ELECTRON ACCELERATION BY WAKEFIELDS OF A SEQUENCE OF BUNCHES IN DIELECTRIC RESONATOR

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The excitation of wakefields by a train of relativistic electron bunches in a cylindrical waveguide, being partially filled with a dielectric, is considered. The finite length of the waveguide along the longitudinal direction is taken into account by the introduction of the wake field trailing edge, which propagates with the velocity equal to the group velocity of the resonance wave. The numerical simulation of the self-consistent dynamics of particles bunches and of the electron acceleration in wake fields is carried out.

PACS: 41.60.-m

I. INTRODUCTION

Recently a lot of papers in which it is proposed to use intensive wakefields excited by charged bunches in a dielectric waveguide for acceleration of charged particles [1,2] has appeared. Alongside with theoretical works experimental researches [3,4] were carried out. The wakefield amplitude is proportional to a charge of an exciting bunch**.** As the obtaining of ultrarelativistic guiding electron bunches with a high charge density is connected to the considerable technical difficulties, one proposed to use a coherent addition of fields of a sequence of relativistic bunches with a rather small charge for excitation of intensive wakefields [4,5].

II. THE FIELD OF UNIFORMLY PROPAGATING BEAM

For problems concerning the excitation of wakefields by the sequence of relativistic bunches in the dielectric waveguide the following target setting is characteristic. The round metal waveguide of a radius b, filled with material having a dielectric permeability ε is considered. Along the axis of a waveguide there is the vacuum drift channel of a radius a**.** In the channel one or several charged bunches go with velocity v_b=const, duration t_b and periodicity T_b ($T_b = f_{mod}^{-1}$, f_{mod} is the frequency of the sequence of bunches). As a rule, in theoretical works the waveguide, infinite along the axis z [1] is considered. The effects connected to the finite length of the system, are shown only for the case of full numerical modelling [2]. The expressions for a field in the waveguide, infinite along the axis, have the following property [1]. In any section of the waveguide, after passing the bunch through it, wakefield oscillations will exist indefinitely for a long time (if to neglect an attenuation). According to these expressions, the wakefield excited by the sequence of bunches in some section of the waveguide, will be proportional to the number of bunches moving through this section. Hence, using a great number of bunches it is possible to obtain corresponding high values of the intensity of an accelerating field. In reality the waveguide has a finite length and the above model is inapplicable.

In works [6,7] the problem of charged bunch injection into the semi-infinite (z>0) waveguide with continuous dielectric filling has been solved. Such statement of a problem is the first approach of the description of a waveguide of a finite length without reflections on the ends (for example if the output end of a waveguide is connected to the ideally matched loading). It has been shown, that the wakefield of the separate bunch has a back front which goes after this bunch with the velocity equal to the group velocity of a resonant wave. Also there is a transition radiation, therefore, the back front of wakefield waves is smoothed out and dispersed. Presence of a moving back front of the field leads to that in any section of a waveguide, after the bunch is propagated through it, the fluctuations excited by it soon will disappear even without taking into account the attenuation.

We believe, that in a dielectric waveguide of a finite length with the vacuum drift channel the wakefield distribution occurs in a similar way, but we shall neglect transitive radiation. Therefore the area of existence of each harmonic with the number s wakefields from the separate bunch will be $z_{gr,s}<z<(t-t_0)v_b$, where $z_{gr,s}=(t-t_0)v_{gr,s}$ is the position of the back front, $v_{gr,s}$ is the group velocity of a resonant harmonic with the number s, t_0 is the moment a bunch injection into the system. The structure of the field (1) is determined as a summation of the infinite number of radial harmonics (the sum on s), and the summation on bunches (the sum on i). In case of a rectangular structure of charge density within the limits of the separate bunch, the resulting field of the sequence N of bunches in the vacuum channel looks like:

$$E_z(r,z,t) = -\frac{8Q_b v_b^2 \gamma_b}{r_b l_b a^2}\sum_{s=1}^{\infty}\frac{I_1(k_{vs}r_b)I_0(k_{vs}r)}{\omega_s^2 I_0^2(k_{vs}a)G_s}\sum_{i=1}^{N}\varphi_{is}(t,z),$$

$$\varphi_{is}(t,z) = \left\{\theta\left[t - T_b(i-1) - \frac{z}{v_b}\right] - \theta\left[t - T_b(i-1) - \frac{z}{v_{gr,s}}\right]\right\} \times \sin\{\omega_s[t - T_b(i-1) - z/v_b]\}$$

$$-\left\{\theta\left[t - t_b - T_b(i-1) - \frac{z}{v_b}\right] - \theta\left[t - t_b - T_b(i-1) - \frac{z}{v_{gr,s}}\right]\right\} \times \sin\{\omega_s[t - t_b - T_b(i-1) - z/v_b]\}$$

$$+\left\{\theta\left[t - T_b(i-1) - \frac{z}{v_{gr,s}}\right] - \theta\left[t - t_b - T_b(i-1) - \frac{z}{v_{gr,s}}\right]\right\} \times \sin[\omega_s z(v_{gr,s}^{-1} - v_b^{-1})],$$

where: Q_b is the bunch charge, γ_b is the relativistic factor, $\theta(x)=1$ for $x>0$ and $\theta(x)=0$ for $x\le 0$, $k_{vs}=\omega_s/(v_b\gamma_b)$, ω_s is the resonance frequency that is determined from the equation

$$\varepsilon k_{vs}\frac{B}{A}-k_{ds}\frac{I_1(k_{vs}a)}{I_0(k_{vs}a)}=0,\ k_{ds}=\frac{\omega_s}{v_b}\left(\frac{\varepsilon v_b^2}{c^2}-1\right)^{\frac{1}{2}},$$

$$G_s=\varepsilon-1-\frac{4\varepsilon}{\pi^2 k_{ds}^2 a^2 A^2}+\varepsilon\frac{B^2}{A^2}+\frac{I_1^2(k_{vs}a)}{I_0^2(k_{vs}a)},$$

$$A=J_0(k_{ds}a)N_0(k_{ds}b)-J_0(k_{ds}b)N_0(k_{ds}a),$$

$$B=J_1(k_{ds}a)N_0(k_{ds}b)-J_0(k_{ds}b)N_1(k_{ds}a).$$

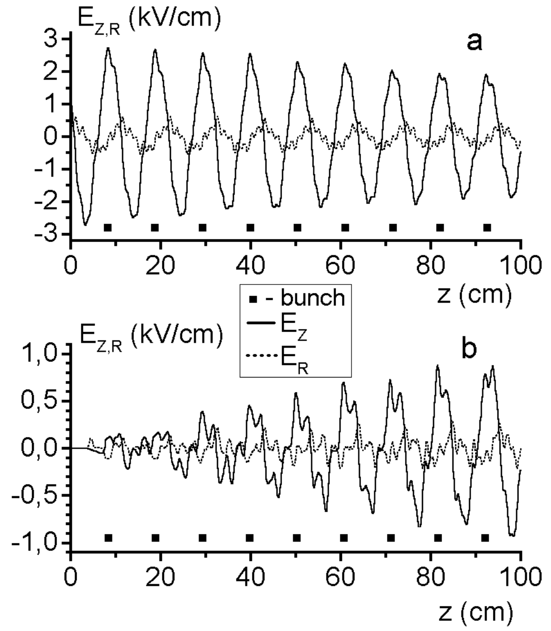

Fig.1. Wakefields from the train of 28 bunches. (a) no the trailing edge, (b) with the trailing edge. The leftmost square corresponds to the last bunch t=10ns, r=0.5cm

For all subsequent numerical calculations we have chosen parameters of a waveguide and the sequence of bunches close to parameters of the experiment on wakefield acceleration carried out in the KIPT [4]: a=1.05 cm, b=4.23 cm, ε=2.1, Q_b=0.32 nC, and the following bunch parameters: energy =2 MeV, length l_b=1.7 cm, radius r_b=0.5 cm. In Fig.1 the fields calculated at the length of 100 cm for the infinite waveguide (Fig.1,a) and semi-infinite one (Fig.1,b) are given. We neglect the effect of the group velocity that leads to the essential overestimation of the excited field intensity and to the qualitatively different longitudinal amplitude distribution of an accelerating field. The field amplitude is linearly growing along the system, the maximum value that is reached near the output end does not depend on the number of bunches passing through the system. A limiting number of the bunches giving the contribution to the amplitude of a field at the system end is equal to

$$N_{\max}\approx l_{sys}(v_b-v_{gr})/l_{\text{mod}}v_{gr}+1,$$

where l_{sys} is the waveguide length, l_{mod} is the spatial period of the sequence of bunches.

III. SIMULATION OF SELF-CONSISTENT EXCITATION AND ACCELERATION

The dimensionless equations of movement of an electron ring in Lagrangian coordinates in a field of the E-wave look like:

$$\frac{dt_L}{dz}=\frac{1}{v_{zL}},\ \frac{dr_L}{dz}=\frac{v_{rL}}{v_{zL}},$$

$$\frac{dv_{rL}}{dz}=\frac{-e}{mv_{zL}\gamma_L}\left[E_r-\frac{v_{zL}}{c}H_\varphi-\frac{v_{rL}}{c^2}(v_{rL}E_r+v_{zL}E_z)\right];$$

$$\frac{dv_{zL}}{dz}=\frac{-e}{mv_{zL}\gamma_L}\left[E_z+\frac{v_{rL}}{c}H_\varphi-\frac{v_{zL}}{c^2}(v_{rL}E_r+v_{zL}E_z)\right],$$

where e and m are the charge and the weight of the electron.

We shall present bunches as a large quantity of rings (macroparticles) with corresponding charges, radii and moments of injections. The self-consistent excitation of wake fields is described by the equations of movement (3) for each macroparticle in a combination to expressions for fields.

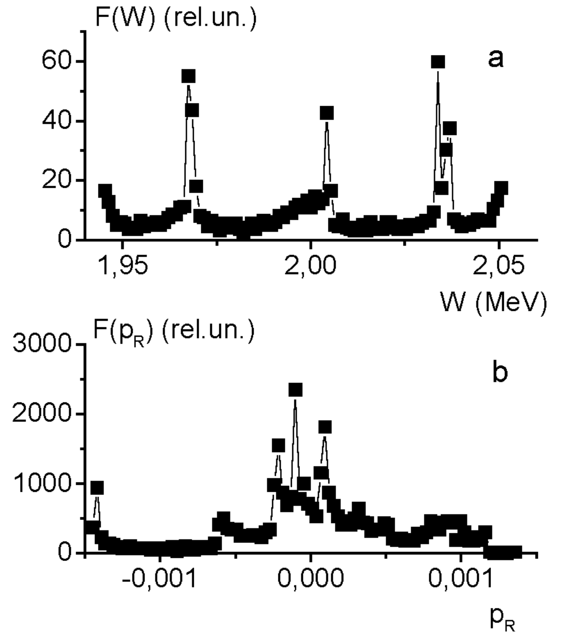

Fig.2. Accelerated low current electron beam. (a) the energy distribution function, (b) the radial momentum distribution function, z=100cm

For research of self-consistent dynamics we have taken a chain of 10 bunches, each of which has been described by 50 particles (10 layers on z and 5 layers on r). We limited ourselves to 10 bunches as such number follows from (2) at l_{sys}=100 cm, l_{mod}=10.52 cm, v_b/c=0.979, $v_{gr}/c\approx$0.5. Results of numerical modelling are the following. First, nonlinear effects (trapping of bunch particles, etc.) are not relieved at used parameters. Second, the resulting field practically does not differ from the field calculated under linear formulas (1). Any particle does not reach a dielectric wall and on the whole it is possible to consider, that the used bunches are steady in the system at the length of 1 m.

As the taking into account of dynamics of low-current bunches practically does not influence a field excited by them, we have considered the following model to study the electron acceleration. We suppose, that in the waveguide of a finite length the field is excited by a regular chain of bunches**.** Neglecting the bunch dynamics and, taking into account the effect of carrying-out the wakefields with the group velocity, we shall consider the accelerating field under formulas (1). Simultaneously with a chain of bunches, the low-current not modulated beam of accelerated electrons is injected into the system. Influence of these electrons against each other and on the electrodynamics of the system is neglected also. Movement of accelerated electrons is described by system (3).

We have taken the accelerating chain of 50 bunches and the monoenergetic accelerated beam with an initial energy of 2 MeV and duration of 18 ns. The typical pattern of longitudinal distribution of the accelerating field is shown in Fig. 1,b. By simulation the accelerated beam was modeled of 2000 particles, and distributed uniformly through phases of the accelerating field. Results showed that the function of accelerated beam distribution on the energy is spread, and accelerated electrons appear (see. Fig.2,a). The peak energy gain does not exceed 50 keV. There is a weak scattering on radial pulses (see. Fig.2,b), however at the length of 1 m accelerated electrons do not reach the dielectric walls.

IV. THE CONCLUSION

The important factor limiting the efficiency of wakefield acceleration of the bunch train in the dielectric waveguide is the effect of carrying-out of wake fields with a group velocity of resonant waves that results in restriction of effective number of bunches giving the contribution to the amplitude of the accelerating field. Our consideration does not take into account the reflection of waves from the output end of the waveguide which always is presented by virtue of the nonideal matching of the waveguide with the free space. The taking into account of this factor will result in prolongation of existence of the field from a separate bunch in the system and in increasing the amplitude of a total excited field.

The work is supported in part by the State Fund of Fundamental Research of Ukraine, Project № 02.07/325.

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УСКОРЕНИЕ ЭЛЕКТРОНОВ КИЛЬВАТЕРНЫМИ ПОЛЯМИ ПОСЛЕДОВАТЕЛЬНОСТИ СГУСТКОВ В ДИЭЛЕКТРИЧЕСКОМ РЕЗОНАТОРЕ

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Рассмотрено возбуждение кильватерного поля последовательностью релятивистских электронных сгустков в волноводе, частично заполненном диэлектриком. Конечная протяженность волновода в продольном направлении учтена введением заднего фронта кильватерного поля, который распространяется со скоростью, равной групповой скорости резонансной волны. Проведено моделирование самосогласованной динамики сгустков и ускорения электронов в кильватерном поле.

ПРИСКОРЕННЯ ЕЛЕКТРОНІВ КИЛЬВАТЕРНИМИ ПОЛЯМИ ПОСЛІДОВНІСТІ ЗГУСТКІВ У ДІЕЛЕКТРИЧНОМУ РЕЗОНАТОРІ

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Розглянуто збудження кільватерного поля послідовністю релятивістських електронних згустків у хвилеводі, частково заповненому діелектриком. Кінцева довжина хвилеводу в подовжньому напрямку врахована уведенням заднього фронту кільватерного поля, що поширюється зі швидкістю, рівної групової швидкості резонансної хвилі. Проведено моделювання самоузгодженої динаміки згустків і прискорення електронів у кільватерному полі.