EXCITATION OF A FLAT COMB USING AN ELECTRON BEAM WITH A VIRTUAL CATHODE

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The numerical simulation method was applied to investigate the excitation of a plate shielded comb slow-wave system by the relativistic electron beam with a limit current exceeding space-charge limiting current. Such a system can be considered as a combination of a vircator and a traveling wave-tube. It has been established that there is a possibility for realization in this system both the single-frequency- and multifrequency modes of high-power microwave radiation generation. The oscillating mode, with given electron beam parameters, is determined by the slow-wave system geometry.

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1. PROBLEM DEFINITION AND MODEL DESCRIPTION

A goal of the study is to investigate the processes of electromagnetic field excitation in a slow-wave structure like a flat shielded comb. A power supply source is an electron beam with a space-charge limiting current. Besides, the cathode-generated radiation is propagating in the structure.

Investigations of combined systems, namely, vircator – slow-wave structure and vircactor-resonator, have a considerable history. For example, paper [1] presents detailed experimental results of investigations on the combined vircator – backward-wave tube system (virtode). The authors of [2, 3] show a possibility in principle of chaotic radiation generation with the use of a virtode. A combination of the vircator with a high-Q cavity (vircator-klystron) is proposed by the authors of [4]. Generation of a high-power microwave radiation by relativistic beam on the base of a vircatron-ubitron combination is described in [5].

In the present study we have applied the simulation method, to investigate a combined vircator – backward-wave tube system in which, unlike [1], the wave energy extraction channel is combined with the propagation region of the electron beam transmitted through the virtual cathode region.

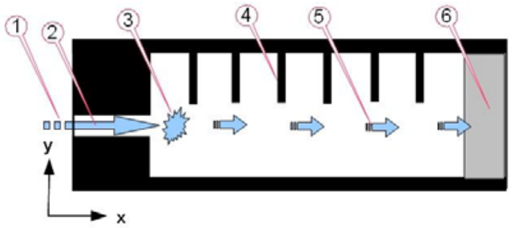

Fig. 1. General view of the calculation region

Fig. 1 presents the general view the model calculation region (without proportion conservation). Here 1 is the injector region being external against the calculation region; 2 – beam transport channel; 3 – virtual cathode localization region; 4 – comb slow-wave structure; 5 – transmitted beam drift region; 6 – electromagnetic wave absorber region for the opened boundary simulation.

A model system is a closed region of infinite extent along the *z* axis with finite sizes L_x, L_y along the *x* and *y* axes respectively. A continuous relativistic electron beam of a given energy and its spread is injected into the system through the left wall (see Fig. 1). Then the beam enters, through the transport channel, into the region of interaction with the slow-wave system field. It is supposed that the electron beam is fully magnetized and therefore the electron motion is possible only along the *x* axis. The particle dynamics is calculated using the two-step leap-frog method for pulses and the second-order predictor-corrector method for coordinates. Electromagnetic fields have three components E_x, E_y, H_z (TE-waves). A guiding constant magnetic field H_x is not used in calculations by the condition of its infinite high intensity. Instantaneous values of the electromagnetic wave field are determined by integration of the rotor Maxwell equations:

$$rot\,\vec{E} = -\frac{1}{c}\frac{\partial \vec{H}}{\partial t}; \qquad rot\,\vec{H} = \frac{1}{c}\frac{\partial \vec{E}}{\partial t} + \frac{4\pi}{c}\vec{j}\,. \tag{1}$$

Here we assume $\mu/\varepsilon = 1$ (vacuum, Gaussian system of units). To find a solution a Yee difference system of equations is used [6]. Equations (1) do not provide the fulfillment of the charge conservation law in the presence of the emission and escape of electrons. Therefore to determine the complete electric field components we introduce into the right part of (2) a correction for the space-charge field (Boris correction [7]) so that

$$\vec{E}^{new} = \vec{E}^{old} - \vec{\nabla}\delta\varphi\,, \tag{2}$$

where $\delta\varphi$ is sought from the Poisson equation

$$\Delta\delta\varphi = \vec{\nabla}\cdot\vec{E} - \rho\,, \tag{3}$$

where ρ is the electron current charge density. The integration method (3) is the sequential overrelaxation.

To calculate the grid values of the charge density ρ and current density j_x we have used the method of weighting by areas (CIC model).

2. MAIN RESULTS

The dependences of the radiation parameters on the interaction region sizes, slow-wave structure energy and on the beam current density have been investigated. If there is no a comb then at the distance approximately equal to $L_x/2$ a virtual cathode arises (2 in Fig. 2).

The electrons reflected from the virtual cathode go backward into the drift channel region (1) and create in it a local charge density excess. As a result, a secondary virtual cathode arises in the drift channel (3). It is seen in Fig. 2 that the transmitted beam is a sequence of coupled electron bunches.

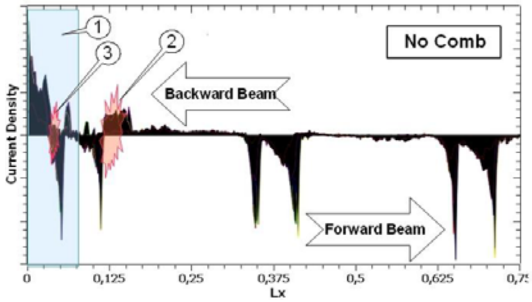

Fig. 2. Instantaneous beam current density profile without a slow-wave structure

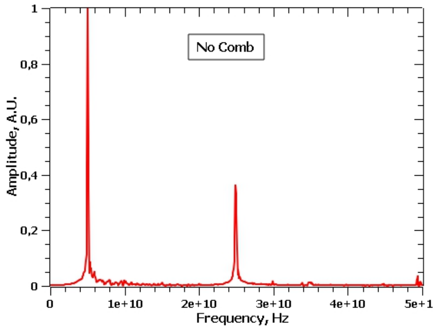

Fig. 3. Vircator radiation spectrum without a slow-wave structure

For this case the amplitude spectrum E_x of the wave field component in the point near the beam region is presented in Fig. 3.

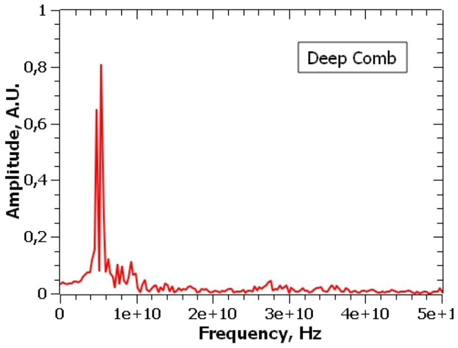

Fig. 4. Vircator radiation spectrum in the case of strong coupling with a slow-wave structure

By placing in such a system a "deep" comb, with a rather strong coupling with the beam, tuned on the fundamental vircator oscillation frequency (or close to it) we observe a single-frequency oscillating mode or neighbouring frequency oscillating mode (Fig. 4). Some broadening of the radiation peak with a frequency of 5 GHz is caused by the "spreading" of the virtual cathode existence domain, as is seen in Fig. 4. At the same time, there is no radiation with a frequency of 25 GHz in the spectrum of Fig. 3 unlike the case of a "pure" vircator. It means that the flat shielded comb with a strong coupling is an effective band-pass filter for the virtual cathode radiation.

As regards the field amplitude change in the case of slow-wave structure introduction into the work space, here a pattern, typical for the traveling-wave tube, is observed. Depending on the comb parameters (for example, a total length) and the beam energy at the system exit, both the increase and decrease (sometimes significant) of oscillation amplitudes, due to the wave energy transfer to electrons, was observed.

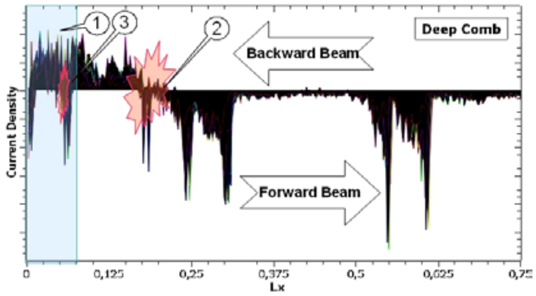

Fig. 5. Instantaneous beam current density profile with a slow-wave structure

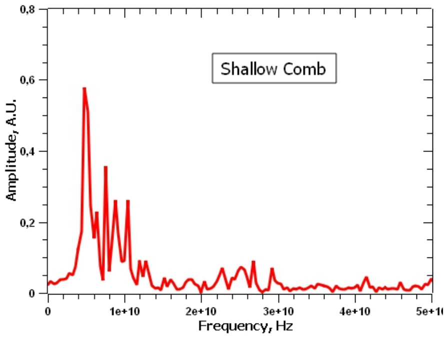

Fig. 6. Vircator radiation spectrum in the case of a weak coupling with the slow-wave structure

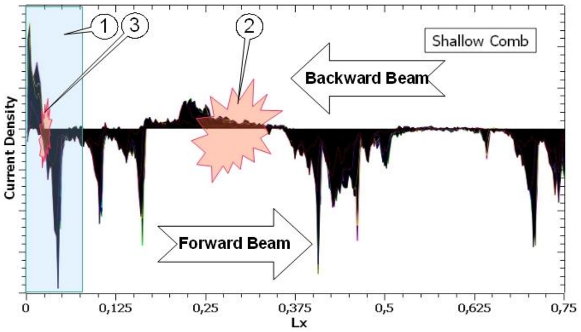

Fig. 7. Instantaneous beam current density profile in the case of a weak coupling with the slow-wave structure

In the case of a weak coupling between the slow wave and the beam (a "shallow" comb) the active band-pass of the structure broadens and a multifrequency oscillating mode is realized.

A typical spectrum shape is presented in Fig. 5.

In Figs. 6, 7 we can see a subsequent broadening and shift of the cathode existence domain. Besides, the "synchronism" of oscillations of two virtual cathodes begins to be disturbed. The exciting electron current density profile becomes a more complex. The multifrequency oscillating mode is, evidently, the result of such an interaction between the slow wave and electron beam.

The presented results were obtained for the numerical model with such parameters. The total system length $L_x = 20$ cm, including the transport channel length of 1.5 cm, the total height $L_y = 1.3$ cm. The comb spacing was 0.5 cm, the depth – to 0.55 cm, the width from the wall – to 0.15 cm. The beam transport channel height was of about 0.2 cm at a distance of 0.4 cm from the low wall. The initial electron beam energy was 0.5 MeV with a spread of 0.1%, the beam thickness was 0.1 cm.

CONCLUSIONS

The combination of a vircator with a comb slow-wave system demonstrates a possibility of realizing different modes for generation of a high-power microwave radiation. The mode of electron beam generation with given parameters is determined by the slow-wave system geometry. Possible practical applications include, especially, the vircator efficiency increase and multifrequency electromagnetic radiation generation.

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ВОЗБУЖДЕНИЕ ПЛОСКОЙ ГРЕБЕНКИ ЭЛЕКТРОННЫМ ПУЧКОМ С ВИРТУАЛЬНЫМ КАТОДОМ

А.М. Горбань, Ю.Ф. Лонин, А.Г. Пономарев

Методом численного моделирования исследовано возбуждение плоской экранированной гребенчатой замедляющей системы релятивистским электронным пучком с током выше предельного. Такую систему можно рассматривать как комбинацию виркатора и лампы бегущей волны. Установлена возможность реализации в ней как одночастотного, так и многочастотных режимов генерации сверхвысокочастотного излучения большой мощности. Режим генерации при заданных параметрах электронного пучка определяется геометрическими параметрами замедляющей системы.

ЗБУДЖЕННЯ ПЛОСКОЇ ГРЕБІНКИ ЕЛЕКТРОННИМ ПУЧКОМ З ВІРТУАЛЬНИМ КАТОДОМ

А.М. Горбань, Ю.Ф. Лонін, А.Г. Пономарьов

Методом чисельного моделювання досліджено збудження плоскої екранованої гребінчастої уповільнюючої системи релятивістським електронним пучком із струмом вище обмеженого просторовим зарядом. Таку систему можна розглядати як комбінацію віркатора і лампи бігучої хвилі. Встановлена можливість реалізації в ній як одночастотного, так і багаточастотних режимів генерації надвисокочастотного випромінювання великої потужності. Режим генерації при заданих параметрах електронного пучка визначається геометричними параметрами уповільнюючої системи.