ELABORATION OF PLASMA-DIELECTRIC WAKEFIELD ACCELERATOR

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Theoretical and experimental investigations of the physical principles of wakefield accelerator based on the excitation of accelerating wakefield in the plasma-dielectric structure by a long sequence of relativistic electron bunches are presented. Enhancing the wakefield intensity is supposed to be achieved by using multibunch regime of excitation for the coherent summation of wakefields of individual bunches and resonator regime for wakefields accumulation. The acceleration of bunches in the total (plasma+dielectric) wakefields is realized by detuning of bunch repetition frequency relatively to the frequency of the excited wakefield. In such a way the sequence of bunches is divided into exciting and accelerated parts due to displacing latter part of bunches into accelerating phases of wakefield excited by a former part of bunches of the same sequence. The influence of plasma in the transit channel on the amplitude of excited plasma and dielectric wakefields and focusing exciting and accelerated bunches is investigated.

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INTRODUCTION

In solving frontier problems of high energy physics particle accelerators have played a main role. The present high-energy frontier colliders producing the center-of-mass energy of 100 GeV [1] give the possibility to study the world of nature, of which the size can be seen into nearly one-trillionth micron. Today we are launching forth into a new energy regime of the order of Tera Elektron Volt [2, 3], in which profound fundamental questions is expected to be answered on the origin of mass, the predominance of matter over antimatter, the existence of supersymmetry and so on. However now elaborated CLIC [2] and ILC [3] accelerators are very close to the limit of what we can practically afford to build using conventional technologies, even collaboratively. The first understanding of this situation was stated in [4], where new approaches to particles acceleration were proclaimed. In particular Ya.B. Fainberg proposed to use plasma waveguides as an accelerating structure. Later, this idea was modified by J.M. Dawson et al. [5, 6] to a wakefield accelerating scheme, in which high-gradient accelerating field is built up as a wakefield excited in plasma by a short high power laser pulse or a short bunch of the large charge.

Another potential candidate for future high gradient particle acceleration, allowing to overcome the accelerating rate limit 100 MeV/m for conventional accelerators, is dielectric loaded (DL) accelerating structures [7], in which wakefield is excited by an intense electron bunch. As it has been shown in theoretical investigations [8] and in the recent experiments [9], the maximum accelerating gradient in dielectric structures, being limited by the electric breakdown due to the tunneling and collisional ionization effects, can be achieved above 1 GeV/m, i.e. on the order higher comparing to the conventional metallic accelerating structures. It allows elaborating the project of ANL 26 GHz, 3 TeV Dielectric-based Short Pulse Two Beam Linear Collider (conceptual layout of one side of a 3TeV e+e- collider as a Higgs Factory) [9].

As a further development of the dielectric wakefield acceleration approach the concept of multi-bunch dielectric wakefield accelerator was proposed and investigated [12, 13]. In the present work the hybrid "plasma-dielectric" modification of multi-bunch dielectric wakefield accelerator with plasma filled transit channel (PDWA) for focusing of bunches and enhancement of wakefield excitation is elaborated.

1. THEORY

PDWA unit under investigation is shown in Fig. 1. In metal waveguide is inserted a dielectric tube having inner radius *a* and outer radius *b*. The transit channel is filled with isotropic plasma of density n_p. Regular sequence of drive bunches and witness bunch travel along transit channel collinearly. Radius of solid drive bunch is r_b, drive bunch charge is Q_0, its length is L_b (homogeneous bunch charge distribution), bunch repetition period is *T*, number of bunches in the train is N_b.

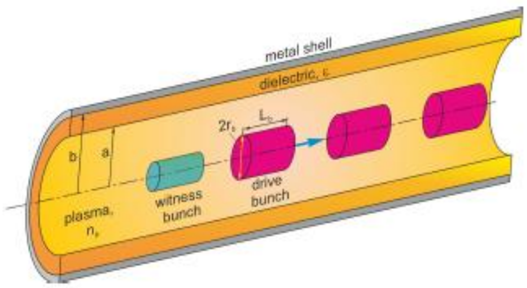

Fig. 1. Sketch of PDWA unit. The transport channel is filled entirely with isotropic plasma

In order to determine accelerating fields we need to solve Maxwell equations with drive bunch sequence as a current source. Solving Maxwell equations we obtain the equation (1) for the axial field in transit channel that has been presented in [14] (see designations there). Wakefield in PDWA consists of two type of waves: dielectric waves (DW), modified by plasma, and plasma wave (PW).

$$E_z = -\frac{4Q_0}{a^2}\sum_{i=1}^{N_b}\sum_s R_s(r_b)e_z^s(r)\Psi_\parallel^s\left[\tau-(i-1)T\right] - \frac{4Q_0}{r_b L_b}e_z^p(r)\sum_{i=1}^{N_b}\Psi_\parallel^p\left[\tau-(i-1)T\right]. \quad (1)$$

At optimal focusing regime when frequency of the first radial mode of DW is much greater than frequency of PW the axial force behind drive bunch is mainly formed by the dielectric wave, and the transverse force is determined by plasma wave [15]. As the plasma density increases, the longitudinal electric field of plasma wave increases, which could enhance the total accelerating gradient. However, firstly, the plasma wave amplitude has an extremum in the plasma density [16] and, secondly, the longitudinal electric field amplitude of the dielectric wave on the axis of the transit channel decreases with increasing plasma density. Thus, the optimum plasma density at which the maximum accelerating field is reached cannot be predicted in advance and is determined below for a set of parameters close to ones of the experimental installation “Almaz-2M”:

Outer radius of dielectric tube…………..……...4.3 cm
Inner radius of dielectric tube……………………1.1 cm
Relative permittivity………………………………2.1
Bunch energy…………………………………… 5 MeV
Bunch charge…………………………………...0.32 nC
Bunch radius……………………………………0.95 cm
Density of drive bunch……………………..$3.9\cdot10^{8}$ cm^{-3}
Bunch repetition rate………………………..2.71 GHz
Frequency of vacuum E_{01} mode………………2.71 GHz

Single drive bunch scenario. For plasma density $n_p=10^{10}$ cm^{-3} the obtained axial (*a*) and radial (*b*) dependences of the total longitudinal and transverse forces [15] are shown in Fig. 2. Hereafter F= eE.

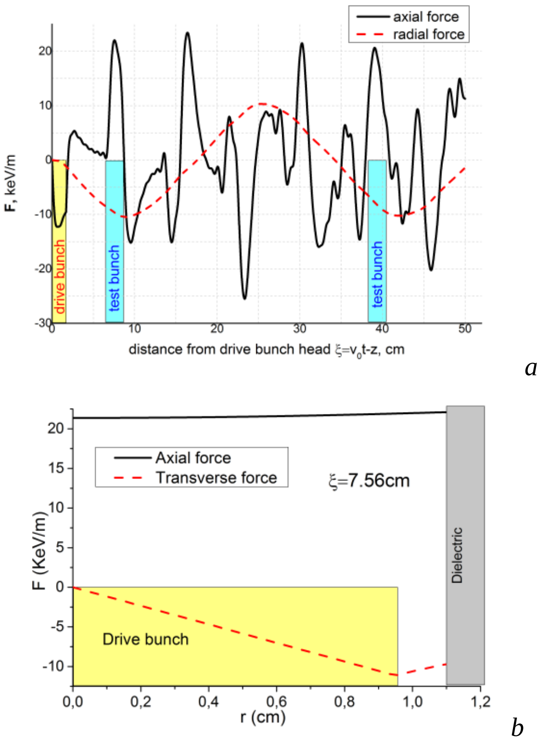

Fig. 2. Axial profile of the longitudinal (solid curve) and transverse (dashes curve) forces acting on a test bunch at a distance of 0.95 cm from the waveguide axis (a); transverse profile of the longitudinal (solid curve) and transverse (dashes curve) forces acting on a test particle at a distance of 7.56 cm from the head of the drive-bunch (b)

In Fig. 2,a it is seen that the accelerated witness bunch placed at distance 7.6 or 39.1 cm from the driving bunch head can be accelerated and focused simultaneously. Moreover the drive bunch is occurred in the focusing phase of the total wakefield too. In Fig. 2,b we see the radially almost uniform accelerating wakefield (mainly DW) and nearly linear growth of transverse wakefield (mainly PW) providing accelerated bunch focusing without aberration.

Sequence of drive bunches scenario. At first consider PDWA unit with fixed dimensions and bunch repetition frequency (reference case) providing coherent excitation of vacuum E_{01}-mode. The results for this case are presented in Fig. 3.

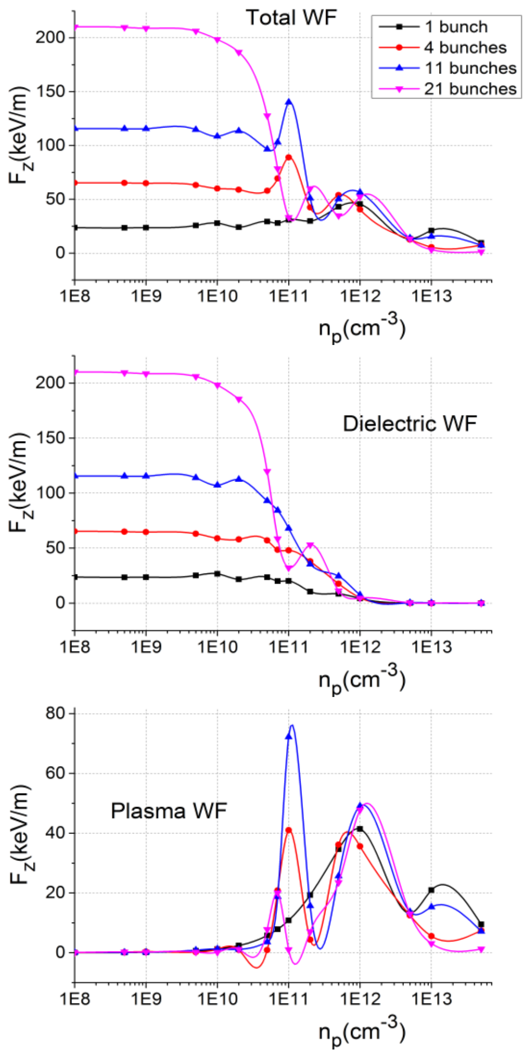

Fig. 3. Wakefield amplitude versus plasma density in the reference case. Top figure is total wakefield (WF), middle figure is dielectric WF (first item in eq.1), bottom figure is plasma WF (second item in eq.1)

As follows from Fig.3 for the single bunch the amplitude of the total wakefield is determined by DW at low plasma density and mainly by PW at high plasma density. The location of maximum of total wakefield is determined by the maximum of PW which occurs under condition $k_pa\approx1$. For sequences of 4 and 11 bunches total wakefield has maximum at plasma density $n_p=10^{11}$ cm^{-3}. At such density dielectric wave and plasma wave are summarized coherently, because their frequencies are close. Wakefields from separate bunches

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are summarized coherently too. When we use 21 bunches the total wakefield at low plasma density is greater than for the previous sequences, but at high plasma density we don't obtain advantages in comparison with single bunch excitation. The first reason of that behavior is resonance destruction between bunch repetition frequency and eigen frequencies of the PDWA. The second reason is resonance destruction between PW and DW. The third reason is plasma column screening of dielectric wave when plasma density exceeds dielectric wave frequency so that dielectric wakefield is not excited. It looks like dielectric wave excitation in dielectric structure is replaced by plasma wave excitation in plasma column.

To avoid these resonances destruction it is needed to beforehand change the vacuum dielectric structure parameters and bunch repetition rate so that at plasma presence these resonances become restored.

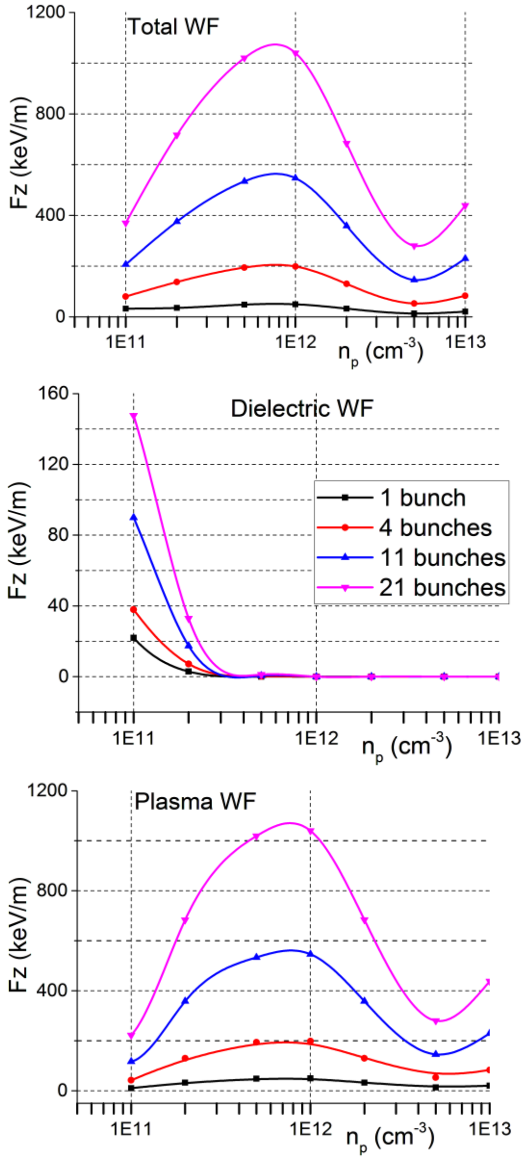


Fig. 4. Wakefield amplitude versus plasma density in the case of the tuning of dielectric wave frequency by changing of inner radius of dielectric tube

The case with the frequency adjustment, when changing the plasma density, synchronously changes frequency of the first radial mode of dielectric wave E_{01} is considered. The frequency adjustment is done by changing inner or outer radii of dielectric tube. Besides the bunch repetition frequency is tuned up to plasma frequency. Results of such adjustment are presented in Fig. 4. Outer radius 4.3 cm is fixed. When changing the plasma density from 10^{11} to 10^{13} cm^{-3} the inner radius is changed from 1.085 to 4.04 cm. The frequency of principal mode of DW (simultaneously with frequency of PW) changes from 2.84 to 28.4 GHz. At any plasma density a bunch repetition frequency is equal to plasma frequency. Fig. 4 shows that total wakefield in case of tuning of eigen frequencies by inner radius change is appreciable greater than in the reference case. Amplitude of wakefield is determined by PW at most part of plasma density interval. Input of DW is appreciable only at plasma density $n_p<2\cdot10^{11}$ cm^{-3}. At high plasma density dielectric wakefield becoms evanescent from dielectric surface to the channel axis.

2. EXPERIMENT

Linear resonant electron accelerator "Almaz-2M" produced the sequence of N = $6\cdot10^3$ bunches each of energy 3.5…4.8 MeV, charge 0.26 nC, radius 0.5 cm, duration 60ps. Bunch repetition frequency can be changed within 2803…2807 MHz. A chamber in which the dielectric structure of round or rectangular cross section can be placed was attached to the accelerator.

"Multi-bunch" coherent excitation. "Multi-bunch" issue concluded to the statement that the intense wake field excited by a bunch with a large charge can be achieved by a long periodic sequence of bunches with a low charge each, but an equivalent total charge. To clarify the possibility of coherent summation of individual bunches fields it is needed to change the number of bunches in the sequence. Because of the difficulty of producing a set of sequences with various number of bunches in the performed studies waveguides of various length were used. The possibility of such a substitution follows from the fact that due to the output of the excited wave from the waveguide of finite length with the group velocity v_g the number of bunches of the sequence of any duration, which contributes to the growth of the total wakefield at the waveguide exit is limited. Maximum number of bunches N, which wakefields during coherent summation increase the amplitude of the total field is directly proportional to the length of the waveguide L: $N=L/\lambda(v_0/v_g-1))$, where λ is length of the excited wave equal to the distance between the bunches, v_0 is bunch velocity. Contrary to [17] with round dielectric waveguide now it was proved experimentally by using a rectangular waveguide with two dielectric plates the opportunity occurs to deflect e electron bunches on the "bare" walls of the waveguide, where no dielectric plates (Fig. 5).

Arranging magnetic field region (N-S) at different distances from the dielectric waveguide exit we can change the interaction length L by shifting a set of magnet poles (N-S) and measure the dependence of the excited wakefield amplitude upon the length of the interaction length. Measurements were carried out at the same length of the whole dielectric waveguide avoiding changes in the conditions of reflections when varying the interaction length.

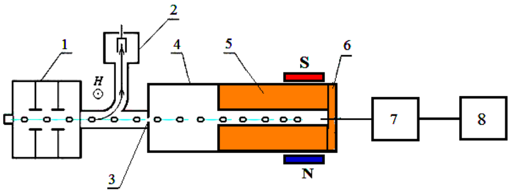


Fig. 5. 1 – accelerator "Almaz-2M"; 2 – magnetic analyzer; 3 – diaphragm; 4 – waveguide; 5 – dielectric; 6 – dielectric plug; 7 − wavemeter VMT-10; 8 – oscilloscope

For such experiment wakefield at the dielectric waveguide exit linearly depends on the interaction length of bunches with dielectric part (Fig. 6), that is consistent with the theoretical prediction, confirming coherent summation of wakefields of bunches.

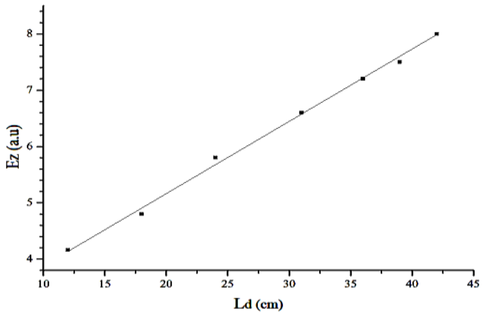


Fig. 6. Dependence of wakefield amplitude on the length of bunches interaction with dielectric waveguide

"Resonator" scheme of excitation [18]. The aim the "resonator" concept is to increase the number of bunches of the sequence, adding wakefields of which increases the total wakefield in comparison with the case of a waveguide case. For excitation of the wakefields in dielectric resonator by a sequence of bunches the resonant conditions of the coincidence of bunch repetition frequency ω_m with Cherenkov radiation frequency ω_0 $(\omega_{rep}=\omega_0)$ and, simultaneously, with the principal eigen frequency of the resonator ω_{r1}, i.e. $\omega_{rep}=\omega_0=\omega_{r1}$ should be fulfilled.

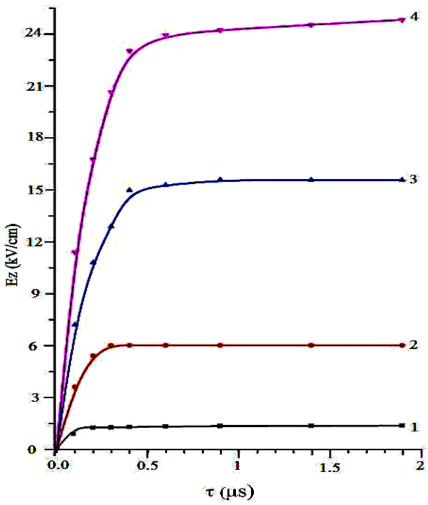


Fig. 7. Dependence of the wakefield amplitude on the duration of bunch sequence for different Q-factors of the resonator: 1 – Q_1=65; 2 – Q_2=268; 3 – Q_3=539; 4 – Q_4=676

In the absence of losses in the resonator (Q=∞) declared conditions should provide coherent summation of wakefield of all bunches and thereby increase the total wakefield to the level of field, excited by a single bunch with a charge equivalent to the total charge of all bunches of the sequence. For finite Q-factor the dependence of the total wakefield upon the resonator Q-factor was experimentally investigated and presented in Fig. 7. It is shown that in the resonator case the total field increases with increasing duration of the sequence and saturates, remaining constant for larger durations. With the growth of the Q-factor the number of bunches of the sequence contributing to the increase in the total wakefield increases. The long sequence of $6{\cdot}10^3$ bunches in our experiment is practically equivalent by saturation amplitude to the sequence of infinite number of bunches.

Bunches acceleration by excited wakefield. Using detuning between bunch repetition frequency and frequency of excited wakefield allows obtaining drive and accelerated bunches from the same sequence. Such possibility arises due to gradual shift of bunches by phase of excited wakefield. In the performed experiments the frequency of dielectric wakefield is fixed and determined by the Cherenkov resonance (coincidence the velocity of bunches and the phase velocity of the excited wave of the dielectric waveguide). The bunch repetition frequency is varied by change of the frequency of master oscillator "Rubin" of klystron amplifier. In this concept of "excitation- acceleration" process using the same sequence of bunches there is no need for additional linac injector for bunches-witnesses production. It simplifies the experimental demonstration of bunches acceleration by the excited wakefield.

In the case of resonance, i.e. coincidence of bunch repetition frequency f_{rep} and frequency of the principal mode of excited wakefield f_0 all bunches are occurred in the decelerating phase and lose energy to excite wakefield. If there is a frequency detuning $\Delta f=f_{rep}-f_0\neq 0$ bunches of the first part of the sequence occurred in the decelerating phases of excited field lose energy to the increase in total wakefield and bunches of the next part of the sequence, shifted to the region of the accelerating phases of wakefield excited by the previous part of the sequence, gain an additional energy. For point and monoenergetic bunches the number of bunches N^* of the first part of the sequence, exciting wakefield, evaluated from the phase shift of N^*-th bunch on π is equal $N^*=f_{rep}/2\Delta f$. The next part of the sequence of bunches of the same duration is accelerated.

Fig. 8,a,b shows obtained energy spectra [19] of the bunch electrons passing through the resonator without dielectric tube when there is no Cerenkov interaction of bunches with the resonator (black spectra, which are close to the initial ones at the resonator input) and through the resonator with a dielectric tube (red spectra obtained after excitation of wakefield and interaction with it) for two cases: resonant one (zero detuning Δf=0, Fig. 13,a) and nonresonant one (nonzero detuning Δf=2.5 MHz, Fig. 13,b). From Fig. 8 follows that at the presence of dielectric in the case of resonance $\Delta f = 0$ the energy spectrum is shifted by 400 keV as a whole to lower energies that is caused by the energy loss of all the bunches on the wakefield excitation. In the case of detuning between the bunch repetition frequency and the frequency of wakefield $\Delta f = f_{rep} - f_0 = 2.5$ MHz a part of bunches of the sequence, shifting over phase, falls into the accelerating phase of the wakefied excited by previous bunches of the same sequence and gain energy. In this case, in the electron energy spectrum there are observed both the electrons losing energy (-150 keV) and electrons gaining additional energy (+ 150 keV).

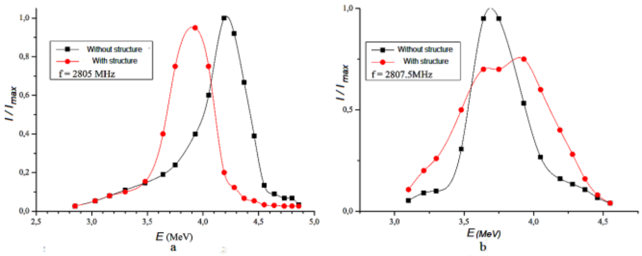


Fig. 8. Energy spectra of electron bunches passing through the resonator without dielectric (black curves) and a resonator with dielectric tube (red curves): a – Δf=0; b – $\Delta f = f_{rep} - f_0 = 2.5$ MHz

Dependences of wakefield excitation and focusing of bunches in plasma-dielectric structure upon plasma density. The scheme of the experimental setup for such investigations is shown in Fig. 9.

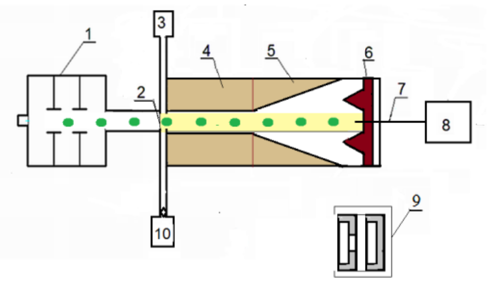


Fig. 9. Scheme of plasma-dielectric structure: 1 – accelerator "Almaz-2M"; 2 – titanium foil; 3 – vacuum meter; 4 – dielectric waveguide; 5 – dielectric microwave matcher; 6 – ferrite absorber; 7 – microwave probe; 8 – oscilloscope Tektronix TDS 6154C; 9 - double Faraday cup; 10 – vacuum pump

Relativistic electron bunches produced by linac "Almaz-2M" (1) penetrate through titanium foil (2) of thickness 30 μ and enter into the dielectric waveguide (4) of round cross section with transit channel of diameter 21 mm filled with plasma.

Plasma in the transit channel of the dielectric waveguide is produced by the head of bunch train when it passes through the neutral gas of the pressure regulated by puffing and pumping. Ionization process in the transit channel occurs due to the beam-plasma discharge (BPD) [20] at pressure 1Torr and due to collisions of bunch electrons with neutrals at higher pressures. It is illustrated in Fig. 10 by enhancing of measured wakefield signal in the said two regions and corresponding beam current reduce on Faraday cup due to beam scattering [21].

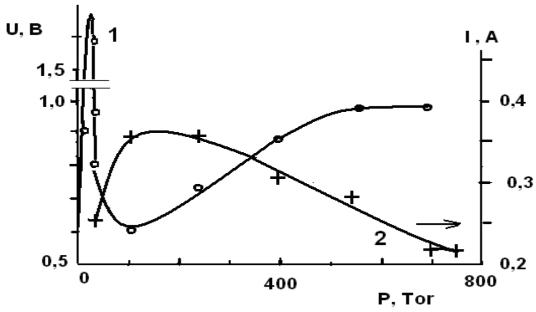


Fig. 10. Dependences of wakefield signal (1) and beam current (2) upon gas pressure in transit channel

Evolution of plasma density in time for various gas pressure measured with a high-frequency probe of Johnsen [22] and open resonator of Moskalev [22] is shown in Fig. 11.

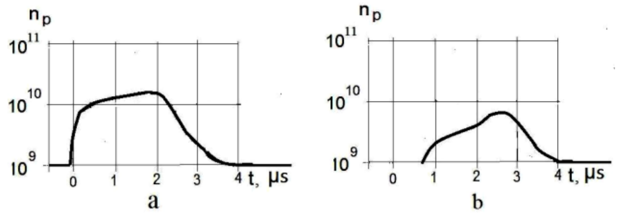


Fig. 11. Dependence of plasma density on time for various gas pressure in transit channel: a) 0.5 Torr, b) 10 Torr

It is seen that for gas pressure P=0.5 Torr plasma density can achieve the resonant value for which plasma frequency is equal both wakefield frequency and bunch repetition frequency.

Wakefield excitation by a sequence of bunches was investigated for waveguide and resonator cases. To realize the waveguide case it is needed to avoid reflections of the excited wakefield. For this purpose, the dielectric tube is ended with dielectric microwave matcher, and on Teflon vacuum plug ferrite absorber is placed. For obtaining single bunch regime the length of the dielectric insert was chosen equal to length of the excited dielectric wave $L = \lambda$. In the case of dielectric waveguide and a single bunch regime the dependence of the amplitude of the excited longitudinal wakefield on the axis for the wide range of the gas pressure is shown in Fig. 12 (red curve).

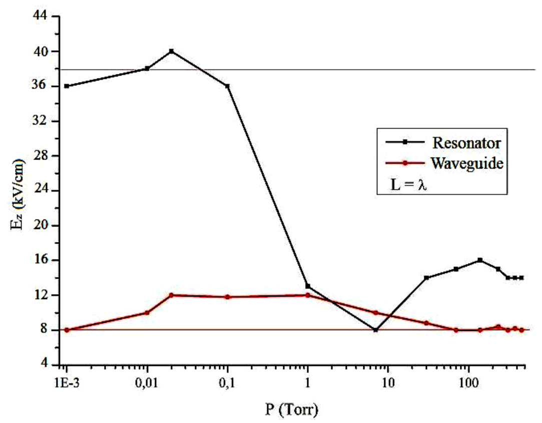


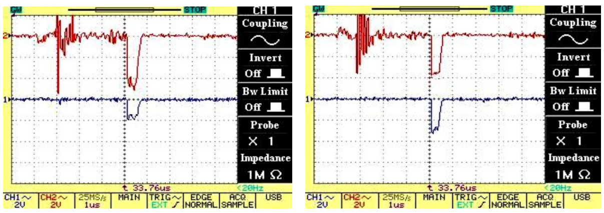
Fig. 12. Dependence of excited wakefield E_z upon neutral gas pressure in the transit channel

It is seen that in the pressure under which BPD develops and plasma is formed the wakefield wave topography in the channel becomes volumetric, that increases the coupling coefficient of the bunch with the wakefield wave and leads to the increase in the excited wakefield amplitude compared with the case without gas injection (see Fig. 12, horizontal red line).

In the case of dielectric resonator realized by removing matching elements and installing metal exit plug under conditions of the double-resonance $\omega_0 = \omega_{rep} = \omega_n$ (coincidence of Cherenkov frequency ω_0 with bunch repetition frequency ω_{rep} and simultaneously with eigen frequency of the resonator ω_n) the wakefield amplitude grows significantly (see Fig. 12, horizontal black line). This is due to the fact that the number of bunches which contribute to the total wakefield is limited only by Q-factor. So it is much more compare with the case of the waveguide, for which the number of bunches, determined by the waveguide length and the group velocity, does not exceed tens of bunches. However in the range of gas pressure where plasma is produced the wakefield signal is decreased up to a single bunch level (see Fig. 12, black curve). It is explained by destroying resonances and plasma column screening.

Focusing driver-bunches. As it follows from Fig. 2,a in the case of the waveguide and a single bunch regime ($L = \lambda$) all driver bunches are occurred in the same own wakefields - decelerating longitudinal dielectric (almost uniform over radius) and focusing radial plasma (almost linearly grows over radius) ones. Radial defocusing dielectric field with its almost uniform over radius longitudinal field is insignificant.

Fig. 13 shows the waveform of the beam current, experimentally obtained [19] with a double Faraday cup (see (9) in Fig. 9) at vacuum P = 10^{-3} Torr (see Fig. 13,a) and at neutral gas pressure in the transit channel of dielectric waveguide P=0.5 Torr (see Fig. 13,b), when plasma is intensively produced by BPD. The increase in current in the second cup while its reducing in the first one for the case of plasma presence (see Fig. 13,b) evidences focusing electron bunches.



a *b*

Fig. 13. Oscillograms of beam current taken from double Faraday cup: top – first cylinder; bottom – second cylinder; a – P = 10^{-3} Torr; б – P = 0.5 Torr

CONCLUSIONS

The coherence at coincidence of bunch repetition frequency and excited wakefield frequency in "multi-bunch" regime and the accumulation of wakefields at multiplicity of eigen frequencies of the resonator to the bunch repetition frequency and excited wakefield frequencies in "resonator" regime provides enhancement of the total wakefield.

Enhancement of total wakefield due to summation dielectric and plasma longitudinal wakefields doesn't occur because for high density plasma dielectric wakefield dos not penetrate into plasma filled transit channel. So dielectric wakefield excitation is replaced by plasma wakefield excitation.

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

The presence of plasma in the transit channel provides focusing both driving and accelerated bunches by excited plasma wave.

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РАЗРАБОТКА ПЛАЗМЕННО-ДИЭЛЕКТРИЧЕСКОГО КИЛЬВАТЕРНОГО УСКОРИТЕЛЯ

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Представлены теоретические и экспериментальные исследования физических принципов кильватерного ускорителя, основанного на возбуждении ускоряющего кильватерного поля в плазменно-диэлектрической структуре длинной последовательностью электронных сгустков. Увеличение амплитуды возбуждаемого кильватерного поля достигается использованием мультибанчевого режима возбуждения для когерентного сложения кильватерных полей отдельных сгустков и резонаторного режима для накопления кильватерных полей. Ускорение сгустков в суммарном (плазменном+диэлектрическом) кильватерном поле реализовано расстройкой частоты следования сгустков относительно частоты возбуждаемого кильватерного поля. Таким путём последовательность сгустков разделяется на возбуждающую и ускоряемую части благодаря возникающему смещению второй части сгустков в ускоряющие фазы кильватерного поля, возбуждённого первой частью сгустков этой же последовательности. Исследовано влияние плазмы в пролётном канале на амплитуду возбуждаемых плазменного и диэлектрического кильватерных полей и фокусировку возбуждающих и ускоряемых сгустков.

РОЗРОБКА ПЛАЗМОВО-ДІЕЛЕКТРИЧНОГО КІЛЬВАТЕРНОГО ПРИСКОРЮВАЧА

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Представлені теоретичні та експериментальні дослідження фізичних принципів кільватерного прискорювача, заснованого на збудженні прискорюючого кільватерного поля в плазмово-діелектричній структурі довгою послідовністю електронних згустків. Збільшення амплітуди збуджуваного кільватерного поля досягається використанням мультибанчевого режиму збудження для когерентного складання кільватерних полів окремих згустків і резонаторного режима для накопичення кільватерних полів. Прискорення згустків в сумарному (плазмовому+діелектричному) кільватерному полі реалізовано розстройкою частоти слідування згустків відносно частоти збуджуваного кільватерного поля. Таким шляхом послідовність згустків поділяється на збуджуючу і прискорювану частини завдяки виникаючому зміщенню другої частини згустків в прискорюючи фази кільватерного поля, збудженого першою частиною згустків цієї ж послідовності. Досліджено вплив плазми в прольотному каналі на амплітуду збуджуваних плазмового та діелектричного кільватерних полів і фокусування збуджуючих і прискорюваних згустків.