04

Study of extracted ion current distribution during counter development of surface dielectric barrier discharge channels

© V.V. Voevodin[1,2], O.I. Korzhova[1], V.Yu. Khomich[1], V.A. Yamshchikov[1]

[1] Institute for Electrophysics and Electric Power, Russian Academy of Sciences, St. Petersburg, Russia
[2] Kutateladze Institute of Thermophysics, Siberian Branch, Russian Academy of Sciences, Novosibirsk, Russia
E-mail: vvvoevodin@ieeras.ru

Received July 23, 2024
Revised October 7, 2024
Accepted October 7, 2024

This paper presents the registration of the spatio-temporal distribution of ion current extracted from dielectric barrier discharge plasma during counter development of its channels. The influence of the distance between discharge electrodes and the polarity of the high voltage on this distribution is shown.

Keywords: dielectric barrier discharge, extracted ion current, pulse voltage, electrohydrodynamics.

DOI: 10.61011/TPL.2025.02.60627.20069

Surface dielectric barrier discharge (SDBD) has been studied extensively for several decades both in Russia and abroad and has found application in various technological processes in air at atmospheric pressure in fields ranging from air flow control to biotechnology [1–3]. A SDBD electrode system normally consists of two electrodes (a wide substrate and a plasma-generating narrow strip electrode) separated by a dielectric (hereinafter referred to as a barrier). An electrode configuration with an additional third electrode placed above the barrier surface and producing the so-called „extracting" electric field [4] has been reported in literature. It enables the production of a directed flux of ions and chemically active particles from the discharge area and high-power electrohydrodynamic flows. The generated ion current is often measured with the use of pointer microammeters [4,5], which do not allow one to evaluate its temporal characteristics.

The area occupied by the discharge plays an important role in plasma technologies. The width of the SDBD zone under atmospheric conditions is limited by a distance of 2–5 mm from the plasma-generating electrode [6,7], which is attributable to the processes of charging of the barrier by ions deposited on it in the development of the discharge. In an effort to increase the area occupied by plasma, experimenters install several parallel plasma-generating electrodes at distance L from each other [6,8]. Research shows that distance L has a direct effect on the electrical characteristics of SDBD due to the interaction of counter discharge channels [9]. In the three-electrode SDBD system, this influence also manifests itself in the characteristics of generated ion current. Indirect measurements of the ion current for SDBD powered by a high-frequency sinusoidal voltage were performed in [5,10]. It was found that the nature of the spatial distribution of extracted charged particles varied with L. At the same time, we know of no published reports on direct measurements of the spatiotemporal distribution of ion current (in particular, measurements for discharges with pulsed supply).

In view of this, it appears relevant to measure such a distribution in experiments at the already constructed setup with a segmented third electrode [11] with SDBD powered by voltage pulses with a nanosecond rise time.

Two designs of a planar electrode system (Fig. 1) with two parallel plasma-generating electrodes *1* made of copper (with a thickness of 50 μm and a working length of 45 mm) spaced by $L = 10$ and 5 mm were used in the present study. The distance from the surface of the dielectric barrier made of 22KhS alumina ceramics to third electrode *3* was 1 cm. The third electrode consisted of twelve 0.5-mm-wide insulated copper strip segments spaced by 0.5 mm. Constant bias voltage U_{DC} was applied to the plasma-generating electrodes and substrate electrode *2* in order to produce a field that extracts ions. Voltage stability was maintained by a high-voltage capacitor (C = 100 nF). The discharge voltage at the electrodes was produced by a pulse generator [12] by short-circuiting them to ground for $\tau = 500$ ns with frequency $f = 2$ Hz; the voltage fall time was 50 ns. The voltage at electrodes *1* connected through a TVO resistor ($R = 1\,\mathrm{k\Omega}$) recovered to U_{DC} in 400 ns and was recorded with the use of a Tektronix P6015A divider. An electronic four-channel nanoammeter designed at the Institute for Electrophysics and Electric Power of the Russian Academy of Sciences was used to measure the spatiotemporal distribution of ion current [11]. Segments of the third electrode were connected to a multiplexor and grounded one by one through the nanoammeter channels. The segments not involved in current recording were grounded bypassing the meter. Horizontal distance D from each segment was measured from the edge of the first plasma-generating electrode. Nanoammeter signals were recorded and logged using a LeCroy Waverunner 104Xi-A oscilloscope. Experiments were performed in atmospheric air at a relative humidity of $30 \pm 4\%$ and a temperature

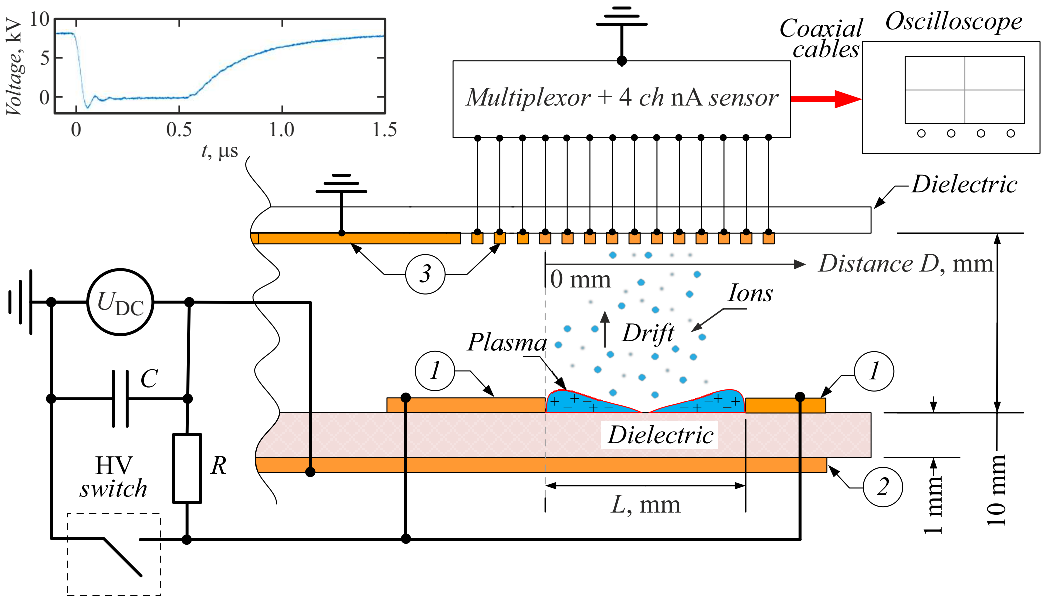

Figure 1. Diagram of the experimental setup and the electrode system. *1* — Plasma-generating electrodes (the corresponding oscilloscope record of voltage is shown in the inset at the top left), *2* — underlying electrode, *3* — third electrode, $C = 100\,\mathrm{nF}$, $R = 1\,\mathrm{k\Omega}$, $U_{DC} = \pm 8\,\mathrm{kV}$ — DC high-voltage source, D — horizontal distance from the edge of the plasma-generating electrode along the third electrode, and $L = 5$, $10\,\mathrm{mm}$ — distance between the plasma-generating electrodes.

of $22 \pm 3°$C. The measuring circuit was calibrated prior to these experiments.

A surface (Fig. 2) reflecting the current amplitude distribution (shown in color) in time and space was plotted based on the oscilloscope records of ion current flowing through the segments. The initial discrete spatial distribution was smoothed during processing with spline interpolation. The recording of nanoammeter signals was started at the moment of closing the high-voltage switch and formation of a voltage pulse at the plasma-generating electrodes. When the oscilloscope records were processed, the time interval from 0 to $20\,\mu$s was cut due to interference induced by capacitive coupling between the third electrode and the plasma-generating electrodes. Integration of the ion current over time allowed us to determine total charge Q_Σ of ions that have reached the third electrode.

The obtained patterns (Fig. 2) revealed that the nature of the distribution of ion current along the third electrode depends on the polarity of applied voltage U_{DC} and is also affected by distance L between the plasma-generating electrodes. With a positive U_{DC} polarity, a displacement current with an amplitude of 100–300 nA induced by the ion cloud motion in the barrier–third electrode gap is recorded within the time interval of $20{-}50\,\mu$s (Figs. 2, a, c). The ion current maximum at $80{-}100\,\mu$s corresponds to the arrival of the main part of positive charge at the measuring segments [11]. Negative particles reach the third electrode approximately $50\,\mu$s earlier (Figs. 2, b, d). This may be attributed to the difference in type of extracted charged particles, since it is known from literature data for humid air that positive $[H_3O^+] \cdot (H_2O)_n$ and negative $[CO_3^-] \cdot (H_2O)_n$, $[O_2^-] \cdot (H_2O)_n$ cluster ions [13] with a mobility of 1.4 and $1.7\,\mathrm{cm^2/(V \cdot s)}$, respectively, are dominant in the drift zone within the considered time interval [14]. Some researchers have suggested the presence of an electronic component in the recorded current [14,15], but pulse interference in the setup has prevented us from drawing any conclusions in this regard.

The amplitude of ion current and total charge Q_Σ recoded at a negative U_{DC} polarity are 1.3–2 and 1.9–3 times higher, respectively, than the values corresponding to its positive polarity. The amplitude data are consistent with the results of other studies in which ion current was measured in a three-electrode configuration [5]. This effect may be attributed to the differences in SDBD structure at different voltage polarities. In the case of $-U_{DC}$, a positive pulse front emerges at electrodes *1* (Fig. 1) when the switch is closed. This corresponds to a pronounced channel SDBD structure, while a more uniform (diffuse) discharge structure forms at a negative pulse front at $+U_{DC}$ [6,7]. The channel discharge form is less susceptible to the self-limiting effect [8]; under otherwise equal conditions, the width of its discharge zone may exceed that of a diffuse discharge by a factor of 1.4.

Two spatial components with a width of 4.5 mm may be identified in the obtained current distribution (Fig. 2) at $L = 10$ mm. Apparently, they are induced by the extraction of charge from the region of development of counter channels from the electrodes. Notably, the quantitative distribution of current of individual components is similar to the one obtained earlier for a system with a single plasma-generating electrode [11]. The non-uniformity of this distribution was caused by distortion of the electric

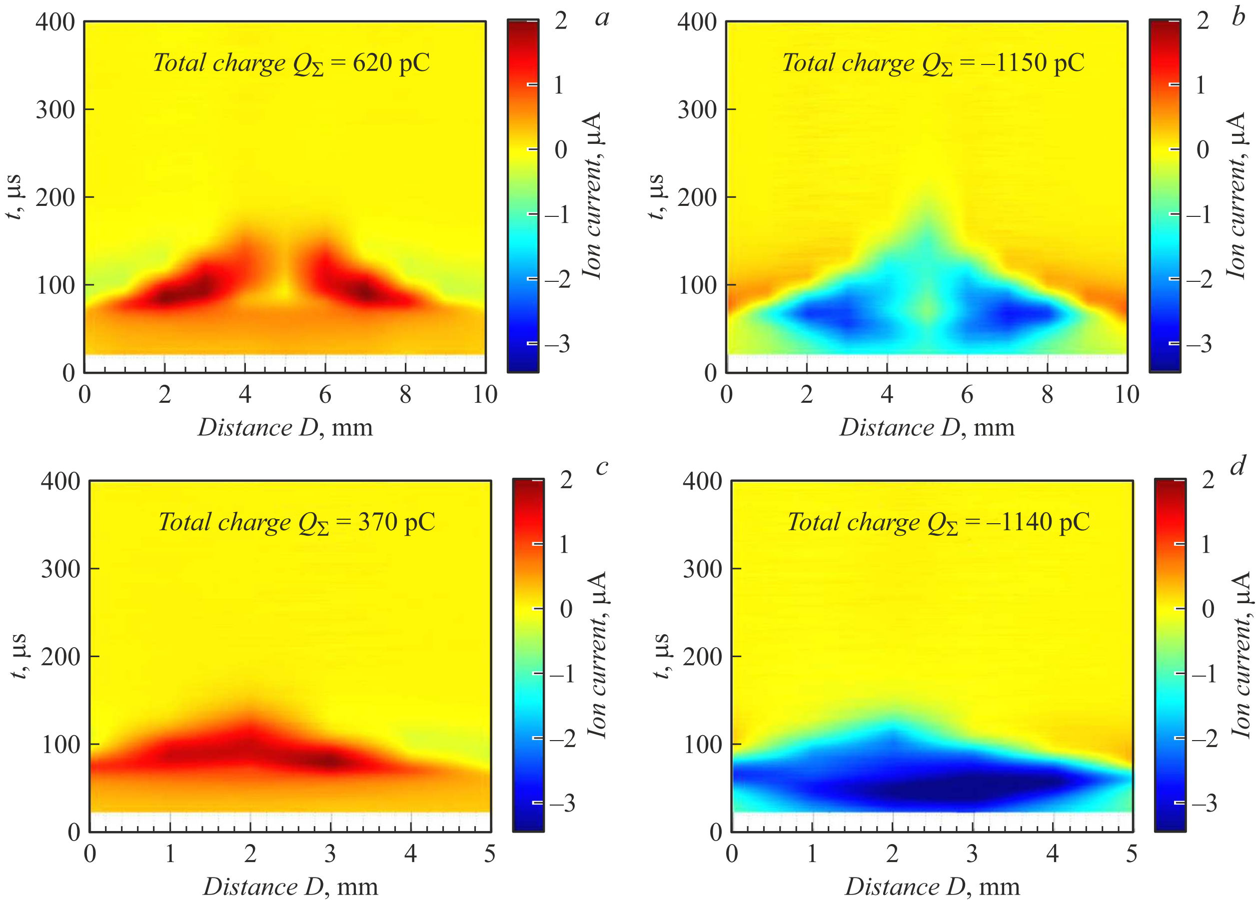

Figure 2. Spatiotemporal distribution of ion current at $U_{\mathrm{DC}} = \pm 8$ kV. *a* — $L = 10$ mm, $+8$ kV; *b* — $L = 10$ mm, -8 kV; *c* — $L = 5$ mm, $+8$ kV; *d* — $L = 5$ mm, -8 kV. A color version of the figure is provided in the online version of the paper.

field in the drift gap by a charge deposited on the barrier with its surface density being as high as 20 nC/cm^2 [11]. When interelectrode distance L decreases to 5 mm, the ion current distribution along the D axis becomes significantly more uniform (Figs. 2, *c*, *d*), and the distribution center gets positioned at a distance of 2–2.5 mm from the plasma-generating electrodes. Its slight displacement (± 0.5 mm) toward one of the electrodes may suggest the need to increase the spatial resolution in further measurements at $L \leqslant 5$ mm by reducing the width of the measuring segments and increasing their number. The enhancement of uniformity of the ion current distribution may also be a consequence of contraction of the region within which the charge deposited on the barrier is not neutralized by a back discharge initiated at the trailing edge of a voltage pulse [6]. As a result, an ion cloud drifting from the barrier is not deformed under the influence of the field of the deposited charge. At a negative U_{DC} polarity, the maximum current value and the total charge increase by a factor of 1.4 and 3, respectively, compared to the case of $L = 10$ mm, which may be attributed to the combined influence of the factor described above and the greater mobility of negative particles.

The obtained data may be used in further studies into the application of surface dielectric barrier discharge as a source of charged particles and for control of gas flows.

Funding

This study was supported financially by the Ministry of Science and Higher Education of the Russian Federation (agreement No. 075-15-2024-543 dated April 24, 2024).

Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] E. Moreau, J. Phys. D: Appl. Phys., **40** (3), 605 (2007). DOI: 10.1088/0022-3727/40/3/S01

[2] S.I. Moshkunov, S.V. Nebogatkin, I.E. Rebrov, V.Yu. Khomich, V.A. Yamshchikov, Plasma Phys. Rep., **38** (13), 1040 (2012).

[3] B.K.H.L. Boekema, M. Vlig, D. Guijt, K. Hijnen, S. Hofmann, P. Smits, A. Sobota, E.M. van Veldhuizen, P. Bruggeman, E. Middelkoop, J. Phys. D: Appl. Phys., **49** (4), 044001 (2016). DOI: 10.1088/0022-3727/49/4/044001

[4] S. Müller, R.-J. Zahn, J. Grundmann, Plasma Process. Polym., **4** (S1), S1004 (2007). DOI: 10.1002/ppap.200732317
[5] S.A. Krivov, I.A. Moralev, A.V. Lazukin, I.V. Selivonin, IEEE Trans. Plasma Sci., **48** (7), 2442 (2020). DOI: 10.1109/TPS.2020.2997979
[6] M.V. Kozlov, M.V. Sokolova, A.G. Temnikov, V.V. Timatkov, I.P. Vereshchagin, Plasmas Polym., **8** (3), 179 (2003). DOI: 10.1023/A:1024809205202
[7] M.V. Sokolova, V.V. Voevodin, Ju.I. Malakhov, N.L. Aleksandrov, E.M. Anokhin, V.R. Soloviev, J. Phys. D: Appl. Phys., **52** (32), 324001 (2019). DOI: 10.1088/1361-6463/ab20ef
[8] A.V. Lazukin, I.V. Selivonin, M.E. Pinchuk, I.A. Moralev, S.A. Krivov, Izv. Vyssh. Uchebn. Zaved., Fiz., **61** (9-2), 152 (2018) (in Russian).
[9] A.V. Lazukin, A.M. Nikitin, G.A. Romanov, Tech. Phys. Lett., **48** (13), 34 (2022). DOI: 10.21883/TPL.2022.13.53567.18812
[10] G. Neretti, A.C. Ricchiuto, C.A. Borghi, J. Phys. D: Appl. Phys., **51** (32), 324004 (2018). DOI: 10.1088/1361-6463/aacfcb
[11] V.Yu. Khomich, I.E. Rebrov, V.V. Voevodin, V.A. Yamshchikov, Ya.E. Zharkov, J. Phys. D: Appl. Phys., **55** (27), 275204 (2022). DOI: 10.1088/1361-6463/ac6548
[12] M.V. Malashin, S.I. Moshkunov, I.E. Rebrov, V.Yu. Khomich, E.A. Shershunova, Instrum. Exp. Tech., **57** (2), 140 (2014). DOI: 10.1134/S0020441214010242.
[13] M.J. Johnson, D.B. Go, Plasma Sources Sci. Technol., **27** (5), 059501 (2018). DOI: 10.1088/1361-6595/aa88e7
[14] B. Zhang, J. He, Y. Ji, IEEE Trans. Dielectr. Electr. Insul., **24** (2), 923 (2017). DOI: 10.1109/TDEI.2017.006542
[15] C.A.P. Zevenhoven, R.D.J. Wierenga, B. Scarlett, H. Yamamoto, J. Electrostat., **32** (2), 133 (1994). DOI: 10.1016/0304-3886(94)90004-3

Translated by D.Safin