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Creating conditions for the formation of an inverse electron distribution function in a glow discharge with a hollow cathode

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Experiments in non-local anode plasma of a glow discharge with a hollow cathode were carried out. A hydrodynamic criterion obtained earlier was used to identify the discharge conditions under which the formation of an inverse electron distribution function is to be expected.

Kyewords: electron distribution function, probe diagnostics, hollow cathode.

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The possibility of amplification of electromagnetic waves in media with an absolute negative conductivity of electron gas has been predicted in [1] almost immediately after the construction of the first gas lasers. Having analyzed the expression for electron conductivity, the researchers demonstrated two conditions must be met for negative conductivity to arise: the existence of an inverse electron distribution function (EDF) $(\partial f_0/\partial w > 0)$ within a certain energy range w and a sufficiently sharp increase in electron transport scattering cross section σ_0 with energy $\big(d(\ln\sigma_0(w))/d(\ln w) > 1\big)$. The latter condition is fulfilled for heavy inert gases at energies above the Ramsauer minimum.

As for the first (primary) condition, various attempts have been made since the 1960s–1970s to determine the conditions for the formation of an inverse EDF (see review [2] and references therein).

However, in contrast to the well-developed laser technology, the practically important issue of forming an inverse EDF has not been solved yet.

One of the main reasons for this lies in the fact that the search for an inverse EDF was performed via forced reduction of the kinetic equation for electrons to a spatially homogeneous medium, where it depends on just a single variable: the kinetic energy of electrons (see [3] for more details).

In actual practice, laboratory plasma objects are always localized in a limited volume and are spatially inhomogeneous. The EDF under such conditions is often called nonlocal in literature (see, e.g., [4]), since one needs to solve the full Boltzmann kinetic equation, which depends on both energy and spatial variables (including the self-consistent ambipolar field), in order to find it.

Unfortunately, such resource-intensive modeling for real gas discharges with a 2D geometry at the minimum is virtually impossible at present.

A hydrodynamic criterion for potential φ and electron density n_e gradients was proposed in [5] as a means for preliminary search for potential plasma media with an inverse EDF:

$$\nabla\varphi \cdot \nabla n_e = -\mathbf{E} \cdot \nabla n_e < 0. \tag{1}$$

Condition (1) was obtained in the following way: the boundary condition for the EDF at zero kinetic energy, where the EDF reaches its maximum,

$$\big(\nabla\varphi \cdot \nabla f_0\big)\big|_{w=0} = -\big(\mathbf{E} \cdot \nabla f_0\big)\big|_{w=0} < 0 \tag{2}$$

was altered by substituting $f_0(\mathbf{x}, w = 0)$ with electron density $n_e(\mathbf{x})$; i.e., proportionality $n_e(\mathbf{x}) \sim f_0(\mathbf{x}, w = 0)$ was used (see [6] for more details).

According to (1), (2), EDF inversion is possible only in heterogeneous plasma, where the electron density in field E accelerating electrons to the anode decreases instead of increasing (and vice versa).

It is convenient to start analyzing criterion (1) from a glow discharge (GD), which is the most thoroughly studied plasma object. The convenience and simplicity of its experimental examination have made a GD the default object for testing new ideas and diagnostics in plasma physics.

A GD is spatially homogeneous and stable at low and medium pressures, when the EDF is non-local. The EDF is considered non-local if electron energy relaxation length λ_ε exceeds characteristic inhomogeneity length L [4]:

$$\lambda_\varepsilon = \lambda/\sqrt{\delta} > 100\lambda > L. \tag{3}$$

Here, λ is the mean free path and $\delta = 2m/M \ll 1$ (m is the electron mass and M is the atom mass). In the case of atomic gases, the fulfillment of condition (3) corresponds to parameter $pL < 3{-}5\,\text{cm}\cdot\text{Torr}$ (p is the gas pressure).

The kinetic analysis of a one-dimensional GD with flat electrodes carried out in [6] revealed the possibility of forming an inverse EDF in the region of transition to the positive column of the Faraday dark space. In practice, the size and position of this region depend on many factors, which affect the multiplicands in criterion (1) in opposite ways in 1D geometry. Since the end result is sensitive

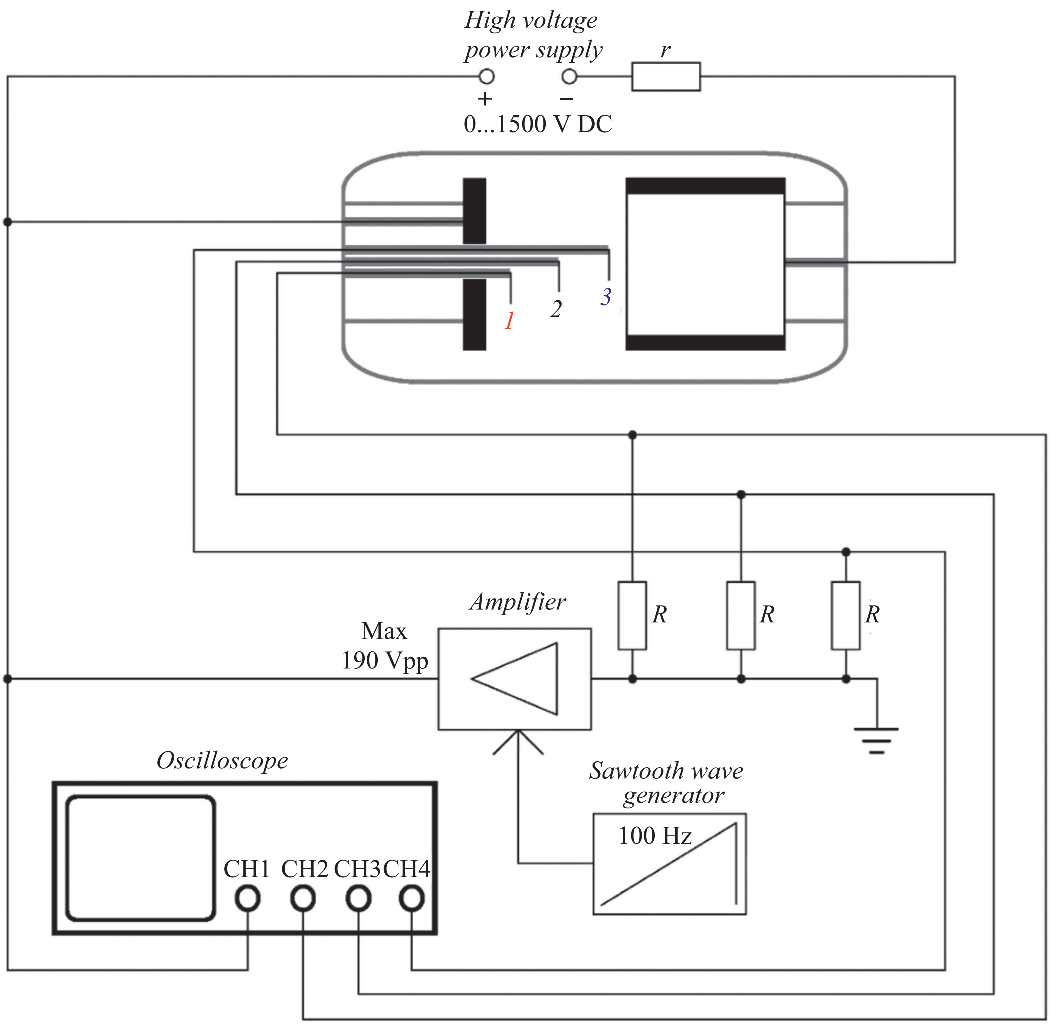

Figure 1. Block diagram of the experimental setup. All designations are explained in the text.

even to minor parameter changes, it is crucial to minimize the above-mentioned uncertainties when one formulates recommendations for an experimental search for conditions with an inverse EDF.

In the present study, we propose to use a two-dimensional modification of a GD with a hollow cathode (HC), which allows for partial spatial separation of the influences of the above factors and makes these influences less dependent of each other, to implement condition (1) in practice.

Indeed, electrons emitted from the HC surface are accelerated by the cathode layer in the radial direction, which is perpendicular to the direction of discharge current [7]. Therefore, the entire ionization region and forming negative glow plasma are concentrated within the HC. In turn, as long as length L of the outer region from the HC end to the anode (for brevity, it is referred to below as anode plasma) is insufficient to form a positive column ($L < \lambda_\varepsilon$), ionization is not observed in it. This weak-field transition region is similar to the Faraday dark space of a classical GD and serves just to transport electrons generated inside the HC to the anode. Since the plasma density in the field extracting electrons to the anode decreases if ionization is lacking, condition (1) will be satisfied.

To verify these assumptions, experiments were performed in a DC GD in helium under pressures ranging from 0.5 to 2.5 Torr in a tube with diameter $2R = 25$ mm between a hollow cylindrical cathode with length $H = 25$ mm and a planar anode located at distance $L = 15$ mm from the HC end (Fig. 1). The discharge was supplied from an adjustable source through a 5 kΩ ballast resistor, which also served to measure the discharge current with a differential probe. Three identical probes 5 mm in length and 0.1 mm in diameter were introduced along the axis of the discharge gap at a distance of 3 mm (probe *1* in Fig. 1), 6 mm (probe *2*), and 9 mm (probe *3*) from the anode, respectively. Probe measurements were carried out using a sawtooth voltage generator, an amplifier, and a high-resolution recording four-channel oscilloscope (Rigol DHO 4204). The used arrangement was specific in that the sawtooth signal of probe displacement from the amplifier output was fed to three probes simultaneously and recorded

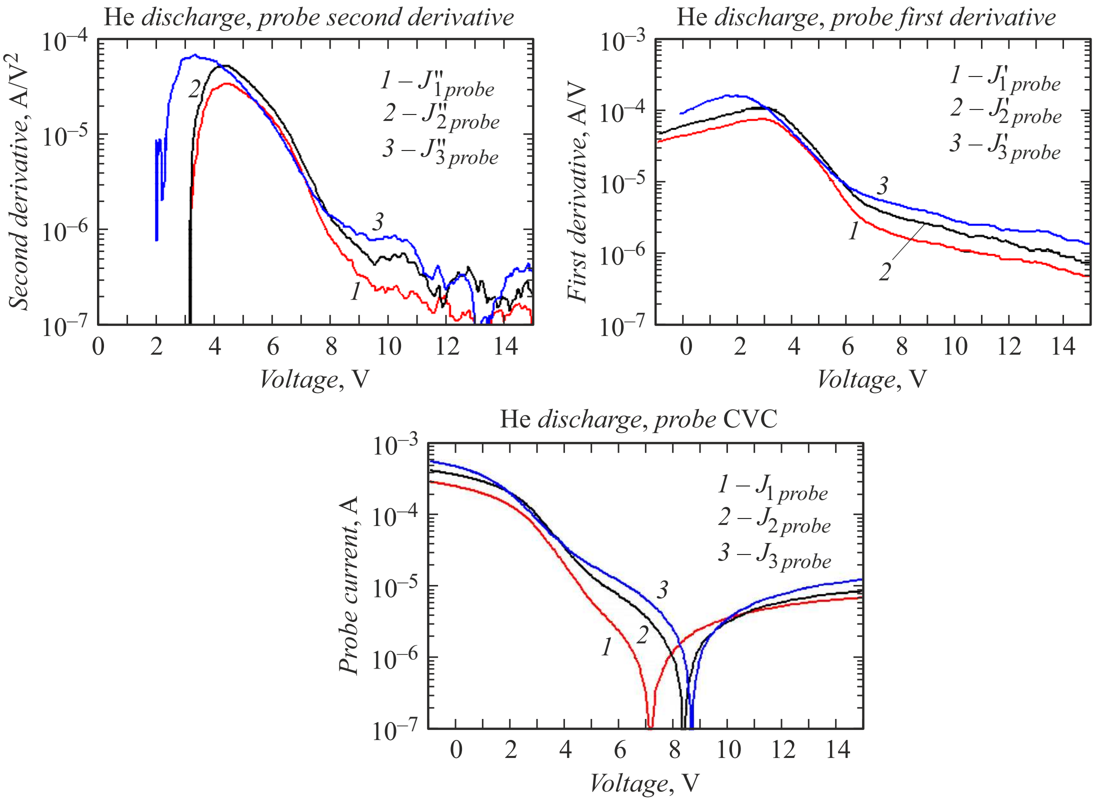

Figure 2. Probe CVCs and their first and second derivatives for a helium pressure of 1.2 Torr.

in the first channel of the oscilloscope. The remaining three oscilloscope channels recorded the currents of three probes.

This arrangement provides three-channel and synchronous probe diagnostics, making it possible to exclude the influence of any random fluctuations of parameters of the discharge under study. The oscilloscope allowed us to record signals with averaging over a large number of oscillograms (in the present study, 1024), thus implementing long-term accumulation of the measured signal. A multipurpose signal generator (Rigol DG1022Z), which was connected to a high-voltage amplifier, was used to generate sawtooth pulses with a frequency of 100 Hz. The latter was fed by a separate power supply. Numerical differentiation of the probe current–voltage curves (CVCs) was performed with additional averaging over 15 time samples of experimental data (moving average method); the total number of time samples of the digital oscilloscope was 1000.

Figure 2 presents typical results of probe measurements. The measured probe CVCs were used to determine temperature T_e and concentration N_e of electrons at three points in space simultaneously (Figs. 3, a, b).

Electron temperature T_e (in eV) was determined based on a linear dependence of the natural logarithm of the electron part of the probe CVC for the probe current density on potential U. The following well-known expression was used:

$$T_e = \frac{\Delta U}{\Delta \ln j}. \tag{4}$$

It can be seen that the electron temperatures are low and correspond to a weak field in plasma of the Faraday dark space without any noticeable ionization. The increase in electron temperature with increasing pressure is associated with shrinking of the Faraday dark space and the formation of a transition region to the positive column (just as an increase in field strength, Fig. 4). Experiments demonstrate that a bright luminous region of the positive discharge column forms near the anode under the examined conditions at a pressure above 3 Torr.

Electron concentration of plasma N_e at three points was determined based on the measured values of probe current density $j(U_p)$ at plasma potential U_p and the obtained values of T_e:

$$N_e = \frac{j(U_p)}{e\sqrt{\frac{eT_e}{2\pi m_e}}}. \tag{5}$$

As expected, electron densities in the considered transition discharge region with low T_e decrease monotonically with decreasing distance to the anode. The reduction in N_e at the approach to the anode was also indicated by weakening of plasma glow (Fig. 3, c), which is proportional to N_e^k, $k > 1$.

Figure 4 presents the results of measurement of potential differences ΔV between the probes for different gas pressures at a discharge current of 4 mA.

It can be seen that difference ΔV increases as one approaches the anode; i. e., the field in anode plasma is negative and accelerates electrons to the anode. As

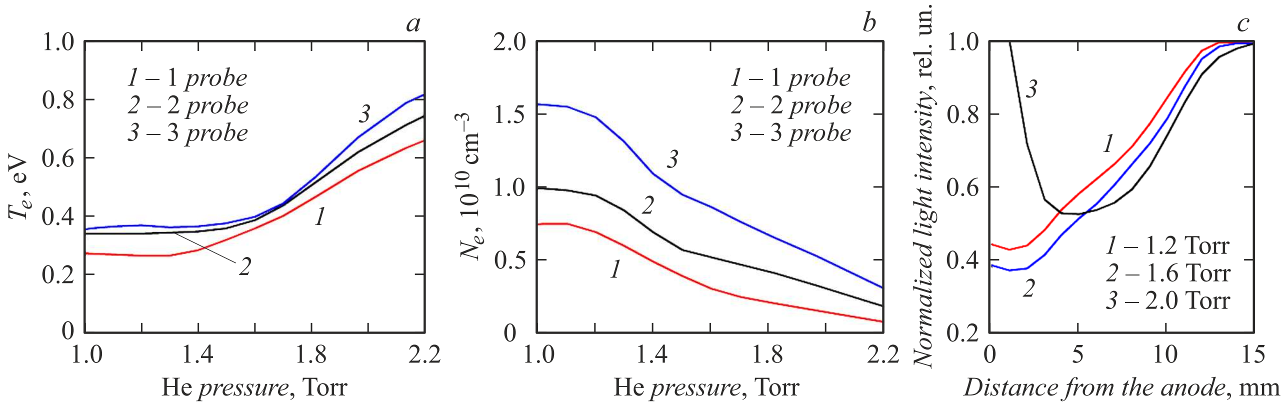

Figure 3. Dependences of the electron temperature (a) and concentration (b) on helium pressure at a current of 4 mA. c — Dependence of the plasma glow intensity on distance to the anode.

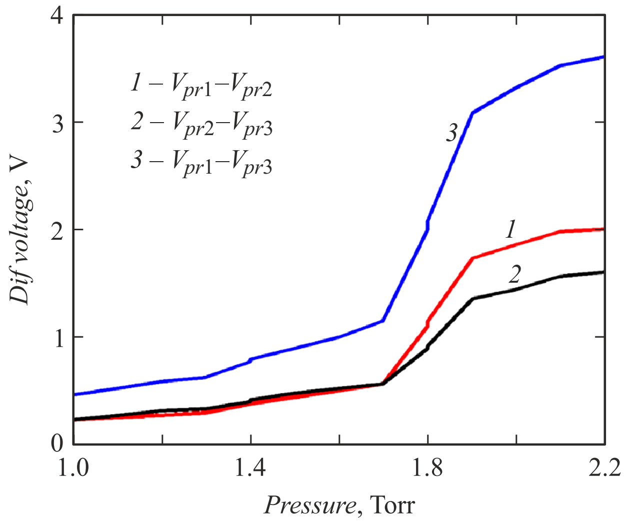

Figure 4. Variations of the potential difference of three probes.

the pressure increases, the absolute values of ΔV and, consequently, the field increase. This is attributable to the above-mentioned increase in T_e, the onset of formation of a luminous region of the positive discharge column with increasing pressure, and the transition to the local mode of EDF formation.

Thus, the results of experiments demonstrate that the conditions of criterion (1), (2) are satisfied in the studied anode plasma of a glow discharge with a hollow cathode; i. e., an EDF inversion is to be expected.

Unfortunately, direct attempts at EDF measurement at low energies based on the second derivative of probe current (Fig. 2) failed owing to the inevitable distortion of the probe characteristic near the plasma potential (due to the need to take into account the voltage drop both in the near-probe layer and in plasma and the effect of electron sink to the probe [8]). We propose to use the upgraded tracking probe technique, which was detailed in Section 4.11 of [8], to take into account the distortions associated with the finite nature of the probe–plasma resistance. In turn, characterization of the electron sink to the probe requires refinement of the theory through the use of numerical methods for reconstructing the EDF from the measured second derivative of the probe current.

Thus, the experiments carried out in a glow discharge with a hollow cathode revealed that the electric field in anode plasma of this discharge pulls electrons to the external anode with the plasma density decreasing toward the anode; i. e., conditions (1), (2) for the formation of an inverse EDF are fulfilled.

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Conflict of interest

The authors declare that they have no conflict of interest.

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