Self-Focusing of Electron Beam in Plasma Channel in Heterogeneous Magnetic Field

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Abstract – Electron beams with high current density j > 20 A/cm^2 present a great interest because of its capacity to transport storage energy through rather long distances to impacted object without any noticeable losses. Besides it is possible to control the beam parameters by means of external filled and additional external conditions of transporting.

In this work the theoretical investigation of transporting and focusing of electron beam propagating in drift tube filled with low pressure air $10^{-2} \div 10^{-4}$ Torr in proper and external fields is presented. It was obtain that the heterogeneity of external magnetic field have noticeable role in transporting of electrons beam compensated by charge. It was shown that changing of magnetic field value and its gradient can be governed by density of the beam current on collector and by energy distribution of electrons.

1. Introduction

Low energy electron beams $\varepsilon_e \sim 10$–40 keV represent big interest for technological tasks because of its capacity to transport storage energy through rather long distances to impacted object without any noticeable losses [1–2].

The transporting of such beams mast is realized in conditions of full charge neutralization in the central area of beam because of low energy at the high current density. The investigation of transporting in different conditions perform by beam envelop method as well as with numerical modeling by PIC method. At that the control of beam parameters can be carry out by external heterogeneous magnetic field.

In that work the theoretical investigation of transporting and focusing of electrons beam propagating in drift tube filled with low pressure air $p \sim 10^{-2} \div 10^{-4}$ Torr is presented.

2. General Equations

Let us regard the transporting and focusing of electron beam with current density j > 20 A/cm^2, propagating in drift tube filled with low pressure air in proper as well as in external magnetic fields. The electrons movement equations in general case of heterogeneous external field $B_z(z)$ can be written as:

$$\ddot{x} = \frac{r_b e\, B_{\varphi,\max} A}{r^2 \beta_z\, \gamma m_o} x - \frac{eB_z}{\gamma m_0 c}\dot{y} + \frac{e\beta_z}{\gamma m_0}\tilde{B}_r y\,; \qquad (1)$$

$$\ddot{y} = \frac{r_b e\, B_{\varphi,\max} A}{r^2 \beta_z\, \gamma m_o} y + \frac{eB_z}{\gamma m_0 c}\dot{x} - \frac{e\beta_z}{\gamma m_0}\tilde{B}_r x\,; \qquad (2)$$

$$\begin{aligned}\ddot{z} = &-\frac{r_b e\, B_{\varphi,\max}}{r^2\, \gamma m_o}(1 - f_M)(\beta_x \cdot x + \beta_y \cdot y) - \\ &-\frac{e}{\gamma m_0}\tilde{B}_r(\beta_x \cdot y - \beta_y \cdot x),\end{aligned} \qquad (3)$$

where

$$\beta_z = \dot{z}/c\,,\ \beta_x = \dot{x}/c\,,$$

$$\beta_y = \dot{y}/c\,,\ \gamma^2 = 1 - \beta_x^2 - \beta_y^2 - \beta_z^2\,,$$

$$\tilde{B}_r = -\frac{1}{2}\frac{\partial B_z}{\partial z}\,,\ B_{\varphi,\max} = -\frac{2}{r_b}\frac{I}{c}\,,$$

$$A = \beta_z^2(1 - f_M) - 1 + f_e\,.$$

Written equation system admit to investigate electrons movement in beam under different conditions with respect to changing of beam radius $r_b(z)$. At that degree of charge f_e and magnetic (current) f_M neutralization defined from results of investigations for creation of plasma by electron beam and analysis of induced process on beam front.

Analytical solving of equations system (1)–(3) can be get only in preposition that charge density is constant, $\beta_z^2 >> \beta_x^2 + \beta_y^2$ and $f_M = f_e = 1$. In general case without those propositions written above system can be solved only numerically.

As it was shown by results of numerical investigations positions of crossovers $z_{c,i}$ (i – number of crossover) and its depth essentially depended from beam current density on drift tube input $j_{b0}(\vec{r})$, and also from gas pressure in drift tube. The gas pressure determinate the plasma density n_p. So at $p = 4\cdot 10^{-4}$ Torr and beam current I = 100–300 A the plasma density n_p come to level $(4 \div 8)\cdot 10^{11}$ cm^{-3}. The time of beam neutralization, taking into account that on the front current rise in time linearly, is defined by formula $\tau_n = 2/S_i\beta_z c$ that for pressure $p = 4\cdot 10^{-4}$ Torr and voltage 16 kV come to $\tau_n \propto 3.47 \cdot 10^{-6}$ s, where S_i is specific ionization.

Influence of gas pressure or creating plasma density on radial dimension of beam can be considered through heterogeneity of charge neutralization degree

$$f_e = 1 - d_f(1 - r^2 / r_{b0}^2), \quad (5)$$

where $d_f = d_f(p) \ll 1$. Heterogeneity f_e is connected with beam focusing which increase density $n_b(r)$.

3. Influence of External Magnetic Field on Beam Focusing

à. Homogeneous magnetic field

For transporting fully neutralized in charge beam in homogeneous magnetic field in self focusing regime it is of interest the magnetic field region

$$B_z^2 < 4 \cdot 1.7 \cdot 10^3 B_{\varphi,\max} \frac{\gamma}{r_b \beta_z} |A|, \quad (7)$$

where it is possible to accomplish rather high level of beam compression in crossover and its stabilization with respect to deviation from axis [3]. Here the field is taken in Gausses, and beam radius in centimeters, $B_{\varphi,\max}$ is self field on the beam bound. Field B_z, defined by (7), depends on current density of transporting beam and longitudinal velocity of electrons. So for beam with $r_{b0} = 2.5$ cm, and with density $n_{b0} = 0.892 \cdot 10^{10}$ cm^{-3} the self magnetic field at the edge of beam is equal to $B_{\varphi,\max} = 16$ G. in crossover region at the external homogeneous field $B_{z,\max} = 50$ G. It is admit to achieve beam compression about five times.

b. Heterogeneous magnetic field

The results of numerical investigation of beam transporting under full charge neutralization in field $B_z(z)$ (solenoid field has limited length including edge effects on the solenoid input and output) are shown on the Figs. 1–6.

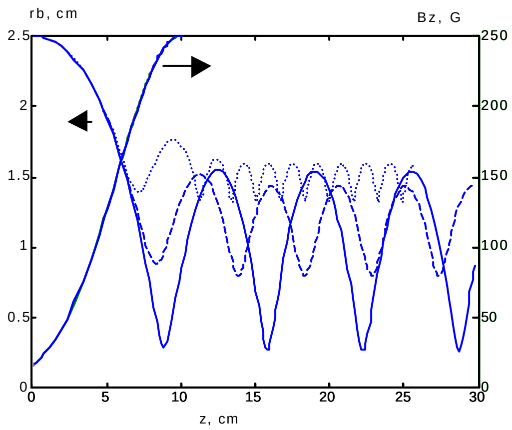

Fig. 1

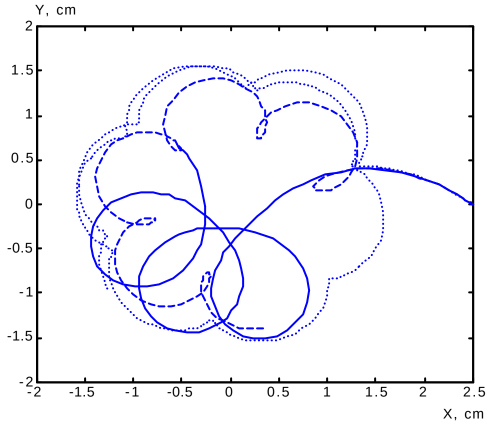

Fig. 2

The electrons beam envelops are shown on the Figs. 1 and 2 in plane (r, z) and plane (y, x) for different heterogeneity: $d_f = 0$ (firm line); 0.1 (dash line) and 0.25 (dotted line). The distribution of external magnetic field $B_z(z)$ is shown also on the Fig. 1, where $B_{z,\max}$ is value of homogeneous field ($B_r = 0$) in region $z > 10$ cm. It is follow from the Figs. 1 and 2, that increasing of charge neutralization heterogeneity lead to decreasing of modulation depth, spatial modulation period and beam envelop radius. At that the electrons movement in self and external magnetic fields consist of two rotations (Fig. 2): first of it with high cyclotron frequency Ω_0 and small radius of rotation about leading center, second of it with slow rotation with frequency $\Omega \ll \Omega_0$ about beam axes with radius r_b. The beam envelop depend on magnetic field $B_{z,\max}$, as far as from gradient value on drift tube input and besides on current density and electrons energy (Figs. 4–7).

It was shown by numerical investigations that big field gradient on drift tube input ($B_r < 0$) with decreasing of field $B_z(z)$ in interval $z < 0.2z_{c,1}$ have almost no influence on beam envelop. In this region of magnetic fields the self magnetic field has dominating influence on electrons movement.

At the comparatively low level of gradient, when slow rise of field B_z in interval $z \le z_{c,1}$ take place, the self magnetic field as well as radial magnetic field affect on beam focusing in region $|\partial B_z / \partial z| \ne 0$ equally. Especially, the influence of radial field is notable near of focus $z \approx z_{c,1}$. Passing to region with zero gradient ($B_r = 0$, it is region with $z > 10$ cm on the fig. 1) the beam of smaller radius is kept by longitudinal magnetic field $B_{z,\max}$ and is transported in drift tube. So, the changing of magnetic field value as well as its gradient can govern the section πr_{col}^2 on output, i.e. beam current density j_{col} at collector.

Numerical investigation of electron beam envelops r_b dependence from magnetic field $B_{z,\max}$ show that (for beam with initial radius $r_{b0} = 2.5$ cm) most change of beam radius take place for beams with smaller density. So for $B_{z,\max} = 600$ G in interval of initial electron energy $\gamma_0 = 1.029 \div 1.088$ the current density on collector is $j_{col} = 30.3 \div 44.2$ À/cm^2 (for $I = 200$ À), what correspond to increasing of initial density from 3 to 4 times. For the case $I = 800$ À current density on collector is $j_{col} = 88.2 \div 99.5$ À/cm^2 for energy range in question, at that initial electrons density increase to $2 \div 2.4$ times.

Depth, position of the first crossover $z_{c,1}$ (Fig. 3) and period of spatial modulation l (Fig. 4) are depends from ratio of self and external magnetic fields (Figs. 3 and 4; $I = 200$ À – curves 1 and 2, $I = 800$ À – curves 3 and 4). When condition $B_r \approx B_\varphi$ is executed, what is realized for beam with current $I = 200$ À, the increasing of magnetic field $B_{z,\max}$ bring to decreasing of $z_{c,1}$ (Fig. 3). At that time when coordinate $z_{c,1}$ practically not changing for beams with current $I = 800$ À and electron energy $\gamma_0 = 1.029 \div 1.088$, that case correspond to $B_r < B_\varphi$. In Fig. 4 it is shown the change period of spatial modulation l electron flow. Decreasing of period l is conditioned by dependency of Larmor radius from beam parameters and external magnetic field. The expression

$$B_z = B_{z\max} \exp\left[-(z_m - z)^2/1.44a^2\right]$$

was used for description of coil magnetic field.

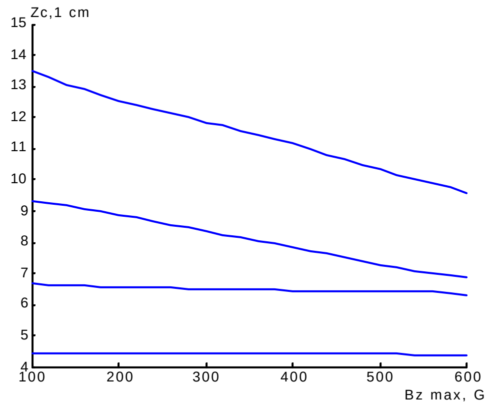

Fig. 3

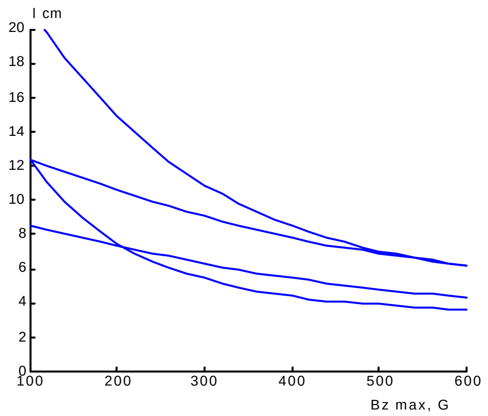

Fig. 4

Parameter a characterizes the magnetic field gradient on distance $z = z_m - a$, magnetic field decrease in two times as compared with maximal value. The field B_r is bigger as more big a. At that function $B_r(z)$ have maximum at coordinate

$$z_{r\max} = z_{\max} - a/1.2 .$$

For magnetic field shown on the Fig. 1 $z_{\max} = 10$ cm, $à = 5$ cm and $z_{r\max} = 5.8$ cm. At that $B_r(z_{r\max}) = 20$ G and $B_\varphi = 16$ G. In Fig. 6 and Fig. 7 it is shown dependencies of radius and longitudinal velocity on parameter a for values $z_{\max} = 10$ cm. Comparing Fig. 1 and Fig. 5 one can notice that first crossover coordinates z_{c1} and $z_{r\max}$ coincide, i.e. most influence on changing of longitudinal velocity take place exactly in $B_r(z_{r\max})$ region.

Beam compression for values $a < 5$ cm take place for account of self magnetic field as well as for account of external magnetic field $B_r(z)$ is decreasing with increasing of parameter a. Significance of longitude component of filed $B_z(z) > B_r(z)$ is increasing at $a > 5$ what in its own turn, bring to weakening of beam compression by self magnetic field.

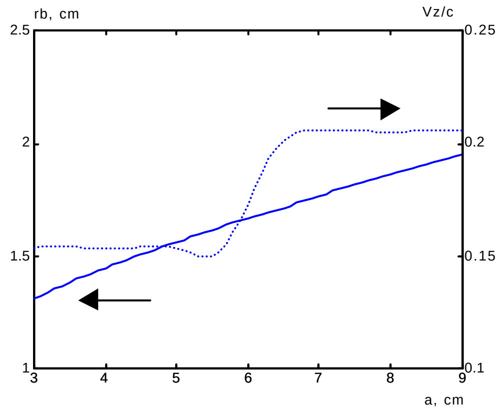

Fig. 5

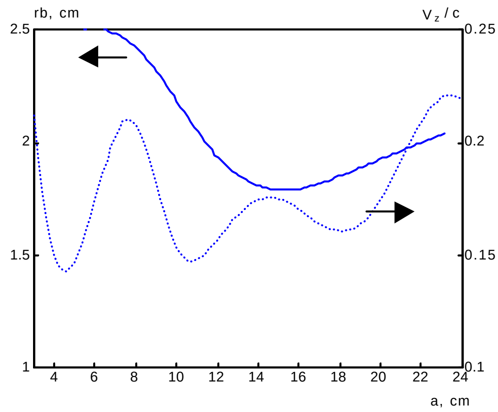

Fig. 6

The dependencies of r_b and β_z at $z_{\max} = 25$ cm are shown on Fig. 6. At the values $a < 7$ cm gradient scale is small in compare with distance between crossovers therefore radial field and constant field ($z > z_m$) have no influence on changing of beam envelop radius. Beam compression take place at $7 < a < 15$, and most compression corresponds $B_r(z) > B_z(z)$ at coordinate z_{ci} and $z_{r\max}$ accordingly.

The electrons beam envelops and the heterogeneous magnetic field distribution of external magnetic field $B_z(z)$ are shown on the Fig. 7 for heterogeneity: $d_f = 0.1$ (firm line); 0.25 (dotted line).

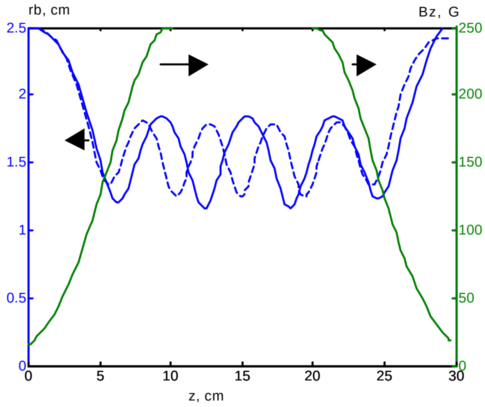

Fig. 7

Heterogeneity of coil magnetic field so as heterogeneity of beam density through it section and spread of electron velocities cause plasma heterogeneity in drift tube. At that the forming of heterogeneous plasma channel with high plasma density near of drift tube axis take place, what increase the effectiveness of electrons beam transporting It explains the transversal dimension of electrons beam prints on collector which were experimentally obtained [1].

Conclusion

Heterogeneity of external magnetic field plays essential role at transporting electrons beam compensated in charge. At that radius of transporting beam envelop and longitudinal velocity of electrons are essentially depended from level of magnetic field gradient, from ratio distance between focuses and width of gradient beam parameters at input.

Changing of magnetic field value can be governed by density of energy transferred on collector by beam.

References

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