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Multistability in a Relativistic Electron Beam with an Overcritical Current

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Abstract—The multistability effect of relativistic electron beam behavior, particularly the coexistence of three modes of typical behavior, is revealed in a numerical investigation. These modes are characterized by a virtual cathode with two, four, or five potential minima in the azimuthal direction rotating around the drift space axis.

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INTRODUCTION

It is known that intensive relativistic electron beams (REBs) are characterized by complicated modes of behavior [1]. In particular, different instabilities (Pierce, Bursian, current–convective, diocotron, sleeping, and so on) are typically observed for them. On one hand, the development of such instabilities can play a positive role. For example, Pierce and Bursian instabilities result in nonstationary virtual cathodes (VCs) whose oscillations are the bases of powerful superhigh frequency devices, e.g., generators (amplifiers) with virtual cathodes or vircathors [2–5]. On the other hand, these instabilities can have a negative impact on powerful superhigh frequency devices and impose constraints on their modes of operation. For example, Pierce and Bursian instabilities limit the maximum current of an electron beam that can be transmitted without reflecting through the equipotential vacuum drift space. Diocotron and sleeping instabilities greatly influence the shape of an intense relativistic electron beam during its propagation and therefore lead to different azimuthal and radial instabilities in it, particularly vortex and spiral structures [6, 7]. This can both upset the operating mode of a device with an intense relativistic electron beam and be used to improve the characteristics of its generation. The problem of interacting and coexisting instabilities in an intense electron beam is important, since at certain parameters of the system, there are conditions that could produce several instabilities simultaneously [1]. It is therefore of interest to investigate the nonlinear behavior of relativistic electron beams and the instabilities that arise in them, and to study their coexistence, since these are important problems in both fundamental and applied vacuum and plasma electronics.

EXPERIMENTAL

In this work, we examine the relativistic vircathor studied in [6, 7]. It is a cylindrical drift space with length $L = 45$ mm and radius $r = 10$ mm. At one end is an annular source of charged particles (an annular cathode) with internal radius $r_{\text{int}} = 3.5$ mm and external radius $r_{\text{exr}} = 5$ mm that injects a tubular monospeed relativistic electron beam. At the other end is a power coaxial output. The form of the current pulse is a step function that is characterized by rise-time τ up to constant value $I_0 = 40$ kA. An external longitudinal uniform focusing magnetic field with induction $B_0 = 1.1$ T is imposed on the system. We performed our numerical simulation using the licensed CST Particle Studio 3D software package for electromagnetic simulations.

During our investigation, we varied rise time τ and found that the relativistic electron beam behavior was characterized by three coexisting typical modes in which a virtual cathode of complicated structure was formed in the azimuthal direction. The first mode was characterized by two electron bunches (two minima of potentials) in the azimuthal direction of the beam rotating around the drift space axis and forming a double-helical vortex structure in the drift space. Such behavior of the relativistic electron beam means that a virtual cathode of complicated structure is formed, and it is characterized by two areas of electron reflection in the azimuthal direction. We refer to such behavior as mode II according to the number of electron bunches and the virtual cathode's areas of reflection. The second and third coexisting modes are characterized by four and five electron bunches (modes IV and V); as a result, quadruple- and quintuple-helical vortices are formed. Figure 1 presents the density dis-

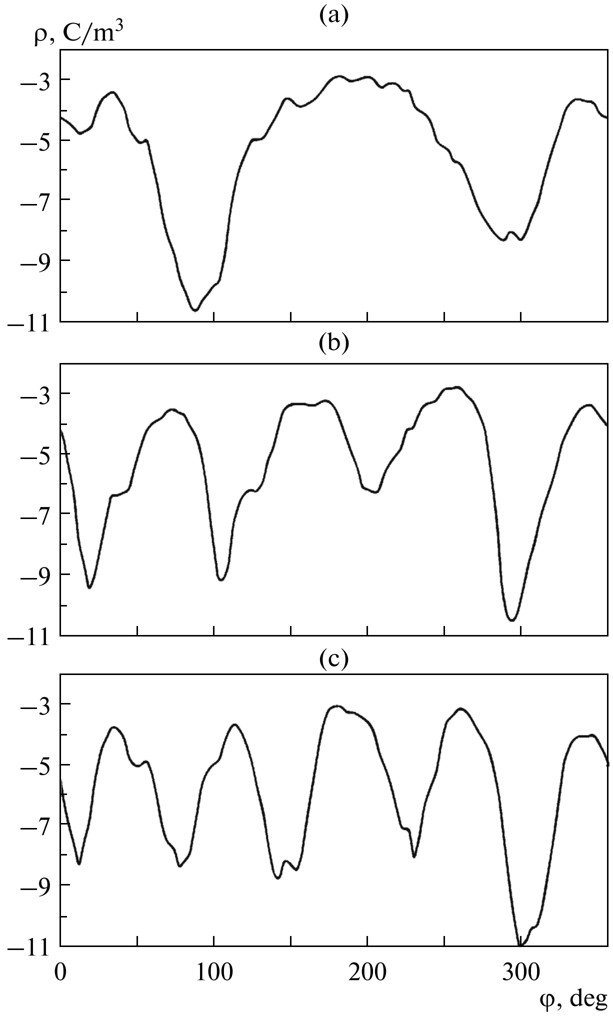

Fig. 1. Relationship between the distribution of volumetric charge density in the area of virtual cathode formation, averaged over the radius and azimuthal coordinate (fragments a, b, c) under different initial conditions (fragment a, $\tau = 50$ ns; b, $\tau = 45$ ns; c, $\tau = 50.5$ ns) for typical modes of relativistic electron beam behavior (fragment a corresponds to mode II; b corresponds to mode IV; and c corresponds to mode V).

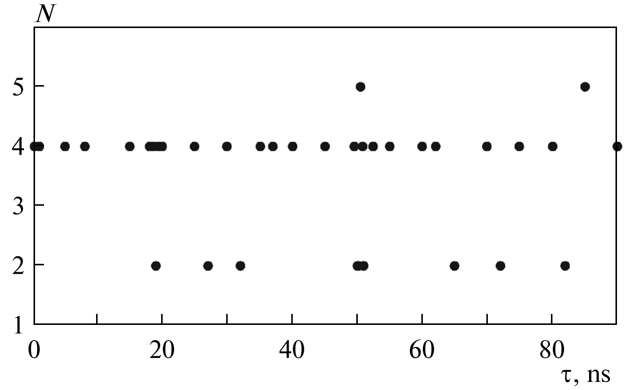

Fig. 2. Relationship between number N of electron bunches formed in the azimuthal direction and the time rise of pulse current τ.

tribution of the space charge in the area of virtual cathode formation, averaged over the radius from the azimuthal coordinate under different initial conditions (different τ) for the typical modes of relativistic electron beam behavior (the density maxima (over magnitude) correspond to the electron bunches that form in the area of the potential minimum (the areas of virtual cathode reflection) in the azimuthal direction). This plot correctly shows the qualitative difference between modes II, IV, and V: there are two, four, and five minima of the potentials and electron bunches in the azimuthal direction that correspond to the virtual cathode's areas of reflection.

If the relativistic electron beam is injected into the drift space with current $I_0 > I_{cr}$ (I_{cr} is the limit vacuum current), Bursian instability develops in the system and a virtual cathode is formed. In addition, the relativistic electron beam is characterized by its own strong magnetic field that produces diocotron instability. These instabilities interact and a virtual cathode is formed that contains complicated structures with several electron bunches (vortices) in the azimuthal direction rotating around the drift space axis. And as a result, vortex structures appear in the drift space. The configuration of these structures (including the number of electron bunches in the azimuthal direction) is the result of one azimuthal mode or another in their competitive activity inside the relativistic electron beam. In [8], it was shown that different azimuthal modes can be observed, depending on the initial conditions; as a result, different numbers of vortex structures form in the azimuthal direction. In the considered system, we were able to create modes II, IV, and V by setting different initial conditions (different τ). Note that at the given values of injected current $I_0 =$ 40 kA and external magnetic field $B_0 = 1.1$ T, mode IV occurred more often than modes II and V. Figure 2 clearly shows the relationship between the number of forming electron bunches in azimuthal direction N and pulse current time rise τ. This is because the excited azimuthal modes corresponding to modes II and V were less stable than mode IV. Note that other azimuthal modes can be excited in the considered system, but since they have a lower increment, the probability of their excitation is low [8] and they were not observed in our investigations.

Let us examine typical Fourier spectra of oscillation for the reverse current generated by electrons reflected from the virtual cathode (Fig. 3). It can be seen that higher harmonics are characteristic of all three modes. The second harmonic was maximal in the spectra corresponding to modes II and IV (Figs. 3a, 3b); this means that the relativistic electron beam's behavior is not linear. A typical feature of these modes is the difference between the frequencies of the main spectral components: frequency $f_2 \approx 45.8$ GHz corresponds to mode II (Fig. 3a), frequency $f_4 \approx 69.6$ GHz corresponds to mode IV (Fig. 3b), and frequency $f_5 \approx 75.4$ GHz corresponds to mode V (Fig. 3c). Note that the frequency of the rotation of electron bunches around the drift space axis coincides with the frequency of each main spectral component. We therefore see a correlation between the virtual cathode structure and the frequency of radiation: if the number of bunches in the azimuthal direction increases, the frequency of the output microwave signal in relativistic vircathor rises as well. From thespectra, we can also see that the amplitudes of the basic spectral components differ for the given modes, and the amplitude is maximal in mode II.

The rotation of electron bunches in the azimuthal direction produces the azimuthal current. We estimate it by approximating the form of electron bunches with an ellipsoid. By means of numerical simulation, we determine the mean volume of electron bunches and their mean density for each mode. If two electron bunches are formed (mode II), the mean volume of one bunch is $V \approx 8.4$ mm^3, and the mean density is $\rho \approx 7$ C/m^3. For mode IV the mean volume is $V \approx 2.8$ mm^3, and the mean density is $\rho \approx 6.75$ C/m^3. For mode V, the mean volume of one bunch is $V \approx 2$ mm^3, and the mean density is $\rho \approx 7$ C/m^3. The rotation of the electron bunches around the drift space axis generates the azimuthal currents $I_2 \approx 2690$ A, $I_4 \approx 1314$ A, $I_5 \approx 1056$ A ($I = V\rho f$; V is the volume of one bunch; ρ is the density of one bunch; and f is the frequency of rotation of the electron bunches, which coincides with the frequency of the main spectral component), which correspond to modes II, IV, and V. It can be seen that the density of the volumetric charge is approximately the same for all modes. The volumes and rotational speeds of the bunches differ, leading to the differences in the azimuthal current. Note that these estimated currents are in good agreement with the amplitudes of the main spectral components of the considered modes (Fig. 3), and that the azimuthal current corresponding to mode IV lies between the currents corresponding to modes II and V ($I_2 > I_4 > I_5$). It follows that if the number of electron bunches in the azimuthal direction is increased (under a fixed magnetic field and injection current), the azimuthal current and the amplitude of spectral components will fall.

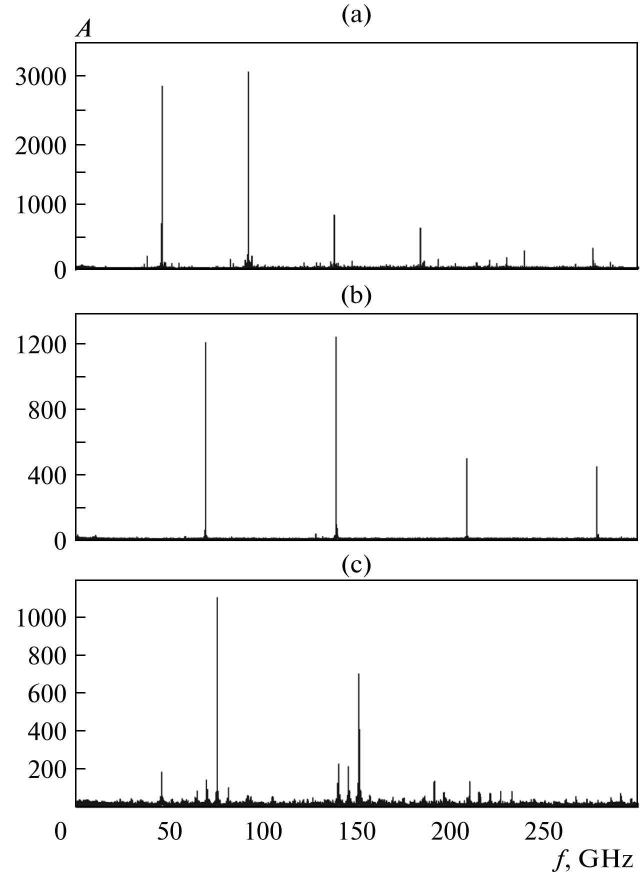

Fig. 3. Typical Fourier spectra of reverse current oscillations generated by electrons reflected from the virtual cathode. Fragment a corresponds to mode II (τ = 50 ns); fragment b corresponds to mode IV (τ = 45 ns); and fragment c corresponds to mode V (τ = 50.5 ns).

CONCLUSIONS

We observed three typical modes of relativistic electron beam behavior. These modes were characterized by virtual cathodes with complicated structure; in particular, two, four, or five potential minima were formed in the azimuthal direction and rotated along with the electron beam around the drift space axis and formed the vortex structures in drift chamber. In addition, all modes were characterized by different oscillation spectra of the reverse current generated by electrons reflected from the virtual cathode. The main feature of these modes was the differences in the basic spectral component, which coincided with the frequency of electron bunch rotation around the drift space axis. It was shown that if the number of bunches in the azimuthal direction was increased, the frequency of output microwave signal rose in the model of a relativistic vircathor. It was also shown that the mean density of the volumetric charge in the bunches was approximately the same for all modes, while the volume and speed of rotation changed.

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REFERENCES

1. Kuzelev, M.V., Rukhadze, A.A., and Strelkov, P.S., *Plazmennaya relyativistskaya SVCh-elektronika* (Plasma Relativistic Microwave Electronics), Moscow: Mosk. Gos. Tekh. Univ., 2002.
2. Dubinov, A.E. and Selemir, V.D., *J. Commun. Technol. Electron.*, 2002, vol. 47, no. 6, p. 575.
3. Benford, J., Swegle, J.A., and Schamiloglu, E., *High Power Microwaves*, CRC Press, 2007.
4. Kurkin, S.A., Frolov, N.S., Rak, A.O., et al., *Appl. Phys. Lett.*, 2015, vol. 106, no. 15, p. 153503.
5. Li, L., Cheng, G., Zhang, L., et al., *J. Appl. Phys.*, 2011, vol. 109, p. 074504.
6. Kurkin, S.A., Hramov, A.E., and Koronovskii, A.A., *Appl. Phys. Lett.*, 2013, vol. 103, no. 043507.
7. Kurkin, S.A., Badarin, A.A., Koronovskii, A.A., et al., *Phys. Plasmas,* 2014, vol. 21, no. 9, p. 093105.
8. Kartashov, I.N. and Kuzelev, M.V., *Plasma Phys. Rep.*, 2010, vol. 36, no. 6, p. 524.

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