THE WAKE-FIELD EXCITATION IN PLASMA-DIELECTRIC STRUCTURE BY SEQUENCE OF SHORT BUNCHES OF RELATIVISTIC ELECTRONS*

I.N. Onishchenko,, V.A. Kiseljob, A.K. Berezin, G.V. Sotnikov, V.V. Uskov, A.F. Linnik, Ya.B. Fainberg
National Science Center, “Kharkov Institute of Physics and Technology,” Kharkov 310108, Ukraine

I. INTRODUCTION

To the excitation of wakefields in dielectric structure some theoretical works are devoted. The project of slow wave structure based on this concept is proposed with the acceleration rate up to 100 MeV/m [4]. On Argonne Lab the efforts are undertaken to investigate experimentally wake-field excitation in dielectric by a single high density bunch of charge 100 nC and of energy 150 MeV [5].

In present work we aim for two goals. Firstly, instead of a single notsimply realized dense bunch, the wake-field is proposed to excite by a sequence of bunches of the same total charge but with a smaller density, obtained in the resonance linear accelerator. Secondly, plasma filling of the beam transit channel in dielectric permits to avoid the excited field sagging at channel axis that arises significantly the excitation efficiency.

The electrodynamics of dielectric and hybrid plasma-dielectric structures, the simulations of processes of wake-field excitation by the sequence of bunches of relativistic electrons are represented in the work.

The experiments are carried out on wake-field excitation in dielectric Teflon tube by long train of bunches. The installation with plasma filling of transit channel in dielectric with plasma of density up 10^13cm_{-3} have been prepared, and preliminary experiments are performed.

II.

The longitudinal component of electric field E_z excited by sequence of N bunches in the form of infinitely thin disks of radius R_b moving in the drift tube of the plasma dielectric structure is given by the expression

$$\begin{aligned}E_z &= \frac{4eN}{R_1}\sum_{i=1}^{N}\sum_{n}\frac{\psi n}{E_n}\frac{J_0(k_{\perp n}R_b)}{k_{\perp n}J_0(k_{\perp n}R_1)}\times\\ &\times\Theta(t-z/v_0-iT_0)\times\\ &\times cos[\omega_n(t-z/v_0)-iT_0],\end{aligned}$$

where

$$\begin{aligned}\psi_n(r) &= \begin{cases}J_0(k_{\perp n}r)/J_0(k_{\perp n}R_1), & r\le R_1,\\ F_0(k_{\perp n}r), & ,R_1\le r\le R_2\end{cases}\\ E_n &= 1+\frac{J_1^2(k_{\perp n}R_1)}{J_0^2(k_{\perp n}R_1)}+\frac{R_2^2}{R_1^2}[F_0'^2(k_{\perp n}R_2)-\\ &-F_0'^2(k_{\perp n}a)-1],\end{aligned}$$

$$\begin{aligned}k_{\perp n}^2 &= -\frac{\omega_n^2}{\nu_0^2\gamma^2}\varepsilon_{3n},\\ æ_n^2 &= -\frac{\omega_n^2}{\nu_0^2}(\beta^2\varepsilon-1),\\ F_0(\alpha r) &= \frac{J_0(\alpha r)Y_0(\alpha R_2)-Y_0(\alpha r)J_0(\alpha R_2)}{J_0(\alpha R_1)Y_0(\alpha R_2)-Y_0(\alpha R_1)J_0(\alpha R_2)},\\ F_0^1 &= \frac{\partial F_0}{\partial(\alpha r)};\varepsilon_{3n}=1-\omega_p^2/\omega_n^2,\end{aligned}$$

The function $\Theta(x)$ is equal 1 if $x>0$ and 0 if $x<0$; v_o is beam velocity, R_1, R_2 are inner and outer radius of dielectric tube, ϵ is dielectric permeability, J_0, J_1 are the zero and first order Bessel functions, Y_0 are the zero-order Weber functions, T_0 is the bunch-to-bunch time, N is the number of particles of bunch. The frequencies ω_n , excited by an electron bunch, are found from the dispersion equation

$$\frac{\varepsilon_{3n}}{k_{\perp n}}\frac{J_1(k_{\perp n}R_1}{J_0(k_{\perp n}R_1}+\frac{\varepsilon}{æ_n}F_0(æ_n a)=0. \tag{1}$$

The dielectric structure was calculated so that for the parameters of the experiment ($\varepsilon = 2.6; \gamma = 5$), the frequency ω_0 should provide the synchronism between the fundamental mode of the excited field (wake-field) and the bunch-repetition frequency ω_M of modulated beam bunches

$$\omega_0(R_1,R_2,\varepsilon,\gamma)=\omega_M. \tag{2}$$

In the vaccuum case ($\omega_p = 0$), the crossing of the beam and fundamental modes for the calculated transverse dimensions $R_1 = 1.1cm$, $R_2 = 3.5cm$ determines the frequency ω_0 satisfying condition (2). At moderate plasma density ($\omega_p\le\omega_0$), the plasma waves are not excited directly ($v_b > v_{ph}$). However, the field topography of main electromagnetic mode becomes volumetric, because $\varepsilon_{3n} < 0_{,,}$ that enhances the efficiency of the wave excitation by the bunch. Note that in the calculation of the slowing plasma-filled structure, one should take into account the resonance frequency shift ω_0 due to plasma filling.

At high plasma densities ($\omega_p > \omega_0$), the wake-field is mainly excited as a plasma wave, and in this case the wake-field in the dielectric can arise due to the parametric coupling between electromagnetic and plasma waves (space periodicity, plasma desnity modulation, etc.).

III.

Experiments have been run to investigate wave excitation in the plasma-dielectric structure by a sequence of relativistic electron bunches. The electron beam was produced by a linear accelerator and had the following parameters: energy – 2 MeV, individual bunch length 60 ps, number of bunches 300 to 600, bunch

*This work was supported in part by International Science Foundation, Grant N U27000.

diameter 1 cm, number of electrons per bunch $2 \cdot 10^9$, beam modulation frequency $f_0 = 2825$ MHz. The energy spectrum of beam electrons could be varied within 8% to 50%. Parameters of the dielectric structure (DS) were: inner radius $R_1 = 1.1$ cm, outer radius $R_2 = 3.5$ cm, length $l = 70$ cm, $\varepsilon = 2.6$. The DS could be filled with plasma by the use of coaxial plasma gun, through the hollow electrode of which the beam passed to the DS. The plasma density could vary between $10^{10} cm^{-3}$ to $10^{13} cm - 3$. For comparison, experiments were carried out with both DS and thin glass tube, whose inner diameter coincides with that of the DS.

Beam current measurements at the output of the system have shown that in the glass tube case the whole accelerator output current ($I_b = 1A$) passed through the tube, whereas only 60-70% of the beam current passed through the vacuum dielectric structure. For a wide energy spectrum ($\Delta W/W = 50\%$), the beam passage through the structure was about 80 to 90%.

Energy spectrum measurements by a magnetic analyzer at the output from DS have shown that for a narrow spectrum ($\Delta W/W = 8\%$) the spectral peak shifts by 500 KeV, i.e., 25% of the beam energy are lost. At the same time, there are some electrons (about 10%) which have energy higher than their initial one. For a small number of bunches (N=300) the shift of the spectral peak decreased down to 100-200 KeV. With a broad spectrum ($\Delta W/W = 50\%$) there were practically no energy losses observed. The measurements of "instantaneous" spectra have shown that the greatest energy losses were in the middle of the beam current pulse ($t = 2\mu$s), while the losses were at the head of the beam pulse.

The probes arranged at the output of the structure have indicated the presence of intense microwave radiation at the wavelength $\lambda = 10 cm$ with both E_z and E_v field components. The spectrum width of radiation ($\Delta f = 10 - 12$ MHz) is not much greater than the spectrum width of the driving generator of the accelerator ($\Delta f_0 = 8$ MHz). The microwave radiation amplitude as a fraction of the number of bunches that have passed through the structure (beam current pulse length) has shown that the field grows by nearly a linear law up to 3000 bunches. Then the saturation sets. The same conclusion follows from the comparison between the oscillogram of the radiation signal and the beam pulse oscillogram.

When the beam with a broad electron energy distribution function passed through the DS, microwave signal amplitude decreased nearly by order of magnitude. With filling the above-mentioned DS with plasma we have observed the decrease in the radiation amplitude at the DS output and the improvement in the beam passage. This is apparently due to the detuning of synchronism (2) with plasma filling, which results in the offset upwards of the dispersion curve corresponding to the fundamental mode. Experiments with fields excitation in the plasma-dielectric system, taking into account this offset, will be continued.

IV. CONCLUSIONS

Based on the results obtained we can draw the following conclusions:

1. As the sequence of relativistic electron bunches passes through a dielectric structure, the energy losses up to 25% of the initial value are experimentally observed. The energy is mainly consumed to excite wakefields whose intensity is 10 KeV/cm on the average. In these fields the bunch electrons acquire the transverse velocity and this results in a significant beam interception (up to 40%).
2. The presence of probe-detected microwave radiation at the DS output, as well as the dependence of microwave radiation amplitude on the number of bunches passed through structure, give evidence for the summation of wake-fields of the first 3000 bunches.
3. The use of a beam with a broad electron energy function essentially diminishes the effects observed. This suggests the conclusion that for the excitation of high-intensity wakefield, it is necessary to use bunches with a minimal energy spread.
4. Plasma filling essentially changes electrodynamic characteristics of the DS. Therefore, in the calculations of DS dispersion, one should take into account the synchronous frequency displacement caused by plasma.

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