CYLINDRICAL CHARGED BUNCHES DYNAMICS IN THE LONGITUDINALLY INHOMOGENEOUS PLASMA

Yu.M. Tolochkevich, T.E. Litoshenko, I.O. Anisimov
Taras Shevchenko National University of Kiev, Radio Physics Faculty, Kiev, Ukraine
E-mail: yura.tolochkevich@gmail.com; taras.litoshenko@gmail.com; ioa@univ.kiev.ua

Results of analytic study and computer simulation of the cylindrical charged bunches' dynamic are presented. Analytic solution was obtained for cold plasma in the given current approximation. Results of the computer simulation of the ion bunch are in a good agreement with theoretical estimations. The wake field has a behavior of the spatial beating because the phase difference between the waves excited by forefront and rearfront varies along the bunch trajectory. Dynamics of the electron bunch differs strongly due to the formation of the microbunches' with complex dynamics. The wake field magnitude increases substantially due to the microbunches' focusing. The first microbunch is better focused longitudinally and defocused in the radial direction in comparison with the next microbunches. It results to different spatial structure of the wake field at the axis and at the periphery of the system.

PACS: 29.27.Bd; 52.59.-f

INTRODUCTION

Wake wave excitation in plasma by charged bunches is one of the actual problems of plasma electronics. Charged particles' acceleration in the strong wake fields became the basis for high-energy electron accelerators [1]. However, the dynamics of electron bunches in the excited wake wave fields is also interesting for the possibility of inhomogeneous plasma diagnostics [2]. The main aim of this work is the study of wake wave excitation by the cylindrical electron bunch in the longitudinally inhomogeneous plasma. Wake field is estimated analytically in the given current approximation for cold plasma in section 1. In section 2 excitation of the wake wave is studied via computer simulation of the ion and electron bunches dynamics in plasma.

1. ANALYTIC CALCULATION

Full analytic solution for the wake field in the longitudinally inhomogeneous plasma is only possible in the given current approximation for cold plasma (for the warm plasma solution can be obtained in the far radiation zone). Plasma density profile is linear, near the right boundary the density is four times more than near the left boundary.

Bunch and plasma parameters are presented in Table. The same parameters were chosen for computer simulation.

Bunch and plasma parameters

System length, z	150 cm
Radius of the system, r	20 cm
Left plasma density	$2\cdot10^{8}$ cm^{-3}
Right plasma density	$8\cdot10^{8}$ cm^{-3}
Bunch density	$8\cdot10^{6}$ cm^{-3}
Initial bunch velocity	$3\cdot10^{9}$ cm/s
Radius of the bunch	2 cm
Bunch duration	$2.0\cdot10^{-8}$ s = 4 T_p

The wake field excited by the cylindrical electron bunch in the cold plasma is given by the following expression:

$$n_1(r,\xi) = -\frac{n_B(r)}{2\pi}\exp\left(\frac{\nu\xi}{2v_0}\right)\left\{\exp\left(\frac{\nu L}{4v_0}\right)\cos\left[\frac{\omega_p(r)}{v_0}(\xi+L/2)+\varphi\right]\times\right.$$

$$\left.\times\theta\left(-\xi-\frac{L}{2}\right)-\exp\left(-\frac{\nu L}{4v_0}\right)\cos\left[\frac{\omega_p(r)}{v_0}(\xi-L/2)+\varphi\right]\theta\left(-\xi+\frac{L}{2}\right)\right\},$$

$$\varphi = arctg\frac{\nu}{2\omega_p}. \qquad (1)$$

Two terms in (1) correspond to wake fields excited by the forefront and rare front of the bunch. One can see that phases of these fields vary non-monotonously in space due the plasma inhomogeneity (Fig. 1).

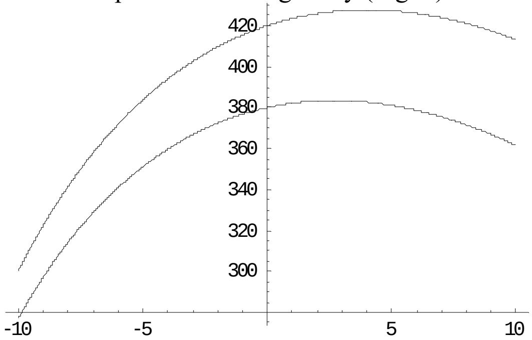

Fig. 1. Spatial wake wave phase distribution, excited by leading and rear fronts of the long charged bunch at the time moment t=12 ns

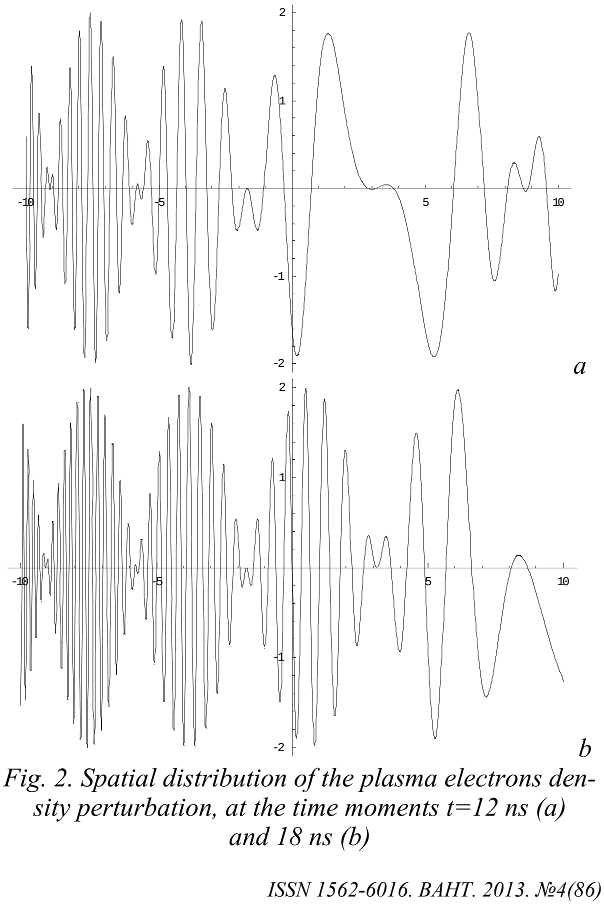

Fig. 2. Spatial distribution of the plasma electrons density perturbation, at the time moments t=12 ns (a) and 18 ns (b)

The phase difference between the waves excited by the bunch forefront and rear front changes along the trajectory for long bunches. As a result, amplitude of the wake field has a form of the spatially periodic beating (Fig. 2). In the model of the cold plasma Langmuir oscillations in the neighbor points are independent. It results in continuous increase of the phase difference between these oscillations. As a result the spatial period of the excited wake wave decreases with time and with the distance from the moving charge (see Fig. 2). Obviously this effect doesn't take place in the warm plasma.

2. SIMULATION OF THE ION BUNCH DYNAMICS IN THE INHOMOGENEOUS PLASMA

Simulation of the proton bunch propagation was studied by 2.5 D electromagnetic PIC code [4]. Plasma electron and ion temperatures were 1 eV and 0.1 eV, respectively.

One can see from Fig. 3 that the ion bunch shape is not perturbed substantially during its motion, so the given current approximation is valid.

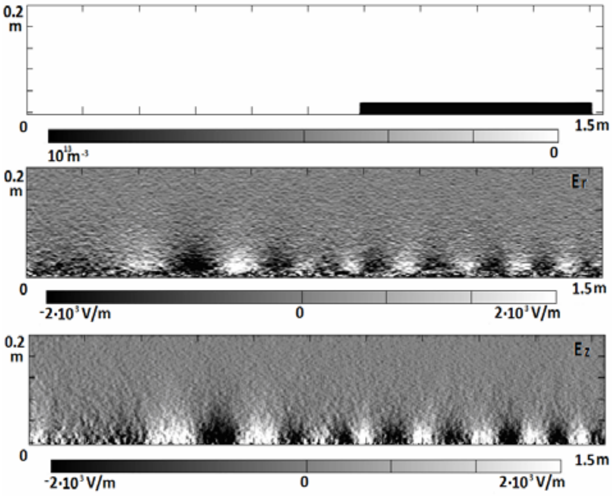

Fig. 3. Spatial distributions of the proton bunch density, radial and axial electric field for t=48 ns

Consequently results of simulation are in good agreement with analytic calculation. Spatially periodic beatings are also present in simulation results (Fig. 4).

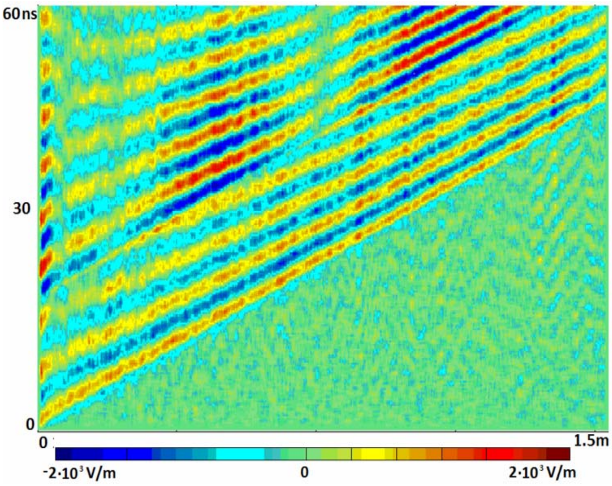

Fig. 4. Space-time distribution of the excited axial electric field near the system axis

These beatings appear only after the rear front passage. Of course, the decrease of the wake wave spatial period predicted by the model of cold plasma doesn't take place. In the warm inhomogeneous plasma the Langmuir wave excited at the plasma frequency is reflected and propagates to the area with the lower plasma density.

3. SIMULATION OF THE ELECTRON BUNCH DYNAMICS IN THE INHOMOGENEOUS PLASMA

The main difference between simulation results for ion and electron bunches is the strong redistribution of the electron bunch density due to the initial wake wave excited by the sharp forefront of the bunch. Electrons of the bunch move in the field of this wave that leads to the microbunches' focusing similar to the simulation for homogeneous plasma [4]. The number of microbunches is defined by the wake wave length at the area of the bunch injection.

The spatial distributions of the bunch density, radial and axial electric field for the time moments 26 ns and 38 ns are presented on the Fig. 5,a,b.

One can see that the first and the second microbunches at $t = 26$ ns have the shape of the hollow cone. The opening angle of this cone increases up to 90° (see Fig. 5,b). Formation of these cones takes place self-consistently with the electric field.

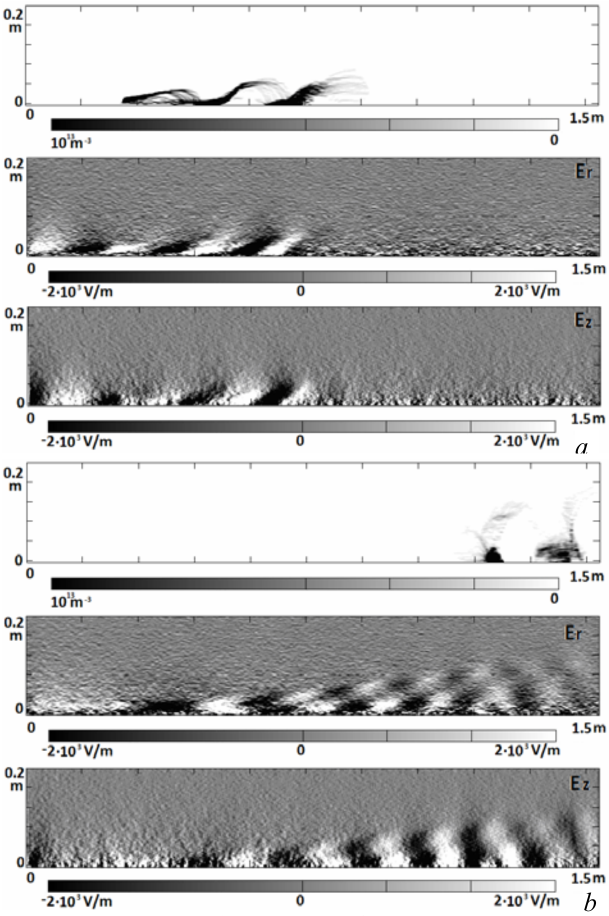

Fig. 5. Spatial distribution of the bunch density, radial and axial electric fields at time points 26 ns (a) and 38 ns (b)

Dynamics of the first microbunch differs substantially from the next ones. It is better focused longitudinally but worse in the radial direction. As a result for the late time points the spatial distributions of electric field at the axis and at the periphery of the system differ strongly. The field at the periphery of the system is excited by the first microbunch, the field at the axis – by the next ones.

With the increase of the plasma electrons' temperature this effect is reduced.

Fig. 6 presents the time dependence of the maximal electric field excited in the system. One can see that the absolutely maximal magnitude of this field is approximately three times larger than magnitude of the field excited by the bunch forefront (initial part of the curve). In the homogeneous plasma the similar result was interpreted via Cherenkov excitation of the wake wave by the resonant sequence of microbunches. But in the inhomogeneous plasma this mechanism is not valid. So this result can be connected with the effective longitudinal focusing of the microbunches.

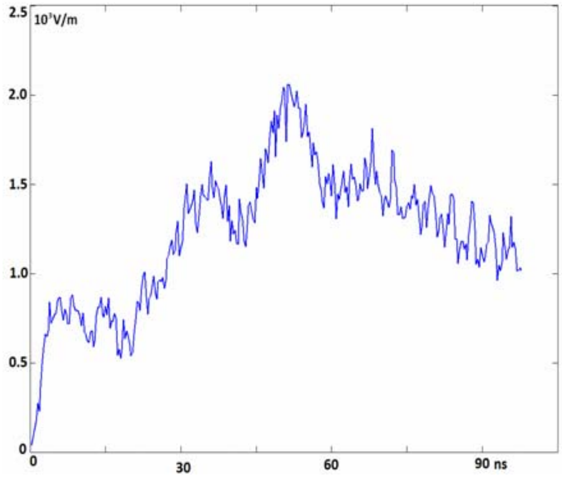

Fig. 6. Time dependence of the maximal longitudinal electric field component near the axis

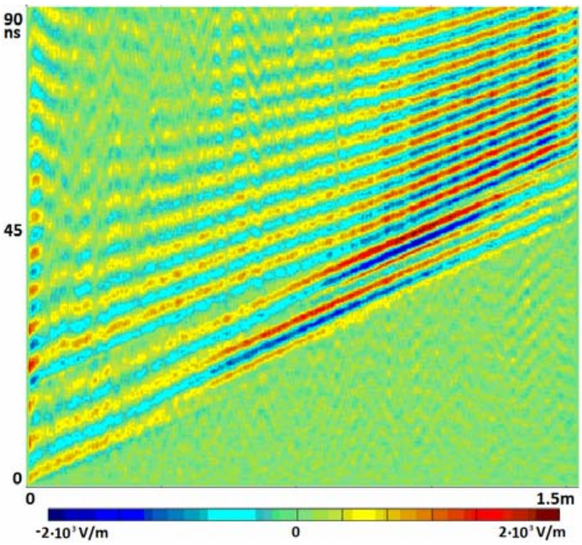

Fig. 7. Space-time distribution of the excited axial electric field near the system axis

Space-time distribution of the axial electric field is given on Fig. 7. The area of the most intensive field becomes immobile for $t > 50$ ns. The similar result was obtained in the simulation for homogeneous plasma [4]. This effect can be connected with the nonlinearity of the excited wave – its magnitude is more than an order higher than the threshold of the thermal nonlinearity.

CONCLUSIONS

1. The wake field excited by the ion bunch in plasma with the linear density profile has a shape of the spatial beatings. These beatings are caused by the variation of the phase difference between the wake waves excited by the forefront and rare front of the bunch.

2. The initially homogeneous cylindrical electron bunch decays to the sequence of microbunches due to the wake wave excited by its forefront. Dynamics of the first microbunch differs strongly from dynamics of the subsequent microbunches. It is better focused longitudinally but worse in the radial direction. As a result the field at the periphery of the system is excited by the first microbunch, the field at the axis – by the next ones.

3. Synchronism between microbunches is broken in the inhomogeneous plasma. So the maximal electric field is substantially smaller in comparison to the homogeneous plasma.

REFERENCES

1. C.G. Geddes D.L. Bruhwiler, et al. Computational studies and optimization of wakefield accelerators // *Journal of Physics: Conference Series.* 2008, v. 125, p. 012002.
2. I.O. Anisimov, K.I. Lyubich. Plasma-object diagnostics via resonant transitional radiation from an electron bunch // *Journal of Plasma Physics.* 2001, v. 66, part. 3, p. 157-165.
3. Yu.M. Tolochkevych, T.E. Litoshenko, I.O. Anisimov. 2.5 D relativistic electromagnetic PIC code for simulation of beam interaction with plasma in axial-symmetric geometry // *Problems of Atomic Science and Technology. Series "Plasma Physics".* 2010, № 4, p .47-50.
4. Yu.M. Tolochkevich, T.E. Litoshenko, I.O. Anisimov. Excitation of the wake wave field in plasma by the long cylindrical charged bunch // *Problems of Atomic Science and Technology. Series «Plasma Physics» (18).* 2012, № 6, p. 139-141.

Article received 05.04.2013.

ДИНАМИКА ЗАРЯЖЕННЫХ СГУСТКОВ В ПРОДОЛЬНО НЕОДНОРОДНОЙ ПЛАЗМЕ

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

Рассматриваются возбуждения кильватерных волн и динамика цилиндрических электронного и ионного сгустков в неоднородной плазме. Концентрация плазмы линейно возрастает вдоль траектории сгустка. В первой части работы представлено аналитическое решение задачи в приближении заданного тока. Для длинных сгустков из-за неоднородности плазмы разность фаз кильватерных волн, возбуждаемых передним и задним фронтами сгустка, изменяется вдоль траектории последнего, поэтому амплитуда кильватерной волны за сгустком испытывает пульсации. Результаты моделирования ионного сгустка хорошо совпадают с аналитическими расчетами, так как для него выполняется приближение заданного тока. Динамика электронного сгустка определяется кильватерным полем, которое возбуждает его передний фронт. В результате сгусток распадается на отдельные микросгустки, количество и характеристики которых определяются длиной кильватерной волны вблизи точки инжекции. Первый микросгусток лучше фокусируется в продольном и хуже – в радиальном направлении сравнительно с последующими. Как следствие, пространственные распределения кильватерного поля на оси системы и на периферии заметно отличаются.

ДИНАМІКА ЗАРЯДЖЕНИХ ЗГУСТКІВ В ПОЗДОВЖНЬО НЕОДНОРІДНІЙ ПЛАЗМІ

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

Розглядаються збудження кільватерних хвиль і динаміка циліндричних електронного та іонного згустків в неоднорідній плазмі. Концентрація плазми лінійно зростає вздовж траєкторії згустку. В першій частині роботи представлено аналітичний розв’язок задачі в наближенні заданого струму. Для довгих згустків через неоднорідність плазми різниця фаз кільватерних хвиль, збуджуваних переднім та заднім фронтами згустку, змінюється вздовж траєкторії останнього, тому амплітуда кільватерної хвилі за згустком зазнає пульсацій. Результати моделювання іонного згустку добре збігаються з аналітичними розрахунками, оскільки для нього виконується наближення заданого струму. Динаміка електронного згустку визначається кільватерним полем, яке збуджує його передній фронт. В результаті згусток розпадається на окремі мікрозгустки, кількість та характеристики яких визначаються довжиною кільватерної хвилі поблизу точки інжекції. Перший мікрозгусток краще фокусується в поздовжньому і гірше – в радіальному напрямку порівняно з наступними. Як наслідок, просторові розподіли кільватерного поля на осі системи і на периферії помітно відрізняються.