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INVESTIGATIONS OF LONGITUDINAL HOLLOW-CATHODE DISCHARGE

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Results of investigations of a longitudinal hollow-cathode discharge are presented for a hollow cathode of 5 mm diameter and a length variable from 8 mm up to 96 mm. Hollow cathodes of such dimensions are used in discharge tubes employed in laser technology.

Axial distributions have been determined for the current density over the cathode surface, discharge current intensity and discharge plasma potential. Also voltage vs current discharge characteristics have been measured.

The measurements have been carried out for discharge in helium at a pressure ranging from 1.67 hPa to 34 hPa. The current intensity varied from 1.86 mA to 250 mA depending on the cathode length.

The investigations covered hollow-cathode discharges in the presence of one anode as well as two anodes located at the opposite ends of the cathode. An axial inhomogeneity of the discharge plasma resulting in nonuniform axial distributions of the cathode and longitudinal currents as well as nonuniform axial distribution of the discharge plasma potential was observed for both cases.

The inhomogeneity of the longitudinal hollow-cathode discharge affects the operation of the laser discharge tube. Some consequences of this inhomogeneity are discussed.

1. Introduction

In the hollow-cathode discharge tubes two principal kinds of electric discharge can be distinguished: the transverse and the longitudinal discharge [1, 2].

The transverse discharge occurs in tubes where the tube geometry and configuration of the electrodes — cathode and anode — makes the electric charge carriers, electrons and ions, move transversely to the hollow cathode axis (Fig. 1a). It is characteristic of the longitudinal discharge that electrons leaving the cathode surface move towards the anode along the hollow cathode axis (Fig. 1b).

Both the transverse and longitudinal discharge, as well as a discharge of intermediate nature, have been applied for the excitation of lasing in various media [1, 2].

The properties of longitudinal hollow-cathode discharge proved especially convenient for the forming of population inversion in the He – Cd mixture, generating the three basic spectral lines: blue, green and red, which can be mixed to produce white light [3].

The importance of this fact from the viewpoint of possible applications has increased the interest in properties of the longitudinal hollow-cathode discharge. The principal parameters of such discharge which decide whether it is applicable to the excitation of lasing media are the current density distribution over the cathode surface, the discharge plasma current distribution, the cathode fall distribution, the electron energy distribution function, the electron number density distribution, etc.

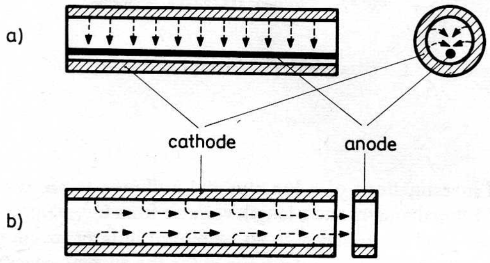


Fig. 1. Schematic diagram of typical hollow cathodes characterized by (a) transverse and (b) longitudinal discharge direction

Papers on the investigations of some of these parameters [4–11] except [9], refer to the longitudinal discharge in hollow cathodes not typical of the laser technology. As the laws of similarity do not hold for the hollow-cathode discharge, the applicability of the results published in [4–11] to the description of the longitudinal hollow-cathode discharge in laser tubes is limited.

This paper presents the results of investigations concerning some properties of the longitudinal discharge in a hollow cathode characterized by parameters typical of discharge tubes used in laser technology.

2. Measuring set-up

The dimensions of the hollow cathode and the measuring range were chosen to be typical of the longitudinal hollow-cathode discharge in lasing mixtures of helium with metal vapours (Cd, Zn, I etc.).

The discharge tube (Fig. 2) consisted of 52 independent annular segments 2 mm thick. The segments were made of stainless steel. Their inner and outer diameters were equal to 5 mm and 20 mm, respectively. Each of the segment rings was separated from the adjacent ones by mica spacers 0.05 mm thick. The rings were put in a pyrex tube in such a way that discharge could occur inside the system of rings only. Separate electric leads to each of the rings made it possible to change the ring polarity freely and to form a hollow cathode of a length variable from 2 mm up to 96 mm. The current to each of the rings could be measured. The measurements were made by measuring the voltage drops across calibrated (6 ohm) resistors connected to respective ring circuits. To facilitate the measurements the voltage drops across the resistors were transferred to a storage oscilloscope via an electronic commutator. Owing to the use of the commutator the measuring time was reduced to a fraction of a second. This decreased the influence of the working gas temperature changes on the results of measurements. Continuous distributions of the cathode current densities were obtained by smoothing the discrete distributions displayed by the oscilloscope. Fig. 3 gives an example of the smoothing operation. The evaluated accuracy of the measurements made in this way was ±5%.

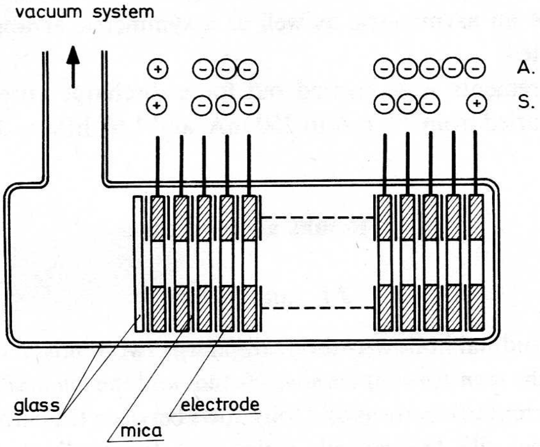


Fig. 2. Hollow cathode draft (52 segments 2 mm thick, with 5 mm I. D.). The polarity of electrodes for asymmetric (A) and symmetric (S) cathode supply is shown

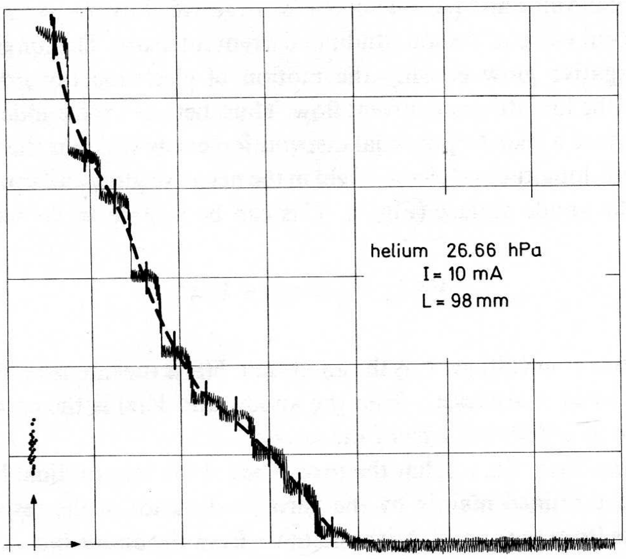


Fig. 3. Oscillograph record showing the cathode current distribution along the hollow cathode. Helium pressure: 26.66 hPa, current intensity; 10 mA, cathode length; 98 mm. The manner of smoothing the stepwise distribution is presented

The experiments included measurements of the density distributions along the cathode and V–I characteristics of the discharge for two geometries of the electrodes: *asymmetric* and *symmetric* (Fig. 2). For the asymmetric electrode configuration the discharge was maintained between the hollow cathode and one annular anode. To obtain a symmetric configuration the hollow cathode was placed between two anode rings ensuring symmetry of the power supply to the discharge. In each case the cathode was separated from each of the anode rings by one distance ring, completely insulated.

It should be noted that in laser tubes designed to obtain a longitudinal hollow-cathode discharge an asymmetric as well as a symmetric arrangement of electrode segments is adopted.

The measurements were carried out for a discharge current intensity and a helium pressure varied from 7.5 mA to 250 mA, and 1.67 hPa to 34 hPa, respectively.

3. Results and discussion

3.1. Introduction

In the longitudinal hollow-cathode discharge two kinds of current can actually be distinguished: the *transverse* or *cathode* current and the *longitudinal* current (Fig. 4). The transverse current of electrons and ions flows between the cathode surface and the negative glow which fills the cathode inside. The longitudinal current is produced mainly by electrons moving in the negative glow region towards the anode. The surface density of the transverse (cathode) current in a particular point of the cathode depends on the cathode fall value and parameters of the negative glow plasma at this point, that is also on the local value of the longitudinal current intensity. The longitudinal electric field in the negative glow causing the motion of electrons towards the anode is responsible for the longitudinal current flow. Thus, between the anode and a point on the cathode surface a specific potential distribution exists which is the resultant of the local cathode fall, longitudinal electric field in the negative glow and sometimes also the anode fall at the anode surface (Fig. 4). This can be written in the following way

$$V = V_a + \int_0^z E(z)\mathrm{d}z + V_c(z), \tag{1}$$

where V is the working voltage, V_a is the anode fall, $E(z)$ is the intensity of electric field in the negative glow at a distance z from the anode, and $V_c(z)$ is the cathode fall at the cathode surface at a distance z from the anode.

It is evident from Eq. (1) that the properties of the longitudinal hollow cathode discharge are determined mainly by the variable distance of the respective cathode surface elements from the anode. As the distance from the anode increases the value of the integral expression (1) increases. This means that at a fixed working voltage the local values of the cathode fall decrease as we go into the cathode. Thus also the local values of the transverse current intensity vary. For a sufficiently long cathode or relatively low working voltage Eq. (1) may not be satisfied for distances from the anode exceeding a certain finite value $z=\xi$. Physically this means that the depth of penetration of the discharge current into the cathode is limited, so that only part of the cathode surface is covered by the discharge. Obviously, an increase of the working voltage will result in an increase of the depth of current penetration into the cathode.

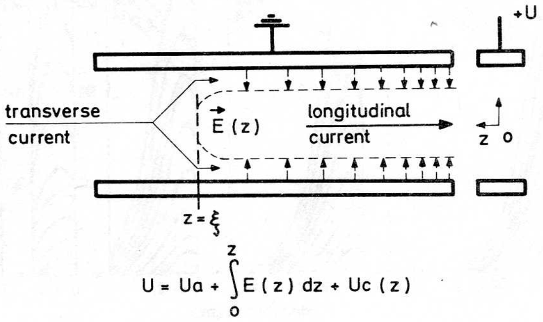


Fig. 4. Transverse and longitudinal current in the hollow cathode (ξ – penetration depth)

This inhomogeneity of the longitudinal discharge resulting from the difference in the distances between the anode and the respective cathode elements should be expected in the measurements.

3.2. Asymmetric electrode geometry

Results of measurements of the cathode current density distributions and voltage-current characteristics for the asymmetric electrode configuration are shown in Figs 5ⓐ—ⓖ and 6ⓐ—ⓖ.

In general, the cathode current distribution over the cathode surface is nonuniform independently of the cathode length, helium pressure and discharge current intensity. This is in agreement with considerations in Paragraph 3.1.

As for the form of the cathode current distribution its variations dependent on the current intensity, cathode length and helium pressure are observed. The variations are larger for short cathodes and for the lowest helium pressure equal to 1.67 hPa, as well as for the highest ones, equal to 24 hPa and 34 hPa.

Fig. 7 shows some oscillograph records of the cathode current distribution for different distances between the hollow cathode and the anode, equal to 2 mm and 50 mm, respectively. They show that the form of the cathode current distribution does not depend on the hollow cathode — anode distance. Similar results were obtained for various ranges of variability of the discharge parameters and distance between the hollow cathode and anode.

From Fig. 8 it is evident that for lower values of the current intensity, and corresponding lower working voltages the depth of discharge penetration into the

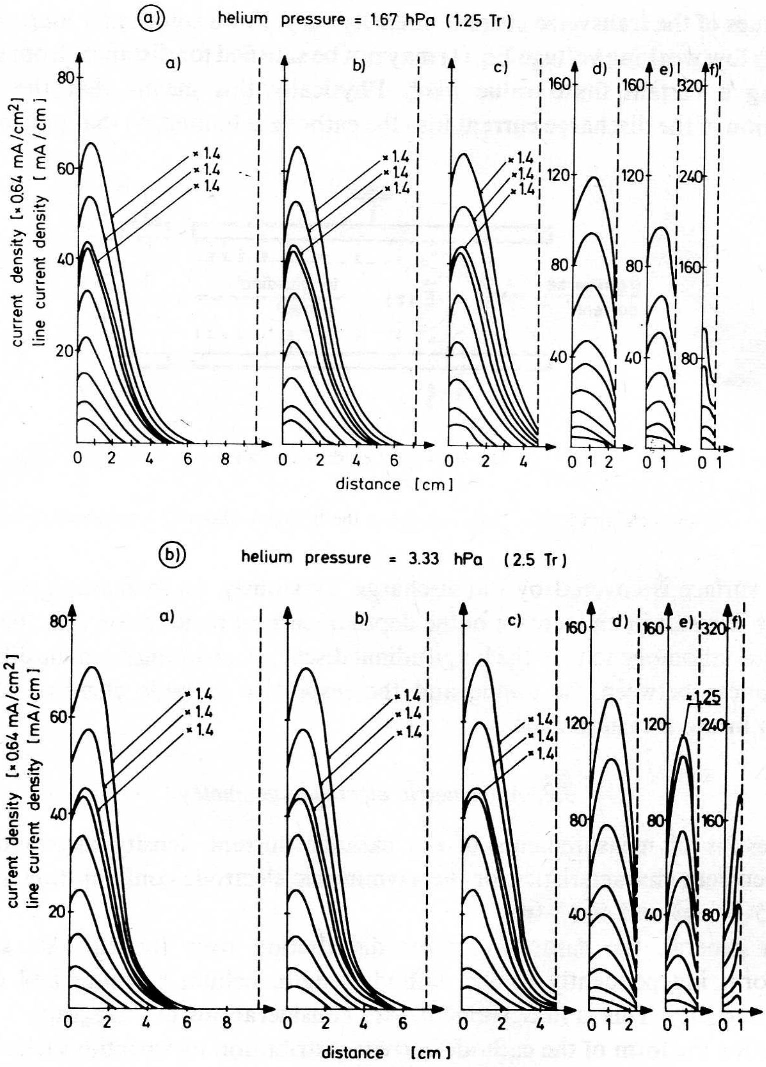
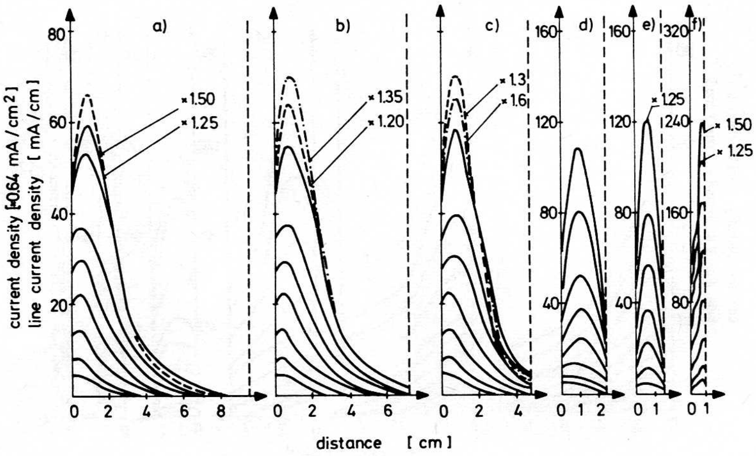


Fig. 5. Distributions of line and surface density of cathode current along the hollow cathode for different cathode lengths, discharge current intensities and helium pressures. Helium pressure: ⓐ – 1.67 hPa, ⓑ – 3.33 hPa, ⓒ – 6.66 hPa, ⓓ – 10.66 hPa, ⓔ – 16.66 hPa, ⓕ – 24 hPa, ⓖ – 34 hPa. Cathode length: a – 96mm, b – 72 mm, c – 48 mm, d – 24 mm, e – 16 mm, f – 8 mm. The curves, from the lowest one upwards, correspond to the following discharge currents: 7.5 mA, 15 mA, 30 mA, 50 mA, 75 mA, 100 mA, 150 mA, 200 mA and 250 mA. Some distribution curves for high current intensities are missing

cathode is small, independently of the helium pressure. The discharge length, amounting to the penetration depth, increases as the discharge current intensity increases. At the same time for the lowest helium pressures, 1.67 hPa and 3.33 hPa, the discharge length increases but slightly for current intensities above 70 mA. As for the

(c) helium pressure = 6.66 hPa (5 Tr)



(d) helium pressure = 10.66 hPa (8 Tr)

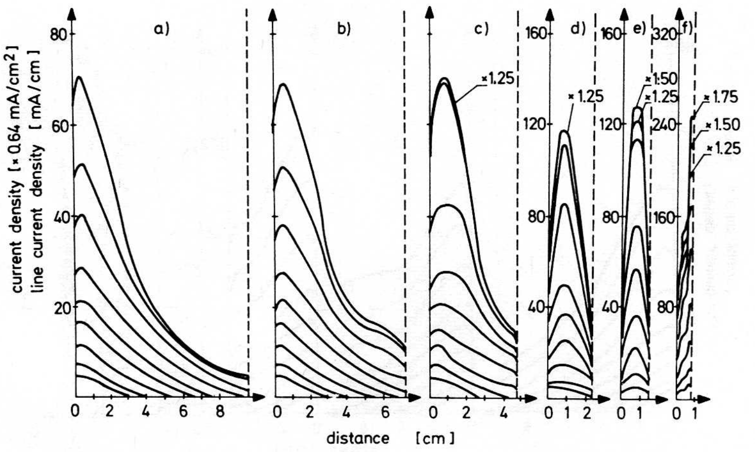
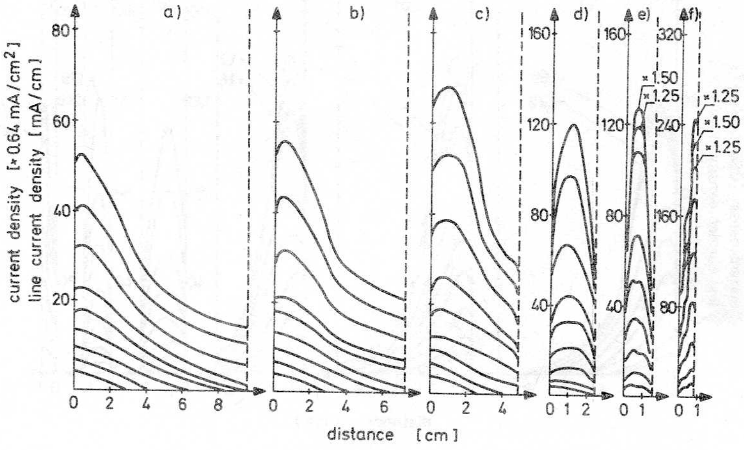


Fig. 5. (cont.)

dependence of the discharge length on the gas pressure it was shown that for a fixed discharge current intensity there is a specific pressure of helium, 16–17 hPa, at which the hollow-cathode discharge length is the largest (Fig. 9). On the other hand, when the working voltage is fixed, the discharge length increases with the helium pressure to reach its steady value on a level characteristic of the particular working voltage at pressures exceeding approximately 20 hPa (Fig. 10).

The results of measurements of the cathode current density can be employed to determine the distributions of the longitudinal current intensity in the hollow cathode.

e) helium pressure = 16.66 hPa (12.5 Tr)



f) helium pressure = 24 hPa (18 Tr)

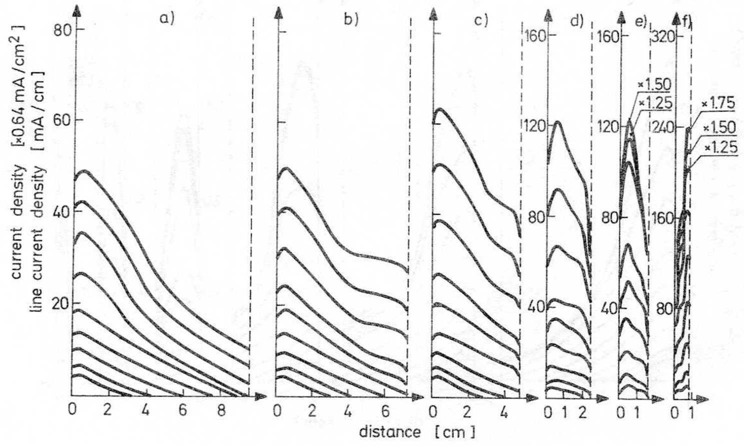


Fig. 5. (cont.)

The dependence of the longitudinal current intensity on the position along the hollow cathode axis is one of features by which this kind of plasma differs from the positive column plasma, where the axial current intensity is constant.

It was shown in [4] and [10] that the cathode current density distributions for hollow cathodes characterized by large diameters, 20 mm and 50 mm, depend for a fixed working gas pressure only on the distance measured from the point defining the discharge penetration depth. Thus they are functions of the quantity $\xi - z$ (see Fig. 4). However, the results of the present work show (Fig. 5) that the cathode current density

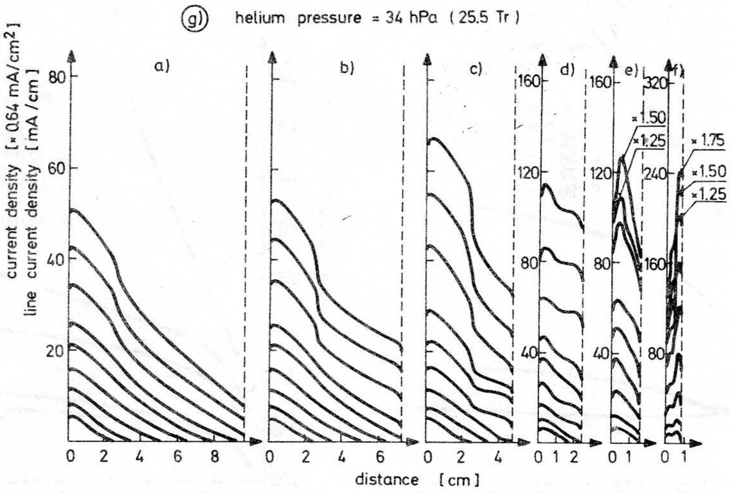


Fig. 5. (cont.)

distributions depend not only on the distance $\xi - z$, but also on the discharge current intensity (and, as in the former case, on the gas pressure).

A similar result was obtained in [6] for a discharge in a hollow cathode of relatively small diameter (14 mm). Based on these results it might be concluded that for a discharge in hollow cathodes characterized by relatively small diameters the relation between the cathode current density and the cathode dimensions and discharge parameters becomes more complex than for cathodes of larger diameters.

This affects directly the method of determining the discharge plasma potential distribution along the hollow cathode axis. It was shown in [4] that for the cathode current density, a function of the distance $\xi - z$ only, it is sufficient, when determining the axial distribution of the discharge plasma potential, to know the working voltage value and the corresponding distribution of the cathode current density. For the reasons presented above this method of determining the plasma potential distribution was inadequate in the case described in this paper.

Therefore, to approximately determine the potential of a plasma inside the hollow cathode measurements were carried out of the floating potential of the odd cathode segments, electrically insulated. The hollow cathode was composed in this case of the even segments. The insulated segments may be regarded as the electric probes. Their floating potential must not differ significantly from the plasma potential.

Fig. 11 shows the results of measurements of the floating potential of insulated segments in the hollow cathode at a selected helium pressure of 16.66 hPa. Based on these measurements it can be concluded that in the hollow-cathode discharge plasma there is a region characterized by a nearly constant potential gradient, i.e. a constant intensity of the longitudinal electric field. This is similar to the situation in the glow

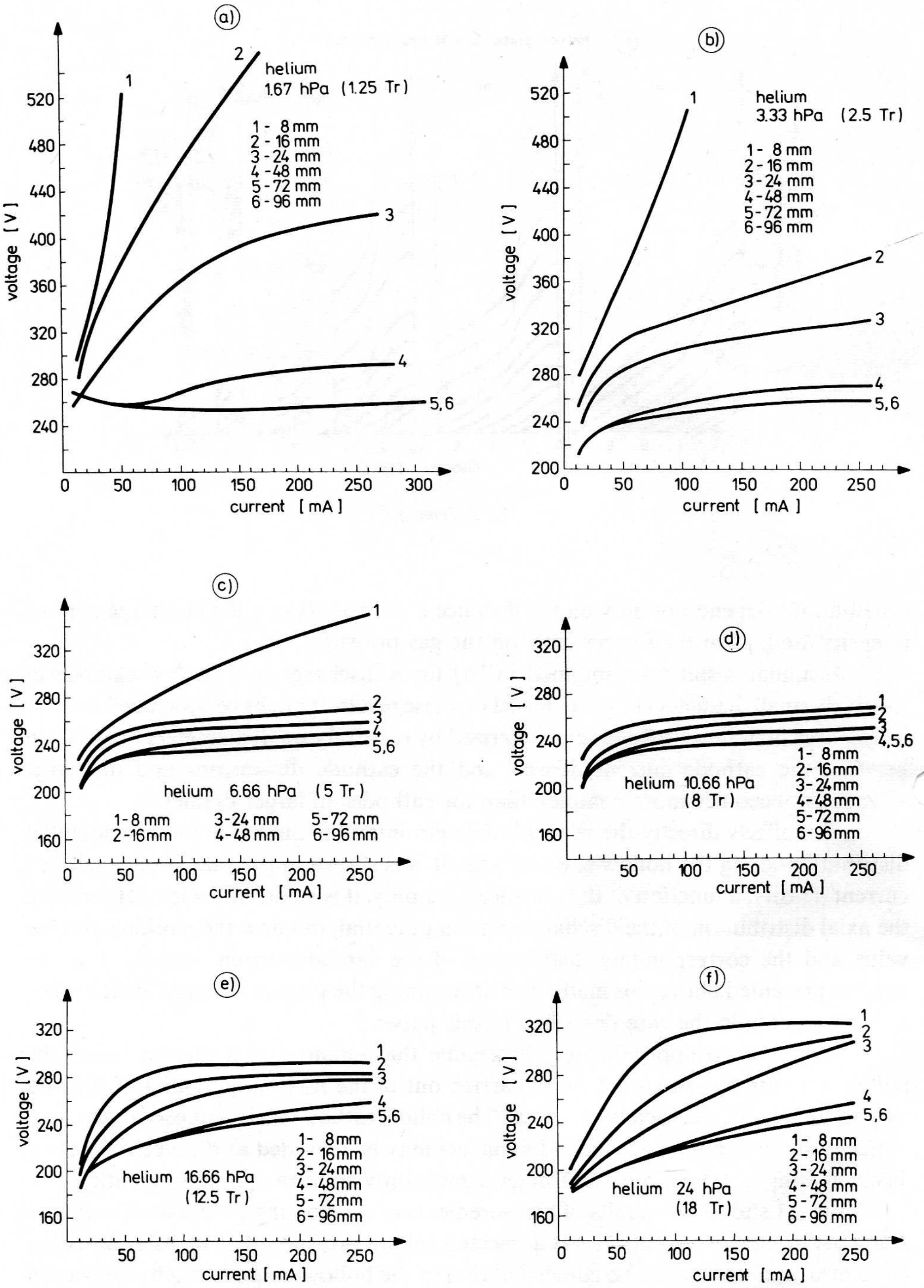


Fig. 6. **Voltage–current characteristics for the longitudinal hollow-cathode discharge in cathodes of different lengths. Helium pressure: ⓐ– 1.67 hPa, ⓑ– 3.33 hPa, ⓒ– 6.66 hPa, ⓓ – 10.66 hPa, ⓔ – 16.66 hPa, ⓕ – 24 hPa, ⓖ – 34 hPa**

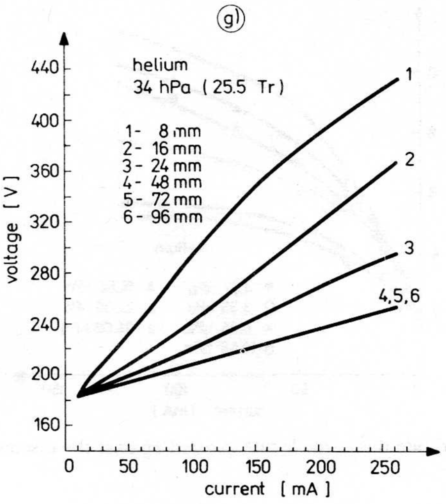
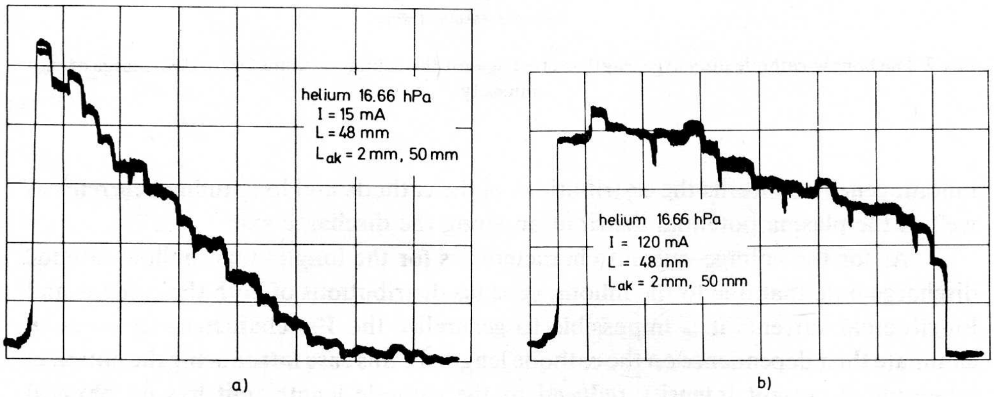


Fig. 6. (cont.)

discharge positive column where the longitudinal electric field is responsible for the drift of electrons toward the anode. Our observation confirms the results of earlier works [7] and [11] where it was suggested that in the longitudinal hollow-cathode discharge three regions may be distinguished, namely the negative glow region, the transient region and the positive column region.

To sum up the results, as presented above, of investigations of the longitudinal hollow-cathode discharge in an asymmetric configuration of electrodes it should be noted that the discharge is inhomogeneous irrespective of the cathode length. The



a) b)

Fig. 7. Examples of double oscillograph records showing the cathode current distributions for different distances between the hollow cathode and anode. The helium pressure was equal to 16.66 hPa, the cathode length was 48 mm and the cathode–anode distance was 2 mm and 50 mm; the current intensity was equal to: a) – 15 mA, b) – 120mA

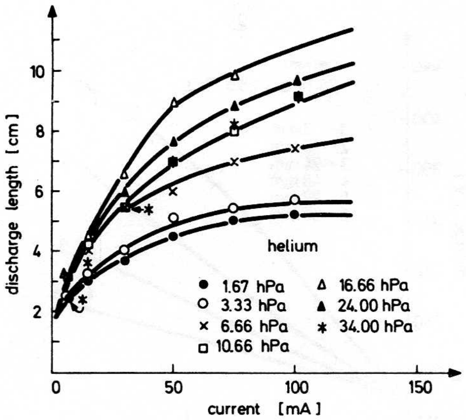


Fig. 8. The hollow-cathode discharge length plotted against the discharge current intensity

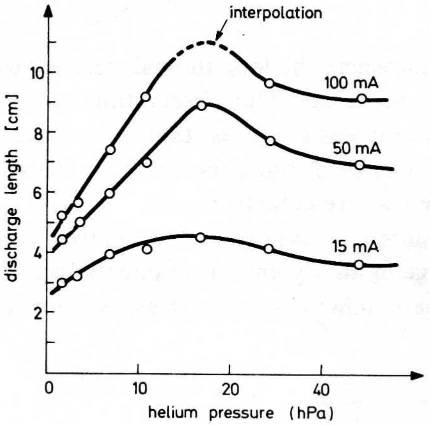


Fig. 9. The hollow-cathode discharge length plotted against the helium pressure for fixed discharge current intensity

inhomogeneity concerns the distributions of the cathode and longitudinal currents as well as the plasma potential distribution along the discharge axis.

As for the voltage–current characteristics for the longitudinal hollow-cathode discharge note that due to the inhomogeneous distributions of both the cathode and longitudinal currents it is impossible to generalize the *V–I* characteristics so as to eliminate their dependence on the cathode length. In this case introducing the notion of longitudinal current intensity reduced to the cathode length unit has no physical meaning. It may only be regarded as the mean value.

From the analysis of voltage–current characteristics and cathode current density distributions it follows that for a fixed gas pressure discharges characterized by

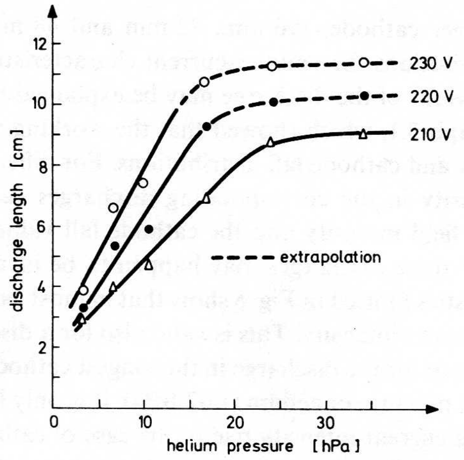


Fig. 10. The hollow-cathode discharge length plotted against the helium pressure for fixed working voltage

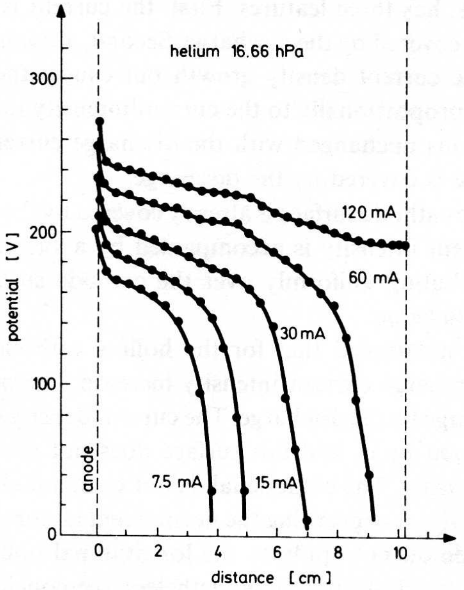


Fig. 11. The floating potential of insulated odd cathode segments for the hollow-cathode discharge with one anode

identical current density distributions occur at the same working voltage, cf. for instance relevant plots for the longest cathodes which are only partly covered by the discharge (Figs 5 and 6). It may happen, however, that identical working voltages correspond to discharges with different cathode current density distributions if only the discharge current intensity and helium pressure remain unchanged. This effect is characteristic of longer cathodes (96 mm, 72 mm and 48 mm), where for different current density distributions the voltage–current characteristics might sometimes be identical. Such behaviour of the discharge may be explained based on the discussion presented in Paragraph 3.1, which showed that the working voltage depends on the electric field intensity and cathode fall distributions. For different distributions of the cathode current density in the corresponding discharges such distributions of the longitudinal electric field intensity and the cathode fall value may develop that the working voltages for these discharges may happen to be identical.

The characteristics plotted in Fig. 6 show that in most cases the working voltage increases with the current intensity. This is valid also for a discharge covering part of the cathode only, except for the discharge in the longest cathodes (48 mm, 72 mm and 96 mm) at the lowest pressure of helium (1.67 hPa). It is only by this behaviour of the voltage following the current intensity rise in the case of cathode whose part only is covered by the discharge that the hollow-cathode discharge differs from the classical glow discharge with flat or convex cathode.

A glow discharge covering only part of the flat or convex cathode, called *the normal glow discharge*, has three features. First, the current is uniformly distributed over the cathode part covered by the discharge. Second, a rise in the discharge current does not result in the current density growth but causes the area covered by the discharge to increase proportionally to the current intensity rise. Finally, the value of the cathode fall remains unchanged with the discharge current rise until the entire surface of the cathode is covered by the discharge.

When the whole cathode surface is already covered by the discharge a further rise in the discharge current intensity is accompanied by a substantial voltage rise, the current density distributing uniformly over the cathode surface. Such discharge is called an *abnormal discharge*.

It was already mentioned that for the hollow cathode the working voltage increases with the discharge current intensity increase, irrespective of the degree of cathode surface coverage by the discharge. The current density is not constant over the cathode surface covered by it, and this surface does not rise proportionally to the discharge current intensity. The cathode fall is not constant either along the cathode axis. Thus, classical notions concerning the normal and abnormal glow discharge with flat or convex cathode do not apply to the longitudinal hollow-cathode discharge, which was already pointed out in [5]. Nonetheless, the conclusions drawn from this fact are frequently neglected in the literature.

The increase of the working voltage with the growth of the cathode surface area covered by the discharge observed for the hollow-cathode discharge may be explained according to Paragraph 3.1, by the necessity of increasing the voltage to draw the electrons out of cathode regions more and more distant from the anode.

Curves plotted in Figs 12 and 13 show the dependence of the working voltage on the helium pressure for different lengths of the hollow cathode and different intensities of the discharge current. The form of these curves is characteristic of the discharge in

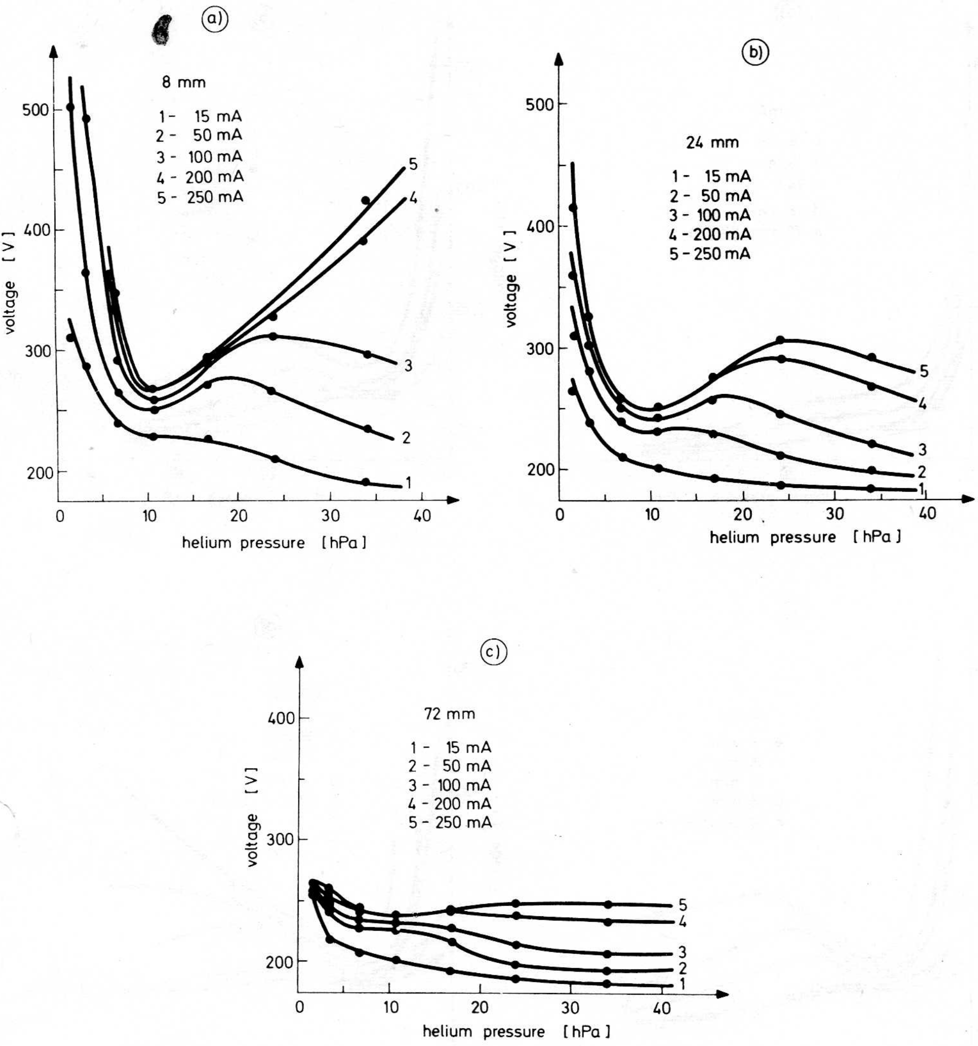


Fig. 12. Working voltage vs helium pressure for different discharge current intensities. Cathode length: a) – 8 mm, b) – 24 mm, c) – 72 mm

which a so-called *hollow-cathode effect* [12] occurs, which consists of the existence of a so-called optimum pressure of the working gas at which a particular intensity of the discharge current is obtained at the lowest working voltage. In the case under consideration the hollow-cathode effect is more distinct for high current intensities and shorter cathodes. It depends thus mainly on the cathode current density.

Figs 14 ⓐ—ⓒ show the dependence of the working voltage on the cathode length. It is evident that for a given discharge current intensity the working voltage rises with

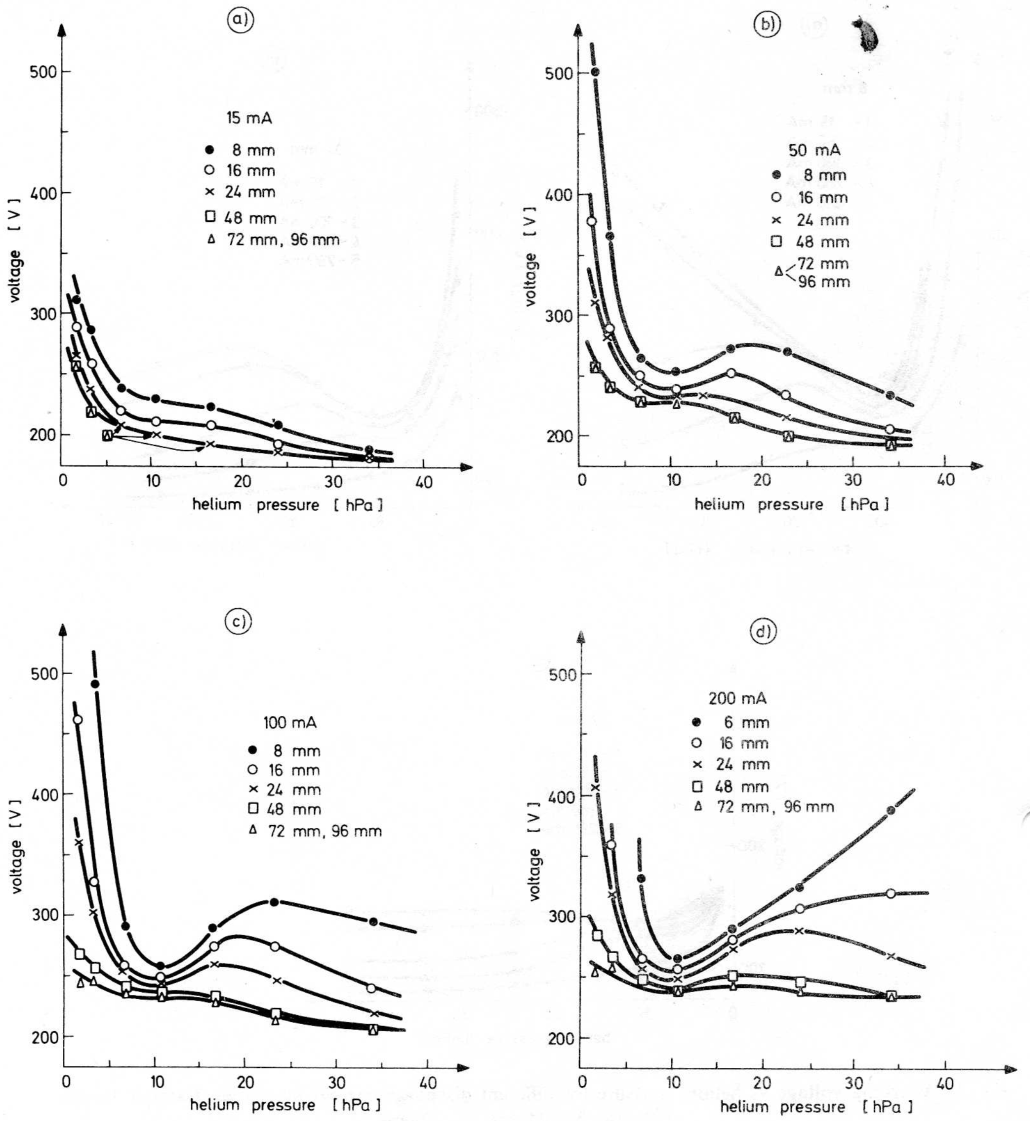


Fig. 13. Working voltage vs helium pressure for different hollow-cathode lengths. Discharge current intensity: ⓐ − 15 mA, ⓑ − 50 mA, ⓒ − 100 mA, ⓓ − 200 mA, ⓔ − 250 mA

the cathode length reduction, the rise being the more distinct the lower is the helium pressure.

The analysis of the results obtained leads to the conclusion that this effect can be attributed not only to the cathode current density rise due to the cathode shortening, but also to the resulting changes of the current distribution over the cathode surface.

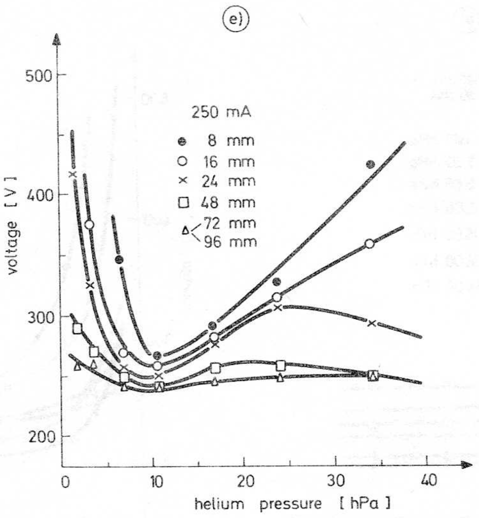


Fig. 13. (cont.)

3.3. *Symmetric electrode geometry*

The longitudinal discharge in a hollow cathode operating in conjunction with two anodes was investigated for one value of helium pressure, 16.66 hPa, most typical of hollow-cathode lasers.

The results are shown in Figs 15 and 16. In a hollow cathode fed symmetrically the current distribution is symmetric with respect to an axis traversing the cathode centre and dividing the system of electrodes into two asymmetric halves composed of one anode and one half of the original cathode. In order to distinguish such a discharge from the *asymmetric discharge* in a hollow cathode operating in conjunction with one anode, it will be called the *symmetric discharge*.

The symmetric discharge as well as the asymmetric one is characterized by nonuniform distribution over the cathode discharge. To facilitate the evaluation of the extent of this nonuniformity cathode current distributions normalized relative to the corresponding mean values of the current density are shown in Figs 17 and 18. Here the horizontal line on the level of unity represents the normalized uniform distribution of the current density irrespective of the discharge current intensity.

It is evident from Figs 17 and 18 that the cathode current density distribution is most nonuniform for the longest cathodes. The lower the current intensity, the more marked is this nonuniformity. In the extreme case (cathode length of 96 mm, discharge current intensity of 30 mA) the difference between the maximum and minimum value of the current density over the cathode surface is more than twice as large as the corresponding mean value of the current density. Shortening of the cathode or increase of the discharge current intensity results in flattening of the distribution nonuniformities. At the same time the saddle-like distribution curves assume a parabolic shape.

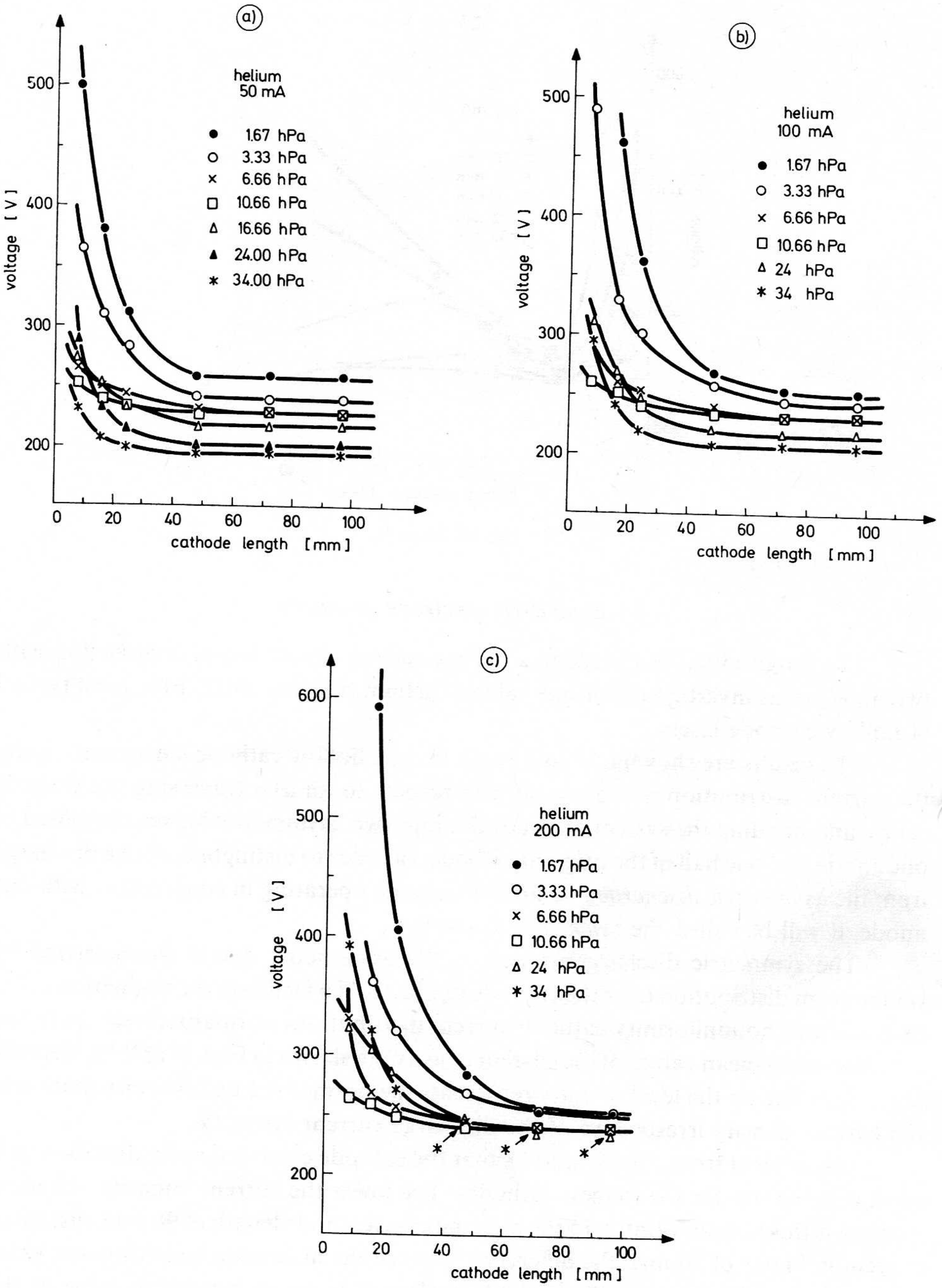


Fig. 14. Working voltage vs hollow-cathode length. Discharge current intensity: ⓐ – 50 mA, ⓑ – 100 mA, ⓒ – 200mA

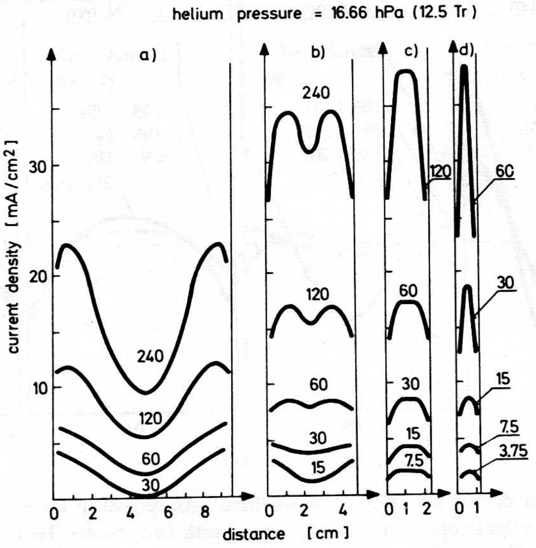


Fig. 15. The cathode current density distribution along the hollow-cathode fed symmetrically. Helium pressure: 16.66 hPa; discharge current intensity: 3.75 mA, 7.5 mA, 15 mA, 30 mA, 60 mA, 120 mA, 240 mA

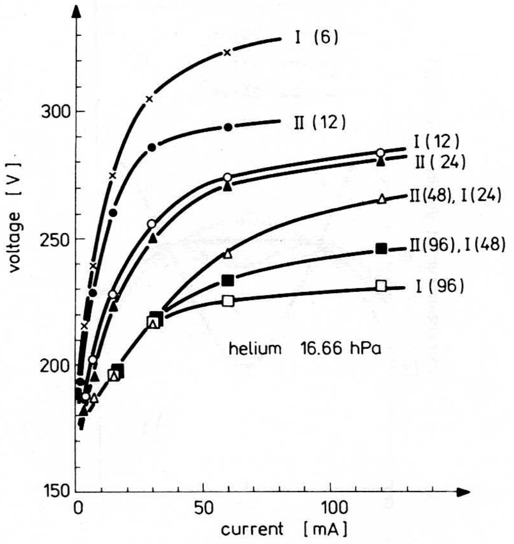


Fig. 16. V–I characteristics for the longitudinal hollow-cathode discharge with (I) one and (II) two anodes. Helium pressure: 16.66 hPa, cathode length: 96 mm, 48 mm, 24 mm, 12 mm and 6 mm. Along the abscissae the anode current intensities are shown

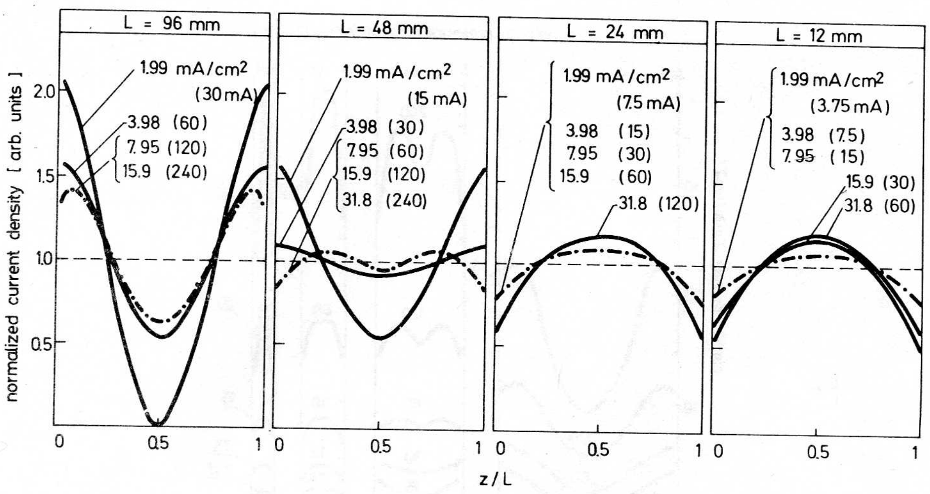


Fig. 17. Cathode current density distributions normalized with respect to the mean value of the current density for the hollow-cathode operating in conjunction with two anodes. Helium pressure: 16.66 hPa, cathode length: 96 mm, 42 mm, 24 mm, 12 mm. Numbers represent mean values of the cathode current density and (in brackets) discharge current intensities, respectively

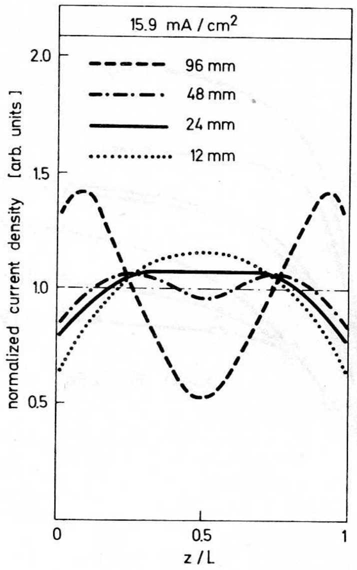


Fig. 18. Discharge density distributions in the hollow-cathode operating in conjunction with two anodes, normalized with respect to the mean value of the cathode current density. Helium pressure: 16.66 hPa, cathode length: 96 mm, 48 mm, 24 mm, 12 mm; mean value of the cathode current density: 15.9 mA/cm^2

This makes it possible to obtain a uniform or nearly uniform distribution of the cathode current density. For instance, a nearly uniform distribution of the cathode current density may be expected for a discharge in a hollow cathode 48 mm long if only the discharge current is kept within the 30 mA–60 mA interval (cf. Fig. 17). Note, however, that this uniformity of the cathode current density is accompanied by a nonuniform distribution of the longitudinal discharge current. Thus, the hollow-cathode discharge in the presence of two anodes is, as a whole, inhomogeneous.

The symmetry of cathode current density distributions in a hollow-cathode discharge where two anodes are used suggests that the discharge consists of two parts, each of them belonging mainly to its anode and the adjacent half of the cathode. The structure of the symmetric discharge may be explained better on the basis of a comparison of working voltages and cathode current density distributions for symmetric and asymmetric discharges, and also for an asymmetric discharge with a cathode shortened by half (Figs 16 and 19), termed briefly the *asymmetric half-discharge*. The following conclusions can be drawn from this comparison:

For the longest cathode (96 mm) all of the above mentioned three distributions of the cathode current density are identical irrespective of the type of discharge, unless the anode current intensity exceeds 15 mA. Potentials of anodes corresponding to these distributions are the same. This means that the symmetric discharge is then composed of two mutually independent asymmetric discharges, each of them occurring only between its anode and the adjacent cathode half. The presence or absence of one asymmetric discharge does not affect the other discharge. Likewise, the symmetric discharge may be regarded as composed of two asymmetric half-discharges.

With a rise of the discharge current intensity in the longest cathode the distributions of the cathode current density in the asymmetric discharge begin to differ from the other two distributions, which remain indistinguishable. The difference appears mainly because in the asymmetric discharge the current may be distributed over an area larger than in the remaining two cases. Consequently, the mean value of the cathode current density per unit length of the cathode surface covered by the discharge is lower, and therefore the working voltage for the asymmetric discharge is lower, too (see e.g. Fig. 16). Similar conclusions may be obtained from the analysis of the discharge in the 48 mm hollow cathode. In spite of insignificant differences between the forms of distributions of cathode current densities for the symmetric discharge and corresponding asymmetric half-discharge the symmetric discharge may still be regarded as consisting of two, nearly independent asymmetric half-discharges.

For cathodes shorter than 48 mm both parts of the symmetric discharge affect each other and cease being independent. This results in differences in the forms of the cathode current density distributions and changes of anode voltages of the symmetric discharge and asymmetric half-discharge. The shorter the cathodes, the larger these differences.

It follows from the above discussion that for the range of parameters as considered here the symmetric discharge in a hollow cathode whose length is 48 mm or

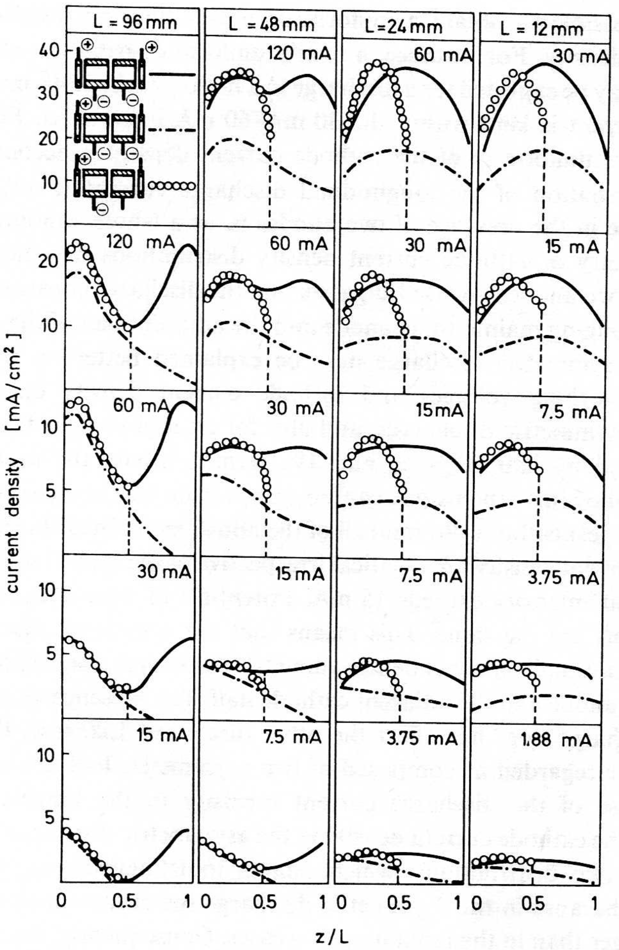


Fig. 19. A comparison of cathode current density distributions for the symmetric discharge (solid line), asymmetric discharge (dash-dot line), and asymmetric half–discharge (circles). Helium pressure: 16.66 hPa, cathode length 96 mm, 48 mm, 24 mm, 12 mm. Current intensities shown (1.88 mA up to 120 mA) denote the anode current values

more may be regarded approximately as composed of two independent asymmetric half-discharges. On the other hand, for cathodes shorter than 48 mm both parts of the discharge interact, which leads to changes in the working voltage value and form of the cathode current density distributions.

The decrease, occurring in the latter case, of the anode voltages in the symmetric discharge compared with the asymmetric half-discharge characterized by the same intensity of the anode current possibly results from the presence of the so-called *pendel electrons* [13] in the central region of the cathode equidistant from both anodes. The presence of such electrons, causing additional ionization of the gas, should lead to a drop of the working voltage. Besides, in the symmetric discharge the contribution of photons to the production of electrons on the cathode surface in the intermediate region is larger than in the case of two asymmetric half-discharges where photons are more likely to escape outside. This may be another reason for the working voltage decrease for the symmetric discharge.

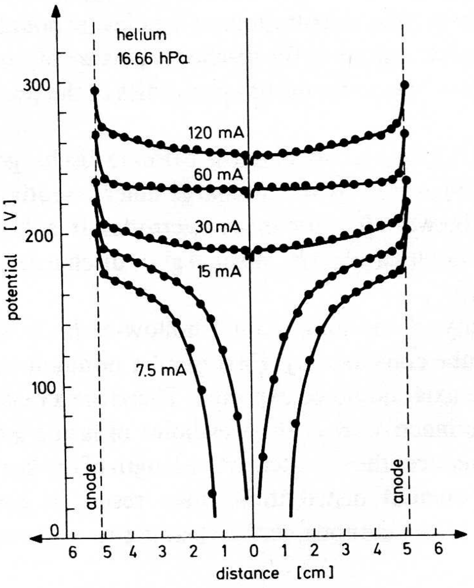


Fig. 20. The floating potential of insulated odd cathode segments in the hollow-cathode discharge with two anodes for different intensities of the anode currents

For the symmetric discharge, as for the asymmetric one, the plasma potential distribution along the cathode was estimated by measuring the floating potential of electrically insulated odd cathode segments (Fig. 20). The measurement confirmed the presence in the discharge of a region of nearly constant longitudinal electric field intensity, suggesting the existence in this region of a plasma exhibiting properties of the positive column.

4. Concluding remarks

The results of investigations presented in this paper lead to the following conclusion:

The longitudinal discharge in a hollow cathode having dimensions typical of the laser technology is axially inhomogeneous irrespective of the configuration of the electrodes, anode and cathode — symmetric or asymmetric. Axial distributions of the cathode current density and longitudinal current as well as axial distributions of the plasma potential are, as a rule, nonuniform. From this point of view minor differences only have been observed between the longitudinal discharge in hollow cathodes typical of laser tubes and the classical hollow-cathode discharge [4–11].

An appropriate choice of the cathode length and current intensity for the symmetric discharge will ensure a uniform cathode current density distribution. However, this will not provide for a uniform distribution of the longitudinal current and corresponding uniform axial distributions of the plasma potential and cathode fall.

The presence in some regions of the discharge plasma of a constant electric field suggests that the plasma in these regions has properties of the positive column plasma of glow discharge.

The properties of the longitudinal hollow-cathode discharge for which only part of the cathode surface is covered by the discharge differ essentially from those of the normal glow discharge between flat or convex electrodes. It is therefore inappropriate to call the former using the classical term "normal glow discharge" rather than "normal hollow-cathode discharge".

The inhomogeneity of the longitudinal hollow-cathode discharge affects the operation of the laser tube considerably. First of all a nonuniform excitation of laser levels along the cathode axis should be expected. Therefore a considerable part of the hollow cathode may be inactive from the viewpoint of lasing even when filled with discharge plasma. This reduces the so called active length of the laser tube. Nonuniform current and plasma potential distributions may result in nonuniform cathodic sputtering and heating of the cathode surface leading to a shortened lifetime of the device.

If operated with a mixture of gases the effect of cataphoresis may be expected to occur in the hollow cathode due to the presence of the longitudinal electric field. Such an effect is undesirable as it might make the continuous laser operation difficult to maintain (e.g. in the He–Kr^+ laser).

The investigations of the symmetric discharge showed that for a laser tube filled with alternating cathode and anode segments an increase of the number of segments for the tube length and discharge current intensity fixed results in a decrease of the working voltage.

The results presented in this paper do not provide a complete answer as to the optimum length of the hollow cathode with longitudinal discharge to be used for lasers. It follows from the analysis of uniformity of the cathode current density distribution and working voltage value for the asymmetric and symmetric discharges that in laser technology the most appropriate application of cathodes is the following: cathodes of a length of 12 to 24 mm are suitable for asymmetric power supply, and those of a length of 24 to 48 mm are suitable for a symmetric configuration. Then the cathode current density distributions are relatively uniform and the working voltages necessary to ensure the appropriate current density are not very high.

However, to answer the question mentioned above fully the microscope parameters of the hollow-cathode discharge plasma should be measured. These are mainly the axial distributions of the electron energy distribution function and electron concentration. An analysis of the results of such measurements should provide the answer required.

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