NOVEL AND ADVANCED ACCELERATION TECHNIQUES

INVESTIGATIONS OF THE PHYSICAL PROCESSES IN MULTIBUNCH DIELECTRIC WAKEFIELD ACCELERATOR*

I.N. Onishchenko
National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
E-mail: onish@kipt.kharkov.ua

The main results of theoretical and experimental researches of the physical processes in a dielectric wakefield accelerator based on the excitation of accelerating wakefield in a dielectric structure by a long sequence of electron bunches are represented. Enhancement of the excited wakefield amplitude is achieved through coherent addition wakefields of individual bunches, wakefields summation of the equidistant transverse modes and wakefields storage in the resonator. Acceleration of bunches in the total wakefield is realized at dividing sequence of bunches in the exciting and accelerated parts in any ratio by an appropriate frequency detuning of bunch repetition frequency relative to the excited principal transverse mode. The change in the dielectric constant and loss tangent of used dielectrics under exposure to 100 MeV electron beam is investigated.

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INTRODUCTION

To investigate nature on the smallest scale, which is composed of the fundamental particles and forces, particle accelerators have played a main role of tools as microscopes. The present high-energy frontier colliders producing the center-of-mass energy of 100 GeV [1] give the possibility to study the world of nature, of which the size can be seen into nearly one-trillionth micron. Today we are launching forth into a new energy regime of the order of TeV [2, 3], in which profound fundamental questions is expected to be answered on the origin of mass, the predominance of matter over antimatter and the existence of supersymmetry and so on. High energy ion accelerators including proton and heavy-ion colliders [4] can reveal in-situ synthesis of the nuclear matter by producing quark-gluon plasmas at the quark-hadron phase transition temperature around one-trillion Ks, which is thought as the high energy density state at 10^{-5} s after the Big Bang of our universe.

However ILC [2, 3], and LHC [4] – scale accelerators are very close to the limit of what we can practically afford to build using conventional technologies, even collaboratively. The first understanding of this situation was stated in [6], where three ideas were declared by Veksler (Dubna), Budker (Novosibirsk), and Fainberg (Kharkov). The only Fainberg proposal to use of plasma waveguides as accelerating structures has survived and was later modified by Dawson et al. [7, 8] as a wakefield accelerating scheme, in which high-gradient accelerating field is built up as a wakefield excited in plasma by a short high power laser pulse or a short bunch of the large charge. Another potential candidate for future high gradient particle acceleration, allowing to overcome the accelerating rate limit 100 MeV/m of conventional accelerators, is dielectric loaded (DL) accelerating structures [9], in which wakefield is excited by an intense electron bunch or a sequence of bunches. As it has been shown in theoretical investigations [10] and in the recent experiments [11], the maximum accelerating gradient in dielectric structures, being limited by the electric breakdown due to the tunneling and collisional ionization effects, can be achieved above 1 GeV/m, i.e. on the order higher comparing to the conventional metallic accelerating structures. Besides, DL structures are more acceptable due to the developed technology of micro-fabrication, homogeneity, UHF-matching etc.

In this work the concept of multi-bunch dielectric wakefield accelerator is investigated [12, 13]. The theoretical and experimental studies of the following problems are carried out:

- "multi-bunch" issue that is concluded to the wakefield enhancement due to the summation of coherent wakefields driven by a regular sequence of electron bunches;
- "multi-mode" issue that is concluded to the wakefield enhancement due to the summation of many equidistant transversal modes of wakefield, excited in rectangular dielectric structure;
- "resonator" issue that is concluded to the wakefield enhancement by using a resonator to avoid the effect of group velocity so that the energy of excited wakefield does not vacate the dielectric structure during the whole sequence of bunches;
- "injection" problem that is concluded to displacing rear tail of the bunch sequence into accelerating phase of the wakefield by means of detuning bunch repetition frequency and excited wakefield frequency;
- "plasma-dielectric" modification with plasma filled transit channel for focusing of bunches and enhancement of wakefield excitation;
- influence of exposure to relativistic electron beam on radiation resistance and dielectric electrodynamic properties of dielectric components (including zirconium ones).

1. WAKEFIELD EXCITATION [14]

1.1. EXPERIMENTAL FACILITY

As a result of works on the restoration of the klystron amplifier, update the electron gun and master oscillator, which were performed at linear resonant electron accelerator "Almaz-2M", the relativistic electron beam, which energy can be varied in the range 2.5…4.8 MeV, pulsed

*Results of these investigations were reported at the satellite meeting "Multibunch dielectric wakefield accelerator" to Int. Workshop on Future Linear Colliders (LCWS14), Belgrade, Serbia, 2014.

current 0.5…1.0 A, pulse duration 0.1…2.0 μs. Beam pulse presents a sequence of N = 300…6000 electron bunches each of charge within 0.16…0.32 nC, radius 0.5 cm, duration 60 ps (i.e. length 1.7 cm) and interval between bunches 300 ps (at bunch repetition frequency 2805 MHz). Bunch repetition frequency can be changed within 2803…2807 MHz. Energy distribution width is within 7…9%. A chamber in which the dielectric structure can be placed was attached to the accelerator "Almaz-2M". In such a way the experimental facility has been created for research of wakefield excitation by a sequence of the relativistic electron bunches in the dielectric structures of round and rectangular cross section and acceleration of electrons by excited wakefields. The scheme of the experimental set up is shown in Fig. 1.

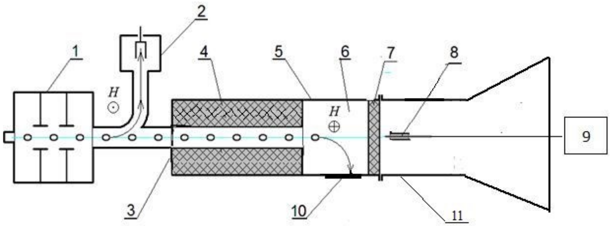

Fig. 1. The scheme of the experimental set up.
1 – accelerator "Almaz-2M"; 2 – magnetic analyzer; 3 – diaphragm; 4 – dielectric structure; 5 – metal waveguide; 6 – traversal magnetic field; 7 – vacuum teflon plug; 8 – microwave probe; 9 – oscilloscope; 10 – glass plate; 11 – waveguide with a horn

The dielectric structure was a copper cylindrical waveguide (5) of the inner diameter of 85 mm, filled with annual Teflon tube (4) (ε=2.04, tgδ=4 10^{-4}) of the outer diameter equal to the inner diameter of the copper waveguide and transit channel of the diameter 2.1 cm for bunches. The length of the dielectric part is 31 cm equal to 3 wavelengths of the principal mode.

Electron energy spectra were measured by a magnetic analyzer (2) at the accelerator exit and by declining electrons with transversal magnetic field (6) on glass plate (10) at the dielectric structure exit.

1.2. "MULTI-BUNCH" EXCITATION

"Multi-bunch" issue concluded to the statement that the intense wake field excited by a bunch with a large charge can be achieved by a long periodic sequence of bunches with a low charge each, but an equivalent total charge. To clarify the possibility of coherent summation of individual bunches fields it is needed to change the number of bunches in the sequence. Because of the difficulty of producing a set of sequences with various number of bunches in the performed studies waveguides of various length were used. The possibility of such a substitution follows from the fact that due to the output of the excited wave from the waveguide of finite length with the group velocity v_g the number of bunches of the sequence of any duration, which contributes to the growth of the total wakefield at the waveguide exit is limited. Maximum number of bunches N, which wakefields during coherent summation increase the amplitude of the total field is directly proportional to the length of the waveguide L: $N=L/\lambda(v_0/v_g-1)$, where λ is length of the excited wave equal to the distance between the bunches, v_0 is bunch velocity.

The dependence of the excited field at dielectric waveguide output on time for the two waveguide length $L=\lambda/4$, $L=\lambda/2$, and $v_g = v_0/2$ is shown in Fig. 2,a,b. It can be seen that the amplitude of the field does not change for $L<\lambda$.

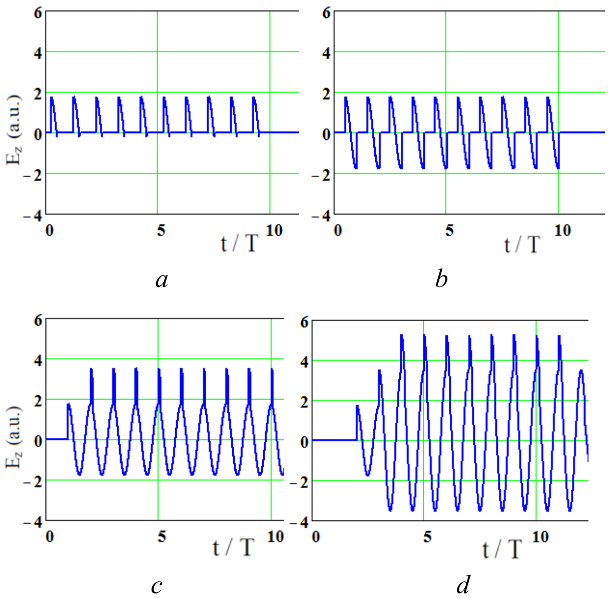

Fig. 2. Dependence of Cherenkov wakefield on time at output end of the dielectric waveguide of length: a – $L=\lambda/4$; b – $L=\lambda/2$; c – $L=\lambda$; d – $L=2\lambda$. Number of bunches $N=10$

With the further increase in the length of the waveguide the excited wakefield is growing stepwise by each length λ (Figs. 2,c,d and 3).

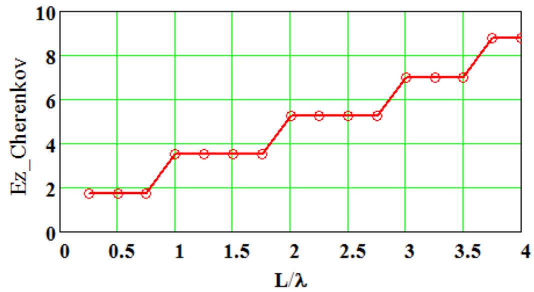

Fig. 3. Dependence of Cherenkov wakefield on waveguide length at the waveguide exit

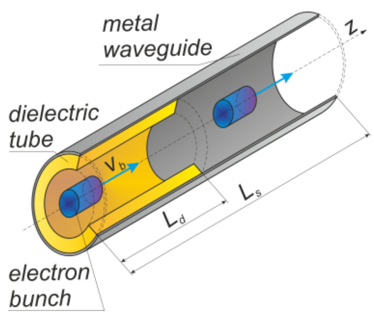

Fig. 4. Model of the dielectric structure, excited by sequence of electron bunches, taken for simulation

To account the transition radiation, which inevitably occurs on electrodynamic jumps in real structures, and reflections of excited fields in imperfectly matched waveguides, the numerical simulation of model of the dielectric structure close to the experiment (Fig. 4) was carried out. Into a metal cylindrical waveguide of length L_s the dielectric part of length L_d is inserted (yellow color). Electron bunches (blue color) propagate along a cylinder axis from left to right.

Fig. 5 shows the dependence of obtained the total excited field on the dielectric structure length.

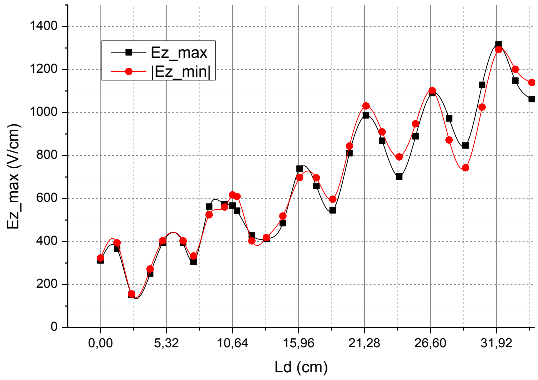

Fig. 5. Maximum and minimum of the longitudinal electric field at exit on of the dielectric part length

Existence of maxima and minima on curves of dependence of a wakefield from length of the dielectric plug is connected with two factors. Firstly, when dielectric lengths are multiple to a half of wavelength of a resonant mode the reflection of a wave excited by a bunch on a dielectric-vacuum boundary is minimum. Such behavior is similar to passing of plane wave through a dielectric plate.

Secondly, the partially reflected wave is coherently added with a direct wave, and the full field grows in a segment of dielectric tube that will lead to increasing of the radiated field in case of the subsequent falling of a wave on boundary of the section of mediums. The situation with growth of a field is similar to accumulation of energy in the resonator.

The experimentally obtained linear growth of the total wakefield excited in the dielectric waveguide by a long sequence of $6{\cdot}10^3$ bunches (each of charge 0.26 nC and duration of 60 ps, bunch repetition frequency 2805 MHz) upon the variable length of the dielectric waveguide (0…35 cm, step 2.5 cm), evidencing the coherent addition of wakefields of the bunches, which fields overlap with increasing of the waveguide length. By such a method the measurement of the values of wakefield excited by 1, 2, 3 and 4 bunches was carried out, agreed with theoretical calculation and numerical simulation.

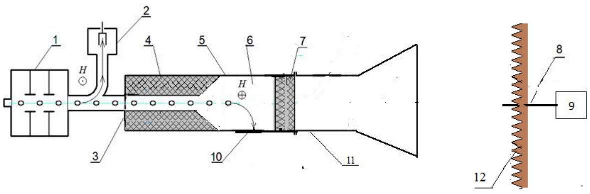

Fig. 6. Scheme of the installation for "matched" dielectric waveguide: 1 – accelerator "Almaz-2M"; 2 – magnetic analyzer; 3 – diaphragm; 4 – insulator; 5 – waveguide; 6 – transverse magnetic field; 7 – vacuum dielectric plug; 8 – RF-probe; 9 – oscilloscope; 10 – glass plate; 11 – additional waveguide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

Improved matching (adiabatic transitions and absorbers) (Fig. 6), which decreases reflections, allows to obtain the dependence of wakefield amplitude on the dielectric structure length (Fig. 7) similar to the obtained one in simulation (see Fig. 5).

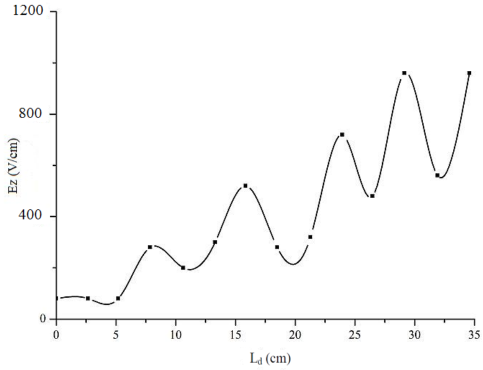

Fig. 7. Dependence of Ez amplitude of excited wakefield on the matched dielectric waveguide length

In the case of dielectric with rectangular cross-section there is the possibility to make influence of reflections the same for various length of bunches interaction with dielectric part of the waveguide. For a rectangular waveguide with two dielectric plates the opportunity occurs to deflect e electron bunches on the "bare" walls of the waveguide, where no dielectric plates (Fig. 8). Arranging magnetic field region (N-S) at different distances from the dielectric waveguide exit we can change the interaction length by shifting (N-S) and measure the dependence of the excited wakefield amplitude upon the length of the interaction length. At that measurements were carried out at the same length of the whole dielectric waveguide avoiding changes in the conditions of reflections when varying the interaction length.

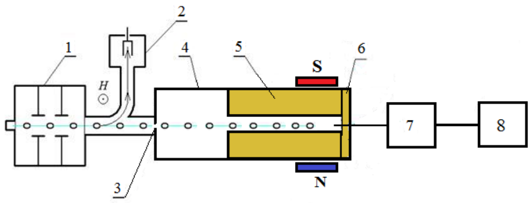

Fig. 8. 1 – accelerator "Almaz-2M"; 2 – magnetic analyzer; 3 – diaphragm; 4 – waveguide; 5 – dielectric; 6 – dielectric plug; 7 – wavemeter VMT-10; 8 – oscilloscope

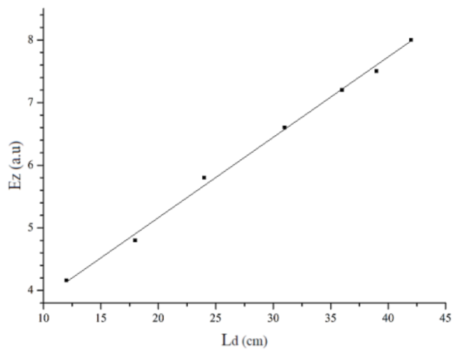

Fig. 9. Dependence of wakefield amplitude on interaction length of bunches with dielectric waveguide

For such experiment wakefield at the dielectric waveguide output linearly depends on the interaction length of bunches with dielectric part (Fig. 9), that is consistent with the theoretical prediction, confirming coherent summation of wakefields of bunches.

1.3. "MULTI-MODE" EXCITATION

The purpose of research "multi-mode" approach to prove that the summation of fields of all transverse modes excited in the dielectric waveguide by a sequence of bunches gives a peaked signal of alternative sign for total wakefield with respectively enhanced amplitude. Most effectively process of addition takes case under frequency spectrum of transverse modes as much as possible the close to the equidistant one. In this case the wakefield looks like sequence of narrow peaks of an opposite polarity of large amplitude.

Let's consider a semi-infinite waveguide, having form of two parallel ideally conducting planes with distance L between them. The waveguide is completely filled with uniform dielectric of permittivity ε. The input is short-circuited by perfectly conductive transverse wall. A sequence of bunches with period T is injected into the waveguide. The following model of transverse profile of bunches density is chosen:

$$R(x_0)=\begin{cases}\cos\left(\dfrac{\pi}{2}\dfrac{x_0}{x_b}\right), & x_b \ge x_0 \ge -x_b,\\ 0, L/2 \ge x_0 \ge x_b, & -x_b \ge x_0 \ge -L/2.\end{cases} \quad (1)$$

In the longitudinal direction bunches are infinitely thin. Expression for the wakefield in semi-infinite plane dielectric waveguide has the form:

$$E_z = E_z^{ch} + E_z^{tr},$$

$$E_z^{ch} = \frac{2\pi^3 Q}{L\varepsilon}\sum_{s=0}^{N-1}\sum_{n=odd}^{\infty}\frac{\cos(k_{\perp n}x_b)\cos(k_{\perp n}x)}{\dfrac{\pi^2}{4}-k_{\perp n}^2 x_b^2}\times$$

$$\left[\theta(t-\frac{z}{v_0}-sT)-\theta(t-\frac{z}{v_g}-sT)\right]\cos\omega_n(t-\frac{z}{v_0}-sT)$$

$$E_z^{tr} = \frac{8\pi Q}{L\varepsilon}\sum_{s=0}^{N-1}\sum_{n=odd}^{\infty}\frac{\cos(k_{\perp n}x_b)\cos(k_{\perp n}x)}{\dfrac{\pi^2}{4}-k_{\perp n}^2 x_b^2}\times$$

$$\left\{\left[\theta(t-\frac{z}{v_{pr}}-sT)-\theta(t-\frac{z}{v_{pr}}-sT)\right]\sum_{m=1}^{\infty}(-1)^m(r_{1s}^{2m}-r_{2s}^{2m})J_{2m}(y_{ns})+\right.$$

$$\left.+\theta(t-\frac{z}{v_g}-sT)\left[J_0(y_{ns})+\sum_{m=1}^{\infty}(-1)^m(r_{1s}^{2m}+\frac{1}{r_{2s}^{2m}})J_{2m}(y_{ns})\right]\right\}. \quad (2)$$

The spatial structure of wakefield excited by a sequence of electron bunches in a multimode regime in the plane dielectric waveguide was calculated by numerical methods for parameters: $L_d = 60\lambda$, number of bunches $N = 20$, number of transverse modes $N_{\mathrm{mod}} = 21$, frequency of the transverse fundamental mode is $f_0 = \omega_0/2\pi = \omega_{rep}/2\pi = 1/T = 2.802$ GHz, transverse size of waveguide $L_x = 5.12$ cm, transverse size of bunches is $x_b/L_x = 0.04$, dielectric permittivity $\varepsilon = 2.1$. The spatial structure of excited wakefield is shown in Figs. 10,a,b.

For experimental investigations of multi-mode scheme for enhancing wakefield amplitude there were made dielectric waveguide of circular cross section filled with dielectric from Teflon (ε = 2.045) and two rectangular dielectric waveguides based on a standard metallic waveguide R26 with two types of dielectric plates from quartz (ε=3.8), whose dimensions were calculated for obtaining single- or multi-mode of operation for wakefield excitation. The calculations were performed taking into account the conditions providing the Cherenkov resonance of bunches with the principal mode at the frequency ω_0, coinciding with the bunch repetition frequency $\omega_{rep} = \omega_0$.

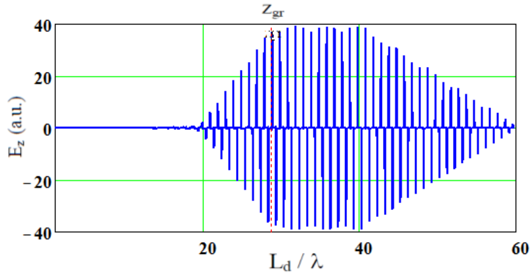

Fig. 10,a. Spatial structure of wakefield at the moment of time $t/T = 60$

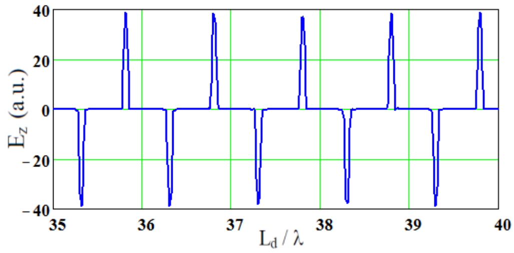

Fig. 10,b. Increased scale wakefield dependence on longitudinal coordinate (fragment of Fig. 10,a)

To measure the frequency spectrum of wakefield excited by a sequence of bunches in such dielectric waveguide, the signal with help of the microwave probe was applied to the wavemeter VMT-10 or directly to the oscilloscope TDS6154 with a bandwidth of 15 GHz. In the first case, the spectrum was determined by the standard procedure for the wavemeter. In the second case, the spectrum was obtained by the method of fast Fourier transform (FFT) or "direct" calculation of the Fourier integral over one period of the waveform, and for the whole duration of experimentally obtained waveform of wakefield signal.

In theoretical studies for determining the frequency spectrum of excited eigen radial modes of the dielectric waveguide a single bunch that moves in an infinite dielectric waveguide is used. Because of the complexity of a single bunch obtaining using accelerator "Almaz-2M", instead of a single-bunch scenario we proposed and used another one. The length of the dielectric waveguide excited by a long sequence of bunches is taken of such value that for the available group velocity the wakefield trains of bunches do not overlap.

For cylindrical dielectric waveguide length L=λ (at $v_g=v_0/2$), i.e. a single-bunch scenario, the experimentally frequency spectrum measured with wavemeter WMT-10 in the range of 2.5…7.5 GHz is shown in Fig. 11. It is seen a prevailing large amplitude of the microwave signal at bunch repetition frequency 2.805 GHz and a wideband frequency spectrum in the range of 4.5…6 GHz of much smaller amplitude. A wideband spectrum is associated with non-multiple frequency of radial modes to the bunch repetition frequency and transition radiation inevitably arisen at the input boundary.

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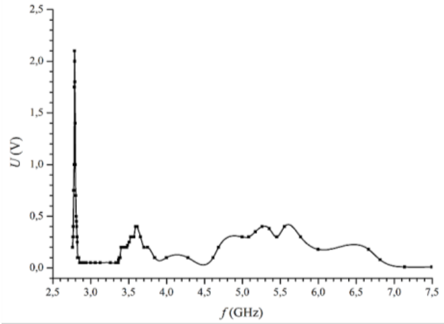
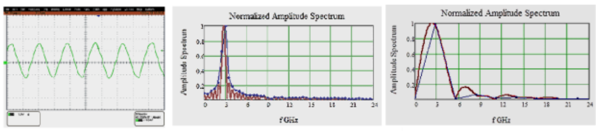


Fig. 11. Spectrum of microwave radiation excited by a long sequence of bunches in cylindrical dielectric waveguide of length L=λ

To determine the frequency spectrum of transition radiation a separate experiment was performed, in which the sequence of bunches prop a through the waveguide without dielectric, but in the presence of a metal diaphragm, which is usually located dielectric. Small peaks of radiation at frequencies of 3.6 GHz and 5.2 GHz were detected, that allows estimating the contribution of transition radiation in the excited spectrum.

Another method for determining the frequency spectra excited in the dielectric waveguide is concluded to frequency filtering of radiation by Teflon vacuum plug of various thicknesses. Waveform of microwave radiation signal was taken by microwave probe, located behind the Teflon plug, and applied to the oscilloscope TDS6154. Taking into account that the maximum passage of the plug observed at its thickness equal to halflength of the incident wave, it is possible by changing the thickness of the plug to pass through the plug the wakefield of selected frequency excited in the dielectric waveguide.

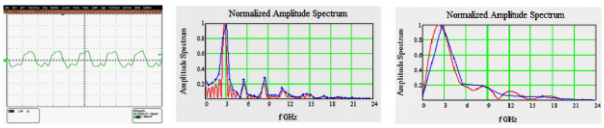
Fig. 12,a shows the oscillogram of microwave radiation excited in the dielectric waveguide of length L_d=3λ at the thickness of the dielectric plug 5 cm, close to a half-wavelength of the principal mode (λ=10.6 cm). At this thickness of dielectric plug principal mode passes the plug with minimal reflection, but radiation of shorter wavelengths pass worse. Fig. 12,b shows the normalized spectra obtained using FFT (blue curve) and with the help of "direct" calculation of the Fourier integral (red curve) for the waveform presented in Fig. 12,a. Fig. 12,c shows the spectra for a sample of length equal to the length of one period of L=λ from the whole waveform. It is evident that for the whole length of the waveform (see Fig. 12,b) only the first mode of the excited wakefield stands out, the other modes do not appear, "spilling" over the nearest frequencies that are multiple to the bunch repetition frequency. For the length of the waveform sample equal to the length of one period (see Fig. 12,c) the second mode at a frequency of 6.7 GHz clearly stands out.



a b c

Fig. 12. Oscillogram of microwave signal at the output of the dielectric waveguide and the normalized frequency spectrum of the signal at the thickness of the Teflon vacuum plug of 5 cm

When the thickness of the plug is decreased to 3.6 cm the amplitude of the microwave radiation with a frequency 2.805 GHz is reduced due to the increase of the reflection coefficient. At oscillograms the waveform distortions are observed (Fig. 13,a) due to the passage through the plug of excited modes of higher frequencies. In this case the spectra obtained from the experimental waveform of whole length by FFT and "direct" calculation of the Fourier integral (Fig. 13,b) show that in addition to the principal mode the oscillations at frequencies that are multiple to the bunch repetition frequency with much smaller amplitude are presented. Spectra obtained by FFT and "direct" calculation of the Fourier integral for the waveform sample of the length equal to the length of one period, taken from the whole waveform is shown in Fig. 13,c. It is seen the frequency of the second and even the third radial modes.



a b c

Fig. 13. Oscillogram of microwave signal at the output of the dielectric waveguide and the normalized frequency spectrum of the signal at the thickness of the Teflon vacuum plug of 3.6 cm

For rectangular dielectric waveguide with multimode excitation by a sequence of bunches the frequency spectrum, measured by wavemeter VMT-10, is shown in Fig. 14.

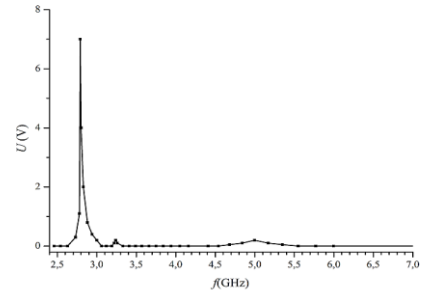


Fig. 14. Spectrum of microwave radiation excited in rectangular dielectric waveguide of length L=λ

Large amplitude at the frequency of the principal mode coinciding with bunch repetition frequency is explained by the fact that for larger values of the dielectric permittivity the reflection from the dielectric-vacuum boundary increases and such structure of length multiple to the halfwavelength of the excited mode becomes a resonator.

For the parameters of relativistic electron bunches and dielectric waveguide of circular cross section, used in the experiments, the frequency spectrum of transverse modes excited by a single bunch in an infinite waveguide were theoretically determined. Although these modes are not equidistant, the summation of their fields allows increasing the amplitude of the excited field by about 30%. Experiments showed that the amplitude of the total wakefield signal exceeds the amplitude of the principal mode signal only 10%. This slight excess of the total signal amplitude compared to the amplitude of the principal mode signal caused firstly by the non-equidistance of excited modes and secondly by detuning between their frequencies and bunch repetition frequency ω_{rep} under conditions of reflections in the imperfect waveguide.

In multi-mode rectangular dielectric waveguide the total signal amplitude higher by more than 60% than the amplitude of the principal mode signal, that is determined by better equidistance of excited modes in the rectangular waveguide.

1.4. "RESONATOR" SCHEME OF EXCITATION

The aim the "resonator" concept is, firstly, to increase the number of bunches of the sequence, adding wakefields of which increases the total wakefield in comparison with the case of a waveguide case, and, secondly, to increase the amplitude of the total wakefield by adding fields of excited equidistant (hence resonant) modes. Remind (see section 1.2) that in the case of a semi-infinite waveguide the maximum number of bunches, which increases the total wakefield, measured at the waveguide exit, is given by the expression $N_{max}=1+L/\lambda(v_0/v_g-1)$. In the "resonator" concept this limitation, caused by the removal of the wakefield from the waveguide exit with the group velocity v_g, is absent, i.e. all bunches of the sequence contribute to the increase in the wakefield amplitude, which grows proportionally to the total number of bunches N_b. In this case, coherent energy losses of the bunch grow with its number, and the total energy loss of the whole sequence is proportional to N_b^2. In the resonator with quality factor $Q=\infty$ all bunches of the long sequence increase the total wakefield in the resonator. The amplitude of the total wakefield (accordingly, the number of bunches, contributing to the field increase) is limited by the finite quality factor Q.

For excitation of the wakefields in dielectric resonator by a sequence of bunches the resonant conditions of the coincidence of bunch repetition frequency ω_m with Cherenkov radiation frequency ω_0 ($\omega_{rep}=\omega_0$) and, simultaneously, with the principal eigen frequency of the resonator ω_{r1}, i.e. $\omega_{rep}=\omega_0=\omega_{r1}$ should be fulfilled. In the case of a planar dielectric resonator for providing summation of wakefields (Cherenkov radiation) of bunches, fields of radial modes and fields of resonator harmonics, i.e. the operation of all three concepts-multibunch, multimode, and resonator ones, the fulfillment of these resonant conditions is imposed the requirements on the length L and the transverse size of the transit channel a of the dielectric resonator. Namely, the resonator length L should be multiple of the number of half-wavelengths of the principal mode. At the resonator length $L = Na\sqrt{\beta_0^2\varepsilon-1},\ \beta_0 = v_0/c$, where ε is dielectric permittivity, N is number of the first longitudinal harmonics of the resonator, being in Cerenkov resonance with the beam at bunch repetition frequency, the longitudinal harmonics with number $l=Nm$, where m is transverse modes number, are automatically equidistant and coincide with the corresponding transverse modes by frequencies. All of them are occurred in Cerenkov resonance with the beam. It provides peaking and increasing the amplitude of the total wakefield at the summation of the sinusoidal fields of the equidistant modes and harmonics. To fulfill the conditions for "multibunch" concept the transverse size of the transit channel a should be chosen accordingly to the expression $a = v_0/2f_{rep}\sqrt{\beta_0^2\varepsilon-1}$, where f_{rep} is the bunch repetition frequency.

It was shown that the eigen transverse modes for a rectangular cross-section are closer to the equidistance ones than the radial modes of round cross-section. By this reason along with the cylindrical resonator the resonator of rectangular cross-section was experimentally investigated with an attempt to find out the summation of the transverse modes and the corresponding increase in the amplitude of the total wakefield.

The wakefield excitation is realized by a long sequence of $6\cdot10^3$ electron bunches in dielectric resonators of 4 configurations:

- cylindrical compound-resonator consisting of two parts: filled with dielectric and empty (without dielectric) ones, each of length multiple their half-wavelength, that allows to carry out diagnostics of bunches and wakefield without disturbing the processes of excitation in the dielectric part (i.e. making equivalent processes in a single dielectric resonator);
- quartz single-mode dielectric resonator of rectangular cross-section;
- quartz multimode dielectric resonator of rectangular cross-section;
- zirconia multimode dielectric resonator of rectangular cross-section at fulfillment of resonant conditions-coincidence of the bunch repetition frequency ω_m with Cherenkov radiation frequency ω_0 ($\omega_m=\omega_0$) and, simultaneously, with the eigen fundamental frequency of the resonator ω_r, i.e. at fulfillment of $\omega_m=\omega_0=\omega_r$.

In the absence of losses in the resonator ($Q=\infty$) and the multiplicity of frequencies of transverse modes (i.e. their equidistance), declared conditions should provide coherent summation of wakefield of all bunches and all excited transverse modes, and thereby increase the total wakefield to the level of field, excited by a single bunch with a charge equivalent to the total charge of all bunches of the sequence. For finite Q-factor the dependence of the total wakefield upon the resonator Q-factor experimentally investigated and found the level of excitation of transverse modes and their contribution to the total wakefied (Fig. 15).

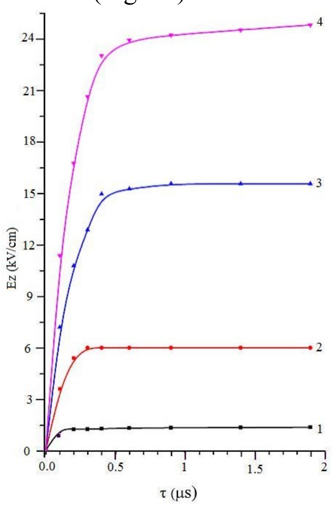


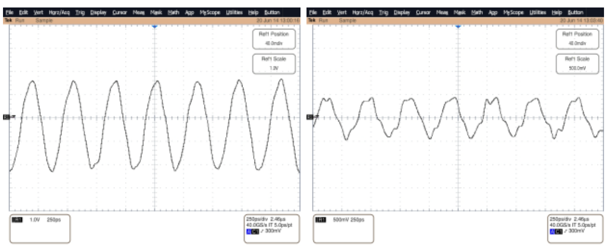
Fig. 15. Dependence of the wakefield amplitude on the duration of bunch sequence for different Q-factors of the compound-resonator: 1 – Q_1=65; 2 – Q_2=268; 3 – Q_3=539; 4 – Q_4=676

It is shown that in the case of a cylindrical compound-resonator with increasing duration of the sequence the total field increases and saturates, remaining constant for larger durations. With the growth of the Q-factor the number of bunches of the sequence contributing to the increase in the total wakefield increases. The long sequence of $6\cdot10^3$ bunches in our experiment is practically equivalent by saturation amplitude to the sequence of infinite number of bunches.

At the achieved maximum Q-factor Q = 676 of the cylindrical compound-resonator, consisting of part of length $L_1 = 3\lambda_d$, filled with Teflon (ε = 2.045; $tg\delta = 2\cdot10^4$), with the transit channel of diameter 21mm and of empty part of length $L_2 = \lambda_v/2$, the sequence of $6\cdot10^3$ electron bunches of charge 0.26 nC and energy 4.5 MeV, with a diameter of 1 cm and a duration of 60 ps, each excites wakefield in an empty part of E_{zv} =24 kV/cm and in the transit channel of the dielectric part E_{zd} =11.8 kV /cm.

Experiments were performed on the excitation of a cylindrical compound-resonator at various lengths of the dielectric part $L_1=\lambda_d$, $2\lambda_d$, $3\lambda_d$; wherein the length of the empty part is the same $L_2 = \lambda_v/2$. It is shown that with increasing length of the dielectric part the excited wakefield increases. A theoretical model of wakefield excitation taking into account change in Q-factor and feedback time delay was elaborated. A quantitative explanation of the observed increase of the wakefield with dielectric part L_1 elongation.

Measurements of the amplitude of the total field and the amplitude of the principal mode field showed that they practically do not differ from each other. The oscillogram of E_{zv} component of the total field at the end of the empty part of the compound-resonator at lengths $L_1=3\lambda_d$ и $L_2 = \lambda_v(\omega_{r1})$, ω_{r1} is fundamental mode frequency, obtained with oscilloscope TDS6154, is shown in Fig. 16. Note that the signals in Figs.16,a,b are attenuated in 36dB and 25dB, correspodingly, to be proper for the oscilloscope. It is seen that in the compound-resonator mainly one mode, the frequency of which coincides with the frequency of bunch repetition frequency of the resonator and $\omega_0 = \omega_{rep} = \omega_{r1} = 2\pi\cdot2.803$ is excited. Wakefield excitation in the compound-resonator by a long sequence of bunches with a repetition frequency of ω_m and frequency filtering in the compound-resonator with eigen frequency ω_{r1} leads to the excitation in the compound resonator of only the principal radial mode with frequency $\omega_0 = \omega_{rep} = \omega_{r1}$.



a *b*

Fig. 16. Oscillograms of wakefield excited by a sequence of $6\cdot10^3$ bunches in the compound-resonator ($a - L_1=3\lambda_d$, $L_2 = \lambda_v(\omega_{r1})$; $b - L_1=3\lambda_d$, $L_2 = 10\lambda_v(\omega_{r2})$), obtained using TDS 6154

The wakefield excitation by a sequence of bunches in multimode (thick plates) dielectric (quartz ε = 2.045; $tg\delta = 2\cdot10^{-4}$) rectangular resonator showed that wakefield increase to E_{zd} =7 kV/cm in comparison with the case of the waveguide due to the wakefield summation of larger number of bunches. Expected amplitude "peaking" and increasing principal mode amplitude caused by the addition of transverse modes in the waveguide case at the excitation by a single bunch, in the experiment with a resonator of rectangular (the same for circular) cross-section and a long sequence of bunches were not observed. The reason for this result is nonresonant transverse modes, besides principal one. As a result, the total wakefield is monochromatic.

The wakefield excitation by the sequence bunches in the single-mode (thin plates) quartz resonator of rectangular cross section at the double frequency $\omega_0=2\omega_{rep}$.was performed. There was realized the excitation of monochromatic wakefield with amplitude E_{zd}=2.8 kV/cm. Monochromaticity in this case follows from the fact that in the appropriate waveguide case one bunch excites mainly one mode at the frequency $\omega_0=2\omega_{rep}$, with which coupling coefficient is maximal. Other modes are almost not excited.

The experiment with such resonator showed the excitation monochromatic wakefield increased compared to the waveguide case due to more number of bunches which wakefields, contribute to the total field.

The wakefield excitation by a sequence of bunches in multimode zirconia dielectric (ε = 23; $tg\delta = 10^{-3}$) rectangular resonator was carried out. At resonant conditions prevailing excitation of principal mode to the level 200 V/cm was observed. Such low level is caused by large loss tangent.

It is demonstrated the presence of excited second radial mode at a frequency 6.7 GHz in the resonator of the cylindrical geometry and the frequencies of several transverse modes for a rectangular geometry, whose contribution to the total wake field is not essential unlike to the case of the waveguide. The reason of this inessentiality, which does not to allow enhancing the total wakefield, is nonmultiplicity of the mode frequencies to the principal mode frequency and therefore not getting into the resonance with bunch repetition frequency and eigen frequency of the resonator.

2. "INJECTION" PROBLEM FOR BUNCHES ACCELERATION [15]

To solve the "injection" problem using introducing detuning between bunch repetition frequency and frequency of excited wakefield, that allows obtaining driving and accelerated bunches from the same sequence. For the case of introduced detuning the theoretical and experimental studies of the wakefield excitation in the dielectric waveguide/resonator by a part of electron bunches-drivers of a periodic sequence and the acceleration by this wakefield of the other part of the bunches-witnesses of the same sequence. Such situation becomes possible due to successive shift of bunches by phase of excited wakefield. In the performed experiments the frequency of dielectric wakefield is fixed and determined by the Cherenkov resonance (coincidence the velocity of bunches and the phase velocity of the excited wave of the dielectric waveguide). The bunch repetition frequency is varied by change of the frequency of master oscillator "Rubin" of klystron amplifier. In this concept of "excitation- acceleration" process using the same sequence of bunches there is no need for additional linac injector for bunches-witnesses producing, which simplifies the experimental demonstration of bunches acceleration in the excited wakefield.

In the case of resonance, i.e. coincidence of bunch repetition frequency f_{rep} and frequency of the principal mode of excited wakefield f_0 all bunches are occurred in the decelerating phase and lose energy to excite wakefield. In the presence of frequency detuning $\Delta f=f_{rep}-f_0\neq 0$ bunches of the first part of the sequence occurred in the decelerating phases of excited field lose energy to the increase in total wakefield and bunches of the next part of the sequence, shifted to the region of the accelerating phases of wakefield excited by the previous part of the sequence, gain an additional energy.

For point and monoenergetic bunches the number of bunches N^* of the first part of the sequence, exciting wakefield, evaluated from the phase shift of N^*-th bunch on π is equal $N^*=f_{rep}/2\Delta f$. The next part of the sequence of bunches of the same duration is accelerated.

Calculated electron energy spectra for monoenergetic bunches in the single-mode approximation for the cases of infinitely thin ring bunches (red) and bunches with rectangular longitudinal and transverse profiles (blue) are shown in Fig. 17. Following parameters of the dielectric waveguide and the sequence of electron bunches are taken: radius of the metal tube is $b = 4.325$ cm, radius of the transit channel is $a = 1.44$ cm, dielectric constant is $\varepsilon = 2.1$, radius of the bunches is $r_b / a = 0.5$, number of bunches in the sequence is $N = 500$, charge of bunch is $Q = 0.32\cdot 10^{-9} C$, detuning value was chosen to be $\Delta f/f_{rep}$= 0.002, $\tau_b = \omega_1 t_b = \pi / 3$ is the duration of a single bunch.

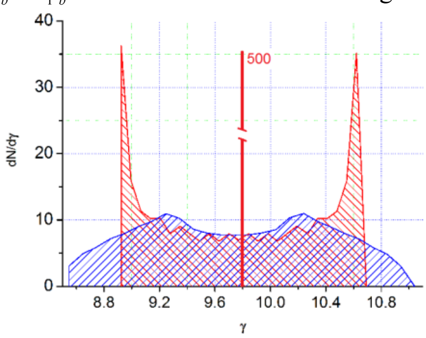
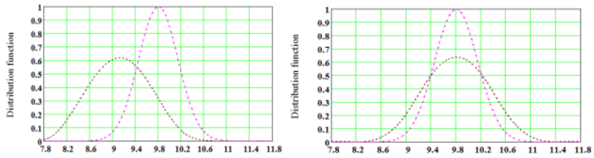


Fig. 17. Electron energy spectra for a sequence of 500 infinitely thin ring bunches (red) and rectangular ones(blue) at detuning $\Delta f/f_{rep}$=0.002

It is seen that in the case of an infinitely thin ring bunches energy spectrum of interacted bunches has two narrow maxima (red) corresponding to the accelerated and decelerated bunches. Maximal increase of the relativistic factor is $\Delta\gamma = 0.9$ or 410 keV for the initial energy 4.5 MeV. For bunches with finite longitudinal and transverse dimensions broadening of the energy spectrum is essential (blue). Instead of narrow peaks two poorly defined maxima are occurred. More broadening of the energy spectrum is caused by existence of accelerating (decelerating) wakefield gradient inside the electron bunches.

Let us take into account also existing in the experiment the initial electron energy spread of the bunch, which is described by a model distribution function $f_0 = \frac{1}{\sqrt{\pi}\Delta\gamma} e^{-\frac{(\gamma-\gamma_0)^2}{\Delta\gamma^2}}$, where $\Delta\gamma$ is characteristic spread of relativistic factor, γ_0 is its averaged value. We consider injection of a sequence of relativistic electron bunches into dielectric resonator without losses in the presence of detuning between the bunch repetition frequency and wakefield frequency. In Fig. 18 the electron energy distribution function before and after interaction for initial energy spread $\Delta\gamma = 0.5$ and number of bunches is $N = 1000$ is presented.



a *b*

Fig. 18. Initial distribution function f_0 (red line), final distribution function f (black line): a – $\Delta f/f_{rep}$ =0; b – $\Delta f/f_{rep}$ = 0.001

It can be seen that for the resonant case *Δf/frep*=0 the distribution function is shifted to the left as a whole, i.e. all electrons lose their energy for wakefield excitation. For the case of detuning $\Delta f/f_{rep}$=0.001 distribution function broadening caused by deceleration and acceleration of electron bunches takes place. Maximize energy in this case is about 175 keV.

Fig. 19,a,b shows obtained energy spectra of the electrons of the beam passing through the resonator without dielectric when there is no Cerenkov interaction of bunches with the resonator (black spectra, which are close to the initial ones at the resonator input) and through the resonator with a dielectric tube (red spectra obtained after excitation of wakefield and interaction with it) for two cases: resonant one (zero detuning Δf=0, see Fig. 19,a) and nonresonant one (nonzero detuning Δf=2.5 MHz, see Fig. 19,b).

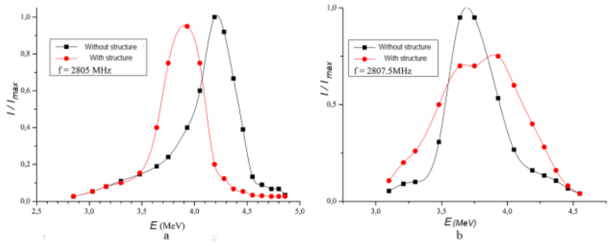


Fig. 19. Energy spectra of electron bunches passing through the resonator without dielectric (black curves) and a resonator with dielectric tube (red curves): a – Δf=0; b – $\Delta f = f_{rep} - f_0$ = 2.5 MHz

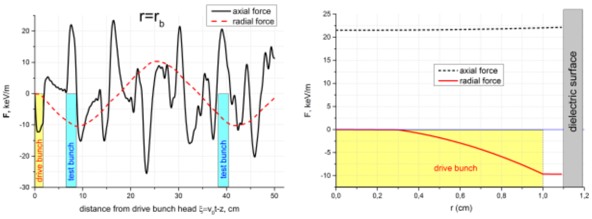
From Fig. 19 follows that at the presence of dielectric in the case of resonance Δf = 0 the energy spectrum is shifted by 400 keV as a whole to lower energies that is caused by the energy loss of all the bunches on the wakefield excitation. In the case of detuning between the bunch repetition frequency and the frequency of wakefield $\Delta f = f_{rep} - f_0$= 2.5 MHz a part of bunches of the sequence, shifting over phase, falls into the accelerating phase of the wakefied excited by previous bunches of the same sequence and gain energy. In this case, in the electron energy spectrum there are observed both the electrons losing energy (-150 keV) and electrons gaining additional energy (+150 keV).

By detuning it can be regulated the number of bunches from the sequence which excite the wakefield, and the number of subsequent bunches from the same sequence that fall into the accelerating phase of the wakefield and gain additional energy. With increase of frequency detuning the conditions arise when wakefield beating is observed with several parts of the sequence consisting of decelerated and accelerated bunches.

3. PLASMA-DIELECTRIC VERSION [16]

The presence of plasma in the channel for bunches transit allows compensating space charge of bunches and preventing bunch electrons hit the dielectric wall, and thus improve the bunches propagation through the channel and increase the excited wakefield amplitude at exit. In addition, plasma changes the dispersion characteristics of waveguide/resonator and wakefield topography in the channel excited by a sequence of bunches at Cherenkov resonance.

Note that in considered case the wakefield consists of the dielectric field modified with plasma and pure plasma field excited at different frequencies, except coincidence of plasma frequency ω_p and frequency of the modified dielectric field ω_0 (ω_p=ω_0). Different frequencies allow in case of the scheme with a single driver-bunch and a single bunch-witness to place bunch-witness in the phase where it will be accelerated by a large longitudinal dielectric field (its radial field for relativistic bunches is insignificant) and focused by a large radial plasma field (Fig. 20).



a *b*

Fig. 20. a – axial profile of longitudinal (solid) and transverse forces (dashed), acting on a test bunch at a distance of 0.95 cm from the waveguide axis; b – radial profile of longitudinal (solid) and transverse (dashed) forces acting on a test bunch located in the first maximum of accelerating field at a distance of 7.56 cm from the head of driver bunch

The performed theoretical studies of electrodynamics of dielectric waveguide with an axial transit channel, filled with plasma show that the presence of plasma in transit channel leads to changes in the topography of the principal mode of the dielectric wakefield, so that in the channel r=0…1.0 cm wakefield becomes volumetric. Caused by this the growth of the coupling coefficient of bunches with a wave provides an increase of the longitudinal field amplitude in the channel more for higher plasma density (Fig. 21).

For a sequence of bunches the situation is complicated by the fact that the presence of plasma in the channel violates the resonance condition of the coincidence bunch repetition frequency ω_{rep} and frequency of the dielectric field ω_0 modified with plasma. As a result at the presence of plasma the total wakefield beat is arisen with significantly reduced amplitude. Nevertheless a single bunch scenario can be realized for the long sequence of bunches if we take the waveguide length $L = \lambda$ (see section 1.2).

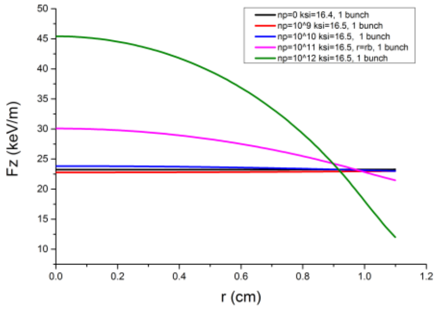


Fig. 21. Topography of wakefield excited by a single bunch in transit channel of cylindrical dielectric waveguide filled with plasma of various plasma densities

The situation becomes more complicated in the resonator case because of the need to comply with additional resonance with the eigen frequencies of the resonator ω_n, i.e. $\omega_{rep} = \omega_0 = \omega_n$

3.1. EXPERIMENTAL SETUP

The scheme of experimental setup is shown in Fig. 22. Relativistic electron bunches penetrate through a titanium foil with a thickness of 30 μ and enter into the dielectric waveguide of round cross section, filled with dielectric with transit channel of diameter 21 mm for the passage of bunches.

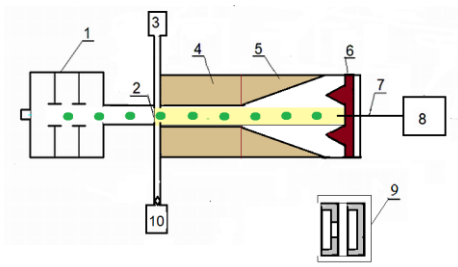


Fig. 22. Scheme of experimental setup: 1 – accelerator; "Almaz-2M"; 2 – titanium foil; 3 – vacuum meter; 4 – dielectric waveguide; 5 – dielectric microwave matcher; 6 – ferrite absorber; 7 – microwave probe; 8 – oscilloscope; 9 – double Faraday cup; 10 – vacuum pump

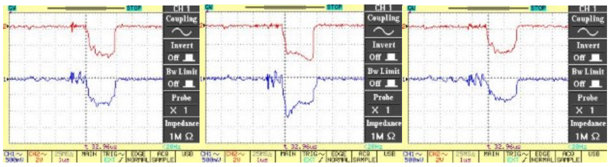
For realization of the waveguide case it is needed to avoid reflections of the excited wakefield. For this purpose, the dielectric insert is ended with dielectric microwave matcher, and on Teflon vacuum cap ferrite absorber is placed. For obtaining single bunch regime the length of the dielectric insert was chosen equal to length of the excited dielectric wave $L = \lambda$.

Plasma in the transit channel of the dielectric waveguide is produced by the beam itself when it passes through the neutral gas of regulated pressure filling the transit channel due to the beam-plasma discharge (BPD) with the excited wakefield developing at pressure 1 Torr and due to the collisional ionization by beam electrons at higher pressures.

To study focusing relativistic electron bunches double Faraday cup (9) is used in which the focusing effect is determined by the presence of the beam current increase in the second cup and a simultaneous decrease in the beam current in the first cylinder.

3.2. EFFICIENCY OF WAKEFIELD EXITATION

As shown by the oscillograms of the microwave signals envelope obtained by means of a microwave probe placed at the exit of the dielectric waveguide having a dielectric insert of length $L = \lambda$ under neutral gas pressure in the transit channel in range 0.02...1 Torr, the amplitude of excited wakefield (see Fig. 22,b) exceeds the amplitude of wakefield excited in the dielectric waveguide without plasma (see Fig. 23,a,c).



a b c

Fig. 23. Oscillograms of the envelope of the microwave signals of wakefields (blue) for various gas pressure: a – $P = 10^{-3}$ Torr; b – 0.5 Torr; c – P = 140 Torr. Red oscillograms – beam current

In the case of a waveguide and a single bunch regime the dependence of the amplitude of the excited longitudinal wakefield on the axis for the wide range of the gas pressure is shown in Fig. 23 (red curve). It is seen that in the pressure under which BPD develops and plasma is formed the wakefield wave topography in the channel becomes volumetric (in agreement with the theory (see Fig. 21)), that increases the coupling coefficient of the bunch with the wakefield wave and leads to the increase in the excited wakefield amplitude compared with the case without gas injection (Fig. 24, horizontal red line).

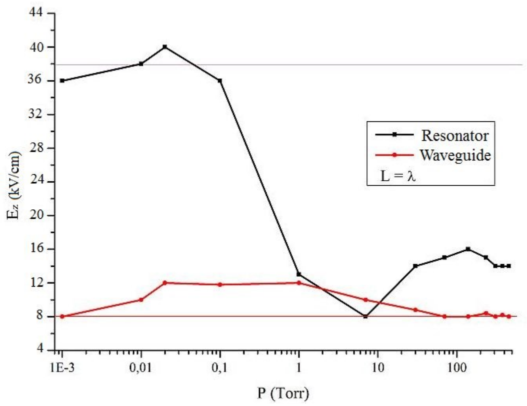
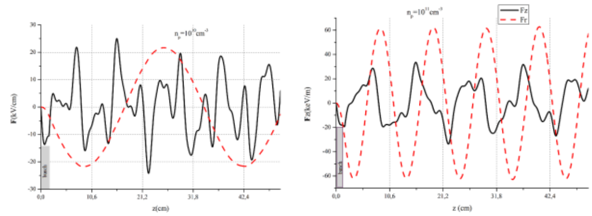


Fig. 24. Dependence of excited wakefield Ez upon neutral gas pressure in the transit channel

In the case of dielectric resonator (matching elements were removed and metal exit plug was installed) under conditions of the double-resonance $\omega_0 = \omega_{rep} = \omega_n$ (coincidence of Cherenkov frequency ω_0 with bunch repetition frequency ω_{rep} and simultaneously with eigen frequency of the resonator ω_n the wakefield amplitude grows significantly. This is due to the fact that the number of bunches which contribute to the total wakefield is limited only by Q-factor (for conventional Q it is hundreds of bunches), whereas in the case of the waveguide the number of bunches, determined by the waveguide length and the group velocity, does not exceed tens of bunches. However, unlike the waveguide case with a single bunch regime in the resonator case all bunches involved in wakefield build-up excitation, i.e. bunch repetition frequency ω_{rep} comes into play, and resonator eigen frequencies ω_n are present.

3.3. FOCUSING DRIVER-BUNCHES

In the case of the waveguide (matched exit) in a single bunch regime ($L = \lambda$) both mentioned resonances are absent and all bunches are in the same conditions of exciting bunches-drivers. Fig. 25 shows theoretically obtained [17] the dielectric and plasma wakefields excited by a single bunch for two plasma densities.

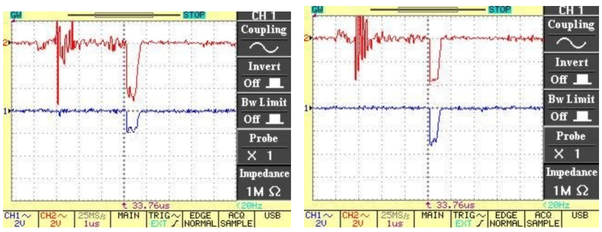


a b

Fig. 25. The total longitudinal component of dielectric and plasma wakefields (solid, black) and transverse component of plasma wakefield (dashed, red) for plasma densities: a – $n_p=10^{10}$ cm^{-3}; b – $n_p=10^{11}$ cm^{-3}.

It is seen that the bunch of finite length and finite radius is occurred in its own wakefield – longitudinal dielectric (decelerating) and radial plasma (focusing) ones. Radial defocusing dielectric field with its almost uniform longitudinal field over radius is insignificant. As a result bunch-driver will be focused by its excited plasma wakefield along with the focusing due to compensation in the plasma of its radial electric field [18].

Fig. 26 shows the waveform of the beam current, experimentally obtained with a double Faraday cup at vacuum $P = 10^{-3}$ Torr (see Fig. 26,a) and at neutral gas pressure in the transit channel of dielectric waveguide P = 0.5 Torr (see Fig. 26,b), when plasma is intensively produced. The increase in current in the second cup while its reducing in the second one for the second case evidences focusing electron bunches, more at a higher plasma density for gas pressure P = 0.5 Torr.



a b

Fig. 26. Oscillograms of beam current taken from double Faraday cup: top – first cylinder; bottom – second cylinder; a – $P = 10^{-3}$ Torr; b – P = 0.5 Torr

4. CHANGE OF ELECTRODYNAMIC AND MECHANICAL PROPERTIES OF DIELECTRIC MATERIALS UNDER ELECTRON BEAM IRRADIATION

Irradiation of samples made from zirconium nanoceramics (ZrO_2-4 wt% MgO) was carried out by using electron linac LUE-40 with electron beam energy up to 100 MeV. There were 20 samples irradiated with different fluencies of the electron beam (from $2 \cdot 10^{16}$ to $2 \cdot 10^{18} cm^{-2}$) and the energy of the particles up to 90 MeV. The change in temperature of samples during irradiation did not exceed 100°C. Studies of the irradiated samples allowed obtaining the information about induced activity and changes in the electrodynamics' and mechanical properties of zirconium nanoceramics. A measurement of change of the dielectric properties of nanoceramic samples with a diameter of 10 mm and thickness 2.5 mm was carried out by using the resonator method with a partial/full filling RF cavity. Comparison of the resonant frequency and Q-factor of resonators before and after irradiation showed the followings:

- permittivity is reduced by (0.23±0.02)%;
- loss tangent was not changed within range ±3%.

To investigate the influence of electron irradiation on the mechanical properties of zirconium nanoceramics two samples ZrO_2-4 wt% MgO with diameter of 10 mm were selected. The first of them was irradiated by electron beam with energy of 45 MeV, the second one was irradiated by electron beam with energy of 89 MeV. The fluence was $2 \cdot 10^{16}$ cm^{-2}. Studies of the samples showed that irradiation leads to phase transitions in the structure of the dielectric, and to phase transformation of cubic zirconia. In the grains under irradiation by the electron beam with energy of 45 MeV the formation of lens-shaped grains of tetragonal phase took place. With increasing electron beam energy to 89 MeV these grains grow and turn into crystals of lamellar shape. These changes in the structure of the zirconium nanoceramics lead to the formation of a composite structure. At that the fragility of the material is decreased and hardness is decreased from 12.2 to 10.8 and 10.5 GPa after irradiation of the ceramic material by the electron beam with energy 45 and 89 MeV, respectively.

CONCLUSIONS

The possibility of wakefield amplitude enhancing in "multibunch", "multimode" and "resonator" regimes of the excitation is theoretically and experimentally investigated. It is shown that the coherence at coincidence of bunch repetition frequency and excited wakefield frequency in "multibunch" regime and the accumulation of wakefields at multiplicity of eigen frequencies of the resonator to the bunch repetition frequency and excited wakefield frequencies in "resonator" regime provides enhancement of the total wakefield. Impossibility to realize coincidence/multiplicity of mentioned frequencies with Cherenkov resonance frequencies of transverse modes because of their nonequidistance causes insufficiently effective enhancing of the total wakefield amplitude.

The acceleration of bunches in wakefield excited by bunches of the same sequence at introduction of detuning between bunch repetition frequency and excited wakefield frequency is demonstrated.

It is found that the presence of plasma in the transit channel leads to the excitation of the plasma wakefield which focuses both driving and accelerated bunches.

Determined that the irradiation of samples made from zirconium nanoceramics (ZrO_2-4 wt% MgO) by 100 MeV electron beam with fluency of order 10^{18} cm^{-2} changes the dielectric permittivity by 0.2%, that is sufficiently to destroy the conditions of Cherenkov resonance in the acceleration process.

Mechanical properties of zirconium nanoceramics are changed too. Fragility is decreased and hardness is reduced.

ACKNOWLEDGEMENT

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ИССЛЕДОВАНИЯ ФИЗИЧЕСКИХ ПРОЦЕССОВ В МУЛЬТИБАНЧЕВОМ ДИЭЛЕКТРИЧЕСКОМ КИЛЬВАТЕРНОМ УСКОРИТЕЛЕ

И.Н. Онищенко

Представлены основные результаты теоретических и экспериментальных исследований физических процессов в диэлектрическом кильватерном ускорителе, основанном на возбуждении ускоряющего кильватерного поля в диэлектрической структуре длинной последовательностью электронных сгустков. Увеличение амплитуды возбуждаемого кильватерного поля достигается за счет когерентного сложения кильватерных полей отдельных сгустков, суммирования полей эквидистантных поперечных мод и накопления полей в резонаторе. Ускорение сгустков в суммарном кильватерном поле реализовано разделением последовательности сгустков на возбуждающую и ускоряющую части в любом соотношении с помощью соответствующей расстройки частоты следования сгустков по частоте возбуждаемой основной поперечной моды. Исследовано изменение диэлектрической проницаемости и тангенс угла потерь применяемых диэлектриков под воздействием радиационного облучения их 100 МэВ-электронным пучком.

ДОСЛІДЖЕННЯ ФІЗИЧНИХ ПРОЦЕСІВ У МУЛЬТІБАНЧЕВОМУ ДІЕЛЕКТРИЧНОМУ КІЛЬВАТЕРНОМУ ПРИСКОРЮВАЧІ

І.М. Оніщенко

Представлено основні результати теоретичних і експериментальних досліджень фізичних процесів у діелектричному кільватерному прискорювачі, заснованому на збудженні прискорюючого кільватерного поля в діелектричній структурі довгою послідовністю електронних згустків. Збільшення амплітуди збуджуваного кільватерного поля досягається за рахунок когерентного складання кільватерних полів окремих згустків, підсумовування полів еквідистантних поперечних мод та накопичення полів у резонаторі. Прискорення згустків у сумарному кільватерному полі реалізовано поділом послідовності згустків на збуджуючу і прискорювану частини в будь-якому співвідношенні за допомогою відповідної розстройки частоти слідування згустків щодо частоти збуджуваної основної поперечної моди. Досліджено зміну діелектричної проникності і тангенс кута втрат застосовуваних діелектриків під впливом радіаційного опромінення їх 100 МеВ-електронним пучком.