LINEAR INDUCTION ACCELERATOR WITH CHARGE AND CURRENT COMPENSATION

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The research of inertial controlled fusion (ICF) on high-current heavy-ion beams is one of the main trends in ICF. Modern techniques of a heavy-ion beam production and acceleration make it possible to obtain high-current beams with high intensity using linear induction accelerators (linacs). ICF purposes require the increasing of the beam intensity and the beam brightness by several orders. The main process that restricts the high-current ion beam intensity is the beam spreading caused by the influence of self-fields of charged particle beam. Self-fields are several orders greater than the external fields used for beam control, acceleration and focusing. Under these conditions, it is impossible to obtain high-current heavy-ion beams of quality necessary for ICF without charge and current compensation of beams.

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1 INTRODUCTION

High-current induction linacs present the most prospective trend of elaboration of a driver for inertial controlled heavy-ion fusion. The driver on the basis of an induction linac is alternative to the drive on the basis of a vacuum resonance accelerator. A high-current linear induction ion accelerator with charge and current compensation has been proposed and studied at NSC KIPT [1, 2]. The compensation within accelerating gaps of such linac is provided by injection of an additional electron beam with specially chosen parameters (dimensions, beam energy, etc.) The compensation of positive space charge within drift gaps is provided by injection of thermal electrons into these gaps.

During the last years, we carried out systematic investigations of the dynamics of relativistic electron and non-relativistic ion beam propagation in both an electric field and an axisymmetric non-uniform magnetic field. Thus, in [3 – 8] the results of investigation into both the acceleration processes and the charge and current compensation in one and two accelerating sections of the induction linac were presented. It was demonstrated that the injection of the electron beam into the magnetoisolated accelerating gaps and the injection of the thermal electrons into drift gaps provided the charge and current compensation. With the aim of increasing the ion beam acceleration rate in the two-cusps linac we have studied the optimal correlation between an accelerating electric field and an electron beam energy [9 – 10]. Also we have obtained the restriction on the wall thickness of annular high-current ion beam, which ensure the uniformity of charge and current compensation in the ion beam cross-section and acceleration stability (in radial direction). These processes occur due to the fact that penetration depth of the accelerating electric field is considerably greater than the beam wall thickness.

This paper presents the results of the distribution function studying of both the accelerated ion beam and the compensating electron beam in the cases of different accelerating electric field values.

2 MATHEMATICAL AND DISCRETE MODEL

Hollow magnetized relativistic electron beam (Larmor radius r_{Le} is substantially smaller than the size of the cusp L_z and the chamber radius r_L) and high-current unmagnetized ion beam (Larmor radius r_{Li} is more greater than L_z and r_L) were injected along *z*-axis of the system consisted of one (or two) magnetoisolated accelerating gaps and a drift one (see. Fig. 1).

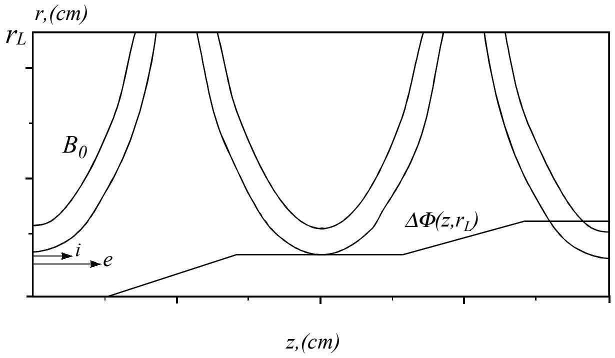

Fig. 1. View of the modeling region.

The beam current densities at $z = 0$ were equal. The ion beam velocity was $v_i = 0.285c$ and the electron beam velocity was $v_e = 0.85c$. The preliminary injection of the thermal electrons with the Maxwellian distribution function with the temperature $T_{ce} = 0.002 m_0 c^2$ into drift gap was used to suppress the positive space charge within this gap.

Numerical simulation of above-described problem is based on the solving of Vlasov equations set for the distribution functions (DF) of particles $f_s\left(\vec{P},\vec{R},t\right)$ in the axisymmetric cylindrical geometry $\left(\partial/\partial\theta = 0,\ \vec{R} = (r,z)\right)$. The self-consistent electric $\vec{E}\left(\vec{R},t\right)$ and magnetic $\vec{B}\left(\vec{R},t\right)$ fields including in

Vlasov's equations are determined by the Maxwell's equations that can be written as the wave equations for the scalar $\Phi(\vec{R},t)$ and vector $\vec{A}(\vec{R},t)$ potentials.

The boundary conditions for the DF of particles of a given sort (*s= e, i* - electrons and ion correspondingly) at $z=0$ is defined by $f_s(m_s\vec{u},\vec{R},t)=\delta(u_r)\delta(u_z-u_{0s})\delta(u_\theta)$ for $r_{\min}\le r\le r_{\max}$ and $u_z>0$. Here $r_{\min}$ and $r_{\max}$ are the minimum and maximum beams radii respectively.

The configuration of the external magnetic field is defined by the expression $A_\theta=-B_0/k\,I_1(kr)\cos(kz)$, where $I_1(kr)$ is the first order modified Bessel function, B_0 is the amplitude of magnetic field, and $k=K\pi/z_L$, K is total number of cusps.

The set of equations and the initial and boundary conditions for the potentials and DF are described in detail in [7].

The units of measurement using in the treatment are determined by relations: $[v]=c$, $[r,z]=c/\omega_{pe}$, $[t]=\omega_{pe}^{-1}$, $[n]=n_{0e}$, $[q]=e$, $[m]=m_0$, $[\vec{J}]=en_{0e}$, $[\Phi,\vec{A}]=m_0c^2/e$, $[E,B]=(4\pi n_{0e}\varepsilon_{ch})^{1/2}$, $[\vec{T}_{ce}]=m_0c^2$, $[P_0]=[\psi]=c^2/\omega_{pe}$, where $\vec{u}=\gamma\vec{v}$, $\vec{v}=\{\dot{r},r\dot{\theta},\dot{z}\}$, $\psi=\gamma r^2\dot{\theta}=P_\theta-\frac{q}{m}rA_\theta$ (P_θ is the dimensionless generalized particle momentum), $\gamma=\left(1+u_r^2+(\psi/r)^2+u_z^2\right)^{1/2}$ is the relativistic factor, $\omega_{pe}=\sqrt{4\pi n_{0e}e^2/m_0}$ is the electron plasma frequency, n_{0e},m_0,e are the initial density, rest mass and charge of the electrons respectively, T_{ce} is the temperature of cold electrons.

The mass ratio was $m_i/m_e=100$, $m_e=20m_0$. The number of particles in the cell was 6000. The number of the nodes was equal to $J_z\times J_r=64\times64$. The time step was varied within the range $0{,}025-0{,}05\omega_{pe}^{-1}$ for solving the equations of motion and $0{,}0125-0{,}025\omega_{pe}^{-1}$ when solving the wave equations.

The discrete model is realized as 2.5-dimensional electromagnetic relativistic axisymmetric numerical code. The calculations were carried out using computer of the Pentium-class.

3 RESULTS OF NUMERICAL SIMULATION

A series of 2.5-D simulation has been performed. The distributions of DF of the electron and ion beams are presented in Fig. 2-Fig. 4 for different values of the initial accelerating electric field.

As one can see, the large spread in both the radial and longitudinal velocities is observed for the electron beam. As for the ion beam, it spreads only by 10-15%.

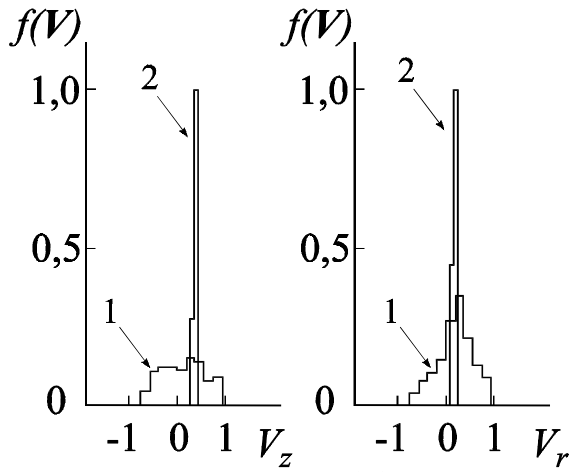

Fig. 2. Distribution function $f(\vec{V})$ *of electrons (1) and ions (2). The initial potential difference is* $\Delta\Phi=30.0m_0c^2/e$.

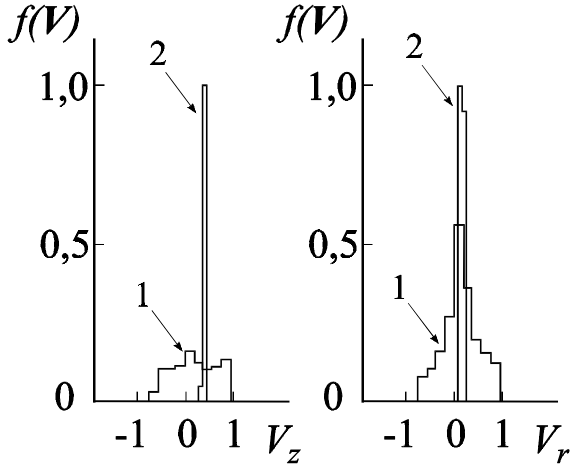

Fig. 3. Distribution function $f(\vec{V})$ *of electrons (1) and ions (2). The initial potential difference is* $\Delta\Phi=15.0m_0c^2/e$.

It should been noticed that the total initial potential difference is the same ($\Delta\Phi=30.0m_0c^2/e$) for cases presented in Fig. 2 and Fig. 3. In the first case this potential difference is applied to one accelerating gap (see Fig. 1) and in the second case there are two accelerating gaps in the system. Having compared these two variants, one can draw the conclusion that the number of ion beam particles with low energy is greater for the case of one-cusp system. In this case the charge compensation of ion beam is weaker. While the ion beam propagates through the system with two accelerating gaps and one drift gap under the same potential difference, the charge compensation is increased due to the thermal electron injection into the drift gap to neutralized the essential positive space charge of ion beam there.

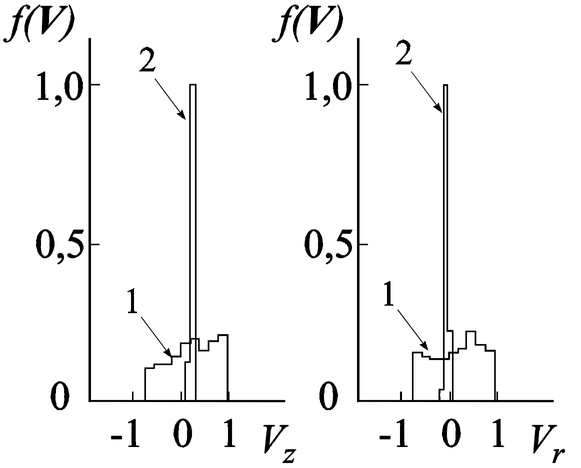

Fig. 4. Distribution function $f\left(\vec{V}\right)$ *of electrons (1) and ions (2). The initial potential difference is* $\Delta\Phi = 0.8\, m_0 c^2 / e$.

If the initial potential difference is rather small ($\Delta\Phi = 0.8\, m_0 c^2 / e$), the kinetic energy of electron beam is sufficient to overcome it. As the result the space charge overcompensation and radial focusing of the ion beam is occur as one can see in Fig. 4.

4 CONCLUSION

In this paper it has been shown that the process of compensation of high-current ion beam as this beam, together with the additional electron beam, propagates through two-sectioned induction linac, is followed by the increase of beam spreading in the radial and longitudinal velocities. Although the electron beam spread is about 100%, it does not impede the charge compensation of the high-current ion beam by electrons. At that time the ion beam spread in the velocities does not exceed 10%.

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