SHORT CYLINDRICAL ELECTRON BUNCH DYNAMICS AND WAKE FIELDS` EXCITATION IN PLASMA WITH THE EXTERNAL MAGNETIC FIELD

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Dynamics of the non-relativistic cylindrical electron bunch injected into the homogeneous plasma along the external magnetic field was studied using computer simulation via PIC method. The initial bunch length was equal to the wake wave length of the background plasmas. The simulation results are compared with the case without magnetic field. It is shown that strong external magnetic field suppresses the radial bunch defocusing but moves to the further longitudinal expansion of the bunch. As a result the area of the wake wave excitation grows substantially. Periodicity of the background plasma current is determined by the excited wake wave.

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INTRODUCTION

The possibility of wake wave excitation in plasma [1] or dielectric [2] environment is widely discussed. Electron bunch or sequence of bunches [3, 9], as well as short powerful laser pulses [4] can be used as an instrument for wake wave excitation. An opportunity to construct a wake wave accelerator of charge particles was experimentally approved [5]. Another reason to study the wake wave excitation is the possibility of inhomogeneous plasma diagnostics via transition radiation of charged particles and bunches [6].

The problem is that, after the bunch injection into plasma, a part of bunches' electrons do not participate in the wake wave excitation because of the radial defocusing in the wake field. The strong magnetic field is able to suppress this defocusing and improve the process of wake wave excitation. The objective of this paper is studying the influence of the longitudinal magnetic field on the dynamics of short cylindrical electron bunch in homogeneous plasma and dynamics of the background plasma electrons, using PIC simulation via 2.5 D electromagnetic code [7].

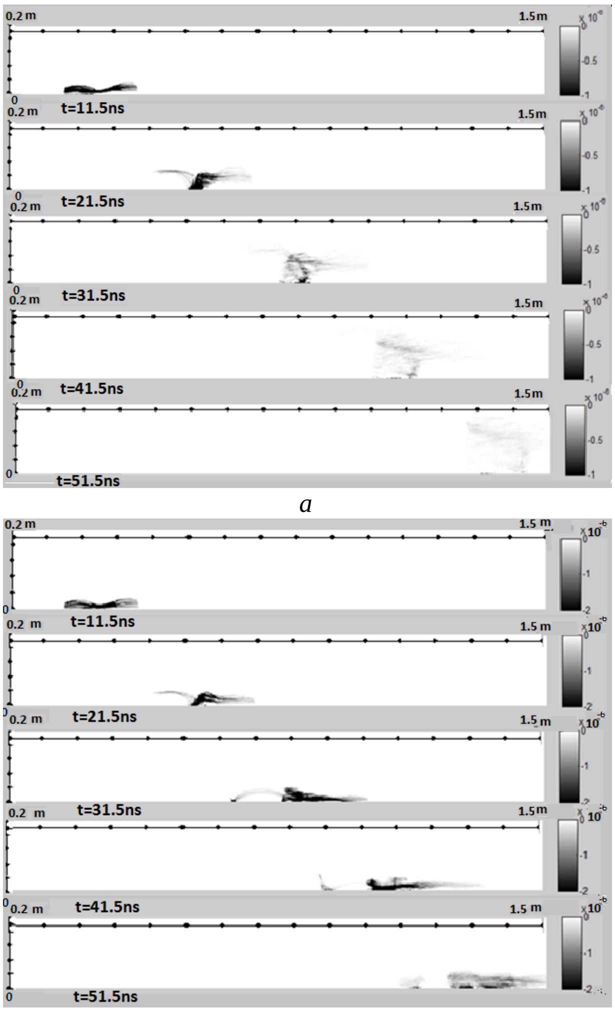
1. SIMULATION PARAMETERS

Simulation is carried out for the following parameters: length of the cylindrical camera is 1.5 m; it's radius is 0.2 m; bunch is injected along it's axis. Plasma density is $5{\cdot}10^8$ cm^{-2}, ion and electron temperatures are 0.2 and 2 eV, respectively. The bunch initial radius is 2 cm; it's initial velocity is $3{\cdot}10^7$ m/s; and its duration is 6 ns. Langmuir frequency of the background plasma is $\omega_p=12.5{\cdot}10^8$ s^{-1}, magnetic field B=1 mT (electron cyclotron frequency $\omega_c=1.5{\cdot}10^7$ s^{-1}), plasma frequency for bunch electrons $\omega_b=2.5{\cdot}10^8$ s^{-1}. Parameters of bunch and plasma were chosen so that the bunch initial length is approximately equal to the wake wave length in the background plasma (unlike [8]).

2. DYNAMICS OF ELECTRON BUNCH

While the electron bunch enters plasma, its forefront excites the wake wave, so the bunch moves in the wake field [9]. Consequently the bunch is substantially deformed during its' passage through plasma.

Fig. 1 presents the distribution of electron bunch density in the systems' half cross section in absence (a) and in presence (b) of the external magnetic field. Figs. 2, 3 demonstrate the corresponding distributions of the velocity components of the bunch electrons.



a

b

Fig. 1. Distribution of the electron bunch density for B=0 (a) and B=1 mT (b) for various time points

In absence of the external magnetic field one can observe the substantial longitudinal focusing of the bunch (see Fig. 1,a, Fig. 2,a). Also almost all the bunch electrons are defocused in the radial direction (see Fig. 2,b). When the bunch reaches the collector, its' density becomes significantly smaller compared to the initial value (see Fig. 1,a). The length of a bunch is not changed significantly.

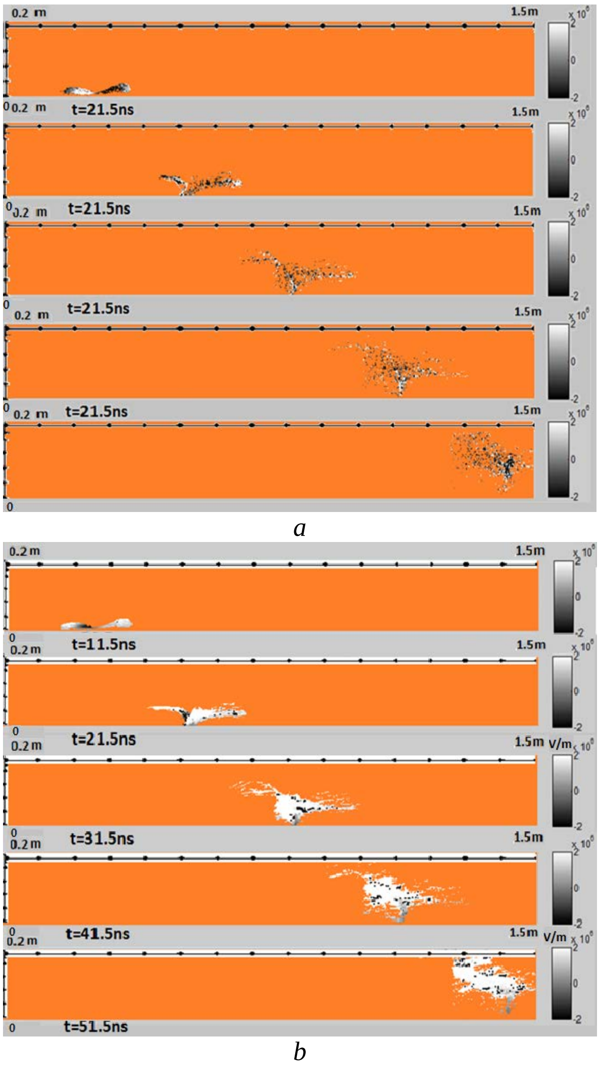


Fig. 2. Distributions of longitudinal (in the reference frame axes connected with the bunch) (a), and radial (b) velocity components of the bunch electrons, B=0

The longitudinal magnetic field suppresses the radial defocusing of the bunch (see Fig. 1,b). Radial expansion of the bunch (see Fig. 3,b) moves to the appearance of the azimuthal component of Lorenz forth and corresponding velocity component (see Fig. 3,c). Azimuthal velocity of electrons moves to the appearance of Lorenz force, directing particles towards the system axis.

From the radial velocities` distribution (see Fig. 3,b) one can see that at the beginning of the bunch motion different parts of bunch move in the different directions: away from systems' axis and towards it. It results in the different directions of the azimuthal rotation (see Fig. 3,c). After the bunch focusing the larger part of bunches' electrons moves synchronously from the system axis and towards it (see Fig. 3,b). At the later stages the motion becomes similar to the stochastic dynamics.

But the bunch longitudinal focusing is significantly suppressed due to the magnetic field (see Fig. 1,b) because the bunch density remains large and Coulomb repulsion is not decreased significantly during the bunch motion.

The backward part of the bunch moves in the accelerating electric field of the wake wave (see Fig. 3,a) and forms the density maximum in the middle of the bunch. The front part of a bunch substantially expands in the longitudinal direction during the bunch motion, so the total bunch length approximately doubles compared to the initial value.

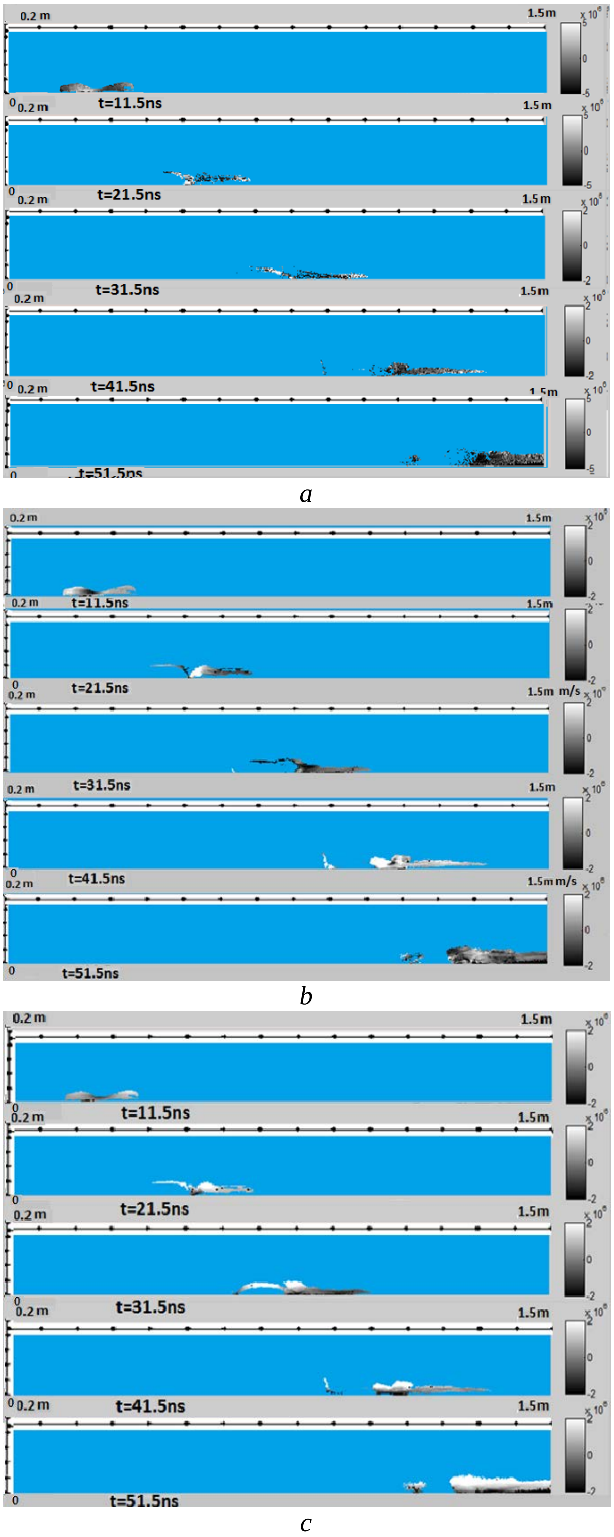
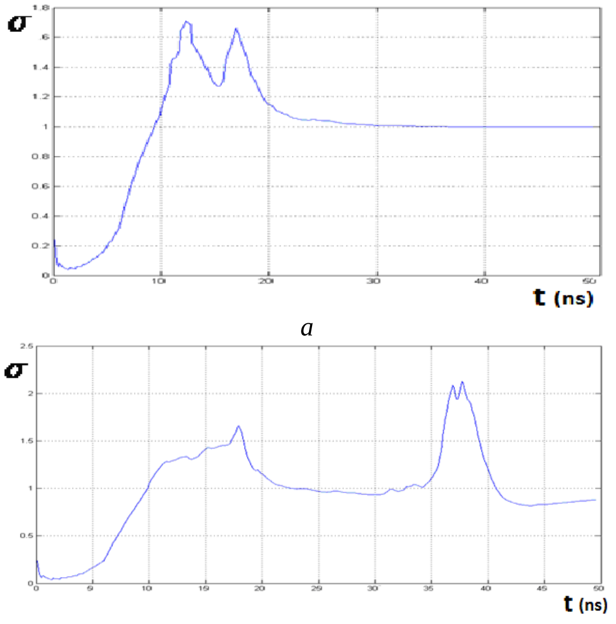


Fig. 3. Distributions of longitudinal (in the reference frame axes connected with the bunch) (a), radial (b) and azimuthal (c) velocity components of the bunch electrons, B=1 mT

From Fig. 3,a one can see that in the late time points the front part of the bunch remains faster than other parts: electrons of the bunch front part do not take part in interaction with wake wave field, and front part is permanently accelerated due to longitudinal expansion of the bunch.

One can notice a small tail with the larger density after the bunch. This tail appears because the bunch length is not precisely equal to the length of Langmuir wave in plasma.



a

b

Fig. 4. Time dependence of the deformation index for B=0 (a) and B=1 mT (b)

Fig. 4 shows the time dependences of the deformation index σ without (a) and with (b) the magnetic field:

$$\sigma = \frac{\int\limits_{-\infty}^{\infty} dz \int\limits_{0}^{r} 2\pi r dr \left[n(\vec{r},t) - n_0(\vec{r},t) \right]^2}{\int\limits_{-\infty}^{\infty} dz \int\limits_{0}^{r} 2\pi r dr n_0^2(\vec{r},t)},$$

where $n(\vec{r},t)$ and $n_0(\vec{r},t)$ are the spatial distribution of the bunch density and the same distribution in the given bunch current approximation, respectively [10]. Peaks on the curves correspond to maximal focusing of the bunch. After the lapse of time the graph (see Fig. 4,a) levels off at the value of 1.0, that means that all the bunch particles are pulverized far from the axis.

In the presence of magnetic field the first peak on the graph corresponds to the bunch focusing due to plasma-beam interaction, and the second peak is a result of the further radial focusing of the bunch due to the magnetic field.

3. THE ELECTRIC FIELD OF EXCITED WAKE WAVE

Figs. 5, 6 show the distributions of radial and longitudinal components of electric field in plasma. Area of the strong electric field is significantly larger in longitudinal direction for system with presence of longitudinal magnetic field in comparison with the case without field [8]. The electric field magnitude of the wake wave becomes higher in the presence of magnetic field. The reason is the higher bunch density at the late time point in plasma with the external magnetic field (see Fig. 1).

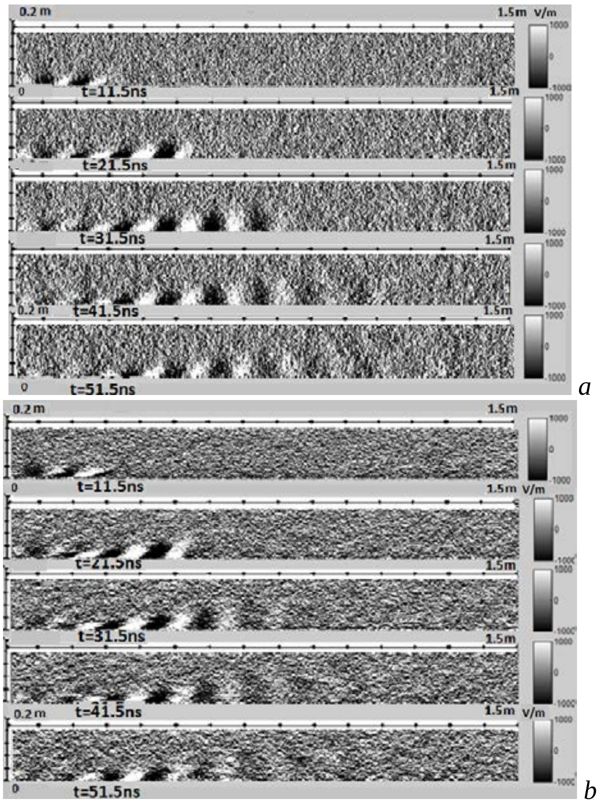


Fig.5. Spatial distribution of radial (a) and longitudinal (b) components of electric field for B=0

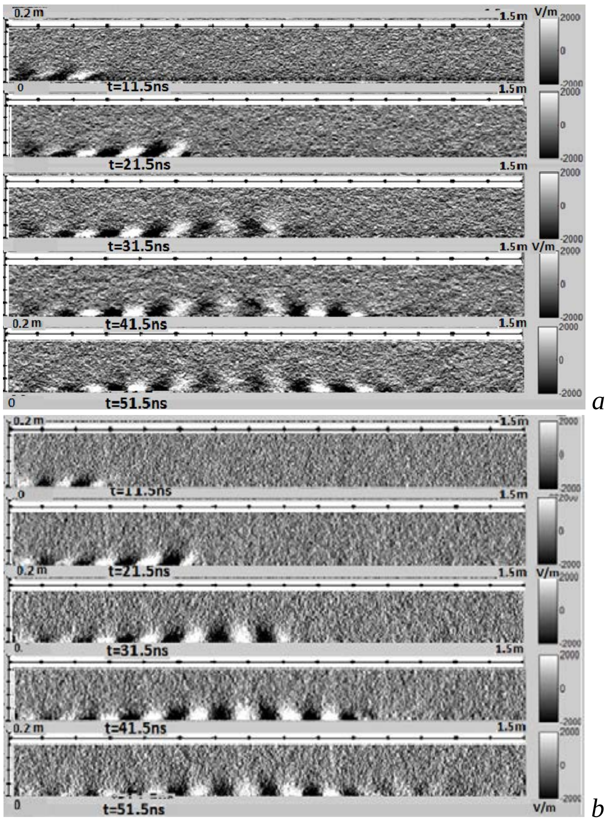


Fig. 6. Spatial distribution of radial (a) and longitudinal (b) components of electric field for B=1 mT

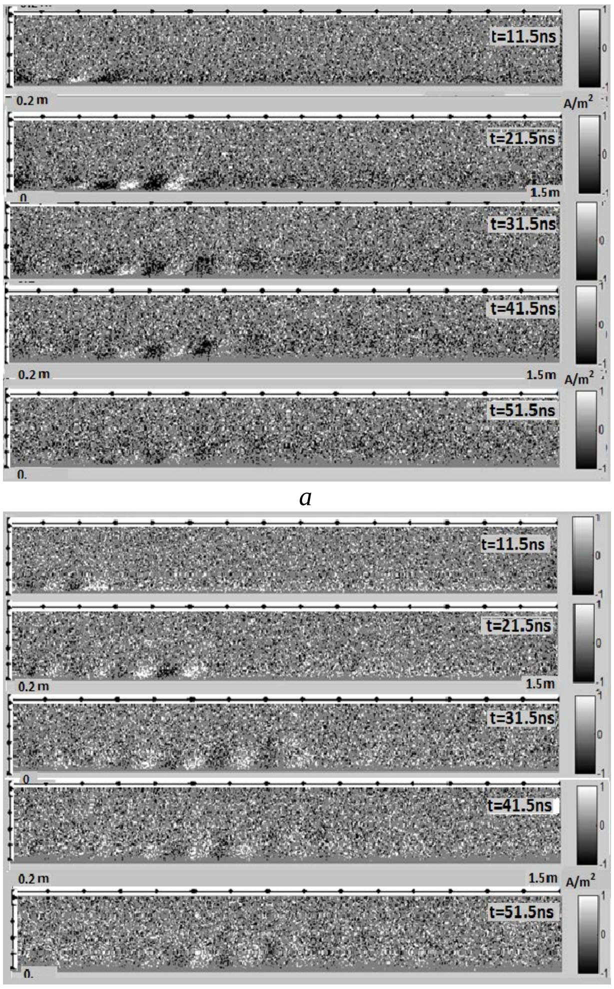
One can see the difference in the shape of the constant phase areas of wake wave in both cases. Thus, areas of the constant phase of wake wave field is displaced in the direction of bunches motion further from the systems' axis. It can be seen that the value of this displacement changes with the distance from injector. The wake wave is excited mostly by the densest part of the bunch. And the shape of this part is changed during its passage through the system (see Fig. 1,a).

In the presence of magnetic field the slope of the densest part of the bunch changes its sign during the motion along the plasma system (see Fig. 1,b). Consequently the slope of the constant phase areas also changes the sign (Fig. 7).

Presence of the external magnetic field does not affect substantially on the radius of the area filled by the excited wake wave.

4. CURRENTS IN THE BACKGROUND PLASMA

Figs. 7, 8 show spatial distributions of radial and longitudinal components of the current density in the background plasma. These distributions are determined by the wake wave field.

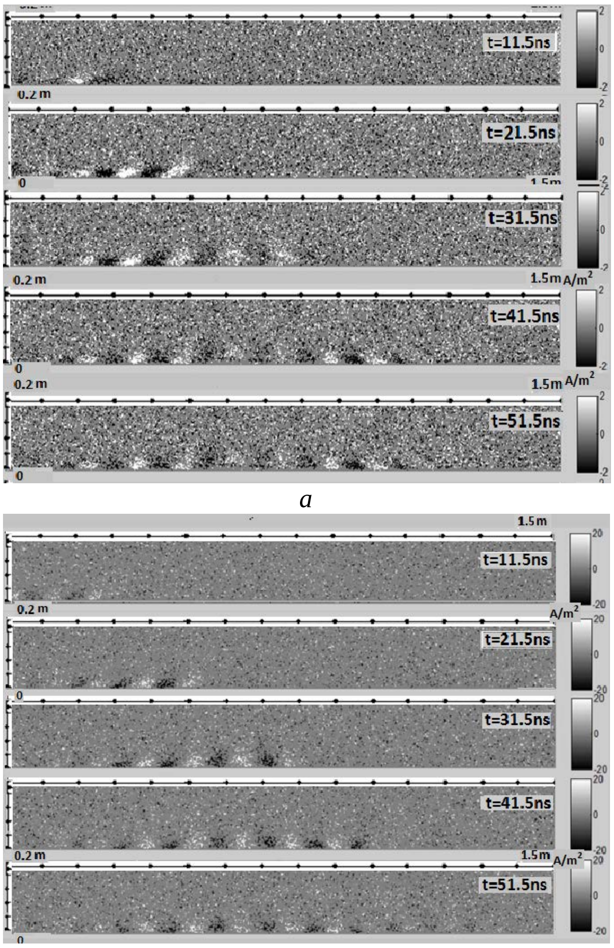


a

b

Fig. 7. Spatial distribution of radial (a) and longitudinal (b) components of the current density in the background plasma for B=0

Without magnetic field radial and longitudinal currents are of the same order, but radial current density is larger (see Fig. 7).



a

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Fig. 8. Spatial distribution of radial (a) and longitudinal (b)components of the current density in the background plasma for B=1 mT

The strong longitudinal magnetic field moves to the significant increase of the longitudinal current while the order of the radial current value remains constant. The azimuthal current density is much smaller relatively to the other components. Consequently the background plasma electrons move mainly along the magnetic field.

CONCLUSIONS

1. External longitudinal magnetic field, directed along the systems' axis, suppresses the radial defocusing of the bunch but provokes its lengthening.

2. Strong external magnetic field moves to the formation of the second maximum (and probably the next maxima) on the time dependence of the deformation index caused by the radial bunch focusing.

3. Strong external magnetic field leads to the continuous acceleration of the bunch forefront by the electric field of the bunch space charge. Direction of the azimuthal velocity of the bunch electrons depends on their initial radial velocity caused by the wake field.

4. Magnetic field causes the expansion of the wake field excitation area due to the radial defocusing suppressing. Peculiarities of the wake field structure are caused by motion of the densest part of the bunch.

5. Structure of the currents in background plasma is determined by the wake field. Magnetic field results in the significant increase of the longitudinal component of the current density.

REFERENCES

1. M.J. Hogan, T.O. Raubenheimer, A. Seryi, P. Muggli, T. Katsouleas, C. Huang, W. Lu, W. An, K.A. Marsh, W.B. Mori, C.E. Clayton and C. Joshi. Wake generation and energy transfer relating to the transport of intense relativistic particle beams in an underdense plasma // *New J. Phys*. 2010, v. 12, p. 055030.
2. A. Tremaine, J. Rosenzweig, and P. Schoessow. Electromagnetic wake fields and beam stability in slab-symmetric dielectric structures // *Phys. Rev. E.* 1997, v. 56, p. 7204.
3. A. Bazzania, M. Giovannozzic, P. Londrillob, S. Sinigardia, G. Turchettia. Case studies in space charge and plasma acceleration of charged beams // *C. R. Mecanique*. 2014, v. 342, p. 647.
4. T. Tajima, J.M. Dawson. Laser Electron Accelerator // *Phys. Rev. Lett*. 1979, v. 43, p. 267.
5. I. Blumenfeld, C.E. Clayton, F.J. Decker, M.J. Hogan, C. Huang. Measurement of the Decelerating Wake in a Plasma Wakefield Accelerator // *Nature.* 2007, v. 445, p. 741.
6. I.O. Anisimov, K.I. Lyubich. Plasma-object diagnostics via resonant transitional radiation from an electron bunch // *J. Plasma Phys*. 2001, v. 66, p. 157.
7. Yu.M. Tolochkevych, T.Eu. Litoshenko, I.O. Anisimov. 2.5D relativistic electromagnetic PIC code for simulation of beam interaction with plasma in axial-symmetric geometry // *Problems of Atomic Science and Technology. Series “Plasma Electronics and New Acceleration Methods”*. 2010, № 4, p. 47-50.
8. M.A. Shcherbinin, I.O. Anisimov. Influence of the external magnetic field on the cylindrical electron bunch injected into plasma // *Problems of Atomic Science and Technology. Series “Plasma Physics”*. 2014, № 6, p. 116-119.
9. T. Katsouleas. Physical mechanisms in the plasma wake-field accelerator // *Physical Review A*, March 1986, v. 3, № 3, p. 2056-2065.
10. I.O. Anisimov, Yu.M. Tolochkevich. Dynamics of One-dimensional Electron Bunch with the Initially Rectangular Density Profile Injected Into Homogeneous Plasma // *Ukrainian Journal of Physics.* 2009, v. 54, № 5, p. 454-460.

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ДИНАМИКА КОРОТКОГО ЦИЛИНДРИЧЕСКОГО ЭЛЕКТРОННОГО СГУСТКА И ВОЗБУЖДЕНИЕ КИЛЬВАТЕРНЫХ ВОЛН В ПЛАЗМЕ В ПРИСУТСТВИИ ВНЕШНЕГО МАГНИТНОГО ПОЛЯ

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Представлены результаты исследования динамики нерелятивистского электронного сгустка, инжектированного в однородную плазму при воздействии внешнего магнитного поля, с помощью компьютерного моделирования методом частиц в ячейках. Начальная длина сгустка равна длине кильватерной волны в фоновой плазме. Результаты моделирований сравниваются с соответствующими результатами без магнитного поля. Показано, что сильное магнитное поле подавляет радиальную дефокусировку сгустка, но приводит к его быстрому расширению в продольном направлении. В результате область возбуждения кильватерной волны существенно возрастает. Наблюдается периодичность в пространственном распределении токов фоновой плазмы, обусловленная структурой кильватерной волны.

ДИНАМІКА КОРОТКОГО ЦИЛІНДРИЧНОГО ЕЛЕКТРОННОГО ЗГУСТКА ТА ЗБУДЖЕННЯ КІЛЬВАТЕРНИХ ХВИЛЬ У ПЛАЗМІ ПРИ ЗОВНІШНЬОМУ МАГНІТНОМУ ПОЛІ

М.А. Щербінін, І.О. Анісімов

Досліджена динаміка нерелятивістського циліндричного електронного згустку, інжектованого в однорідну плазму вздовж силових ліній зовнішнього магнітного поля, за допомогою комп’ютерного моделювання методом крупних частинок. Початкова довжина згустка дорівнює довжині кільватерної хвилі у фоновій плазмі. Результати моделювань порівнюються з відповідними результатами за відсутності магнітного поля. Показано, що сильне зовнішнє магнітне поля пригнічує радіальне дефокусування згустка, але призводить до інтенсивнішого розширення згустка в поздовжньому напрямку. У результаті область збудження кільватерної хвилі суттєво зростає. Спостерігається періодичність у просторовому розподілі струмів фонової плазми, що визначається структурою кільватерної хвилі.