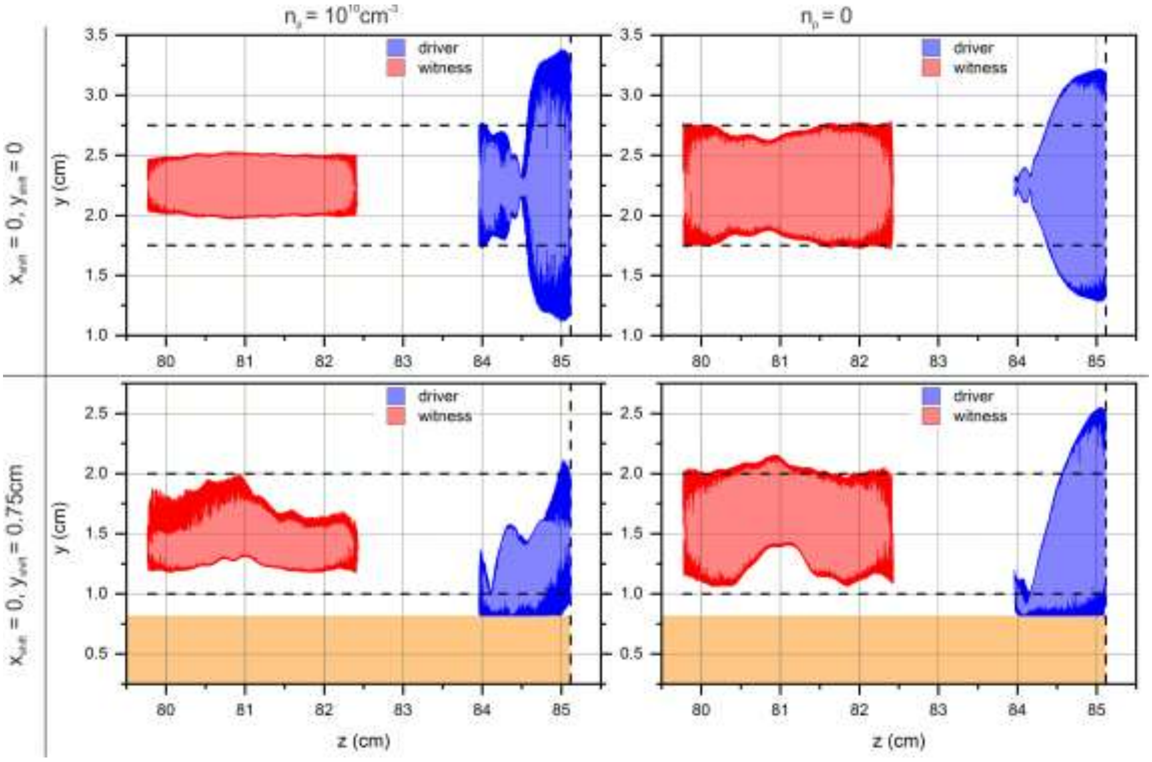

Fig. 3. The position of the electrons of the test and the last drive bunch just before exiting the waveguide in the YZ plane. The orange rectangles show the position of the dielectric plate

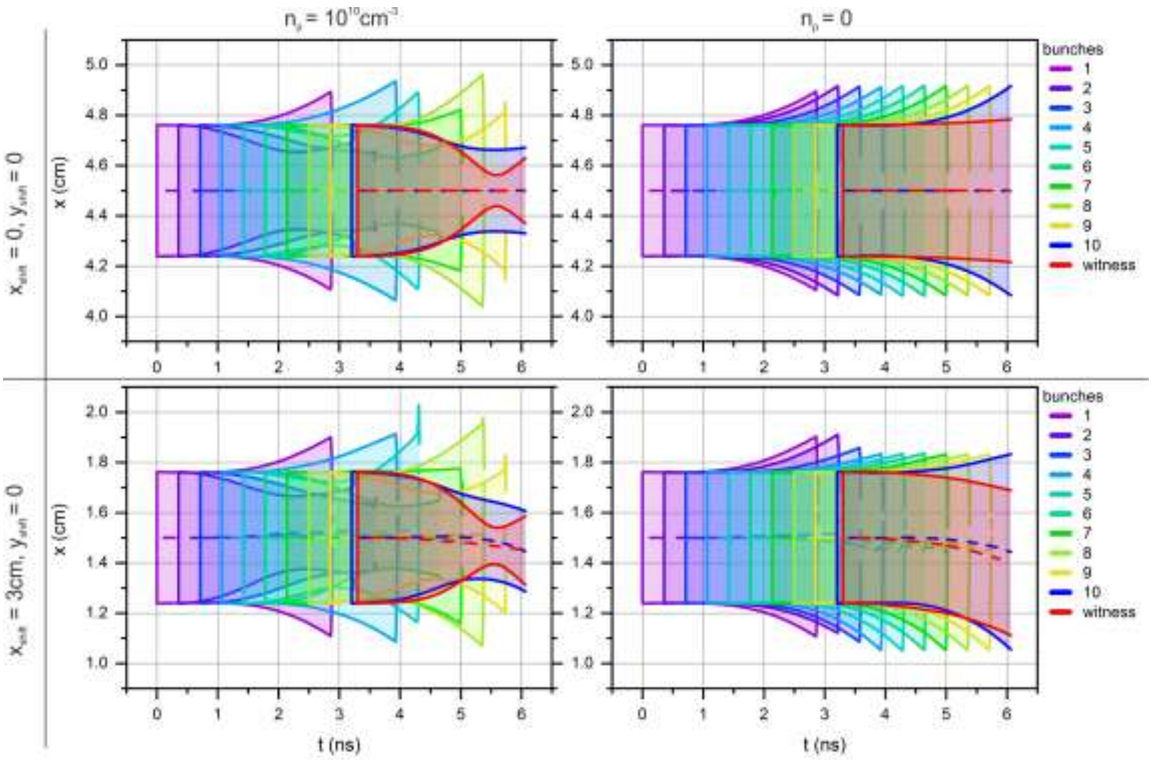

Fig. 4. Root-mean-square deviations of bunches particles from their mean position during off-axis injection in the direction along the dielectric plate (along the x coordinate) as a function of time

The left column of the graphs corresponds to the structure with plasma filling the drift channel, and the graphs in the right column correspond to the structure without plasma. Fig. 3 shows that the presence of plasma leads to focusing of the test bunch along its entire length and increased defocusing of the drive bunch.

In our analysis we found that drive bunch defocusing leads to the fact that in the presence of plasma already at the shift value of $y_{shift} \geq 0.25$ cm the drive bunch particles are deposited on the dielectric plate, which is not observed in the absence of plasma. Thus, if without plasma filling the shift from the axis to the dielectric plate can be in the $0 \geq y_{shift} \geq 0.3$ cm range, then in the presence of plasma the shift range should be twice less.

Fig. 4 shows the root-mean-square deviations of bunches particles (solid curves) from their average position (dashed lines) during injection with a shift along the plate (see pink circle 3 in Fig. 1) as a function of time. The upper row of Fig. 4 presents the case of axial injection $x_{shift} = 0$, $y_{shift} = 0$. The bottom row shows the case of the largest considered shift of the bunches from the axis in the x-direction, $x_{shift} = 3$ cm, $y_{shift} = 0$. In Fig. 4 in the same way as in Fig. 2, it can be seen that the presence of plasma significantly affects the motion of bunches and leads to the focusing of the test bunch relative to the average position of its particles.

Note that unlike the test bunch, which is focused along its entire length thanks to a specially chosen injection with a delay t_{del}, focusing of the drive sequence bunches is observed only for the rear part of the bunches, while the front initial part of them is defocused. However, the drive bunches defocusing for the x-shift direction is significantly less than for the y-direction. Therefore, the shift of bunches along the dielectric plates can be significantly greater than in the perpendicular direction.

In the absence of plasma in the drift channel, the test bunch does not change its size. However, it shifts as a whole in the direction of the original shift. In bunches of the drive sequence, the front part is defocused and the back one is focused. Additional displacements as a whole driver bunches practically do not have. Additional displacement of the test bunch in the shift direction and defocusing of the drive bunches lead to the fact that the permissible range of bunches shift along the dielectric plates in the vacuum structure should be somewhat smaller than in the plasma structure.

Fig. 5 shows the position of the electrons of the test bunch in red, and the last driver bunch in blue just before its exit from the waveguide when injected with a shift relative to the axis of the structure in the direction along the plane of the dielectric plate in the XZ plane. In the absence of plasma filling of the drift channel (right column of graphs), it can be seen that there is a weak defocusing of the test bunch and a rather strong defocusing (almost twice) of the drive bunch. In addition, during injection with a shift relative to the x axis, the test bunch is rotated so that its front part approaches the axis, and the back part, on the contrary, moves away from it to the waveguide boundary direction.

In the presence of plasma in the drift channel (left column of the graphs), it can be seen that the defocusing of the drive bunch is insignificantly greater than the defocusing in the absence of plasma. In contrast, the test bunch is focused along its entire length and rotates as a whole in the XZ plane just as it would in plasma absence. At the same time, the test bunch does not go beyond its initial size, indicated by horizontal dotted lines.

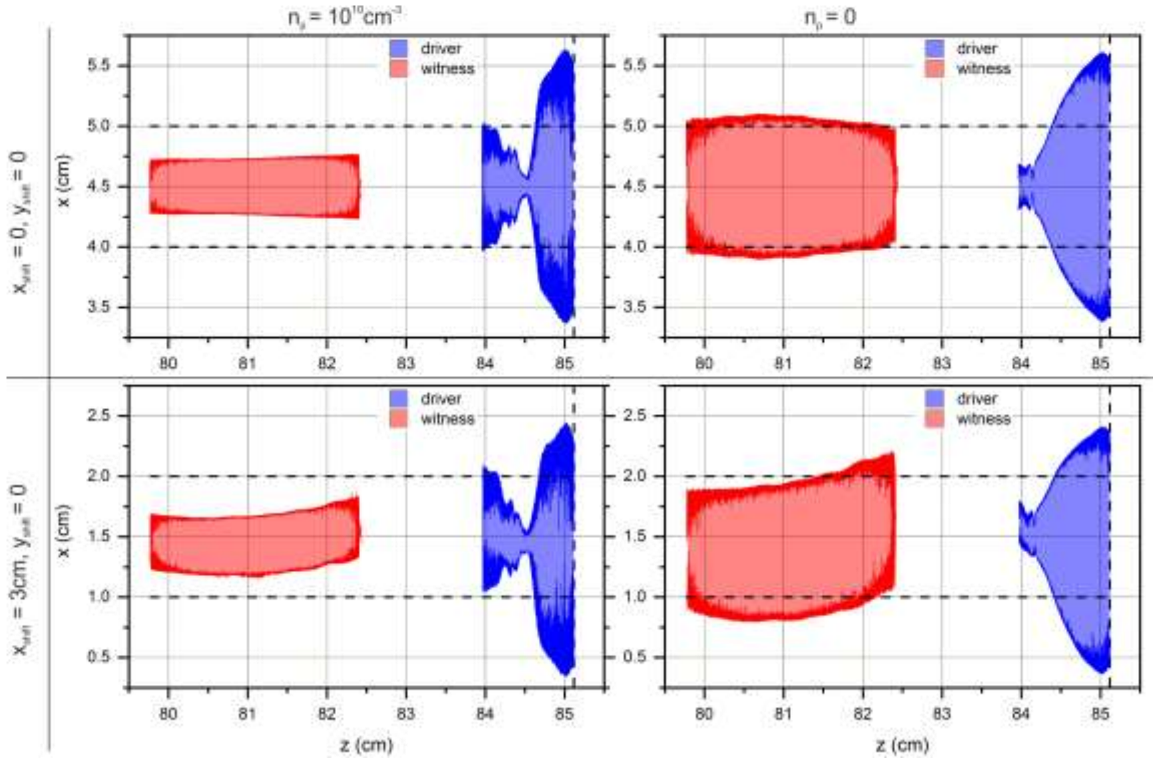

Fig. 5. Position of the electrons of the test and the last drive bunch just before exiting the waveguide in XZ plane

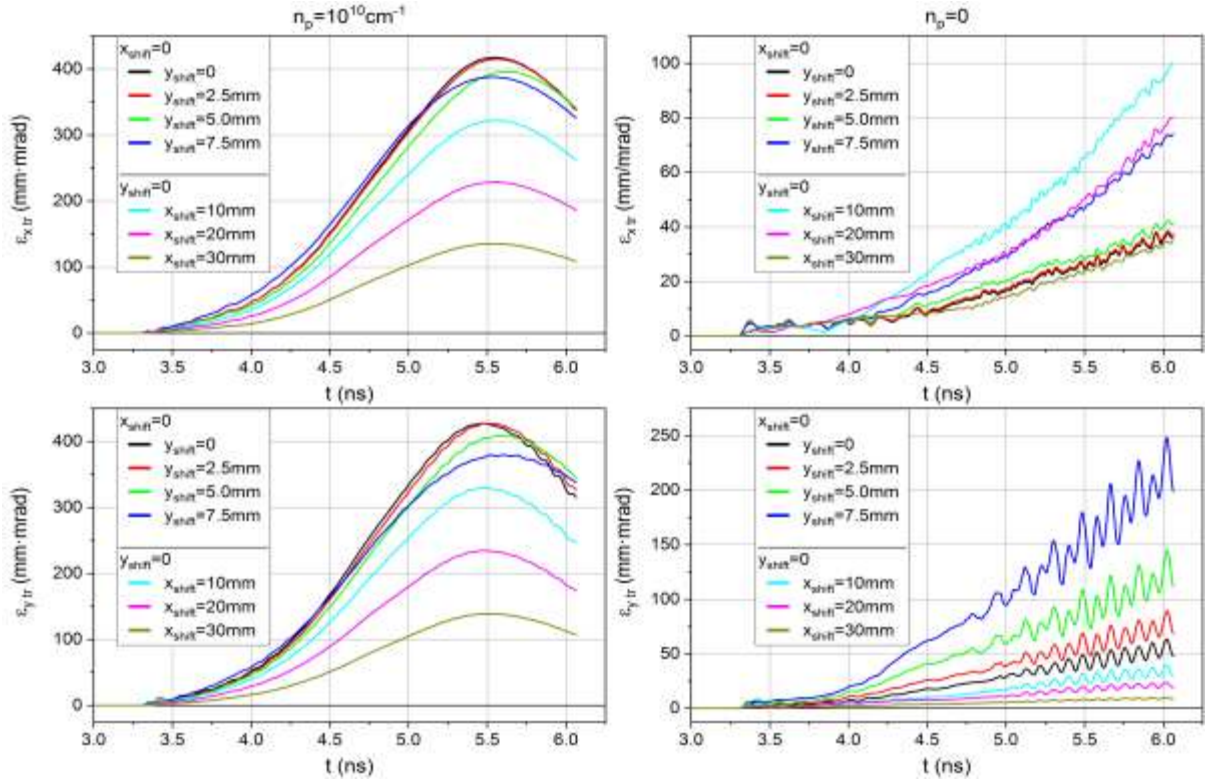

Fig. 6. The test bunch emittance during its acceleration after off-axis injection as a function of time

Despite the defocusing and rotation of the bunches, their electrons do not reach the conducting boundary of the waveguide at the considered values of the shift both in the case of the presence and absence of plasma in the drift channel.

Fig. 6 shows the evolution of the test bunch emittance during its acceleration during off-axes injection. To calculate the emittance, we used the following equations [22] (1) and (2):

$$\varepsilon_{x\,tr} = \sqrt{\langle x^2\rangle\langle (x')^2\rangle - \langle x\cdot x'\rangle^2}\,, \tag{1}$$

$$\varepsilon_{y\,tr} = \sqrt{\langle y^2\rangle\langle (y')^2\rangle - \langle y\cdot y'\rangle^2}\,, \tag{2}$$

where

$$\langle x^2\rangle = \sum_{i=1}^{N} q_i x_i^2 \Big/ Q,\ \langle x\cdot x'\rangle = \sum_{i=1}^{N} q_i x_i \left(v_{xi}/v_{zi}\right) \Big/ Q;$$

$$\langle (x')^2\rangle = \sum_{i=1}^{N} q_i \left(x_i'\right)^2 \Big/ Q = \sum_{i=1}^{N} q_i \left(v_{xi}/v_{zi}\right)^2 \Big/ Q;$$

$$\langle y^2\rangle = \sum_{i=1}^{N} q_i y_i^2 \Big/ Q,\ \langle y\cdot y'\rangle = \sum_{i=1}^{N} q_i y_i \left(v_{yi}/v_{zi}\right) \Big/ Q;$$

$$\langle (y')^2\rangle = \sum_{i=1}^{N} q_i \left(y_i'\right)^2 \Big/ Q = \sum_{i=1}^{N} q_i \left(v_{yi}/v_{zi}\right)^2 \Big/ Q,$$

q_i, x_i, y_i, v_{xi}, v_{yi}, v_{zi}, are charge; transverse coordinates x and y; transverse velocities along the x and y coordinates and longitudinal velocity of the macroparticle; Q is the total bunch charge; N is the number of macroparticles in the bunch.

The top row in Fig. 6 corresponds to emittances calculated by equation (1), and the lower one by equation (2).The left column of the graphs corresponds to the structure with plasma filling the drift channel. It can be seen that the emittance has rather great values, but it slightly decreases when the shift increases. The maxima on the emittance curves correspond to the largest test bunch focusing (see Figs. 2 and 4, left column). The right column of the graphs in Fig. 6 corresponds to the structure without plasma filling. In this case, the emittances are considerably lower than in the structure with plasma, but have significant fluctuations. Hence, the plasma performs the role of the emittance stabilizing, although it increases its value.

Energy spread in our simulations for unequally weighted macroparticles is computed using the next equation:

$$\sigma_\delta(\%RMS) = \left(\Delta E_{RMS}/\langle E\rangle\right)\cdot 100\,,$$

where

$$\Delta E_{RMS} = \sqrt{\langle E^2\rangle - \langle E\rangle^2},\ \langle E^2\rangle = \sum_{i=1}^{N} q_i E_i^2 \Big/ Q,$$

$$\langle E\rangle = \sum_{i=1}^{N} q_i E_i \Big/ Q,\ E_i = \gamma_i - 1,$$

γ_i is the relativistic factor of the macroparticle.

As can be seen in Fig. 7, the energy spread increases with shift y_{shift} increasing and also with filling the structure with plasma, but decreasing with x_{shift} increasing. So, if during axial injection the spread reaches 1.94 and 1.46, then at y_{shift} = 0.75 cm the spread will already be 2.36 and 1.73%, and then at x_{shift} = 3 cm the spread will be 0.61 and 0.55%, respectively for the structure with plasma filling and without plasma.

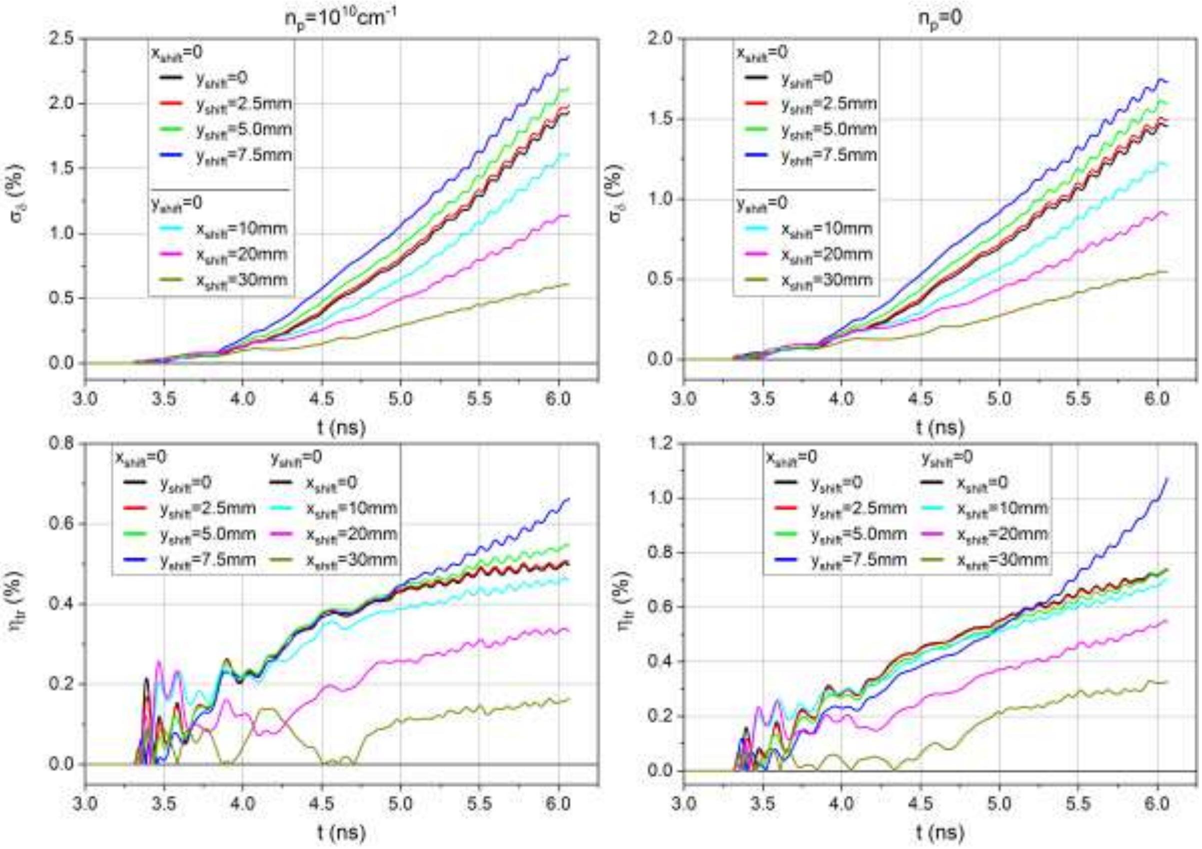

Fig. 7. The test bunch electrons energy spread and the efficiency of energy transfer to the test bunch from the driver sequence as a function of time

The following equation was used to calculate the energy transfer efficiency of the driver bunch to the test one:

$$\eta_{tr} = \left[\sum_{i=1}^{N_{ac}} m_i^{ac}\left(\gamma_i^{ac}-\gamma_{0i}^{ac}\right) \Big/ \sum_{i=1}^{N_{dr}} m_i^{dr}\left(\gamma_i^{dr}-\gamma_{0i}^{dr}\right)\right]\cdot 100,$$

where m_i^{ac} and m_i^{dr} are the masses of the macroparticles of the test and drive bunches; γ_i^{ac}, γ_i^{dr} are relativistic factors of macroparticles of the test and drive bunches; γ_{0i}^{ac}, γ_{0i}^{dr} are their initial values; N_{ac}, N_{dr} are the number of macroparticles in the test bunch and in the last bunch of the driver sequence that are in the system.

The energy transfer efficiency is shown in the bottom row of Fig. 7. During plasma filling (left graph), the energy transfer efficiency in the time interval 3.3–4.9 ns does not change much from the shift y_{shift}, but then the dependence of the injection of the test bunch and at 6.06 ns it reaches 0.74% with axial injection and 1.07% with shift $y_{shift} = 0.75$ cm and 0.16% with shift $x_{shift} = 3$ cm.

CONCLUSIONS

The results of numerical three-dimensional PIC modeling of the study of wake field excitation and self-consistent dynamics of charged particles injected with a shift relative to the axis into a three-zone rectangular dielectric-plasma accelerating structure is presented.

The carried out numerical simulation confirmed the predictions of the analytical theory [1], demonstrating the acceleration of the test electron bunch with its simultaneous focusing during the plasma filling the drift channel. This made it possible to inject bunches with shift without their charge loss on the dielectric or the metal surfaces. It is shown that, in the structure without plasma, there is no focusing of bunches as a whole, but non-axial injection of bunches is also permissible, although in a slightly smaller range of shifts.

The calculated parameters of bunches made it possible to estimate the limit values of the shift at which the electron bunches will not touch the dielectric plates and metal surfaces.

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REFERENCES

1. G.V. Sotnikov et al. Analytical and numerical studies of underdense and overdense regimes in plasma-dielectric wakefield accelerators // *Nucl. Instrum. Meth. in Physics Research A*. 2014, v. 740, p. 124-129.
2. G. Sotnikov et al. Excitation of wakefields by relativistic electron bunches in the dielectric waveguide filled with radially in-homogeneous plasma // *EPJ Web of Conferences*. 2017, v. 149, h. 02011.
3. G.V. Sotnikov et al. Focusing of Drive and Test Bunches in a Dielectric Waveguide Filled with Inhomogeneous Plasma // *Journal of Instrumentation*. 2020, v. 15, C09001.
4. A. Biagioni et al. Wake fields effects in dielectric capillary // *Nucl. Instrum. Meth. in Physics Research A.* 2018, v. 909, p. 247-251.

5. I.N. Onishchenko et al. Elaboration of Plasma-Dielectric Wakefield Accelerator // *Problems of Atomic Science and Technology. Series "Plasma Physics" (22).* 2016, N 6(106), p. 133-139.
6. K. Galaydych et al. Theory of wakefields excited by an off-axis drive bunch in a plasma-dielectric waveguide // *Nucl. Instrum. Meth. in Physics Research A.* 2022, v. 1034, p. 166766.
7. A. Tremaine et al. Electromagnetic wake fields and beam stability in slab-symmetric dielectric structures // *Phys. Rev. E.* 1997, v. 56, N 6, p. 7204-7216.
8. T.B. Zhang et al. Stimulated dielectric wake-field accelerator // *Phys. Rev. E.* 1997, v. 56, N 4, p. 4647-4655.
9. S.Y. Park et al. Theory for Wake Fields and Bunch Stability in Planar Dielectric Structures // *AIP Conference Proceedings.* 2002, v. 647(1), p. 527-541.
10. T.C. Marshall et al. Femtosecond planar electron beam source for micron-scale dielectric wakefield accelerator // *Phys. Rev. ST Accel. Beams.* 2001, v. 4, N 12, p. 121301(7).
11. T.C. Marshall et al. Wake fields excited in a micron-scale dielectric rectangular structure by a train of femtosecond bunches // *AIP Conference Proceedings.* 2002, v. 647(1), p. 361-370.
12. C. Wang et al. Strong wakefields generated by a train of femtosecond bunches in a planar dielectric microstrucrure // *Phys. Rev. ST Accel. Beams.* 2004, v. 7, N 5, p. 051301(11).
13. L. Xiao et al. Field analysis of dielectric-loaded recrtangular waveguide accelerating structure // *Phys. Rev. E.* 2001, v. 65, N 1, p. 016505(9).
14. G.V. Sotnikov et al. 3D analysis of wake field excitation in a dielectric loaded rectangular resonator // *AIP Conference Proceedings*. 2006, v. 877, p. 888-894.
15. C. Wang, J.L. Hirshfield. Theory for wakefields in a multizone dielectric lined waveguide // *Phys. Rev. ST Accel. and Beams.* 2006, v. 9, p. 031301.
16. G.V. Sotnikov et al. A five-zone two-channel dielectric wakefield structure for two beam acceleration experiments at Argonne national laboratory // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations".* 2008, N 3 (49), p.148-152.
17. I.N. Onishchenko et al. Concept of dielectric wakefield accelerator driven by a long sequence of electron bunches // *IPAC 2013: Proceedings of the 4th International Particle Accelerator Conference*. 2013, p. 1259-1261.
18. G.P. Berezina et al. Transformation ratio increase at wakefield excitation in the dielectric structure by a shaped sequence of relativistic electron bunches // *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations" (66).* 2016, N 3 (103), p. 69-73.
19. V. Kiselev et al. Dielectric wake-field generator // *BEAMS 1998 – Proceedings of the 12th International Conference on High-Power Particle Beams*, 2, art. No 816963, p. 756-759.
20. I.N. Onishchenko, G.V. Sotnikov. Synchronization of wakefield modes in the dielectric resonator // *Technical Physics*, 2008, v. 53, p. 1344-1349.
21. Ju.V. Egorov. *Chastichno zapolnennye volnovody*. Moskva: "Sovetskoe radio", 1967, 216 s. (in Russian).
22. K. Floettmann. Some basic features of the beam emittance // *Phys. Rev. ST Accel.* 2003, Beams 6, 034202;
https://link.aps.org/doi/10.1103/PhysRevSTAB.6.034202

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ДОСЛІДЖЕННЯ ПАРАМЕТРІВ ЕЛЕКТРОННИХ ЗГУСТКІВ ПРИ НЕОСЬОВІЙ ІНЖЕКЦІЇ У ТРЬОХЗОННУ ПРЯМОКУТНУ ДІЕЛЕКТРИЧНО-ПЛАЗМОВУ ПРИСКОРЮВАЛЬНУ СТРУКТУРУ

П.І. Марков, Р.Р. Князєв, Г.В. Сотніков

Подано результати чисельного тривимірного PIC-моделювання самоузгодженої динаміки неосьових заряджених частинок під впливом збудженого кільватерного поля в тризонній прямокутній діелектрично-плазмовій прискорювальній структурі, які показали можливість одночасного прискорення тестового електронного згустка та його фокусування, що дозволило транспортувати неосьові згустки. У вакуумній структурі фокусування згустка повністю відсутнє, але можливий стабільний транспорт згустка на кінцевій довжині системи, хоча і в дещо меншому діапазоні поперечних зсувів. Оцінено граничне значення допустимих зміщень згустків, які дозволяють пропускати згустки через резонатор скінченної довжини без втрат заряду на діелектричних або металевих поверхнях.