IGNITION OF THE BEAM-PLASMA DISCHARGE IN THE INITIALLY NEITRAL GAS

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Initial stage of the beam-plasma discharge was studied via computer simulation for 2D electrostatic model. Stripped non-relativistic electron beam was injected into initially non-ionized helium. At the first stage transversal expansion of the beam was observed caused by its space charge. At the same time helium ionization via electron impact took place. Later beam focusing has been developed due to the space charge of the ions. Development of the beam-plasma instability as well as the background plasma heating was observed at the last stage of the simulation.

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INTRODUCTION

Study of the beam-plasma discharge (BPD) is interesting for construction of the powerful sources of dense plasma, interpretation of results of an active experiments in the ionosphere plasma, etc.

Mechanism of the BPD development is based on the beam-plasma instability (BPI). BPI moves to the formation of a high-frequency electromagnetic field that accelerates electrons of the background plasma. Forced oscillations of these electrons are destructed due to the collisions with heavy particles (i.e. neutral atoms and ions). Collisions lead to the heating of the electron gas. Finally the heated electrons result to the intense ionization of the neutral component, i.e. BPD ignition [1].

The leading role of BPI in the background plasma heating was demonstrated in our previous modelling [2]. However, initially ionized medium with a relatively high ionization level was considered, that corresponds to the late stages of the BPD development. In this paper, we attempted to investigate the development of BPD in an initially non-ionized gas via computer simulation using PIC method [3].

1. COMPUTER SIMULATION OF THE BPD

Analytic study of BPD in the real geometry is extremely complex, so computer simulation is often used, including the large particles in cell methods [3]. All the results outlined below are obtained by the original PLS package [4]. Electrostatic non-relativistic model was used. Elementary interactions (elastic collisions between electrons and neutral molecules, excitation and ionization of neutral molecules and dissociative recombination) were described using Monte Carlo method. The coefficient of dissociative recombination for helium was β_d=2.3 cm^3/s. The neutral gas was considered to be homogeneous and its density was constant in time.

2. PROPAGATION OF ELECTRON BEAM IN THE VACUUM

First the motion of electron beam in a vacuum was studied. It is well known that such motion is accompanied by the formation of the space charge. Virtual cathode appears for the beam current exceeding some critical value. It leads to the reflection of a part of the electrons back to the injector and to the limitation of the output current [5, 6].

Let us evaluate the critical current for a two-dimensional model of motion of the stripped beam in a rectangular volume bounded by conducting grounded planes (Fig. 1). Beam moves along *x*-axis, *y*=0 is the plane of symmetry.

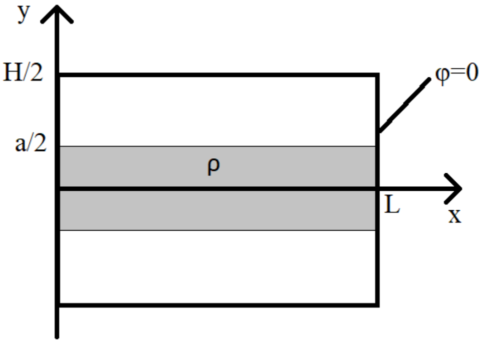


Fig 1. Geometry of the considered model

Infinite longitudinal magnetic field is considered to suppress the transversal motion of electrons.

Consider the electron beam as a uniform plane layer of charge density ρ and width a. Then the potential distribution along plane y=0 can be found from the following equations and boundary conditions:

$$\begin{cases} \dfrac{\partial \varphi}{\partial y} = 0, \\ \dfrac{\partial^2 \varphi}{\partial x^2} = -\dfrac{\rho}{\varepsilon_0}, \\ \varphi(0) = \varphi(L) = 0. \end{cases} \quad (1)$$

Taking into account that $\rho = \frac{J}{v}$, where J is the beam current density, and v is the beam electrons` velocity, from (1) one can obtain:

$$\varphi = \frac{JLa}{\varepsilon_0 v}\left(1 - \left(\frac{2x}{L} - 1\right)^2\right). \quad (2)$$

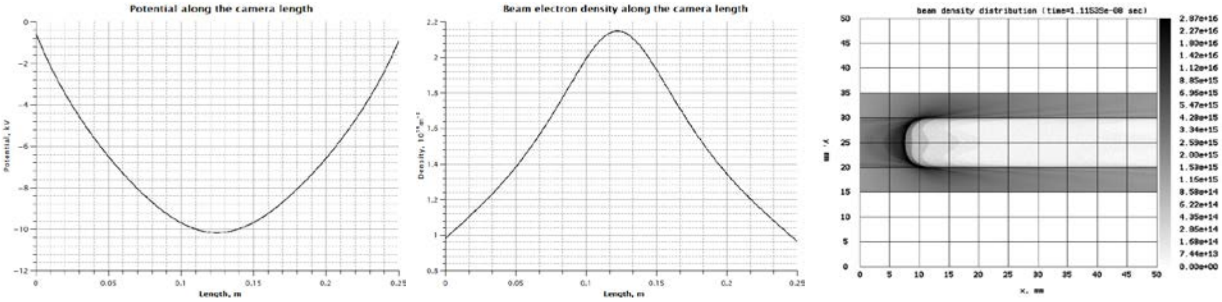
Then equality of the initial kinetic energy of the electrons $W_{kin} = \frac{mv^2}{2}$ and the maximal potential energy $W_{kin} = -e\varphi_{\max}$ and expressing the velocity via the accelerating voltage move to the formula for the critical current density:

$$Ja = \frac{\varepsilon_0}{L}\sqrt{\frac{2e}{m}}U^{\frac{3}{2}}. \quad (3)$$

Inhomogeneous spatial distribution of electrons should be taken into account for more accurate consideration.

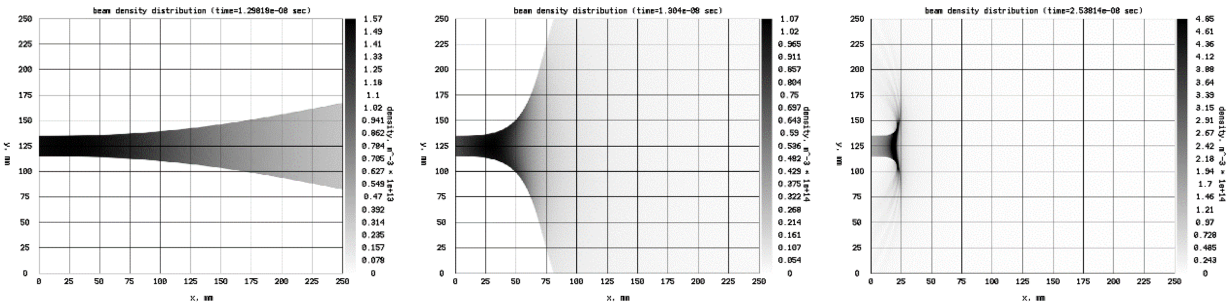
For the model shown in Fig. 1, simulation was performed, and the critical current was estimated. Fig. 2 shows the distributions of potential (a) and beam electrons density (2). The critical current obtained from the simulation was twice lower then analytical estimation. It can be explained by a doubling of the initial beam electrons` density in the centre of the beam (*x*=*L*/2). While the beam current significantly exceeds the critical value, the virtual cathode is formed near the injector. Reflection of the significant part of the electrons back to injector takes place. Reflection of electrons occurs from the vicinity of the middle beam plane, where the maximum of the potential is placed. So the cavity is formed in the beam (see Fig. 2,c).

In the absence of the longitudinal magnetic field the beam expansion due to electrostatic forces and its reflection from the space charge area take place (Fig. 3).



a *b* *c*

Fig. 2. Potential (a) and density (b) distributions along x direction at the middle plane of the beam for beam current close to critical value (U = 5 kV, J = 300 A/m^2, a = 2 cm) and beam electrons' spatial distribution (c) for current that is significantly larger than critical value (U$_a$ = 1 kV, J = 1 kA/m^2, a = 2 cm, L=H=5 cm)



a *b* *c*

Fig. 3. Spatial distributions of the beam electrons' density for the initial current density 10^{2}A/m^2 (a), 3·10^{2}A/m^2 (b) and 10^3 A/m^2 (c). Beam width a=2 cm, U$_a$ =5 kV

3. PROPAGATION OF ELECTRON BEAM IN THE GAS

The beam dynamics in the gas was studied by simulation for system with parameters listed in Table. The simulation results are shown on Figs. 4, 5.

Simulation parameters

Gas pressure	p = 0.1 Torr
Gas temperature	T = 0.025 eV
Beam width	d = 1 cm
Camera length	L = 25 cm
Camera height	H = 25 cm
Beam acceleration voltage	U = 5 kV
Beam current density	J = 10^3 A/m^2

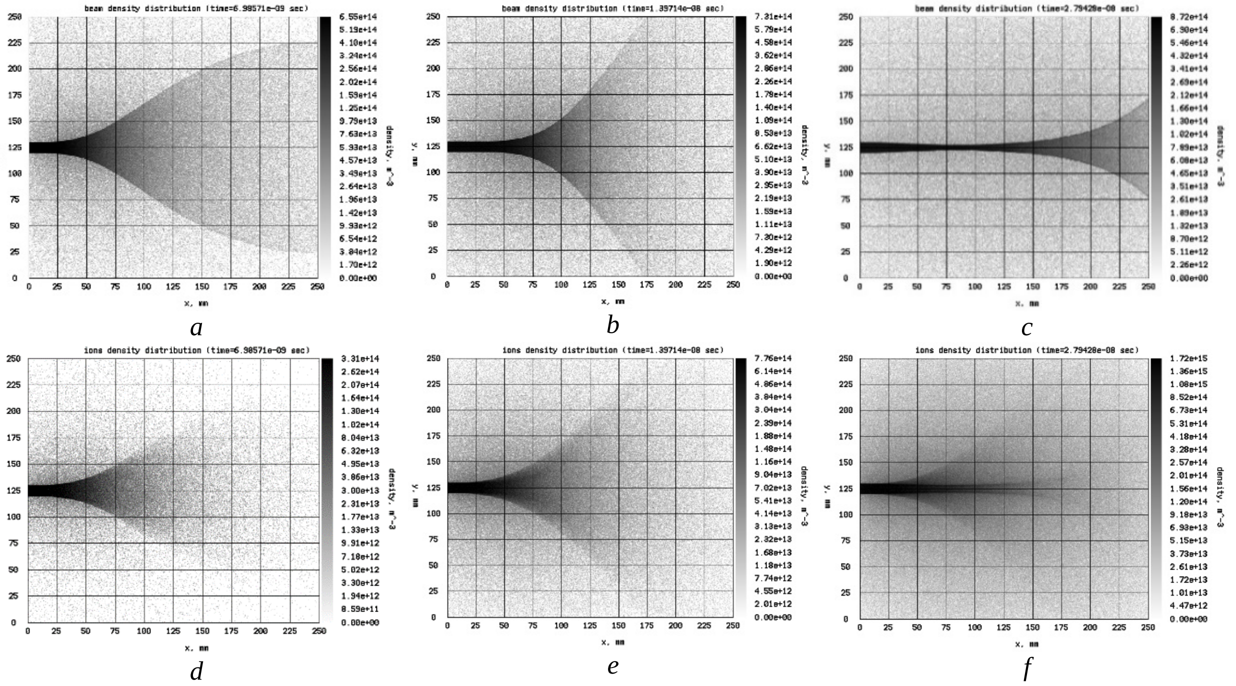
Electron beam motion in a gas is accompanied by the scattering of electrons due to the elastic collisions and gas ionization. The electrons appeared due to the ionization are accelerated (mainly in the transverse direction) by the space charge field. Its potential is of the order of the accelerating voltage for the overcritical beam current. Beam electrons collide with neutral atoms resulting to the formation of plasma with very high electrons temperature (up to 1 keV) in the camera (see Fig. 5,g).

Over time, ions appeared due to the electron impact ionization compensate the spatial charge of the beam. It leads to beam focusing (see Fig. 4). At this moment, the effective energy transfer from the beam to the plasma electrons ceases and plasma electron temperature gradually decreases Fig. 4,b,e,g. At this stage, it is often possible to observe transverse waves along the beam that violate the transverse symmetry of the system. The field of such waves is not very ample and practically doesn't heat up the background plasma.

At a later stage of the discharge, the density of plasma formed by ionization becomes sufficient for the development of an BPI.

For the development of BPI period of plasma oscillations must be substantially less than transit time of the beam electrons and the average time between electron-neutrals collisions). The development of BPI forms an effective mechanism for energy transfer from the beam to the background plasma. Consequently, the temperature of the electrons grows again (see Fig. 5,i). This effect gives rise to the increase of the ionization velocity (vicinity of the point A, Fig. 6).

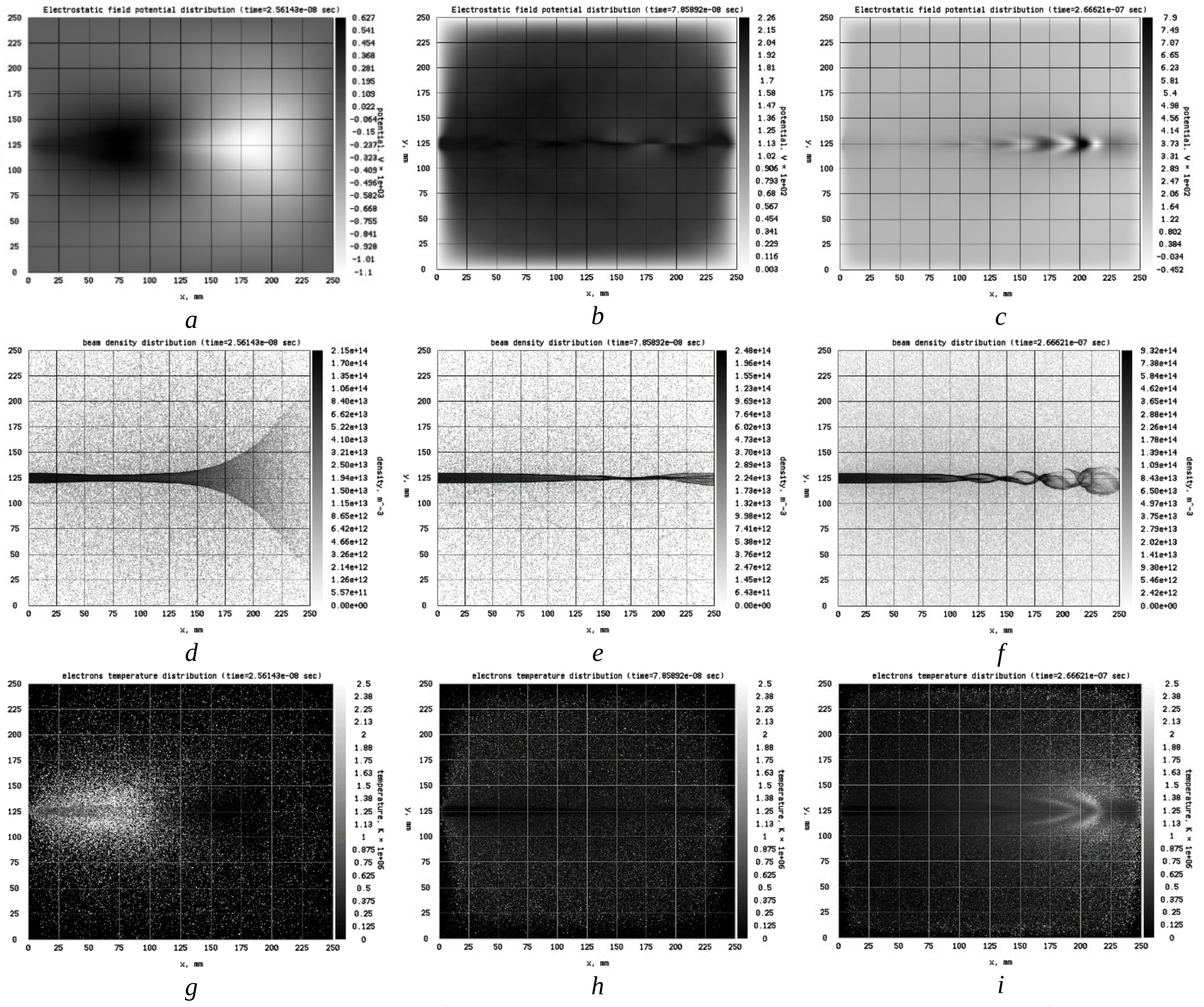
Note that temporal evolution of the electron beam behaviour in the initially neutral gas described above qualitatively agrees with the results of the laboratory experiment [8].



a *b* *c*

d *e* *f*

Fig. 4. Spatial distributions of the beam electrons' density (a, b, c) and ions' density (d, e, f) for time points t=7·10^{-10}s (a, d), t=1.4·10^{-8} s (b, e) ma t=2.8·10^{-8} s (c, f)



a *b* *c*

d *e* *f*

g *h* *i*

Fig. 5. Spatial distributions of electric potential (a, b, c), beam electrons` density (d, e, f) and electron temperature of the background plasma (g, h, i) for time points t=2.56·10^{-8} s (a, d, g), t=7.85·10^{-8} s (b, e, h) and t=2.67·10^{-7} s (a, d, g)

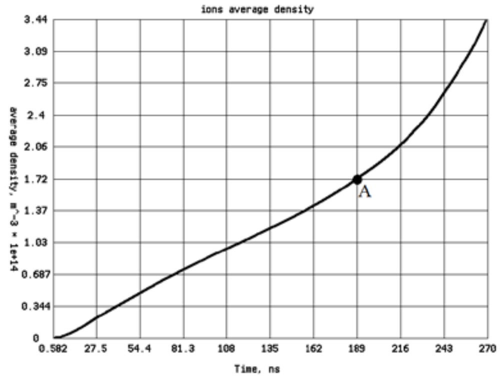


Fig. 6. Time course of the average ion density

Over time, the BPI development area shifts further from the injector to the right wall of the camera, which leads to the BPI suppression. The reason for this phenomenon is likely to be the significant plasma density gradient along the beam due to ionisation inhomogeneity. It looks as if the BPD development can be accompanied by quasiperiodic excitation and suppression of BPI.

CONCLUSIONS

Critical current for the beam motion in vacuum obtained from the simulation is in a good agreement with analytic estimation. It confirms the correctness of PLS operation.

The initial stage of the electron beam motion in a gas is accompanied by ionization of gas and beam focusing due to compensation of beam space charge by ions fild. The virtual cathode disappears and beam current that can flow in the system is much larger than the critical current in vacuum.

The ionization of the neutral gas by an electron beam leads to the gradual accumulation of plasma, that starts to interact with the beam through the BPI development.

In addition to the transverse beam density oscillations inherent to BPI longitudinal oscillations of the beam are observed. They violate the system symmetry with respect to the central plane.

The BPI development substantially enhances the transfer of energy from electron beam to plasma. Elastic electron-neutral collisions lead to significant background plasma heating and an increase of the velocity of the gas ionization. At this stage, impact ionization by an electron beam practically does not affect the overall plasma density dynamics.

Significant gradient of the plasma density along the beam affects the BPI development and can suppress the BPI.

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ЗАЖИГАНИЕ ПЛАЗМЕННО-ПУЧКОВОГО РАЗРЯДА В ИЗНАЧАЛЬНО НЕИОНИЗИРОВАННОМ ГАЗЕ

Д.И. Дадыка, И.А. Анисимов

С помощью компьютерного моделирования для двухмерной электростатической модели исследована начальная стадия плазменно-пучкового разряда. Ленточный электронный пучок инжектировался в первоначально нейтральный гелий. На первом этапе наблюдалось поперечное разбухание пучка, обусловленное его объемным зарядом. В то же время происходила ионизация гелия электронным ударом. Затем наблюдалась фокусировка пучка благодаря объемному заряду ионов. На последней стадии моделирования развивалась плазменно-пучковая неустойчивость и происходил разогрев фоновой плазмы.

ЗАПАЛЮВАННЯ ПЛАЗМОВО-ПУЧКОВОГО РОЗРЯДУ В ПОЧАТКОВО НЕІОНІЗОВАНОМУ ГАЗІ

Д.І. Дадика, І.О. Анісімов

За допомогою комп'ютерного моделювання для двовимірної електростатичної моделі досліджена початкова стадія плазмово-пучкового розряду. Стрічкоподібний електронний пучок інжектувався в первісно нейтральний гелій. На першому етапі спостерігалося поперечне розбухання пучка, зумовлене його об'ємним зарядом. В той же час відбувалася іонізація гелію електронним ударом. Потім спостерігалося фокусування пучка завдяки об'ємному заряду іонів. На останній стадії моделювання розвивалася плазмово-пучкова нестійкість і відбувався розігрів фонової плазми.