https://doi.org/10.46813/2025-158-031

PLASMA TRANSITION THROUGH THE BARRIER OF EXTERNAL STRONG MAGNETIC FIELD IN HIGH-CURRENT PLASMA DIODE

Ya. Hrechko[1], *I. Sereda*[1], *M. Azarenkov*[1,2]
[1]*V.N. Karazin Kharkiv National University, Kharkiv, Ukraine;*
[2]*National Science Center "Kharkiv Institute of Physics and Technology", Kharkiv, Ukraine*
E-mail: ya.hrechko@karazin.ua

This paper investigates the effect of a strong pulsed magnetic field on the primary plasma dynamics and the formation conditions of a high-current discharge stage in a low pressure plasma diode. A magnitude estimate of the external magnetic field sufficient to stabilize the plasma cord in the space near the high-voltage electrode has been made. The dependences of the transition time of the primary plasma of the discharge gap on the external magnetic field strength and the stored energy in the capacitor bank under different initial conditions have been presented.

PACS: 52.50.Dg, 52.59.-f

INTRODUCTION

Plasma sources of powerful radiation in a wide frequency range are in significant demand in various industries: from use in scientific research to applications in the field of technology. In particular, sources of vacuum ultraviolet (VUV) radiation are important. This radiation with a wavelength of 10…100 nm is currently used for the needs of micro- and nanoelectronics [1], microscopy [2], chemical analysis, production of optical materials [3], medicine [4], astrophysics, etc. The advantage of using plasma radiation sources is their compactness and relatively low cost, compared to the use of synchrotron radiation, which is generated in charged particle accelerators with storage rings.

High power and efficiency are the necessary requirements for radiation sources in the VUV range. This encourages the development of such radiation sources based on low-pressure high-current pulse discharges, which provide high current density and the effect of rapid plasma self-heating to high temperatures necessary for the generation of the corresponding radiation. These are discharges such as Z-pinch, Θ-pinch, "plasma focus", capillary discharge and various combinations thereof, including laser plasma.

The authors of the papers [5, 6] have been showed the possibility of generating powerful (up to 1 MW) directional VUV radiation from a plasma of multiply ionized tin atoms formed in a high-current plasma diode. It has been determined that the main mechanism of radiation generation is the beam mechanism of plasma heating, due to the formation of a double electric layer of space charge (DL) in the plasma [6]. Almost all of the active discharge voltage is concentrated on the DL, and the counter-acceleration of intense electron and ion beams occurs in the electric field of the layer. These beams, when collectively interacting with the plasma, transfer energy to it and, in millionths of a second, heat it to temperatures sufficient to produce the corresponding radiation. Moreover, a connection between the directivity of VUV radiation and the shape of plasma formation has been established. This result is important, since using powerful directional radiation it is possible to significantly increase the efficiency of existing radiation sources.

However, there is a problem associated with stabilizing the plasma cord, which can bend in different directions during the discharge. Several methods of spatial stabilization of the plasma cord in discharges of this type are known. One of them is the method of stabilizing the plasma cord by the discharge tube wall in a capillary discharge. Plasma generation in capillary discharges is carried out using pulsed power supplies (with voltages up to 600 kV), consisting of a pulse transformer, a forming line and a switch [7]. But a significant disadvantage of capillary discharges is the use of plasma-confining capillaries. The inner wall of the capillary is in very close contact with the plasma, which leads to the destruction of the capillary after one or several pulses with high power density. Another way to stabilize a plasma cord is to use external strong magnetic fields, the magnitude of which would significantly exceed the intrinsic magnetic field that arises when the discharge current flows.

The purpose of this work is to determine the effect of a strong magnetic field created by a pulse coil on the primary plasma dynamics and the formation conditions of a high-current discharge stage in a plasma diode with a limited working surface of a high-voltage electrode.

1. EXPERIMENTAL SETUP

Fig. 1 shows a scheme of the discharge cell of the high-current pulsed plasma diode. The plasma diode consists of two electrodes placed opposite each other at a distance of 5 cm which could vary up to 10 cm depending on the experimental conditions. A high-voltage rod electrode *HVE* with a diameter of 0.25 cm is connected directly to the capacitor bank with capacity C_0 of 2 μF and the charging voltage V_0 of up to 12 kV. The polarity of the high-voltage electrode connection could vary depending on the experimental conditions. The other electrode is grounded *GE* and has a tubular configuration with an outer and inner diameter of 1 and 0.8 cm, respectively. The side surface of the high-voltage electrode is closed with a ceramic insulator *CI*, so that only the electrode end remains working. This contributes to the concentration of a high discharge current density of up to 0.8 MA/cm^2 on the electrode working surface and the formation of the DL in the near-electrode area.

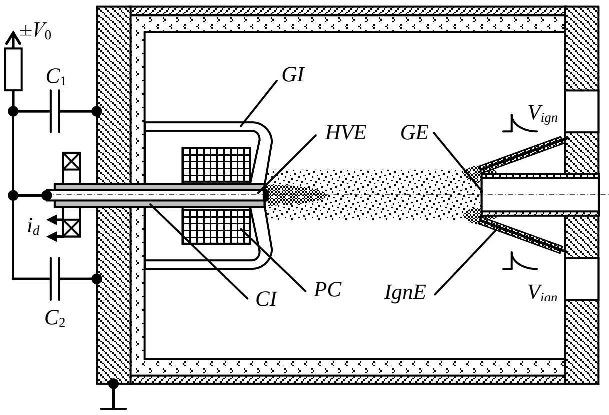

Fig. 1. The scheme of the discharge cell of the high-current pulsed plasma diode. HVE – high voltage electrode; GE – grounded electrode; CI – ceramic insulator; PC – pulsed magnetic field coil; GI – glass insulator; IgnE – ignition electrode

The discharge excitation occurs at low pressure (~ $1.33\cdot10^{-4}\ldots1.33\cdot10^{-3}$ Pa) under conditions of primary plasma formation that fills and closes the discharge gap. The primary plasma is created due to a surface breakdown between the grounded electrode and the ignition electrodes *IgnE*, after applying a voltage pulse V_{ign} of ~ 1 kV to them. After the discharge gap is closed by the primary plasma, the capacitor bank is discharged and a discharge current with an amplitude of up to 40 kA and an oscillation period of 3.5 µs begins to flow. An inductive current sensor is used to diagnose the discharge current i_d. As the discharge current flows, the working surface of the high-voltage electrode heats up and evaporates. There is intensive ionization by primary plasma electrons and the formation of a dense near-electrode plasma with a density of up to $10^{16}\ldots10^{17}$ cm^{-3}. The total duration of the discharge is 10…20 µs.

2. RESULTS AND DISCUSSION

To stabilize the plasma cord in the space near the high-voltage electrode by an external magnetic field, it is necessary to determine the magnitude of the intrinsic magnetic field that arises when the discharge current flows. The azimuthal magnetic field strength H_θ near the high-voltage electrode when the discharge current flows can be estimated using the expression:

$$H_\theta = \frac{2i}{rc}. \quad (1)$$

Here i – discharge current; r – distance to the axis.

In order to counteract the expansion of near-electrode plasma, it is also necessary that the pressure of the magnetic field significantly exceeds the gas-kinetic pressure of the plasma:

$$\frac{H^2}{8\pi} >> n_e k T_e. \quad (2)$$

The ratio between the magnetic and gas kinetic pressures can be estimated based on the discharge current magnitude. Such an estimate will be correct under the conditions of the DL existence in the discharge. This is due to the fact that in this case the discharge current has a maximum value i_{max}, which corresponds to the concentration n_e and the temperature T_e of the plasma in the area with the lowest conductivity of the plasma cord:

$$i_{\max} \approx \frac{1}{4} e \sqrt{\frac{8k\langle T_e\rangle}{\pi\, m_e}} \cdot \int_{S_i} n_e \cdot d\vec{s}\,. \quad (3)$$

Here $\langle T_e \rangle$ is the averaged electron temperature over the cross section of the discharge cord; S_i is the cross-section of the plasma cord in the area with the lowest conductivity. In the case of a cylindrical configuration of the plasma cord, the average value of the plasma electrons density $\langle n_e \rangle$ in the area with the lowest conductivity is determined by the expression:

$$\langle n_e \rangle = \frac{i_{\max}}{\pi\, r_d^2 e \sqrt{\dfrac{k\langle T_e\rangle}{2\pi m_e}}}. \quad (4)$$

Here r_d – plasma cord radius. Thus, the magnetic field, which creates a magnetic pressure equal to the gas-kinetic pressure of the near-electrode plasma, H_p is determined (according to eq. 3, eq. 4) by the expression:

$$H_p = \frac{1}{r_d}\sqrt{8\cdot\sqrt{2\pi m_e}\cdot\frac{i_{\max}}{e}\cdot\sqrt{k\langle T_e\rangle}}\,. \quad (5)$$

Fig. 2 presents the dependences of the strength of the intrinsic azimuthal magnetic field H_θ and the magnetic field, which creates a magnetic pressure equal to the gas-kinetic pressure of the dense near-electrode plasma, H_p on the discharge current. The graphs are given for a plasma electron temperature of 10 eV and a high-voltage electrode diameter of 0.25 cm. One can see that in the entire range of the discharge current the intrinsic azimuthal magnetic field of the discharge current is almost an order of magnitude greater than the magnetic field necessary to counteract the gas-kinetic pressure of the plasma. Therefore, whenever the DL formation is observed, magnetic compression of the plasma cord occurs. Periodic expansion of the plasma cord occurs when the discharge current decreases during the oscillation process. Thus, during magnetic stabilization of the plasma cord, it is necessary to focus on the intrinsic azimuthal magnetic field of the discharge current. This value reaches 5 MA/m at the discharge current of up to 40 kA and high-voltage electrode diameter of 0.25 cm.

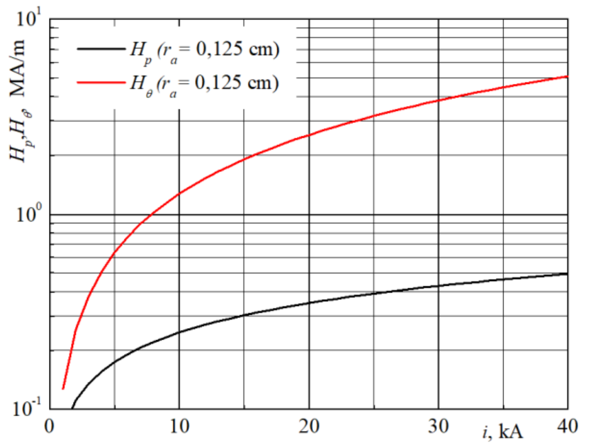

Fig. 2. The dependences of the magnetic field strength on the discharge current

An external stabilizing magnetic field with a strength of up to 5 MA/m was created by a pulse coil *PC*, which was located axially with a high-voltage electrode, as shown in Fig. 1. The pulse coil with an outer and inner diameter of 0.35 and 0.1 cm, respectively, and a length of 0.23 cm, contained 200 turns of copper wire with a diameter of 0.116 cm. Externally, the coil was protected from contact with the plasma by a glass insulator *GI*, which was hermetically glued to a ceramic tubular insulator *CI*, which covered the side surface of the high-voltage electrode. All free space in the glass was filled with silicone compound, which completely sealed the coil and excluded its contact with the plasma. The inductance and active resistance of the coil were $L_c = 370$ µH and $R_c = 0.23$ Ω, respectively. The pulse coil was powered by a capacitor bank with a capacity of 600 µF and charging voltage of up to 1.8 kV.

Fig. 3 shows the distribution of the magnetic field strength along the discharge axis. The data are normalized to the value of the current flowing through the coil. For the calculation accuracy, the distribution has been obtained in three different ways: analytical calculation, computer simulation (using the FEMM 4.2 software) and direct measurement. The analytical calculation was carried out using the expression:

$$H_{zo}\left(z_p\right)=\frac{H_f}{2(b-a)}\times \left(h_1\cdot\ln\frac{b+\sqrt{b^2+h_1^2}}{a+\sqrt{a^2+h_1^2}}+h_2\cdot\ln\frac{b+\sqrt{b^2+h_2^2}}{a+\sqrt{a^2+h_2^2}}\right). \qquad (6)$$

Here p – the point where the magnetic field is determined; a – the inner and b – the outer radii of the coil; h_1 and h_2 – the distances from point p to the right and left ends of the coil, respectively. A good agreement can be seen between the data obtained in different ways.

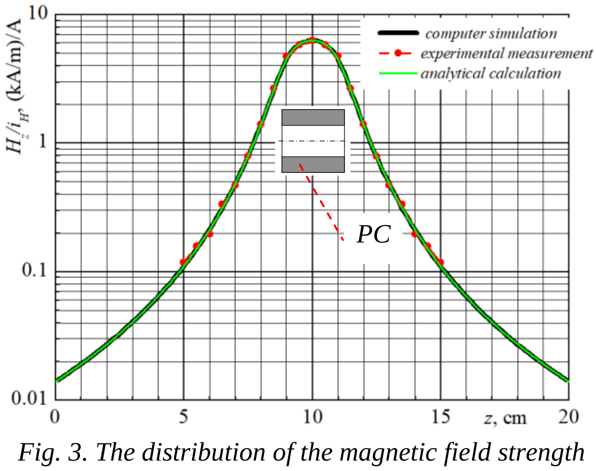

Fig. 3. The distribution of the magnetic field strength along the discharge axis normalized to the coil current

The distribution shows that the primary plasma is formed at relatively small (H_z/i_H ~ 0.05 kA/m·A) external fields and goes in the direction of the increased magnetic field (H_z/i_H ~ 2 kA/m·A). That is, a certain magnetic barrier is created, which the plasma must overcome before closing the discharge gap and the high-current discharge stage begins. To determine the effect of a strong magnetic field on the dynamics of the primary plasma and the formation conditions of the high-current stage of the discharge, studies were conducted on the transition time of the primary plasma through the magnetic barrier from the grounded to the high-voltage electrode. The plasma transition time was determined from the dynamics of the discharge current (Fig. 4) as the difference between the delay time of the high-current inductive stage of the discharge (the moment when the current begins to flow) and the delay time of the ignition voltage pulse, which is a constant value for a fixed value of the ignition voltage (~ 1.2 µs for V_{ign} ~ 1 kV).

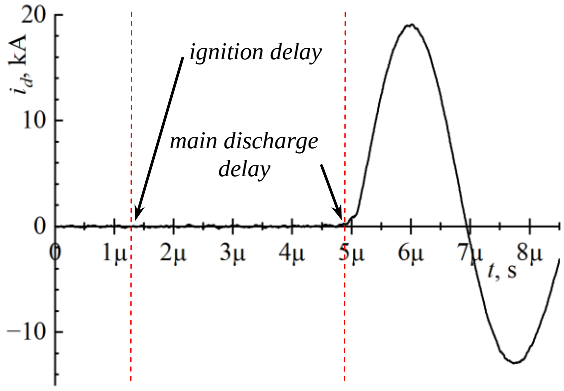

Fig. 4. The discharge current waveform

Fig. 5 shows the dependence of the transition time of the primary plasma of the discharge gap on the strength of the external magnetic field. The dependence was obtained at a capacitor bank charging voltage V_0 of ~ 8 kV with different initial polarity of the high-voltage electrode connection and inter-electrode distance. At a distance between the electrodes of 5 cm (solid line) in the absence of an external magnetic field, the plasma transition time for the case of positive (red line) and negative (black line) polarity practically coincides. However, in the presence of an external strong magnetic field, in the case of positive polarity the transition time increases, and in the case of negative polarity it decreases. Such a dependence on the magnetic field is completely unexpected, since in the absence of a magnetic field, changing the polarity doesn`t lead to significant differences. At the same time, the dependence on the magnitude of the magnetic field strength is insignificant for two cases.

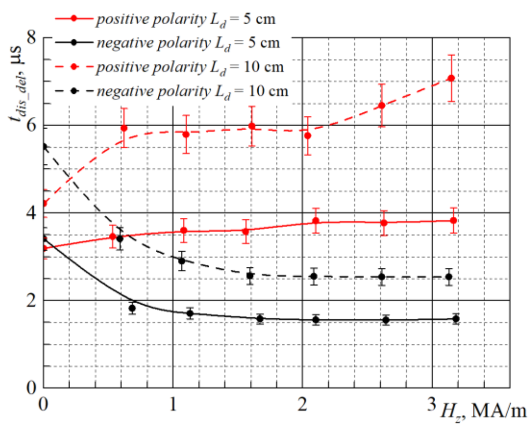

Fig. 5. The dependence of the transition time of the primary plasma of the discharge gap on the strength of the external magnetic field

To verify this result, studies with an increased inter-electrode distance of up to 10 cm (dashed line) were conducted. The studies have shown that the dependence has a similar nature, only the plasma transition time for the two polarities has increased.

Fig. 6 shows the dependence of the transition time of the primary plasma of the discharge gap on the stored energy. These dependences are presented for the case of the absence of an external magnetic field (dashed line) and the presence of a magnetic field with a strength of H_z = 1.19 MA/m (solid line) at the inter-electrode distance of 5 cm. The red curves color corresponds to the positive electrode polarity, black – to the negative polarity.

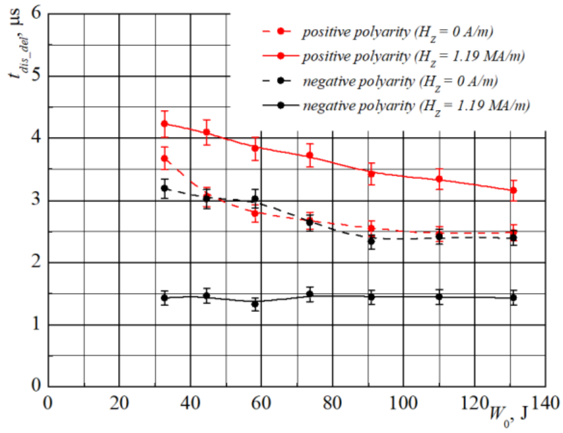

Fig. 6. The dependence of the transition time of the primary plasma of the discharge gap on the stored energy in the capacitor bank

One can see that as the stored energy increases, the curves for positive and negative polarity practically coincide and have similar behavior in the case of absence of an external magnetic field. At the stored energy up to 90 J, a decrease in plasma transition time is observed; above 90 J – the time doesn`t change. In the presence of an external strong magnetic field, in the case of positive polarity, the plasma transition time increases compared to the case without a magnetic field and decreases as the stored energy increases. In the case of negative polarity, the plasma transition time decreases compared to the case without a magnetic field and doesn`t change with increasing stored energy.

CONCLUSIONS

Thus, it has been shown that a strong pulsed magnetic field with the strength of up to 5 MA/m affects the dynamics of the primary plasma, namely, the plasma transition time of the discharge gap. At a positive initial polarity of the high-voltage electrode connection, an increase in the plasma transition time from the grounded electrode to the high-voltage electrode is observed. At a negative polarity, on the contrary, a decrease is observed. The dependence on the magnetic field magnitude is almost insignificant. Studies with a doubled inter-electrode distance have shown a similar result, only with increased values of the plasma transition time.

Analysis of the dependence of the plasma transition time of the discharge gap on the stored energy has shown that in case of the presence of an external strong magnetic field, at the positive polarity, the plasma transition time increases compared to the case without a magnetic field and decreases as the stored energy increases. At the negative polarity, the plasma transition time decreases compared to the case without a magnetic field and doesn`t change with increasing stored energy. At the same time, the curves for positive and negative polarity practically coincide and have similar behavior in the case without a magnetic field. Determining the cause of such an effect of a strong magnetic field on the primary plasma transition at the negative polarity of the high-voltage electrode connection requires further research into the high-current discharge stage, namely the study of the dynamics of the dense near-electrode plasma and the discharge dynamic characteristics.

REFERENCES

1. O.O. Versolato. Physics of laser-driven tin plasma sources of EUV radiation for nanolithography // *Plasma Sources Science and Technology*. 2019, v. 28(8), p. 083001.
2. W. Eschen et al. Material-specific high-resolution table-top extreme ultraviolet microscopy // *Light: Science & Applications*. 2022, v. 11(1), p. 117.
3. L. Drescher et al. Extreme-ultraviolet refractive optics // *Nature*. 2018, v. 564(7734), p. 91-94.
4. T. Al-Sadek, N. Yusuf. Ultraviolet radiation biological and medical implications // *Current Issues in Molecular Biology*. 2024, v. 46(3), p. 1924-1942.
5. I.V. Borgun et al. The formation of a power multi-pulse extreme ultraviolet radiation in the pulse plasma diode of low pressure // *Acta Polytechnica*. 2013, v. 53(2), p. 117-122.
6. I.V. Borgun et al. Double electric layer influence on dynamic of EUV radiation from plasma of high-current pulse diode in tin vapor // *Physics Letters A*. 2013, v. 377(3-4), p. 307-309.
7. S.R. Mohanty et al. A novel fast capillary discharge system emitting intense EUV radiation: Possible source for EUV lithography // *Microelectronic Engineering*. 2003, v. 65(1-2), p. 47-59.

Article received 09.06.2025

ПРОХОДЖЕННЯ ПЛАЗМИ КРІЗЬ БАР’ЄР ЗОВНІШНЬОГО СИЛЬНОГО МАГНІТНОГО ПОЛЯ В СИЛЬНОСТРУМОВОМУ ПЛАЗМОВОМУ ДІОДІ

Я. Гречко, І. Середа, М. Азарєнков

Досліджується вплив сильного імпульсного магнітного поля на динаміку первинної плазми та умови формування сильнострумової стадії розряду в плазмовому діоді низького тиску. Зроблена оцінка величини зовнішнього магнітного поля, достатнього для стабілізації плазмового шнура у просторі біля високовольтного електрода. Представлено залежності часу проходження первинної плазми розрядного проміжку від величини зовнішнього магнітного поля та енергозапасу конденсаторної батареї за різних початкових умов.