The Use of Higher Harmonics for Sub-THz Generation in Relativistic Virtual Cathode Oscillator

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***Abstract*—We study the microwave generation regimes with intense higher harmonics taking place in a high-power virtual cathode oscillator (vircator) consisting of a relativistic electron beam with a virtual cathode. It has been shown that the system under study demonstrates the tendency to the sufficient growth of the amplitudes of higher harmonics in the spectrum of current oscillations in the virtual cathode region with the increase of beam current. The obtained results allow us to consider relativistic vircators as promising high power mmw-to-THz sources.**

I. INTRODUCTION

Relativistic beam-plasma systems using virtual cathode (VC) oscillations for an electromagnetic radiation generation are the perspective devices of vacuum and plasma high-power microwave electronics [1]. Virtual cathode oscillators (such as vircators, reditrons, virtodes, etc.) are a special class of bremsstrahlung microwave generators whose operation is based on the formation of a VC in an electron beam with overcritical current [1]. The important and attractive features of vircators are high output microwave radiation power, a simple construction (particularly, vircators can operate without external focusing magnetic field), the possibility of a simple frequency tuning and regime switching (tunability), low demands on the quality of the electron beam [1, 2].

In practical cases the fundamental generation frequency of known vircator modifications lies usually in the range [1,20] GHz. At the same time, the creation of effective high-power generators in poorly developed sub-THz/THz ranges is an actual problem of the modern plasma physics and high-power microwave electronics [3]. Such devices may be used for the purposes of spectroscopy, tomography and medical imaging, submillimeter astronomy, communication, security etc. [3]. So, the increase of the generation frequency and the advancement of vircators to a sub-THz range on retention of their high output power are important and actual problems for practical purposes now. The promising way to solve this problems is the use of the higher harmonics of the fundamental frequency of vircator in the strongly nonlinear regimes of its operation. Analyzing relativistic vircators it is necessary to take into account effects being insignificant for the weakly relativistic systems, in particular, the influence of the self-magnetic fields of a relativistic electron beam [4]. For that reason, the 3D fully electromagnetic self-consistent CST Particle Studio package is used in this work for the accurate numerical investigations of generation processes in the relativistic vircator model. In this Report we show the results of the 3D numerical study of higher harmonics generation processes in the relativistic vircator with the relativistic electron beam (REB) with current I in the presence of external uniform axial magnetic field with induction B.

II. RESULTS

The system under study (see Fig. 1) consists of the perfect electric conducting finite-length cylindrical waveguide region (the electron beam drift chamber) of the length L, the radius R, with a grid electrode on the left side and a coaxial waveguide port on the right side. An axially-symmetrical monoenergetic annular relativistic electron beam with the current I_0, the initial electron energy W_e (850 keV in this work), the external radius R_b and the thickness d is injected through the left (entrance) electrode. Electrons can leave the waveguide region by reaching the side wall or the right (collector) end of the drift chamber. In the present Report the values of the geometric parameters were chosen as: L=45 mm, R=10 mm, R_b=5 mm, d=1.5 mm. The external uniform magnetic field with the induction B_0 is applied along the longitudinal axis of the waveguide. Note, that the frequency of the fundamental component (the first harmonic) in the spectrum is determined by the value of the disturbed plasma frequency [5].

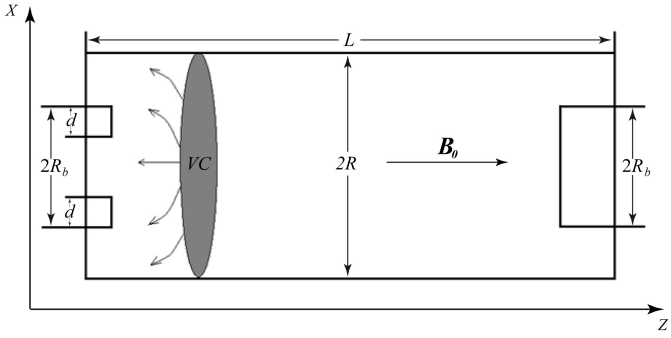

Fig. 1: The investigated model, L and R – the length and the radius of the drift chamber, correspondingly; I_0 – the beam current, W_e – the initial beam energy, R_b and d – the external radius and the thickness of the beam, correspondingly; B_0 – the induction of the external magnetic field; "VC" denotes schematically the virtual cathode area.

We have shown that the system under study demonstrates the tendency to the sufficient growth of the amplitudes of higher harmonics in the spectrum of current oscillations in the VC region with the increase of beam current [5]. In particular, the regime map in the plane (I, B) has been obtained (see Fig. 2). It demonstrates the basic tendency of the system regimes switchings: with the beam current increase for different magnetic fields we see firstly the switching from the subcritical to supercritical regime and then the increase of the second harmonic of the fundamental component that leads finally to its domination in the spectrum. At the same time, the amplitudes of the higher harmonics with numbers n>2 also increase with the growth of the beam current. The time series

and amplitude spectrum of the current oscillations in such character case with the maximal second harmonic is shown in Fig. 3; the intense 3rd (~128 GHz) and 4th (~170.6 GHz) harmonics are also presented in the spectrum.

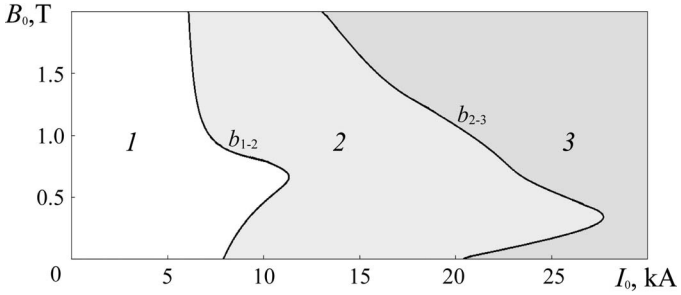

Fig. 2: The typical operating regimes of the vircator in the "beam current I_0 – external magnetic field B_0" plane. Region (*1*) corresponds to subcritical regime without VC formation (when beam current $I_0<I_{cr}(B_0)$), (*2*) – supercritical regime when the fundamental harmonic ω_{VCO} in the spectrum of current oscillations is maximal, (*3*) – regime when the second harmonic of the fundamental component $2\omega_{VCO}$ is maximal. Symbols $b_{1\text{-}2}$ and $b_{2\text{-}3}$ denote boundaries between the corresponding regimes.

Note, that the boundaries between the regimes, $b_{1\text{-}2}$ and $b_{2\text{-}3}$, have the similar form in Fig. 2. The curve $b_{1\text{-}2}$ is the dependency of the critical beam current, $I_{cr}(B_0)$, on the external magnetic field value. Its form and the presence of the area of the critical current growth are determined by the process of azimuthal (diocotron) instability development in a REB [6]. The azimuthal instability development results in the decrease of space charge density at the VC area and, as a consequence, the increase of the critical beam current. So, the analogous behavior of both boundaries indicates that the azimuthal instability also influences on the conditions of the switching from regime *2* to regime *3*, and this switching occurs when space charge density at the VC area overcomes a certain character value.

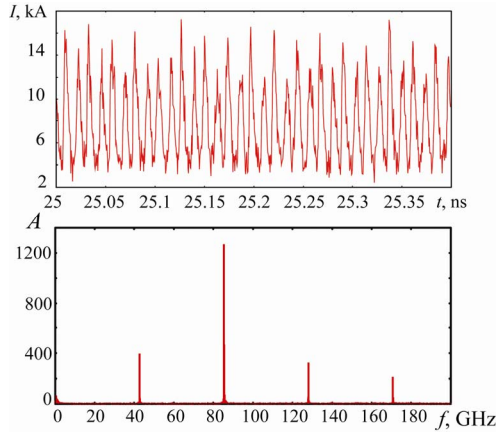

Fig. 3: The time series and amplitude spectrum of the current oscillations in the typical regime when the second harmonic (~85.3 GHz) of the fundamental VC frequency is maximal; I = 28 kA, B = 1.2 T.

Actually, when I_0~22 kA or I_0~28 kA all six harmonics (except 6th harmonic for I_0~22 kA) demonstrate the clearly defined local maxima for such external magnetic field, and the second harmonic strongly predominates over others for these values of the beam current. Note, that practically for all values of the beam current corresponding to the development regime of the vircator operation (I_0>20 kA) the second harmonic has a maximal amplitude (the exception is the weakly overcritical regime (I_0<20 kA) where the fundamental harmonic is maximal).

Fig. 4 shows the dependencies of the amplitudes of the 1st-6th harmonics of the fundamental component in the spectrum of the current oscillations of the beam reflected from VC on the injected beam current I_0. The carried out analysis allows to define the beam currents when the higher harmonics are mostly developed in the spectrum and maximal energy is stored in these components.

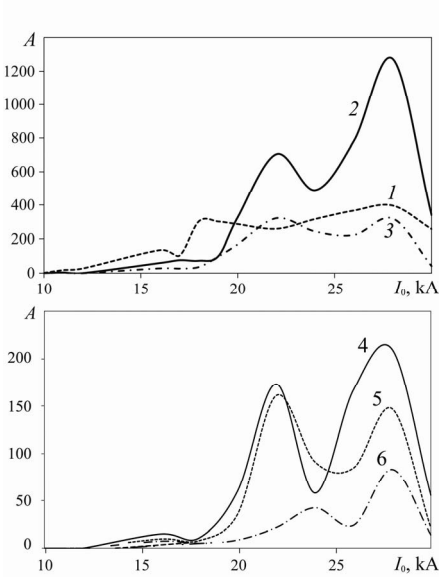

Fig. 4: The dependencies of the amplitudes of the first (curve *1*), the second (*2*), the third (*3*), the fourth (*4*), the fifth (*5*) and the sixth (*6*) harmonics of the fundamental component in the spectrum of current oscillations on the beam current I_0 for the fixed external magnetic field B_0=1.2 T.

III. Summary

The obtained results allow us to consider virtual cathode oscillators as promising high-power mmw-to-THz sources. This study of physical processes in REB has been supported by the Ministry of Education and Science of the Russian Federation (Project 3.59.2014/K) and President's program (Project MK-5426.2015.2). The investigations of the higher harmonics amplitudes behavior on the system parameters have been supported by the Russian Scientific Foundation (Grant 14–12–00222).

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