STRUCTURES' FORMATION IN INHOMOGENEOUS PLASMA EXCITED BY THIN MODULATED ELECTRON BEAM

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

Interaction of thin modulated electron beam with inhomogeneous non-isothermal plasma is studied using 2D PIC electrostatic simulation. On the early stage of interaction intensive HF oscillations of electric field are observed in local plasma resonance region. Pondermotive force of these oscillations disturbs an initial profile of plasma density. On the later stage of interaction ring-like pulse of plasma density propagates out of the resonance region. Velocity of this pulse depends on its intensity and exceeds the ion sound velocity. This fact demonstrates the nonlinear nature of the pulse.

PACS: 52.35.Sb, 52.65.R

1. INTRODUCTION

Excitation of resonance regions in the inhomogeneous plasma is a subject of intensive research during last decades [1]. This topic closely relates to such applications as transillumination of plasma barriers, plasma diagnostics, construction of UHF generators and amplifiers of direct radioemission etc.

Experiment [2] demonstrated that in region of resonant interaction a cavity of plasma density was formed. There are two different mechanisms that can cause this effect. In the first case pondermotive force presses plasma out of the region of intensive inhomogeneous HF electric field [3]. An ambipolar electric field appears in this case due to the difference in electron and ion masses.

The second scenario is a self-focusing of HF electric field in plasma cavity. Theoretically this process is described by Zakharov equations, firstly reported in [4].

Nonlinear terms of hydrodynamic equations for ion fluid were taken into account in [5] in order to prove the existence of ion-sound solitons in plasma with hot electrons. These solitons are of KdV type that means the dependence of velocity of soliton on its amplitude. Experimental observation of these phenomena was reported in [6].

Propagation of ion sound solition in the inhomogeneous plasma was investigated by means of perturbation theory and by numerical integration in [7]. It was shown that in the inhomogeneous media a solitary wave irreversibly losses its energy due to the formation of trail pulses behind it.

1D PIC simulation of the modulated electron beam with the local plasma resonance region was studied in [8]. Cavity formation was observed. This effect terminates intensive excitation of the Langmuir waves in the resonance region. Late stage of interaction differs for isothermal plasma and plasma with hot electrons. For the first case the step of plasma density is formed, for the second one quasi-periodical generation of ion-sound pulses is observed.

2D PIC simulation showed that thin modulated electron beam excites a strong HF electric field in the local plasma resonance region of inhomogeneous plasma. Pressure of this field causes a deformation of initial plasma profile.

This report presents the results of PIC simulation of interaction of thin modulated electron beam with inhomogeneous non-isothermal plasma. The focus of the work is on evolution of disturbed plasma profile.

2. PIC CODE AND SIMULATION PARAMETERS

Simulation was performed using 2-dimensional electrostatic PIC code [9]. Thin modulated electron beam was injected into rectangular volume filled with non-isothermal plasma with initially linear density profile. Parameters of simulation are shown in Table 1.

Table 1

Length of the simulation region, m	0.6
Width of the simulation region, m	0.1
Plasma density (x=0.3 m), m^{-3}	$3.2\cdot10^{14}$
Mass of ions, m_e	1836
Temperature of electrons, eV	2.0
Temperature of ions, eV	0.15
Initial beam width, m	0.01
Beam velocity, m/s	$3.0\cdot10^{7}$
Frequency of beam modulation, s^{-1}	$1.0\cdot10^{9}$
Initial beam density, m^{-3}	$1.0\cdot10^{12}$
Modulation depth of the beam	100%
Grid size	2048×256
Time step, s	$5.0\cdot10^{-11}$
Number of big particles	$1.0\cdot10^{7}$

Zero boundary conditions of Dirichlet type (electric potential is 0) are applied on the left and right boundaries $x = const$, and periodic boundary conditions are applied on the top and bottom boundaries $y = const$.

These boundary conditions allow us to simulate beam-plasma interaction in quasi-1D geometry. We can also assume that beam-plasma interaction will not change qualitatively after imposing of Dirichlet type conditions on all boundaries.

3. SIMULATION RESULTS

The early stage of interaction ($0<t<3T_i$, T_i – period of plasma ions' oscillations) of thin modulated electron beam with inhomogeneous plasma was investigated. Intensive HF oscillations of electric field were observed in resonance region. Under the action of pondermotive force initial density profile of plasma was disturbed. Results of simulations of the late stage of interaction ($3T_i<t<8T_i$) is presented in this section.

3.1. DYNAMICS OF DENSITY PERTURBATION

Space-time dependencies of electric field (a) and perturbation of plasma density (b) on the axis of the system (y = 0.05 m) are shown on the Fig.1. One can see that intensive HF electric field is excited in the resonance region on the early stage of interaction. After that it decays rapidly at time $t = (1\text{-}2)T_i$. This effect is caused by deformation of initial plasma profile which takes place at the same time under the action of pondermotive force (compare Fig.1,a,b). Similar effects for 1D simulation were studied in [8].

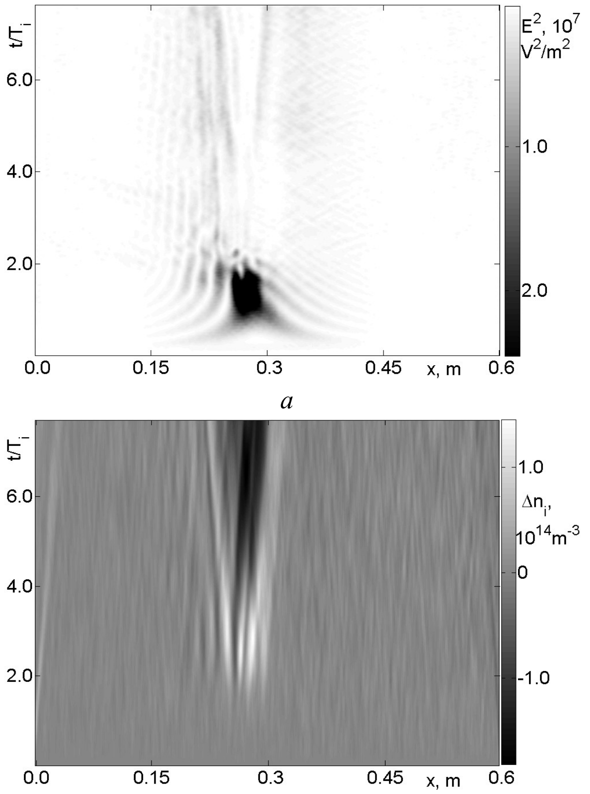

Fig.1. Dependencies of intensity of electric field (a) and perturbation of ions' density (b) on the axis of the system on time

Intensity of electric field changes quasi-periodically along the system axis at time $t = 2T_i$. This field pattern can be interpreted as interference between the incident wave of beam current and backward Langmuir wave.

Plasma density perturbation is formed in accordance with the distribution of electric field intensity. One can see that minima of density perturbation correspond to maxima of electric field on the early stage of interaction. Similar dependencies for electric field and plasma density perturbation were also observed in 1D simulation [8]. At time interval $2T_i<t<8T_i$ perturbation of plasma density evolves without intensive electric field in the system.

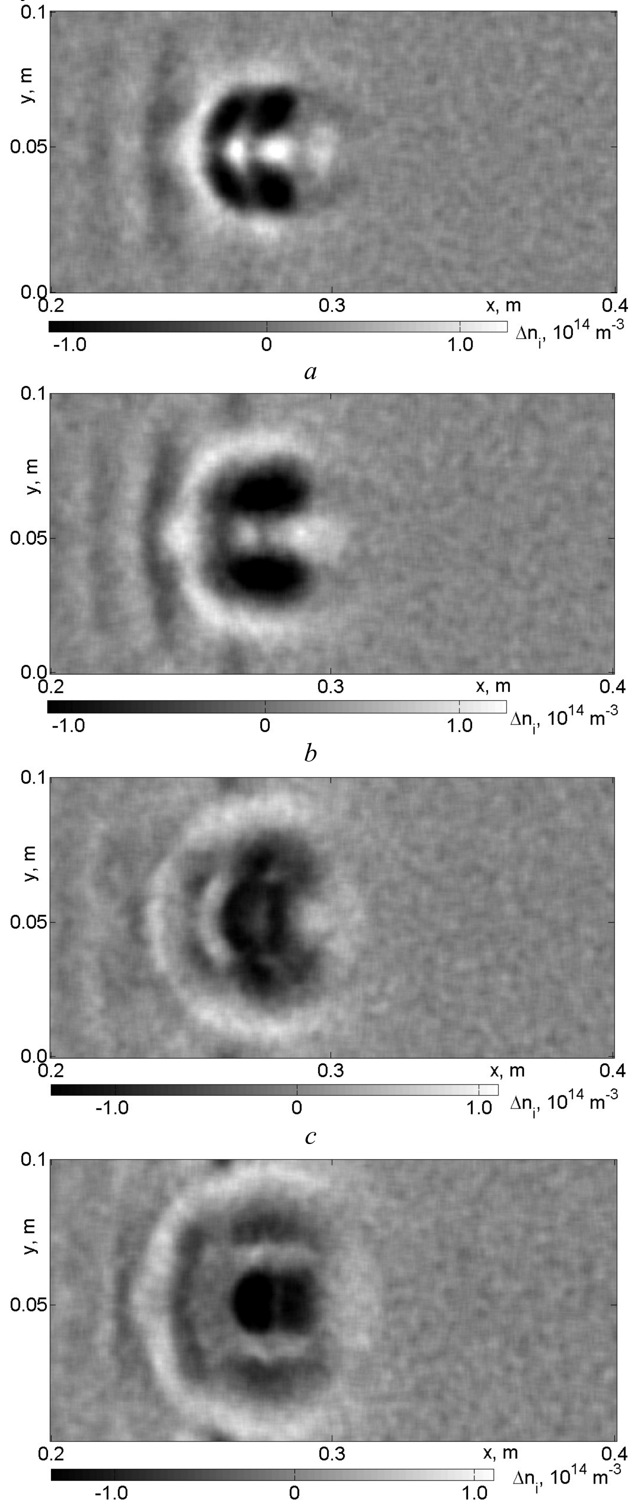

Fig.2. Spatial distributions of ions' density perturbation for time moments a) t_1=2.3T_i; b) t_2=3.5T_i; c) t_3=4.6T_i; d) t_4=7.0T_i

Spatial distributions of ions' density perturbation are shown on Fig.2,a-d for different time moments. One can see that at the time moment t=2.3T_i, right after the fading of electric field in the resonance region, perturbation of plasma density is a cavern edged by dense plasma

(Fig.2,a). There are a few "islands" of dense plasma inside the cavern.

Plasma density perturbation around the cavern propagates into unperturbed plasma as ring-like pulse (Fig.2,b-d). Velocity of this pulse is $v_{i,exp}$=2.1·10^5 m/s. This value exceeds the ion sound velocity for the parameters of simulation $c_s = (k_b T_i/m_e)^{1/2}$ =1.6·10^5 m/s. Further discussion of this phenomenon follows in Sect. 3.2.

Islands of dense plasma inside the cavern evolve along with the outer pulse. One can assume that this is a diffusive process. As a result the second ring-like pulse is formed (Fig.2,d). Propagation of pulses of dense plasma from the region of intensive beam-plasma interaction was earlier observed in 1D PIC simulations [8].

3.2. EXCITATION OF SOLITARY WAVES IN INHOMOGENEOUS PLASMA BY THE THIN MODULATED ELECTRON BEAM

The fact that the velocity of observed ring-like pulse is higher than that of ion sound can point on its nonlinear nature. As was discovered in [5] solitary waves of KdV type can exists in plasma with cold ions. Velocity of these waves linearly increases with their amplitude.

A series of numerical experiments was performed to verify this for our system. The dependence of velocity of pulse on its amplitude is presented in Table 2.

Table 2

Wave amplitude $\delta n/n_0$	Velocity of pulse, v/c_s
0.05	1.0
0.5	1.4
0.8	1.7

The first line in Table 2 corresponds to ordinary ion sound waves. Other two lines correspond to solitons of different amplitudes. One can see that observed dependence is linear as predicted by the theory.

Note that true KdV solitons exist for 1D model only. In our case the wave amplitude decreases with the growing of the ring radius, so non-linear effects take place not far from the source of this wave.

3.3. ELECTRIC FIELD IN THE SYSTEM ON THE LATE STAGE OF INTERACTION

Electric field doesn't disappear completely after the deformation of the initial density profile as one can see from Fig.1,a. But on the late stage of interaction it exists mostly outside the resonance region. Spatial distributions of ion concentration (a) and field intensity (b) at time moment t=4.4T_i are shown on Fig.3. One can see that electric field appears as a number of localized bursts. These bursts appear in depressions of plasma concentration as one can see from comparison of Fig.3,a,b.

The size of all bursts in x direction is about L_b~1.2cm. Plasma density in regions of bursts' localization is $n_{p,bur}$~2.9·10^{14} m^{-3}. The length of the corresponding Langmuir wave of frequency ω_0 that propagates in plasma with density $n_{p,bur}$ is λ_L~2.1 cm. Thus $L_b \sim \lambda_L/2$ and one can conclude that bursts of electric field appear due to the excitation of ground state of plasma depression which can be treated as an open resonator. This process is relevant to the nucleation stage of Langmuir collapse [10]. Therefore the field bursts can be treated as an excitation of localized plasma states [10].

Field distribution depicted on Fig.3 is not stationary. Bursts appear and disappear in accordance to the current distribution of plasma density.

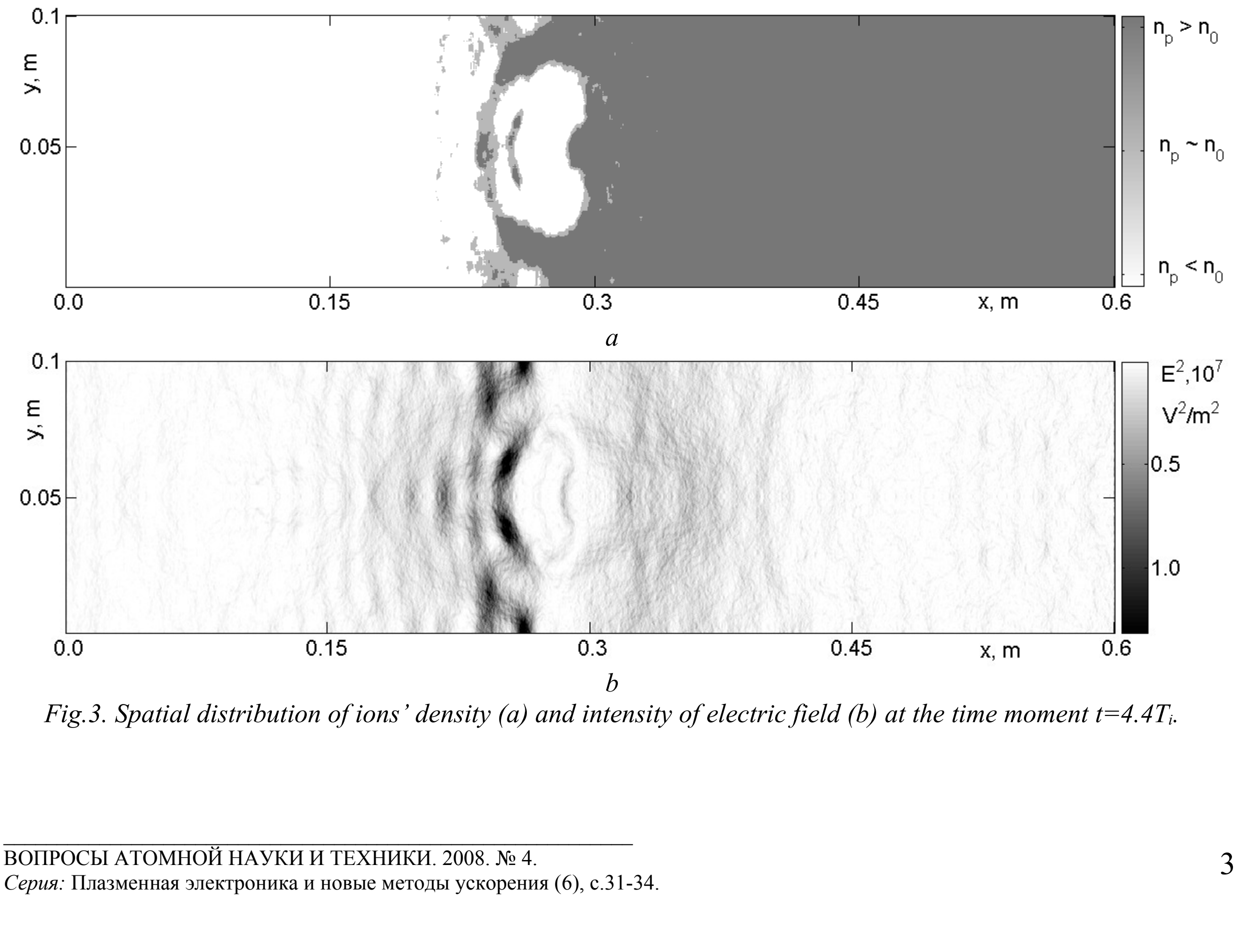

Fig.3. Spatial distribution of ions' density (a) and intensity of electric field (b) at the time moment t=4.4T$_i$.

CONCLUSIONS

1. Resonance interaction of modulated electron beam with plasma can be divided on three stages: excitation of intensive HF electric field in resonance region, deformation of initial density profile of plasma under the action of this field and further evolution of this perturbation.

2. Due to the action of pondermotive force of the HF electric field on plasma a ring-like pulse of dense plasma is formed. This pulse is similar to soliton as its velocity depends on its amplitude.

3. On the late stage of interaction electric field in plasma exists as a number of localized bursts. These bursts have size about $\lambda_l/2$ and are excited in depressions of plasma concentration.

REFERENCES

1. M.V. Kuzelev, A.A. Rukhadze, P.S. Strelkov. *Plasma Relativistic Microwave Electronics*. Moscow: "N.E. Bauman MGTU Publishing House", 2002 (in Russian).
2. H.C. Kim, R.L. Stenzel, A.Y. Wong. Development of "cavitons" and trapping of rf field // *Phys. Rev. Lett. (33)*. 1974, №15, p.886-889.
3. G.J. Morales, Y.C. Lee. Generation of density cavities and localized electric fields in a nonuniform plasma // *Phys. Rev. Lett. (33)*. 1974, №17, p.1016-1019.
4. V.E. Zakharov. Collapse of Langmuir waves // *Zh. Eksp. Teor. Fiz. (62)*. 1972, №5, p.1745-1758 (in Russian).
5. H. Washimi, T. Taniuti. Propagation of ion-acoustic solitary waves of small amplitude // *Phys. Rev. Lett. (17)*. 1966, №19, p.996-998.
6. H. Ikezi, R.J. Taylor, D.R. Baker. Formation and interaction of ion-acoustic solitons // *Phys. Rev. Lett. (25)*. 1970. №1, p.11-14.
7. K. Ko, H.H. Kuehl. Korteweg-de Vries soliton in a slowly varying medium // *Phys. Rev. Lett. (40)*. 1978, №4, p.233-236.
8. I.O. Anisimov, O.I. Kelnyk, T.V. Siversky, S.V. Soroka. Interaction of the modulated electron beam with inhomogeneous plasma: plasma density profile deformation and Langmuir waves excitation // *Problems of Atomic Science and Technology. Series "Plasma physics" (11)*. 2005, №2, p.122-124.
9. I.O. Anisimov, T.Eu. Litoshenko. 2D electrostatic simulation of the modulated electron beam interaction with inhomogeneous plasma // *Problems of Atomic Science and Technology. Series "Plasma physics" (12)*. 2006, №6, p.175-177.
10. P.A. Robinson. Nonlinear wave collapse and strong turbulence // *Rev. Mod. Phys. (69)*. 1997, №2, p.507-573.

Статья поступила в редакцию 08.05.2008 г.

ФОРМИРОВАНИЕ СТРУКТУР В НЕОДНОРОДНОЙ ПЛАЗМЕ, ВОЗБУЖДАЕМОЙ ТОНКИМ МОДУЛИРОВАННЫМ ЭЛЕКТРОННЫМ ПУЧКОМ

Т.Е. Литошенко, И.А. Анисимов

Взаимодействие тонкого модулированного электронного пучка с неоднородной неизотермической плазмой исследуется с помощью двумерного электростатического метода крупных частиц в ячейках. На начальном этапе взаимодействия интенсивные ВЧ-колебания электрического поля наблюдаются в области локального плазменного резонанса. Пондеромоторная сила этих колебаний возмущает начальный профиль плотности плазмы. На следующем этапе взаимодействия кольцеобразный импульс концентрации плазмы распространяется от резонансной области. Скорость этого импульса зависит от его интенсивности и превышает скорость ионного звука. Это указывает на нелинейную природу импульса.

ФОРМУВАННЯ СТРУКТУР В НЕОДНОРІДНІЙ ПЛАЗМІ, ЗБУДЖУВАНІЙ ТОНКИМ МОДУЛЬОВАНИМ ЕЛЕКТРОННИМ ПУЧКОМ

Т.Є. Літошенко, І.О. Анісімов

Взаємодія тонкого модульованого електронного пучка з неоднорідною неізотермічною плазмою досліджується за допомогою двовимірного електростатичного методу великих частинок в комірках. На початковому етапі взаємодії інтенсивні ВЧ-коливання електричного поля спостерігаються в області локального плазмового резонансу. Пондеромоторна сила цих коливань збурює початковий профіль густини плазми. На наступному етапі взаємодії кільцеподібний імпульс густини плазми поширюється від резонансної області. Швидкість цього імпульсу залежить від його інтенсивності і вища за швидкість іонного звуку. Це вказує на нелінійну природу імпульсу.