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Excitation of Electromagnetic Waves in a Vircator by Radially Diverging Beam

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Abstract. This paper presents the theoretical and experimental study of the excitation of electromagnetic waves in the TEM-mode in coaxial vircator with radially divergent electron beam. Excitation of electromagnetic oscillations, emission spectrum, instability increment of electromagnetic oscillations, and formation of a virtual cathode are investigated using the kinetic equation and numerical simulation (PIC code KARAT). It was shown that the resonant interaction of the electron beam is most effectively done with the TEM-mode. The possibility of TEM-mode excitation with its subsequent transformation into TE_{10}-mode of a rectangular waveguide has been experimentally demonstrated.

Introduction

Currently, special importance is given to design and production development of polymer coatings and small thickness materials which are able to absorb electromagnetic radiation in the wavelength ranged from 0.9 to 12 cm. Therefore it is of interest to create sources of electromagnetic radiation with the appropriate parameters for the study of the interaction of electromagnetic radiation with materials. Generators of electromagnetic radiation based on the systems with a virtual cathode (vircators) have attracted attention due to the lack of restrictions on current because of the space charge. This allows creating generators with high power of radiation. Of all the types of vircators the most promising is vircator of a triode-type with virtual cathode (VC) [1]. Triode with VC is compact, simple in design concept; there is no external magnetic field to focus the electron beam. In the triode the electron oscillation occurs between a real cathode located at the ground potential and the virtual cathode around the grid anode at the high positive potential. With such a formation of the oscillating electron flow a phase bunching of the electrons in the stream associated with their phase selection most effectively occurs [2], which leads to the generation of electromagnetic radiation with a higher efficiency in power compared with other types of vircators. However, having such positive qualities the triode with VC is limited in its practical use. This is primarily due to the fact that in the generator the excitation of electromagnetic waves occurs in oversize resonant volume, which leads to the generation of a multimode microwave radiation. Therefore, when designing a vircator the choice of the most effective mode with which the interaction of oscillating electrons of the beam and the virtual cathode is an important condition for the single-mode lasing. In this regard a vircator with radially diverging beam is of interest, which is an analog of the triode with VC [3]. A vircator diagram is shown in Fig. 1. In the triode with VC a cathode is at a ground potential and an anode is at a high positive potential. The possibility of generating electromagnetic radiation in a coaxial vircator with radially diverging beam was pointed out in [4-6]. In this vircator an axially symmetric beam most effectively interacts with nondispersive TEM-mode, which can be transmitted through the coaxial line and transformed with small losses to TE_{10}-mode in rectangular waveguide which is of practical interest.

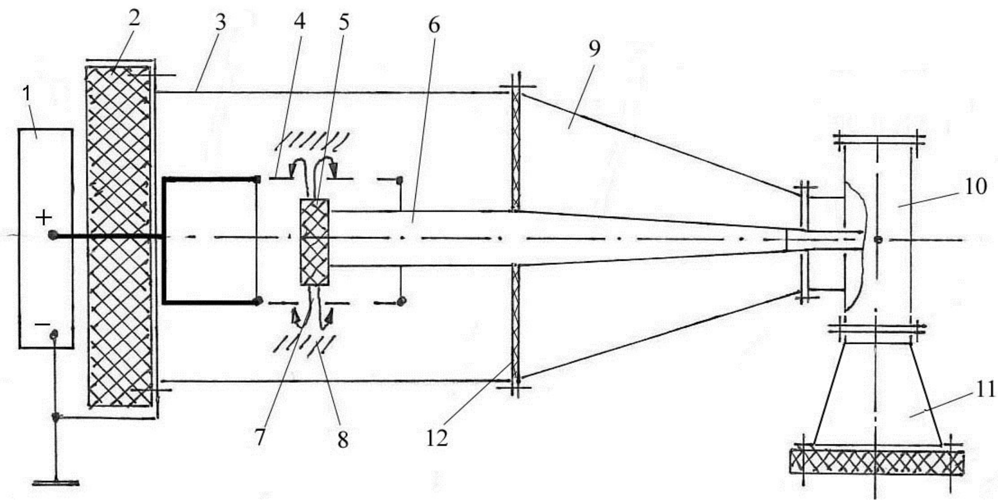

Fig. 1. Experimental setup. 1 - voltage source; 2 - vacuum insulator; 3 - camera of a vircator; 4 - grid anode; 5 - cathode; 6 - inner conductor of the coaxial line; 7 - flow of electrons; 8 - virtual cathode; 9 - cone coaxial line; 10 - coaxial-waveguide transition; 11 - rectangular antenna; 12 - radio transparent aperture.

To understand all the advantages of the coaxial vircator it is necessary to carry out a detailed study. This paper presents the results of theoretical and experimental studies on the excitation of electromagnetic oscillations in a TEM-mode in a coaxial vircator with radially diverging beam. Excitation of electromagnetic oscillations, emission spectrum, instability increment of electromagnetic oscillations, and formation of a virtual cathode are investigated using the kinetic equation and numerical simulation (PIC code KARAT).

Theory of excitation

Investigation of the excitation of electromagnetic oscillations by electron flow in the resonant system has been carried out on the basis of the kinetic equation in cylindrical coordinates (r, θ, z) [6]. Radial motion represents non-linear oscillations in the potential well $U(r)$, formed by the external accelerating field and the field of the space charge of the beam. Excitation of electromagnetic oscillations occurs at a frequency of coherent oscillations ω, close to the frequency of oscillating electrons Ω_0 in the potential well formed by external accelerating field and the field of the space charge. Under these conditions, the growth increment of electromagnetic oscillations at eigenfrequencies of the resonator $(\omega \approx \omega_\lambda \approx \Omega_0)$ is defined by the expression

$$\varsigma = \frac{\sqrt{3}}{2}\{\Lambda Z\,|K|\}^{1/3}\,\Omega_0 - \frac{\Delta x}{x_0}\Omega_0 - \frac{n}{R_A}\Delta v_\theta - k_z \Delta v_z - \frac{l\Omega_0}{\delta Q_\lambda} \quad . \tag{1}$$

Increment is a maximum for a flow of monoenergetic oscillators. Here $K = (\partial\Omega/\partial x)_0 (x_0/\Omega_0)$ is nonlinearity parameter of electron oscillations in the potential well; $\Delta v_{\theta,z}$ and $\Delta x/x_0$ are spreads of velocity and amplitude of the oscillations, Λ is parameter proportional to the density of electrons in the region of VC, Z is impedance, depending on the type and parameters of the excited oscillations of the resonant system with a quality factor Q.

Radiation efficiency can be obtained from the exit condition of excitation of electromagnetic oscillations on a stationary mode due to violation of the resonant interaction [7].

$$\eta = \frac{2}{\sqrt{3}}\frac{\varsigma}{l\Omega_0}\frac{1}{|K|}\left|1 + \frac{\gamma_0 - 1}{\gamma_0} + 2K\right|, \tag{2}$$

Here γ_0 – relativistic factor (relative energy of an electron at the anode). From these relations it follows that the radiation efficiency depends on the geometry of the diode, the external voltage, the energy spread of electrons and the type of the excited oscillations. The greatest growth of the excited oscillations and vibrations correspond to the radiation efficiency at the first harmonic l=1, leading to oscillations of the gravity center of the electron beam of oscillating electrons and virtual cathode.

For the parameters of vircator: accelerating voltage is 500 kV, cathode radius is 5.5 cm, anode radius is 6.7 cm, vircator camera radius is 17.5 cm, radiation frequency is 3 GHz. Fig. 2 shows the dependence of the impedance Z of the length of the cathode h for several oscillations. The figure shows that the highest radiation efficiency is achieved when setting the resonant excitation system on TEM-mode.

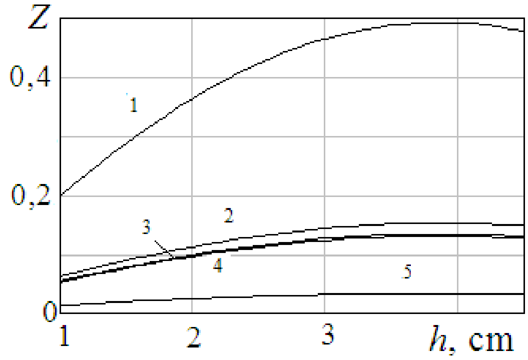

Fig. 2. Dependence of impedance on the cathode length; 1 – TEM, 2 – TM_{01}; 3 – TE_{01}; 4 – TM_{11}; 5 – TE_{11}

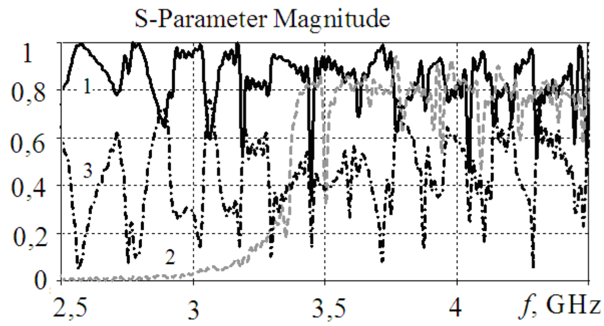

Fig. 3. Frequency dependence of the wave energy transfer coefficient : 1 – TEM, 2 – TE_{11}, 3 – TE_{01}

Numerical simulation and experimental study

We have carried out numerical simulations of coaxial vircator shown in Fig. 1 with the following parameters: voltage – 500 kV; cathode radius – 5.5 cm; grid anode radius – 6.7 cm; the camera radius of vircator – 17.5 cm; inner electrode radius of the cylindrical coaxial line – 5 cm; wave impedance of cone coaxial line – 75 ohms; cone line length – 50 cm; total length of vircator – 100 cm. The simulation has showed that wave TEM has the highest rate of energy transfer coefficient in the electrodynamic system of vircator (Fig. 3). The wave TM_{01} has a close configuration of a field with TEM wave, so when the wave energy of TM_{01} is transmitted (critical frequency of 1.37 GHz) it is transformed into the TEM wave. When the frequencies are below 3.4 GHz the asymmetric modes (TE_{11} wave) at the output of vircator are absent due to conicity of the coaxial line.

In the simulation and experimental studies it has been found that the current and the radiation power have a nonlinear dependence on the length of the cathode (Fig. 4). There is an optimal length of the cathode (h_0=2.4 cm), at which the maximum of radiation power is observed (Fig. 4b). For small lengths of cathode the most of electrons are reflected from the virtual cathode because of the intrinsic magnetic field of the beam and do not return in a span of a cathode-virtual cathode and is not involved in the oscillator movement. As the length of the cathode increases to h_0=2.4 cm, the number of electrons oscillating in the region of cathode - virtual cathode increases. The increase in power is connected with an increase in depth of phase modulation of electrons and increase of number of electrons resonantly interacting with the field of wave [7]. With further increase in the length of the cathode to h > 2.4 cm the intrinsic magnetic field of the beam increases the spread of electron velocities, which leads to increased spread of electron oscillation amplitude, increase in the width of the frequency spectrum and decrease of radiation power.

When the length of the cathode was optimal, the power distribution of radiation, frequency and width of the radiation spectrum was measured at the output of the rectangular antenna of vircator in free space. The measurements have shown that the maximum power level of radiation is observed on the antenna axis. Radiation is linearly polarized. It is typical for the wave type TE_{10} of a rectangular waveguide, which is formed during transformation of TEM wave in a coaxial-waveguide transition of vircator. Radiation was observed at a frequency of $f = 3.1$ GHz, spectral width was not greater than $\Delta f = 100$ MHz.

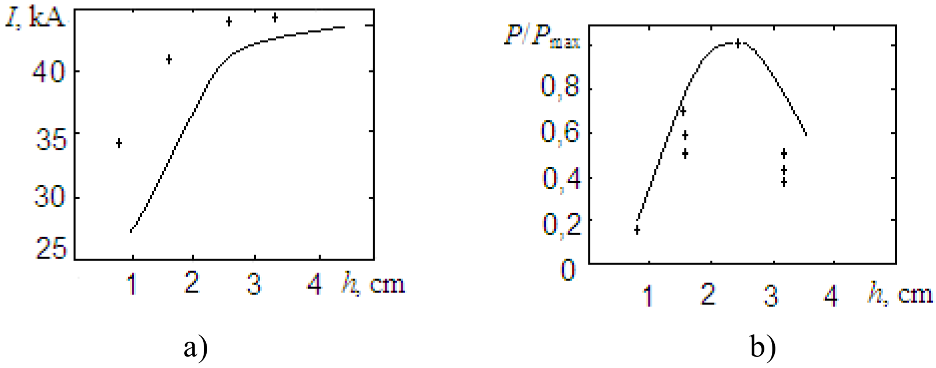

Fig. 4. Dependence of the current of vircator (a) and the relative radiation power (b) on the width of cathode: + - experiment, solid line - calculation

Conclusion

We have theoretically and experimentally studied the influence of geometry and system parameters on the excitation of microwave radiation of vircator with radially diverging beam. It has been shown that the resonant interaction of the electron beam is most effectively done with the TEM-mode. Vircator with radially diverging beam with the experimental parameters at frequencies below 3.4 GHz is a single-mode microwave generator on TEM wave. We have experimentally demonstrated the possibility of transforming TEM wave to TE_{10} wave of a rectangular waveguide at the output of vircator.

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