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Electron energy distribution function (0–40 eV range) in helium in a high-voltage discharge in a hollow cathode used for lasers

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Abstract. This paper presents results of measurements of the electron energy distribution function (EEDF) in the range 0–40 eV and the electron density for the helium plasma of a high-voltage discharge (HVD) in a hollow cathode as used for He–inert gas and He–metal lasers. The EEDF has been measured employing the method of the second derivative of the electric probe current–voltage characteristic. The results show that the shape of the EEDF for the HVD in the hollow cathode is similar to that for the conventional transverse hollow-cathode discharge (HCD) operating at low voltage. However, the increase of the operating voltage in the hollow cathode results in energetic redistribution of electrons and a selective change of the efficiency of atomic processes. It appears then that the relative number of electrons within the energy interval from several eV to 20 eV is lower in the HVD than in the conventional HCD. This is believed to be the result of the lower efficiency of the excitation of metastable states of helium in the HVD. Above the energy of 35 eV the relative number of electrons in the HVD is higher than that in the conventional HCD. Thus ionisation seems to be one of the most favoured atomic processes in the HVD.

1. Introduction

Recently the hollow-cathode discharge (HCD) has been used to obtain lasing in inert gases and their mixtures with metal vapours (Schuebel 1980, Rozsa 1980, Gerstenberger *et al* 1980). The advantage of using the HCD for the excitation of the lasing gas media is an improvement of the excitation efficiency of highly energetic ion states due to a more suitable electron energy distribution function (EEDF). Besides, the EEDF may be more freely regulated in the HCD than in the positive column used in many common lasers.

Regulation of the EEDF is possible in the so-called high-voltage discharge (HVD) in a hollow cathode developed by Rozsa (1975). It has been observed that insertion of an anode system inside the cathode results in a 3–4 times increase of the operating voltage. This in turn must raise the number of electrons in the 'tail' of the EEDF. As a result, the degree of excitation of high-energy ionic laser states is improved in such discharges (Rozsa *et al* 1977a, b, c, Janossy *et al* 1978, Mizeraczyk *et al* 1981, Iijima 1982a, b, Kawase 1982).

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It was the aim of this work to measure the EEDF in the HVD in a hollow cathode in helium under conditions close to the working conditions of He–inert gas or He–metal lasers. It covers the next stage of an investigation aimed at comparing the properties of various kinds of discharge in a hollow cathode (Mizeraczyk and Urbanik 1983).

The measurements were done employing a Langmuir electric probe which appeared to be a sufficiently reliable means of measuring the EEDF in a hollow cathode for electron energies up to 40 eV. Despite the restriction of the range of measurement of electron energies to 0–40 eV, the results obtained may be used for explaining some important atomic processes in a HVD in a hollow cathode.

2. Experimental details

A discharge tube of a design as employed in laser technology was used in the experiment (figure 1). The cathode was made of a stainless steel cylinder, 10.5 mm in diameter and 10 cm long. Six tungsten rods each of 1.5 mm diameter were symmetrically placed along the cylinder and formed the anode structure. The distance between the surfaces of anodes and cathode was 0.5 mm. The cathode was cooled with water. A tungsten probe 0.5 mm long, of 0.05 mm diameter, was located in the middle of the cathode axis. This means that all the results obtained refer to the hollow cathode axis, which is also the axis of the laser beam.

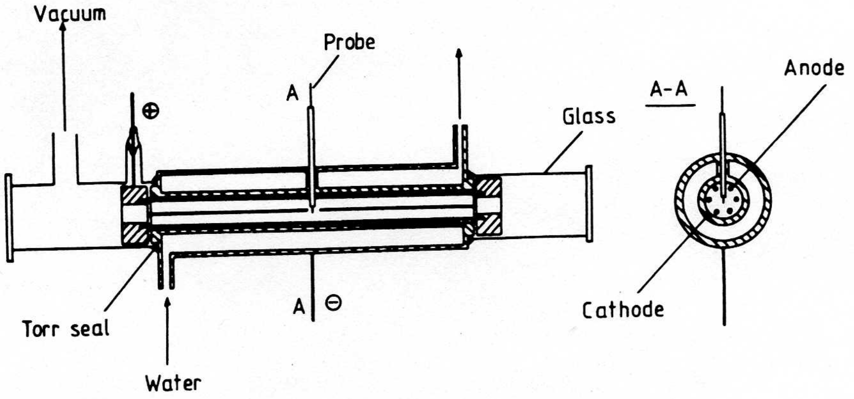

Figure 1. Schematic diagram of the discharge tube.

The pressure of helium was varied from 4 hPa to 20 hPa (1 hPa = 1 mbar). The discharge current was varied from 20 mA to 275 mA except for the cases when the probe current was too large, causing probe sputtering, or too small relative to the sensitivity of the measuring set-up.

The EEDF was obtained employing the Druyvesteyn (1930) method, involving the measurement of the second derivative of the electric probe current–voltage characteristic. The electron concentration was determined from the measurement of the probe current for a probe at the plasma potential (e.g. Swift and Schwar 1970). The measuring set-up and procedure have been described elsewhere (Mizeraczyk and Urbanik 1983). The results were obtained with repeatability better than 10%.

Also, the voltage–current characteristics of the HVD and the intensities of the He

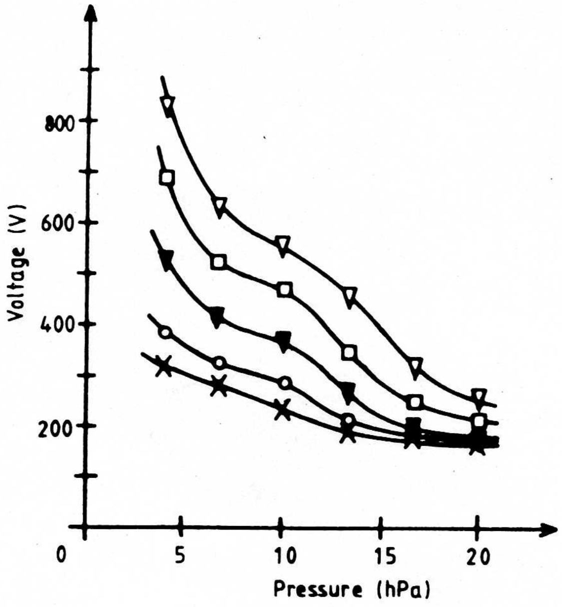

Figure 2. Dependence of the operating voltage on helium pressure, for various discharge currents (mA): (×) 10, (○) 20, (▼) 50, (□) 100, (▽) 150.

587.6 nm and He 501.6 nm lines at the tube axis were measured. These data are useful for better understanding of the HVD.

3. Results

Figures 2 and 3 show the operating voltage and the intensities of the He lines versus the helium pressures. The plots presented in these figures do not show the local minimum typical for discharges with the hollow-cathode effect (Mizeraczyk and Urbanik 1983, Mizeraczyk and Neiger 1984). This means that besides the higher operating voltage the

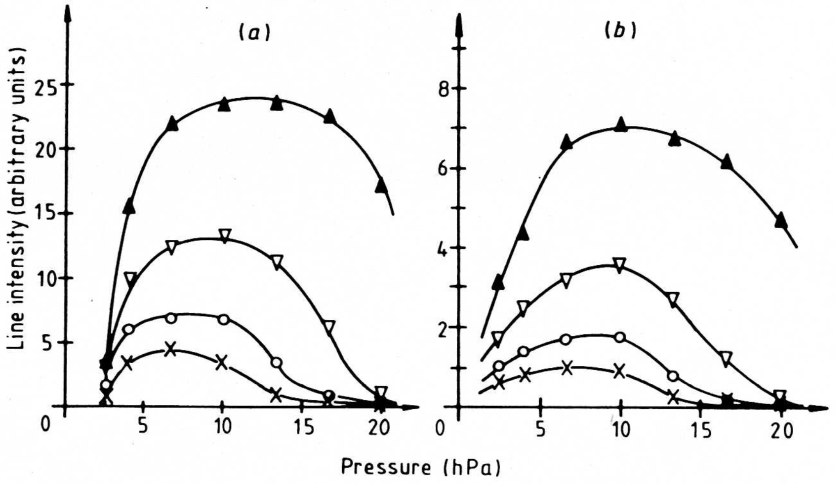

Figure 3. Intensities of the He 587.6 nm (*a*) and 501.6 nm (*b*) lines as functions of helium pressure, for various discharge currents (mA): (×) 50, (○) 100, (▽) 200, (▲) 500.

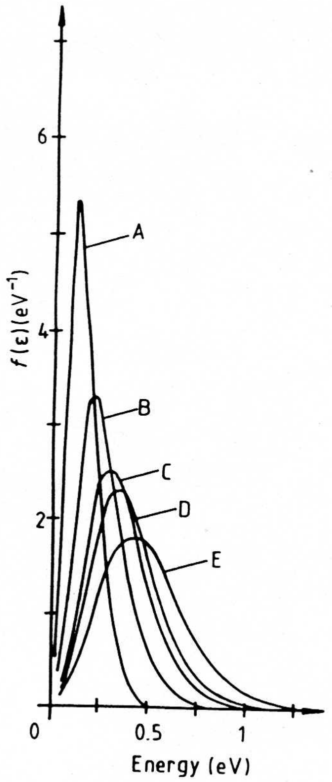

Figure 4. EEDF (low-energy part) for the HVD in a hollow cathode. Helium pressure 13.3 hPa; discharge current (mA): (A) 50, (B) 100, (C) 150, (D) 175, (E) 225.

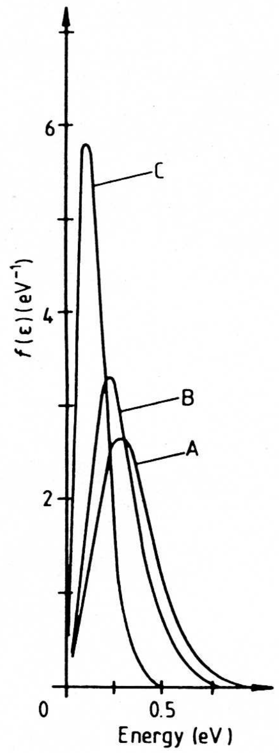

Figure 5. EEDF (low-energy part) for the HVD in a hollow cathode. Discharge current 100 mA; helium pressure (hPa): (A) 6.7, (B) 13.3, (C) 20.

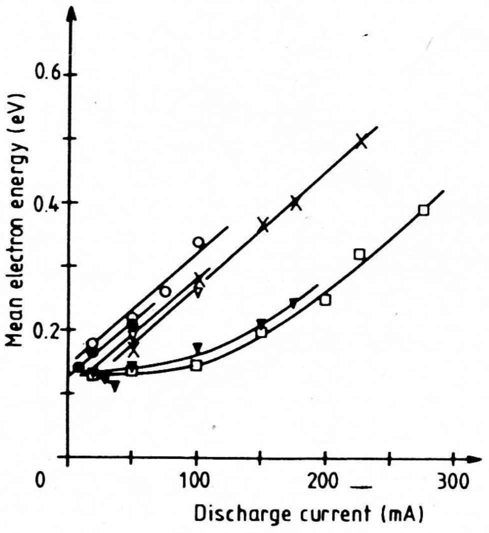

Figure 6. Mean energy of electrons in the HVD versus the discharge current, for various helium pressures (hPa): (●) 4, (○) 6.7, (▽) 10, (×) 13.3, (▼) 16.7, (□) 20.

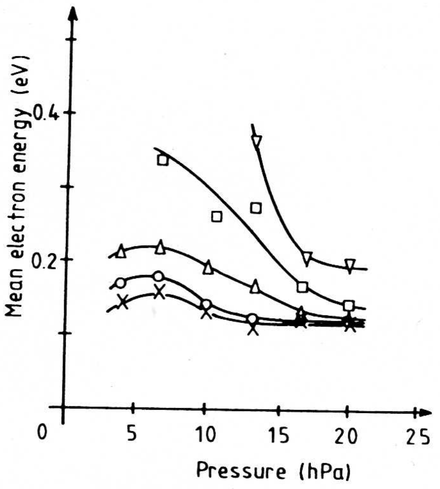

Figure 7. Mean energy of electrons in the HVD versus the helium pressure, for various discharge currents (mA): (×) 10, (○) 20, (△) 50, (□) 100, (▽) 150.

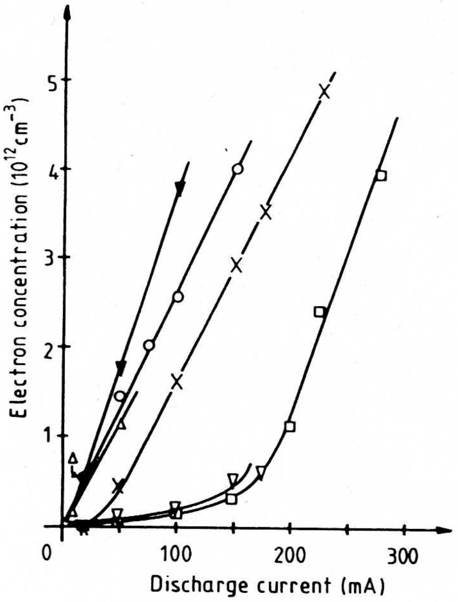

Figure 8. Concentration of electrons in the HVD versus the discharge current, for various helium pressures (hPa): (△) 4, (○) 6.7, (▼) 10, (×) 13.3, (▽) 16.7, (□) 20.

absence of the hollow-cathode effect is a characteristic property of the HVD in a hollow-cathode tube.

The results of measurements of the EEDF are presented in the low-energy (from 0 to about 1.5 eV) and in the high-energy (from a few eV up to 40 eV) ranges separately.

Figures 4 and 5 illustrate the low-energy parts of the EEDF, denoted as $f(\varepsilon)$, for different currents and helium pressures. It follows from them that the absolute majority of electrons has an energy lower than 1 eV. For a fixed helium pressure the number of

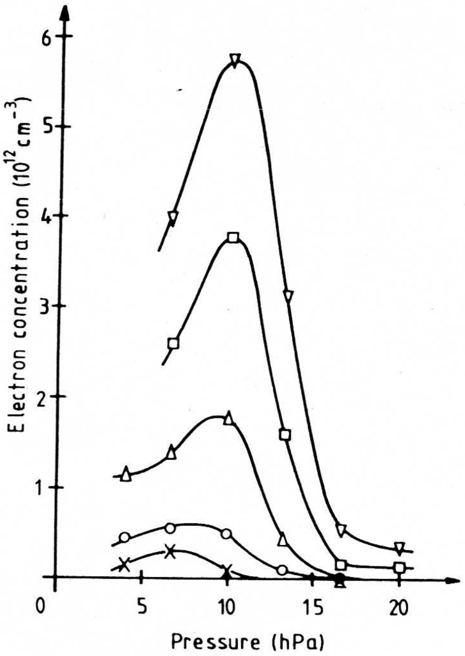

Figure 9. Concentration of electrons in the HVD versus the helium pressure, for various discharge currents (mA): (×) 10, (○) 20, (△) 50, (□) 100, (▽) 150.

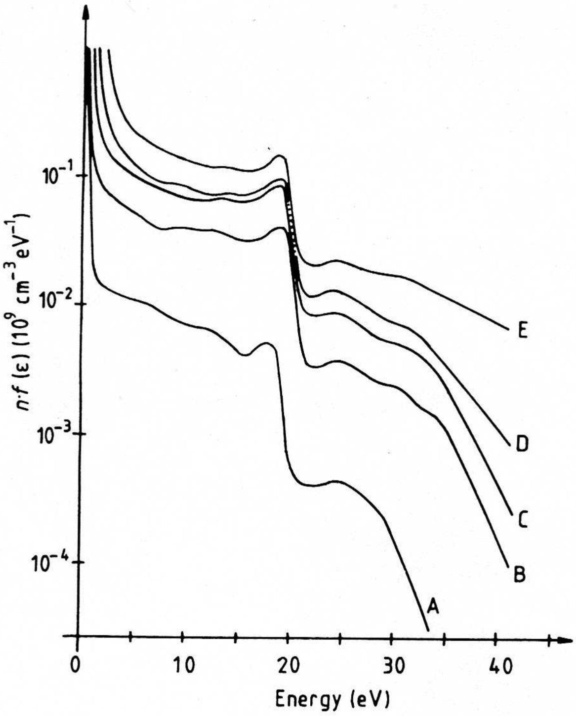

Figure 10. Electron energy distribution (high-energy part) for the HVD. Helium pressure 13.3 hPa; discharge current (mA): (A) 50, (B) 100, (C) 150, (D) 175, (E) 225.

slow electrons increases as the discharge current decreases, while for a fixed current it increases with decreasing helium pressure.

The mean energy of electrons varies from about 0.1 eV to 0.7 eV (figures 6 and 7) depending on the helium pressure and current. It increases as the discharge current increases and decreases as the helium pressure increases.

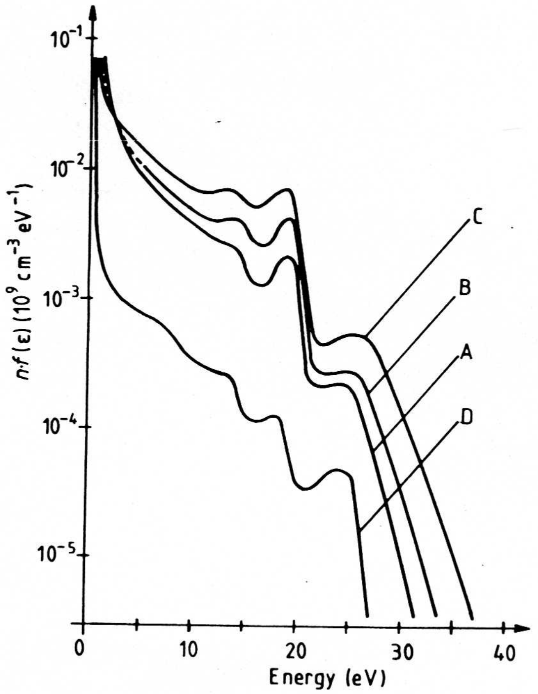

Figure 11. Electron energy distribution (high-energy part) for the HVD. Discharge current 20 mA; helium pressure (hPa): (A) 4, (B) 6.7, (C) 10, (D) 16.7.

The electron concentration increases approximately linearly as the discharge current increases (figure 8) only if the negative glow fills the centre of the hollow cathode. The deviation from linearity for lower discharge currents and higher helium pressures concerns the discharge conditions in which the negative glow is situated near the surface of the cathode and does not embrace the centre of the tube.

For a fixed current the maximum value of the electron concentration occurs when the pressure of helium is between about 7 hPa to 10 hPa depending on the discharge current (figure 9).

Figures 10–12 show the plots of the high-energy parts of the electron energy distribution $n \cdot f(\varepsilon)$, where n is the electron concentration, useful when calculating the rates of various reactions between electrons and plasma particles. However, because of the restriction in using the Langmuir probe mentioned above, the energy range of $n \cdot f(\varepsilon)$ is limited to about 40 eV.

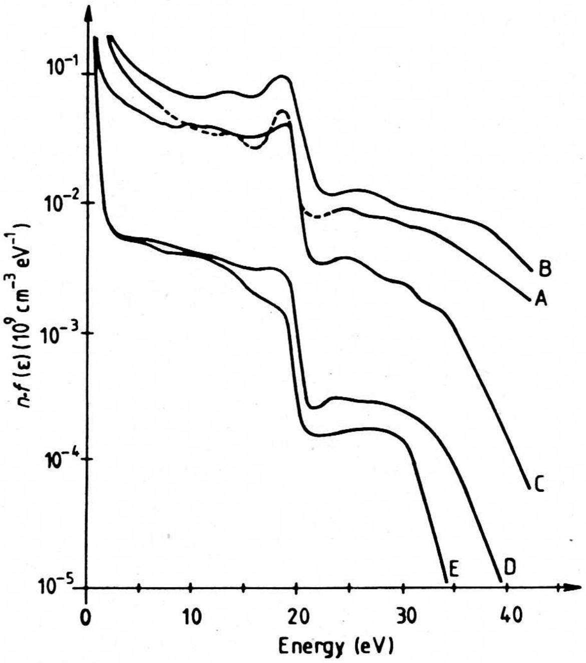

Figure 12. Electron energy distribution (high-energy part) for the HVD. Discharge current 100 mA; helium pressure (hPa): (A) 6.7, (B) 10, (C) 13.3, (D) 16.7, (E) 20.

It is seen from figures 10–12 that for a fixed helium pressure the number of electrons with energies falling within the 1–40 eV interval increases as the discharge current increases. The dependence of the distribution $n \cdot f(\varepsilon)$ upon the pressure of helium is more complex. The number of electrons with energies from a few eV up to 40 eV increases with rising helium pressure up to about 10 hPa and then decreases.

The $n \cdot f(\varepsilon)$ plots show that above the energy of 1 eV the number of electrons rapidly decreases with rising energy. This drop is markedly reduced for energies between 5 eV and 20 eV. The distribution $n \cdot f(\varepsilon)$ reaches a maximum near 20 eV, and then decreases sharply. Further, an insignificant rise of the number of electrons at about 26 eV is observed. Beyond this energy the number of electrons decreases monotonically.

4. Discussion and conclusions

The forms of the EEDF (in the range 0–40 eV) in the HVD and in the conventional transverse HCD (Mizeraczyk and Urbanik 1983) are similar in most important parts. Thus one many conclude that similar atomic processes determine the EEDF in both the discharges. These processes have been described elsewhere (Mizeraczyk and Urbanik 1983).

However, some differences between the plasmas of the two discharges are seen from the results presented.

The plots of the low-energy parts of the EEDF are markedly 'narrower' than those for the conventional transverse HCD. This means that the mean energy of electrons in the HVD is lower than that in the HCD. Thus the plasma of the HVD is favourable to those collision processes demanding slow electrons.

As mentioned above, the number of electrons with energies from a few eV to 20 eV increases with rising helium pressure up to about 10 hPa, and then it decreases. This is different from the HCD, where the number of electrons within that energy range decreases as the helium pressure increases. This difference may be explained as follows.

In a hollow cathode the majority of electrons with energies from a few eV up to 20 eV is produced in the processes of collisions between metastable atoms of helium (Soldatov 1971, Soldatov and Prilezhaeva 1971). Therefore, the more the metastable atoms of helium in the discharge the greater is the number of electrons within the above energy range. The metastable atoms of helium are mainly produced in collision processes between helium atoms in the ground state and electrons of energies higher than about 20 eV. However, the electrons with energies higher than about 400 eV are ineffective in producing the metastable atoms because of the small cross-sections for those processes at these electron energies (Fujimoto 1979, Singh *et al* 1983). In the HVD at low helium pressure the tail of the EEDF extends up to 600–800 eV, corresponding to the cathode-fall voltage (Gill and Webb 1977). Therefore, the electrons with energies from about 400 eV up to 600–800 eV produce hardly any metastable helium atoms. When the pressure of helium increases the tail of the EEDF shortens because of the decrease of the operating voltage. This does not significantly change the amount of electrons producing the metastable atoms until the operating voltage decreases below about 400 eV. This occurs for a helium pressure of about 10 hPa. Thus, the number of metastable helium atoms increases as the helium pressure increases to 10 hPa, since for the approximately constant number of exciting electrons the number of helium atoms taking part in the collisions increases. Further increase of the helium pressure and decrease of the operating voltage accompanying it lead to a decrease of the number of electrons, active in producing the metastable atoms. The decrease of the number of 'active' electrons must be so significant that despite the increase of the helium pressure the number of metastable atoms decreases. The number of electrons with energies from a few eV up to 20 eV follows the initial increase and the subsequent decrease of the number of metastable helium atoms with rising helium pressure. The mechanism of production of the metastable helium atoms in the HVD, described above, is consistent with the results of measurement of the concentration of metastable helium atoms (Kawase 1982).

In the conventional transverse HCD the operating voltage is considerably lower (about 200–300 V) and all the electrons in the tail of the EEDF have a great effect on the number of metastable atoms. For that reason the decrease of the operating voltage with rising helium pressure causes such a decrease of the 'active' electrons that despite the increase of the helium pressure the number of metastable atoms decreases. As a result,

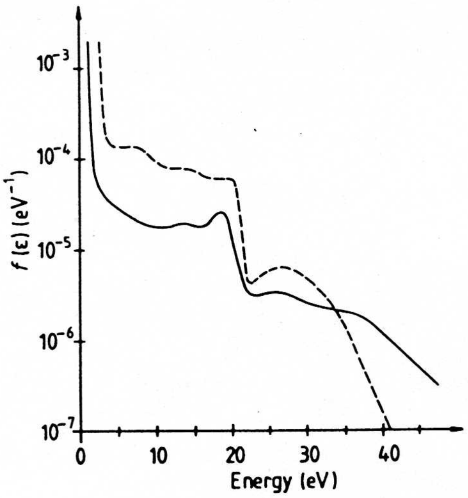

Figure 13. Comparison of the EEDF for the HVD and the transverse HCD (broken curve, Mizeraczyk and Urbanik 1983) for the same electron concentrations. Helium pressure 10 hPa, discharge current 100 mA, electron concentration 3.9×10^{12} cm^{-3}.

the number of electrons of energies from a few eV up to 20 eV decreases as the helium pressure increases.

One may similarly explain the behaviour of the intensities of the He 587.6 nm and 501.6 nm lines as a function of helium pressure (figures 3(*a*), (*b*)). At lower helium pressure there is a relatively large number of electrons which are too fast to efficiently excite the spectral lines. As the helium pressure increases and the operating voltage decreases the electron energy distribution $n \cdot f(\varepsilon)$ becomes better 'adjusted' to the cross-sections for the excitation of the lines. This results in an increase of the intensities of the lines. With further increase of helium pressure the electrons become too slow, efficiency of excitation of the spectral lines decreases and their intensities also decrease.

The relative number of electrons with energies from a few eV up to 20 eV is lower in the HVD than in the HCD (figure 13). This is consistent with the results of Kawase (1982), who found a relatively low concentration of the metastable helium atoms responsible for the production of those electrons.

The number of electrons with energies above 20 eV decreases more slowly in the HVD than in the HCD. However, the relative number of electrons in the HVD becomes higher than that in the HCD for electron energies higher than about 35 eV. This is an effect of the higher operating voltage.

Summing up, the change of the EEDF in the HVD in a hollow cathode, caused by introducing the system of anodes into it, leads to a selective change in the efficiency of the excitation of atoms and ions. The collision processes with wide energetic cross-sections, for example the ionisation, become favoured in the HVD. This may be significant for the operation of some He–inert gas or He–metal lasers excited by charge-transfer processes. On the other hand, some processes of relatively narrow energetic cross-sections, for example the production of He 2^3S metastable atoms by processes of direct electron impact, are less efficient in the HVD. This is expected to be a reason for lower efficiency of excitation of the Cd$^+$ $5s^{2}\,{}^2D_{5/2}$ state (laser line 441.6 nm, Mizeraczyk *et al* 1981, Kawase 1982) in the HVD, pumped by Penning collision processes between the He 2^3S metastable atoms and Cd atoms (Ainsworth and McIntosh 1983).

It can therefore be concluded that an increase of the operating voltage in a hollow cathode does not always lead to an increase in the efficiency of the selected atomic process. However, the possibility of regulating the operating voltage by changing the number of anode rods in the cathode allows to some extent an adjustment of the EEDF to the selected atomic process.

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