Electron beam parametric interaction with the hyperlimiting current in systems with drift space

V. P. Grigoriev, T. V. Koval, and V.A. Semeshov

Institute Cybernetic Centre, Tomsk Polytechnic University, Sovetskaya Str. 84, 634034 Russia
Tel: +7-3822-563429, Fax: +7-3822-563429, E-mail: grig@am.tpu.ru

Abstract – The virtual cathode systems are the power electromagnetic radiation sources. There are of interest the problems of phase modulation and the radiation saturation mechanism in such systems. The parametric interaction in virtual cathode triodes has been considered by the authors earlier and there have been defined the excitation conditions of the parametric resonance on the basic harmonic.

In this work there has been considered the mechanism of the electromagnetic oscillations generation in vircators and reflex triodes with a drift space by taking into account the peculiarity of the systems with traversed electrons. The theory is based on the parametric interaction of the electron flow with the potential well oscillations in a nonlinear system. This approach gives possibility to investigate the electrons motion dynamics, the electrons phase modulation and the radiation saturation mechanism in virtual cathode systems. The investigations are conducted as by analytical methods so PIC code calculations.

1. Introduction

Generators of electromagnetic oscillations on the base of system with virtual cathode (VC) attract attention in connection with its constructive simplicity and ability to obtain rather high radiation power levels. At that it is possible to use as radiation sources the electrons reflected from VC and oscillating in potential well as well as modulated stream of floating-drift electrons [1-3]. But because of low radiation efficiency it is needed to carry out more detailed investigation of electron interaction mechanisms in such systems and to found conditions for increasing of radiation efficiency.

The radiation mechanism in vircators and triodes with virtual cathode was regarded by authors of [1-2] by using of kinetic equation method. In papers [4] the excitation of electromagnetic oscillations in triodes with VC was investigated from the point of view nonlinear parametrical interaction of electrons with generic field at VC oscillations. This approach permits to establish the mechanism of electron stream modulation of oscillating electrons and to pick out main regularities of this phenomenon as well as to determine the saturation of radiation level in triodes with VC.

In this paper the results of theoretical investigation of phase modulation of electron stream in vircators at parametrical interaction of floating-drift electrons with potential oscillations of eigen field of beam. At that most interesting case when general electron stream bounded with floating-drift electrons current of which (limiting current) substantially depends from electron energy and geometry of drift space. The model of parametrical interaction was constructed with using results of numerical modeling of virtual cathode forming by big particles method. On this base the analytical and numerical results about phase modulation of floating-drift electron stream were obtained.

2. Problem statement

Let us regard system (Fig. 1) located in metallic cylindrical camera with radius R_c and with height h including the accelerating diode C-A1and two drift spaces: (I) – A1-A2 between anodes and (II) – A2-Cl between second anode and collector. Anodes are transparent for electrons with geometrical transparency χ ($0 \le \chi \le 1$). The gaps (I) and (II) were selected from condition of smallness of reflected electrons number in compare with floating-drifted ones.

Let us conducts the analysis of numerical modeling of VC forming dynamics and electron movements in system in question on the base of PIC code [5]. It follows from analysis of numerical calculations that full current passing through drift space with length $L < R_c$ is going due to screening of beam's space charge by butt metallic faces. At high transparency of anodes it have place for $L \le 2\sqrt{2}\ \ d$, if beam current not exceeds the critical one(d is diode gap).

Potential is depending from radius of electron beam with finite dimensions. The most potential sag and electron braking by eigen field have a place on the beam axis $r = 0$. Approximately this dependence can be described by Bessel function of zero order $J_0(\mu_{01} r/R_c)$, where μ_{01} is first root of Bessel function ($J_0(\mu_{01}) = 0$). The value and the coordinate of potential minimum have a periodical dependence from time with frequency ω depending from electron energy and geometry of drift space.

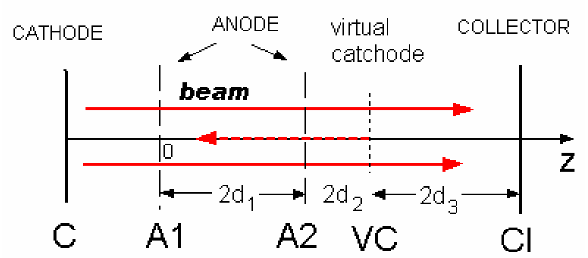

Fig. 1. Scheme of particles movements

The analysis of electron beam dynamics in space charge field as well as virtual cathode forming shows that different regimes of generation of electromagnetic radiation can be realized in the given system depending from geometrical dimensions choosing and accelerating voltage.

In regime with floating-drift electrons the potential sag is forming in drift space I without of virtual cathode formation, but in drift space II the virtual cathode forms in near axis region on beam only $r \sim 0$. When radius is nonzero there is have a place the potential deep sag, but without forming of virtual cathode. For selected regime (Fig. 2) it is typical the appearance of some quantity of reflected electrons near of beam axis and considerable floating-drift electron stream.

Presence of VC and reflected electrons assures appearance of oscillations of potential minimum needed for parametrical interactions and phase modulation of floating-drift electrons in drift space. At that potential oscillations in gaps A1-A2 and A2-C1 occurs at the same frequency ω, but with phase shift caused by finite time of flight of reflected electrons through distance $d_1 + d_2$. In that case additional drift space plays a role of preliminary modulator where electron beam is weakly frequency-modulated by periodical potential action.

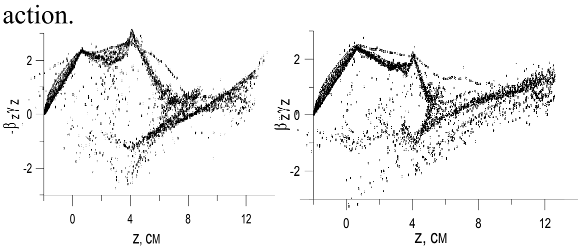

Fig. 2. Phase-plane portraits of electron beam at time moments differing on $t = \pi / \omega$

3. Parametrical interaction

On the base of realized analysis let us show the model describing dynamic of parametrical electron interaction in systems in question and let us explain the mechanism of radiation saturation.

Let us regard the electron movement in both drift spaces I and II. Let us put in the region numbers $i = 1$, 2 and 3 corresponding to gaps A1-A2, A2-VC and VC-C1. It is useful to pass to variances $x_i = 2\pi z / d_i$: $0 \le x_1 \le 2\pi$ for gap A1-A2, $0 \le x_2 \le \pi$ for gap A2-VC and $0 \le x_3 \le \pi$ for gap VC-C1. In the field $U_i = (z, b_i, \omega, t)$ speed of electrons moving in region i is changing according to the law:

$$\frac{\dot{x}_i^2}{2} = H_i + \Omega_i^2 \cos x + \Omega_i^2 (\cos x - 1) b_i \cos(\omega t + \varphi) \qquad (1)$$

where $\Omega_i = \left(\frac{eU_i}{2m_0} \frac{\pi^2}{d_i^2} \right)^{1/2}$

is eigenfrequency, connected with time of flight for region i, b_i and ω_i are amplitude and frequency of oscillations of potential well minimum, i = 1, 2; H_i is Hamiltonian. The maximal electron speed on anodes and on collector is equal $\dot{x}_0 = \sqrt{2}\sqrt{H_i + \Omega_i^2} \equiv v_0$ at coordinate values: $x = 0$ (anode A1), $x = 2\pi$ (anode A2) and $x = 4\pi$ (collector Cl).

The motion equation getting from equation (1) look like

$$\ddot{x} + \Omega_i^2 [1 + b_i \cos(\omega_i t + \varphi)] \sin x = 0 \,. \qquad (2)$$

At $H_i \le \Omega_i^2$ equation (2) is describing nonlinear oscillations of electron in potential well, at $H_i > \Omega_i^2$ - is nonlinear movement of floating-drift electrons.

Frequency modulation caused by oscillations of potential minimum and ensuring the parametrical interaction is describing by functions $b_i \cos(\omega t + \varphi)$. In that case exactly the parametrical action of oscillations of potential well minimum is not changing the value of maximal speed v_0 on anode and collector (Fig. 3) but is changing electron transit time of drift space, what lead to phase modulation of electrons. In such point of view it is reasonable to solve equation (1) in order to determine the coordinate of electron movement.

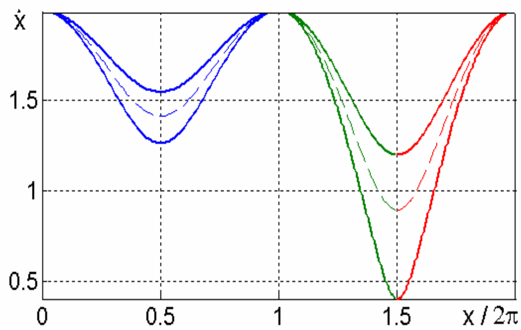

Fig.3. Distribution of electron speed

For a start let us regard the analytical solving of problem put by in order to clear up mechanism of phase modulation. For floating-drift electrons inequality $H_i > \Omega_i^2$ is true and mean speed of electrons movement in drift space is equal $v_{Hi} = \sqrt{2H_i}$ C, where C is correction factor.

In such a case primitive integral of movement (2) as a approximation b_i = 0 and $w_i^2 = \Omega_i^2 / v_{Hi} << 1$ looks like

$$x_i = v_{Hi}t + w_i^2 \sin(v_{Hi}t). \quad (3)$$

Solution of (2) is also solution of equation:

$$\ddot{x}_i + \Omega_i^2 \sin(v_{Hi}t) = 0. \quad (4)$$

Consequently, movement of floating-drift electrons (2) in drift space can be described by electron movement equation (4) in periodic potential ($T_i = 2\pi / v_{Hi}$). Comparison of numerical solution of equation (2) and analytical solution (3) gives the correction factor C = 1.28.

Assuming the smallness of parameter b_i, $w_3^2 << w_2^2$ and $v_{H1} \approx 2\omega, v_{H2,3} \approx \omega$ it is possible to get from equation (1) estimations of phase incursion at electron passing trough full interaction region $\phi = \phi_0 - \Delta\varphi$, where:

$$\phi_0 = \pi(2\omega / v_{H2} + \omega / v_{H1} + \omega / v_{H3}),$$

$$\Delta\varphi = 4w_1^2 b_1 \cos(\varphi) - 2\sqrt{2} w_2^2 b_2 \cos(\varphi + \hat{\varphi}). \quad (5)$$

Here ϕ_0 is the phase incursion at electron passing trough full interaction for, φ is initial phase of electron, $\hat{\varphi}$ is difference of phases of oscillations between potential minima I and II.

It is follow from equation (5), that the most phase shifting has a place at zero difference of phases between oscillations of potential well minima for first and second drift spaces. The most phase shifting can be obtained at $\Omega_1 / \omega \approx 1$. Phase modulation disappears at $\Omega_1 / \omega \approx 0$, i.e. at absence of potential sag.

In the most general case the task was solved numerically.

Results of numerical integration of equation (1) for electrons with different phases are shown on the Fig.4-6. Dependence of phase $\omega t / 2\pi$ from electron coordinate is shown on Fig. 3. As evident from electron phases (Fig. 3) the electron grouping have a place.

This grouping connected with that that electrons are moving in different potential distributions at different moments of injection which determines electron phase with regard to potential sag deviations. As a result time of flight of this drift gap is changing and phase displacement occurs what lead to electron stream modulation at the same electron energy in the drift space output.

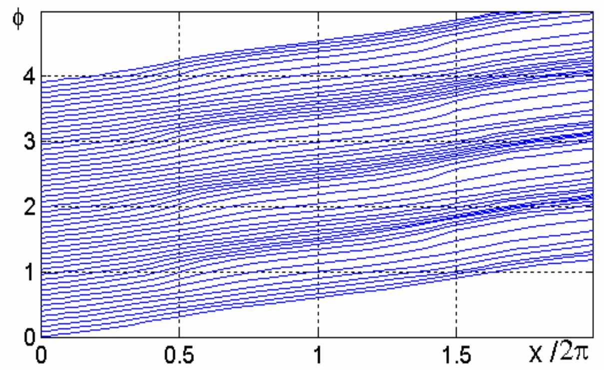

Fig.4. Changing of electron phase from coordinate for different initial values

It must be pointed that interaction time of floating-drift electrons with fluctuation of potential minimum is restricted by very small time of flight through drift gap in contrast to parametrical interaction of oscillating electrons with virtual cathode fluctuation [4-5].

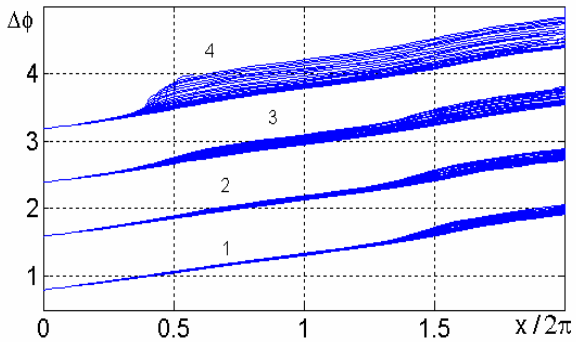

Fig. 5. Changing of phase shifting from coordinate. 1- Ω_1 / ω = 0.2, 2 – 0.4, 3 – 0.6, 4 – 0.9

Because of that electron stream modulation in usual vircator are sufficiently small [3]. In regarded system the deep modulation can be achieved owing to increasing of interaction time of electrons with potential when additional drift gap A1-A2 is using. Indeed, preliminary modulation of electron stream have a place in first drift gap A1-A2 as a result of parametrical interaction of beam with fluctuations of potential minimum, and magnification of modulation occurs in region A2-C1, where more deep potential sag can be ensured without special efforts.

As it was shown by calculations, modulation depth is depending from potential sag level U_i, mismatch of frequencies, oscillation amplitudes b_i and phase difference $\hat{\varphi}$ between potential minimum oscillations.

The maximum phase shifting can be estimated as $\Delta\varphi/2\pi$ and width of clot correspondingly as

$\Delta l = \lambda(1-\Delta\varphi/2\pi)$, where $\lambda = 2\pi\, c/\omega$ is wavelength. Figures 5 and 6 demonstrate changing of phase shifting from coordinate of electrons with different initial phases. Fig. 5 shows that increasing of potential sag depth leads to increasing of depth of electron phase modulation.

Notice that results mentioned above was obtained in absence of external electromagnetic wave equivalent to feedback in real set up. It means that electron stream modulation in vircator is conditioned by electrons interaction with volume charge field. Therefore the using of external electromagnetic wave as an active feedback in order to realize additional modulation demands to make agree parameters of wave and of potential field. Otherwise this mechanism can be found rival ones and that will suppress the beam modulation and therefore radiation power of it in resonance system.

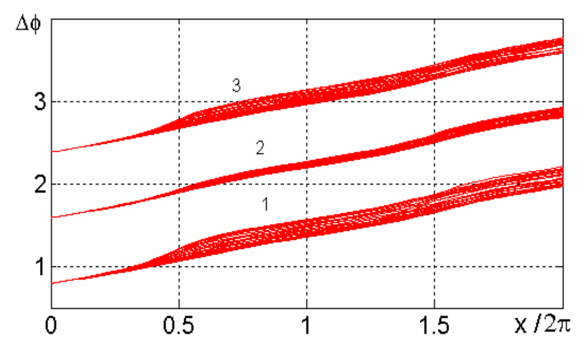

Fig. 6. Changing of phase shifting from coordinate 1 - $\phi_{ext} = \pi/2$, 3 – $\phi_{ext} = 0$; 2 - $f = 0$

Aforesaid is suggested by numerical and analytical solutions. The solution of equation (1) taking into consideration item $f\sin(\omega_{ext}t + \phi_{ext})$ responsible for field of external wave with amplitude f in the gap A1-A2 can be written as

$$\Delta\varphi \approx \Delta\varphi_0 + \breve{f}\cos(\varphi + \phi_{ext}).$$

Here ϕ_{ext} is phase difference between potential minimum oscillations and external wave. Results of numerical investigation with the regard for external wave are shown on fig.6.External wave (feedback) increase modulation depth at $\phi_{ext} = \pi/2$ and decrease it at $\phi_{ext} = 0$. Modulation depth is increasing at increasing of amplitude of external wave.

4. Conclusion

Electron stream modulation in vircator is conditioned by electrons interaction with oscillations of generic field potential of space charge.

Modulation depth is defined by interaction time of floating-drift electrons with potential oscillations and potential sag level in drift gap.

Dependence of interaction time and potential sag level from system parameters enables to create most favorable conditions for electron stream modulation choosing accelerating voltage and drift space geometry.

Increasing of modulation can be received thanks to increasing of time interaction creating additional drift space.

External field or feedback under certain conditions carries in additional contribution in passing electrons modulation. One of a number factors limiting increase of radiation power is pinching of electrons flow (which absent in reflecting triodes) and transversal component of electron speed in region of interaction with electromagnetic wave.

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