INVESTIGATION OF GAS DISCHARGE BURN CONDITIONS IN A PENNING GEOMETRY IN GRADIENT MAGNETIC FIELDS

A.N. Ozerov, Yu.V. Kovtun, E.I. Skibenko, V.B. Yuferov

National Science Center "Kharkov Institute of Physics and Technology", Kharkov, Ukraine

E-mail: ozerov@kipt.kharkov.ua; Ykovtun@kipt.kharkov.ua

Conditions of gas discharge burn in a Penning geometry the gradient magnetic field have been investigated. The values of the ignition voltage and volt-ampere characteristics of the gas discharge depending on the working gas pressure without and with a magnetic field are measured experimentally. The integral optic plasma radiation discharge value dependences on the working gas pressure are obtained. The values of the power released in the discharge cell and of the gas discharge plasma conductivity are determined.

PACS: 52.80.-s; 52.80.Sm

INTRODUCTION

The gas discharge plasma formed in the Penning cell is used in many technical devices which are widely used for solving both physical and applied problems, for example, in the charged particle sources [1, 2], ion pumps and vacuum gauges [3, 4] etc. The Penning discharge (reflex discharge) has several modes depending on the pressure and magnetic field values [5]. In the case of low gas pressure ($p \leq 1.33 \cdot 10^{-2}$ Pa) in the interelectrode space a negative volume discharge is predominant. Under higher gas pressures ($p > 1.33 \cdot 10^{-2}$ Pa) the whole interelectrode space is filled with plasma. The reflex discharge under pressures above $p > 1.33 \cdot 10^{-2}$ Pa is often used as a base for formation of plasma sources. In investigations of the reflex discharge and for the development of the reflex-discharge based devices one uses mainly uniform magnetic fields [6]. Not many articles are aimed to the study of the reflex discharge. Therefore, for the purpose of obtaining additional information about the magnetic field gradient influence on the discharge burn conditions, widening the ranges of reflex discharge parameter variation and its application region it is interesting to arrange and carry out experimental investigations of the reflex discharge in gradient magnetic fields.

1. EXPERIMENTAL SETUP

Investigation of the gradient magnetic fields was carried out using an experimental facility which is schematically represented in Fig. 1,a. A vacuum chamber is made as a stainless-steel hollow cylinder (volume $13.86 \cdot 10^3$ cm^3, length 648 mm, internal diameter 185 mm). In the central part of the chamber on the periphery of circle installed are pipes for: vacuum pumping, working gas puffing, entry of devices for plasma diagnostics. The mirror magnetic field (mirror ratio ~3.17) was formed with the use of two solenoids (see Fig. 1,a). Magnetic field distribution along the facility axis is shown in Fig. 1,b. In more detail the experimental facility is described in [7].

Geometry of the discharge gap is a system of electrodes of a hollow cylinder-plane type. The first electrode is assembled of two electrically-coupled stainless-steel cylinders having 95 mm in internal diameter. The second electrode is made in the form of a copper disc having 80-mm in diameter. Two modes of discharge burning with a different polarity of electrode system powering were investigated. Depending on the electrode polarity either the Penning discharge or the hollow-cathode discharge was burned. Experiments were carried out under the following initial conditions: working gas-air at pressure 1…250 Pa, magnetic field induction value B ≤ 0.023 T, discharge voltage to 610 V. The discharge voltage and current were measured with digital voltmeter and ammeter. The radiant flux from the discharge plasma in the wavelength range λ = 180…100 nm was recorded using a photochronograph made on the basis of a photodiode FDUK-13Y. Discharge gap glow was recorded using a digital camera.

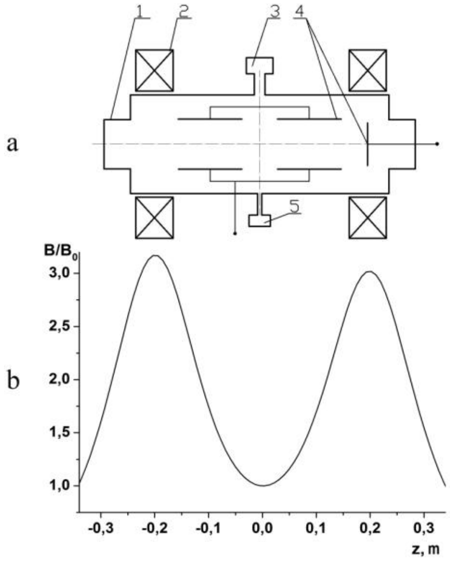

Fig. 1. Facility for plasma formation in the high-gradient magnetic field: a – schematic representation; b – magnetic field distribution along the axial axis. 1 – vacuum chamber; 2 – solenoids; 3 – vacuum system; 4 – system of electrodes; 5 – working gas puffing system

2. EXPERIMENTAL RESULTS AND DISCUSSION

The Penning discharge [3, 6] and the hollow-cathode discharge [8-10] are most often self-maintained gas discharges with cold cathodes. The electrical breakdown and self-maintained discharge ignition in the low-pressure gases occurs as a result of the Townsed breakdown having a character of an electron avalanche multiplication [11, 12]. Curves of discharge ignition in the constant uniform field are described either by the Paschen law [11, 12] or by the modified Paschen law [13, 14]. A feature of the Penning discharge and hollow-cathode discharge is the electric field nonuniformity in the discharge gap. In the case of magnetic field superposition in parallel to the discharge gap axis, the breakdown and ignition of these discharges take place in the crossed $E \times B$ fields. Now a theoretical consideration of these discharges becomes much more complicated. Therefore often it is necessary to carry out the experimental investigations and measurements.

For the Penning discharge the discharge gap breakdown voltage as a function of the pressure without a magnetic field and in the magnetic field is shown Fig. 2.

In the case without a magnetic field the U_{min} value in the minimum corresponds to the Stoletov point where the ionization power of the electron is maximal and the multiplication conditions are optimal.

In the region of high P (in the right wing of the Paschen curve) the threshold value of U_{min} increases almost proportionally to P. Such a behavior of the breakdown voltage is explained by the fact that in the case of increased pressures or long gaps the electron has a possibility for making many ionizing collisions on the path length.

In the region of low P (in the left wing of the Paschen curve) the probability of collisions is insignificant. To reach a sufficient multiplication a very strong field is required. Therefore, the voltage breakdown quickly increases with P decreasing. Because of the effective ionization cross-section limitation the ionization coefficient is limited too.

Analysis of the discharge breakdown gap dependence in the gradient magnetic field has shown the following peculiarities:

– the Stoletov point displaces down and to the left, i.e. the breakdown arises under lower pressures (P = 8 Pa) and low voltages (U_{min} = 308 V). For comparison, in the absence of magnetic field U_{min} = 334 V and P = 16 Pa;

– the left wing of the Paschen curve wing displaces towards lower pressure, thus the breakdown voltage goes down under equal pressure. It is because the magnetic field bends the electron path to the anode which becomes longer. Consequently, the probability of the electron collision with a neutral atom or gas molecule increases. , that leads to the ionization;

– the right wing of the Paschen curve, in the case with a magnetic field, goes up that evidences on the breakdown voltage increase under the same gas pressure. The increase of the breakdown voltage can be explained by the fact that in the region of high pressures, because of the curved path of electron motion, the probability of electron-neutral atom collision increases. However, in this case the electron gains a less energy than in the case without a magnetic field. Therefore, it is necessary to increase the electric field strength for the ionization process can be realized.

In Fig. 3 for the Penning discharge a family of volt-ampere characteristics (VAC) as a function of gas pressure with and without a magnetic field is shown.

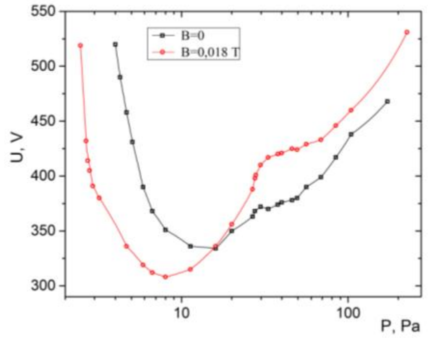

Fig. 2. Breakdown voltage as a function of gas pressure with and without a magnetic field for the Pinning discharge

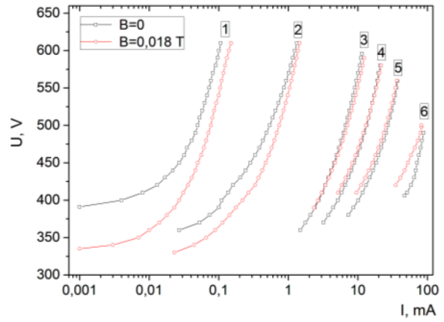

Fig. 3. VAC of the Penning discharge under different gas pressures in the discharge gap with and without a magnetic field: 1 – 6 Pa; 2 – 11 Pa; 3 – 28 Pa; 4 – 39 Pa; 5 – 65 Pa; 6 – 172 Pa

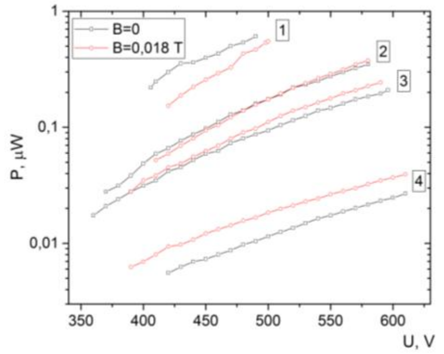

Fig. 4. Optic plasma radiation flux as a function of applied interelectrode voltage under different gas pressures (Penning discharge): 1 – 172 Pa; 2 – 39 Pa; 3 – 28 Pa; 4 – 11 Pa

The discharge currents are increasing with gas pressure increase, as well as, with electrode voltage increase. The intensity of the optic plasma radiation flux increases too, as is seen from Fig. 4.

At low pressures (6…11 Pa) and equal voltage on the discharge gap the current is higher in the case of the discharge in the magnetic field than without a magnetic field. As the gas pressure increases to 28…39 Pa the discharge currents in VAC become closer to each other in the both cases. Further increase of the gas pressure to ≥ 39 Pa leads to the situation that the discharge current is higher without a magnetic field than in the case with a magnetic field.

A maximum absorbed power in the Penning discharge, in the pressure range being studied, was

43 W under pressure of 172 Pa without a magnetic field and 92 Pa in the magnetic field. A maximum conductivity of the gas-discharge plasma-filled gap was 181 μS and 164 μS respectively. A minimum adsorbed power observed under low pressures was not higher than ~ 1 W.

In Fig. 5 the curves for the breakdown voltage as a function of the pressure in the hollow-cathode discharge are shown. In the case with a magnetic field the Stoletov point goes up and to the left, i.e. the breakdown is observed under lower pressures (P =5 Pa) and high voltages (U_{min} = 337 V). For comparison, in the absence of magnetic field the break parameters are: U_{min} = 325 V and P = 7 Pa. Under low pressures (left wing) the breakdown voltages have similar values and the same character of the change versus pressure as for the first case in the Penning discharge. In the first wing the magnetic field has no appreciable influence on the breakdown voltages unlike the first case where this influence is evident.

The volt-ampere characteristics as a function of gas pressure with and without a magnetic field in the hollow-cathode discharge are presented in Fig. 6.

In the case of magnetic field absence the gas pressure decrease leads to the discharge voltage increase under equal discharge current and to the sharp increase of the positive derivative of the discharge current. In the case with a magnetic field quite the contrary the gas pressure decrease leads to the discharge voltage decrease, the positive derivative of the current being changing insignificantly. A maximum adsorbed power in the hollow-cathode discharge in the case of magnetic field absence was obtained under pressure of 172 Pa and was equal to 65 W, and a maximum conductivity of the gas-discharge plasma filled gap in this case was 446 μS.

With a magnetic field a maximum adsorbed power was 72 W under gas pressure of 65 Pa. A maximum conductivity of the gas-discharge plasma filled gap was 510 μS under pressure of 40 Pa. A minimum adsorbed power was observed under low pressures and did not exceed ~ 10 W.

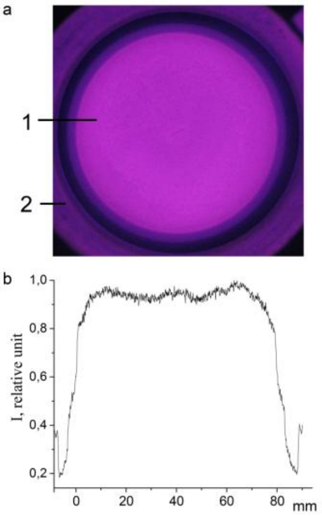

Fig. 7. Penning discharge (P=126 Pa, U=400 V, I=21.9 mA). a – photo: 1 – cathode; 2 – anode; b – plasma glow intensity

In Fig. 7,a and 8,a presented are the photos of the Penning discharge and hollow-cathode discharge, and in

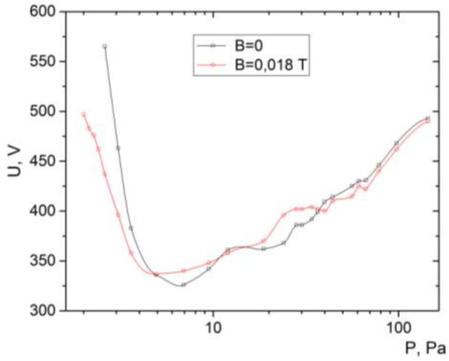

Fig. 5. Breakdown voltage as a function of gas pressure with and without a magnetic field for the hollow-cathode discharge

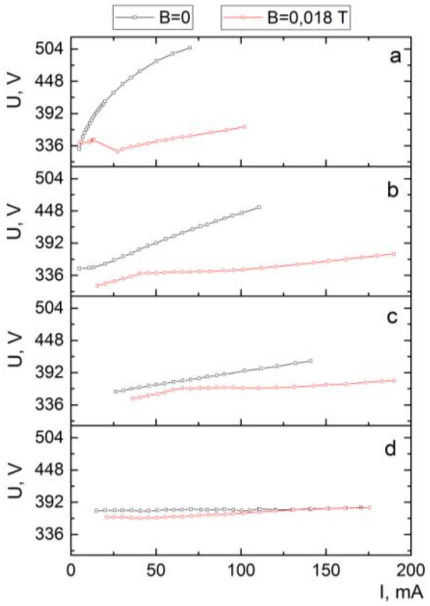

Fig. 6. VAC of the hollow-cathode discharge under different gas pressures in the discharge gap with and without a magnetic field: a – 12 Pa; b – 40 Pa; c – 65 Pa; d – 172 Pa

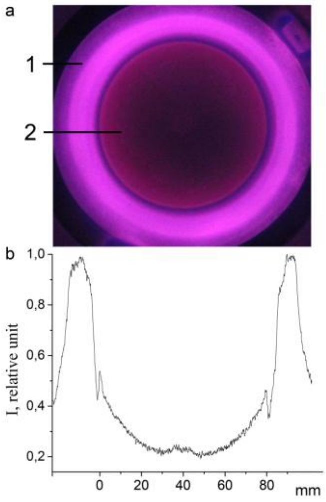

Fig. 8. Hollow-cathode discharge (P=126 Pa, U=375 V, I=79.3 mA). a – photo: 1 – cathode; 2 – anode; b – plasma glow intensity

Figs. 7,b and 8,b – the plasma glow intensity of these discharges. In the first case a plasma cylindrical columnwith a base near the disk cathode is formed, in the second case an annular plasma glow is observed near the hollow cylindrical cathode along its full length.

CONCLUSIONS

The investigation has been carried with two burning modes in the gradient magnetic fields: Penning discharge and hollow-cathode discharge. The following problems were under study:

– for the both modes the dependences of the breakdown voltage under different gas pressures with and without a magnetic field were obtained. For the both cases the values of U_{min} in the minimum (i.e. in the Stoletov point) were determined;

– the volt-ampere characteristics, obtained under different gas pressures, which essentially differ from one another depending on the gas burning mode and magnetic field strength, were measured;

– the values of the power released in the discharge cell and the values of the gas-discharge plasma conductivity were estimated. Depending on the discharge mode and on the presence or absence of a magnetic field the above-mentioned parameters have recorded deviations from the average values;

– the photorecording of the plasma under different conditions has been carried out and the plasma glow intensity was determined.

REFERENCES

1. I.G. Brown. *The Physics and Technology of Ion Sources*. WILEY-VCH Verlag. 2004.
2. A.A. Bizyukov, Vl.V. Bobkov, A.Y. Kashaba, K.N. Sereda. Improvement of Penning ion sources // *Problems of Atomic Science and Technology. Series “Plasma Physics”*. 2000, № 3(5), p. 153-155.
3. F.M. Penning. Ein neues manometer für niedrige gasdrucke, insbesondere zwischen 10^{-3} und 10^{-5} mm // *Physica*. 1937, v. 4, p. 71-75 (in Russian).
4. N. Yoshimura. *Vacuum Technology*. Verlag: "Springer", 2008.
5. W. Schuurman. Investigation of a low pressure penning discharge // *Physica*. 1967, v. 36, p. 136-160 (in Russian).
6. E.I. Toader, W.G. Graham, C.M.O. Mahony, P.G. Steen. Characterization of a high-density, direct-current reflex discharge plasma source operating in Ar and N_2 // *Rev. Sci. Instrum*. 2002, v. 73, p. 2974-2980.
7. Yu.V. Kovtun, A.N. Ozerov, E.I. Skibenko, V.B. Yuferov. Electrophysical installations with high-gradient magnetic field to study the properties of the plasma reflex discharge // *Bulletin of the NTU "KhPI". Series "Techniques and Electrophysics of High Voltage"*. 2014, № 50 (1092), p. 98-109.
8. B.I. Moskalev. *Hollow Cathode Discharges*. Moscow: "Energia", 1969 (in Russian).
9. V.Yu. Bazhenov, S.V. Matsevich, V.M. Piun, V.V. Tsiolko. Hollow cathode discharge in low pressure oxygen: transient mode // *Problems of Atomic Science and Technology. Series «Plasma Electronics and New Methods of Acceleration»*. 2015, № 4, p. 177-180.
10. V.I. Kolobov, A.S. Metel. Glow discharges with electrostatic confinement of fast electrons // *J. Phys. D: Appl. Phys.* 2015, v. 48, p. 233001.
11. Y.P. Raizer. *Gas Discharge Physics.* Berlin Heidelberg: "Springer-Verlag", 1991.
12. M.A. Liberman, A.J. Lichtenberg // *Principles of plasma discharges and materials processing* / John Wiley & Sons, INC Publication, 2005, p. 757.
13. V.A. Lisovskii, S.D. Yakovin. A modified Paschen law for the initiation of a dc glow discharge in inert gases // *Technical Physics*. 2000, v. 45, p. 727-731.
14. V.A Lisovskiy, S.D. Yakovin, V.D. Yegorenkov. Low-pressure gas breakdown in uniform dc electric field // *J. Phys. D: Appl. Phys.* 2000, v. 33, p. 2722-2730.

Article received 15.10.2016

ИССЛЕДОВАНИЕ РЕЖИМОВ ГОРЕНИЯ ГАЗОВОГО РАЗРЯДА В ГЕОМЕТРИИ ПЕННИГА В ГРАДИЕНТНЫХ МАГНИТНЫХ ПОЛЯХ

А.Н. Озеров, Ю.В. Ковтун, Е.И. Скибенко, В.Б. Юферов

Проведены исследования режимов горения газового разряда в геометрии Пеннинга в градиентом магнитном поле. Экспериментально измерены величины напряжения зажигания и вольт-амперные характеристики газового разряда в зависимости от давления рабочего газа при отсутствии и наличии магнитного поля. Получены зависимости величины интегрального оптического излучения плазмы разряда от давления рабочего газа. Определены значения мощности, выделившейся в разрядной ячейке, а также проводимости газоразрядной плазмы.

ДОСЛІДЖЕННЯ РЕЖИМІВ ГОРІННЯ ГАЗОВОГО РАЗРЯДА В ГЕОМЕТРІЇ ПЕННІНГА В ГРАДІЄНТНИХ МАГНІТНИХ ПОЛЯХ

О.М. Озеров, Ю.В. Ковтун, Е.І. Скібенко, В.Б. Юферов

Проведено дослідження режимів горіння газового розряду в геометрії Пеннінга в градієнтному магнітному полі. Експериментально виміряні величини напруги запалювання та вольт-амперні характеристики газового розряду в залежності від тиску робочого газу при відсутності і наявності магнітного поля. Отримано залежності величини інтегрального оптичного випромінювання плазми розряду від тиску робочого газу. Визначено значення потужності, що виділилася в розрядної комірці, а також провідності газорозрядної плазми.