Plasma Channel Forming by Electron Beam in a Low-Pressure Air in Magnetic Field

V.P. Grigoriev, T.V. Koval, and A.G.Potashev

Tomsk Polytechnic University , 30 Lenin Ave., Tomsk, 634034, Russia
Tel: +7-3822-563429, Fax: +7-3822-563429, E-mail: grig@am.tpu.ru

Abstract – Electron beams with power density 10^6–10^9 W/cm^2 are used for modification of the materials surface. The question of the transporting of high current low-energy beam in a low-pressure gas filled electro-dynamic system is of current interest.

In this work there is presented a model and there has been conducted theoretical research of the plasma channel forming under the low-energy beam transporting in low-pressure air in an external magnetic field.

There has been shown the magnetic field influence on the plasma channel parameters and the current neutralization of electron beam in dependence on the gas pressure and the drift tube geometry. The comparison with experimental data is conducted.

1. Introduction

The high current electron beams of low-energy have used wide application for the solution of the problems of the materials surface layers modification. However it is necessary to resolve number of problems for the efficient application of energy stored in electron beams. One of the most important problems is the implementation of an electron beam transport to a target with the small losses. These difficulties are connected with beam parameters used and the restrictions on the system parameters. Really, for the electrons energy range used $E_e \sim 10 \div 30$ keV the ultimate currents in technologic installations are on the level of tens amperes, but in the same time it is required to conduct beams with the currents $I_b \sim (1–2)$ kA. Therefore it is necessary to maintain the full charge neutralization and high enough current one for the transport problem solution. It can be ensured most simple by a beam injection in the preliminary created plasma or in a neutral gas of the specific pressure. Besides there is an external magnetic field is used much to maintain the more stable beam propagation.

It is not possible to apply the extant models of the electron beams transport in gas and plasma [1, 2], as they are oriented on the high enough plasma densities, gas pressures $p > 0{,}1$ Torr and the short current pulses.

The technologic systems peculiarity is the exploitation of electron beams with the pulse duration till tens microseconds and the gas pressure $p = (10^{-4} \div 10^{-3})$ Torr. In these specifications the investigation of the plasma channel formation under beam propagation in gas is necessary to carry out with taking into account the processes of ionization and the plasma decay because of recombination and diffusion and others processes of arising and destruction of particles in dependence on the gas kind.

In the report there is presented the plasma channel formation model under an electron beam propagation in low-pressure air with given an external magnetic field and the results investigation of plasma channel parameters and the current neutralization of a beam in dependence on the beam current , the pulse duration and a gas pressure.

2. Basic Equations

Let consider the plasma channel formation under the electron beam propagation along the axis of the cylindrical drift tube of radius R_b filled with air at pressure (10^{-4}–10^{-3}) Torr. On the assumption of cylindrical symmetry the basic model equation can be written in the form:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial A_z}{\partial r}\right)+\frac{\partial^2 A_z}{\partial z^2}=-\frac{4\pi}{c}(j_{bz}+j_{pz})\,; \tag{1}$$

$$\frac{1}{\nu_{ef}}\frac{\partial \mathbf{j}_p}{\partial t}=-\mathbf{j}_p+\sigma\mathbf{E}-\frac{\Omega_e}{B\nu_{ef}}[\mathbf{j}_p,\mathbf{B}]\,; \tag{2}$$

$$\mathrm{E}_z=-\frac{1}{c}\frac{\partial A_z}{\partial t}\,;\ \mathrm{B}=(\mathrm{B}_r,\mathrm{B}_\theta,\mathrm{B}_z)\,; \tag{3}$$

$$\frac{\partial n_i^{(1)}(r,z,t)}{\partial t}=<\sigma_i^{(1)}\mathrm{v}_b>n_g^{(1)}n_b+n_eK_i^{(1)}n_g^{(1)}- -\alpha_{r1}n_i^{(1)}n_e-\frac{1}{r}\frac{\partial}{\partial r}\left(rD_{A\perp}\frac{\partial n_i^{(1)}}{\partial r}\right); \tag{4}$$

$$\frac{\partial n_i^{(2)}(r,z,t)}{\partial t}=<\sigma_i^{(2)}\mathrm{v}_b>n_g^{(2)}n_b+n_eK_i^{(2)}n_g^{(2)}- -\alpha_{r2}n_i^{(2)}n_e-\frac{1}{r}\left(rD_{A\perp}\frac{\partial n_i^{(2)}}{\partial r}\right); \tag{5}$$

$$n_e(r,z,t)=n_i^{(1)}(r,z,t)+n_i^{(2)}(r,z,t)-n_b(r,z,t) \tag{6}$$

$$\sigma = \frac{\omega_p^2}{\nu_{ef}} \frac{1}{c}; \qquad (7)$$

$$D_{A\perp} = (\varepsilon_e + T_i) \frac{\nu_{ea} c}{\Omega_e^2}. \qquad (8)$$

Here $A_z(\mathbf{r}, t)$ – the vector potential of the field, created by the plasma and beam currents; $j_{bz}(\mathbf{r}, t)$ – the longitudinal density of electron beam current, that is defined by the beam current pulse on the drift space inlet; $\mathbf{j}_p(\mathbf{r}, t)$ – the density of the plasma current inducted under the electron beam propagation; $\mathbf{B}(\mathbf{r}, t)$, $\mathbf{B}(\mathbf{r}, t)$ – the vectors of the magnetic and electric field intensity; $n_b(\mathbf{r}, t)$ – the beam electrons density, defining the electrons distribution along the beam axis and in its cross section; v_b – the beam electrons velocity; $n_i^{(1),(2)}$ – the molecular ions densities of nitrogen ″1″ and oxygen ones ″2″ accordingly, $n_g^{(1),(2)}(\mathbf{r}, t) = n_g^{(1),(2)}(\mathbf{r}, t = 0) - n_i^{(1),(2)}(\mathbf{r}, t)$ – the molecule densities of nitrogen and oxygen in the drift space at the arbitrary instant of time t; $\sigma(\mathbf{r}, t)$, $\nu_{ef}(\mathbf{r}, t)$ – the plasma conductivity and the effective frequency of electron collisions; $\varepsilon_e(\mathbf{r}, t)$ – the specific energy of electrons of plasma, taking place in the strong electromagnetic fields. Below ε_e will be identified with the electrons temperature (in [eV]).

For air in the range $\varepsilon_e \sim 0.1$–50 eV the collisions frequency ν_{ef} has view [3]:

$$\nu_{ef} = 2.2 \cdot 10 p \left(\frac{\varepsilon_e}{0.026} \right)^{1/2} + 0.29 \cdot 10^{-5} \frac{n_i}{\varepsilon_e^{3/2}} L,$$

p is the air pressure [Torr], L is the Coulomb logarithm:

$$L = 23.4 - 1.15 \lg n_e + 3.45 \lg \varepsilon_e,$$

$\sigma_i^{(1),(2)}$ is the ionization cross sections of the nitrogen and oxygen molecules, that are connected with the specific ionization coefficient of air S and gas pressure [4, 5]. In the work has been used as the experimental values $\sigma_i^{(1),(2)}$ so the theoretical ones [6].

$$\sigma_i = \pi r_0^2 (m_e c^2)^2 \sum_{\mathrm{k}} \frac{n_k}{E_e^2} \frac{E_e}{U_{ik}} \left(1 + \frac{2}{3} \ln \frac{E_e}{U_{ik}} \right),$$

r_0 is classical electron radius, n_k, U_{ik} is electrons number on the k-th shell of atoms and the ionization potential of the k-th shell, $\alpha_{r1,2}$ are the dissociative recombination coefficients for nitrogen and oxygen accordingly.

$$\alpha_{r1} = 2.0 \cdot 10^{-7} (0.026 / \varepsilon_e)^{0.39} \text{ cm}^3\text{/s},$$

$$\alpha_{r2} = 2.1 \cdot 10^{-7} (0.026 / \varepsilon_e)^{0.56} \text{ cm}^3\text{/s},$$

$K_i^{(1),(2)}$ is the constants of the ionization by thermal plasma electrons .

The angle brackets in (4)–(5) denote the averaging under the beam electrons velocities.

In the equations (1)–(8) there have been included the processes that have an essential effect on the plasma channel formation in the air pressure range considered. Such processes, as the complex ions N_4^+, O_4^+ and the negative ions O_2^- formation can be neglected.

The presented nonlinear equations system, added by the initial values for the potential, the beam current and plasma densities has been solved numerically.

The results of numerical simulation, that are presented in Figs. 1–6, display the dynamics of the plasma channel formation and the current neutralization in dependence on the electron beam parameters on the drift tube inlet.

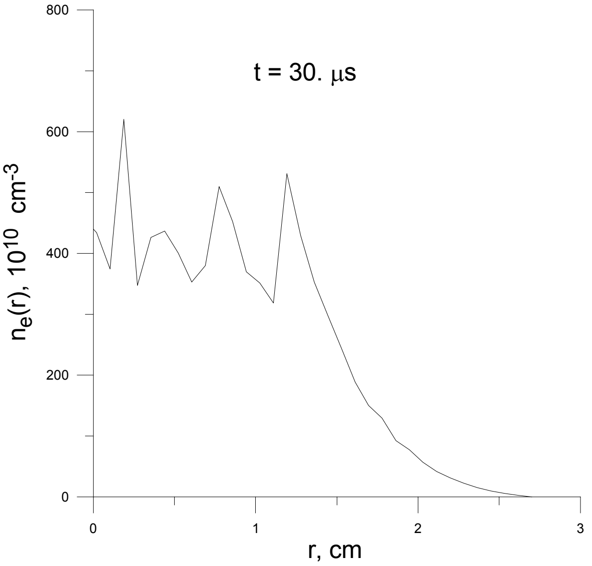

Fig. 1. The radial profile of the plasma electron density, $p = 10^{-4}$ Torr, $r_b = 1.25$ cm

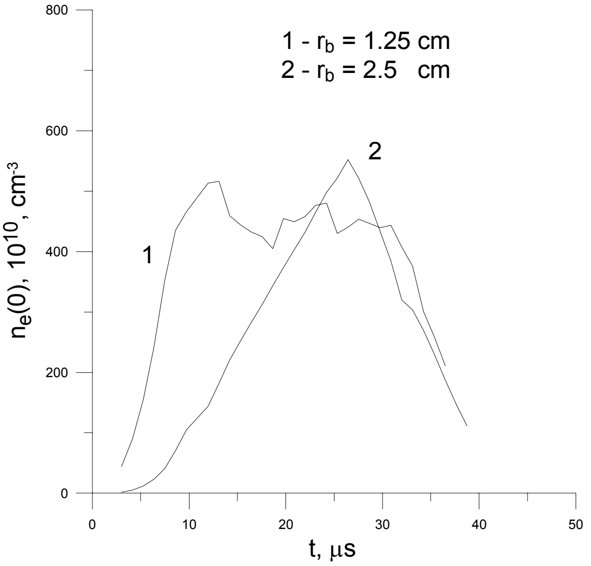

Fig. 2. The plasma electron density dependence on time at the drift tube axis $r = 0$

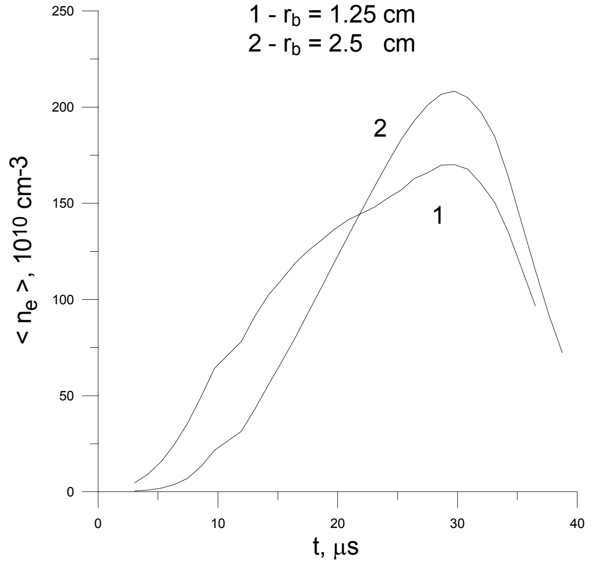

Fig. 3. The dependence of the density n_e plasma averaged over the plasma cannel cross section

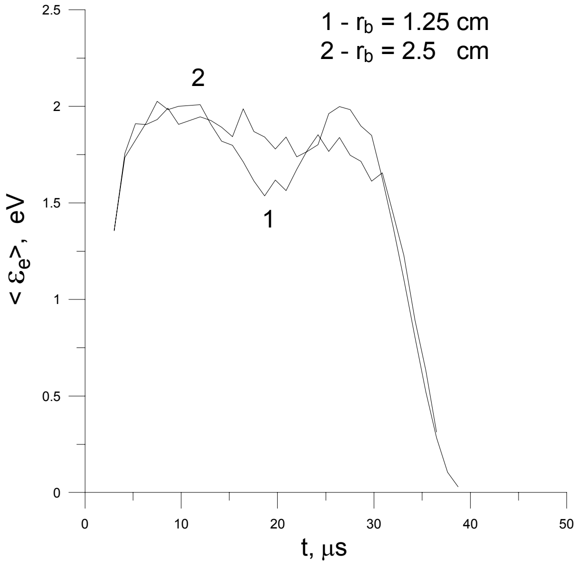

Fig. 4. The plasma electrons “temperature” averaged over the plasma cannel cross section versus time

In Figs. 1–5 are shown curves describing the plasma creation dynamics under the injection of beam with the pulse duration 35 μs, the electrons energy $\varepsilon_b = 20$ keV and maximum current 540 A into the drift tube of radius $R_c = 2.7$ cm at air pressure $2 \cdot 10^{-4}$ Torr. The current pulse was taken from an experiment in accordance with work [3].

As it follows from the curves conduct that there has been originated the high-ionized plasma with the electron density ~ $5 \cdot 10^{12}$ cm^{-3} under the beam injection. The average plasma electrons density is sustained on the level $4 \cdot 10^{12}$ cm^{-3} in the region of uniform beam and falls abruptly out of beam (Fig. 1). The typical dependence of the density n_e on the plasma channel axis versus time is shown in Fig. 2 and one averaged over the plasma cannel cross section in Fig. 3. The plasma electrons “temperature” versus time is shown in Fig. 4. For the given system parameters the plasma electrons “temperature” is connected with the electric field of a electron beam, therefore the plasma electrons have the highest “temperature” $\varepsilon_e \sim 2 - 2.5$ eV in the beam region. The comparatively low level of ε_e is conditioned by the rather weak current of the injected beam.

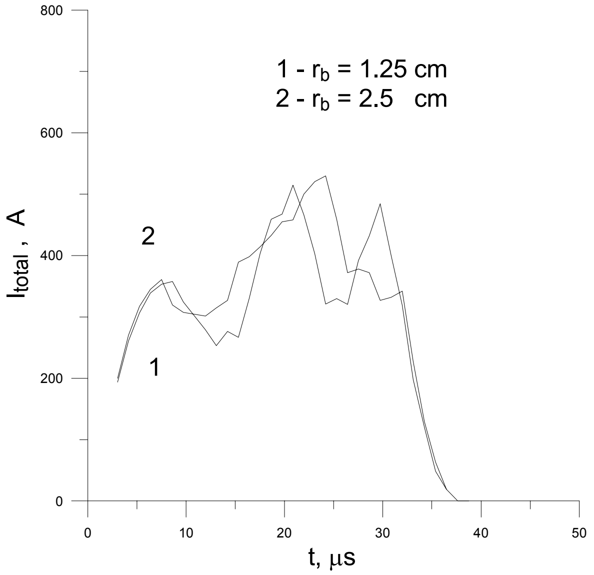

Fig. 5. The total current $I_{\text{total}} = I_b + I_p$ in the drift space

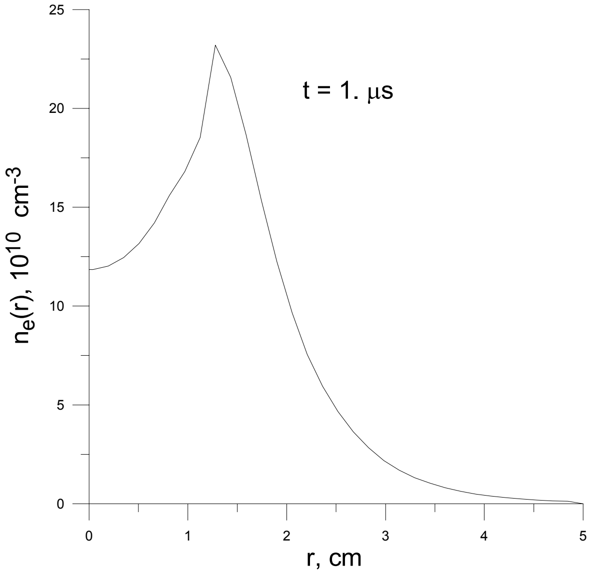

Fig. 6. The radial profile of the plasma electron density, $p = 10^{-4}$ Torr, $I_{b,\max} = 15$ kA, $r_b = 3$ cm, $R_c = 5$ cm, $E_e = 20$ keV

Besides the plasma channel parameter there have been the plasma current $I_p = 2\pi\int_0^{Rc} j_p(\bar{r},t)rdr$ and the total current $I_{\text{total}} = I_b + I_p$. The study of the structure and value of the plasma current (and hence the current neutralization rank) in dependence on the beam parameters, a gas pressure and the drift chamber geometry is necessary to determine and create the circumstances of the optimal electron beam transport. The total current dependence versus time for the electron beams with the different current density is shown in Fig. 5.

The plasma channel formation was investigated for a beam at the more low pressure $p = 10^{-4}$ Torr, the pulse duration 2 µs, $I_{b,\max} = 15$ kA and $r_b = 3$ cm in the drift tube $R_c = 5$ cm. The results of the plasma density calculation are presented in Fig. 6. For suchlike system parameters the electrons "temperature" lays down ~ 4–5 eV, and the current neutralization rises substantially.

References

[1] V.P. Grigoriev, A.V. Zakharov, N.A. Kondratiev, V.I. Smetanin, Yu.P.Surikov, *in Proc. 8th Int. Conf. on High Power Particle Beams*, 1990, pp. 659–664.

[2] S.K. Iyyengar and V.K. Rohati, IEEE Trans. Plasma Sci. **14**, 277 (1986).

[3] V.N. Devyatkov, N.N. Koval, P.M. Schanin, V.P. Grigoriev and T.V. Koval, Laser and Particle Beams **21**, p.p. 243–248 (2003).

[4] V.E. Golant, A.P. Zhilinsky, I.E. Saharov, *Foundation of Plasma Physics*, Moscow, Atomizdat, pp. 47–113, (1977).

[5] M. Knoll, J. Eichmeier, *Technical Electronics*, Moscow, Energy, V. **1** (1971).

[6] M. Gryzinski, Phys. Rev. **138**, pp. 336–338 (1965).