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THE EFFICIENCY OF A FOCUSING SYSTEM BASED ON THIN DIAPHRAGMS IN THE ION SOURCE WITH A CORONA DISCHARGE

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Abstract. In this work, a charged particle beam transport in an ion source with a corona discharge, the source being equipped with a focusing system based on thin diaphragms in the standing gas and at atmospheric pressure, has been studied experimentally. The efficiency of the ion beam transportation through the focusing system was shown to depend on the distance between the corona needle and the diaphragm system, on the potential difference between the diaphragms of the focusing system and on the value of the corona discharge current. The results of comparing the efficiency of the ion beam transport in the ion source with using the focusing system and without it are presented. The use of the focusing system allowed to increase several times the current entering the collector through the diaphragm of the smallest diameter, and to raise the current entering the plane of this diaphragm by an order of magnitude.

Keywords: ion source, mass spectrometer, corona discharge, focusing system, ion transport

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ЭФФЕКТИВНОСТЬ ФОКУСИРУЮЩЕЙ СИСТЕМЫ НА ОСНОВЕ ТОНКИХ ДИАФРАГМ В ИОННОМ ИСТОЧНИКЕ С КОРОННЫМ РАЗРЯДОМ

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Аннотация. Проведено экспериментальное исследование транспортировки пучка заряженных частиц в ионном источнике с коронным разрядом с фокусирующей системой на основе тонких диафрагм в стоячем газе при атмосферном давлении. Показано, что эффективность транспортировки ионного пучка через систему фокусировки зависит от расстояния от коронирующего острия до системы диафрагм, разности потенциалов между диафрагмами фокусирующей системы и величины тока коронного разряда. Представлены результаты сравнения эффективности транспортировки ионного пучка в ионном источнике с фокусирующей системой и без нее. Использование фокусирующей системы позволяет в несколько раз увеличить ток, приходящий на коллектор через диафрагму наименьшего диаметра, и повысить на порядок ток, приходящий на плоскость этой диафрагмы.

Ключевые слова: ионный источник, масс-спектрометр, коронный разряд, фокусирующая система, транспортировка ионов

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Introduction

Atmospheric pressure ionization sources have long been widespread in mass spectrometry for solving problems of organic and bioorganic chemistry, pharmacology, proteomics, ecology, and so on [1–3].

The sensitivity of a mass spectrometer depends on the transport efficiency of the ion source with atmospheric pressure injecting ions into the high-vacuum mass analyzer through a gas interface consisting of a differential pumping system (DPS) with ion optics. While ion losses are observed at all stages of the DPS, the maximum losses of the ion beam occur during transition from the region with atmospheric pressure through the nozzle to the first stage of the DPS and can amount to two orders of magnitude or more of the total current of the ion source [4].

A promising technique reducing ion losses is to focus the ion beam onto the nozzle. Such focusing was carried out in [5] by placing a hemispherical grid electrode between the spray capillary and the nozzle. This solution had a number of drawbacks, in particular, limited transparency of the grids and distortion of the field structure due to deposition of microdrops. The ion beam in the experiments in [6–8] was focused by an additional electrode (aperture) installed in front of the nozzle; the thickness-to-diameter ratio of the aperture ranged from 1 to 5.

However, the numerical simulations of ion trajectories in electrostatic fields in dense gas indicate that focused ion beam systems based on thin apertures have the best potential in terms of focusing efficiency (the above ratio should be several tens). Theoptical setup of such a focusing system is considered in [9], proposing an electrode configuration based on thin apertures (0.1 mm thick) with decreasing opening diameters. The reason why the thinnest possible apertures were chosen is that the system has more pronounced focusing properties due to the absence of local defocusing regions in the aperture channels.

In this paper, we experimentally considered the procedure for increasing the transport efficiency of an ion beam using a focusing system based on thin apertures in a source with a corona discharge in a stagnant gas. This is intended to improve the transport efficiency by focusing the ions in an electrostatic field. The aperture of the focusing system with the smallest diameter becomes a nozzle separating the atmospheric pressure region from the first stage of the SDO in the gas interface of the mass spectrometer.

Ion optics of focusing system based on thin apertures in source with corona discharge

The ion optics of the experimentally investigated focusing system based on thin apertureus in a source with corona discharge source is shown in Fig. 1. The setup consists of a corona point (needle), four thin apertures (d_1–d_4) 0.1 mm thick with decreasing opening sizes and a planar electrode serving as a collector. The sizes of aperture openings, in descending order, are 4.00 mm; 2.65 mm; 1.20 mm and 0.50 mm. The distances between the thin apertures and the distance between the last aperture and the collector are 1 mm. A potential U_n is applied to the corona point to ignite the discharge, and some pulling potential U_c is applied to the collector. Aperture *4*, which has the smallest diameter, separates the region with atmospheric pressure from the first stage of the DPS and acts as the nozzle.

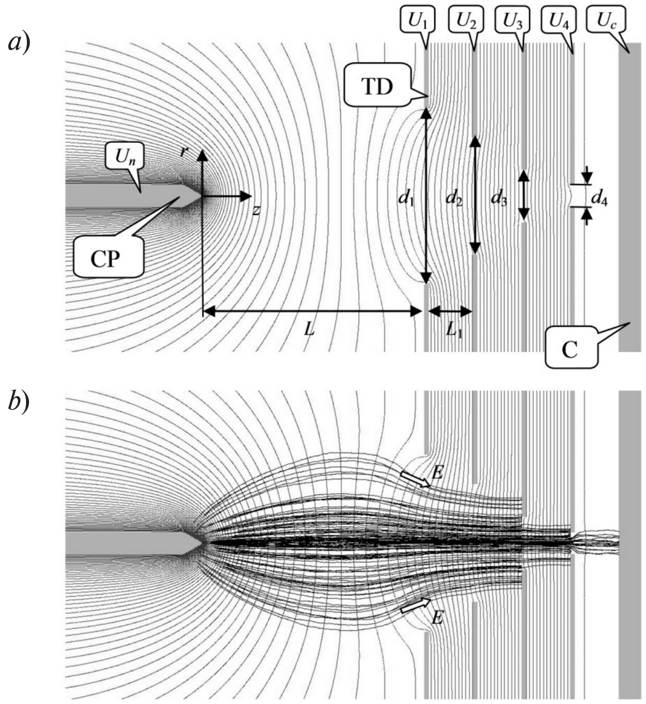

Fig. 1. Ion optics of focusing system based on thin apertures (*a*); trajectories of positively charged ions (*b*): corona point (needle) CP, set of thin apertures TD (d_1–d_4), collector C; equipotential lines of the electrostatic field E in the plane passing through the optical axis. Geometrical and electrical parameters of the setup: $L = 5$ mm, $L_1 = 1$ mm, $d_1 = 4$ mm, $d_2 = 2.65$ mm, $d_3 = 1.2$ mm, $d_4 = 0.5$ mm, $U_n = 7$ kV, $U_1 = 3$ kV, $U_2 = 2$ kV, $U_3 = 1$ kV, $U_4 = 0$ V, $U_c = -1$ kV. The thickness of the apertures *1*–*4* is 0.1 mm

If the same potential difference between adjacent apertures $\Delta U < 0$ ($\Delta U = U_{i+1} - U_i$, $i = 1 - 3$) is applied for positively charged ions, the system in question has focusing properties, since the electrostatic field strength in the gaps between adjacent apertures increases due to a decrease in aperture diameters. Fig. 1 also shows the equipotential lines of the electrostatic field in a plane passing through the optical axis, as well as the trajectories of positively charged ions; the geometric and electrical parameters of the ion optical setup and their values are given in the caption.

Numerical simulation of the electrostatic field and trajectories of charged particles in a dense gas (air) under normal conditions ($T = 300$ K, $p = 760$ Torr) without taking into account the effects introduced by the space charge was carried out in the SIMION 8.0 software package [10] using statistical diffusion simulation (SDS) [11], a user program that is part of the package Positive nitrogen ions ($m = 14$ u) with an initial spherical spatial distribution ($d = 1.5$ mm) were taken as a model beam.

Notably, the focusing properties of the given ion optical setup depend on the magnitude of the potential difference ΔU applied between thin apertures: the focusing properties are enhanced with increasing ΔU, and weaken with decreasing ΔU. The computations for the ion optical setup considered indicate that the proportion of ions entering the collector is about 4.2%, and about 27% in the plane of the aperture with the smallest diameter (d_4 = 0.5 mm).

Experimental setup

Fig. 2 shows the experimental setup constructed to study the transport efficiency of the ion beam in a source with a focusing system.

The setup incorporates the ion optics of the focusing system described above, consisting of a corona point (needle) *7*, a coaxially arranged system of thin apertures *1–4* 0.1 mm thick and a collector *5*. The diameter of the opening in the first aperture (*1*) is 4 mm, 2.65 mm in the second (*2*), 1.2 mm in the third (*3*), 0.5 mm in the fourth (*4*). All the apertures are insulated from each other and from collector *5* by ceramic inserts *6* 1 mm thick. Electrodes *1–3* and *5*, *7* of the experimental setup have independent power supply from regulated highly stable high-voltage power supplies *20–24*. Zero potential is applied to aperture *4*.

All electrodes of the system are also connected to electrometer amplifiers with gain coefficients from $10^{-6}$to 10^{-8}A/V, allowing to measure the current flowing through the electrodes. The corona point is mounted on a platform with a mechanical drive allowing to vary the distance from the point to the nearest aperture of the focusing system.

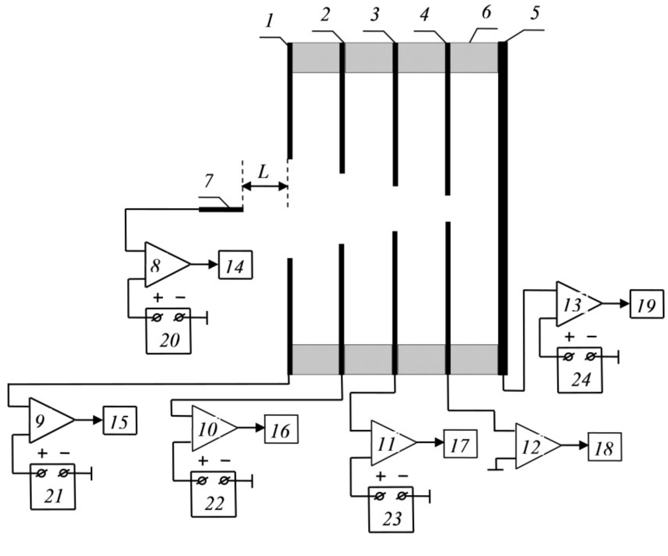

Fig. 2. Experimental setup with ion beam focusing in a system of thin apertures:
thin apertures *1–4*, collector *5*, ceramic inserts *6*, corona point (needle) *7*, electrometers *8–13*, digital current meters 14–19, highly stable high-voltage power supplies *20–24*. Thin apertures are 0.1 mm thick, ceramic inserts are 1 mm thick

Computational results and discussion

The experiment was aimed at studying ion beam transport in the system described above (see Figs. 1 and 2) with varying electrical and geometric parameters, namely:

ΔU is the value of the potential difference between the apertures,

I_d is the corona discharge current,

L is the distance from the corona point to the nearest aperture.

The current balance condition in the system was monitored during all experimental measurements; the condition is satisfied if the discharge current is equal to the sum of the currents flowing into the apertures and the collector. The obtained experimental dependences were reproduced with sufficient accuracy (<10%) in independent series of measurements.

Fig. 3, *a* and *b* shows the current in the collector I_c and the sum of the currents in the fourth apperture and the collector $I_4 + I_c$ as functions of collector potential U_c at different potential differences ΔU between the apertures for a positive corona discharge current $I_d = 1$ μA and a distance $L = 6$ mm. The collector potential was varied in the range from 0 to −1000 V, and ΔU in the range from −300 to −900 V. In practice, the maximum value of $\Delta U = -900$ V was limited by the condition of electrical breakdown between the apertures at atmospheric pressure.

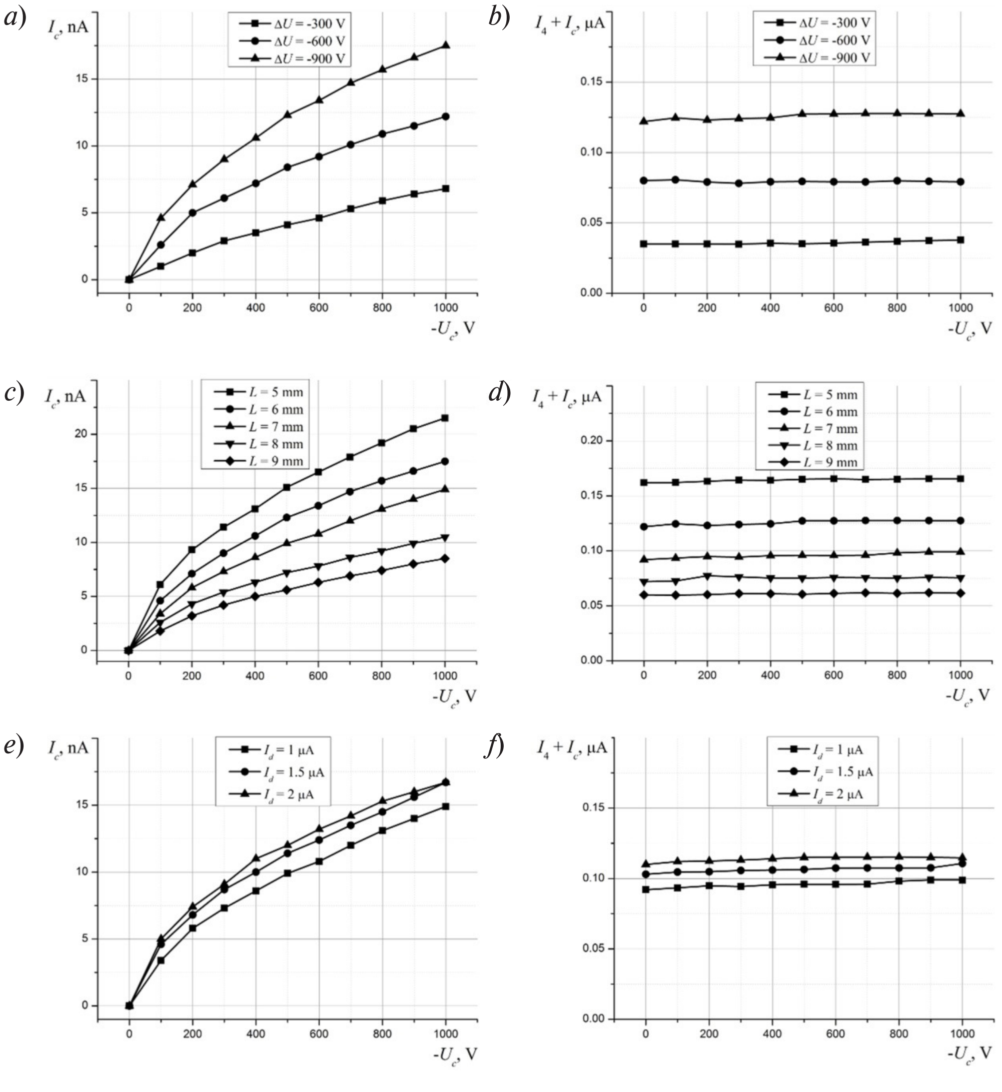

Fig. 3. Current characteristics of ion source with focusing system for varied parameters ΔU (*a*, *b*), L (*c*, *d*) and I_d (*e*, *f*).
The figure shows the dependences for the collector current I_c (*a*, *c*, *e*) and the sum of currents $I_4 + I_c$ (*b*, *d*, *f*) on the collector potential U_c at fixed $I_d = 1$ μA and $L = 6$ mm (*a*, *b*), $\Delta U = -900$ V and $I_d = 1$ μA (*c*, *d*), $\Delta U = -900$ V and $L = 7$ mm (*e*, *f*)

Analyzing the obtained experimental results, we found that the potential difference between the apertures ΔU has a significant effect on the redistribution of currents in the apertures of the system, which is consistent with the results of numerical simulation. If the potential difference between the apertures ΔU is increased, the focusing properties of the system are enhanced: the currents I_1 and I_2 flowing into the first and second apertures decrease, while the currents I_3 and I_4 flowing into the third and fourth apertures as well as the current I_c flowing into the collector, increase. An increase in the potential difference ΔU from −300 to −900 V allows to achieve an increase in the current in the collector I_c by about 2.5 times and the sum of the currents flowing into aperture *4* and collector $I_4 + I_c$, by about 3.5 times for the collector voltage $U_c = -1000$ V.

We should also note that varying the collector voltage has no apparent effect on the redistribution of current between the first three apertures, only affecting the redistribution of current between the fourth aperture and the collector.

Fig. 3, *c* and *d* shows the current in the collector I_c and the sum of currents in the fourth aperture and collector $I_4 + I_c$ as functions of collector potential U_c for different distances L from the corona point to the first aperture at the corona discharge current $I_d = 1$ μA and the potential difference between the apertures of the focusing system $\Delta U = -900$ V. As follows from the dependences presented, the transport efficiency of the ion beam to the fourth aperture and to the collector deteriorates with increasing L: the maximum values of the collector current I_c and the sum of currents $I_4 + I_c$ decrease by about 2.5 times with increasing distance from the corona point to the apertures from 5 to 9 mm. This effect is explained by an increase in the length of the defocusing segment of the field in the vicinity of the ion source when the corona point is removed from the aperture system.

Fig. 3, *e* and *f* shows the experimental dependences for currents I_c and $I_4 + I_c$ on the collector potential U_c for different values of the corona discharge current I_d. If the corona discharge current is increased by two times from 1 to 2 μA, the current in the collector I_c and the sum of the currents $I_4 + I_c$ increase in absolute magnitude but very slightly (by 1.15 times). However, the ratios of currents I_c and $I_4 + I_c$ to the corona discharge current I_d fall by about 1.7 times. The observed deterioration in the transport efficiency of the ion beam with an increase in the corona discharge current is undoubtedly due to enhanced space charge effects, accompanied by spatial broadening of the ion beam.

It is logical to compare the beam transport efficiency in a corona discharge ion source with a focusing system to that in a source without a focusing system. For this purpose, the focusing system with thin apertures was modified by replacing ceramic inserts between the apertures with PTFE gaskets 0.1 mm thick. A quasiplanar concentric-ring counterelectrode under zero potential was thus constructed from the initial aperture system. The modified experimental setup is shown in Fig. 4.

The beam transport efficiencies in the initial (see Fig. 2) and the modified (Fig. 4) system were compared at equal distances L from the corona point to the nearest apertures. Fig. 5 shows a comparison of the currents in the collector I_c and the sum of the currents $I_4 + I_c$ in the ion source with a focusing system (for $\Delta U = -900$ V, which provided the maximum possible focusing effect) and without it for different values of the corona discharge current I_d and distances L from the corona point to the nearest aperture. These experimental results point to a noticeable increase in the magnitude of the current I_c flowing from the collector in the setup with a focused beam which increases by 3.0–3.7 times (depending on the experimental conditions). The sum of the currents $I_4 + I_c$ flowing into the fourth aperture and collector in the focusing geometry exceeds that for an ion source without focusing by about an order of magnitude (by 8.3–11.1 times).

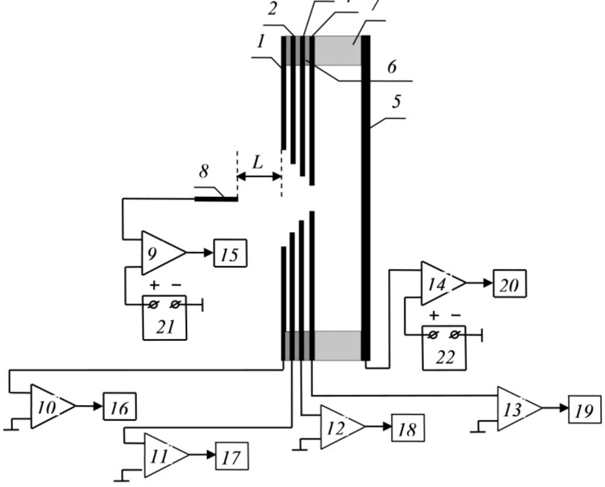

Fig. 4. Modified experimental setup with quasiplanar counterelectrode:
thin apertures *1–4*, collector *5*, PTFE gaskets *6*, ceramic *7*, corona point (needle) *8*, electrometers *9–14*, digital current meters *15–20*, highly stable high-voltage power supplies *21* and *22*.
Thin apertures and PTFE gaskets are 0.1 mm thick, the ceramic insert is 1 mm thick

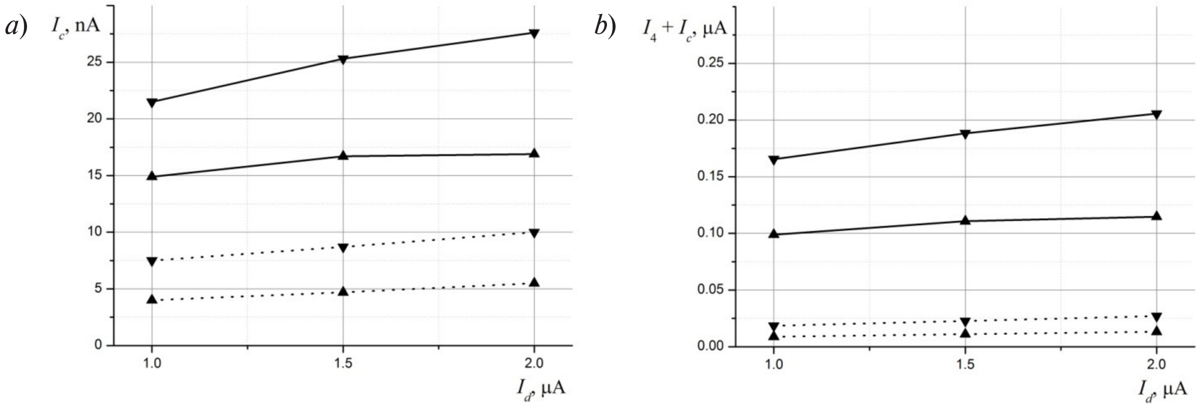

Fig. 5. Comparison for dependences of current in the collector I_c (*a*) and sum of currents $I_4 + I_c$ (*b*) in the ion source on discharge current I_d obtained with the focusing system ($\Delta U = -900$ V, solid lines) and without it (dotted lines) at distances $L = 7$ mm (▲) and 5 mm (▼)

In general, the focusing system in the ion source with corona discharge allows transporting up to 2% of the corona discharge current to the collector through the aperture with the smallest diameter (aperture 4) and up to 15% of the discharge current to the plane of aperture 4 in stagnant gas.

Conclusion

We experimentally studied the properties of a focusing system based on thin apertures in an ion source with corona discharge (the system is proposed in [9]). We obtained the experimental dependences characterizing the influence of the system's geometric and electrical parameters on the efficiency of ion transport. This efficiency increases with an increase in the potential difference between the apertures and decreases with an increase in the corona discharge current and the distance from the corona needle to the aperture system. Comparing the efficiency of ion transport in ion sources with and without a focusing system shows that focusing the ion beam produces a threefold increase in the collector current and an increase by about an order of magnitude in the sum of currents flowing into the aperture with the smallest diameter and the collector. This proves that the correct approach was taken to configure the geometry of the focusing system.

A logical extension of this paper is a study into ion beam transport in an aperture system accounting for gas flow in the vicinity of the inlet nozzle of the gas interface in the mass spectrometer.

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