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INFLUENCE OF EMITTANCE ON TRANSVERSE DYNAMICS OF THE ACCELERATED BUNCHES IN PLASMA-DIELECTRIC WAKE FIELD ACCELERATOR

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In this paper transverse dynamics of charged bunch particles in plasma-dielectric wake field accelerator on an example of a gigahertz range dielectric waveguide is researched, bunch parameters correspond to bunches obtainable at Argonne National Laboratory. Analytical expressions for calculating wakefields and equations for modeling bunch particle motion are provided. The behavior of the boundary bunch particle for different values of the initial emittance was modeled. It was shown, that the amplitude of motion of the boundary bunch particles changes on time.
KEYWORDS: acceleration, focusing, wake field, bunches, dielectric waveguide, plasma, emittance

ВЛИЯНИЕ ЭМИТТАНСА НА ПОПЕРЕЧНУЮ ДИНАМИКУ УСКОРЯЕМЫХ СГУСТКОВ В ПЛАЗМЕННО-ДИЭЛЕКТРИЧЕСКОМ КИЛЬВАТЕРНОМ УСКОРИТЕЛЕ

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В работе исследуется поперечная динамика заряженных частиц пучка в плазменно-диэлектрическом кильватерном ускорителе на примере диэлектрического волновода гигагерцового диапазона, параметры пучков соответствуют пучкам, получаемым в Аргонской лаборатории. Приведены аналитические выражения для расчета кильватерных полей и уравнения для моделирования движения частиц сгустка. Промоделировано поведение краевой частицы пучка при разных значениях начального эмиттанса. Получены зависимости для огибающих пучка для разных значений начального эмиттанса. Показано что амплитуда движения краевых частиц пучка изменяется со временем.
КЛЮЧЕВЫЕ СЛОВА: ускорение, фокусировка, кильватерные поля, пучки, диэлектрический волновод, плазма, эмиттанс

ВПЛИВ ЕМІТТАНСА НА ПОПЕРЕЧНУ ДИНАМІКУ ПРИСКОРЮВАНИХ ЗГУСТКІВ В ПЛАЗМОВО-ДІЕЛЕКТРИЧНОМУ КІЛЬВАТЕРНОМУ ПРИСКОРЮВАЧІ

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В роботі досліджується поперечна динаміка заряджених частинок згустку в плазмово-діелектричному кільватерному прискорювачі на прикладі діелектричного хвилеводу гігагерцового діапазону, параметри згустків відповідають згусткам, які отримуються в Аргонській лабораторії. Подано аналітичні вирази для розрахунку кільватерного поля та рівняння для моделювання руху частинок згустку. Промодельована поведінка граничної частинки згустку при різних значеннях початкового еміттансу. Отримані залежності для оминаючих згустку при різних значеннях початкового еміттансу. Показано що амплітуда руху граничних частинок згустку має залежність від часу.
КЛЮЧОВІ СЛОВА: прискорення, фокусування, кільватерні поля, згустки, діелектричний хвилевод, плазма, еміттанс

Accelerator physics is actual, thriving branch of modern physics. One of the new methods of acceleration, that allows significantly reducing weight and sizing characteristics of accelerators, is method of accelerating charged particles by wakefields [1,2]. An important characteristic of any accelerator is luminosity of the accelerated bunch, which is determined by the density of the bunch and its phase volume. The final phase volume is determined by the transverse dynamics of the particles, so knowing it, we can judge about transverse stability and final phase volume of accelerated bunch. In this paper transverse dynamics of charged bunch particles in plasma-dielectric wakefield accelerator on an example of a gigahertz range dielectric waveguide is researched. Parameters of charged particles bunches are taken in accordance with the experiments carried out in the Argonne Laboratory. Excitation of electromagnetic fields by concentrated sources in the hybrid plasma-dielectric structure allows increasing the rate of acceleration. This provides simultaneous radial-phase focusing. Compared with pure plasma variant [3-5], hybrid plasma-dielectric structures [6] provide greater wave stability and are less sensitive to the temporal and spatial changes of the plasma density [7]. The goal of this work: study the behavior of accelerated charged particles bunch in plasma-dielectric wake field accelerator, to analyze the transverse dynamics of bunch in PDWA with different values of the initial emittance of bunch.

STATEMENT OF THE PROBLEM

Consider a structure that is infinitely long waveguide with an annular dielectric shell (look figure Fig.1). The dielectric constant of this shell is ε . Inside the dielectric shell (in the transit channel) there is plasma with density n_p . Along the axis of the waveguide drive bunch moves, which excites the wake field [8]. After some time, collinear to drive bunch, accelerated bunch is injected. Delay time is selected so accelerated bunch was simultaneously at maximum of accelerating field.

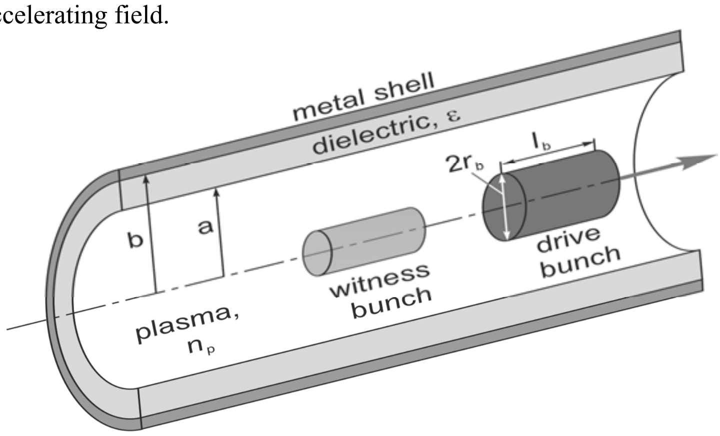

Fig. 1. Geometry of structure.
a – the inner radius of the dielectric shell; b – the outer radius of the dielectric shell; n_p – plasma density; r_b – bunch radius; l_b – bunch length; ε - dielectric constant.

In works [8,9] possibility of simultaneous radial focusing and longitudinal acceleration of charged particles bunch in such structure was shown. The appearance of the focusing force is due to the excitation of plasma (Langmuir) waves. Langmuir wave, in some plasma densities, makes a predominant contribution to the transverse force that exerts on accelerated bunch. At the same time, the contribution of plasma waves in the longitudinal force is negligible. Longitudinal force is mainly determined by the wave corresponding to the eigen modes of a dielectric [10].

Therefore, plasma in the transit channel is responsible for the focusing force, and dielectric shell – for accelerated force. With some density of the plasma, longitudinal field of the Langmuir wave significantly less than the total longitudinal field of dielectric modes. However, the radial electric field of the Langmuir wave still far exceeds the total transverse field of dielectric modes. These two types of waves – Langmuir and dielectric – generally have different spatial periods; therefore, the maximum of total longitudinal field can correspond to a minimum of a full transverse field. Thereby, when placing a test bunch in the maximum of dielectric wave accelerating field we can simultaneously focus it by Langmuir wave's field.

While solving the problem of focusing the accelerated bunch we must not forget that there is also a defocusing force. The main causes of defocusing forces are Coulomb field and the initial emittance of the bunch. It was shown [11], that the influence of the Coulomb field on the focusing of charged particles bunches in the plasma-dielectric structures with the density of the plasma and bunch charges, with which we work, is negligible. We assume that terms describing the quasi-static component of wake field are equal to zero. This will greatly simplify the expression, describing electromagnetic fields, excited by driver bunch in plasma dielectric accelerator.

BASIC EQUATION

The nature of the transverse motion of the particles is determined by solution of the equation of the envelope [12]:

$$\frac{d^2r}{dz^2}+\frac{e\beta H_\varphi(r,z,t)}{m\gamma\beta^2c^2}\left(\frac{dr}{dz}\right)^2+\frac{eE_z(r,z,t)}{m\gamma\beta^2c^2}\frac{dr}{dz}-\frac{e\left(E_r(r,z,t)-\beta H_\varphi(r,z,t)\right)}{m\gamma\beta^2c^2}-\frac{emit_n^2}{r^3\beta^2\gamma^2}=0\,. \qquad (1)$$

To solve the equation (1) we must specify γ and t. The equations describing γ and t are:

$$\frac{dt}{dz}=\frac{1}{\beta c}\,, \qquad (2)$$

$$\frac{d\gamma}{dz}=\frac{eE_z(r,z,t)}{mc^2}, \qquad (3)$$

where e,m – the charge and mass of the electron, $\beta=\sqrt{1-1/\gamma^2}$, z – axial coordinate, $emit_n$ - normalized emittance.

In the equation (1) E_z,E_r,H_φ are the components of wake field excited by drive bunch. They do not consider the influence of accelerating bunch on the excited wake field. The detail obtaining of these expressions was described in the paper [8]. Here they are:

$$E_z(r,z,t)=\begin{cases}-\frac{4Q\Theta_p}{L_br_b}\left[\frac{1}{r_bk_p}-\frac{I_0(k_pr)}{I_0(k_pa)}\Delta_1(k_pr_b,k_pa)\right]-\frac{8Q\Theta_s}{aL_br_bw_s\kappa_pD'(w_s)}\frac{I_0(\kappa_pr)}{I_0(\kappa_pa)}\frac{I_1(\kappa_pr_b)}{I_0(\kappa_pa)}, r<r_b\\ -\frac{4Q\Theta_p}{L_br_b}\frac{I_1(k_pr_2)}{I_0(k_pa)}\Delta_0(k_pa,k_pr)-\frac{8Q\Theta_s}{aL_br_bw_s\kappa_pD'(w_s)}\frac{I_0(\kappa_pr)}{I_0(\kappa_pa)}\frac{I_1(\kappa_pr_b)}{I_0(\kappa_pa)}, r_b\le r<a\\ -\frac{8Q\Theta_s}{aL_br_bw_s\kappa_pD'(w_s)}\frac{I_1(\kappa_pr_b)}{I_0(\kappa_pa)}\frac{F_0(\kappa_dr,\kappa_db)}{F_0(\kappa_da,\kappa_db)}, a\le r<b\end{cases}, \qquad (2)$$

$$E_r(r,z,t)=\begin{cases}\dfrac{4Q\Theta_p}{L_b r_b^2}\dfrac{1}{I_0(k_p a)}\Big[I_1(k_p r)\big[r\Delta_1(k_p r,k_p a)-r_b\Delta_1(k_p r_b,k_p a)\big]-\\ -\Delta_1(k_p a,k_p r)rI_1(k_p r)\Big]+\dfrac{8Q\Theta_s}{aL_b r_b w_s\kappa_p D'(w_s)}\dfrac{1}{\sqrt{1-\beta^2\varepsilon_p(w_s)}}\dfrac{I_1(\kappa_p r)}{I_0(\kappa_p a)}\dfrac{I_1(\kappa_p r_b)}{I_0(\kappa_p a)},r<r_b\\ -\dfrac{4Q\Theta_p}{L_b r_b}\dfrac{I_1(k_p r_b)}{I_0(k_p a)}\Delta_1(k_p a,k_p r)+\dfrac{8Q\Theta_s}{aL_b r_b w_s\kappa_p D'(w_s)}\times\\ \times\dfrac{1}{\sqrt{1-\beta^2\varepsilon_p(w_s)}}\dfrac{I_1(\kappa_p r)}{I_0(\kappa_p a)}\dfrac{I_1(\kappa_p r_b)}{I_0(\kappa_p a)},r_b<r<a\\ -\dfrac{8Q\Theta_s}{aL_b r_b w_s\kappa_p D'(w_s)}\dfrac{1}{\sqrt{\beta^2\varepsilon_d-1}}\dfrac{I_1(\kappa_p r_b)}{I_0(\kappa_p a)}\dfrac{F_1(\kappa_d r,\kappa_d b)}{F_0(\kappa_d a,\kappa_d b)},a<r<b\end{cases},\quad(3)$$

$$H_\varphi(r,z,t)=\begin{cases}\dfrac{8Q\beta\Theta_s}{aL_b r_b w_s\kappa_p D'(w_s)}\dfrac{\varepsilon_p(w_s)}{\sqrt{1-\beta^2\varepsilon(w_s)}}\dfrac{I_1(\kappa_p r)}{I_0(\kappa_p a)}\dfrac{I_1(\kappa_p r_b)}{I_0(\kappa_p a)},0<r<a\\ -\dfrac{8Q\beta\Theta_s}{aL_b r_b w_s\kappa_p D'(w_s)}\dfrac{\varepsilon_d}{\sqrt{\beta^2\varepsilon_d-1}}\dfrac{I_1(\kappa_p r_b)}{I_0(\kappa_p a)}\dfrac{F_1(\kappa_d r,\kappa_d b)}{F_0(\kappa_d a,\kappa_d b)},a<r<b\end{cases},\quad(4)$$

where

$$\begin{aligned}\Theta_p&=\left\{\Theta\left(t-\frac{z}{v}\right)\sin w_p\left(t-\frac{z}{v}\right)-\Theta\left(t-\frac{z}{v}-\frac{L_b}{v}\right)\sin w_p\left(t-\frac{z}{v}-\frac{L_b}{v}\right)\right\}\\ \Theta_s&=\left\{\Theta\left(t-\frac{z}{v}\right)\sin w_s\left(t-\frac{z}{v}\right)-\Theta\left(t-\frac{z}{v}-\frac{L_b}{v}\right)\sin w_s\left(t-\frac{z}{v}-\frac{L_b}{v}\right)\right\}\end{aligned},\quad(5)$$

$$\begin{aligned}F_0(x,y)&=J_0(x)N_0(y)-N_0(x)J_0(y)\\ F_1(x,y)&=-J_1(x)N_0(y)+N_1(x)J_0(y)\end{aligned},\quad(6)$$

$$\begin{aligned}\Delta_0(x,y)&=I_0(x)K_0(y)-K_0(x)I_0(y)\\ \Delta_1(x,y)&=I_1(x)K_0(y)+K_1(x)I_0(y)\end{aligned}\quad(7)$$

$\Theta(\chi)$ - Heaviside function, $J_0(x),J_1(x),N_0(x),\mathrm{N}_1(x)$ - Bessel and Neymann functions 1st and 2nd order respectively, v - velocity of bunch, $\varepsilon(w)=\varepsilon_p(w)=1-w_p^2/w^2$, if $r<a$ and $\varepsilon(w)=\varepsilon_d$ if $a\le r<b$; $w_p=\sqrt{4\pi e^2 n_p/m}$ - the plasma frequency, ε_d - the dielectric constant of the dielectric shell. $I_0(\mathrm{x}),I_1(\mathrm{x}),\mathrm{K}_0(\mathrm{x}),\mathrm{K}_1(\mathrm{x})$ - modified Bessel and Macdonald functions zero and first order respectively. $k_p=w_p/v$, $\kappa_p^s=\kappa_p(w=w_s)$, $\kappa_d^s=\kappa_d(w=w_s)$, $D'(w_s)=\left.\dfrac{dD(w)}{dw}\right|_{w=w_s}$;

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

where $\gamma_d=\varepsilon_d/\sqrt{\beta^2\varepsilon_d-1}$.

The eigen frequencies of the dielectric modes w_s are determined by solving the dispersion equation $D(w)=0$.

TYPICAL DISTRIBUTION OF FORCES

In order to demonstrate the characteristic of distribution of forces, exerting on accelerated bunch in plasma-dielectric structure, we will give the results of numerical calculations. To conduct the numerical simulation was chosen dielectric waveguide gigahertz range. Parameters of charged particles bunches are taken in accordance with the experiments carried out in the Argonne Laboratory (Table).

The calculation results for the plasma density $n_p=3\cdot n_b=7.455\cdot10^{11}cm^{-3}$ are shown in Fig.2-Fig.3. In Fig. 2 axial distributions of the longitudinal and transverse forces are shown. They are exerting on a test particle spaced 2 mm from the axis of the waveguide i.e. at the boundary of the bunch. From comparing the dependencies, we can see that placing a test bunch at a distance 1.5 cm or 5.6 cm from the head of the leading bunch ensures the acceleration of charged particles with their simultaneous radial focusing. As shown in figure, radial force has nearly harmonic dependence on longitudinal coordinate with period ~ 4 cm. Langmuir wave makes a predominant contribution to the radial force. At the same time its contribution to the longitudinal strength, accelerating test particles, is predominantly small.

Longitudinal force is mainly determined by the dielectric waveguide eigen modes, its complicated dependence on the longitudinal coordinate related with the excitation of several radial modes of a dielectric waveguide.

Table

Parameters of plasma-dielectric accelerator used in calculations

Outer radius of dielectric tube	5.11 mm
Inner radius of dielectric tube	4.0 mm
Dielectric constant ε : (fused silica)	3.75
Bunch length L_b	2.0 mm
Bunch radius r_b	2.0 mm
Plasma radius	4.0 mm
Bunch energy	14 MeV
Bunch charge	1 nC
Density of drive bunch	$2.485 \cdot 10^{11} cm^{-3}$

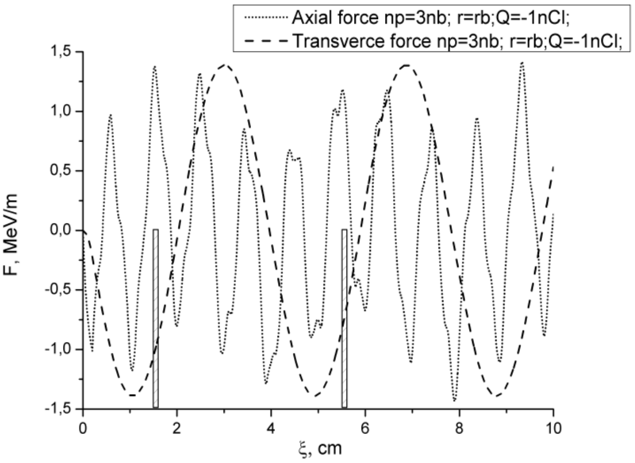

Fig. 2. Axial profile longitudinal (dotted line) and transverse force (dash line), exerting on a test particle, located at a distance 0.2 cm from waveguide axis. $\xi = v_0 t - z$, the head of the leading bunch is in $\xi = 0$.

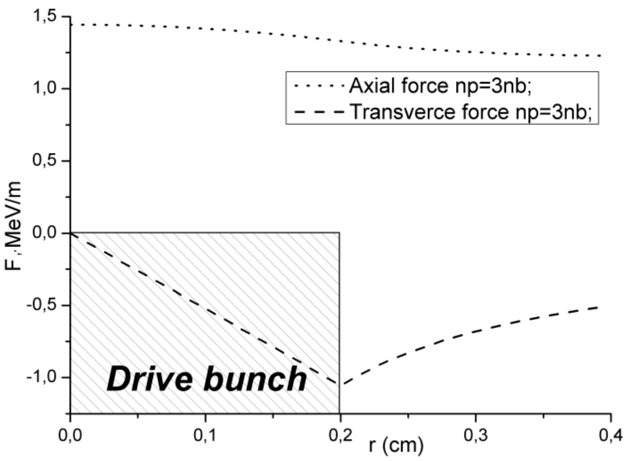

Fig. 3. Transverse profile longitudinal (dotted line) and transverse (dash line) forces, exerting on a test particle, located at a distance 1.5 cm from head of the leading bunch.

Radial dependence of the longitudinal and transverse forces, exerting on a test particle, located in the first accelerating field maxima, at the distance 1.5 cm behind the head of the leading bunch is shown in Fig. 3. Longitudinal force varies little in the transverse cross-section of the transport channel, and radial force is focusing on the entire cross-section of the channel.

RESULTS OF NUMERICAL MODELING

To model transverse dynamics charged particles bunches in plasma-dielectric wakefield accelerator the same parameters were used, as for demonstration of the typical distribution of forces in a given structure (Table 1).

Let's write the second order differential equation (1) as a system of two first order differential equations. In addition to the system of equations, differential equations (2) and (3), required for solving equation of the envelope.

$$\begin{cases} \dfrac{dr}{dz} = y \\ \dfrac{dy}{dz} = -\dfrac{e\beta H_\varphi(r,z,t)}{m\gamma\beta^2c^2}\left(\dfrac{dr}{dz}\right)^2 - \dfrac{eE_z(r,z,t)}{m\gamma\beta^2c^2}\dfrac{dr}{dz} + \dfrac{e\left(E_r(r,z,t) - \beta H_\varphi(r,z,t)\right)}{m\gamma\beta^2c^2} + \dfrac{emit_n^2}{r^3\beta^2\gamma^2} \\ \dfrac{dt}{dz} = \dfrac{1}{\beta c} \\ \dfrac{d\gamma}{dz} = \dfrac{e}{mc^2}E_z(r,z,t) \end{cases} . \qquad (9)$$

The initial conditions for such a system will have the form $\left.\dfrac{dr}{dz}\right|_{z=0} = 0, r|_{z=0} = r_b, t|_{z=0} = t_0\, \gamma|_{z=0} = \gamma_0$ (10), where r_b - radius of charged particles bunch, $t_0 = 1.5 / v_0$ – time of entry of the bunch, $v|_{z=0} = v_0$, $\gamma_0 = 1/\sqrt{1-\beta_0^2}$, $\beta_0 = v_0 / c$.

For the numerical solution of system of differential equations of the first order (11) we use the method of Runge-Kutta of fourth order. Results of modeling can be represented as a graph. The graph represents the so-called "bunch envelope". In Fig.4-7 bunch envelopes with different values of the initial emittance are given.

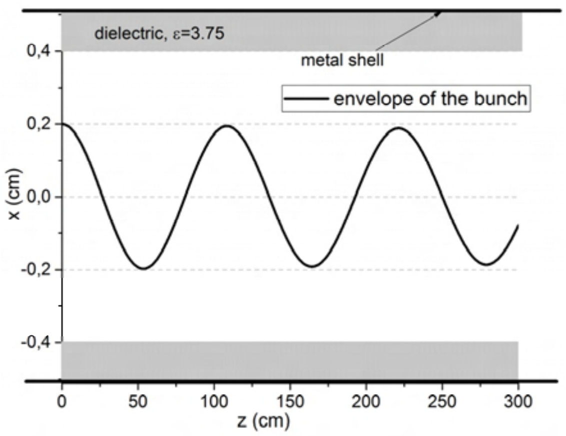

Fig. 4. The trajectory of motion of the boundary bunch particle when $emit_n = 0$

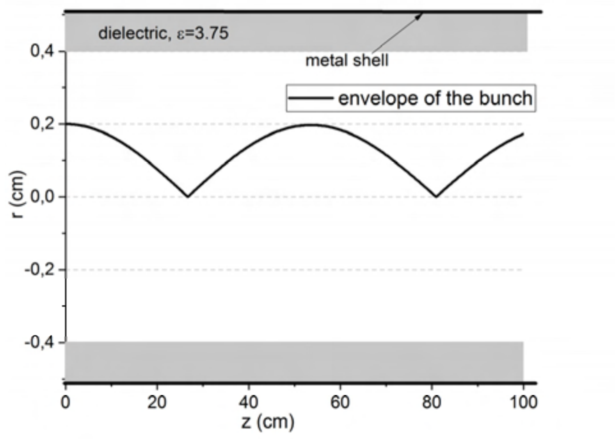

Fig. 5. The envelope of the bunch with emittance $emit_n = 10^{-6} cm \cdot rad$

Trajectory of the boundary bunch particles without initial emittance is shown in Fig.4. It is well seen, that under the influence of focusing force the bunch shrinks, then there is «flipping over» and the bunch is expanded back. Focusing force exerts symmetrically, so particle flown in the "lower" part of the bunch get radial breaking and is focused to axis again. X coordinate in the positive area is the radius of the bunch. In the negative area under the radius of the bunch is meant the absolute value of X. The sign "-" indicates that the boundary particle moved to another part of the bunch relative to the axis. The envelope of the same bunch, but with the finite initial emittance is shown in Fig.5. The envelope of the bunch is always in the positive area. Since real bunches always have the initial emittance, we can make conclusion, that the bunch is never inverted relative to its axis.

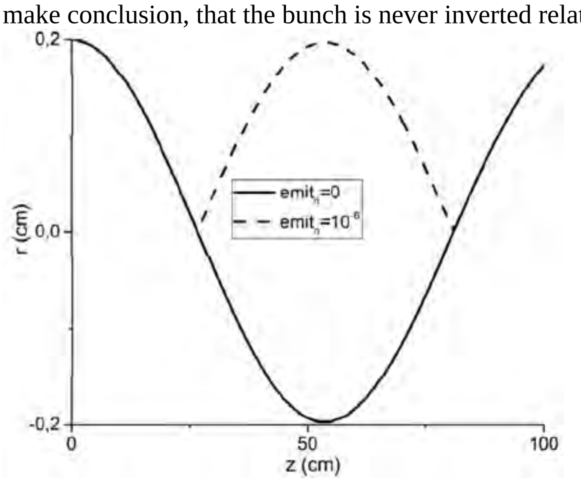

Fig. 6. Envelopes of bunches when emittance $emit_n = 10^{-6} cm \cdot rad$ – dash line and –solid line if $emit_n = 0$ respectively.

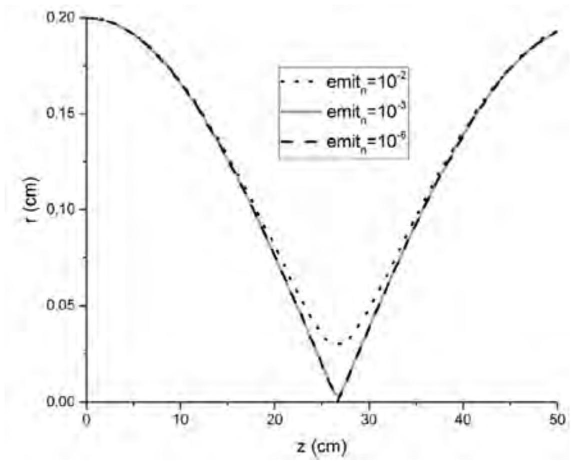

Fig. 7. Envelopes of bunches when emittance $emit_n = 10^{-2} cm \cdot rad$ – dotted line, $emit_n = 10^{-3} cm \cdot rad$ – solid line and $emit_n = 10^{-6} cm \cdot rad$ – dash line.

Trajectories of the boundary bunch particles excluding emittance and with small emittance $emit_n = 10^{-6} cm \cdot rad$ are shown in Fig.6. The trajectory of the particle in the presence of small emittance is exactly a copy of the particle's trajectory without emittance; in condition of bunch reaching to the axis this particle is reflected.

Trajectories of motion of the boundary bunch particles with three different initial values of emittance are shown in Fig.7. From Fig.7 we can see, that with emittance $emit_n = 10^{-3} cm \cdot rad$ ((green solid line) particle is not able to reach bunch axis, so bunch is not split up into a series of spherical bunches. When emittance $emit_n = 10^{-2} cm \cdot rad$ it is already well visible, that the presence of initial emittance does not allow bunch to shrink to the point or «flipped over».

Envelopes of bunch at different values of the initial emittance are shown in Fig.8. Transverse dynamics of bunches by increasing the initial value of the emittance is well visible. As follows from Fig.8, at the value of normalized initial emittance $emit_n = 3 \cdot 10^{-3} cm \cdot rad$ (line 6) it is possible to focus the electron bunch (its diameter is halved). If accelerated bunch has worse quality, it cannot be possible to do good focusing in the accelerator with parameters shown in the

Table 1. During the numerical simulation it was also found, that the amplitude of radial oscillations of the boundary particles of bunch damps with time. With an increase of emittance the rate of damping is also increases. It is well seen in Fig.9 that over time the amplitude of motion of the particles is decreases. This is related with acceleration of the particles by wakefield. To analyze this let's look at equation (1). If witness bunch is in accelerating phase - γ is increasing. The terms that have in the denominator γ - decreases. In the summand which describe emittance – γ included in the minus second degree. In the summand, which describe emittance – γ included in the minus second degree. Initial emittance included in the numerator, so the larger the emittance is – the more noticeable this effect is.

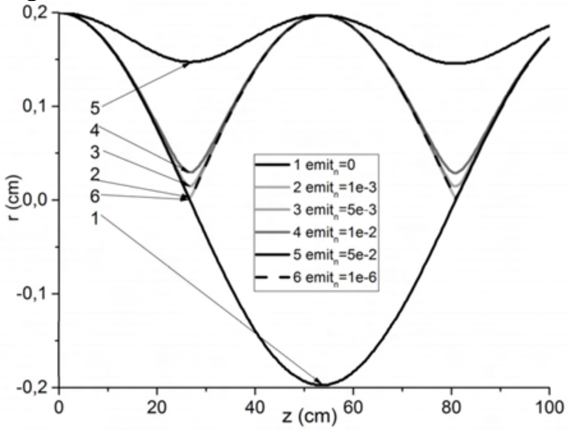

Fig. 8. Envelopes of bunches with different emittance.

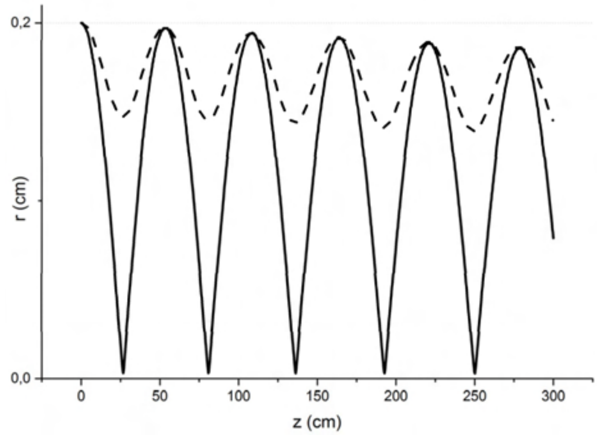

Fig. 9. Envelopes of bunches with emittances $emit_n = 10^{-3} cm \cdot rad$ – solid line, $emit_n = 5 \cdot 10^{-3} cm \cdot rad$ – dash line.

Let's confirm the above by the analytical estimate. Summand with the radial electric field of plasma wave and summand with the emittance gave the main contribution in the equation of the envelope (1) of relativistic electron bunch. Neglecting the other terms and assuming fulfillment of the condition $\omega_p r / c \ll 1$, the equation of the envelope reduces to the form:

$$\frac{d^2 r}{dz^2} \approx -\frac{Kr}{\gamma} + \frac{emit_n^2}{r^3 \gamma^2}, \tag{11}$$

where K - focusing parameter, which depend from structure parameters and drive bunch charge. Envelope of bunch oscillate around equilibrium radius. The expression for the equilibrium radius r_0 of envelope is:

$$r_0 = \left(\frac{emit_n^2}{K\gamma} \right)^{1/4}. \tag{12}$$

With an increase of normalized initial emittance an equilibrium radius of bunch is also increases, that is confirmed by dependences shown in Fig.8. In addition, as it follows from (14), with an increase of bunch energy an equilibrium radius decreases. The damped dependences of the envelope during the acceleration process, given in Fig.9, distinctly demonstrate it. In order to find the value of normalized initial emittance for which effective radial focusing is possible, expression (14) could be rewritten in the another form:

$$emit_n = \frac{1}{4} r_b^2 \left(K\gamma \right)^{1/2}, \tag{13}$$

where the value of an equilibrium radius r_0 of the accelerating bunch was taken equal to half of its starting radius r_b. From expression (15) can be well seen that with the increases of the accelerating bunch energy or drive bunch charge, requirements to quality (initial emittance) of accelerating bunch, for its significant compression, decreases.

CONCLUSIONS

In this paper the dependence of the transverse dynamics of charged particles bunches on the initial emittance was investigated. Emittance limiting values for which the transverse dynamics of charged particles bunches remains stable were founded. The transition from a pinch to stable dynamics was shown. It has been found that the amplitude of movement of the boundary bunch particles decreases with time. Amplitude of the bunch's border movement decreases with the increasing of the initial value of the emittance. This effect is more noticeable for the larger emittance.

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