Distribution of metastable and resonance atoms in cathode region of low-pressure He-Xe discharge

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Transport phenomena in a plasma localized within a small geometric region have been studied experimentally and theoretically. A low-pressure He-Xe discharge in the spot mode was considered as a typical example of such plasma. Resulting spatial distributions of excited xenon atoms and various approaches for theoretical description of the relevant transport mechanisms are discussed.

Low-pressure glow discharges in the mixtures of xenon with rare gases are extensively studied for use as mercury-free lighting sources [1, 2]. The main drawback of such lamps is a short lifetime, which is mainly limited by the performance of the electrodes and their interaction with discharge plasma. Therefore, the physical processes particularly in the cathode region have to be studied in detail. Excited atoms significantly impacts the properties of the cathode region. The formation mechanisms principally differ for the metastable and resonance atoms. The discharge in the spot mode gives the opportunity to study the differences in the transport due to the diffusion and the radiation trapping.

In the present work the cathode region of a He-Xe low-pressure glow discharge with a thermionic emitting cathode in spot mode has been studied experimentally by means of space resolved laser atom absorption spectroscopy. The plasma inhomogeneity was considered in the subsequent analysis of the obtained data. Measured spatial density distributions of the two lowest excited xenon states Xe($1s_5$) and Xe($1s_4$) are discussed with the results based on simultaneous solution of the diffusion equation and the equation of the radiation transport.

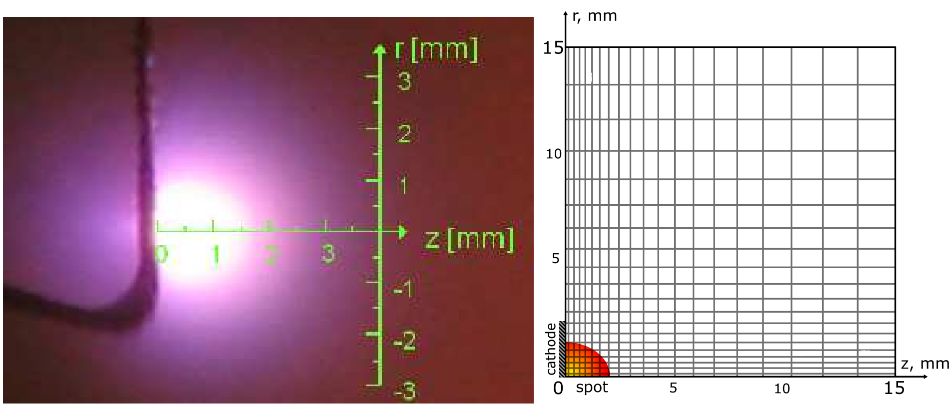

Fig. 1: Visible emission of the discharge in the mixture He+2%Xe at 5 Torr and 40 mA (left) and the model of discharge geometry (right).

Experimental study was performed in a He+2% Xe dc discharge at a total pressure of 5 Torr and the discharge current of 40 mA, which corresponds to realistic lamp conditions. Inside of a cross shaped discharge tube with parallel windows at each side, a flat iron mesh electrode pasted with an emitter of Ba-Sr-Ca oxide as a cathode and a tungsten coil electrode as an anode are mounted face to face in a distance of about 20 mm. The discharge tube design allowed for measuring in both axial (along the discharge axis) and radial (across the axis) directions. The visible spot plasma has an axial dimension of about 3.5 mm and a radial dimension of about 6 mm (Fig. 1). The positive column is not observed for the small cathode-anode distance.

The results of measurements have been analyzed by means of a numerical model, which is based on the solution of the system of balance equations for the densities of metastable and resonance xenon atoms. For a dc plasma this system has following representation

$$D_{\mathrm{m}}\Delta N_{\mathrm{m}}(\mathbf{r}) - \gamma_{\mathrm{rm}}N_{\mathrm{r}}(\mathbf{r}) + \gamma_{\mathrm{mr}}N_{\mathrm{m}}(\mathbf{r}) = W_{\mathrm{m}}(\mathbf{r}) \tag{1}$$

$$AN_{\mathrm{r}}(\mathbf{r}) - A\int_V N_{\mathrm{r}}(\mathbf{r}')K(\mathbf{r},\mathbf{r}')\mathbf{dr}' + \gamma_{\mathrm{rm}}N_{\mathrm{r}}(\mathbf{r}) - \gamma_{\mathrm{mr}}N_{\mathrm{m}}(\mathbf{r}) = W_{\mathrm{r}}(\mathbf{r}). \tag{2}$$

Here $N_{\mathrm{m,r}}(\mathbf{r})$ are the densities of the metastable and resonance atoms, D_{m} is the diffusion coefficient of the metastable atoms, A denotes the probability of spontaneous emission from the resonance state. The frequencies $\gamma_{\mathrm{mr,rm}}$ characterize the transfer between the metastable and resonance atoms due to collisions and radiation (with participation of highly excited atoms). Finally, $W_{\mathrm{m,r}}(\mathbf{r})$ are the excitation rates for the metastable and resonance atoms, respectively. The integral operator $K(\mathbf{r},\mathbf{r}')$ gives the probability for the photon emitted at point $\mathbf{r}'$ to pass the distance $|\mathbf{r}-\mathbf{r}'|$ and to get absorbed at point $\mathbf{r}$. The integration over the whole plasma volume is necessary to determine the resulting density of resonance atoms in each volume point $\mathbf{r}$. The analysis of the equation system has been performed in three approximations: (i) transport operators replaced by the effective probabilities, (ii) discretization of diffusion transport operator and effective probability for radiation transport [3, 4], and (iii) discretization of diffusion transport operator and matrix method for radiation transport operator [5]. Results have been compared with measured spatial distributions.

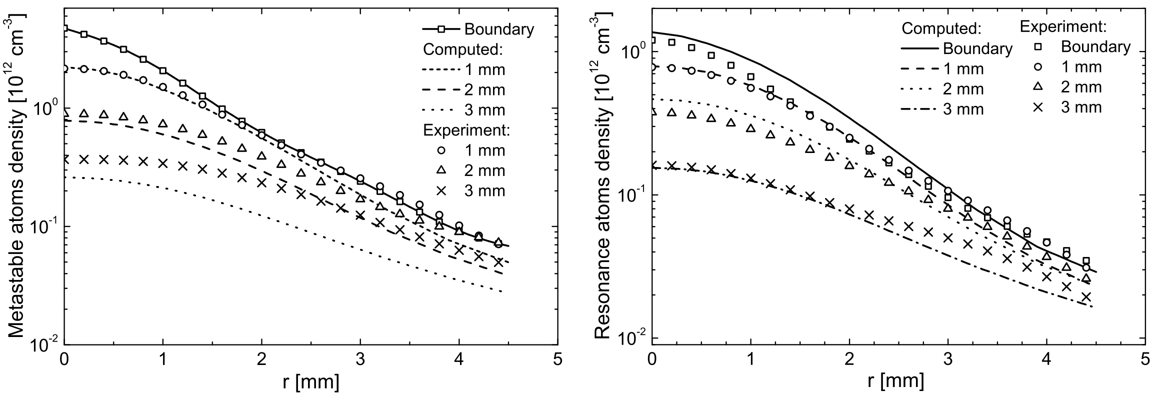

Fig. 2: Spatial distributions of metastable atoms (a) and resonance atoms (b). Results for model (iii).

Generally, the highest density is found right before the cathode in the center of the spot plasma. It decreases monotonously in the radial and axial directions leading to a density reduction by almost one order of magnitude for distances greater than 3 mm. For the metastable xenon atoms a 3–4 fold higher density than for the resonant Xe atoms is found. The best representation of experimental results have been achieved using approach (iii) (Fig. 2). Detailed description of different numerical approaches and discussion of the role of both transport mechanisms will be given.

References

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