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Charge estimation at the output of the micro-hollow cathode discharge

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In this work, an experimental assessment of the amount of charge carried out from a coaxial plasma reactor with a micro-hollow cathode is carried out depending on the supply voltage and the rate of gas pumping through the active zone of the reactor. It is shown that the amount of charge carried out of the reactor is determined not only by the pumping of the gas discharge gap and the distance to the target, but also by the discharge mode. A comparative analysis of different power supply modes revealed a significant difference in the efficiency of charge generation and transport: under DC high voltage, the extracted charge is five times higher than that obtained in pulsed mode. This difference is attributed to both a higher discharge ignition frequency and longer duration of ionization processes in the continuous regime. At the same time, it has been demonstrated that combining a controllable pulsed high-voltage power supply with adjustable gas flow enables flexible control over the charge extraction dynamics, thereby providing the capability for precise, localized, and dose-controlled plasma treatment.

Keywords: micro-hollow cathode discharge; pumping; charge; discharge mode.

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Introduction

Plasma technologies using cold plasma are applied in various fields, including: medicine, agriculture, industry, materials production technologies, energy, and others [1–6]. There are different methods of cold plasma generation. The installations using surface and volume barrier discharges [7–9], and corona discharges [10, 11] are most common. Due to advanced applications as part of devices of illumination [12], micro-propulsion, and precision surface processing, there is significant interest in micron-sized plasma [13, 14], which can be generated in a microhollow cathode discharge, where the cathode contains a cavity tens to hundreds of microns in diameter [15]. Such a micro-discharge can be generated at the very low power consumed: single watts, even at the atmospheric pressure. Furthermore, the microhollow cathode

discharge can achieve power densities of up to 100 kW/cm³, making it a unique plasma source.

Typically, a process setup for cold plasma generation includes a plasma reactor with a system of electrodes with the electrical discharge burning between them, a high-voltage power source supplying this reactor, and a working medium flow system that transports the plasma from the reactor's active zone to the processing surface area. Air or inert gases (such as argon, neon, etc.) are often used as the working medium. The type of the high-voltage source is determined by the type of electrical discharge used in the in a given technology. High-voltage sources of both direct and sinusoidal industrial frequency voltage, as well as sources of pulses with various waveforms, are employed [16, 17, 18].

Depending on the design of the plasma reactor, electrode system, and presence of gas

flow, plasma sources are categorized as direct and indirect. In the case of a direct source, the plasma is generated between the electrodes, one of which is the object. In the case of an indirect source, the plasma is first generated within the reactor and then delivered to the object, which can be either at the floating or ground potential [19]. Indirect plasma sources are sometimes also referred to as plasma jets. The parameters of plasma jets, the transferred charge, and their composition depend both on the discharge parameters, voltage on the reactor electrodes, working medium flow rate rate, and on the target onto which the jet is

directed, its material, electrical potential, and distance from the source [18].

This paper evaluates the charge transported from a coaxial-design plasma reactor being pumped, where a microhollow cathode discharge is formed, when different voltage waveforms – direct current and rectangular nanosecond pulses – are applied to the reactor electrodes.

Experimental Setups

The diagram and photo of the experimental setup are shown in Fig. 1.

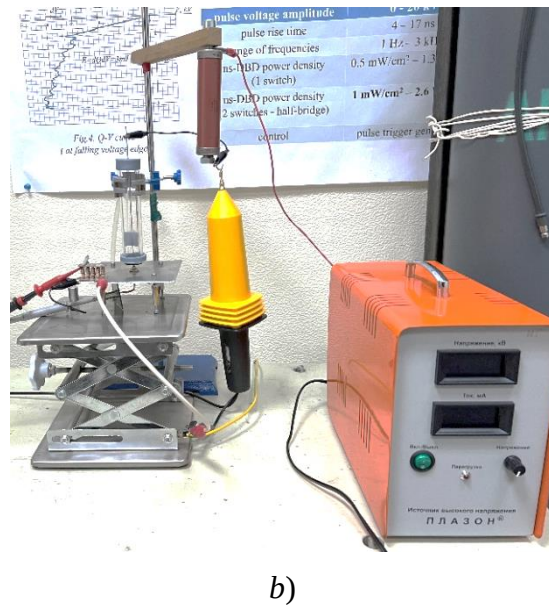
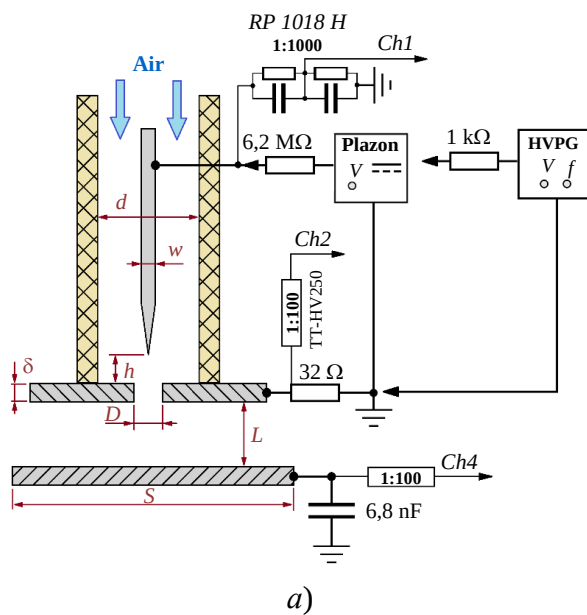


Fig. 1. Diagram (a) and photo (b) of the experimental setup

Two different high-voltage power sources were used in the experiments. Experiments of the first series used a high-voltage pulse generator (HVPG) capable of producing positive polarity pulses with the amplitude of up to 6 kV, duration of 600 ns, rise time of 25–30 ns, and repetition frequency from 100 Hz to 3 kHz [20]. Experiments of the second series used a DC high-voltage power source "Plazon" IVNR-30/10 with the maximum output voltage of up to 30 kV and load current of up to 10 mA. The discharge reactor consisted of a quartz glass tube with an internal diameter $d = 24$ mm, with a refractory tungsten needle with a diameter of $w = 1$ mm positioned in the center and sharpened on one end to a tip radius of $r \approx 0.2$ mm. The high voltage from the generator was applied to the needle via

the current-limiting resistor with the resistance of $1 \text{ k}\Omega$ resistor when powered by the HVPG and with the resistance of $6.2 \text{ M}\Omega$ when powered by Plazon power source, respectively. Perpendicular to the needle, at the distance of $h = 1$ mm, a flat electrode made of nickel foil with the thickness of $\delta = 0.15$ mm and having a hole with the diameter of $D = 1$ mm was positioned. The discharge was ignited between the needle and the flat nickel electrode. With the air pumped through the reactor tube and out through the cathode hole, discharge products were carried out directionally. The cathode was grounded through the $32 \text{ }\Omega$ shunt resistor. The voltage across the shunt was measured using TT-HV250 probe with an attenuation factor of 100 and fed into channel 2 of Keysight four-channel digital storage

oscilloscope featuring the 500 MHz bandwidth. The discharge current in the reactor was determined from the voltage drop across this shunt. The voltage drop across the reactor was measured directly at the positive high-voltage electrode (the needle) using high-voltage probe RP 1018 H with the attenuation factor of 1000. The signal from this probe was sent into channel 1 of the oscilloscope. At distance L from the reactor nozzle, a conductive circular target with the diameter of $S = 25$ mm was placed. To measure the charge, the target was grounded through high-voltage capacitor KVI-3 with the capacitance of 6800 pF. The voltage from this measuring capacitor was fed via the probe with the attenuation factor of 10 into channel 4 of the oscilloscope. Distance L from the cathode to the target varied.

Experimental Results

Based on the oscillographic measurements of the voltage across the measuring capacitor, the curves of the charge transported to the target vs. the air flow rate, $Q_{\text{trans}} = f(V)$, were obtained for the reactor supplied with both DC and pulse voltage. The air flow rate through the reactor was changed using a compressor.

It should be noted that when the reactor was powered by the DC voltage depending on the average current, the discharge was generated in two modes: self-pulsing mode at currents up to 1 mA, and continuous burning mode at higher currents, which was also observed in the studies [21, 22].

The curves of the transported charge at the fixed distance to the target for the self-pulsing mode and for powering with rectangular pulses are shown in Figure 2. The curves derived show that at equal air flow rates, the magnitude of the charge transported when the reactor is powered by a DC source is 5 times as high as the charge generated when the reactor is powered by a pulse voltage source.

This difference is partly related to the different discharge pulse frequencies. When powered by the pulse voltage source, the discharge ignition frequency in the plasma reactor was determined by the source's operating frequency (3 kHz), which is more than two times as low as the self-pulsing frequency (when powered by the DC source) (Fig. 3a). The discharge current pulse duration at half maximum was approximately 30–40 ns when powered by the DC source, while it was about 250 ns when powered by the pulse voltage source. In self-pulsing mode, the frequency is determined by the gap capacitance [22], which is characteristic of the microhollow cathode discharge. Furthermore, in self-pulsing mode, the voltage waveform across the discharge gap has a sawtooth shape due to the charging process of the system's intrinsic capacitance. During the gradual voltage growth, ionization processes begin slightly before the ignition voltage is reached, thus extending the charge accumulation time respectively.

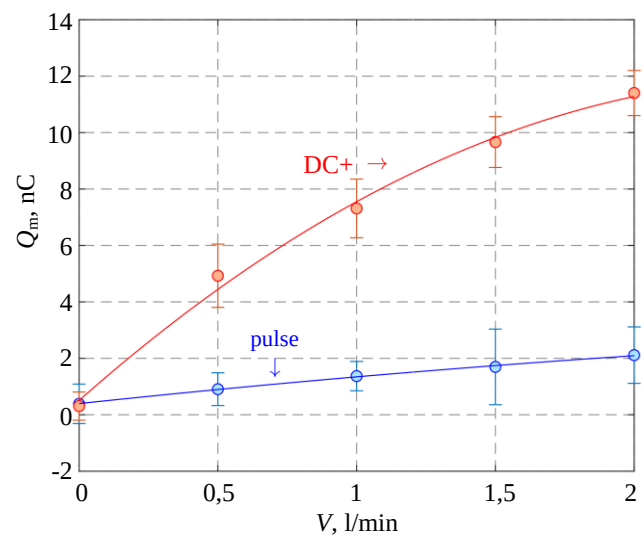


Fig. 2. The charge transported to the target vs. the flow rate through the reactor at the pulse (blue curve) and DC voltages of positive polarity (red curve) (distance to the target $L = 3$ mm)

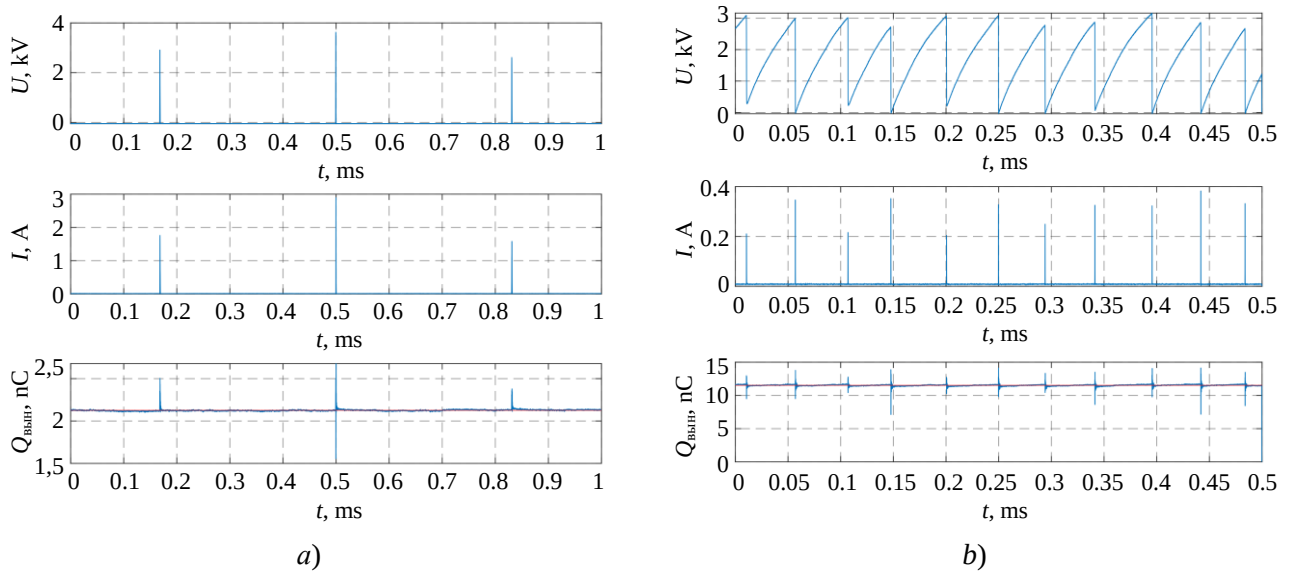


Fig. 3. Oscillograms of the voltage across the discharge gap, discharge current, and charge transported to the target at the air flow rate of 2 l/min, with the reactor powered by: (a) – HVPG, (b) – Plazon source

Based on the electrostatic field pattern in the reactor's active zone near the cathode at the atmospheric pressure and 30 % humidity, drift velocity of positive nitrogen ions V^{u+} was estimated.

The field pattern, as well as the graph of the electric field strength along the shortest field line (line No. 5 from the bottom), are shown in Figs. 4a and 4b, respectively. The electric field calculation was performed using BETAFIELDS software for finite-element modeling. The software uses high-order (second and third) triangular finite elements, and gradients are calculated by the SPR gradient recovery method

[23]. The calculation model accounted for the geometry of the electrode system and electrical properties of the reactor's construction materials. The model did not account for the space charge.

Since the electric field strength near the cathode surface is relatively weak being less than 1 kV/mm, the mobility can be considered constant, and the ion drift velocity can be assumed to depend linearly on the field strength. According to data of paper [24], under the conditions corresponding to the experiment, the mobility of positive nitrogen ions in air is $k_p = 1.42 \times 10^{-4} \text{ m}^2/(\text{V} \cdot \text{s})$.

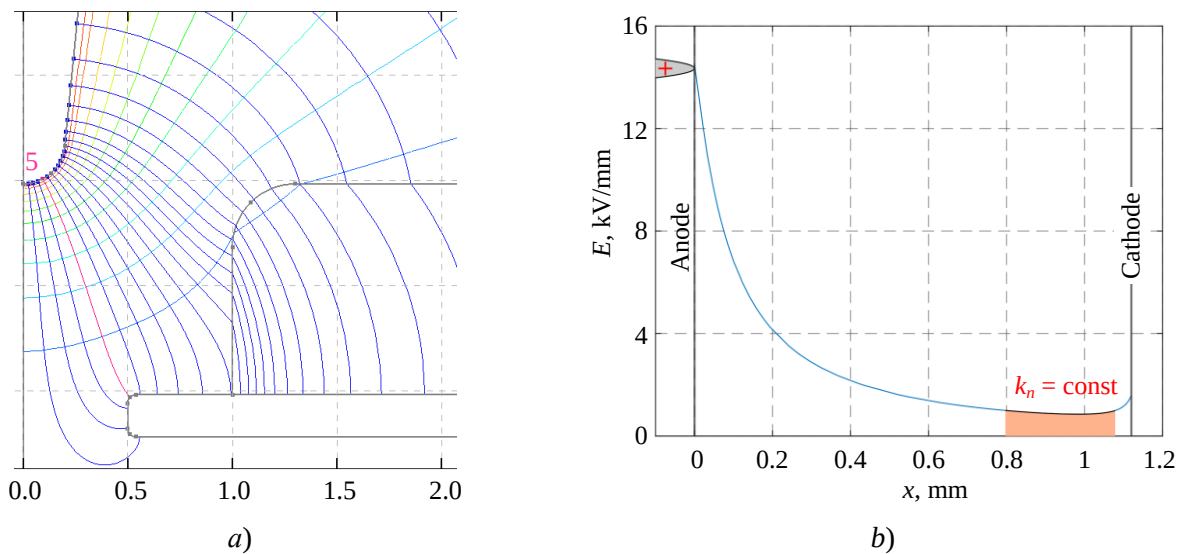


Fig. 4. Estimation of positive ion drift velocity: (a) – electric field pattern in the reactor's active zone, (b) – curve of the electric field strength along the shortest field line (line No. 5).

When inserting the values of the electric field strength and ion mobility, the characteristic drift velocity of positive ions near the cathode surface is approximately 120 m/s, which is only an order higher than the characteristic flow velocities of the pumped gas (42 m/s at the flow rate of 2 l/min).

Conclusion

An experimental evaluation of the charge transported from the coaxial plasma reactor with the microhollow cathode was conducted. The amount of charge was established to be directly dependent on the velocity of gas flow through the discharge gap. The charge amount was found to be different for different voltage waveforms applied to the reactor electrodes. When the reactor was powered by the DC voltage source,

the magnitude of the transported charge was 5 times higher than the charge obtained when powered by the pulse voltage source, which is explained by the larger number of discharge ignition events within a fixed time interval, as well as by the longer duration of ionization processes. However, despite the efficient charge generation using the high-voltage DC source, the use of the regulated high-voltage pulse source combined with the adjustment of the air flow rate through the reactor could allow controlling the dynamics of the transported charge accumulation process. This, in turn, can be useful, for example, for ensuring localized treatment of surfaces made from the most sensitive materials.

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