# ELECTRODES DIMENSIONS EFFECT ON THE SELF-SUSTAINED PLASMA-BEAM DISCHARGE POWER

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The possibility of increasing the active power inputted into the discharge is shown by reducing the working surface area of the high-voltage electrode in high-current pulsed plasma diode of low-pressure. Under conditions of double electric layer formation, the power densities up to 2 GW/cm$^2$ are achieved in the discharge at initial stored energy up to 200 J.

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## INTRODUCTION

High-gradient temperature impact on the solids surface allows to significantly improve the properties of the structural materials surface layer and achieve the effects that can not be obtained by traditional processing methods [1]. Due to the high thermal conductivity of the materials to produce temperature gradients at level $10^5…10^7$ deg/cm, the pulsed impact on a surface with a power flux density $10^5…10^9$ W/cm$^2$ is necessary. Fast energy input into the substance causes the flowing therein of intense thermal and deformation processes, leading to a change of the material structure and phase composition. This increases the strength, wear resistance and corrosion resistance of the material [2]. One of the methods of forming the necessary energy flows is impact on the solid of intense fluxes of charged particles and plasma, which opens the prospects in creating the new radiation technologies of materials processing [3].

The possibility of obtaining the intense energy fluxes with a necessary power density at relatively small (up to 200 J) initial stored energy is shown in this work. For this purpose, a high-current pulsed plasma diode of low pressure with a limited working surface of the high-voltage electrode is used. This system can be used both for experimental studies of influence of the intense energy fluxes impact on the solids properties, and in the physics of gas discharge, plasma heating, and generation of powerful directional plasma radiation in the vacuum ultraviolet range [4].

The feature of this system is the excitation of a self-sustained plasma-beam discharge (SPBD) – the most powerful type of gas discharge [5, 6]. At discharge currents from hundreds amperes to mega amperes (here, as in the arc, the emission of electrons from the cathode is supported by cathode spots), the discharge voltage can range from hundreds volts to hundreds kilovolts. The high voltage of the SPBD is due to the fact that, unlike the arc, a double electric layer of space charge (DL) is formed in the plasma column. All active discharge voltage is concentrated on it [7]. The intense electron and ion beams are accelerated in the DL [8], but main part of the power comes from the electron beam. The dissipation of the beam energy due to the beam-plasma interaction in dense plasma occurs in the local region. Thus, by controlling the location of the DL, it is possible to set the region of energy input into the discharge.

In this work, the DL formation and the localization of the energy release region was provided near the high-voltage electrode of the plasma diode. Therefore, based on the SPBD excitation conditions, the working surface of this electrode was specially chosen much less than the surface of the other electrode. As additional experimental studies showed, the size of the energy release region did not exceed 1 cm, and it was located above the electrode surface.

In general, the work is related to the studying of the effect of the working surface dimensions of the high-voltage electrode on the level of the active power inputted into the discharge.

## 1. EXPERIMENTAL SETUP

The general scheme of the experiment is presented in Fig. 1. The discharge cell of the plasma diode was located in the vacuum chamber *1* with working pressure of ~ $10^{-6}$ Torr. The cell consisted of a tubular *2* and rod *3* electrodes, which were on the same axis at a distance of 5 cm from each other. The diameter and length of the tubular electrode were 1 cm and 3 cm, respectively. The diameter of the rod electrode varied within 0.15…0.5 cm. The limitation of the working surface of the rod electrode was carried out using a ceramic insulator *4*, which completely covered the side surface of the electrode. Only electrode end was remained as the working surface. The insulator included a ceramic crest that prevented the plasma propagation along the insulator to the electrode holding flange.

The current switch was eliminated from the discharge circuit, and the electrodes were directly connected to the supply capacitor banks $C_1$ and $C_2$ with total capacitance of $C = 1.914$ μF. The capacitor banks was charged to voltage $V_0 = 6…12$ kV through the charging resistance $R_0$. Initially, a positive high potential was applied to the rod electrode (high-voltage electrode), and the tubular electrode was under ground potential (grounded electrode).

The main discharge in the diode was excited after the discharge gap was filled with the primary plasma *5* ($n_{pl} = 10^{12}…10^{13}$ cm$^{-3}$), which was created due to the surface breakdown between the tubular electrode and ignition electrodes *6*. For this purpose, a positive potential of $V_{ig} = 1…2$ kV was applied to the ignition electrodes.

The main discharge included two stages. In the first stage, all voltage applied to the discharge was concentrated near the high-voltage electrode surface on the DL. Primary plasma electrons, accelerating in the DL, irradiated the working surface of the high-voltage electrode. This led to its intense evaporation, ionization of the vapor, and the formation of dense near-electrode plasma *7*, which served as the main energy release zone.

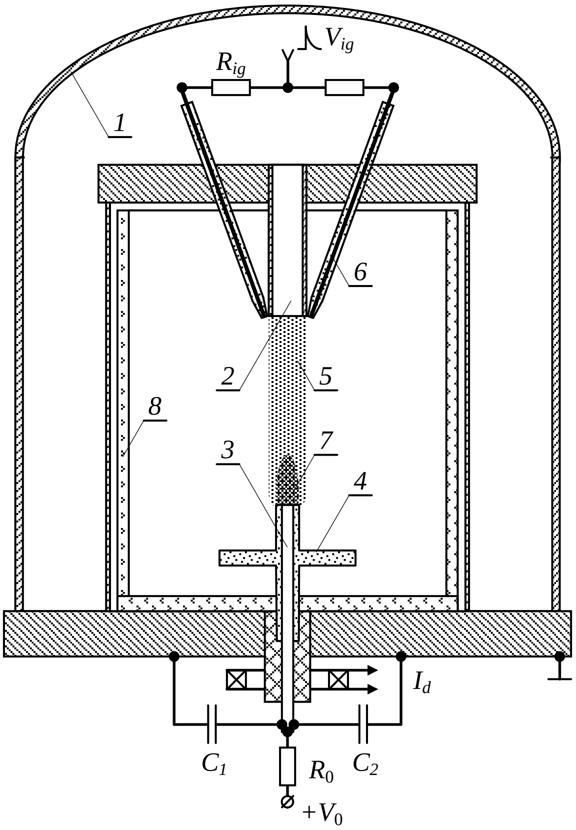


*Fig. 1. Schematic representation of the experimental setup*

The density of this plasma was $n_{pl} = 10^{16}…10^{17}$ cm$^{-3}$. As soon as the discharge active resistance became less than twice wave resistance, the discharge passed to the second high-current inductive stage with damped oscillations and periods duration of ~ 3.5 µs. The maximum current amplitude reaches up to 35 kA. To avoid the appearance of a peripheral discharge, all current-carrying elements were protected by a glass insulator *8*.

The dynamics of discharge current and voltage were studied in the experiments. They were measured using the induction current sensor and the capacitive voltage divider, respectively. Signals were recorded with a digital oscilloscope *Tektronix TDS 2014*. The region of energy input into the plasma was estimated from the luminescence in the visible spectrum region using a high-speed photo-registration system based on an electron-optical converter.

## 2. RESULTS AND DISCUSSIONS

To determine the effect of the working surface dimensions of the high-voltage electrode on the level of the active power inputted into the discharge, electrodes with diameter of 0.5, 0.25 and 0.15 cm were used in the work. The diameter of the tubular grounded electrode remained unchanged. The calculation of the discharge active power was based on the time dependence of the discharge current using the original calculation technique. A complete description of this technique is presented in paper [9].

Fig. 2 shows the dynamics of the discharge current (*a*), the active power generated in the circuit (*b*) and inputted into the discharge (*c*) at a charging voltage $V_0$ = 12 kV and the high-voltage electrode diameter $d_a$ = 0.25 cm. The solid line in Fig. 2,*b* corresponds to the total active power generated in the whole circuit; the dashed line – only at the active resistance of the supply circuit. The difference between them corresponds to the active power inputted into the local discharge region, under DL formation conditions (see Fig. 2,*c*). One can see that the level of active power generated in the circuit reaches ~ 130 MW, and the level of power locally inputted into the discharge is ~ 80 MW at the initial stored energy of ~ 140 J. In this case, the power density near the working surface of the high-voltage electrode with diameter $d_a$ = 0.25 cm is ~ 1.6 GW/cm$^2$. Also it should be noted that the main part of the energy is released in the 1st half-period of the discharge current oscillations. In this regard, further in the paper compares only the energy released in the 1st half-period.

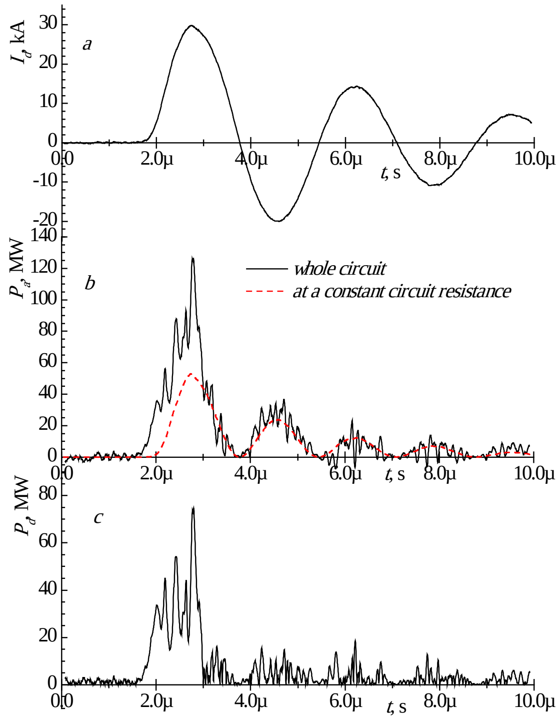


*Fig. 2. Dynamics of the discharge current (a), the active power generated in the circuit (b) and inputted into the discharge (c) at a charging voltage $V_0$ = 12 kV and the high-voltage electrode diameter $d_a$ = 0.25 cm*

Fig. 3 presents the dependence of the maximum discharge current on the initial stored energy for different high-voltage electrode diameters. The solid line corresponds to the electrode diameter of 0.5 cm, the dashed line – 0.25 cm, the dotted line – 0.15 cm. One can see that the discharge current decreases with decreasing the high-voltage electrode diameter. However, due to the limited working surface of the high-voltage electrode, the discharge current density increases significantly. When the electrode diameter decreases from 0.5 to 0.15 cm, the current density near the electrode increases from 0.16 MA/cm$^2$ to 1.6 MA/cm$^2$ at the same initial stored energy ~ 140 J.

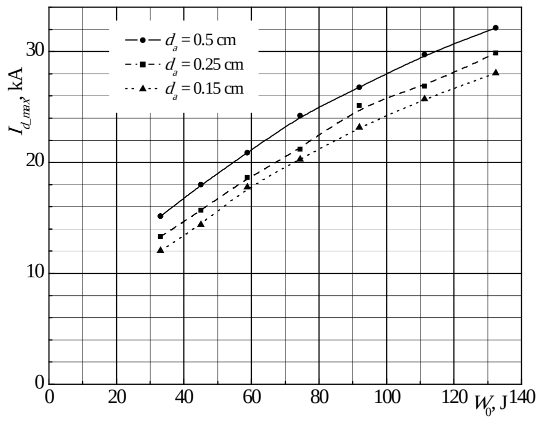


*Fig. 3. Dependence of the maximum discharge current on the initial stored energy for different high-voltage electrode diameters*

The dependence of the maximum discharge current on the high-voltage electrode diameter and the initial stored energy can be represented by the following relationship:

$$I_{\max} = 1{,}225 \cdot d_a^{0{,}383} \cdot W_0^{0{,}636 \cdot d_a^{-0{,}1}}, \qquad (1)$$

where $[I_{max}]$ = kA, $[d_a]$ = mm, $[W_0]$ = J.

Fig. 4 shows the dependence of the energy (*a*) and the specific energy (*b*) released in the discharge in the 1st half-period, under the DL formation conditions, on the initial stored energy for different high-voltage electrode diameters. The type of lines corresponds to Fig. 3. One can see that the level of energy released in the discharge increases substantially as the high-voltage electrode diameter decreases. It was noted that the level of power generated in the circuit remains unchanged, and the level of power inputted into the discharge, under the DL formation conditions, increases significantly as the diameter decreases. When the electrode diameter decreases from 0.5 to 0.15 cm, the power density near the working surface of the high-voltage electrode increases from 0.15 to 2.5 GW/cm$^2$ at the same initial stored energy ~ 140 J.

Also it should be noted that for the electrode diameter of 0.5 cm the energy share released in the discharge almost unchanged (within 15%) as the initial stored energy increases. But when the diameter decreases, the energy share decreases up to 30% as the initial stored energy increases. This is clearly seen from Fig. 5, which presents the dependence of the specific energy released in the discharge in the 1st half-period, on the high-voltage electrode diameter for the averaged values of the charging voltage. The solid line corresponds to the averaged values for the charging voltages $V_0$ = 6 and 7 kV, the dashed line – for $V_0$ = 11 and 12 kV. One can see that two groups of charge voltages are clearly distinguished when the electrode diameter decreases from 0.5 to 0.15 cm. This fact should be taken into account when carrying out the technological operations on the impact of intense energy flows on the solid surface.

It should be noted an interesting fact. It was found that there is no need to limit the electrode working surface at the reduced electrode diameter (less than 0.2 cm).

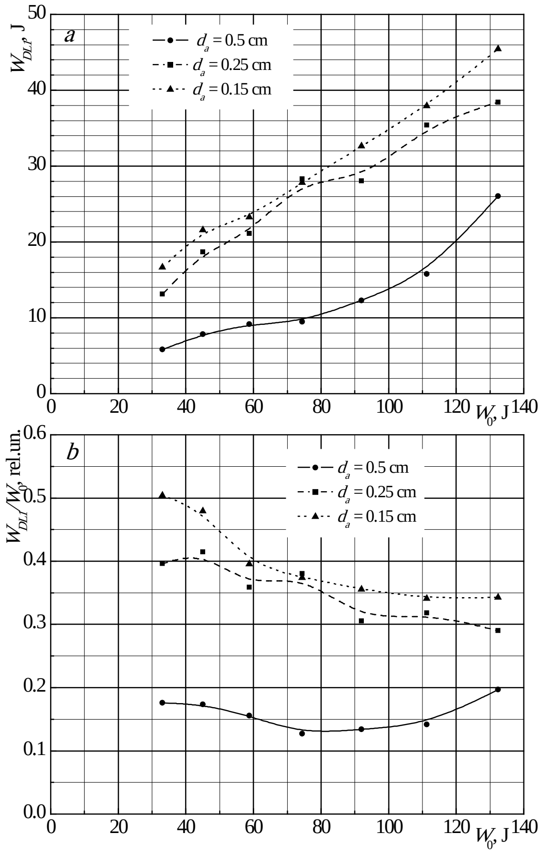


*Fig. 4. Dependence of the energy (a) and the specific energy (b), released in the discharge in the 1st half-period, on the initial stored energy for different high-voltage electrode diameters*

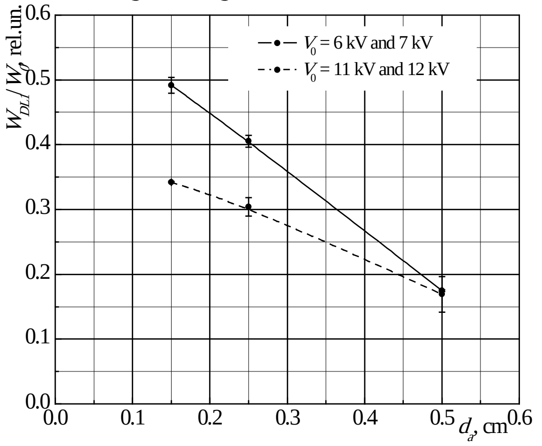


*Fig. 5. Dependence of the specific energy, released in the discharge in the 1st half-period, on the high-voltage electrode diameter for the averaged values of the charging voltage*

This is due to the fact that at the electrode diameter is less than 0.2 cm the dense near-electrode plasma is displaced to the electrode end by the intrinsic magnetic field of the discharge current. The DL formation occurs at the front of this plasma. At the electrode diameter of more than 0.2 cm, such effect was not observed, since the intrinsic magnetic field is not sufficient to hold the plasma at the electrode end. Fig. 6 shows the dependence of the magnetic field strength of the maximum discharge current on the initial stored energy for different high-voltage electrode diameters. The solid line corresponds to the electrode diameter of 0.5 cm, the dashed line – 0.25 cm, the dotted line – 0.15 cm. One can see that at the electrode diameter of 0.15 cm the value of the intrinsic magnetic field reaches ~ 75 kOe at the initial stored energy of ~ 133 J.

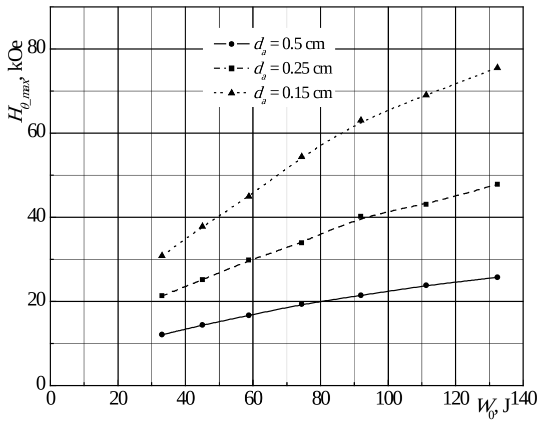


*Fig. 6. Dependence of the magnetic field strength of the maximum discharge current on the initial stored energy for different high-voltage electrode diameters*

In addition, the high-speed photographic registration of the discharge gap in the visible wavelength range was carried out. The studies have shown the process of plasma displacement by the intrinsic magnetic field on the high-voltage electrode end.

## CONCLUSIONS

Thus the studies have shown that the level of power inputted into the discharge increases by 40…50% when the working surface area of the high-voltage electrode is reduced by an order (from 0.2 to 0.02 cm$^2$). The energy released in the discharge increases up to 70%. At the same time, the discharge current is insignificant (~ 10%) decreases. It is noted that for the electrode diameter of 0.5 cm, the energy share released in the discharge varies within 15% as the initial stored energy increases. However, when the electrode diameter is reduced to 0.15 cm, the energy share decreases up to 30% as the initial stored energy increases. Also it is mentioned that under conditions when the pressure of the discharge current intrinsic magnetic field exceeds the discharge gas kinetic pressure, there is no need to limit the working surface of the high-voltage electrode, since the dense plasma is displaced to the electrode end by the intrinsic magnetic field.

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## ВЛИЯНИЕ РАЗМЕРОВ ЭЛЕКТРОДОВ НА МОЩНОСТЬ САМОСТОЯТЕЛЬНОГО ПЛАЗМЕННО-ПУЧКОВОГО РАЗРЯДА


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Показана возможность увеличения активной мощности, локально вводимой в разряд, за счет уменьшения площади рабочей поверхности высоковольтного электрода в сильноточном импульсном плазменном диоде низкого давления. В условиях образования двойного электрического слоя в разряде достигается плотность мощности до 2 ГВт/см$^2$ при начальном энергозапасе до 200 Дж.


## ВПЛИВ РОЗМІРІВ ЕЛЕКТРОДІВ НА ПОТУЖНІСТЬ САМОСТІЙНОГО ПЛАЗМОВО-ПУЧКОВОГО РОЗРЯДУ


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Показана можливість збільшення активної потужності, що вводиться в розряд, за рахунок зменшення площі робочої поверхні високовольтного електрода в сильнострумовому імпульсному плазмовому діоді низького тиску. В умовах утворення подвійного електричного шару в розряді досягається густина потужності до 2 ГВт/см$^2$ при початковому енергозапасі до 200 Дж.