Modelling of multiple-hollow-cathode-discharge laser

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Abstract. A laser tube configuration for metal vapour lasers with hollow cathode sputtering is theoretically studied. The construction consists of a main hollow cathode and a few hollow cathode holes. Optimal conditions for laser oscillation are realised inside the main cathode, while the current density in the side hollow cathodes is higher and the discharges that occur in the hollow cathode holes can be used as additional sources of metal atoms produced by sputtering. To study the processes in the discharge and the unique capabilities of the construction the PLASIMO modelling platform is used.

1. Introduction
Cathode sputtering has been widely used to produce a metal vapour in the active volume of hollow-cathode-discharge (HCD) laser tubes [1], [2]. The efficient creation of metal atoms by sputtering depends mostly on the discharge conditions. One of the issues that are common for all hollow-cathode geometries and metal vapour lasers with hollow cathode sputtering is an efficient obtaining of the necessary metal atom density. In order to obtain high metal atom density, a high sputtering rate is needed, but the cathode geometry should simultaneously stay unchanged. However, the cathode shape is inevitably change during the operation, due to the sputtering process and re-deposition of metal. This reduces the lifetime of the laser tube. In this work the PLASIMO modelling platform [3], [4] is used to study the discharge in the multiple hollow cathode design. Based on the results of systematic studies on the longitudinal sputtering HCD cooper ion laser the optimal parameters and the best configuration for efficient laser operation are determined [5], [6], [7], [8]. The version of multiple HCD [9] is suggested aiming to overcome the issue mentioned above. Its features are demonstrated by a numerically study of the discharge.

2. Modelling
2.1. Study setup
The discharge tube design [9] is presented in figure 1. The construction consists of a main cylindrical cathode $C$ with a length of 0.1 m, an inner diameter of 0.005 m, and an outer diameter of 0.02 m. Two ring anodes $A_01$ and $A_02$ are located at both sides of the cathode $C$. The geometrical parameters of the main cathode are selected to ensure optimal conditions for laser oscillation.
The main used ratios [10] are: \( pd = \text{const} = 9.2 \text{ kPa mm} \), and \( L = 5r \), where \( p \) is the gas pressure, \( L \) is the length of the cathode, \( d \) and \( r \) are the diameter and radius of the cathode, respectively. Three side cathode holes (CHs) are arranged along the length of the cathode \( C \) with a distance of 0.04 m between them. Rod anodes \( A_1, A_2 \) and \( A_3 \) are placed in each of the side cathodes. The CH's are used as an additional metal vapor source, because of the higher current density.

**Figure 1.** Studied discharge tube design.

2.2. Input data

The PLASIMO modelling platform is used to develop a model to study on the plasma behaviour in the multiple HCD. The used model is a 2-dimensional time-dependent multi-fluid model [11]. Because of the model symmetry only half of the construction outer diameter and half of the distance between the holes are simulated. The used model geometry is presented in figure 2.

**Figure 2.** Computational domain used for simulation.
The gas mixture is He - 5% Ar and the gas-mixture pressure is 1.3 kPa. The refractory metal used for the cathodes is copper (Cu). The applied voltage is –300 V. The included species in the model are Ar, Ar*, He, He*, Cu, He+, Ar+ and Cu+ with their mobility and diffusion coefficient. Thirteen reactions are included in the model and their rate coefficient are listed in table 1, as follows: direct ionization by electron collision (reactions 3, 4 and 7), excitation (reactions 1 and 5), stepwise ionization (reactions 2 and 6), charge transfer (reaction 12), Penning ionization (reactions 9, 10 and 11), ionization through the metastable levels (reactions 8 and 13).

Table 1. List of reactions included in the model.

| №  | Reactions                                      |
|----|------------------------------------------------|
| 1  | $e + \text{He} \rightarrow e + \text{He}^*$     |
| 2  | $e + \text{He}^* \rightarrow e + e + \text{He}^+$ |
| 3  | $e + \text{He} \rightarrow e + e + \text{He}^+$  |
| 4  | $e + \text{Cu} \rightarrow \text{Cu}^+ + e + e$  |
| 5  | $e + \text{Ar} \rightarrow e + \text{Ar}^*$      |
| 6  | $e + \text{Ar}^* \rightarrow e + e + \text{Ar}^+$|
| 7  | $e + \text{Ar} \rightarrow e + e + \text{Ar}^+$  |
| 8  | $\text{He}^* + \text{He}^* \rightarrow e + \text{He} + \text{He}^+$ |
| 9  | $\text{He}^* + \text{Ar} \rightarrow \text{He} + \text{Ar}^+ + e$ |
| 10 | $\text{He}^* + \text{Cu} \rightarrow e + \text{He} + \text{Cu}^+$ |
| 11 | $\text{Ar}^* + \text{Cu} \rightarrow e + \text{Ar} + \text{Cu}^+$ |
| 12 | $\text{Ar}^* + \text{Cu} \rightarrow \text{Ar} + \text{Cu}^+$    |
| 13 | $\text{Ar}^* + \text{Ar}^* \rightarrow \text{Ar}^+ + e + \text{Ar}$ |

2.3. Model description
The time evolution of each active species density $p$ is described by the particle balance equation

$$\frac{\partial n_p}{\partial t} + \nabla \cdot \mathbf{\Gamma}_p = S_p.$$  \hspace{1cm} (1)

To obtain the active species density, namely electrons, ions and excited atoms, the balance equations are solved. The net source term $S_p = \sum_r c_{p,r} R_r$ is determined by the reactions occurring in the discharge. The net stoichiometric particle number of the species created in one reaction $r$ with the corresponding reaction rate $R_r$ is $c_{p,r}$.

The flux density $\mathbf{\Gamma}_p$ is obtain under the drift-diffusion approach

$$\mathbf{\Gamma}_p = \mu_p \mathbf{E} n_p - D_p \nabla n_p,$$  \hspace{1cm} (2)

where $\mathbf{E}$ is the electric field, $\mu_p$ is the mobility and $D_p$ is the diffusion coefficient. The electron balance equation describes the time evolution of the electron density

$$\frac{\partial n_e}{\partial t} + \nabla \cdot \mathbf{\Gamma}_e = S_e.$$  \hspace{1cm} (3)

The energy flux density is given by

$$\mathbf{\Gamma}_e = \frac{5}{3} \mu_e \mathbf{E} n_e - \frac{5}{3} D_e \nabla n_e.$$  \hspace{1cm} (4)
3. Results

The model is applied to two cases: first, when only the main cathode $C$ is sputtered, and the second, when the sputtering is applied to both cathodes, i.e. main and side cathodes. In the first case, the side cathodes are assumed to be with a negligible sputtering and the sputtering occurs only in the main cathode $C$. In the second case, the side cathodes $C_i$ sputter, as well as the main cathode $C$.

The on-axis potential distribution presented in figure 3(a) is typical for the longitudinal HCDs. Comparing the theoretical result for the case of the main cathode sputtering and the case of both cathodes sputtering, it is shown that the axial potential profiles are similar in both cases. A small axial variation of the potential is observed in the cathode centre, as follows: from $(-8 \div -10) \text{ V}$ at $z = 0 \text{ mm}$ to $(-40 \div -43) \text{ V}$ at $z = 20 \text{ mm}$.

The potential distribution results in higher electron energies and consequently more efficient electron impact ionization in the cathode cylinder centre. The electron density in the longitudinal direction decreases at the cathode ends, while in radial direction the electron flow is directed to the cathode cavity centre. The axial electron density profiles are presented in figure 3(b) for both cases. The electron density is higher in the case, when the sputtering is applied to both cathodes.

![Graph](image1.png)

(a) On-axis potential.

![Graph](image2.png)

(b) Axial electron density distribution.

Figure 3. On-axis potential (a) and axial electron density distribution (b) are presented in the cases when the sputtering is applied only to the main cathode and when the both cathodes are sputtered.

The maximum of the axial density distribution of the sputtered Cu atoms figure 4(a) and Cu ions figure 5(a) are located at the main cathode centre. In the case with the sputtered side cathodes the current density is higher and metal vapour production increases. The Cu atom density is also concentrated in the cathode cavity centre. Due to the higher density of electrons and copper atoms in the main cathode centre, the maximum of the Cu$^+$ density is also located in the main cathode centre at $z = 0 \text{ mm}$.

The calculated average densities of the Cu atoms figure 4(b) and Cu ions figure 5(b) increase in the second case, when the both cathodes are sputtered. The results show that the mean copper atom density is $1.6 \times 10^{18} \text{ m}^{-3}$ in the first case, when only the main cathode is sputtered, while the mean Cu atom density is $4.5 \times 10^{18} \text{ m}^{-3}$ in the case, when both cathodes are sputtered. The mean value of the Cu$^+$ density is $6.7 \times 10^{14} \text{ m}^{-3}$ in the first case, while the same value is $1.9 \times 10^{15} \text{ m}^{-3}$ in the case, when both cathodes are sputtered.
4. Conclusions
To study the HCD in the multiple hollow cathode construction, where the sputtering is separately applied to the main cathode and to the side cathodes, PLASIMO’s 2-dimensional time-dependent multi-fluid model is used.

The results from the model show that the axial potential profiles are similar in both cases: the first, when only the main cathode is sputtered, and the second, when both cathodes are sputtered. The axial density distributions of the sputtered Cu atoms and the Cu ions have maximums in the centre of the active volume in both cases.

The average densities of the Cu atoms and Cu ions are also calculated in both cases. In the case when the additional cathodes together with the main cathode are sputtered, the densities of copper atoms and copper ions significantly increase in the active volume.
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