CHAPTER – 5

THE RADIAL PROFILES OF THE DENSITIES AND SPECTRAL EMISSION IN THE He-Ne LASER DISCHARGE
5.1 Introduction:

The quantitative study of physical processes taking place in the discharge column needs the accurate knowledge about the power distribution across the output laser beam and therefore the study of the radial profiles becomes indispensable. The variation of the densities and other parameters along the radius of the tube (across the discharge tube) are known as radial profiles of the densities or the parameters. In a plasma column the densities of the particles and electrons, the electron temperature, the plasma resistivity etc do not have constant value across the plasma column. As the plasma resistivity varies across the discharge tube the current density also varies and as a result the different parts of plasma gets heated to different extent. This nonuniform heating of the plasma column gives rise to the further variation of the plasma parameters across the discharge tube. The investigation of the radial distribution of the densities and the spectral emission of the discharge gives large amount of information (1-10) than any other technique of procuring data. The laser discharge is characterized by several profiles. The important among them are the radial profiles of the densities of electrons, atoms and ions. The radial profiles of the spectral emission of the discharge also help in giving tremendous amount of information about the discharge. The radial profiles of electron and ion temperature also play vital role by determining values of several other parameters.

The metal ion laser discharge is characterized by several radial profiles. Among the important ones are radial profiles of the densities of i) electrons, ii) atoms, iii) ions iv) the electron temperature, v) the gas temperature and
vi) the spectral emission of the discharge etc. A. L. McKenzie (4) has measured the radial profiles of the densities of CdI, CdII, HeI and triplet metastable state of helium in the He-CdII laser discharge. The measurements were carried out at a discharge current of 300mA and the helium pressure of 5 Torr and cadmium oven temperature of 235°C. His interpretations about these results include the following postulates and assumptions.

1) The upper laser state of 4416A transition 5s^2 2D_{5/2} is dominantly populated by Penning collisions with helium atoms in metastable state.

2) The profile of 4416A is shallower than the profile of 3250A because of smoothing out effect due to radial field and diffusion.

3) The electron collisional deexcitation of 5s^2 2D_{5/2} is negligible.

4) The rates of processes of Duffendack reaction and penning reaction are identical.

Spatially resolved profiles of sidelight emission from particular upper laser levels of ZnII were recorded over a wide range of discharge conditions by Gill and Webb (11). This work may not give the information required for the study of radial distribution of the parameter in the discharge. The radial profiles of the spectral emission of the He-Zn laser discharge and the densities of HeI, HeII, ZnI, ZnII have been experimentally measured by Gill and Web (11, 12). The radial profiles of ZnII emission laser lines at 6102A, 4912A and 5894A were recorded (11) for discharge currents in the range of 0-300mA. The profiles show a weak dependence of their shape on the side arm temperature. But one significant feature common to all profiles is the change over from the convex to the concave shape, which occurs as the helium pressure is raised.

We (13) have performed few calculations and obtained the radial profiles of the emission of the spectrum lines of He-CdII laser discharge.
The theoretically obtained profiles (13) show very good agreement with the experimental work(4).

It is assumed by several workers that the intensity distribution across the laser output is Gaussian. The research workers D. P. McLeod, et al (14) has investigated the radial profiles of gain in the helium neon laser discharge (15-18). However, they have not given the satisfactory explanation of the phenomenon-taking place in the discharge.

In the present work the radial profiles in the He-Ne laser discharge have been obtained by the method of numerical calculations of various rate coefficients and rates. The present calculations explain all the radial profiles satisfactorily.

The ionization and recombination rate coefficient of the ionic species of the helium and neon may be computed as a function of the electron temperature using Burgess formulation (19). The laser discharge may operate at steady state conditions and we may write

\[ N_z \alpha_z N_e = N_{z+1} S_{z+1} N_e \]  

(5.1)

Where \( N_z \) and \( N_{z+1} \) are the densities of the ions with charge \( z \) and \( z+1 \), \( \alpha_z \) is the ionization rate coefficient, \( S_{z+1} \) is the recombination rate coefficient and \( N_e \) is the electron density.

The fractional abundances of various species of the ions in the discharge may be obtained by using equation 5.1.

5.2 Excitation rate coefficients

It has been an established fact that the laser levels of the neon atoms in the He-Ne laser discharge are dominantly excited by the electron impact excitation (20). The rate of excitation of a laser state is the product of the density of neon atoms in the ground state, the electron density and the excitation rate coefficient. When the neon atoms are excited to the upper
laser state, they may undergo spontaneous emission or stimulated emission.
The rate of change of upper laser state density may be expressed as
\[
\frac{dN_u}{dt} = N_m N_0 P + N_0 N_e R - N_u S (N_u - N_l) \quad (5.2)
\]
where \( N_m \) is the helium metastable state density, \( N_0 \) is number of neon atoms in ground state, \( P \) is the penning excitation rate coefficient, \( \tau_u \) is the radiative life time of the upper laser state, \( S \) is the stimulated emission rate including the factor of intensity of the stimulating radiation.

The penning excitation rate is negligible as compared to the electron impact excitation rate. When the discharge is operated in the steady state condition and the stimulated emission is absent. The rate of excitation of the upper laser state is equal to the rate of spontaneous emission. Hence in order to calculate the radial profiles of spectral emission the radial profile of the electron impact excitation of the upper laser state may be considered.

5.3 The radial profiles of the densities and spectral emission

It is assumed that the electron density across the discharge tube varies like zero order Bessel function (21) having maximum at the axis and zero at the walls and the behaviour of the profile may be mathematically expressed as
\[
N_e(R) = N_e(0) \{1 - (R/R_0)^2\} \quad (5.3)
\]
where \( N_e(R) \) is the electron density at a distance \( R \) from the axis, \( N_e(0) \) is electron density at the axis and \( R_0 \) is radius of the discharge tube.

The variation of electron temperature across the discharge tube plays a vital role in the determination of shape of various radial profiles. Therefore an appropriate electron temperature profile must be considered for the study of other radial profiles. The electron temperature mainly determines the fractional abundance in the gas discharge. In fact the electron temperature is the fundamental parameter of the laser plasma, which is determined
together by the accelerating electric field, collisions between particles and cooling of the plasma electrons due to walls.

The electron temperature also is assume to behave like zero order Bessel function which is expressed as

$$T(R) = T(0) \{1 - (R/R_0)^2\}$$

(5.4)

where,

$T(R)$ - is the electron temperature in eV.

$T(0)$ - is the electron temperature at the axis.

$R$ - is radial distance at a point in discharge plasma column tube from the axis

$R_0$ - is the radius of the discharge tube.

With these assumptions the radial profiles of the densities of various species of ions and the spectral emission of the ions in the discharge column may be obtained.

5.4 Radial profiles of neutral and singly ionized neon in the discharge:

We have evaluated the spatial distribution of the density of NeI and NeII ions in the discharge tube at different axial temperatures. The radial distribution of the electron temperature across the tube is assumed to be given by equation (5.4). The radial profiles of the NeI and NeII ions in the discharge tube have been evaluated at different electron temperatures from 1eV to 10eV. The spatial distributions of NeI and NeII ions show different behaviour at low electron temperature and at high electron temperature. Therefore, the curves of spatial distribution are plotted at low and high electron temperatures in different figures. Though the radial profiles at high electron temperature at the axis have been evaluated for various values up to 10 eV, the curves are plotted only up to 5 eV and the other curves have not been plotted because the corresponding data show similar trend. It is clear that the curves are symmetric about the tube axis because it has been assumed that the tube has an axial symmetry. The radial profiles of the
density of neutral neon are obtained for various electron temperatures at the axis. At very low electron temperature at the axis the neutral neon density profile exhibits horizontal line parallel to the radius axis. As the electron temperature is increased the profile shows dip at the axis and the dip increases as the electron temperature is increased. At very low electron temperature the density of NeII ions is maximum at the axis and minimum at the walls. As the electron temperature is increased the peak becomes flatter and shows the dip at the axis and two side peaks. Further increase in the electron temperature results in shifting of the peaks towards walls. 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 Neon atoms present at the axis gets converted into NeII ions showing the peak.

5.5 Radial Profiles Of Spectral Emission Of The Discharge:
When the discharge is in steady state, the rate of emission of radiation at certain wavelength is equal to the rate of excitation of the upper state of the transition emitting the radiation at that wavelength. Thus the intensity of the spectral emission at a wavelength $\lambda$ would be proportional to the factor $N_{NeI} R_u N_e$.

The radial profiles of spectral emission of the laser discharge are the basis of calculation of the laser power output. These radial profiles are evaluated by using the values of fractional abundance of NeI and corresponding temperature in the discharge tube. The radial profiles of the electron impact excitation rate coefficient are first determined by using the equation

$$R = 6.7 \times 10^7 \int \sigma_s E \exp \left(-E/T_e\right) dE \text{ cm}^3 \text{ sec}^{-1}$$

(5.5)
The values of $\sigma_s$ are obtained from the report of Wade T Rogers et al (22). The computer programme in BASIC language has been developed to evaluate these radial profiles. After evaluating the radial profiles of the electron impact excitation rate coefficient these values of the EIE rate coefficient are then multiplied by the corresponding values of the fractional abundances of NeI ($f_z R_0 N_e$) to obtain the values of the spectral emission. The process has been repeated for all radii values from 0 through 2.5mm with a difference of 0.1mm. Thus for variation of radial profiles of electron temperature the radial profiles of the spectral emission of the discharge have been computed for the different electron temperatures.

5.6 Results and discussion

From the knowledge of the fractional abundances, the particle densities and electron density, various radial profiles may be obtained. The fractional abundances of HeI, HeII, HeIII, NeI, NeII, NeIII and NeIV as a function of electron temperature from 0 through 10 eV. The radial profiles of neutral neon atoms have been obtained for 1.5, 2, 3 and 5 eV electron temperatures at the axis and the results are displayed in figure (5.1). As the electron temperature near the discharge walls is zero, the entire species is in neutral form and therefore factional abundance of neutral neon is maximum (approximately 1) near the walls. The electron temperature is maximum at the axis and consequently the neon gets ionized and hence the fractional density of neutral neon is less at the axis. The degree of ionization of neon goes on increasing as the electron temperature at the axis is increased. If the electron temperature at the axis is about 0.5eV entire neon may be in neutral form and the neon density is uniform across the discharge tube and a horizontal line parallel to the radius axis represents the profile at 0.5 eV.

In order to get clear understanding of the radial profiles of the spectral emission we plot the radial profiles of the spectral emission of the
discharge at the electron temperatures 1.5, 2.5, 3, 5 eV at the axis are also displayed in figure (5.2). The profiles clearly show that at low electron temperature the profile has shallow deep and the deep go on increasing as the temperature is increased.

The radial profiles of the spectral emission of He-Ne laser discharge at wavelength 6328A have been obtained for 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5 and 5 eV electron temperature at the axis and the results are displayed in figure (5.5). The radial profiles of the spectral emission do not show any variation in the intensity across the discharge tube at 1eV temperature at the axis. A horizontal line lying on radius axis shows the radial profile at 1eV temperature. If the electron temperature at the axis is maintained at 1.5 eV the profile shows single small peak at the axis and the intensity of radiation goes on decreasing towards the walls. The intensity becomes almost zero at \( R = \pm 1.2 \text{ mm} \). If the electron temperature at the axis is raised to about 2 eV, the radial profile of the spectral emission exhibits single peak at the axis and the intensity goes on decreasing towards walls of the discharge tube. The intensity of the radiation becomes zero at \( R = \pm 1.5 \text{ mm} \). The peak height of the radial profile for \( T_0 = 2 \text{eV} \) is about 4.5 times more than the peak height of the radial profile for \( T_0 = 1.5 \text{eV} \). If the electron temperature at the axis is increased to 2.5 eV the peak of the radial profile becomes broader and it exhibits flat small plateau like structure at the axis. The intensity of radiation for this radial profile becomes zero at \( R = \pm 1.9 \text{ mm} \). The radial profile of the spectral emission of the discharge at \( T_0 = 3 \text{eV} \) shows deep at the axis having two side peaks appearing at \( R = \pm 1.2 \text{ mm} \). The radial profile shows small deep at the axis. The intensity of the radiation becomes zero at \( R = \pm 2\text{mm} \). The radial profile for \( T(0) = 3.5 \text{ eV} \) at the axis exhibits the prominent deep at the axis. It has peak at \( R = \pm 1.4 \text{ mm} \) and the intensity becomes zero at about \( \pm 2.1\text{mm} \).
The radial profiles at higher electron temperatures at the axis show that as the electron temperature at the axis is increased the deep at the axis go on increasing and the two side peaks go on shifting towards the discharge tube walls.

The radial profiles obtained in the present work may be compared very well with the experimental results of Spoor and Latimer (16) who have obtained the radial profiles of the gain by changing the gas pressure and the discharge current. It is obvious that the electron temperature increases as the discharge current is increased. The low temperature radial profile of spectral emission may be compared with low current radial distribution of the gain. Almost all the radial profiles obtained by Spoor and Latimer may be compared with those displayed in figures 5.6, 5.7, 5.8 and 5.9. The radial profiles obtained in the present work also show agreement with the recent experimental observations made by (16, 18).

We have studied the three dimensional appearance of the radial profiles of the ions at different electron temperatures on the axis. The three dimensional representation of densities as a function of radial distance are displayed in the figures 5.3, 5.4. We have considered a square array of 5cm by 5cm. At the center of the array we have assumed the axis of the discharge tube. The distribution of different ionic species around the axis of discharge tube is displayed in respective figures. The electron temperature profile is assumed to be given by equation 5.4

5.7 Comparison between experimental results and theoretical computations:

In order to test the validity of the model calculations we have designed a simple experiment to obtain the intensity distribution across the laser output beam and compared with calculated profiles. The experimental
arrangement used to obtain the radial profile of the laser power output is shown in the figure 5.10

![Experimental arrangement diagram](image)

**Figure 5.10**: Experimental arrangement used to measure beam profile

The experimental arrangement consists of helium neon laser 15μm pinhole, 0.5 μm pinhole and detector. The 15μm pinhole is used to block stray light from entering into the detector. The 0.5 μm pinhole attached to the detector is moved across the laser beam along diameter of the beam. The intensity of the laser beam is monitored as a function of distance and the results are shown in the figure (5.11). The comparison between experimental values and theoretical results show that there is good agreement between the two. Hence we can say that the model developed by us explains the experimental results related to the radial profiles. The other radial profiles may be compared with the experimental profiles by changing the operating conditions of the He-Ne laser discharge.

**5.8 Conclusions:**

The computations in the present work show that as the electron temperature at the axis is changed the shape of the radial profile of the spectral emission also changes. At low electron temperature at the axis the radial profile of the intensity distribution across the laser beam can have Gaussian shape. At higher electron temperature at the axis the shape of the radial profile of the intensity does not remain Gaussian. The profiles
obtained in the present work show good agreement with the experimental observation of other researchers (14-16). The present work also shows that for explaining the experimentally observed radial profiles the variation of electron temperature across the discharge tube must be taken into consideration. Furthermore the consideration of idea of the fractional abundance of the ionic species of the atoms in the discharge tube is also very much essential and the fractional abundance of the active species must be included in the calculations of the spectral emission and laser output power. The computations show that the electron impact excitation plays vital role in producing the atoms in upper laser state. The agreement between the experimental values and theoretical results show that the use of idea of fractional abundance in the gaseous laser systems is fully justified. The laser output beam is Gaussian if the electron temperature on the axis is relatively low.
References:

1) C. Breton, C. Demichellis and M. Mattioli
   J Quantum Spect Rad Trans 19, p 367 (1978)

2) TFR Group
   Plasma Physics 20, p 207 (1978)

3) TFR Group

4) A. L. McKenzie

5) T. Ihjima, O. Karastu and I. Oguru

6) A. L. McKenzie
   Ph. D. Thesis St. Andrews University (1975)

7) A. L. McKenzie
   J Phys B: At and Mol Phys 10, p 2023 (1977)

8) T. Goto

9) K. Watanabe, S. Watanabe and T Sakurai

10) T. Goto, Y. Shimuzu, S. Hattori and T. Sakuri

11) P.Gill and C. E. Web

12) P.Gill and C. E. Web

13) B. H. Pawar, S. P. Bhandari, S. V. Sonar

14) Duncan P. McLeod.
    Photonics 2001

Ch. 5 THE RADIAL PROFILES...
   Optical Comm. July 2000
16) S. Spoor and I. D. Latimer.
17) V. A. Tsarkov, M. I. Molchanov
   Optics and Spec. 35 1973. 191
18) Y. V. Troitski, V. P. Chebotaev.
19) C. Breton, C DeMichelis and M Mattioli
   J Quantitative Spectroscopy and Radiative Transfer 19 (1978) 367
20) S Tsurubuchi, K Arakawa, S Kinokuni and K Motohashi
21) D. P. McLeod
   Web cite Paradise.net.nz/dlmcleod/paper7.pdf
22) Wade T Rogers, Gorden H. Dunn, J Ostgaard Olsen, Melissa
   Reading and G. Seefani
Fig. 5.1 Radial Profiles Of The Fractional Abundance Of NeI At Various Electron Temperature On The Axis Of The Discharge Tube
Fig. 5.2 3D View Of Radial Profiles Of Neon Atoms (NeI) In The Discharge Tube For Various Electron Temperatures At The Axis.
Fig. 5.3 Radial Profiles Of Neon Atoms (NeI) In The Discharge Tube For 1.5eV Electron Temperature On The Axis.
fig. 5.4 Radial Profiles Of Neon Atoms (NeI) In The Discharge Tube For 2eV Electron Temperature On The Axis.
Fig. 5.5 Radial Profiles Of Spectral Emission Of NeI Ion In The Discharge At Various Electron Temperatures At The Axis.
Fig. 5.6 Radial Distribution Of The Spectral Emission Of Ne I Ion In The Discharge Tube For 1eV Electron Temperature At Axis.
Fig. 5.7 Radial Distribution Of The Spectral Emission Of NeI Ion In The Discharge Tube For 2eV Electron Temperature At The Axis.
Fig 5.8 Radial Distribution Of The Spectral Emission Of NeI Ion In The Discharge Tube For 3eV Electron Temperature At The Axis.
Fig. 5.9 Radial Distribution Of The Spectral Emission Of Ne I Ion In The Discharge Tube For 4eV Electron Temperature At The axis.
Fig. 5.11 Comparison Between Experimentaly Observed And The Computed Radial Profiles At 1.5 eV Temperature At The Axis.