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Comparison of Radial Helium Emission Line Profiles in Transverse and Longitudinal Hollow Cathode Discharges

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Abstract

Results of measurements of the radial distributions of intensities of the He I and He II spectral lines emitted by the transverse and longitudinal hollow cathode discharges direct current excited are presented. The results show that both hollow cathode discharges exhibit different excitation efficiency of the spectral lines. The metastable level $2s^3S$ seems to be important for excitation of He I emission lines.

1. Introduction

The hollow cathode discharge (HCD) is used as an efficient excitation source for noble gas and He (or Ne)-metal vapour lasers (e.g. [1]). Recently the HCD has been used for generation of white-light laser radiation (simultaneous emission of the three fundamental colours: red, green and blue) in a He – Cd vapour mixture [2 – 7]. Such a laser could easily find application in quickly developing new techniques of image and information processing, of medical inspection and of measurement. However, the still insufficient state of understanding of physical phenomena in the HCD and the technological difficulties (cathode material sputtering, nonuniform metal vapour distribution) are the main obstacles hampering development of HCD lasers.

Hollow cathodes of different geometric forms and different arrangement with respect to the anodes were used for constructions of HCD lasers. It was shown, however, that the geometric configurations of hollow cathodes are not equivalent with regard to the efficiency of laser state excitations [3]. This mainly concerns media for which a relatively low excitation current is sufficient, as for example for a mixture of He and Cd used for white light laser generation.

The reason of the influence of the HCD geometry upon the efficiency of the laser line excitation has been extensively searched [8 – 10]. Investigations in anode-hollow cathode segments of different geometry showed that the existence of two kinds of discharges, namely the transverse discharge (TD) and the longitudinal discharge (LD) are the cause of different electrical and optical properties. Into the group of hollow cathodes with transverse discharge should be included all those cathodes in which the motion of the electric carriers occurs in the direction transverse to the axis of the cathode (Fig. 1a). In a hollow cathode with a longitudinal discharge the anode is located in such a manner that electrons leaving the cathode surface finally have to move along the cathode axis (Fig. 1b).

The electrical differences between both types of hollow cathode discharges, the TD and LD, have been sufficiently enlightened [8 – 10]. On the other hand, the optical properties of both discharges can be hardly compared because of lack of data. In particular, more data on radial distribution of optical properties of both discharges are needed for understanding and improving the HCD lasers.

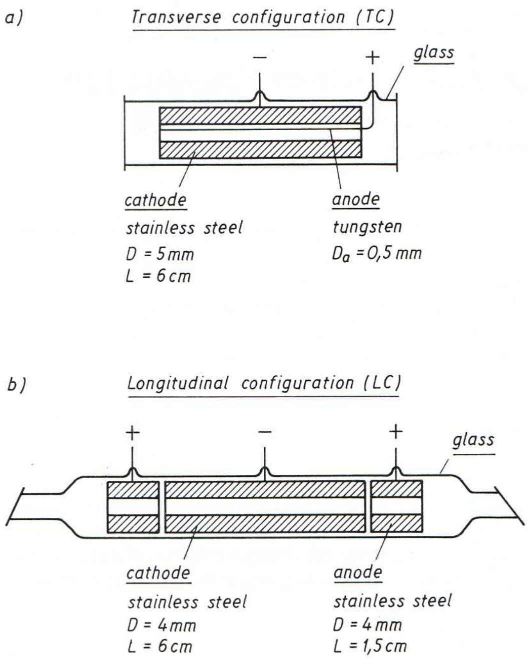

Fig. 1. Electrode configurations used for radial profile measurements in hollow cathode discharges (*D*-diameter, *L*-length).

The aim of this work was to compare the optical properties of the d.c.-excited hollow cathode TD and LD produced in helium under conditions close to those typical for $He-Cd^+$ laser operation. The data existing in the literature [11–14] are not sufficient to be used for the comparison because they concern quite different discharge conditions (pulsed or gas flow regime). The investigations concerned measurements of the radial distributions of intensities of He I and He II emission lines.

2. Experiment

The investigations were carried out using two HCD tubes the electrode configuration of which made it possible to form the TD and LD. The geometry of these both configurations (transverse: TC, longitudinal: LC) is shown in Fig. 1. The cathodes were made of vacuum outheated stainless steel. The discharges were excited with a current stabilized d.c.-voltage power supply. Ballast resistors of a few kΩ were used. The maximum discharge current was 150 mA. Because the diameters of the cathodes differ, for an equal mean current density the discharge current of 75 mA in the TC corresponds to a discharge current of about 60 mA in the LC. The He pressure ranged from 5 to 33 hPa. The sustaining voltage, higher in the case of the TC, lay between 170 and 300 V (Fig. 2). The voltage of 170 V at low discharge current corresponds to the normal cathode fall voltage which seems to be equal in both cases.

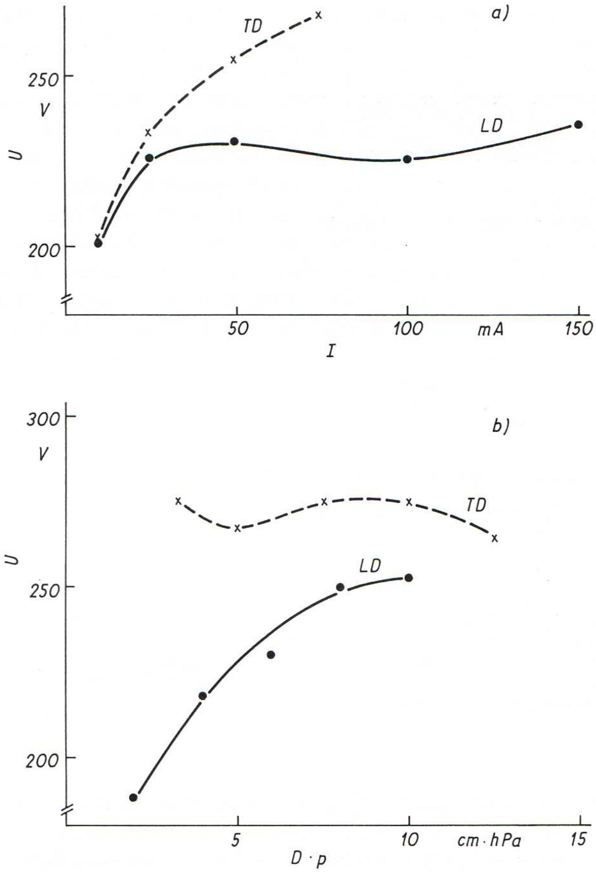

Fig. 2. Sustaining voltages U of the TD and LD as a function of:
a) the discharge current I (He pressure 15 hPa)
b) the product $D \cdot p$ of cathode bore diameter and He pressure (discharge current $I = 75$ mA).
TD: broken line, LD: solid line.

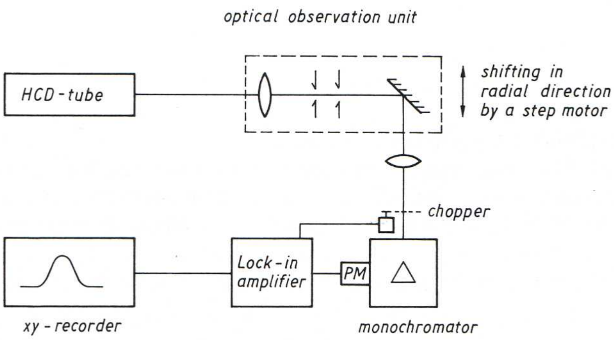

Fig. 3. Scheme of experimental set-up.

The experimental arrangement used for the radial profile measurement (RPM) of intensities of He I and He II emission lines in the TD and LD is schematically shown in Fig. 3. The optical observation unit, designed according to the so called Webb-technique [15], allowed a scanning in steps of the hollow cathode discharge with a spatial resolution of about 0.4 mm in the transverse direction with respect to the hollow cathode axis. The comparison of the intensities between the TD and the LD is due to a changed observation aperture not directly possible. Small peaks of radial profiles (Fig. 4 and 5), sometimes to see in the vicinity of the cathode wall (especially for high radiation intensities) are false light effects caused by reflections from the cathode wall. The chopped light signal was phase sensitively detected and recorded by a set-up consisting of a monochromator, photomultiplier, lock-in nanovoltmeter and xy-recorder. The RPMs were carried out for the He I and He II lines listed in Tab. 1.

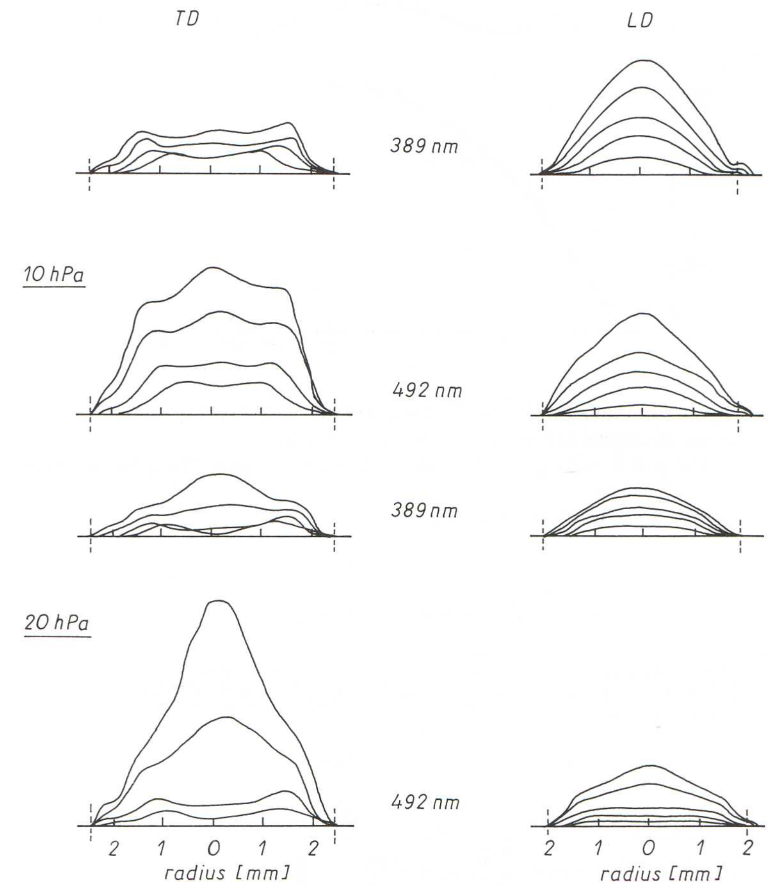

Fig. 4. Current dependence of the He I emission line radial profiles of the TD and LD (the curves from the lowest one upwards correspond to I = 10; 25; 50; 75 mA for TD, and to I = 10; 25; 50; 100; 150 mA for LD).

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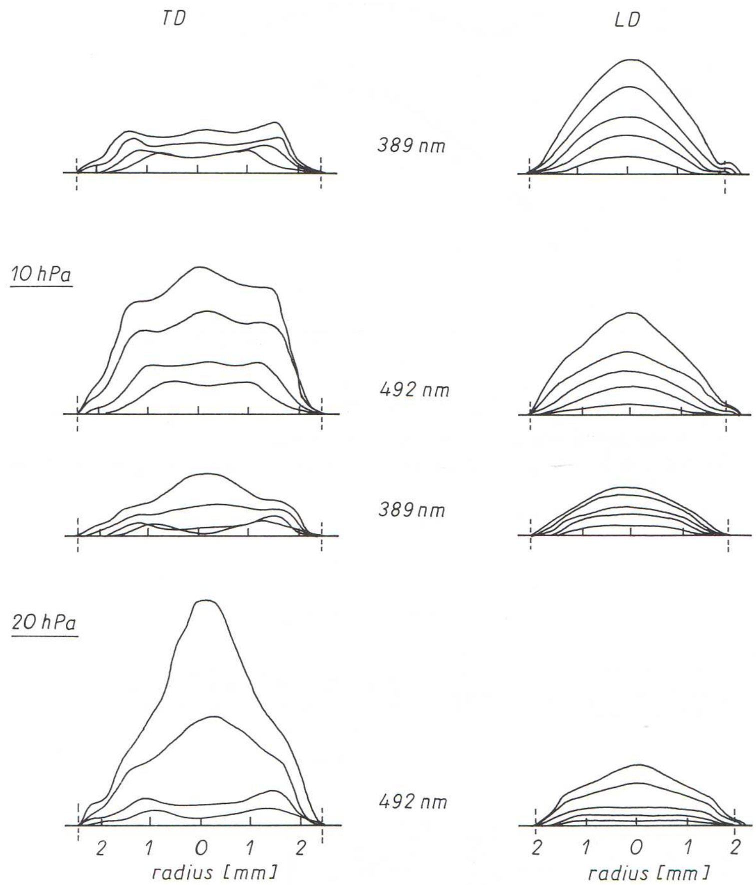

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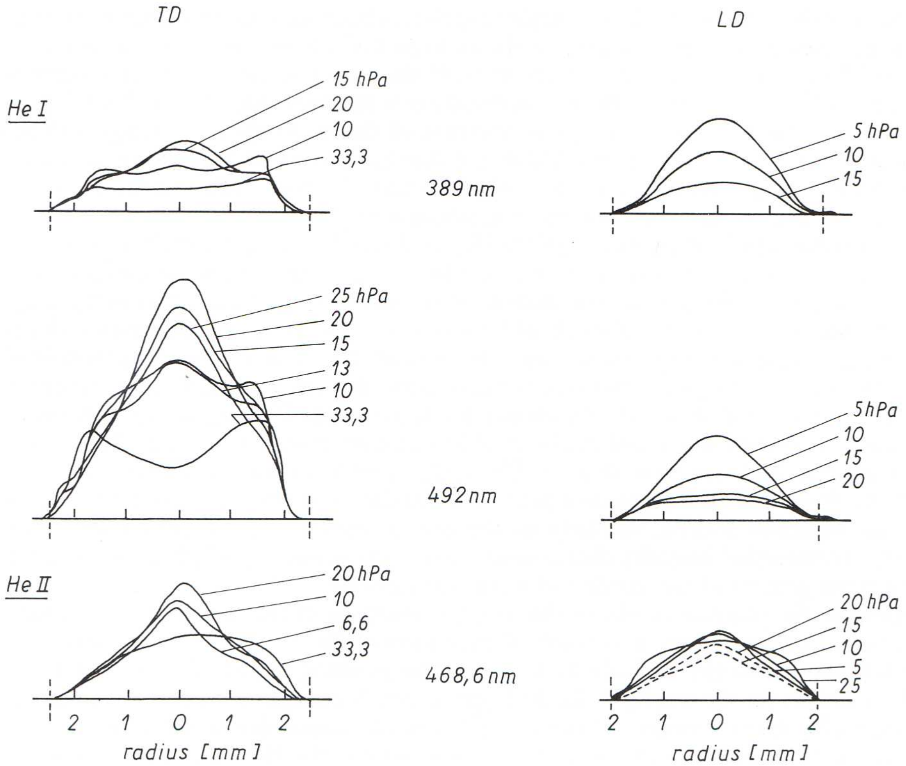

Fig. 5. Pressure dependence of the He I and He II emission line radial profiles of the TD and LD (TD: $I = 75$ mA, LD: $I = 50$ mA, He II: — — — intensity * 0.33).
Dotted lines in Fig. 4 and Fig. 5 denote the cathode walls. Outside the cathode walls a stray light was monitored.

Tab. 1
He I and He II spectral lines used for the RPM. E_1 and E_u denote the excitation energies of the lower and upper states of the corresponding transition, E_m is the energy at which the corresponding electron excitation function has its maximum.

	λ (nm)	Transition	E_1 (eV)	E_u (eV)	E_m (eV)
He I	388.9	$3p\ ^3P - 2s\ ^3S$	19.82	23.01	32
	492.2	$4d\ ^1D - 2p\ ^1P$	21.22	23.74	50
	501.6	$3p\ ^1P - 2s\ ^1S$	20.61	23.09	100
He II	468.6	$4f\ ^2F^0 - 3d\ ^2D$	72.96	75.60	200

3. Results and Discussion

3.1 Transverse configuration (TC)

A simplified model of the TD assumes that electrons after leaving the cathode surface are accelerated in the cathode dark space, gain their maximum energy at the edge of the negative glow and loose their energy in collisions with species of the negative glow. As it was shown in [8] the plasma of the TD (neglecting the cathode dark space) is axially uniform and has properties of the negative glow, i.e. the main part of the electron energy distribution function (EEDF) occupies a narrow energy interval, the values of the mean electron energy are low (from 0.3 to 1 eV), the electron concentration is relatively high (5×10^{12} cm^{-3}), an increase of the current intensity causes an increase of the mean electron energy and the relative number of fast electrons in the EEDF tail, and an increase of He pressure decreases both the mean electron energy and the number of fast electrons. The conditions of the investigated TD are comparable with those mentioned in [8].

The radial distributions of intensities of the He I and He II lines across the TD are shown in Fig. 4 at two constant He pressures and in Fig. 5 at constant discharge currents. The figures show that the intensity distributions of He I lines have maxima either at the edge or in the middle of the negative glow or in both regions. The number and position of the maxima depend on the discharge current and He pressure. At low discharge currents (Fig. 4) the distributions have only the maxima at the glow edge. With increasing discharge current, the central minimum vanishes and a maximum develops instead. This maximum is the most pronounced at a He pressure equal to about 20 hPa and disappears for higher He pressure even at relatively high currents (Fig. 5). The radial profile of the He II line exhibits a maximum in the centre of the negative glow. The maximum is the most pronounced at a He pressure of about 20 hPa, similarly as the central maxima of the He I lines. Small asymmetries in the radial intensity distributions are caused mainly by small deviations from symmetric arrangement of the anode rod inside the cathode.

According to the physical model of the TD, the existence of the maximum of the He I line intensity at the glow edge is a result of excitation of the He atoms by fast electrons entering the glow from the cathode dark space. The position of the glow edge maxima essentially depends on the length of the dark space, which changes with discharge current and pressure [20]. As the energy of these fast electrons decreases due to collisions suffered by electrons on their way in the negative glow, a minimum of the He I line intensity appears in the centre. With increasing discharge current the concentration of electrons and He^+ ions as well as the relative number of fast electrons in the negative glow of the TD increases [8], following the increase of the sustaining voltage (Fig. 2). This is accompanied by development of the maximum of the He I line intensity in the centre of the negative glow.

The collision processes responsible for the appearance of the radial dependences of He I and He II lines are still in discussion in the literature [12, 14, 16]. At relatively low He pressures (e.g. 10 hPa) it seems that the intensity maxima at the glow edge and in the glow centre are due to similar processes since both maxima increases almost identically with increasing discharge current (Fig. 4). The main process which is likely responsible for both maxima at low He pressure is the collision of the He atoms in the ground state with fast electrons streaming from the cathode dark space. At higher He pressures (e.g. 20 hPa) the maximum in the glow centre increases faster than the maximum in the glow edge with increasing discharge current (Fig. 4). Additionally, Fig. 5 and Fig. 8b, which illustrates the radial profile shape variation (broadening behaviour, dip creation) underline that at higher He pressures also processes different from the direct electron collision excitation influence the maximum in the glow centre. These processes are likely the dielectronic recombination of He^+ ions with slow electrons, which contributes to the population of radiative He I states [14], and the electron collision excitation of He atoms in the $2s^3S$ state to the radiative He I states. The probability of the former process in the TD at the pressure of about 20 hPa is relatively high because of high concentrations of both the slow electrons and He^+ ions [8]. The possible latter process is justified by the relatively high density of He atoms in the $2s^3S$ state in HCD at the pressure of about 20 hPa [11, 16]. The contribution of the He atoms in the metastable $2s^3S$ state to the excitation of radiative HeI states seems to be confirmed by the results presented in Fig. 7 showing the He pressure dependence of the central intensities of the 388.9 nm, 492.2 nm and 501.6 nm He I lines normalized to the corresponding intensity at the He pressure at 10 hPa. The behaviour of the intensities of the two first lines is similar to that of the $2s^3S$ metastable number density in the HCD presented in Fig. 4b of [11]. This similarity suggests that these radiative He I states are considerably excited by impacts of slow electrons with He atoms in the $2s^3S$ state, which is high populated towards the discharge axis [16], explaining the strong maximum in the middle of the He I intensity distribution better than the dielectronic recombination process.

The radial profiles of the 468.6 nm He II line show a linear increase of the central intensity $J(R = 0)$ with increasing discharge current at low He pressures (s. Fig. 6), which suggests that this line is mainly excited by the direct collision process between fast electrons and He atoms in the ground state. At higher He pressure, however, faster than linear increase of the central intensity of the 468.6 nm He II line with increasing current involves the possibility of step processes. Collisions of fast electrons with the He^+ ions in the ground state or with He $2s^3S$ atoms seems to play an essential role in excitation of He II higher states. The strong middle peak in the radial He II intensity distribution for a great pressure region (see Fig. 8c — high value of the intensity ratio) is an indication for the occurrence of very fast electrons (beam electrons) in the central region of the negative glow. Such energetic electrons nonperturbed by collisions on their flight to the discharge centre have a relatively high concentration on the axis of a cylindrical discharge (see discussion of [14] and calculations of [19]. The decisive role of fast electrons in exciting the 468.6 nm He II line seems to be clear because of the correlation between the intensity ratio and the sustaining voltage which controls the number of fast electrons in the TD [8]. For higher pressure ($\gtrsim$25 hPa) the number of fast electrons is not sufficient for efficient excitation on the discharge axis which consequently leads to a strong broadening of the He II intensity radial profiles. The beam electrons show a faster Maxwellization in this pressure region [21], leading to relatively stronger excitation outside of the discharge axis.

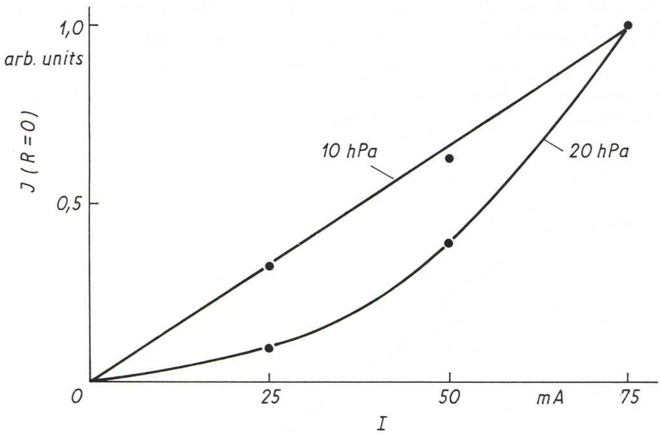

Fig. 6. Current dependence of the 468.8 nm — He II emission line in the centre of the TD (for each pressure normalized to the intensity at I = 75 mA).

3.2 Longitudinal Configuration (LC)

It was shown in [9, 10] that dependend on the discharge parameters and on the cathode length the LD can have along its entire length either properties of the negative glow or those of the positive column, or can contain both these discharge zones simultaneously. In the LD having properties of the positive column (at low He pressure and low density of discharge current) the main part of the EEDF is broad, the mean electron energy is high (up to 10 eV), the electron concentration is low (less than 10^{12} cm^{-3}), and an axial electric field (up to 15 V/cm) is present in the discharge. Besides, the mean electron energy and the relative number of electrons in the EEDF tail decrease with the discharge current increase. Because of possible coexistence of the zones of different electrical and optical properties along the LD, the comparison of the TD and LD properties by observing the end-lights emitted can only be made in a phenomenological way.

In general the results obtained show that properties of the LD differ from those of the TD. The main differences observed are the following:

1. The current and the pressure dependence of the sustaining voltages of both discharges differ (Fig. 2).
2. At low currents and/or low He pressures the He I line intensity profiles in the LD do not exhibit central minima existing in the TD. The excitation of He I lines in the centre of the LD is relatively strong compared to that of the TD (Fig. 8b).
3. The plots of central intensities of 388.9 nm and 492.2 nm He I lines versus He pressure in the LD do not exhibit maxima as those in the TD (Fig. 7). The intensities of He I lines in the LD decrease with increasing He pressure, what means that they do not follow the sustaining voltage when changing He pressure (Fig. 8a) as they do in the TD.
4. The differences between the intensities of 388.9 nm and 492.2 nm He I lines in the centre of the LD are not as large as in the TD (see Fig. 8a). A plausible reason for these differences in the TD could be the better population of high lying He I energy levels by dielectronic recombination [14].

The behaviour of the He II radial profiles in the LD is similar to that of the TD. The He II intensity ratio $J(R = 0)/J(R/2)$ in the LD follows not the sustaining voltage in dependence on the He pressure like it is the case for the TD. The different behaviour of the He I lines in the LD in relation to the TD can be explained by unique properties of the plasma of the LD. Depending on He pressure and discharge current density the LD properties along the cathode axis can change from those typical of the negative glow to those similar to the positive column of the glow discharge. Therefore a deep analysis and explanation of the behaviour of intensities of He I and He II in the LD when changing the

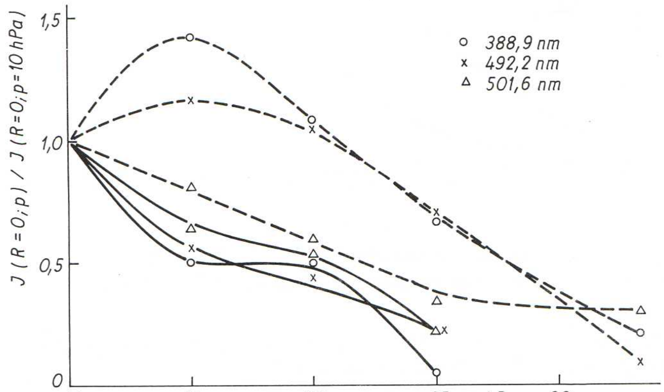

Fig. 7. Pressure dependence of the intensities of the He I lines on the discharge axis normalized to the corresponding intensity at He pressure of 10 hPa (I = 50 mA). TD: broken line, LD: solid line.

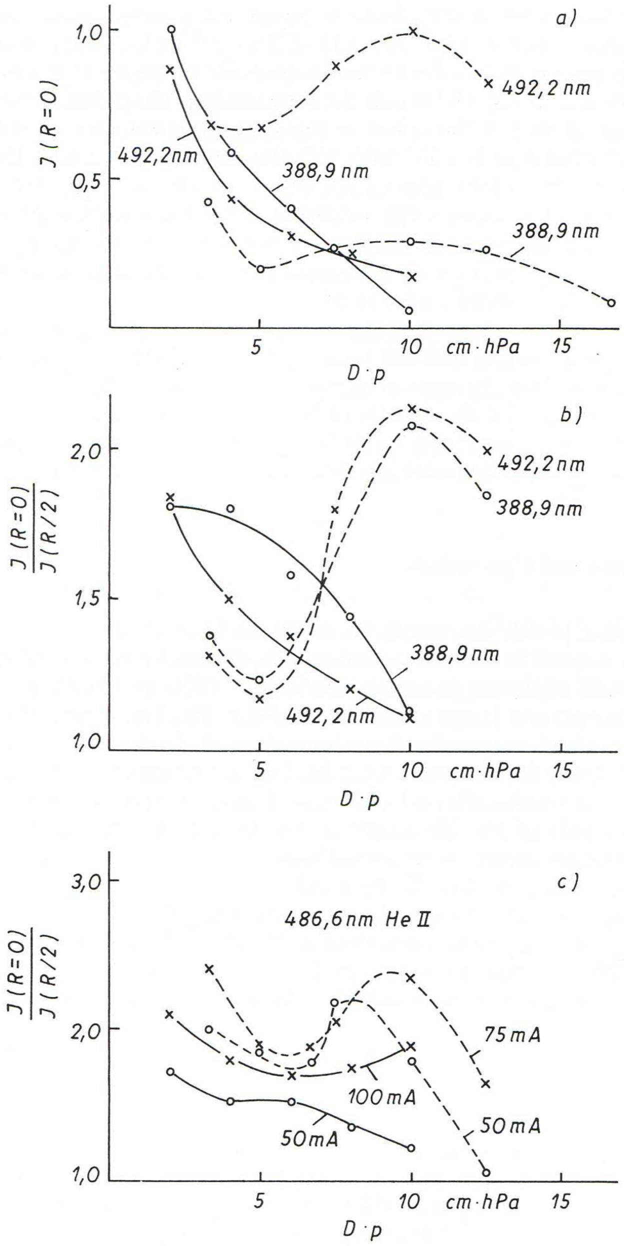

Fig. 8. Intensity $J(R = 0)$ (arbitrary units) and intensity ratio $J(R = 0)/J(R/2)$ in dependence on $D \cdot p$ for:
a), b) He I: I = 75 mA; TD: broken line, LD: solid line.

discharge parameters is complicated. At low He pressure and low discharge current the positive column properties dominate in the LD and such optical effects typical for the positive column as the strongest emission of He I lines from the centre of the discharge and a decrease of the intensity of the He I lines with increasing He pressure [18] are easily observed. As in the LD the correlation between the sustaining voltage and the number of fast electrons is not as straightforward as in the TD, the correlation between the sustaining voltage and the intensity of the He I lines is not observed. On the other hand, at higher He pressure and higher discharge current the properties of the negative glow play a dominant role in the LD. As a result the cathode dark space is shortened and the possibilities for excitation by fast electrons are better with increasing He pressure outside the cathode axis (broadening of the He I radial profile, see Fig. 8b).

Although it is not possible to show that the excitation of the He I lines starts from the metastable level, it is worth adding that the number density of He atoms in the $2s^3S$ state is relatively high in the LD. Our absorption measurements to which we had employed two identical LC modules showed that the density of He $2s^3S$ atoms in the LD at 100 mA and 20 hPa is about $5 \cdot 10^{12}$ cm^{-3}, similarily as in [12, 17]. This suggests that the role of the He $2s^3S$ atoms in excitation of the states of higher energies is also considerably in the LD.

4. Summary and Conclusions

The results of the radial profile measurements of the He I and He II spectral lines emitted by two He discharges excited in hollow cathodes with different positioning of the anodes confirmed previous results of plasma parameter studies [8–10] that the optical and electrical properties of the transverse and longitudinal HCD differ. The both discharge, realized in the so called transverse and longitudinal configuration of discharge electrodes, exhibit different excitation efficiency for instance of the He I spectral lines.

Although the presented results allowed only speculation on the excitation mechanisms in both discharges, the role of the He atoms in the metastable state $2s^3S$ in excitation processes in both discharges seems to be considerable.

The results obtained can not directly be used for estimation of usefulness of both hollow-cathode discharges for excitation of laser species in the He-metal vapour laser media because adding a metal-vapour lasing component to the He in the HCD changes its plasma parameters and optical properties. However on the basis of these results some estimation of behaviour of the lasing media in both hollow cathode discharges can be made.

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