NEUTRALIZATION OF LONG AND SHORT PULSE ION BEAMS

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Abstract

The results of computer simulations of time-dependent charge and current neutralization of high-current ion beams (IB) by cold electrons emitted from a plane to a half-space are presented. The cases of long and short injected ion pulses of sharp and linear current rise times are considered. It is shown that the system of cold electrons and ions passes to the same stationary state independent of the initial and boundary conditions.

Introduction

For the application of IB in inertial fusion research it is necessary to understand the physics of beam propagation through vacuum, low-pressure gases, plasma channels etc. [1-5]. One of the most simple and attractive schemes is the transport of IB in vacuum by neutralizing its charge and current with electrons emitted from the channel surface under the action of IB self-field.

Let us consider the simplest one-dimensional equilibrium model of IB neutralization. This model has been described in several articles [2-5] and here we shall recall only the main result.

Ion flow of current density J and kinetic energy W is injected through the plane at axial position $x = 0$ to the half-space $x > 0$. On the plane of zero potential there is a plasma of infinite emission capability – the source of electrons. If the velocity of ions is constant, then the potential distribution under the condition $d\Phi/dz(0) = 0$ may be written as

$$z = \sqrt{2}\left[-\sqrt{2\alpha\sqrt{\Phi} - \Phi} + \arcsin(\sqrt{\Phi}/\alpha - 1) + \pi\alpha(2k + 1)/2\right],$$

where $k = 0, 1, 2 \ldots$, $\Phi = e\varphi/W$. This solution describes periodic modulation of the electrostatic potential in space with period $2z_m = 2\sqrt{2}\pi$ and amplitude $\Phi_m = 4\alpha^2$. Here $\alpha = (J_e/J)\sqrt{m_e/m_i}$, $z^2 = 2x^2\omega_{pi}^2/v_i^2$ – nondimensional longitudinal coordinate, ω_{pi} – ion plasma frequency, J_e-current density of electron flow. It will be noted that the value of the parameter α is free for the case of half-space.

Computer simulation of IB neutralization

Kinetics of the neutralization has been investigated by means of computer simulation. Ions, thin sheets of a given velocity, were injected through the plane electrode. Electrons, infinitely thin sheets of zero initial velocity, start from the plane under the influence of the electric field of ion flow.

A number of electrons may be extracted from the plasma to yield the boundary condition of space-charge limited flow $E(0) = 0$ as the field of the sheets is independent of the distance to the injection plane. Below the results are given for initial velocity of ions equal to 0.05c. Nondimensional coordinate and time are measured in the units $x_o^2 = m_e c^3/eJ$ and $t_o = x_o/c$.

Calculations show that the influence of generated fields on the motion of ions is quite small if emission of electrons starts simultaneously with injection of ions. The results given below are for the case of ion flow of uniform density moving into the half-space with constant velocity. Such an approach allowed the field of ions to be calculated analytically.

Fig. 1 illustrates the longitudinal distribution of electron velocities (phase map) for the definite times indicated at the right, and the corresponding distributions of electron density, total, direct and back currents, electrostatic potential and the distribution function of electrons. The solid curve represents ion velocity and the end of the curve corresponds to pulse front of ion flow. These results are given for sharp rise-time of the ion current and are similar to results [2-4]. It will be noted that at the initial time the maps give the same results as for the stationary state provided $J_e = J$ and $v_{em} = 2v_i$.

These results show that thermalization of electron flow sets in practically instantaneously. For example, if the ion current density $J = 170$ A/cm^2 then the nondimensional time $T = 5$ is $t = 1.5$ ns in real time scale.

An first sight it seems that thermalization is due to oscillation of the single powerful virtual cathode at the front of ion flow. Such a mechanism was advocated in [2-4]. To check this assumption we repeated the calculation in the case of linear current rise-time (Fig.

2) up to T = 40. The time of thermalization is greater in this case, and the oscillating mode is conserved for a greater time. Blow-up of electron flow starts not from the front of ion flow but from the body, when several macroelectrons are reflected from the ion flow front and disturb a subcritical virtual cathode of sufficient power in the body of the flow. This virtual cathode explodes and the explosion expands to the left and to the right and leads to decay of the other subcritical virtual cathodes. Such a process results in the transition of the system consisting of two divided cold flows to a quasiuniform mixed system. Finally, the system goes over to a stationary state similar to the previous one in the case of a sharp ion front.

We considered the cases of long pulse ion beams of duration greater than time of thermalization. It is interesting to consider the neutralization of short ion bunches. These results are given in Fig. 3.

The phase maps for the times T = 2 and T = 6 are presented for the cases of triangular and constant density ion bunches of duration τ = 2. It is seen that the results are approximately similar to the previous ones, differing as to width of electron velocity distribution.

If a train of ion bunches is injected and the distance between the bunches is greater than the length of the bunches then their neutralization is independent of each other. The few interchange electrons do not appreciably influence the situation.

References

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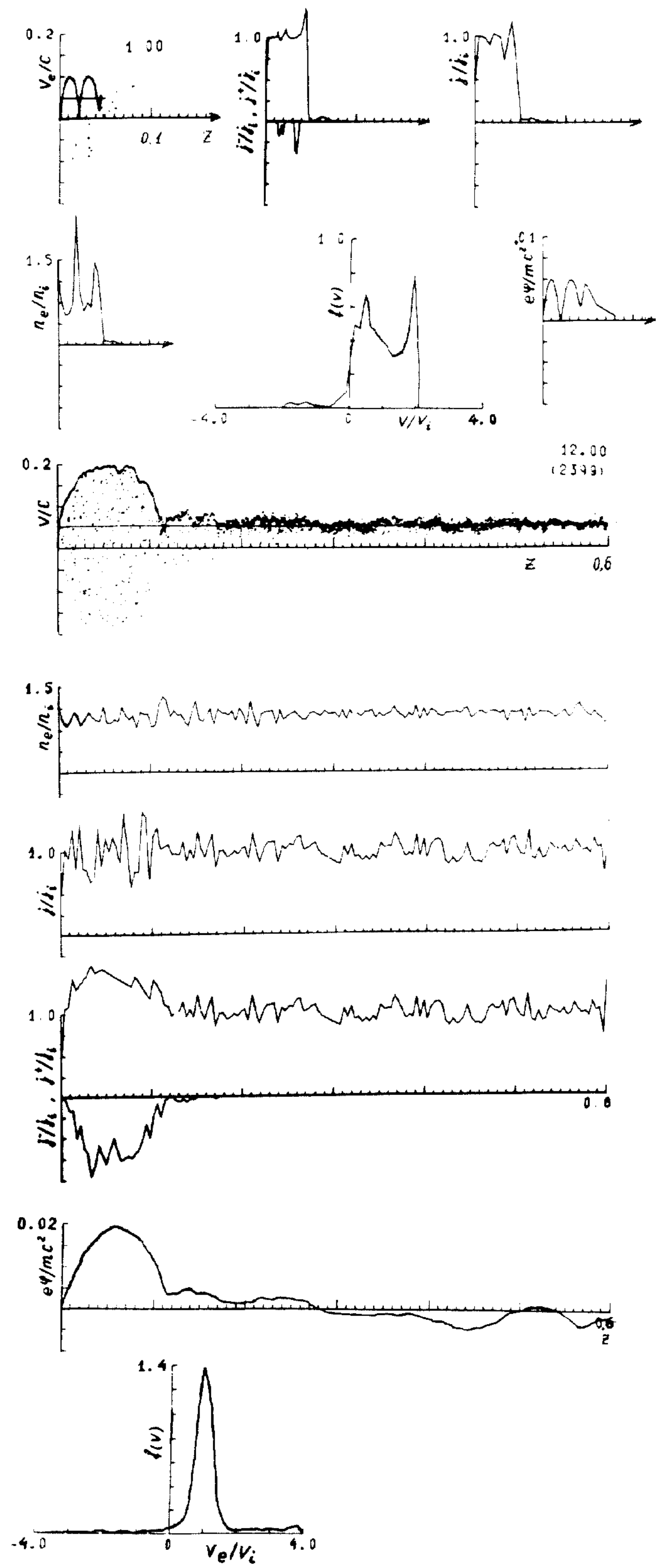
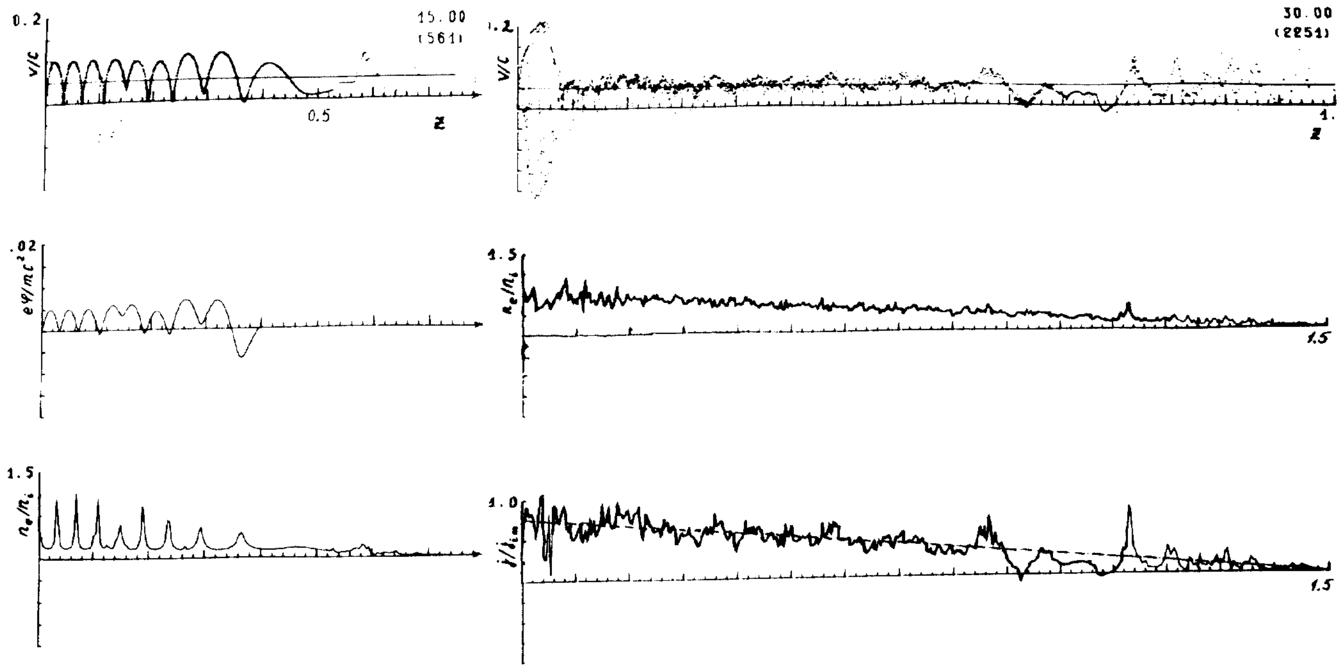


Fig. 1. Phase maps and the distributions of the indicated parameters at T = 1 and T = 12 in the case of ion beam with sharp front



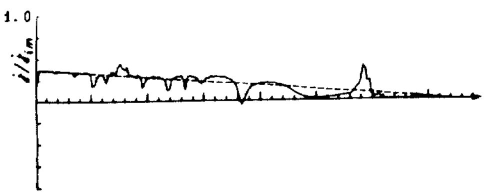


Fig. 2. Phase maps and the distributions of the indicated parameters at T = 15 and T = 30 in the case of ion beam with linear current rise time up to T = 40

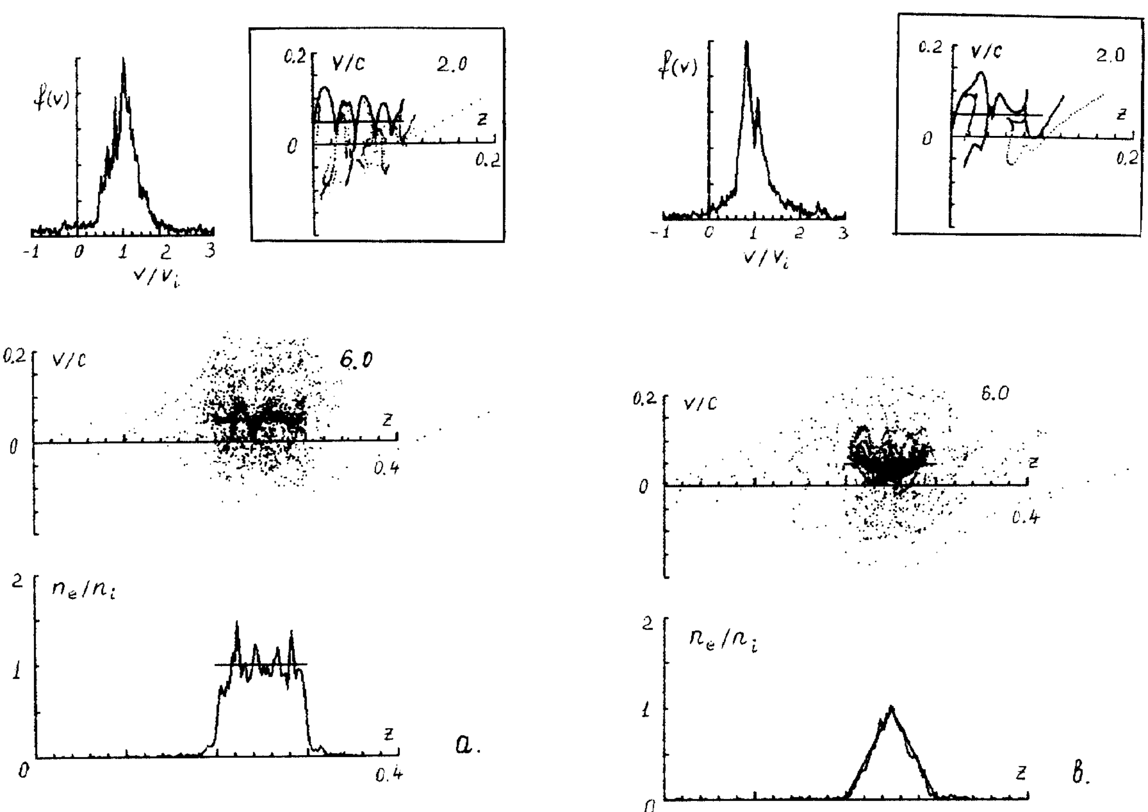


Fig. 3.