Formation of charged particles' flows in the background plasma at the initial stage of the beam-plasma instability

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Interaction of electron beams with plasma is one of the most important problems of plasma physics. Most analytical studies of the beam-plasma instability paid the primary attention to instability mechanisms at the linear stage of the beam-plasma interaction [1]. Non-linear effects play an essential role in the beam-plasma interaction [2-4]. Background plasma nonlinearities were observed in numerous experiments. Among plasma nonlinearities one can mention, for instance, modular instability of the Langmuir waves, exited in plasma by the electron beam, and the following deformation of plasma density profile with the consequent collapse of cavities [5]. Kinetic effects, which accompany the development of beam-plasma instability, for instance, plateau formation on beam-plasma systems' distribution function [6], were also studied. However, kinetic effects in the background plasma, which take place during the development of beam-plasma instability, are not entirely studied.

The aim of the present work is to study the formation of background plasma charged particles' (both electrons and ions) flows at the initial stage of the beam-plasma instability via computer simulation. We consider the initial stage as the time period during which the significant deformation of ions' density profile is not observed; in other words, redistribution of plasma density doesn't lead to reverse influence on the HF-field distribution in plasma.

To study the formation of plasma particles' flows, one-dimensional computer simulation using modified package PDP1 [7] was carried out. Simulation was carried out for several beams' current densities for the given beams' velocity, and for three different beams' velocities for given current density.

Fig.1a,b presents instantaneous space distributions of plasma electrons' and ions' averaged velocities for the time point t=60Tp, correspondingly. These distributions were obtained via averaging over plasma period the averaged velocities of particles located in the small space interval Δx. As it is clear from Fig.1, at the initial stages of the beam-plasma instability plasma electrons are accelerated primarily in the direction of the beams' injector. At the same time, plasma ions are accelerated both to the injector and to the collector.

Fig.2 demonstrates space distributions of plasma electrons' averaged velocities, moving only to the right (Fig.2a) and only to the left (Fig.2b). Plasma electrons' averaged velocities distribution, presented on Fig.1a, is the sum of the distributions presented on Fig.2.

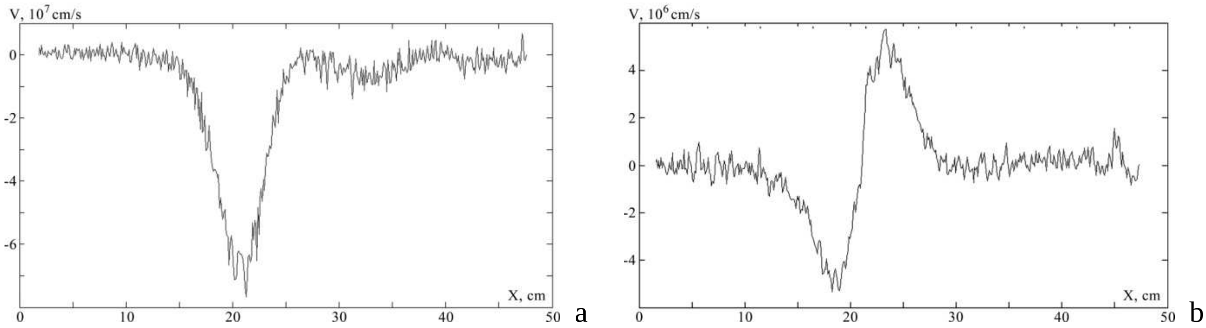

Fig. 1. Instantaneous space distributions of plasma electrons (a) and ions (b) averaged velocity, averaged over the plasma period, for the time point $t=60T_p$.

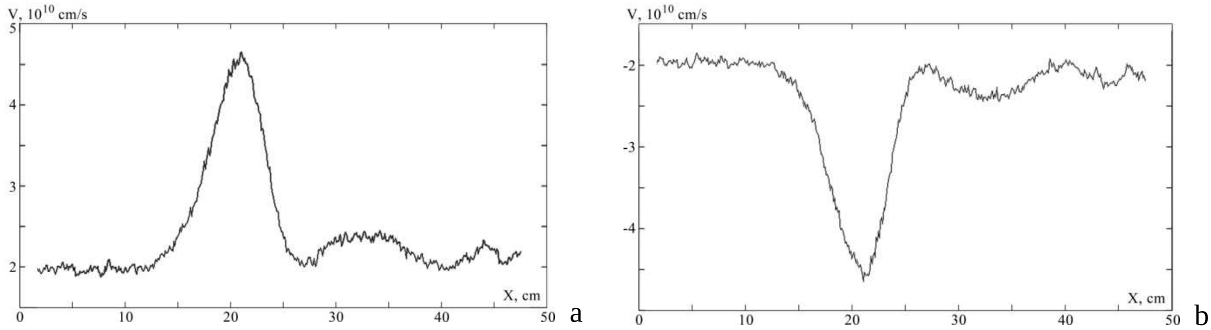

Fig. 2. Instantaneous space distributions of plasma electrons moving only to the right (a) and only to the left (b), for the time point t=60Tp.

To explain the reason of plasma electrons' flow formation, presented on Fig. 1a, we considered an instantaneous space distribution of electric field, exited by the electron beam, averaged over the plasma period, for the time point $t=60T_p$ (Fig.3). This distribution corresponds to the slow (in the time scale of plasma period) component of averaged electric field. Under the influence of negative field, plasma electrons are accelerated to the collector. Consequently they appear in the area of larger positive field, and finally they start to move to the beams' injector. Otherwise, negative field accelerates ions to the injector, and positive field – to the collector. Thus, electrons of the background plasma are accelerated to the injector, while ions are accelerated both to injector, and (primarily) to the collector.

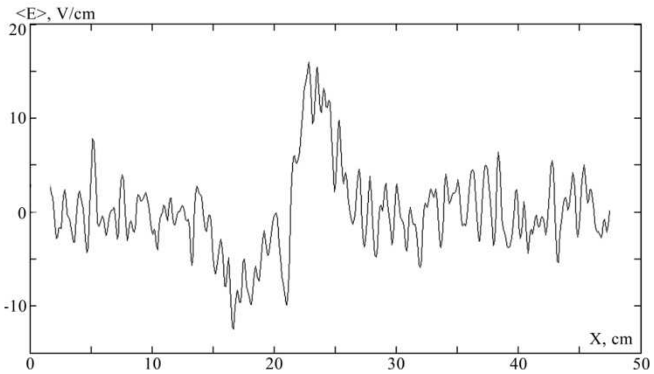

Fig. 3. Instantaneous space distribution of the electric field averaged over the plasma period for the time point t=60Tp, for the time point t=60Tp.

Spatial distribution of the quasi-stationary electric field allows to explain the formation of particles' flows in the background plasma (at least, at the qualitative level). Thereby, the electron beam, which is decelerated by the exited HF-electric field, indirectly transfers its impulse exactly to plasma ions.

The quasi-stationary electric field formation is a result of plasma electrical neutrality perturbation owing to the plasma electrons' extrusion from the area of intensive HF electric field (ponderomotive force) [8]. Instantaneous spatial distribution of HF electric fields' intensity, averaged over the plasma period, for the time point t=60Tp is presented on Fig.4a. Present mechanism is a first stage of background plasma striction nonlinearity development under the influence of inhomogeneous HF electric field, exited by the electron beam. At the next stage quasi-stationary electric field results to the redistribution of plasma ions' density, so quasi-neutrality breaking is restricted. As it is clear from Fig. 4a, HF electric fields' intensity gradient is larger from the side of collector comparing to its' gradient from the side of injector. Thus, the magnitude of corresponding electric field has to be larger, which is in good accordance with Fig. 3.

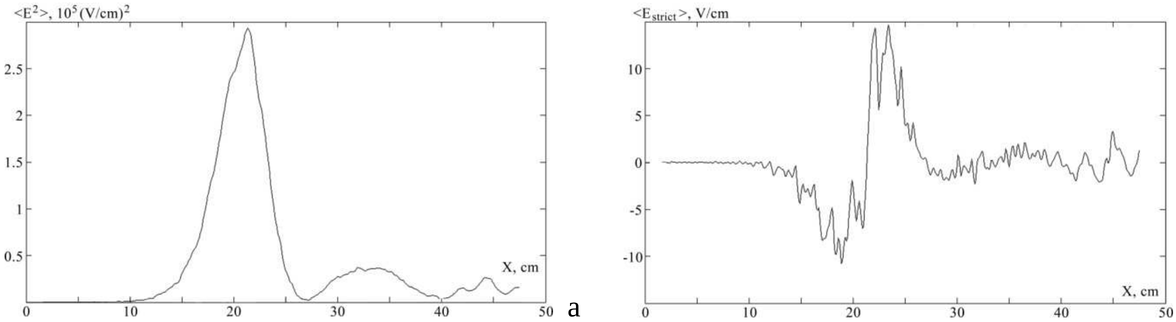

Fig. 4. a – Instantaneous spatial distribution of HF electric fields' intensity, averaged over plasma period, for the time point t=60Tp; b – instantaneous spatial distribution of striction field, caused by the gradient of HF electric fields' intensity for the time point t=60Tp.

Fig.4b demonstrates instantaneous spatial distribution of the striction field, averaged over the plasma period, for the time point t=60T_p. This field is related with the HF electric fields' intensity gradient by the expression:

$$E_{str} = \frac{e}{4m\omega_p^2}\frac{d}{dx}\left\langle E^2 \right\rangle,$$

where $\omega_p = 2\pi/T_p$ is the electron plasma frequency, $\left\langle E^2 \right\rangle$ is the HF electric field intensity, averaged over the plasma period. Comparison of Fig.4b and Fig.3 demonstrates that exactly the striction field makes the main contribution in the formation of quasi-stationary electric field, which results to the formation of plasma particles' flows. Asymmetry of the HF field intensity distribution results to the formation of the background plasma electrons' flow directed to the electron beam injector.

CONCLUSIONS

1. At the initial stages of the beam-plasma instability the flow of plasma electrons appears in the area of the intensive HF electric field. This flow is formed as the sum of two opposite flows, which appear due to the plasma electrons' oscillations in the potential well. The result flow is directed to the beams' injector (oppositely to the direction of the beam motion). In the same region the flows of plasma ions appear with both directions. Moreover, the ions' flow, directed along the electron beams' propagation direction, is more intensive.

2. The cause of plasma particles' flows formation is quasi-stationary electric field, which change its' direction in space. Area of negative field is located nearer the injector, while region of positive field is located further from the injector, and its' absolute value is larger.

3. Calculation shows that the cause of quasi-stationary electric field formation is plasma electrons' extrusion from the region of intensive HF electric field. Peculiarities of the quasi-stationary field space distribution are defined by the distribution of HF field intensity.

Preliminary results of this work are presented in [9-10].

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