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Research of transportation efficiency of low-energy high-current electron beam in plasma channel in external magnetic field

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Abstract. Effective high current (5-20 kA) and low energy (tens of keV) electrons beam transportation is possible only with almost complete charging neutralization. It is also necessary to use quite high current neutralization for elimination beam self-pinching effect. The research is based on the self-consistent mathematical model that takes into account beam and plasma particles dynamic, current and charge neutralization of electron beam and examines the transportation of electron beam into a chamber with low-pressure plasma in magnetic field. A numerical study was conducted using particle in cell (PIC) method. The study was performed with various system parameters: rise time and magnitude of the beam current, gas pressure and plasma density and geometry of the system. Regularities of local virtual cathode field generated by the beam in the plasma channel, as well as ranges of parameters that let transportation beam with minimal losses, depending on the external magnetic field were determined through a series of numerical studies. In addition, the assessment of the impact of the plasma ion mobility during the transition period and during steady beam was performed.

1. Introduction

Growing interest in application-oriented use of low-energy high-current electron beams (LHEB) is predetermined by their unique opportunities for high energy density transportation at rather long distances without essential losses, and also effective transmission of this energy to object of influence. High energy density (up to 20 J/cm^2) and short pulse duration (several μs) make it possible to use electron beams in different technological processes connected with changing the state and properties of material surface [1].

High efficiency of LHEB transportation is possible only with almost full charge neutralization [2]. For this, LHEB should be transported in the pipe with low-pressure plasma or neutral gas (10^{-1} … 10^{-2} Pa). Besides, self-magnetic field can cause beam pinching, lowering efficiency of transportation. However, sufficient current neutralization and external magnetic field can be used to reduce this effect. Particular issue in such beam systems is potential possibility excitation of instabilities, e.g. Pierce instability, beam-drift instability, current thresholds of which can be below than beam current. Thus LHEB transportation in plasma and external magnetic field with high efficiency represents a sophisticated challenge. The purpose of this work is to determine the optimal parameters for LHEB transportation.

This paper describes mathematical model, equations and results of numerical research of LHEB transportation efficiency in the pipe filled with plasma in the external magnetic field in depending on system parameters.

2. Basic equations of the physical model

The mathematical model of self-consistent dynamics of the beam in the space charge and magnetic fields in the drift area, filled with plasma with the homogeneous density n_p, is based on the description of beam and plasma electrons by macroparticles [2]. The model is generated for the area coinciding with the tube and has dimensionality 2.5 (three-dimensional on dynamics, two-dimensional on fields).

Following assumptions were used in the model:

- Axial symmetry of processes $\frac{\partial}{\partial\theta}=0$;
- Prevalence of the longitudinal current of the beam: $J_z >> J_r$, J_θ;
- The plasma ions have huge mass with respect to electrons that is why they are considered immobile and density homogeneous and constant $n_i=n_p$.

Dynamics of beam and plasma electrons is described by system of relativistic equations in a cylindrical coordinate system:

$$\begin{cases} \dfrac{d\left(\gamma_\alpha \dot{z}\right)}{dt} = -\dfrac{e}{m_0}\left(\dot{r}B_\theta + E_z\right) - \nu_{ef}\dot{z} \\ \dfrac{d\left(\gamma_\alpha \dot{r}\right)}{dt} = -\dfrac{e}{m_0}\left(r\dot{\theta}B_z^* - \dot{z}B_\theta + E_r\right) + \gamma_\alpha r\dot{\theta}^2 - \nu_{ef}\dot{r} \\ \dfrac{1}{r}\dfrac{d\left(\gamma_\alpha r^2\dot{\theta}\right)}{dt} = \dfrac{e}{m_0}\left(\dot{r}B_z^*\right) - \nu_{ef}r\dot{\theta} \end{cases} \tag{1}$$

where m_0 is an electron rest mass; e is an elementary charge; E_z, E_r, B_θ are components of self electromagnetic field of the beam; B_z*=const is component of an external magnetic field; γ_α is the relativistic factor of particles α; α is plasma and beam electrons; ν_{ef} is effective collision frequency [3]. As shown in calculations, processes of additional gas ionization and plasma recombination can be neglected because they are practically in a dynamic equilibrium at he given parameters.

The fields is described by Poisson equations for the scalar potential Φ and longitudinal component of the vector potential A_z. Densities of charge and a beam current are related by the continuity equation:

$$\operatorname{div}\mathbf{J} + \frac{\partial\rho}{\partial t} = 0 \tag{2}$$

The total charge density in equation (2) is presented by the correlation:

$$\rho = \rho_b + \left(\rho_i + \rho_e\right) \tag{3}$$

where ρ_b, ρ_e are charge densities of beam and plasma electrons; $\rho_i = n_p e = const$ is charge density of plasma ions. The initial condition for the charge density of beam electrons is set as $\rho\big|_{t=0}=0$, which corresponds to the absence of the beam in the drift tube.

Boundary conditions for potentials are set from requirements of ideal conductivity of the surface of tube walls ($r=R$) and potentials continuity on the tube axis ($r=0$) and at tube end faces ($z=0$ and $z=L$):

$$\left.\frac{\partial\Phi}{\partial r}\right|_{r=0} = 0 \quad \Phi\big|_{r=R} = 0 \qquad \Phi\big|_{z=0} = \Phi\big|_{z=L} = 0 \tag{4}$$

$$\left.\frac{\partial A_z}{\partial r}\right|_{r=0} = 0 \quad A_z\big|_{r=R} = 0 \qquad \left.\frac{\partial A_z}{\partial z}\right|_{z=0} = \left.\frac{\partial A_z}{\partial z}\right|_{z=L} = 0 \tag{5}$$

Fields components are calculated using formulas of potentials differentiation:

$$E_z = -\frac{\partial \Phi}{\partial z} - \frac{\partial A_z}{\partial t} \quad E_r = -\frac{\partial \Phi}{\partial r} \quad B_\theta = -\frac{\partial A_z}{\partial r} \tag{6}$$

3. Research of transportation efficiency

Numerical simulations of the LHEB transportation were performed with the following parameters that were used in real LHEB guns [4-5]: energy of beam electrons E_0=20..40 keV, beam current I_0=15 kA, plasma temperature 2 eV, gas pressure p=10^{-1} Pa, gas ionization degree 10 %, plasma density n_p=$10^{10}\ldots10^{12}$ cm^{-3}, magnetic field induction B_z = 0..3 kGs. Pipe geometric parameters: L=20 cm, R=10 cm; beam radius: R_b=4.3 cm. The current impulse has leading edge (τ) with the linear increasing, and constant current (I_0) after τ.

Plasma density, external magnetic field induction and leading edge were selected as investigated parameters on which transportation efficiency depends. The relation of the maximum output current to current of pulse (I_b/I_0) was accepted the transportation efficiency criterion.

Dependence of transportation efficiency on plasma density in the case of fixed values of external magnetic field (Bz * = 1 kGs), injection energy E_0=20 keV and pulse leading edge (τ = 300 ns) is demonstrated in Figure 1. The analysis of the results shows that high efficiency is reached at the plasma density equal to or greater than the maximum density of the beam $n_{b0} = I_0 / (I_A S_b r_e \beta_{z0})$, where I_A is Alfevn current, S_b is area of the beam cut, r_e is classical radius of an electron, β_{z0} is velocity of beam electrons relative light speed with initial energy E_0. For the above parameters, the beam density was ~ 2 10^{11} cm^{-3}.

Insufficient efficiency of transportation at a lower plasma density is caused by insufficient charge neutralization for the beam electrons, which leads to the formation of a virtual cathode at the beginning of the drift pipe (Figure 2).

The presented results for the current differ from approximated estimates on limiting vacuum current [6]. That is due to the fact that in the paper the dynamic task is considered and during beam transportation transverse current density changes from uniform to tubular. As a result of this effect we get higher beam current in comparison with approximate stationary estimates.

Figure 3 shows dependence of transportation efficiency of the beam vs external magnetic flux, in the case of fixed values of plasma density (line 1 - n_p=$2.5\ 10^{11}$ cm^{-3}, line 2 - n_p=$1.8\ 10^{11}$ cm^{-3}) and leading edge (τ = 300 ns). Quite high transport efficiency (90%) is reached at values of the external magnetic field greater than or equal to self-magnetic field of the beam, which can be estimated by the formula:

$$B_b = \frac{1}{4\pi} \frac{2I_0}{cR_b} \sqrt{\frac{\mu_0}{\varepsilon_0}} . \tag{7}$$

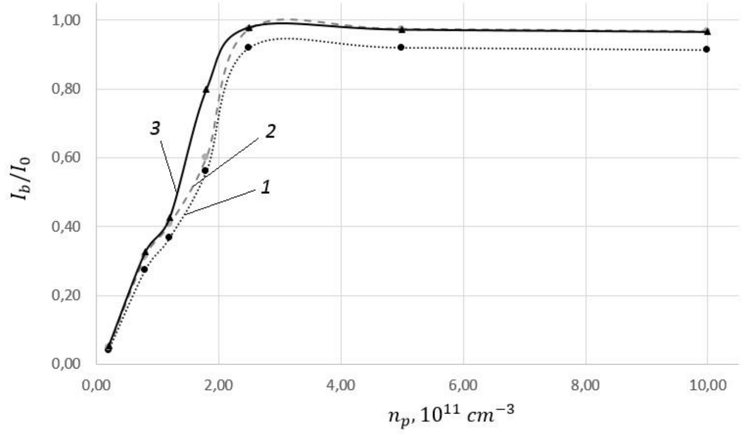

Figure 1. I_b/I_0 vs plasma density: I_0 *= 15 kA*, τ *= 300 ns*, E_0*=20 keV*, *t = 300 ns, lines: 1-* B_z*=1 kGs, 2-* B_z*=1.5 kGs, 3-*B_z*=3 kGs*

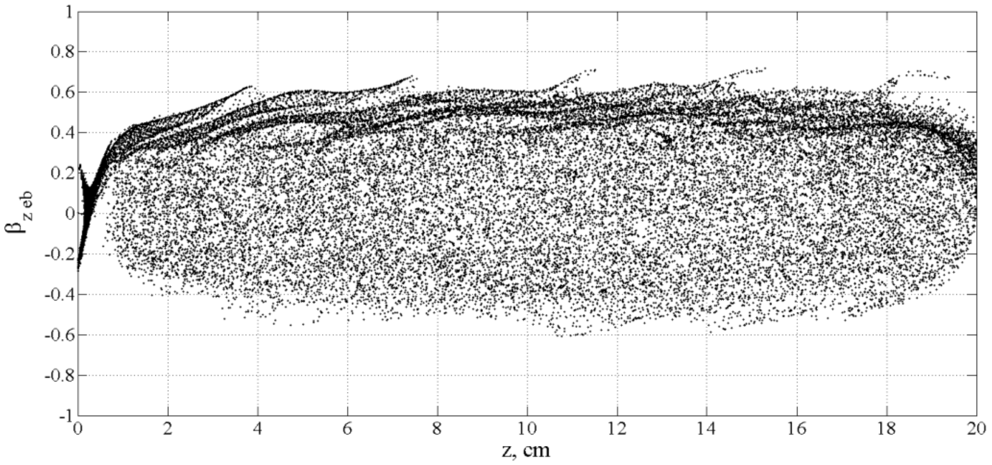

Figure 2. Phase portrait of the beam electrons I_0 *= 15 kA*, τ *= 300 ns*, E_0*=20 keV*, B_z *= 1 kGs*, n_p*=1.2* 10^{11} cm^{-3}, *t = 300 ns*

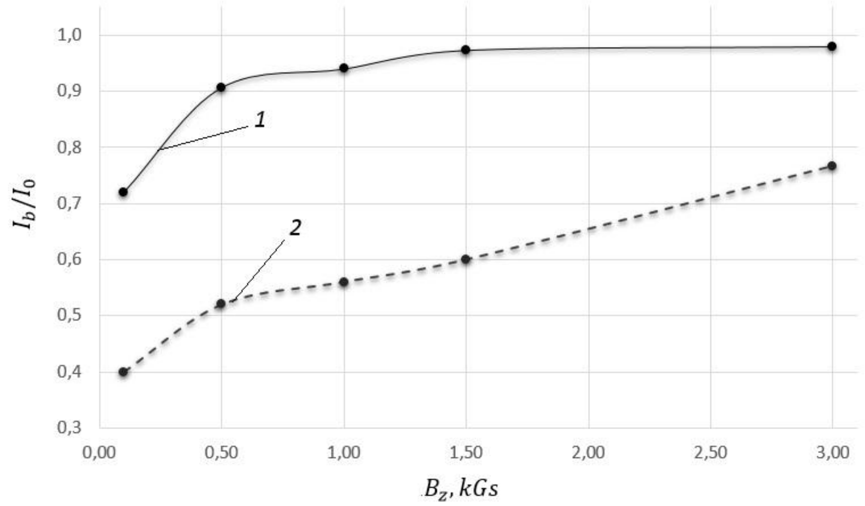

Figure 3. I_b/I_0 vs external magnetic flux: I_0 *= 15 kA*, τ *= 300 ns*, E_0*=20 keV*, *t = 300 ns, lines: 1-* n_p*=2.5* 10^{11} cm^{-3}, *2-* n_p*=1.8* 10^{11} cm^{-3}

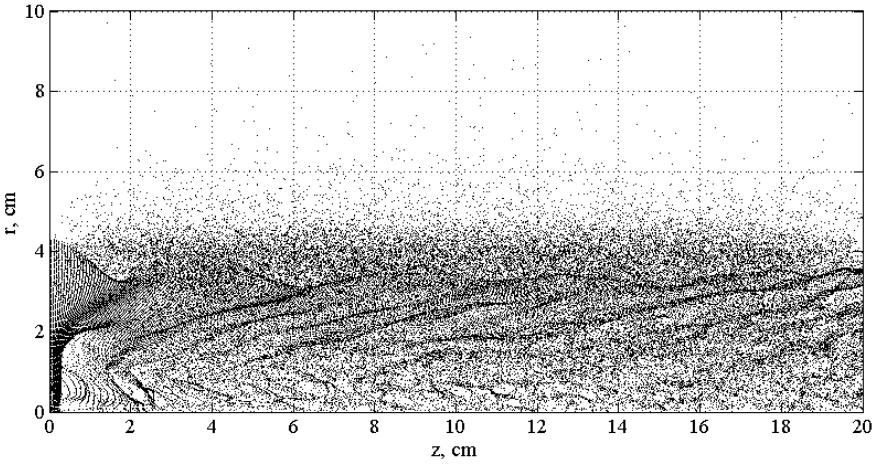

Figure 4. Configuration portrait of the beam electrons: $I_0 = 15\ kA$, $\tau = 300\ ns$, $E_0=20\ keV$, $t = 300\ ns$, $B_z = 0.5\ kGs$, $n_p=2.5\ 10^{11}\ cm^{-3}$

The value of the self-magnetic field for the initial beam parameters was 0.06 T. The lower value of the external magnetic field leads to insufficient weakening of its self-magnetic field and, as a consequence, self-pinching of the beam (Figure 4) and the formation of the virtual cathode.

When assessing the impact of leading edge (Figure 5) on the transportation efficiency, causes sufficiently small values are of the primary interest. The virtual cathode is formed at short leading edge (< 50 ns) even with the sufficient charge and current neutralization, because plasma electrons do not have time to leave the drift area quickly enough. However, virtual cathode dissipates by forces that extrude plasma electrons from the drift area and as a result the further beam transportation has minimal losses.

The increase of injection beam energy is known to lead to the increase of the limit of vacuum currents. This means that the effective beam transportation requires less plasma density in the drift pipe. It is well confirmed by numerical calculations (see Figure 6).

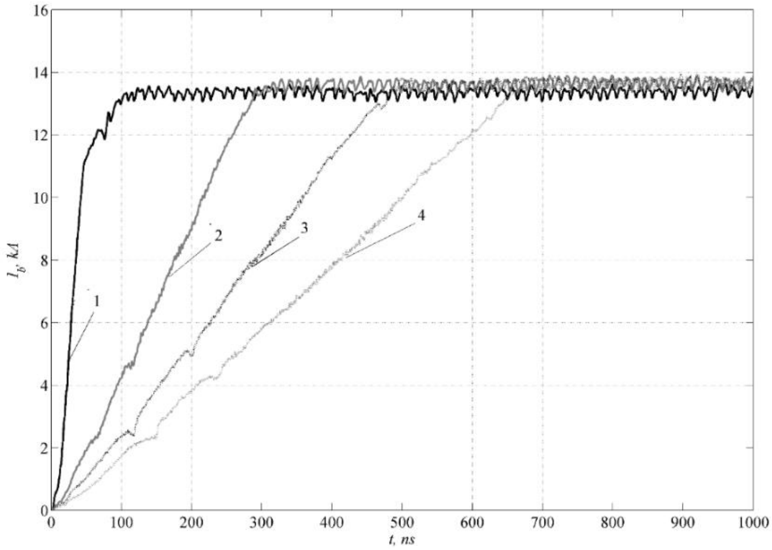

Figure 5. I_b current with different leading edge: $I_0 = 15\ kA$, $n_p = 2.5\ 10^{11}\ cm^{-3}$, $B_z = 1\ kGs$, $E_0 = 20\ keV$ lines: 1 – $\tau = 50\ ns$, 2 – $\tau = 300\ ns$, 3 – $\tau = 500\ ns$, 4 – $\tau = 700\ ns$.

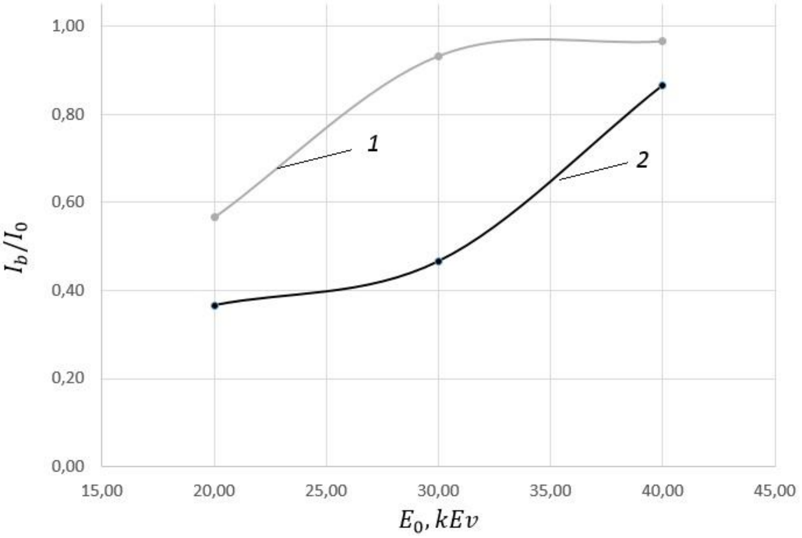

Figure 6. Ib/I0 dependence on injection beam electrons energy E0: I0 = 15 kA, τ = 300 ns, Bz = 1 *kGs*, lines: 1 – n_p=1.8 10^{11} cm^{-3}, 2 – n_p=1.2 10^{11} cm^{-3}.

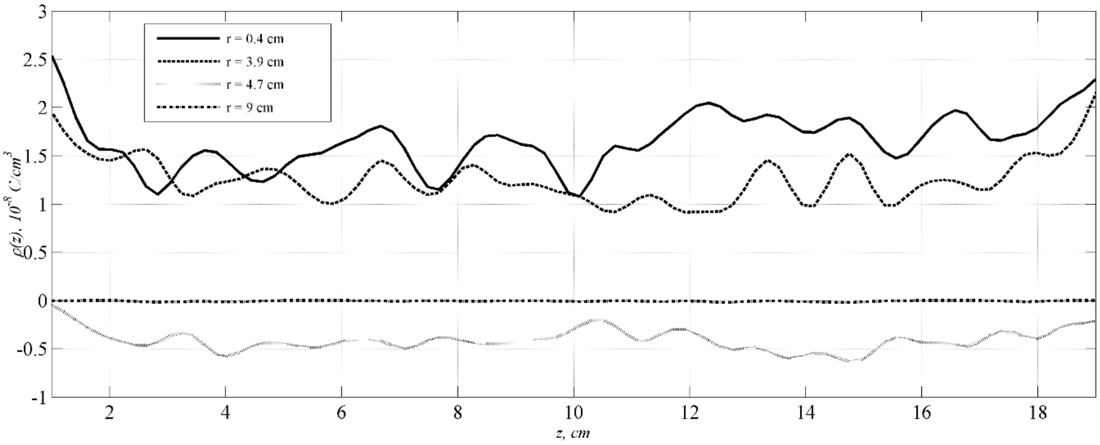

Figure 7. Total charge density ρ*(z)*: I_0=15 *kA*, τ =300 *ns*, B_z=1.5 *kGs*, n_p=2.5 10^{11} cm^{-3}, E_0=20 *keV*.

Figures 7 shows typical dependences of total charge density of the system in a longitudinal cut at the time point after beam transient period. There are oscillations of charge density distribution in space and time with frequency of the order of the Langmuir frequency (3-7 GHz) in the system. Due to inertial processes there can appear local areas with prevailing positive or negative charges.

4. Summary

Research of dynamics of plasma electrons leaving the beam drift area shows that the beam is transported in the overcompensation state with a maximum in near-axis area, which is confirmed in experiments [4] (Figure 7). This can be explained by the fact that the exit velocity of the plasma electrons on the initial injection stage exceeds the input electron beam velocity due to its inhibition in the transient mode.

Thus, there is positive scalar potential with a maximum at the drift pipe center (on axis z), which accelerates electrons at the beginning segment of the drift pipe. With increasing time, the flow of the plasma electrons becomes lower than the injected beam current and increases the negative charge influence in the beam drift area. Such dependence of scalar potential is due to boundary conditions at drift pipe end faces. Further research of transportation efficiency in case of different boundary conditions presents interest.

Beam instabilities are not observed apparently because the beam energy dispersion during of the transportation is rather considerable.

Thus as a result of numerical calculations based on the presented model, quantitative estimates of the beam and plasma parameters required to reach the highest efficiency of LHEB transportation can be obtained.

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