RADIAL DISTRIBUTIONS OF THE CHARGED PARTICLES
IN A He–Kr HOLLOW CATHODE DISCHARGE

J. MIZERACZYK a, F. HOWORKA b and K. ROZSA c

a Institute of Fluid-Flow Machines, Polish Academy of Sciences, 80-952 Gdańsk, Fiszera 14, Poland
b Institut für Ionenphysik der Universität Innsbruck, Technikerstr. 25, A 6020 Innsbruck, Austria
c Central Research Institute for Physics, H-1525 Budapest, POB 49, Hungary

Received 7 February 1990

Radial distributions of He⁺, He²⁺ and Kr⁺ were measured in a hollow cathode discharge in He and in He–Kr mixtures using a mass spectrometer. The dimensions of the discharge were similar to those used in He–Kr⁺ hollow cathode discharge lasers. From the ion densities the electron density was derived. Introducing krypton into the helium discharge results in decreasing both the densities of He⁺ and He²⁺ ions. During this process the radial distributions of the He⁺, He²⁺ and electron density change from parabolic into saddle-like profiles. The changes of radial profiles of the charged particles in the He–Kr hollow cathode discharge may affect the lasing properties of the mixture.

1. Introduction

The knowledge of space distributions of neutral and ion species in lasing gas mixtures excited by an electric discharge is necessary for understanding the laser properties of the mixtures and the excitation mechanisms leading towards population inversion. Particularly, the problem seems to be of importance for lasing media consisting of mixtures of gases, or mixtures of gases and metal vapours excited by an electric discharge of cylindrical geometry. The axial and radial distributions of the neutral and ion species of the He–metal vapour ion lasers were studied for the case of the excitation in the positive column only. The results helped to obtain uniform distributions of the lasing species along the positive column in the positive column He–Cd⁺ laser [1]. They gave also a new viewpoint on the current saturation effect of the positive column He–Cd⁺ laser power output [2,3]. To the authors’ knowledge the axial and radial distributions of the neutral and ion laser species of the He–metal vapour or the noble gas mixture ion lasers excited in the hollow cathode discharge (HCD) have not been measured yet.

In this work the results of mass spectrometric measurements of the radial distributions of He⁺, He²⁺, Kr⁺ and electron density in the He–Kr laser mixture excited in the HCD are presented. The He–Kr⁺ HCD laser, generating blue and violet lines, is one of the most promising lasers from the HCD laser group [4].

Although the technology of some HCD lasers approach commercialization level, the excitation mechanisms and operating behaviour of these lasers are not fully understood. Our study delivers new data which might be useful for better understanding properties of the He–Kr⁺ HCD laser as well as other He–metal vapour ion HCD lasers, including the He–Cd⁺ laser. It must be said, however, that further measurements in He–metal discharges are necessary to support the conclusions presented below.

2. Experimental

We only give a short description of the experimental setup used, since it has already been published in detail [5]. A cylindrical hollow cathode (length 30 mm, inside diameter 5 mm) was sampled in two radial positions (central and 1.5 mm off-axis) with respect to a fixed sampling probe (free metal
area 1 mm², hole diameter 50 μm). The extracted ions were introduced into a 60° magnetic mass spectrometer. The anode was positioned outside the cathode, so the HCD geometry was of a longitudinal type [6].

The probe potential was held at space potential of the discharge plasma, which was near the potential of the anode. The discharge conditions were close to those of the He–Kr⁺ HCD laser (He pressure 10–40 mbar, Kr pressure up to several tenths of mbar, Kr pressure up to several tenths of mbar, average discharge current density up to 30 mA/cm²). The Kr pressure of the discharge was estimated on the base of the operating voltage which is increasing with the increasing Kr partial pressure in the range investigated [7]. Neglecting the net space charges right at the cathode fall region and assuming that the density of ions at the cathode surface is zero, a probable profile of the radial distributions of the ions can be obtained from the two measured points.

3. Results

Our measurements show that in the pure helium HCD the density of He⁺ and He₂⁺ ions on- and off-axis increase with increasing discharge current (figs. 1, 2), and decrease with increasing He pressure (fig. 3).

Fig. 1. Density of He⁺ ions as a function of discharge current in the longitudinal discharge on the axis of the hollow cathode (length 30 mm, diameter 5 mm). He pressure (mbar): • 10.7; x 13.3; ■ 16; △ 21.3; + 26.7; ▽ 30; □ 33.3; ○ 40.

Fig. 2. Density of He₂⁺ ions as a function of discharge current in the longitudinal discharge on the axis of the hollow cathode (length 30 mm, diameter 5 mm). He pressure (mbar): • 10.7; x 13.3; ■ 16; △ 21.3; + 26.7; ▽ 30; □ 33.3; ○ 40.

Fig. 3. Density of He⁺ (○), He₂⁺ (●), and electrons (□, ■ according to ref. [8]) as a function of He pressure in the longitudinal discharge at 100 mA on the axis of the hollow cathode (length 30 mm, diameter 5 mm).

3). The density of He⁺ ions is higher than the density of He₂⁺ in the pressure range up to about 35 mbar. Around 10 mbar the He⁺ density is about 10
times higher than the density of the He$_2^+$ ions. At higher pressures (above 40 mbar) the He$_2^+$ density is higher than the He$^+$ density. The density of electrons, simply calculated from the ion currents, increases with the discharge current and decreases with decreasing He pressure. This confirms earlier results obtained by a Langmuir probe method [8].

The absolute values of the electron density obtained here are in good agreement with those obtained by the probe method (fig. 3). The profiles of the radial distribution of He$^+$, He$_2^+$ ion and electron density in the pure He HCD look diffusion dominated (fig. 4). Saddle-like profiles can hardly be supposed from the experimental data.

Fig. 5 shows the densities of He$^+$, He$_2^+$ and Kr$^+$ ions on the axis and off-axis of the HCD in the He–Kr mixture as functions of the operating voltage and Kr partial pressure. It is seen from fig. 5 that both the He$^+$ and the He$_2^+$ ion densities decrease with increasing Kr pressure. After a sharp increase, the Kr$^+$ density decreases as well. However, the ion densities on the axis are changing with increasing Kr density faster than those off the hollow cathode axis. This results in changes of the radial distributions of densities of all the ions, He$^+$, He$_2^+$ and Kr$^+$, from parabolic to saddle-like profiles (fig. 6).

The electron density in the He–Kr HCD, calculated from all the ion currents, increases slightly with increasing Kr pressure at low Kr pressures (fig. 5). The rate of the electron density increase is in a reasonable agreement with that obtained by the probe method [7]. After the increase at very low Kr pressure the electron density decreases when Kr concentration increases. Similarly to the change of the radial distributions of the ions, the electron density profile also changes from the parabolic into the saddle-like one as the Kr concentration is increased (fig. 6).

4. Discussion and conclusions

The measurements of He$^+$, He$_2^+$ and Kr$^+$ ion densities and their radial distributions in the He and He–Kr mixture HCDs presented in this paper revealed
some properties of the HCD in mixtures. These properties have some meanings for operation of the He–metal vapour and the noble gas mixture ion HCD lasers.

It can be seen from fig. 5, that there is a sharp decrease of the Kr⁺ ion concentration in the discharge if the Kr pressure exceeds 0.1 mbar. The output power of the He–Kr⁺ laser also decreases and finally vanishes at these Kr pressures [9]. This is in a good agreement with the expected excitation mechanism stating that in production of the Kr⁺ ions excited to the upper laser level the ground state Kr⁺ ions are involved (energy transfer collisions between the ground state Kr⁺ ions and metastable He atoms [10]).

It can be also seen from fig. 5, that there is an optimum Kr pressure at which the parabolically distributed density of Kr⁺ ions (fig. 6) in the He–Kr HCD is the highest. This results in effective lasing on the axis of the hollow cathode discharge, and helps to obtain increased output power in TEM₀₀ mode. At higher Kr pressure (and He pressure as well), where the favorable laser conditions are shifted from the axis towards the cathode surface due to the saddle-like profiles of the Kr⁺ ion distribution, the laser mirrors have to be re-aligned so that the optical axis of the laser resonator should be near the cathode wall. Then the diffraction losses become higher and only a part of the lasing capable plasma can be used for laser operation resulting in a very poor efficiency of the laser.

The high concentration of He⁺ ions at the low He pressure range in the HCD (fig. 3) supports the expected excitation mechanism of the red laser lines of the He–Cd⁺ HCD laser via thermal energy charge transfer between He⁺ ions and ground state Cd⁺ ions [11]. The laser green lines which are originating from the lower levels of the red transitions have increased efficiency via cascade transition from the red lines in this He pressure range.

At higher He pressures, however, the red lines of the He–Cd⁺ HCD laser cease to oscillate but the green laser lines are still strong [12]. A possible mechanisms of excitation of the upper levels of the green transitions is collisions between the vibrationally excited He⁺ ions and the ground state Cd atoms. Our measurements have shown that although at this He pressure range the He⁺ ion density becomes comparable to that of the He⁺ ions, the absolute value of the He⁺ ion density is low. Therefore involvement of the He⁺ ions in excitation of the He–Cd⁺ laser green lines is an open question. A new light on the matter is expected from mass spectrometric measurements in a He–Cd discharge which are planned.

References
