DYNAMICS OF ONE-DIMENSIONAL ELECTRON BUNCH WITH THE RECTANGULAR PROFILE OF DENSITY, INJECTED INTO PLASMA

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Dynamics of electron bunch with initially rectangular density profile injected into plasma was studied for 1D model using PIC method. Dependencies of maximal beam density and maximal amplitude of wake wave field upon the model parameters (plasma density and temperature, beam density, velocity and duration) were obtained and interpreted. Deformation index as a qualitative characteristic of deformation of the bunch initial density profile is proposed, its dependencies on the model parameters were studied.
PACS: 52.35.Fp, 52.40.Mj, 52.65.Rr

1. INTRODUCTION

Dynamics of electron bunches in plasma is a topic of increasing importance due to its broad range of applications. The prominent place among them take the acceleration of electrons by wake fields, injected in plasma by relativistic electron bunches, and heterogeneous plasma diagnostics [1-2]. For the realization of proposed techniques of diagnostics it is necessary to understand, which shape of electron bunch should have be minimally deformed during its motion in plasma. Dynamics of rectangular electron bunch in plasma was studied in [3-6]. But there were no interpretations of results obtained. That is why, the main aim of this work is research and explanation of received dependencies and effects that arise during the motion of electron bunch with initially rectangular density profile in plasma.

2. DYNAMICS OF ELECTRON BUNCH IN THE WAKE WAVE FIELD

Electron bunch moves initially in the wake field raised by its leading front. As a result it splits into micro-bunches, and its dynamics is similar to well-known effect of phase focusing (see Fig.1a). Near the phase focus wake field is no more raised by leading front, but by coherent sequence of micro-bunches and reaches much greater magnitude (Fig.1b). Further bunches defocus due to overtaking of particles, and the wake field decreases. Velocity of electrons on the bunch's leading front, where the wake field is close to zero, hardly changes during its motion in plasma. At the same time electrons on the bunch's back front are decelerated due to the wake field.

When bunch velocity increases, the length of the wake wave, raised by it, increases: $\lambda=2\pi v/\omega_p$, where ω_p is Langmuir frequency of background plasma. As a result the number of electrons in a bunch on the length of a wake wave increases. Thereby maximal density of electrons in a micro-bunch will increase with the speed increase. Thus amplitude of wake wave electric field raised by this micro-bunch will also increase.

By increase of initial bunch density the field of the excited wave also increases, and dependence is close to linear. Indeed, by the electron bunch density increase the charge carried by this bunch also grows, consequently, micro-bunches amplitude and correspondent wake wave field will increase. Till the bunch length is less then the length of wake wave, increase of bunch duration leads to growth of maximal concentration. By further bunch duration growth, the number of micro-bunches increases. Correspondingly, the magnitude of the field coherently excited by that micro-bunches in plasma is also increased slowly.

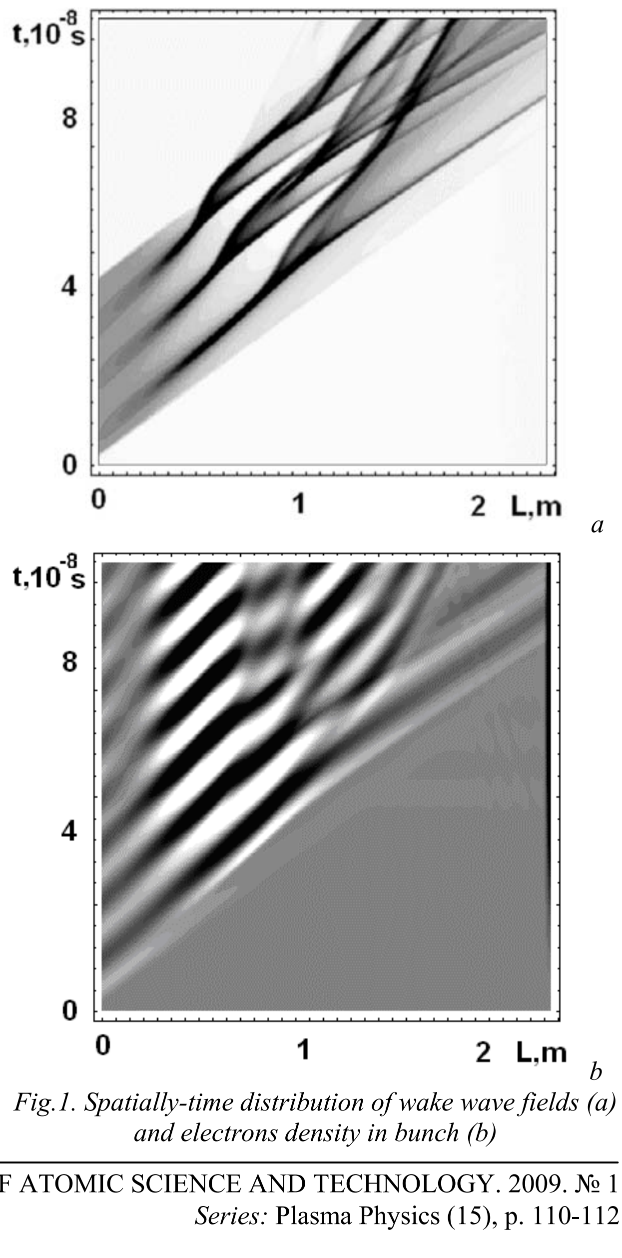

Fig.1. Spatially-time distribution of wake wave fields (a) and electrons density in bunch (b)

By increase of background plasma density the wake wave amplitude decreases. Possible explanation of this effect is connected with the fact that the frequency of plasma's eigen oscillations is proportional to $n_p^{1/2}$. Thus, by increase of the background plasma density the wake wave's duration decreases. Correspondingly, the micro-bunches length decreases, too. The last effect leads to decrease of the electron density amplitude in that micro-bunches.

3. DEFORMATION INDEX AND ITS DEPENDENCE ON THE MODEL PARAMETERS

To characterize bunch deformation during its motion in plasma it is convenient to introduce some integral characteristic which would describe this process – deformation index

$$\sigma = \frac{1}{n_0^2 L}\left\{ \int_{-\infty}^{0} n^2(x)dx + \int_{0}^{L}\left[n_0 - n(x)\right]^2 dx + \int_{L}^{+\infty} n^2(x)dx \right\},$$

where n_0 and L are initial bunch density and length, respectively, n(x) is the bunch density spatial distribution in the current moment of time.

On a small distance from the injector the deformation index monotonously grows with the increase of this distance. This effect corresponds to gradual micro-bunch focusing. Deformation index maximum is reached at the moment of maximal focusing of the first micro-bunch. Then the first bunch begins to fall to pieces due to overtaking of electrons, so the deformation index decreases. Next local maximums are reached at the moments of maximal focusing of second and third micro-bunches, and also shaping of secondary density maximums.

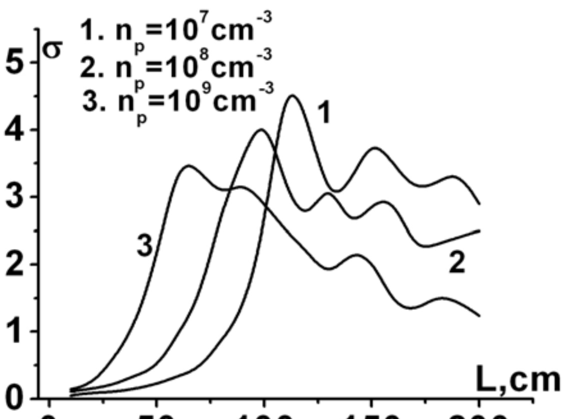

Fig. 2. Spatial dependence of the deformation index for different background plasma densities. The initial bunch density and velocity are $2\cdot10^5$ cm^{-3} and $2\cdot10^9$ cm/s, respectively

Deformation parameter increment decreases on short distance from injector by growth of initial velocity of the bunch. Really, at growth of velocity the lengths of wake waves and, accordingly, micro-bunches increases. As a result for focusing of micro-bunches greater time is spent.

Deformation parameter increment increases on short distances from injector with increase of injected bunch length. When the bunch length is short (in scale of the wake wave length) all its electrons will come across in almost identical phase of a field and everyone will simultaneously slow down or be accelerated. For long bunch there will be a grouping caused by essentially different character of changes of initial speeds.

At growth of bunch density the electric field amplitude raises. It results to the increase of initial density profile distortion.

At growth of the background plasma density (Fig.2) both wake wave field and maximal bunch density decrease. It results to reduction of a deformation index at significant distances from injector. In the same time for larger density of plasma focusing of the first micro-bunch occurs at shorter distances from injector. It moves to corresponding spatial dependence of deformation index.

4. CONDITIONS OF THE BUNCH MINIMAL DEFORMATION

From the simulation results it is possible to obtain a conditions of the least deformation of an electron bunch with initially rectangular density profile during its motion in homogeneous plasma.

1. Duration of a bunch should be much less than period of Langmuir oscillations of background plasma.
2. Bunch velocity should be as much as possible. One can expect that the relativistic increase of the electrons' mass will lead to additional decrease of the bunch deformation (our calculations were carried out for non-relativistic case).
3. The density of a bunch should be as small as possible.
4. If the distance of the bunch motion is less than length of the first density maximum formation, then smaller deformation of the bunch density is reached in less dense plasma.

5. CONCLUSIONS

1. Dynamics of the electron bunch with initially rectangular density profile in a field of wake wave is similar to the phase focusing of the electron beam with initial velocity modulation. At little distances from injector the wake wave is excited by the bunch forward front. At large distances this wave is excited mainly by micro-bunches formed due to focusing of initial bunch by the wake field.

2. Dependencies of the maximal bunch density and maximal wake field upon the model parameters are defined, primarily, by the variation of micro-bunches' length at the parameters' modification. Sometimes it can be caused by excitation of wake wave with coherent sequence of micro-bunches.

3. The proposed deformation index (analogue of dispersion for random process) can be the integral characteristic of deformation of the initial bunch density profile. During the motion of a bunch with initially rectangular density profile through plasma the deformation index first grows, than reaches a maximum value at the moment of the first micro-bunch focusing, and further decreases non-monotonously. Dependence of

deformation index on the model parameters is defined mainly by the factors that determine values of the maximal bunch density and maximal wake field.

4. Use of short weak bunches for inhomogeneous plasma diagnostics via transition radiation [2-3] results in the little amplitude of this radiation. This amplitude can be increased if plasma inhomogeneity is situated at the distance of the first micro-bunch focusing. In this case the bunch with duration equal to the wake wave period can be used.

In this work only bunches with primarily rectangular density profile were considered. But the amplitude excited by a bunch wake waves as well as the bunch deformation rate essentially depends on the shape of its initial density profile [7]. Study of this dependence can be a subject of the further researches.

Preliminary results of this work were reported in [8-9].

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Article received 22.09.08

ДИНАМИКА ОДНОМЕРНОГО ЭЛЕКТРОННОГО СГУСТКА С ПРЯМОУГОЛЬНЫМ ПРОФИЛЕМ КОНЦЕНТРАЦИИ, ИНЖЕКТИРОВАННОГО В ПЛАЗМУ

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Была исследована динамика одномерного электронного сгустка с прямоугольным начальным профилем концентрации, инжектированного в однородную плазму, с применением компьютерного моделирования методом крупных частичек в ячейках. Была объяснена зависимость максимальной концентрации электронного сгустка и максимальная амплитуда кильватерной волны в зависимости от параметров модели (концентрации плазмы, концентрации сгустка, начальной скорости и продолжительности сгустка). Вводится показатель деформации в качестве характеристики деформации начального профиля концентрации сгустка и исследуется его зависимость от параметров модели.

ДИНАМІКА ОДНОВИМІРНОГО ЕЛЕКТРОННОГО ЗГУСТКУ З ПРЯМОКУТНИМ ПРОФІЛЕМ КОНЦЕНТРАЦІЇ, ІНЖЕКТОВАНОГО У ПЛАЗМУ

І.О. Анісімов, Ю.М. Толочкевич

Було досліджено динаміку одновимірного електронного згустку з прямокутним початковим профілем концентрації, інжектованого в однорідну плазму, за допомогою комп'ютерного моделювання методом крупних частинок в комірках. Було пояснено залежність максимальної концентрації електронного згустку і максимальну амплітуду кільватерної хвилі в залежності від параметрів моделі (концентрації плазми, концентрації згустку, початкової швидкості і тривалості згустку). Вводиться показник деформації в якості характеристики деформації початкового профілю концентрації згустку і досліджується його залежність від параметрів моделі.