WAKEFIELD EXCITATION IN DIELECTRIC WAVEGUIDES BY A SEQUENCE OF RELATIVISTIC ELECTRON BUNCHES

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The results of theoretical and experimental studies of the wakefield excitation in a dielectric waveguide of a finite length by a long sequence of relativistic electron bunches was carried out to reveal the possibility of the wakefield amplitude enhancement at summing coherent fields of separate bunches when the bunch repetition frequency coincides with the excited field frequency. In accordance with the theory the stepwise increasing dependence of the wakefield amplitude upon the dielectric waveguide length was experimentally obtained.

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INTRODUCTION

Particle accelerators, as unique tools for solving the frontier high energy physics problems, have excessive sizes and cost that requires great efforts and large financial expenses for their building. Discovery of a new particle like the Higgs boson, crucial in determining the consistency of the standard model, requires a focus on the creation of Higgs factory, based on the collider with the necessary energy and luminosity of the colliding beams. If basing on traditional methods of acceleration, such colliders are also large in size and high in cost. This motivates research and development aimed at finding and implementing new methods of high-gradient acceleration into accelerator physics and technology to decrease the collider size. Promising of these is the acceleration in the wakefield excited in plasma or dielectric structure by intensive bunch or a powerful laser pulse.

This presentation relates to the concept of the electron accelerator based on the acceleration with the wakefield excited in a dielectric structure by a regular sequence of relativistic electron bunches. It is a variant of two-beam accelerator, in which electron bunches are accelerated with wakefields excited in the dielectric structure by a regular sequence of relativistic electrons. Wakefields as a Cerenkov radiation, excited in the THz range, are considered as promising ones for the new methods of acceleration.

By accelerating rate dielectric wakefield methods are intermediate (more than 1 GeV/m) between traditional methods with metal structures (less than 0.1 GeV/m) and plasma wakefield method (up to 100 GeV/m). However, in spite of the limitation of the accelerating rate due to the dielectric breakdown contrary to plasma case, the dielectric section in future colliders has an advantage since it is devoid of the problems with positron part of wakefield collider and ion collapse that are inevitable for plasma section.

As it has been reported early [1] in NSC KIPT for enhancing the amplitude of the excited wakefield the concept of a dielectric wakefield accelerator has been proposed, in which three approaches should be used together: "multi-bunch" scheme [2, 3] to increase the wakefield by the coherent summation of the wakefields of the individual bunches of the long sequence; "multi-mode" scheme [4, 5] to increase the wakefield by the summation of a lot of equidistant transverse modes of the wakefield excited in the dielectric structure of rectangular cross-section; "resonator" scheme [6, 7] to increase the wakefield by the use of the resonator, which provides energy accumulation of excited wakefields for the whole sequence of bunches, i.e. allows avoiding travelling of energy away from the structure with the group velocity [8, 9], which restricts the number of bunches, which wakefields build-up leads to the total wakefield increase. In this paper the theoretical and experimental investigations in details of the "multi-bunch" scheme are presented.

1. STATEMENT OF THE PROBLEM

Investigations of the "multi-bunch" scheme are concluded to finding the dependence of the wakefield amplitude at a dielectric waveguide exit upon the number of exciting bunches. Early we have found [10] the waveform of the excited wakefield after a single bunch or a sequence of them. Wakefield after a single bunch consists of Cerenkov radiation and posterior transition radiation of slightly less intensity originated at the waveguide entrance. The length l of the Cerenkov radiation train behind the bunch is

$$l = L\left(1 - \frac{v_g}{v_0}\right), \qquad (1)$$

where L is distance from the waveguide entrance to the exciting bunch propagating inside of the waveguide, v_g is group velocity of wakefield wave, v_0 is velocity of the bunch. At the exit of waveguide of the length L_0 the duration of wakefield pulse will be observed

$$\tau = \frac{l}{v_g} = \frac{L_0}{v_0}\left(\frac{v_0}{v_g} - 1\right). \qquad (2)$$

At the injection of a resonant sequence of bunches (bunch repetition frequency coincides with wakefield frequency $f_{rep} = f_0$) into the dielectric waveguide of finite length L_0, not all bunches of the sequence increase the total wakefield due to the removal of the excited field from the output end of the waveguide with the group velocity v_g. Maximal number of bunches, wakefields summation of which leads to the increase in the total wakefield is given by the expression:

$$N_{max} = \frac{L_0}{\lambda}\left(\frac{v_0}{v_g} - 1\right), \qquad (3)$$

where $\lambda = 2\pi/k_z = 2\pi f_{rep}/v_0$ *is* wavelength of the excited wakefield mode, k_z is its longitudinal wavenumber. Injection of subsequent bunches over N_{max} does not increase the total wakefield. The spatial longitudinal distribution of wakefield along the waveguide of finite length L_0 evolves from stepwise triangular form for $N<N_{max}$ to stepwise linearly growing up to the entrance for $N \geq N_{max}$. At that the temporal behavior of the wakefield at the waveguide exit is stepwise linearly growing in time for $N<N_{max}$ up to saturation for $N \geq N_{max}$.

According to (3) varying the length of the dielectric waveguide L allows to observe wakefied at the waveguide exit from various N_{max} including N_{max} =1, 2, 3,… . Thus, instead of the resonant sequence of various small number of bunches, which is difficult to realize in the experiments, especially a single bunch or several bunches, without cutting long sequence (6000 bunches in our experiment) by unique technique, we can use dielectric waveguides of various lengths compared with wavelength. In particular, for the waveguide of the length less the excited wavelength a "single bunch" scenario can be realized, because wakefield trains of all bunches do not overlap, so that the field envelope of the entire sequence has an wakefield amplitude the same as for a single bunch. Therefore, the dependence of the total wakefield on number of injected bunches we investigate by means of the dependence of the total wakefield on the length of the dielectric waveguide.

There are two variants of the realization of this idea. For cylindrical geometry of dielectric waveguide electron bunches propagate along the axis and interact with dielectric through its whole length. For this case we change the active dielectric length by varying its whole length by means of a set of dielectric pieces. In the second variant used for rectangular dielectric waveguide there is the possibility to deflect bunches by magnetic field at needed distant from waveguide entrance due to the presence of two walls without dielectric plates. For this case the length of dielectric waveguide is constant and interaction length is varied by the length of the bunches way before deflecting.

2. THEORY

For the purpose of the better interpretation of the experimental results of dependence of an excited longitudinal electric wakefield the PIC simulation close to the experimental conditions was performed. The matter is that the experimental measurements of a longitudinal electric field are fulfilled in vacuum part of the metal waveguide. The wakefield excited in dielectric is partially reflected at dielectric-vacuum boundary. Thus, in a dielectric part of the waveguide the field can accumulate. Having measurements of an electric field in vacuum area it is necessary to draw a conclusion on value of the same field in the dielectric part.

Below results of researches of dependence of the longitudinal electric field E_z measured in different points of dielectric structure, upon length of the dielectric part are presented.

The geometry of researched dielectric structure is shown in Fig. 1.

For numerical calculations we used the experimental parameters (see in section V). We supposed that the input end of a waveguide is short-circuited, and the output end is open into the free space. For reduction of influence of the reflected wave on a measured field in a waveguide the output end of a waveguide was complemented by the free space with length, equal to two wavelengths of the lowest excited mode. For the given cross sizes of the dielectric part and energy of electrons of a bunch the wavelength is calculated to be $\lambda = 10.64$ cm.

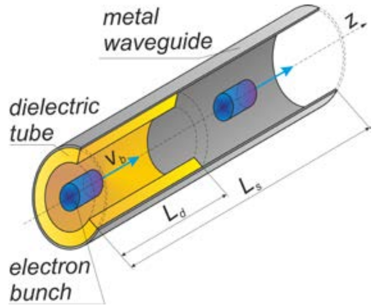

Fig. 1. General view of the dielectric structure, excited by sequence of electron bunches. Into a metal cylindrical waveguide of length L_s the dielectric part of length L_d is inserted (yellow color). Electron bunches (blue color) propagated along a cylinder axis from left to right

To prove the coherency of summation of wakefields of N bunches in accordance with the statement of the problem we should change the dielectric part length L_d and observe stepwise linear growth of longitudinal dielectric field amplitude $E_{z\_total}=NE_{z\_single}$ with L_d increasing, at that $N=L_d/\lambda$, $N<N_{max}$. For $N \geq N_{max}$ E_{z_total} saturates and does not grow with further increasing of N.

In Fig. 2 dependences of the maximum and minimum (module) values of a longitudinal electric field on the axis of the structure on length of the dielectric part are shown. The electric probe is located on a structure axis. The structure was excited by sequence of 21 bunches.

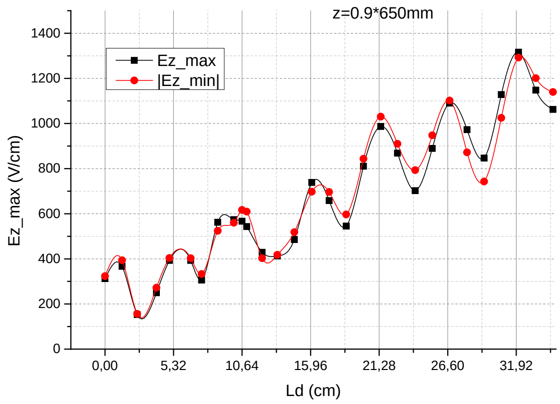

Fig. 2. Maximum and minimum of the longitudinal electric field at distance $z = 0.9L_s$ from waveguide entrance depending on of the dielectric part length. Markers show calculated points, between calculated points spline interpolation is carried out. Vertical grid lines are drawn by each half length of the lowest resonant wave

From Fig. 2 follows that the longitudinal electric field in vacuum part of structure in average grows linearly with increasing of the dielectric part length oscillating with the period equal to half wavelength of the lowest excited mode. Oscillations evidence the reflection of excited wakefield on the dielectric-vacuum boundary leading to wakefield accumulation at the dielectric part multiple to half wavelength as it occurs in the resonator (i.e. waveguide is not perfect). Transition radiation contributes essentially (it is comparable with Cerenkov radiation) only at $L_d<\lambda$, i.e. for "single bunch" scenario. Its contribution at larger L_d is smaller because it is not coherent contrary to Cerenkov radiation of resonant sequence of bunches, which wakefielfs are coherently added by a stepwise way. Looking aside from transition radiation and oscillations caused with reflections we can conclude that Cerenkov radiations of resonant bunches are summated coherenly giving resulting linear growth with dielectric part length (i.e. with number of bunches) with the step after each subsequent bunch.

Dependence of wakefield in structure on time is presented in Fig. 3. Dielectric part length L_d=32.1 cm was approximately equaled to three wavelengths of the lowest resonant mode. Structure was excited by a sequence of 42 bunches; the bunch repetition period is 0.356 ns. Stepwise rising field is a characteristic feature of the coherent addition of wakefields in the resonator that confirms the existence of reflections in the system leading to oscillatory behavior of the wakefield dependence on L_d.

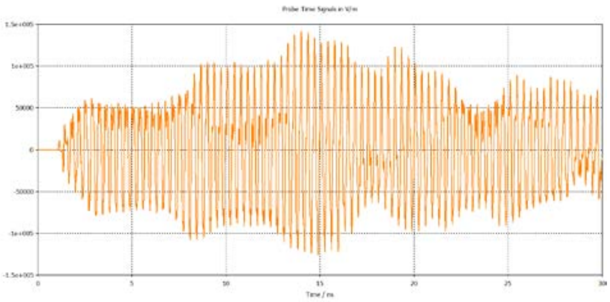

Fig. 3. Temporal dependence of longitudinal electric field E_z on axis at $z = L_d$

3. EXPERIMENTAL SETUP

The scheme of the experimental setup on which the experiments were performed on the wakefield excitation in the dielectric structure of cylindrical and rectangular cross-section by a sequence of relativistic electron bunches is shown in Fig. 4.

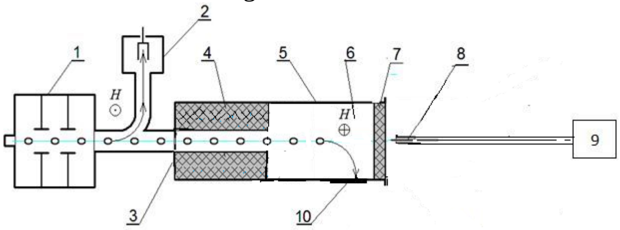

Fig. 4. 1 – accelerator "Almaz-2M"; 2 – magnetic analyzer; 3 – diaphragm; 4 – dielectric structure; 5 – waveguide; 6 – transverse magnetic field; 7 – Teflon vacuum plug; 8 – microwave probe; 9 – oscilloscope; 10 – glass plate

Relativistic electron beam energy is 4.5 MeV, pulse beam current – 0.8 A, pulse duration 2 µs. Each pulse represents a sequence of N = 6000 electron bunches with a duration of 60 ps each, interval between bunches 300 ps bunch charge 0.26 nC. Frequency of bunch repetition f_{rep}=2805 MHz.

To study the multi-bunch regime of wakefield excitation we used copper cylindrical waveguide with an inner diameter of 85 mm and a wall thickness of 2 mm, filled with dielectric (Teflon ε=2.04, tgδ=4·10^{-4}). Outer diameter of the dielectric insert is 85 mm and the diameter of the channel in the dielectric insert equal 2.1 cm was calculated so that the bunch repetition frequency f_{rep} coincides with the wakefield frequency f_0 excited in the dielectric waveguide ($f_{rep}=f_0$).

In experiments the amplitude of the excited wakefield was measured by microwave probe, at changing the dielectric part length by using a set of cylindrical dielectric inserts with channel for bunches, each 2.66 cm in length corresponding to 1/4 of the excited wave length. Theoretical calculations have shown that for the parameters of our experimental installation the principal mode E_{01} of excited Cerenkov wakefield has group velocity v_g=0.492 c. According to (3), this means that for the length of the dielectric waveguide $L=\lambda$ the excited Cerenkov wakefields of bunches do not overlap and therefore are not summated. As a result, the amplitude of the total field of the entire sequence of bunches is equal to the amplitude of the first bunch wakefield, i.e. scenario of the excitation by a single bunch is realized. The gradual increase in the length of the dielectric part to 35 cm allows to investigate the evolution of the wakefield excitation successively by a sequence of 1, 2, 3 and 4 bunches. Note that at the input boundary of a dielectric waveguide the transition radiation is generated, which should be measured by taking $L<<\lambda$, and subtracted from the total signal.

4. EXPERIMENTAL RESULTS

Experiments were started at "initial" structure (see Fig. 4) without careful matching to approach to waveguide mode of operation. Measurements of the amplitude of the excited wakefield depending on the dielectric length of the dielectric waveguide (manufactured as a set of filling Teflon inserts of length ΔL=0.25 λ, each) were carried out at the bunch repetition frequency 2805 MHz, which coincides with the frequency of the excited wakefield. Preliminary experiments have shown that at increasing the length of the dielectric part, along with linear growth of the wakefield amplitude, assumed in accordance to (3), the periodic oscillations of increasing amplitude were observed (Fig. 5). Spatial period of these oscillations is multiple to a half wavelength of the principal mode. Such behavior of the obtained dependence may be arisen due to the partial reflection of the excited wake wave from the dielectric part exit end, as well as from the exit of the metallic waveguide and from a vacuum dielectric plug.

As it can be seen from Fig. 5, even in the absence of dielectric in the waveguide ($L_d=0$) at the dielectric waveguide exit RF-signal is registered. It can be caused by the transition radiation excitation during bunches propagation through the input boundary of the dielectric waveguide (metallic diaphragm). Its value is reduced by 2 times, if after diaphragm the dielectric insert of length (L_d=1 cm) much smaller than the excited wavelength is placed so we can neglect excited Cerenkov radiation. When subtracting this transition radiation field, it becomes possible to investigate the assigned task finding the dependence of the amplitude of total Cerenkov wakefield on the length of dielectric part, and hence upon the number of coherently exciting bunches.

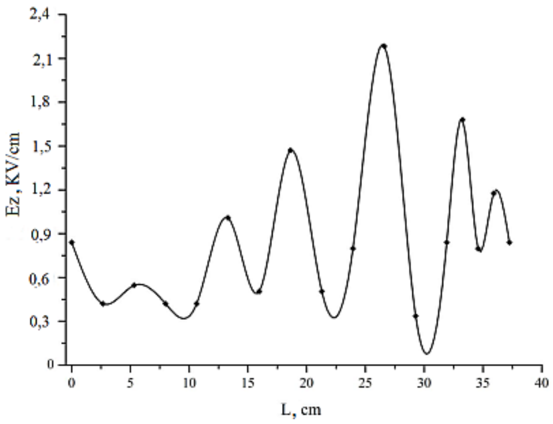

Fig. 5. Amplitude of E_z of excited wakefield on the dielectric part length

To reduce the level of reflections, a series of changes in the installation were performed, allowing reducing the reflection coefficient, i.e. to improve the standing wave ratio (SWR) of the dielectric structure so it becomes "matched" structure. These include:

– installation of a dielectric cone at the exit of the dielectric waveguide to reduce reflection from the dielectric-vacuum boundary;

– installation of a conical horn at the exit of the experimental setup to reduce reflection from the output end of the metallic waveguide;

– optimization of the thickness of the dielectric vacuum plug, for which the reflection coefficient at a given wavelength is minimal.

SWR dependence for the "initial" configuration on the length of a set of filling inserts made from Teflon (step ΔL=0.25 λ) exactly such as in beam experiment (see Fig. 5) for the "initial" structure is shown in Fig. 6 (1).

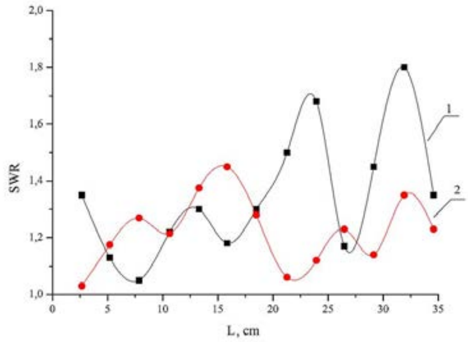

Fig. 6. SWR dependence for round cylindrical dielectric waveguide tract upon length of Teflon filling:
1 – "initial" dielectric structure;
2 – "matched" dielectric structure

Observed periodic changes SWR (from 1.05 to 1.8), caused by the reflections of the incident wave from the output end of a set of cylindrical dielectric inserts, from the end of the waveguide and from the dielectric vacuum plug.

SWR dependence for the "matched" configuration of waveguide-dielectric structure on the dielectric waveguide length within L=(0…0.25) λ, with optimum thickness of vacuum dielectric plug d=0.5 λ, with a conical copper horn at output of waveguide-dielectric structure, and with absorbing ferrite load behind the horn is shown in Fig. 6 (2).

From the comparison of SWR dependency round dielectric waveguide tract on length of Teflon filling for the initial and the matched configuration of the structure it can be seen that the made modifications allow to lower essentially SWR of matched configuration of dielectric structure.

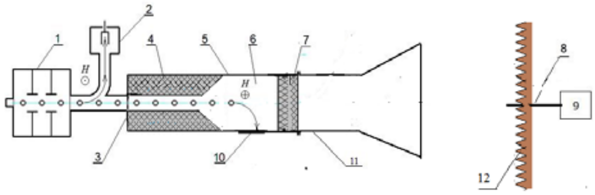

Fig. 7. Scheme of the installation for "matched" dielectric waveguide: 1 – accelerator "Almaz-2M"; 2 – magnetic analyzer; 3 – diaphragm; 4 – insulator; 5 – waveguide; 6 – transverse magnetic field; 7 – vacuum dielectric plug; 8 – RF-probe; 9 – oscilloscope; 10 – glass plate; 11 – additional waveguide with horn; 12 – ferrite absorber

If all conditions for reflections reducing in the "matched" waveguide dielectric structure are satisfied the measurements of total amplitude of the excited wakefield depending on the length of the dielectric waveguide (and hence on number of bunches) were performed at the experimental setup shown in Fig. 7.

Dependence of the excited wakefield amplitude on the length of the dielectric waveguide is shown in Fig. 8. From Fig. 9 follows that the amplitude of the excited wakefield increases proportionally to the length of the dielectric part, i.e. according to (3) also to the number of bunches, evidencing coherent wakefield summation for N_{max} bunches.

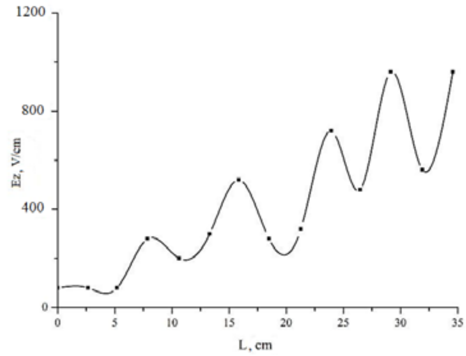

Fig. 8. Dependence of the amplitude of the excited wakefield on the length of the dielectric waveguide

Measurement of the energy loss of relativistic electron bunches. To compare the energy loss of bunches with the magnitude of the excited wakefield the measurements of the energy spectra of electrons as they pass through the dielectric structure were made. On the energy spectra of electrons we can judge by the imprints on the glass plate of the beam electrons deflected by transverse magnetic field. Energy losses were determined by comparing the imprints of the beam electrons passing through the empty waveguide and through the waveguide filled with dielectric inserts. Independently the energy spectra were found with help of magnetic analyzer at the accelerator exit and the dielectric structure exit.

Measurements were carried out at a length of dielectric L_d = 29.14 cm and L_d = 26.48 cm, i.e. at maximum and minimum amplitudes of the wakefield (see Fig. 8) and also in the absence of dielectric in the waveguide.

It has been shown that at the length of the dielectric structure L_d = 26.48 cm, imprints of electron beam passing through the structure almost coincide with the imprints of the beam electrons passed through the empty waveguide. With a length of dielectric L_d = 29.14 cm shift of imprint about 3 mm was observed, which, according to the calibration of imprints by magnetic analyzer, corresponds to energy loss of electron bunches 80 keV (see Fig. 9).

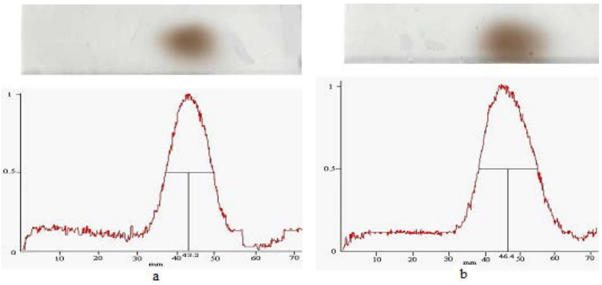

Fig. 9. Imprints of electron bunches deflected by transverse magnetic field: in the absence of dielectric and for dielectric of length 26.48 cm (a); for dielectric of length 29.14 cm (b)

These results were confirmed by measuring the energy spectra of bunches by magnetic analyzer, placed at dielectric structure exit. The resulting spectra of the beam electrons passed waveguide without dielectric structure and with dielectric 29.14 cm length are shown in Fig. 10, from which it follows that the energy loss of electron bunches was 100 keV. For dielectric of length L = 26.48 cm spectrum practically does not shift.

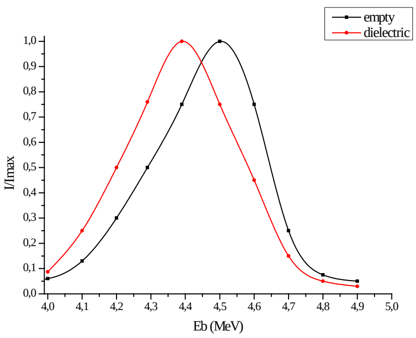

Fig. 10. Electron energy spectra: waveguide without dielectric (black); with dielectric of length 29.14 cm (red)

Since by theoretical calculations a single bunch excites wakefield E_z=150 V/cm, then the coherent addition of the fields of 4 bunches with dielectric structure of the length 30 cm of the energy loss for the “matched” structure with small reflections should constitute 18 keV, which are within the accuracy of measurement and cannot be registered neither by magnetic analyzer nor by imprint of the bunches on the glass plates. Recorded in the experiment energy losses of bunches constitute 80…100 keV correspond to “initial” waveguide when an accumulation of wakefield to large amplitudes takes place. Indeed, at dielectric of length 29.14 cm wakefield reaches of order 1…2 keV/cm, which leads to energy loss of bunches comparable by order to value with the measured one by magnetic analyzer.

Rectangular cross-section. For rectangular waveguide filled with two dielectric plates there is the possibility to deflect bunches to the waveguide walls, which are without dielectric plates. By placing magnetic field at various distances from the waveguide entrance we can vary the length of bunches interaction with dielectric waveguide and measure dependence of wakefield amplitude on active dielectric length at fixed dielectric waveguide length. Such linear dependence is presented in Fig. 11 that validates theoretical prediction (3).

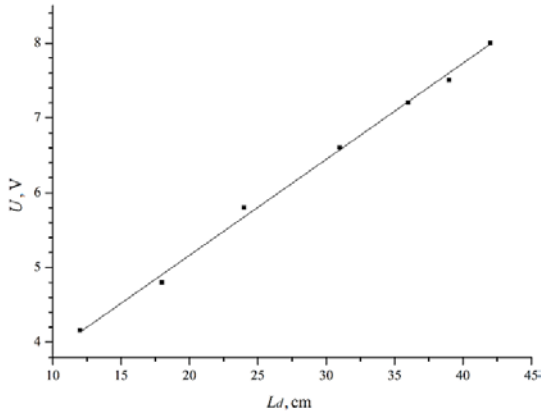

Fig. 11. Dependence of wakefield amplitude on interaction length of bunches with dielectric waveguide

CONCLUSIONS

It is shown that in the dielectric waveguide structure, while passing through it a regular sequence of relativistic electron bunches coherent summation of wakefields excited by bunches is occurred. At that the number of bunches, whose wakefields are coherently summated determined by the length of the dielectric structure and group velocity of the excited wave.

Energy loss of bunches, measured by magnetic analyzer, corresponds to the value of the excited wakefield amplitude.

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ВОЗБУЖДЕНИЕ КИЛЬВАТЕРНОГО ПОЛЯ В ДИЭЛЕКТРИЧЕСКИХ ВОЛНОВОДАХ ПОСЛЕДОВАТЕЛЬНОСТЬЮ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОННЫХ СГУСТКОВ

В.А. Киселев, И.Н. Онищенко, Г.В. Сотников

Проведены теоретические и экспериментальные исследования возбуждения кильватерного поля в диэлектрическом волноводе конечной длины длинной последовательностью релятивистских электронных сгустков для выяснения возможности увеличения амплитуды кильватерного поля суммированием полей отдельных сгустков при совпадении частоты повторения сгустков с частотой возбуждаемого поля. Согласно теории получено экспериментально ступенчатое увеличение амплитуды кильватерного поля в зависимости от длины диэлектрического волновода.

ЗБУДЖЕННЯ КІЛЬВАТЕРНОГО ПОЛЯ В ДІЕЛЕКТРИЧНИХ ХВИЛЕВОДАХ ПОСЛІДОВНІСТЮ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОННИХ ЗГУСТКІВ

В.О. Кисельов, І.М. Оніщенко, Г.В. Сотніков

Проведено теоретичні та експериментальні дослідження збудження кільватерного поля в діелектричному хвилеводі кінцевої довжини довгою послідовністю релятивістських електронних згустків для з'ясування можливості збільшення амплітуди кільватерного поля підсумовуванням полів окремих згустків при збігу частоти повторення згустків з частотою збуджуваного поля. Згідно з теорією отримано експериментально ступеневе збільшення амплітуди кільватерного поля залежно від довжини діелектричного хвилеводу.