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Current-voltage characteristics and electron beam generation efficiency in a high-voltage abnormal glow discharge

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Investigations of I-V characteristics and electron beam generation efficiency in a high-voltage abnormal glow discharge in the direct current mode in helium at a pressure range of 2.17−10.2 Torr under conditions of minimizing controlled and uncontrolled impurities in the working medium have been carried out. The non-monotonically increasing character of the I-V characteristics is demonstrated and electron beam generation efficiencies of $\sim 80\%$ are obtained.

Keywords: gas discharge, helium, electron beam, efficiency.

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High-voltage abnormal glow discharges (AGDs) have long been used as sources of electron beams (EBs) that do not require differential pumping [1–8]. Electrons are accelerated in the space charge region at the cathode (cathode potential drop) to which almost the entire discharge voltage is applied. This predetermines the dominance of the monokinetic component of the electron distribution function. Despite many years of research, AGDs continue to attract attention due, on the one hand, to the ease of achieving the required parameters and, on the other hand, to the emergence of novel previously undiscovered properties. It was demonstrated in [4] that the current–voltage characteristics (CVCs) of AGDs depend largely on the experimental conditions. With thorough degassing of the discharge volume and conditioning of the cathode, the CVCs acquire an *S*-shaped form (in $U-I$ coordinates). In contrast, the introduction of molecular impurities gives rise to monotonically increasing CVCs. The presence of molecular impurities (especially uncontrolled ones) in a gas medium contributes to a change in the role, composition, and energy of particles bombarding a cold cathode. Provided that the emission properties of the cathode depend on the emitting layer modification by working particles implanted into the surface, the functional AGD parameters (discharge voltage and current, electron beam generation efficiency, and current flow pattern) are specified by the purity of the working medium and the emitting surface state.

The aim of the present study is to examine the CVCs and the efficiency of electron beam generation in an abnormal glow discharge in helium in the direct current mode at elevated (higher than 1 kV) voltages under the condition of „physical purity" (i.e., minimization of controlled and uncontrolled impurities in the working medium and the cathode material).

Discharge experiments were performed in a cell with planar polished electrodes: a cathode made of reaction-sintered silicon carbide and a copper anode with interelectrode distance $d_{ca} = 3$ cm. The electrodes are separated by a glass cylinder and a multilayer insulator made of Al_2O_3 ceramic plates with an internal hole diameter of 1.6 and 2.3 cm, which limit the discharge area to 2 cm^2. A heater was mounted on the cell to degas the discharge volume, and the cathode was secured to an insulating ceramic plate on an aluminum stand with a separate heater. The stand served as a heat sink in the experiments. Combined with a cooler, it helped maintain the discharge volume temperature at $T \leqslant 50^\circ$C and enabled stable operation up to a level of power input $P = UI = 60$ W (U and I are the discharge voltage and current, respectively) into the discharge. A DC source with adjustable voltage $U = 0-5$ kV and ballast resistance $R = 20-600\,\mathrm{k\Omega}$ was used.

Experiments were carried out in helium with a volume percent no less than 99.9999%, which was fed into the cell at a rate of 100−150 ml/min through a carbon trap cooled with liquid nitrogen. The purity of the working gas was estimated by the ratio of intensities of the molecular bands of hydrogen, nitrogen, and oxygen. The helium pressure was measured using a Thyracont VCC200MA4 capacitive sensor with an accuracy of $\pm 0.25\%$.

The cell was degassed before each cycle of discharge parameter measurements. This procedure involved heating the cell to $T = 100^\circ$C and evacuating it to a pressure below 10^{-6} Torr with a turbomolecular pump. This was followed by cathode discharge conditioning, which consisted in increasing the voltage every 5 min from 200 V to the working level in 50−100 V steps with the discharge volume evacuated after each iteration. Following these manipulations, the actual leakage of the vacuum system and the discharge cell was $\sim 10^{-6}$ Torr/h, which is two orders of magnitude lower than the values achieved earlier in [4].

Energy efficiency η of the electron beam generation was measured using a calorimetric method. The energy efficiency is understood as energy fractions $\eta_{ds}(\eta_{col}) = P_{ds}(P_{col})/P$, where P_{ds} is the power lost in the discharge gap and P_{col} is the power dissipated at the anode (electron collector). The overall efficiency of electron beam generation by a discharge is $\eta = \eta_{ds} + \eta_{col}$. The values of η_{ds} and η_{col} were determined in the following way. Preliminary measurements of the calibration dependences of temperature variation ΔT at the wall and the anode of the cell with power of the built-in heaters were performed without a discharge. Comparing the values of temperature at the cell wall and the anode measured during a discharge with known calibration curves, one may determine the corresponding powers P_{ds}, P_{col} and calculate η_{ds}, η_{col}, and η.

As an example, Fig. 1, *a* presents a family of AGD current–voltage characteristics in coordinates $I{-}U$ at helium pressure $p_{\text{He}} = 2.17$, 4.67, 7.67, and 10.2 Torr. The AGD mode with consistently reproducible CVCs was achieved after ~ 50 h of cathode conditioning and cell degassing. It is evident from Fig. 1 that dependences $I(U)$ change in nature as the pressure grows, ceasing to increase monotonically at $p_{\text{He}} \geqslant 5$ Torr. Sections of current reduction with increasing voltage emerge, and the maximum reduction is observed at the highest probed gas pressure. At $p_{\text{He}} = 10.2$ Torr, the maximum current is achieved at $U \approx 400$ V. As the voltage increases to $U \approx 1100$ V, the discharge current decreases; with a further increase in U, I starts growing once again. This CVC behavior is indicative of a change in the discharge type: the transition from a normal discharge to an abnormal one and then to a discharge with runaway electrons and eventual formation of a photoemission-controlled discharge [4,5].

According to the data of earlier studies [6–8], high-voltage discharges generating electron beams with kiloelectronvolt energies based on the runaway effect feature CVCs of the $j \sim p^x U_c^y$ form (j is the current density and U_c is the cathode potential drop, which is virtually equal in the region of high U_c values to voltage U applied to the discharge gap) with the exponents of power assuming the values of, e.g., $x = 2$, $y = 3$ in [6]; $x = -1.5$, $y = 2.5$ in the calculations performed in [7]; or $x = 1{-}2$, $y = 1{-}3.5$ in [8]. The CVCs obtained in the present study may be converted into coordinates $j/p_{\text{He}}^2{-}U$ and $j/N_{\text{He}}^2{-}U$, where N_{He} is the concentration of working gas atoms. The average temperature was estimated in a similar way as in [5] and in accordance with [9]. The resulting dependences are shown in Fig. 1, *b*. The inset of this figure makes it clear that the $j/N_{\text{He}}^2(U)$ dependences for all the examined helium pressures match perfectly with exponent of power $x = 2.08 \pm 0.10$. This indicates that the high-voltage AGD CVCs are characterized by the fulfillment of similarity conditions. Figure 1, *c* illustrates the dynamics of variation of parameters $y_{j/p_{\text{He}}^2}(U)$ and $y_{j/N_{\text{He}}^2}(U)$, which are extremal

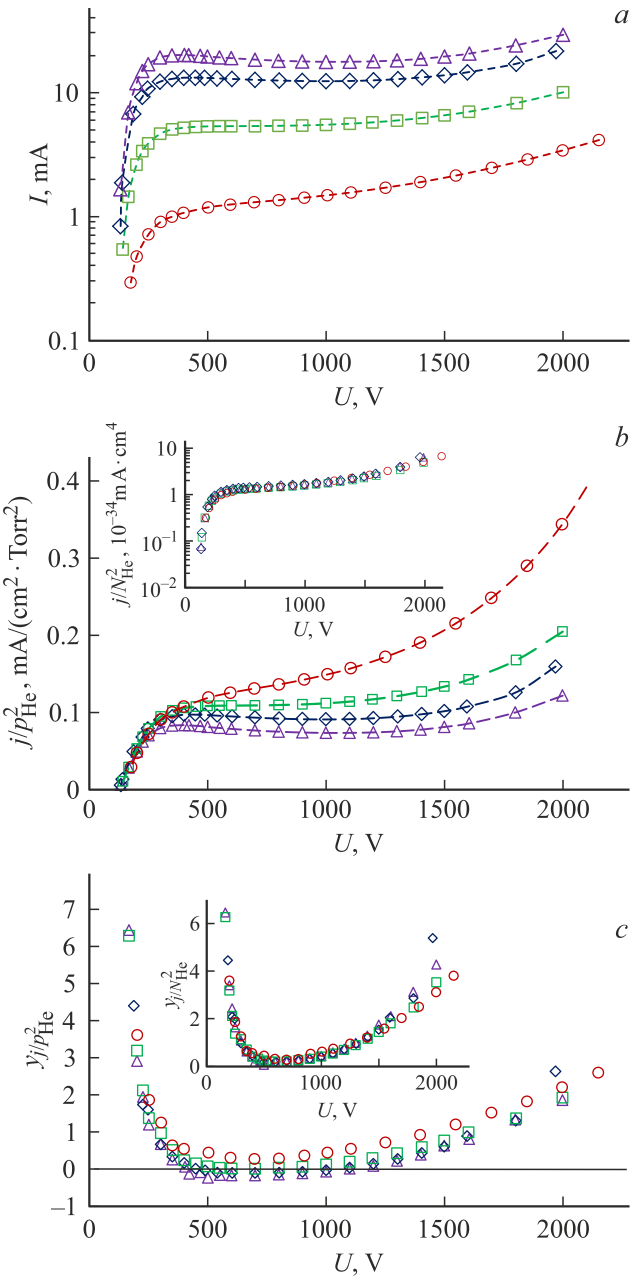

Figure 1. Family of AGD current–voltage characteristics in coordinates $I{-}U$ (*a*) and dependences $j/p_{\text{He}}^2(U)$ ($j/N_{\text{He}}^2(U)$ in the inset) (*b*) and $y_{j/p_{\text{He}}^2}(U)$ ($y_{j/N_{\text{He}}^2}(U)$ in the inset) (*c*). p_{He}, Torr: circles — 2.17, squares — 4.67, diamonds — 7.67, and triangles — 10.2.

functions with a minimum at voltage $U = 400{-}900$ V within the entire studied range of voltages and pressures, for dependences $j/p_{\text{He}}^2(U)$ and $j/N_{\text{He}}^2(U)$, respectively. It is noteworthy that dependences $y_{j/p_{\text{He}}^2}(U)$ feature an interval of values $y_{j/p_{\text{He}}^2}(U) < 0$ at $p_{\text{He}} > 4.67$ Torr.

Figure 2 presents the results of measurements of efficiencies η and η_{col} for pressures $p_{\text{He}} = 4.67$, 7.67, and 10.2 Torr. The general trend is that η grows sublinearly with increasing voltage (at constant pressure) and with increasing pressure (at constant voltage). A maximum of $\eta \approx 80\%$ was achieved at $U = 2800$ V and $p_{\mathrm{He}} = 10.2$ Torr. The value of η_{col} (fraction of EB energy reaching the anode) increases in this case with U, but has an inverse dependence on pressure: $\eta_{col} \sim 1/p_{\mathrm{He}}$. This suggests that the overall efficiency of EB generation increases at higher gas pressures (as the electron energy losses increase) due to a reduction in the fraction of power dissipated in the discharge gap.

It is not without interest to compare the obtained values of η with the results reported in [4,8], where the efficiency of EB generation in an AGD in helium was measured calorimetrically. AGD studies in [4] were performed with a titanium cathode in the following experimental conditions: interelectrode distance $d_{ca} = 2.1$ cm, $p_{\mathrm{He}} = 1-16$ Torr, a highest attainable vacuum of $\sim 10^{-5}$ Torr, and a typical leakage of 10^{-4} Torr/h. The authors of [8] examined Mo–MgO and LaB_6 cathodes ($d_{ca} = 13$ cm, $p_{\mathrm{He}} = 0.5-3$ Torr, and the vacuum level in the setup did not exceed $\sim 10^{-4}$ Torr). Figure 3 presents a comparison of the $\eta(p_{\mathrm{He}})$ dependences for different U obtained in the present study and in [4,8]; the η value from [10], which was calculated as $\eta = \gamma/(\gamma+1)$, where γ is the secondary electron emission coefficient, is also indicated. It is evident that significantly higher electron beam generation efficiencies are achieved in „cleaner" discharge conditions within the studied U range.

The obtained results make it clear that the investigated high-voltage AGD maintained in the most „clean" conditions achievable is characterized by the following specific features:

— in conformity with the results of AGD studies with other kinds of cold cathodes (titanium, molybdenum [4,5]), typical monotonically increasing CVCs in coordinates $j-U$ assume a form with a negative exponent of power in the dependence of j on U as the pressure rises;

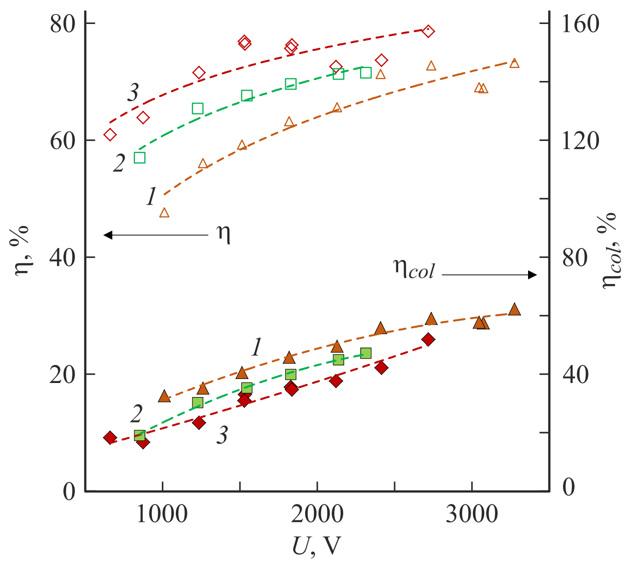

Figure 2. Dependences $\eta(U)$ and $\eta_{col}(U)$ at $p_{\mathrm{He}} = 4.67$ (*1*), 7.67 (*2*), and 10.2 Torr (*3*).

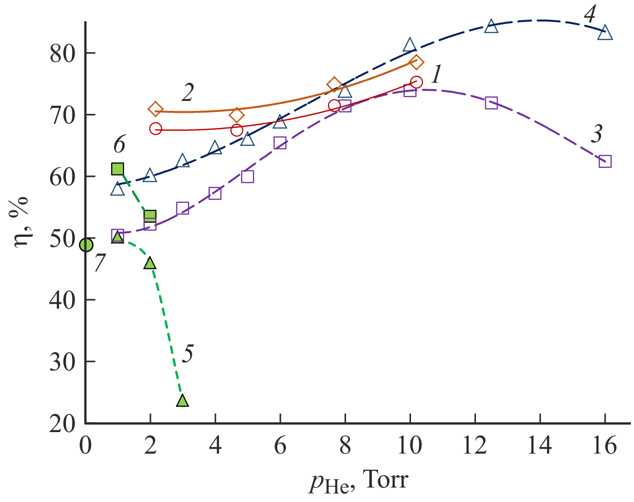

Figure 3. Dependences $\eta(p_{\mathrm{He}})$. *1*, *2* — Data from the present study: SiC cathode, $U = 2400$ and 2700 V, respectively; *3*, *4* — Ti-cathode, $U = 2500$ and 3500 V, respectively; *5* — LaB_6 cathode, $U = 3500$ V; *6* — Mo–MgO cathode, $U = 3500$ V; and *7* — Al cathode, $U = 4000$ V.

— the discharge persists at significantly higher pressures of the working gas (helium) while preserving a high efficiency of electron beam generation and is characterized by an increase in EB generation efficiency with increasing pressure;

— under otherwise equal conditions, the examination of the cathode reveals a suppression of sputtering of the emitting surface.

The above features combined make such discharges promising for the development of clean plasma technologies.

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Conflict of interest

The authors declare that they have no conflict of interest.

References

[1] M.A. Zav'yalov, Yu.E. Kreindel', A.A. Novikov, *Plazmennye protsessy v tekhnologicheskikh elektronnykh pushkakh* (Energoatomizdat, M., 1989) (in Russian).

[2] A.I. Golovin, A.I. Shloido, Usp. Prikl. Fiz., **4** (5), 439 (2016) (in Russian).

[3] A.S. Klimov, A.A. Zenin, D.B. Zolotukhin, A.V. Tyun'kov, Yu.G. Yushkov, Usp. Prikl. Fiz., **7** (3), 249 (2019) (in Russian).

[4] P.A. Bokhan, P.P. Gugin, D.E. Zakrevsky, M.A. Lavrukhin, Plasma Phys. Rep., **45** (11), 1035 (2019). DOI: 10.1134/S1063780X19100015.

[5] P.A. Bokhan, P.P. Gugin, M.A. Lavrukhin, V.A. Kim, G.V. Shevchenko, D.E. Zakrevsky, Plasma Sources Sci. Technol., **31** (12), 125009 (2022). DOI: 10.1088/1361-6595/acaac6
[6] K.A. Klimenko, Yu.D. Korolev, Sov. Phys. Tech. Phys., **35**, 1084 (1990).
[7] .N. Ul'yanov, High Temp., **43** (5), 641 (2005). DOI: 10.1007/s10740-005-0107-3.
[8] J.J. Rocca, J.D. Meyer, M.R. Farrell, G.J. Collins, J. Appl. Phys., **56** (3), 790 (1984). DOI: 10.1063/1.334008
[9] M.J. Kushner, B.E. Warner, J. Appl. Phys., **54** (6), 2970 (1983). DOI: 10.1063/1.332499
[10] P. Hartmann, H. Matsuo, Y. Ohtsuka, M. Fukao, M. Kando, Z. Donkó, Jpn. J. Appl. Phys., **42** (1), 3633 (2003). DOI: 10.1143/JJAP.42.3633

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