EXCITATION OF THE FOCUSING WAKEFIELDS BY A RELATIVISTIC BUNCH IN ISOTROPIC CAPILLARY DISCHARGE PLASMA*

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Abstract

The present paper offers research of wake waves by the relativistic electron bunch in the capillary tube filled with plasma. Analytical expressions for the electromagnetic field component with approaching “hard” bunches have been obtained. Numerical calculations of the appearing fields for capillary tubes samples have been made. The transversal and axial structure of wake fields in the slowing structure with plasma in the transport channel has been researched in detail. The regimes in which focusing of the accelerated bunch is clearly seen have been studied. The results of numeric PIC modeling of fields in the structure under consideration have been provided.

INTRODUCTION

One of the promising ways of accelerating by wake fields excited by relativistic electron bunches uses plasma, created by the same bunches [2] or by external sources, as the slowing medium [1]. The capillary discharge can be used as an external source [3, 4]. The capillary tube is the slowing structure, therefore eigen waves of dielectric structure, modified by the presence of plasma in the transport channel, as well as plasma waves are excited in the tube channel when electron bunches are travelling in it. Below we research the influence of electrodynamic properties of the capillary tubes material on wake waves excitation.

NUMERICAL CALCULATIONS

For the cylinder all-over bunch having the radius r_b and the length L_b, and with homogeneously distributed density of particles:

$$n(r_0, t_0) = \frac{Q/e}{\pi L_b r_b^2}\left[\Theta(t_0) - \Theta(t_0 - L_b / v_0)\right]\Theta(r_b - r) \ , \qquad (1)$$

where Q is bunch charge, -e is electron charge.

Final expressions for the wake field components were presented in the paper [5]. Here are the results of the wake field calculations. For our calculations we choose the dielectric waveguide with dimensions presented in the Table 1, with the dielectric tube made of fused silica. In the same table electron bunch parameters are given. Plasma parameters are given in Table 2. The results of calculations for plasma with such parameters are shown in Figures 1-2.

Table 1: Dielectric structure (Fused silica).

Parameter	Value
Outer radius of dielectric tube	0.6 mm
Inner radius of dielectric tube	0.5 mm
Relative dielectric constant, ε	3.75
Bunch energy	5 GeV
Bunch charge	3 nC
Bunch length L_b (box charge distribution)	0.2 mm
Bunch radius r_b (box charge distribution)	0.45 mm
Density of drive bunch electrons, n_b	$1.47\cdot10^{14}$ cm^{-3}
Vacuum wavelength of 1st radial mode of the vacuum DWA	~1 mm
Vacuum wavelength of 2nd radial mode	~0.3 mm
Vacuum wavelength of 3rd radial mode	~0.16 mm

Table 2: Parameters of the plasma

Plasma density	$4.41\cdot10^{14}$ cm^{-3}
Plasma wavelength	1.59 mm
Radius of plasma	0.5 mm

Fig.1 shows axial distribution of the axial force, acting on the probing particle. It follows from the dependence, given in Fig. 1, that we can ensure acceleration of charged particles with their simultaneous radial focusing by placing the testing bunch at some distance from the drive bunch head. As it can be seen in the Figure, the radial force almost harmoniously depends on the axial coordinate with the period of approximately 0.16 cm, i.e. the Langmuir wave makes the greatest contribution into the radial force. At the same time, its contribution into the axial force, accelerating test particles, is predominantly small. The axial force is predominantly determined by the eigen modes of the dielectric waveguide; its complex behavior from the axial coordinate is caused by excitation several radial modes of the dielectric waveguide. For the used in analytical calculations parameters of the dielectric waveguide, bunch and plasma, the focusing force amplitude is approx. 300MeV/m, which equals the focusing magnetic field induction ~1T.

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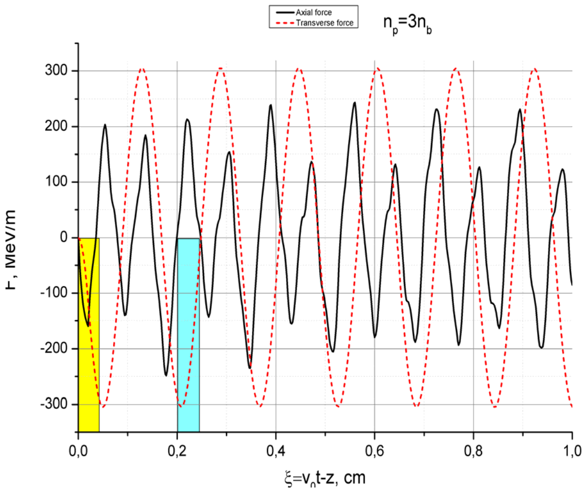

Fig.1: Analytical code. Plasma-filled transport channel, plasma density $n_p = 3n_b$. Axial profile of the axial force (black line) and axial profile of transverse force (red line) at the distance r = 0.45 mm from waveguide axis. Drive bunch (yellow rectangular) moves from right to left. Cyan rectangular shows possible location of test (accelerating) bunch.

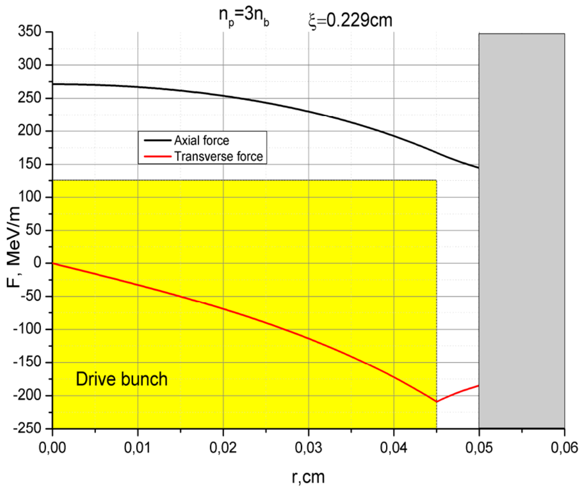

Fig. 2: Analytical code. Plasma-filled transport channel, plasma density $n_p = 3n_b$. Transverse profile of the longitudinal (black line) and transverse forces (red line), acting on a test particle, located at a distance of 0.23 cm from the head of the drive bunch.

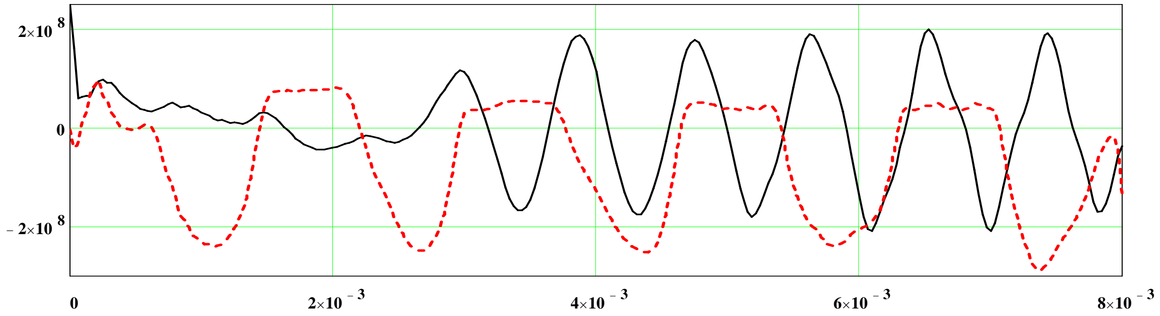

Fig.3: OOPIC simulations of plasma-filled transport channel, plasma density $n_p = 3n_b$. Axial profile of the axial force (black line) and axial profile of transverse force (red line) at the distance r=0.45mm from waveguide axis. Drive bunch (yellow rectangular) moves from left to right, travel time t=26.7psec. Distance (x-axis) is measured in m, forces (y-axis) are in eV/m.

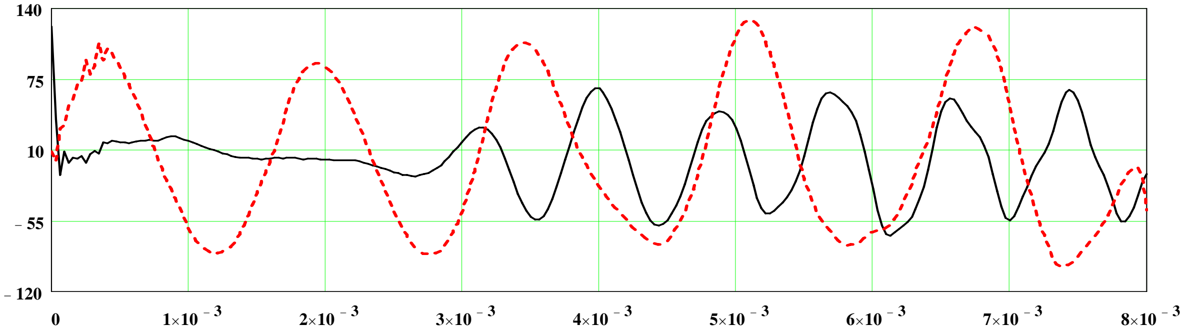

Fig.4: OOPIC simulations of plasma-filled transport channel. Drive bunch charge is 1nC. Axial profile of the axial force (black line) and axial profile of transverse force (red line) at the distance r=0.45mm from waveguide axis. Drive bunch (yellow rectangular) moves from left to right, travel time t=26.7psec. Distance (x-axis) is measured in m, forces (y-axis) are in MeV/m.

Fig. 2 shows the radial dependence of axial and transverse forces, acting on the test particle, placed in the first of the maximums of the accelerating field, at the distance of 0.23 cm behind the drive bunch head. The axial force changes insufficiently in the transport channel

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cross section, while the radial force remains focusing along all the channel section.

The results, presented in Fig. 1-2, obtained through analytical expressions [5], are true for the approximation of linear plasma $n_b \gg n_p$ (overdense regime). Another extreme case $n_b \ll n_p$ (underdense or blowout regime), with a focusing provided by plasma ions, remaining in the transport channel after plasma ions have been pushed out of it by the intense drive bunch. In order to verify the analytical theory applicability [6], we have made full numeric simulation of wake fields excitation in the plasma dielectric structure under investigation. For calculations we used both our own PIC code and OOPIC code realized for Linux [7]. The results of modeling, made with both codes, coincide well.

Fig. 3 shows the results of the numeric modeling with the use of OOPIC code of wake fields behavior in the slowing environment. Comparison of the curves in Fig.3 with corresponding curves in Fig. 1 confirms acceptable coincidence of the results of PIC modeling at self-consistent account of the plasma dynamics and analytical results. The accelerating and focusing fields coincide quite well. The greatest difference is observed in defocusing areas of the wake field. This difference can be explained for by the pushing out of plasma electrons to the dielectric surface and the appearance of the local under dense plasma area. This explanation is confirmed by the results of the OOPIC modeling for the bunch with the charge decreased by 3 times, with the plasma electrons loss being much smaller. Fig. 4 shows axial distribution of the accelerating and focusing forces for the drive bunch with the charge 1nC. As it followed from Fig. 4. we observe a more exact correspondence with the analytical calculations (taking into account the normalization for the bunch charge), given in Fig.1.

CONCLUSIONS

Research of wake fields excited by the electron bunch in the plasma dielectric waveguide shows that filling up of the dielectric waveguide vacuum transport channel with isotropic plasma of a definite density results in the set up of the focusing wake field which accelerates a witness bunch. The uncovered mechanism of the test bunch focusing in terms of plasma density as well as other parameters of the dielectric waveguide has been optimized. Optimal regimes for the accelerated bunch focusing in the drive bunch wake fields have been found. The results obtained at complete numeric modeling with taking into account a non-linear plasma particles dynamics coincide accurately enough with the theoretical calculations in a definite range of the plasma density and the drive bunch density ratio.

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