CONCEPT OF PLASMA-DIELECTRIC WAKEFIELD ACCELERATOR. THEORY AND EXPERIMENT

G.P. Berezina, K.V. Galaydych, R.R. Kniaziev, A.F. Linnik, P.I. Markov, O.L. Omelayenko, I.N. Onishchenko, V.I. Pristupa, G.V. Sotnikov, V.S. Us
National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine
E-mail: onish@kipt.kharkov.ua

The wakefield excitation by a long sequence of relativistic electron bunches in a dielectric waveguide/resonator of round cross-section with transit channel filled with plasma of various densities was theoretically and experimentally investigated.

PACS: 41.60.-m, 41.75.Lx, 41.75.Ht, 96.50.Pw

INTRODUCTION

The acceleration of charged particles by wakefields excited by a laser pulse or bunches of charged particles at their propagation in the slowing down structures, is a perspective direction in high energy physics, which develops rapidly. With extra high accelerating gradients wakefield methods of acceleration allows to achieve energy of accelerated particles in TeV range at much shorter length than in conventional accelerators. One of the advanced method of acceleration is the acceleration by wakefields excited by relativistic electron bunches in dielectric structure [1]. The presence of plasma in the transit channel for bunches allows to compensate space charge of bunches and prevent the falling electrons of bunches on dielectric walls, and consequently to improve the passage of bunch through the channel and increase amplitude of the excited wakefield at the exit. In addition, plasma changes dispersion characteristics of waveguide/resonator and topography of the wakefield in the channel, excited by a sequence of bunches on Cherenkov resonance. Notice that the excited wakefield consists of dielectric field, modified with plasma and directly plasma fields excited on different frequencies, except for the case of coincidence of plasma frequency and frequencies of modified dielectric field. Different frequencies allow, in case of the scheme with a single bunch-driver and a single bunch-witness, to place the latter one into the region of phases, where it will be accelerated by the high longitudinal field of dielectric wave (radial field for relativistic bunches is negligible) and focused by the high radial plasma field [2].

In this paper, wakefield excitation by a sequence of relativistic electron bunches in a cylindrical dielectric waveguide/resonator which trasit channel is filled with isotropic plasma are investigated. Based on the theoretically obtained expressions for the components of the electromagnetic field the spatial structure of transverse and longitudinal forces are studied and to consider enhancing excited wakefields and focusing accelerated bunches by them due to the plasma filled channel. Modernization resonant electron accelerator "Almaz-2M" is carried out, that allowed to obtain a sequence of $6 \cdot 10^3$ electron bunches, each of 1.7 cm length, 1 cm in diameter, charge 0.26 nC, and energy 4.5 MeV. The period bunch repetition 300 ps. Dielectric structure of circular cross-section is designed and manufactured. The system of dosed inlet of neutral gas into the axial channel of the structure and pumping is constructed, which enables to obtain in the channel plasma of different density due to ionization of the neutral gas directly by the front part of the bunch sequence. Preliminary experiments on wakefields excitation in hybrid plasma-dielectric structure are presented.

1. THEORY

1.1. ANALYTICAL EXPRESSIONS FOR EXCITED FIELDS

To investigate the influence of the dielectric medium on the excitation of plasma wakefield we find wakefield excited by an electron bunch moving in a plasma waveguide with an annular dielectric insert. Plasma waveguide is homogeneous plasma cylinder of radius *a*, surrounded by perfectly conducting metal tube of radius *b*. The dielectric insert fills the space between the venal tube and plasma. The excitation of the waveguide will be considered in the approximation of linear isotropic plasma of density n_p. Driving axis electron bunch has radius r_b and length L_b. At some distance from the driver-bunch an accelerated witness-bunch is placed. Geometry of the wakefield structure is shown in Fig. 1

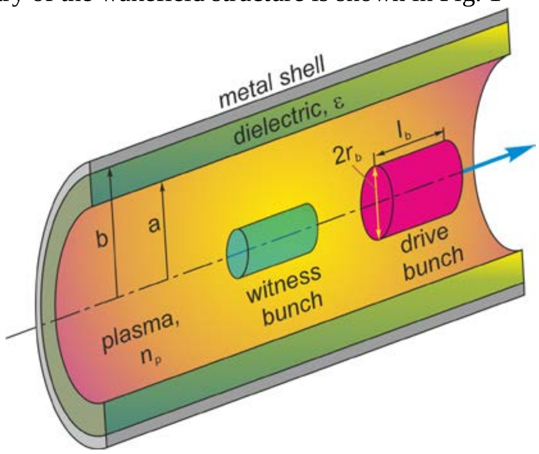


Fig. 1. Geometry of plasma-dielectric wakefield accelerating structure

Excited azimuthally symmetric wakefield is described by the following set of Maxwell equations:

$$\frac{\partial E_r}{\partial z} - \frac{\partial E_z}{\partial r} = -\frac{1}{c}\frac{\partial H_\varphi}{\partial t},$$
$$-\frac{\partial H_\varphi}{\partial z} = \frac{1}{c}\frac{\partial D_r}{\partial t}, \qquad (1)$$
$$\frac{1}{r}\frac{\partial}{\partial r}\left(rH_\varphi\right) = \frac{1}{c}\frac{\partial D_z}{\partial t} + \frac{4\pi}{c} j_z,$$

where E_r, E_z are radial and longitudinal components of the electric field; D_r, D_z are radial and longitudinal components of the electric induction; H_φ is azimuthal component of magnetic field.

First, determine the wakefield of a bunch shaped as an infinitely thin axially symmetric ring of radius r_0 for which the current density is given by

$$j_z = \frac{Q}{2\pi r}\delta(r-r_0)\delta(\tau-t_0), \quad (2)$$

where $\tau = t - z/v_0$; t_0 is time, when bunch crosses the plane $z=0$; v_0 is its speed, Q is bunch charge; δ is Dirac delta function.

Using (2) the dependence of the forced solution of the system (1) on time and longitudinal coordinates is determined only by variable. τ Performing Fourier transform in the variable τ

$$(\vec{E}_\omega, \vec{H}_\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} d\tau(\vec{E},\vec{H})\exp(i\omega\tau) \quad (3)$$

from the system (1)-(2) we obtain the equation for the Fourier transform of the longitudinal component of the electric field:

$$\frac{1}{r}\frac{\partial}{\partial r}\left[r\frac{\partial E_{z\omega}}{\partial r}\right] - \frac{\omega^2}{v_0^2}\left[1-\beta_0^2\varepsilon(\omega)\right]E_{z\omega} =$$
$$= i\frac{Q}{\pi v_0^2}\frac{\omega}{\varepsilon(\omega)}\left[1-\beta_0^2\varepsilon(\omega)\right]\frac{\delta(r-r_0)}{r}\exp(i\omega t_0)\cdot \quad (4)$$

The radial component of the electric field and the component of the azimuthal magnetic field are expressed by $E_{z\omega}$:

$$E_{r\omega} = i\frac{c}{\omega}\frac{\beta_0}{\beta_0^2\varepsilon(\omega)-1}\frac{\partial E_{z\omega}}{\partial r}, \quad H_{\varphi\omega} = \beta_0\varepsilon(\omega)E_{r\omega}, \quad (5)$$

$\beta_0 = v_0/c$; $\varepsilon(\omega) = \varepsilon_p(\omega) = 1-\omega_p^2/\omega^2$; if $r<a$ and $\varepsilon(\omega) = \varepsilon_d$ if $a \le r < b$; $\omega_p = \sqrt{4\pi e^2 n_p/m}$ is plasma frequency; $-e$ and m are charge and mass of electron; ε_d is relative permittivity of dielectric insert which we assume independent on frequency.

Equation (4) is equivalent to the system consisting from three equations written in each of partial areas $r<r_0$, $r_0<r<a$ and $a<r\le b$. Solving it with taking into account boundary conditions:

$$\begin{gathered} E_{z\omega}(r=0)<\infty,\ E_{z\omega}(r=b)=0,\ E_{z\omega}(r=r_0-0)=E_{z\omega}(r=r_0+0), \\ E_{z\omega}(r=a-0)=E_{z\omega}(r=a+0),\ H_{\varphi\omega}(r=a-0)=H_{\varphi\omega}(r=a+0), \\ H_{\varphi\omega}(r=r_0+0)-H_{\varphi\omega}(r=r_0-0)=\frac{Q}{\pi c r_0}\exp(i\omega t_0) \end{gathered} \quad (6)$$

we obtain:

$$E_{z\omega}(r<a) = -i\frac{Q\omega}{\pi c^2}\frac{1-\beta_0^2\varepsilon_p(\omega)}{\beta_0^2\varepsilon_p(\omega)}I_0(\kappa_p r_<)\left(K_0(\kappa_p r_>) + \frac{I_0(\kappa_p r_>)K_0(\kappa_p a)}{I_0(\kappa_p a)}\frac{1}{D(\omega)}\right.$$
$$\left.\times\left[\frac{\varepsilon_p(\omega)}{\sqrt{1-\beta_0^2\varepsilon_p(\omega)}}\frac{K_1(\kappa_p a)}{K_0(\kappa_p a)} - \gamma_d\frac{F_1(\kappa_d a,\kappa_d b)}{F_0(\kappa_d a,\kappa_d b)}\right]\right)\exp(i\omega t_0), \quad (7)$$
$$E_{z\omega}(a\le r\le b) = -i\frac{Q}{\pi a c\beta_0}\frac{1}{D(\omega)}\frac{I_0(\kappa_p r_0)}{I_0(\kappa_p a)}\frac{F_0(\kappa_d r,\kappa_d b)}{F_0(\kappa_d a,\kappa_d b)}\exp(i\omega t_0).$$

In (7) I_0, I_1 and K_0, K_1 are modified Bessel and Macdonald functions of zero and first order, accordingly;

$$F_0(x,y) = J_0(x)N_0(y) - N_0(x)J_0(y),$$
$$F_1(x,y) = -J_1(x)N_0(y) + N_1(x)J_0(y),$$

$J_0(x), J_1(y)$ та $N_0(x), N_1(y)$ – Bessel and Neumann functions of zero and first order, accordingly;

$$\kappa_p^2 = \frac{\omega^2}{v_0^2}\left(1-\beta_0^2\varepsilon_p(\omega)\right);\ \kappa_d^2 = \frac{\omega^2}{v_0^2}\left(\beta_0^2\varepsilon_d - 1\right);$$

$\gamma_d = \varepsilon_d/\sqrt{\beta_0^2\varepsilon_d - 1}$. Sign $<(>)$ means the least (most) values of r та r_0. The dispersion function that is included in the denominator of expressions (7) has the form:

$$D(\omega) = \frac{\varepsilon_p(\omega)}{\sqrt{1-\beta_0^2\varepsilon_p(\omega)}}\frac{I_1(\kappa_p a)}{I_0(\kappa_p a)} + \gamma_d\frac{F_1(\kappa_d a,\kappa_d b)}{F_0(\kappa_d a,\kappa_d b)}. \quad (8)$$

Other components of the electromagnetic field are expressed by $E_{z\omega}$ using (5).

Performing inverse Fourier transform, after calculating integrals using the theory of residues we obtain final expressions for wakefield of the bunch in the shape of an infinitely thin ring:

$$E_z(r_0,t_0,r,\tau) = -\frac{2Q}{a^2}\Theta(\tau-t_0)\begin{cases} k_p^2 a^2\dfrac{I_0(k_p r_<)}{I_0(k_p a)}\Delta_0(k_p a, k_p r_>)\cos\omega_p(\tau-t_0) \\ +\dfrac{2a}{v_0}\displaystyle\sum_s\dfrac{I_0(\kappa_p^s r_<)}{I_0(\kappa_p^s a)}\dfrac{I_0(\kappa_p^s r_>)}{I_0(\kappa_p^s a)}\dfrac{\cos\omega_s(\tau-t_0)}{D'(\omega_s)},\ r<a, \\ \dfrac{2a}{v_0}\displaystyle\sum_s\dfrac{I_0(\kappa_p^s r_0)}{I_0(\kappa_p^s a)}\dfrac{F_0(\kappa_d^s r,\kappa_d^s b)}{F_0(\kappa_d^s a,\kappa_d^s b)}\dfrac{\cos\omega_s(\tau-t_0)}{D'(\omega_s)},\ a\le r\le b, \end{cases} \quad (9)$$

$$E_r(r_0,t_0,r,\tau)=\frac{2Q}{a^2}\Theta(\tau-t_0)\begin{cases} k_p a^2\dfrac{d}{dr}\left(\dfrac{I_0(k_p r_<)\Delta_0(k_p a,k_p r_>)}{I_0(k_p a)}\right)\sin\omega_p(\tau-t_0) & \\ +\dfrac{2a}{v_0}\sum\limits_s\dfrac{I_1(\kappa_p^s r_<)}{I_0(\kappa_p^s a)}\dfrac{I_0(\kappa_p^s r_>)}{I_0(\kappa_p^s a)}\dfrac{\sin\omega_s(\tau-t_0)}{D'(\omega_s)\sqrt{1-\beta_0^2\varepsilon_p(\omega_s)}}, & r<a, \\ \dfrac{-2a}{v_0\sqrt{\beta_0^2\varepsilon_d-1}}\sum\limits_s\dfrac{I_0\left(\kappa_p^s r_0\right)}{I_0\left(\kappa_p^s a\right)}\dfrac{F_1(\kappa_d^s r,\kappa_d^s b)}{F_0\left(\kappa_d^s a,\kappa_d^s b\right)}\dfrac{\sin\omega_s\left(\tau-t_0\right)}{D'(\omega_s)}, & a\le r\le b,\end{cases} \tag{10}$$

$$H_\varphi(r_0,t_0,r,\tau)=\frac{4Q}{ac}\Theta(\tau-t_0)\begin{cases}\sum\limits_s\dfrac{\varepsilon_p(\omega_s)}{\sqrt{1-\beta_0^2\varepsilon_p(\omega_s)}}\dfrac{I_0(\kappa_p^s r_0)}{I_0(\kappa_p^s a)}\dfrac{I_1(\kappa_p^s r)}{I_0(\kappa_p^s a)}\dfrac{\sin\omega_s(\tau-t_0)}{D'(\omega_s)}, & r<a, \\ \dfrac{-4\varepsilon_d}{\sqrt{\beta_0^2\varepsilon_d-1}}\sum\limits_s\dfrac{I_0\left(\kappa_p^s r_0\right)}{I_0\left(\kappa_p^s a\right)}\dfrac{F_1(\kappa_d^s r,\kappa_d^s b)}{F_0\left(\kappa_d^s a,\kappa_d^s b\right)}\dfrac{\sin\omega_s\left(\tau-t_0\right)}{D'(\omega_s)}, & a\le r\le b,\end{cases} \tag{11}$$

where $\Theta(x)$ is Heaviside function; $k_p=\omega_p/v_0$; $\kappa_p^s=\kappa_p(\omega=\omega_s)$; $\kappa_d^s=\kappa_d(\omega=\omega_s)$; $D'(\omega_s)=\left.\dfrac{dD(\omega)}{d\omega}\right|_{\omega=\omega_s}$,

and eigen frequencies ω_s are determined from the solution of the dispersion equation:

$$D(\omega_s)=0. \tag{12}$$

The first terms in the expressions for the electric field (9)-(10) describe plasma wakefield ($\varepsilon_p=0$, $\omega=\omega_p$). It is localized in the transit channel. This field does not depend on the parameters of the dielectric structure and becomes zero on the boundaries of the channel. These terms in (9)-(10) coincide with the expressions for electric fields plasma oscillations in an isotropic plasma waveguide [3]. If in these expressions the radius the plasma cylinder $a\to\infty$, we obtain expressions for wakefield in infinite plasma [4]. Other terms in (9)-(11) describe the electric field of eigen oscillations of dielectric structure (for brevity, we will call them dielectric ones). Note that according to (11) in plasma wakefield there is no magnetic field H_φ.

Expressions (9)-(11) do not contain terms that describe the quasi-static field of the bunch space charge. Quasi-static additives can be obtained by generalizing solutions for dielectric wakefield on the case of purely imaginary eigen frequencies $\omega_s\to i\omega_s$. But as shown by numerical calculations [5] for relativistic bunches the quasi-static field is too small compared with the propagating wakefield. Further we neglect it.

To find wakefield of pencil bunch of finite length with arbitrary charge distribution inside it necessary to integrate expression (7) over all r_0, t_0 with corresponding distribution function $n(r_0,t_0)$.

1.2. NUMERICAL CALCULATIONS

For numerical calculations of excited wakefield we take dielectric waveguide (see Fig. 1) with a=1.1 cm, b=4.3 cm, permittivity ε_d=2.1 (Teflon), and accordingly to the accelerator "Almaz-2M" [6] electron bunch of energy 4.5 MeV, charge Q=-0.32 nC, radius r_b=1.0 cm, and length l_b=1.7 cm. We assume that the charge distribution inside the bunch is uniform and described by:

$$n(r_0,t_0)=\frac{2v_0}{L_b r_b^2}\left[\Theta(t_0)-\Theta(t_0-L_b/v_0)\right]\Theta(r_b-r), \tag{13}$$

Fig. 2 shows the dependence of eigen frequencies of plasma-dielectric waveguide on plasma density.

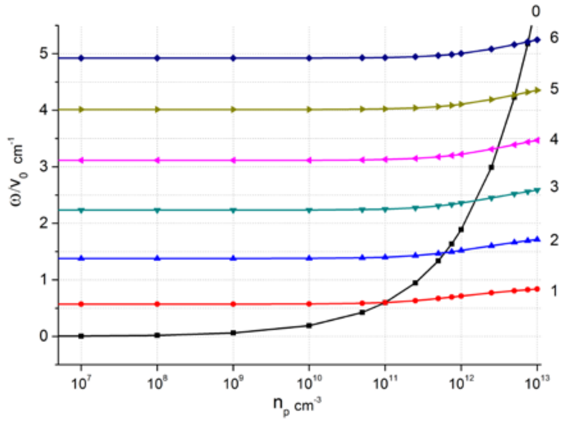


Fig. 2. Eigen frequencies of plasma-dielectric structure depending on plasma density: curve 0 – plasma wakefield; 1-6 – the first 6 solutions of dispersion equation (8) and (12) for ω_s

For the considered range of plasma densities eigen frequencies of dielectric wakefields are weakly dependent on plasma density. This allows to independently governing the frequencies and amplitudes of dielectric and plasma wakefields.

As follows from Fig. 2 Cherenkov resonant frequency of the first dielectric radial mode in the absence of plasma is $\omega=17.025\cdot10^9$, or spatial period is ~10.6 cm. It is known [3, 4] that the amplitude of the plasma wakefield is maximal at a certain plasma density. For the above given parameters of the waveguide and bunch amplitudes of longitudinal and transversal electric fields are maximal at approximately the same density plasma $n_p=n_p^m\sim10^{12}\,\text{cm}^{-3}$, which corresponds to the dimensionless parameter k_pa=2. Calculations show that for such plasma density plasma wakefield greatly exceeds the total dielectric wakefield (i.e. of all excited radial modes). So the resulting wakefield is formed mainly by plasma wakefield, which longitudinal and transverse components are shifted in phase by $\pi/2$. It means that accelerated bunch will not be focused. With decrease in plasma density the amplitude of both longitudinal and transverse components of plasma wakefield are reduced. At a certain density plasma longitudinal field of plasma wakefield becomes less than the total longitudinal field of dielectric modes. But radial component of plasma wakefield is large enough yet.

These two types of waves – plasma and dielectric fields – have different spatial periods. Therefore, there is a phase, where the maximum of the total longitudinal field can correspond to the minimum of the total transverse field full cross field. Thus, placing accelerated bunch at phase of maximum accelerating field (mainly dielectric one) it can be simultaneously focused by transverse field (mainly plasma one).

Figs. 3-6 show the results of calculations for plasma density n_p=10^{10}cm^{-3} (plasma frequency ω_p = 5.64·10^9, wavelength λ_p = 2πv_0 / ω_p = 33.2 cm).

Fig. 3 shows the distribution of axial longitudinal and transverse forces acting on a accelerated bunch located at a distance 0.95 cm from the structure axis. Comparing above dependencies it follows that placing accelerated bunch at a distance 7 or 39.1 cm from the head of driver-bunch provides simultaneous the acceleration and radial focusing accelerated bunch.

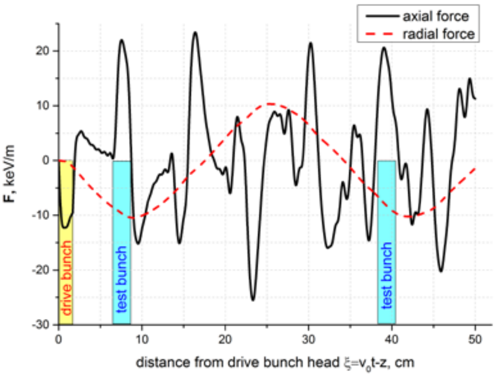


Fig. 3. Axial profile of longitudinal (solid line) and transverse (dashed line) forces, acting on accelerated bunch located at a distance 0.95 cm from the structure axis

As seen from the figure, the radial force has nearly harmonic dependence on the longitudinal coordinate with a period equal to ~ 33 cm, i.e. plasma field makes predominant contribution to the radial force. At the same time, its contribution to the accelerating longitudinal force is contrary small. Longitudinal force mainly determines by dielectric eigen modes.

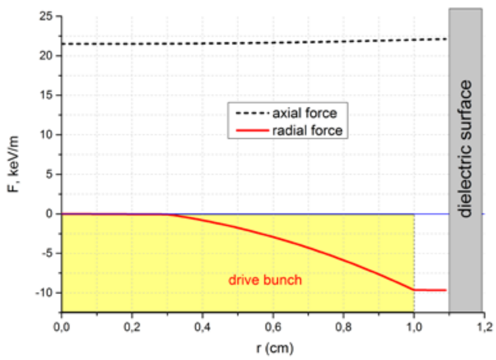


Fig. 4. Transverse profile of longitudinal (solid line) and transverse (dashed line) forces, acting on the accelerated bunch, located in the first maximum of accelerating field at a distance 7.562 cm from the head of driver-bunch

Fig. 4 shows the radial dependence of the longitudinal and transverse forces acting on the accelerated bunch, located in the first maximum of accelerating field at a distance 7.562 cm from the head of driver-bunch.

Figs. 5 and 6 present separately components in the full force shown in Fig. 3. It is seen that plasma wakefield makes predominant contribution to the focusing force, while the total field of the dielectric eigen modes makes predominant contribution to the accelerating gradient.

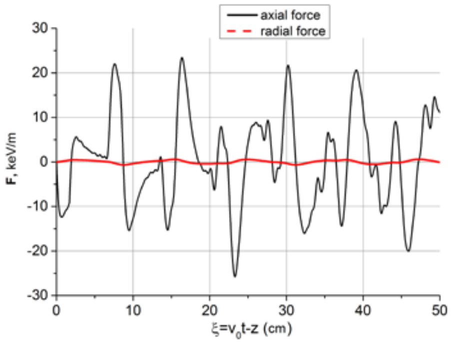


Fig. 5. Axial profile of longitudinal (black line) and transverse (red line) forces of dielectric wakefield, acting on accelerated bunch located at a distance 0.95 cm from the structure axis

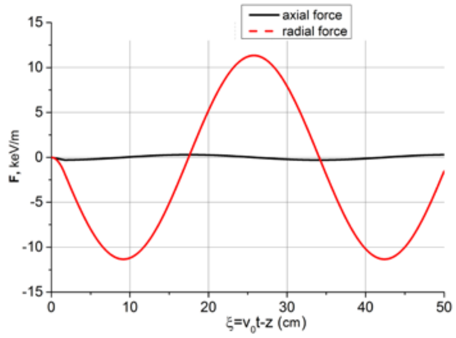
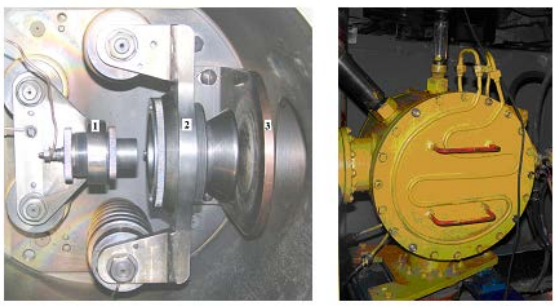


Fig. 6. Axial profile of longitudinal (black line) and transverse (red line) forces of plasma wakefield, acting on accelerated bunch located at a distance 0.95 cm from the structure axis

2. EXPERIMENTAL INVESTIGATIONS

2.1. UPDATING ELECTRON ACCELERATOR «ALMAZ-2M»

Updated electron gun. The efforts to update the electron gun of the accelerator included the change of lanthanum-hexaboride (LaB_6) cathode, the increase of the cathode emission by more intensive heating with electron beam bombardment and optimization of electron-optics parameters. The general view of an electron gun and the gun chamber is shown in Fig. 7.



a *b*

Fig. 7. Electron gun: 1 – unit of electron beam heater of the cathode; 2 – cathode unit; 3 – anode (a); b – electron gun chamber (b)

As a result the 2-times increase of electron gun current from 0.7 A to 1.4 A is obtained at the electron gun cathode voltage 80 kV.

Restoration of the master oscillator. In our experiments for the wakefield excitation in dielectric structures it is necessary to vary the bunch repetition frequency in order to achieve its coincidence with the eigen frequency of the exited wakefield if it is need to excite maximal wakefield by the whole sequence of bunches, or to make detuning between these frequencies that allows for one part of bunch sequence to be occurred in the accelerating phases of wakefield excited by another part of bunch sequence, and thus to realize accelerated witness-bunches without additional injector. This problem of bunch repetition frequency variation can be solved by using a klystron amplifier, wherein the frequency of the master-oscillator can be changed in a required range.

For these purposes we restored master-oscillator, based on magnetron MI-30, 10 kW HF-signal (in the frequency range 2750…2850 MHz) of which was amplified by klystron KIU-12M up to the power 15…20 MW. Measurements of the microwave signal amplitude of the master-oscillator on the frequency were performed (Fig. 8).

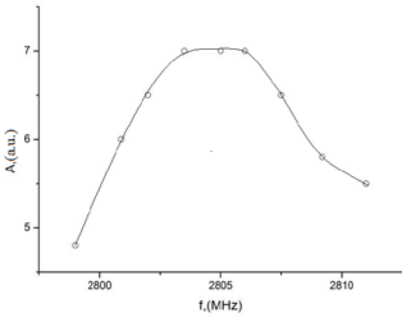


Fig. 8. Dependence of amplitude of the microwave signal upon master-oscillator frequency

It is shown that the maximum amplitude of the microwave signal was found in the frequency range 2803…2807 MHz.

The output power of the master-oscillator was measured by means of the calibrated detector and the 40dB attenuator. Oscillogram of the envelope of the microwave signal of the master-oscillator is shown in Fig. 9.

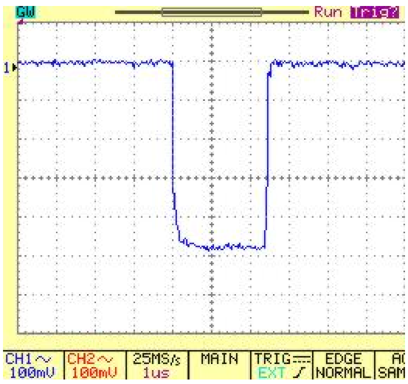


Fig. 9. Oscillogram of the envelope of the microwave signal of the master-oscillator

Restoration of the klystron KIU-12M. As a source of high-frequency power for linear electron accelerator «Almaz-2M» pulsed klystron amplifier KIU-12M is used. The problem of klystron KIU-12M restoration is caused by complete elimination of their production. In this connection the technology of restoration of the klystron has been developed and implemented. It allowed to achieve the parameters of the restored klystron which are close to those of produced industrial klystrons. In particular, Fig. 10 shows the level of the pulsed output power of the restored klystron upon anode voltage, measured at pulse duration 2 μs and repetition frequency 50 Hz.

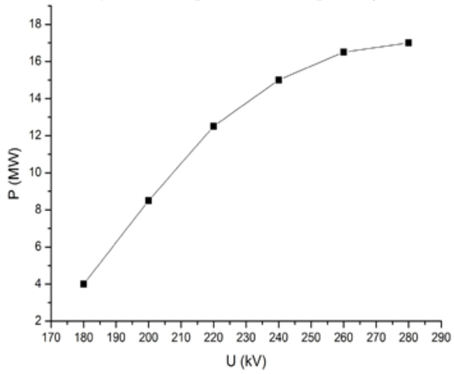


Fig. 10. The the output pulse power of the klystron dependence of upon anode voltage

Fig. 11 shows a photograph of the restored klystron KIU-12M. Updated electron accelerator «Almaz-2M» with modernized electronic gun, restored master-oscillator and klystron KIU-12M is shown in Fig. 12.

Fig. 11. Photo of restored klystron KIU-12M

Fig. 12. Electronic accelerator «Almaz-2M». Electron beam parameters: energy 4.5 MeV, pulsed current of 0.8 A, pulse duration 2 μs. The number of bunches $6{\cdot}10^3$, each of length 1.7 cm, diameter 1 cm, and charge 0.26 nC. Period of bunch repetition 300 ns

2.2. MEASUREMENTS OF BEAM PARAMETERS

Experimental setup.

The scheme of the facility is shown in Fig. 13.

The sequence of relativistic electron bunches obtained using a linear resonant electron accelerator (1), is transported through the waveguide partially filled with dielectric. By means of the magnetic analyzer (2) located at the accelerator exit it is possible to measure electron energy distribution for bunches injected in the dielectric structure (4). The output end of the waveguide is closed by the teflon plug (7) to provide vacuum inside the dielectric structure and allow excited wakefields to propagate through it into atmosphere to be for measured by means of the microwave probe (8). For measurements of electron energy distribution of the bunches after interaction with dielectric structure the teflon plug can be exchanged by a metal flange with a window made from a titanic foil of thickness 50 μm through which the bunches can cross and propagate into atmosphere.

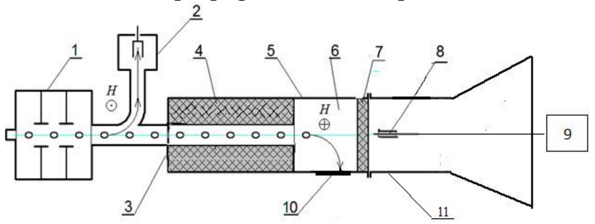
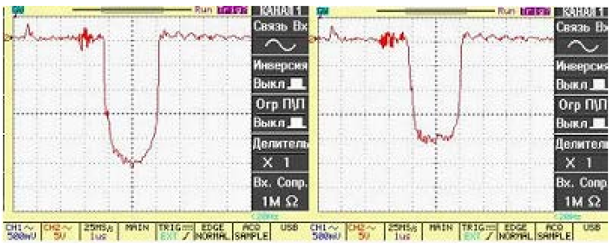


Fig. 13. 1 – accelerator "Almaz-2M"; 2 – magnetic analyzer; 3 – diaphragm; 4 – dielectric structure; 5 – waveguide; 6 – traversal magnetic field; 7 – vacuum teflon plug; 8 – microwave probe; 9 – oscilloscope; 10 – metal collector; 11 – waveguide with a horn

Measurements of the beam parameters.

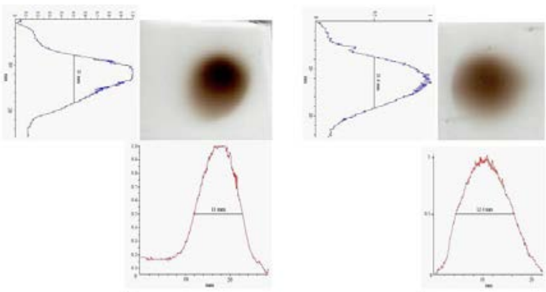
Beam current. For measuring beam current of updated accelerator electron beam was injected into atmosphere through the titan foil. By means of a Faraday cup located behind the titan foil, the beam current was measured with and without switching on the output focusing magnetic lens of the accelerator. Oscillograms of the beam current for these cases are shown in Figs. 14,a,b.

As sensitivity of oscilloscope was 5 V/div for the first case the amplitude of signal from the Faraday cup is equal 25 V (see Fig. 14,a). Taking into account that load resistance was 25 Ω we can conclude that the value of beam current was 1 A. Without switching on the focusing lens the beam current was 0.8 A (see Fig. 14,b).



a *b*

Fig. 14. Oscillograms of electron beam current on accelerator exit: focusing lens switched on (a); focusing lens switched off (b)



a b

Fig. 15. Beam imprints on the glass plates located at the accelerator exit in vertical (left) and horizontal (below) planes: focusing lens switched on (a); focusing lens switched off (b)

Transverse sizes of the beam. By the treatment of the distribution of the intensity of the darkening of the glass plates placed behind the output foil, the traversal distribution of the beam density and the traversal sizes of the beam at the accelerator exit were measured (Fig. 15). From the Figs. 15,a,b one can conclude that the beam diameters estimated as a half-width of the glass darkening distribution are: 11 and 11 mm in vertical and horizontal planes, correspondingly, for switched on focusing lens; and 11.6 and 12.4 mm in vertical and horizontal planes, correspondingly, for switched off focusing lens.

Electron energy spectrum of the beam. Electron energy spectra of the beam ejected from the accelerator and measured by the magnetic analyzer (2), at various frequencies of the master oscillator (i.e. various bunch repetition frequencies), are shown in Fig. 16.

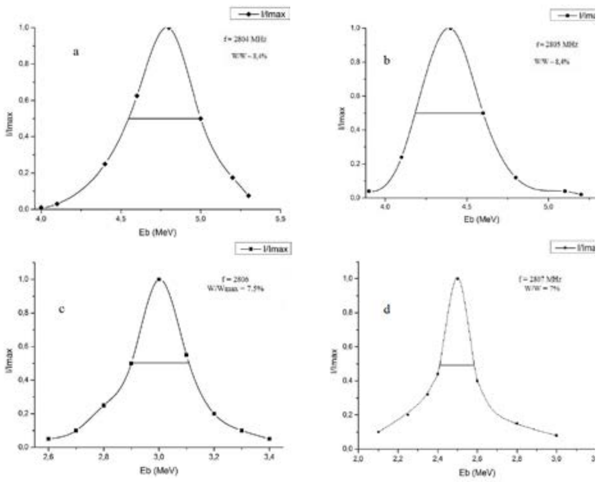
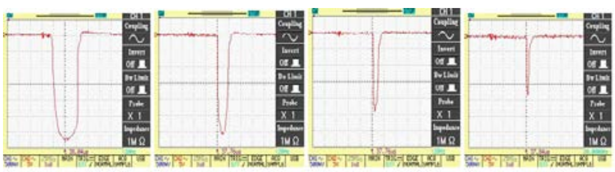


Fig. 16. The energy spectra of electrons in the beam at different frequencies of the master oscillator: f=2804 MHz (a); f=2805MHz (b); f=2806 MHz (c); f=2807 MHz (d)

The optimal operation mode of the accelerator presented in Fig. 16, at which the current is large (up to 1 A), and the half-width of an electron energy spectrum is small (within 7…9%), occurs for frequencies in the range of 2804…2807 MHz. Changing frequency of the master oscillator, it is possible to change of the electron beam energy within 2.5…4.8 MeV.

Variation of the beam pulse duration. Changing the duration of the beam pulse, i.e. the number of bunches in the consequence can be achieved by shift in time the microwave pulse of the master oscillator relatively to the high-voltage pulse of the klystron amplifier. Beam pulse duration is determined by the time overlap of these two pulses. The beam pulse durations 2.0, 1.0, 0.5, and 0.1 μs (sequence of 6000, 3000, 1500, and 300 bunches, correspondingly) obtained in such a way for three time shifts 0, 1.0, 1.5, and 1.9 μs are shown in oscillograms of Fig. 17.



a *b* *c* *d*

Fig. 17. Pulse duration of beam current for time shift τ: τ =0 μs (a); τ =1.0 μs (b); τ =1.5 μs (c); τ =1.9 μs (d)

3. PRELIMINARY EXPERIMENTS ON WAKEFIELD EXCITATION

Dielectric structure of circular cross-section. The measured permittivity value ε of Teflon was equal $\varepsilon = 2.04 \pm 0.01$, and $tg\delta = 2\cdot10^{-4}$. Accordingly to these data the dielectric cylindrical structure consisting of a copper tube with inner diameter d_2 = 85 mm and the dielectric insert with inner and outer diameter d_1=21.1 mm; d_2=85 mm, was calculated and made (Fig. 18).

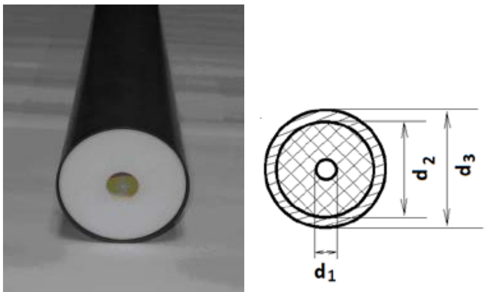
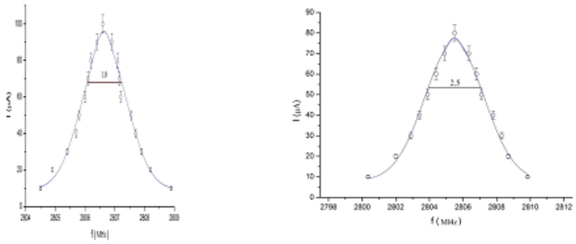


Fig. 18. Dielectric waveguide of circular cross-section; d_1=21.1 mm; d_2=85 mm; d_3=89 mm

The measurements of the value of change in the *Q* factor of the metal resonator of length 65 cm when filling it with the dielectric insert of length 44 cm. In Fig. 19 the resonance curves of the metal resonator without insert (Fig.19,a) and with an insert (Fig.19,b) are presented. From these curves it follows that the *Q* factor of the empty metal resonator $Q_0=\omega_0/2\delta = f_0/\Delta f$=2806 ($2\delta=\Delta\omega=2\pi\ \Delta f$) decreases to Q_d =1122, when the dielectric insert was input in the resonator.



a *b*

Fig. 19. Resonance curves for: resonator without (a), and with insert (b)

Experimental observation of the excited wakefield. Using oscilloscope TDS 6154C, 15 GHz we firstly in our experiments obtained the realization of 3 GHz oscillations (Fig. 20) of the wakefield excited by electron bunches passing through the dielectric structure of circular cross-section (copper tube, 65 cm long and 8.5 cm by inner diameter) filled with Teflon insert of length 35 cm, transit channel diameter 2.11 cm.

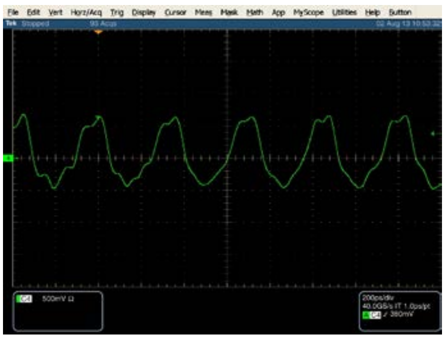


Fig. 20. Oscillogram of wakefield excited in a dielectric waveguide

4. PRODUCTION OF PLASMA IN AXIAL CHANNEL

The scheme and photo of experimental setup is shown in Fig. 21. Relativistic electron bunches produced by resonant electron accelerator “Almaz-2M” penetrates through a titanium foil with a thickness of 30 μm and enter into the dielectric waveguide of circular cross-section, filled with Teflon insert which has the transit channel of diameter 2.1 cm for the passage of bunches. To avoid reflections of the excited wakefield the dielectric insert is ended with dielectric cone, and on Teflon vacuum plug a ferrite absorber is placed.

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.

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 due to the beam-plasma discharge development at pressure around 1Torr by the excited wakefield and due to the collisional ionization by beam electrons at higher pressures.

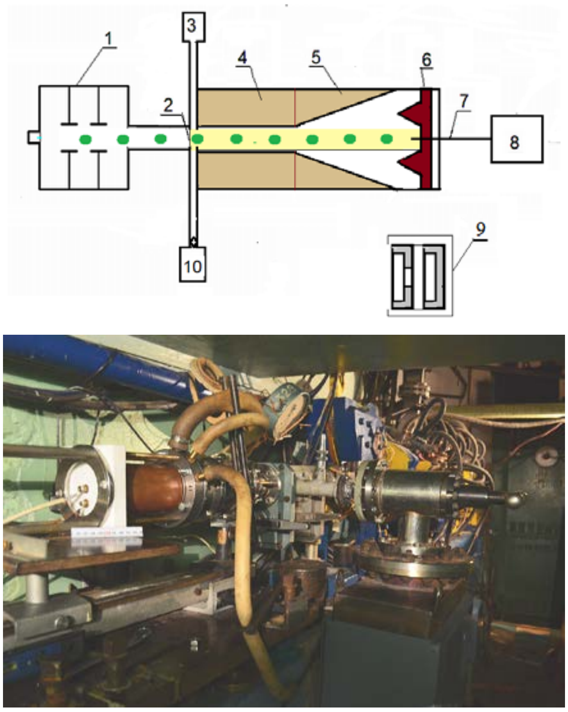
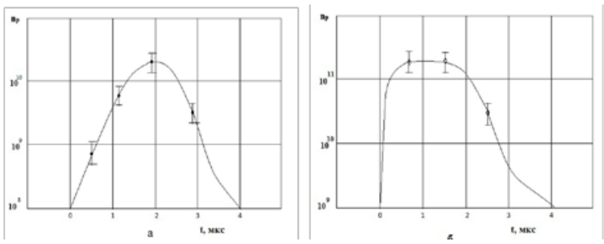


Fig. 21. Scheme of experimental setup: 1 – accelerator "Almaz-2M"; 2 – titanium foil; 3 – leak valve; 4 – dielectric waveguide; 5 – matching dielectric cone; 6 – ferrite absorber; 7 – microwave probe; 8 – oscilloscope GD-840S; 9 – double Faraday cup; 10 – vacuum pump

Plasma density was measured by HF probe or using an open barrel shaped cavity [7] with and without dielectric insert at neutral gas pressure $P=10^{-3}\ldots760$ Torr.

Measurements showed that at the injection of relativistic electron bunches into waveguide without dielectric plasma of average density $10^{10}\ldots5\cdot10^{10}$ см$^{-3}$is formed and in the presence of a dielectric plasma density is increased by more than twice and the rate of plasma density increase is significantly high (Fig. 22).



a *b*

Fig. 22. Temporal dependence of the plasma density formed by injecting bunches through the neutral gas at pressure of P = 600 Torr: without (a), and with dielectric (b)

CONCLUSIONS

Dispersion equation is obtained and topography of wakefields generated by relativistic electron bunches in hybrid plasma-dielectric structure is studied. The rate of acceleration and focusing force for accelerated bunch is determined.

Experimental installation "Plasma-dielectric wakefield accelerator" is designed and built which includes upgraded linear electron accelerator "Almaz-2M", plasma-dielectric structures and diagnostic equipment to investigate electron bunches and excited wakefields are designed and manufactured.

This work was supported by NAS of Ukraine program "Perspective investigations on plasma physics, controlled thermonuclear fusion and plasma technologies", Project P-1/63-2015.

REFERENCES

1. I.N. Onishchenko, V.A. Kiselev, A.F. Linnik, G.V. Sotnikov. Concept of dielectric wakefield accelerator driven by a long sequence of electron bunches // *Proc. IPAC*. 2013, p. 1259.
2. R.R. Knyazev, G.V. Sotnikov. Focusing wakefield for accelerated bunch in a plasma-dielectric waveguide // *J. of Kharkiv University*. 2012, № 1001, p. 64-68.
3. V.A. Balakirev, N.I. Karbushev, O.O. Ostrovsky, Yu.V. Tkach. *Theory of Cherenkov amplifiers and generators on relativistic beams*. Kiev: “Naukova dumka”, 1993, p. 161.
4. R. Keinigs and M. E. Jones. Two-dimensional dynamics of the plasma wakefield accelerator // *Phys. Fluids*. 1987, v. 30, № 1, p.252-263.
5. R.R. Kniaziev, G.V. Sotnikov. Quasistatic field influence on bunches focusing by wakefields in the plasma-dielectric waveguide // *Proc. IPAC*. 2013, p. 1256.
6. I.N. Onishchenko, A.K. Berezin, V.A. Kiselev, G.V. Sotnikov, et al. The wake-field excitation in plasma-dielectric structure by sequence of short bunches of relativistic electrons // *Proc. Particle Accelerator Conf. PAC'95 (IEEE, 1995)*. p. 782.
7. I.N. Moskalev, A.M. Stefanovsky. *Diagnostics of plasma by using open cylinder resonators*. Moscow: «Atomizdat», 1985, p. 145.

Article received 10.06.2015

КОНЦЕПЦИЯ ПЛАЗМЕННО-ДИЭЛЕКТРИЧЕСКОГО КИЛЬВАТЕРНОГО УСКОРИТЕЛЯ. ТЕОРИЯ И ЭКСПЕРИМЕНТ

Г.П. Березина, К.В. Галайдыч, Р.Р. Князев, А.Ф. Линник, П.И. Марков, О.Л. Омелаенко, И.Н. Онищенко, В.И. Приступа, Г.В. Сотников, В.С. Ус

Теоретически и экспериментально исследовано возбуждение кильватерных полей длинной последовательностью релятивистских электронных сгустков в диэлектрическом волноводе/резонаторе круглого сечения с пролетным каналом, заполненным плазмой различных плотностей.

КОНЦЕПЦІЯ ПЛАЗМОВО-ДІЕЛЕКТРИЧНОГО КІЛЬВАТЕРНОГО ПРИСКОРЮВАЧА. ТЕОРІЯ І ЕКСПЕРИМЕНТ

Г.П. Березіна, К.В. Галайдич, Р.Р. Князєв, А.Ф. Лінник, П.І. Марков, О.Л. Омелаєнко, І.М. Оніщенко, В.І. Приступа, Г.В. Сотніков, В.С. Ус

Теоретично і експериментально досліджено збудження кільватерних полів довгою послідовністю релятивістських електронних згустків у діелектричному хвилеводі/резонаторі круглого перетину з пролітним каналом, який заповнено плазмою різної густини.