Parametric Interaction of the Electron Beam in the Vircator

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Abstract – Systems with virtual cathode are the effective generators of electromagnetic pulses. The questions of the phase modulation of electrons so as the mechanism of saturation of radiation in such system are very important. Earlier the parametrical interaction in virtual cathode triodes was considered.

In this work, the parametrical interaction of electron beams in vircators in presence of passing electrons is examined. The system parameters corresponding to the most effective interaction are determined. Electrons modulation is realized by space charge field due to parametrical interaction of potential field minimum (minimums) on passing electrons. External field or feedback under certain conditions carries in additional contribution in passing electrons modulation.

1. Introduction

Electromagnetic oscillation generation in the virtual cathode (VC) system (reflecting triodes and vircators) occurs with forming of VC and appearance of oscillation electrons in potential well. In the absence of passing electrons oscillation excitation mechanism is connected with oscillators' non-linearity, caused by space charge field and relativistic effects. In such a case electron flow instability is developed and VC oscillations are happened. Frequency of excited oscillations is multiple to frequency of oscillating electrons and is determined by potential well form mainly [1].

In systems with passing electrons (vircators), interaction of passing electrons with oscillating electrons cloud take place equally with excitation of electromagnetic oscillation on oscillating electrons. In this case quasi-potential oscillations on frequency $\omega = k_z v_0$, modulating passing electron flow, are appearing, and generation of two modes can be realized [1]. Two modes generation can be realized in systems with passing electrons under condition of forming two virtual cathodes too [1].

In the works [2, 3], the excitation of electromagnetic oscillations in VC triodes was concerned from the point of view non-linear parametrical interaction of electrons under the VC oscillations. This approach admits more sharply pick out one of mechanisms modulation of electron stream and saturation of radiation.

In this article the results of theoretical investigation of phase modulation and saturation of radiation in vircators under parametrical interaction of oscillating and passing electrons in non-linear system are presented.

The investigation was carried out analytically with using results of numerical modeling by PIC method.

2. Numerical Modeling

Let us regards two systems with passing electrons both of which consist from flat parallel electrodes.

Vircator I consist of accelerating diode and drift space (anode-collector).

Vircator II consist of accelerating diode, drift space I (between two anodes) and drift space II (between second anode and collector).

The lengths of drift tubes were chose from the condition of smallness of reflected electrons.

2.1. Vircator I

The numerical experiments are show that, when the drift space in reflecting triode (vircator I) is organized due to shielding of space charge field by front walls under the $L \le 2\sqrt{2}\ \ d$ condition, full passage of current to collector takes place [4], if electron beam current is not exceeded critical one [5]

$$I_c = \frac{\gamma\ \ mc^3}{e}\frac{r_b}{2d}, \quad (1)$$

where γ is relativistic factor, c is speed of light, m is electron mass, e is electron charge, d is diode gap, r_b is radius beam .

Under increasing of L front walls influence becomes weaker and virtual cathode is forming. In this case potential minimum, its coordinate, passing electrons current, coordinate of VC (under forming of VC) have periodical time dependencies with characteristic oscillation period depended on electron beam density.

The numerical experiment parameters are. Accelerating voltage is 900 kV, cathode radius is $r_b = 3$ cm, diode gap is $d = 2$ cm, electron beam current is exceeding of critical one (1) and effect pinching electron beam by own magnetic field H_φ becomes apparent. This effect is relaxed with decrease of cathode radius.

In the case, when quantity of oscillating electrons substantially smaller then passing ones, the phase modulation of passing electrons is happened first of all due to potential field because of parametrical interaction electrons with potential minimum oscillations in drift space [2–3].

In the resonance system passing electrons bunches are radiating on the resonator frequency $\omega_0 = \omega_\nu(k'_\perp, k'_z)$. The additional electron capture by non-linear stationary wave takes place under the excitation of electromagnetic wave by passing electrons.

2.2. Vircator II

In this system the different modes of generation can be realized depending on choose of geometric sizes and accelerating voltage. Particularly next can be realized.

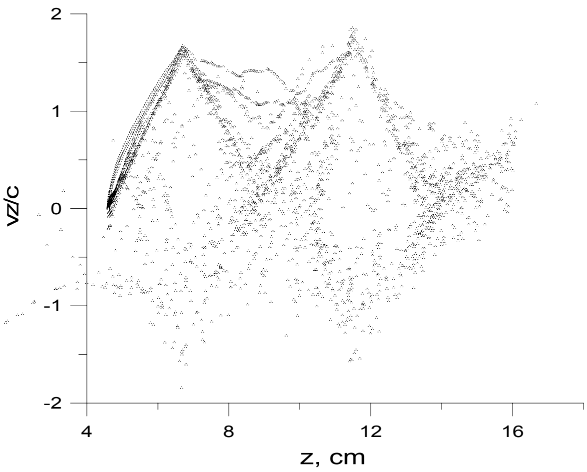

Fig. 1

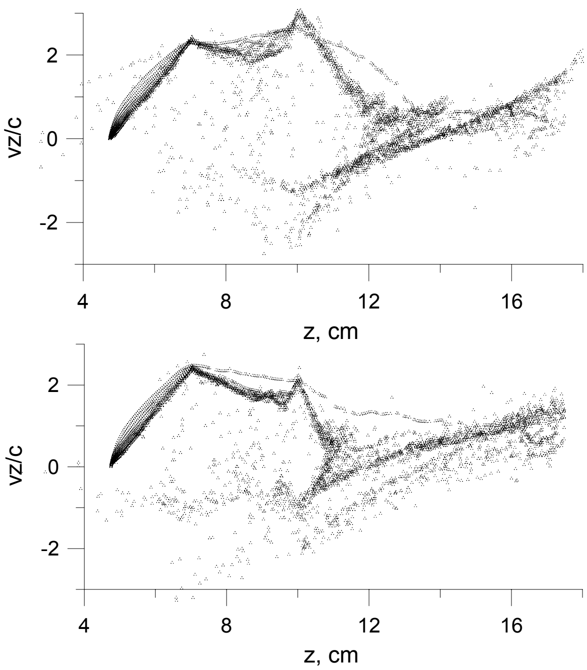

Fig. 2

1) The forming of two virtual cathodes. In this case the feedback is realized through the oscillating electrons cloud and stable operation of stationary oscillations is happened on the frequency ~ $2\Omega_0$. In this mode the phase-plane portrait of electron flow is sown on the Fig. 1.

2) The generation of electromagnetic oscillation in critical parameters region, when in the drift space 1 is a weak "sag" of potential and in the drift space 2 is a strong "sag" of potential but VC not forming yet [6]. In this case the electron beam in the drift space 1 is modulated weak under effect of periodic potential on the mode ω_1. Then, more deep modulation of passing electrons flow is occur due to parametrical interaction of passing electrons with potential minimum oscillations in space 2. In resonance system the modulated electrons flow will excite electromagnetic oscillations, which can intensify modulation due to feedback choose under the certain conditions [6].

The phase-plane portraits of electron beam are shown on the Figs. 2 and 3. The electron beam paths are shown on the Fig. 4. Figs. 3 and 4 represent effect of electron flow pinching.

The periodical character of fields is suggested by Fig. 5, n is number of time steps. The investigations of time dependency of fields shows that components E_r, E_z, H_φ have periodical dependency and in such a case the oscillation frequency coincides with frequency of potential minimum oscillation z_{VC}.

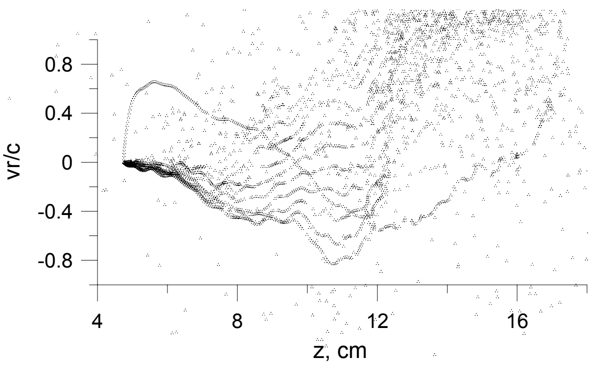

Fig. 3

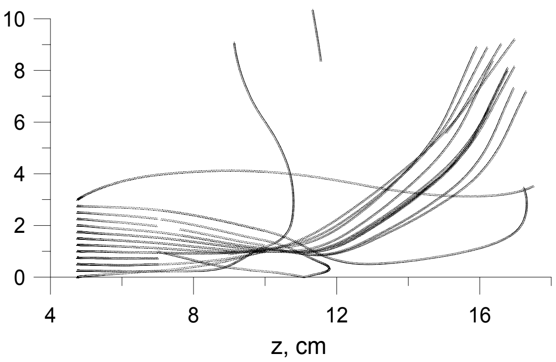

Fig. 4

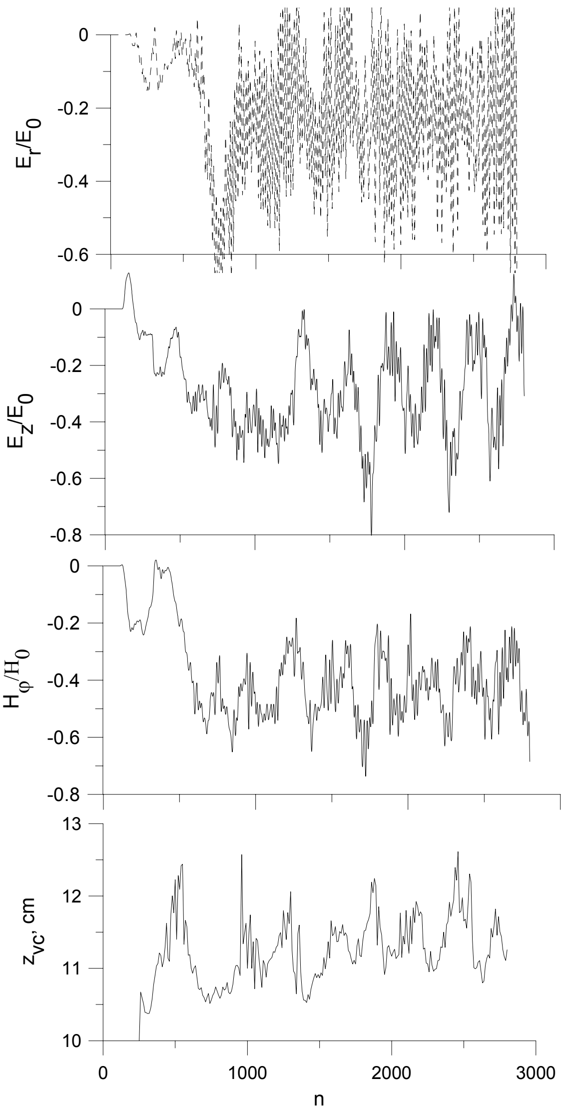

Fig. 5

3. Parametrical Interaction

The results of numerical modeling conducted by PIC method permits to develop model describing dynamics of parametrical interaction electrons in suggested systems and to clarify mechanism of radiation saturation.

Potential field in which electrons are moving can be described by expression

$$U(x,t) = -U_{0i}\ \ (1 - b_i \cos\omega_i\ \ t)\cos a_i x\,, \qquad (2)$$

where b_i и ω_i – amplitudes and frequencies of oscillations potential minimum in region i, $i = 1, 2$. Constant a_i determines spatial scale of heterogeneity. For oscillation movement of electrons in potential well $U(x) \le E$, the parametrical interaction is equivalent to oscillations of potential well's edge. This investigation was carried out in works [2–3]. Here E is electron energy maximum.

When $U(x) < E$ expression (2) represents potential field for passing electrons. Tacking into account own magnetic field of beam H relativistic movement of electron in this field can be written as

$$\ddot{x} = -\frac{a_i e U_{0i}}{mc} B(t)\sin(a_i x) + \frac{eH}{mc\gamma}\dot{y},$$
$$\ddot{y} = -\frac{eH}{mc\gamma}\dot{x}, \qquad (3)$$

where

$$B(t) = \left[1 - b\cos(\omega_i\ \ t + \Delta\varphi)\right],$$

a_i – length of drift space.

In the Figs. 7 and 8 are shown electrons tracks (diode area is not represented, $d = 1.2$ cm), which were obtained from the solving of equation system (3). On the Fig. 6 are represented the configurations of potential field discriminated by different "sag" of potential: dash line corresponded to Fig. 7, firm line – Fig. 8. This result not suggests presence of external wave, which is equivalent to feedback in real device [6] for more clear view of electrons alignment in potential fields.

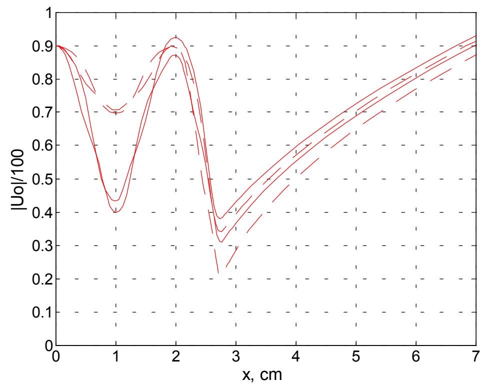

Fig. 6

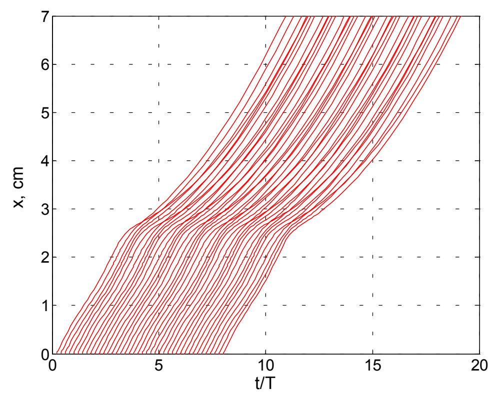

Fig. 7

It is evident from Fig. 7 that modulation of electrons flow takes place in the drift space 1 as a result of parametrical interaction of beam (preliminary modulated in drift space 1) with oscillations of potential minimum in drift space 2. At that the strongest bunching is happened in the most big potential "sag" region.

In Fig. 8 it is shown bunching process with the big potential "sag" in region 1. From the comparison of Figs. 7 and 8 it is follows that the depth of passing electrons flow modulation is fundamentally increasing with increasing of potential sag in drift space 1. This modulation is conditioned by parametrical interaction of potential minimum oscillations on moving particles.

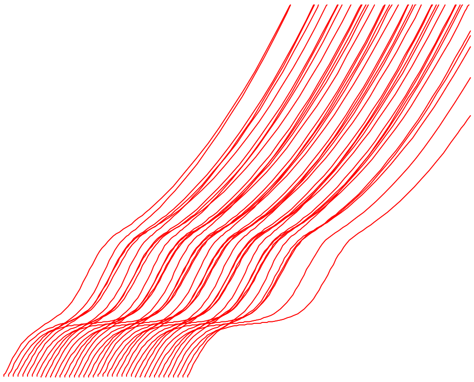

Fig. 8

4. Radiation Power

Electron radiation power on the resonator frequency $\omega_2 \approx \omega_\nu$ is given by expression

$$P = I_0 U_0 \sum_{\nu} G_\nu(k_z, k_\perp)\; f(t, Q_\nu, \Delta\omega)\,, \qquad (4)$$

where $I_0 = 17$ kA, $U_0 = 500$ kV, G_ν is impedance of resonance [2], Q_ν is quality of resonance volume, k_z и $k_\perp$ is longitudinal and transversal wave numbers, $\omega_\nu / c = \sqrt{k_z^2 + k_\perp^2}$ is eigenfrequencies of resonance volume 2, $\Delta\omega = \omega_1 - \omega_2$ is difference of frequencies of potential wells minimums oscillations.

Time dependence of charge particle radiation power is determined by tightening of particle phase to stationary phase.

Coherent radiation power of bunching electrons flow can be obtained if to integrate the expression (4) by electrons stationary phases. In this case $f \sim \frac{\omega_2}{\omega_\nu} Q_\nu \frac{N_{st}^2}{N^2}$, where N_{st} – number of resonance electrons with phase difference below than $\lambda_\nu = \omega_2 / 2Q_\nu$. The electron bunch is forming under the resonance conditions $\omega_2 \cong \omega_\nu$ and coherent radiation is happened on the frequency $\omega_2 - \Delta_\nu$. At that the optimal ratio between frequencies mismatch $\Delta\omega$, Δ_ν and λ_ν, when radiation power is maximal exists.

5. Conclusions

In vircator on passing electrons radiation generation occurs under exciting of electromagnetic oscillations in resonance system by modulated passing electrons flow. Electrons modulation is realized by space charge field due to parametrical interaction of potential field minimum (minimums) on passing electrons.

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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