

Electron Energy Distribution Function (0–40 eV Range) in Helium in a Longitudinal Hollow-Cathode Discharge Used for Lasers

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This paper presents results of measurements of the electron energy distribution function (EEDF) in the range 0–40 eV, and the electron density and the space potential for the helium plasma of a longitudinal discharge in a hollow cathode as used for He-inert gas and He-metal vapour lasers. The results show that the EEDF and also the mean electron energy, the electron density and the plasma potential differ from those typical of the transverse hollow-cathode discharge.

Introduction

There exist two kinds of glow discharges in a hollow cathode, depending on the position of the anode: the transverse (THCD) and the longitudinal hollow-cathode discharge (LHCD). In the THCD the movement of the electric charge carriers, electrons and ions, is perpendicular to the axis of the hollow cathode (Figure 1). In the LHCD the electrons move along the axis of cathode. It has been found, but not understood, that the efficiency of simultaneous lasing on three basic spectral lines: blue, green and red, in He-Cd mixtures is greater in the LHCD than in the THCD [2]. In the present work the electron energy distribution function (EEDF), the mean energy and concentration of the electrons, and the plasma potential in the LHCD in helium under conditions close to the working conditions of He-inert gas or He-metal vapour lasers are measured. The plasma parameters in the THCD at conventional and high operating voltages were determined earlier ([3], [4]) and shall be compared with the results of the present work.

Using a Langmuir electric probe, the EEDF in a hollow cathode was measured for electron energies up to 40 eV.

Experimental Details

The experimental arrangement was the same as described in [3] and [4]. A discharge tube with a

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hollow cathode typical for He-inert gas or He-metal vapour lasers was used (Figure 2). The cathode was a stainless-steel cylinder of 49.3 mm length and 5 mm inner diameter. The length of the anode was 10 mm. A cylindrical tungsten probe, 0.5 mm long and 0.05 mm in diameter, was located in the middle of the cathode axis.

The helium pressure was varied from about 2 mbar to 30 mbar. The discharge current was varied from 20 mA to 200 mA except for cases when the probe current was too large, causing probe sputtering, or too small compared to the sensitivity of the measuring set-up.

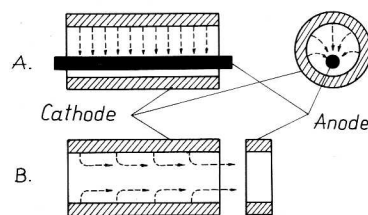


Fig. 1. Schematic diagram of typical hollow cathodes for transverse (A) and longitudinal (B) discharge.

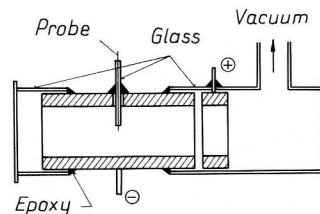


Fig. 2. Longitudinal hollow cathode with measuring probe.

Results

Typical results of measurements of the main parts of the EEDFs, denoted in the figures as $f(\epsilon)$, are shown in Figs. 3–5. The tails of the EEDFs, presented as plots of $n \cdot f(\epsilon)$, where n is the concentration of the electrons, are shown in Figs. 6–8. It follows from them that the properties of the EEDF in the LHCD differ from those of the THCD [3]. In the THCD the vast majority of electrons (at least 99%) has energies < 5 eV. Such EEDFs are called energetically “narrow”. In the LHCD one can conventionally distinguish three types of the EEDF: “broad” – with appreciable energies from 0 to

about 25 eV, “narrow” – with the main part lying between 0 and 5 eV, and “intermediate”. The mean electron energy in our EEDFs changes from about 0.5 eV to 10 eV (Figure 9). The range of the mean electron energies in the THCD is distinctly smaller (0.3 eV–1 eV).

Figure 10 shows the potential difference between the anode and the plasma in the centre of the tube at helium pressures equal to 6.7 mbar or lower. This suggests that there exists an electric field along the axis of the LHCD.

The dependence of the electron concentration in the middle of the HC on the discharge current in the LHCD (Fig. 11) is different from that in the

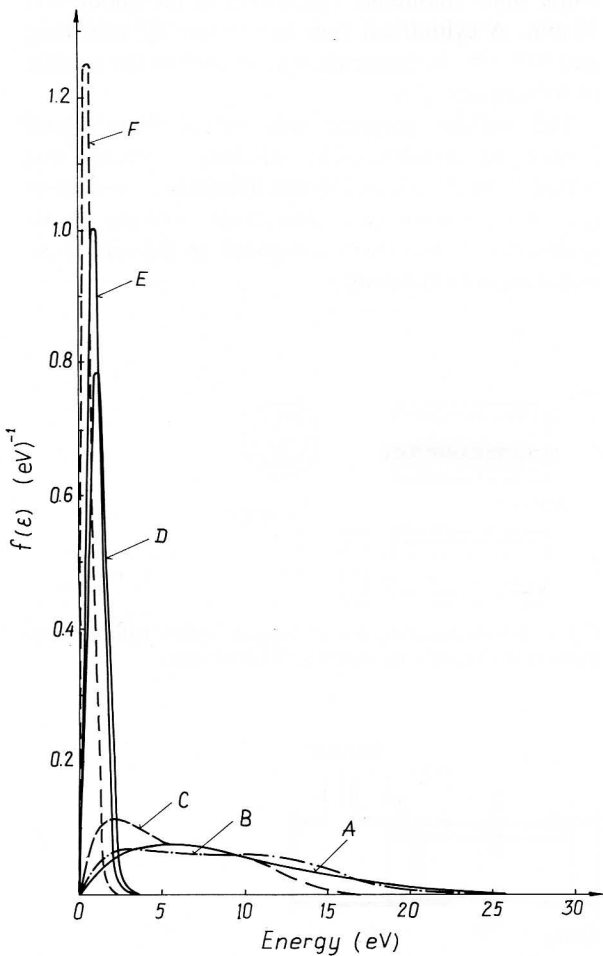


Fig. 3. EEDF for longitudinal HCD. Discharge current 120 mA. Helium pressure (mbar): A 2.3, B 3.3, C 6.7, D 13.3, E 20, F 33.3.

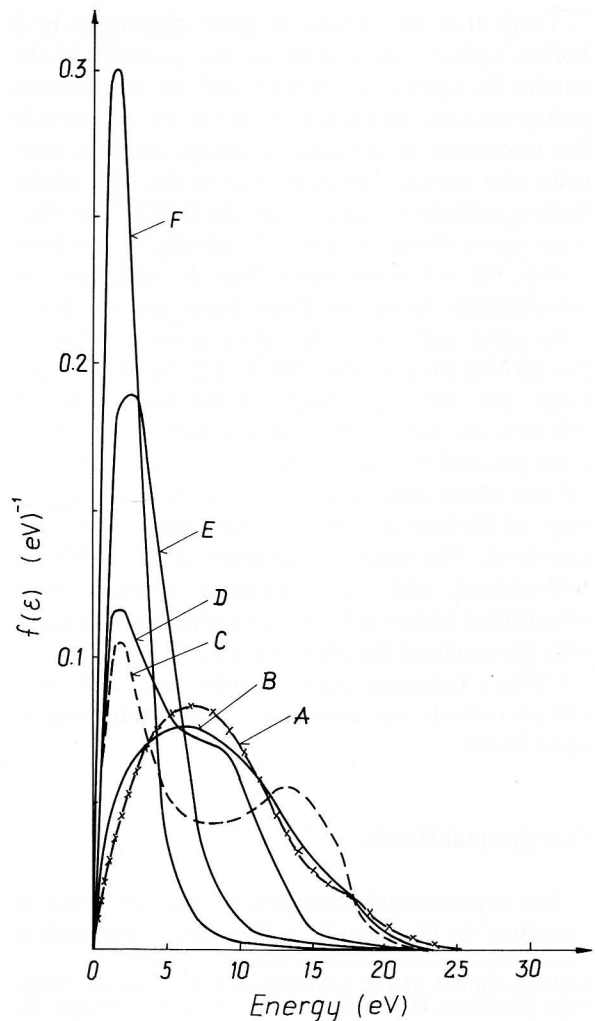


Fig. 4. EEDF in longitudinal HCD. Helium pressure 6.7 mbar. Discharge current (mA): A 30, B 40, C 80, D 120, E 160, F 200.

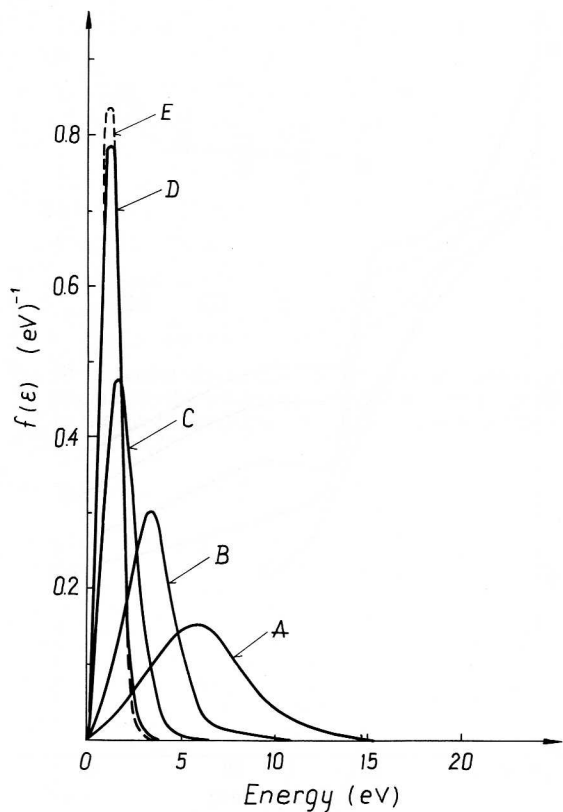


Fig. 5. EEDF in longitudinal HCD. Helium pressure 13.3 mbar. Discharge current (mA): A 20, B 40, C 80, D 120, E 160.

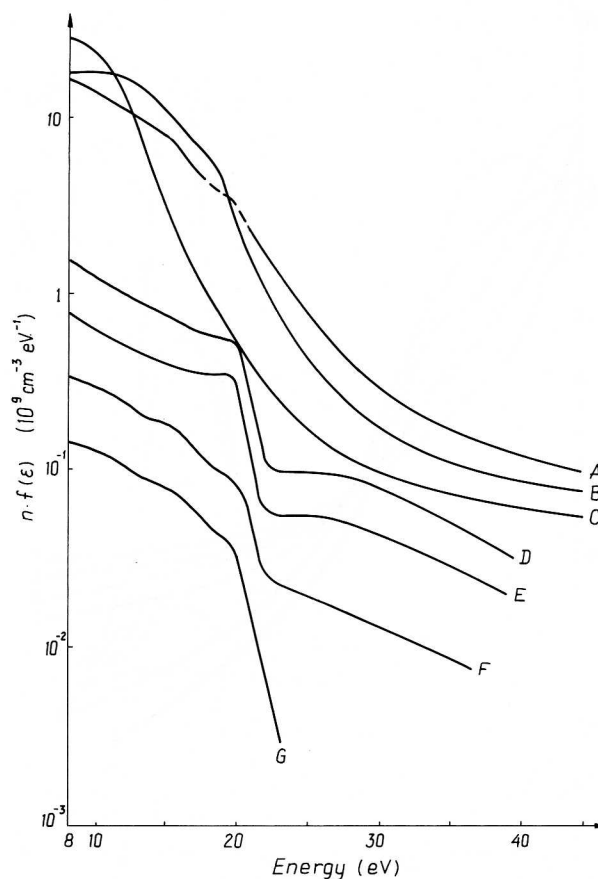


Fig. 6. EEDF (high-energy part) in longitudinal HCD. Discharge current 120 mA. Helium pressure (mbar): A 2.3, B 3.3, C 6.7, D 13.3, E 20, F 26.7, G 33.3.

THCD [3]. In the LHCD at moderate values of helium pressure (6.7–20 mbar) the curves show a kink at a certain discharge. This characteristic discharge current decreases with increasing helium pressure. In the THCD the electron concentration increases approximately linearly with increasing current and the kinks are not observed.

The dependence of the electron concentration on the helium pressure in the LHCD is similar to that in the THCD (Figure 12). The maximum of the electron concentration in the LHCD occurs at a helium pressure of about 15 mbar.

Figures 6–8 show that for a fixed current the number of electrons with energies within 20–40 eV decreases as the helium pressure increases. At a fixed helium pressure the number of electrons with energies in this interval increases with increasing current. Similar trends are observed in the THCD. However, the structure of the high-energy part of

$n \cdot f(\epsilon)$, resulting from the collision processes [3] appears in the LHCD at helium pressures ≥ 13.3 mbar, whereas in the THCD such a structure is observed for as low helium pressure as 6.7 mbar. Besides, this structure is in the THCD considerably more distinct than in the LHCD.

Discussion and Conclusions

As it was mentioned above, the EEDFs in the range 0–40 eV in the LHCD differ from those in the THCD. The most marked differences occur at low helium pressures and low discharge currents. Under these conditions the EEDFs are energetically “broad”, whereas the EEDFs in the THCD are markedly “narrower”. At higher values of the

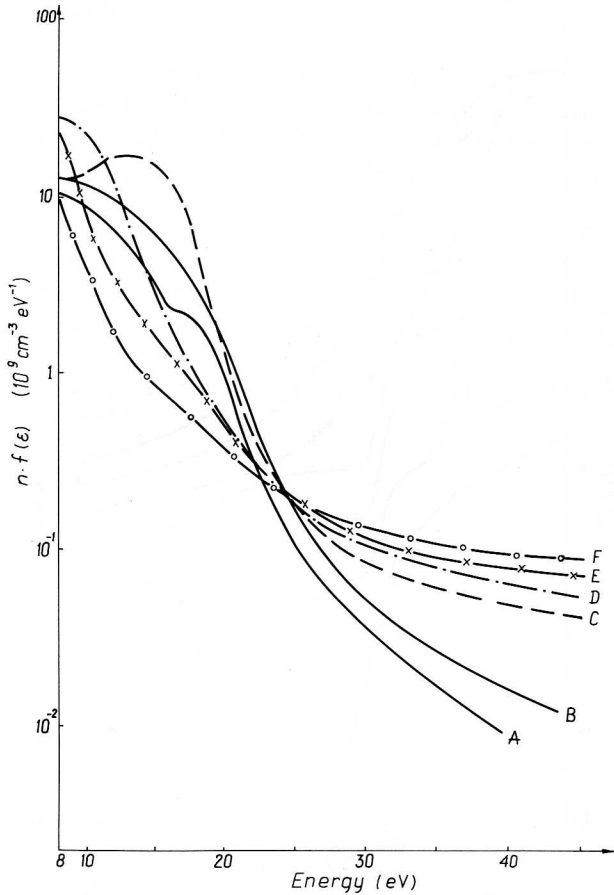


Fig. 7. EEDF (high-energy part) in longitudinal HCD. Helium pressure 6.7 mbar. Discharge current (mA): A 30, B 40, C 80, D 120, E 160, F 200.

helium pressure and the discharge current the EEDFs in the LHCD are as "narrow" as those in the THCD. This means that the form of the EEDF in the LHCD may be regulated to some extent by changing either the helium pressure or the discharge current.

The mean electron energy in the LHCD can be changed from a relatively high value for helium pressures < 6.7 mbar to a small one for the helium pressures > 13.3 mbar. Such a broad range of mean electron energies is not accessible in the THCD. As in the THCD, the mean electron energy in the LHCD decreases with increasing helium pressure. However, with increasing discharge current the mean electron energy in the LHCD behaves differently from that in the THCD, i. e. it decreases as the discharge current increases, whereas the mean elec-

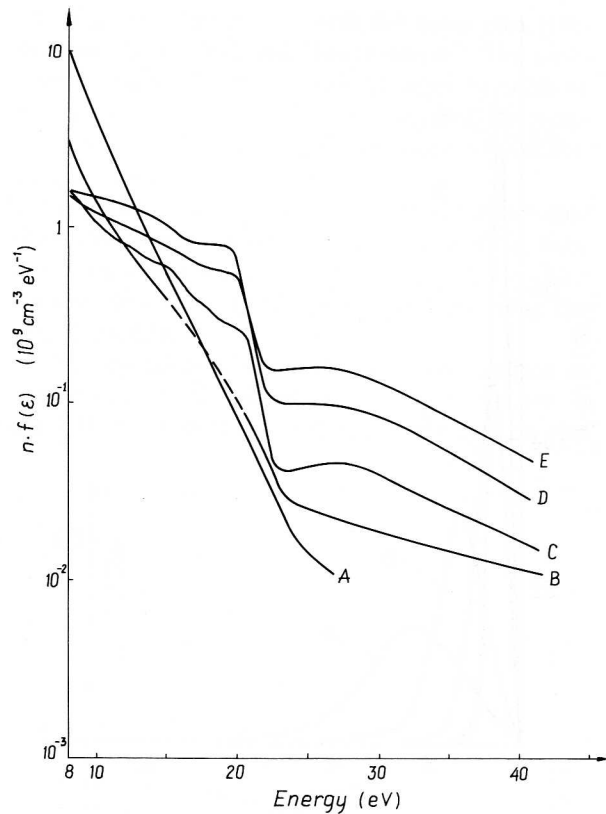


Fig. 8. EEDF (high-energy part) in longitudinal HCD. Helium pressure 13.3 mbar. Discharge current (mA): A 20, B 40, C 80, D 120, E 160.

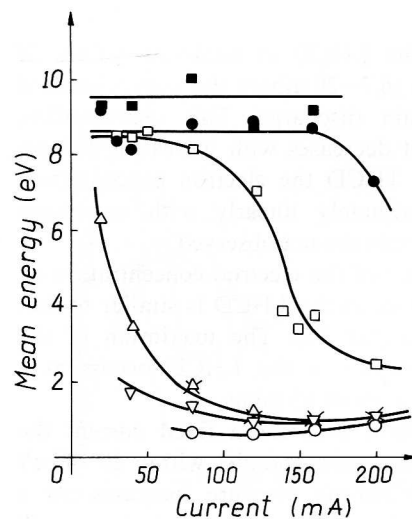


Fig. 9. Mean energy of electrons in longitudinal HCD plotted against the discharge current, for various helium pressures (mbar): ■ 2.3, ● 3.3, □ 6.7, △ 13.3, × 20, ▽ 26.7, ○ 33.3.

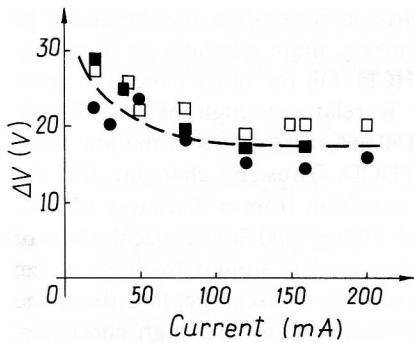


Fig. 10. Potential difference ΔV between the anode and the plasma in the centre of longitudinal HCD plotted against the discharge current, for helium pressures (mbar): ■ 2.3, ● 3.3, □ 6.7.

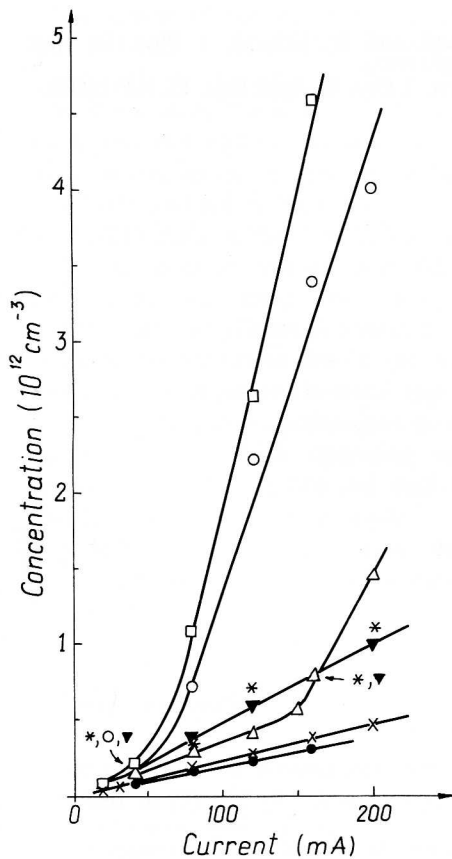


Fig. 11. Concentration of electrons in longitudinal HCD plotted against the discharge current, for various helium pressures (mbar): ● 2.3, × 3.3, △ 6.7, □ 13.3, ○ 20, * 26.7, ▼ 33.3.

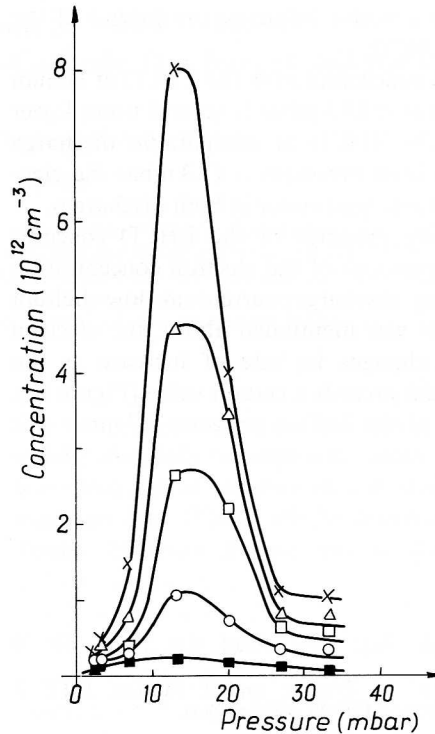


Fig. 12. Concentration of electrons in longitudinal HCD plotted against the helium pressure, for discharge currents (mA): ■ 40, ○ 80, □ 120, △ 160, × 200.

tron energy in the THCD slightly increases with increasing current. Thus the changes of the electron mean energy in the LHCD due to changes of the helium pressure and the discharge current are similar to those in the positive column of glow discharges. An insignificant increase of the mean electron energy in the LHCD with increasing discharge current at the highest helium pressures and discharge currents (Fig. 9) is an exception and resembles the situation in the THCD.

The presence of the axial electric field, suggested by the potential difference between the anode and the plasma (Fig. 10), seems to be responsible for the relatively high mean electron energies in the LHCD at low helium pressures, similarly as in the positive column of glow discharges.

The density of electrons with energies between 20 and 40 eV decreases with increasing helium pressure and increases with increasing current (Figs. 6–8), as in the THCD. This suggests that the number of fast electrons in both discharges depends mainly on the operating voltage, and the axial electric field

seems to have a minor influence on the tail of the EEDF in the LHCD.

The electron concentration in the LHCD at helium helium pressures < 13.3 mbar is several times lower than that in the THCD at comparable discharge currents. At helium pressures > 13.3 mbar the electron concentrations are similar in both discharges.

An interesting property of the LHCD concerns the unusual behaviour of the electron concentration with increasing discharge current at low helium pressures. As it was mentioned above, the electron concentration changes its rate of increase as the discharge current exceeds a certain value (Figure 11). For example, at the helium pressure 6.7 mbar this characteristic value amounts to 160 mA. Below 160 mA the electron concentration is low compared to that characteristic of the THCD and increases relatively slowly as the current increases. Above

160 mA the electron concentration and the rate of its increase are relatively high, similarly to those observed in the THCD. On the other hand, the mean electron energy is relatively high below 160 mA, whereas above 160 mA it decreases to the low value typical of the THCD. Thus, by changing the discharge current, transition from a discharge of relatively high mean energy and low concentration of electrons, i. e. of properties similar to those of the positive column of a glow discharge, to a discharge of relatively low mean energy and high concentration of electrons, typical of the negative glow and the THCD, can be realized. The THCD does not provide such a possibility of changing the character of the discharge. At helium pressures > 13.3 mbar the properties of the LHCD are similar to those of the THCD, for any discharge current.

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