THE NONLINEAR THEORY OF INTERACTION OF ION STREAMS WITH VIRTUAL CATHODE OF THE HIGH-CURRENT RELATIVISTIC ELECTRON BEAM

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Nonlinear LF dynamics of interaction of the longitudinal ion stream with the electron virtual cathode formed by high-current relativistic electron beam which is injected in the cylindrical drift chamber is investigated. Both the case of coincided radii of electron and ion beams, and the case when the radius of ion beam exceeds the radius of electron beam are considered.

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1. INTRODUCTION

Low-frequency (LF) interaction of ions with high-current relativistic electron beams (HREB) of a large duration (about μs and more) plays the important role in beam dynamics and is explicitly exhibited in great number of electron devices and facilities on HREB base. Among them there are microwave generators with microsecond duration, in particular, vircators [1], pasotrons [2] and facilities for collective acceleration of ions by quasi-static electric fields of a virtual cathode (VC) [1], which is formed in the drift chamber when HREB current exceeds the limiting vacuum current. The purpose of the present paper is clearing up of the physical pattern of electron VC evolution at its interaction with an ion stream. Electron VC is a high-nonlinear multi-stream formation therefore the examination of its behaviour at interaction with ion streams is possible only with engaging of numerical methods. The basic results of the carried out examinations are presented in the given paper.

2. PHYSICAL MODEL. BASIC EQUATIONS

The drift chamber represents a semi-infinite metal pipe with the end face in the range of injection of high-current relativistic electron beam. From the end face of the drift chamber ($z = 0$) two tubular beams of charged particles are injected: HREB and nonrelativistic ion beam. The system is located in the homogeneous magnetic field, directed along the axis of the system. Electrons of HREB are magnetized, and the effect of magnetic field on ions motion is neglected. Such situation, as a rule, is implemented in the experimental conditions [3]. The electron beam current exceeds the limiting vacuum current so in the drift chamber electron VC is formed. Injected ions will hit the area of electron VC and in part or completely neutralize the field of VC space charge.

For theoretical description of nonlinear dynamics of ion stream interaction with electron VC the following approach is used. Let us define the indefinitely thin ring macroscopic particles both for electrons, and for ions. The laws of ring motion of macroscopic particles are described by the time dependence of the longitudinal coordinate $z_{i,e} = z_{Li,e}(t, t_{0i,e})$ and the radius $r_i = r_{Li}(t, t_{0i})$ (for electrons only the longitudinal coordinate). The index "e" corresponds to electrons of HREB, and "i" corresponds to ions, t is the current time, $t_{0e,i}$ is the injection time of corresponding particles. The electrical potential of the system of electron and ion macroscopic particles (Green function) is defined from the Laplace equation with the corresponding right part. The boundary conditions consist of vanishing of the electrical potential on walls of the drift chamber. Summing (integration) over all macroscopic particles, which are in volume of the drift chamber in current time, gives the expression for the electrical potential of the electron - ion system:

$$\Phi = -\frac{2}{a}\sum_{n=1}^{\infty}\frac{J_0\left(\lambda_n \frac{r}{a}\right)}{\lambda_n J_1(\lambda_n)}\left\{\begin{array}{l} J_0\left(\lambda_n \frac{r_{Le}}{a}\right)\int_0^t I_e(t_{0e})dt_{0e}\left[e^{-\frac{\lambda_n}{a}(z+z_{Le})} - e^{-\frac{\lambda_n}{a}|z-z_{Le}|}\right] - \\ -\int_0^t I_i(t_{0i})J_0\left(\lambda_n \frac{r_{Li}}{a}\right)dt_{0i}\left[e^{-\frac{\lambda_n}{a}(z+z_{Li})} - e^{-\frac{\lambda_n}{a}|z-z_{Li}|}\right]\end{array}\right\} \quad (1)$$

The integration in (1) is executed over moments of injection time of electrons and ions, λ_n are the root of cylindrical functions $J_0(x)$, a is the radius of the drift chamber, $I_{e,i}$ is the current of electron and ion beams. Knowing the electrical potential of the system of electron and ion beams, it is easy to find the longitudinal and radial component of self-consistent electric field which will be determined by the position of all electrons and ions injected in the drift chamber from the moment $t = 0$ up to the current t. Further, having substituted expressions for electric field in motion equations for electrons and ions, the set of self-consistent equations may be obtained.

3. THE RESULTS OF THE NUMERICAL ANALYSIS

Numerical simulation of ion relaxation of electron VC has been carried out for the case of electron and ion beams with equal initial radiuses, as well as for the case when the initial ion radius exceeds the HREB radius. Calculations were carried out for the following parameters of the system: HREB current is 5.6 кA, energy of electrons is 280 keV, ion beam currents are 370 A and 1.1 кA, energy of ions is 25 keV, radius of the electron beam is 1.6 cm, radius of the drift chamber is 2.5 cm. The model ratio of ion mass to electron mass is equal to 40. The ratios of particles number per unit of length of ion beams to HREB N_i/N_e are equal 1.5 and 4.5. We will dwell on the most simple case when HREB and ion stream have conterminous initial radii at N_i/N_e=4.5. The numerical analysis has shown, that in this case the ion virtual anode (VA) is formed as well as the electron VC in the drift chamber. Ion VA is located close to the end face of the drift chamber (on the distance, approximately, 1.5 mm), therefore it simulates well the plasma emitter of ions with unlimited emissive capacity. The ion current is limited by a space charge (the plasma anode). On the initial stage of the process the electron VC starts to move deep into the drift chamber under action of the electric field of ion space charge (see fig.1).

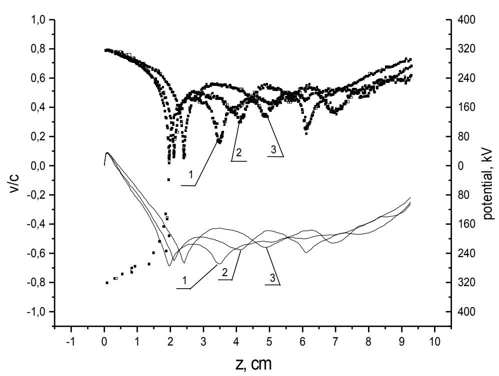

Fig.1. Phase portrait of electron beam (1–t=1.6 ns; 2–t=2 ns; 3–t=2.4 ns). Electric potential (lower curves 1-3 correspond to above-mentioned moments of time. I_e=5.6 kA, R_e=R_{0i}=1.6 cm, N_i/N_e=4.5

Here behind the electron VC the wave perturbation of the potential is formed with a length, approximately, 8cm, containing three spatial periods, which propagates deep into the drift chamber with the phase velocity essentially exceeding the velocity of the electron VC and close to the velocity of the accelerated ion stream. The energy of the accelerated ions in the field of the electron VC space charge is about the initial energy of electrons – 280 keV. As ions accumulate the wave perturbation of potential damps, the electron VC moves slowly deep into drift chamber and, eventually, disappears. As a result of the complex process of electron VC relaxation the double-flow electron-ion stream is formed in the system.

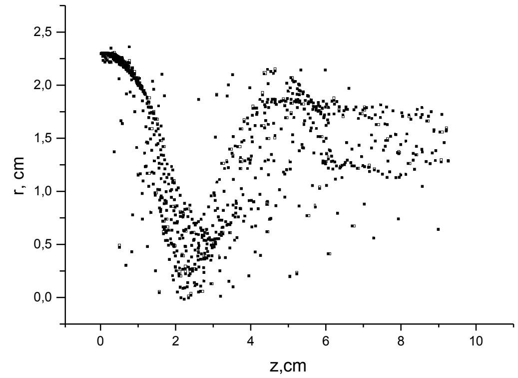

Fig.2 Longitudinal and radial coordinates of ions at the moment of time. t=2.6 ns, I_e=5.6 kA, R_e=1.6 cm, R_{0i}=2.3 cm, N_i/N_e=1.5

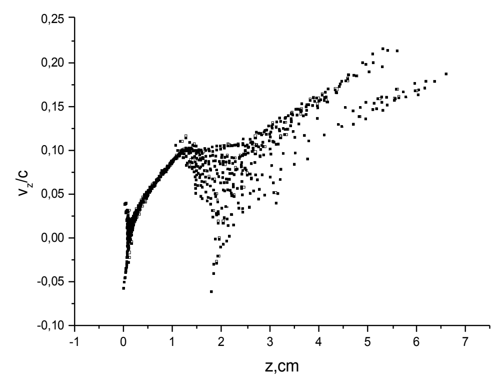

Fig.3 Phase portrait of ions at the moment of time t=1.6 ns, I_e=5.6 kA, R_e=1.6 cm, R_{0i}=2.3 cm, N_i/N_e=1.5

In the case, when the initial radius of ion beam (r_i = 2.3cm) is more than HREB radius, the non-stationary ion VA is formed at N_i/N_e=1.5. The position of the ion VA oscillates with time both in longitudinal, and in radial directions. Accordingly the angle of ion beam injection into the drift chamber makes oscillations. Radial motion of ions in the field of the electron VC space charge leads to their focusing on the axis of the system (fig.2). In the focus the positive potential of ions essentially increases and second ion VA is appeared. At the same time the part of ions on the leading edge of ion beam gains additional acceleration in the field of ion VA space charge during its formation (fig.3).

The maximum energy of accelerated ions at the leading edge of the ion beam mounts to 400 keV. In the radial direction HREB and accumulated ions form the radial potential well in which ions make transversal oscillations. The phase portrait of ions (v_r ,r) and the shape of the potential well are presented in fig.4. As the angle of injection of passed ion current into the drift chamber oscillates, the position of the ion focus located behind the electron VC, oscillates in the longitudinal direction. The ion focus approaching to the area of the electron VC increases the potential there and the electron VC disappears, that, in turn, leads to ion focus moving deep into the drift chamber. Thus the electron VC is recovered. There were observed four such relaxation oscillations leading to LF modulation of HREB. After that accumulation of ions in the area of electron VC leads to VC disappearing. The frequency of HREB modulation for the chosen model ratio of ion and electron masses is equal, approximately, 800 MHz. In recalculation on nitrogen ions this frequency makes 32 MHz.

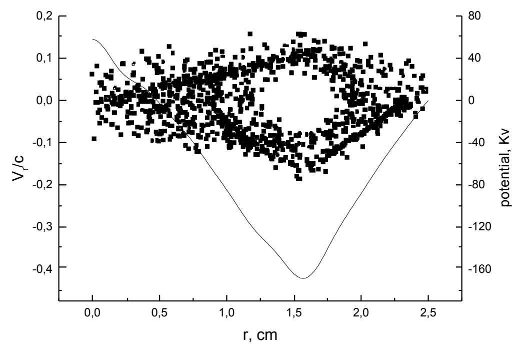

Fig.4. Phase portrait of ions v_r, r and potential distribution in the point z=0.9 cm in the cross-section of the drift chamber at the moment of time t=11.6 ns

I_e=5.6 кA, r_e = 1.6 cm, r_i = 2.3 cm, N_i/N_e=1.5

4. CONCLUSIONS

Thus, LF electron VC relaxation under the action of the ion stream was investigated. The self-consistent system of the nonlinear integral differential equations, which describes the above-mentioned process, was obtained and examined by numerical methods. It is shown, that in the case of conterminous radii of electron and ion beams, the ion stream leads to excitation of coherent wave structure behind the area of the electron VC. Accumulation of ions in the system eventually leads to the damping of this structure and forming of laminar electron-ion flow. If the radius of ion stream exceeds the HREB radius the pattern of nonlinear interaction of the ion stream with the electron VC becomes essentially richer. In the area of the ion stream injection the non-stationary ion virtual anode is formed, the position of which oscillates both in the longitudinal, and in the radial directions. The radial focusing of ions in the area of the electron VC space charge leads to formation of ion VA in the area of focusing. The position of ion focus oscillates with time in the longitudinal direction. At the same time, the electron VC periodically disappears and appears again, that is the use of deep LF modulation of HREB density.

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НЕЛИНЕЙНАЯ ТЕОРИЯ ВЗАИМОДЕЙСТВИЯ ИОННЫХ ПОТОКОВ С ВИРТУАЛЬНЫМ КАТОДОМ СИЛЬНОТОЧНОГО РЕЛЯТИВИСТСКОГО ЭЛЕКТРОННОГО ПУЧКА

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Исследована нелинейная НЧ динамика взаимодействия продольного ионного потока с электронным виртуальным катодом, образованным сильноточным релятивистским электронным пучком, который инжектируется в цилиндрическую камеру дрейфа. Рассмотрен как случай совпадающих радиусов электронного и ионного пучков, так и случай, когда радиус ионного пучка превышает радиус электронного пучка.

НЕЛІНІЙНА ТЕОРІЯ ВЗАЄМОДІЇ ІОНИХ ПОТОКІВ З ВІРТУАЛЬНИМ КАТОДОМ СИЛЬНОТОЧНОГО РЕЛЯТИВІСТСЬКОГО ЕЛЕКТРОНОГО ПУЧКА

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Досліджена нелінійна НЧ динаміка взаємодії повздовжнього іонного потоку з електронним віртуальним катодом, утвореним потужнострумовим релятивістським електронним пучком, який інжектується в циліндричну камеру дрейфу. Розглянуто як випадок співпадаючих радіусів електронного та іонного пучків, так і випадок, коли радіус іонного пучка перевищує радіус електронного пучка.