MEASUREMENT OF THE PLASMA DENSITY IN TWO MODES OF PULSED DISCHARGE BURNING IN THE PENNING CELL

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The paper presents the experimental evidence of two modes of pulsed discharge burning in the Penning cell. The modes have different values of maximally reached plasma density and its dynamics change.

PACS: 52.80.-s; 52.80.Sm

INTRODUCTION

The gas-discharge plasma formed in the Penning cell is used in a series of technical devices and charged-particle sources based on the Penning discharge (reflex discharge). They are widely applied for solving physical and applied problems in many fields such as physics of atomic and electron collisions, plasma physics, vacuum engineering, accelerating techniques, applied plasma technologies etc.

In the reflex discharge, with the use of a cylindrical cathode, more than one discharge modes are revealed depending on the pressure and magnetic field values [1], e.g. a non-self-maintained discharge, light magnetic field (LMF) mode, high magnetic field (HMF) mode, transition mode (TM), high pressure (HP) mode and extremely high pressure (EHP) mode when the electron free path is shorter than the system length. Parameters of the discharge and plasma formed in different modes are very different. In some cases the pulsed Penning discharge can transform into the arch discharge with cathode spot formation [2, 3]. In previous investigations [5, 6] on the gas-metal multicomponent plasma formed by the pulsed high-current reflex discharge [4] we have observed the cathode spot traces on the cathode end surface.

In the present paper we report the measurement results on the density of the plasma formed in the Penning cell in two modes of pulsed discharge burning.

1. EXPERIMENTAL INSTALLATION AND DIAGNOSTIC TECHNIQUES

Investigations on the plasma density were carried out with the help of the installation "MAKET" [4] being a high-current high-voltage pulsed discharge in the Penning cell.

The installation "MAKET" is schematically presented in Fig.1. Discharge chamber (1) is a cylinder made of Ch18N10T stainless steel having 200 cm length and 20 cm internal diameter. On the side surface in the cross-section A-A and B-B at a distance of 35 cm from cathodes (4), several diagnostic ports (3) are provided for connecting plasma diagnostics tools. A magnetic field of a mirror configuration (mirror ratio is 1.25) is initiated by solenoid (2) comprising six coils. A maximum magnetic field induction is $B_0 \leq 0.9$ T. The magnetic field pulse duration is 18 ms. A vacuum chamber is pumped out to the pressure of $1.33 \cdot 10^{-4}$ Pa, then the igniting gas is fed. Gas-metal plasma is formed as a result of the discharge by a capacitor bank C of 560 μF capacity, voltage to 5 kV via a ballast resistor R between cold cathodes (4) of 10 mm in diameter and anode 1 (vacuum chamber). The plasma is formed in the medium of igniting gas and cathode *Ti* material.

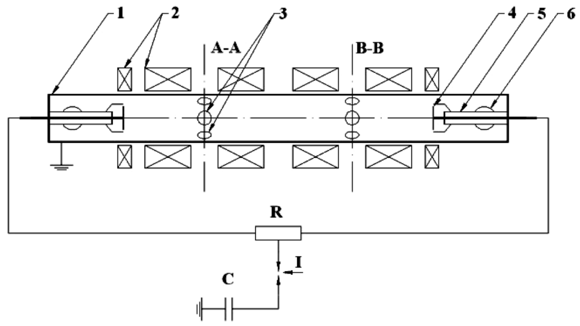


Fig. 1. Schematic representation of the experimental installation "MAKET": 1 – gas discharge chamber (anode); 2 – magnetic system; 3 – diagnostic ports; 4 – cathodes; 5 – insulator; 6 – vacuum-pumping system; A-A, B-B – diagnostic port cross-sections; C – capacitor bank; R – ballast resistor; I – ignitron

The pulsed discharge gas-metal plasma density was measured by the microwave interferometry method. Plasma probing was performed across the plasma column by means of an ordinary O-wave. In this case the external magnetic field influence can be neglected as the O-wave is polarized so that the wave magnetic field vector is parallel to the external magnetic field vector. The phase shift of the wave crossing the plasma is related with an average plasma electron density at the probing frequency much exceeding the collision frequency and the electron density $N_p<N_c$ is related by the relationship: $N_p(t) = N_c\left[2\frac{\Delta\Phi(t)\lambda}{2\pi L} - \left(\frac{\Delta\Phi(t)\lambda}{2\pi L}\right)^2\right]$, where $\Delta\Phi$ is the phase shift of the probing microwave signal; L – plasma formation dimension in the probing direction; N_c – critical electron concentration $N_c = \frac{4\pi^2\varepsilon_0 m_e c^2 e^{-2}}{\lambda^2}$, where ε_0 is the electric constant; e – electron charge; c – velocity of light in free space; λ – probing wave length.

When N_c, is reached, i.e. the probing frequency is equal to the plasma frequency, the electromagnetic wave is reflected from the plasma layer with N_c that is evidenced by the microwave signal cutoff on the interferometer. At $\Delta\Phi<\pi$ the probing microwave signal phase shift can be evaluated from the relationship [7]: $\Delta\Phi = arccos\left(1 - \frac{2A_x}{A_0}\right)$, where A_x is the signal amplitude in the instant of measurement; A_0 is the amplitude change due to the phase shift change from 0 to π (a square law response of the detector is assumed).

Besides the density measurement, the discharge current was measured by means of the Rogowski loop.

2. EXPERIMENTAL RESULTS

The plasma density dynamics in time was investigated under the following conditions: igniting Ar gas pressure in the range from 0.133 to 4.7 Pa ($N_0 = 3.5\cdot10^{13}$ …$1.25\cdot10^{15}$ cm^{-3}), magnetic induction of 0.2 T, discharge current of 2 kA, voltage of 4.5 kV. The cathodes, used in experiments, were made of monometallic titanium or composite titanium, titanium deposited on copper by the vacuum-arc method. The coating thickness was 2…5 μm. Investigations of the plasma density, using microwave interferometers of a different wavelength λ, permitted measurements in the range of N_p = $3.5\cdot10^{11}…2.4\cdot10^{14}$ cm^{-3}.

Investigations have shown that under similar initial conditions two modes of pulsed discharge burn in the Penning cell are distinguished. The plasma density obtained in these modes is appreciably different.

For the first mode a characteristic feature is formation of a dense multicomponent gas-metal plasma, the density of which reaches $\leq 2\cdot10^{14}$ cm^{-3} with a high degree of ionization $\leq 2\cdot10^{14}$ cm^{-3} [4]. The time for formation of the density equal to $1\cdot10^{13}$ cm^{-3} is $\tau \sim 70$ μs, and the lifetime of the density $N_p \geq 1\cdot10^{12}$ cm^{-3} is $\tau \sim 6…12$ ms. One of the main processes, leading to the cathode material destruction, and, consequently, to the material entry into the plasma is the sputtering. In this case the titanium ion content in the plasma is 30...50% and more [4]. This mode is observed throughout the range of experimental conditions most frequently and, in essence, is a dominant discharge mode.

In the second mode the maximum plasma density ranges from $\sim 2\cdot10^{12}$ to $9\cdot10^{12}$ cm^{-3}, and the degree of ionization is $\leq$ 25%. The plasma radiation spectrum, similarly to the first mode, contains the lines of *Ar*, *Ti* ions. The distinguishing feature of the second discharge mode is a random character of its realization against a background of the first mode. In the range of experimental conditions under study we have not observed the region of its pulse-to-pulse constant existence. The change of the igniting Ar gas by H_2 or Kr-Xe-N_2-O_2 gas mixture gives similar results. A number of discharges in the second mode make several percents of the total number ~ 6400 pulses.

Now let us consider the plasma density dynamics for two discharge modes. Fig. 2 represents the signals of the microwave interferometer with λ=0.8 cm obtained in one measuring session. Analysis of oscillograms shows that in the first case (see Fig.1,a) a microwave signal cutoff is observed, consequently, the plasma density is $N_p \geq N_c = 1.7\cdot10^{13}$ cm^{-3} of duration $\tau_{cutoff} \approx$ 1.4 ms. In the second case (see Fig.1,b) a microwave signal cutoff is absent and $N_p < N_c = 1.7\cdot10^{13}$ cm^{-3}. The results of oscillogram processing are given in Fig. 3. Conventionally, the time dependence of an average gas-metal plasma density for both discharge modes can be divided into three parts. The first part presents the development and plasma density increasing to $N_{p1} \geq 1.7\cdot10^{13}$ cm^{-3} in the case of the first discharge mode and to $N_{p2} \approx 8\cdot10^{12}$ cm^{-3} in the second discharge mode. The second part is the plasma density lifetime, and in the first discharge mode the plasma density can reach $N_{p2} \approx 8\cdot10^{12}$ cm^{-3} and higher values. Then the part of density decrease and plasma decay takes place.

Let us consider the plasma decay stage for two discharge modes. The time dependence of the density value $1/N_p$ (Fig. 4) shows that at the initial stage of plasma decay in the time interval from 0.75 to 2.3 ms (the second discharge mode) and 1.56 to 2.55 ms (the first discharge mode) it corresponds to the linear law of density changing. In the time interval 2.3…2.89 ms (the second discharge mode) and 2.55…4.1 ms (the first discharge mode) the N_p^{-1} value changes by the exponential law. According to [8] it means that in the first time interval the recombination dominates, and in the second interval another loss mechanism prevails, i.e. the diffusion process becomes dominant.

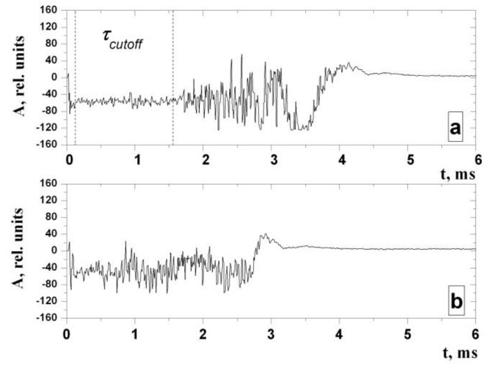


Fig. 2. Oscillogram of the microwave interferometer signal with λ=0.8 cm: (a) in the presence of the microwave signal cutoff; (b) without microwave signal cutoff (P = 0.271 Pa, $U_{dis.}$ = 4 kV)

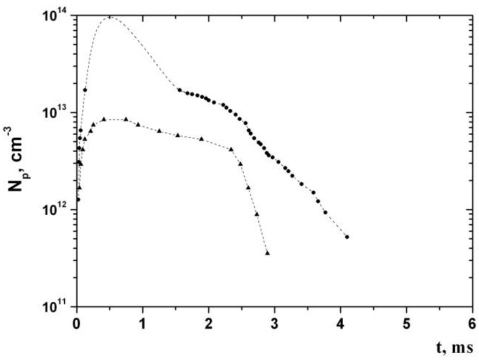


Fig. 3. Average plasma density as a function of time in the first (●) and in the second (▲) discharge modes (P = 0.271 Pa, $U_{dis.}$ = 4 kV)

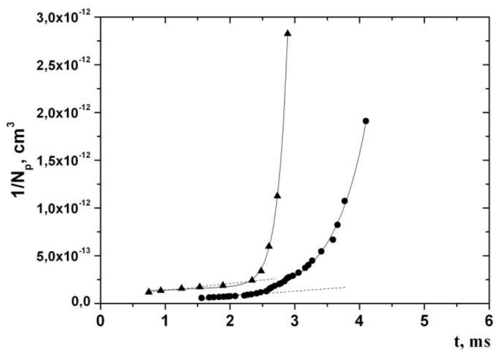


Fig. 4. Time dependence of N_p^{-1} during the phase of plasma decay in the first (●) and in the second (▲) discharge modes (P = 0.271 Pa, $U_{dis.}$ = 4 kV)

So, two modes of pulsed discharge burning in the Penning cell differ not only by the maximum density but, also, by the different plasma density dynamics in time.

3. DISCUSSION OF EXPERIMENTAL RESULTS

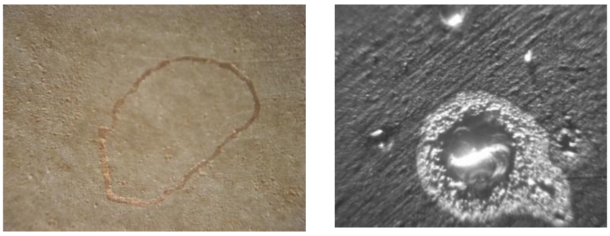
The difference observed in the plasma density and in its dynamics in time, probably, is related with different physical mechanisms of plasma formation in the Penning cell volume in the two discharge modes. In the discharges with cold cathodes, including in the Penning discharge (reflex discharge) [9, 10] the ionization of neutral gas molecules (atoms) takes place. This process occurs due to the primary electrons emission from the cathode surface under applied voltage onto the interelectrode gap and to the secondary emission initiated by the particle interaction with the cathode surface.

Plasma electrons also can take part in the gas ionization process [10]. The condition of the self-sustaining discharge stationarity using cold cathodes can be written as [9]: $\gamma_{eff} \cdot N_i = 1$, where γ_{eff} is the effective secondary-emission coefficient [11] depending on the kind and energy of particles, material and surface state of cathodes [11, 12];$\cdot N_i$ is the number of ions formed in the volume. The processes under study are characteristic for the first discharge mode [4, 10].

The value of γ_{eff}, and, consequently, discharge parameters are changing due to the particle interaction. However, this does not explain such significant plasma density change in the second discharge mode. Moreover, on the cathode surface the cathode spot traces are observed (Fig. 5). Hence, despite the use in the power supply circuit (see Fig.1) of a ballast resistance limiting the discharge current, the discharge changing into the arc mode is possible.

As is known [3, 13] the cathode spot generates a plasma stream composed of ion component (including multicharged ions) and electron component, neutral particles and macroparticles. The interaction of the plasma stream, generated by the cathode spot, with the gas target leads to the gas ion formation [3].

Several methods for ignition of arc are known [3, 14]. In the NSC KIPT available methods of arc excitation, including the Penning and "pool cathode" electrode systems, have been investigated. The investigation results are summarized in [3]. The results of investigations on the pulsed Penning discharge transition to the arch mode are given in papers [2, 15, 16]. In [15] coherent potential oscillations on the cathodes have been discovered when the Penning discharge was transformed into the arc mode. A characteristic time of transition to the arc was less than 10 μs under voltage more than 1 kV on the discharge gap. The investigation results [16] show that the characteristic time of Penning discharge transformation into the arc mode, using the mercury-pool cathode, decreases to 8…0.25 μs ($U_{dis.}$ = 2…10 kV, B = 0.21…0.4 T) with the voltage build-up in the discharge gap and magnetic field induction increasing. In [2] the number of pulsed Penning discharge transitions to the arc was determined for different cathode materials under the following experimental conditions: voltage $U_{dis.}$ = 4 kV, discharge pulse duration of 30 and 100 μs, discharge pulse density of 200 kA/m^2, gas (H_2 or D_2) pressure in the range of 3.33…8 Pa, B = 0.3 T. The results obtained have shown that the number of transitions to the arc depends on the purity of cathode material and cathode surface, as well as, on the discharge current density. In the case of a Mo cathode with U_{dis}= 2 kV and current density of 60 kA/m^2 the percentage of transformation into to the arc is 0.002% and with 120 kAm^2 it is 0.1%, respectively. In [17], unlike [2], the number of transformations into the arc, at a constant density of the current onto the cathode, increases when the voltage, applied to the discharge gap with preliminary produced Ar plasma, increases.



a *b*

Fig. 5. Appearance of the cathode working surface; a – fragment of the composite cathode working surface (4×5.8 mm), ×25; b – fragment of the monometallic cathode surface (1.25×1.8 mm), ×100

One of the mechanisms related with cathode spot formation is the charging and subsequent breakdown of dielectric inclusions and films on the cathode surface [2, 3, 18]. As is noted in [19], in the high-current discharge mode a strong electric field near the cathode and high ion current density can lead to the formation of cathode spots.

In [2, 15-17] parameters of the plasma formed were not measured. In the stationary vacuum-arc sources the density and temperature of plasma electrons in the discharge plasma volume are $N_e \approx 10^9…10^{11}$ cm^{-3} and $T_e \approx$ 1…3 eV respectively [3, 20]. The results of measurements [3, 21-23] on the stationary arc-discharge plasma parameters in the pressure range from 10^{-3} to10 Pa in the N_2 atmosphere show that in the case of pressure increasing the electron temperature decreases and the electron density increases to the pressure of ≈ 2 Pa [23]. It is due to the interaction of the plasma stream, generated by the cathode spot, with the gas target. The plasma formed by the high-current pulse vacuum-arc discharge in the magnetic field (P=10^{-4} Pa, $I_{dis.}$ ≤3 kA, B≤0.3T) was investigated in [24]. When the discharge current $I_{dis.}$ = 1.5 kA and the magnetic field B=0.1 T, depending on the cathode material, the ion density is $N_i \approx (0.8…3.3)\cdot 10^{13}$ cm^{-3} at electron temperature $T_e \approx$ 0.7…5.5 eV. In [24] the characteristics of the plasma formed by the vacuum-arc discharge burning in the Penning cell (P=$1.3\cdot 10^{-5}$ Pa) were investigated. It has been found that for the discharge current $I_{dis.}$ = 150 A of 900 μs duration, without magnetic field, the density and temperature are $N_e \approx (4…6)\cdot 10^{12}$ cm^{-3}, $T_e \approx$ 3.5…4 eV; at B=0.08…0.13 T, respectively, $N_e \approx (2…3)\cdot 10^{13}$ cm^{-3}, $T_e \approx$ 8…10 eV.

So, from this consideration of the arc ignition conditions and arc-formed plasma stream parameters it follows that in our case the plasma in the second discharge mode can be formed due to the discharge transformation into the arc mode with formation of cathode spots formation by the plasma stream interacting with the gas target.

CONCLUSIONS

From this study it can be concluded the following:

1. Experimental results evidence on the existence of two modes of pulsed discharge burning in the Penning cell. These modes differ by .the maximum obtainable plasma density values and plasma change dynamics.

2. A characteristic property of the first mode is formation of a dense compact multicomponent gas-metal plasma, the density of which reaches values of $\leq 2{\cdot}10^{14}$ cm^{-3} with a high degree of ionization up to 100%. In the second mode the maximum plasma density is ranging from $\sim 2{\cdot}10^{12}$ to $9{\cdot}10^{12}$ cm^{-3}, and the degree of ionization is $\leq 25\%$.

3. The difference in the plasma density and its dynamics observed for two modes, apparently. is related with different physical mechanisms of plasma formation in the Penning cell.

REFERENCES

1. W. Schuurman // *Physica.* 1967, v. 36, № 1, p. 136-160.
2. J.H. Holliday, G.G. Isaacs // *Brit. J. Appl. Phys.* 1966, v. 17, № 1, p. 1575-1583.
3. I.I. Aksyonov, A.A. Andreev, V.A. Belous, et al. V*acuum arc. Plasma sources, coating deposition, surface modification*. K.: « Naukova dumka », 2012, p. 727 (in Ukrainian).
4. Yu.V. Kovtun // *Problems of Atomic Sciense and Technology. Series "Plasma Electronics and New Methods of Acceleration"* (8). 2013, № 4(86), p. 38-43.
5. Yu.V. Kovtun, A.I. Skibenko, E.I. Skibenko, et al. // *Technical Physics.* 2011, v. 56, № 5, p. 623-627.
6. Yu.V. Kovtun, A.I. Skibenko, E.I. Skibenko, V.B. Yuferov // *Problems of Atomic Science and Technology. Series "Vacuum, pure materials and superconductors"*. 2011, v. 19, № 6(76), p. 85-91.
7. I.B. Pinos, E.N. Sizaya, A.I. Skibenko, et al.: Preprint 82-1-KhFTI. KFTI AS UkSSR, 1982, p. 28.
8. J.B. Hasted. *Physics of Atomic Collisions*. Butterworths, London, 1964.
9. M.D. Gabovich. *Physics and Techology of plasma ion sources.* M.:"Atomizdat", 1972, p. 304 (in Russian).
10. Yu.V. Kovtun. *Dense multicomponent gas-metal reflex-discharge plasma.* Ph.D. thesis. Kharkov, 2012, p. 182.
11. A.V. Phelps, Z. Lj. Petrovic // *Plasma Sources Sci. Technol*. 1999, v. 8, p. R21-R44.
12. A.P. Bokhan, P.A. Bokhan, D.Eh. Zakrevsky // *Zhournal Tekhnicheskoj Fiziki*. 2005, v. 75, № 9, p. 126-128 (in Russian).
13. A. Anders. *Cathodic Arcs*. *From Fractal Spots to Energetic Condensation.* Springer Science, 2008, p. 540.
14. B. Juttner // *Plasma Physics and Controlled Fusion*. 1984, v. 26, № 1A, p. 249-258.
15. A.F. Zlobina, Yu.E. Kreindel, V.A. Nikitsky // *Zhournal Tekhnicheskoj Fiziki*. 1971, v. 41, № 10, p. 2156-2158 (in Russian).
16. V.B. Belyaev, I.M. Tsinman, N.E. Shimanov // *Ehlektronnaya Tekhnika. Seriya 3. Gasorazryadnyye pribory.* 1970, v. 3(18), p. 45-51 (in Russian).
17. O. Lloyd, C.F. Gozna, G. Jervis-Hunter // *J. Phys. D.* 1970, v. 3, № 11, p. 1670-1677.
18. D.I. Proskurovsky, V.F. Puchkarev // *Zhournal Tekhnicheskoj Fiziki.* 1979, v. 49, № 12, p. 2611-2618 (in Russian).
19. A.A. Bizyukov // *Problems of Atomic Science and Technology.* 1998, № 6(7), 7(8), p. 142-144.
20. V.M. Lunev, V.D. Obcharenko, V.M. Khoroshikh // *Zhournal Tekhnicheskoj Fiziki.* 1977, v. 47, № 7, p. 1486-1490 (in Russian).
21. I.I. Demidenko, N.S. Lomino, V.D. Ovcharenko, et al. // *Khimiya Vysokikh Energii*. 1986, v. 20, № 5, p. 462-467 (in Russian).
22. N.S. Lomino, V.D. Ovcharenko, A.A. Andreev // *IEEE Plasma Science*. 2005, v. 33, № 5, p. 1626-1630.
23. V.M. Khoroshikh, S.A. Leonov, V.A. Belous, et al. // *Journal of Kharkiv National University № 784, physical series: Nuclei, Particles, Fields*. 2007, v. 4(36), p. 108-112.
24. R.S. Dallaqua, E. Del Bosco, R.P. da Silva, S.W. Simpson // *IEEE Plasma Science*. 1998, v. 26, № 3, p. 1044- 1051.

Article received 23.01.2015

ИЗМЕРЕНИЕ ПЛОТНОСТИ ПЛАЗМЫ В ДВУХ РЕЖИМАХ ГОРЕНИЯ ИМПУЛЬСНОГО РАЗРЯДА В ЯЧЕЙКЕ ПЕННИНГА

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

Экспериментально зафиксировано существование двух режимов горения импульсного разряда в ячейке Пеннинга, которые отличаются друг от друга величиной максимально достижимой плотности плазмы и динамикой ее изменения.

ВИМІРЮВАННЯ ГУСТИНИ ПЛАЗМИ В ДВОХ РЕЖИМАХ ГОРІННЯ ІМПУЛЬСНОГО РОЗРЯДУ В КОМІРЦІ ПЕННІНГА

Ю.В. Ковтун, А.І. Скибенко, Е.І. Скібенко, В.Б. Юферов

Експериментально зафіксовано існування двох режимів горіння імпульсного розряду в комірці Пеннінга, які відрізняються один від одного величиною максимально досягнутої густини плазми та динамікою її зміни.