DYNAMICS PECULARITIES OF THE SPACE-CHARGE DOMINATED ELECTRON BEAMS INTERACTING WITH A SURFACE IN CROSSED FIELDS

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Abstract

Problems of nonlinear dynamics of space-charge dominated electron beams in crossed ExB-fields are discussed. The review of the results of computer simulations of electron flows self-organization inside magnetically isolated coaxial diodes (magnetron gun) is given. Magnetron guns of usual and inverse polarities are considered. The main reasons of the self-organization process and development of regular space structures of the flows are: non-linear azimuthal instability of the flow under condition of strong nonuniform secondary self-sustaining emission and pure thermionic emission, and the dominant influence of a feedback on the emitting surface on the dynamics of electron curles. The dynamics of intense electron flows in systems with curvature radius of electrons compared with the amplitude of "bethatron" oscillations differs from usual systems. Several examples are shown including the storage of particles inside the gap, the development of dense electron curles, the utilization of such systems for generation of high-frequency oscillations.

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1 INTRODUCTION

The physical characteristics of the processes under consideration are partially presented in works [1] – [4].

Theoretical and experimental investigations of the dynamics of space-charge dominated rectilinear beams considered as a new physics 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×B-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 evere of pre-generation operation of a classical magnetron or magnetic insulation disturbance in high-current coaxial diodes. This paper reports on computer simulations of an electron cloud formation inside a smooth-bore magnetron. Computer simulations have been performed using electromagnetic PIC code KARAT [5] for the magnetron diode (MD) with different parameters, and with an external voltage source $V_0(t)$ connected to MD via an RL-circuit. The yield of secondary electrons from the cathode takes into account the dependence of the yield on the energy of electrons and the angle between the direction of electron velocity and the perpendicular to the cathode surface, and also the threshold of secondary emission.

2 PHYSICAL PROCESSES IN DEVICES WITH CROSSED FIELDS

2.1 *Dynamics of self-sustaining secondary emission beam in MD*

The process of electron cloud formation inside an axisymmetrical MD under the condition of homogeneous initial emission of low current primary beam from a cathode starts due to inevitable presence of electric field fluctuations in rotating flow of electrons stored inside the gap for the time of the growth of the external voltage. Weak azimuthal instability is amplified by nonuniform secondary emission and a feedback on the surface of the cathode.

The feedback on the surface of the cathode exerts the dominant influence on the growth of the instability and on arising of a transverse leakage current to the anode across the external magnetic field exceeding the critical magnetic field of magnetic insulation. This feedback is conditioned by right phasing of a part of secondary emitted electrons by rotating crossed E×B-field. These electrons are captured inside rotating modulated electron flow and stay inside the gap for many revolutiones around the cathode, maintaining its azimuthal and time structures. Another part of secondary emitted electrons can stay inside the gap only for a small time comparable with the period of cyclotron motion because they are forced to return to the cathode by the radial component of rotating crossed E×B-field, which changes its direction during the rotation of the flow as a whole. The secondary-emission current exceeds the primary-beam current by more than an order of magnitude and subsequently exerts a determining action on the operation of the MD. The MD passes over to a condition of self-sustaining emission and the primary beam could be switched off.

The regime of self-sustaining secondary emission in MD is characterized by the average radial component of electric field on the cathode surface, which is close but not equal to zero. At given azimuth of the cathode surface it oscillates with a frequency equal to the average rotating frequency of the flow as a whole times the number of bunches. Fig. 1 (top) the time behaviour of radial electric field near the surface of the cathode of MD with parameters close to experimental [6].

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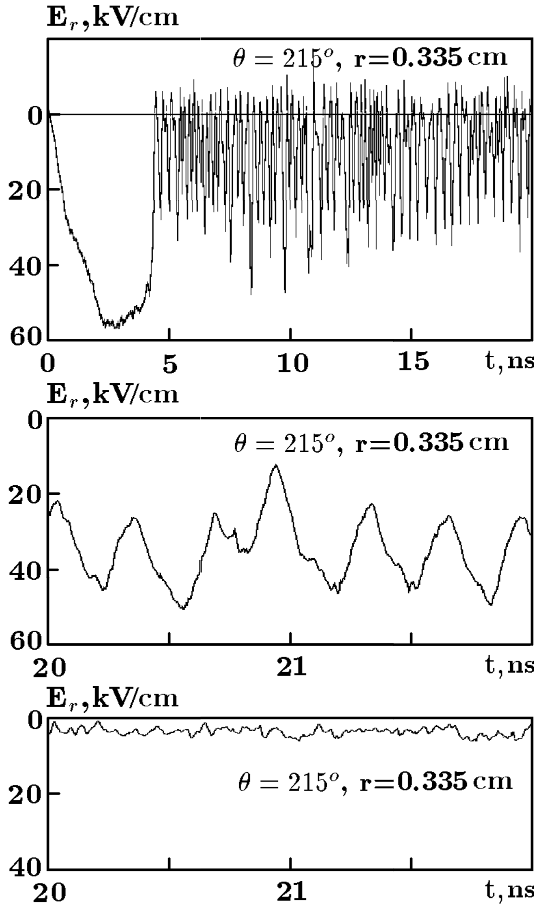

Figure 1: Behaviour of the radial electric field near the surface of the cathode for the aforementioned cases.

2.2 *Dynamics of primary beam and of mixed secondary and primary beams in MD*

Investigation of an instability of pure primary beam of different currents up to space-charge limited current homogeneously emitted from a cathode of MD (an MD with a thermionic cathode without secondary emission) shows that under condition of space-charge limited current no azimuthal instability occurs. Deep azimuthal modulation of the flow and leakage current to the anode arises only if the condition of saturated regime (normal component of electric field does not equal zero) of a cathode is satisfied. The behaviour is conditioned by the same feedback on the emitting surface providing additional correct azimuthal modulation of emitted particles similar to the case of secondary emission. The difference is that the radial electric field does not change its direction on the surface of the cathode, but oscillates with large amplitude. In the middle of Fig. 1 the time behaviour of radial electric field near the surfaces of the cathode of the MD without secondary emission and the cathode operating in the saturated regime is shown. The bottom figure shows the case of space-charge limited current of primary electrons.

In the case when the current of primary beam is comparable with the current of secondary-emission beam the behaviour of the electron flow for later time is similar to the case of space-charge limited primary beam. The charge of primary beam emitted homogeneously from the cathode influenced the character of secondary emission and smoothes over a nonuniformity of secondary emission due to additional suppression of radial electric field on the cathode surface. Secondary-emission current increases initially and then drops to a value which provides the fall of radial electric field on the cathode surface to close to zero. Azimuthal modulation of the flow and leakage current to the anode do not exist in this case. However, they arise for a time if the current of primary beam decreases approximately by an order of its initial value.

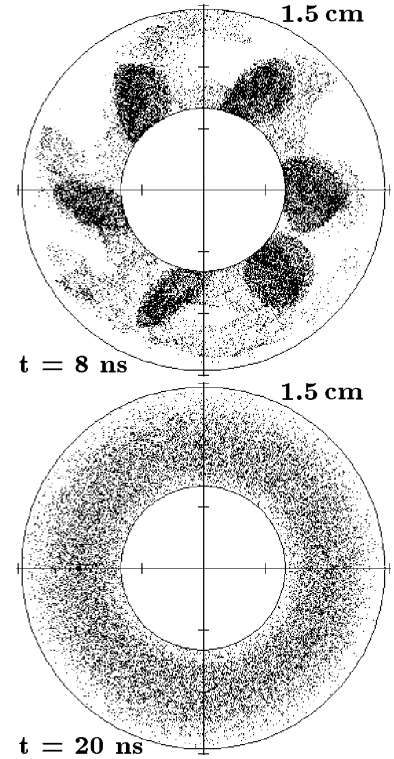

Figure 2: Configurations of flow at t = 8 ns and t = 20 ns.

2.3 *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.

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 cantimiter of length axially in a compact system with crossed fields. In this case, the lateral dimensions are several cantimeters, the voltage is at the level of 100 – 200 kV and the external magnetic field is about of 3 kGs.

Computer simulations were performed using electromagnetic PIC-code KARAT [5] in two-dimensional $r - \theta$ geometry. For subsequent acceleration of captured flow, one can use a bethatron field and cut electrodes that do not hinder the formation of electron flow nor the penetration of the external longitudinal magnetic field.

The main idea consists in the following. After formation in an 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 existance 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 with a large number of particles. Fig. 2 shows azimuthal structures of flows at different instants.

2.4 Inverse magnetron diode

It was very desirable to use inverse MD instead of usal MD to store more number of particles as the surface of the cathode is larger for the same transversal dimension of the MD and the current can be increased. Unfortunately, for a set of parameters the beam in the inverse MD is unstable. The example of interesting structures is shown in Fig. 3. The beam consisists of several well spaced intense bunches. The voltage at inverse MD is 160 kV, the peak current of each bunch is about of 1 kA and the full number of particles inside the gap is as greater as 4×10^{12}. This structure changes with the variation of the voltage and the most part of particles can be lost at the eletrodes.

The instability of the electron flow in inverse MD with intense spikes of secondary emission current from external cathode of large surface can be used to generate RF-ocsillation, i.e., inverse MD with the external circuit can be used as a modulator. The modulator works on the dynatron effect inside vacuum inverse coaxial diode with magnetic isolation supplied by an external pulsed high-voltage source connected to the modulator through RL-circuit. Under conditions of permanent emission of primary electron beam from an external electrode (cathode)

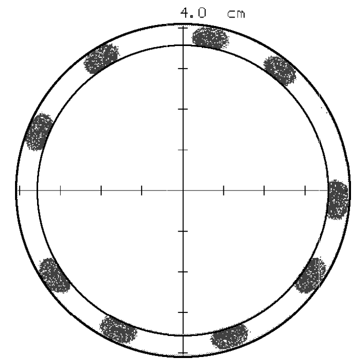

Figure 3: The example of periodic structures in inverse magnetron diode.

and the growth of the voltage at the diode the storage of primary electrons arises inside the gap. Oscillations of the voltage due to oscillating regime of diode charging and/or azimuthal instability of rotating electron flow stimulates back-bombardment flow electrons to the cathode and leads to power spikes of secondary emission current exceeding primary one. As the result, the amplitude of oscillations in quasi-resonant circuit grows and the system can turn to self-supporting oscillations, i.e. like to avtogenerator. For a set of parameters of the diode and the external circuit this device can work like to RF-amplifier. The amplitude, the average voltage and the frequency of oscillations can be changed by varying a part of parameters. Examples of calculations demonstrating physical features of processes in inverse MD are presented in an accompanying report [4].

3 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, for high-efficiency relativistic magnetrons, and for electron guns. The review of the results of computer simulations of different processes inside usual polarity and inverse polarity magnetron diodes is given.

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