NOVEL AND ADVANCED ACCELERATION TECHNIQUES

FOCUSING OF ELECTRON BUNCHES IN THE PLASMA-DIELECTRIC RECTANGULAR SLOWING-DOWN STRUCTURE

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Results of analytical and numerical researches of excitation of wakefield and dynamics of the charged particles in the plasma-dielectric rectangular slowing-down structure are provided. Based on that the analytics in linear approach for overdense plasma shows that at the certain density of plasma the superposition of plasma and dielectric waves allows to accelerate test bunch with its simultaneous focusing, we have made simulation by the "particle in cell" method of excitation of wakefield for several cases with different plasma density. The carried-out numerical modeling has confirmed predictions of the analytical theory, having shown an acceleration of test bunch with its simultaneous focusing.

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INTRODUCTION

Acceleration of charged particles by wakefields excited by relativistic electron bunches in dielectric structures is an actively developing direction for new methods of acceleration [1, 2]. The experimental research carried out, at ANL and SLAC, confirmed [3, 4] the suitability of this method of acceleration of charged particles. The dielectric wakefield accelerator is now considered to be a promising candidate for future electron-positron colliders in the TeV energy range [5].

Despite, as shown theoretically and experimentally, possibilities of obtaining a high acceleration rates, one problem that is not solved completely remains – difficulties with stabilization of the transverse motion of the drive and accelerated bunches and thereby obtaining accelerated bunches of particles with a small emittance. In this article the possibility of using plasma filling the drift channel of a dielectric structure is considered for this purpose. Such plasma can be created as a result of a capillary discharge in a dielectric tube [6]. The use of plasma for focusing an accelerated bunch is not a new proposition. The focusing properties of plasma were investigated in PWFA both in the linear condition [7, 8] and in a non-linear regime [9, 10]. But in the linear condition the peak of an accelerating field corresponds to zero focusing field, and in the non-linear regime the region of acceleration is localized only near a drive bunch because of plasma destruction caused by a nonlinear plasma wave.

In order to avoid these restrictions using a plasma-dielectric structure was proposed [11, 12]. As we will demonstrate below, this idea has shown acceleration of test bunch with its simultaneous focusing.

Historically the majority of researches on wakefields in dielectric structures are carried out for cylindrical configurations. Recently considerable interest is shown to planar and rectangular configurations of dielectric structures. It is caused by the following advantages of such structures [13]:

- simplicity of production;
- easy tuning of operating frequency by means of adjustment of metal walls of wave guide, free from dielectric;
- for given frequency and acceleration voltage they can accumulate more energy, than cylindrical configurations that leads to decreasing of beam loading;
- additional internal focusing − structure of the transverse forces operating on electron beam is similar available at quadrupole focusing;
- the possibility of implementation of multimode operation of excitation leading to significant increase in wakefield amplitude.

STATEMENT OF THE PROBLEM

Rectangular dielectric waveguide under investigation represents the metal waveguide having the cross sizes $a\times b$ with two dielectric slabs (dielectric permittivity is equal to ε), covering opposite wide walls of a waveguide (Fig. 1).

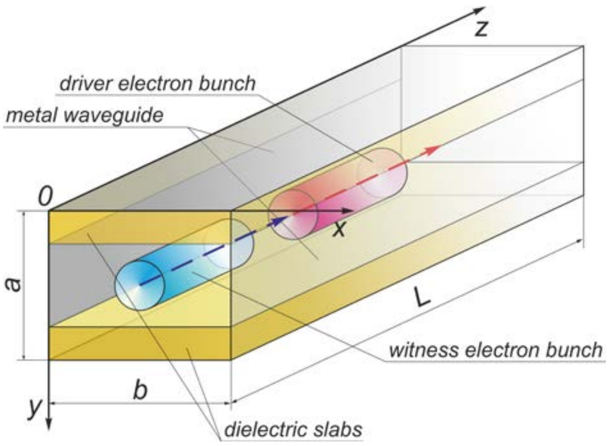

Fig. 1. Schematic view of a rectangular dielectric waveguide. Yellow bricks show dielectric slabs, pink cylinder shows driver electron bunch and blue cylinder shows witness bunch

The drift channel of dielectric structure is filled with plasma.

The driver electron bunch, passes through the axis of slowing-down structure and excites wakefield.

In certain delay time t_{del} after the driver bunch the witness bunch is injected in system and gets under influence of wakefield of the driver.

Parameters of driver bunch at numerical simulation have been chosen such, as in the experimental installation "Almaz-2".

Dielectric slab dimensions for given bunches and waveguide were calculated using theory of excitation of multizone dielectric waveguides [14, 15], this consideration was expounded in ref. [16]. In Table parameters used in calculation are given.

Parameters used in calculation

Waveguide	R32				
Dimensions (a×b), mm	34.04×72.14				
Operating frequency, GHz	5.594				
Slab dimensions (are located along wide wall of a waveguide), mm	5.7×72.14				
Waveguide length L, cm	99.26				
Relative dielectric constant ε (quartz)	3.8				
Bunch energy E_0, MeV	4.5				
Driver bunch charge, nC	0.26				
Witness bunch charge, nC	0.026				
Driver and witness bunch diameter, mm	10.0				
Driver and witness bunch axial RMS dimension 2σ (Gaussian charge distribution), mm	17.0				
Drive and witness full bunch length used in PIC simulation, mm	34.0				
Plasma density n_p, ×10^9cm^{-3}	2.5	5	10	15	20
Delay time t_{del} of witness bunch, ns	0.623	0.462	0.266	0.266	0.266

GENERALITIES

The Lorentz force $\mathbf{F}=\left(F_x, F_y, F_z\right)$ affecting on the electron moving with initial relativistic speed $\mathbf{v}=\mathbf{v}_0=v_{z0}\cdot\vec{k}$ in external electric $\mathbf{E}=\left(E_x, E_y, E_z\right)$ and magnetic fields for case of non-magnetic dielectric has form:

$$\begin{aligned} F_x &= -|e|\cdot\left(E_x-\beta_0\cdot H_y\right); \\ F_y &= -|e|\cdot\left(E_y+\beta_0\cdot H_x\right); \\ F_z &= -|e|\cdot E_z, \end{aligned} \qquad (1)$$

where $\beta_0=v_{z0}/c$, e is electron charge, c is light speed in vacuum, H_x, H_y are components of magnetic field strength.

For the electrons injected with energy $E_0=4.5$ MeV $\beta_0=0.9948$ and force (1) is completely defined by dependence of fields on coordinates and time as change of electrons speed is negligible.

Focusing of bunch is provided by cross force components F_x and F_y, while, acceleration carries out longitudinal force component F_z.

It is expected that when filling the drift channel of rectangular dielectric waveguide with plasma, similar to the cylindrical configuration [11, 12], transverse components of fields obtain certain axial profiles that allows choosing such arrangement of the witness bunch in relation to the driver when transverse forces will squeeze the witness, while longitudinal force will accelerate it.

RESULTS OF 3D-PIC CODE SIMULATION

During numerical simulation using our 3D-PIC code we analyzed wakefield configuration and dynamics of electron bunches at their motion in the drift chamber. Several numerical experiments for the different plasma density n_p have been made.

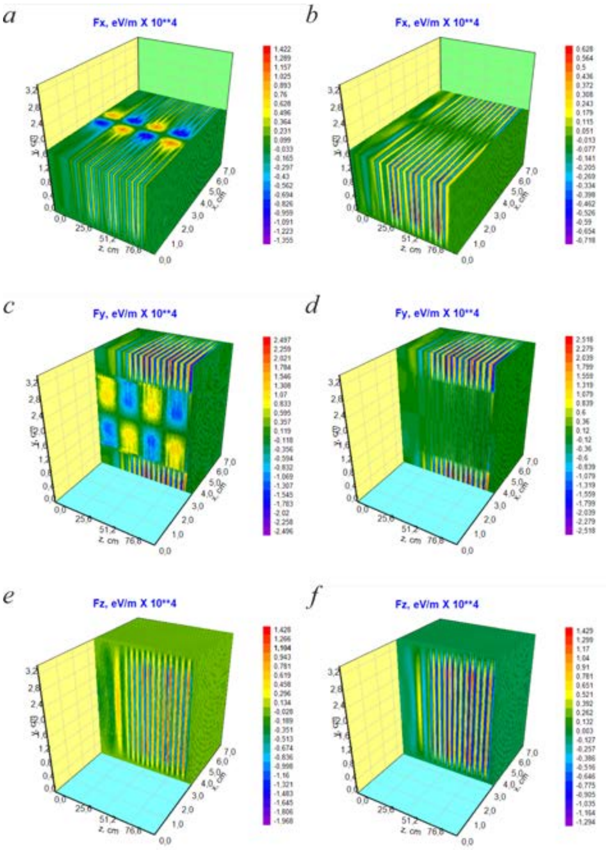

Fig. 2. Snapshots of Lorentz force components for time point 3.2 ns: a, b – cross F_x in the midplane of waveguide $y=a/2=1.702$ cm; c, d – cross F_y in the midplane of waveguide $x=b/2=3.607$ cm; e, f – longitudinal F_z in the midplane of waveguide $x=b/2=3.607$ cm. Plasma density in pictures: a, c, e – $n_p=5\cdot10^9\,\text{cm}^{-3}$; b, d, f – $n_p=0$

In Fig. 2 comparative snapshots of Lorentz force components for time point 3.2 ns for dielectric waveguide with plasma filling of the drift channel, $n_p=5\cdot10^9\,\text{cm}^{-3}$ (see Fig. 2,a,c,e) and without plasma (Fig. 2,b,d,f) are shown.

Comparing transverse components of force F_x in Fig. 2,a and Fig. 2,b, and also F_y in Fig. 2,c and Fig. 2,d, we see that in the system filled with plasma in the area of location of electron bunches there are strong forces affecting on the witness bunch and focusing it. In waveguide without plasma filling transverse forces are concentrated mainly on the structure periphery where bunches are not present. Therefore in dielectric waveguide without plasma focusing of bunches is practically absent.

For the explanation of the mechanism of focusing in Fig. 3 are shown the configuration space combined with dependences of longitudinal F_z and transverse forces F_y, F_x, and also cross profile of bunches for $n_p = 5\cdot10^9\,\text{cm}^{-3}$ ($n_b/n_p = 0.21$). Plasma (Langmuir) frequency is $f_p = 0.635\,\text{GHz}$.

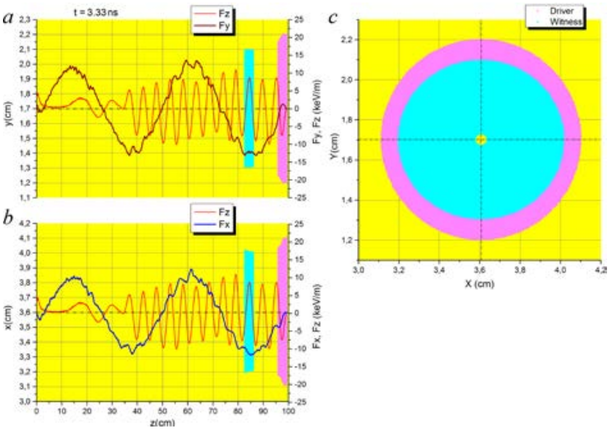

Fig. 3. The configuration space combined with dependences of longitudinal $F_z(z)$ and transverse forces $F_y(z)$, $F_x(z)$, and also cross profile of bunches for $n_p = 5\cdot10^9\,cm^{-3}$

The field $F_z(z)$ was measured on bunch axis ($x = 3.607\,\text{cm}$, $y = 1.702\,\text{cm}$), field $F_y(z)$ – along the upper edge of bunch ($x = 3.607\,\text{cm}$, $y = 2.202\,\text{cm}$), and field $F_x(z)$ – along the right edge of bunch ($x = 4.107\,\text{cm}$, $y = 1.702\,\text{cm}$).

The witness is injected in system through delay time $t_{del} = 0.4623\,\text{ns}$ after injection of the driver. One can see in Fig. 3, that this provides synchronization of witness with the accelerating and focusing wakefield phases: the witness bunch is in positive phase of longitudinal force F_z and in negative phase of transverse forces F_y and F_x. The cross profile of bunches shows that at the exit end of waveguide focusing of the witness occurs on azimuth. Its diameter decreases to 8.75 mm, i.e. by 1.143 times from initial diameter 10 mm.

In Fig. 4,a the phase plane energy vs. longitudinal coordinate combined with dependence of longitudinal force $F_z(z)$ is depicted. In Fig. 4,b distribution function of electrons of the driver and witness bunches on energy is shown at that initial bunch energy is $E_0 = 4.5\,\text{MeV}$.

As appears from the schedules provided in Fig. 4, electrons of the driver bunch, exciting wakefield, are slowed down while electrons of the witness bunch are accelerated in this field.

Thus, as it is possible to see in Figs. 3 and 4, we succeed to focus the witness bunch and to accelerate it at the same time.

At changing of plasma density the behavior of system will not change essentially. However, as the plasma frequency defining the period of the transverse focusing forces changes it is necessary to correct delay time t_{del} so that not to leave acceleration phase, remaining at the same time in focusing phase of the witness bunch.

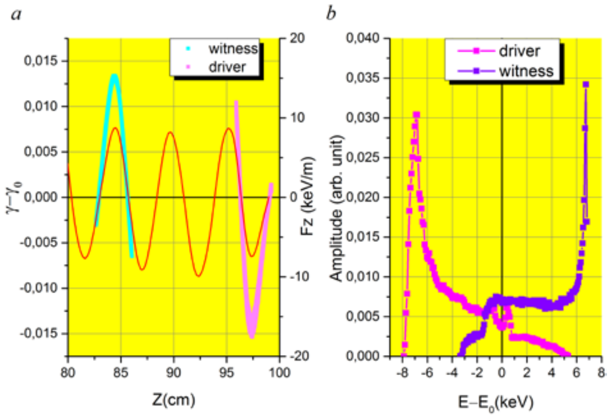

Fig. 4. The phase plane energy vs. longitudinal coordinate combined with dependence of longitudinal force $F_z(z)$ (a); distribution function of electrons of the driver and witness bunches on energy, $E_0 = 4.5\,MeV$ (b)

At further increase in plasma density up to $n_p = 2\cdot10^{10}\,\text{cm}^{-3}$ in behavior of system it is not observed any basic changes. Only increases the transverse focusing forces and, respectively, focusing of the witness bunch improves. In Fig. 5 influence of change of plasma density on focusing of the witness bunch is shown.

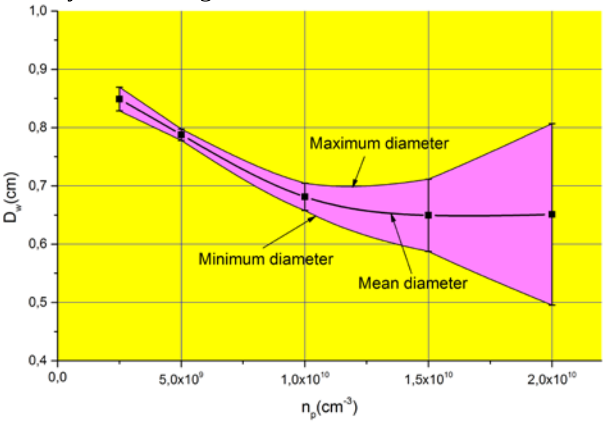

Fig. 5. Diameter of the witness bunch depending on plasma density. Measurements of diameter were taken in time 3.2 ns when the driver bunch appears at the waveguide exit

Nonmonotonic variation of diameter of the witness bunch at changing of plasma density which is visible in Fig. 5 explains Fig. 6. Here configuration spaces combined with dependences of longitudinal F_z and transverse F_y forces for different plasma density are shown. At the high plasma density $n_p = 2\cdot10^{10}\,\text{cm}^{-3}$ the phase of maximum of the accelerating longitudinal force F_z does not match minimum of the focusing transverse force F_y. Therefore, placing the witness bunch in phase of the best acceleration, we receive different extent of focusing for the "head" and "tail" of bunch. Approximately trapezoid profile of longitudinal section of the witness bunch as it is possible to see it in Fig. 6,e is consequence of it. At the plasma density $n_p = 1.5\cdot10^{10}\,\mathrm{cm}^{-3}$ phasing between maximum of the accelerating force F_z and minimum of the focusing force F_y improves that leads to reduction of distortion of axial profile of the witness bunch (see Fig. 6,d). At $n_p = 10^{10}\,\mathrm{cm}^{-3}$ variation of diameter at the beginning and the end of the witness bunch there is even less (see Fig. 6,c). The best phasing between maximum of the accelerating force F_z and minimum of the focusing force F_y in the studied system is achieved at the plasma density $n_p = 5\cdot10^{9}\,\mathrm{cm}^{-3}$. Thus the distortion of axial profile of the witness bunch is minimal (see Fig. 6,b). In Fig. 6,a the case of the smallest plasma density investigated by us is shown $n_p = 2.5\cdot10^{9}\,\mathrm{cm}^{-3}$. At such density of plasma the witness bunch starts bringing distortions in configuration of transverse components of electromagnetic fields and, therefore, in distribution of the transverse focusing forces F_x and F_y. It leads to that, despite good phasing between the accelerating and focusing, a distortion of axial profile of witness bunch increases.

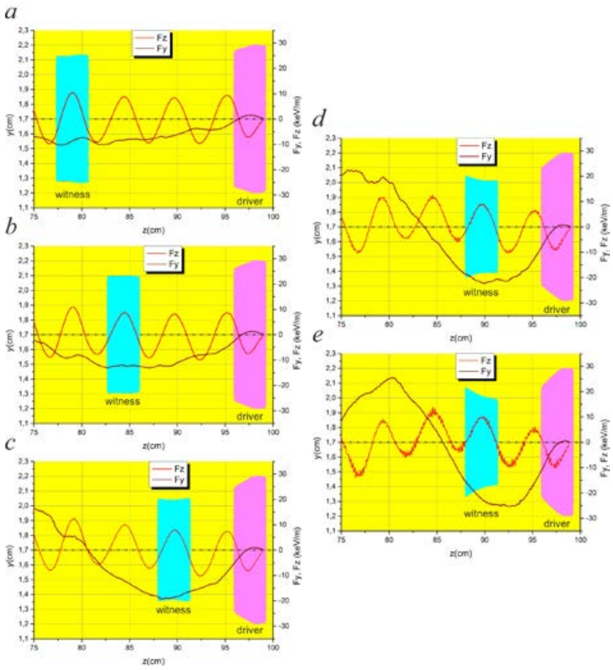

Fig. 6. The configuration space combined with dependences of longitudinal $F_z(z)$ and transverse $F_y(z)$ forces for different plasma densities: $a - n_p = 2.5\cdot10^{9}\,\mathrm{cm}^{-3}$; $b - n_p = 5\cdot10^{9}\,\mathrm{cm}^{-3}$; $c - n_p = 10^{10}\,\mathrm{cm}^{-3}$; $d - n_p = 1.5\cdot10^{10}\,\mathrm{cm}^{-3}$; $e - n_p = 2\cdot10^{10}\,\mathrm{cm}^{-3}$

For increasing of amplitude of the accelerating field it is possible to increase charge of driver bunch, or to use periodic sequence of driver bunches with repetition rate multiple to the operating frequency of dielectric waveguide. In the experimental installation “Almaz-2” the second way is used. In this connection it’s interesting to trace configuration of bunches at their passing through the drift chamber in presence and absence of plasma filling the drift channel.

In Fig. 7 the configuration space, combined with dependences of longitudinal $F_z(z)$ and transverse forces $F_y(z)$ and $F_x(z)$ at injection of bunch sequence with repetition rate of 2.8047 GHz is shown. This frequency is equal the half of eigen frequency of vacuum dielectric waveguide. Plots at the left in Fig. 7 correspond to case of plasma density $n_p = 1\cdot10^{10}\,\mathrm{cm}^{-3}$. Right plots are obtained for the vacuum case $n_p = 0$. The observation time in Fig. 7 is 5.4 ns. At this moment the 16th bunch starts entering the resonator.

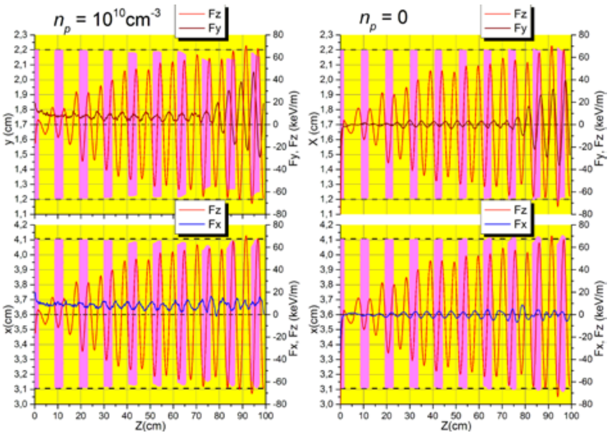

Fig. 7. Configuration space, combined with dependences of longitudinal $F_z(z)$ and transverse forces $F_y(z)$ and $F_x(z)$ at injection of sequence of bunches. $n_p = 1\cdot10^{10}\,\mathrm{cm}^{-3}$ (at the left) and $n_p = 0$ (at the right)

One can see from the Fig. 7 that in the second half of the resonator, at $z > 60$ cm bunches on plots at the left have the smaller cross size, than on plots at the right that testifies to focusing of sequence of driver bunches in plasma filled system.

CONCLUSIONS

The carried-out numerical simulation has confirmed predictions of the analytical theory, having shown acceleration of test bunch with its simultaneous focusing in rectangular dielectric waveguide with plasma filling of the drift channel. This behavior of witness bunch is similar the same focusing in cylindrical plasma dielectric wakefield structure.

Focusing of the witness bunch happens uniformly on azimuthal angles.

With increasing of plasma density the focusing increases.

Filling of the drift channel with plasma promotes focusing of periodic sequence of driver bunches.

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ФОКУСИРОВКА ЭЛЕКТРОННЫХ СГУСТКОВ В ПЛАЗМЕННО-ДИЭЛЕКТРИЧЕСКОЙ ПРЯМОУГОЛЬНОЙ ЗАМЕДЛЯЮЩЕЙ СТРУКТУРЕ

П.И. Марков, Р.Р. Князев, И.Н. Онищенко, Г.В. Сотников

Представлены результаты численных исследований возбуждения кильватерных полей и динамики заряженных частиц в плазменно-диэлектрической прямоугольной замедляющей структуре. Основываясь на том, что аналитика в линейном приближении для сверхплотной плазмы показывает, что при определенной плотности плазмы суперпозиция плазменной и диэлектрической волн позволяет ускорять тестовый сгусток с его одновременной фокусировкой, мы выполнили моделирование методом “частица в ячейке” возбуждения кильватерных полей для нескольких случаев с разной плотностью плазмы. Проведенное численное моделирование подтвердило предсказания аналитической теории, продемонстрировав ускорение тестового сгустка с одновременной его фокусировкой.

ФОКУСУВАННЯ ЕЛЕКТРОННИХ ЗГУСТКІВ У ПЛАЗМОВО-ДІЕЛЕКТРИЧНІЙ ПРЯМОКУТНІЙ СПОВІЛЬНЮВАЛЬНІЙ СТРУКТУРІ

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

Представлено результати чисельних досліджень збудження кільватерних полів і динаміки заряджених часток у плазмово-діелектричній прямокутній сповільнюваній структурі. Ґрунтуючись на тому, що аналітика в лінійному наближенні для надщільної плазми показує, що при певній щільності плазми суперпозиція плазмової й діелектричної хвиль дозволяє прискорювати тестовий згусток з його одночасним фокусуванням, ми виконали моделювання методом “частинка у гнізді” збудження кільватерних полів для декількох випадків з різною щільністю плазми. Проведене чисельне моделювання підтвердило пророкування аналітичної теорії, продемонструвавши прискорення тестового згустка з одночасним його фокусуванням.