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Discussion

Nonlinear dynamics and bifurcation mechanisms in intense electron beam with virtual cathode

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ABSTRACT

In this paper we report on the results of investigations of nonlinear dynamics and bifurcation mechanisms in intense electron beam with virtual cathode in micrometer-scaled source of sub-THz electromagnetic radiation. The numerical analysis is provided by means of 3D electromagnetic particle-in-cell (PIC) simulation. We have studied evolution of the system dynamics with the change of beam current value by means of Fourier and bifurcation analysis. The bifurcation diagram has identified a number of the alternating regions of beam current with regular or chaotic regimes of system dynamics. The study of spatiotemporal dynamics of formed electron structures in the beam has revealed the physical mechanisms responsible for the regimes switchings in the system.

1. Introduction

Spatially extended dynamical systems attract great attention of scientific community as they are able to demonstrate a large number of nonlinear wave phenomena and processes [1–4]. The most significant among others are formation of patterns, coherent structures and development of spatiotemporal chaos. Investigation of mentioned nonlinear phenomena and their properties in the spatially extended media helps researchers to understand the nature of complex processes taking place in the real physical systems.

Analysis of nonlinear dynamics has traditionally a great importance for such fields of modern science as microwave and terahertz (THz) electronics where microwave and THz oscillators exhibit properties of spatially extended dynamical systems [5–11]. In this sense both vacuum electron and solid state devices demonstrate a number of interesting and important nonlinear features. The example of solid-state device that has properties of nonlinear active medium is the semiconductor superlattice (SSL) — prospective solid-state source of THz radiation [12–14]. In a recently published paper the dynamics of SSL has been studied in the framework of bifurcation analysis [15]. It has been also found out that a number of unexpected nonlinear phenomena emerge while coupling SSL to the external resonator [5].

Beam-plasma systems also demonstrate behavior being peculiar to active nonlinear media and, as a consequence, the study of nonlinear dynamics of intense electron beams is of particular interest at present time. Intense electron beams drifting in vacuum tubes, from the viewpoint of collective dynamics of charged particles, show a variety of nonlinear phenomena including chaotic dynamics and patterns formation [16,17,6–9,18,11]. It is well-known that as a beam current exceeds the space-charge limiting current, I_{SCL}, the moving intense beam loses its stability and performs spatiotemporal oscillations [19–23]. These oscillations are caused by the formation in the beam of the non-stationary electron pattern, the so-called virtual cathode (VC), — the coherent electron structure that represents a dense cloud of charged particles and limits the propagation of the most parts of the beam. This effect of virtual cathode formation is used in high-power microwave devices called “Vircators” [19,20,24,25,23]. Virtual cathode oscillations usually have a complex form (often relaxation-like) due to the collective interaction of a large number of charged particles with self-consistent electric field and the presence of the internal electron feedback. The dynamics of VC is known to be sensitive to the variation of the control parameters, particularly, the beam current and energy [31,26–28,6,29,30]. Variations of the

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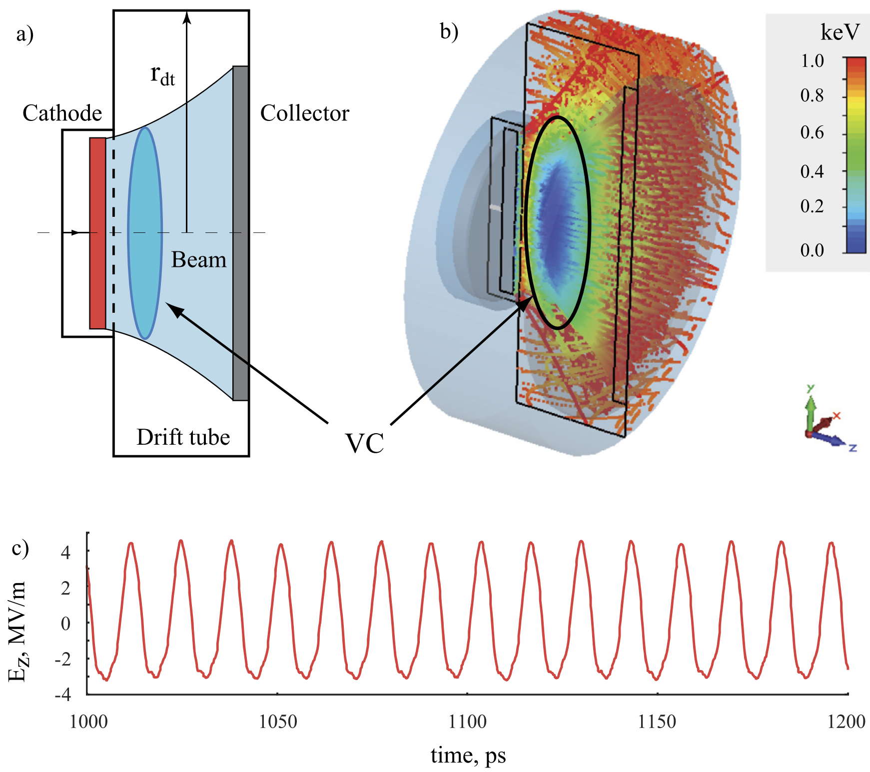

Fig. 1. (*a*) Schematic view of nanovircator with electron beam. Electron beam is highlighted with blue. It drifts from the cathode area (red brick) to the collector (gray brick) through the cylindrical drift tube of radius r_{dt}. (*b*) Cross-section view of the considered system in CST Particle Studio 2016. The region of the dense electron structure is denoted as "VC". Here, the charged particles are colored according to the value of their energy. (*c*) Typical time series of electric field relaxation-like oscillations in the VC area, $I_0 = 2.52$ A. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

control parameters provide rich set of complex nonlinear phenomena including pattern formation and regimes of spatio-temporal chaos [31–36].

In this paper we present the results of investigations of dynamics of the spatially extended system comprising the intense electron beam with the overcritical current and perform the analysis of mechanisms of the transition to chaos and the formation and destruction of coherent structures in such system. This study has been carried out in the framework of consideration of the "nanovircator" model — micrometer-scaled source of sub-THz electromagnetic radiation [37–39]. The choice of this model is determined by the growing interest to the research and development of compact sources of broadband sub-THz and THz radiation [40,23]. Besides, a systematic study of electron beam behavior and mechanisms of a chaotic oscillations in "nanovircator" has not been held so far. Moreover, the obtained results reveal the general properties of the intense electron beam dynamics in the vircator systems without the external magnetic field.

2. Nanovircator model and simulation details

We examine a dynamics of the overcritical electron beam with the help of the well-proven numerical 3D electromagnetic PIC-simulation tool [41,42] — CST Particle Studio (CST PS) 2016 licensed software [43]. It is based on the self-consistent solution of Maxwell's equations by means of finite-difference time-domain (FDTD) method and relativistic motion equations that describe particles behavior [42,44,45]. FDTD method is based on the discretization of Maxwell's equations written in differential form in Cartesian coordinate system. In this case, the meshes for the fields E and H are shifted relative to each other by half the step of the discretization of time and each of the spatial variables; such a complex grid is called Yee grid [46]. Maxwell's finite-difference equations make it possible to determine the fields E and H at a given time step based on the known values of the fields in the previous step. So, CST PS computes the electromagnetic fields according to Maxwell's equations to give a solution to the equation of motion for the particles [52]. This allows the evaluation of the Lorentz force in an explicit time-domain scheme where the time step is controlled by the size of the mesh grid in accordance with the Courant–Friedrichs–Lewy condition [47]. The particle movement imprints a current density that is written back into Maxwell's equation allowing the current and charge conservation. In order to accurately discretize the geometry of the different objects constituting the whole structure, CST PS uses a hexahedral grid with a perfect description of rounded solids, the so-called perfect boundary approximation (PBA) [48].

For more information about mathematical and numerical methods used in CST PS see Ref. [43]. The accuracy and efficiency of calculations via CST PS are proved by both solving test electromagnetic problems and simulation of different types of microwave devices and its components [49–52,25].

The schematic view and visualization in three dimensions of the system investigated in CST PS are presented in Fig. 1. One can see, that the electron active medium is formed in this system as a concentration of particles emitted from the cathode surface and propagating to the collector through the drift tube. We considered the short drift tube with length $L = 0.15$ mm and radius $r_{dt} = 0.28$ mm to realize the fast transition to the non-equilibrium state of the electron beam in this system. The detailed description of "nanovircator" geometry is given in Ref. [37]. The external magnetic field equals to zero.

Taking into account the given geometrical parameters and according to Bogdankevich–Rukhadze law [21], the non-stationary electron structure, VC, is formed in the electron beam at current $I_{SCL} = 2.25$ A for the beam initial energy $U_0 = 1.0$ keV. Note,