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# ACCELERATION AND FOCUSING OF POSITRON BUNCH BY ELECTRON BUNCH WAKEFIELD IN THE DIELECTRIC WAVEGUIDE FILLED WITH PLASMA

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*Abstract*

The results of numerical PIC-simulation of accelerated positron bunch focusing in the plasma dielectric wakefield accelerator are presented. The wakefield was excited by drive electron bunch in quartz dielectric tube, embedded in cylindrical metal waveguide. The internal area of dielectric tube has been filled with plasma different transverse density profiles, created in capillary discharge, with the vacuum channel along waveguide axis. Results of numerical PIC simulation have shown that it is possible a simultaneous acceleration and focusing of test positron bunch in the wakefield. The dependence of transport and acceleration of positron bunch on size of vacuum channel is studied.

## INTRODUCTION

The dielectric wakefield accelerator (DWA) is the promising applicant at construction electron-positron collider in TeV power range [1-5].

Despite the possibilities of obtaining high rates of wakefield acceleration shown theoretically and experimentally, one problem which is not solved completely remains. It consists in stabilization of the transverse motion of the drive and accelerated bunches and, thus, in receiving the accelerated particles bunches with small emittance. This DWA shortcoming can lead to beam breakup instability (BBU) [6].

To improve bunch transport and their stability we proposed to fill the drift channel of DWA with plasma of certain density [7-10] (PDWA). The reason of improvement of transverse stability consists in excitation in the drift channel of the plasma wave possessing the focusing properties [7, 8, 11, 12]. For improvement of transportation of the drive and accelerated bunches the vacuum channel in radially inhomogeneous plasma can be used [13].

Although the first analytical studies have shown the possibility of focusing accelerated positron bunches in PDWA [7, 8], a full numerical simulation, taking into account the self-consistent dynamics of the drive electron and accelerated positron bunches, taking into account the group velocity effects [14], has not yet been carried out.

It should be noted that transport of positron bunches remains a challenge in PWFA studies [15-17]. In the present work positron bunch acceleration by wakefield of drive electron bunch in PDWA and its focusing in radially inhomogeneous plasma with the vacuum channel is investigated.

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## PROBLEM DEFINITION

In our researches the dielectric tube with inner radius $a$ and outer $b$, inserted into cylindrical metal waveguide was used. The internal area of dielectric tube between radiuses $r_{p1}$ and $a$ was also filled by plasma. Thus, there was vacuum tube of radius $r_{p1}$ around the system axes.

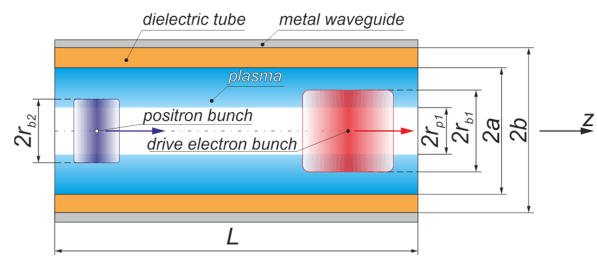


Figure 1: Schematic type of longitudinal section of the plasma dielectric wakefield accelerator of positrons.

The drive electron bunch of cylindrical form with radius $r_{b1}$ passed through the slowing-down structure along its axis and excited wakefield. Through certain delay time $\tau_{del}$ after the drive bunch the positron bunch with absolute value of charge by 60 times smaller, than at the drive was injected in system along its axis. Structure with the drive electron and witness positron bunch we call the plasma dielectric wakefield accelerator of positrons (PDWAP). The schematic type of PDWAP longitudinal section is shown in Fig. 1. Where the pink cylinder shows the drive electron bunch, the violet cylinder shows the positron bunch. With blue color the area filled with plasma, and orange the dielectric tube are depicted.

The parameters used in calculations are specified in Table 1.

For plasma density dependence on radius we use dependence received numerically by N. A. Bobrova *et al.* for the model of capillary discharge [18]. On vacuum-plasma border at $r = r_{p1}$ stepped $n_p(r)$ behaviour as functions of radius r was supposed (see Fig. 2), where $n_p(r)$ models for two cases are shown: the plasma cylinder which is completely filling the internal area of dielectric tube (dotted line) and the plasma cylinder with inner radius $r = 0.4$ mm (continuous curve).

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Table 1: Parameters of the Waveguide, Drive and Witness (Test) Bunches, Used in Calculations

| | |
|---|---|
| Inner radius of dielectric tube, *a* | 0.5 mm |
| Outer radius of dielectric tube, *b* | 0.6 mm |
| Inner radius of the plasma cylinder, $r_{p1}$ | 0÷0.5 mm |
| Waveguide length, *L* | 8÷24 mm |
| Dielectric permittivity, *ε* | 3.75 (quartz) |
| Energy of bunches, $E_0$ | 5 GeV |
| Drive electron bunch charge | –3 nC |
| Witness (test) positron bunch charge | 0.05 nC |
| Size of longitudinal root-mean-square deviation of drive bunch charge, 2*σ* (Gaussian charge distribution) | 0.1 mm |
| The full length of drive bunch used at PIC-simulation | 0.2 mm |
| Size of longitudinal root-mean-square deviation of witness (test) bunch charge | 0.05 mm |
| The full length of witness bunch | 0.1 mm |
| Drive electron bunch diameter, $2r_{b1}$ | 0.9 mm |
| Test positron bunch diameter, $2r_{b2}$ | 0.7 mm |
| Paraxial plasma density at $r_{p1} = 0$ | $2\times10^{14}$ cm$^{-3}$ |

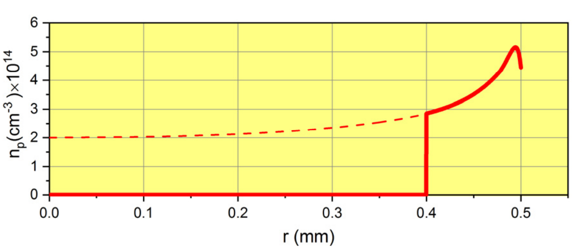


Figure 2: Models of plasma density dependence on radius.

## RESULTS OF 2.5-DIMENSIONAL PIC-SIMULATION

At numerical simulation by means of the 2.5D PIC code created by us we studied wakefield topography and dynamics of electron and positron bunches at their motion in the drift chamber. For each model of plasma density dependence on radius we investigated multiple choices with the different initial inner plasma cylinder radius $r_{p1}$ changing in the range from 0 to 0.5 mm.

In Fig. 3 snapshots of the Lorentz force components operating on test positron in PDWAP for $t = 26.69$ ps are shown for case $r_{p1} = 0$ (that is, for continuous filling the drift channel with plasma). The dotted line has shown the test bunch position. It can be seen that in the chosen position of the accelerated bunch it is possible to accelerate and focus the bunch simultaneously.

For illustration of influence of paraxial vacuum tube radius $r_{p1}$ on focusing and acceleration of test bunch in Fig. 4 has shown the phase space combined with dependences of longitudinal $F_z(z)$ and transverse forces $F_r(z)$ at $r =$ 0.35 mm for the same time as in Fig. 3 at different $r_{p1}$ values: a) $r_{p1} = 0.5$ mm, b) $r_{p1} = 0.35$ mm, c) $r_{p1} = 0.2$ mm and d) $r_{p1} = 0$.

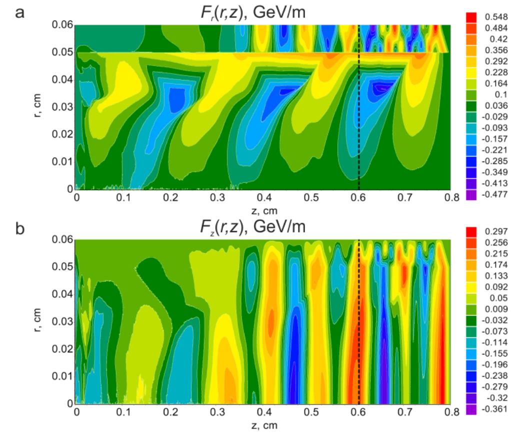


Figure 3: Color maps and level lines for transverse $F_r(r,z)$ (above, a) and longitudinal $F_z(r,z)$ (below, b) component of Lorentz force, acting on test positron.

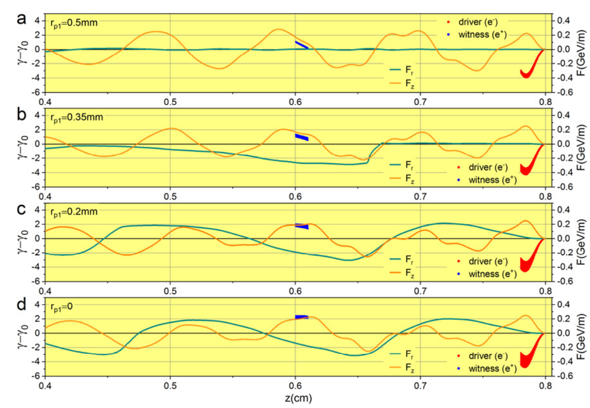


Figure 4: Phase space energy – longitudinal coordinate, combined with dependences of longitudinal and transverse forces for different $r_{p1}$ values and also energy change of the accelerated and drive bunches.

The test bunch delay $\tau_{del} = 6.34$ ps was chosen such as to provide the bunch acceleration in the third local maximum of the longitudinal force $F_z$. For the cases b), c) and d) this delay also provided the transverse focusing by the transverse force $F_r$. This time was chosen basing on the simulation of the wakefield excitation at the absence of a test bunch (unloaded field) in the case of a channel completely filled with plasma and was the same for all cases.

Let's notice that case a) corresponds to plasma absence in the drift channel, and case d) corresponds to its full filling with plasma. By blue color energy of the accelerated positron bunch, by red color energy of drive electron bunch are shown.

As appears from the graphs on Fig. 4a) for lack of plasma in the drift channel the transverse force $F_r$ does not arise. Thereof there is no focusing of test bunch also.

When $r_{p1} = 0.35$ mm (case b) the negative transverse force $F_r$ focusing the positron bunch is the greatest. When $r_{p1} = 0.2$ mm and $r_{p1} = 0$ (cases c and d) the negative transverse force value is slightly less than in case b. Hence

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the best focusing of positron bunch must observe in the case when $r_{p1} = 0.35$ mm.

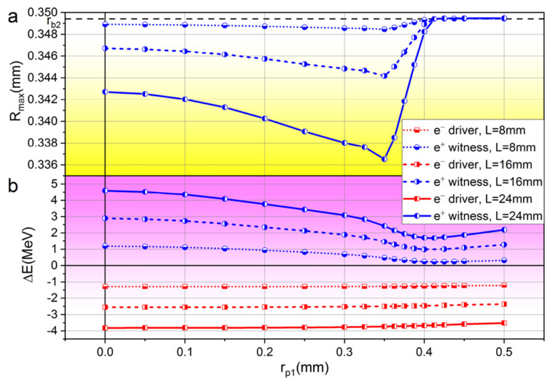

Figure 5: a) Bunch radius $R_{max}$ of test positron bunch and b) its energy gain $\Delta E$ and energy loss of drive electron bunch versus the radius of the vacuum channel $r_{p1}$.

The behavior of the radii of the drive and accelerated bunches $R_{max}$ with variation of the vacuum channel radius $r_{p1}$ from 0 to 0.5 mm for different waveguide lengths $L$: 8 mm, 16 mm and 24 mm at the times $t$: 26.69 ps, 53.38 ps and 80.07 ps (every time corresponds the time when the drive bunch has reached the structure end), respectively is shown in Fig. 5a) (above). As appears from the curves shown in Fig. 5a) at $r_{p1}$ increase from 0 to 0.35 mm causes the improvement in the test bunch focusing, whereas with a further increase in $r_{p1}$ up to 0.415 mm the focusing becomes worse. When $r_{p1} > 0.415$ mm and test bunch moves in the vacuum channel, i.e. when the plasma tube is outside of test bunches, focusing is absent.

Figure 5b) (below) shows the energy gain of test bunch (blue curves) and energy loss of drive bunch (red curves) versus the radius $r_{p1}$ of the vacuum channel for the same lengths and times as in Fig. 5a). With $r_{p1}$ increase the test bunch energy decrease that is connected with bunch drift out from the optimum phase of the longitudinal accelerating force $F_z$ (see Fig. 4).

To explain the behavior of the transverse size of the test bunch, shown in Fig. 5a), let us analyze the behavior of the plasma electrons in the drift channel. Figures 6a) and 6c) show the plasma electron densities $n_{pe}(r,z)$ for the time $t = 26.69$ ps at $r_{p1} = 0$ and $r_{p1} = 0.35$ mm, accordingly. Figures 6b) and 6d) depict the corresponding plasma ion densities $n_{pi}(r,z)$.

As it appears from the plots in Fig. 6, the drive bunch electrons push out the plasma electrons to the periphery of the drift channel. As a consequence, the excess of plasma ions is formed behind the drive bunch. These ions attract the plasma electrons pushed out by the drive, and the last ones turn to the waveguide axis. Here it should be noted that the plasma ion density during the delay time of the test bunch $\tau_{del} = 6.34$ ps remains practically the same.

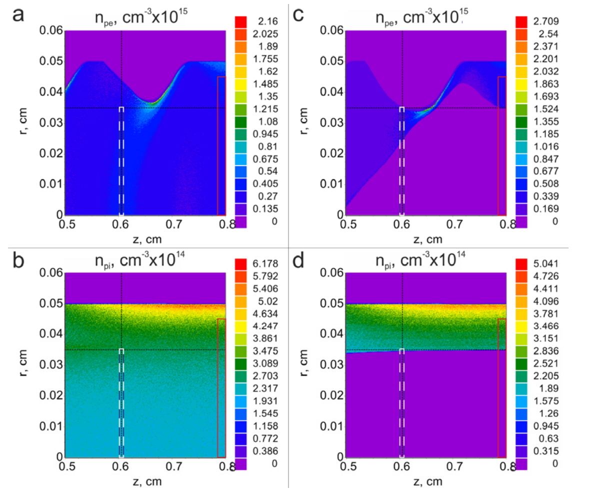

Figure 6: Plasma electrons density (above) and plasma ion density (below) for $r_{p1} = 0$ (a) (at the left) and $r_{p1} = 0.35$ mm (on the right). The red and blue-white rectangles show positions of drive and test bunches.

The above described processes lead to the formation of the region with an excess plasma electrons density where the test positron bunch is present. Surplus of electrons pulls positrons in the axis direction. In addition to this the plasma ion excess located over positron bunch push positrons in the same direction. It leads to test bunch focusing. In the case of full plasma filling of the drift channel, at $r_{p1} = 0$ (see Figs. 6a) and 6b)) the excess plasma electron density is partially compensated by ions that leads to weakening of focusing.

## CONCLUSION

Results of numerical PIC-simulation research of wakefield excitation and self-consistent dynamics of the charged particles in the plasma-dielectric cylindrical slowing-down structure of terahertz frequency range for model of the plasma received as a result of capillary discharge with a nonuniform transverse profile in waveguide are provided.

The carried-out numerical simulation has confirmed predictions of the analytical theory, having shown acceleration of test positron bunch with its simultaneous focusing.

It is shown that the vacuum channel in the plasma improves focusing of the accelerated positron bunch. There exists the optimum vacuum channel radius. When the plasma tube surrounds test positron bunch focusing quickly decreases with growth of the vacuum channel radius.

The best acceleration of the test bunch happens in case when plasma completely fills the drift channel, however at that there is not the most optimum test positron bunch focusing.

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## REFERENCES

[1] W. Gai, "Advanced accelerating structures and their interaction with electron beams", *AIP Conf. Proc.*, vol. 1086, pp. 3-11, 2009. doi:10.1063/1.3080940

[2] Eric R. Colby, "Present limits and future prospect for dielectric acceleration", in *Proc. of 35th Int. Conf. on high energy physics*, Paris, France, 2010.

[3] W. Gai *et al.*, "Experimental demonstration of dielectric structure based two beam acceleration", *AIP Conf. Proc.*, vol. 569, pp. 287-293, 2001. doi:10.1063/1.1384360

[4] M. C. Thompson *et al.*, "Breakdown limits on gigavolt-per-meter electron-beam-driven wakefields in dielectric structures", *Phys. Rev. Lett.* vol. 100, p. 214801, 2019. doi:10.1103/PhysRevLett.100.214801

[5] W. Gai, J. G. Power, and C. Jing, "Short-pulse dielectric two-beam acceleration", *J. Plasma Physics,* vol. 78, p. 339, Apr. 2012. doi:10.1017/S0022377812000037

[6] C. Li, W. Gai, C. Jing, J. G. Power, C. X. Tang, and A. Zholents, "High gradient limits due to single bunch beam breakup in a collinear dielectric wakefield accelerator", *Phys. Rev. ST Accel. Beams*, vol. 17, p. 091302, 2014. doi:10.1103/PhysRevSTAB.17.091302

[7] R. R. Kniaziev *et al.*, "Focusing of electron and positron bunches in plasma-dielectric wakefield accelerators", *Problems of Atomic Science and Technology. Series "Plasma electronics and new acceleration techniques",* vol. 4, no. 86, p. 84, 2013.

[8] G. V. Sotnikov *et al.*, "Analytical and numerical studies of underdense and overdense regimes in plasma-dielectric wakefield accelerators", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* vol. 740, p. 124, 2014. doi:10.1016/j.nima.2013.10.087

[9] P.I. Markov *et al.*, "Focusing of electron bunches in the plasma-dielectric rectangular slowing-down structure", *Problems of Atomic Science and Technology. Series "Nuclear Physics Investigations"*, vol. 3, no. 103, p. 57, 2016.

[10] R. R. Kniaziev and G. V. Sotnikov, "Influence of emittance on transverse dynamics of accelerated bunches in the plasma–dielectric wakefield accelerator*", Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* vol. 829, p. 121, 2016. doi:10.1016/j.nima.2016.03.097

[11] A. Biagioni *et al.*, "Wake fields effects in dielectric capillary", *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment,* vol. 909, p. 247, 2018. doi:10.1016/j.nima.2018.01.028

[12] R. Pompili *et al.*, "Plasma lens-based beam extraction and removal system for plasma wakefield acceleration experiments", *Phys. Rev. ST Accel. Beams*, vol. 22, p. 121302, 2019. doi:10.1103/PhysRevAccelBeams.22.121302

[13] G. V. Sotnikov, P. I. Markov, and I. N. Onishchenko, "Focusing of drive and test bunches in a dielectric waveguide filled with inhomogeneous plasma", *Journal of Instrumentation*, vol. 15, no. 09, p. C09001, 2020. doi:10.1088/1748-0221/15/09/C09001

[14] V. A. Balakirev *et al.*, "Excitation of a wake field by a relativistic electron bunch in a semi-infinite dielectric waveguide", *Journal of Experimental and Theoretical Physics*, vol. 93, p. 33, 2001. doi:10.1134/1.1391517

[15] V. Lebedev *et al.*, "Efficiency versus instability in plasma accelerators", *Phys. Rev. ST Accel. Beams,* vol. 20, p. 121301, 2017. doi:10.1103/PhysRevAccelBeams.20.121301

[16] S. Diederichs *et al.*, "Positron transport and acceleration in beam-driven plasma wakefield accelerators using plasma columns", *Phys. Rev. ST Accel. Beams,* vol. 22, p. 081301, 2019. doi:10.1103/PhysRevAccelBeams.22.081301

[17] S. Diederichs *et al.*, "High-quality positron acceleration in beam-driven plasma accelerators", *Phys. Rev. ST Accel. Beams*, vol. 23, p. 121301, 2020. doi:10.1103/PhysRevAccelBeams.23.121301

[18] N. A. Bobrova *et al.*, "Simulations of a hydrogen-filled capillary discharge waveguide", *Phys. Rev. E*, vol. 65, p. 016407, 2001. doi:10.1103/PhysRevE.65.016407