# INITIAL STAGE OF THE BEAM-PLASMA DISCHARGE IN HELIUM: SIMULATION VIA PIC METHOD

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Initial stage of the beam-plasma discharge (BPD) in Helium was studied using 1D simulation via particle-in-cell method. Several regimes were observed and described depend on ranges of beam current density and gas pressure: absence of BPD ignition, BDP ignition with the small degree of additional ionization, and "regular" BPD mode with the significant heating of the background plasma electrons by the beam-plasma instability HF field.

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## INTRODUCTION

The recent interest to the beam-plasma discharge (BPD) is caused by its possible practical applications. BPD as well as other types of discharges can be a source of non-equilibrium plasma. Its electron temperature can reach ~10 eV [1], so BPD can be used for carrying out plasma-chemical reactions with the energy threshold [2, 3]. Deposition technologies, including chemical vapor deposition (CVD) and plasma enhanced CVD (PECVD) also can be based on BPD. In these cases plasma ions are accelerated by the external potential and bombard the substrate.

For technological purposes it is necessary to manage plasma parameters easy. BPD plasma parameters can be varied by changing electron beam current or accelerating voltage. At low current densities of the beam BPD is not realized, only electron beam focusing by ions takes place [4]. At high pressures BPD is not realized too, because the beam electrons can't get the necessary energy at the mean free path. Ignition of the BPD is connected with the development of beam-plasma instability (BPI).

Although BPD was discovered 50 years ago and many works related to it were carried out, most of them are experimental [5-10]. The first attempts to describe BPD theoretically were made by Ya. B. Fainberg et al. [11-12]. In [11] only temporal dynamics of the plasma density and electron temperature were calculated. The spatial dynamics of the system was not studied.

The analytical BPD theory [1] describes its development only in general terms. BPI and ionization of the background plasma by the excited HF field are not considered self-consistently. However, the plasma density variation in time and space, the dependence of cross sections on interaction energy cannot describe BPD analytically. Full description can be done only using computer simulation [13-16].

The main goal of this work was simulation of the BPD initial stage in helium for various current densities of the electron beam and wide range of gas pressures. The objectives were to analyze the ionization degree of neutral gas in the later stages of simulation and to investigate the conditions when intense electric field is excited in the system and how this field affects the process of neutral gas ionization.

## 1. SIMULATION MODEL AND PARAMETERS

BPD ignition is caused by the electron beam injection into neutral or partially ionized gas. In the first case plasma initially appears due to ionization of neutral gas by electron beam impact. Usually the electron beam is weak and the beam electron density is much less than the initial background plasma density.

One-dimensional package PDP1 [17] was used for simulation of the BPD initial stage. Electron beam was injected into the interelectrode space filled by the partially ionized plasma. Three kinds of particles (beam electrons, plasma electrons and ions) were taken into account. Neutral gas was considered as background. Several elementary processes (elastic electron-neutral collisions, neutrals' excitation and ionization by electron impact) were taken into account in the package. Interaction of electrons with neutral gas was considered only for plasma electrons. Thus the electron beam interaction with plasma took place only due to excitation of HF electric field.

Initially the gas was partially ionized with degree $3\cdot10^{-4}\ldots3\cdot10^{-7}$. Main simulation parameters were taken close to experimental values [4] and are given in Table.

*Table Simulation parameters*

| | |
|---|---|
| Gas type | Helium |
| Gas pressure | $p=10^{-3}$; $10^{-2}$; 0.1 Torr |
| Gas temperature | T=0.025 eV |
| Interelectrode length | L=1 m |
| Initial plasma density | $n_{e0}=10^{10}$ cm$^{-3}$ |
| Plasma electron temperature | $T_{e0}=1$ eV |
| Debye length | $r_D=0{,}01$ cm |
| Langmuir oscillations period | $T_{pe}=1\cdot10^{-9}$ s |
| Beam acceleration voltage | $U_a=5000$ V |
| Beam density | $n_b=1.5\cdot10^7$; $3.0\cdot10^7$; $7.5\cdot10^7$; $1.5\cdot10^8$; $3\cdot10^8$ cm$^{-3}$ |
| Beam current density | $j_b=100$; 200; 500; 1000; 2000 A/m$^2$ |
| Beam electron's transit time | $2.4\cdot10^{-8}$ s |
| Number of cells | $2\cdot10^4$ |
| Simulation time step | $1\cdot10^{-12}$ s |
| Simulation time | $(0.8\ldots1.0)\cdot10^{-7}$ s |

## 2. SIMULATION RESULTS

The spatial-temporal dynamics of the main system characteristics is presented on Fig. 1. The current and pressure correspond to the boundary between regimes of the moderate and strong ionization.

According to the results of simulation there are three typical modes of the beam interaction with weakly ionized plasma.

At low pressures BPI is developed, beam is modulated by excited BPI HF field. However, additional gas ionization is not observed as the mean free path of electrons in a neutral gas are comparable to the system length.

At higher pressures mean free path decreases, and as a result, BPD ignites. However, the increase of the degree of the gas ionization does not exceed its initial value.

At high current densities and higher pressures the gas ionization is significant. Plasma density can exceed an order of the initial background value. In this mode ionization of the background plasma first starts closer to the left electrode. But variation of the background plasma density leads to moving of BPI from this area. Consequently, the area of intense electric field and intense gas ionization moves away from the injector. Therefore, the final distribution of plasma density can be non-monotonous.

Simulation interval is four times larger than the electron beam flight time between electrodes and equal to 100 electron plasma periods.

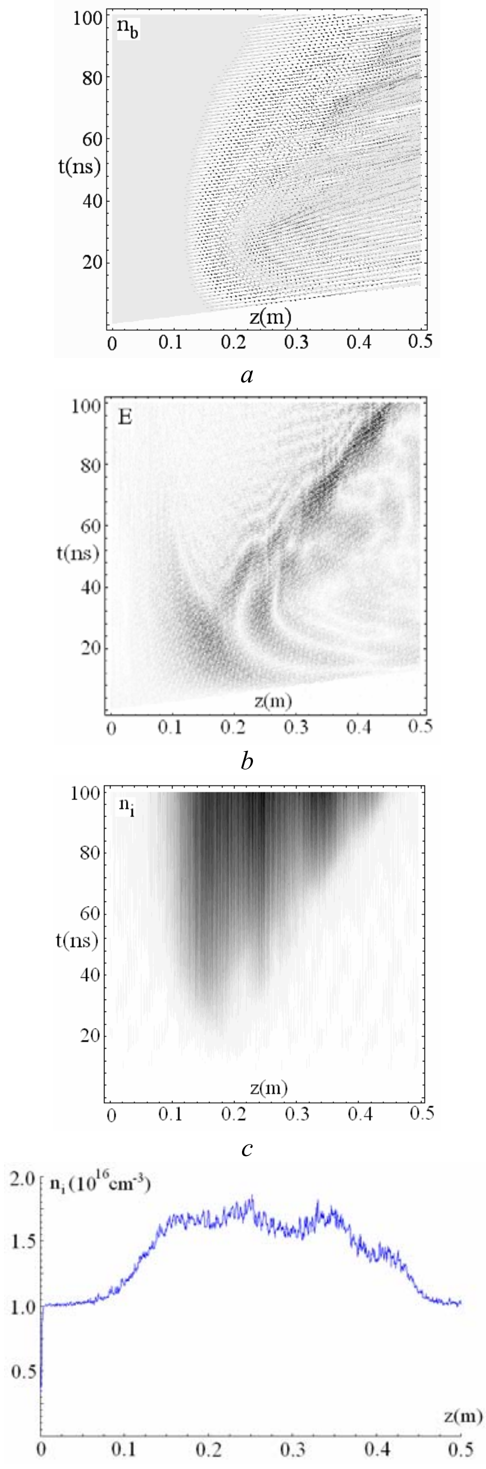
The electron beam density distribution is shown on Fig. 1,a. Dark areas correspond to the electron bunches; their slope is determined by the beam velocity. Electron beam in the left part of space is homogeneous and monokinetic. The beam homogeneity breaks down as a result of BPI development in the right half space. Beam is modulated by density, so bunches are formed. However, they decay later due to the electrons' mixing.

The HF electric field is excited in the same area (Fig. 1,b). Average electron beam density is correlated with the distribution of electric field due to bunches' interaction with potential wave. The most intensive electric field occurs near the middle of the system closer to the right electrode. This field assists plasma heating and gas ionization. However, plasma density increases due to ionization, so Cherenkov resonance condition breaks. It leads to the gradual shift of the region of maximum electric field and ionization to the right half space (see Fig. 1,b).

One can see few maxima at the final plasma density distribution (Fig. 1,d). From Fig. 1,a it's clear that the first maximum is formed earlier (approximately at t=25 ns). It can be associated with the first splash of the electric field in Fig. 1,b, which is observed at t=10…30 ns. Next maxima formation occurs in the area where the field periodically reaches its maximum, starting from t=40 ns.

The program does not take into account the plasma diffusion in the transverse direction and its recombination. So the plasma density at each point in space only increases in time.

In further research it would be interesting to consider the collisions of beam electrons with neutral atoms and recombination processes in the background plasma, as well as to explore the possibility of stationary mode. It would also be interesting to consider 2D and 3D system geometry.



*a*

*b*

*c*

*d*

*Fig. 1. Space-time dependence of the beam electron density (a), electric field (b), plasma ion density (c) and spatial distribution of plasma ion density (d) at time moment $t = 1.1 \cdot 10^{-7}$c (d). Beam current density $j=200\ A/m^2$, neutral gas pressure p=0.1 Torr*

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## НАЧАЛЬНАЯ СТАДИЯ ПЛАЗМЕННО-ПУЧКОВОГО РАЗРЯДА В ГЕЛИИ: МОДЕЛИРОВАНИЕ МЕТОДОМ КРУПНЫХ ЧАСТИЦ

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Исследована начальная стадия развития плазменно-пучкового разряда (ППР) в гелии с помощью одномерного компьютерного моделирования методом крупных частиц. В зависимости от плотности тока пучка и давления газа в системе наблюдалось три характерных режима: отсутствие зажигания ППР; зажигание ППР с малой дополнительной ионизацией; "регулярный" режим ППР, сопровождающийся заметным нагревом электронов фоновой плазмы высокочастотным электрическим полем плазменно-пучковой неустойчивости.

## ПОЧАТКОВА СТАДІЯ ПЛАЗМОВО-ПУЧКОВОГО РОЗРЯДУ В ГЕЛІЇ: МОДЕЛЮВАННЯ МЕТОДОМ МАКРОЧАСТИНОК

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Досліджено початкову стадію розвитку плазмово-пучкового розряду (ППР) у гелії шляхом одновимірного комп'ютерного моделювання методом макрочастинок. Залежно від густини струму пучка та тиску газу в системі виявлено три характерних режими: відсутність запалювання ППР; запалювання ППР з малою додатковою іонізацією; "регулярний" режим ППР, що супроводжується помітним розігрівом електронів фонової плазми високочастотним електричним полем плазмово-пучкової нестійкості.