https://doi.org/10.46813/2023-146-033

EFFECT OF ELECTRON COLLISIONS WITH RESIDUAL NEUTRAL GAS ON CHARACTERISTIC OSCILLATION FREQUENCIES IN SYSTEMS OF ELECTRON FLOWS WITH A VIRTUAL CATHODE

O. Manuilenko[1,2], V. Novikov[3], A. Pashchenko[1], I. Pashchenko[1], I. Shapoval[1], V. Yuferov[1]
[1]National Science Center “Kharkov Institute of Physics and Technology”, Kharkiv, Ukraine;
[2]V.N. Karazin Kharkiv National University, Kharkiv, Ukraine;
[3]Proton-21, Kyiv, Ukraine
E-mail: anatolijpashchenko@gmail.com

A system of the hydrodynamic equations describing the electron flows in a diode with a virtual cathode is considered. Collisions are considered by introducing the corresponding braking force into the equations of motion. The stationary states of the electron flows are described. In a linear approximation, formulas are obtained for the frequencies of electron oscillations in a diode with a virtual cathode, considering the effective frequency of electron collisions. The expression for the decrement of oscillations due to the presence of collisions is obtained.

PACS: 41.85.Ar

INTRODUCTION

For many years, interest in the study of the generation of high-power microwave radiation using high-current relativistic beams in electrodynamic systems in which generation occurs due to oscillations of the electron flow in the potential well formed by a virtual cathode [1] (vircator) has not waned.

Many works are devoted to the study of the dynamics of the electron flow in a flat vacuum diode, including those taking into account the space charge. According to studies (see, for example, [2 - 8]), the electron flow in a diode can be in two stationary states, which differ in the nature of the distribution of the space charge field. When changing the parameters of the diode, for example, the incoming current, sharp transitions occur between these states [5, 6].

For example, in [5], the electron flow stability in a short-circuited diode was considered, an equation for the perturbations growth rate was obtained and the increments dependence on the flow parameters was constructed, in which the electrons dynamics is completely determined by electrostatics forces.

In papers [9, 10], stationary states of streaming flows and their linear stability were studied, considering collisions of electrons with the medium.

The vircator action [1] is based on the virtual cathode (VC) instability excitation, which occurs when the injection current exceeds a certain limit value.

In the simplest case, a planar system with a VC consists (Fig. 1) of a diode (gap K$_1$-A, region I with length l_1) that creates an electron flow, and a drift space A-K$_2$ (regions II and III), in which the electron flow forms a VC and which has a length of l_2. In the diode, a certain potential difference pulse is applied to the cathode-anode gap $\varphi(t)$.

In this work, when studying the dynamics of electron flows, electrostatic forces are supplemented (as in [9, 10]) by collisions of electrons with a medium with a collision frequency ν_e.

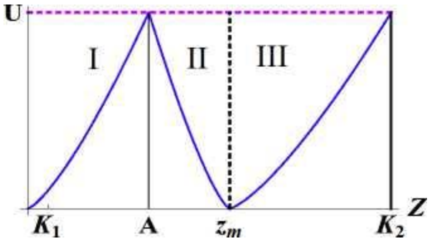

Fig. 1. Qualitative scheme of potential distribution in a planar system with VC. The position of the VC is marked with a dot z_m*. Here II is the region with the incident and reflected flows, and III is the region with the passed flow*

The influence of collisions on the dynamics of the electron flow is taken into account through the effective drag force proportional to the electron velocity.

1. ELECTRON FLOWS WITH A VIRTUAL CATHODE. HYDRODYNAMIC MODEL EQUATIONS

As in [8], we describe the processes occurring in the diode and collector gaps under the influence of a voltage $\varphi(t)$ slowly changing with time in the hydrodynamic approximation. Consider region II with incident and reflected flows. The equations in this model consist of the equations of motion, the continuity equation, and the Maxwell equation for the electric field. In contrast to [8], we add to the equation of motion the braking force proportional to the speed.

The incident flow will be denoted by index 1, and the reflected flow by index 2. Then:

$$\frac{\partial u_k}{\partial t}+u_k\frac{\partial u_k}{\partial z}+\nu_e u_k=-\frac{e}{m}E_2, \qquad (1)$$

$$\frac{\partial n_k}{\partial t}+\frac{\partial (n_k u_k)}{\partial z}=0, \quad k=1,2, \qquad (2)$$

$$\frac{\partial E_2}{\partial z}=-\frac{4\pi e}{\varepsilon}\left(n_1+n_2\right). \qquad (3)$$

Here E_2 – field strength in the area II; n and u – density and speed of the electron flow; e – elementary charge; m – electron mass; ε – dielectric constant;

ν_e – electrons collision frequency with the medium.

After passing through the potential difference $\varphi(t)$ in the diode gap, the electron beam flies into the collector gap with a certain speed u_0 and a certain density n_0. To analyze processes in a diode with a virtual cathode, it is convenient to use “natural” dimensionless variables: coordinates $\xi = \frac{z}{l_2}$, potential $\phi = \frac{e\varphi(t)}{mu_0^2}$ and collision frequency $\nu_{eff} = \nu_e \frac{u_0}{l_2}$. In such variables, the process equations look the simplest and are determined by two parameters: the characteristic plasma frequency of the electron flow $\omega_0^2 = \frac{4\pi n_0 e^2}{m\varepsilon}$ and dimensionless parameter $q_2 = \frac{\omega_0^2 l_2^2}{u_0^2}$, on which the dynamics of the virtual cathode depend. In the general case, both the plasma frequency and the characteristic region size have their own values for each characteristic region. In the virtual cathode region, this size is indicated by index 2 and, accordingly, the parameter q_2 has the same index. A detailed analysis of the equations, neglecting the collision frequency in the ideal case ν_e=0, was carried out in [8], where important relations for the VC dynamics were obtained. On Fig. 2 are shown, depending on the parameter q_2, at the top – the electron flow reflection coefficient from the VC region:

$$k_r(q_2) = \left(1 - \left(\frac{2}{9q_2}\right)^2 \left(1 + \sqrt{1 + 9q_2}\right)^2\right)^{1/2}, \qquad (4)$$

and below – the VC position:

$$\xi_m = \frac{z_m}{l_2} = \sqrt{\frac{2}{9q_2\left(1 + k_r(q_2)\right)}}. \qquad (5)$$

The upper figure shows the critical value of the parameter $q_{22} = \frac{16}{9}$, at which VC is formed. The lower figure, which shows the dynamics of the VC, shows the effect of hysteresis. When the parameter values decrease (with a decrease in the potential difference pulse) to a critical value $q_{21} = \frac{8}{9}$ – there is a charge breakdown from the VC region.

In [9, 10], the influence of collisions on the dynamics of electron flows was considered and the dependences of the limit values of the parameter q_2 on the collision frequency were obtained for a wide range of changes in the collision frequency. It is important to note that from the theory of processes in a VC constructed, one can obtain a linear transition from the presence of collisions to the limit state with ν_e=0:

$$q_{22} \approx \frac{16}{9}(1 - \beta\nu_e), \quad q_{21} \approx \frac{8}{9}(1 - \beta\nu_e), \quad \beta\nu_e < 1. \qquad (6)$$

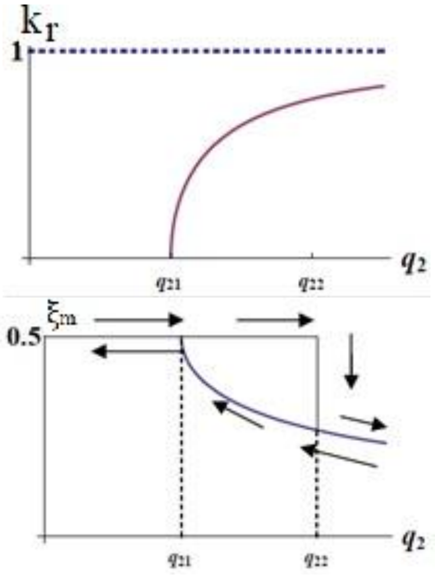

Fig. 2. Dependence of the reflection coefficient $\alpha(q_2)$ and the position of the virtual cathode $\xi_m(q_2)$ from parameter q_2

The value of the parameter β determines the effective boundary frequency of collisions and depends on the features of the medium with which the electron flow interacts.

1.1. EQUATIONS FOR ELECTRON FLOWS PERTURBATIONS

Let us consider the dynamics of perturbations of states in regions with VC. For any characteristics of the process, we will use the representation $f_k = f_{k0} + f_k'$, where the index 0 is used to indicate the values in the stationary mode, and the prime is used to indicate the perturbations of the values. After substitution $f_k = f_{k0} + f_k'$, we obtain equations for the perturbations of all quantities in the linear approximation in perturbations:

$$\frac{\partial u_k'}{\partial t} + u_{k0}\frac{\partial u_k'}{\partial z} + u_k'\frac{\partial u_{k0}}{\partial z} + \nu_e u_k' = -\frac{e}{m}E_2', \qquad (7)$$

$$\frac{\partial n_k'}{\partial t} + \frac{\partial}{\partial z}\left(n_{k0}u_k' + u_{k0}n_k'\right) = 0, \quad k = 1, 2, \qquad (8)$$

$$\frac{\partial E_2'}{\partial z} = -\frac{4\pi e}{\varepsilon}\left(n_1' + n_2'\right). \qquad (9)$$

In this case, the equations for the main quasi-stationary state can be written as:

$$u_{k0}\frac{\partial u_{k0}}{\partial z} + \nu_e u_{k0} = -\frac{e}{m}E_{20}, \quad k = 1, 2, \qquad (10)$$

$$\frac{\partial}{\partial z}\left(n_{k0}u_{k0}\right) = 0. \qquad (11)$$

For further estimates, it should be noted that we are interested in fluctuations in the region of the flux turning point near the potential extremum.

1.2. HARMONIC OSCILLATIONS IN THE VIRTUAL CATHODE REGION

To estimate the impact of collisions on the oscillation frequencies in the virtual cathode region, we substitute the perturbations of all quantities in the form of harmonic functions and obtain equations for the amplitudes of oscillations with a certain frequency.

Oscillations in the region of the virtual cathode occur simultaneously both in region II of two streams and in region III of one passed stream. It is easy to show that oscillations occur with the same frequency both in region II and in region III. For estimates, we can restrict ourselves to simpler calculations in region III.

Let us use the fact that, with sufficient accuracy for estimates, we can assume that the flow velocities and the coordinate derivatives of the densities are equal to zero: $\left(\partial/\partial z\right)u_{30}=0$ and $u_{30}\approx 0$. We get the equation:

$$\omega\left(\omega+i\nu_e\right)=\omega_0^2\,, \tag{12}$$

and obtain an expression for the oscillation frequency in the VC region:

$$\omega\left(\nu_e\right)=\sqrt{\omega_0^2-\frac{1}{4}\nu_e{}^2}+i\left(-\frac{\nu_e}{2}\right). \tag{13}$$

The impact of collisions on the oscillation frequency leads to some restrictions on the generation conditions in devices with a virtual cathode.

CONCLUSIONS

In the present work, when studying the dynamics of electron flows, collisions of electrons with the medium are added to the electrostatic forces, the influence of which on the dynamics of the electron flow is considered through the effective braking force proportional to the electron velocity. The model under consideration is described and equations are obtained for the parameters of stationary regimes and for the increments of the evolution of perturbations. The dependence of oscillation frequencies in the virtual cathode region on the collision frequency is obtained, which can be used in the future to optimize the parameters of high-current generators with a virtual cathode in charged particle flows and residual gas in the diode.

REFERENCES

1. A.A. Rukhadze, S.D. Stolbtsov, V.P. Tarakanov. Vircators // *Radio engineering and electronics*. 1992, v. 37, p. 385.
2. R.B. Miller. *An introduction to the Physics of Intense Charged Particle Beams*. New York and London: Plenum Press, 1982.
3. D.I. Trubetskov, A.E. Hramov. *The lections on microwave electronics for the physicians*. M.: “Fizmatlit”, 2004, v. 2.
4. V.I. Kuznetsov, A.Ya. Ender. About the selfsustained states of flat vacuum diode with electron beam // *Zhurnal Technicheskoy Fiziki*. 2013, v. 83, № 12, p. 1-10 (in Russian).
5. A.V. Pashchenko, B.N. Rutkevich. Electron flow stability in diode // *Fizika Plasmy*. 1977, v. 6, № 4, p. 774-779 (in Russian).
6. A.V. Pashchenko, B.N. Rutkevich. Dynamics of transitions between the stationary states in diode // *Radiotekhnika i Elektronika*. 1979, v. 24, № 1, p. 152-157 (in Russian).
7. V.A. Buts. Theory of electron beam stability in diode // *Zhurnal Technicheskoy Fiziki*. 1974, v. 44, № 8, p. 1656-1661 (in Russian).
8. I.I. Magda, A. Pashchenko, et al. Modification of the Child-Langmuir-Boguslavsky law for the diode gap in the system with virtual cathode // *Problems of Atomic Science and Technology. Series “Nuclear Physics Investigations”.* 2012, № 4, p. 133-137.
9. A. Pashchenko, V. Ostroushko. Electron flow stability in the gas filled diode // *Problems of Atomic Science and Technology. Series “Nuclear Physics Investigations”.* 2017, № 3, p. 72-76.
10. A. Pashchenko, V. Ostroushko. Electron flow dynamics in resistive gap // *Problems of Atomic Science and Technology. Series “Nuclear Physics Investigations”.* 2017, № 6, p. 58-62.

Article received 09.06.2023

ВПЛИВ ЗІТКНЕНЬ ЕЛЕКТРОНІВ ІЗ ЗАЛИШКОВИМ НЕЙТРАЛЬНИМ ГАЗОМ НА ЕФЕКТИВНІ ЧАСТОТИ КОЛИВАНЬ У СИСТЕМАХ ПОТОКІВ ЕЛЕКТРОНІВ З ВІРТУАЛЬНИМ КАТОДОМ

О. Мануйленко, В. Новіков, А. Пащенко, І. Пащенко, І. Шаповал, В. Юферов

Розглянуто систему гідродинамічних рівнянь, що описують потоки електронів у діоді з віртуальним катодом. Зіткнення введено у рівняння руху за допомогою відповідної гальмівної сили. Описано стаціонарні стани потоків електронів. У лінійному наближенні отримано формули для частот коливань електронів у діоді з віртуальним катодом з урахуванням ефективної частоти зіткнень електронів. Отримано вираз для декременту коливань через наявність зіткнень.