Spatial Distribution of Ionic Species In The He-Cd$^+$ Laser Discharge

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Abstract : To calculate the power delivered by the laser discharge column, it is essential to study the distribution of densities and other parameters along the radius of the tube which are known as Radial Profiles. The detailed study of the radial profiles to a large extent gives the idea of the excitation mechanism in the discharge tube. The radial profiles of the spectral emission obtained by the calculations show close agreement with the experimentally measured profiles. By taking into consideration the concept of the fractional abundance the explanation regarding the behavior of the radial profiles at various electron temperatures is given in more detailed manner.

***Key Words* - excitation, fractional abundance, electron temperature, radial**

I. INTRODUCTION

The gas laser medium in the discharge tube consists of mixture of electrons, atoms and ions of rare gas as well as active materials. The densities of these particles are found to be non uniform in the different parts of the discharge tube. As a result of this different parts of the plasma get heated to different extent. This non uniform heating of plasma gives rise to variation of plasma parameters across the discharge tube. This plasma parameter affects the contribution of the excitation process to the laser plasma output. The He-Cd$^+$ laser discharge is characterized by several radial profiles. Among the important ones are the radial profiles of the densities of (1) electrons (2) cadmium atoms (3) CdII ions (4) CdIII ions (5) the radial profile of the electron temperature (6) the radial profile of the gas temperature (7) radial profiles of spectral emission of the discharge etc.

A L Mckenzie [1, 2] in the year 1977 has measured the radial profiles in the He-Cd$^+$ laser discharge. The end light intensities of the spectral lines of the CdII emission at the wavelengths 4416 A°, 3250 A°,3536 A°, 2265 A°, 2144 A°, 6355 A°, 6360 A°, 6338 A°, 5378 A°, 2313 A°, 2321 A°, 2195 A°, 2749 A°, 2573 A°, 5337 A° and he also measured the radial profiles of the densities of CdI, CdII, HeI and the metastable states of the helium atoms. The interpretations of these results include the following postulates and assumptions.

1) The upper laser state of 4416A° transitions $5s^2\ ^2D_{5/2}$ is dominantly populated by the Penning collision with the helium atoms in the metastable state.
2) The profile of 4416 A° is shallower than the profiles 3250 A° because of the smoothing out effect due to the radial profiles field and emission.
3) The electron collisional deexcitation of the $5s^2\ ^2D_{5/2}$ is negligible.
4) The rates of the process of the Duffenduck reaction and the Penning reactions are identical.

Stepwise excitation of the laser states is the most dominant process of excitation. In the calculation of the radial profiles of the spectral emission of the discharge, the contribution of stepwise excitation is only considered. The excitation rate of a state by the stepwise excitation process is equal to the term $N_{Cd}N_eR_u$. The variation of the parameters which determines the excitation and deexcitation give rise to the radial profiles of the spectral line.

The radial profiles of positive column He-Se$^+$ laser discharge were extensively studied by Mckenzie [3]. The radial profiles at all the wavelengths show similar behavior. Each of the spectrum line profile has a dip at the axis and the dip goes on increasing as the discharge current is increased for a constant helium pressure.

In the year 1967 T Ihjma et al [4] carried out experiment for the measurement of spectral emission of Ar$^+$ laser discharge. He observed that the radial profile show the dip at the tube axis. The experimental results of Mckenzie were reconsidered by Goto et al [5] and they interpreted in different way. The assumptions of Goto et al are listed below.

1) The upper state of 6360 A° transition is dominantly populated by the Duffenduck reaction and hence its intensity is given by

$$I_{6360} = N_{Cd}\ N_{He}^+\ T \qquad 1$$

$$N_{Cd}\ \alpha\ I_{6360} / N_{He} \qquad 2$$

2) The cadmium ions are produced by the electron collision and the ionization rate is constant in the region for r/R < 1.6/2.5 = 0.64. Hence the density N_{Cd}^+ is proportional to the term $N_e.N_{Cd}$. The profile of N_{Cd}^+ may be obtained from the relation

$$N_{Cd}\ \alpha\ I_{2144} / N_{He} \qquad 3$$

3) The profile of the stepwise excitation of $5s^2\ {}^2D_{5/2}$ is assumed to be same as the profile of I_{2144}

4) The drift velocity equal to 50 cm/sec. In the life time 0.8 μsec of the upper state of 4416 A° the ions moves through very small distance. Hence smoothing out effect of the state $5s^2\ {}^2D_{5/2}$ must be very small.

5) The density of the upper laser state is given by

$$Nu1 = \frac{(M+P)}{\left(A+N_eD_e+\frac{1}{T}\right)} \tag{4}$$

Watanabe et al [6] have measured the radial profiles of the densities of the Cd atoms for different values of helium pressure, the discharge current and cadmium vapor pressure. The radial profiles obtained in the experiment were explained by considering diffusion model.

In the year 1963 Goto et al [7] studied several experimental and theoretical aspects of the radial profiles in the $He\text{-}Cd^+$ laser discharge tube near the optimum values of the discharge parameters. They measured the radial profiles of the spectral emission at the wavelengths 4416 A°, 3250 A°, 6360 A°, 6355 A°, 2144 A°, 2265 A°, 2749 A°, 2313 A° and 2195 A°. The radial profiles of the densities of CdI, CdII and helium atoms in the metastable states also are measured. The experimental observations for a typical values of parameters show agreement with the calculated values. The calculation assumes that the electron temperature is constant across the discharge tube for $r/R < 0.7$ (where r is the distance from the tube axis and R is the radius of the tube). The intensity of the spectrum lines at different wavelengths are assumed to be proportional to the various factors and the proportionality relations are given as

$$I_{4416}\ \alpha\ \frac{(M+P)}{(A+N_eD_e)} \tag{5}$$

$$I_{2144}\alpha\frac{(M+C)}{A} \tag{6}$$

$$I_{6390}\ \alpha\frac{T}{A} \tag{7}$$

where M is excitation rate coefficient from the ground state of CdII, P is Penning excitation rate coefficient, T is Duffenduck excitation rate coefficient, A is Einstein's coefficient, n_e is the electron density and D_e is electron impact de excitation rate, C is Cascading rate coefficient

The proportionality equations for the rate coefficient are assumed to be given by

$$M\ \alpha\ n_e N_{Cd} \tag{8}$$

$$P\ \ \alpha\ N_{Cd} N_m \tag{9}$$

$$T\ \ \alpha\ N_{He} N_{Cd} \tag{10}$$

$$S\ \ \alpha\ \ n_e N_{Cd} \tag{11}$$

$$N_{He} = \ n_e N_{Cd} \tag{12}$$

The comparisons of the theory and the experiment is little doubtful because in the equation for the I_{4416} and I_{2144} the multiplying factors of M and P and M and C are not identical. Hence I_{4416} and I_{2144} may not be proportional to M+P and M+C. Recently Pawar et al [8] have performed few calculations and obtained the radial profiles of the radial profiles of the emission of the spectral lines of the $He\text{-}Cd^+$ laser discharge. The theoretically obtained profiles [8] show very good agreement with the experimental results [1-7].

In the present work we studied of the radial profiles of the electron temperature, densities of CdI, CdII and electrons. In the calculations of the radial profiles of the electrons, cadmium atoms, CdII ions the variation of temperature across the discharge tube plays vital role. Therefore an appropriate electron temperature profile has to be considered. The fractional abundance in the gas discharge is mainly determined by the electron temperature. The radial profile of the electron temperature in the discharge is assumed to be given by the equation

$$T(R) = T_0\ \{1-(R/R_0)^2\} \tag{13}$$

where T_0 is axial temperature in eV ,R is radial distance at a point in the tube and R_0 is radius of the discharge tube.

The radial profile of the electron density is also assumed to have shape similar to the zero order Bessel function of first kind. Therefore for our present calculations we assume these profiles to have the same shape as that of electron temperature profile.

Radial Profiles Of Neutral Cadmium Atoms

We have obtained the radial profiles of the densities of the cadmium atoms at different axial temperatures from 1 to10 eV. The curves for some representative values of T_0 from 1 to 5eV are plotted on the same scale for the comparison in the figure

1. In this calculations, we assumed that the radial profiles of the electron temperature can be given by equation $T(r)= T(0)\ [1-(r/R)^2]$. The electron temperature along the axis of the discharge tube is maximum and falls on either sides diminishing to a zero value at the walls.

All the radial profiles show a common feature that the density of CdI is maximum at the walls and it decreases as one proceeds towards the axis where it has a minimum value. The rate of decrease of density of CdI increases very rapidly as the axial temperature is increased. The dip on the curve is observed at the axis at low temperature becomes more and more pronounced for the higher axial electron temperature which indicates that the density of CdI at the axis decreases with the axial temperature and at 4 eV the density of CdI is practically zero within the radius for R = ± 1.75 cm i.e. all the cadmium atoms has been converted into their ionic form. The results may be compared with the experimental results of Watanabe et al [6]. The increase in the electron temperature increases the dip at the axis. The results are in very good agreement with the work of Watanabe et al [6].

Radial Profiles Of Singly Ionized Cadmium In The Discharge Tube

We have calculated the spatial distribution of the density of CdII ions in the discharge tube at different axial temperatures. The radial distribution of electron temperature across the discharge tube is assumed to be given by the equation 13. The radial profiles of CdII ions in the discharge tube have been calculated at different axial temperature from 1 to 10 eV. The spatial distribution of CdII ions shows different behavior at low electron temperature and at high electron temperature.

At very low electron temperature the density of CdII ions is maximum at the axis and minimum at the walls. As the electron temperature is increased the peaks become flatter and show the shift upwards showing the increase of the density of CdII ions at the axis. This is because of the fact that the axis is at maximum electron temperature and the walls are at minimum electron temperature so that more number of cadmium atoms present at the axis get converted into CdII ions showing the peak.

As the axial temperature is increased the peak starts becoming flatter. At certain axial temperature 1.5 eV the shape of the curve changes from convex to concave showing a dip at the axis figure 2. If the electron temperature is increased further the curves corresponding to more than 1.5 eV shows that the dip becomes prominent with two side peaks. And if the electron temperature is increased still further the side peaks become sharper and they show their shift towards the walls of the discharge tube.

Many times it is desirable to have normalized results with the common values at the axis and different values elsewhere. In order to carry out such a comparative study, the densities are normalized to the values at the axis and the normalized curves are as shown in the figure 2. These curves are more convenient for the interpretations as all of them coincide at the axis. These curves show close agreement with the experimental study carried out by Mckenzie [2].

II. RESULTS AND DISCUSSION

In order to give the physical feeling about the radial profiles we investigate three dimensional radial profiles and present the results. We have plotted a graph for the intensity as a function of distance from the axis. The distance of any point from the axis is obtained by drawing a radius vector from the axis to the corresponding point. For this we have considered an array of points having dimension 5mm x 5mm. At the center of the array it is assumed that the axis of the discharge tube coincides. We have calculated the intensity difference at different points around the axis and they are displayed in the figures 3,4 and 5 for the electron temperatures 1 eV, 2 eV and 4 eV respectively.

For 1 eV temperature on the axis, the profiles show a peak on the axis. The intensity goes on decreasing as one move towards the walls. The profile is hill shaped. For electron temperature of 2 eV the profile show a dip on the axis. As one moves away from the axis the intensity initially increases then reaches its maximum value and then falls down gradually. Intensity is maximum at R = 1.8 cm for the electron temperature 2 eV. The profile has shape like hill with a dip on the top. For 4 eV temperatures on the axis, the profile shows a pronounced dip on the axis. As the points of observation moves from the axis to the walls, in this case also the intensity initially increases from the value on the axis, reaches its maximum value and then gradually starts to fall down and then finally declines to zero near the walls. In this case two side peaks appears which goes on shifting towards the wall as one increases the temperature on the axis. The profile in this case is well shaped.

For 1 eV temperature the fractional density of CdII ions is very large on the axis. Moreover, the rate of excitation is also very large so the profile shows a peak on the axis. As we move away from the axis the fractional density of CdII and the excitation rate coefficient go on decreasing so the intensity also goes on decreasing. For 2 eV temperatures though the excitation rate is high on the axis but the fractional density of CdII ions on the axis is lower as compared to the density of CdII ions at the axis at 1 eV temperature. Due to which the profile show a dip on the axis. The peak of the fractional density of CdII ions has shifted away from the axis that is why the intensity of the output laser beam shows a maxima at a distance of R = 1.8 cm. If we move away further from the axis then the fractional density of CdII ions decreases and hence the intensity gradually falls down. As shown in the figure 5 the intensity at the axis is very low for the temperature 4 eV on the axis. As at about 3 eV temperature the ionization of CdII into CdIII starts taking place and the fractional density of CdII ions starts decreasing at a very fast rate and density of CdI ions is nearly equal to zero. Due to which the intensity at the axis is nearly zero for 4 eV temperatures on the axis and thus a pronounced dip appears on the axis. The peak of the intensity of radiations is very near to the walls. As the temperature on the axis is increased the side peaks shift from the axis towards the walls.

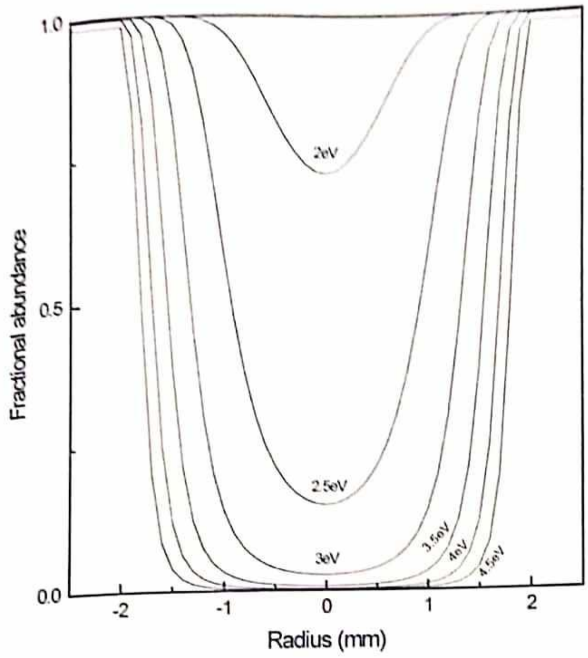

Fig.1 Radial distribution of Cd I for different axial temperature T_0

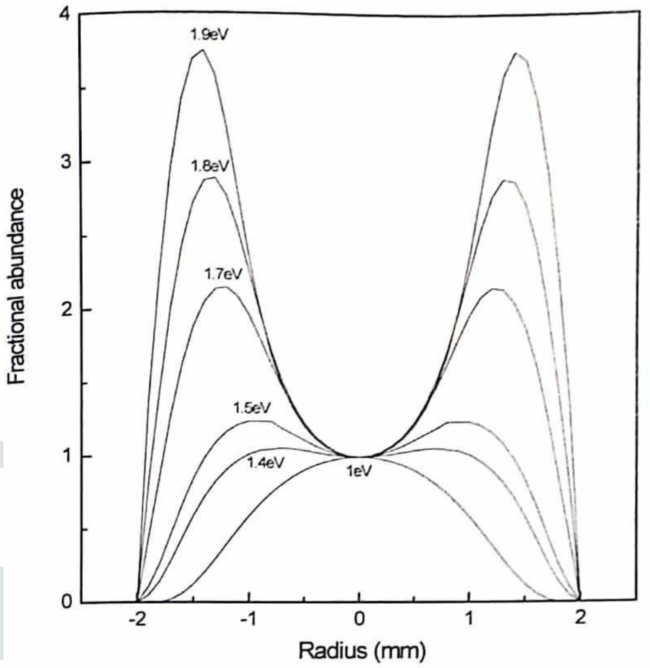

Fig.2 Normalized radial profiles of density of Cd II ions for different axial temperature T_0

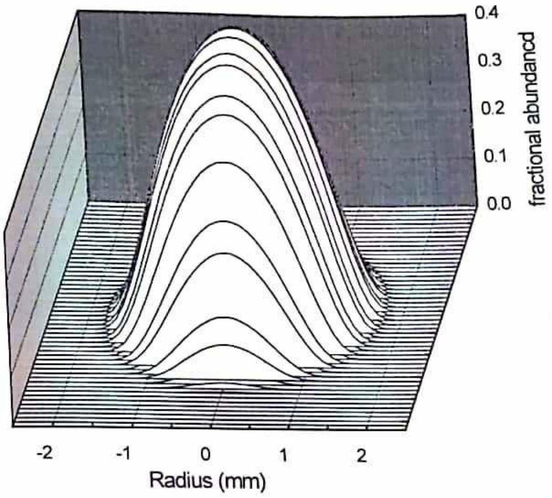

Fig3: Fractional abundance of Cd II ion for axial temperature = 1 eV

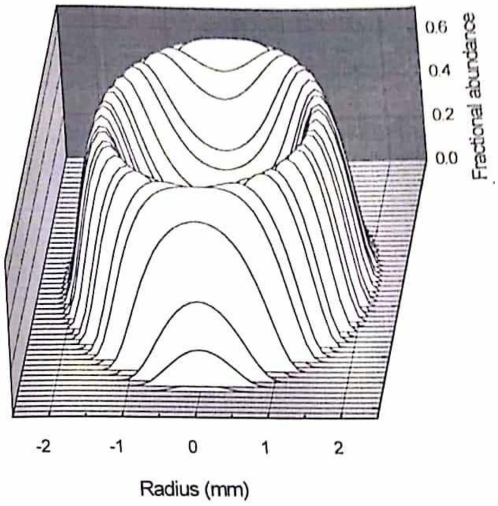

Fig4: Fractional abundance of Cd II ion for eV axial temperature = 2 eV

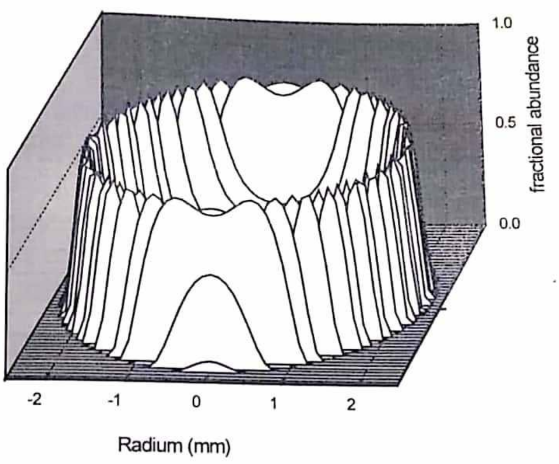

Fig4: Fractional abundance of Cd II ion for eV
axial temperature = 4 eV

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