

# Axial distributions of the plasma parameters of a longitudinal discharge in helium in hollow cathodes used for lasers

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**Abstract.** This paper presents results of the measurements of distributions of the electron energy distribution function, the mean energy and concentration of electrons, and the plasma potential along the axis of a longitudinal discharge (LD) in hollow cathodes which are used for He-inert gas and He-metal lasers. The measurement technique employs the second derivative of the electric probe current-voltage characteristics. The results show that the LD in cathodes longer than about 15 mm is axially inhomogeneous. The LD consists of two zones having the properties of the negative glow (NG) and the positive column (PC) of glow discharge, respectively, and a transitional zone between them. The relative lengths of the zones depend on the helium pressure and the discharge current. At low helium pressures ( $\sim 6.7$  mbar) and discharge currents ( $\sim 20$  mA) almost the whole cathode is occupied by the PC-type plasma. As the helium pressure and discharge current increases the NG-type plasma lengthens at the expense of the PC-type zone. The LD in cathodes shorter than 15 mm has NG-type plasma along nearly all its length, as long as the helium pressure is higher than about 6.7 mbar. In this aspect it resembles a transverse discharge in a hollow cathode. The results obtained prove that the positioning of the anode outside the cylindrical hollow cathode may, under special conditions, essentially influence the properties of the discharge occurring in the cathode.

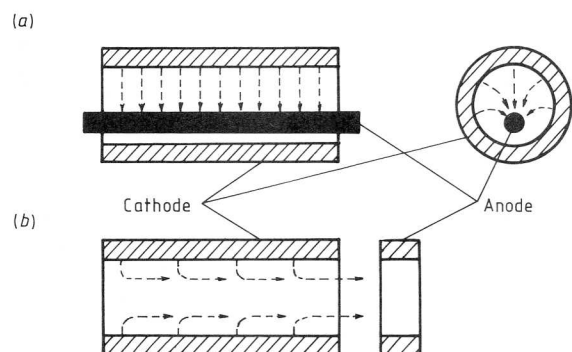
## 1. Introduction

Papers by Borodin *et al* (1967), Moskalev (1969), Zykova and Kutscherenko (1976) and Mizeraczyk (1983, 1985) on investigations of a longitudinal discharge (LD) in cylindrical hollow cathodes having various diameters and lengths showed that the LD may, under special conditions, be axially inhomogeneous, contrary to another kind of discharge in a hollow cathode, known as the transverse discharge (TD) (Mizeraczyk and Urbanik 1983). The reason for the non-uniformity of the plasma is the axial motion of electrons toward the anode, caused by an internal positioning of the anode with respect to the cathode (figure 1).

Axial inhomogeneity of the LD plasma results in different properties of the LD and the TD in hollow cathodes having relatively small inner diameters (3-10 mm). This fact is of a great importance since both discharges are used in producing laser radiation (Mizeraczyk *et al* 1984). However, to the best of the author's knowledge, there is no other publication on the axial properties of the LD in hollow cathodes as used in laser technology than his own (Mizeraczyk

1983), concerning measurements of the axial distributions of the cathode current density.

It is the aim of this work to measure the plasma parameters, the electron energy distribution function (EEDF), the mean energy and concentration of electrons, and the plasma potential along the axis of the LD in helium in hollow cathodes typical of He-inert gas and He-metal vapour lasers.



**Figure 1.** Schematic diagram of hollow cathodes characterised by (a) transverse and (b) longitudinal discharge direction.

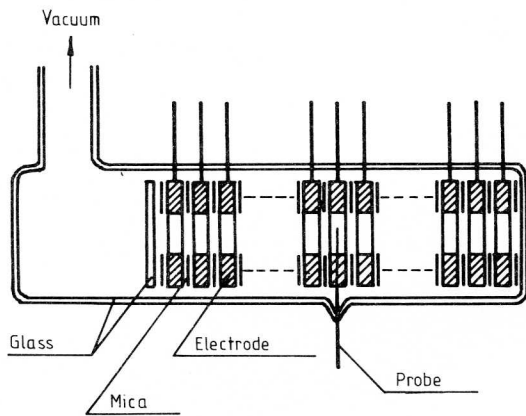


Figure 2. Hollow cathode with measuring probe.

## 2. Experiment

The discharge tube (figure 2) was a cylinder consisting of 25 independent annular segments 2 mm thick and 5 mm inner diameter each. The segments were made of stainless steel. Each of the segment rings was separated from the adjacent ones by mica spacers 0.1 mm thick. A tungsten cylindrical probe, 0.5 mm long and 0.05 mm diameter, was passed through the wall of the middle ring and located at the cathode axis. The cathode cylinder, formed from the rings, was put in a Pyrex tube in such a way that a discharge could only occur inside the system of rings. Separate electric leads to each of the rings made it possible to use the ring either as an anode or a constituent of the cathode. Owing to this a hollow cathode of a variable length could be formed and it could freely be 'shifted' with regard to the fixed probe. The 'shifting' was realised by disconnecting from a power supply a certain number of the rings at one end of the cathode and connecting to the power supply the same number of them at the opposite end of the cathode. Such a procedure produces a minimum disturbance to the plasma while using the conventional probing of the plasma with a movable probe may introduce serious errors due to the contribution of the probe moving facilities to the plasma disturbance.

The discharges in the hollow cathodes of 7.7, 15.5 and 31.1 mm lengths were investigated. The cathodes having lengths of 7.7 and 15.5 mm are representatives of the group of short laser cathodes, whereas the cathode of 31.1 mm length belongs to the hollow cathodes of medium lengths. Probing the discharge in longer cathodes was unfeasible in this experiment. However, the results of 'stationary' measurements of the plasma parameters in the centre of the LD in a relatively long hollow cathode (49.3 mm, Mizeraczyk 1985) essentially supplement the data of this work. Combining both results allows for more general conclusions concerning discharges in laser hollow cathodes of all lengths.

The EEDF was obtained employing the Druryvesteyn (1930) method, involving the measurement

of the second derivative of the electric probe current-voltage characteristic. This method allows for measuring the EEDF in the 0 to about 40 eV range. The mean energy of electrons was calculated from the EEDF. The electron concentration was determined from the measurements of the current flowing to the probe at the plasma potential, that is, when the second derivative was equal to zero. The plasma potential was measured with respect to the grounded anode. The measuring set-up and procedure have been described elsewhere (Mizeraczyk and Urbanik 1983).

The operating conditions were close to those of the He-inert gas or the He-metal vapour lasers. The helium pressure was varied from 2.3 to 26.7 mbar. The discharge current ranged from 10 to 150 mA depending on the cathode length and the helium pressure. The results were obtained with a repeatability better than 10%.

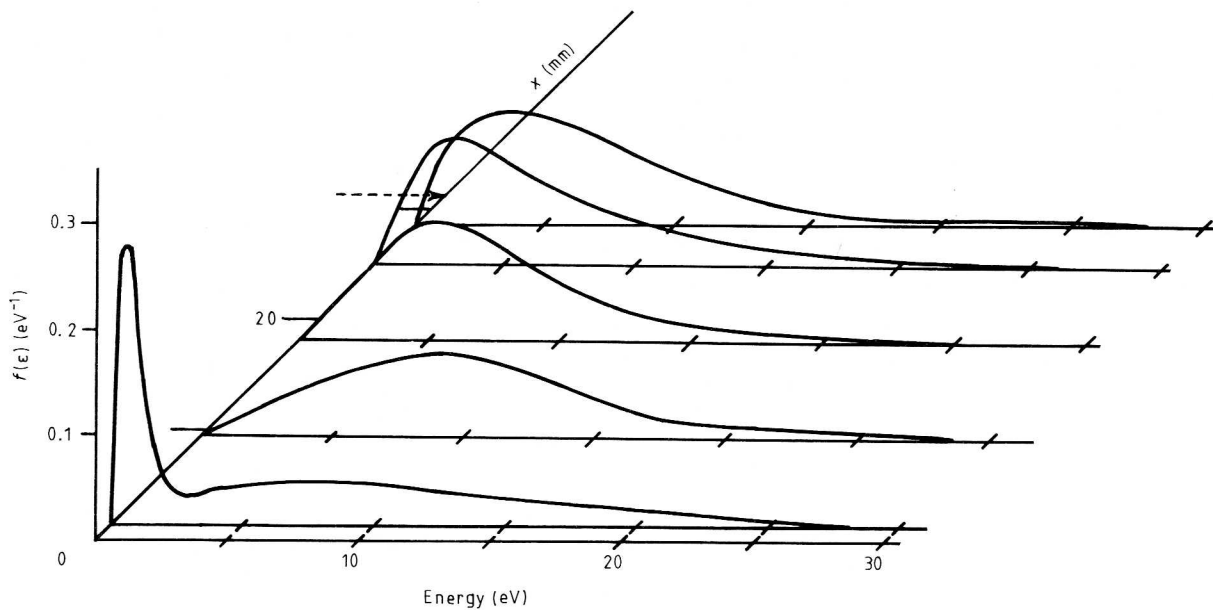
## 3. Results

### 3.1. The 31.1 mm length cathode

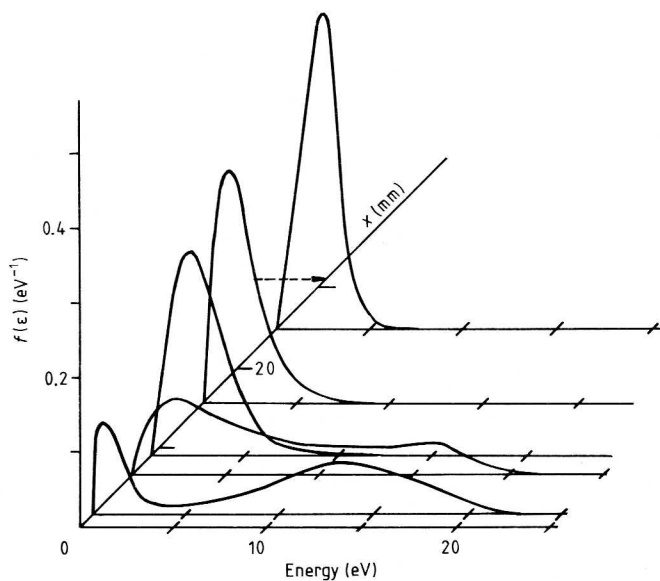
The results show that the axial distributions of the plasma parameters of the LD depend in a complex way on the helium pressure and the discharge current.

**3.1.1. Influence of the helium pressure.** For low helium pressures (e.g. for 2.3 mbar), at a fixed current of 50 mA the bulk of the EEDF is 'broad' and almost does not change its form along the cathode (figure 3). Increasing the helium pressure up to 13.3 mbar causes axially non-uniform 'narrowing' of the EEDF. For instance, at the helium pressure of 6.7 mbar (figure 4) the EEDF changes its form from 'broad' at the anode to 'narrow' at the opposite end of the cathode. As the helium pressure is higher than or equal to 13.3 mbar, the plots of the EEDF are 'narrow' and similar to each other (figure 5). Only the EEDFs measured in the neighbourhood of the anode differ from the others. Raising the discharge current up to 150 mA does not cause essential change of the character of dependence of the EEDF upon the helium pressure.

As seen in figures 6 and 7, at a helium pressure higher or equal to 13.3 mbar, a characteristic of the tail of the EEDF is the so-called 'collisional' structure, similar to that occurring in the TD due to collision processes between the plasma particles (Mizeraczyk and Urbanik 1983). At lower helium pressures the plots of the tail of the EEDF as a function of the electron energy are monotonic, without the structure mentioned above. The distribution of the relative number of electrons in the tail of the EEDF does not vary along the cathode irrespective of the discharge current, as long as the helium pressure is higher or equal to 13.3 mbar. On the other hand, at helium



**Figure 3.** EEDF  $f(\varepsilon)$  for the LD in the hollow 31.1 mm cathode at different distances  $x$  from the anode. Discharge current 50 mA; operating voltage 222 V; helium pressure 2.3 mbar. The broken arrow indicates the cathode end.

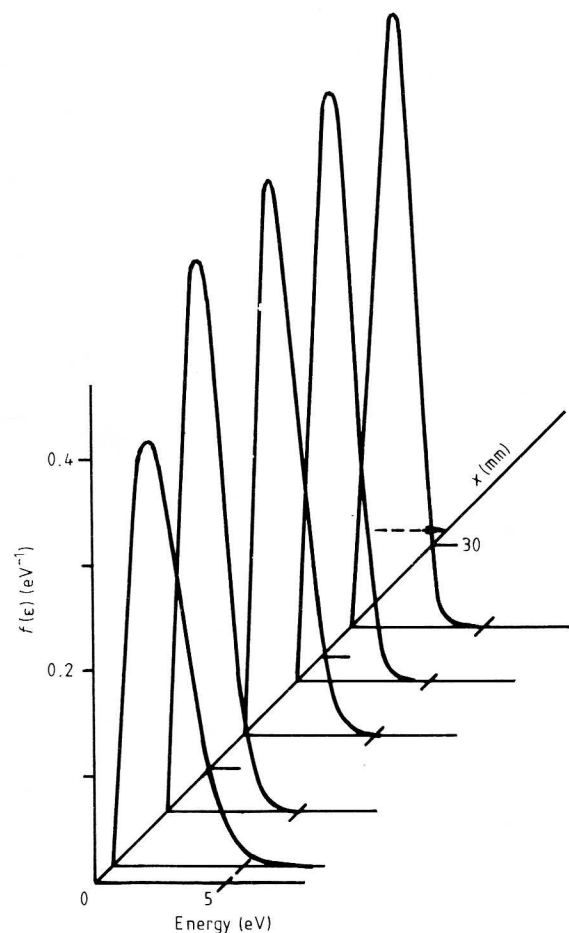


**Figure 4.** EEDF  $f(\varepsilon)$  for the LD in the hollow 31.1 mm cathode at different distances  $x$  from the anode. Discharge current 50 mA; operating voltage 211 V; helium pressure 6.7 mbar. The broken arrow indicates the cathode end.

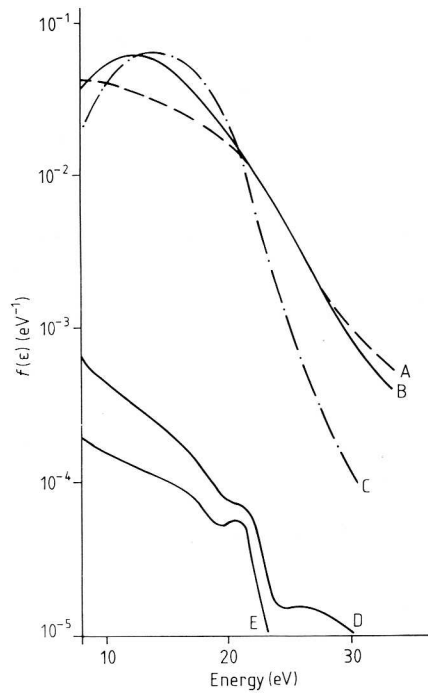
pressures lower than 13.3 mbar, the distribution of the relative number of electrons in the tail of the EEDF depends on the distance from the anode.

It can be seen in figure 8, that:

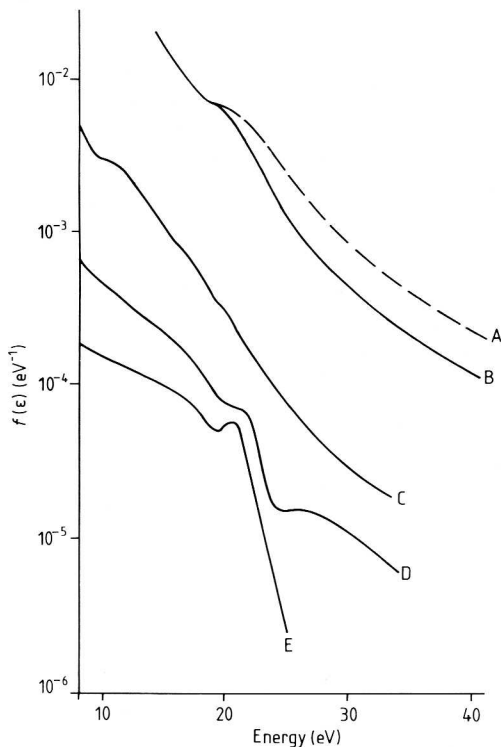
(i) The plasma potential is not constant along the cathode at the helium pressure lower than 13.3 mbar. It means that the axial electric field exists in the LD at lower helium pressures. At pressures of helium higher or equal to 13.3 mbar the gradient of the plasma potential exists in the region adjacent to the



**Figure 5.** EEDF  $f(\varepsilon)$  for the LD in the hollow 31.1 mm cathode at different distances  $x$  from the anode. Discharge current 50 mA; operating voltage 216 V; helium pressure 13.3 mbar. The broken arrow indicates the cathode end.



**Figure 6.** EEDF  $f(\varepsilon)$  (high-energy part) for the LD in the hollow 31.1 mm cathode at a distance  $x = 1.35$  mm from the anode. Discharge current 50 mA; helium pressure (mbar): (A), 2.3; (B), 3.3; (C), 6.7; (D), 13.3; (E), 20.



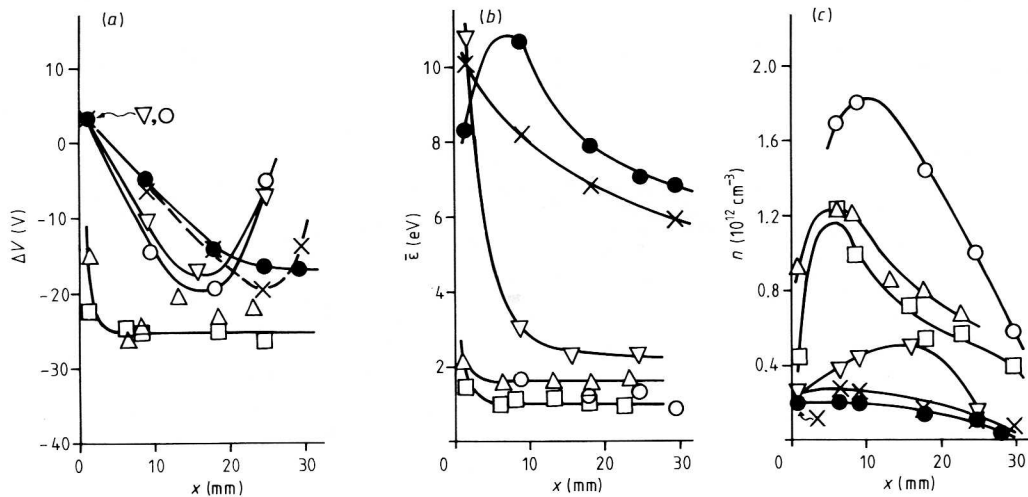
**Figure 7.** EEDF  $f(\varepsilon)$  (high-energy part) for the LD in the hollow 31.1 mm cathode at a distance  $x$  from the anode. Discharge current 50 mA, helium pressure (mbar): (A), 2.3 (at  $x > 9$  mm), (B), 3.3 (at  $x \geq 9$  mm); (C), 6.7 (at  $x \geq 9$  mm), (D), 13.3 (at  $x \geq 1.35$  mm); (E), 20 (at  $x \geq 1.35$  mm).

anode only. Beyond this region the plasma potential is constant and lower than that of the anode by a value approximately equal to the ionisation potential of the helium atom (about 24.5 V). The increase of a plasma potential in front of an anode is a well known phenomenon of forming the so-called positive anode fall, which in the case of low electron concentration increases its value by additional ionisation, providing in this way for a sufficient number of electrons to maintain the anode current, set by an external power supply (Francis 1956).

(ii) The mean energy of electrons decreases with increasing distance to the anode, as the helium pressure is lower than 13.3 mbar. At helium pressures higher or equal to 13.3 mbar the mean energy of electrons is constant along the LD, except for the anode region of the cathode.

It is evident from the above, that at helium pressures higher or equal to 13.3 mbar the LD is nearly homogeneous as far as the axial distributions of the plasma potential and mean energy of electrons are considered. However, the axial distribution of the electron concentration never becomes uniform along the LD in the 31.1 mm length cathode (figure 8(c)), regardless of the helium pressure (also at currents up to 150 mA). The axial distributions of the electron concentration in the LD are similar to those of the cathode current density (Mizeraczyk 1983), which seems to be reasonable because of a correlation that should exist between the number of electrons emitted by the cathode and their concentration at the cathode axis.

**3.1.2. Influence of the discharge current.** At helium pressures lower than 13.3 mbar (e.g. at 6.7 mbar, figures 4, 9, and 10) the increase of discharge current varies the form of the EEDF along the cathode. At low discharge currents (e.g. at 10 mA) the EEDF is uniformly 'broad' along the whole cathode. Increasing the discharge current causes axially non-uniform 'narrowing' of the EEDF, that is, the further from the anode the 'narrowing' process is more pronounced. As a result, at moderate values of the discharge current (e.g. at 50 mA) the EEDF varies its form from 'broad' at the anode to 'narrow' at the opposite end of the cathode. As the discharge current is raised further (e.g. up to 75 mA), the process of 'narrowing' the EEDF comprises also that part of the cathode which is close to the anode. This makes the EEDF almost uniformly 'narrow' along the larger part of the cathode. In the same manner the 'narrowing' process affects the tail of the EEDF. The 'narrowing' of the EEDF with increasing discharge current is accompanied by decreasing the mean energy of electrons, ranging from about 10 eV to 2 eV (figure 11(b)). The distribution of the plasma potential does not vary along the cathode with increase of the discharge current, except for the case when discharge current is changed from 10 mA up to 20 mA (figure 11(a)). The electron concentration increases non-linearly with the discharge

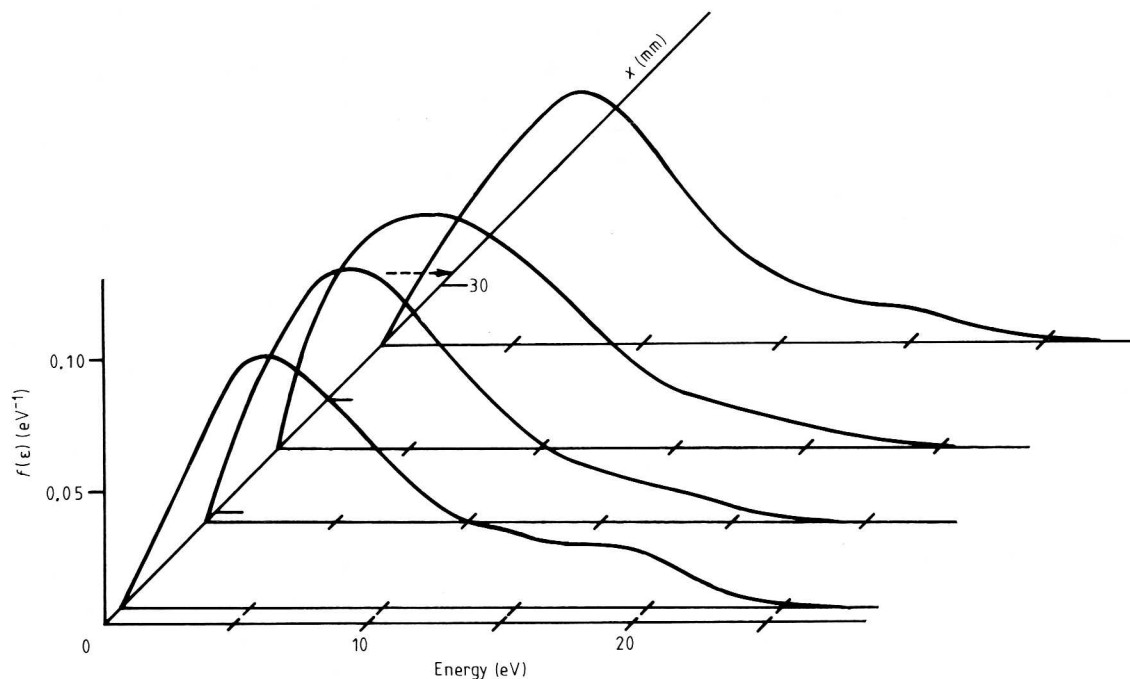


**Figure 8.** Distribution of (a) the plasma potential  $\Delta V$ , (b) the mean energy of electrons  $\bar{\epsilon}$ , and (c) the electron concentration  $n$  along the LD in the hollow 31.1 mm cathode. Discharge current 50 mA, helium pressure (mbar): (●), 2.3; (×), 3.3; (▽), 6.7; (○), 10; (△), 13.3; (□), 20;  $x$ , distance from the anode. The operating voltages (in V) are 222, 213, 211, 216 and 195, respectively.

current. Since this increase is spatially non-uniform, the profile of the axial distribution of the electron concentration varies, as shown in figure 11(c). A similar effect occurs for the axial distribution of the cathode current density (Mizeraczyk 1983).

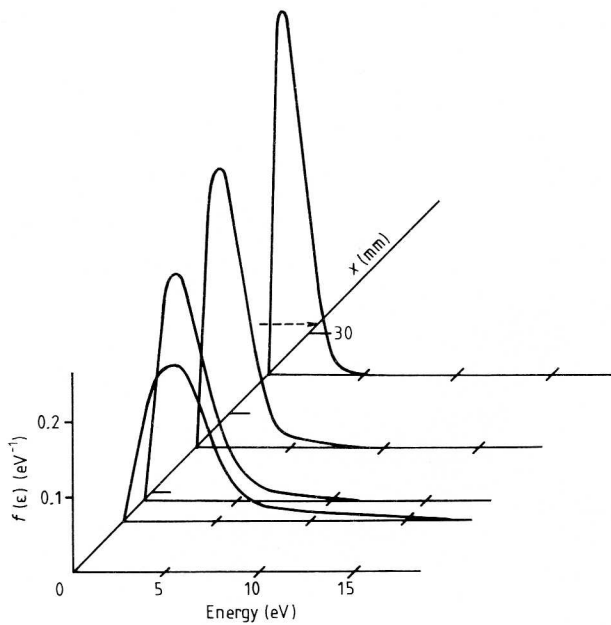
At helium pressures higher or equal to 13.3 mbar the influence of the discharge current on the axial distributions of the plasma parameters of the LD is not as marked as at lower pressures. At higher helium pressures (e.g. at 20 mbar, figure 12) the plasma potential and the mean energy of electrons

are approximately constant along the cathode regardless of a value of the discharge current, except for the region adjacent to the anode. This concerns also the form of the bulk of the EEDF. The axial distribution of the electron concentration varies with increasing discharge current but the maximum position of the distribution in respect to the anode remains almost constant (figure 12(c)). A similar characteristic is exhibited by the cathode current density (Mizeraczyk 1983). The relative number of electrons in the tail of the EEDF increases with discharge current approxi-



**Figure 9.** EEDF  $f(\epsilon)$  for the LD in the hollow cathode of 31.1 mm length at different distances  $x$  from the anode. Helium pressure 6.7 mbar; discharge current 10 mA; operating voltage 156 V. The broken arrow indicates the cathode end.





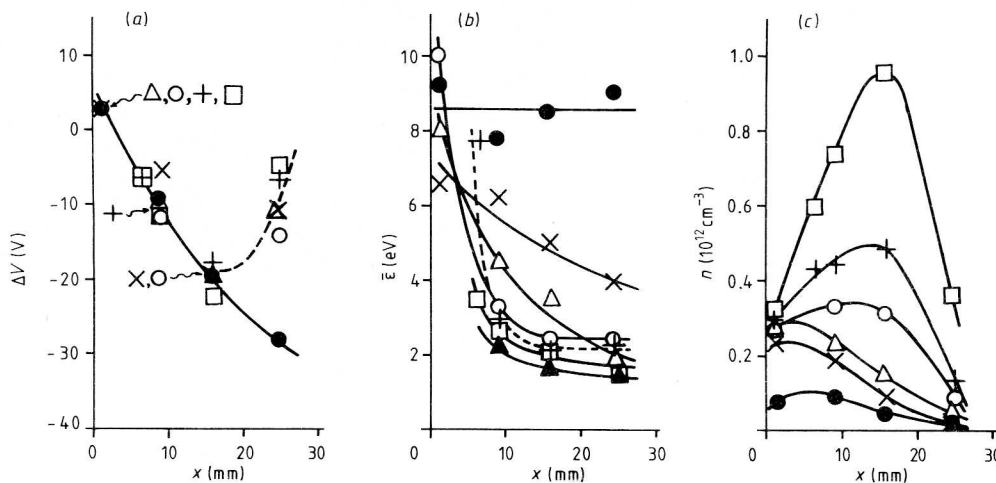
**Figure 10.** EEDF  $f(\epsilon)$  for the LD in the hollow 31.1 mm cathode at different distances  $x$  from the anode. Helium pressure 6.7 mbar; discharge current 75 mA; operating voltage 217 V. The broken arrow indicates the cathode end.

mately uniformly along the entire length of cathode. This is a reverse tendency to that observed at lower pressures of helium.

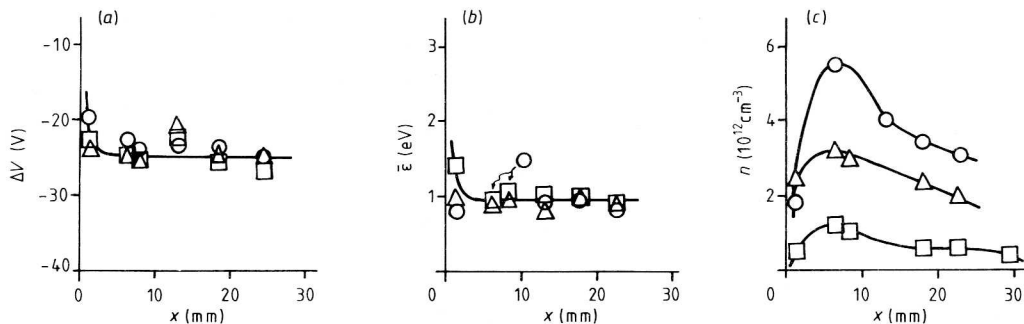
### 3.2. The 15.5 mm length cathode

The discharge in the 15.5 mm length cathode becomes nearly homogeneous at the helium pressure as low as 6.7 mbar, regardless of the discharge current in the range from 10 mA to 50 mA (figure 13). Both the plasma potential and the EEDF as well as the mean energy of electrons do not vary along the cathode. Only the electron concentration decreases at the cathode end, opposite to the anode, probably due to diffusion of electrons out of the discharge region. The absence of the gradient of the plasma potential along the cathode means that there is no axial electric field in the discharge.

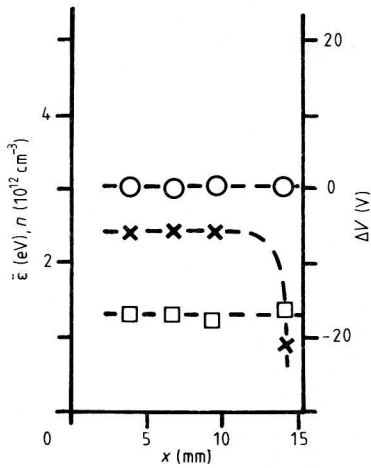
Changes in the helium pressure and discharge current affect the values of the plasma parameters uniformly along the cathode, almost maintaining their nearly constant axial distributions (this rule does not concern the case of the lowest helium pressures, i.e. 2.3 and 3.3 mbar). This is the reason why in the fol-



**Figure 11.** Distributions of (a) the plasma potential  $\Delta V$ ; (b) the mean energy of electrons  $\bar{\epsilon}$ , and (c) the electron concentration  $n$  along the LD in the hollow 31.1 mm cathode. Helium pressure 6.7 mbar; discharge current (mA): (●), 10; (×), 20; (△), 30; (○), 40; (+), 50; (□), 75; (▲), 100;  $x$ , distance from the anode. The operating voltages (in V) are 156, 170, 185, 196, 211, 217 and 224, respectively.



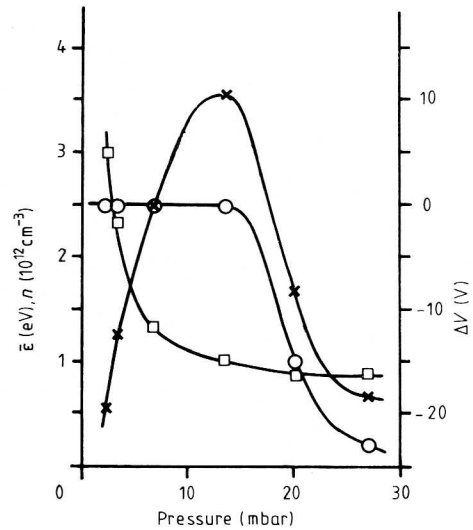
**Figure 12.** Distributions of (a) the plasma potential  $\Delta V$ ; (b) the mean energy of the electrons  $\bar{\epsilon}$ , and (c) the electron concentration  $n$  along the LD in the hollow 31.1 mm cathode. Helium pressure 20 mbar; discharge current (mA): (□), 50; (△), 100; (○), 150;  $x$  distance from the anode. The operating voltages (in V) are 195, 231 and 264, respectively.



**Figure 13.** Distributions of (○), the plasma potential  $\Delta V$ ; (□), the mean energy of electrons  $\bar{\epsilon}$ ; and (×), the electron concentration  $n$  along the LD in the hollow 15.5 mm cathode. Helium pressure 6.7 mbar; discharge current 40 mA; the operating voltage 206 V;  $x$ , distance from the anode.

lowing, the presentation of the axial distributions of the plasma parameters is given up and the description is confined to the phenomena occurring in the middle of the cathode length.

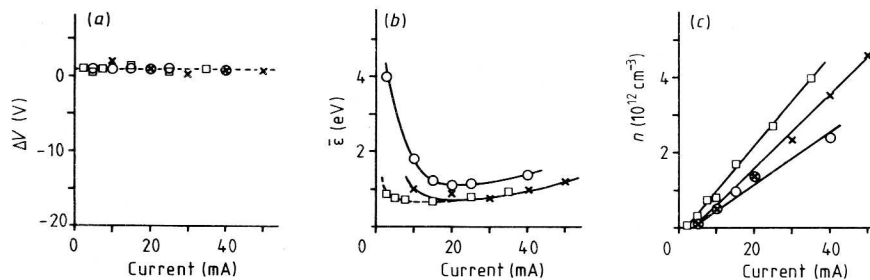
**3.2.1. Influence of the helium pressure.** Increasing the helium pressure in the 15.5 mm cathode results in 'narrowing' the bulk of the EEDF and decreasing the mean energy of the electrons (figure 14). At helium pressures higher or equal to 6.7 mbar the EEDF is as 'narrow' as in the TD. Raising the helium pressure above 13.3 mbar causes a drop of the plasma potential. At the helium pressure equal to 30 mbar the plasma potential is lower than the potential of the anode by a value close to the ionisation potential of the helium atom. The electron concentration rises as the helium pressure is increased up to 13.3 mbar, and then decreases. The relative number of electrons in the tail of the EEDF, which has distinctive 'collisional' structure when the helium pressure is higher or equal to 13.3 mbar, decreases with the helium pressure.



**Figure 14.** Dependence of (○), the plasma potential  $\Delta V$ ; (□), the mean energy of electrons  $\bar{\epsilon}$ ; and (×), the electron concentration  $n$  upon the helium pressure for the LD in the hollow 15.5 mm cathode at a distance  $x = 6.5$  mm from the anode. Discharge current 40 mA.

**3.2.2. Influence of the discharge current.** At lower helium pressures (e.g. at 6.7 mbar) the mean energy of electrons slightly decreases and then rises with an increasing discharge current (figure 15(b)). This increase of the mean energy of electrons at higher currents resembles that of the TD. Similarity of the LD in the cathode of 15.5 mm length to the TD is also confirmed by relatively low values of the mean energy of electrons (lower than those in the cathodes of lengths 31.1 and 49.3 mm, Mizeraczyk (1985)), as well as by relatively high values of the electron concentration and its linear growth with the discharge current increase (figure 15(c)). It is worthwhile to note that in spite of a relatively high electron concentration in the cathode of 15.5 mm length the 'collisional' structure of the tail of the EEDF is hardly pronounced at low helium pressures, and the relative number of electrons in the tail decreases as the discharge current rises.

At higher helium pressures (e.g. at 13.3 mbar) the



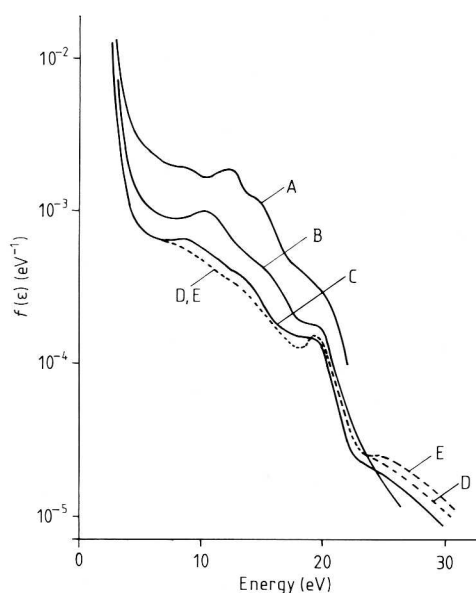
**Figure 15.** Dependence of (a), the plasma potential  $V$ ; (b), the mean energy of electrons  $\bar{\epsilon}$ ; and (c) the electron concentration  $n$  upon the discharge current for the LD in the hollow cathodes of lengths: 7.7 mm (□), helium pressure 6.7 mbar; measured at a distance  $x = 3.95$  mm from the anode), and 15.5 mm (○), (×), helium pressure 6.7 and 13.3 mbar, respectively; measured at a distance  $x = 6.5$  mm from the anode).

LD in the cathode of 15.5 mm length has the features of the TD: the bulk of the EEDF is 'narrow', the mean energy of electrons slightly decreases and then increases with the discharge current (figure 15(b)), the electron concentration, having relatively high values, rises proportionally to the discharge current (figure 15(c)), the 'collisional' structure is characteristic of the tail of the EEDF, and the relative number of electrons with energies between 23 eV and 40 eV increases slightly as the discharge current increases.

Regardless of the helium pressure the plasma potential does not depend on the discharge current (figure 15(a)).

### 3.3. The 7.7 mm length cathode

The discharge in the 7.7 mm cathode has the features of the TD at the helium pressure as low as 6.7 mbar. As long as the helium pressure is higher or equal to 6.7 mbar the discharge is axially homogeneous, if we neglect a decrease of the electron concentration at the cathode end, similar to that observed in the 15.5 mm cathode (figure 13). There is no axial electric field in the LD in the 7.7 mm cathode, and the plasma potential is close to the anode potential (figure 15(a)). The bulk of the EEDF is 'narrow', the mean energy of electrons is low and it rises with increasing the discharge current (figure 15(b)). A relatively high electron concentration in the discharge (figure 15(c)) is likely to be the reason for the appearance of the 'collisional' structure in the tail of the EEDF (figure 16), which is usually absent in the LD at such a low helium pressure. Also the increase of the relative number of



**Figure 16.** EEDF  $f(\epsilon)$  (high-energy part) for the LD in the hollow cathode of 7.7 mm length at a distance  $x = 3.95$  mm from the anode. Helium pressure 6.7 mbar, discharge current (mA): (A), 5; (B), 10; (C), 15; (D), 25; (E), 35. The operating voltages (in V) are 234, 236, 237, 241 and 244, respectively.

electrons with energies within the 23–40 eV interval with raising the discharge current (figure 16) seems to be caused by the relatively high electron concentrations.

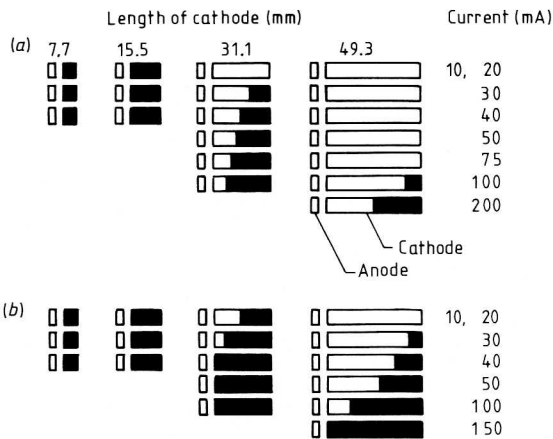
## 4. Résumé and conclusions

The results, presented above, for axial probing of the LD in laser hollow cathodes (of 5 mm diameter and 7.7, 15.5 and 31.1 mm lengths), along with the results of measurements of the plasma parameters in the middle of the LD in relatively long hollow cathodes (of 5 mm diameter and 49.3 mm length, Mizeraczyk 1985) show that the LD may, under certain conditions, be inhomogeneous and its properties may vary along the cathode axis. This inhomogeneity concerns axial variations of the EEDF, the mean energy and concentration of electrons, and the plasma potential. Their presence and character depend on the cathode length, the helium pressure and the discharge current.

The LD in short cathodes (the 7.7 and 15.5 mm lengths) is approximately uniform axially when the helium pressure is higher than or equal to 6.7 mbar. At these pressures there is no axial electric field along nearly the whole of the cathode, the mean energy of electrons is low and it rises with an increase of the discharge current and a decrease of the helium pressure, the electron concentration is relatively high. The negative glow of the TD has similar properties and in this aspect both discharges, the LD in short cathodes and the TD, are indiscernible, in spite of different positioning of the anodes in them.

In the long cathodes (the 31.1 and 49.3 mm lengths) the discharge is axially inhomogeneous. It consists of zones having different properties. In the part of the cathode furthest from the anode, the EEDF is 'narrow', the mean energy of electrons is low, and the electron concentration is relatively high. These are typical features of the negative glow of the TD. The part of the discharge in the neighbourhood of the anode, neglecting the anode fall region, is characterised by 'broad' EEDFs, high values of the mean energy of electrons, and relative low values of the electron concentration. In this part there is a relatively strong axial electric field. All these features indicate that the plasma of that part of the cathode has similar properties to those of the positive column of glow discharge. It should be noted, however, that the mean energy of electrons in the LD is dependent upon the distance from the anode, whereas it is constant along the positive column. Between the two main parts of the LD a diffusive transitional zone may appear. Existence and dimensions of the zones depend on the helium pressure and the discharge current. At low helium pressures (i.e., below 13.3 mbar) the majority of the cathode is occupied by the positive column-type plasma. As the discharge current increases the positive column-type zone shrinks, and the negative glow-type plasma extends to fill the remainder of the cathode. At higher helium pressures (i.e., 13.3 mbar and above)





**Figure 17.** Distributions of the main zones of the LD (■, the negative glow-type, □, the positive column-type) in hollow cathodes having different lengths. Helium pressure (mbar): (a), -6.7; (b), -13.3.

the partition of the cathode length between the zones becomes more favourable for the negative glow-type plasma. It may fill nearly the entire cathode at sufficiently high currents. This condition is similar to that existing in the TD.

Distributions of the main zones of the LD in hollow cathodes having different lengths are schematically shown in figure 17. The basis which enabled making the figure was an observation that the LD plasma with electrons having their mean electron energy lower than about 2.5 eV has the features of the negative glow, whereas the features of the plasma with the mean energy of electrons higher than 2.5 eV are typical of the positive column.

The EEDFs in the LD have two types of tails. The relative number of electrons in the tails of the first type decreases monotonically with increasing electron energy

(e.g. figure 7), while the tails of the second type does not exhibit monotonic 'collisional' structure (e.g. figure 16). The experimental results allow for concluding that the 'collisional' structure of the tail of the EEDF of discharges in hollow cathodes appears at high values of the product of the electron concentration and the helium pressure.

The results presented in this work show that an outside positioning of the anode with regard to the cylindrical hollow cathode may essentially affect the properties of the electrical discharge occurring in the cathode. This effect seems to be more pronounced in the cathodes narrower and longer than those used in this experiment.

### Acknowledgments

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