LOW PRESSURE GAS DISCHARGE IN MAGNETICALLY INSULATED DIODE

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The characteristics of the low pressure discharge in crossed electric and magnetic fields is described in this work for the case of magnetically insulated diode and electron anode layer with free cathode boundary. The theory is compared with experimental characteristics of Hall-type ion source “Radical” such as breakdown curves, current-voltage characteristics, dependences of discharge current on magnetic field and pressure. As a result of the carried out analysis, the mechanism of the discharge evolution dependence on boundary conditions is proposed. The mechanism of discharge initiation based on combined ionization of gas by electron avalanches and high energy γ-electrons is considered as well.

PACS: 52.80.-s

INTRODUCTION

In last decades, the considerable interest to experimental and theoretical research of accelerators with the closed drift of electrons in crossed EH fields is observed [1]. It is caused by the wide application of such type ion sources in the role of charged particle accelerators, space thrusters and in ion plasma technologies [2]. At the same time, despite the extensive researches, numerical and analytical models of such systems which could allow carrying out engineering calculations are not developed up to now.

The present study continues the investigation of this discharge started in previous papers [3, 4]. The aim of this paper consists in the comparative analysis of the analytical model with experimental data for current-voltage characteristics, discharge current dependences on magnetic fields strength and pressure, as well as identification of the discharge mechanism.

Two cases of the discharge with different boundary condition are considered (Fig. 1a,b):

a) the electron anode layer with free cathode boundary;

b) the cathode boundary is fixed by the conductive grid with transparency of 50% (the case of magnetically insulated diode).

In the both cases in this discharge, two groups of electrons take part in working gas ionization: primary high energy electrons emitted from the cathode and secondary electrons, produced in anode layer. So the variation of boundary condition changei the balance of electrons in anode layer and the mechanism of discharge.

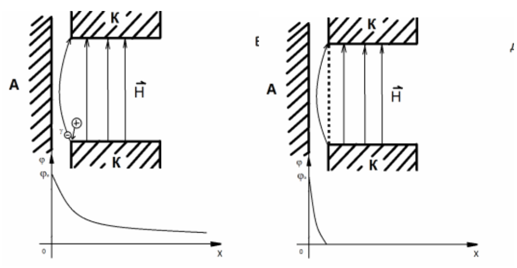

Fig. 1. Schematic model of “Radical” ion source discharge gap

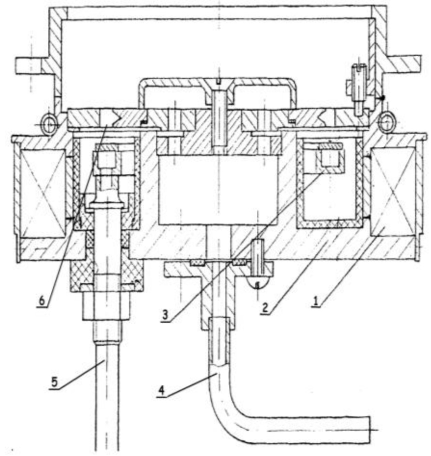

Fig. 2. Schematic layout of “Radical” ion source: 1 – solenoid; 2 – cathode; 3 – anode; 4 – gas inlet; 5 – cooling water inlet for anode ; 6 – anode layer of electrons

1. EXPERIMENTAL SETUP

The research is carried out on experimental installation with the ion source "Radical". The source is a kind of gas discharge in crossed **E** and **H** fields with the cold cathode. In such sources the closed drift of electrons in the space anode-cathode is realized. The ionization of working gas is provided by high-energy electrons which are kept in specially arranged electromagnetic trap. The design of the ion source is presented on Fig. 2.

The electron trapping in the space anode-cathode (with the length of 4 mm) is provided by potential "well" and lens-shaped configuration of magnetic field. Ions, unlike the electrons, are practically not influenced by magnetic field and are accelerated in electric field. Therefore, the tubular ion beam with an initial diameter of about 100 mm is formed.

2. EXPERIMENTAL RESULTS

The ignition curves and current-voltage characteristics are measured under different discharge boundary conditions. On Fig. 3 the ignition curves with free and fixed discharge boundary are presented. As it follows from the figure, qualitative difference of breakdown character is observed. One can see that the discharge switch-off at high anode voltage appears in magnetically insulated diode.

The current-voltage characteristics of the ion source with different boundary conditions for various magnetic fields strengths are presented on Figs. 4, 5. The comparative analysis of the characteristics shows, that up to anode voltage of 2 kV the discharge current has linear character in the both cases. However, above the 2.5 kV the discharge switches off in the case of the grid application in the ion source.

On Figs. 6, 7 the dependences of the anode current

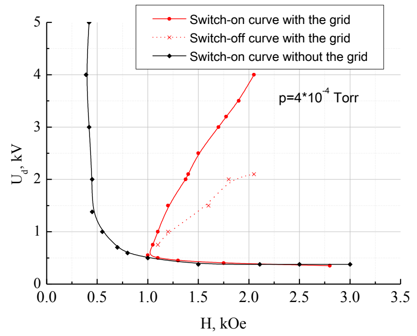

Fig. 3. The ignition curves of the discharge under different boundary conditions

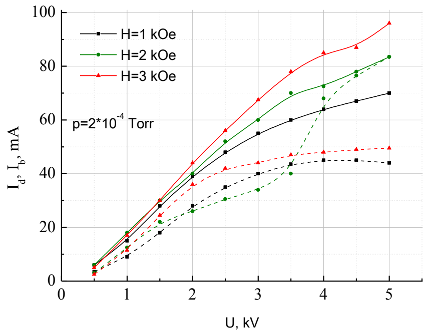

Fig. 4. The current-voltage characteristics of the ion source without the grid for different magnetic field strength, $P=2{\cdot}10^{-4}$ Torr

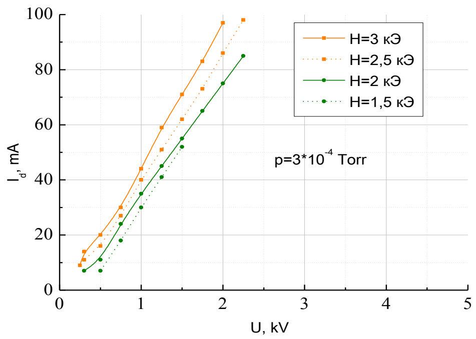

Fig. 5. The current-voltage characteristics of the ion source with the grid for different magnetic field strength, $P=2{\cdot}10^{-4}$ Torr

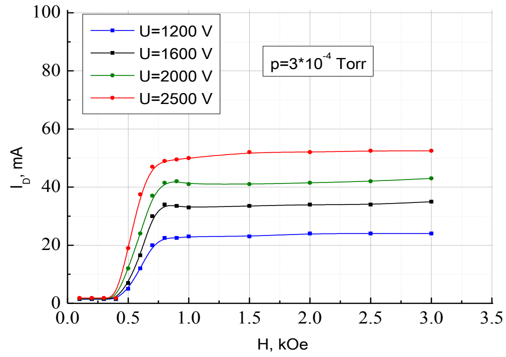

Fig. 6. The anode current versus the magnetic field strength in the ion source without the grid, $P=3{\cdot}10^{-4}$ Torr

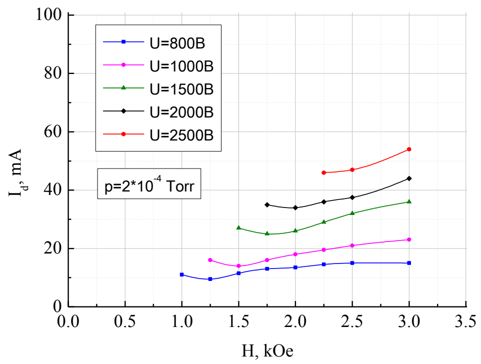

Fig. 7. The anode current versus the magnetic field strength in the ion source with the grid. $P=3{\cdot}10^{-4}$ Torr

on the magnetic field strength in ion source with different boundary conditions are presented.

One can see from the figures that qualitative difference of dependences also takes place. The initial part of characteristics at magnetic field strength H = (0.5…1) kOe demonstrates continuous growth in the ion source without the grid. On the contrary, the abrupt switch-on of the discharge takes place in magnetically insulated diode.

3. THEORETICAL MODEL

In the papers [3, 4], the 1D fluid model of anode electron layer, based on electron current and power balance in a discharge is presented. The theoretical model considers ionization in the electromagnetic trap by two groups of electrons: the primary high-energy γ -electrons emitted from the cathode as a result of ion bombardment, and the secondary plasma electrons which appear in the volume of the sheath. The solutions of the balance equitation in the parametric form for dimensionless current, coordinate and potential are:

$$j' = E' + (N-1),$$

$$X = E' - 1 - (N-1)\cdot \ln\left|\frac{E' + (N-1)}{N}\right|,$$

$$U` = U`_0 + \frac{1}{2}\left[E'^2 - 1\right] - (N-1)\cdot X\ ,$$

where the dimensionless variables are as follows:

$$E' = \frac{E}{E_0},\ j' = \frac{j}{-\nu_i E_0 / 4\pi e},\ X = \frac{x}{-b_\perp E_0 / \nu_i},\ U` = \frac{\varphi}{b_\perp E_0^2 / \nu_i}.$$

The boundary conditions for the development of electron avalanches are:

$$x = 0,\ \mathrm{E} = \mathrm{E}_0,\ j = j_b,\ \varphi = \varphi_0,\ E_0 = \sqrt{\frac{\varepsilon_i \nu_i}{e b_\perp}}.$$

The parameter $N = j_b / j_0$ corresponds to the dimensionless current at the electron avalanches boundary ($j_0 = \nu_i E_0 / 4\pi e$ is normalized current).

The dimensionless current-voltage characteristics and current-coordinate dependences for different values of N are presented on the Figs. 8, 9.

It should be mentioned, that normalized current j_0 and coordinate X are proportional to magnetic field strength H. Dotted lines on Figs. 8, 9 correspond to the modes with fixed anode layer thickness for different value of H.

The comparison of experimental and calculated characteristics for ion source with the grid (mode of magnetically insulated diode) is presented on the Figs. 10, 11.

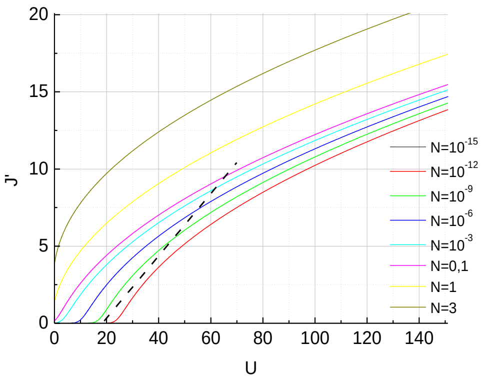

Fig. 8. The dimensionless current-voltage characteristics of the ion source for different values of the parameter N

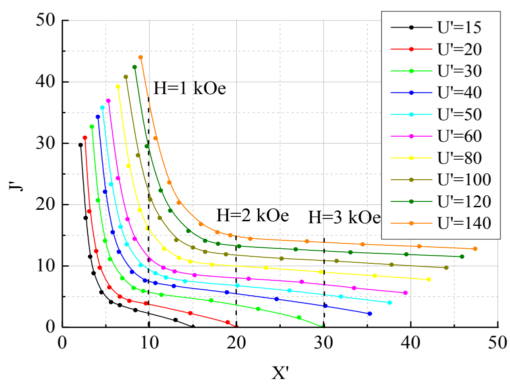

Fig. 9. The dimensionless current-coordinate dependences in the anode layer for different values of the dimensionless potential U`

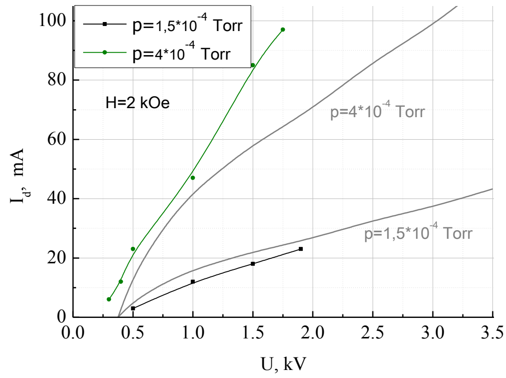

Fig. 10. The experimental and calculated current-voltage characteristics of the ion source with the grid for various pressures of working gas

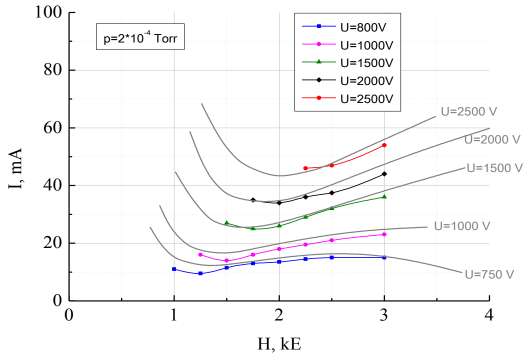

Fig. 11. The experimental and calculated current-magnetic field strength characteristics of the ion source with the grid for various anode voltages

CONCLUSIONS

In the present paper, the basic characteristics of the discharge in crossed EH fields with free and fixed cathode boundary (ignition curves, current-voltage characteristics, current-magnetic field strength dependences) are studied. The following results are obtained.

- Breakdowns on the bottom branch of the ignition curves for the discharge with free and fixed cathode boundary are equivalent ones. So the initial stages of the discharge current-voltage characteristics for both cases are identical and correspond to the mode with «oscillating» electrons [4].
- The presented theoretical model, based on the current and energy balance of electrons, demonstrates a good agreement with experimental results.
- Stationary states of the discharges at $U < 2.5$ kV correspond to the mode with constant anode layer thickness and different value of initial electron current $0 < N < \gamma$ at the cathode boundary.
- For the case of free cathode boundary case (part of the current-voltage characteristics at $U > 2.5$ kV, $H < 1$ kOe) the anode layer thickness changes according to the mode with constant $N \approx \gamma$.

The obtained results are of interest for the further development of the theory of discharge in crossed **E×H** fields and for magnetron sputtering systems.

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Article received 23.12.2014

МЕХАНИЗМ РАЗРЯДА НИЗКОГО ДАВЛЕНИЯ В МАГНИТОИЗОЛИРОВАННОМ ДИОДЕ

А. Джамирзоев, С. Яковин, А. Зыков

Исследованы характеристики разряда низкого давления в скрещенных ExH-полях со свободной и фиксированной катодной границей (случай магнитоизолированного диода). Получены новые экспериментальные данные для вольт-амперных характеристик и зависимости разрядного тока от давления и напряженности магнитного поля. Показано, что стартовые участки вольт-амперных характеристик для обоих случаев идентичны и соответствуют режиму с «осциллирующими» электронами. Также представлена теоретическая модель, основанная на уравнениях баланса токов и энергии электронов, и проведено сравнение с экспериментом. Полученные результаты представляют интерес для дальнейшего развития магнетронных распылительных систем и плазменных ускорителей с замкнутым дрейфом электронов.

МЕХАНІЗМ РОЗРЯДУ НИЗЬКОГО ТИСКУ В МАГНІТОІЗОЛЬОВАНОМУ ДІОДІ

А. Джамірзоєв, С. Яковін, О. Зиков

Досліджено характеристики розряду в схрещених ExH-полях з вільною та фіксованою границею (режим магнітоізольованого діода). Здобуто нові експериментальні дані для вольт-амперних характеристик та проаналізовано їхні залежності від тиску та напруженості магнітного поля. Показано, що стартові ділянки вольт-амперних характеристик в обох випадках є ідентичними та відповідають режиму з «осцилюючими» електронами. Також представлено теоретичну модель, яка базується на струмовому та енергетичному балансі електронів, а також проведено порівняння з експериментом. Здобуті дані є корисними для подальшого розвитку магнетронних розпилювальних систем та плазмових прискорювачів із замкнутим дрейфом електронів.