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NUMERICAL SIMULATION OF EXCITATION OF WAKEFIELD BUBBLE OF PLASMA ELECTRONS BY SHORT DENSE BUNCH OF RELATIVISTIC ELECTRONS

V.I. Maslov[1], I.N. Onishchenko[1], O.M. Svystun[2]
[1]NSC Kharkov Institute of Physics & Technology
61108 Kharkov, Ukraine
[2]Karazin Kharkov National University
61077 Kharkov, Ukraine
E-mail: svistun_elena@mail.ru
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The numerical simulation by 2.5D code LCODE of properties and excitation of wakefield bubble of plasma electrons by short dense bunch of relativistic electrons has been performed in this paper. It has been shown that abrupt back front of bubble becomes less abrupt at decrease of bunch-driver length. Abrupt back front of bubble becomes more abrupt at increase of bunch-driver current. At bubble excitation by short electron bunch with not very large density bubble can be formed in the second wavelength and bubble is not formed in the first wavelength. At larger bunch density the bubble is not formed in the first wavelength on small time and it can be formed on large time. The bunch focusing by bubble becomes more homogeneous with growth of bunch current.
KEY WORDS: laser pulse, wakefield bubble, relativistic electron bunch, numerical simulation.

ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ВОЗБУЖДЕНИЯ КИЛЬВАТЕРНОЙ ПОЛОСТИ ЭЛЕКТРОНОВ ПЛАЗМЫ КОРОТКИМ ПЛОТНЫМ СГУСТКОМ РЕЛЯТИВИСТСКИХ ЭЛЕКТРОНОВ

В.И. Маслов[1], И.Н. Онищенко[1], Е.Н. Свистун[2]
[1] ННЦ Харьковский физико-технический институт
61108 Харьков, Украина
[2] Харьковский национальный университет им. В.Н. Каразина
61077 Харьков, Украина
Проведено 2.5D кодом LCODE численное моделирование свойств и возбуждения кильватерной полости электронов плазмы плотным коротким сгустком релятивистских электронов. Показано, что увеличение крутизны заднего фронта полости при достижении его опрокидывания уменьшается при уменьшении длины сгустка-драйвера. С увеличением тока сгустка увеличивается крутизна заднего фронта полости. При возбуждении полости коротким электронным сгустком с определенной малой плотностью полость может сформироваться на второй длине кильватерной волны, а на первой она не формируется. При большей плотности сгустка полость на малых временах на первой длине волны не формируется, а на больших временах она может сформироваться. С ростом тока сгустка улучшается однородность его фокусировки полостью.
КЛЮЧЕВЫЕ СЛОВА: лазерный импульс, кильватерная полость электронов, релятивистский электронный сгусток, численное моделирование.

ЧИСЛОВЕ МОДЕЛЮВАННЯ ЗБУДЖЕННЯ КІЛЬВАТЕРНОЇ ПОРОЖНИНИ ЕЛЕКТРОНІВ ПЛАЗМИ КОРОТКИМ ЩІЛЬНИМ ЗГУСТКОМ РЕЛЯТИВІСТСЬКИХ ЕЛЕКТРОНІВ

В.І. Маслов, І.М. Оніщенко[1], О.М. Свистун[2]
[1] ННЦ Харківський фізико-технічний інститут
61108 Харків, Україна
[2] Харківський національний університет ім. В.Н. Каразіна
61077 Харків, Україна
Проведено 2.5D кодом LCODE числове моделювання властивостей та збудження кільватерної порожнини електронів плазми щільним коротким згустком релятивістських електронів. Показано, що збільшення крутості заднього фронту порожнини при досягненні його перекидання зменшується при зменшенні довжини згустка-драйвера. Зі збільшенням струму згустку збільшується крутість заднього фронту порожнини. При збудженні порожнини коротким електронним згустком з обумовленою малою щільністю порожнина може сформуватися на другій довжині кільватерною хвилі, а на першій вона не формується. При більшій щільності згустку порожнина на малому часовому періоді на першій довжині хвилі не формується, а на великому часовому періоді вона може сформуватися. Зростання струму згустку покращує однорідність його фокусування порожниною.
КЛЮЧОВІ СЛОВА: лазерний імпульс, кільватерна порожнина електронів, релятивістський електронний згусток, числове моделювання.

At high intensity of a short laser pulse, at fast dissipation of laser pulse or at large density of short electron bunch which excites the wakefield in underdense regime, $n_b>>n_0$, the significant change in electron-bunch-driver interaction with a plasma can be realized. For instance, the possibilities of wakefield soliton excitation as well as electron wakefield bubble formation (the blowout regime) are appeared**.** Here n_b, n_0 are electron densities of bunch and plasma. At drive of large radial impulse to plasma electrons the wakefield perturbation can be represented as hole in electrons phase space or electron bubble in 3D space in strong non-linear regime. A soliton has been formed on oscillation mode with dispersion law closed to linear one. In numerical simulation [1] the formation of electromagnetic soliton has been observed at wakefield generation. Observed electron bubble in 3D space [2-8] and perturbation, observed in [1], [9], at certain conditions can be represented as soliton hump of electric potential. Nowadays electron wakefield bubble [2-8] is widely investigated, because it provides the self-injection of plasma electrons into accelerating field, it provides greatest accelerating rates of electrons and radial stability of both driver and witness. In this paper results of numerical simulation by 2.5D code LCODE [10] of electron wakefield bubble excitation by dense short bunch of relativistic electrons in underdense regime, $n_b >> n_0$, are presented. We consider cylindrical system in azimuth symmetrical approximation. We change plasma electron density and bunch current in wide range. Particle-in-cell code LCODE treats plasma and bunch electrons as ensembles of macro-particles. Code LCODE was developed for simulation of long-term dynamics of electron beams in plasma wakefields up to strongly nonlinear regime. We change simulation parameters in wide range, but plasma density is very small in comparison with bunch density and bunch radius is smaller than c/ω_p. Here c is the light velocity, ω_p is the plasma electron frequency. We consider initial bunch and plasma electrons cold.

The purpose of this paper is the numerical simulation of properties and excitation of wakefield bubble, which provides the greatest accelerating rates of electrons and which now is intensively investigated all over the world.

NUMERICAL SIMULATION OF PROPERTIES AND EXCITATION OF PLASMA ELECTRON WAKEFIELD BUBBLE BY SHORT DENSE RELATIVISTIC ELECTRON BUNCH

Let’s consider results of numerical simulation by 2.5D code LCODE [10] of excitation of plasma electron wakefield bubble by dense narrow short bunch of relativistic electrons.

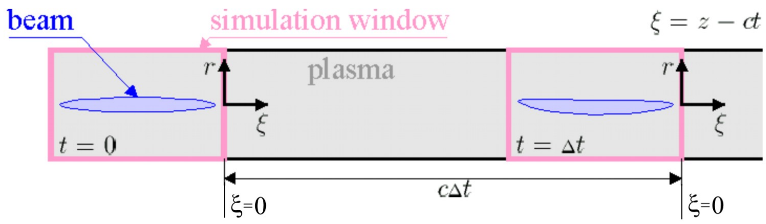

Fig.1. Geometry of the problem.

In our simulation we used the cylindrical coordinates (r, φ, z) and concomitant simulation window (fig.1). Simulation window moves with the light velocity *c*. In the concomitant window particle of bunch will be slowly displaced in the direction of decrease of concomitant coordinate of $\xi = z\text{-}ct$.

In our simulation we used the kinetic model of plasma, simulated by macro-particles. Each plasma macro-particle is characterized by 6 quantities: transverse coordinate (*r*), three components of momentum (p_r , p_φ , and p_z), mass *M* and charge *q*.

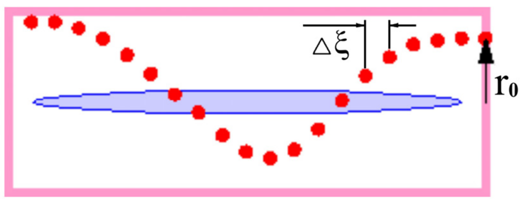

Fig.2. A trajectory of macro-particle of plasma is in an simulation window.

Longitudinal coordinate (ξ) is not parameter, but argument: macro-particle = group of particles which initially were at a given radius. All particles started from r_0 copy of each other (fig.2). Parameters of macro-particles are initialized ahead of the beam (at $\xi = 0$) and then calculated slice-by-slice:

$$\frac{d\vec{p}}{d\xi} = \frac{d\vec{p}}{dt}\cdot\frac{dt}{d\xi} = \frac{q}{\upsilon_z - c}\cdot\left(\vec{E} + \frac{1}{c}\left[\vec{\upsilon}\times\vec{B}\right]\right),$$

$$\frac{dr}{d\xi} = \frac{\upsilon_r}{\upsilon_z - c}, \qquad \vec{\upsilon} = \frac{\vec{p}}{\sqrt{M^2 + p^2/c^2}}.$$

Plasma current and charge density obtained by summation over plasma macro-particles lying in given radial interval:

$$\vec{j} = A\sum_i \frac{q_i\vec{\upsilon}_i}{c - \upsilon_{z,i}}, \qquad \rho = A\sum_i \frac{q_i}{c - \upsilon_{z,i}}, \qquad A \text{ – normalization factor.}$$

All input and output values are in dimensionless form. Units of measure are determined by universal constants and some density n_0 (is the initial plasma density, $n_0 = 2.1\cdot 10^{14}\,\text{cm}^{-3}$). All times are in units of ω_p^{-1}, where $\omega_p = \sqrt{4\pi n_0 e^2/m}$ is the electron plasma frequency. All distances are in units of c/ω_p, all densities are in units of n_0, all fields are in units of $\sqrt{4\pi n_0 mc^2}$, wakefield potential is in units of mc^2/e, beam and plasma momenta are in units of mc.

The solitary bubble has interesting and important properties in comparison with other bubbles. Fig. 3-5 correspond to solitary bubble of plasma electrons, when oscillated plasma electrons are returned to the original radial position with zero radial velocity. In the back front of the solitary bubble the electrical field and potential approximately equal zero, the longitudinal momentum of the bunch electrons and plasma density approximately equal to the unperturbed values. It is realized at certain conditions at length of electron-bunch-driver, approximately equal to the bubble length $L_{dr} \approx L_{bub}$. I.e. soliton wakefield bubble can be formed by relativistic electron bunch with length close to the bubble length.

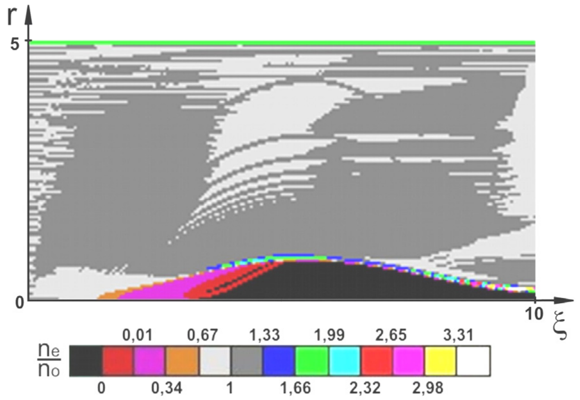

Fig. 3. Spatial distribution of plasma electron density n_e in the field of soliton wakefield bubble, formed by dense narrow short bunch of relativistic electrons with the bunch's length close to bubble length.

Fig. 6 corresponds to the bubble, formed by electron bunch with length, shorter than bunch length in the case of the solitary bubble. One can see in Fig. 6 that bubble back front is steeping**.**

At certain bunch length inverting of bubble back front is occurred. Fig. 7 corresponds to the bubble, formed by electron bunch with length, shorter than bunch length, corresponding to fig. 6. From comparison of fig. 6 and fig. 7 one can see that steeping of bubble back front is decreased at further decreasing of bunch length.

Fig. 8 corresponds to the bubble, formed by electron bunch with current, larger than bunch current, corresponding to fig. 7. From comparison of fig. 7 and fig. 8 one can see that with increase of bunch current the steeping of bubble back front is enhanced.

Usually such parameters of bunch are used that the bubble is formed on first wake wave length. It is shown in

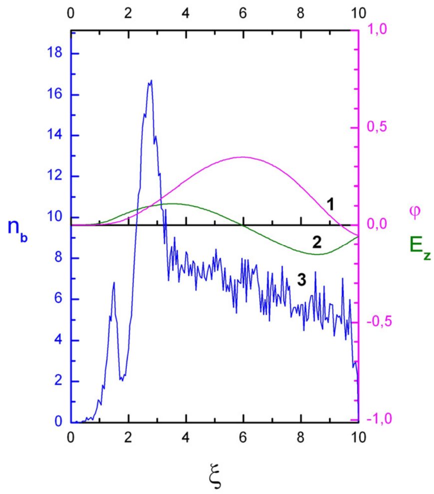

Fig. 4. Longitudinal distribution of electron bunch density n_b (3), electric potential φ (1) and longitudinal electric field E_z (2) of soliton wakefield bubble of plasma electrons along the axis.

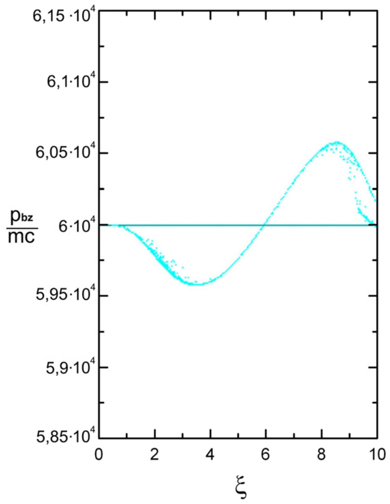

Fig.5 Longitudinal phase space of bunch-driver electrons in consequently interaction with the field of soliton bubble.

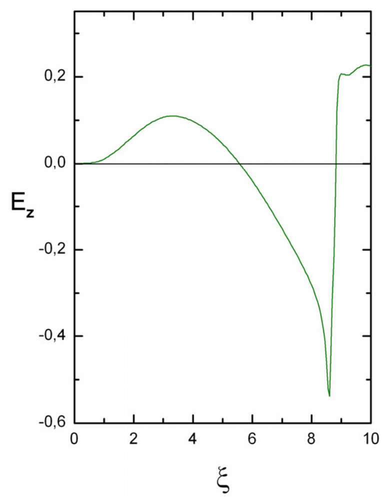

Fig.6. Steeping of bubble back front at decreasing of electron bunch-driver length.

fig. 9 that at wakefield excitation by short electron bunch with certain low density the bubble can be formed on second wave length while it can't be formed on first wave length.

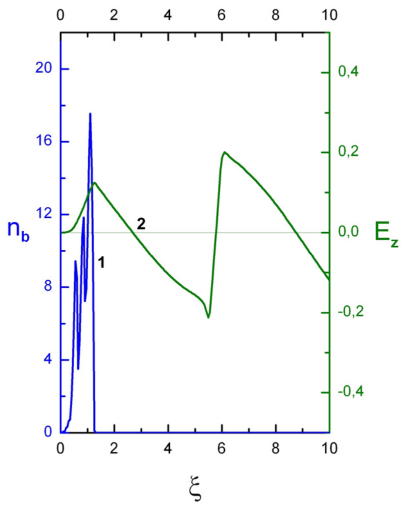

Fig. 7. Decreasing of bubble back front steeping at overcritical decrease of electron bunch-driver length.
1 - electron bunch density, 2 - longitudinal electric field

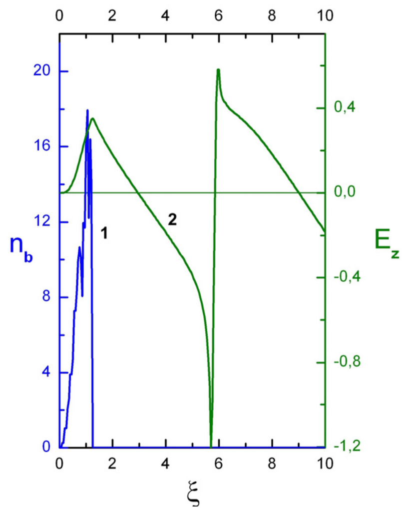

Fig. 8. Enhancing of bubble back front steeping with increase of bunch current.
1 - electron bunch density, 2 - longitudinal electric field

Fig. 10 corresponds to the bubbles, formed by electron bunch with current, larger than bunch current, corresponding to fig. 9. The shape of bunches is shown in fig. 10 on times much more than time of bunch penetration in plasma on bubble length. This shape of bunches on times, comparable with time of bunch penetration in plasma on bubble length, has view similar to fig. 9. From comparison of fig. 9 and fig. 10 one can see that the bubble is not formed on the first wave length on small times, comparable with time of bunch penetration in plasma on bubble length, but it can be formed on large times, much more than time of bunch penetration in plasma on bubble length.

At large bunch density, $n_b \gg n_0$, the bubble appears on the 1st wave length. But on small times, comparable with time of bunch penetration in plasma on bubble length, shape of bunch has view similar to fig. 10. At large times, much more than time of bunch penetration in plasma on bubble length, the bubble becomes more expressed with time (see fig. 11).

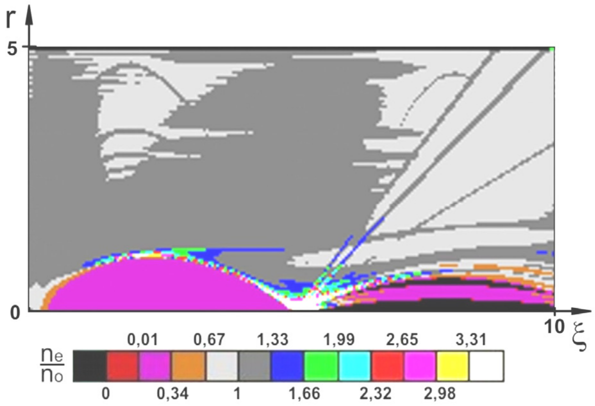

Fig.9. Occurrence of the electron bubble on the second wave length of the excited wakefield while on the first wave length there is no bubble.

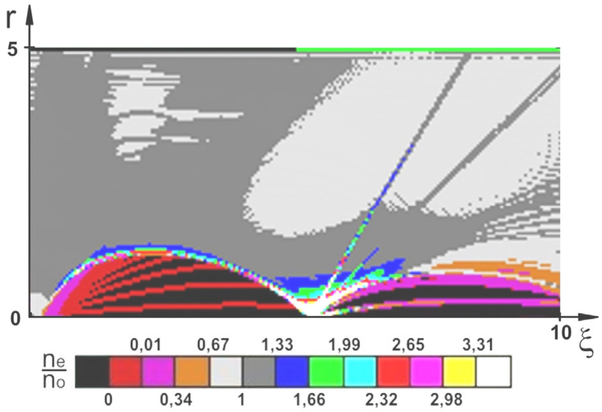

Fig. 10. Spatial distribution of the plasma electrons at excitation of bubble by short electron bunch on times much more than time of bunch penetration in plasma on bubble length.

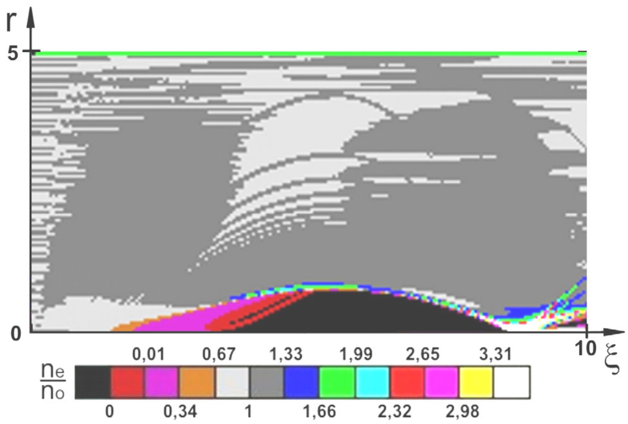

Fig 11. Spatial distribution of plasma electrons at excitation of bubble by short electron bunch at large time.

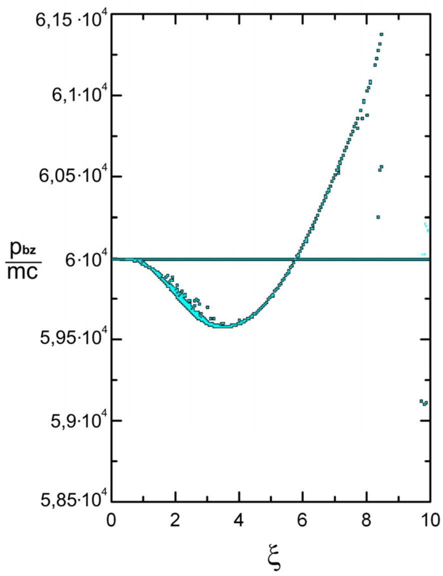

Fig. 12. Longitudinal phase space of bunch-driver electrons in result of interaction with field of bubble.

If bunch length exceeds the half of the bubble length, electrons from its tale are accelerated. Really let's consider a bunch-driver, which length is little less than bubble length. From fig. 12 we can see that electrons from the bunch tale are accelerated and electrons from the bunch first front are decelerated, providing the bunch longitudinal phase stability.

The location of electron bubble (i.e. region with positive volume charge) on main part of the wave length of the perturbation (bubble) leads to both electron bunch-driver and electron witness are located in focusing fields on significant part of perturbation. One can see from fig 13, if the bunch is little shorter than bubble the bunch electrons from its first front are worth focused in comparison with the rest bunch electrons. Also the bunch electrons from wakefield steeping are defocused in radial direction.

In fig. 14 it was shown that with the bunch current increase the focusing homogeneity improves.

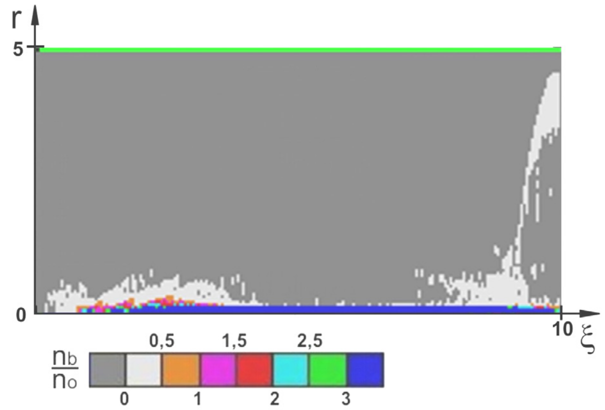

Fig. 13. Spatial distribution of bunch electrons with its length a little shorter than length of bubble.

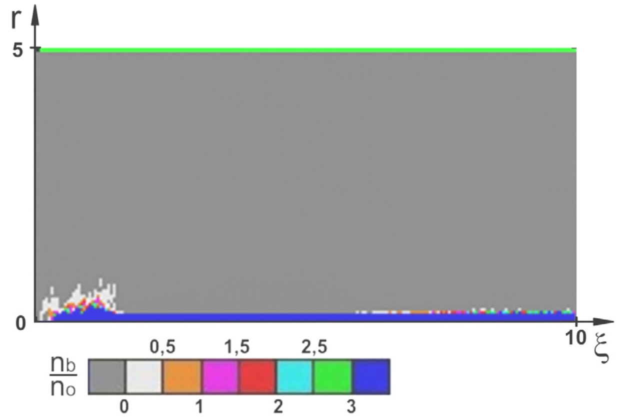

Fig. 14. Spatial distribution of bunch electrons after focusing by bubble.

CONCLUSION

In this paper it was shown that soliton wakefield bubble can be formed by relativistic electron bunch with length close to bubble length. With decreasing of electron bunch length the bubble back front becomes abrupt. At certain bunch length the inverting of bubble back front is realized. The bubble back front steeping is enhanced with increasing of the bunch current. At excitation of bubble by short electron bunch with certain low density the bubble can be formed on second wave length while on first wave length the bubble can not be formed. At larger density the bubble on small time on first wave length can not be formed while it is formed on large time.

The location of electron bubble (i.e. region with positive volume charge) on main part of the wave length of the perturbation leads to both electron bunch-driver and accelerated electrons are located in focusing fields on significant part of perturbation. Electrons from the first front of electron bunch are badly focused. Also the electrons are defocused in radial direction from abrupt region of wakefield. With increasing of the bunch current the homogeneity of its focusing improves.

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