DIELECTRIC WAKEFIELD RESEARCHES

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Excitation of wakefields in cylindrical dielectric waveguide/resonator by a sequence of relativistic electron bunches was investigated using an electron linac «Almaz-2» (4.5 MeV, $6\cdot10^3$ bunches of duration 60 ps and charge 0.32 nC each). Energy spectrum of electrons, radial topography and longitudinal distribution of wakefield, and total energy of excited wakefield were measured by means of magnetic analyzer, high frequency probe, and a sensitive calorimeter.

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1. INTRODUCTION

Dielectric wakefield acceleration (DFWA) is one of the novel methods of high gradient acceleration of charged particles, along with laser acceleration in plasma and vacuum. Three issues arise in connection with intense wakefield excitation in a dielectric. The wakefield in a dielectric (Cherenkov radiation) excited by charged particles can be enhanced by using a regular sequence of relativistic electron bunches (multi-bunch operation) [1], interference of many transverse modes to enlarge peak amplitude (multi-mode operation) [2], and resonant accumulation of wakefield in a cavity resulting from many bunches (resonator concept) [3]. We wish to exploit the third approach while retaining the other two. In the present work we attempt to clarify by theory and experiments the process of wakefield excitation in a cylindrical dielectric waveguide and resonator using a long sequence of relativistic electron bunches. The temporal evolution and spatial distribution of the excited wakefield are investigated by HF probes for both waveguide and resonator cases and comparison was made. Electron energy loss measured by a magnetic analyzer and the total energy of the excited HF wakefield measured by a calorimeter were compared to determine the energy balance. Conclusions concerning the increase in the number of coherently contributing bunches and the efficiency enhancement in the resonator approach are made.

2. THEORY

For a semi-infinite dielectric waveguide without a channel for the bunches the problem of wakefield excitation was solved analytically [4]. There are two new peculiarities compared to the case of the infinite waveguide: appearance of transition radiation and wakefield removal with group velocity from the waveguide entrance. As a result, the net field amplitude grows from the entrance to the trailing edge of the first bunch field and then decreases to the position of the first bunch. The field amplitude at a given cross-section grows and after the passage of several bunches it saturates; however, the saturation level does not depend on the total number of bunches but is determined by the distance to the entrance.

The more complicated problem of including a hole for the bunches was solved in cylindrical geometry for a waveguide of finite length [5] and for a resonator [6]. Due to wakefields moving along the system with group velocity, the number of bunches whose wakefields can be coherently added giving maximum amplitude at the waveguide exit, is restricted in the first case by

$$N_{\max} \approx 1 + L/\Delta z\left(v_0/v_g - 1\right) \qquad (1)$$

where L is waveguide length, Δz is distance between bunches, v_0 and v_g are the bunch velocity and group velocity, respectively. The presence of the hole results in the appearance of oscillations with the group velocity of light in vacuum. These oscillations move ahead of bunch and form a weak field precursor. For the resonator, a single bunch excites a multibunch wakefield which is the same as the field in a semi-infinite waveguide [4] until it is reflected from the resonator exit. Excitation by a sequence of bunches results, first in the excitation of only the resonant fundamental mode, the frequency of which coincides with the bunch repetition frequency (mode-locking) and, secondly, in the linear growth of the field amplitude with time in proportion to the number of injected bunches. The saturation level is determined by a nonlinear electron-wave interaction for the KIPT experiment with 4 MeV bunches [6]. It might be supposed that for higher energy (e.g. an experiment with 0.5 GeV bunches) the saturation could be caused the Q-factor of the resonator.

To demonstrate both multimode and multibunch regimes in a resonator case, the rectangular dielectric resonator (still without a vacuum channel) which provides equidistant resonant modes, was theoretically investigated [7]. It was shown that multimode operation is realized under the condition:

$$L = Na\sqrt{\beta_0^2\varepsilon - 1}, \quad \beta_0 = v_0/c \qquad (2)$$

i.e. the length of the resonator L should be a multiple N of half-integer wave lengths of the resonant fundamental mode; a is transverse size; the other transverse size b is supposed much larger, ε is permittivity. For coherent summing of wakefields from injected bunches the coincidence of the fundamental mode frequency and the frequency f of bunch repetition should be fulfilled. This condition sets the transverse size of the resonator

$$a = v_0/2f\sqrt{\beta_0^2\varepsilon - 1} \qquad (3)$$

Conditions (5) and (6) are the basis of the resonator concept of the rectangular DWFA.

3. EXPERIMENT

Experiments to study the excitation of wakefields in a cylindrical dielectric structure (waveguide or resonator) were performed using the linear resonant electron accelerator "Almaz-2" at NSC KIPT.

3.1. EXPERIMENTAL SETUP

The scheme of the installation is shown in Fig.1. Electron beam had the following parameters: energy was 4.5 MeV, current was 0.5 A, impulse duration was 2 μsec, modulation frequency was 2820 MHz. In such a way we had a regular sequence of $6 \cdot 10^3$ bunches, 60 psec duration each with time interval between them 300 psec. Diameter and length of each bunch were 1.5 cm and 1.8 cm, accordingly.

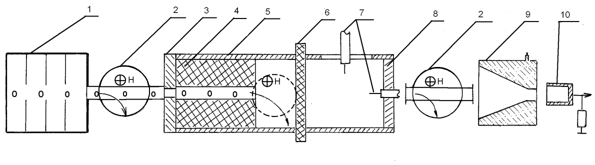

Fig.1. Scheme of experimental installation: 1 - linac; 2 - magnetic analyzer; 3 - apperture; 4 - dielectric; 5 -copper tube; 6 - teflon plate; 7 - HF probes; 8 - movable metal screen; 9 - calorimeter; 10 - Faraday cup

Such sequence of electron bunches was injected into dielectric structure made from Teflon Φ-4 (permittivity ε=2.1, $tg\delta=1.5 \cdot 10^{-4}$ for frequency $f=3 \cdot 10^9$ Hz). At entrance copper aperture of thickness 0.5 cm for no allowing halo electrons to penetrate into dielectric, and with a hole 2 cm diameter for bunches. Length of dielectric structure was changed up to 65 cm, outer diameter was 8.6 cm, diameter of the hole for injected bunches was 2.2 cm. Dielectric structure was placed into copper tube of length 100 cm.

In empty part of the tube after dielectric the movable high frequency (HF)-probes were installed. To separate vacuum chamber and to propagate out excited HF power into atmosphere the dielectric plate of thickness 0.8 cm was used, through which measured power loss was less 2%. At exit a movable metal screen or a matched load were applied to provide resonator of variable length or waveguide approaches, correspondingly. Before and after dielectric structure (waveguide/resonator) magnetic analyzers were used for energy spectrum measurements. Besides, transversal magnetic field can be applied to obtained electron energy spectrum as a whole on the glass plate of 3 cm thickness. In all cases the flow of bunch electrons (beam current) was measured with help of Faraday cup. The total power of excited wake fields was measured by specially constructed sensitive calorimeter [4].

3.2. WAKEFIED RESEARCHES

To measure amplitude of wake field the signal from HF-probes was transmitted by coaxial cable to attenuator and then to wavemeter on λ=10.7 cm (for comparison measurements were also performed without wavemeter). Further the signal propogated to detector DK-I-2M and to the oscilloscope. Preliminary calibration of the detector has shown that in the working range of current 0.04…12 mA the dependence of detector current upon amplitude of HF-field of the source was linear. Hence the signal from detector measured in the dielectric wake field experiment was proportional to the amplitude of excited wave. In order to avoid influence of electrons on measurements bunches were deflected on the tube walls by means of permanent magnetic field.

Transversal topography of excited field is found to be almost azimuth symmetrical. In Fig.2,a the radial dependence of E_r – component of the field is depicted (curve 1) with wavemeter. It is seen that this component is negligible on the axis and maximal on the radius 4 cm, i.e. near the tube wall. By the way at absence of dielectric amplitude of this field much smaller (curve 2) that proves Cherenkov nature of the excited field. The dependence of E_r – component without wavemeter complicated by higher modes is shown in Fig.2,b

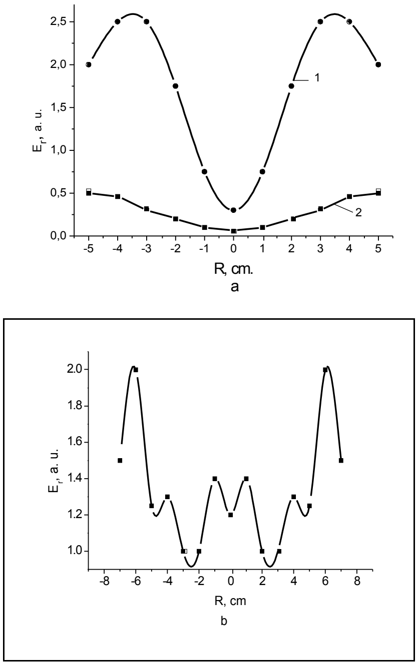

Fig.2. Radial dependence of E_r (a - with wavemeter on λ=10.7cm, b-without)

Radial dependence of longitudinal E_z – component of the field is shown in Fig.3 with maximum on the axis and negligible value near the wall. The dependence of E_z – component without wavemeter complicated by higher modes is shown in Fig.3,b.

Such topography of the excited field allows to conclude that in the present experiment E_{01} – wave is excited. To judge about the part of higher radial modes the beyond-cutoff waveguides were used. It was proved that their total contribution is less than a half of fundamental mode. This means that in present experiment with cylindrical dielectric wave guide the sequence of $6 \cdot 10^3$ bunches excite mainly fundamental mode. This results confirms theoretical conclusion [5] explained by lack of coincidence of fundamental frequency and bunch repetition frequency with difference frequency between non-equidistant frequencies of higher modes. Under these conditions only resonant fundamental mode survives. Other modes are almost suppressed due to the interference.

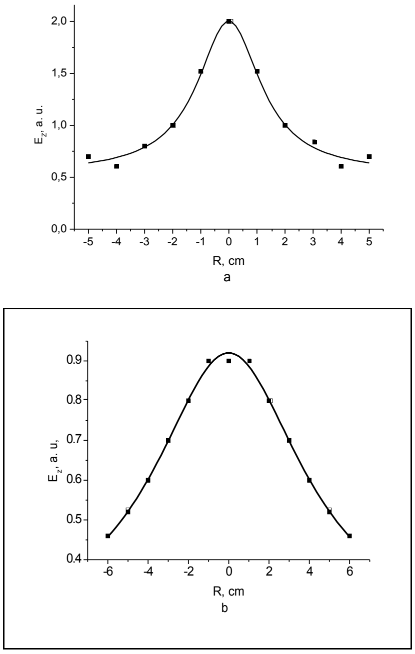

Fig.3. Radial dependence of E_z (a - with wavemeter on λ=10.7 cm, b - without)

Longitudinal distribution of excited fields in the semi-infinite waveguide (with entrance end) was measured by the following way. Because of difficulties to input HF-probes into the hole for bunches in dielectric without spoiling the interaction of the bunches with dielectric structure we cut dielectric cylinder into several pieces of various length (1,2,5, and 10 cm) and measured electric field at exit of dielectric structure composed of some number of dielectric pieces to assemble needed length. As exits of each composition was matched by means conical dielectric piece to avoid reflection these measurements are equivalent to longitudinal measurements in the whole dielectric structure. The results of measurements of E_z after passing of a long train of $6{\cdot}10^3$ bunches are depicted in Fig.4 (curve 1). It was observed the linear growth of amplitude of longitudinal component of the field along the dielectric waveguide. It proves theoretical result [6] accordingly to which at the time when $N_{max} = 1+L/\Delta z(v_0/v_g-1)$ bunches passed through the structure the linear stationary longitudinal distribution of E_z has been established. The incline of this linear distribution is determined by group velocity and bunch charge.

In the case of resonator the longitudinal distribution of E_z obtained by measuring E_z at the exit end of each insert consisting of needed number of dielectric pieces is depicted in Fig.4 (curve 2). At that dielectric inserts were placed into the same copper tube with reflecting entrance and exit ends. By this way the dielectric resonator of variable length was realized. Note that dielectric fills only part of metal resonator length, so we have somewhat complicated resonator Nevertheless it allow revealing all peculiarities of wake field excitation. As it is seen from Fig.4 electric field amplitude is much more (almost by order) comparatively to the waveguide case. At that the longitudinal dependence has resonant character.

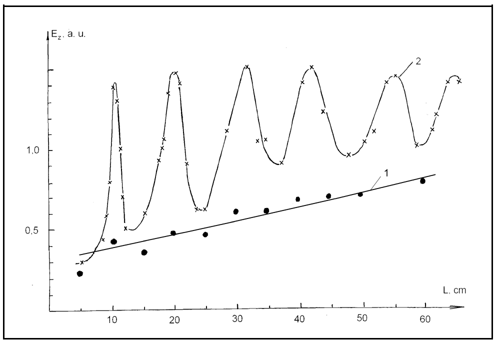

Fig.4. E_z of wake field in dependence on dielectric length: 1 - waveguide; 2 - resonator

Both results are due to proposed speculation and theoretical estimations. Accumulation of wake field in dielectric resonator of appropriate length was proposed in [7] that aims to enlarge the number of coherently contributing bunches. In experiment deriving from amplitude values at assumption that amplitude is proportional to number of contributing bunches we conclude that resonator allows to enlarge the number of contributing bunches approximately by 4 times for length 10 cm and 2 times for length 65 cm. In principle for ideal resonator this number for resonator should be infinite. Observed saturation of amplitude in time (see below) is probably caused by nonlinear interaction of “averaged” electron with excited wave, resulting in averaged zero energy exchange. Resonant dependence is caused by effective excitation at coincidence (or multiplicity) of eigen resonator frequencies with frequency of bunches repetition. The noticeable growth of resonance half-widths δL with length L increase can be explained by the following way. Deviation δL of length L near resonant longitudinal mode $k_l = \pi l/L$ results in frequency detuning $\delta\omega$ of Cherenkov resonance between beam ($\omega_l = k_l v_0$) and resonator oscillations ($\omega_{ml}^2 = c^2(k_l^2+k_m^2)/\varepsilon$): $\delta\omega = |\delta\omega_l - \delta\omega_{ml}| = \omega_0(1-c^2/\varepsilon v_0^2)\,\delta L/L$. Here k_l, k_m are longitudinal and transverse wavenumbers, $\omega_0 = v_0\pi l/L$ is resonant frequency, near which we consider detuning $\delta\omega$. Supposing that detuning $\delta\omega$, needed to disadjust Cherenkov resonance, is constant for arbitrary length L we find: $\delta L = \delta\omega L/\omega_0(1-c^2/\varepsilon v_0^2)$, i.e. $\delta L \sim L$, that is in accordance with theoretical results [5]. For application it means that for shorter resonator the requirements on the precision of the resonator length fabrication should be stronger.

To judge about the influence of radial field on transversal declining of electrons the imprints of electrons on glass plate were used. In Fig. 5 the imprints are depicted for bunches at accelerator exit (picture 1), after bunches passage dielectric resonator of length 30 cm (picture 2), and of length 65 cm (picture 3). It is seen that diameter of bunches became larger with dielectric length increasing due to scattering by intense radial wake field excited in resonator. For the waveguide case noticeable expansion of bunches diameter is not observed because of much smaller excited wake field. Visible asymmetry of the imprints requires further investigation.

Electrons are dispersed so that many of them leave the channel for beam and propagate in dielectric changing its structure.

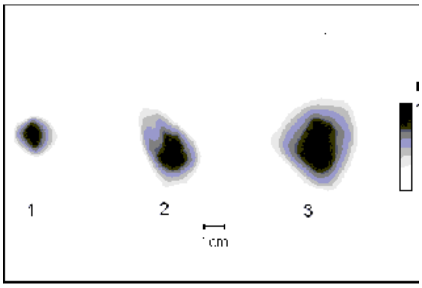

Fig.5. Imprints of electron bunches on glass plate:
1 - at accelerator exit; 2 - dielectric resonator of length 30 cm; 3 - dielectric resonator of length 65 cm

It confirms by measuring beam current with movable Faraday cup of diameter 3 cm for three cases: without dielectric, with dielectric length 30 cm, and length 65 cm. Comparatively to vacuum case current decrease was 15% and 30% for 30 cm and 65 cm, accordingly. It should be noted that as it follows from theory, in spite of electrons loss the long dielectric resonator is excited to the same field amplitude as for lossless case. It can be explained by very long train of bunches in our experiment – so bigger number of bunches participate in excitation process to compensate partial loss of electrons and achieve the same level of saturation.

3.3. WAVEGUIDE AND RESONATOR APPROACHES

To determine increase of number of coherently contributing bunches in resonator approach we have changed the duration of beam current impulse. It was achieved by time delay of HF-impulse of master oscillator of klystron feeding linac with respect to high voltage impulse applied to klystron. It results in duration change of HF-power impulse applied to accelerating section and in obtaining beam duration in the range τ=0.1…2.0 μsec without changing other beam parameters. So we could compose trains of bunches beginning with minimal number of bunches 300.

Results of measuring of excited field amplitude dependence upon number of passing bunches, i.e. upon beam impulse duration, for both approaches are shown in Fig. 6 for dielectric length 30 cm. It is seen that for waveguide case (curve 1) amplitude achieves its saturation caused by group velocity effect [6] at time less 0.1 μsec (i.e. N_{max}<300). According to theory [5] for experimental conditions $v_0/v_g=2$, so $N_{max}^{theory}=3$. Unfortunately instrumental possibilities do not allow to make less number of injected bunches. For resonator case (curve 2) saturation time much more and makes 0.3 μ sec (i.e. N= 900 bunches). Accordingly field amplitude is much larger. Hence the number of contributing bunches in waveguide case can be estimated by amplitudes ratio 4 for L=30 cm and should be approximately N_{max}=225. It greatly exceeds theoretical value. Such discrepancy with theory should be explained in further researches, along with revealing the physical mechanism of amplitude saturation. At the moment we suppose that the main reason of saturation is nonlinear particle-wave interaction that is essential for low electron energy.

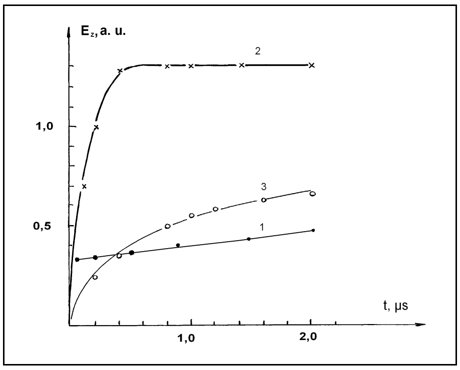

Fig.6. Amplitude of wake field in dependence on impulse duration (number of bunches) for dielectric length 30 cm: 1 - waveguide; 2 - resonator, current 0.5 A; 3 - resonator, current 0.25 A

For smaller in 2 times beam current (curve 3) field amplitude grows slower and does not achieve saturation during beam impulse. It confirms by oscillograms of signals from HF probes (Fig.7) for beam current 0.25A (upper oscillogram) and 0.5A (bottom oscillogram). For bigger current signal quickly achieves its maximum and further practically repeat beam current signal, meanwhile for smaller current signal slowly grows during all current impulse no achieving saturation. It is agreed with temporal dependence of excited field for resonator and waveguide cases (Fig.6).

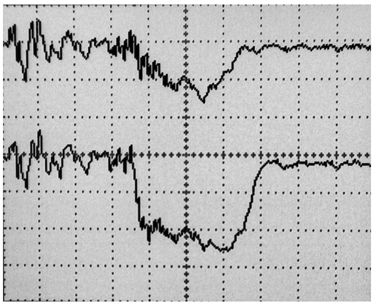

Fig.7. Oscillograms of E_z signal:
Upper-beam current 0.25 A; Bottom- 0.5 A

3.4. ENERGY LOSS OF ELECTRON BUNCHES

To judge about electron energy losses the energy spectra of electron were measured by magnetic analyzers at accelerator exit (initial spectrum) and after passing dielectric resonator at distance 100 cm from linac exit (spectrum after excitation). In Fig.8 initial spectrum (1) and spectrum after excitation (2) are presented for dielectric length 30 cm (Fig.8,a) and length 65 cm (Fig.8,b). It can be derived that energy loss is 7% and 12%, correspondingly. A small number of accelerated electron are also observed.

These results are in accordance with researches of electron bunches imprints on glass plate after deflecting in magnetic field and passing copper tube wall. In Fig.9 imprint 1 corresponds to the case of dielectric absence, imprint 2 corresponds to dielectric resonator of length 65 cm. It is seen the displacement of spectrum as a whole on about 0.5 MeV into low energy side (loss for wake field excitation) and spectrum transformation into high energy side (evidence of electrons acceleration in wake field).

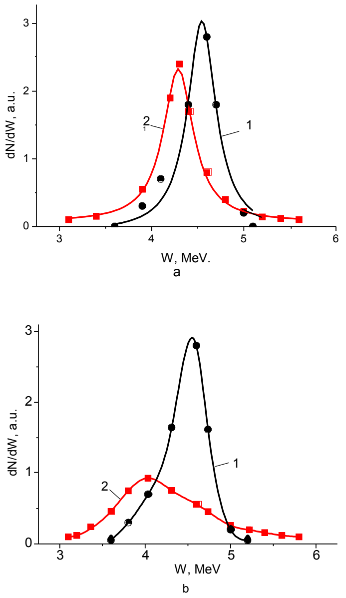

Fig.8. Electron energy spectra measured by magnetic analyzer: 1-initial spectrum at accelerator exit; 2 -after passing resonator; (a) – dielectric length 30 cm; (b) - dielectric length 65 cm

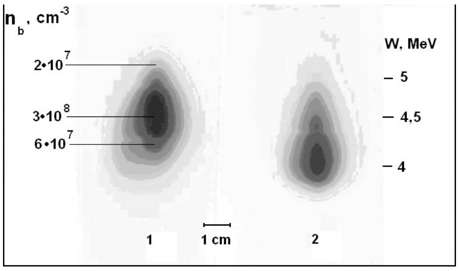

Fig.9. Energy spectra of electrons deflected and passed through tube wall: 1 - without dielectric; 2 - dielectric resonator of length 65 cm

For a half of beam current (Fig.10 curve 2) energy loss much less comparatively to full current (Fig.10 curve 1). It is explained by lower amplitude of excited wake field. It should be marked that in both cases beam current after passing dielectric resonator are almost equaled. It means that for full current many electrons are dispersed by radial electric field more intense for resonator case. It needs to be taken into account at estimation of number of coherently contributing bunches and saturation for various dielectric lengths.

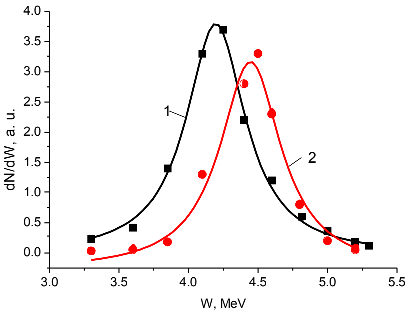

Fig.10. Electron energy spectra measured by magnetic analyzer for dielectric resonator of length 65 cm:
1 - current 0.5 A; 2 - current 0.25 A

To compare energy loss of bunches on wake field excitation in waveguide case with resonator case the HF-absorbing load was placed at dielectric exit in order to avoid radiation reflection at analyzer installing. To compare energy loss of bunches on wake field excitation in waveguide case with resonator case the HF-absorbing load was placed at dielectric exit in order to avoid radiation reflection at analyzer installing.

In Fig.11 initial energy spectrum (curve 1) and spectrum for waveguide with absorbing load (curve 2) are shown. It is evident that for waveguide case energy loss is much smaller comparatively to resonator (Fig.8,b) and makes only 3%.

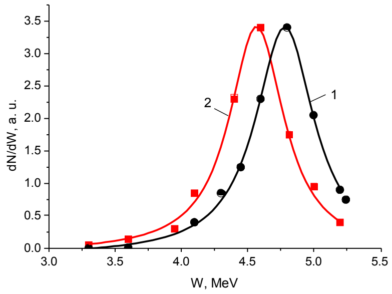

Fig.11. Electron energy spectra measured by magnetic analyzer for dielectric length 65 cm:
1-initial spectrum;
2-after passing dielectric waveguide 65 cm

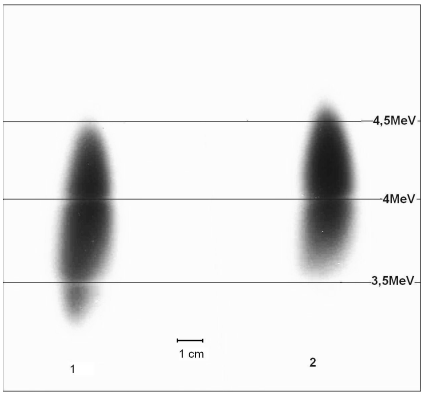

Fig.12. Energy spectra of electrons deflected and passed through tube wall: 1 - resonator; 2 - waveguide

Qualitative confirmation of it was demonstrated by making imprints of deflected electrons, which passed through tube wall. In Fig.12 imprint 1 and 2, accordingly for waveguide with absorbing load and resonator of the same length 65 cm are presented. It is seen that for waveguide energy loss essentially less (about 3%) comparatively to resonator case, for which it makes 12% (Fig.8,b).

3.5. CALORIMETER MEASUREMENTS

The total energy of excited wake fields was measured by specially constructed sensitive calorimeter [1]. Electron bunches were deflected with magnetic field or passing them through hole in calorimeter. It was measured that total excited energy in waveguide case makes 1.4% of initial beam energy. At that the dependence on number of bunches in train is similar to observed one in field amplitude measurements (Fig.6, curve 1). To explain discrepancy of this result with twice more beam energy loss we measured damping of excited field in the used tube. It occurred that damping is 3 dB, i.e.2 times. So we conclude that all beam energy loss is expended on wake field excitation with reasonable balance.

CONCLUSIONS

Temporal dynamics and spatial distribution of wake field excited in cylindrical dielectric waveguide and resonator by a sequence of relativistic electron bunches have been investigated theoretically and in experiments.

1. Radial topography of excited wake field was studied and it was established that excited modes are of *E*-type with predominant E_{01}-mode.

2. By changing number of bunches in sequence from $3\cdot10^2$ up to $6\cdot10^3$ it was shown that in waveguide case wake field amplitude is built up by a small number of bunches less than 300 that is caused by excited field leaving with group velocity the interaction region of waveguide.

3. Resonator concept was verified, accordingly to which at right choice of resonator parameters and bunches repetition frequency, to make resonator length and distance between bunches multiple to wavelength of fundamental mode, all bunches coherently contribute and amplitude of wake field grows essentially. In presented experiment with resonator the number of coherently contributing bunches and field amplitude have increased by order for dielectric length 10.7 cm and 5 times for dielectric length 65 cm.

4. Electron energy spectra for waveguide and resonator approaches are measured from which it was derived that for electron beam of energy 4.5 MeV and current 0.5 A, and dielectric length 65 cm energy loss during interaction were 12% and 3% for resonator and waveguide, accordingly.

5. Calorimeter measurements being in accordance with HF-probes results allow to determine whole excited wake field energy. It is 2.8% of initial energy loss of electrons that is in satisfactory agreement with results of energy spectra measurements. Hence it is proved that all electron energy loss is expended on wake field excitation.

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ИССЛЕДОВАНИЯ КИЛЬВАТЕРНЫХ ПОЛЕЙ В ДИЭЛЕКТРИКЕ

В.А. Киселев, А.Ф. Линник, Т.С. Маршалл, Н.И. Онищенко, В.В. Усков

Исследовано возбуждение кильватерных полей в цилиндрическом диэлектрическом волноводе/резонаторе последовательностью релятивистских электронных сгустков на линейном электронном ускорителе «Алмаз-2» (4.5 МэВ, $6\cdot10^3$ сгустков длительностью 60 пс и зарядом 0.32 нКл каждый). Измерены энергетические спектры электронов, радиальная топография и продольное распределение кильватерного поля и его энергия с помощью магнитного анализатора, ВЧ-зондов и чувствительного калориметра.

ДОСЛІДЖЕННЯ КІЛЬВАТЕРНИХ ПОЛІВ У ДІЕЛЕКТРИКУ

В.О. Кисельов, А.Ф. Линник, Т.С. Маршалл, М.І. Онищенко, В.В. Усков

Досліджено збудження кільватерних полів у циліндричному діелектричному хвилеводі/резонаторі регулярною послідовністю релятивістських електронних згустків на лінійному електронному прискорювачі «Алмаз-2» (4.5 МеВ, $6\cdot10^3$ згустків тривалістю 60 пс і зарядом 0.32 нКл кожний). Виміряні енергетичні спектри електронів, радіальна топографія та поздовжній розподіл кільватерного поля та його енергія за допомогою магнітного аналізатора, ВЧ-зондів і чутливого калориметра.