SELFORGANISATION AND DYNAMICS PECULIARITIES OF INTENSE ELECTRON BEAMS IN COMPACT CROSSED FIELDS SYSTEMS

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The review of the results of computer simulations of electron flow self-organisation inside magnetically isolated coaxial diodes (magnetron gun) is given. Magnetron guns of usual and inverted polarities are considered.
PACS number: 29.17.+w

1 INTRODUCTION

The main reasons of the self-organisation process and development of regular space structures of the flows inside magnetron guns are: non-linear azimuthal instability of the flow under condition of strong non-uniform secondary self-sustaining emission and pure thermionic emission, and the dominant influence of a feedback on the emitting surface on the dynamics of electron curls. The dynamics of intense electron flows in systems with curvature radius of electrodes 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 curls, the utilisation of such systems for generation of high-frequency oscillations [1 – 5].

Computer simulations have been performed using the electromagnetic PIC code KARAT [6] for magnetron diodes (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 SELF-SUSTAINING SECONDARY EMISSION IN MD

The regime of self-sustaining secondary emission in MD is characterised by the average radial component of electric field on the cathode surface, which is close but not equal to zero. At the given azimuth of the cathode surface it oscillates with a frequency equals to the average rotating frequency of the flow as a whole times the number of bunches.

Feedback on the emitting surface, promoting the development of a strong azimuthal instability, is particularly effective when using a cathode with secondary emission of electrons. The sharp non-uniform character of secondary emission, depending in turn on the 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 suppressed by the negative value of the field, and the emission of particles in proper phases is sharply increased.. The type of operation of a MD with a secondary-emission cathode depends on the maximal voltage and rate of a 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 exceeds a certain maximal value in the process of rising voltage it 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. The sharp drop in the secondary emission current leads to elimination of the "mismatched" part of the electron flow, and the particles remaining in the gap form, in the main, form captured circulating flow.

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.

3 PRIMARY BEAM AND MIXED SECONDARY AND PRIMARY BEAMS OF COMPARABLE CURRENTS IN MD

Investigation of instability of the pure primary beam of different currents up to the 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 the 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 a large amplitude.

In the case when the current of primary beam is comparable with the current of the secondary-emission beam the behaviour of the electron flow for later time is similar to the case of the space-charge limited primary beam. The charge of the primary beam emitted homogeneously from the cathode influenced the character of secondary emission and smoothes over a non-uniformity of secondary emission due to additional suppression of the radial electric field on the cathode surface. Secondary-emission current increases initially and then drops to a value that provides together with the primary beam the fall of the radial electric field on the cathode surface 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.

4 CAPTURE AND ACCUMULATION OF ELECTRONS IN MD

The conditions for possible interruption of the 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 realise a process of accumulation and capture of the 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 bethatron-type systems. Such systems can also be used as injectors for classic accelerators.

It is possible to store an electron flow having a number of particles at the level of 10^{12} per centimetre of length axially in a compact system with crossed fields. In this case, the lateral dimensions are several centimetres, the voltage is at the level of 100 - 200 kV and the external magnetic field is about of 3 kGs. 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 an external longitudinal magnetic field.

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 stabilising 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 with a large number of particles.

5 SECONDARY EMISSION IN INVERTED MD

It was very desirable to use inverse MD instead of usual 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. 1.

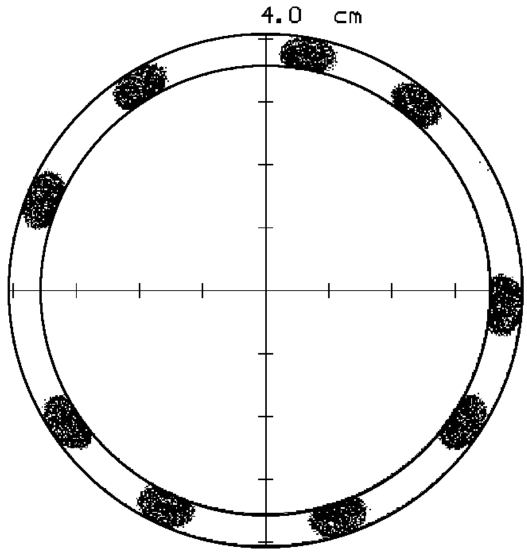

Fig. 1. The example of a periodic structure in the inverted magnetron diode of small aspect ratio.

The circulating beam consists of several well spaced intense bunches. The voltage at inverse MD is 160 kV and is rising, the peak current of each bunch is about of 2 kA and the full number of particles inside the gap is as greater as 4×10^{12} per centimetre of axial length. This structure is changed with the variation of the voltage and the most part of particles could be lost at the electrodes.

As a rule, when analysing the non-stationary dynamics of intense beams in such devices, the external circuit is not considered. The regime of operation, for that or other reasons, is chosen from the condition of aperiodic charging of a capacitance, which diode represents. At the same time, inclusion of an external RLC-circuit with a source of voltage $V_0(t)$ in the scheme of calculation is necessary. This is particularly so when modelling non-stationary processes.

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-oscillation, 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) 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.

In the usual magnetron diode, where the inner electrode serves as the cathode, these oscillations promote rapid growth of the secondary-emission process. However, characteristics of the beam insignificantly differ from the case of aperiodic charging. In an inverted magnetron diode, where the outer electrode serves as the cathode, these oscillations can increase and develop into self-sustaining regime in a certain range of parameters.

The difference in the behaviour of direct and inverted-polarity diodes is that in a certain range of parameters the beam in an inverted diode is strongly unstable with respect small voltage variations and the large cathode surface permits briefly drawing from it large secondary-emission currents, thereby securing deeper modulation of the voltage on the diode. After withdrawing the charge in the gap, the diode again begins to charge and if the emission of the primary beam is continuos the process is repeated.

Results of calculation for a magnetron diode with anode radius r_a = 0.66 cm and cathode radius r_c = 1.06 cm are presented below. The diode is immersed in a magnetic field B_0 = 3 kGs. By way of example, here was chosen a trapezoidal form of external voltage pulse. The rise time and fall of $V_0(t)$ was 8 ns and the flat top had a duration of 8 ns. The chosen coefficient of secondary emission was the standard for a metal [1]. The voltage amplitude at the external source was 50 kV.

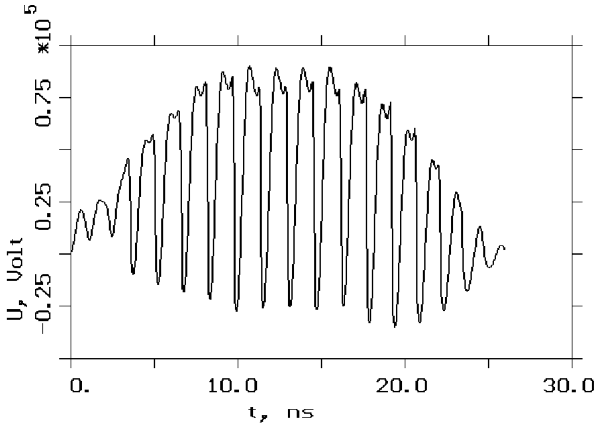

Fig. 2. Behaviour of the voltage on the inverted diode.

6 CONCLUSION

Problems of non-linear dynamics of space-charge dominated electron beams in crossed E×B-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 inverted polarity magnetron diodes is given.

Work is supported by RFFI under grant 00-02-16182.

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