DEFORMATION OF THE PLASMA CONCENTRATION PROFILE DUE FIELD OF THE MODULATED ELECTRON BEAM: NUMERICAL SIMULATION

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Deformation of the concentration profile of the weakly inhomogeneous plasma due to the modulated electron beam was studied via computer simulation using big-particles-in-cells method. At the first stages the electric field increase in the local plasma resonance region was observed. It resulted to the density cavity formation. For the isothermic plasma the density cavity transformed into the plasma concentration jump. For plasma with the hot electrons ion-acoustic turbulence was observed at the late time points.
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1. INTRODUCTION

Deformation of the plasma concentration profile due to the field of the incident electromagnetic wave was often discussed (see, e.g., [1-2]). For the obliquely incident *p*-polarized waves of the moderate power the concentration profile deformation occurs mainly in the local plasma resonance region (LPRR). It has a form of the quasi-periodical generation of the density cavities [1] or formation of the sharp concentration jump [2]. Similar effects were predicted in [3] for the field excited by modulated electron beam moving through the inhomogeneous plasma. This problem was studied in [4-5] using numerical solution of the non-linear equations set for the electric field and plasma concentration. For this case problem was solved in the given beam current' approximation.

Deformation of the inhomogeneous plasma profile due to the field of the modulated electron beam is treated in this work. Numerical simulation was carried out using the big-particles-in-cells method [6-7] (i.e. self-consistent approximation) for one-dimensional model.

## 2. NUMERICAL SIMULATION METHOD AND PARAMETERS SELECTION

The program used for simulation is the modification of the PDP1 code [4], but it has some additional resource. It gives the possibility to introduce modulation of the electron beam velocity or density and inhomogeneity of the initial plasma concentration profile.

In our simulation the beam density was modulated sinusoidally with the depth of 100%. The beam current and velocity v_0 as well as the characteristic inhomogeneity length L were selected so that the charge density profile in LPRR did not differ strongly from the sinusoidal shape (fig.1).

After the beam passage through LPRR significant deformation of the electron bunches' profile did not occur. This result justifies the validity of the given current approximation for this problem that was used in [4-5].

Initial concentration profile was linear. Concentration varied from $0.5n_c$ to $1.5n_c$ (n_c is the critical electron concentration for the beam modulation frequency). Thus LPRR was placed in the middle of the simulation region. Mass of the plasma ions was selected so that characteristic time of the ion concentration profile deformation did not exceed the time of simulation (a few hundreds periods of Langmuir oscillations). Ions of hydrogen satisfy this condition.
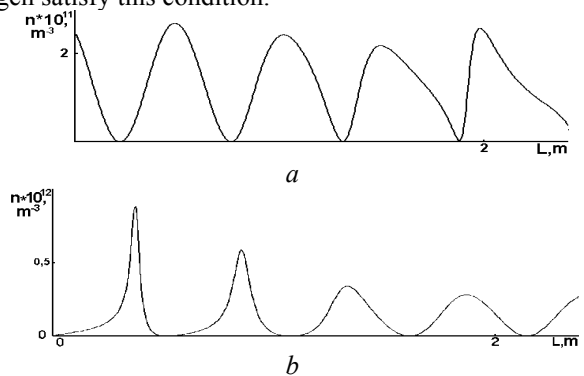
Fig.1. Space distribution of the beam electrons' concentration in the steady-state regime for L=2.5m, ω/2π =1.3·10⁸Hz, |v₀|=7·10⁷m/s, Tₑ=25eV: a − v₀>0; b − v₀<0

Both cases of the beam velocity sign ($v_0>0$ – beam moving into the dense plasma and $v_0<0$ – beam moving from the dense plasma) were studied. Simulation was carried out for isothermic plasma ($T_e=T_i$) and plasma with hot electrons ($T_e>>T_i$).

3. FIELD EXCITATION AT THE INITIAL TIME POINTS

At the initial time points after the injection start the space periodicity and motion direction of the electric field wave are similar to the current wave of electron beam (Fig.2).

However after some time periods of modulation the space period of electric field starts decreasing while its magnitude in the LPRR gradually increases. Field spatial distribution is symmetrical relatively to the LPRR for these time points. The field magnitude in LPRR increases during some units or some tens of the modulation periods. The increase time is directly proportional to the plasma inhomogeneity length and inversely proportional to the thermal velocity of the plasma electrons. The field increase can be non-monotonic (in agreement with the calculation [8]).

Later the spatial field distribution is modified. Periodic oscillations in supercritical plasma disappear. In the subcritical plasma Langmuir wave is formed moving
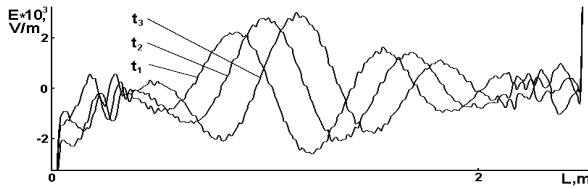
Fig.2. Time evolution of the electric field spatial distribution at the initial time points after the injection start ($v_0>0$, $f \cdot t_1 \approx 6$; $t_1 < t_2 < t_3$)

out from the dense plasma. Oscillations in the LPRR have now the phase velocity directed antiparallelly to the beam velocity (Fig.3).
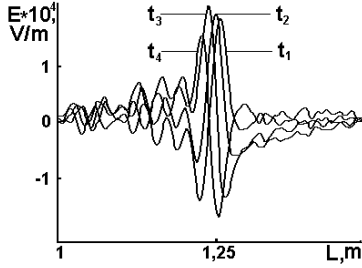

Fig.3. Space-time course electric field in LPRR ($v_0>0$, $f \cdot t_1 \approx 67$; $t_1 < t_2 < t_3 < t_4$)

In this case condition of the weak plasma inhomogeneity $k_0 L >> v_0^3/c v_{Te}^2$ (where $k_0 = \omega/c$, v_0 and v_{Te} are the beam velocity and thermal velocity of the plasma electrons respectively, L is the inhomogeneity size) is not satisfied. Therefore the simulation results do not depend sufficiently from the sign of the beam velocity [9-10].

At the late time points deformation of the ion concentration profile predicted in [3-5] was observed in the LPRR.

4. DEFORMATION OF THE CONCENTRATION PROFILE OF ISOTHERMIC PLASMA

Firstly the short-wave perturbation (in the scale of the LPRR width) appears. Instantaneous ion and electron concentration profiles strongly differ on this stage (Fig.4a). Later the density cavity is formed in this region (Fig.4b). Sometimes local maximum of the plasma concentration is observed in the center of the cavity (Fig.5).

In the isothermic plasma ($T_e = T_i$) at the late times points the density cavity is transformed. Its left border is smoothed (Fig.6a). At the same time its right border becomes like a step. It results to the cavity transformation into the plasma concentration jump (Fig.6b). This result agrees qualitatively with the calculation [2]. This calculation was carried out for the plasma concentration profile deformation due to the HF electric field (stationary case).

This concentration profile lasted out for the long period (the time of about some hundreds of the modulation periods). It indicates the balance between the plasma thermal pressure and the HF electric field excited in the LPRR by the modulated electron beam.

After the interval of about a thousand of the modulation periods the concentration profile is smoothened due to the diffusion. It results to the decrease of the concentration jump.

The case of the beam moving from the dense plasma was also examined. It does not differ significantly from the previous case (as well as the linear stage of the process).
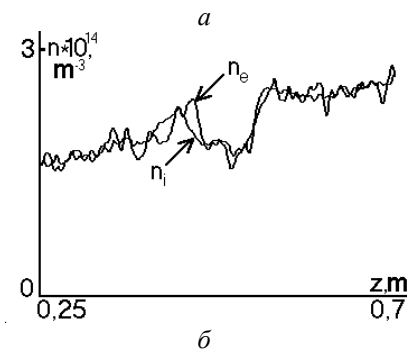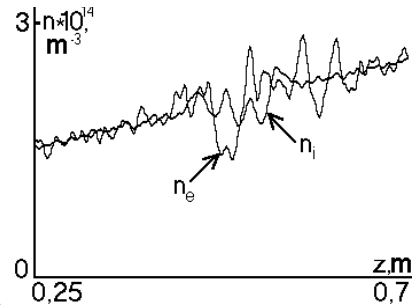

a

б

Fig.4: a – deformation of the ion concentration profile ($f \cdot t_1 \approx 65$); b – formation of the density cavity ($f \cdot t_1 \approx 120$). n_e, n_i is concentration of electron and ion respectively. $L=1m$, $T_e=6eV$
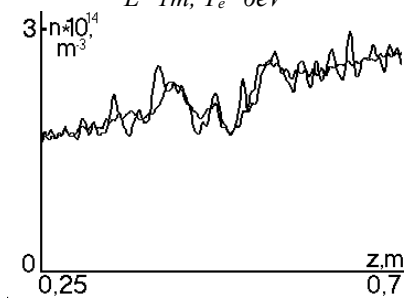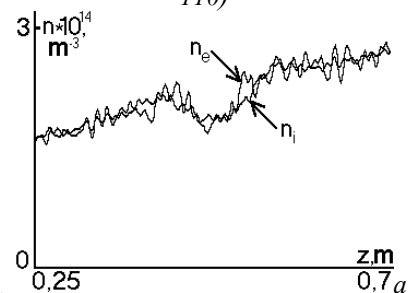

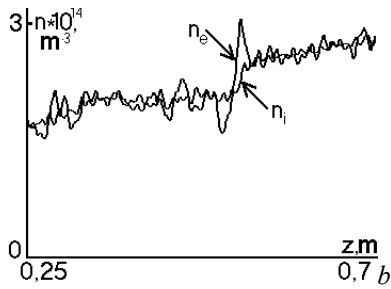*Fig.5. Local maximum in the center of the cavity ($f \cdot t_1 \approx 110$)*

a

Fig.6. L=2.5m, T_e=25eV: a – transformation of cavity (f·t_1≈143); b – forming of concentration jump (f·t_1≈195)

a

b

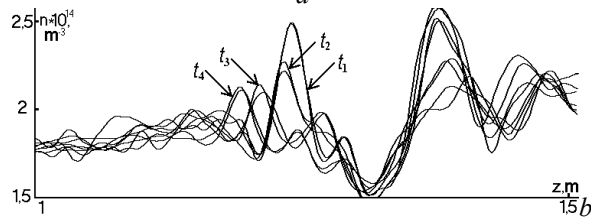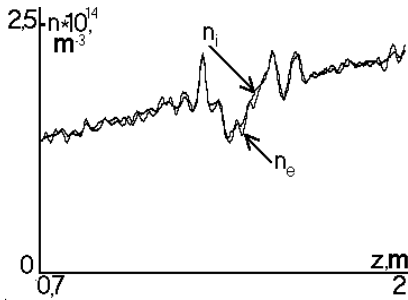*Fig. 7 a – excitation of ion-acoustic wave (f·t_1≈235),
b – motion of ion-acoustic wave ($t_4 > t_3 > t_2 > t_1$)*

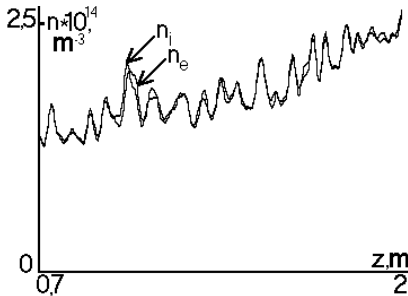*Fig.8. Plasma concentration profile for the late time points (f·t_1≈1650)*

5. DEFORMATION OF THE CONCENTRATION PROFILE OF PLASMA WITH HOT ELECTRONS

When the electron plasma temperature is considerably larger relatively to the ion temperature (plasma with hot electrons) the ion-acoustic type' perturbations propagated from the cavity are observed (Fig.7). This effect was predicted in [4] for the weakly non-linear regime. Velocity of these ion perturbations measured from the computer simulation was near to the ion-acoustic wave' velocity calculated for the simulation parameters. Electron concentration profile almost accurately repeats the ion concentration profile (Fig.7).

After the period of about two thousands of the modulation periods the ion concentration profile becomes strongly indented in the wide region around the local

plasma resonance point (Fig.8). This result may be explained by the ion-acoustic turbulence excitation.

6. CONCLUSION

1. Interaction of the modulated electron beam with the inhomogeneous plasma has been studied by means of computer simulation using big-particles-in-cells method.

2. The field in the local plasma resonance region excited by the modulated electron beam results to the deformation of the plasma concentration profile in this region. At the initial time points the density cavity is formed on the spot of LPRR.

3. Character of the plasma concentration profile on the spot of LPRR at the late time points depends strongly upon the relation of the temperatures of plasma electrons and ions. In the isothermic plasma ($T_e=T_i$) the density cavity is transformed into the plasma concentration jump. In the plasma with hot electrons the ion concentration profile becomes strongly indented in the wide region around the spot of LPRR due to the ion-acoustic turbulence excitation.

4. Quasi-periodical generation of the density cavities in the LPRR that was obtained in [2] due to homogeneous external HF field was not observed in this simulation.

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