LOW-FREQUENCY PROCESSES AT INTERACTION OF ION FLOWS WITH RELATIVISTIC ELECTRON BEAMS

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Nonlinear process of excitation of LF oscillations is investigated at radial injection of ion stream into the drift chamber in which tubular REB is propagated. The mechanism of LF ion oscillation excitation is investigated.

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1. INTRODUCTION

Ion low-frequency (LF) oscillations play an important role in dynamics of high-current relativistic beam couplings (REB) of big duration (several mcs and more). Ion LF processes are exhibited mostly in microwave plasma filled generators (e.g. in vircators with plasma anode [1], passotrons [2, 3], in collective ion accelerators [4]. In vircators with plasma anode intensive ion streams are formed in the anode. In collective ion accelerators depending on the mechanism of acceleration ions can get into the system in longitudinal direction (Lewis diodes), appear in volume as a result of ionization of residual ion, and also get into the drift chamber in radial direction from wall stratum of plasma created after hitting of part of the REB on walls of the drift chamber [5]. Being propagated in the field of space charge of REB, ions will make radial oscillations which will reduce in turn in excitation of LF oscillations of electric field, ion densities, etc. In the present paper on a simple physical analog mechanisms of excitation of LF ion oscillations are investigated at radial injection of ion stream in area of REB propagation.

2. PROBLEM STATEMENT. BASIC EQUATIONS

Let into infinite cylindrical metal drift chamber of radius a tubular REB with interior radius r_1 and exterior r_2 is propagated. On a surface of the drift chamber $r = a$ the density of radial ion current $j_i(t)$ is set. Under force of space charge of REB ions will make radial oscillations. The electric field of space charge of REB will be described in approximation of the given parameters of the beam (fixed density and velocity). Dynamics of ion component we will describe completely as self-consistent. The radial electric field of space charge of the tubular REB is described by expression

$$E_r = -\frac{2I_b}{v_e a}\frac{1}{R}F(R),$$

where I_b is current of REB, v_e - its velocity,

$$F(R) = \begin{cases} 1 & , \quad R \geq R_2, \\ \dfrac{R^2 - R_1^2}{R_2^2 - R_1^2} & , \quad R_2 \geq R \geq R_1, \\ 0 & , \quad R \leq R_1, \end{cases}$$

$$R = r/a, \qquad R_{1,2} = r_{1,2}/a.$$

The field of space charge of ions we will describe in terms of Lagrangian variables.

The dimensionless set of motion equations of ions in a self-consistent field of ion stream and in a field tubular REB is

$$\frac{d^2R_L}{d\tau^2} + \frac{1}{R_L}F(R_L) = \frac{\alpha}{R_L}\int_0^{\tau} \Psi(\tau'_0)\chi(R_L - R'_L)d\tau'_0, \quad (1)$$

where $\tau = \omega_0 t$ – the dimensionless time, $\omega_0 = \frac{c}{a}\sqrt{\frac{2m}{M}\frac{I_b}{I_A}\frac{c}{v_e}}$ – the specific oscillation frequency of ions in electric field of space charge of the REB, c - velocity of light, $I_A = 17kA$, $\alpha = \frac{I_{0i}}{I_b}\frac{v_e}{\omega_0}$, $R'_L \equiv R_L(\tau, \tau'_0)$, m – weight of electrons, M – weight of ions, $\chi(x)$ – unit Hevyside function. We have presented ion current as $I_i = I_{0i}\Psi(t_0)$, where $\Psi(t_0)$ – the function describing a pulse shape of the injected ion current, $\max\Psi(t_0) = 1$.

Starting conditions to the equation (1) are following

$$R_L(\tau_0, \tau_0) = 1, \quad \left.\frac{dR_L}{d\tau}\right|_{\tau = \tau_0} = -U_{0i},$$

where $U_{0i} = v_{0i}/a\omega_0$ – the dimensionless initial radial velocity of ions.

On known trajectories of ions $R_L(\tau, \tau_0)$ the dimensionless potential in the volume of the drift chamber is determined under the formula

$$\frac{e\Phi}{mc^2} = -\frac{c}{\omega_0}\frac{I_{0i}}{I_A}\int_0^{\tau} d\tau_0 L(R, R_L(\tau, \tau_0)),$$

$$L(R, R_L) = \begin{cases} \ln R & , \quad R > R_L \\ \ln R_L & , \quad R < R_L \end{cases}.$$

3. ANALYSIS OF NUMERICAL RESULTS

Motion equations (1) and electric potential (2) have been designed by numerical methods for various currents of injection of ion stream and for fixed parameters of REB: current is $I_b = 4.6kA$, energy is $E_e = 280keV$, interior radius the is REB $r_1 = 1.4cm$, exterior radius is $r_2 = 1.7cm$. For the determinancy ions of hydrogen were considered. Initial energy of ions is $E_i = 25keV$, radius of the drift chamber is $a = 2.5cm$. In the system the constant ion current is injected, $\Psi(\tau_0) = 1$.

On fig.1 dependencies of electric potential on time on exterior boundary of the beam for three values of ion current, $I_{0i}(\grave{A}/cm)$ are presented. In the case of low-current ion beam $I_{0i}=70\grave{A}/cm$ oscillation were excited after, approximately, in $80ns$ after the beginning of injection. In the case of high-current ion beams $I_{0i}=400\grave{A}/cm$ and $I_{0i}=1000\grave{A}/cm$ oscillations were excited much earlier. For all indicated values of current damp with time. Time of oscillation damping and their stationary level practically do not depend on ion beam current. At major currents the time structure of LF oscillations practically coincides. To understand the nature of such behaviour of LF oscillations at various ion beam currents we will address to phase portraits of ions $(v_r/c,r)$, where v_r - radial velocity of ions.

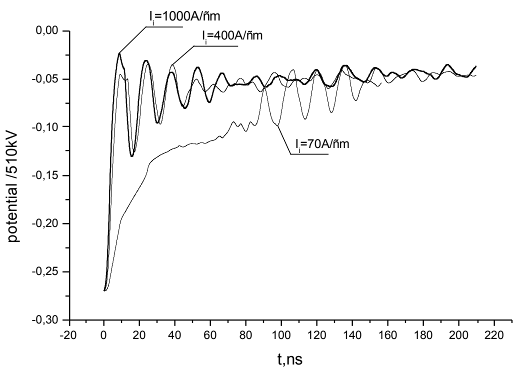

Fig. 1. Dependencies of potential on exterior boundary of tubular REB on time for various values of ion current: I_b =4.6kA, E_e=280keV, E_i=25keV, r_1=1.4cm, r_2=1.7cm, a=1.5cm

On fig.2 phase portraits of ions for low-current beam are presented. The analysis of these portraits shows, that from the moment of the beginning of injection ions begin movement in the field of space charge of REB to the axis of system. After crossing the axis two-flow current is formed: concurrent and divergent radial ion streams. On the axis of system their velocity are equal and opposite in sign. Decelerating of ions in own field of space charge in paraxial area reduces in reduction of stream velocities on axis and in at the moment $t=19.3ns$ velocity of concurrent and divergent streams on axis convert in a zero. Continued decelerating of concurrent stream reduces in displacement from the axis of the point of falling stream stop. The ions which have appeared between the axis and the point of stop are accelerated and inject by particles the divergent stream. As a result in paraxial area on a phase plane three-flow current is formed: two-flow divergent current and one-flow concurrent current (fig.2a). Thus ions of divergent stream, having reached the wall of the drift chamber, leave the system, and in paraxial area there is an accumulation of particles reducing in fast growth of potential. Then ions of divergent stream form a bunch that as approaching a wall of the drift chamber raises potential in the field of ion stream injection. As a result at the moment $t=74ns$ in injected ion stream ion virtual anode (VA) appears. Ion VA is non-stationary. Its position, transmitted and reflected currents oscillate with frequency, much higher, than frequency of potential oscillations.

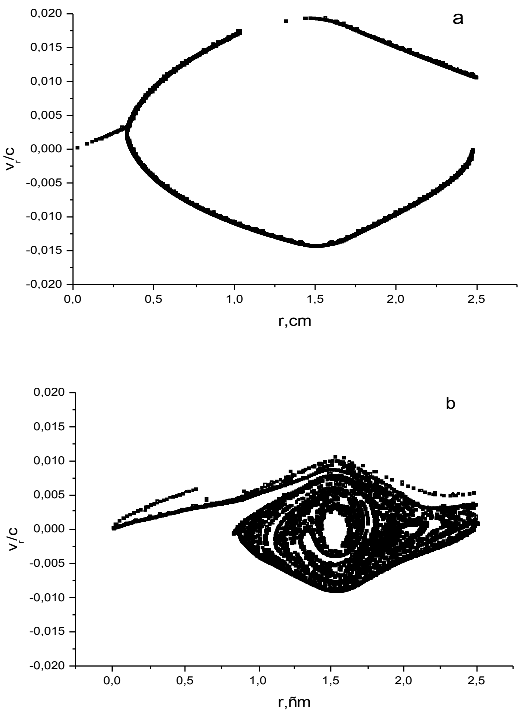

Fig. 2. Phase portraits of ions: a – $t=23.5ns$, b – $t=156ns$; I_{0i} =70A/cm

The part of ions of the bunch is lost on the wall of the drift chamber, and the rest ions, having reflected from a potential barrier in the area of wall, move to axis of the system (rotation on a phase plane). The potential decreases again and ion VA disappears. Rotation of ion bunch is accompanied by ion losses on the wall of the drift chamber and by birth of new bunches. The ions near the wall, which partially leave the system and continuously injected ions, create a potential barrier near the wall of the drift chamber. On the other hand, ions which are constantly present in the area of axis, form a potential barrier in central area of the drift chamber.

Losses of ions on the wall are compensated by increase of emission current from ion VA. These processes go in a step with LF oscillations of electric potential. Rotation of bunches on the phase plane, accompanying by continuous birth of new ones (process of bunch "division"), reduces in formation of the complex multi-flow current (fig.2b) and eventually in turbulization of radial ion stream motion. Such turbulent state is a reason of phase mixing of particles and damping of coherent ion oscillations of potential. The stationary state is established, which is characterized by, approximately, constant number of ions in the system. Ion stream to the wall is compensated by ion stream from stationary VA, constantly present near to walls (fig.2b).

In the case of high-current ion beam ($I_{0i}=400\grave{A}/cm$) ion VA is formed very quickly and is constantly present. Phase portraits for high-current ion beam are presented on fig.3. The boundaries of tubular REB are $r_1=1.4cm$ and $r_2=1.7cm$. The first maximum of potential ($t = 10.6ns$) corresponds to bunch formation. The majority of ions are inside the REB. In the point of minimum of potential ($t = 17.2ns$) two bunches which majority is outside of the REB are clearly visible on a phase plane (fig.3a). At that the part of particles is lost on the walls. Rotation of two bunches reduces in their displacement to the centre of the drift chamber and in increase of potential.

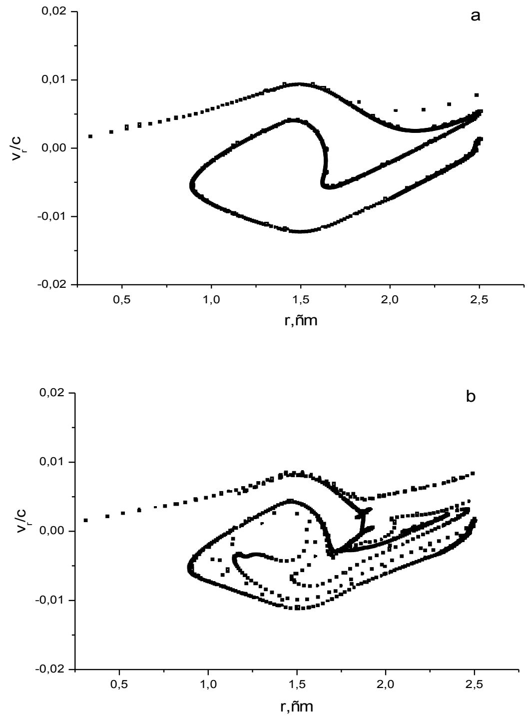

Fig. 3. Phase portraits of ions. a – $t = 17.2ns$, b – $t = 32ns$; I_{0i} =400A/cm

At $t = 25ns$ on exterior boundary of REB potential has maximum. In the point of the second minimum of potential ($t = 32ns$) bunches are again on a periphery of the system (fig.3b). The part of ions is lost on the wall of the drift chamber. It is interesting to note, that the drift of ions from a system is accompanied by increase of transmitted ion current and decrease of reflected from VA ions. Phase mixing of particles leads to the same stationary state, as in the case of low-current beam.

4. CONCLUSION

Thus, in the paper process of excitation of LF ion oscillations is investigated at radial injection of ion stream from a surface of the drift chamber in the area of high-current REB propagation. At small ion currents ($I_{0i} = 70\grave{A}/cm$) ion VA is not formed in paraxial area. In the system there is a two-flow ion current. Interaction of the ion streams propagating in opposite directions, reduces in formation of ion bunches, which, rotating on a phase plane, are continuously dividing. Accumulation of ions in the system leads eventually to formation of ion VA near the wall. The reason of excitation of LF oscillations is formation of ion bunches and their coherent radial oscillations in potential well. And their damping is stipulated by division of bunches during their radial oscillations and phase intermixing of ions. Eventually stationary state is established with, approximately, constant number of ions in the system. Losses of ions as a result of their hit on the wall are compensated by the ions injected in the system by virtual anode.

As for the high-current ion streams (I_{0i} = 400*A*/*cm*, 1*kA*/*cm*) in this case VA is formed very quickly. The pattern of LF oscillation excitation in regime of virtual anode practically does not depend on current of ion injection, because ion VA is the emitter which current is limited by space charge. Transmitted ion current is determined by current of REB and sizes of the drift chamber. In the high-current case in comparison with low-current the time of stabilization of oscillations is essentially reduced and their amplitude is increased. The study is supported by STCU project №1569.

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НИЗКОЧАСТОТНЫЕ ПРОЦЕССЫ ПРИ ВЗАИМОДЕЙСТВИИ ИОННЫХ ПОТОКОВ С РЕЛЯТИВИСТСКИМИ ЭЛЕКТРОННЫМИ ПУЧКАМИ

В.А. Балакирев, Н.И. Онищенко, И.Н. Онищенко

Исследован нелинейный процесс возбуждения НЧ колебаний при радиальной ионной инжекции в камеру дрейфа, в которой распространяется трубчатый РЭП. Изучен механизм возбуждения НЧ ионных колебаний.

НИЗЬКОЧАСТОТНІ ПРОЦЕСИ ПРИ ВЗАЄМОДІЇ ІОННИХ ПОТОКІВ З РЕЛЯТИВІСТСЬКИМИ ЕЛЕКТРОННИМИ ПУЧКАМИ

В.А. Балакірєв, М.І. Онищенко, І.М. Онищенко

Досліджений нелінійний процес збудження НЧ коливань при радіальній іонній інжекції у камеру дрейфу, в якій розповсюджується трубчатий РЕП. Досліджений механізм збудження НЧ іонних коливань.