Plasma source based on ring-shaped anode layer thruster for a bipolar electron-optical system

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Abstract. The conceptual design of pulsed plasma source for plasma-optic application and materials modification are investigated. The source is based on plasma thruster’s technology, that were developed by Goncharov’s group in Institute of Physics (Kiev, Ukraine). The plasma device with its two modified closed-drift anode layer thrusters can operate in low-current high-voltage mode and in high-current plasma mode. Most attention in the paper is focused on the latter mode being similar to a glow discharge with a positive column. The study shows that under certain conditions, the discharge with closed electron drift can be accompanied by non-self-sustained hollow-cathode discharges with oscillating electrons which greatly decrease the auxiliary discharge voltage. Presented in the paper the current–voltage characteristics of this type of high-current discharge and the spatial distributions of plasma parameters are measured in the discharge region with double Langmuir probe techniques. The maximum plasma densities on the central cathode axis are (6.5÷6.8)×10¹² cm⁻³.

1. Introduction

Closed-drift plasma thrusters with a short acceleration zone, termed an anode layer, are used in gridless ion sources [1] suitable for surface finishing, polymer etching, and synthesis of different coatings, e.g., diamond-like carbon films. Because of the space charge compensation by electrons magnetically confined in the anode layer, this type of ion sources provides higher ion beam current densities compared to similar sources with several grids or with a multi-aperture ion-optical system. The main physical processes developing in discharge systems of anode layer plasma thrusters are quite well understood [1–4]. In an anode layer thruster, two discharge modes are possible. In one of the modes, the current–voltage characteristic is linear, the discharge current is relatively low and increases monotonically with applied voltage, and most of the discharge in which ions are produced falls on a thin layer near the anode. The ions generated in the discharge are accelerated away from anode in a strong electric field produced in the anode layer.

Here we focus on the second or so-cold high-current discharge mode, being relatively new in nonrelativistic plasma electronics. At comparatively high pressures, the discharge in an anode layer plasma thruster switches from its low-current high-voltage mode to high-current low-voltage...
operation, providing that the current in its external circuit is sufficient. In this mode, the discharge region is almost entirely filled with plasma whose potential is somewhat lower the anode potential such that most of the potential fall (several hundred volts) occurs in the cathode layer. We have designed several anode layer plasma sources for the bipolar electron-optical systems of technological electron guns [6–8].

2. Experimental setup
The operating modes and characteristics of the plasma source (in other words the plasma generator) were studied on an experimental setup (figure 1) with two discharge cells I, II built in the cathode hollow formed by electrodes 4. The electron beam was transported along the longitudinal axis of the system. In a number of experiments, the electron source was replaced by a sectional collector to measure the plasma homogeneity from the hollow cathode. As can be seen from figure 1, the cross section of the electrode system is similar in geometry to conventional anode layer plasma thrusters. The design of the plasma source as well as the choice of the number and geometry of its discharges cells for electron beam formation in a plasma-filled optical system is considered in detail in our previous papers [6–8]. The plasma generator and the electron source are outside the vacuum chamber, allowing one to freely access the magnets and to easily cool the magnets and cathodes of the plasma generator. The magnetic field was produced by permanent magnets 6 shaped as cubes of dimensions 10×10×10 mm³ and was varied with the number of magnets. The field configuration is typical for periodic focusing systems with permanent magnets [5] and was specified so that the electron beam focus located at least 8–10 cm rightward from the output face of the generator. As a result, the magnetic field induction between the pole tips was of the first and second cell was 0.017 T and 0.015 T, respectively.

The cathode material of the generator is soft magnetic low-carbon steel, and the anode material is nonmagnetic stainless steel. The anodes are located in toroidal cavities with special ceramic insulators whose skirt prevents the surface coating. All other metal elements are made of stainless steel or aluminum alloy. The plasma-forming gas (argon, nitrogen, air) is supplied to each toroidal cavity with separate controllers. The discharge gaps of the cells are powered by an independent power supply with a pulse duration of up to 300 µs and pulse repetition frequency of up to 100 Hz. The short-circuit current is 30 A.

3. Results and discussion
The operation of the proposed device is based on a discharge with closed electron drift and a discharge with electron oscillation along magnetic field lines in a cathode hollow. Like conventional anode layer ion sources, the device operates in two modes. Its low-current high-voltage mode provides a
collimated axially convergent ion beam with a positive space charge region such that an electrostatic plasma lens suitable for negative-ion focusing is formed near the axis [7]. This operational mode can be used for argon or oxygen plasma cleaning as well as coating of outer pipe wall and cylindrical pieces. The discharge is localized near the anode, as it happens in anode layer ion sources.

![Image](plasma-illumination-cathode-hollow.png)

**Figure 2.** Plasma illumination in the cathode hollow of the plasma source.

As the pressure is increased (above $5 \times 10^{-4}$ mm Hg in our experiments), the anode layer increases to the hollow cathode radius and the discharge switches to high-current operation or plasma mode. The discharge current increases more than an order of magnitude, and the internal volume of the device is filled with plasma perceived by eye as optically opaque (figure 2). Judging from the intensity and color of its glow, the plasma in the discharge gap reveals three regions: a bright region near the axis, a rather pale region spanning from it to the cathode, and a narrow violet region at the cathode pole tips.

![Image](plasma-density.png)

**Figure 3.** Plasma density and electron temperature distributions on the axis (a) and in the radial plane (b) with $n_p(r)$ for the $z$ coordinate 0 cm (point 3), 1.5 cm (point 2), and 3 cm (point 1).

According to probe measurements, the plasma density is highly inhomogeneous, and the inhomogeneity falls on the near-axis region facing the anode and pole tips. Figure 3a shows the on-axis plasma density distribution during the operation of only one discharge cell (cell II) in argon at a discharge current of 11 A, gas flow rate of 14 cm$^3$·min$^{-1}$, and pressure of $7 \times 10^{-4}$ mm Hg. The maximum on-axis density in the experiments is $\sim 6.7 \times 10^{12}$ cm$^{-3}$. The region with high plasma density spans a distance of about the cathode’s hollow diameter, and outside this region, the radial plasma density distribution becomes enough homogeneous (figure 3b, curve 3). The electron temperature distribution is rather homogeneous except for a noticeable increase in the near-anode region (figure...
3b). Such an increase in near-anode temperature is found in anode layer ion sources [4].

At large distances from active cell II (toward the electron source), the plasma density shows an interesting behavior: it is stabilized and then grows again. We guess that the main discharge in the active cell initiates the non-self-sustained hollow-cathode discharge in inactive cell I (not connected to the power supply). The region adjacent to inactive-cell anode I glows, which is clearly seen from the side of the electron source, and the glow intensity increases when the anode is brought to the cathode potential. Figure 4 shows the discharge current in the active cell (second cell) $I_d$ and its voltage $U_d$ (main discharge) for the inactive-cell anode under floating potential and under cathode potential. Grounding the anode decreases the discharge voltage by almost 50 V, and hence, the discharge current grows. Besides, the main discharge is formed much faster. The increase in the discharge voltage within the pulse is associated with gas burning [3]. The discharge voltage continues to increase under positive potential at the anode. Our previous studies show that with two cells being active, the discharge voltage increases by almost one third, and this decreases the discharge current in the power supply circuit of each cell according to the load characteristics of their power supplies [8]. The use of more than one cell was dictated by the need to get round the problem of limited discharge current due to discharge transition to an arc with a cathode spot and with a rather extended highly dense plasma region. The identified effect allows the use of only one discharge cell, the more so the plasma density attained near the electron emitter is several times the plasma density in a bipolar electron-optical system in earlier studies on electron beam transport.

![Figure 4](image1.png)

**Figure 4.** Discharge current $I_d$ and voltage $U_d$ for anode I at different potentials, and anode current $I_a$ for grounded anode I.

![Figure 5](image2.png)

**Figure 5.** Discharge current–voltage characteristics for collector under floating potential (1) and cathode potential (2).

The dependence of the discharge on the collector potential is the same but stronger. From the current–voltage characteristics of the discharge in figure 5 it is seen that when the collector is grounded, i.e., under cathode potential, the discharge voltage is much lower than its value under floating or positive potential (the floating potential of the electrode placed in plasma is positive). The cathodes are grounded, and the anode is at high voltage. The ion-electron emission from the collector surface bombarded by ions with energies equal to the near-cathode potential difference gives rise to additional high-energy electrons which greatly contribute to the gas ionization. As a result, due to two additional discharges, the discharge voltage decreases from 500–550 V to 350 V, all other things (discharge current, gas kind and flow rate) being equal, and this is beneficial in energy terms both for the power supplies and for the electrode system of the plasma generator.

4. Conclusion
Thus, our study of the plasma source with two anode layer discharge cells built in the cathode hollow shows that a non-self-sustained discharge in addition to the main discharge in cross fields can be ignited in the generator under certain conditions. As a result, the discharge voltage decreases greatly
(almost by one third) and the current in the circuit of the auxiliary discharge grows. Thus, the energy spent in the generation of plasma decreases and so does the power dissipated at the electrodes. This effect is expected for use in an extended plasma-filled optical system with a single discharge cell to considerably simplify the design of electron guns.

The high-current discharge mode features a region with high plasma density. With one discharge cell being active, the width of this region is about 6 cm. The high plasma density in the region (with an average of $4 \times 10^{12}$ cm$^{-3}$ and maximum of about $7 \times 10^{12}$ cm$^{-3}$) makes the plasma generator promising for use in surface treatment technologies, e.g., for treatment of cylindrical products. Because the discharge occupies the whole internal volume of the cathode cavity, the surfaces of plasma-contacting structural parts are sputtered, being the cause of possible surface contamination of treated objects. After solving the problem of surface protection from such sputtering, the plasma generator can be used to advantage in surface finishing technologies as well.

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