Efficiency Enhancement of Coaxial Device with Two Charged-Particle Beams by Controlling its Limiting Currents

Tetyana Yatsenko and Kostyantyn Ilyenko
Department of Vacuum Electronics, Institute for Radiophysics and Electronics, NAS of Ukraine, Kharkiv, Ukraine
Email: yatsenko.tetyana.yu@gmail.com

Abstract—**Efficiency enhancement of electron devices with two concentric magnetically-confined annular charged-particle beams with the help of non-zero bias voltage applied to the inner conductor of a coaxial drift-tube is studied. The inner conductor bias voltage not greater than ±50 kV is capable of controlling the limiting currents of two electron beams on the level up to 15 %.**

I. INTRODUCTION

Creating powerful two-frequency TWTs for various applications and developing millimetre and submillimetre coaxial multibeam microwave oscillators have substantial theoretical and practical interest [1,2]. It is important to adjust output parameters of the microwave radiation by controlling the currents of charged-particle (e.g. electron) beams in such devices. In the approximation of strong magnetic field, we study one type of control of limiting currents of two concentric magnetically-confined annular charged-particle beams in unbounded coaxial drift-tube [3-8] with a bias voltage applied to the inner conductor of drift-tube.

II. RESULTS

We find analytically and numerically the potential created by the system of two concentric annular charged-particle beams propagating in an ideally conducting coaxial drift-tube with the help of the Poisson equation, assuming that the charged-particles move along the infinitely strong magnetic field lines (along the z-axis) [4,5],

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial\varphi}{\partial r}\right)=\begin{cases}0, & r_1\le r<r_{i1}, r_{o1}\le r<r_{i2},\\ & r_{o2}\le r\le r_2;\\ -\dfrac{4\pi\,|I_{0k}|}{c\beta_{\|k}(r_{ok}^2-r_{ik}^2)}, & r_{ik}\le r<r_{ok},\\ & k=1,2\end{cases}\qquad(1)$$

where $r_1, r_2, r_{i1}, r_{o1}, r_{i2}, r_{o2}$ are the radii of the inner and outer tube conductors and the inner and outer radii of the first and second beams, respectively; $|I_{01}|$, $|I_{02}|$ are the injection currents of beams;

$$\beta_{\|k}=\sqrt{1-\frac{\gamma_k^2}{\gamma_{\|k}^2}\frac{1}{\left(\gamma_k-\dfrac{q\varphi}{m_q c^2}\right)^2}},\quad r_{ik}\le r<r_{ok},\qquad(2)$$

is the longitudinal dimensionless velocity of k-th beam in the units of speed of light c in vacuo; γ_k and $\gamma_{\|k}=\gamma(1+\gamma_k^2\beta_{\perp k}^2)^{-1/2}$ are the relativistic factor and dimensionless longitudinal beam kinetic energy; $\beta_{\perp k}$ is the transversal velocity of beam; m_q, q are the mass and charge of charged-particles, respectively.

The boundary conditions for equation (1) have the form

$$\begin{gathered}\varphi(r_1)=V_0,\qquad \varphi(r_2)=0,\\ \varphi(r_{ik}-0)=\varphi(r_{ik}+0),\quad \varphi(r_{ok}-0)=\varphi(r_{ok}+0),\\ \left.\frac{\partial\varphi}{\partial r}\right|_{r_{ik}-0}=\left.\frac{\partial\varphi}{\partial r}\right|_{r_{ik}+0},\quad \left.\frac{\partial\varphi}{\partial r}\right|_{r_{ok}-0}=\left.\frac{\partial\varphi}{\partial r}\right|_{r_{ok}+0},\quad k=1,2,\end{gathered}\qquad(3)$$

where V_0 is the bias voltage applied to the inner conductor of the unbounded coaxial drift tube.

Under the assumption that the longitudinal beams velocities, $\beta_{\|k}$, are equal to their respective injection values, $\beta_{\|0k}$, i.e. in the approximation of constant longitudinal velocities, the solution to Eq. (1) with boundary conditions (3) can be found analytically:

$$\varphi(r)=\begin{cases}\varphi_1(r), & r_1\le r<r_{i1},\\ \varphi_2(r), & r_{i1}\le r<r_{o1},\\ \varphi_3(r), & r_{o1}\le r<r_{i2},\\ \varphi_4(r), & r_{i2}\le r<r_{o2},\\ \varphi_5(r) & r_{o2}\le r\le r_2,\end{cases}\qquad(4)$$

where

$$\varphi_1(r)=-\frac{V_0\ln(r/r_2)}{\ln(r_2/r_1)}+\frac{|I_{01}|G_1\ln(r/r_1)}{c\beta_{\|01}}+\frac{|I_{02}|G_2\ln(r/r_1)}{c\beta_{\|02}},$$

$$\varphi_2(r)=-\frac{V_0\ln(r/r_2)}{\ln(r_2/r_1)}+\frac{|I_{02}|G_2\ln(r/r_1)}{c\beta_{\|02}}+\frac{|I_{01}|}{c\beta_{\|01}}\left(\frac{G_1\ln(r/r_1)}{\ln(r_2/r_1)}+\frac{2r_{i1}^2}{r_{o1}^2-r_{i1}^2}\ln(r/r_{i1})-\frac{r^2-r_{i1}^2}{r_{o1}^2-r_{i1}^2}\right),$$

$$\varphi_3(r)=-\frac{V_0\ln(r/r_2)}{\ln(r_2/r_1)}+\frac{|I_{01}|(G_1-2\ln(r_2/r_1))\ln(r/r_2)}{c\beta_{\|01}}+\frac{|I_{02}|G_2\ln(r/r_1)}{c\beta_{\|02}},$$

$$\varphi_4(r)=-\frac{V_0\ln(r/r_2)}{\ln(r_2/r_1)}+\frac{|I_{01}|(G_1-2\ln(r_2/r_1))\ln(r/r_2)}{c\beta_{\|01}}+\frac{|I_{02}|}{c\beta_{\|02}}\left(\frac{G_2\ln(r/r_1)}{\ln(r_2/r_1)}+\frac{2r_{i2}^2}{r_{o2}^2-r_{i2}^2}\ln(r/r_{i2})-\frac{r^2-r_{i2}^2}{r_{o2}^2-r_{i2}^2}\right),$$

$$\varphi_5(r)=-\frac{V_0\ln(r/r_2)}{\ln(r_2/r_1)}+\frac{|I_{01}|(G_1-2\ln(r_2/r_1))\ln(r/r_2)}{c\beta_{\|01}}+\frac{|I_{02}|G_2\ln(r/r_2)}{c\beta_{\|02}},$$

$$G_k=1+2\ln(r_2/r_{ok})+\frac{2r_{ik}^2}{r_{ok}^2-r_{ik}^2}\ln(r_{ik}/r_{ok}),\quad k=1,2.$$

The dependence of the dimensionless scalar potential of two coaxial beams $f(\rho) = q\varphi(r)/(m_q c^2)$ on the dimensionless radius $\rho = r/r_2$ is received with the help of numerical modelling of nonlinear Poisson equation (1) and is shown in Fig. 1. For similar values of the injected currents of two coaxial beams in the centre of the drift tube the "plateau" forms where the value of the potential varies only slightly. So, the slope angle of the plateau could be adjusted by not-so-large values of bias voltage applied to the inner conductor of drift tube (outer conductor is grounded). Thus, handling of limiting current of the first beam, if the second beam current is being held fixed, can be put into effect for a sufficiently wide range of values with admissible applied bias voltages.

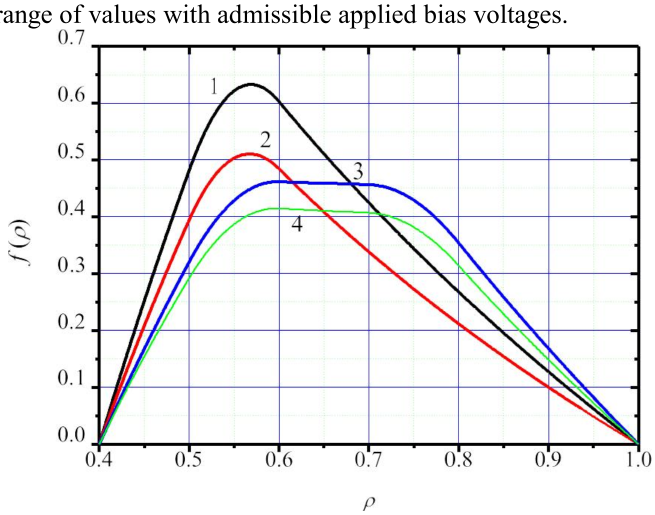

Fig. 1. Dependence of potential $f(\rho)$ on radius ρ. 1 (2) is the numeric (analytic) solution to Eq. (1) for $I_{01} = 20$ kA and $I_{02} = 0$ kA, respectively; 3 (4) is the numeric (analytic) solution to Eq. (1) for $I_{01} = I_{02} = 10$ kA, respectively. $\gamma_1 = \gamma_2 = 2$, $\beta_{\perp 1} = \beta_{\perp 2} = 0$, $r_1 = 1$ cm, $r_2 = 2.5$ cm, $r_{i1} = 1.25$ cm, $r_{o1} = 1.5$ cm, $r_{i2} = 1.75$ cm, $r_{o2} = 2$ cm, $V_0 = 0$ kV.

The dependence of dimensionless limiting current of the first beam $I_{1,\mathrm{lim}}^{\mathrm{num}} / I_A$ on the dimensionless bias voltage $\upsilon_0 = qV_0/(m_q c^2)$ is shown in Fig. 2 (V_0 is the bias voltage), where $I_{\mathrm{lim}}^{(\mathrm{t})}$ is the maximal value of the injection current $|I_{01}|$ for which the solution of Poisson equation (which describes the potential created by the system of two concentric annular charged-particle beams) exists; $I_{\mathrm{lim}}^{(\mathrm{b})}$ is defined in [4,5]

$$I_{\mathrm{lim}}^{(\mathrm{b})} = \max_{|I_{01}|} \left\{ \frac{2|I_{01}|}{\beta_{\parallel 01}(r_{o1}^2 - r_{i1}^2)} \int_{r_{i1}}^{r_{o1}} r\beta_{\parallel}(r)dr \right\};$$

and $I_{\mathrm{lim}}^{(\mathrm{m})}$ is that value of the injection current, $|I_{01}|$, for which the value $I_{\mathrm{lim}}^{(\mathrm{b})}$ is actually reached; $I_A = m_q c^3 / |q|$ is the Alfvén current ($I_A \approx 17$ kA for the electrons); m_q, q are the rest mass and particle charge; c is the light velocity in vacuum. The limiting current of the first beam undergoes changes by almost 15 % if the dimensionless bias voltage changes in the range $-0.1 \div 0.1$; this corresponds to the bias voltage variation from -50 to 50 kV (Fig. 2). The dependence of all three limiting currents (regardless of the definition) on the potential applied to the inner conductor of the drift tube is qualitatively identical as all lines have about the same slope (Fig. 2).

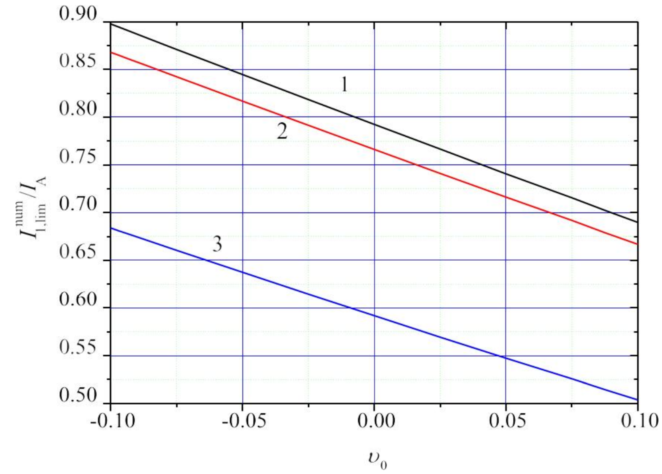

Fig. 2. Dependence of limiting current $I_{1,\mathrm{lim}}^{\mathrm{num}} / I_{\mathrm{A}}$ on bias voltage υ_0 applied to the inner conductor of drift-tube. 1 – $I_{\mathrm{lim}}^{(\mathrm{t})} / I_{\mathrm{A}}$; 2 – $I_{\mathrm{lim}}^{(\mathrm{m})} / I_{\mathrm{A}}$; 3 – $I_{\mathrm{lim}}^{(\mathrm{b})} / I_{\mathrm{A}}$. $\gamma_1 = \gamma_2 = 2$, $r_1 = 1$ cm, $r_2 = 2.5$ cm, $r_{i1} = 1.25$ cm, $r_{o1} = 1.5$ cm, $r_{i2} = 1.75$ cm, $r_{o2} = 2$ cm, $I_2 = 13.675$ kA (γ_i is the relativistic factor and r_{ik} and r_{ok} are the inner and outer radii of the *k*-th beam; r_1, r_2 are the inner and outer radii of the drift-tube).

III. Summary

In the strong magnetic field approximation, we have shown that it is possible to vary the limiting currents of two concentric magnetically-confined annular electron beams in coaxial drift-tube on the level up to 15 % with bias voltages of absolute value no more than 50 kV applied to the inner drift-tube conductor, thus, possibly, allowing for an increase in efficiency of multibeam electron devices of this type.

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