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Investigating Mechanisms of Generation in a Virtual Cathode System Using a 3D Electron Flow Model

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Abstract—The process of virtual cathode (VC) formation in the electron beam of a vircator system with additional deceleration in a 3D electromagnetic model of electron flow are studied in detail. It is shown that the microwave radiation generated in this system is characterized by high level of noise, due to the complex and turbulent behavior of the flow in the drift space.

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INTRODUCTION

The investigation of charged particle beams is of great importance for understanding the physical properties of electron and ion devices. In addition, it can be used in high-power electronics to study high-intensity electromagnetic pulse generation in vacuum and plasma devices. Intense relativistic electron flows are now widely use in a number of applications including plasma heating, inertial confinement fusion, high-intensity microwave radiation, and so on [1–8]. Studying spatiotemporal electron beam oscillations during the process of virtual cathode (VC) formation is an important and promising field of research in vacuum and plasma microwave electronics that currently attracts considerable attention from the scientific community. Microwave devices with electromagnetic generation based on forming VCs in beams with supercritical current are referred to as vircators [2]. VC-based generators were first developed in the 1970s and have been of scientific interest ever since, due to their unique set of characteristics. These include simplicity of design (vircators are capable of operating without an external magnetic field), easily adjustable frequency and oscillatory behavior, and high output power [2, 4, 9]. These aspects ensure the fundamental and applied value of works investigating the nonlinear behavior of electron flows with VCs.

It is known that VC formation is associated with the nonradiative Pierce instability that arises in a beam. Such instability is created when the beam current exceeds a certain critical value [1, 4, 10–12]. A number of experimental and theoretical studies have been performed to investigate the processes that lead to the formation of nonstationary VCs in intense electron beams and discovering the mechanisms of generation in beam-plasma systems with VCs. A detailed analysis of VC formation was performed via 1D simulations of a fully magnetized electron flow (6, 11, 13–17). Investigating the nonlinear nonstationary behavior of an electron flow with supercritical perveance within a fully electromagnetic 3D model is thus of great interest. This model allows us to obtain results close to the experimental data in course of numerical investigations. The CST Particle Studio software suite designed for analyzing the processes in charged particle flows is used to ensure the effectiveness of this kind of numerical investigation.

MODEL SYSTEM

We investigated electron flow behavior in the process of VC formation using the model of a low-voltage vircator in [3, 13–17]. This device is essentially a medium-power nonrelativistic generator of broadband microwave radiation. This model is of special interest to researchers, since earlier experimental works showed that the electron flow in this system displays complex behavior with a high degree of turbulence. In addition, several effects of interest have been observed for nonautonomous behavior [18–20]. VC formation occurs in this nonrelativistic low-voltage system owing to additional electron flow deceleration in the drift space. Flow deceleration is determined by the negative potential difference between the accelerating electrode and the collector.

The main design feature of the device is that it is divided into two parts: an electron gun and a drift tube. The hot cathode responsible for electron emission is located in the gun. The cathode is surrounded by a circular electrode that focuses the electron flow within the electron gun space. The electron flow emitted by the cathode is accelerated by another two electrodes.

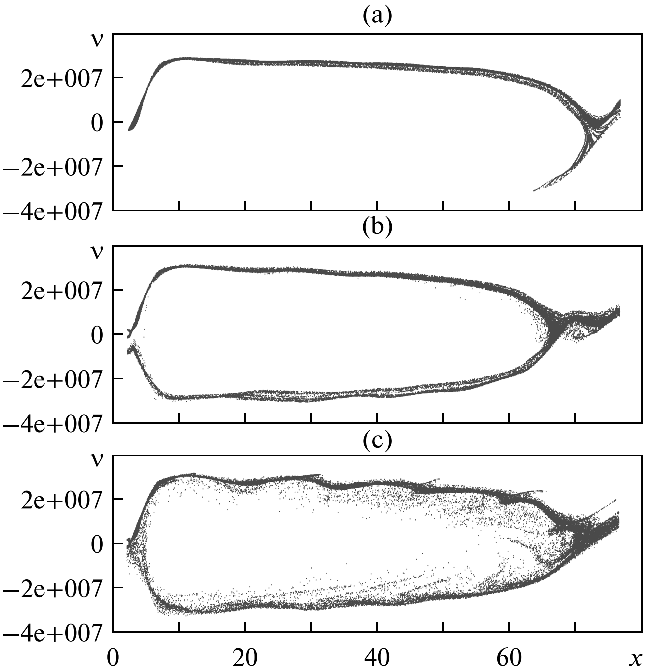

Fig. 1. Phase portraits of the electron flow in our low-voltage vircator: (a) $t = 7$ ns; (b) $t = 15$ ns; (c) $t = 34$ ns.

When the electron flow leaves the electron gun space, it enters the drift space, the radius of which is much larger than that of the electron gun tube. The difference between the radii lowers the critical beam current at which a nonstationary VC is formed in the drift space. Magnetic focusing of the electron flow is performed using a solenoid to avoid divergence of the electron flow in the gun part and the drift space.

NUMERICAL SIMULATION

Our fully electromagnetic 3D model of an intense electron flow was created using the licensed software suite CST Particle Studio (CST PS). This software allowed us to perform numerical simulations of processes that occur in actual microwave electronic devices when their main design features, injected flow parameters, and applied voltages are known.

The electron flow model in the above geometry of the device being investigated was developed by means of numerical simulation in the CST PS environment, which allowed us to analyze mechanisms of generation and VC formation in a low-voltage vircator system. All parameters were assigned in accordance with the experimental vircator model in [3, 14, 15]. The electron flow was formed in our numerical model by the cathode emitting electrons with an initial energy of 1 eV and beam current $I_0 = 400$ mA. The electron flow entered the accelerating field generated by the electrodes with voltage $V_0 = 1.5$ kV. When the dense electron flow with radius $r_{eg} = 3.5$ mm accelerated in the electron gun tube enters the drift tube with the above geometry and radius $r_d = 15$ mm, beam current $I_0 =$ 400 mA becomes critical. The electron flow enters the decelerating field in the drift space generated by the collector and determined by the potential difference between the cathode and the collector, $V = -500$ V. The electron flow is focused by the constant magnetic field of the solenoid with a maximum of $B_0 = 0.1$ T.

Analysis of the beam's behavior in the low-voltage vircator showed that oscillatory behavior occurs in the system with the specified parameters. Two VCs are formed in the flow: one within the drift space of the electron flow and one in the gun part. Phase portraits of the electron flow in the low-voltage vircator are presented in Fig. 1. It can be seen that VC formation in the drift space (Fig. 1a) is the primary process that results in the reverse charged particle flow, which is reflected toward the injection area in portions. The counter flow raises the charge density in the area of the electron source and creates instability in the near-cathode area, resulting in the formation of a secondary VC with oscillations at the frequency of the first VC (Fig. 1b). The formation of the nonstationary VC in the gun part modulations the flow at the entrance to the drift space and enhances oscillations of the primary VC. The generated VCs thus interact by exchanging portions of the reflected electron bunches. It is worth noting that the mutual behavior of the two pronounced VCs results in major complication of the flow structure over time as several electron structures are generated with a high velocity spread (Fig. 1c).

Oscillations of the VC in the drift tube lead to space-time oscillations of the electromagnetic field. Investigations of field evolution at the fundamental VC oscillation frequency in the system showed that the traveling wave propagates from the entrance to the drift space to the collector.

The characteristic oscillations of the longitudinal field component in the area of VC formation near the collector end of the device (a) and its spectral characteristic (b) are presented in Fig. 2. It can be seen that field oscillations display irregular behavior that affects the spectrum; i.e. it includes the fundamental frequency $f_0 = 1.7$ GHz that corresponds to VC oscillations with high noise levels comparable to the second harmonics of the fundamental frequency. The noise pedestal is explained by the charge carrier oscillations (on different time scales that correspond to different electron bunches inducing electromagnetic field oscillations at different frequencies) being typical for the considered flow.

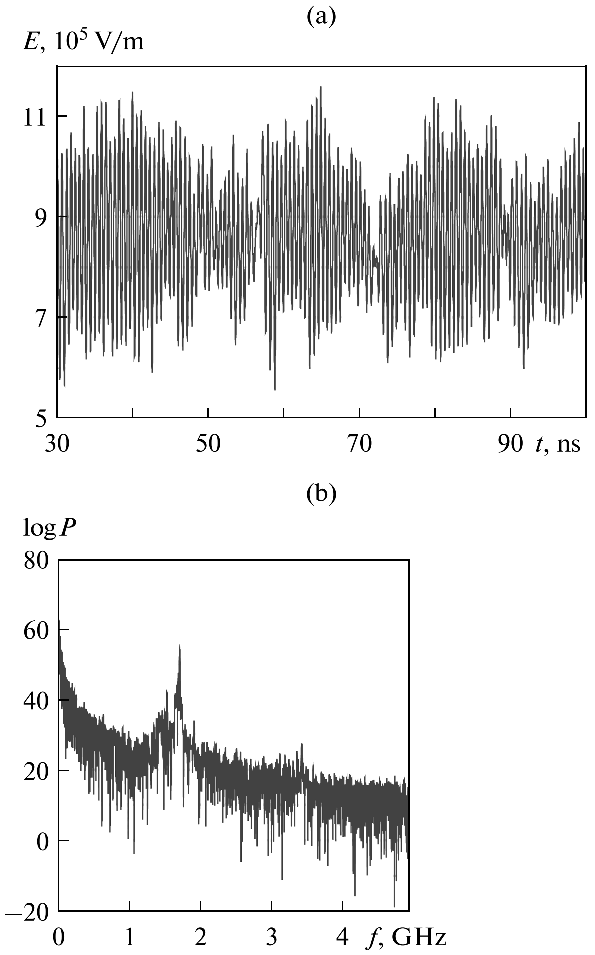

Fig. 2. (a) Temporal implementation of oscillations of the longitudinal component of electric field at $x = 60$ mm and (b) its spectral composition.

CONCLUSIONS

Features of the generation and formation of electron structure were revealed using a 3D electromagnetic model aimed at investigating the nonstationary behavior of a nonrelativistic electron flow in a VC-based low-voltage generator. It was shown that microwave radiation is generated in such a device, due to the formation and mutual oscillatory behavior of two virtual cathodes. It was also shown that an intense charged particle beam in a low-voltage vircator is characterized by a high velocity spread and high levels of turbulence, ensuring the broadband spectrum of the generated radiation and a high noise pedestal.

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