Model of Collective Acceleration of Ions in Spark Stage of Vacuum Discharge[1]

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Abstract – A new mechanism of the collective acceleration of ions at the spark stage of a vacuum discharge is proposed. It has been shown that this acceleration can take place in the presence of a plasma cloud in the electrode gap with strong electronic instability developing in this plasma. The appearance of accelerated ions of the interelectrode plasma is accompanied by a jump in the diode current.

1. Introduction

This work is devoted to a numerical simulation of the process of collective acceleration of ions in a vacuum spark. The appearance of groups accelerated ions at the spark stage of a vacuum discharge was studied experimentally [1–3]. It was measured that the ions (also called "anomal ions") are accelerated in the direction opposite to the direction of the electric field induced by the applied voltage U_0. Energy of these ions can exceed $z{\cdot}e{\cdot}U_0$. The results of investigations showed that the anomalous acceleration of ions under such conditions takes place only in the regime of unstable vacuum spark [2]. This regime is characterized by sharp outbursts of the discharge current (with an amplitude 2–5 times the average level) and is accompanied by a significant increase in the electron beam current density along the direction of ion acceleration. In addition to these current jumps, another distinguishing feature of the unstable vacuum spark regime is an increase in the potential of peripheral layers of the cathode plasma flare, which reaches up to 80% of the applied voltage.

To explain this phenomenon, several mechanisms have been proposed. According to the first one [4], the ions are accelerated by the electrostatic field of a deep nonstationary potential well which is formed by the electron beam. According to the second scenario [5], the ions are accelerated due to the cumulative effect resulting from the compression of a plasma jet by its own magnetic field. However, the cumulative mechanism fails to explain the charge dependence of the energy of anomalous accelerated ions observed in experiment [3].

A comparatively new scenario was proposed in [6]. Actually, it is a further development of the model introduced in [4] with the real ion motion and plasma-beam interaction taken into account. According to [6], the acceleration takes place when a plasma cloud is presented in the interelectrode gap, where strong electron instability is developed under the action of an electron beam emitted from the cathode plasma.

Calculation in [6] was performed using 1D electrostatic particle in cell (PIC) method. Here we continue to study the scenario proposed in [6] with help of 2D electromagnetic PIC approach.

2. Physical model

Analogously to [6], it is assumed that an interelectrode gap contains the plasma cloud with density on the order of 1012–1013 cm^{-3}. The origin of the interelectrode plasma is not considered in this model. This cloud can represent, for example, plasma generated in the course of discharge initiation, anode plasma, or residual plasma retained after the explosion of an adjacent microprotrusion.

It is supposed also that close to the cathode we have another much more dense plasma cloud. Here, however, cathode plasma is not modeled directly as it was done in [6]. It is assumed that the cathode plasma can provide as high electron emission current density as we need. The emission current from the cathode is restricted only by space charge.

The task geometry and electrode arrangement is shown schematically in Fig. 1. 2D flat geometry is currently used. The anode and the third electrode have the same potential U_0.

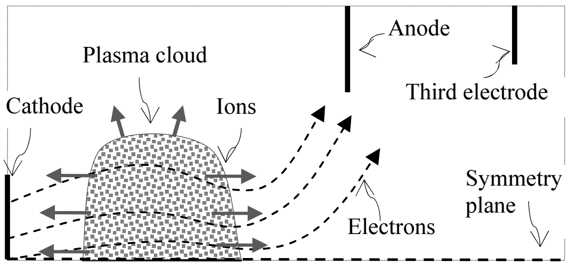

Fig. 1. Sketch of task geometry

Plasma is treated like a fully collisionless one, thus, the following system of equation was used:

$$\frac{d\vec{V}_{e,i}}{dt} = \frac{q_{e,i}}{m_{e,i}}\left(\vec{E} + \frac{1}{c}\left[\vec{V}_{e,i}\vec{B}\right]\right), \qquad (1)$$

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$$\frac{d\vec{r}_{e,i}}{dt} = \vec{V}_{e,i}, \tag{2}$$

$$\rho = \sum_{e,i} q_{e,i} n_{e,i}, \quad \vec{J} = \sum_{e,i} q_{e,i} n_{e,i} \vec{V}_{e,i}, \tag{3}$$

$$\frac{\partial \vec{A}}{\partial t} - c^2 \Delta \vec{A} = 4\pi c \vec{J}_T \tag{4}$$

$$\Delta\phi = -4\pi\rho, \quad \Delta\eta = \vec{\nabla}\vec{J}, \tag{5}$$

$$\vec{J}_T = \vec{J} - \vec{\nabla}\eta, \quad \vec{B} = \vec{\nabla}\vec{A}, \tag{6}$$

$$\vec{E} = -\nabla\phi - \frac{1}{c}\frac{\partial A}{\partial t}, \tag{7}$$

where different parameters have the usual meaning (for details see [7]).

The forces were interpolated and the charge redistributed with help of bilinear averaging over the four nearest grid points; i.e. so called cloud in cell (CIC) variant of PIC method was used. To calculate the fields the approach using potentials (A, φ) in coulomb gauge [7] was used. The fast direct poisson solver from IML library was used for solution of the equations (5). Electrodes were introduced by the method of capacity mAtrix [8].

The results are presented here were obtained using the following configurations. The cathode–anode separation was 1 cm. The anode had a slit of 4 mm lateral extension. Behind the anode, at a distance of 1 cm, the third electrode was located which was at the potential of the anode. This region simulated a drift space. The third electrode had the slit of 5 mm size. Interelectrode plasma initially was a smoothed rectangle of 10×1.5 mm. The plasma consists of single, double, and triple charged copper ions taken in the equal amounts.

3. Calculation results

The results of numerical calculations revealed the following pattern of physical processes in a vacuum diode in the presence of the interelectrode plasma described above. When the voltage is applied to the anode (and the third electrode), electrons are emitted only from the right-hand (facing anode) boundary of the interelectrode plasma. Since this plasma has no contact with the cathode, the interelectrode cloud is rapidly polarized and acquires a positive potential. As a result, a potential difference arises between the plasma cloud and the cathode, and the cathode begins to emit electrons as well.

The cathode electron beam interacts with interelectrode plasma by means of electric field (no collisions). Strong electron beam instability is developing due to the interaction. The instability developing turns with time to the Langmuir turbulence. For this reason, electrons in the cloud are heated and rapidly leave the interelectrode gap. Since ions move much slower than electrons, the potential of the cloud increases. This increase intensifies the cathode electron beam which, in turn, increases the positive potential of the interelectrode plasma cloud, and so on. As a result, this plasma acquires a potential that is several times the anode potential U_0 (Fig. 2, *a*) and a potential difference between the anode and the interelectrode cloud becomes negative. Under these conditions, ions on the right-hand boundary of this cloud are accelerated toward the anode (Fig. 2, *b*). At that the ion accelerating field can exceed the nominal field value by factor of more than ten (Fig. 2, *b*). Simultaneously, ions on the left-hand boundary of this cloud are accelerated toward the cathode. The electron beam forms a virtual cathode in the drift space between the anode and third electrode, thus some part of electrons return to the cathode (Fig. 3). Therefore, ions bypassing the anode keep accelerating in this drift space. Described mechanism of ion acceleration ceases to operate when the interelectrode cloud decays.

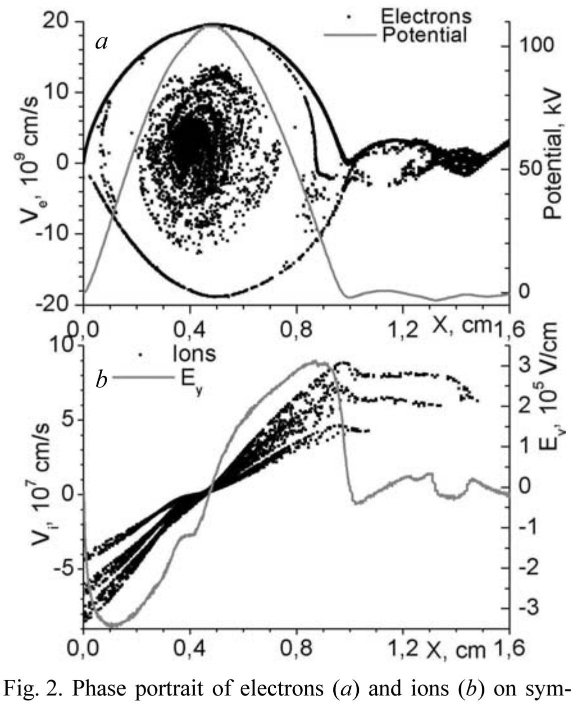

Fig. 2. Phase portrait of electrons (*a*) and ions (*b*) on symmetry plane. Time is 20 ns, U_0 is 20 kV

The ion acceleration scenario described above is approximately identical for both 1D and 2D cases. But the 2D electromagnetic description brings a new behavior. The electron beam passing through the interelectrode cloud becomes partially neutralized. Thus, beam starts to contract under action of self magnetic field. This constriction reaches the maximum close to the right side of the cloud (Fig. 4, *c*). It leads to the formation of an electron bunch in front of the plasma cloud (Fig. 4, *a*). That, in turn, increases the ion accelerating electric field. Moreover, a well constricted ion jet is formed in the area of electron bunch (Fig. 4, *b*).

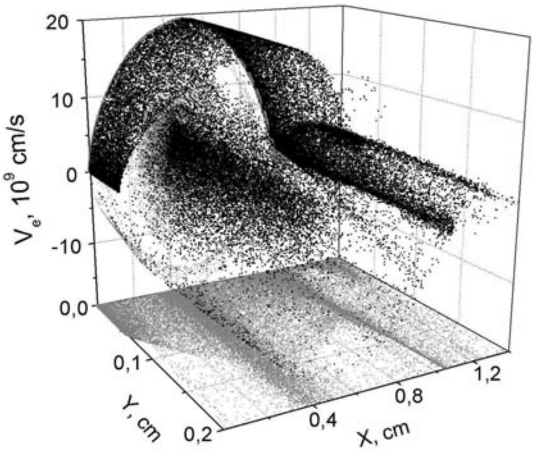

Fig. 3. Phase portrait of electrons. Only *X*-component of velocity is shown. Time is 20 ns, U_0-20 kV

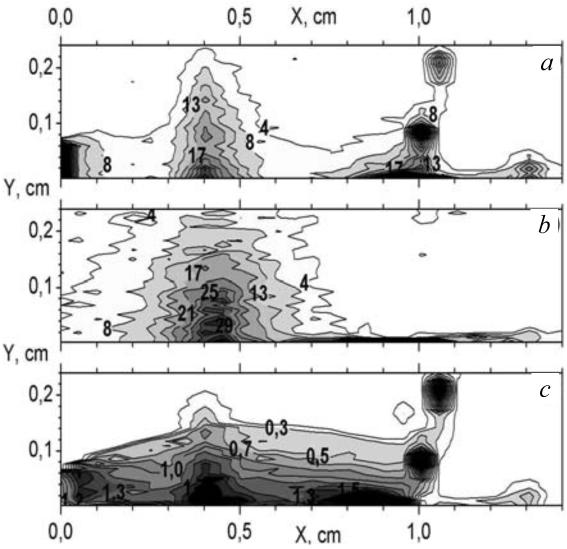

Fig. 4. *a*) electron density 10^{12} cm^{-3}, *b*) ion density, *c*) current density kA/cm^2. Time is 20 ns, U_0-20 kV

Therefore, due to the beam constriction the collective ion acceleration is more intensive in the case of 2D electromagnetic modeling. The comparison of energy of ions obtained in 2D geometry and 1D ones is shown in Fig. 5. It is seen that the maximum of ion energy in 2D case reaches level about $4.5 \cdot z \cdot e \cdot U_0$. In the 1D case it is only about $2 \cdot z \cdot e \cdot U_0$. It is necessary to tell, however, that the 1D case has not exactly the same geometry. The anode in 1D case treated as a semitransparent grid [6]. However, the test 2D pure electrostatic calculation, performed to exclude the effect of electrode arrangement, confirmed the conclusion.

Figure 6 shows a plot of the anode current versus time. As can be seen, the mean current density profile has a dome shape that is indicative of the current buildup. Strong oscillations of the anode current density reflect the fact of strong instability in the plasma. Decay of the interelectrode cloud leads to termination both of these oscillations and of the ion acceleration process.

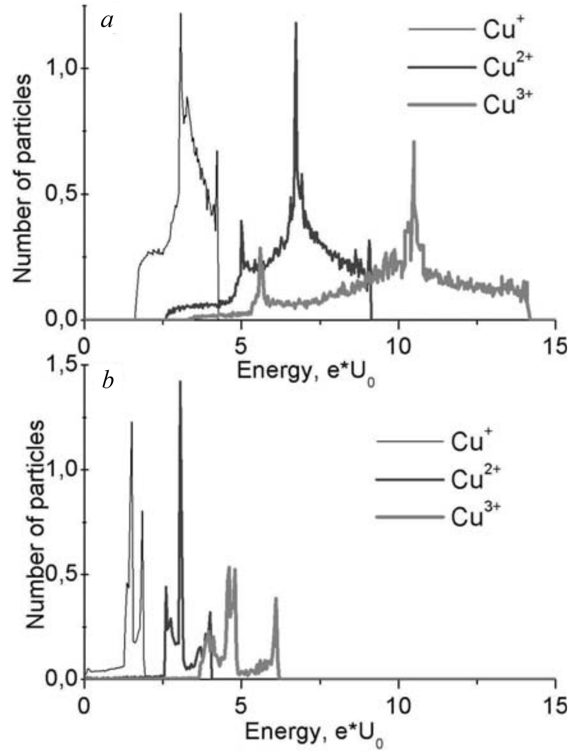

Fig. 5. Time integrated energy spectrum of ions on the anode position, *a*) 2D EM calculation *b*) 1D electrostatic calculation. U_0-20 kV

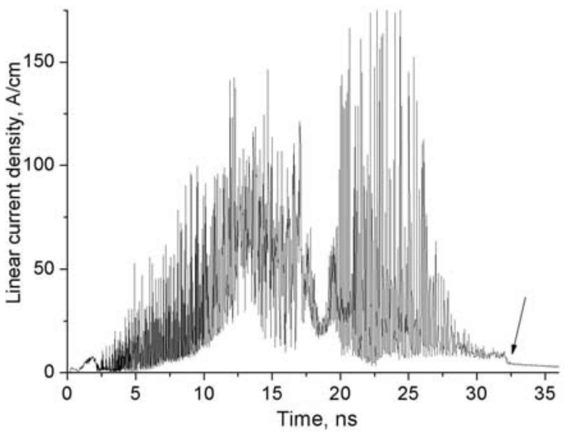

Fig. 6. Current on the anode vs. time. Arrow shows time of total decay of plasma cloud

4. Conclusion

A new mechanism explaining the phenomenon of collective ion acceleration in the spark stage of vacuum discharge was proposed. According to this, the additional acceleration takes place when a plasma cloud is present in the interelectrode gap, where strong electron instability is developed under the action of an electron beam emitted from the cathode plasma. Only ions of the interelectrode plasma are involved in the acceleration process. Beam constriction by action of magnetic field leads to the additional increasing of ion energy and formation of ion jet.

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