EXCITATION OF SURFACE WAKEFIELD IN THE DIELECTRIC WAVEGUIDE WITHOUT METAL CASING BY THE SEQUENCE OF ELECTRON BUNCHES

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Results of theoretical and experimental studies of surface wakefield excitation in tubular dielectric tube without metal casing by a sequence of relativistic electron bunches were presented. The wakefield excitation in dependence of the transverse dimensions of the dielectric tube were investigated. The excited wakefield had the maximum amplitude at the optimum tube thickness, for which the bunch repetition frequency was equal to the frequency of the excited surface wakefield.

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INTRODUCTION

At present a dielectric cylindrical waveguide is intensively studied to use in wakefield acceleration of charged particles. A wakefield acceleration provides higher gradient of the accelerating field comparatively to the conventional methods. The excited field characteristics depend on the parameters of a dielectric waveguide, charge and duration of the bunch, which is injected into the dielectric structure. Fields with the accelerating gradient greater than 1 GeV/m were obtained in experiments on wakefield excitation in the dielectric structure by a single short large charge bunch [1]. It has been shown [2, 3] that instead of a single electron bunch with a large charge a sequence of bunches with a relatively small charge can be used when increasing of the excited wakefield intensity is achieved due to coherent superposition of the wakefields of separate bunches at coincidence of bunch repetition frequency with the frequency of the excited wakefield. In [2, 3] the used dielectric structure was a metal waveguide, partially filled with a dielectric. In some cases, the dielectric tube without metal casing is used. In this paper we present the results of theoretical and experimental studies of the wakefield excitation in tubular dielectric tube without metal casing by a sequence of relativistic electron bunches, depending on the thickness of dielectric tube.

1. THEORY

Dispersive properties of dielectric cylindl andtubular waveguide structures are investigated in [4 - 6], where it was shown that the surface azimuthally symmetric and asymmetric slow waves can propagate in them only when

$$\frac{\omega}{c} < k_z < \frac{\omega}{c}\sqrt{\varepsilon}\,, \qquad (1)$$

where ε is a relative permittivity of the dielectric; ω is the wave frequency; c is the light velocity; k_z is the propagation constant.

The characteristic property of these waves is the existence of the cutoff frequency ω_c below which the wave can not propagate. The only mode, which has the zero cutoff frequency, is azimuthally asymmetric wave HE_{11}, for which $m = 1$. On the contrary to metal waveguides at the cutoff frequency the phase velocity of wave is equal to the light velocity. When $\omega<\omega_c$, we have the leaky wave. Its phase velocity exceeds the light velocity. At that coaxial dielectric radiates into space and losses its property of a guiding structure.

To study the dispersion properties of the dielectric waveguide mode we consider the infinite at longitudinal direction a cylindrical dielectric tube with inner and outer radii b_1, b_2 (Fig. 1).

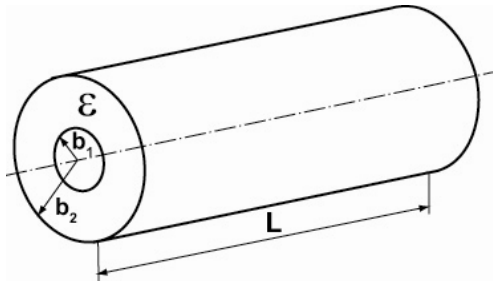

Fig. 1. Tubular dielectric waveguide without metallic casing

We considered azimuthally symmetric slow $E-$ wave with components E_z, E_r, H_φ. The following dependence of the field components of the coordinates and time is supposed as

$$E_z, E_r, H_\varphi \sim \exp[i(k_z z - \omega t)]\,,$$

where ω and k_z satisfy (1). Using the well-known boundary conditions for the field components at $r = b_1$, b_2, we obtain the following dispersion equation for surface waves:

$$\frac{K_1(\chi_0 b_2)}{K_0(\chi_0 b_2)} = -\frac{\varepsilon\chi_0[J_1(\chi_d b_2)V_1 + N_1(\chi_d b_2)V_2]}{\chi_d[J_0(\chi_d b_2)V_1 + N_0(\chi_d b_2)V_2]}\,, \qquad (1)$$

where

$$V_1 = -\frac{\chi_d}{\varepsilon\chi_0} I_1(\chi_0 b_1) N_0(\chi_d b_1) + I_0(\chi_0 b_1) N_1(\chi_d b_1)\,,$$

$$V_2 = \frac{\chi_d}{\varepsilon\chi_0} I_1(\chi_0 b_1) J_0(\chi_d b_1) - I_0(\chi_0 b_1) J_1(\chi_d b_1)\,,$$

$$\chi_0 = \sqrt{k_z^2 - \left(\frac{\omega}{c}\right)^2}\,, \quad \chi_d = \sqrt{\varepsilon\left(\frac{\omega}{c}\right)^2 - k_z^2}\,,$$

$J_{0,1}(x), N_{0,1}(x), I_{0,1}(x), K_{0,1}(x)$ are the Bessel and Neumann functions, and the corresponding modified functions.

Solutions of the equation (2) for ε=10, b_2=2 cm and some thicknesses of the dielectric tube $\Delta b = b_2 - b_1$ are presented in dimensionless variables $\frac{\omega}{c}b_1$, k_zb_1 in Fig. 2. The line IV shows the dependence $\omega=k_zV_0$, which allows finding the frequency of Cherenkov resonance for wakefield excitation. In our experiment electron energy is 4.5 MeV, that corresponds to the velocity of electron in terms of the light velocity V_0/c = 0.995. On the vertical axis the value $\frac{\omega_m}{c}b_1$ = 0.5, corresponding to the bunch repetition frequency of $\omega_m/2\pi$ =2.805 GHz, is indicated by a dotted line.

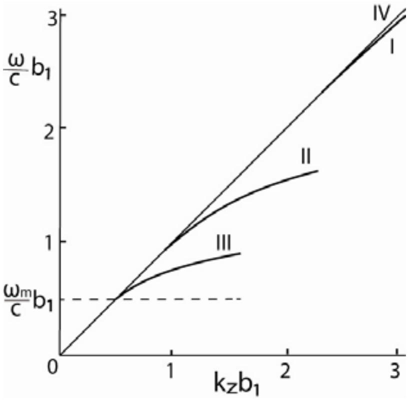

Fig. 2. Dispersion curves for a dielectric surface wakefield: I – Δb = 0.3 cm; II – Δb = 0.7 cm; III – Δb = 1.05 cm. The straight line IV corresponds to the function $\omega = k_zV_0$. Dotted line indicate bunch repetition frequency

Dispersion curves I, II, III are calculated for thicknesses of the dielectric tube Δb = 0.3 cm, Δb = 0.7 cm, Δb = 1.05 cm, respectively. Lines I, II, III left start at the values of the phase velocity equal to the velocity of light that corresponds to a non-zero critical frequency for asymmetric waves.

Dispersion curves I, II, III are calculated up to the values of the dimensionless propagation constant k_zb_1, for which these curves intersect the straight line IV in the points corresponding to Cherenkov's resonance, i.e. where surface wakefield of the dielectric waveguide is excited. The resonant excitation of the wakefield occurs at the point of intersection of the lines III and IV, where the wave frequency is equal to the bunch repetition frequency f_0 = 2.805 GHz. For such excitation allowing to achieve maximum of the wakefield amplitude the thickness of the tube wall should be taken Δb = 1.05 cm.

2. EXPERIMENT

The experiments were conducted at the installation, that is shown schematically in Fig. 3. The sequence of N=6000 relativistic electron bunches was produced by a linear resonance accelerator. Energy of electron bunches was 4.5 MeV, bunch repetition frequency was 2805 MHz. Bunches were ejected from the accelerator through the titanium foil of thickness 30 µm. Bunch diameter at the accelerator exit was 1 cm, bunch duration was 60 ps with a time interval between them 360 ps, the charge of the each bunch was 0.16 nC. Such sequence of bunches passed through the cylindrical dielectric waveguide (sapphire, ε = 10, $tg\delta = 2\cdot10^{-4}$).

Efficiency of wakefield excitation was measured by the microwave probe, located at the exit of the dielectric tube, that allowed measuring the excited field component E_z.

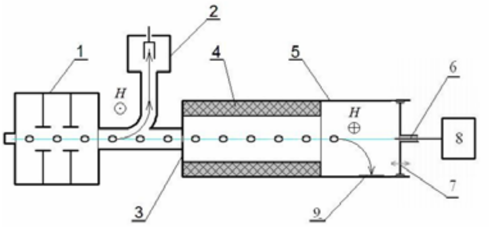

Fig. 3. The experimental setup: 1 -electron accelerator, 2 – magnetic analyzer; 3 – Ti diaphragm; 4 – dielectric structure; 5 – copper waveguide 6 – microwave probe; 7 – plug; 8 – oscilloscope; 9 – glass plate

The oscillogram of the microwave signal from the probe (E_z component of the field) for the sapphire tubes with the outer and inner radii b_1=1.6 cm, b_2=1.9 cm (Δb=0.3 cm), and length 42 cm is shown in Fig. 4. In this case the amplitude of the excited field is low. It can be explained by the fact that, since the eigen frequency ω_0 of the field excited in such dielectric tube as it is theoretically calculated (see curve I in Fig. 2) does not coincide with the bunch repetition frequency $\omega_М$.

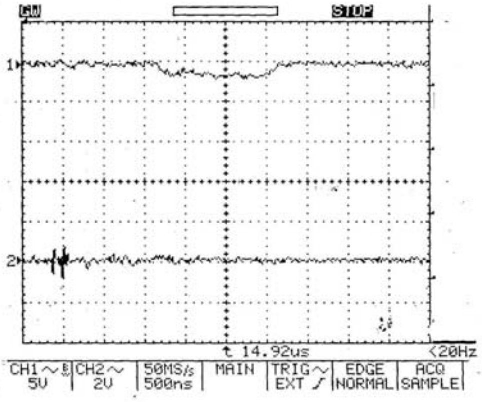

Fig. 4. The oscillogram of the excited field E_z component (top) for the case Δb=0.3 cm

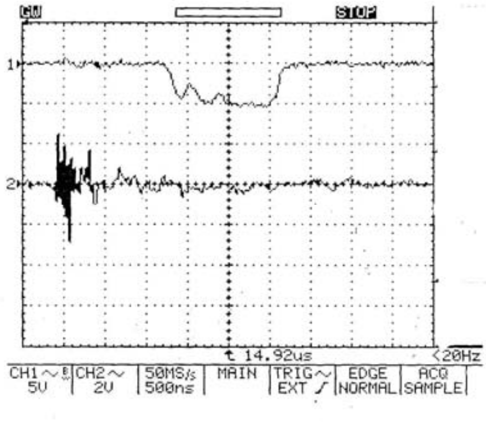

Fig. 5. The oscillogram of the excited field E_z component (top) for the case Δb=0.7 cm

The amplitude of the microwave signal is increased more than twice when the thickness of a tube wall is increased to Δb=0.7 cm (b_1=1.2 cm, b_2=1.9 cm). In this case the condition of the resonance $\omega_М=\omega_0$ is not satisfied, but the frequencies are much closer to each other than in the first case (see curve II Fig. 2).

At this time we have not sapphire tube of the "resonant" thickness Δb=1.05 cm (b_2=1.9 cm, b_1=0.85 cm), so the "resonant" experiment will be carried out in the future.

From the other side we can approach to the resonant conditions by means of varying the bunch repetition frequency using master generator for klystron amplifier.

In Fig. 6 the experimental dependence of the amplitude E_z in arbitrary units upon the bunch repetition frequency is presented for the tube thickness Δb=0.7 cm (b_1=1.2 cm, b_2=1.9 cm).

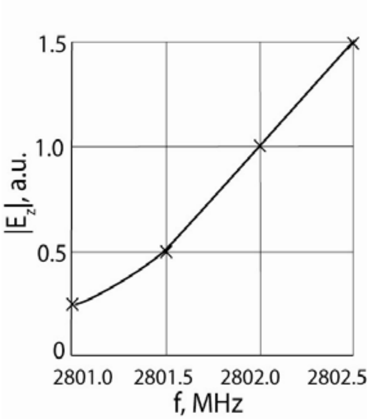

Fig. 6. The dependence of the amplitude of the longitudinal component E_z of excited wakefield upon the bunch repetition frequency

It is seen from the Fig. 6 that closer the bunch repetition frequency to the intersection point of curves II and IV (Cherenkov resonance frequency) that more the excited wakefield amplitude component E_z. It is in accordance to the previous experiment with tube thickness variation.

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ВОЗБУЖДЕНИЕ ПОВЕРХНОСТНЫХ КИЛЬВАТЕРНЫХ ПОЛЕЙ В ДИЭЛЕКТРИЧЕСКОМ ВОЛНОВОДЕ ПОСЛЕДОВАТЕЛЬНОСТЬЮ ЭЛЕКТРОННЫХ СГУСТКОВ

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Представлены результаты теоретических и экспериментальных исследований возбуждения поверхностных кильватерных волн в трубчатом диэлектрическом волноводе без металлического кожуха последовательностью релятивистских электронных сгустков. Исследованы условия возбуждения кильватерного поля в зависимости от поперечных размеров диэлектрической трубки. Возбуждаемое кильватерное поле имеет максимальную амплитуду при оптимальной толщине трубки, для которой частота следования сгустков совпадает с частотой возбуждаемой поверхностной волны.

ЗБУДЖЕННЯ ПОВЕРХНЕВИХ КІЛЬВАТЕРНИХ ПОЛІВ У ДІЕЛЕКТРИЧНОМУ ХВИЛЕВОДІ ПОСЛІДОВНІСТЮ ЕЛЕКТРОННИХ ЗГУСТКІВ

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Представлені результати теоретичних та експериментальних досліджень збудження поверхневих кільватерних хвиль в трубчатому діелектричному хвилеводі без металевого кожуха послідовністю релятивістських електронних згустків. Досліджені умови збудження кільватерного поля в залежності від поперечних розмірів діелектричної трубки. Кільватерне поле, яке збуджується в структурі, має максимальну амплітуду при оптимальній товщині трубки, при якій частота слідування згустків співпадає з частотою збуджуваної поверхневої хвилі.