Modeling of explosive electron emission and electron beam dynamics in high-current devices

S.V. Anishchenko and A.A. Gurinovich
Research Institute for Nuclear Problems, Bobruiskaya 11 str, Minsk 220030, Belarus
E-mail: sanishchenko@mail.ru

Abstract. Based on a detailed analysis of explosive electron emission in high-current electronic devices, we formulate a system of equations that describes the expansion of the cathode plasma and the generation of high-current electron beams. The system underlies the numerical algorithm for the hybrid code which enables simulating the charged particles’ dynamics in high-current vircators with open resonators. Using the Gabor-Morlet transform, we perform the time-frequency analysis of vircator radiation.

1. Introduction
A lot of algorithms and computer codes have been developed that permit studying different phenomena in high-current electronic devices. The explosive electron emission is particularly interesting, because during this process plasma changes from nonideal, having strong particle interaction, to practically collisionless, emitting a high-density electron beam in the presence of an external electric field. The beam acts as an active medium in high-power microwave generators – e.g. vircators [4] (Fig. 1).

Figure 1. Vircator. Schematic diagram

Vircators, or the sources of electromagnetic radiation with an oscillating virtual cathode, have been the subject of theoretical and experimental studies for more than 30 years. The interest in vircators is natural: the devices based on an oscillating virtual cathode can produce high-power signals. Already in the first experiments with vircators, the output power was reported to achieve more than 100 MW [4]. The radiation in the source is generated owing to the development of Pierce instability of the electron beam injected through a semi-transparent anode mesh of a high-current diode into an equipotential cavity (drift tube), where the oscillating virtual cathode –
the electron bunch that reflects a fraction of electrons backward to the anode – is formed. The accelerated motion of charged particles is accompanied by the emission of electromagnetic waves.

The present paper suggests a variant of a hybrid code in which the beam dynamic is computed in the kinetic and plasma dynamics – in the hydrodynamic approximations. The second section gives a detailed analysis of explosive emission processes leading to the formation of cathode plasma in a vircator, substantiates the applicability of a hydrodynamic approach to the cathode plasma description. Section 3 provides the time-frequency analysis of radiation of a vircator with an open resonance cavity.

2. Explosive electron emission
A high-current diode is started by applying the voltage $U$ to the interelectrode gap of a high-current diode (Fig. 1) and thus inducing the field-emission current from the cathode surface. This current is a flow of electrons tunneling from metal to vacuum under the action of the electric field \cite{4}. Moving in a metal, the electrons heat up the cathode surface. Because of the surface defects of the conductor (microprotrusion tips), dielectric inclusions, oxide and other inorganic films, layers of the adsorbed gas, emerging intergrain boundaries, crater edges, and pores cracks) the microscopic electric field near the cathode is nonuniform. Particularly, the value of the field in the vicinity of microprotrusion tips is increased compared to the average value, and so the tips are rapidly heated and explode when the specific energy density amounts to $\sim 10^4 \text{ J/g}$. When the electric field strength $U/h$ attains values of the order of $1 \text{ MV/cm}$, the explosion delay is about $1 \text{ ns}$. Microexplosions result in plasma formation and intense thermionic emission from the expanding plasma surface. The plasma initiated on the cathode surface leads to further heating of the cathode areas and charging the dielectric films, and thus favors the formation of new emitting regions.

The properties of the cathode plasma change significantly during the expansion. Being a nonideal plasma with strong interparticle interaction at the moment of hydrodynamic expansion of the tip, it turns into ideal plasma as its density gradually decreases and the collision rate reduces.

Explosive electron emission is considered by the example of a graphite cathode. Graphite cathodes are extensively used in high-current electronics for their durability and low vacuum breakdown field strength. In our simulation we shall neglect the phenomena related to the transition of plasma from a nonideal to a rarefied state, occurring at a distance of about $100 \text{ \mu m}$ from the cathode surface \cite{2, 4}. There are three reasons why such a simplification is needed. First, computations of microprocesses on the cathode increase the computation time. Second, a detailed information about the cathode state is often missing. Third, most experimental data about the cathode plasma refer mainly to that expansion stage when the plasma is already ideal.

It was experimentally determined that microexplosions initiate the emission from the cathode surface of a plasma flux of velocity $v \approx 2 \cdot 10^6 \text{ cm/sec}$. The temperature of the electronic component of the flux is $T_e \approx 5 \cdot 10^4 \text{ K}$ \cite{4}, while the temperature $T_i$ of its ionic component is by a factor of five smaller.

Knowing the experimentally measured cathode mass loss per 1 coulomb ($K \approx 1.4 \cdot 10^{-6} \text{ g/C}$ \cite{7}), the total diode current $I$, and the area $S$ of the emission region, we can readily determine the ion concentration $n_{0i} = n_{0e} K I/m_i S \nu$ and the pressure $P_0 = n_i k(T_e + T_i)$ of the cathode plasma. Let $I = 20 \text{ kA}$ and $S = 30 \text{ cm}^2$, then $n_{0i} = 3.0 \cdot 10^{15} \text{ cm}^{-3}$ and $P_0 \approx 1 \text{ kPa}$.

The main parameter characterizing the transport and relaxation properties of cathode plasma is the electron-ion collision rate $\nu_{ei} = 5.5 \Lambda_e n_0 T_e^{-3/2} \approx 10^{10} \text{ sec}^{-1}$ \cite{8}. Because the value of $\nu_{ei}$ is small, the local thermodynamic equilibrium between electrons and ions is set up in a time interval as long as $m_i/m_e \nu_{ei} \approx 2 \text{ mcs}$. The electron heat conductivity can be neglected because the entire process of explosive emission lasts for about a microsecond, and so the characteristic distance over which the temperature can be expected to equalize is as small as $0.5 \text{ cm}$. Hence, a
two-component plasma expands adiabatically, and this motion can be described by the following hydrodynamical equation:

\[ \frac{d\vec{V}}{dt} = -\nabla P/\rho, \]

written in the Lagrangian form. The pressure \( P \) relates to the density \( \rho \) as \( P = P_0(\rho/\rho_0)^{5/3} \) (\( \rho_0 \) and \( \rho_0 \) are the plasma pressure and density at the cathode surface, respectively).

Note also that carbon plasma in the interelectrode gap remains completely ionized due to the small rate of charged particle recombination. For this reason, its Langmuir frequency is \( \omega_c = \sqrt{e^2n_0/4\pi m_e} \approx 500 \text{ GHz} \), being much greater than the characteristic frequency of beam oscillations \( 1 - 10 \text{ GHz} \) [4]. As a consequence, the electric field hardly penetrates the plasma. That is why when simulating the processes occurring in the diode, we can consider the plasma and cathode potentials to be equal.

We solve hydrodynamical equations by means of the particle-in-cell method (PIC), widely used in hydrodynamics and plasma physics simulations. The code for the solution of hydrodynamical equations is based on a somewhat modified version of the algorithm [10] developed for magnetohydrodynamical applications. Our algorithm differs from that described in [10] by the absence of the magnetic fields that play only a minor role in the absence of the pinch effect.

In a high-current diode, the beam is generated through thermal electron emission from the expanding cathode plasma, whose electron temperature is of the order of \( 10^4 \text{ K} \). Because the thermionic current density \( j_T = en_e\sqrt{kT_e/2\pi m_e} \approx 10 \div 20 \text{ kA/cm}^2 \) is one-two orders of magnitude greater than the limiting charge current density in the diode, \( j_{CL} = \frac{en_e^2(2\phi/m_e^{3/2})}{9\pi d^2} < 1 \text{ kA/cm}^2 \) (\( \phi \sim 500 \text{ kV}, d \sim 1 \text{ cm} \)), the emission capability of the cathode plasma can be considered unlimited; the cathode can be considered as an electric-field-screened spatial charge of the beam.

The motion of electrons can be studied in the framework of collisionless plasmadynamics [3].

3. Analysis of radiation from the vircator

On the basis of the described theory, we developed a computer code for simulation of vircators with open resonant cavity (Fig. 1). As has been shown in [5, 6] a noticeable stabilization of the radiation frequency in such vircators can be achieved when one of the the resonator’s eigenfrequencies \( \omega_0 \) is approximately the same as the frequency \( \omega_h \) of the electrostatic oscillations of the beam. The latter depends on the cathode-anode gap \( h \) in a most straightforward way.

This naturally raises the question of how the cathode plasma expansion affects the output characteristics of vircator radiation. To find the answer, we performed a numerical simulation of a vircator, in which charged particles interact with the transverse mode \( TM_{010} \) of the electric field of a cylindrical resonator. The vircator parameters were as follows: the cathode-anode gap \( h = 1.6 \text{ cm} \), the cathode radius \( R_c = 3.2 \text{ cm} \), the resonator radius \( R_a = 7.5 \text{ cm} \), and the resonator length \( L_a = 6.0 \text{ cm} \). The mode \( TM_{010} \) had the eigenfrequency \( f_0 = 3.4 \text{ GHz} \) and the damping constant \( \lambda_0 = 0.025\omega_0 \), which corresponds to the resonator Q-factor equal to 20. At modes different from \( TM_{010} \), the resonator Q-factor was considered much lower.

Numerical calculations show that a virtual cathode is formed and the oscillations of the transverse electromagnetic field are excited at the frequency \( \sim 3.6 \text{ GHz} \) when the current exceeds the threshold current \( (I_0 \approx 9 \text{ kA} ) \). When the current further grows by a factor of 2.5, the generation frequency increases monotonically. This is readily seen by the Gabor-Morlet wavelet transform of the oscillation amplitude \( q_0 \) of the field oscillator [3, 11]:

\[ q_0(t, s) = \int_{-\infty}^{+\infty} q_0(\eta)\pi^{-1/4}e^{i\eta^2}e^{-\eta^2/2}d\eta, \]

(2)
Figure 2. Time-frequency diagram of radiation from the vircator.

where $s$ is set equal to 6.7 ns.

One can infer from Fig. 2 that the cathode plasma expansion leads to a 5.5% shift of the basic generation frequency in 300 ns (from 3.6 GHz to 3.8 GHz).

4. Conclusion
A thorough analysis of the explosive emission processes in high-current electronic devices was given. It allowed us to formulate the physical model that describes the expansion of the cathode plasma and the generation of high-current electron beams used for excitation of transverse electromagnetic oscillations in open-cavity resonators. On the basis of the physical model, we developed a numerical algorithm and a computer code for simulating charged particle dynamics in high-currency devices. The code was used for time-frequency analysis of radiation generated by an open-resonator vircator with a low Q-factor ($Q \sim 20$). It was shown that when the vircator current is increased by a factor of 2.5 compared to the threshold current the basic frequency of radiation grows by 5 – 6%.

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