# OPTIMIZATION OF HIGH-CURRENT ION BEAM ACCELERATION AND CHARGE COMPENSATION IN TWO CUSPS OF INDUCTION LINAC

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Abstract

Results of the numerical simulation of the hollow high-current ion beam (HHCIB) dynamics in two magnet-isolated accelerating gaps separated by the drift gap are presented. The previous study has shown that the good charge and current compensations of the ion beam by the specially injected electron beam occur in the accelerating gaps of the induction linac. However in the drift gap the high positive electric potential due to the positive space charge of HHCIB was obtained because the essential difference between the electron and ion drift velocities exists under this compensation method. This disadvantage impairing the brightness of the ion beam can be considerably reduced by the additional injection of the thermal electrons into the drift region. In present report the some cases of the cold electron injection into drift gap are considered. The more optimal regime for the effective charge and current compensations of HHCIB without loss in the stability of ion beam was found.

## I. INTRODUCTION

In the last ten years the production of charge compensation high-current beams by means of the linear high-current accelerator (linac) with magnet-isolated accelerating gaps are promising for controlled thermonuclear fusion research [1], [2]. The one of the many problems, which requires the particular attention, is the good charge compensation of the ion beam for suppressing the space-charge forces impairing the ion beam brightness. As shown our early numerical investigation [3]–[5] the ion beam is effectively neutralized only in the magnet-isolated accelerating gaps with the electron beam. The aim of the present work was the numerical optimization of the ion and electron beams propagation through the two magnet-isolated accelerating gaps separated by the drift gap.

## II. EQUATIONS AND MODEL

To describe the collisionless plasma dy namics of beams the set of relativistic Vlasov's equations for the distribution functions of particles $f(\vec{p},\vec{R},t)$ in the axisymmetric $(\partial/\partial\theta = 0)$ cylindrical geometry $\vec{R}=(r,z)$ has been used for the investigation of the transient and stationary processes in linac (here $\vec{p}$ is momentum). The self-consistent electric $\vec{E}(r,z)$ and magnetic $\vec{B}(r,z)$ fields including in Vlasov's equations are determined by the Maxwell's equations, the right hands of which are defined as the zeroth and first moments of the distribution functions.

From the set of Vlasov's equations can be obtained the set of the particles dynamic equations using the relations $\vec{u} = \gamma\vec{v}$, $\vec{v} = \{\dot{r}, r\dot{\theta}, \dot{z}\}$, $\psi = \gamma r^2\dot{\theta} = P_\theta - \frac{q}{m} r A_\theta$, ($P_\theta$ 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. The Maxwell's equations using the Lorentz gauge $(div\vec{A}+\frac{1}{c}\frac{\partial\phi}{\partial t}=0)$ can be reduced to the wave equations for the scalar $\phi(r,z)$ and vector $\vec{A}(r,z)$ potentials.

The units of measurement using in the next treatment are defined by relations: $[v] = c$, $[r,z] = c/\omega_{pe}$, $[t] = \omega_{pe}^{-1}$, $[n] = n_{0e}$, $[q] = e$, $[m] = m_0$, $[\phi, A] = m_0c^2/e$, $[E,B] = (4\pi n_{0e} m_0 c^2)^{1/2}$, $[j] = en_{0e}c$, $[P_\theta] = [\psi] = c^2/\omega_{pe}$, $[T_{ce}] = m_0c^2$, where $\omega_{pe} = (4\pi n_{0e}e^2/m_0)^{1/2}$ 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 initial velocity of a given sort ($s$) of particles is defined by the boundary conditions for the distribution functions at $z=0$: $f_s(m_s\vec{u},\vec{R},t) = \delta(u_r)\delta(u_z-u_{0s})\delta(u_\theta)$ at $r_{min}\le r\le r_{max}$ and $v_z>0$. Here $r_{min}$ and $r_{max}$ are the minimum and maximum beams radii respectively which define the initial $r$-coordinates of particles, $u_{0s} = V_s/(1-{V_s}^2)^{1/2}$, $V_s$ is a beams velocity. At $(r=0, r=r_L)$ set the reflection regime. The particles exit free from the simulation region at $z=z_L$. At the initial time the particles are absent in modeling region.

The boundary conditions for the potentials are

$$\left.\begin{array}{l} z=0: \\ z=z_L: \end{array}\right\}, \quad \frac{\partial A_z}{\partial z} = -\frac{1}{r}\frac{\partial(rA_r)}{\partial r},$$

$$\frac{\partial A_r}{\partial z} = \frac{\partial A_\theta}{\partial z} = 0,$$

$$\phi\big|_{z=0} = 0, \phi\big|_{z=z_L} = \phi_L;$$

$$\begin{array}{ll} r=0: & \partial\phi/\partial r = 0 \\ & \partial A_z/\partial r = A_r = \partial A_\theta/\partial r = 0, \\ r=r_L: & \phi=\phi(z) \quad A_z=A_r=A_\theta=0; \end{array}$$

where $\phi(z) = n\Delta_\phi$, $n = 0,\ldots,\mathcal{K}$ in the drift gap, and $\phi(z) = (n-1)\Delta_\phi + +\frac{\Delta_\phi}{\Delta_z}(z-(3n-2)\Delta_z)$, $n = 1,\ldots,\mathcal{K}$ in the accelerating gaps, $\Delta_\phi = (\phi_L-\phi_0)/\mathcal{K}$, $\Delta_z = z_L/(3\mathcal{K})$ are the potential difference across the accelerating gap and the length of one, $\mathcal{K}$ is the total number of cusps. The initial conditions for the self-consistent fields are $\Delta\phi = A_z = A_r = A_\theta = 0$ (here $\Delta$ is Laplasian).

The configuration of the external magnetic field is defined by the expression $A_\theta = -\frac{\mathcal{B}_0}{k} I_1(kr)\cos(kz)$ where $I_1(kr)$ is the first order modified Bessel function, $\mathcal{B}_0$ is the amplitude of magnetic field, and $k = \mathcal{K}\pi/z_L$.

The dynamics of particles is analyzed numerically using the modified discrete scheme of *Belova, et.al.* [3].

## III. DISCUSSION OF RESULTS

Our previous investigations [3]–[5] of the interaction of a hollow magnetized electron beam with a hollow high-current unmagnetized ion beam injecting along $z$-axis into external magnetic field of both one- and two- cusps have shown that (i) charge and current compensations of the ion beam by the specially injected electron beam occur; (ii) the ion beam is stable for the time greater than the reciprocal Larmor and Langmuir ion frequencies; (iii) the brightness of the ion beam is impaired in the drift gap between two accelerating gaps of linac since the large positive space charge is generated by ions uncompensated by the retarded electrons of relativistic electron beam.

With the aim of optimization of the ion beam propagation through the drift gap of the two cusps linac we have studied the three ways of the ion beam compensation by the additional cold electrons injection. In all cases the beam current densities were equal to $q_e n_{0e} V_e = q_i n_{0i} V_i$. The mass ratio was $m_i/m_e = 100$, $m_e = 20m_0$, the number of particles in the cell was $N_e = 64$, $N_i = 180$. The electron and ion beam velocity were supposed $V_e = 0.85$, $V_i = 0.285$ respectively. The minimum and maximum beams radii were $r_{min} = 30$ and $r_{max} = 32.5$.The length and radius of the chamber were $z_L = 157.5$ and $r_L = 157.5$. The amplitude of the external field was $\mathcal{B}_0 = 1.76$ . The potential difference across one cusp was equal to $\Delta\phi = 0.8$. The velocities of cold electrons were defined by Maxwellian distribution function with the temperature $T_{ce} = 0.002$.

In first case the thermal electrons injection in drift gap has been started when the ion beam passed $2/3z_L$ of linac. By which time the ion beam was significantly spread and the cold electron cloud could not effectively compensate the ion beam. The maximum of the scalar potential has diminished moderately.

In second case the original injection of the thermal electrons was used. At first the cold electrons were injected into the ion beam which came out from the first cusp. Thereafter the injector of thermal electrons was localized at the center of the drift gap. And finally the thermal electrons were injected into ion beam coming out from the second cusp. That is the injection has been started when the ion beam passed $1/3z_L$, $1/2z_L$, $2/3z_L$ of linac. In this case the thermal electrons formed the negative bulk charge considerable compensating the charge and current of ion beam. This way of injection can be easy performed in a computational simulation and shown the encouraging results but it has not a perspective in real experiments. The results have shown that the thermal electron injection is to ahead of the front of an ion beam.

Finally in third case the thermal electrons injection was started at the initial stage of injection of both the relativistic electron beam and the high-current ion beam to linac. The calculations were continued in during about ten reciprocal Larmor ion frequency. The results of the simulation are demonstrated in fig.1,2. Fig.1 shows the distribution of $\rho(r,z)$, $\phi(r,z)$ and $j_z(r,z)$ for case without the thermal electrons injection (a), and with the additional injection of cold electron into the drift gap (b) once the ion beam has passed both of cusps. The maximum of the scalar potential in fig.1b is considerably low than in fig.1a. The distribution of the scalar potential shows that the system as a whole was charged negative. A great negative potential aid in additional focusing the ion beam. Fig.2 demonstrates the distribution functions of the electrons and ions at the stationary state for the case without thermal electron compensation (a) and for case with thermal electron compensation (b), and in fig.2c the time dependencies of the space-average ion beam velocity are compared. The maximum of the ion velocity were about $0.32$ as shown in fig.2c. It is seen that the ion beam is effectively accelerated and has the high brightness in this simulation.

## IV. CONCLUSIONS

The performed investigations of the beams propagation through the magnet-isolated accelerating gap of the induction linac has shown that the charge and current compensations of HHCIB by the accompanying relativistic electron beam and the thermal electron injection into drift gap are effectively. The aim of the following studies is to be a search of the optimal values of both accelerating field and electron beam energies.

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## References

[1] A.I. Faltens and D. Keeffe, "Review of Induction Linac," *Proc. of the 1981 Lin. Accel. Conf.*, Santa Fe, **LA-9234c**, pp. 205-208.

[2] V.I. Karas', V.A. Kiyashko, E.A. Kornilov, Ya.B. Fainberg, *Nuclear Instruments and Methods in Physics Research*, **A278**, 245 (1989).

[3] N.G. Belova, V.I. Karas', Yu.S. Sigov, *Fiz. Plazmy*, **16**, 209 (1990) [*Sov. J. Plasma Phys.* **16**, 115 (1990)].

[4] N.G. Belova, V.I. Karas', *Part. Accel.*, **37-38**, 225 (1992).

[5] N.G. Belova, V.I. Karas', *Proc. of 1993 IEEE Part. Accel. Conf.*, Washington DC, **Vol.1**, pp. 664-666.

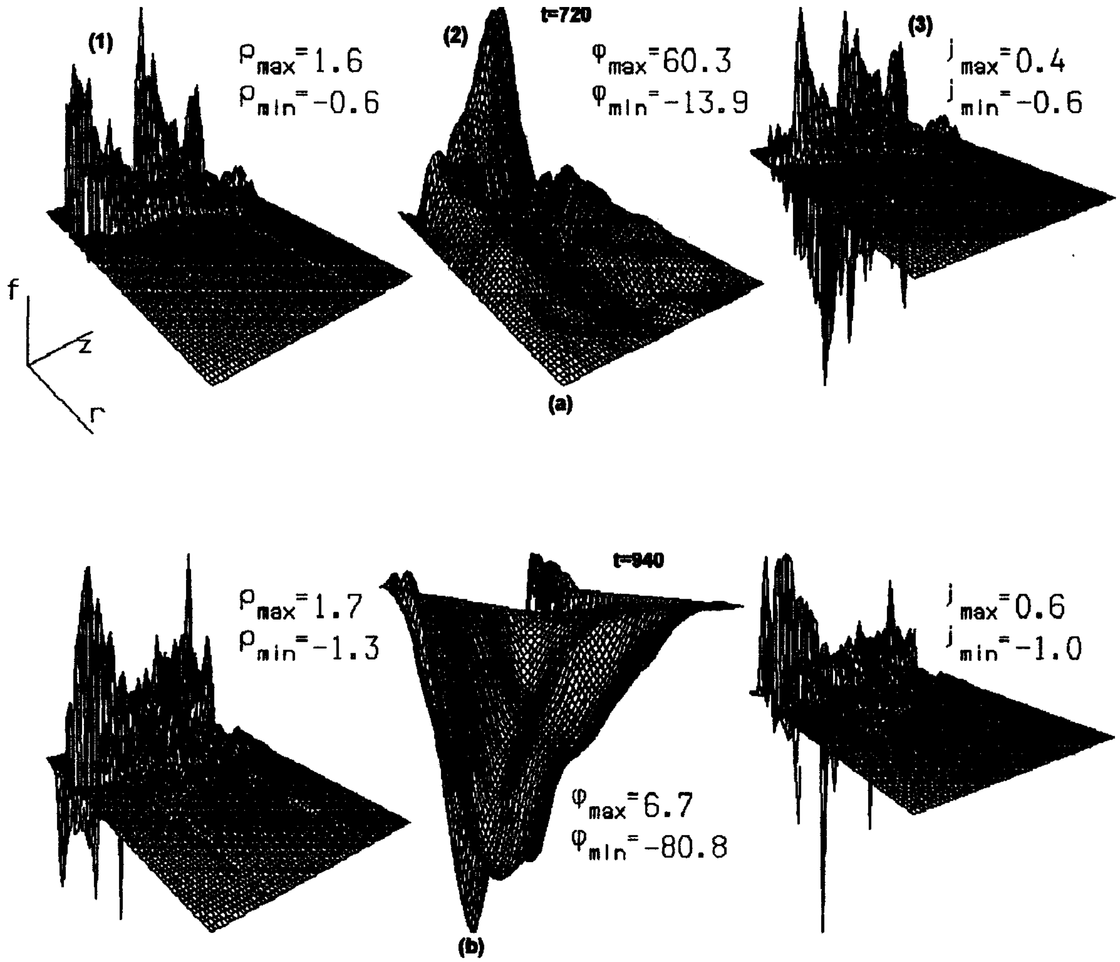


Figure 1. Distributions of the total charge density $\rho(r,z)$, scalar potential $\phi(r,z)$, axial current density $j_z(r,z)$ at $t = 640$ for the case without additional electron injection $(a)$ and with one $(b)$.

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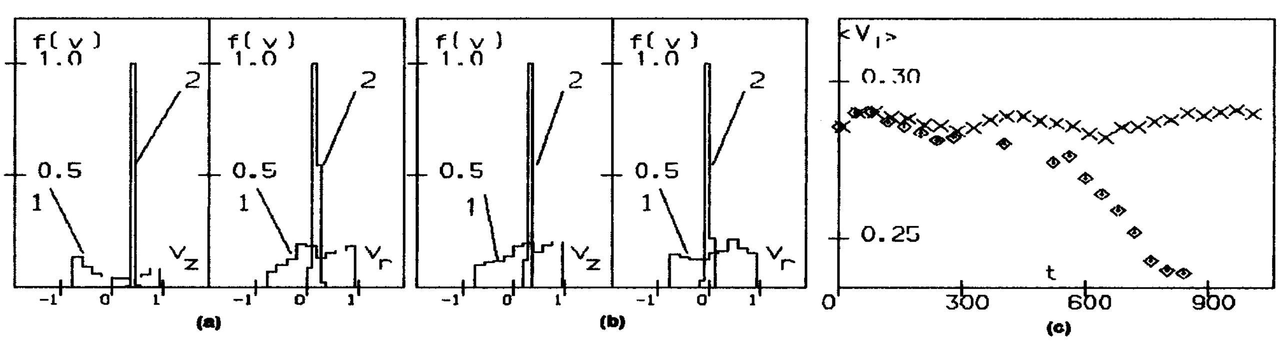


Figure 2. Distributions functions $f(V)$ of electron (1) and ion (2) beams versus the longitudinal $(V_z)$ and transverse $(V_r)$ velocities at the stationary state ohne the thermal electron injection $(a)$ and with the thermal injection $(b)$. Distributions of the averaged ion velocity $< V_i >$ $(c)$ versus the time ohne the thermal electron injection $\diamond$ and with one $\times$.