CHARGE AND CURRENT NEUTRALIZATION OF HIGH-CURRENT ION BEAMS

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The results of computer simulations of time-dependent charge and current neutralization of high-current ion beams (HIB) by cold electrons emitted from a plane to half-space and to a drift region are presented. The cases of injection of sharp and linear current rise times for time delayed emission and simultaneous emission of electrons relative to the time of injection of HIB, are considered. It is shown that the system of cold electron and ion flow passes to the same stationary state independent of the initial and boundary conditions. The main characteristics of this state are: the existence of a nearwall layer and a plasma column neutralized on the average in charge and current (in the case of the space) and in charge (in the case of drift region).

Introduction

For the application of HIB in inertial fusion research it is necessary to understand the physics of beam propagation through vacuum, low-pressure gases, plasma channels etc. [1-4]. One of the most simple and attractive schemes is the transport of HIB in vacuum by neutralizing its charge and current with electrons emitted from a surface of the channel under the action of the HIB self-field.

The results of experiments on the propagation of HIB in a vacuum with a longitudinal magnetic field [6] and without external fields [7] show close to 100% charge neutralization and quite high current neutralization of HIB by accompanying electrons. In the absence of an external magnetic field the net current of the electron-ion flow was less than 5% of the HIB current [7] and was greater than 50% in a longitudinal magnetic field [6], i.e., if the net charge was approximately equal to zero, then the velocity of electrons exceeded the velocity of ions in the latter case and was approximately equal to the ion velocity in the former. Evidently the longitudinal magnetic field does not let the flows to mix in the transversal direction.

Equilibrium State Model

Let us consider the simplest one-dimensional equilibrium model of HIB neutralization by cold electrons. This model has been described in several articles (see, for example, [3-5]) and here we shall recall only the main results.

Ion flow of current density J_i 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 possibility - the source of electrons. If the velocity of ions is constant, then Poisson's equation may be written as $d^2\Phi/dz^2 = \alpha/\sqrt{\Phi} - 1$, where $\Phi = e\varphi/W$, $\alpha = (J_e/J_i)\, m_i/m_e$, J_e - electron current density, $z^2 = 2x^2\omega_{pi}^2/V_i^2$ - nondimensional longitudinal coordinate, ω_{pi} - ion plasma frequency. The solution of this equation may by written as

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

where $k = 0, 1, 2 \ldots$ Here we used the condition $d\Phi/dz(0) = 0$ for spacecharge limited flow. This solution describes periodic modulation of the electrostatic potential in space with period $2z_m = 2\cdot\sqrt{2}\cdot\pi$ and amplitude $\Phi_m = 4\alpha^2$. It will be noted that the value of the parameter α is free for the case of half-space.

Computer Simulation of Time-Dependent HIB Neutralization

Kinetics of the neutralization processes has been investigated by means of computer simulation. Ions, infinitely thin sheets of definite charge/mass ratio and of initial velocity V_i, were injected through the plane electrode of zero potential. Electrons, the same 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 $E(x) = 0$ as the field of the sheets is independent of the distance to the injection plane. Below the results are given for the initial velocity of ions $V_i = 0.05c$. Nondimensional coordinate and time are measured in the units of $x_o = \sqrt{m_e c^3/eJ_i}$ and $t_o = x_o/c$.

Calculations show that the influence of generated fields on the motion of ions is quite small and the variation of ion velocity is less than 1 - 2% of its initial value 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 half-space with constant velocity. Such an approach al-

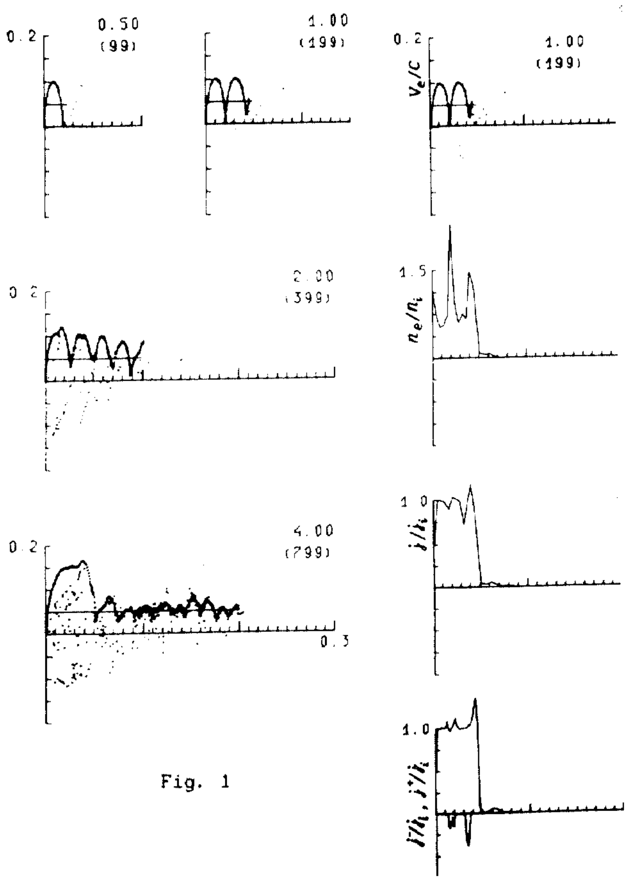

Fig. 1

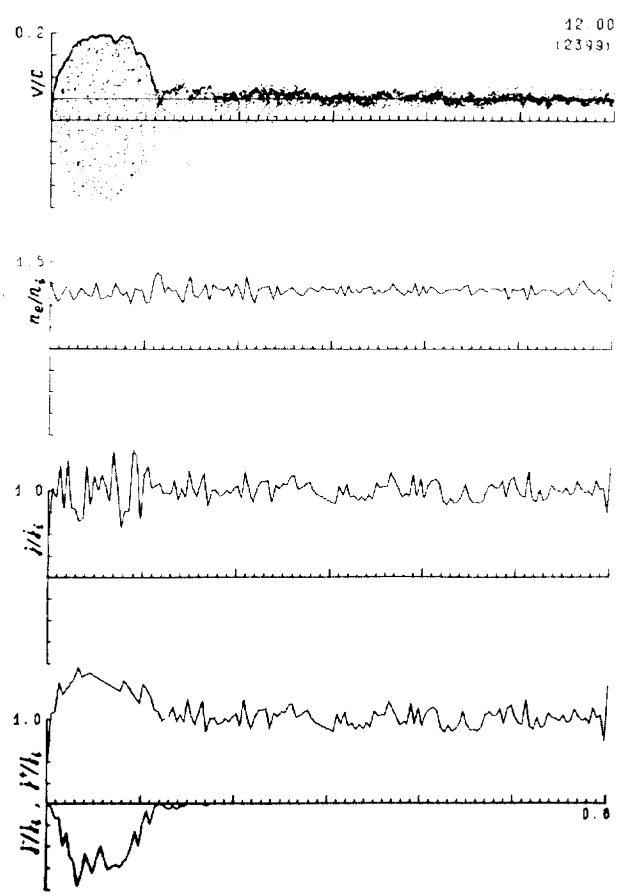

Fig. 2

lowed the field of ions to be calculated analytically.

Figs. 1 and 2 illustrate in a consistent manner the longitudinal distributions 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 ions velocity and the end of the curve corresponds to pulse front of ion flow. These results are obtained for sharp rise-time of the ion current and are similar to results [3-5]. It will be noted that at the initial time the maps give the same results as for the stationary state provided $J_e = J_i$, when maximum electron velocity $V_{em} = 2 \cdot V_i$.

These results show that thermalization of electron flow sets in practically instantaneously. For example, if the ion current density J_i = 170 A/cm then the non-dimensional time T = 5 is t = 1.5 ns in real time scale. For this time, the front of ion flow traverses a distance of 2.25 cm from the injection plate.

At first sight it seems that thermalization is due to oscillation of the single-power virtual cathode at the front of ion flow. Such a mechanism was advocated in [3-5]. To check this assumption we repeated the calculation in the case of linear current rise-time (Fig.3) up to T = 40. It is seen that the time of thermalization is greater in this case, and and the oscillating mode (similar to the stationary state) is conserved for a greater time. Blow-up of electron flow starts not from the front of ion flow but from the body, when one or several macroelectrons are reflected from the region of ion flow front. These electrons disturb (without reflection of electrons) one of the subcritical virtual cathodes of sufficient power in the body of the flow. The explosion of this virtual cathode expands to the left and to the right and leads to decay of the other subcritical virtual cathodes. Such process result in the transition of the system consisting of two divided cold flows to a quasiuniform mixed system of larger entropy and temperature. Finally, the system goes over to a stationary state similar to the previous one in the case of a sharp ion front.

The same results are obtained in the cases of sharp and linear current rise-time of HIB injected into a drift region consisting of two equipotential plates, except for the decrease of average electron velocity to zero at the end.

To illustrate the dependence of current neutralization on time delay between the injection of HIB and the start of electron emission we calculated the dynamics of electrons when the drift region was filled initially with moving ions. These results (Fig.4) show the high degree of current overneutralization, at least at

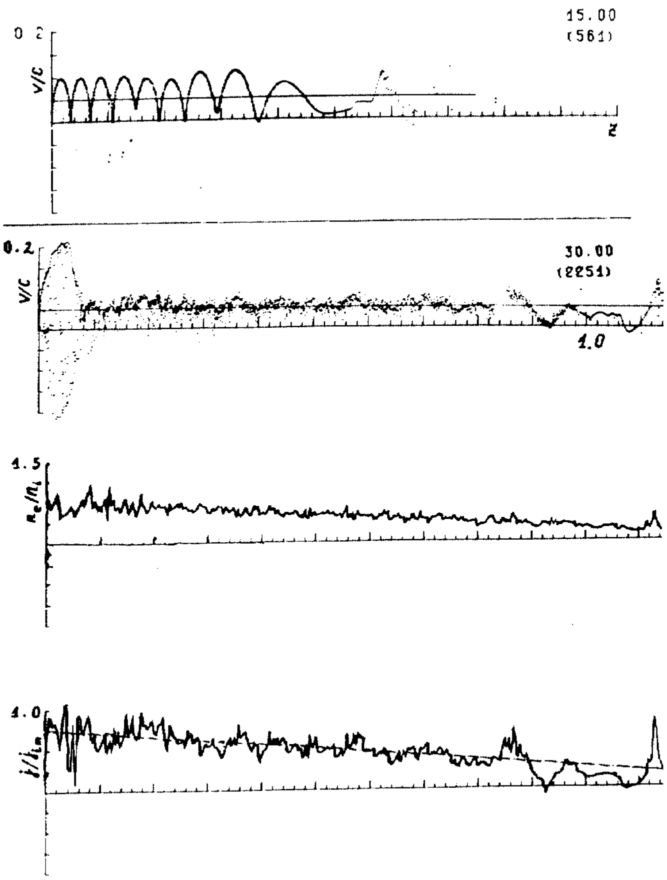

Fig. 3

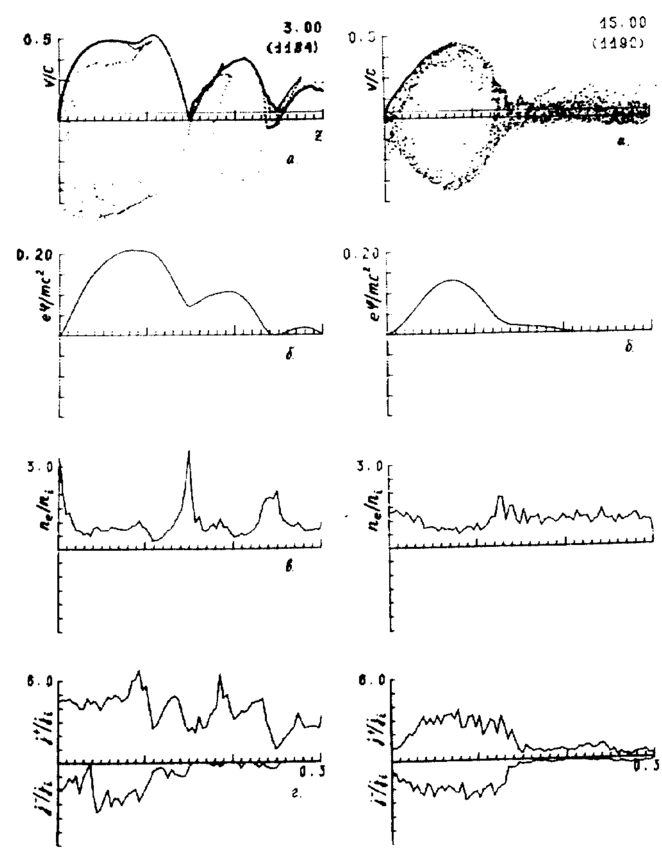

Fig. 4

initial times.

In practice, the fields of the particles act on those not far distance as these fields are screened by the chamber walls or due to heat of electron-ion flow. Therefore, the degree of current neutralizatiion have to depend on the distance of screening. The dependences of average electron velocities on time in the case of drift region are illustrated in Fig.5 for three distances of screening $\lambda = \infty$, d/3 and d/10, where d is the distance between two electrodes. It is seen that in the last case the current neutralization of HIB remains conserved.

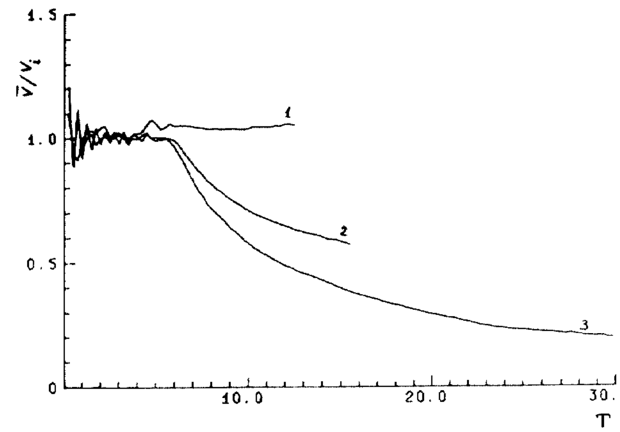

Fig.5 Dependences of average electron velocity on time in drift region for three distances of screening: d/10 (1), d/3 (2), ∞ (3).

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