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

J Mizeraczyk† and W Urbanik

Institute of Fluid Flow Machines, Polish Academy of Sciences, Fiszera 14, Gdańsk-Wrzeszcz, Poland

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Abstract. We present results of measurements of the electron energy distribution function (EEDF) in the range of 0–40 eV for the plasma of a transverse hollow-cathode discharge in helium as used in laser technology. The measurement technique employs the second derivative of the electric probe current–voltage characteristic. The results show that the EEDF for the transverse hollow-cathode discharge is neither Maxwellian nor Druyvesteynian and the influence of some elementary processes on the shape of the EEDF is discernible. The presence of the EEDF maximum at 26 eV is believed to suggest the importance of recombination in atomic processes occurring inside a hollow cathode.

1. Introduction

Many kinds of laser discharge tubes with cylindrical hollow cathodes have been used to obtain lasing in helium–metal vapour mixtures. They may, however, be systematised by distinguishing between two principle types of electric discharge occurring in a hollow cathode, namely, the transverse and the longitudinal discharge. Positioning of the hollow cathode and anode with respect to each other determines the type of the electric discharge in a particular configuration.

The transverse discharge exhibits an axial and radial symmetry of motion of the electric charge carriers, electrons and ions (figure 1).

In the longitudinal discharge, electrons leaving the cathode surface move towards the anode along the hollow cathode axis. Therefore the discharge properties vary along the cathode axis (Mizeraczyk 1983).

The electrical and optical properties of the transverse and longitudinal discharges are different. It is necessary to be familiar with them if the hollow cathode is to be used in practice as a source of spectral or laser lines. A spectacular example of the consequence of differences between properties of both discharges concerns simultaneous lasing at the three basic lines: blue, green and red. This lasing may be achieved with relative ease in the longitudinal hollow cathode in He–Cd mixtures and is difficult to obtain in the transverse discharge (Fujii *et al* 1980).

† Present address: Lehrstuhl für allgemeine Elektrotechnik und Elektrooptik, Ruhr University, D-4630 Bochum-Querenberg, Federal Republic of Germany.

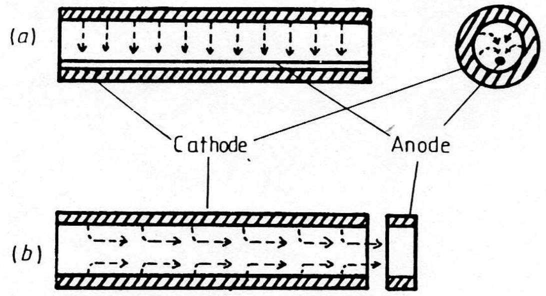

Figure 1. Schematic diagram of typical hollow cathodes for transverse (*a*) and longitudinal (*b*) discharge.

The knowledge of the electron energy distribution function (EEDF) is crucial to understanding the properties of the plasma of the electric discharge. Many theoretical and experimental studies on the EEDF in a hollow-cathode discharge (HCD) have been published. The usefulness of the available data on the EEDF for analysis of phenomena occurring in laser discharge tubes with hollow cathodes is limited due mainly to the fact that the majority of these measurements were carried out in hollow cathodes of diameters 2 to 4 times larger than those employed in laser technology (3–10 mm). The working gas pressure was in turn several times lower. The only measurements of EEDF in the HCD in helium directly concerning He–metal lasers were made by Medicus and Olson (1973). The EEDF in helium in hollow cathodes of the diameters employed for lasers were reported by Soldatov *et al* (1970), Soldatov (1971) and Soldatov and Prilezhaeva (1971). The work of Gill and Webb (1977) concerning the EEDF in the negative glow led to a good understanding of the operation of He–metal lasers.

The present work is concerned with measurements of the EEDF in the transverse HCD in helium under conditions close to the working conditions of He–metal lasers. It covers the first stage of an investigation aimed at comparing the properties of the transverse and longitudinal HCD. The second half of the task is still in progress.

The measurements were done using the Langmuir electric probe which appeared to be a sufficiently reliable means of measuring the EEDF for electron energies up to 40 eV. The restriction of the range of electron energies associated with the adoption of the Langmuir probe technique seems to have a minor influence on the use of the results obtained for explaining some important atomic processes in the hollow cathode.

2. Measurements of EEDF, plasma potential and electron concentration

The Druyvesteyn method (1930) for determining the EEDF based on measurements of the second derivative (SD) of the electric probe electron current relative to the probe–plasma voltage is commonly used. According to this method the isotropic EEDF $f(\varepsilon)$ is related to the SD of probe electron current by

$$n \cdot f(\varepsilon) = \frac{2}{e^2 \cdot S}\left(\frac{2mV}{e}\right)^{1/2} \frac{\mathrm{d}^2 I_e}{\mathrm{d}V^2}. \tag{1}$$

Here V is the difference between the probe potential and the plasma potential (often called the probe bias potential), n is the electron concentration, I_e is the electron current of the probe, S is the probe surface area, and m and e denote the electron mass and charge, respectively. The quantity $n \cdot f(\varepsilon)$ gives the electron energy distribution, with $\varepsilon = eV$.

The Druyvesteyn formula is valid for negative bias of the probe relative to the plasma, when electrons are repelled and ions attracted by the probe. In this region the total current of the probe I is the sum of the electron current I_e and ion current I_i. If the condition $d^2I_e/dV^2 \gg d^2I_i/dV^2$ is satisfied, then the SD of the total probe current may be measured and taken approximately to be equal to the SD of the electron current of the probe. In other words, the SD measurements of the electron current I_e may be replaced by those of the current–voltage (I–V) characteristic of the probe.

The method of measuring the SD of the I–V characteristic of the probe is also useful for determining the plasma potential. In the opinion of most investigators the plasma potential is equal to the potential of a probe to which such bias voltage is applied at which the SD of the I–V characteristic is equal to zero (e.g. Luijendijk and Van Eck 1967).

Measurements of the probe current for a probe at the plasma potential provides the value of the electron concentration n, as it is known (e.g. Swift and Schwar 1970) that the current is expressed by the formula

$$I_{e0} = \tfrac{1}{4} en\bar{v}S \tag{2}$$

where $\bar{v}$ is the mean velocity of electrons in the plasma. The mean velocity of electrons may be easily calculated, knowing the EEDF.

It is believed now that determination of the electron concentration based on the probe current measurements for the probe at the plasma potential is one of the more accurate methods (Boyd and Twiddy 1959, Nuhn and Peter 1977).

3. Discharge tube and measuring set-up

A discharge tube with a hollow cathode designed for operation as a transverse discharge (figure 2) was used in the experiments. The cathode was made of a stainless-steel cylinder whose inside diameter, 6 mm, was typical of cathodes employed in laser technology. The cathode length was 60 mm. The anode, made of tungsten wire of 0.5 mm diameter, was placed at a distance of 0.5 mm from the cathode surface. 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 of probe measurements as presented in this paper refer to the hollow cathode centre, which, in laser applications, is the most important part of the discharge.

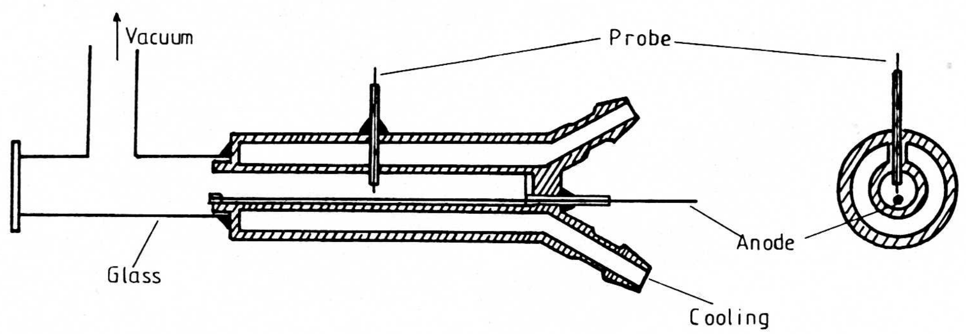

Figure 2. Hollow cathode with measuring probe.

The pressure of helium was varied from 2 hPa to 40 hPa†. The current was varied from 20 mA up to 100 mA except for cases when the probe current was too large, causing probe sputtering, or too small from the viewpoint of the sensitivity of the measuring set-up.

The widely used second harmonic method was adopted for determination of the SD of the I–V characteristic of the probe (Luijendijk and Van Eck 1967). The method consists in introducing a harmonic voltage of small amplitude a and frequency f to the electric circuit of the probe whose potential V with respect to the plasma potential is constant. As a result, beside the DC current component a periodic component will appear. This will not be purely sinusoidal because of the nonlinearity of the I–V characteristic of the probe. Thus harmonics of the probe current will appear. It may be shown (e.g. Branner *et al* 1963) that for small amplitude a of the perturbing signal, the amplitude of the second harmonic of the probe current, $I(2f)$, is proportional to the square of the amplitude a and the SD of the I–V characteristic. That is

$$I(2f) = \text{const.}\, a^2 \frac{\mathrm{d}^2 I}{\mathrm{d}V^2}. \qquad (3)$$

It follows from formulae (1) and (3) that in the range of negative probe bias in which the inequality $\mathrm{d}^2I_e/\mathrm{d}V^2 \gg \mathrm{d}^2I_i/\mathrm{d}V^2$ holds good, the amplitude of the probe current second harmonic multiplied by $V^{1/2}$ is proportional to the EEDF at the energy defined by the probe bias voltage V. Thus the variation of the EEDF with energy may be determined when the probe bias is changed.

The design of the equipment for the determination of the second harmonic of the probe current (proportional to the SD of the I–V characteristic) as a function of the voltage between the probe and plasma potential, was based on that described by Branner *et al* (1963), and Luijendijk and Van Eck (1967). The lock-in technique was adopted to improve the signal-to-noise ratio.

The following assumptions were made in interpreting the probe data:

(1) The EEDF is isotropic. This was justified by the results of Borodin and Kagan (1965), and Afanaseva *et al* (1966).

(2) The pressure effect on the probe results of measurements of the EEDF in hollow cathodes may be neglected (Case 1971, Soldatov *et al* 1975, Sicha 1979).

(3) The changes of the ion current with the negative bias of the probe are much smaller than the corresponding changes of the electron current, i.e. $\mathrm{d}^2I_e/\mathrm{d}V^2 \gg \mathrm{d}^2I_i/\mathrm{d}V^2$, provided the negative probe potential is not too close to the plasma potential and not higher than about 40 eV (Medicus 1968, Medicus and Olson 1973, Boyd and Twiddy 1959). This assumption is in contradiction to the theoretical results of Dovzhenko *et al* (1975, 1977), and Richards *et al* (1975) based on semi-empirical formulae for calculation of the ion probe current. In the authors' opinion, correction for the ion current effect would at present give doubtful results because the behaviour of the ion current of the probe is not yet well understood.

(4) The distortions of the SD of the probe characteristic curve due to emission of secondary electrons is negligible (Swift and Schwar 1970, Emeleus 1979).

Deposition of sputtered cathode particles on the probe was sufficiently reduced by using an appropriate insulating sheath on the probe and also by cleaning the probe

† Here a hectoPascal (1 hPa = 100 Pa) is used as the unit of pressure rather than the recommended SI unit, because of the simplicity of referring it to more familiar units (1 hPa = 1 mbar = 0.75 Torr).

surface with an electron current of 5–10 mA prior to each measurement.

The sputtering of the probe under the influence of its current was eliminated by limiting the measuring range of the probe current so that the probe characteristic did not change with time.

The reason for choosing the amplitude of the perturbing signal to be 0.2 V was the observation that within a wide range of amplitude variability (0.05–2 V), the waveform of the second harmonic of the probe current remained unaffected, while its amplitude was strictly proportional to the square of the amplitude of the perturbing signal. This was taken as confirmation of the correct operation of the apparatus.

It was possible to measure the EEDF with a detection sensitivity varying 10^6 times, as the noise and instability of the HCD are much lower than, e.g., those in the positive column of the glow discharge. In the most sensitive range of the measurements (20–40 eV) the results were obtained with repeatability better than 10%. Every plot of the EEDF presented in this paper is the average value obtained from at least three measurements.

4. Results

It is convenient to present the results of measurements of the EEDF in the low-energy and in the high-energy ranges separately. The first energy range, from zero to a few electron volts (5 eV at most), accounts for the vast majority of electrons. The other range concerns electrons of energies from a few eV up to 40 eV.

Figures 3 and 4 illustrate the low-energy parts of the EEDF for different currents and

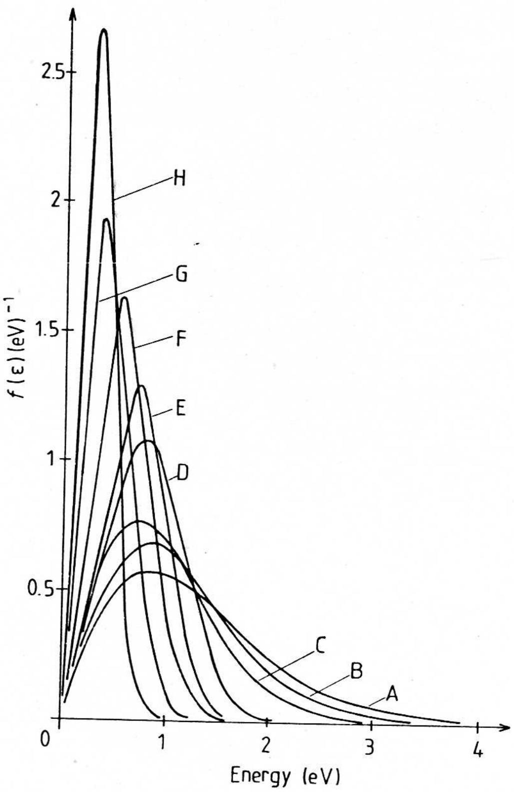

Figure 3. EEDF (low-energy part) for transverse HCD. Discharge current 100 mA. Helium pressure (hPa): A 2, B 4, C 6.7, D 13.3, E 16.6, F 20, G 26.7, H 40.

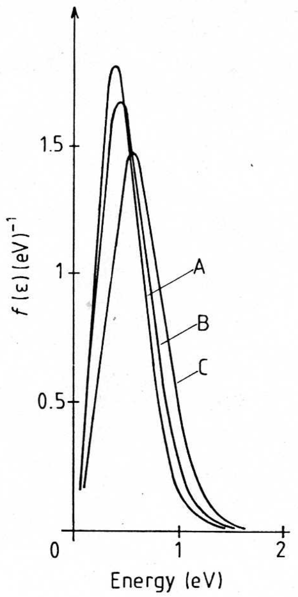

Figure 4. EEDF (low-energy part) for transverse HCD. Helium pressure 10 hPa. Discharge current (mA): A 30, B 50, C 60.

helium pressures. It follows from them that for a fixed discharge current the number of slow electrons at the hollow cathode axis increases as the helium pressure increases, while for a fixed helium pressure it increases with decreasing current.

The mean energy of electrons in the transverse HCD varies from about 0.3 eV to 1 eV depending on the helium pressure and current, except in the case of 2 hPa pressure. The mean energy increases as the discharge current increases and decreases as the helium pressure increases (figures 5 and 6).

The electron concentration at the discharge tube axis exhibits an approximately linear increase as the discharge current increases (figure 7). For a fixed current the maximum value of the electron concentration occurs when the pressure of helium is about 8–10 hPa (figure 8).

Figures 9 and 10 show the high-energy parts of the electron energy distribution $n \cdot f(\varepsilon)$, useful when calculating the rates of various reactions occurring between electrons and plasma particles, for energy of electrons up to 40 eV.

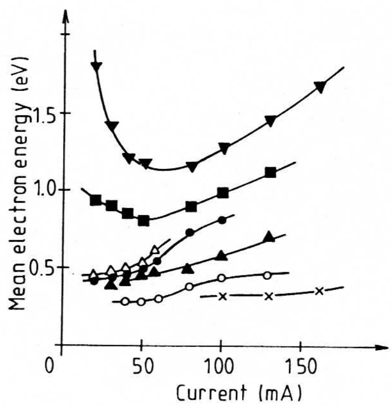

Figure 5. Mean energy of electrons in transverse HCD plotted against the discharge current, for various helium pressures (hPA): ▼ 2, ■ 6.7, △ 10, ● 13.3, ▲ 20, ○ 26.7, × 40.

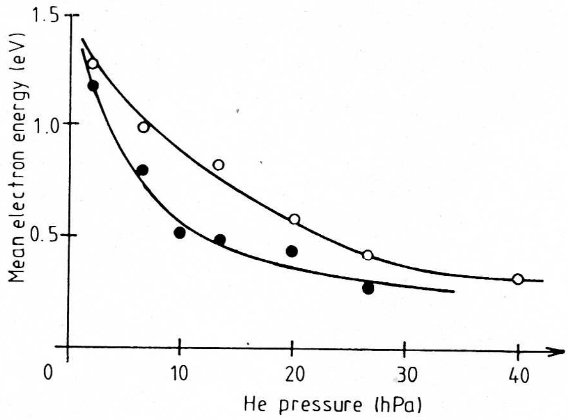

Figure 6. Mean energy of electrons in transverse HCD plotted against the helium pressure, for discharge currents of (●) 50 and (○) 100 mA.

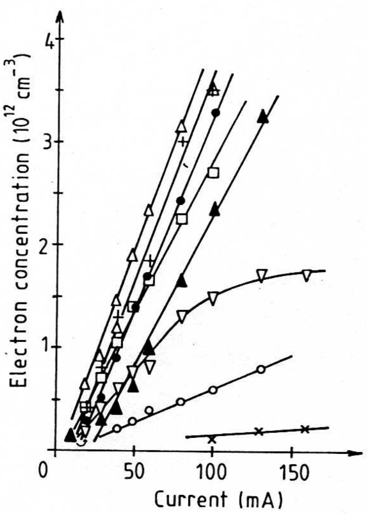

Figure 7. Concentration of electrons in transverse HCD plotted against the discharge current, for various helium pressures (hPa): ▽ 2, □ 4, + 6.7, △ 10, ● 13.3, ▲ 20, ○ 26.7, × 40.

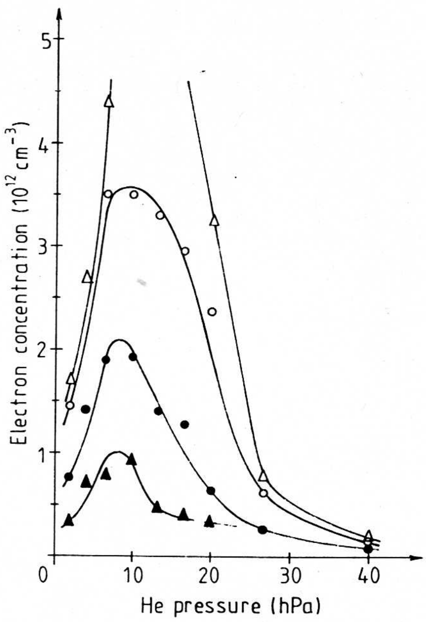

Figure 8. Concentration of electrons in transverse HCD plotted against the helium pressure, for discharge currents (mA): ▲ 30, ● 50, ○ 100, △ 130.

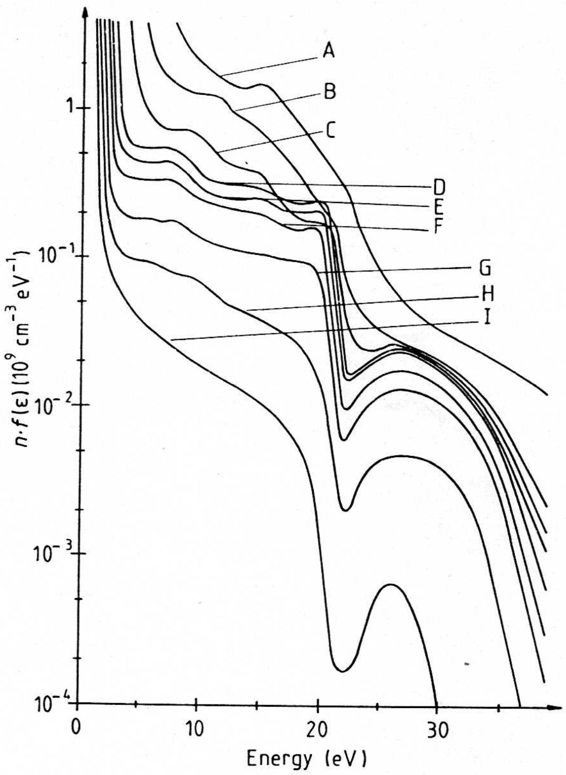

Figure 9. Electron energy distribution (high-energy part) for transverse HCD in helium. Discharge current 100 mA. Helium pressure (hPa): A 2, B 4, C 6.7, D 10, E 13.3, F 16.6, G 20, H 26.7, I 40.

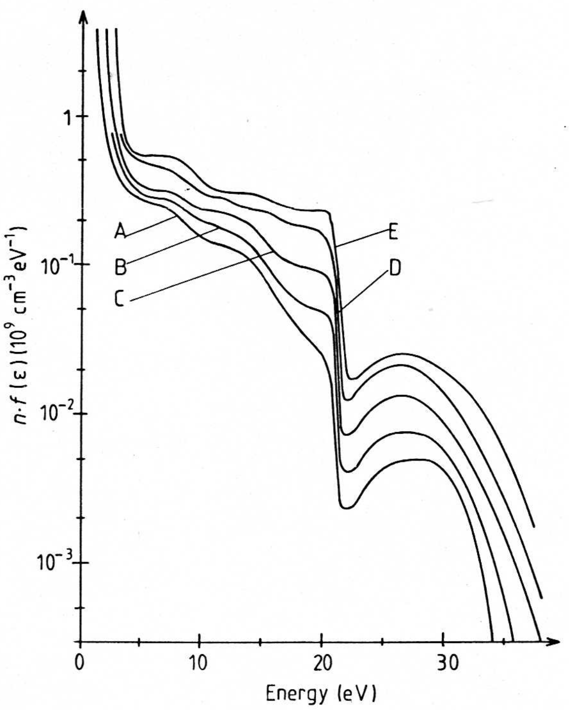

Figure 10. Electron energy distribution (high-energy part) for transverse HCD in helium. Helium pressure 10 hPa. Discharge current (mA): A 20, B 30, C 50, D 80, E 100.

In general the number of electrons whose energies exceed 5 eV is negligible compared with the total number of electrons. For instance, at a discharge current of 100 mA the number of electrons whose energies fall within the 5–20 eV interval is equal to 0.7%, 0.1%, and 0.1% of the total number of electrons for helium pressures equal to 4 hPa, 13.3 hPa, and 26.7 hPa, respectively. The fraction of the so called 'fast electrons' having energies in excess of 20 eV was equal, under the conditions specified, to 0.025%, 0.014%, and 0.009%. These values agree with results presented by Soldatov (1971), and Medicus and Olson (1973). However, it should be pointed out that these values are based on calculations neglecting the electrons with energies higher than 40 eV.

From figures 9 and 10 a general rule may be inferred to the effect that for a fixed current the number of electrons whose energies exceed 5 eV decreases with rising helium pressure, and increases with rising current when the pressure of helium is fixed.

It is seen from the $n \cdot f(\varepsilon)$ diagrams that after a rapid drop in the number of electrons in the so called 'tail' of the low-energy part of the distribution (for $\varepsilon < 5$ eV), a marked reduction in the rate of decrease occurs for energies between 5 and 20 eV. The next dramatic drop in the number of electrons is observed near an energy of 20 eV. Further on, a distinct, if slight, rise of $n \cdot f(\varepsilon)$ at about 26 eV is observed. Beyond this energy the number of electrons decreases monotonically.

The most marked rise of the electron energy distribution $n \cdot f(\varepsilon)$ within the 5–20 eV range and near 26 eV was observed for medium pressures of helium (10–20 hPa). It was more distinct for higher discharge current.

5. Discussion and conclusions

From our experiment on the type of transverse HCD used for lasers, the measured EEDF is seen to be in agreement (at least in the most important aspects) with the earlier results of Soldatov *et al* (1970), Soldatov (1971), Soldatov and Prilezhaeva (1971) and Medicus and Olson (1973).

It is evident from comparison of our results with those presented, for example, by Borodin and Kagan (1965, 1966, 1967), and Borodin *et al* (1967) that the EEDF for transverse and longitudinal HCD do indeed differ from each other. A more detailed comparison of the EEDF for both types of HCD will be possible only after a similar experiment has been carried out for a longitudinal hollow cathode discharge as used for laser excitation. Nevertheless the results obtained confirm the necessity to distinguish between two types of hollow cathode.

The low-energy part of EEDF, containing more than 99% of the total number of electrons, differs in form from the Maxwell and Druyvesteyn distributions for the same mean energy (figure 11). It may be easily shown (figure 12) that the number of slow electrons characterised by a mean energy of about 0.5 eV is in this type of hollow-cathode discharge at least 10 times larger than in the positive column of a glow discharge with a Maxwellian EEDF and similar laser properties (discharge tube diameter 3 mm, helium pressure 4 hPa, discharge current 120 mA, mean electron energy higher than 3 eV, Mizeraczyk (1975)). This means that the hollow cathode provides conditions favourable for superelastic collisions of electrons with metastable atoms and ions of helium whose cross-sections peak near zero electron energy. To this category of collisions belong the process of metastable helium atom de-excitation to the ground state and superelastic collisions which convert metastable helium atoms from the singlet to the triplet state. Also a high rate of three-body recombination can be expected, since these

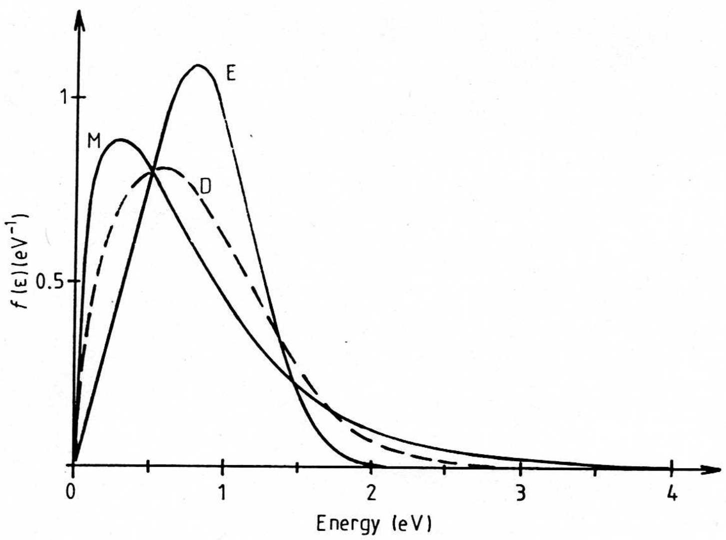

Figure 11. EEDF (low-energy part) obtained experimentally (E) compared with the Maxwellian (M) and Druyvesteyn (D) distribution functions for the same mean electron energy ($\bar{\varepsilon} = 0.82$ eV) in a helium discharge at 13.3 hPa pressure and 100 mA current.

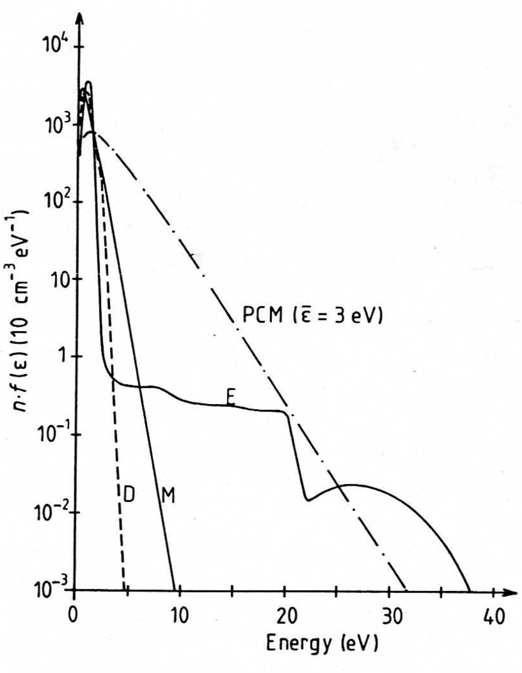

Figure 12. Electron energy distribution obtained experimentally (E) compared with the Maxwellian (M) and Druyvesteyn (D) distributions for the same mean energy ($\bar{\varepsilon} = 0.82$ eV) and concentration ($n = 3.3 \times 10^{12}$ cm^{-3}) of electrons. Also shown is the Maxwellian electron energy distribution for the positive column of the discharge characterised by the mean energy of electrons equal to 3 eV and concentration of electrons equal to 3.3×10^{12} cm^{-3}. Helium pressure 13.3 hPa, current 100 mA.

processes are characterised by a cross-section which decreases rapidly with increasing electron energy (Deloche *et al* 1976).

The unconventional form of the EEDF at high energies is the result of a number of collision processes which lead to an increase of the number of electrons in one range of the energy spectrum at the expense of another range or to the conversion of potential energy of excited atoms and ions into kinetic energy of electrons.

The relatively large number of electrons within the energy range from several eV to 20 eV is, most probably, the result of electron production in collision processes between triplet metastable helium atoms or in the processes of metastable helium atom conversion from the singlet or triplet state to the ground state due to collisions with electrons (Soldatov *et al* 1970, Soldatov 1971, Soldatov and Prilezhaeva 1971). For other collision processes increasing the number of electrons within this range see Deloche *et al* (1976).

In spite of the reduced rate of decrease of the EEDF over the energy range from several eV to 20 eV, the number of electrons in this region is considerably smaller than that in a positive column exhibiting similar laser properties. For this reason one should expect the rates of processes whose efficiency depends on the number of electrons with energy amounting to a dozen or so electron volts to be lower for the transverse HCD than in the positive column. Among such processes, excitation of radiating singlet and triplet states of helium due to collisions of both metastable helium atoms with electrons, and ionisation of metastable helium atoms by collisions with electrons may be mentioned. This means that in the HCD, helium metastables are not as important for production of excited atoms and ions as in the positive column.

The loss of electrons near 20 eV and above occurs due to collisions of fast electrons with ground-state helium atoms, resulting in the production of excited helium atoms He* and in a decrease of electron energy according to the reaction

$$\mathrm{He}(1\mathrm{S}_0) + \mathrm{e} + (\varepsilon \geqslant 19.82\ \mathrm{eV}) \rightarrow \mathrm{He}^* + \mathrm{e}. \tag{4}$$

The local maximum in the electron energy distribution in the vicinity of 26 eV is particularly important as electrons whose energies exceed 20 eV are capable of exciting and ionising helium atoms. A local maximum at 26 eV may be observed also in the diagrams presented by Soldatov *et al* (1970), Soldatov (1971), Soldatov and Prilezhaeva (1971) and Medicus and Olson (1973).

In the authors' opinion the feature at 26 eV is caused by the three-body recombination associated with the transfer of the entire potential energy of the ion to a free electron

$$\mathrm{He}^+ + \mathrm{e} + \mathrm{e} \rightarrow \mathrm{He} + \mathrm{e} + (\varepsilon = 24.58\ \mathrm{eV}). \tag{5}$$

The influence of helium pressure and discharge current on the behaviour of the EEDF maximum at 26 eV seems to confirm the hypothesis associating its development with recombination. The 26 eV maximum depends strongly, as does the recombination probability, on the energy of electrons, decreasing rapidly with increasing energy. For low pressures of helium (2–6.7 hPa), when the energy of electrons is relatively large, the maximum of EEDF at 26 eV is virtually absent (figure 9). Also no rapid rise of the EEDF maximum at 26 eV with increase in current is observed. A consistent explanation of this is that, despite increase of the total number of electrons, the number of very slow ones capable of recombining with ions decreases.

In all the measured EEDF, the number of electrons decreases rapidly above 40 eV. However, the calculations based on the measured EEDF showed that the number of electrons with energies above 40 eV is sufficiently high to play an important role in the excitation of states whose cross-sections slowly vary with electron energy and which reach their maximum values at high electron energies (ε_m). As is seen from figure 13, the excitation rate of the He singlet state 3^1P ($\varepsilon_m = 100$ eV; St John *et al* 1964) by direct electron impact, calculated with the EEDF restricted to 40 eV, does not follow the behaviour of the intensity of the corresponding spectral line (501.6 nm), which might be expected to be proportional to the excitation rate in the first approximation. On the other hand, a relatively good correspondence is obtained between the intensity of the spectral line (587.6 nm), emitted from the He triplet state 3^3D ($\varepsilon_m = 34$ eV, St John *et al* 1964), and the electron excitation rate, calculated as above. These estimates were based on approximations in which the decrease of electron number density with energy above 40 eV was assumed to be linear (falling to zero at an energy corresponding to the operating voltage of the discharge) or alternatively, and more plausibly, followed a Maxwellian decrease over the same energy range. The estimates show that the discrepancy presented in figure 13 is most probably due to neglecting the fraction of electrons

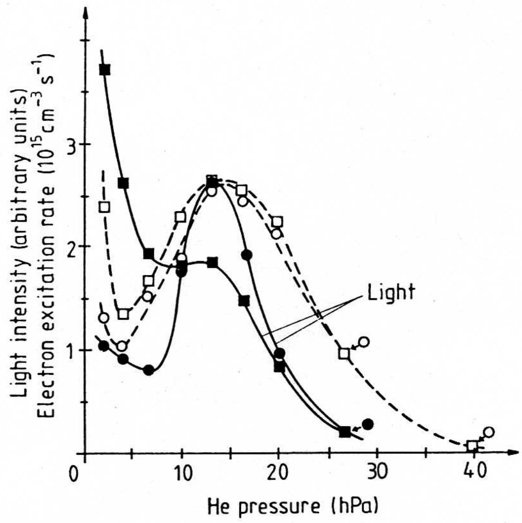

Figure 13. Spectral line intensities (experiment) and corresponding electron excitation rates (calculation). Discharge current 100 mA. ○, ● 3^3D, 587.6 nm; □, ■ 3^1P, 510.6 nm (scale ×3).

with energies higher than 40 eV in calculating the excitation rate of the state with relatively high ε_m. The calculated excitation rates are under-valued particularly at lower helium pressures. The error in calculating the excitation rate of the state 3^3D due to the neglect of the tail of the EEDF with $\varepsilon > 40$ eV is estimated (on the basis of the approximation involving linear decrease of the EEDF) to be less than 10% in the conditions typical of hollow-cathode discharges.

Summing up, it may be said that in the HCD the rates of excitation of helium atoms by electron impact to states with relatively low ε_m (e.g. singlet S, triplet S, P, D; St John *et al* 1964) depend mainly on the number of electrons with energy less than about 40 eV. In this sense the restriction of the range of electron energies associated with our adoption of the Langmuir probe technique is of less importance. On the other hand, the use of the EEDF restricted to 40 eV for the calculation of the rates of excitation processes of states with ε_m markedly higher than 40 eV may lead to significant errors, as had been shown. To understand the excitation processes occurring mainly in the high electron energy range, i.e. much above 40 eV, the results obtained for the negative glow by Gill and Webb (1977) with the help of the retarding-field analyser remain still the most reliable.

The optimum pressure for excitation of radiation in the HCD is due to a compromise between the helium pressure and the number of fast electrons, to which the rates of excitation of helium atoms are in the first approximation proportional. The decrease of the number of fast electrons with increasing helium pressure (figure 9) results in the maximum of excitation rate at a certain pressure, which in the case presented is about 13 hPa (figure 13).

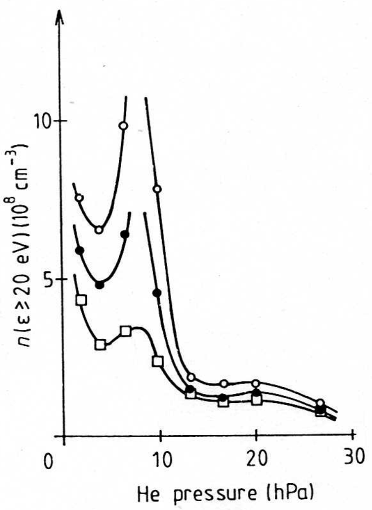

Figure 14. Concentration of fast electrons in transverse HCD plotted against the helium pressure with operating voltage as a parameter. Operating voltage (V): □ 240, ● 250, ○ 260.

Some of the above conclusions may be applied to explain phenomena occurring in laser discharges in He–metal vapour mixtures. The discharge in helium may be regarded as an initial state, which can acquire the capacity of lasing upon introduction of metal vapour. However, the introduction of metal vapour into a discharge in helium changes the properties of the discharge. First of all the number of fast electrons deciding on the excitation efficiency decreases. In the positive column of glow discharge this effect is caused by reduction of the axial electric field and rise of electron energy losses via inelastic collisions with metal atoms (Mizeraczyk 1975). In the transverse HCD, collisions with metal atoms are responsible for the reduction of the number of fast electrons.

However, according to the suggestions of Gill and Webb (1977), and Vainer *et al* (1979), the loss of fast electrons upon introduction of metal vapour into a discharge in helium should be smaller in the HCD than in the glow discharge positive column. This is evidenced by the rise of the hollow-cathode working voltage with the metal vapour pressure increase (Piper and Webb 1973, Vainer *et al* 1979, Mizeraczyk *et al* 1981), this voltage controlling, as can be seen from our measurements (figure 14), the number of fast electrons. Thus the loss of fast electrons due to inelastic collisions with metal atoms is partly compensated by the increase of fast electrons due to the working voltage increase. Such a phenomenon does not occur in the positive column and therefore drastic reduction of the number of fast electrons is observed there on introduction of metal vapours. The partial compensation of fast electron losses in the HCD makes possible the adoption of a higher percentage of metal vapour in the He–metal mixture, leading to improved lasing properties of the mixtures.

The importance of the working voltage value for the excitation of atoms in the transverse HCD reflected in attempts to increase this by changing the electrode geometry (Rozsa 1980), leading to higher efficiency of excitation.

It should be pointed out finally that the role the recombination processes play in the HCD remains unexplained, although the maximum of the EEDF near 26 eV as observed in the presented experiment seems to confirm earlier hypotheses on the importance of these processes for the collisional–radiational balance in the HCD (Willett 1974, Khvorostovskii 1980, Kuen *et al* 1981).

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