INVESTIGATION OF MULTIBUNCH WAKEFIELD EXCITATION IN DIELECTRIC COMPOUND-RESONATOR

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Theoretical and experimental studies of the wakefield excitation in a dielectric compound-resonator by the train of electron bunches injected from the "Almaz-2M" accelerator are presented. The compound-resonator is a metal waveguide of circular cross section into which a dielectric plug is inserted. The plug fills a part of the length of the resonator. The dependence of the wakefield measured at the end of the resonator on the length of its vacuum part is studied theoretically and experimentally, and the experimental dependences are compared with theoretical calculations.

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INTRODUCTION

Dielectric loaded structures show promise for generating strong accelerating fields by relativistic electron bunches (DWA) [1 - 4].

The electric field strengths in DWA can be significantly increased due to the coherent addition of fields from a large number of sequence bunches [5]. In the dielectric waveguide, the excited wakefield is carried out from the structure with a group velocity [6]. The resonator eliminates the effect of field removal [7, 8].

Under real experimental conditions, the interaction region of bunches with a dielectric structure is closed by an input diaphragm and an exit plug or short-circuited piston (plunger). Measurements of the excited fields are made in the vacuum part of the compound-resonator, and it is necessary to determine from these measurements the field in the dielectric part of the resonator.

The natural frequencies of such a resonator are unknown in advance. It is necessary to determine them and find the positions of the plunger, which ensure the maximum field in the resonator. In what follows, we will theoretically and experimentally investigate dependence a wakefield amplitude from the length of the vacuum part of the compound-resonator. Also we will present the results of experimental studies of axial electric field on the length of the dielectric-lined waveguide of compound-resonator. As shown in [9] change of the dielectric tube length in is equivalent to the change of a number of bunches in the train. For the resonator case such studies hadn’t carried out yet.

1. THEORY

1.1. STATEMENT OF THE PROBLEM. EXPRESSIONS FOR AN EXCITED FIELD

We consider a cylindrical metallic resonator, partially filled (in longitudinal direction) with dielectric material. We will suppose that the input and output of the resonator are transparent for the externally injected electron bunches and nontransparent for an excited electromagnetic field. Fig. 1 demonstrates an overview of the compound-resonator under investigation.

We will describe the electron bunches in terms of macroparticles and model by hollow cylinders. Therefore the charge and current density we can write as follows:

$$\rho = \sum_{p \in V_R} q_p \delta(\mathbf{r} - \mathbf{r}_p(t)), \quad \mathbf{j} = \sum_{p \in V_R} q_p \mathbf{v}_p(t) \delta(\mathbf{r} - \mathbf{r}_p(t)), \qquad (1)$$

where q_p is a charge of a macroparticle, $\mathbf{r}_p$ and $\mathbf{v}_p$ are its coordinates and velocity respectively. Summation in the expressions of the charge and current density is carried out over the particles, which are being in the volume of the resonator (V_R). Dynamics of bunch particles is described by equations of motion in the electromagnetic fields, excited by bunches:

$$\frac{d\mathbf{p}_p}{dt} = q_p \left(\mathbf{E} + \frac{1}{m_p c \gamma_p} \mathbf{p}_p \times \mathbf{B} \right), \quad \frac{d\mathbf{r}_p}{dt} = \frac{\mathbf{p}_p}{m_p \gamma_p}, \qquad (2)$$

where $\gamma_p^2 = 1 + \left(\mathbf{p}_p / m_p c \right)^2$.

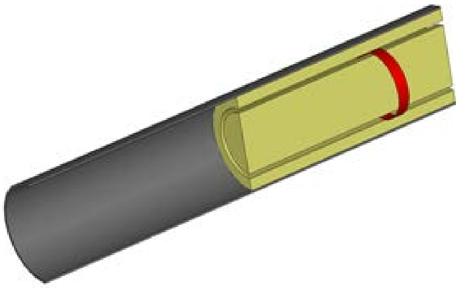

Fig. 1. Overview of a metallic cylindrical resonator (grey color), partially loaded with dielectric (yellow color), excited by a sequence of electron bunches. The electron bunches (red color) move from right to left. Thickness of the vacuum channel is small in comparison with resonator radius

It is possible to present the excited fields as a sum of solenoidal and potential components, which are mutually orthogonal and satisfy to the boundary conditions, vanishing their tangential components at metal walls of the resonator [10]:

$$\mathbf{E} = \mathbf{E}^{\mathbf{t}} + \mathbf{E}^{\mathbf{l}}, \quad \mathbf{H} = \mathbf{H}^{\mathbf{t}}, \qquad (3)$$

where the solenoidal components $\mathbf{E}^{\mathbf{t}}$ and $\mathbf{H}^{\mathbf{t}}$ ($\mathrm{div}(\varepsilon \mathbf{E}^{\mathbf{t}}) = 0, \ \mathrm{div}(\mu \mathbf{H}^{\mathbf{t}}) = 0$) satisfy to the first and the second Maxwell equations

$$\mathrm{rot}\mathbf{H}^{\mathbf{t}} = \frac{\varepsilon}{c} \frac{\partial \mathbf{E}^{\mathbf{t}}}{\partial t} + \frac{4\pi}{c} \mathbf{j}, \quad \mathrm{rot}\mathbf{E}^{\mathbf{t}} = -\frac{\mu}{c} \frac{\partial \mathbf{H}^{\mathbf{t}}}{\partial t}, \qquad (4)$$

and the potential electric field $\mathbf{E}^{\mathbf{l}}$ satisfies to the Gauss law

$$\mathrm{div}(\varepsilon \mathbf{E}^{\mathbf{l}}) = 4\pi\rho. \qquad (5)$$

The solenoidal part of the excited field can be found by expanding into solenoidal modes of the empty (without current source) dielectric resonator [10]. Analytical expressions for the fields $\mathbf{E}^{\mathbf{t}}$ and $\mathbf{H}^{\mathbf{t}}$ have the form:

$$\mathbf{E}^{\mathbf{t}} = -\sum_{s} \mathbf{E}_s(\mathbf{r}) \int_0^t dt' \cos\omega_s(t-t') R_s(t'),$$
$$\mathbf{H}^{\mathbf{t}} = i\sum_{s} \mathbf{H}_s(\mathbf{r}) \int_0^t dt' \sin\omega_s(t-t') R_s(t'), \qquad (6)$$

where the functions $\mathbf{E}_s$ and $\mathbf{H}_s$ describe the spatial structure and satisfy the Maxwell sources-free equations:

$$H_{\varphi s}(z \le d) = -\frac{i\omega_s\varepsilon}{c} J_1(k_{\perp n} r)\cos k_{1s} z,$$
$$H_{\varphi s}(d < z \le L) = -\frac{i\omega_s\varepsilon}{c} J_1(k_{\perp n} r)\frac{\cos k_{1s} d \cos k_{2s}(L-z)}{\cos k_{2s}(L-d)},$$
$$\frac{\partial H_\varphi}{\partial z} = \frac{i\omega\varepsilon}{c} E_r, \ \frac{1}{r}\frac{\partial}{\partial r}\left(r H_\varphi\right) = -\frac{i\omega\varepsilon}{c} E_z. \qquad (7)$$

It should be noted, that due to azimuthal symmetry of the problem we will consider TM modes only. Functions $R_s(t)$ are defined as follows:

$$R_s(t) = \frac{1}{N_s}\left\{ \sum_{p\in V_{1R}} q_p v_{pz} J_0(k_{\perp n} r_p)\cos k_{1s} z_p + \right.$$
$$\left. \sum_{p\in V_{2R}} \varepsilon q_p v_{pz} J_0(k_{\perp n} r_p)\frac{\cos k_{1s} d \cos k_{2s}(L-z_p)}{\cos k_{2s}(L-d)} \right\}, \qquad (8)$$

where V_{1R}, V_{2R} are the volumes of dielectric and vacuum parts of resonator respectively, and N_s are the norms of the resonator eigen modes

$$N_s = \frac{\omega_s^2\varepsilon^2 b^2}{4c^2} J_1^2(\lambda_n^{(0)})\left(\frac{d}{2} + \frac{\sin 2k_{1s} d}{4k_{1s}} + \right.$$
$$\left. \left(\frac{\cos k_{1s} d}{\cos k_{2s}(L-d)}\right)^2 \left(\frac{L-d}{2} + \frac{\sin 2k_{2s}(L-d)}{4k_{2s}}\right)\right) \qquad (9)$$

Eigen frequencies of the compound resonator ω_s are determined from the equation

$$k_1 tg k_1 d + \varepsilon k_2 tg k_2(L-d) = 0, \qquad (10)$$

where $k_{1s}^2 = \varepsilon\omega_s^2/c^2 - k_{\perp n}^2$, $k_{2s}^2 = \omega_s^2/c^2 - k_{\perp n}^2$ are the axial wave numbers in dielectric and vacuum respectively, $k_{\perp n} = \lambda_n^{(0)}/b$ are the radial wave numbers, $\lambda_n^{(0)}$ are the roots of Bessel function $J_0(\lambda_n^{(0)}) = 0$, c is the velocity of light in vacuum. Detailed analytical expressions for the potential field can be found in [11].

1.2. SIMULATION RESULTS

The analytical expressions for the excited fields components with motion equations of bunch particles allow to investigate the resonator excitation numerically. In this part we have investigated the influence of resonator parameters variations (resonator length only) on the resonator excitation in terms of amplitude of electric field.

For simulations we used the following parameters of structure and a bunch train: resonator radius $b = 4.25$ cm, length of a dielectric insertion $d = 30.318$ cm, dielectric material is teflon with dielectric permittivity $\varepsilon = 2.045$, the initial bunch energy equals to 4.5 MeV, a bunch charge is 0.32 nC, bunch radius $r_b = 5$ mm, longitudinal bunch rms-size σ_z=8.7 mm, a repetition rate in the train of bunches f_0=2.805 GHz. We varied a length of the resonator L from a working point value, which equals 50.036 cm. This working point provides: (i) – resonance excitation (due to coincidence of one of eigen frequencies of the resonator with a repetition frequency of bunches) and (ii) – the main mechanism of excitation of the resonator is Cherenkov radiation [2]. Fig. 2 demonstrates the simulations results of these variations.

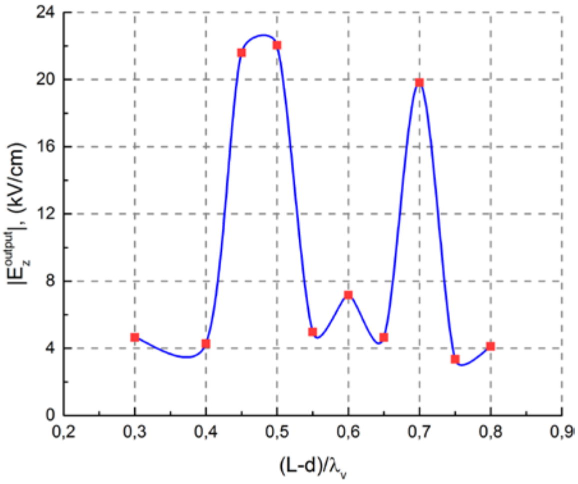

Fig. 2. Dependence of the maximal amplitude of the excited longitudinal electric field versus length of vacuum part (in terms of vacuum wavelength at 2.805 GHz) of the resonator. Rectangles show computed points. The electric probe was located on an axis at the output of the resonator. The resonator was excited by a train of 300 bunches

2. EXPERIMENT

2.1. EXPERIMENTAL SETUP

The scheme of the experimental setup is shown in Fig. 3.

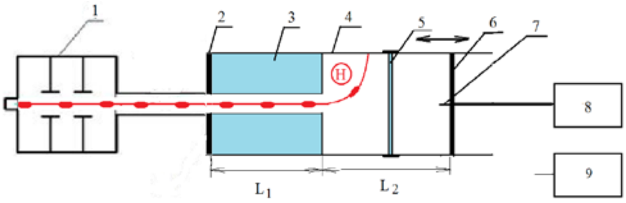

Fig. 3. Scheme of the experimental setup with the cylindrical compound-resonator: 1 – linac "Almaz-2M"; 2 – metal diaphragm; 3 – dielectric; 4 – copper waveguide; 5 – vacuum dielectric plug; 6 – short circuited plunger; 7 – microwave probe; 8 – wave-meter VMT-10; 9 – oscilloscope Tektronix TDS6154

The main element of the setup is the dielectric resonator. Nondestructive diagnostics of excited wakefields supposes not to distort the evolution of the wakefields excitation in the only dielectric resonator. Before it is shown theoretically that in the composite resonator of the length L (we call it "compound-resonator"), consisting of a metallic resonator filled with dielectric along a such length L_1, so that on the dielectric part of it fit an integer number of half-waves excited in dielectric part and converted to an integer number of half-waves in empty (without dielectric) part of the length L_2, topography of fields in the dielectric part and the eigen frequencies of the compound-resonator are the same as for a single dielectric resonator length L_1. The difference between these two approaches differ only by of feedback time – for a single dielectric resonator $t_{1delay}=2L_1/v_{g1}$, for the compound-resonator $t_{2delay}=2(L_1/v_{g1}+L_2/v_{g2})$, where v_{g1} and v_{g2} are the group velocities in in the dielectric and the empty part, correspondingly.

In the experimental setup compound-resonator is a circular copper waveguide (4) with an inner diameter of 85 mm, and the diaphragm (2) at its entrance with aperture of diameter 12 mm for entry of bunches, filled on the length $L_1=\lambda_d$, $2\lambda_d$, $3\lambda_d$,…(λ_d =10.634 cm is the length of the excited wave in the dielectric) with dielectric insert (3) from Teflon (ε = 2.045; $tg\delta = 2\cdot10^{-4}$) with the transit channel of diameter 21.1 mm for the passage of bunches. Dimensions of copper waveguide and dielectric insert are chosen so that the frequency of the wave excited in the dielectric part, coincided with bunch repetition frequency ($\omega_0 = \omega_m$). The empty part of the compound-resonator by length $L_2=\lambda_v/2$, (λ_v=39 cm is wavelength in the empty part) is the space between the dielectric insert and a movable short-circuited plunger (6). The latter serves for fine adjustment of the length of the empty part by obtaining the maximum signal of field with the microwave probe (6) installed into the plunger. Empty part of the compound-resonator allows to display bunches on the waveguide wall and glass plate after they interacted with the dielectric part. To deflect bunches by magnetic field on the waveguide wall is provided between the end of the vacuum dielectric insert (3) and vacuum teflon plug (5).

The sequence of relativistic electron bunches produced by the linear resonant electron accelerator "Almaz-2M" (1). Electron energy is 4.5 MeV, the pulsed current 0.8 A, pulse duration 2 µs. Each pulse is a sequence of $N=6\cdot10^3$ electron bunches with charge of 0.26 nC, diameter of 1 cm and duration of 60 ps each. The bunch repetition frequency can be varied within $\omega_m/2\pi$=2.800…2.808 GHz.

E_{zv} component of excited field was measured in the empty part of the compound-resonator using a microwave probe (6), located in the center of a short-circuined plunger. As it is known, and it has also been shown by numerical simulations, E_{zd} component of excited field in the dielectric part can be found by using the condition $E_{zd} = E_{zv}/\varepsilon$.

2.2. EXPERIMENTAL RESULTS

2.2.1. WAKEFIELD EXCITATION IN THE COMPOUND-RESONATOR

If the required dimensions L_1 and L_2 are not accurately chosen and experimentally implemented in the compound-resonator, they can be adjusted to the bunch repetition frequency by using a movable short circuited plug (6). Resonance is determined by the position of the plunger at which the E_{zv}-signal of total wakefield is maximal. Fig. 4 shows three such maxima of the total wakefield, measured with the calibrated microwave probe (7), at $L_1=3\lambda_d$ and the corresponding positions of the plunger, at which $L_2 = \lambda_v/2$, λ_v и $3\lambda_v/2$ (integer half-waves in empty part). Thus, the compound-resonator behaves accordingly to assumptions and below it is used to study the wakefield excitation by bunches in its dielectric part as in a single dielectric resonator of length L_1 by measuring fields in its empty part.

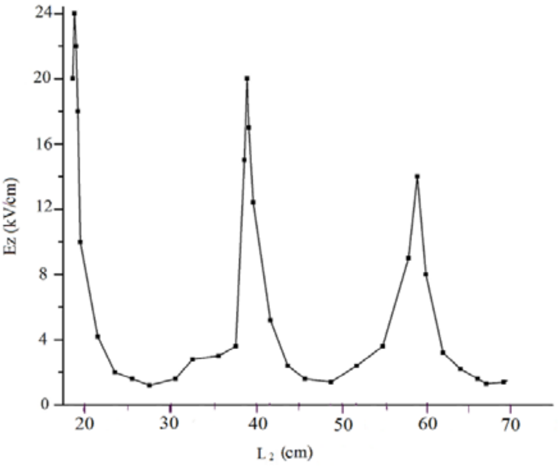

Fig. 4. Amplitude of E_{zv} component of the field in the empty part of the compound-resonator in dependence on the position of the plunger relatively to the end of the dielectric part (i.e. on L_2)

The longitudinal component of the excited field measured at the end of empty part of the compound-resonator L_2 =19.5 cm (slightly less than $\lambda_v/2$ due to the vacuum dielectric plug (5) presence in the empty part) is equal E_{zv}=24 kV/cm and, correspondingly in the chanюnel of the dielectric part $E_{zd}=E_{zv}/\varepsilon$=11.8 kV/cm.

2.2.2. WAKEFIELD AMPLITUDE DEPENDENCE ON THE LENGTH OF THE DIELECTRIC PART OF THE COMPOUND-RESONATOR

The length of the dielectric part was chosen multiple wavelengths of the dielectric part $L_1=\lambda_d$, $2\lambda_d$, $3\lambda_d$ at $L_2=\lambda_v/2$, in order not to violate the principle of the compound-resonator operation. The results of measuring the dependence of the wakefield amplitude upon the length L_2 of empty part for these three cases are presented in Fig. 5,a,b,c, respectively. It can be seen that the wakefield amplitude increases with the length of the dielectric part and for the considered three cases is 7.2, 14.0, 24.0 kV/cm, accordingly

To explain the obtained experimental results we consider the evolution of the wakefield excitation in the compound-resonator. Distracting from the accompanying in coherent transition radiation, for short bunches the excited wakefields accumulation in the compound-resonator can be schematically represented as follows. As in the case of the waveguide for three cases of dielectric part length $L_1=\lambda_d$, $2\lambda_d$, $3\lambda_d$ because of group velocity in a dielectric part (v_{g1} =0.492 c, c is speed of light) coherent adding only 1, 2 and 3 bunches (N_{coh}), respectively, for the three lengths of the dielectric part leads to the field amplitude increase. This increase is represented, respectively, in the form of one, two or three steps, each of value the amplitude of the wakefield of a single bunch E_0.. Subsequent bunches during the feedback time $t_{2delay}=2(L_1/v_{g1}+L_2/v_{g2})$, where v_{g2}=0.273 c, only support this amplitude at the compound-resonator exit, i.e. during this time a "shelf" of constant in time amplitude originated. For the three considered lengths of the dielectric part $L_1=\lambda_d$, $2\lambda_d$, $3\lambda_d$ the "shelf" duration is equal to t_{2delay}=6.22, 7.67, 9.12 ns, respectively. Hereof, the number of "blank" bunches, not contributing to the growth of the amplitude $N_{const} = t_{2delay}/T$, ($T=2\pi/\omega_m$ is bunch repetition period), consequently is equal to N_{const}.=17, 21, 25.

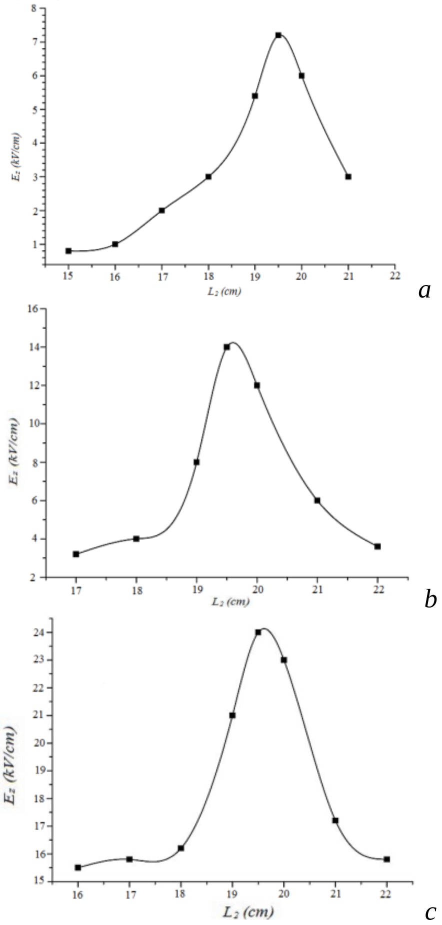

Fig. 5. Dependence of the excited field amplitude upon the length L_2 of empty part for three cases: a – $L_1=\lambda_d$; b – $L_1=2\lambda_d$; c – $L_1=3\lambda_d$

The next portion of N_{coh} coherent bunches gives a new step increase in the amplitude, which at this new level supported by a new portion of N_{const} bunches, etc. As a result of the injection into the compound-resonator N bunches amplitude of the total field will be equal to

$$E_{total}= N_{coh}E_0(N/(N_{coh}+N_{const})). \qquad (11)$$

The average increase in the amplitude of the wakefield on the number of injected bunches is qualitatively shown in Fig. 6 by blue line. If we consider a finite Q-factor of the compound-resonator, then at the summation of wakefields it is needed to take into account that the field of the k-th portion of ($N_{coh}+N_{const}$) bunches attenuates in $\exp(-\omega_0 k(N_{coh}+N_{const})T/2Q) = \exp(-k(N_{coh}+N_{const})\pi/Q)$ times. As a result, when $N=k(N_{coh}+N_{const}) \to \infty$ the amplitude of the total wakefield achieves saturation E_{sat} (red curve in Fig. 6), equaled to

$$E_{sat} = N_{coh}E_0(1+e^{-(Ncoh+Nconst)\pi/Q}+e^{-2(Ncoh+Nconst)\pi/Q}+\ldots +e^{-k(Ncoh+Nconst)\pi/Q}+\ldots 0)=N_{coh}E_0(Q/\pi(N_{coh}+N_{const})). \qquad (12)$$

From (11) and (12) we can find the number of bunches N^*, which excites in the compound-resonator without a loss ($Q=\infty$) the same wakefield, as infinite sequence of bunches excites in the compound-resonator with a finite Q-factor, i.e. $E_{total}(N^*)=E_{sat}$:

$$N=N^*=Q/\pi. \qquad (13)$$

At that N^* bunches excite in the compound-resonator with a finite Q-factor the wakefield E^*, less than field of saturation E_{sat}. Assuming N^* multiple of ($N_{coh}+N_{const}$), we find $E^*= E_{sat} - N_{coh}E_0e^{-N*\pi/Q}(1+e^{-(Ncoh+Nconst)\pi/Q}+ +e^{-2(Ncoh+Nconst)\pi/Q}+\ldots+e^{-k(Ncoh+Nconst)\pi/Q}+\ldots 0)=E_{sat}(1-e^{-1})$, i.e.

$$E_{sat} - E^*=E_{sat}/e. \qquad (14)$$

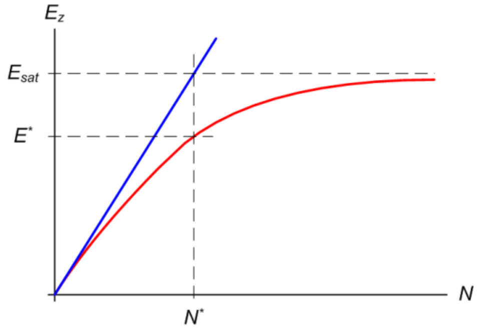

Fig. 6. Dependence of the wakefield amplitude Ez on the number of injected bunches for the resonator without losses $Q=\infty$ (blue) and with the finite Q-factor (red)

The number of bunches $N=6\cdot 10^3$ used in the experiment excites wakefield E_N, which differs from the saturation field E_{sat} for infinite sequence of bunches ($N\to\infty$) by a very small value $E_{sat} - E^N=E_{sat}\, e^{-N\pi/Q}$. Therefore in the oscillograms of the envelope of microwave wakefield excited by a sequence of $N=6\cdot 10^3$ bunches amplitude E_N is almost coincides with the amplitude of saturation $E_N=E_{sat}$.

To estimate the ratio of the wakefield excited in the considered three cases, according to (2) it is necessary for these cases to know Q, N_{coh} и N_{const}. Q-factors were measured by half-widths of the resonance line of the fundamental mode frequency using the oscillator G4-80 (frequency range 2.56…4.0 GHz) and were found to be Q_1 = 438, Q_2 =511, Q_3=676.

Parallel to the reliability of these measurements the Q-factors of compound-resonators were also determined by measuring the increase of the duration of the trailing edge of the microwave signal in comparison with the duration of the trailing edge of the beam current pulse. Such increase was caused by the finite time of the microwave field attenuation in the compound-resonator τ_{damp} = 2Q/ω (see (2)).

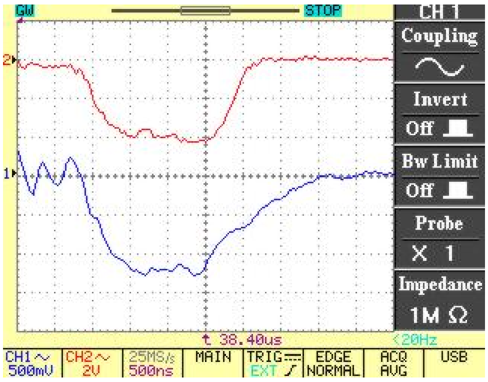

Fig. 7. Oscillograms of the beam current pulse (top) and microwave radiation (bottom) at Q_3=676

For Q-factor Q_3 Fig. 7 presents the waveform of the pulse of the beam current (red) and the envelope of the microwave radiation (blue) that shows the delay in the trailing edge of the envelope of microwave signal, that allows to evaluate the Q-factor of the compound-resonator. The results of measurements by both methods agree to within 20%.

The measured values of the Q-factors Q_i, as well as the above calculated amount of coherent N_{coh} and "blank bunches» N_{const} for the considered three cases, allow together with (12) to found, in the frame of this scheme of the evolution of amplitude excitation, the ratio of wakefields excited in compound-resonators of three configurations: $E_{z1}:E_{z2}:E_{z3}=1:1.89:3.13$. This ratio shows the same trend of wakefield growth with lengthening of the dielectric part, as well as experimentally obtained: 7.2:14.0:24.0 → 1:1.94:3.33.

CONCLUSIONS

Enhancement of total wakefield in the compound dielectric resonator due to coherent summation of fields from bunches of regular train is studied experimentally and theoretically. All observation of excited wakefield are made at the output end of the resonator.

It is shown that the dependence the longitudinal electric field on the length of vacuum part of compound resonator has sharp maxima close values multiple to integer vacuum half wavelength at the frequency of excited wakefield in the dielectric part. In this place, the experimental measurements coincide with theoretical computations. Besides the theoretical calculation show additional maximum near three quarter of the vacuum wavelength not observed in experiments. This mismatch requires additional studies.

The dependence of the longitudinal electric field on the length of dielectric tube of compound-resonator was experimentally studied. It is shown that when increasing the dielectric tube length the longitudinal electric field gains proportionally. The simple qualitative explanation of such behavior is given.

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ИССЛЕДОВАНИЕ МУЛЬТИБАНЧЕВОГО ВОЗБУЖДЕНИЯ КИЛЬВАТЕРНЫХ ПОЛЕЙ В ДИЭЛЕКТРИЧЕСКОМ КОМПАУНД-РЕЗОНАТОРЕ

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Представлены теоретические и экспериментальные исследования возбуждения кильватерных полей в диэлектрическом компаунд-резонаторе последовательностью электронных сгустков, инжектируемых из ускорителя «Алмаз-2М». Компаунд-резонатор представляет собой металлический волновод круглого сечения, в который вставлена диэлектрическая втулка. Втулка заполняет часть длины резонатора. Теоретически и экспериментально исследована зависимость кильватерного поля, измеряемого на конце резонатора, от длины его вакуумной части и приводится сравнение экспериментальных зависимостей с теоретическими расчетами.

ДОСЛІДЖЕННЯ МУЛЬТИБАНЧОВОГО ЗБУДЖЕННЯ КІЛЬВАТЕРНИХ ПОЛІВ У ДІЕЛЕКТРИЧНОМУ КОМПАУНД-РЕЗОНАТОРІ

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Представлено теоретичні і експериментальні дослідження збудження кільватерних полів у діелектричному компаунд-резонаторі послідовністю електронних згустків, інжектуючих з прискорювача «Алмаз-2М». Компаунд-резонатор являє собою металевий хвилевід круглого перетину, в який вставлена діелектрична втулка. Втулка заповнює частину довжини резонатора. Теоретично і експериментально досліджена залежність кільватерного поля, вимірюваного на кінці резонатора, від довжини його вакуумної частини і наводиться порівняння експериментальних залежностей з теоретичними розрахунками.