BEAM DYNAMICS

ELECTRON FLOW DYNAMICS IN RESISTIVE GAP

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It is considered the evolution of electron flow in the short-circuited gap with taking into account of the braking force proportional to velocity. The linear analysis of the stationary states stability is made. For the states with a small instability increment it is considered the nonlinear evolution of perturbation. The numerical simulations of the transitions from the unstable modes to the stable ones with the removing of the charge surplus from the gap are carried out.

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INTRODUCTION

There are many works devoted to study of electron flow dynamics in the flat vacuum diode. In [1], the classification of the self-sustained states of one-stream flow with study of their stability is presented. Before, the electron flow stability in the short-circuited diode was considered in the paper [2]. In it, the equation for the increments of perturbation development was obtained and the dependence of the increments on the flow parameters was built. The results of the paper [2] also were presented in the monograph [3]. In [4], the transition from unstable to stable stationary state corresponding to the same entrance current was studied. An external field accelerating the electrons, as a rule, makes the flow more stable [5]. In the model considered in the paper [2] the electron motion is completely determined by electrostatic forces. In the paper [6], the stationary states of one-stream flow and their linear stability were studied with taking into account of collisions through effective braking force proportional to electron velocity. In the present work, this study is supplemented with the numerical simulations of the stationary state instability development and consideration of the process in the case of small instability increment.

1. MODEL EQUATIONS

Let us consider one-dimensional electron flow under the electrostatic forces and the braking force proportional to electron velocity with the ratio β_0 of relevant acceleration to velocity ($\beta_0 > 0$). To write the dimensionless equations, let us denote by e_0 the elementary charge ($e_0 > 0$), by m_0 the electron mass, by ε_0 electric constant, by j_0 the current density at entrance and let us take the following units: the gap width z_0 for length, the entrance velocity v_0 for velocity, the ratios $t_0 = z_0/v_0$, $n_0 = j_0/(e_0 v_0)$, and $E_0 = (m_0 v_0^2)/(e_0 z_0)$ for time, electron density, and field strength, respectively. It is assumed that $z = 0$ for entrance, so, $z = 1$ for exit. The equations in the dimensionless Euler variables have the form

$$\partial_t n + \partial_z (nv) = 0, \ \partial_t v + v\partial_z v = -E - \beta v,$$
$$\partial_z E = -qn, \qquad (1)$$

where $\beta = (\beta_0 z_0)/v_0$, $q = e_0^2 n_0 z_0^2 (\varepsilon_0 m_0 v_0^2)^{-1}$, the quantities v, n, and E are dependent on the variables (z,t), ∂ is partial derivative, its index indicates the variable, with respect to which the derivative is taken. Parameter q is proportional to the entrance electron current and the flow dynamic may be effectively controlled by it. It is expedient to use Lagrange variables to simplify the equations solving. Let $z_e(\tau,t)$ and $v_e(\tau,t)$ be coordinate and velocity at the time t of the electron, which has come in gap at the time τ ($\tau < t$). Let $n_e(\tau,t)$ and $E_e(\tau,t)$ be electron density and field strength in the point $z = z_e(\tau,t)$ at the time t. It is assumed that during the considered stage of the process all electrons are moving in positive z direction and $z_e(\tau,t)$ monotonously decreases with τ increase, that is, electrons do not outrun one another, though the distance between them may be changed. An electron motion in Lagrange variables obeys to the equations

$$\partial_t (n_e \partial_\tau z_e) = 0, \qquad (2)$$
$$\partial_t z_e = v_e, \qquad (3)$$
$$\partial_t v_e = -E_e - \beta v_e, \qquad (4)$$

in which the quantities z_e, v_e, n_e and E_e are dependent on the variables (τ,t). From (1), assuming that $z = z_e$, one gets the equalities

$$\partial_\tau E_e(\tau,t) = \partial_z E(z,t)\partial_\tau z_e(\tau,t) = -q n_e(\tau,t)\partial_\tau z_e(\tau,t). \qquad (5)$$

From (2), (3) and (5), with taking into account of $z_e(t,t) = 0$, $v_e(t,t) = 1$, and $n_e(t,t) = 1$, it follows

$$[\partial_\tau z_e(\tau,t) + v_e(\tau,t)]_{t=\tau} = \partial_\tau z_e(\tau,\tau) = 0,$$
$$[\partial_\tau z_e(\tau,t)]_{t=\tau} = -v_e(\tau,\tau) = -1,$$
$$n_e \partial_\tau z_e = [n_e(\tau,t)\partial_\tau z_e(\tau,t)]_{t=\tau} = -1, \qquad (6)$$
$$\partial_\tau E_e(\tau,t) = q. \qquad (7)$$

Integration of (7) gives the equality

$$E_e(\tau,t) = E_{e0}(t) + (\tau - t)q, \qquad (8)$$

where $E_{e0}(t) = E_e(t,t)$. The equality (8) is deduced in the assumption that electrons do not outrun one another, and so, $\partial_\tau z_e(\tau,t)$ is negative and $n(z,t)$ is bounded positive, in connection with (6), anywhere in the gap.

For $m = 1,2,3,\ldots$, let us define the functions $e_m(x) = (-1)^m \left[\exp(-x) - \sum_{k=0}^{m-1} (-x)^k / k!\right]$. For them the equalities $\partial_x e_{m+1}(x) = e_m(x)$, $\partial_x e_1(x) = \exp(-x)$, and $e_m(0) = 0$ take place. The integration of (4) and (3), with the field strength from (8), gives the equalities

$$v_{\rm e}(\tau,t) = -\int_\tau^t d\xi e^{\beta(\xi-t)} E_{\rm e0}(\xi) + $$
$$+ e^{\beta(\tau-t)} + q\beta^{-2} e_2(\beta t - \beta\tau) \quad ,$$
$$z_{\rm e}(\tau,t) = -\int_\tau^t d\xi \beta^{-1} e_1(\beta t - \beta\xi) E_{\rm e0}(\xi) + $$
$$+ \beta^{-1} e_1(\beta t - \beta\tau) + q\beta^{-3} e_3(\beta t - \beta\tau) \quad . \qquad (9)$$

For the electron, which goes out from the gap at time t, let us denote by $T(t)$ the time during which it moves through the gap. That is, this electron has come in the gap at the time $t - T(t)$ and the equality holds.

$$z_{\rm e}(t - T(t), t) = 1 . \qquad (10)$$

At the given time instant t the gap is filled with electrons, which came into the gap after the time instant $t - T(t)$, and so, as the entrance current density and the gap width are unit, the dimensionless electron density averaged over the gap is equal to $T(t)$. If the applied voltage value $V(t)$ is given then the condition should be imposed.

$$\int_t^{t-T(t)} d\tau E_{\rm e}(\tau,t) \partial_\tau z_{\rm e}(\tau,t) = -V(t) . \qquad (11)$$

From (10) and (11) with substitution of (8) and (9) one can get the equations

$$-\int_0^{T(t)} d\xi \beta^{-1} e_1(\beta\xi) E_{\rm e0}(t-\xi) + $$
$$+ \beta^{-1} e_1(\beta T(t)) + q\beta^{-3} e_3(\beta T(t)) = 1 , \qquad (12)$$
$$E_{\rm e0}(t) = -V(t) - q^2 \beta^{-4} e_4(\beta T(t)) + $$
$$+ q[T(t) - \beta^{-2} e_2(\beta T(t))] + $$
$$+ q\int_0^{T(t)} d\xi \beta^{-1} e_1(\beta\xi)[T(t) - \xi] E_{\rm e0}(t-\xi) . \qquad (13)$$

Also, substitution of (8) to (11) and integration by parts with taking into account of (10) gives the equality

$$E_{\rm e0}(t) - q\int_{t-T(t)}^t d\tau [1 - z_e(\tau,t)] = -V(t) . \qquad (14)$$

The flow may be stationary under stationary external conditions. If the gap is short-circuited ($V(t) = 0$), and if the quantities $E_{\rm e0}$ and T are independent on t then the equations (12) and (13) are reduced to the equalities

$$E_{\rm e0} \beta e_2(\beta T) = q e_3(\beta T) + \beta^2 e_1(\beta T) - \beta^3 , \qquad (15)$$
$$E_{\rm e0} \beta [\beta^3 - q e_3(\beta T)] = $$
$$= q\beta^2 [\beta^2 T - e_2(\beta T)] - q^2 e_4(\beta T) \qquad (16)$$

(the last equality is written in [6] with the incorrect last sign). Excluding $E_{\rm e0}$ from (15) and (16), one can obtain the equality

$$q^2 \beta^{-4} [e_3^2(\beta T) - e_2(\beta T) e_4(\beta T)] + $$
$$+ q\beta^{-2} \{ e_2(\beta T)[\beta^2 T - e_2(\beta T)] + $$
$$+ e_3(\beta T)[e_1(\beta T) - 2\beta] \} + $$
$$+ \beta[\beta - e_1(\beta T)] = 0, \qquad (17)$$

which gives q for the given β and T. If β is fixed and q and $E_{\rm e0}$ are connected through the equalities (15), (16) then the derivatives of q and $E_{\rm e0}$ with respect to T are connected by the equalities

$$\beta^{-2} e_2(\beta T) \partial_T E_{\rm e0} - \beta^{-3} e_3(\beta T) \partial_T q = v_{\rm e1} , \qquad (18)$$
$$C_q \partial_T q = [q\beta^{-3} e_3(\beta T) - 1] \partial_T E_{\rm e0} , \qquad (19)$$

in which $C_q = q\beta^{-4} e_4(\beta T) - E_{\rm e0}/q$ and $v_{\rm e1}$ is the stationary value of the exit velocity $v_{\rm e}(t - T(t), t)$.

The stationary mode may be unstable. Let us consider development of small perturbation caused by the short-time non-zero applied voltage $V'(t)$. Denoting the perturbations with prime, from (12) and (13), in linear approximation, one can obtain the equations

$$T'(t) = (v_{\rm e1}\beta)^{-1} \int_0^T d\xi e_1(\beta\xi) E'_{\rm e0}(t-\xi) , \qquad (20)$$
$$E'_{\rm e0}(t) + V'(t) = $$
$$= q\beta^{-1} \int_0^T d\xi e_1(\beta\xi)(T - \xi) E'_{\rm e0}(t-\xi) . \qquad (21)$$

Assuming absence of perturbations at $t < 0$, applying Laplace transformation to the equations (20) and (21), denoting the transforms with tilde, as in the example $\tilde{f}(\kappa) = \int_0^\infty dt e^{-\kappa t} f'(t)$, and defining the functions

$$F_E(b,x) = bx^{-1}(b+x)^{-1} + $$
$$+ (b+x)^{-2} e_1(b+x) - x^{-2} e_1(x) ,$$
$$F_T(b,x) = (b+x)^{-1}[x^{-1} e_1(x) - e^{-x} b^{-1} e_1(b)] ,$$
$$D(\kappa) = qT^2 \beta^{-1} F_E(\beta T, \kappa T) - 1 ,$$

one can obtain the equations

$$\tilde{E}_{\rm e0}(\kappa) = [D(\kappa)]^{-1} \tilde{V}(\kappa) ,$$
$$\tilde{T}(\kappa) = v_{\rm e1}^{-1} T^2 F_T(\beta T, \kappa T) \tilde{E}_{\rm e0}(\kappa) .$$

The equation for the increment κ of self-consistent linear perturbation development has the form

$$D(\kappa) = 0 . \qquad (22)$$

Instability of stationary state is characterized by the inequality $\mathrm{Re}(\kappa) > 0$. If β is fixed and q and κ are connected through the equation (22) then for the derivatives with respect to T one gets the equality

$$TF_{E2}(\beta T, \kappa T) \partial_T \kappa + q^{-1} F_E(\beta T, \kappa T) \partial_T q + $$
$$+ 2T^{-1} F_E(\beta T, \kappa T) + \beta F_{E1}(\beta T, \kappa T) + $$
$$+ \kappa F_{E2}(\beta T, \kappa T) = 0, \qquad (23)$$

where $F_{Ej}(x_1, x_2) = (\partial/\partial x_j) F_E(x_1, x_2)$ ($j = 1,2$).

In the case of small value of instability increment, the initial evolution of perturbation is slow. For the stationary state, in which $\partial_T q = 0$, the equations (18), (19) are reduced to the form $\beta^{-2} e_2(\beta T) \partial_T E_{\rm e0} = v_{\rm e1}$, $[q\beta^{-3} e_3(\beta T) - 1] \partial_T E_{\rm e0} = 0$ and give $\partial_T E_{\rm e0} > 0$,

$$q\beta^{-3} e_3(\beta T) = 1 . \qquad (24)$$

Then the equation (22) has the root $\kappa = 0$, and for it, from (23) it follows $\partial_T \kappa = b_\kappa > 0$, where $b_\kappa = [\beta T e_3(\beta T) - 2e_4(\beta T)]^{-1} \beta^2 e_2(\beta T)$. Also, with use of (24) one can get the equality

$$\beta[\beta T e_3(\beta T) - e_4(\beta T)] = e_2(\beta T) e_3(\beta T) . \qquad (25)$$

Let us denote $q_{\rm c}$, $T_{\rm c}$, and $E_{\rm c}$ the values of q, T, and $E_{\rm e0}$ in this stationary critical state of indifferent equilibrium. For the given β they may be found from (25), (24), and (15). For the states near to this state one gets $q-q_c \approx (2C_q)^{-1} q_c v_{e1} (T-T_c)^2$, $\kappa \approx b_\kappa (T-T_c)$, $E_{e0}-E_c \approx a_E$, where $a_E = (T-T_c) v_{e1} \beta^2 / e_2(\beta T_c)$ and the values of C_q, v_{e1}, and b_κ should be taken for the critical state. The quantity a_E is negative for the stable states and positive for the unstable ones. Let $\breve{E}_{e0}(t)$ and $\breve{T}(t)$ be the differences of $E_{e0}(t)$ and $T(t)$ with their stationary values. As the case of slow time evolution is considered, the integrals in (12) and (13) may be estimated with use of the approximate equality $\breve{E}_{e0}(t-\xi) \approx \breve{E}_{e0}(t) - \xi \partial_t \breve{E}_{e0}(t)$. From (14) with $V(t)=0$, assuming that (10) is kept, taking into account the summands up to the products and squares of perturbations, and denoting

$$\bar{E}_0(t) = \breve{E}_{e0}(2t/|\kappa|)/|a_E|, \qquad (26)$$

one comes to the approximate equation

$$\partial_t \bar{E}_0(t) \approx 2\,\mathrm{sign}(a_E)\bar{E}_0(t) + \bar{E}_0^2(t).$$

In the cases $\pm a_E > 0$ its solution has the form

$$\bar{E}_0(t) \approx 2\bar{E}_0(0)\{\mp \bar{E}_0(0) + [2 \pm \bar{E}_0(0)]\exp(\mp 2t)\}^{-1}.$$

It corresponds to one obtained in [7] for the case $\beta = 0$.

2. STATIONARY STATES AND EVOLUTION OF PERTURBATIONS

The characteristics of the electron flow are essentially dependent on the braking coefficient β value. The transitions between one-stream and two-stream modes are controlled by the parameter q value. In the case $\beta = 0$ (studied in [2]), for $q < 8/9$ the flow is one-stream with symmetric distribution of electron density, velocity, field strength and potential with respect to the middle of the gap. If the parameter q increases (for example, with aid of entrance electron current slow increase), but remains less than $16/9$ then one-stream mode remains stable. If q becomes greater than $16/9$, then the stationary one-stream mode disappears through the following instability: the increase of the electron charge in the gap decelerates electrons more and leads to the further charge increase. As a result, inside the gap, virtual cathode (the point with zero field strength and zero electron velocity) is formed, and some part of electron flow is rejected from it. If the parameter q decreases after formation of virtual cathode then for $q \in (8/9, 16/9)$ the flow mode remains two-stream. And only if q becomes less than $8/9$ then two-stream mode disappears, and the surplus of space charge goes away from the gap and forms the current pulse.

If $\beta > 0$ then the distributions of the electron velocity and density, field strength and potential is non-symmetric with respect to the middle of the gap for any q value. In particular, the point of zero field strength is shifted downstream. Such its position follows from the stationary mode equations: $nv = 1$, $v\partial_z v = -E - \beta v$, $\partial_z E = -qn$, and $\partial_z \Phi = -E$, where Φ is potential. From them, it follows $\partial_z(\Phi - v^2/2) = \beta v$, $\partial_\Phi (E^2/2) = E\partial_\Phi E = -\partial_z E = q/v$, and $\partial_\Phi z = -1/E$. Let z_s be the coordinate of the zero strength point, let the points z_- and z_+ be connected by the relationships $z_- < z_s < z_+$ and $\Phi(z_-) = \Phi(z_+)$, and let the lower indexes $+$ and $-$ will be used for the values of the quantities in the points z_+ and z_-, respectively. Integration of the equality $\partial_z(\Phi - v^2/2) = \beta v$ from z_- to z_+ gives the inequalities $v_+^2 < v_-^2$ and $v_- > v_+ > 0$, and then the inequalities $(\partial_\Phi E^2)_+ > (\partial_\Phi E^2)_- > 0$ hold. Their integration yields $E_+^2 > E_-^2$, $0 < E_- < -E_+$, and as $\partial_\Phi z = -1/E$, one gets $0 < (\partial_\Phi z)_+ < -(\partial_\Phi z)_-$, $0 < z_+ - z_s < z_s - z_-$. Taking $z_- = 0$, $z_+ = 1$ leads to $1/2 < z_s < 1$.

In the Fig. 1, the correspondence between the value of dimensionless velocity in the point of zero field strength, v_s, and the value of parameter q is shown for the different braking coefficient β values. The curves with greater β in the interval $\beta \in (0,1)$ give smaller q values for the same v_s values, as both the space charge field and the braking force decelerate electrons.

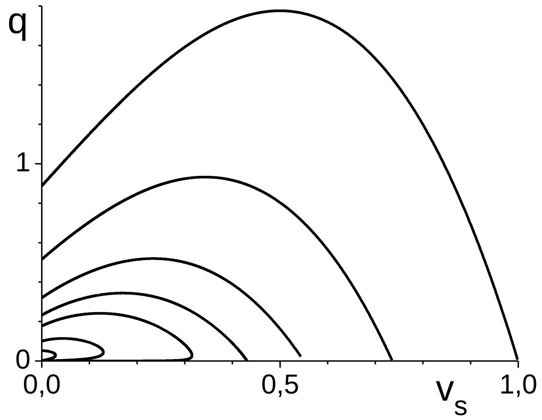

Fig. 1. Dimensionless entrance current q versus the flow velocity in the point of zero field strength v_s, for the different values of braking coefficient β: 0 (upper curve), 0.5, 0.8, 0.95, 1.05, 1.2, and 1.30685

If $\beta > 1$ then the stationary modes with too small q values are impossible, as without aid of the space charge field, under the action of the braking force only, according to the equation $v\partial_z v = -\beta v$, electron has to stop at the point $z = 1/\beta$, which is situated inside the gap (as $\beta > 1$), and such stopping cannot take place in a stationary mode. The smallest q value corresponds to zero value of v_s.

For any β, the point of q maximum corresponds to zero increment and divides the curve on the parts corresponding to stable and unstable stationary modes. The parts of curves, which go out from the maximum to the left, and come to the line $v_s = 0$, correspond to the unstable modes. The parts of curves, which first go out from the maximum to the right, and eventually come to the line $q = 0$ (if $\beta \in (0,1)$) or to the line $v_s = 0$ (if $\beta > 1$), correspond to the stable stationary modes.

But at some β value (near to 1.30685) the point of q maximum (with q value near to $4.87 \cdot 10^{-2}$) comes to the line $v_s = 0$ and all one-stream modes possible for this and greater β values are stable. For such β values the curve on the plot q versus v_s gives two values of q for $v_s = 0$, and for any q between them there is one value of v_s. But if β becomes equal to some another number (near to 1.36111) then both points of the curve at $v_s = 0$ meet each other at q near to $1.33 \cdot 10^{-2}$, and for the greater β values one-stream modes are impossible.

At the large q values the cause of impossibility of one-stream mode existence is too large decelerating force of the space charge field in the part of the gap nearer to entrance. At the small q values and $\beta > 1$, the cause of impossibility of one-stream mode existence is insufficiently large accelerating force of the space charge field in the part of the gap nearer to exit, so that such force cannot overcome the braking force and it is incapable to push all the flow through this part of the gap. In the two-stream mode only the part of input flow passes the whole gap, and the electrostatic field may be capable to push some part of input flow through the whole gap if the space charge of the rejected part of flow is large enough.

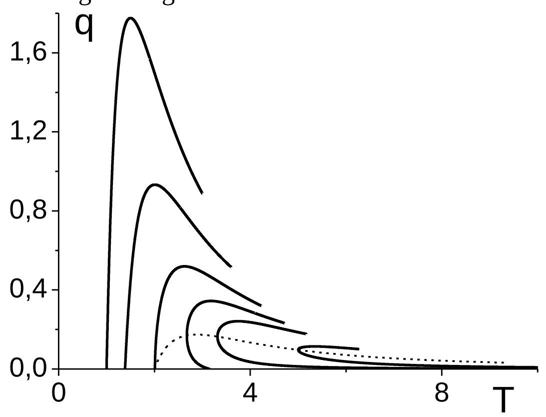

Fig. 2. Dimensionless entrance current q versus the time T of electron motion inside the gap, for the different β values: 0 (left curve), 0.5, 0.796812, 0.95, 1.05, and 1.2

In the Fig. 2 the connection between the dimensionless entrance current q and the time T of electron motion inside the gap is drawn with the solid curves corresponding to the different fixed β values. As it is mentioned above, the dimensionless electron density averaged over the gap is equal to T, and so, the difference between T values for two intersections of a solid curve with a line of constant q corresponds to the charge surplus, which is removing from the gap during the transition from the unstable stationary state to the stable one. The dash curve connects the points with infinite $\partial_T q$ on the different solid curves. Such points correspond to zero determinant of the linear equation system (18), (19) and zero discriminant of the square equation (17). The ends of the solid and dash curves at $q > 0$ are related to the limit $v_s \to 0$. The dash curve comes to the line $q = 0$ at $T = 2$ and the corresponding β is the root of the equation $1 - \beta = \exp(-2\beta)$ (approximately, 0.796812).

The transitions from unstable to stable stationary state corresponding to the same entrance current are accompanied with the removing of the charge surplus from the gap [4]. The calculations for development of perturbations after short-time small voltage application were carried out. At the linear stage the perturbations grow as exponents and the process characteristics for the same sign of the applied voltage coincide after the corresponding time shift. At the nonlinear stage the process development character depends on the sign of the applied voltage. Namely, if the applied field accelerates electrons then the transition may go as one-stream, but if the initial perturbation is decelerating then one-stream mode is destroyed.

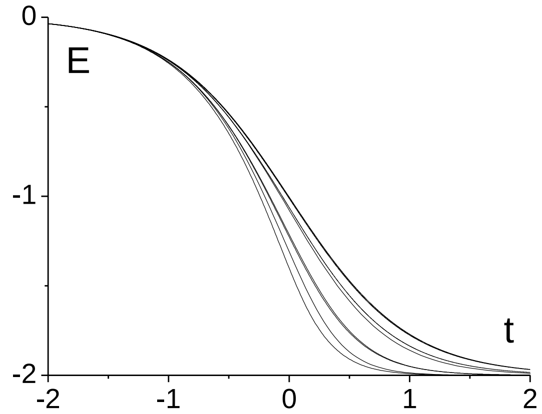

Fig. 3. Reduced strength perturbation at entrance versus reduced time in transition from unstable to stable stationary state after accelerating pulse application

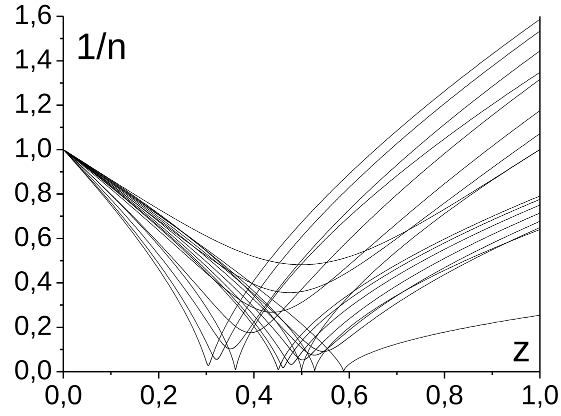

Fig. 4. Dependences of reciprocal density on coordinate at the stage of one-stream flow after application of decelerating pulse

In the Fig. 3 it is shown the dependence of the reduced strength perturbation at entrance on the reduced time in transition from unstable to stable stationary state after accelerating pulse application. The reduction is made with linear transformations of time and strength similar to ones used in the definition of the function $\bar{E}_0(t)$ (26) in the case $a_E > 0$. The curves correspond to the following values of (β, q): (0, 0.889), (0.6, 0.449), (0, 1.333), (0.6, 0.61), (1.2, 0.1007), (1.2, 0.1075), (0, 1.776), (0.6, 0.786) (from left to right). Relevant instability increments are approximately equal to 1.099, 0.602, 0.894, 0.502, 0.0991, 0.0738, 0.0715, and 0.0297, respectively. The right curves are very near to one corresponding to $\bar{E}_0(t)$ dependence. Comparatively large decrease rates of the left curves are connected with large perturbation dumping decrements in the corresponding stable states.

In the Fig. 4 the dependences of reciprocal density $1/n(z,t)$ on coordinate z at the stage of perturbation development after application of decelerating pulse when the flow remains one-stream are shown. There are taken the following (β , q) in order of minimums from left to right: (0, 1.776), (0, 1.333), (0.6, 0.61), (0, 0.889), (0.6, 0.449), (1.2, 0.1007). The pairs (0, 1.776) and (0.6, 0.61) are presented by series, in which the curves with the lowest minimum correspond, respectively, to time lags 0.1 and 0.2 before the one-stream flow violation, and for each next curve this lag is doubled, except the last curves in series (7^{th} and 6^{th}, respectively), which correspond to the unstable stationary states. For the both series, the point of maximum density moves against the flow. The other pairs are presented by the distributions just before the one-stream flow violation. For greater β and smaller q the point of the violation is nearer to exit.

CONCLUSIONS

The electron flow in the short-circuited gap is considered with taking into account of the braking force proportional to velocity. Explicit solution of the equations is obtained with use of Lagrange variables, which gives comparatively simple expression for electric field, at the stage of the process, when electrons do not outrun one another, though the distance between them may be changed. Appearing of braking force and increase of braking coefficient leads to changes of the input current intervals, in which stationary states are stable or unstable. For small braking coefficient, the flow with sufficiently small input current is stable, in some interval of input current the stable and unstable one-stream flows may exist, and for sufficiently large input current one-stream flow is impossible. Also, the one-stream flow is impossible in the case when input current is very small and the braking coefficient is so large, that in absence of the electric forces electron stops inside the gap. But for small input current values sufficient for one-stream flow existence the flow is stable. The unstable one-stream flows disappear at some sufficiently large value of braking coefficient. And for the braking coefficient values greater then some still greater threshold value, one-stream flow is impossible.

The numerical simulations for the case when two stationary one-stream modes correspond to the same entrance current value and the unstable mode is perturbed by the short-time small voltage application show that the transition from the unstable to stable mode may go in the frames of one-stream flow if the voltage direction corresponds to electron acceleration. The decelerating direction leads to appearance of two-stream flow.

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ДИНАМИКА ПОТОКА ЭЛЕКТРОНОВ В ПРОМЕЖУТКЕ С СОПРОТИВЛЕНИЕМ

А. Пащенко, В. Остроушко

Рассмотрена эволюция потока электронов в короткозамкнутом промежутке с учетом тормозящей силы, пропорциональной скорости. Выполнен линейный анализ устойчивости стационарных состояний. Для состояний с малым инкрементом неустойчивости рассмотрена нелинейная эволюция возмущения. Выполнено численное моделирование переходов от неустойчивого состояния к устойчивому с удалением избыточного заряда из промежутка.

ДИНАМІКА ПОТОКУ ЕЛЕКТРОНІВ У ПРОМІЖКУ З ОПОРОМ

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Розглянуто еволюцію потоку електронів у короткозамкненому проміжку з урахуванням гальмівної сили, пропорційної до швидкості. Виконано лінійний аналіз стійкості стаціонарних станів. Для станів з малим інкрементом нестійкості розглянуто нелінійну еволюцію збурення. Виконано числове моделювання переходів від нестійкого стану до стійкого з видаленням надлишкового заряду з проміжку.