Structures' Formation in Inhomogeneous Plasma Excited by Thin Modulated Electron Beam

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Interaction of a thin modulated electron beam with inhomogeneous non-isothermal plasma is studied using 2D PIC electrostatic simulation. On the early stage of the interaction intensive HF oscillations of the electric field are observed in the local plasma resonance region. The ponderomotive force of these oscillations disturbs the initial profile of plasma density.

On the later stage of the interaction a ring-like pulse of the 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.

Keywords: modulated electron beam, inhomogeneous plasma, ponderomotive force, nonlinear structures.

1. Introduction

Excitation of resonance regions in the inhomogeneous plasma has been 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, amplifiers of direct radioemission etc.

Experiment [2] demonstrated the formation of a plasma density cavity in the region of the resonant interaction. There are two different mechanisms that can cause this effect. In the first case the ponderomotive force presses plasma out of the region of the 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 mechanism is a self-focusing of the HF electric field in the plasma cavity. Theoretically this process is described by Zakharov equations, originally reported in [4].

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

Propagation of the ion-sound soliton 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 allowed observing the cavity formation [8]. This effect terminates excitation of the Langmuir waves in the resonance region. The late stage of the 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 [9] showed that thin modulated electron beam excites a strong HF electric field in the local plasma resonance region of the inhomogeneous plasma. Pressure of this field causes a deformation of the initial plasma profile. Only cavity formation stage is reported in [9].

The effect of the deformation of a plasma density profile by the HF electric field pressure was observed experimentally in [10]. The resonance region of the inhomogeneous plasma was excited by an electromagnetic wave. It was shown that pulses of plasma density propagate from the resonance region upward and downward the gradient of density.

In this report we present the results of PIC simulation of interaction of thin modulated electron beam with inhomogeneous non-isothermal plasma. The evolution of the disturbed plasma profile is in the focus of the work.

2. PIC code and simulation parameters

Simulation was performed using the 2-dimensional electrostatic PIC code [10]. The thin modulated electron beam was injected into a rectangular volume filled with the non-isothermal plasma with initially linear density

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profile. Parameters of the simulation were chosen similar to experiments [11, 12] (see Table 1).

Table 1. Parameters of simulated beam-plasma system.

Length of the simulation region, m	0.6
Width of the simulation region, m	0.1
Plasma density (x=0.3m), m^{-3}	$3.2{\cdot}10^{14}$
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	$3.0{\cdot}10^{7}$
Frequency of beam modulation, s^{-1}	$1.0{\cdot}10^{9}$
Initial beam density, m^{-3}	$1.0{\cdot}10^{12}$
Modulation depth of the beam	100%
Grid size	2048x256
Time step, s	$5.0{\cdot}10^{-11}$
Number of big particles	$1.0{\cdot}10^{7}$

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 the 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 the interaction ($0<t<3T_i$, where T_i is a period of plasma ions' oscillations) of a thin modulated electron beam with an inhomogeneous plasma was investigated in [9]. Intensive HF oscillations of electric field were observed in the resonance region. Under the action of the ponderomotive force the 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

The space-time dependencies of the electric field (a) and the perturbation of plasma density (b) on the axis of the system (y = 0.05m) are shown in Fig.1. One can see that the intensive HF electric field is excited in the resonance region on the early stage of the interaction. After that it decays rapidly and is $E^2 < 1.0{\cdot}10^7$ V^2/m^2 at time $t = 2.0T_i$. This effect is caused by the deformation of the initial plasma profile which leads to the violation of the resonance condition. Similar effects were observed with 1D simulation [8].

The intensity of the electric field has the quasi-periodic dependence on x coordinate along the system axis at time $t = 2T_i$. This field pattern can be interpreted as an interference between the incident wave of the beam current and the backward Langmuir wave (well known Airy pattern, see e.g. [13]).

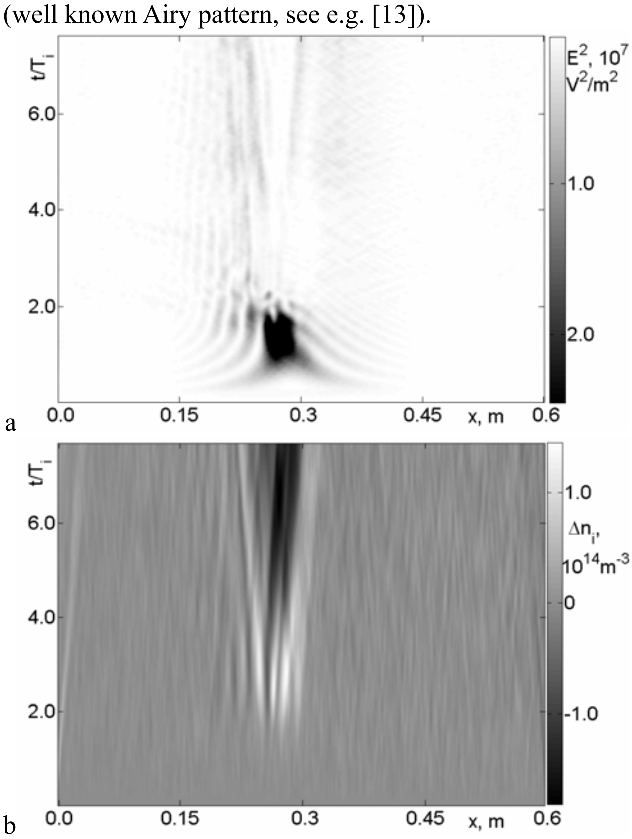

Fig. 1. The spatiotemporal dependencies of the intensity of the electric field (a) and the perturbation of ions' density (b) on the axis of the system.

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

The spatial distributions of the ion density perturbation are shown in Fig. 2a-d for different time moments. One can see that at the time moment $t=2.3T_i$, right after the fading of the electric field in the resonance region, the perturbation of plasma density is a cavern, which is edged by dense plasma (Fig. 2a). There are a few "islands" of dense plasma inside the cavern.

The plasma density perturbation around the cavern propagates into unperturbed plasma as ring-like pulse (Fig. 2b-d). The velocity of this pulse is $v_{i,exp}=2.1{\cdot}10^4$ m/s. This value exceeds the ion sound velocity for the parameters of simulation $c_s = (k_bT_e/m_i)^{1/2} = 1.4{\cdot}10^4$ m/s. Further discussion of this effect continues in Sec. 3.2.

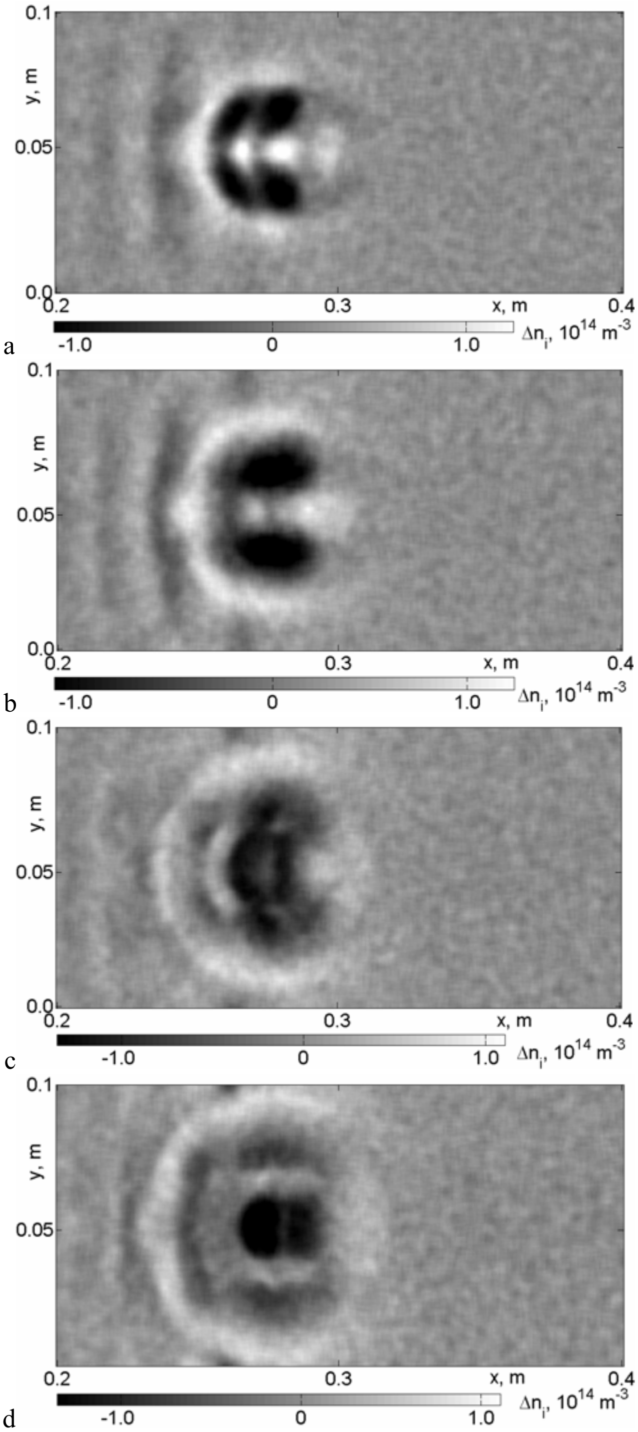

Fig. 2. Spatial distributions of ions' density perturbation for time moments a) t_1=2.3T_i; b) t_2=3.5T_i; c) t_3=4.6T_i; d) t_4=7.0T_i.

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

3.2. Excitation of solitary waves in an inhomogeneous plasma by the thin modulated electron beam

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

Table 2. The dependence of the velocity of the pulse on its amplitude.

Wave amplitude $\delta n/n_0$	Velocity of pulse, v/c_s
0.05	1.0
0.5	1.5
0.8	1.7

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

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

Note that the true KdV soliton exists for 1D model only. In our case the wave amplitude decreases with growth 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

The electric field does not disappear completely after the deformation of the initial density profile as one can see from Fig. 1a. But on the late stage of the interaction it exists mostly outside the resonance region. The spatial distributions of ion concentration and field intensity at the time moment t=4.4T_i are shown in Fig. 3. One can see that the electric field has a form of a number of localized bursts appearing in the depressions of plasma concentration (Fig. 3a and 3b).

The size of all bursts in x direction is about L_b~1.2cm. The plasma density in the regions of bursts' localization is $n_{p,bur}$~2.9·10^{14} m^{-3}. The Langmuir wave of frequency ω_0 that propagates in plasma with density $n_{p,bur}$ has the wavelength λ_L~2.1cm. Thus L_b~λ_L/2 and one can conclude that the bursts of the 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 [13]. The field bursts can be treated also as an excitation of localized plasma states [13].

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

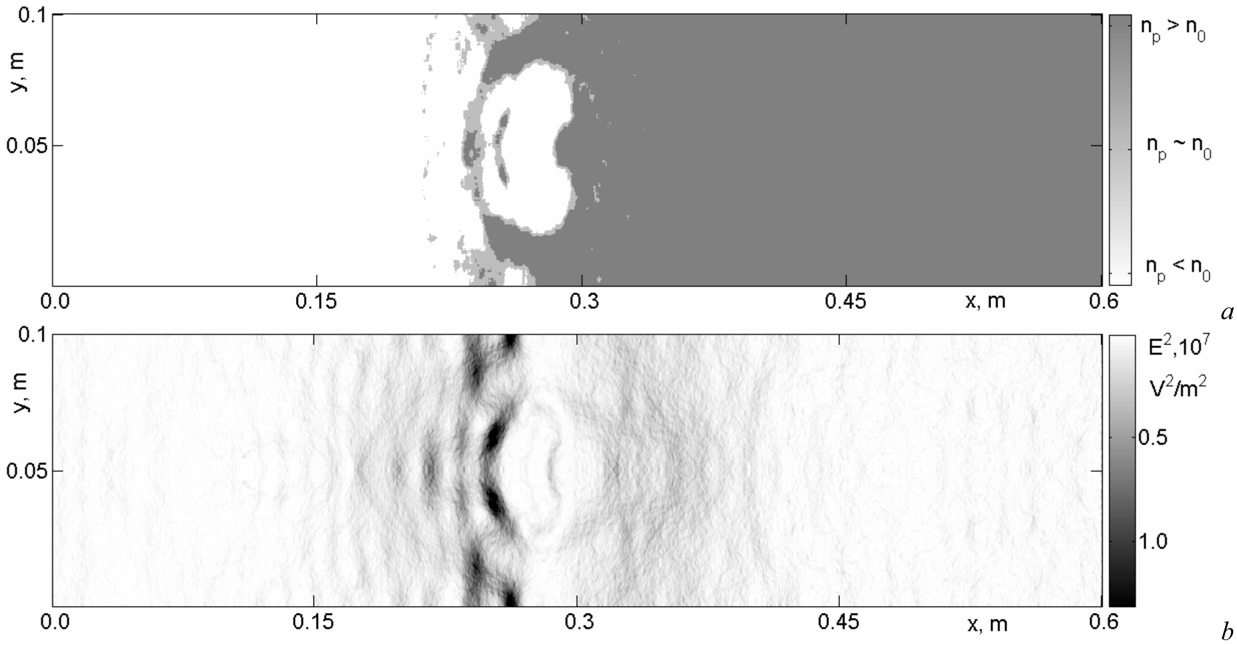

Fig. 3. The spatial distribution of the ion density (a) and the intensity of the electric field (b) at the time moment t=4.4T_i.

4. Conclusions

1. The resonant interaction of modulated electron beam with plasma can be divided into three stages: excitation of a HF electric field in the resonance region, deformation of the initial density profile of plasma under the action of this field and further evolution of this perturbation.
2. Due to the action of the pondermotive force of the HF electric field on plasma a ring-like pulse of dense plasma is formed. This pulse is similar to soliton, because its velocity depends on its amplitude.
3. On the late stage of the interaction the electric field in plasma exists as a number of the localized bursts. These bursts have size about $\lambda_L/2$ and are excited in depressions of plasma concentration.

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