Novel Schemes of High-Power Relativistic Vircators

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***Abstract* — The following novel schemes of relativistic generators with virtual cathode were proposed and investigated in terms of enhancing output power, efficiency and generation frequency: multibeam vircator; vircator with elliptical resonator; vircator with photonic crystal. The carried-out analysis and obtained results have shown efficiency of the proposed vircator schemes.**

Keywords—vircator, virtual cathode, high-power microwaves, relativistic electron beam, photonic crystal, multibeam vircator.

I. Introduction

Relativistic generators with virtual cathode (vircators, virtodes, reditrons, etc.) are one of the most promising and actively investigated extremely high-power sources of electromagnetic signals in the microwave and sub-THz ranges. Such devices can be used in systems for acceleration of ion beams, for studying electromagnetic compatibility, probing the atmosphere, etc. [1]. The main advantages of vircators are very high output power, easy control of spectral characteristics, low requirements for the electron beam quality, in certain modes – wide frequency band of generated signals, and simplicity of design, including the possibility of operating without external magnetic field.

However, the main disadvantages of generators with relativistic electron beams with supercritical current are their low efficiency and relatively low generation frequency. Many researchers have been making constant attempts to enhance the energy conversion efficiency of vircators [2].

One of the possible solutions to the problem of low efficiency and advancement to the millimeter-wave band is the development of novel vircator schemes and the modification of old ones. This paper is devoted to the presentation and analysis of the following promising schemes of vircators: multibeam vircator, vircator with elliptical resonator, vircator with photonic crystal.

II. Main Results

A three-dimensional particle-in-cell (PIC) electromagnetic code was used to simulate complex non-stationary processes of electron-wave interaction in the considered systems.

Vircator with Elliptical Resonator

The scheme of vircator with elliptical resonator is shown in Fig. 1a. The dynamics of electron beam in this scheme was analyzed. The results of global optimization were obtained by changing the control parameters of the system. We have studied the influence of the electron beam current and the geometric parameters of the elliptical resonator (radii of semiaxes) on output power of the vircator on the working mode. We have found the optimal values of these parameters (see Fig. 2a-c).

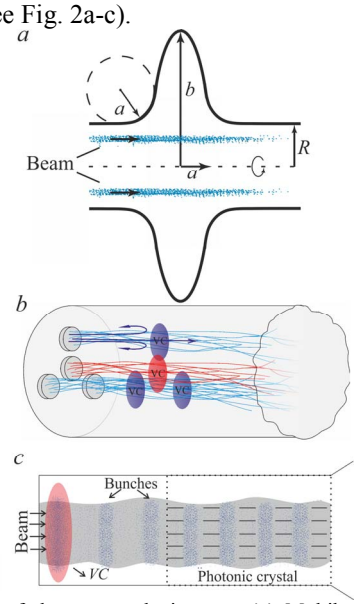

Fig. 1. Schemes of the proposed vircators. (*a*) Multibeam vircator. (*b*) Vircator with elliptical resonator. (*c*) Vircator with photonic crystal.

We have carried out optimization of power output of the vircator and proposed a variant of matching of cylindrical working chamber of the vircator with coaxial power output based on a smooth increase of the inner conductor radius from 0 in the chamber to Rc in the waveguide (Rc is the inner radius of the coaxial waveguide), thus enhancing vircator efficiency. We have investigated the dependence of output power of the vircator with elliptical resonator on Rc at the presence of the matching (Fig. 2d) that demonstrates also the existence of optimum.

Also, we have analyzed dynamics of relativistic electron beam in the proposed scheme. We observed a significant increasing of spatial amplitude of virtual cathode oscillations in the investigated model compared to the classical vircator. This effect is caused by the intense interaction of virtual cathode with high-Q eigenmode of the electrodynamical structure. We have found out that virtual

cathode should be formed directly in the resonator to achieve maximum output power.

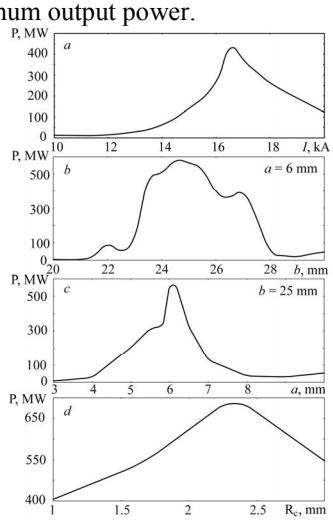

Fig. 2: The dependencies of output power of vircator with elliptical resonator on the following control parameters: (*a*) on the value of injected current *I* at *a* = 6 mm, *b* = 23.5 mm; (*b*) on the major semiaxis *b* of the forming ellipse at *I* = 16.5 kA, *a* = 6 mm; (*c*) on the minor semiaxis *a* at *I*=16.5 kA, *b* = 25 mm; (*d*) on the radius R_c of the inner conductor of the coaxial power output at *I*=16.5 kA, *b*= 25 mm, *a*= 6 mm.

We have shown that elliptical type of the resonator makes it possible to provide a better efficiency of interaction of the relativistic electron beam with electromagnetic field due to better localization of the field being excited in elliptical resonator. It leads to a significant increase in the efficiency of the vircator up to 5-7%. At the same time, effective advance in the millimeter-wave range is possible for vircator with elliptical resonator due to the presence of regimes with intense higher harmonics of the fundamental frequency of virtual cathode oscillations.

Multibeam Vircator

Multibeam scheme of vircator is the system, in which several electron beams with supercritical currents are loaded onto common resonator (Fig. 1b). This scheme is considered as promising for increasing generation power and frequency [3]. The possibility of effective interaction of several virtual cathodes in a single interaction space was analyzed, and conditions of effective addition of powers of each beam at the output load were determined.

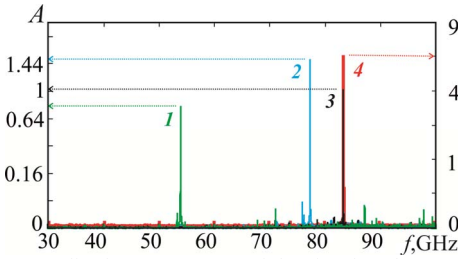

Fig. 3. The normalized power spectra of the signal at the waveguide port output in the model of multibeam relativistic vircator when one electron beam is injected into the system with a current of 12 kA (green spectrum 1), 14 kA (blue spectrum 2), or 16 kA (black spectrum 3) and when three electron beams are injected with currents of 12 kA, 14 kA, and 16 kA (red spectrum 4, right scale). The spectra are normalized to the power of the main spectral component of the output signal generated in a single-beam system with a current of 16 kA. The value of the induction of an external magnetic field is *B* = 1 T; the energy of the injected electron beams W_e = 1 MeV.

The effect of synchronization of virtual cathodes in the model of a multibeam relativistic vircator was discovered for the first time. This effect is important both from the fundamental and applied points of view because it can allow shifting relativistic vircators to a higher frequency range without substantially increasing the total current in the system. This result can be achieved using one relativistic electron beam with the highest current as the beam that determines the frequency, and the remaining (N-1) beams with lower currents as supporting beams, which "pump" the necessary energy into the system.

Thus, to increase the vircator generation frequency (which is determined by the plasma frequency) and the power at a given frequency, it is not necessary to increase the total current injected into the system, compared with the single beam. However, it is sufficient to increase only the current of one of the N beams (base). As a result, due to synchronization, VCs in all electron beams will oscillate at one frequency, which is set by the VC oscillations frequency in the base beam, which will lead to an increase in the output signal power at this frequency (Fig. 3).

Vircator with Photonic Crystal

The scheme of vircator with photonic crystal is shown in Fig. 1c. We have studied the properties of microwave generation in a virtual cathode oscillator with a photonic crystal composed of metal grids. Our simulation results show the high efficiency of photonic crystal structure utilization in comparison with the standard scheme of an axial virtual cathode oscillator: operation efficiency reaches 20% at the optimal parameters [4]. We have shown that the dispersion characteristics of the photonic crystal make it possible to synchronize the phase velocity of electromagnetic wave with electron beam propagating after a virtual cathode, that increases substantially the efficiency of vircator generation.

We have revealed that photonic crystal located in the drift tube of the axial vircator permits us to significantly improve the efficiency of microwave generation due to a number of factors: (i) high interaction impedance with passing REB, (ii) distributed electromagnetic feedback with VC, and (iii) efficient electromagnetic energy output compared to the traditional cylindrical waveguide.

The obtained results demonstrate that the virtual cathode oscillator with a photonic crystal can be considered as a prospective high-power microwave source where the vircator operation mechanism and photonic crystal properties complement each other to produce high-power electromagnetic radiation.

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