CHARGED BUNCHES' DYNAMICS IN THE SELF-EXCITED WAKE FIELD IN PLASMA

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Results of the computer simulation of the charged bunches' dynamics in the wake field in homogeneous and inhomogeneous plasmas are presented. Simulation was carried out for proton and electron bunches in electron-proton plasma using PIC method. Results of simulation are compared with analytic calculations. Mechanisms of the wake field excitation are discussed.

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INTRODUCTION

The problem of the wake field excitation by electron bunches and influence of these fields on the bunches' dynamics is interesting due to the possibility to construct the compact electron accelerators using the wake waves [1]. It is also interesting because of the possible diagnostics of the inhomogeneous plasma using transition radiation of the charged particles and beams [2]. This work contains the study of ion and electron bunches' dynamics caused by the wake waves excitation in homogeneous and inhomogeneous plasma without magnetic field. The most convenient solution of the problem is the computer simulation via PIC method. 1D electrostatic code and 2.5D electromagnetic code of axially symmetric geometry [3] were used to simulate the interaction of ion and electron bunches with plasma. Results of analytic calculations are also presented.

1. 1D SIMULATION OF ELECTRON BUNCHES WITH INITIALLY RECTANGULAR AND TRIANGULAR DENSITY PROFILES IN THE HOMOGENEOUS PLASMA

The simplest geometry for the study of the charge bunches' dynamics in the excited wake field is 1D model. Simulation was carried out for bunches with initially rectangular [4] and triangular [5] density profiles. Results for rectangular profile are presented on Fig. 1. Bunch electrons move in the initial wake field excited by the bunch forefront forming the sequence of microbunches [6]. This sequence excites the wake wave via Cherenkov resonance mechanism. Later the microbunches' decay is observed. Fig. 2 demonstrates the density evolution of the initially triangular bunch. Perturbation of the bunch density profile can be described by the deformation index:

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

where n_0 and L are initial bunch density and length, $n(x)$ is the bunch density distribution. Spatial dependence of the deformation index for bunches with initially rectangular (1) and triangular (2) profiles are presented on Fig. 3. The triangular bunch profile is perturbed much more slowly because its initial forefront is much longer than for the rectangular bunch, and the initial wake field is weaker.

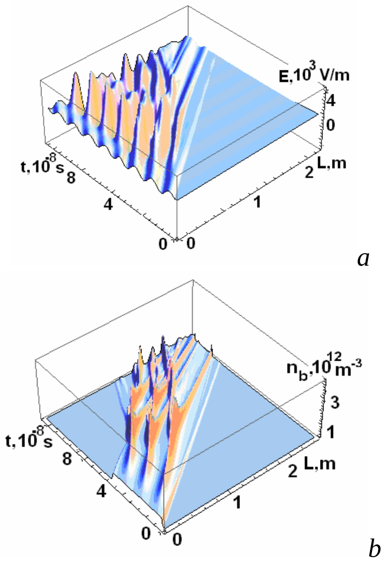

Fig. 1. Space-time distributions of wake fields (a) and bunch density (b) for the initially rectangular profile: $v_b=3\cdot10^{9}$cm/s; $T_b=3T_{Langm}=3.3\cdot10^{-8}$ s; $n_b=1.1\ 10^{6}$cm^{-3}; $n_p=10^{8}$cm^{-3}; $T_e=2\cdot10^5$ K

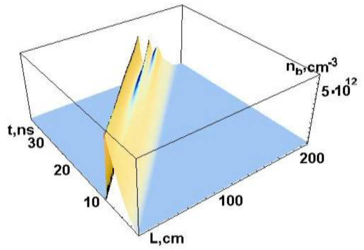

Fig. 2. Space-time distribution of the bunch density for the initially triangular profile. Simulation parameters are the same as in Fig. 1

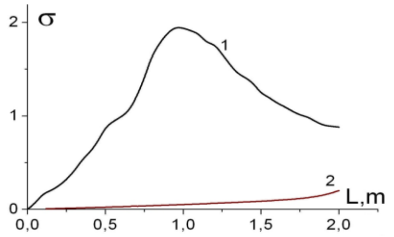

Fig. 3. Spatial dependence of the deformation index for bunches with initially rectangular (1) and triangular (2) profiles. Simulation parameters are the same as in Fig. 1

2. ANALYTIC CALCULATION AND 2D SIMULATION FOR CYLINDRICAL CHARGED BUNCHES IN THE HOMOGENEOUS PLASMA

2.1. ANALYTIC RESULTS FOR COLD PLASMA IN THE GIVEN CURRENT APPROXIMATION

Analytic calculation was carried out for the cold plasma model in the approximation of the given bunch current [7], i.e. the influence of the wake field on the bunch motion wasn't taken into account. The calculation result is plotted on Fig. 4. For the cold plasma model the wake field is excited only in the areas where the bunch passed. The wake fields excited by the forefront and back front interfere in the area after the forefront (they are almost in antiphase on Fig. 4).

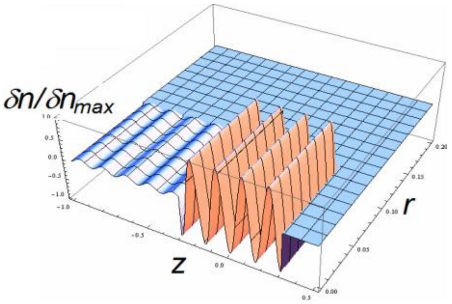

Fig. 4. Plasma density excitation by the charged bunch (analytic solution)

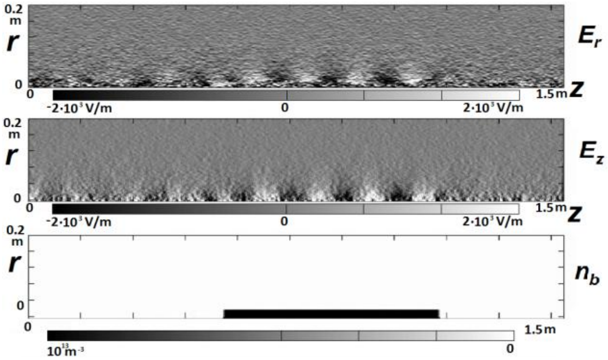

Fig. 5. Spatial distributions of E_r, E_z and n_b for the ion bunch: $n_p=5\cdot10^8$ cm^{-3}; $n_b=8\cdot10^6$ cm^{-3}; $v_b=3\cdot10^9$ cm/s; $t_b=2\cdot10^{-8}$ s$=4T_{Langm}$; $T_e=1$eV; $T_i=0.1$ eV

2.2. SIMULATION RESULTS FOR THE ION BUNCH

Simulation of the proton bunch propagation was carried out via 2.5D PIC code [7]. Results (Fig. 5) are in qualitative agreement with analytic calculation in the given current approximation, because during the bunch motion through plasma its charge distribution doesn't changed significantly. Plasma temperature results in the wake field excitation outside the volume where the bunch passed.

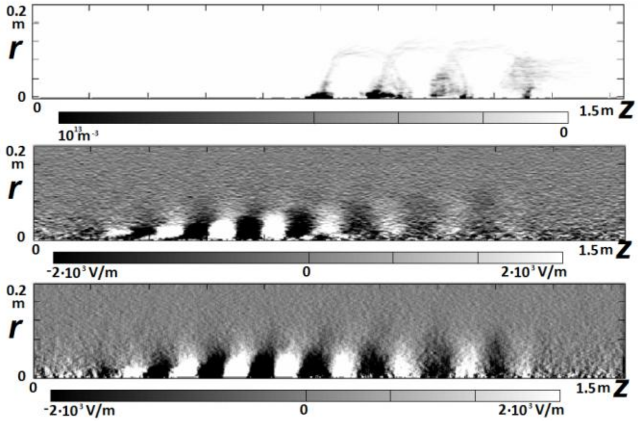

Fig. 6. Spatial distributions of n_b, E_r and E_z for the electron bunch. Simulation parameters are the same as on Fig. 5

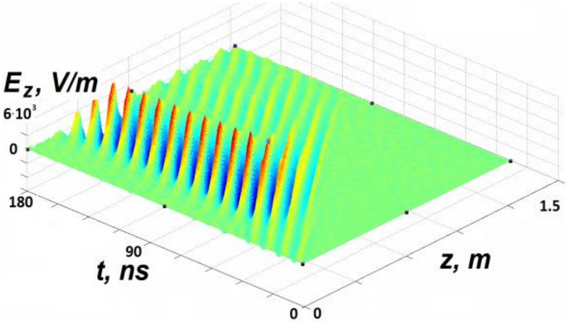

Fig. 7. Space-time distribution of the longitudinal electric field near the system axis

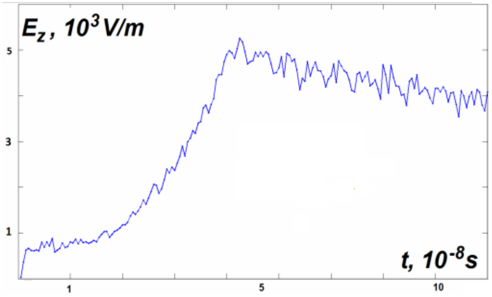

Fig. 8. Dependence of the maximum wake wave amplitude on time

2.3. SIMULATION RESULTS FOR THE ELECTRON BUNCH

The main difference between results for ion and electron bunches is the strong redistribution of electron bunch density due to the initial wake wave excited by the sharp forefront of the bunch [6,7]. 2D simulation demonstrates both longitudinal and radial focusing and defocusing of the electron bunch (Fig. 6). The area of the most intensive wake field along the first half of the bunch trajectory remains almost constant due to the small group velocity of the wake waves (Fig. 7). Maximal wake wave magnitude grows approximately 10 times relatively to its initial value caused by the bunch forefront (Fig. 8). This effect can be explained via Cherenkov mechanism (compare with Section 2) that is self-consistent with the microbunches' dynamics. On the other hand this result can also be interpreted as the beam-plasma instability development (for long bunches).

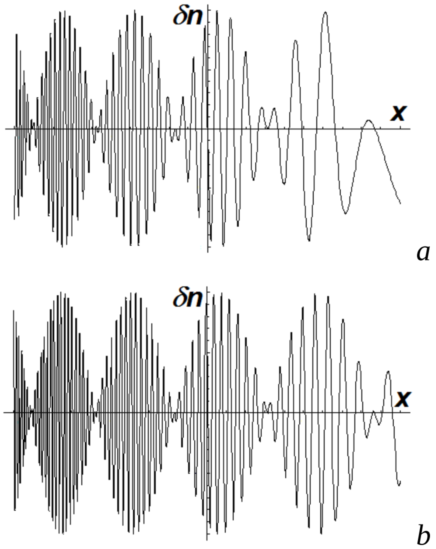

Fig. 9. Spatial distributions of the plasma density perturbation caused by the long charge bunch (given current approximation) in the longitudinally inhomogeneous plasma for $\omega_{p0}t$=60 (a), 80 (b)

3. ANALYTIC CALCULATION AND 2D SIMULATION FOR THE CASE OF LONGITUDINALLY INHOMOGENEOUS PLASMA

3.1. ANALYTIC RESULTS

In this section we discuss results [8] for the longitudinally inhomogeneous plasma with the linear density profile:

$$n(z)=n_0(1+z/L).$$

Sketches of the spatial distributions of the plasma density perturbation caused by the long charge bunch obtained from the analytic calculation for cold plasma in the given bunch current approximation are presented on Fig. 8. For the cold plasma model oscillations in the neighboring points don't affect each other. So in the inhomogeneous plasma the phase difference between such oscillations grows monotonously in time (Fig. 9). Of course, this phenomenon can't be observed experimentally. On the other hand the background plasma inhomogeneity along the bunch trajectory moves to the variation of the phase difference between the wake waves excited by the forefront and back front. Consequently the spatial beatings of the wake field after the back front are excited (see Fig. 9).

3.2. SIMULATION RESULTS FOR THE ION BUNCH

In the numerical simulation plasma density was varied from $2{\cdot}10^8$ to $8{\cdot}10^8$ cm^{-3}. Other parameters are the same as in the previous section. Simulation results demonstrate that in the inhomogeneous plasma the given current approximation for the ion bunch is also satisfied (compare with Section 3.2). Fig. 10 demonstrates the spatial beatings of the wake field predicted by the analytic theory (compare with Fig. 9).

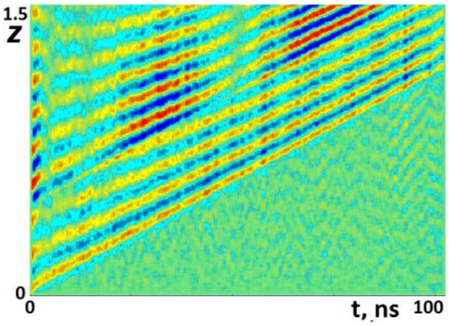

Fig. 10. Space-time distribution of the longitudinal electric field near the system axis (ion bunch in the inhomogeneous plasma)

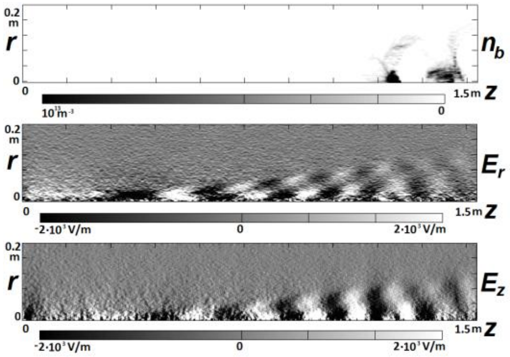

Fig. 11. Spatial distributions of n_b, E_r, and E_z for the electron bunch in the longitudinally inhomogeneous plasma

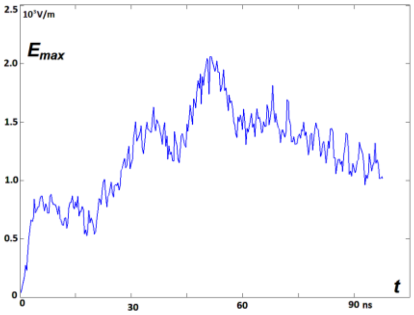

Fig. 12. Dependence of the maximum wake wave amplitude on time for the longitudinally inhomogeneous plasma

3.3. SIMULATION RESULTS FOR THE ELECTRON BUNCH

For the longitudinally inhomogeneous plasma periodicity of the wake wave near the system axis and at the periphery can differ (Fig. 11). This difference is causedby different behavior of the first microbunch and the next ones. The first microbunch is better focused longitudinally, the next ones are better focused radially. As a result the wake field at the periphery is excited mainly by the first microbunch, near the system axis – by the next ones [8].

Fig. 12 demonstrates that maximal amplitude of the electric field in the longitudinally inhomogeneous plasma also grows relatively to the value caused by the bunch forefront, but its maxim is smaller then in the homogeneous plasma (see Fig. 8). Cherenkov resonance condition is not fulfilled now, so this effect can be caused simply by the microbunches' focusing.

CONCLUSIONS

1. Dynamics of the solitary charged bunch in plasma is caused by the wake field excited by this bunch.
2. Approximation of the bunch given current for the calculation of the wake field is valid for ion bunches on the length of the order of $10^1…10^2$ wake waves. For electron bunches it becomes invalid at the length of the order of wake wave.
3. Initially the wake field is excited by the bunch forefront. For electron bunches this field moves to the formation of the microbunches' sequence and further Cherenkov excitation of the wake field. This effect can be also interpreted as the beam-plasma instability development.
4. Additional mechanism of the wake wave growth is caused by the microbunches' focusing and consequent increase of their charge density. It can also take place in the inhomogeneous plasma unlike the Cherenkov resonance.

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ДИНАМИКА ЗАРЯЖЕННЫХ СГУСТКОВ В ВОЗБУЖДЕННЫХ ИМИ КИЛЬВАТЕРНЫХ ПОЛЯХ В ПЛАЗМЕ

Ю.М. Толочкевич, И.А. Анисимов, Т.Е. Литошенко

Представлены результаты компьютерного моделирования динамики заряженных сгустков в кильватерном поле в однородной и неоднородной плазмах. Моделирование методом крупных частиц в ячейках выполнялось для электронных и протонных сгустков в электронно-протонной плазме. Результаты моделирования сравниваются с аналитическими расчетами.

ДИНАМІКА ЗАРЯДЖЕНИХ ЗГУСТКІВ У ЗБУДЖЕНИХ НИМИ КІЛЬВАТЕРНИХ ПОЛЯХ У ПЛАЗМІ

Ю.М. Толочкевич, І.О. Анісімов, Т.Є. Літошенко

Подано результати комп'ютерного моделювання динаміки заряджених згустків у кільватерному полі в однорідній та неоднорідній плазмах. Моделювання методом крупних частинок у комірках виконувалося для електронних та протонних згустків у електронно-протонній плазмі. Результати моделювання порівнюються з аналітичними розрахунками.