

Features of the distribution of parameters in a short glow discharge plasma with a flat and hollow cathode

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Received May 5, 2025

Revised July 4, 2025

Accepted July 22, 2025

Probe measurements of short discharges in helium without a positive column have been performed with hollow and flat cathodes. It has been established that at low pressures when the discharge consists only of a cathode layer and negative glow plasma, the anode is dark and the anode voltage drop is negative. As pressure increases and a region of Faraday dark space forms, a luminous area appears on the anode which increases as the positive discharge column forms, and the anode voltage drop becomes positive.

Keywords: probe potential, glow discharge, hollow cathode discharge, flat cathode discharge, anode voltage drop.

DOI: 10.61011/TPL.2025.12.62789.8126

Since the mobility of electrons is approximately two orders of magnitude (or more) higher than the mobility of ions, current in non-magnetic plasma is carried primarily by electrons. Predominantly ion current flows to the cathode, and electron current flows to the anode. Therefore, a restructuring of flows of charged particles and their coupling with plasma occur in the near-electrode regions of a gas discharge.

In contrast to the well-characterized longitudinally homogeneous positive column (PC) of a glow discharge, the characteristics of plasma in the near-electrode regions remain understudied. The main reasons for this are the small scale and sharp spatial heterogeneity in the distribution of their key parameters, which complicates diagnostics. In turn, since near-electrode regions are smaller than the electron energy relaxation length, the traditional hydrodynamic model is inapplicable to them and a kinetic analysis is required (see, e.g., [1,2] for more details). It should be noted that in terms of maintaining a stable discharge, the anode discharge region is just as important as the cathode one. However, the former receives less attention and the processes in it have been studied much less thoroughly [1,2]. Two mechanisms of anode discharge phenomena are traditionally distinguished.

The first one was formulated by Langmuir: since the drift electron current in plasma is significantly weaker than the thermal (chaotic) electron current from the layer to the anode, the electric field in the anode layer (anode fall, AF) should slow electrons down, and no luminous region should form near the anode. This corresponds to a negative AF with its potential equal to several electron temperatures T_e . Since electrons are in a potential well, the spatial distribution of their density corresponds to the traditional Boltzmann distribution with a dependence on potential energy and temperature.

At the same time, von Engel has pointed out that, under certain conditions, the ion current may increase monotonically

with increasing distance from the anode, approaching its value in the PC. In this case, ions are produced in a thin positive AF, a bright glow is observed near the anode, and no Boltzmann distribution is found [1,2]. If the density of electrons decreases toward the anode in such highly non-equilibrium plasma with a field pulling electrons to the anode, the electron distribution function (EDF) may be inverted (see [3] for details).

It bears reminding that the prediction and implementation of inverse population of excited states of atoms and molecules provided an opportunity to design a broad spectrum of lasers that are used widely in various engineering applications. In a manner similar to the inverse population of excited states in lasers, a medium with an inverse EDF in gases with a Ramsauer minimum of the elastic scattering cross section may amplify electromagnetic waves. Therefore, the search for plasma media with an electron density decreasing toward the anode in a field accelerating to the anode is of great interest in the context of solving the problem of forming an inverse EDF [3].

The analysis performed by Tsendin in [2] revealed that even the physical mechanisms still remain unclear, and there is no quantitative criterion for the sign of the anode potential drop relative to plasma of the positive column of a discharge. At the same time, the issue of the anode drop sign in a short (without PC) glow discharge with flat electrodes has a definite interpretation in both theoretical and experimental contexts [1,4].

As long as a discharge consists of a cathode layer (cathode fall, CF) and negative glow (NG) plasma only, the maximum plasma density, which corresponds to the minimum potential and the point of reversal of the electric field sign, is located in the NG [1]. Therefore, electrons in NG plasma are in a potential well with a Boltzmann density distribution, and the sign of the AF potential is negative (the mechanism described by Langmuir) [1,4]. Its magnitude is on the order of the electron temperature:

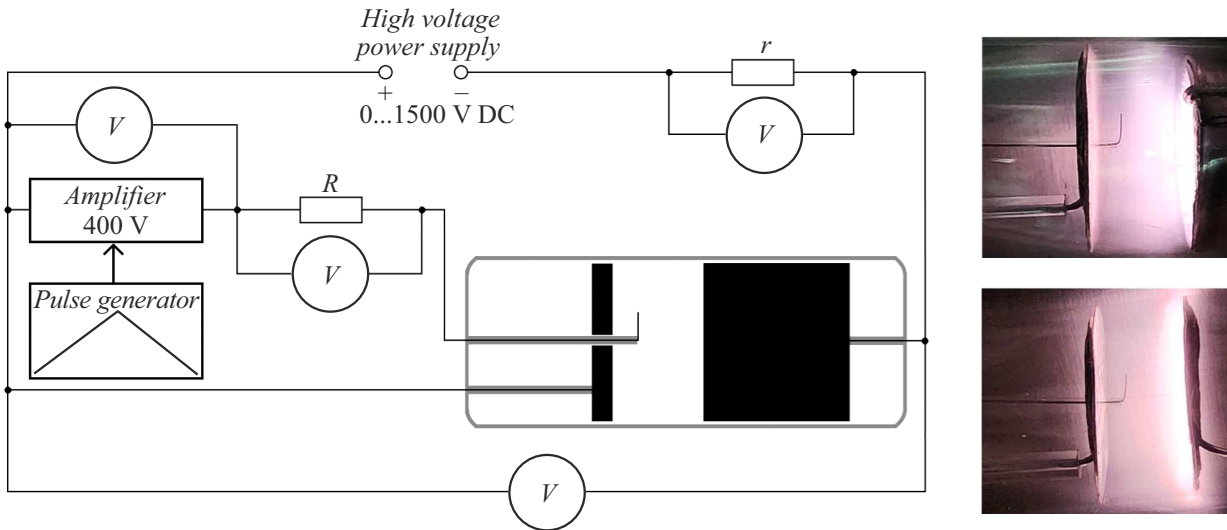


Figure 1. Diagram of the discharge diagnostic system and images of discharges in helium with hollow and flat cathodes (insets).

$e\varphi_A \approx T_e \ln(M_i/m_e)$, where m_e and e are the electron mass and charge, M_i is the ion mass, and φ_A is the anode potential. The overall potential variation in this well is insignificant (less than 1–2 eV), since it is specified by a relatively low (below 1 eV) temperature of trapped electrons T_e ; the anode itself does not glow [1,4].

Since the field in a PC is direct and accelerates electrons to the anode, with an increase in parameter pL (an increase in glow discharge length L or pressure p) with subsequent formation of a Faraday dark space (FDS) after NG, the field changes sign again in this transition region to the PC. The AF potential is positive (on the order of the gas ionization potential), and a bright luminous film forms on the anode [1,4]. As the value of parameter pL increases further, the luminous region grows from the anode to the cathode and a PC forms.

Anode plasma has already been studied both theoretically and experimentally for a short discharge with flat electrodes. However, a hollow cathode discharge, which differs in its physical parameters from a corresponding discharge with flat electrodes, is of interest in certain applications [5].

In the present study, experiments in short discharges with flat and hollow cathodes in helium were carried out. The results for the discharge with flat electrodes are generally consistent with the data from [4]. In turn, the patterns for discharges with a hollow cathode and flat electrodes are qualitatively similar: a negative AF potential is observed at low pressures, but the potential becomes positive with an increase in pressure when the field pulls electrons to the anode at a relatively low value of T_e . As the pressure increases further, the electron temperature grows and a brightly glowing PC forms.

The experimental setup shown in Fig. 1 was used to perform measurements in discharges with flat and hollow cathodes. The distance between the electrodes (15 mm), the discharge tube diameter (25 mm), the flat anode, and the probe were the same for both types of discharges. A probe

holder made of a quartz capillary with an outer diameter of 1 mm was inserted through the center of the flat anode, and the probe itself (0.2 mm in diameter and 5 mm in length) was bent by 90° relative to the axis of the discharge cell and positioned at a distance of 3 mm from the flat anode.

An adjustable constant voltage source (HSPY-1500-005, up to 1500 V) was used to ignite a discharge. It was connected to the discharge cell through ballast resistor r (5 k Ω). To measure the probe current–voltage curves, a high-voltage (up to 400 V) amplifier of a triangular signal fed from a generator (Rigol DG1022Z) and current-measuring resistor R (1 k Ω) were introduced into the probe circuit. The probe characteristics and the discharge voltage and current were recorded by a high-resolution four-channel oscilloscope (Rigol DHO 4204). A differential probe (Rigol RP1100D) connected to ballast resistor r was used to record the discharge current. Ultrapure helium was used to ignite a discharge. The insets in Fig. 1 show images of the discharge in helium with hollow and flat cathodes.

It was found in the course of measurements that a simple measurement of the floating potential is unsuitable for reliable determination of a negative AF potential; instead, data on the space potential are required. The zero position of the second derivative of the probe current with respect to its potential was used for this purpose. This system allowed us to perform measurements in an automated mode at different helium pressures.

Figure 2 presents the results of measurements of the discharge voltage with flat and hollow cathodes at the same discharge current value (4 mA). It is evident that the discharge voltage generally decreases with increasing pressure, which is typical of a short (without a positive column) discharge with rising current–voltage curves [1]. The sharp dip in the dependence for the discharge curves with a flat cathode and the non-monotonic nature of the dependence for the discharge with a hollow cathode within the pressure

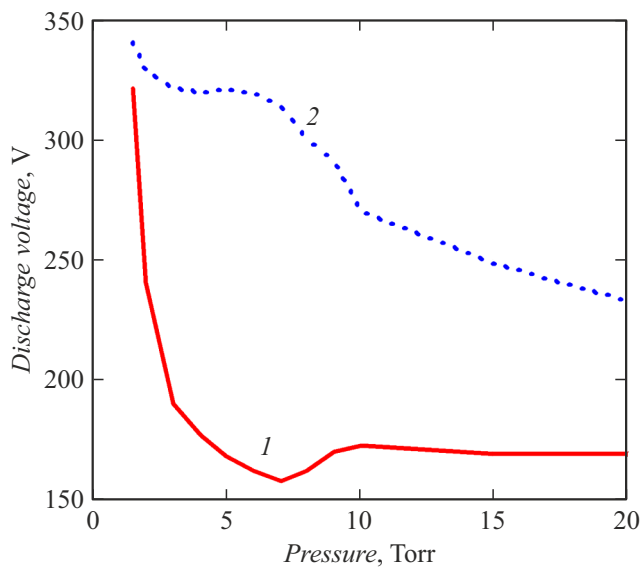


Figure 2. Discharge voltages with flat (1) and hollow (2) cathodes.

range of 3–10 Torr may be attributed to the S-shaped form of the Paschen curve [6].

Figure 3 shows the dependences of the floating potential of the probe (curves 1a, 2a) and the space potential (curves 1b, 2b) on helium pressure for the discharge with flat and hollow cathodes at a current of 4 mA. It turned out that they remain negative under all the examined conditions. This corresponds to a field that pulls electrons to the anode (i. e., the von Engel scenario). However, the non-observation of a Langmuir scenario for the discharge with flat electrodes at low pressures, when it consists of the CF and NG plasma only, contradicts both theory [1] and experiment [4]. As expected [1,4], the electron temperature was measured to

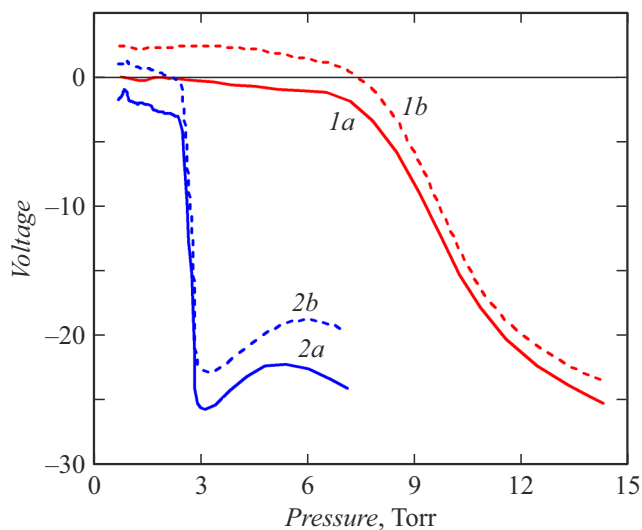


Figure 3. Dependences of the floating potential of the probe (1a, 2a) and the space potential (1b, 2b) on helium pressure for the discharge with flat (1a, 1b) and hollow (2a, 2b) cathodes.

be low (less than 1 eV; Fig. 4). Therefore, the potential difference between plasma and the anode is on the order of just 1 V at low pressures, necessitating a more thorough determination of its value. It is known (see, e.g., [7]) that the potential of an isolated probe is more negative (by several T_e) than the plasma potential. This conceals the actual pattern. Indeed, the dependences of the space potential, which are represented by curves 1b, 2b in Fig. 3, resolve the paradox.

Figure 3 makes it clear that the discharge with both flat and hollow cathodes undergoes an abrupt transition from weakly positive anode potentials (Langmuir scenario) to negative ones (von Engel scenario), which are on the order of the helium excitation potential, with an increase in gas pressure. Two features should be noted here. The transition is more pronounced and is observed at lower pressures in the discharge with a hollow cathode. This is largely attributable to the fact that electrons in the hollow-cathode discharge are multiplied in a strong radial field perpendicular to the axial current in the direction of the anode. Therefore, NG plasma is concentrated inside the hollow cathode in all cases. At the same time, the discharge current and the beam of fast electrons from the cathode layer, which form NG plasma, have the same axial direction. Therefore, both the NG length and the position of the second point of field reversal to the anode depend on the range of fast electrons and the NG–FDS coupling in a more complex way.

Another characteristic feature is the existence of a significant range of conditions where the electron temperature in the field pulling toward the anode (von Engel scenario) is low (Fig. 4) and corresponds to the FDS transition region instead of the PC.

Thus, the results of experiments revealed that the conditions established in the near-anode region of a discharge with a hollow cathode are such that the electron con-

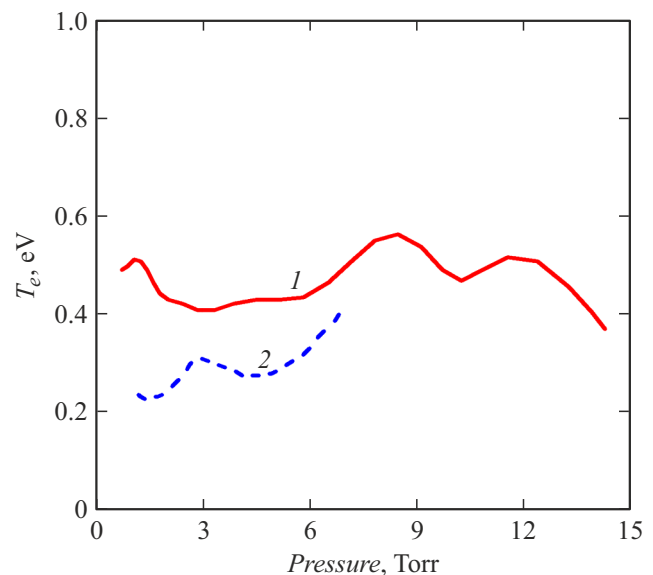


Figure 4. Electron temperatures for the discharge with flat (1) and hollow (2) cathodes.

centration decreases in the field accelerating electrons to the anode. As was demonstrated in earlier studies, an inverse electron distribution function may form under these conditions. Thorough examination of this issue is a separate and rather complex problem. Since this requires recording the electron distribution function at low energy values, the main difficulty lies in the inevitable distortion of the probe characteristics near the space potential due to the finite resistance of plasma and to the drain of electrons to the probe.

Conflict of interest

The authors declare that they have no conflict of interest.

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Translated by D.Safin