DYNAMICS AND CAPTURE OF SPACE-CHARGE DOMINATED ELECTRON BEAMS IN CROSSED-FIELDS SYSTEM*

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INTRODUCTION

Theoretical and experimental investigations of the dynamics of space-charge dominated rectilinear beams considered as a new physic subject, are receiving more and more attention in recent years. At the same time, a similar but more complex subject, space charge dominated beams in crossed E_xB-fields, finds practical applications and has been investigated over a long period of time but without notable success in theory. Suffice it to note that there does not yet exact a clear theoretical description ever of the pre-generation operation of a classical (low-voltage) magnetron or the regime of magnetic insulation disturbance in high-current coaxial diodes. The physics of instruments with crossed fields is complex due to the strong nonlinearity of the processes and the necessity to take into account nonstationary effects.

PHYSICAL PROCESSES IN DEVICES WITH CROSSED FIELDS

The physical characteristics of the processes under consideration are partially presented in works [1 -- 7]. Usually, to describe electron flow in so-called magnetron diodes (MD), one uses stationary models of Brillouin flow, in which it is not possible to describe the escape of particles from an emitting surface, or kinetic dual-velocity flow, in which it is possible [1]. For system in which extraction of the electron beam in the axial direction is absent, the applicability of such analytical models is complicated by the influence of the pre-history of flow formation. In particular, we can immediately note that for such systems the increase of voltage on the MD should lead to capture of some of the emitted particles in acceleration gap which circulate around the cathode without returning to it. Hence, the value of the radial electric field on the cathode surface depends not only on emission current but also on the magnitude of accumulated circulating charge in the acceleration gap.

Dividing the flow into two components, namely, one circulating during many turns and maintaining information on possible nonuniformities, and the other emitting from the cathode and retuning to the cathode during a time of the order of a period of cyclotron rotation, leads to conditions arising for the development of azimuthal instability of the flow. However, without the provision of a number of additional conditions, this instability causes only weak azimuthal modulation of the flow and is not accompanied by the development of leakage current at the anode across an external magnetic field exceeding the threshold value for magnetic insulation.

Strong azimuthal modulation of flow accompanied by the development of leakage current at the anode, i.e., passing over of azimuthal instability to a strongly nonlinear regime in which an exchange of energy and momentum occurs between particles and the rotating self-consistent crossed E×B-field, can occur in two cases. First, if emission current is not too large and information about the developing structural flow is not carried to the cathode by the returning flow of electrons. Second, if feedback exists on the emitting surface of the cathode providing proper phasing of emitted particles that increases the degree of azimuthal variation of flow and, accordingly, discards part of the emitted particles not in proper phase.

Instability is saturated at a level of leakage currents at the anode, which can amount to several percent of I_{CL} (Child-Langmuir current). Then, electron flow constitutes a self-organizing, regular (in the azimuthal direction), rotating structure of dense electron bunches. Such a structure rotates with approximately the same angular velocity and exists for a long time. Dynamic equilibrium is established between the current of emitted particles and return current to the cathode and current to the anode. The special feature of this dynamic equilibrium is the long presence of emitted particles in the acceleration gap, which considerably exceeds the period of cyclotron rotation [1 − 4].

Feedback on the emitting surface, promoting the development of strong azimuthal instability, is particularly effective when using a cathode with secondary emission of electrons. The sharp nonuniform character of secondary emission, depending in turn on flow structure, leads to the formation of alternating radial electric field at a given cathode azimuth due to rotation of the modulated flow as a whole. The average radial electric field at the cathode can be close to zero. At the same time, the emission of particles in improper phases is simply suppressed by the negative value of the field, and the emission of particles in proper phases is sharply increased due to boundary effects [5, 6]. The type of operation of a MD with a secondary-emission cathode depends on the maximal voltage and rate of voltage rise on the gap. For low voltages, characteristic for classical magnetrons, a regular azimuthal structure of flow arises on the flat top of a pulse and is maintained over a long period of time.

For higher voltages (above approximately 100 kV), the regular structure is formed on the long leading edge of the voltage, and when passing over to the flat top there begins a debunching of the original structure and formation of a new one, with a different number of azimuthal variations, if the voltage does not exceeds a certain maximal value. Exceeding this maximum in the process of rising voltage results in disruption of the self-maintenance regime of secondary emission. The physical feature of such a regime is that, at high voltage and accumulation of a large space charge in dense bunches, the energy spectrum of electrons returning to the cathode is significantly shifted in the direction of larger energies and exceeds that is optimal for maximal yield of secondary electrons.

Practically, such systems represent a new class of flows with a variable number of particles. The growth of azimuthal instability in such a system is possible only under conditions when accumulated information in the flow is no carried to the electrodes. In particular, for uniform emission of a primary beam with current comparable with the current of secondary emission, instability develops weakly.

A demonstrative example is the development of instability in pure primary beam emitting uniformly in azimuth. The results of computer simulations show that in a regime of current limited by space charge, azimuthal instability does not develop at all. However, it does become strong and accompanied by significant leakage current if it turns out that the cathode is operating in a regime of saturation. Then, the normal component of the electric field at the cathode differs from zero and the development of weak azimuthal instability increases as in the case of nonuniform secondary emission due to proper phasing of emitted particles. The difference will respect to the case of nonuniform secondary emission is only that the radial electric field at the cathode surface is not alternating, i.e., there is no direct suppression of emission from the cathode. However, large oscillation of field due to azimuthal bunching of beam promotes bunching of some of the electrons with proper phases relative to the rotating E×B-field, which are in the gap for a long time. It also promotes the return of electrons in improper phases (and, accordingly, not matched with the field) back to the cathode in significantly less time. In the case of uniform space charge limited emission, information about the development of weak instability comes to the cathode by returning particles. The density of those close to the cathode is high and only a small number of them can exist in the flow for a long time.

CAPTURE AND ACCUMULATION OF BEAM IN CROSSED FIELDS

The conditions for possible interruption of secondary emission current for the aforementioned reasons or, for example, by increasing the external voltage, which is accompanied also by the initial discarding of a part of the flow and its subsequent detachment from the cathode, require special attention. This is because they permit to realize a process of accumulation and capture of electron beam in crossed fields which circulates so that electrons cannot return to the cathode nor reach the anode.

The number of particles in a captured circulating beam can be sufficiently large for possible subsequent acceleration, including with high-frequency cycles, for example, in betatron-type systems. Such systems can also be used as injectors for classic accelerators.

Below, the example is given which illustrate the possibility of accumulating an electron flow having a number of particles at the level of 10^{12} per centimeter of length axially in a compact system with crossed fields. In this case, the lateral dimensions are several centimeters, the voltage is at the level of 100 − 200 kV and the external magnetic field is about of 3 kG.

Computer simulations were performed using electromagnetic PIC-code KARAT [8] in two-dimensional r - θ-geometry. Examples of calculations demonstrating physical features of processes in 2D and 3D-geometries are presented in an accompanying report [7]. For subsequent acceleration of captured flow, one can use a betatron field and cut electrodes that do not hinder the formation of electron flow nor the penetration of an external longitudinal magnetic field.

The main idea consists in the following. After formation in a MD of electron flow with regular structure, total charge in the system still remains less than the limiting value and can be increased by raising the voltage on the MD. Growth of voltage leads to re-bunching of flow and change of azimuthal structure due to feedback disruption. During this process, azimuthal modulation of flow disappears and the flow becomes close to uniform in azimuth. Significant momentum spread of particles has a stabilizing effect on the existence of such a flow. A further increase in voltage results in the detachment of the flow from the cathode. The return bombardment of the cathode ceases, secondary emission current disappears, and leakage current at the anode is practically absent, i.e., there forms between the electrodes of the MD a captured circulating flow. Fig. 1 shows azimuthal structures of flows at different instants.

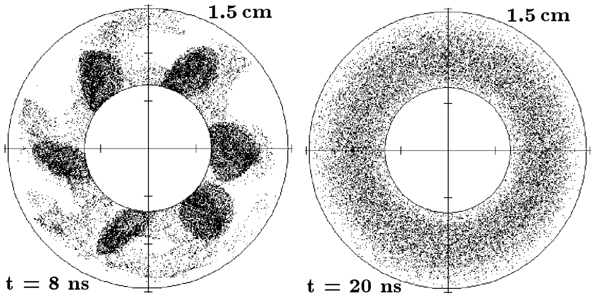

Fig. 1: Configurations of flow at t = 8 ns and t = 20 ns.

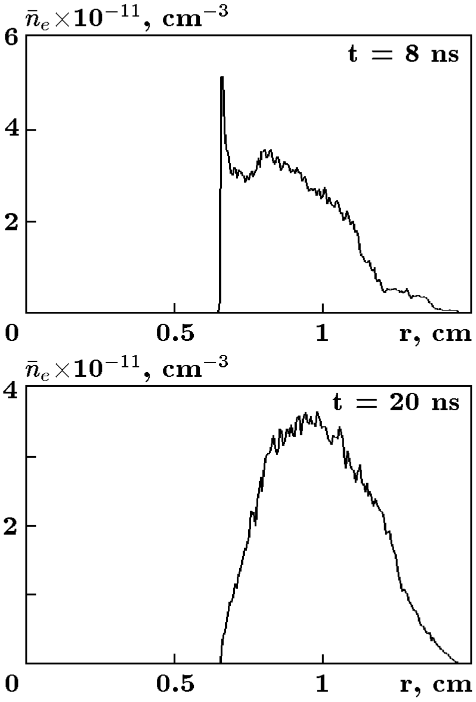

Fig. 2: Averaged densities at t = 8 ns and t = 20 ns

The distribution of density along the radius, averaged over the azimuth, is presented in Fig. 2 for these two instants. The dynamics of accumulation of particles and voltage profile are shown in Fig. 3.

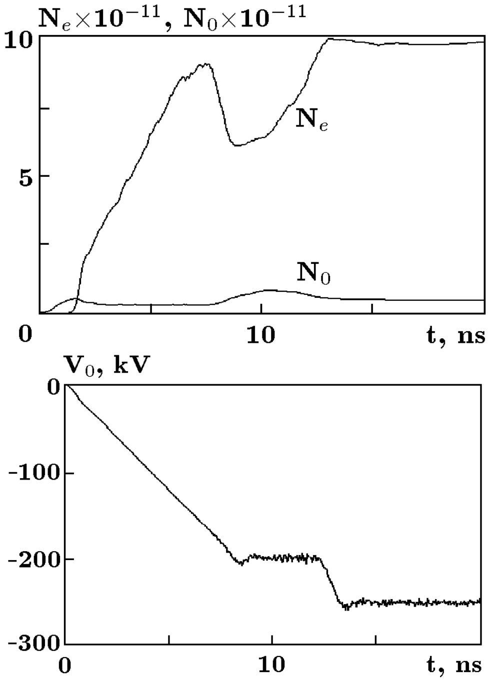

Fig. 3: Dynamics of accumulations of secondary electrons and the form of the voltage.

CONCLUSION

Problems of nonlinear dynamics of space-charge dominated electron beams in crossed ExB-fields are discussed from the point of view of the investigation of schemes of intense electron beam formation for compact cyclic accelerators and for high-efficiency relativistic magnetrons. The review of the results of computer simulations of an electron clouds formation due to nonlinear azimuthal instability inside magnetron is given. A scheme of electron storage and capture of electron beams in crossed fields is proposed.

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