NEW METHODS OF CHARGED PARTICLES ACCELERATION

https://doi.org/10.46813/2023-146-053

ELABORATION OF THE PLASMA-DIELECTRIC WAKEFIELD ACCELERATOR WITH A PROFILED SEQUENCE OF DRIVER ELECTRON BUNCHES

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A theoretical and experimental study of wakefield excitation by a profiled sequence of relativistic electron bunches in the plasma-dielectric structure, the parameters of which provide the conditions for the excitation of a small decelerating field for all driver bunches with simultaneous growth with the number of bunches of the accelerating total wakefield was carried out. Theoretically, the transformation ratio was found for the parameters of the experiment as the ratio of the total wakefield of the sequence to the field that decelerates driver bunches. In the performed experiments, the total wakefield was measured by the microwave probe. The magnitude of the decelerating field is determined by the shift of the maximum of the spectrum measured by the magnetic analyzer before and after wakefield excitation in the structure. The obtained transformation ratio increases with the number of bunches in the sequence and significantly exceeds this one for a nonprofiled sequence.

PACS: 41.75.Ht; 41.75.Lx

INTRODUCTION

Currently, high-energy physics requires beams of charged particles in the TeV energy range to solve fundamental problems. The relevant existing colliders – hadron LHC [1] and lepton CLIC [2] and ILC [3]) – using traditional acceleration methods have become extremely huge and expensive. The development of advanced methods of charged particles acceleration with an accelerating rate of several orders higher than traditional ones is necessary to radically reduce the dimensions and cost of future colliders.

CERN has presented an updated strategy for high-energy physics – 2020 UPDATE OF THE EUROPEAN STRATEGY FOR PARTICLE PHYSICS [4]. In order to develop the physics program of the future cyclic lepton collider, it is proposed to increase its energy to 175 GeV, and its perimeter to 100 km. By analogy with the successful long-term operation of the LEP-LHC, after the lepton collider operation program it is planned to build in the same tunnel the hadron collider for energy up to 100 TeV using the LHC as an injector.

Taking into account the wide-ranging theoretical and experimental studies of new acceleration methods and the achieved significant results in the wakefield method of acceleration in plasma with an acceleration rate of about 50 GeV/m, three orders of magnitude higher than the traditional one – with a beam driver at a length of 0.9 m doubling the energy of a 42 GeV electron bunch [5]; and with a laser driver at a length of 9 cm reaching an energy of 4.2 GeV [6] – within the framework of the updated European strategy for high-energy physics, at the initiative of the International Committee of Future Accelerators ICFA (International Committee of Future Accelerators), the collaboration "ALEGRO" (Advanced LinEar collider study GROup) was created, which offered to build with the joint efforts of many countries the e+/e -/gamma collider "ALIC" (Advanced Linear International Collider) of 30 TeV with radically smaller dimensions, which is based on new methods of acceleration [7].

The paper presents the development of the wakefield method of charged particles acceleration at a high accelerating rate, which was started in cooperation with ANL [8 - 10] and was motivated by the creation of a collaboration ALEGRO for the construction of the collider ALIC within the framework of the updated European high-energy physics strategy.

The purpose of the presented researches is to increase the transformation ratio in the multi-bunch plasma-dielectric wakefield accelerator, that is defined as a ratio of the energy gain by the accelerating electron bunch to the energy losses of the driver bunches. It is achieved by appropriate charge profiling of the bunch sequence.

1. STATEMENT OF THE PROBLEM

One of the important problems in the wakefield method of acceleration is overcoming the limitation of the transformation ratio, defined as the ratio of the energy gain by the accelerating bunch to the energy lost by the driver bunch for the wakefield excitation.

$$R \equiv \frac{W_w}{\Delta W_d} = \frac{E_+ L}{E_- L} = \frac{E_+}{E_-} = 2\,, \qquad \text{(A)}$$

which, according to Wilson's theorem, in the linear approximation for a collinear scheme with two bunches does not exceed R = 2. This result is due to the fact that with an increase in the charge Q of the driver bunch, not only the magnitude of the accelerating field (i.e. the acceleration rate) is increased, but the distance at which the driver bunch is slowed down also decreases to the same extent. One way to overcome this limitation is to use a profiled driver bunch or a profiled sequence of bunches.

If the parameters of the sequence of electron bunches (the length of the bunches L_b, the spatial period of bunch following L_m, the profile of the sequence by the charge of the bunches) and the plasma-dielectric structure (the wavelength λ of the excited eigen mode) are chosen as follows

$$\begin{aligned} &L_b = \lambda, \\ &L_{\mathrm{m}} = L_b + \lambda, \\ &Q_1 : Q_2 : Q_3 = 1:3:5:... \end{aligned} \tag{B}$$

then each bunch is occurred in the wakefields of previous bunches and in its own wakefield, namely in the $E_0/2$ field, where E_0 is the excited wakefield behind the first bunch (Fig. 1).

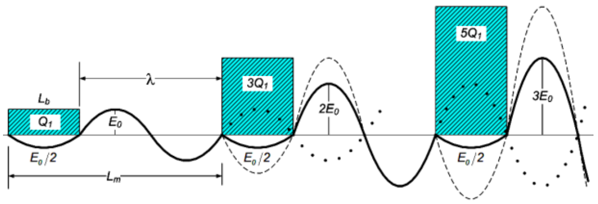


Fig. 1. Interference of the wakefields of the first three bunches of the profiled sequence Q_1:Q_2: Q_3=1:3:5, which move to the left. The wakefield of the 1st bunch – solid curve; 2nd bunch – dotted curve; 3rd bunch – dotted curve; the total wakefield is the bold curve

It can be seen from Fig. 1 that for the uniformity of the slowing down fields of each bunch, it is necessary to profile the bunches by charge as 1:3:5:... Only with this profiling, also for each bunch, the total wakefield of the previous bunches together with the field of the bunch itself give the resulting field $E_0/2$. At the same time, behind each bunch, the total wakefield grows as NE_0, where N is the number of bunches As a result, the transformation ratio R=NE_0/E_0/2=2N instead of R=N/(N-1/2) for the case of nonprofiled sequence of N bunches with charge Q_1.each. A similar approach was also considered in [11 - 13].

In the experiments, the parameters of the plasma-dielectric structure and the profiled sequence of bunches do not fully correspond to the optimal ones (B) in the given scheme, in which the transformation ratio increases proportionally to the number of bunches in the sequence. It is because parameters of the sequence produced with accelerator "Almaz-2M" (length of the bunches L_b, and period of their following L_m) are fixed. In the set of equations (B), it is possible to vary only the length of the eigenwave λ of the structure excited by the sequence of bunches. The frequency of bunches following f_m=2.805 GHz, i.e. L_m=10.64 cm, is fixed due to the accelerator, the geometry of the dielectric structure is chosen so (a=2.93 cm, b=4.19 cm, ε =2.045) that the length of the eigenwave λ excited by the bunches in the sum with the length of the bunch l_b=1.7 cm (unfortunately also fixed due to the accelerator, it should be $l_b=\lambda/2$) was equal to the period of bunches following $L_m=\lambda+l_b$.

Therefore, the structure becomes non-resonant in contrast to the resonant one ($L_m=\lambda$) for obtaining the maximum wake field. The charge of bunches increases linearly with the number in the sequence, but not as 1:3:5:... In the experiment the transformation ratio was found as the ratio of the total wakefield excited by the profiled sequence of bunches, which is measured by a microwave probe, to the field decelerating driver bunches, which is determined by the energy losses of the driver bunches finding from the shift of their energy spectrum measured by a magnetic analyzer.

2. THEORY AND NUMERICAL RESULTS

2.1. LINEAR THEORY OF WAKEFIELD EXCITATION

The investigated electrodynamic structure is a metal waveguide of cylindrical configuration, partially filled with a dielectric with a channel for charged particles (drive and test bunches). The channel is filled with homogeneous cold plasma. A charge-profiled regular sequence of drive relativistic electron bunches is injected into the plasma channel parallel to the waveguide axis without transverse displacement, and propagates along the structure, exciting a wakefield. The main goal of this section is to study the longitudinal structure of the wakefield components in the case of its excitation by a profiled sequence of drive bunches, and to determine the transformation ratio.

In order to construct the analytical expressions for the components of the wakefield, excited by driver electron bunches, it is necessary to start with the case of a point particle, that is, to construct the corresponding expressions for the Green's function. We assume that a particle of charge q moves with a constant velocity v along the structure axis (z direction). W can write down its current density as follows:

$$j_z = q\frac{\delta(r-r_0)}{r}\delta(\varphi-\varphi_0)\delta(\xi-t_0), \tag{1}$$

where r_0 and φ_0 are its transverse coordinates, $\xi = t - z/v$, and t_0 is the particle injection time into the structure at $z=0$. The electromagnetic field components, and the charge and current densities we expressed in terms of Fourier transformation as follows:

$$\begin{aligned} \mathbf{E}(r,\varphi,\xi) &= \sum_{m=-\infty}^{+\infty} e^{im\varphi}\int_{-\infty}^{+\infty} d\omega \mathbf{E}_m^{\omega}(r,\omega)e^{-i\omega\xi}, \\ \mathbf{H}(r,\varphi,\xi) &= \sum_{m=-\infty}^{+\infty} e^{im\varphi}\int_{-\infty}^{+\infty} d\omega \mathbf{H}_m^{\omega}(r,\omega)e^{-i\omega\xi}, \\ j_z(r,\varphi,\xi) &= \sum_{m=-\infty}^{+\infty} e^{im\varphi}\int_{-\infty}^{+\infty} d\omega j_{zm}^{\omega}(r,\omega)e^{-i\omega\xi}. \end{aligned} \tag{2}$$

The wave equations for the Fourier transforms of the axial electric and magnetic fields E_{zm}^{ω} та H_{zm}^{ω} obtained from Maxwell's equations have the following form:

$$\begin{aligned} &\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial E_{zm}^{\omega}}{\partial r}\right) - \frac{m^2}{r^2}E_{zm}^{\omega} - \kappa^2 E_{zm}^{\omega} = \frac{4\pi i\kappa^2 j_{zm}^{\omega}}{\omega\varepsilon(\omega)}, \\ &\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial H_{zm}^{\omega}}{\partial r}\right) - \frac{m^2}{r^2}H_{zm}^{\omega} - \kappa^2 H_{zm}^{\omega} = 0, \end{aligned} \tag{3}$$

where $\kappa^2(\omega) = (\omega/v)^2(1-\beta^2\varepsilon(\omega))$, $\beta = v/c$. The Fourier transforms of the electric field E_{rm}^{ω}, $E_{\varphi m}^{\omega}$ and magnetic field H_{rm}^{ω}, $H_{\varphi m}^{\omega}$ can be expressed in terms of the axial components E_{zm}^{ω} and H_{zm}^{ω}. We consider the case of the bunches injection along the axis of the waveguide without an offset, so only azimuthally uniform field components ($m = 0$) will be excited.

The radial force F_r is expressed through the Fourier transform of the axial component E^{ω}_{zm} as follows

$$\frac{F_r}{q} = -iv\frac{\partial}{\partial r}\int_{-\infty}^{+\infty} d\omega \frac{E^{\omega}_{zm}}{\omega} e^{-i\omega\xi}. \quad (4)$$

Taking the inverse Fourier transform for the Green functions F_{Gz} and F_{Gr} of the wakefield components (Green's functions) in the plasma channel we obtain the following expressions for the axial force:

$$\frac{F_{Gz}}{q} = -2qk_p^2\left(\frac{I_0(k_p r)}{I_0(k_p a)}\Delta_0(k_p a, k_p r_0)\theta(r_0 - r) + \frac{I_0(k_p r_0)}{I_0(k_p a)}\Delta_0(k_p a, k_p r)\theta(r - r_0)\right)\cos\omega_p(\xi - t_0)\theta(\xi - t_0) \quad (5)$$
$$-\sum_{s=1}\frac{4qI_0(\kappa_{ps}r)I_0(\kappa_{ps}r_0)}{a\omega_s D'(\omega_s)I_0^2(\kappa_{ps}a)}\cos\omega_s(\xi - t_0)\theta(\xi - t_0),$$

and for the radial force:

$$\frac{F_{Gr}}{q} = 2qk_p^2\left(\frac{I_1(k_p r)}{I_0(k_p a)}\Delta_0(k_p a, k_p r_0)\theta(r_0 - r) - \frac{I_0(k_p r_0)}{I_0(k_p a)}\Delta_1(k_p r, k_p a)\theta(r - r_0)\right)\sin\omega_p(\xi - t_0)\theta(\xi - t_0) \quad (6)$$
$$+\sum_{s=1}\frac{4qv\kappa_{ps}I_1(\kappa_{ps}r)I_0(\kappa_{ps}r_0)}{a\omega_s^2 D'(\omega_s)I_0^2(\kappa_{ps}a)}\sin\omega_s(\xi - t_0)\theta(\xi - t_0),$$

where ω_p is a plasma frequency, $k_p = \omega_p / v$ is a plasma wavenumber, a is an inner radius of the dielectric tube, $\Delta_n(x,y) = I_n(x)K_0(y) - (-1)^n K_n(x)I_0(y)$, I_n and K_n are the modified Bessel and Macdonald functions of the nth order, $\kappa_{ps} = \kappa_p(\omega_s)$, $\varepsilon_p(\omega) = 1 - \omega_p^2/\omega^2$ is the plasma permittivity, $D'(\omega_s) = dD(\omega_s)/d\omega$, θ is the Heaviside function. The frequencies the eigen modes for the plasma-dielectric waveguide ω_s resonant with the bunch ($k_z = \omega / v$) are found using the numerical solution of the dispersion equation, which has the form:

$$D(\omega) \equiv \frac{\varepsilon_p}{\kappa_p}\frac{I_1(\kappa_p a)}{I_0(\kappa_p a)} + \frac{\varepsilon_d}{\kappa_d}\frac{F_1(\kappa_d a, \kappa_d b)}{F_0(\kappa_d a, \kappa_d b)} = 0, \quad (7)$$

where $\kappa_p^2 = (\omega/v)^2(1 - \beta^2\varepsilon(\omega))$, ε_d is dielectric permittivity, $\kappa_d^2 = (\omega/v)^2(\beta^2\varepsilon_d - 1)$, b is outer radius of the dielectric tube, $F_0(x,y) = J_0(x)Y_0(y) - Y_0(x)J_0(y)$, $F_1(x,y) = -J_1(x)Y_0(y) + Y_1(x)J_0(y)$, J_n and Y_n are the nth order Bessel and Webber functions respectively. The field components expressions for the finite-size driver bunch can be obtained basing on the point particle solution by the integration over the injection time t_0 and transverse position r_0. We suppose that each driver bunch in the profiled sequence of bunches has a square profile of the charge density in both longitudinal and transverse directions (uniform distribution). The charge of each bunch in the train grows as an odd number. As a result the final expressions for the axial and radial forces acting on the bunch particles have the following form:

$$\frac{F_z(r \le R_b, \xi)}{q} = -\frac{4Q_b}{R_b L_b}\sum_{i=1}^{N_b}\frac{2i-1}{2N_b - 1}\left(\frac{1}{k_p R_b} - \frac{I_0(k_p r)}{I_0(k_p a)}\times \Delta_1(k_p R_b, k_p a)\right)\Psi_{\parallel}^{(p)}(\xi) - \frac{8Q_b}{R_b L_b}\sum_{i=1}^{N_b}\sum_{s=1}\frac{(2i-1)}{(2N_b - 1)}\times \quad (8)$$
$$\frac{v}{a\kappa_{ps}\omega_s^2 D'(\omega_s)}\frac{I_0(\kappa_{ps}r)I_0(\kappa_{ps}R_b)}{I_0^2(\kappa_{ps}a)}\Psi_{\parallel}^{(s)}(\xi),$$

$$\frac{F_r(r \le R_b, \xi)}{q} = -\frac{4Q_b}{R_b L_b}\sum_{i=1}^{N_b}\frac{2i-1}{2N_b - 1}\frac{I_1(k_p r)}{I_0(k_p a)}\times \Delta_1(k_p R_b, k_p a)\Psi_{\perp}^{(p)}(\xi) + \frac{8Q_b}{R_b L_b}\sum_{i=1}^{N_b}\sum_{s=1}\frac{(2i-1)}{(2N_b - 1)}\times \quad (9)$$
$$\frac{v^2}{a\omega_s^3 D'(\omega_s)}\frac{I_1(\kappa_{ps}r)I_1(\kappa_{ps}R_b)}{I_0^2(\kappa_{ps}a)}\Psi_{\perp}^{(s)}(\xi),$$

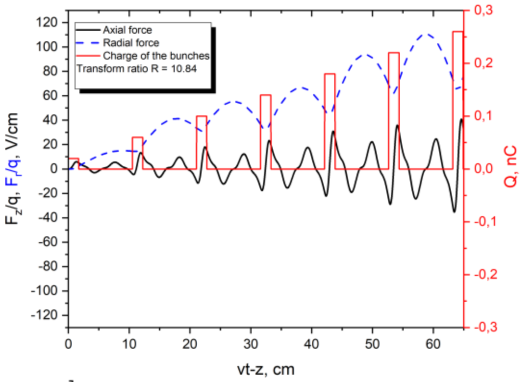
where R_b is the bunch radius, L_b is the bunch length, N_b is a number of the drive bunches in the sequence and Q_b is the charge of the last bunch. An axial structure of the bunch-excited wakefield components, is describe by the functions $\Psi_{\parallel}^{(p,s)}(\xi)$ and $\Psi_{\perp}^{(p,s)}(\xi)$, which has the form:

$$\Psi_{\parallel}^{(p,s)} = \theta(\xi - (i-1)T_r)\sin\omega_{p,s}(\xi - (i-1)T_r) - \theta(\xi - (i-1)T_r - T_b)\sin\omega_{p,s}(\xi - (i-1)T_r - T_b),$$
$$\Psi_{\perp}^{(p,s)} = \theta(\xi - (i-1)T_r)\left(1 - \cos\omega_{p,s}(\xi - (i-1)T_r)\right) - \theta(\xi - (i-1)T_r - T_b)\left(1 - \cos\omega_{p,s}(\xi - (i-1)T_r - T_b)\right), \quad (10)$$

where T_r is a bunch repetition time, $T_b = L_b / v$.

2.2. NUMERICAL ANALYSIS

The constructed linear theory of wakefield excitation by a charge-profiled regular sequence of driver bunches allows to carry out a numerical analysis of the spatio-temporal structure of the electromagnetic field in the plasma-dielectric accelerating structure. For the numerical analysis in the gigahertz frequency range we used the parameters of the waveguide and the train of electron bunches accessible at Kharkov Institute of Physics and Technology (linac "Almaz-2M") {1st option}: energy of electron bunch is W= 2.5 MeV, the inner radius $a = 2.9$ cm and the outer radius $b = 4.25$ cm of the dielectric tube, the dielectric permittivity $\varepsilon_d = 2.045$ (Teflon), so that the mode with a wavelength λ = 7.12 cm resonant with the bunches is excited; the length of the bunches L_b=1.7 cm, the radius of the bunches R_b=0.5 cm, distance between the bunches $L_{\mathrm{mod}} = 10.58$ cm, the plasma density n_p= 10^{10} cm^{-3}. The dielectric material was assumed to be dispersionless ($\varepsilon_d \ne \varepsilon_d(\omega)$). The main goal of the numerical investigations in this section is to analyze the possibility of obtaining a high value of the transformation ratio and simultaneous radial focusing both drive and witness electron bunches. Fig. 2 demonstrates the longitudinal distributions of an axial force $F_z / q = E_z$ and a radial force $F_r / q = E_r - \beta H_\varphi$, acting both on the driver bunches and accelerated bunch for the case $N_b = 7$.



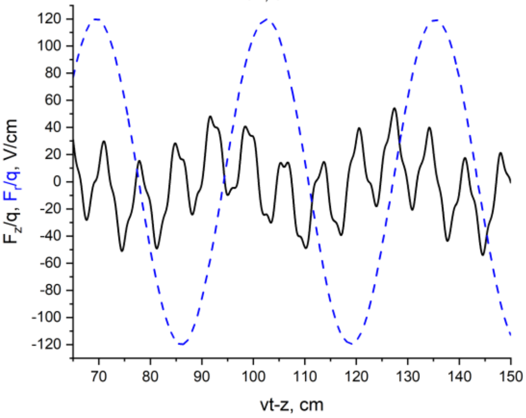


Fig. 2. The axial profiles of the longitudinal (solid line) and radial (dashed line) forces excited by the bunches, at the distance $r = R_b$ from the waveguide axis for the case $N_b = 7$. The upper figure shows the distribution within the sequence, the lower figure shows the distribution behind the last bunch. The profiled sequence of bunches (rectangles) move from right to left, the first bunch position in the sequence corresponds to $vt - z = 0$

It can be seen that the profile of the axial force is irregular, both in the region inside the sequence of driver bunches and behind the last driver bunch. The main reason of the irregularity is following. The axial force is provided both by the field of eigenmodes of the plasma-dielectric waveguide and by the field of the plasma wave, while the radial force is provided mainly by the field of the plasma wave. The presented force distributions demonstrate that for the given parameters of the waveguide and bunches: (i) the axial force changes sign inside the drive bunches, which leads to transform ratio decrease, their filamentation and energy spread, (ii) the force decelerating the drive bunches oscillates along the sequence of drive bunches, which leads to uneven energy losses of these bunches, (iii) all drive bunches are in an increasing (by amplitude) focusing field, with amplitude oscillating along the sequence, which is a positive property of the plasma-dielectric structure, which, in turn, leads to an improvement in the transverse stability of the drive bunches, and can provide a longer length of the accelerating structure, (iv) due to the difference in the wavelengths of the working eigenmode of the structure (7.1215 cm) and the length of the plasma wave (33.22 cm), it is possible to choose the injection time of test accelerated electron or positron bunches, that can be accelerated and focused at the same time. The amplitude of the transverse field increases due to the coherent summation of the fields from the sequence of bunches, while the driver bunches remain in the focusing phases of the field. The transformation ratio, calculated as the ratio of the maximum amplitude of the accelerating electric field, after the last driver bunch, to the average amplitude of the decelerating electric field is equal to $R \approx 11$. To increase the transformation ratio, in ongoing research, it is proposed to use a long sequence of drive bunches with odd charges. This gives a combination of increase as due to increase N_b, as well as due to the reduction of the field that decelerates the driver bunches. Fig. 3 illustrates longitudinal distributions F_z / q and F_r / q, that correspond to the case $N_b = 15$. Fig. 3 shows that in this case compared to the previous one the accelerating field (which is determined by the charge of the last bunch of the sequence) has the same amplitude value, while the average decelerating electric field decreases. In this way, the transformation ratio increases. In this case is equal to $R \approx 18$.

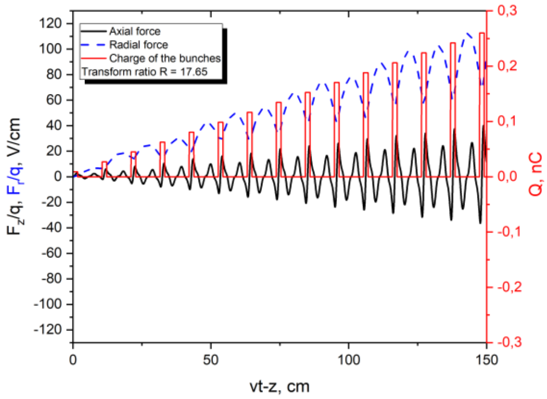


Fig. 3. Longitudinal profiles of axial (solid line) and radial (dashed line) forces excited in the waveguide at a distance $r = R_b$ from the axis for the case $N_b = 15$

It should be noted, that the parameters for which the numerical analysis was carried out are not optimal, and in order to ensure the uniform deceleration of all drive bunches in the profiled sequence and their uniform energy loss, it is necessary: (i) the repetition period of the bunches of the sequence must be equal to the sum of the wavelength of the first radial mode λ_1 and the length of the driver bunch, i.e. $L_{mod} = \lambda_1 + L_b$, (ii) choose the length of each bunch equal to half of the working mode wavelength $L_b = \lambda_1 / 2$. It should be separately noted, that the excitation of the focusing fields leads, in turn, to a decrease in the requirements for external focusing systems in order to suppress transverse instabilities that may occur during the passage of bunches along the accelerating structure.

The results of the theoretical consideration for the second set of experimental parameters {option 2}, in which the change in the eigen wave length of the structure by the appropriate choice of the diameter of the channel for the charged particles allows the condition $L_{mod} = \lambda_1 + L_b$ to be fulfilled, necessary for the stay of the whole driver bunch in the decelerating field, obtained earlier [14] and shown in Fig. 4.

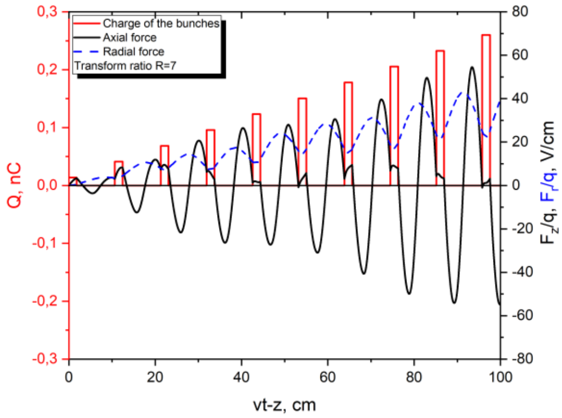


Fig. 4. Longitudinal profiles of axial (solid line) and radial (dashed line) forces excited at a distance $r = R_b$ from the axis with $N_b = 7$, for 2nd option with another a=2.19 cm and W=4.5 MeV, for which λ_1 =8.84 cm

It can be seen that all driver coils are completely in the braking field, the amplitude of which oscillates along the sequence. Oscillations are eliminated when the condition $L_b = \lambda_1 / 2$ is fulfilled, which cannot be satisfied in our experiment.

Therefore the theoretical studies of the wakefield excitation in the cylindrical plasma-dielectric waveguide by a regular charge-profiled sequence of drive electron bunches have been carried out. A possibility of increasing the transform ratio due to a simultaneous increase of the drive bunches number and a decrease of an average field decelerating them has been demonstrated. A spectral analysis of the excited electromagnetic field was carried out. It is shown that the excitation of the axial electric field is provided both by the field of the eigenmodes of the plasma-dielectric waveguide and by the field of the plasma wave, while the excitation of the radial force is provided mainly by the field of the plasma wave.

3. EXPERIMENTS ON THE TRANSFORMATION RATE INCREASE

3.1. FORMATION OF A PROFILED SEQUENCE WITH THE NECESSARY NUMBER OF BUNCHES

The electron gun modulator generates a voltage pulse applied to the cathode with duration of 4 μs and an amplitude of 80 keV. The pulse has a flat top of 2.5 μs and gentle fronts. The forming lines of the master-generator "Rubin" and the klystron amplifier KIU-2M provide rectangular pulses with duration of 2 μs. All three modulators are triggered by pulses with adjustable delay for each channel Fig. 5.

During normal operation of the accelerator, there is no delay between the pulses that trigger the modulators of the master magnetron generator and the klystron amplifier, so that the microwave power pulse of the klystron amplifier reaches the flat part of the voltage pulse on the gun. In this case, a rectangular pulse of an accelerated beam (that is, an nonprofiled sequence of bunches) with a duration of 2 μs is formed at the output of the accelerator.

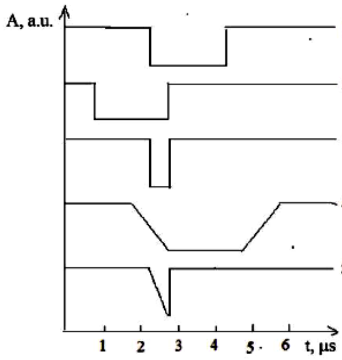
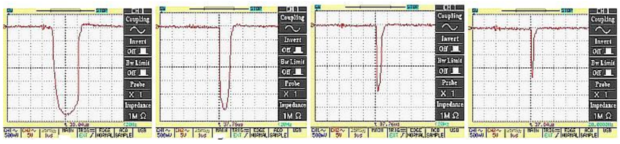


Fig. 5. Arrival time of pulses from the main nodes of the accelerator "Almaz-2M"

By shifting the pulses of the master generator and klystron amplifier KIU-2M relative to each other, it is possible to control the duration of the microwave pulse entering the input of the accelerator section and, accordingly, the duration of the beam pulse at the output of the accelerator. When the delay is shifted by 1, 1.5, and 1.9 μs, the duration of the current pulse is 1, 0.5, and 0.1 μs, respectively. Pulses of the beam with a duration of 0.1 obtained in this way; 0.5; 1.0, and 2.0 μs (the number of clots, respectively, 300, 1500, 3000, and 6000) are shown on the oscillograms in Fig. 6.



a b c d

Fig. 6. Duration of the beam current pulse: a – τ = 2 μs; b – τ = 1 μs; c – τ = 0.5 μs; d – τ = 0.1 μs

If such pulses are applied with an appropriate time delay to the linearly increasing leading edge of the gun voltage pulse, a linearly profiled beam pulse of the needed duration (i.e. a profiled sequence with an adjustable number of bunches) is formed at the accelerator output. Experimentally obtained oscillograms of profiled sequences of two durations are shown in Fig. 7.

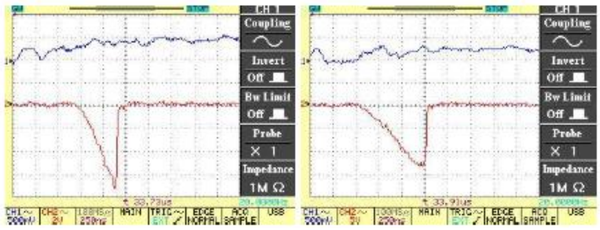


Fig. 7. Oscillograms of profiled sequences of electron bunches with a duration of 0.4 μs (1200 bunches) and 0.75 μs (2250 bunches)

3.2. EXCITATION OF WAKEFIELDS BY A PROFILED SEQUENCE OF BUNCHES

The scheme of the experimental setup, on which the wakefield excitation in the plasma-dielectric structure (4) by the profiled sequence of bunches, produced by the accelerator “Almaz-2M” (1) was studied, is shown in Fig. 8.

The amplitude of the excited wakefield Ea, needed for the witness-bunch acceleration, was measured by microwave probes (8). The amplitude of the retarding field Er was determined by the shift of the energy spectrum of the bunch electrons caused by the energy loss for exciting wakefield and the acceleration length. Energy spectra were measured using a magnetic analyzer (2, 6, 11, 12).

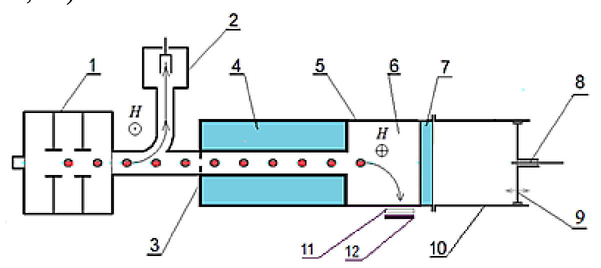


Fig. 8. Scheme of the experimental setup:
1 – accelerator “Almaz-2M”; 2 – magnetic analyzer; 3 – input diaphragm; 4 – Teflon tube; 5 – metal resonator; 6 – transverse magnetic field; 7 – vacuum plug; 8 – microwave probe; 9 – plunger; 10 – additional waveguide; 11 – glass plate; 12 – collector

The signal from the microwave probe was fed to the TDS 6154 oscilloscope. The oscillogram obtained during the injection of a sequence of bunches into the structure lasting 400 ns (1200 bunches) with a linearly increasing charge of the bunches is shown in Fig. 9. It can be seen that the amplitude of the total wakefield increases during the pulse, that is, with the number of bunches. At the same time, according to the simulation (see above), the retarding field remains at the level of the retarding field of first bunch. Therefore, the transformation coefficient increases with the number of bunches.

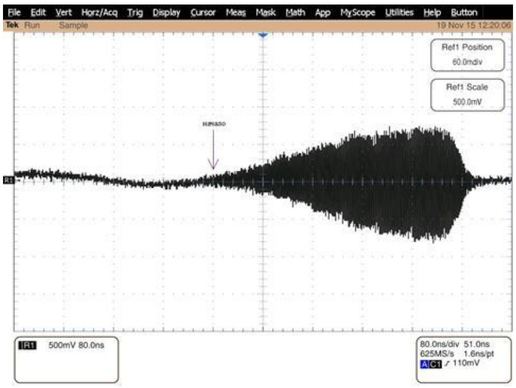


Fig. 9. Oscillogram of the microwave signal of the wakefield excited in the plasma-dielectric structure by a profiled sequence of electron bunches with a duration of 400 ns

In the experiment, the amplitude of the wakefield is measured by a microwave probe, the voltage from which is recorded by an oscilloscope. To obtain the field amplitude in V/m, the microwave probe was calibrated using the SPECTRAN device, which measures electromagnetic radiation in a stationary mode in open space, namely, microwave power density in W/m^2, and electric field strength in V/m.

The design of the microwave probe is selected so that its sensitivity allows sensing in open space the electromagnetic radiation generated at a frequency of 2.8 GHz by the G4-80 generator, which can be measured by the SPECTRAN device. Such a microwave probe is an LCD coaxial cable with a bare central core length ¼ λ with a ground detector. The detector is needed due to the lack of an oscilloscope with an ultra-fast sweep.

It is shown that at the maximum generated microwave power, the voltage obtained from the microwave probe of 1.5 mV corresponds to the SPECTRAN readings of the microwave power density of 40.08 mW/m^2, or the electric field strength of 3.886 V/m. Therefore, 1 mV of voltage from the output of the microwave probe corresponds to the intensity of the measured electric field of 2.6 V/m. At the same time, in the pulse generation mode, the front of the voltage pulse from the probe is less than 100 ns.

3.3. ENERGY LOSSES OF DRIVER BUNCHES FOR THE WAKEFIELD EXCITATION

The amplitude of the wakefield, in which the driver bunches are decelerated, is estimated by their energy losses along the excitation length, which are determined by the shift of their energy spectrum. Energy spectra were obtained using magnetic analyzers at the entrance and the exit of the plasma-dielectric structure.

Test measurements of energy spectra of the non-profiled sequence of bunches at the entrance to the structure (black curve) and at its exit (red curve) are presented in Fig. 10. The shift of the energy spectrum towards lower energies indicates the loss of energy by driver bunches for wakefield excitation. The value of the spectrum displacement $\Delta W = 0.15$ MeV (see Fig. 10) corresponds to relative losses $\Delta W/W = 3\%$.

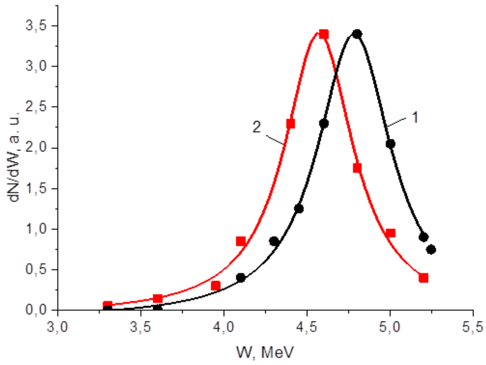


Fig. 10. Energy spectra of electrons measured by a magnetic analyzer for a structure with a length of 65 cm: 1 – initial spectrum;
2 – spectrum after wakefield excitation

For control in the middle part of the chamber, the bunches were turned by magnetic field, passed through the wall of the vacuum chamber with the same insignificant energy losses for all electrons, and gave impressions on a glass plate. The blackening on the plate by the bunch electrons turned various angles depending on their energy also reflected its energy spectrum, which coincided with the spectrum obtained by magnetic analyzer.

For a profiled sequence of bunches, the measured energy losses ΔW by bunches for wakefield excitation at a known length of excitation L allow finding the decelerating field $E_d = \Delta W/L$.

The transformation coefficient R is defined as the ratio of the accelerating field E_a, measured by the microwave probe, to the decelerating field E_d, measured by the magnetic analyzer:

$$R = E_a L/E_d L = E_a/E_d.$$

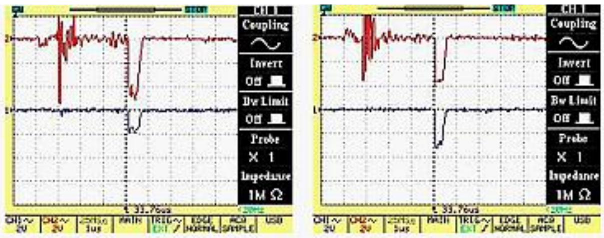
Experimentally obtained transformation rate for the 1st variant of the set of experimental parameters (section 2.2) $R=E_a/E_d = 8$, is close to the theoretical one, although smaller due to the incomplete fulfillment in theory of the initial conditions of the available experience (profile of charge increase from the number of clots, number of involved bunches). In addition, in this 1st option of obtaining the value $R = E_a/E_d$ is not a transformation rate in its pure form due to the fact that, as shown in 2.2, for such a set of parameters the energy of the part of the driver is transformed not only in accelerated witness drivers, but also in another part of this driver.

Experimental measurements of the transformation ratio for the 2nd option $L_m = L_b + \lambda$ (section 2.2) require the creation of another structure according to its eigen wavelength λ, because parameters of the sequence of bunches L_m and L_b are provided by the accelerator and are therefore fixed. The results of the further experiments will be presented in the following publications.

3.4. FOCUSING A SEQUENCE OF BUNCHES BY WAKEFIELD EXCITED IN PLASMA-DIELECTRIC STRUCTURE

Driving bunches, exciting the wakefield in a plasma-dielectric structure, are in the decelerating longitudinal dielectric field and in the focusing radial plasma field. The radial defocusing field of the dielectric wave, with its longitudinal field almost uniform in radius, is weak. Therefore, the driver bunches are focused by the wakefield excited in plasma.

Fig. 11 shows beam current oscillograms obtained experimentally using a double Faraday cylinder consisting of two cylinders – the first cylinder with a central hole for recording the peripheral part of the bunches and the second cylinder for recording the central part of the bunches that passed through the hole in the first cylinder.



a b

Fig. 11. Beam current oscillograms recorded by GDS-840C oscilloscope from a double Faraday cylinder (upper curve corresponds to the first cylinder, lower curve corresponds to the second cylinder) for two gas pressures: 10^{-3} Torr (a); 0.5 Torr (b)

The oscillograms are given for the vacuum case at a neutral gas pressure in the transient channel of the dielectric waveguide of 10^{-3} Torr (see Fig. 11,a), when no plasma is formed, and the plasma case at a pressure of 0.5 Torr (see Fig. 11,b), when the plasma is intensively formed due to the development of beam-plasma discharge. An increase in the current in the second cylinder and at the same time its decrease in the first cylinder in the presence of plasma (see Fig. 11,b) indicates the focusing effect on the driver bunches. For accelerated bunches, simultaneous acceleration and focusing is provided by the choice of right injection phase using appropriate plasma density.

CONCLUSIONS

Theoretical and experimental studies of the wakefield excitation by a profiled sequence of electron bunches in a non-resonant plasma-dielectric structure were carried out for the available parameters of the structure and the sequence of bunches on the KIPT experimental installation.

The possibility of a radical increase in the transformation ratio due to the profiling sequence of the bunches was shown. Such sequence makes it possible to obtain a total accelerating wakefield increasing with the number of bunches and a non-increasing and much smaller field decelerating driver bunches. It was found that both driver and accelerated bunches are focused in this case by excited plasma wakefield.

ACKNOWLEDGEMENTS

This work was supported by NAS of Ukraine Program "Plasma physics and plasma electronics: basic researches and applications", Project П4/60-2022.

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Article received 02.07.2023

РОЗРОБКА ПЛАЗМОВО-ДІЕЛЕКТРИЧНОГО КІЛЬВАТЕРНОГО ПРИСКОРЮВАЧА З ПРОФІЛЬОВАНОЮ ПОСЛІДОВНІСТЮ ДРАЙВЕРНИХ ЕЛЕКТРОННИХ ЗГУСТКІВ

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Виконано теоретичне та експериментальне дослідження збудження кільватерного поля профільованою послідовністю релятивістських електронних згустків у плазмово-діелектричній структурі, параметри якої забезпечують умови для збудження малого сповільнюючого поля для всіх драйверних згустків з одночасним зростанням з кількістю згустків прискорювального сумарного кільватерного поля. У теорії для параметрів експерименту знайдено коефіцієнт трансформації як відношення повного кільватерного поля послідовності до поля, що сповільнює драйверні згустки. В експерименті сумарне кільватерне поле вимірювалося мікрохвильовим зондом. Величина сповільнюючого поля знаходилась по зсуву максимуму енергетичного спектра, вимірюваного магнітним аналізатором до та після збудження кільватерного поля у структурі. Отриманий коефіцієнт трансформації зростає зі збільшенням кількості згустків у послідовності та значно перевищує такий для непрофільованої послідовності.