Regularities and Mechanisms of Development of Instabilities in the System with Intense Relativistic Electron Beam

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Abstract: *We have investigated analytically and numerically the development and interaction of Bursian/Pierce and diocotron instabilities in a relativistic electron beam propagating in a cylindrical drift chamber, depending on the beam geometry, current and the magnitude of the external uniform magnetic field. We have found out that the interaction of instabilities results in the formation of a virtual cathode with a complicated rotating helical (vortex) structure and several reflection regions (electron bunches) in the azimuthal direction. We have shown shown that the number of electron bunches in the azimuthal direction depends on the system parameters. We have discovered the connection between the number of bunches and the generation frequency.*

Keywords: beam instabilities; virtual cathode; diocotron instability; Bursian instability; critical current; relativistic electron beam; high-power microwaves; vircator.

Introduction

Relativistic electron beams (REBs) are of considerable interest for modern high-power electronics. Active studies of the processes of REB transport and different types of REB instabilities are motivated, first of all, by the wide scope of REB applications. Intense beams of charged particle are used in many modern generators and amplifiers of microwave and terahertz ranges [1], such as gyrotrons, vircators, relativistic traveling wave tubes, backward wave tubes, magnetrons, free-electron lasers, et al. Propagating in the drift space, REBs often demonstrate complex dynamics of space charge, resulting in the formation of electron structures [2-4]. Under certain conditions, various types of instabilities (diocotron, slipping, Pierce, Bursian, and others) can develop in the REB [2].

Bursian/Pierce instability develops when an electron beam with a current density exceeding a certain critical value propagates in the drift chamber [1]. This instability imposes restrictions on the maximum current that can be transported through the equipotential drift space and leads to the appearance of a nonstationary virtual cathode (VC), the intense oscillations of which are utilized in a whole class of high-power microwave devices – VC-based oscillators and amplifiers (vircators) [1]. Bursian/Pierce instability is caused by a local decrease in the beam potential under the action of the beam space charge [5].

In the course of diocotron instability, the nonuniformity of the current density (or velocity) in an annular electron beam leads to the appearance of uncompensated electrical fields and electron drift, which, in turn, results in the amplification of the nonuniformity and fragmentation of the beam into current filaments [5]. In particular, diocotron instability can lead to the appearance of vortex and helical structures in the beam, which can negatively affect the operation of a high-power electrovacuum or beam-plasma devices.

The problem of the interaction and coexistence of Bursian and diocotron instabilities that can simultaneously develop in the REB under certain conditions has been actively investigated over the past few years [2-4]. The present work provides an overview of the most important recent results obtained in this area by our scientific group. Special attention is paid to the effect of the annular beam wall thickness on the dynamics of the system. We note that, in addition to their fundamental importance, such results are obviously of practical importance, because information on the processes occurring in the REB during these instabilities can be used to develop new types of high-power microwave and terahertz generators and amplifiers, as well as to optimize the existing ones.

System Under Study

The system under study consists of a perfect electric conducting finite-length cylindrical equipotential waveguide region (an electron beam drift chamber) of the length L=45 mm, the radius R=10 mm, with an entrance transparent grid electrode on the left side and an output coaxial waveguide port on the right side. An axially-symmetrical monoenergetic annular REB with the current I, the initial electron energy W_e (850 keV in this work), the external radius R_b=5 mm and the thickness d=1.5 mm is injected through the entrance electrode. Electrons can leave the waveguide region by reaching the side wall or the right (collector) end of the drift chamber. The external uniform magnetic field with induction B is applied along the longitudinal (z) axis of the waveguide. We suppose that the injected REB is formed by a magnetically insulated diode.

Results

We have paid special attention to the effect of the annular beam wall thickness d and the external magnetic field B_0 on the simultaneous development and interaction of

Bursian and diocotron instabilities. The beam wall thickness d was varied from 0.4 to 4 mm, while the external magnetic field was varied from 0 to 2 T. It is found that, in this parameter range, from two to nine electron bunches rotating in the azimuthal direction can form in the beam. To illustrate typical regimes of the REB dynamics with developed Bursian and diocotron instabilities, Fig. 1 shows the distributions of the space charge density in the VC region in the plane. We note that each bunch periodically dumps its charge, due to which electron filaments stretched along the beam axis form in the system. During the further beam propagation and rotation into the drift space, these filaments transform into a characteristic helical structure.

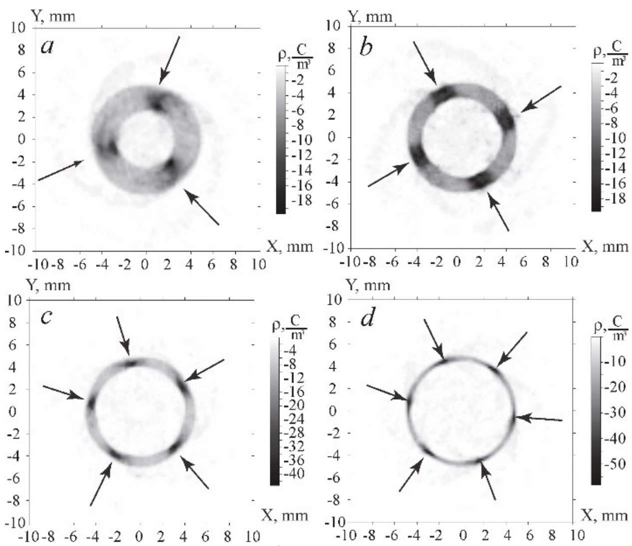

Figure 1. Distributions of the space charge density in the plane in the VC region for regimes with different numbers N of electron bunches: (*a*) N = 3 (at B_0 = 0 T and d = 2.5 mm), (*b*) N = 4 (at B_0 = 0 T and d = 1.5 mm), (*c*) N = 5 (at B_0 = 0 T and d = 1 mm), (*d*) N = 6 (at B_0 = 0 T and d = 0.5 mm)

To more thoroughly analyze the processes occurring in the REB during the simultaneous development of Bursian and diocotron instabilities, we divided the (d, B_0) plane (beam wall thickness vs. external magnetic field) into regions corresponding to different numbers of electron bunches formed in the REB (see Fig. 2). Fig. 2 demonstrates that, at certain values of the beam wall thickness, the REB dynamics changes abruptly, namely, as d decreases, the number of the formed electron bunches increases from two to nine via a sequence of stepwise transformations of dynamic regimes. We note that the smaller the beam wall thickness d, the lesser variation in d is required for switching between the regimes. It is also seen that the effect of the external magnetic field is more complicated and its variation can lead to an increase or a decrease in the number of electron structures formed in the REB.

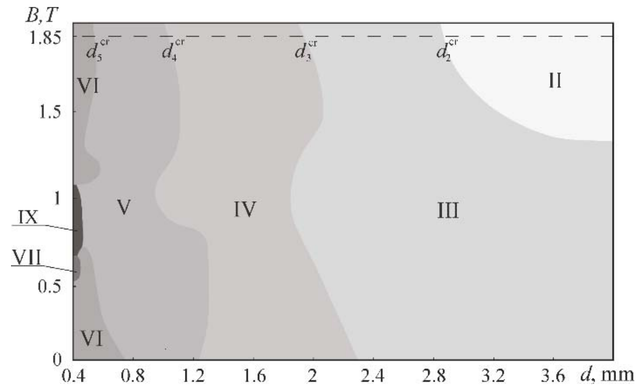

Figure 2. Characteristic regimes of REB dynamics in the (d, B_0) plane (beam wall thickness vs. external magnetic field). Regions with different numbers of electron bunches are shown with shades of gray. The Roman numbers denote the number of electron bunches in the azimuthal direction. Here, d_2^{cr}, d_3^{cr}, d_4^{cr}, and d_5^{cr} are the critical values of the beam wall thickness for regimes with N = 2-5.

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