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Development of Diocotron Instability in the Squeezed State of a Relativistic Electron Beam

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Abstract—Nonlinear nonstationary processes in a beam-plasma system containing a hollow intense relativistic electron beam with an overcritical current in the squeezed state are studied numerically. The emergence and development of diocotron instability in the squeezed state, which leads to formation of vortex structures, is analyzed in detail, and the effect the magnitude of the external magnetic field has on the processes of structure formation in the beam is investigated.

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INTRODUCTION

At present, the problem of the propagation of extensive relativistic electron beams (REBs) is the object of detailed study by specialists working in the area of particle physics, plasma physics, and high-power vacuum microwave electronics. The interest in studying these electron systems is motivated by extensive REBs being commonly used in a number of practical tasks, from generating broadband and extra-power microwave and terahertz radiation to operation in particle accelerators, particularly those of ions [1].

High-current REBs are characterized by the high intensity of their intrinsic electric and magnetic fields, and by the high density of their space charge. The motion of charged particles in an intense electromagnetic field is thus consistent with a change in the field under the action of movement of these particles [2, 3], so the emergence of the slightest spatial inhomogeneity in REB characteristics (distribution of velocity, density, position of charge carriers) leads to the development of different types of beam instabilities, due to the interaction between the waves of the space charge and the electromagnetic waves [2, 3]. Among the most common instabilities frequently observed in experiments are those of Pierce and Bursian [4, 5], the diocotron and slipping instabilities [6–8], and the Weibel instability [9, 10]. One result of the evolution of these instabilities at the nonlinear stage is the development of complex spatial-temporal dynamics in a beam, including modes of REB turbulent motion and the formation of electron structures.

The wave processes of the development of the types of beam instabilities indicated above, along with the reasons for the unstable behavior of the beam, are well known and have been thoroughly described in the literature [4–10]. Such cases are considered mainly when an electron beam propagates in the drift space in the subcritical mode, i.e., with beam currents below the limiting vacuum current. At present, studies aimed at revealing specific features of the emergence and coexistence of different types of beam instabilities are of great interest [11–16]. The effect the emergence of azimuthal instability in a beam with a virtual cathode has on the characteristics of the output electromagnetic radiation in particular is described in [16].

Of particular interest is investigating nonlinear nonstationary processes and the development of instabilities in an extensive REB in the squeezed state. The term "squeezed state of a beam" was introduced in [17] and refers to the formation of a spatially distributed virtual cathode in a beam under certain conditions. This state of an electron beam is characterized by a high density of the space charge and by a low energy level of charged particles in the region of squeezed state. The squeezed state of an electron beam can thus be treated as a single-component charged plasma [11].

In this work, the processes of forming the squeezed state of a relativistic beam were simulated numerically using the three-dimensional electromagnetic PIC-code in the CST Particle Studio computer simulation environment. Sspecial attention was given to processes of diocotron-instability development in the squeezed state of an REB in the short-length drift space. The presence of azimuthal modes in the squeezed-state structure of the beam was found in particular, and the effect the magnitude of the external magnetic field had on the shape and arrangement of electron structures formed under the action of diocotron instability in the squeezed state was investigated.

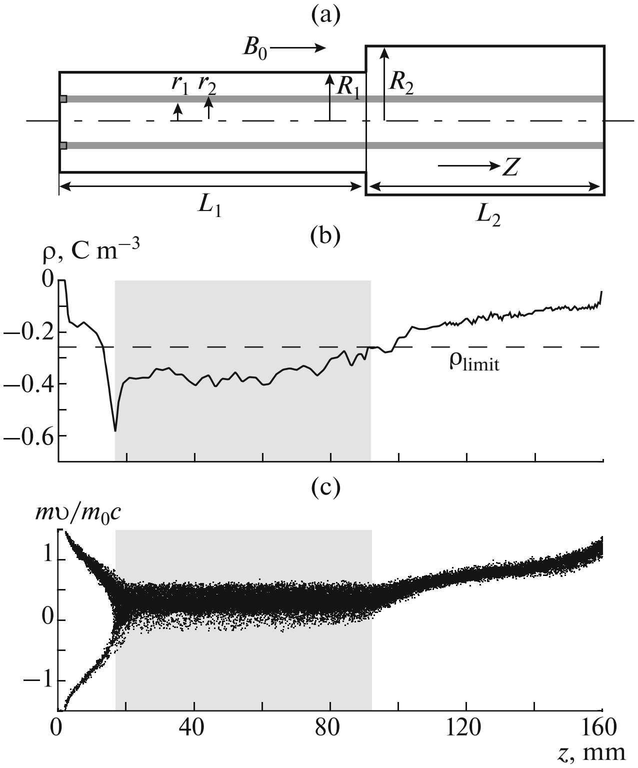

Fig. 1. (a) Schematic of the investigated beam-plasma system containing a hollow electron beam in the cylindrical drift space with a jump in radius. (b) Distribution of the volume density of the space charge of the beam along the z axis. (c) Phase portrait of a relativistic electron beam in the mode of forming the squeezed state of the beam. Here, mv is the relativistic momentum of the particle, m_0 is the electron mass, and c is the speed of light. The region of creation of the squeezed state of the beam is marked with grey in panels b and c.

INVESTIGATED MODEL

The squeezed state of a relativistic beam can be formed using, e.g., the scheme shown in Fig. 1a. A hollow REB with inner radius r_1, outer radius r_2, and energy V_0 is injected into the drift space formed by two metallic cylindrical tubes with different radii R_1, R_2 and lengths L_1, L_2. In this case, condition $R_2 > R_1$ must hold. In this work, the geometric parameters of the beam and the drift space were fixed, along with the energy of the injected particles. These parameters were $r_1 = 6$ mm, $r_2 = 8$ mm, $R_1 = 15$ mm, $R_2 = 22$ mm, $L_1 = 90$ mm, $L_2 = 30$ mm, and $V_0 = 400$ keV. The beam was contained by external longitudinal magnetic field B_0, which was homogeneous in space. The magnetic field magnitude was varied in a range of 0.5 to 6.0 T.

The beam was assumed to move in a ideal vacuum inside the drift space, while the tubes were separated with a thin grid electrode. It is known that as a hollow electron beam propagates in a cylindrical drift tube, the reflections of particles appear under action of space-charge forces if the beam current exceeds limiting vacuum value I_{cr}. The critical current value is then inversely proportional to the radius of the drift tube: $I_{cr} \sim R^{-1}$. There are two values of the critical vacuum current for this scheme of the drift space: the critical current of the first tube I_{cr1} and the critical current of the second tube I_{cr2} ($I_{cr2} < I_{cr1}$). When an electron beam with current I_0, satisfying condition $I_{cr2} < I_0 < I_{cr1}$ is injected into the drift space, a virtual cathode is created at the entrance of a tube with radius R_2, while the reflected part of the beam induces the development of a dense low-energy electron cloud distributed in the space from the grid electrode to the region of beam injection (for more detail, see [11, 17]).

The formation of the squeezed state is revealed by the phase portrait of the beam (constructed in the coordinates of normalized pulse–longitudinal coordinate z), and by the distribution of space-charge density $\rho(z)$ (Figs. 1b, 1c, respectively). It can be seen that the space charge concentrated in the squeezed-state region is roughly double that in the drift beam, while the average momentum of charged particles in the squeezed-state region differs from that of injected particles by an order of magnitude.

DEVELOPMENT OF DIOCOTRON INSTABILITY

Diocotron instability becomes apparent in extensive electron beams in the form of rotating vortex electron bunches representing the azimuthal mode of the beam [6]. This type of beam instability typically arises when beams are transmitted over long distances.

As was shown in this work, however, the diocotron instability in the squeezed state of a beam develops over much shorter distances. Let us consider the process of formation and characteristics of the squeezed state of a beam in the system under study, and then analyze the development of diocotron instability.

To start, we analyze the process of space-charge accumulation in the beam as a result of creating the squeezed state of the beam in the first chamber of the drift space with magnitude $B_0 = 5.0$ T of the external magnetic field. In Fig. 2, the solid line corresponds to the dependence of the space-charge density of the beam in the first tube on beam current I_0 for the described configuration of the drift space. The analyzed charge density is calculated by integrating the volume density of the space charge over the perpendicular section of the beam in plane $z = 45$ mm:

$$Q(z = 45) = \int_{r_1}^{r_2}\int_{0}^{2\pi} \rho(r, \phi, z = 45)\, d\phi dr. \qquad (1)$$

It can be seen that with a beam current of less than 2.5 kA, the charge density in the beam grows according to linear law $Q \sim I_0$, which corresponds to stable transmission of the beam in the drift space. When the

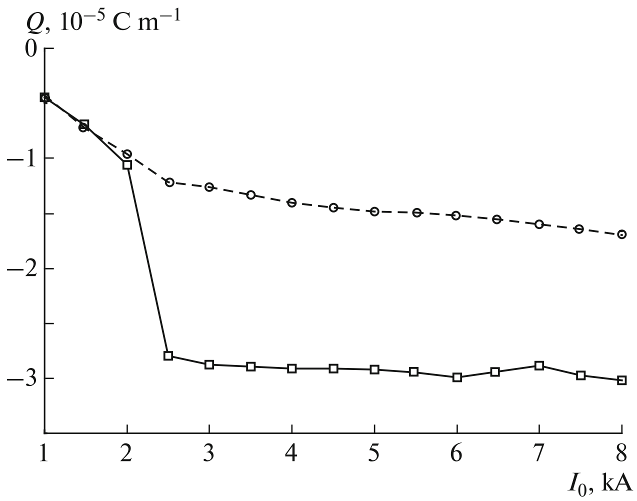

Fig. 2. Space-charge density Q, calculated in plane z = 45 mm as a function of the injection current I_0 of a beam. The solid curve corresponds to the drift space with a jump in radius ($R_2 < R_1$); the dashed curve corresponds to a drift space with constant radius R_1.

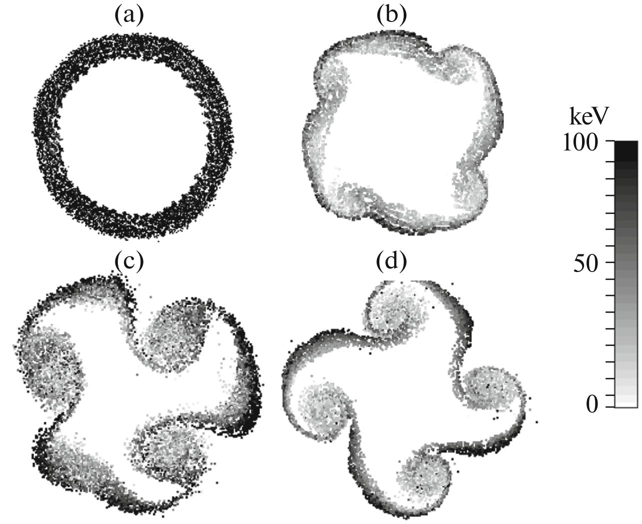

Fig. 3. Profiles of a relativistic electron beam in drift space (a) with constant radius R_1 and (b–d) with jumps in radius $R_2 < R_1$. Magnetic field magnitudes are (a, b) B_0 = 5.0; (c) B_0 = 1.0; (d) B_0 = 2.0 T.

beam current exceeds a value on the order of 2.5 kA, charge density Q in the first chamber of the drift space grows abruptly: a virtual cathode is created in the second drift tube, and the reflected flow of particles results in the squeezed state of the beam being formed in the first tube. Comparing the obtained dependence of the charge density on the beam current and the similar dependence for when the drift space has no jump in radius and $R_2 = R_1$, we can see that the charge in the beam does not accumulate stepwise with a rise in current, but continues to grow linearly.

Let us move to studying the mechanisms behind the development of diocotron instability and the formation of the vortex structure in the beam. We fix beam current I_0 = 3.0 kA. The beam profile is analyzed at distance z = 90 mm and time t = 25 ns when there are no longer any transitional processes in the beam. Figure 3a shows the beam profile in a drift space with constant radius R_1. It is clear that the beam keeps the initial shape specified upon injection from the annular cathode, so the particles drift stably along the z axis. With the same values of the beam current and magnetic field, rotating vortices are observed on the REB profile in a drift space with a radius jump, $R_2 > R_1$, and with the squeezed state of the beam formed in the first chamber (see Fig. 3b). This deformation of the electron-beam profile is a classical illustration of the development of diocotron-instability. A comparison of the beam profiles in Figs. 3a and 3b shows that the creation of a squeezed state in the beam contributes to the effects of the unstable behavior of the beam (from the viewpoint of diocotron instability), and to the formation of clearly pronounced azimuthal rotational modes of REBs. The rapid development of diocotron instability in the squeezed state of the beam is due to the much higher density of the space charge, and by a wide scatter in velocities of charged particles, compared to the stable transmission of the beam. The high density of the space charge enhances the effects associated with the layering of the distribution of the longitudinal velocity of particles over the radius, leading to the formation of vortex structures in the azimuthal direction.

The shape of the structure of rotating electron patterns in the REB profile depends in this case on the magnitude of the longitudinal magnetic field. Figures 3c, 3d show beam profiles with B_0 = 1.0 T and B_0 = 2.0 T, respectively. It can be seen that with weak magnetic fields, the particle trajectories diverge more strongly in the radial direction, while vortex structures form with insufficient density: electron bunches consisting of low-energy particles are followed by peculiar tails of high-velocity particles. With a strong magnetic field on the order of 5.0 T or more, the electron vortices are localized in space. In addition, a different number of vortices along the beam azimuth is observed, depending on the magnitude of the magnetic field. With weak magnetic fields of less than 1.5 T, there are three rotating bunches of electrons in the beam profile, while four bunches are characteristic of magnetic fields of more than 1.5 T. A similar effect was discovered in [15].

This difference in the formation of vortex structures for different magnetic fields is due to the electron system seeking the most stable position at which the Coulomb forces of interaction between the electron bunches are balanced [15]. With strong magnetic fields, in which particle trajectories are more localized in space, the charge density in the beam is high, and splitting into a larger number of bunches is needed to reach equilibrium. With weak external magnetic fields, particles travel more freely in the radial direction, and the density of bunches formed in the azimuthal direction is not as great, so Coulomb equilibrium is reached with fewer rotating electron clouds.

CONCLUSIONS

Specific features of dynamics of the REB in the squeezed state were studied in a three-dimensional computer PIC-simulation in the licensed CST Particle Studio environment. Special attention was given to analyzing processes in the squeezed state of the beam that result in the development of diocotron instability at short distances. The mechanisms responsible for acceleration of the processes of diocotron-instability development in the squeezed state of a beam were investigated. The process of the formation of rotating vortex structures in the beam profile and the factors that affect the beam shape and the number of vortices were also studied in detail.

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