NON-STATIONARY EFFECTS IN SPACE-CHARGE DOMINATED ELECTRON BEAMS

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Abstract

Problems of non-linear dynamics of space charge dominated electron beams in plane and in coaxial electron guns are discussed from the point of view of non-stationary behaviour of beams. The results of computer simulations of beam formation are presented for several simple plane diode geometries and for the gun with large compression of annular beam. Emphasised is non-stationary behaviour combined with edge and hysteresis effects. Non-stationary effects in crossed electron and magnetic field are considered from the point of view a development of schemes of intense electron beam formation for compact accelerators and RF-devices. The results of computer simulation of beam formation inside coaxial guns are described under condition of secondary self-sustaining emission. Possibilities of electron storage and capture due to transient processes are discussed.

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HYSTERESIS EFFECTS IN LINEAR BEAMS

Fringe Effects in Simple Drift and Accelerating Regions

In sources of electron beams of high brightness, applicable and developed for FELs and linear colliders, there have begun to be used in recent times photocathodes that permit forming "cold" beams initially. One of the problem in these investigations concerns the magnitude of current taken from the photocathode. Naturally, the classical CL-law is applicable only for a stationary regime with current limited by space charge for the following conditions: voltage constant; geometry close to one-dimensional; emissive power of the cathode unlimited.

For a purely stationary flow that is one-dimensional and unlimited in the transverse direction, the dependence of the passing current I_{out} on injection current I_{inj} is represented by the so-called "lambda-curve" (Fig. 1) [1] Three solutions are possible for the region from I_{cr1} to I_{cr2} in such a flow. One of these is with a virtual cathode and partial passage of the beam (lower part of solid curve) and the other two (merging into one) are without a virtual cathode and with complete passage of the beam. It is considered that the last two states are unstable and when I_{cr1} is exceeded the beam always goes to the lower part of the curve with formation of a virtual cathode. For unlimited increase of injected current the virtual cathode asymptotically approaches the plane of injection and through the region there passes only current equivalent to the CL-current for a plane diode of the same dimensions, with voltage corresponding to the energy of injected electrons. For non-relativistic energy of particles, $I_{cr1} = 4 I_{CL}$, $I_{cr2} = 2 I_{cr1}$.

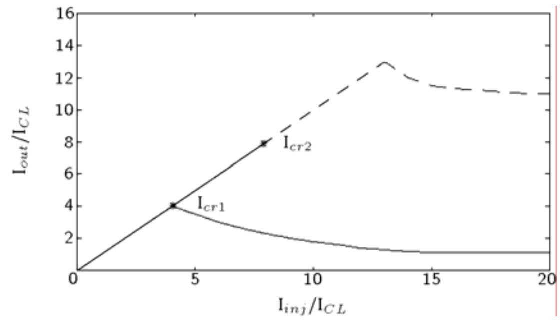

Figure 1: λ-curve

Let us consider the case when two-dimensional effects appear most effective. The drift region is chosen in the form of a cylindrical resonator having the diameter much larger than the longitudinal dimension, and the diameter of injected beam equals to the length of the resonator. In Fig. 1, the value of current is presented in units corresponding to CL-current ($I_{CL} = \pi r_e^2 j_{CL}$, $j_{CL}d^2 = 6.6$ A for 20 kV on the diode). The solid line in Fig. 1 show the analytical dependence for one-dimensional stationary flow and the dotted line the calculated dependence for established regime when injecting beams of various currents. The established beam configuration for 200-A injected current is shown in Fig.2 and is very similar to

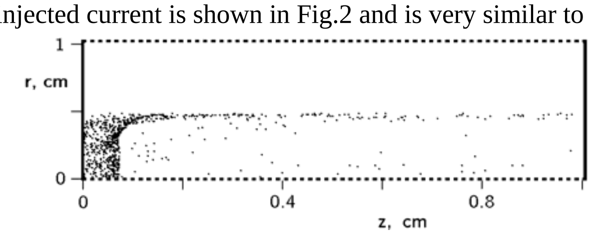

Figure 2: Beam with "whiskers".

that considered in [2]. It should be noted that the main part of the current is concentrated in "whiskers", the thickness of which decreases with increasing injected current. With increasing transverse dimensions the influence of "whiskers" on the inner part of the beam is weakened due to preventing of field by electrodes and electrons with density of current close to the Child-Langmuir begin take "emitted" from the virtual-cathode region. Since the total CL-current will increase proportionally to r^2 and the current in the "whiskers" not more than r, the contribution of the "whiskers" becomes small relative to current from a larger area, but lower current density. This corresponds to one-dimensional flow unlimited in the transverse direction.

Hysteresis Effects in a High-Voltage Electron Gun

Spatial-temporal hysteresis effects to a significant extent appeared in an electron gun has been designed to produce a beam for generation of high-power microwaves and IR-radiation [3]. It has the following design parameters: energy of electrons 350-450 keV, beam current > 100 A, longitudinal momentum spread < 1%, pulse duration 10 μs, repetition rate up to 10 Hz.

A plane, ring-shaped, cathode, having a 28-mm average radius and a 6-8 mm width, is used to produce an annular beam. The cathode surface is screened by two focusing electrodes to operate in a space-charge limited regime. The focusing system must form a laminar beam inside the accelerating gap at rather low magnetic field and transport the beam to an experimental region of about 50-cm length. Inside this region, the beam radius is 2.5 mm and annular thickness less than 1 mm due to a large magnetic field of 15 kGs.

Code KARAT [4] was used to calculate beam dynamics and the results were tested by means of stationary code SAM [5]. Simulation of emission of particles in the KARAT code could be realised by two methods. Giving constant (or variable) emission current exceeding the space-charge limited current and increasing the voltage on the gun to a certain given value (thermionic cathode); giving constant voltage on the gun and increasing emission current from the cathode in time in accordance with a desired law (photocathode).

Fig. 3 shows averaged (high-frequency components filtered off) behaviour of beam current at the gun output for various modelling conditions. Dependencies 1 - 3 correspond to conditions of photocathode operation and dependence 4 to conditions of thermionic cathode operation. Current discrimination is clearly seen at 195 A, with subsequent drop to values that approximately correspond to the value of beam current in the stationary state. The fourth dependence is plotted for the case when emission current is held constant at 400 A while the voltage on the diode increases.

NON-STATIONARY EFFECTS IN CROSS-FIELDS GUNS

Physical Processes

The physical characteristics of the processes under consideration are partially presented in works [6-14]. 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 [7, 13]. 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. 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. 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.

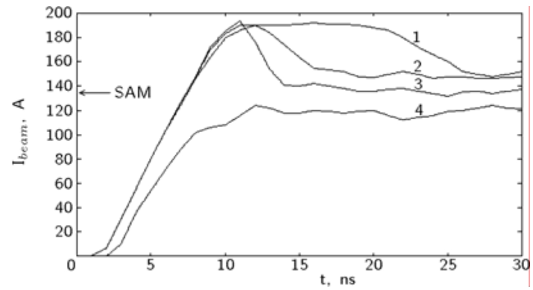

Figure 3: Hysteresis effects in high-voltage gun

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.

Instability is saturated at a level of leakage currents at the anode, which can amount to several percent of I_{CL}. 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. Example of such structure is shown in Fig. 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.

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

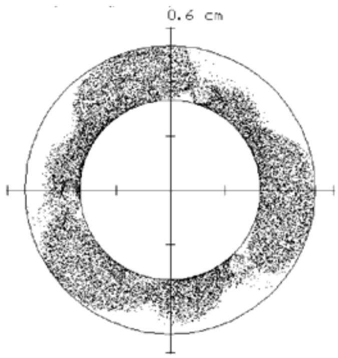

Figure 4: Regular structure of electron flow in crossed fields

electric field at the cathode differs from zero and the development of weak azimuthal instability increases as in the case of non-uniform secondary emission. due to proper phasing of emitted particles. The difference 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.

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. 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 centimetre of length axially in a compact system with crossed fields, the voltage is at the level of 100 – 200 kV and the external magnetic field is about of 3 kG.

After formation in a MD of electron flow with regular structure growth of voltage leads to re-bunching of flow. 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. Fig. 5 shows azimuthal structures of flows at different instants.

CONCLUSIONS

Problems of non-linear dynamics of space-charge dominated electron beams in linear and circular geometry’s interacting with a surface are discussed. The review of the results of computer simulations is given.

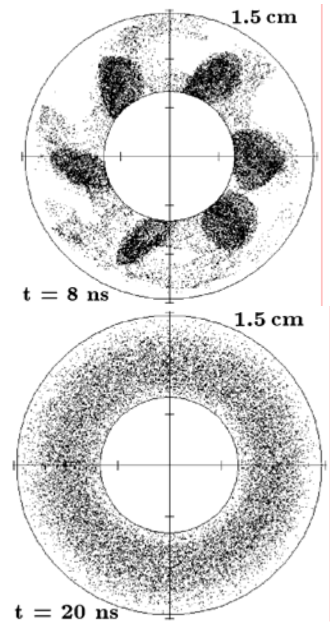

Figure 5: Configurations of flow at t = 8 ns and t = 20 ns

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