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

G. V. Sotnikov†, R. R. Kniaziev, P. I. Markov
National Science Center, Kharkov Institute of Physics and Technology, Kharkov, Ukraine

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.

† sotnikov@kipt.kharkov.ua
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tbody>
<tr>
<td>Inner radius of dielectric tube, (a)</td>
<td>0.5 mm</td>
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<tr>
<td>Outer radius of dielectric tube, (b)</td>
<td>0.6 mm</td>
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<tr>
<td>Inner radius of the plasma cylinder, (r_{p1})</td>
<td>0.5 mm to 0.5 mm</td>
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<tr>
<td>Waveguide length, (L)</td>
<td>8±24 mm</td>
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<tr>
<td>Dielectric permittivity, (\varepsilon)</td>
<td>3.75 (quartz)</td>
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<tr>
<td>Energy of bunches, (E_0)</td>
<td>5 GeV</td>
</tr>
<tr>
<td>Drive electron bunch charge</td>
<td>(-3) nC</td>
</tr>
<tr>
<td>Witness (test) positron bunch charge</td>
<td>0.05 nC</td>
</tr>
<tr>
<td>Size of longitudinal root-mean-square deviation of drive bunch charge, (2\sigma) (Gaussian charge distribution)</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>The full length of drive bunch used at PIC-simulation</td>
<td>0.2 mm</td>
</tr>
<tr>
<td>Size of longitudinal root-mean-square deviation of witness (test) bunch charge</td>
<td>0.05 mm</td>
</tr>
<tr>
<td>The full length of witness bunch</td>
<td>0.1 mm</td>
</tr>
<tr>
<td>Drive electron bunch diameter, (2r_{b})</td>
<td>0.9 mm</td>
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<tr>
<td>Test positron bunch diameter, (2r_{p2})</td>
<td>0.7 mm</td>
</tr>
<tr>
<td>Paraxial plasma density at (r_{p1} = 0)</td>
<td>(2 \times 10^{14}) cm(^{-3})</td>
</tr>
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**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 \(F_z(r, z)\) and transverse forces \(F_r(r, z)\) 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) \(r_{p1} = 0\).

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

**Figure 5:** a) Bunch radius \( R_{\text{max}} \) 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 \( R_{\text{max}} \) 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 \( n_{p1}(r, z) \) 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 \( n_{i1}(r, z) \).

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 \( \tau_{\text{def}} = 6.34 \) 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 wake-field 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.

**ACKNOWLEDGEMENTS**

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REFERENCES


