Influence of Ionization Processes on Virtual Cathode Formation

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***Abstract* — The paper presents the results of the study of the influence of plasma effects on the processes occurring in high-power electronic systems. The results are obtained using electromagnetic PIC code for a promising class of high-power microwave devices – relativistic vircators (generators and amplifiers with a virtual cathode). A detailed study of the behavior of critical current of a relativistic electron beam with a change of the control parameters of the system (concentration of residual gases, external magnetic field parameters, energy of electron beam and shape of current pulse) is carried out. The results obtained within the framework of the research are intended to broaden the fundamental concepts about the dynamics of intense electron beams in a plasma.**

Keywords— Critical current, ionization, plasma effects, virtual cathode, vircator, numerical simulation

I. Introduction

As part of this work, a study was conducted of the processes of plasma effects on the processes occurring in high-power electronics systems, which was performed using an electromagnetic PIC code applied to a promising class of high-power microwave devices — relativistic vircators (generators and amplifiers on a virtual cathode (VC)) [1-3].

The choice of vircators as an object for research is due to several reasons. First, they are promising sources of microwave and sub-THz radiation with record levels of output power. Vircators are also distinguished by their simplicity of design, the ability to work without an external focusing magnetic field, the simplicity of controlling the spectral and energy characteristics of generation, the wide frequency band of the generated signals, and low demands on the quality of the electron beam. Another reason for interest in vircators from the point of view of basic research is that plasma effects in this class of devices develop intensively and significantly affect their operation due to extremely high space charge densities and low electron velocities in the VC region. Thus, the consideration of plasma effects in vircators is fundamentally necessary.

Moreover, vircators are good model systems from the point of view of other high-power electronics schemes, since they contain all the basic elements character to this class of devices. This allows one to extend the results to other high-power electronic devices.

This research is also important from a practical point of view, because allows to clarify known results by taking into account plasma effects, to conduct more reliable optimization of vircator schemes, suggests ways to suppress undesirable phenomena associated with the formation of plasma and ions, and options for using the detected effects (for example, for pulse generation, ion acceleration, etc.), From the fundamental point of view, the conducted studies make it possible to reveal the new regularities of the dynamics of intense relativistic electron beams (REBs), in particular, in the process of development of various types of instabilities in them, taking into account plasma effects and the interaction of beam electrons with charged plasma particles.

II. System under Study

Simulation of ionization processes in the collision of an electron with an atom is based on the Monte-Carlo method, which performs a random electron-atom collision, which leads to the formation of an electron-ion pair. It is assumed that the drift space of the transit vircator is uniformly filled with a neutral gas. The gas density ρ, pressure p and temperature T of the gas are the same for the entire simulated space and are constant throughout the calculation, i.e. they are not affected by ionization processes.

Note, that the collision frequency depends on the gas density, the type of scattering cross-section, and the relative velocity between electron and neutral atom. At the same time, the scattering cross-section depends on the energy of the incident particle. By virtue of these features and to reduce the required computational resources in this model, the velocity of neutral atoms is neglected, considering that electrons move much faster. Thus, accounting for various types of gas is carried out by setting the dependence of the scattering cross-section on the energy of the incident particle and atomic weight.

A collision occurs only if the incident particle is an electron with an energy greater than the threshold. The speed of the formed ions obeys the Maxwell-Boltzmann distribution, which is determined by a given residual gas temperature. Thus, the aforesaid allows to carry out effective numerical fully electromagnetic three-dimensional simulation of a relativistic vircator with a high degree of accuracy and reliability.

In the framework of this work, the behavior of the REB critical current was investigated when the control parameters of the system were changed. Residual gas was selected as hydrogen.

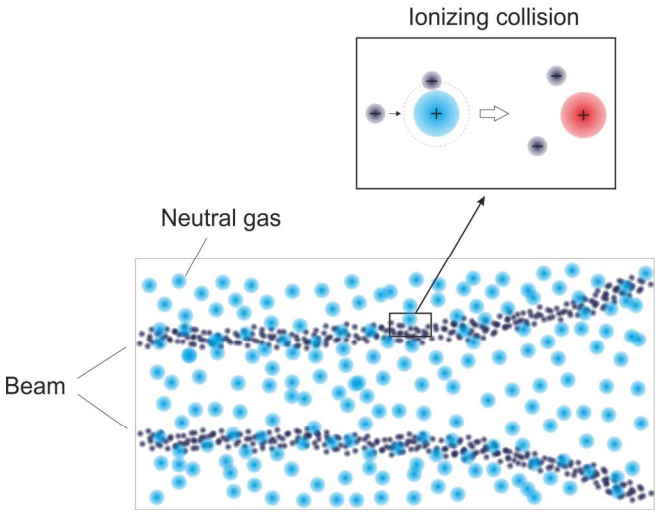

Fig. 1. Investigated scheme.

In the presence of residual gas in drift space, ionization occurs and, as a consequence, the formation of an ion background, which compensates to some extent the negative space charge and, accordingly, reduces the retarding force acting on the beam. Thus, two competing processes coexist in the drift space: the formation of an ioc background, which compensates the accumulated negative space charge, and the accumulation of a negative space charge. Note, that in the process of electrons deceleration, the probability of ionization of neutral gas by an electron increases. It follows from the above that if the rate of accumulation of a negative charge in the region of the minimum of the potential does not exceed the rate of ionization and the accumulation of a positive charge, then a VC cannot form. At the same time, the time of VC formation depends on the magnitude of the supercriticality of beam current, and the following trend is observed: the higher the supercriticality, the faster the potential sags in the system and VC is formed. Thus, in the case of the presence of a neutral gas in the drift space, the value of the critical current is influenced by the ratio between the rates of accumulation of negative and positive charge formed during ionization of the gas.

III. Main Results

Investigation of the effect of residual gas pressure on the critical current showed that with the commonly used in practice vacuum level (10^{-3} - 10^{-6} Torr), the critical current remains almost constant. However, when the pressure of residual gas in the drift space reaches a certain characteristic value, the critical current increases significantly. This is due to the fact that the ionization rate increases significantly with pressure increase because of increased collision probability.

Note, that the number of ions in the system increases significantly with time due to the low speed of the latter in comparison with the passing electrons. In view of this, it becomes important to study the effect of the beam current pulse shape on the critical current. For this purpose, the dependence of the critical current on the rate of increase of the injected current was obtained. A beam with a smoothly increasing current value was injected in the developed model of the relativistic generator. For a number of beam current rise rates, the corresponding critical current values were obtained. Since the value of the injected current continuously varied during the calculation, the critical current was chosen on the basis of the fact that about 1.5 ns is required for the formation of a VC and the appearance of the first reflections, at a given beam energy. Thus, from Fig. 2 it is clearly seen that the magnitude of the critical current depends substantially on the shape of the beam pulse. Indeed, with a decrease in the rate of rise of a current pulse, the critical current in the system increases significantly.

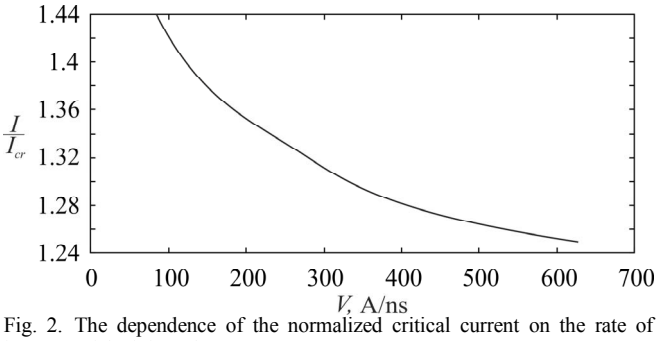

Fig. 2. The dependence of the normalized critical current on the rate of increase of the injected current.

The influence of the energy of the injected REB on the critical current in the system was investigated. The following dynamics was revealed: the lower the beam energy, the stronger the value of the critical current in a gas-filled space differs from the critical current in a vacuum. This phenomenon is caused, firstly, by the fact that a decrease in the energy of ionizing REB leads to an increase in the probability of ionizing collisions (in accordance with the scattering cross-section) and, secondly, by the fact that the formation time of a VC decreases with decreasing energy.

Acknowledgment

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