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On the High-Voltage Regime of the Discharge in Hollow-Cathode Tube

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Abstract. A comparison of the operating characteristics of the high-voltage regime of the discharge in a hollow-cathode tube, the hollow-cathode discharge (HCD) and the discharge to a plane cathode are presented. The disappearance of the hollow-cathode effect and the transition to a high-voltage discharge after inserting several anode rods into the cathode cylinder is exhibited. The similarity between the operating characteristics of such a high-voltage discharge and of a plane cathode discharge is shown. The loss of ions at the anode rods, as well at insulators or floating conductors is believed to be the reason behind the increase of the operating voltage and the disappearance of HCD characteristics. Practical means of increasing the operating voltage are mentioned.

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In recent years HCD has been widely used to exite noble gas and noble gas-metal vapour mixtures [1–3]. However, research is needed to improve the degree of excitation of high-lying atomic and ionic levels in such discharges. One possibility is to increase the operating voltage, which in turn produces faster electrons needed for effective excitation of these high-lying levels.

Rozsa [4] has developed a structure with an internal anode system in which the operating voltage is 3–4 times higher than that in a conventional HCD. The discharge in such a structure has proved to be efficient both in noble gas [5, 6] and in metal-vapour/noble-gas mixtures [7–9].

Recently, Iijima [10] found that covering part of the inner wall of a hollow-cathode by insulators raises the operating voltage compared to the conventional HCD. This has been shown to yield improved operation of the He–Zn^+ laser.

These examples in the existing literature indicate that the high-voltage regime of discharges is of considerable practical importance. On the other hand, some important properties of such a discharge are still not fully understood.

It is aim of this work to compare the operating characteristics of the high-voltage discharge in a hollow-cathode tube with those of the conventional HCD and of the discharge to a plane cathode. In the opinion of the authors, this comparison allows much better understanding of the high-voltage discharge.

1. The Experimental Set-Up

Three discharge tubes were used to compare the electrical operating characteristics of the high-voltage discharge in the hollow-cathode tube, the conventional HCD, and the discharge to a slightly curved open cathode, containing only the negative zones of the glow discharge (cathode dark space, negative glow and eventually Faraday dark space).

The hollow cathode in which a high-voltage discharge was realized is a 10 mm-I.D., 10 cm-long stainless steel cylinder. Six tungsten rods of 1.5 mm diameter are placed along the cylinder and form the anode structure. The distance between the surfaces of anodes and cathode is 0.5 mm. A schematic diagram of the geometry of the electrodes is shown in Fig. 1a.

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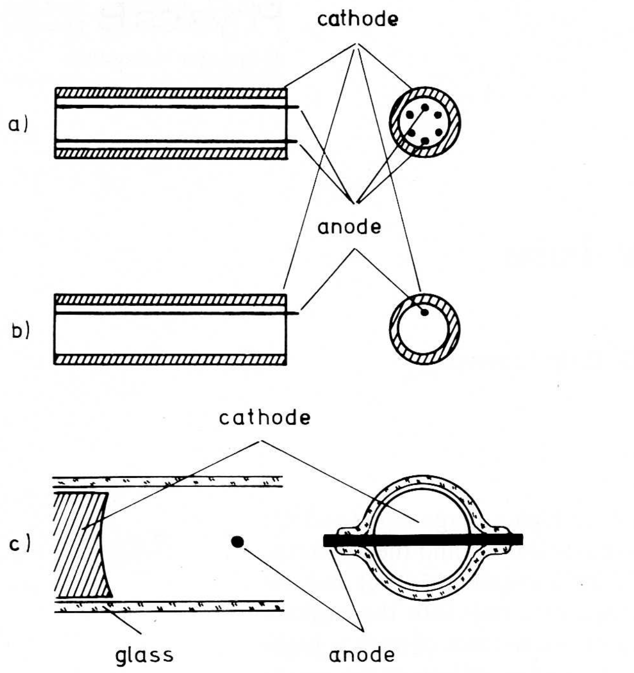

Fig. 1a–c. Schemes of the electrode configuration in: (a) high-voltage discharge with internal anode system, (b) conventional HCD, and (c) discharge to plane electrode

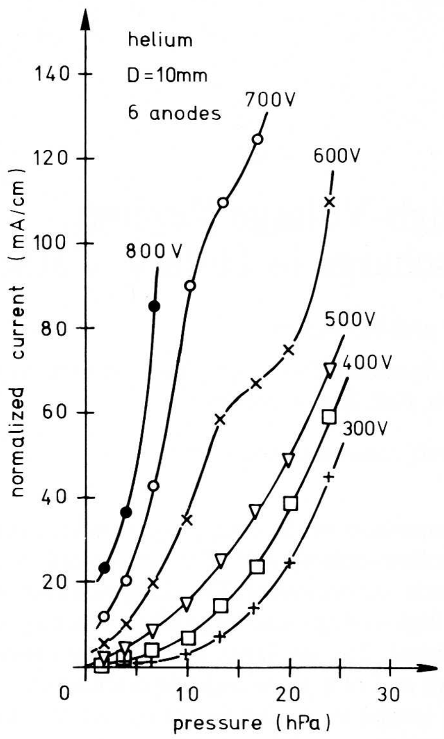

Fig. 2. Current-helium pressure dependence at constant operating voltage for the high-voltage discharge in the hollow-cathode tube. Discharge current is normalized to unit length of cathode (1 hPa = 1 hecto Pascal = 1 mbar)

The conventional HCD tube was of similar design. The difference was the existence of only one anode rod (Fig. 1b).

The electrode configuration of the "plane cathode" discharge is shown in Fig. 1c. The discharge active surface of cathode is a circular stainless steel plane of 15 mm diameter and curvature of 20 mm. The anode is a tungsten rod of 1.5 mm diameter placed at a distance of 20 mm from the cathode plate. This ensures a constant distance between cathode surface and anode rod, which is important for the uniformity of the cathode current density. The rear and side parts of the cathode are shielded against the discharge with the help of glass. This cathode as well as the hollow cathodes described above were cooled with water.

Half-wave rectified 3 Hz ac supply was used to excite the discharge. This together with the routine cleaning procedure ensured high purity of the operating gas. The electric characteristics were monitored on an oscilloscope.

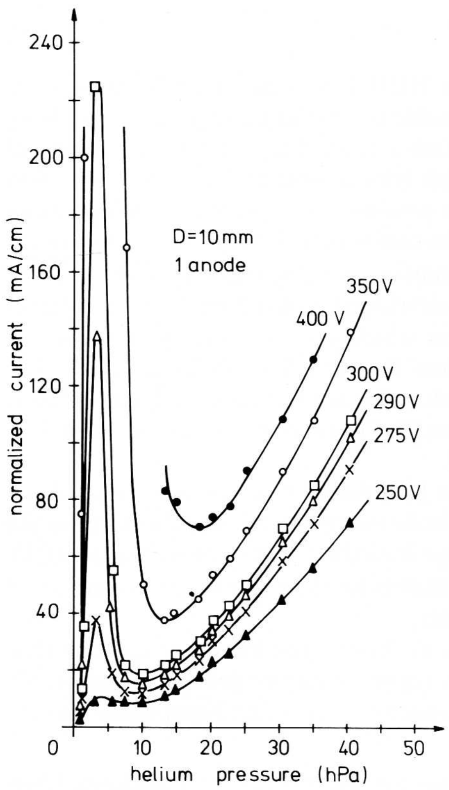

Fig. 3. Current-helium pressure dependence at constant operating voltage for the HCD. Discharge current is normalized to unit length of cathode

2. Results

Figures 2–4 show the diagrams of discharge currents (I) vs. the helium pressure (p) at constant operating voltage (V) for the high-voltage discharge in the hollow-cathode tube (Fig. 2), the conventional HCD (Fig. 3) and the plane cathode discharge (Fig. 4). It is

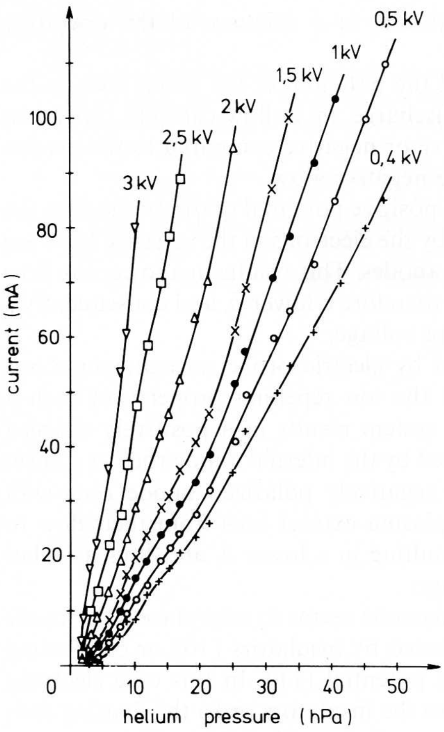

Fig. 4. Current-helium pressure dependence at constant voltage for the discharge to the plane cathode

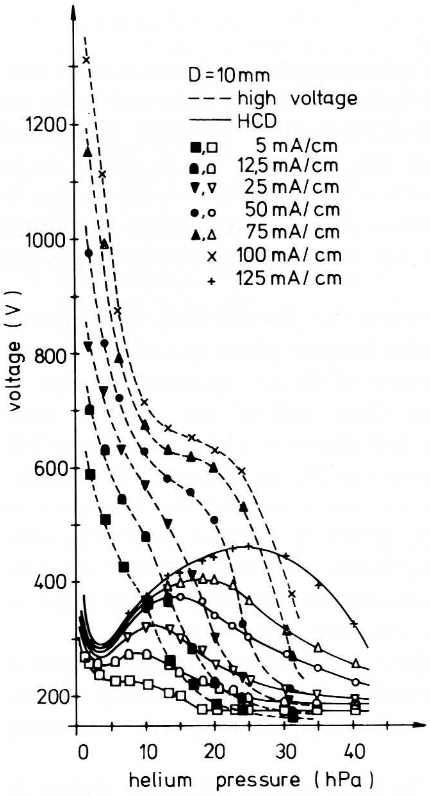

Fig. 5. Voltage-helium pressure characteristics at constant discharge current density for the high-voltage discharge (broken lines) and the conventional HCD. (Some experimental points are not shown to retain clarity)

seen that the $I=f(p)$ characteristics of the high-voltage operation regime and the conventional HCD differ significantly. The $I=f(p)$ behaviour for the high-voltage discharge resembles that for the discharge to the plane cathode. The $I=f(p)$ plots for the conventional HCD are typical of this kind of discharge and show pronounced enhancement of the current at optimum helium pressure of about 4 hPa (the hollow cathode effect).

A similar conclusion may be drawn concerning the behaviour of the $V=f(p)$ characteristics at constant discharge current (Figs. 5 and 6). The property of the conventional HCD, consisting of the existence of an optimum helium pressure at which the operating voltage needed to obtain a particular current is minimum, no longer holds for the high-voltage discharge. The latter seems to behave as a discharge to the plane cathode.

Therefore calling the high voltage regime of the discharge in hollow-cathode tube as a "high voltage HCD" seems to be inadequate, as far as the discharge mechanism is concerned.

Another common property of both the high-voltage and the plane cathode discharges is the increased value of the operating voltage, needed to obtain a certain current, compared to the conventional HCD.

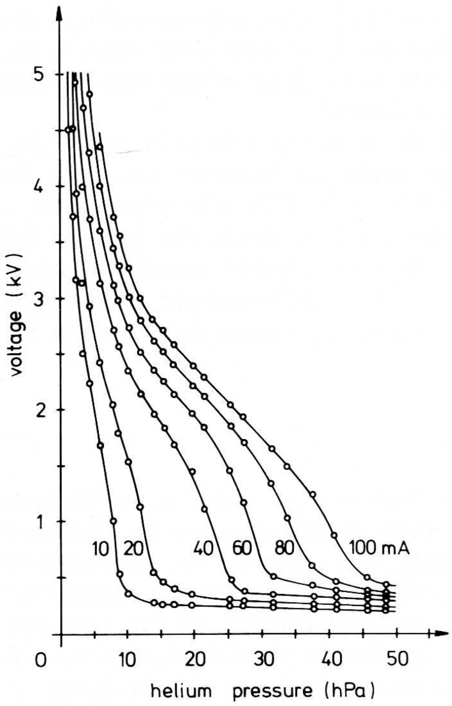

Fig. 6. Voltage-helium pressure characteristics at constant discharge current for the discharge to the plane cathode

3. Discussion

The experimental results presented above indicate that the conventional hollow-cathode structure loses its specific HCD properties after inserting additional anode rods into it. The behaviour of the discharge in hollow-cathode tube with an internal anode system is similar to that with a plane cathode. Both discharges are characterized by relatively high operating voltages.

It is generally assumed that the relatively high operating voltage of the discharge to plane cathodes is caused by the open geometry of the arrangement. In view of this probably less than half of the positive ions, metastable atoms and photons, which are responsible for releasing electrons at the cathode and thus maintain the discharge, can reach the cathode. Therefore, in the open discharge geometry a higher operating voltage is needed to produce the same number of electrons at the cathode and compensate for the effect of loss of the agents producing these electrons.

The loss of the positive ions, metastable and photons is remarkably decreased in the closed geometry of conventional HCD resulting in a lower operating voltage.

The situation in the high-voltage discharge regime in hollow-cathode tubes seems to be similar to that observed in discharge to plane cathodes. In this case, however, the increased losses of the electron producing agents are caused not by the open geometry of the discharge but by the insertion of the anode rods.

Earlier experiments [11] excluded the reduction of the photoelectric effect due to a "shadowing" effect by the anode rods as the main cause of the high voltage demand for this discharge.

The increase of the operating voltage in such a discharge may be explained however according to Druyvesteyn and Penning [12] who argued that a significant number of ions enters the cathode fall region from the negative glow and become an important producer of electrons at the cathode. Accordingly, the condition of discharge maintenance assumes the form

$$M=\frac{1+\gamma^{-1}}{1+\delta}, \qquad (1)$$

where M is the multiplication factor of the electron avalanche in the cathode fall region, γ is the secondary emission coefficient, and δ denotes the percentage of ions of the negative glow entering the cathode fall region. As the factor M depends on the operating voltage [13], the coefficients γ and δ define the operating voltage required to maintain the discharge. A decrease of δ, due to a lower ion flow to the cathode, causes an increase of the operating voltage, while an increase of δ results in a decrease of the operating voltage.

The polarity of the potential of the anode rods in the high-voltage discharge in hollow-cathode tubes can be either positive or negative compared to the plasma potential of the negative glow.

In the case of a positive potential of the anode rods the ions produced by the electrons in the negative glow are repelled by the anodes. This results in a lower ion flow to the cathode, therefore a lower δ, and consequently a higher operating voltage.

We have found by electric probe measurements (see also [14]) that the ion repelling property of such a cathode-anode system results in a positively charged plasma embraced by the internal anode rods at a lower potential. The negatively polarized anode rods with respect to the plasma extract ions from their flow to the cathode, resulting in a lower δ, and thus a higher operating voltage.

A similar phenomenon seems to take place if the anode rods are substituted by insulators [10] or conducting rods at floating potential [11]. In this case electrons diffuse rapidly to the insulators or to the floating rods charging them negatively so that they will attract ions and repell electrons. Some ions from the ion flow to the cathode are attracted to the insulator (or floating rod) wall and are neutralized there. Therefore the coefficient δ decreases causing again an increase of the operating voltage.

The internal anode-rod system may also reduce the number of metastable atoms which also produce electrons at the cathode. However, as it was shown [11], this effect seems to be of only minor importance.

Following the above reasoning one may conclude that the high-voltage regime of discharges in hollow-cathode tubes may be obtained by elimination of the hollow-cathode effect, which in conventional HCD is caused mainly by an enhancement of ion flow to the cathode surface. The discharges with high operating voltage, which are practically needed, e.g. for excitation of high-lying laser levels, may be realized by using either an open cathode geometry, an internal system of anodes, an internal system of insulators, or internal conducting rods at floating potential. All these methods lead to a decrease of the ion flow to the cathode which in turn requires an increased operating voltage for discharge maintenance.

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