CHAPTER 2
PROPERTIES OF CVL DISCHARGE

2.1 Experimental parameters:

In many applications a laser beam with high peak power and uniform intensity distribution across the beam is desired. The CVL output is characterized with pulse width, pulse shape, pulse height and pulse repetition rate. The output power of lasers can be increased by increasing discharge plasma volume which can be achieved by using large bore discharge tube. The problem with large bore tubes is that the output beam becomes annular not giving uniform intensity distribution across the laser beam. The properties of the output of the laser beam are determined by discharge parameters like:

1) Discharge current pulse shape, 2) Temperature of discharge electrons, 3) Buffer gas pressure, 4) The temperature and partial pressure of copper in the tube, 5) The density of the metastable state, 6) Diameter of the discharge tube and 7) The laser cavity.

2.1.1) Current pulse shape:

The discharge current pulse shape plays a vital role in the excitation of laser states which in turn controls the power output of the laser. In CVL, the fluorescence lifetime of upper laser state is 40 nsec and that of lower laser state is 700 nsec. We require discharge current pulse of fast rise time. The shape of the current pulse is determined by charge stored \( C = Q/V \) by the
capacitor, the impedance of the spark gap or thyretron and variation of the resistivity of the discharge across the tube. The pulse rise time is only controlled by the properties of the spark gap like the distance between the spark electrodes, shape of the electrodes, material of the electrodes and the gas between the electrodes etc. In thyretron switches the rise time is determined by the characteristics of the thyretron. After firing the discharge pulse the current rises to the peak value and then decreases and becomes zero. The decay time of current pulse depends upon rate at which the electrons are cooled and disappear in recombination or near the cold walls. The discharge looses the energy through spectral emission and to the walls through collision.

2.1 2) The electron temperature:

The electron temperature plays an important role in several processes like ionization, recombination, excitation and deexcitation of energy states etc. The electron temperature also influences gas temperature. The discharge current pulse width is of the order of 300 nsec (1-4). In transversely excited lasers the pulse width may be comparatively shorter (of the order of 20 nsec) (5-6). The transversely excited system would give maximum efficiency as the laser is self terminating and the fluorescence lifetime of the upper laser state is 40 nsec.

The electron temperature in the discharge tube is controlled by heating due to electric field and losses by spectral emission and losses to the walls. The impedance of the circuit differs from system to system as length and
diameter of discharge tube differs from system to system. The electron
temperature is not uniform across the discharge tube since the walls act as
infinite sink of energy. The plasma on the axis of discharge tube is away
from the walls so it is less affected by cooling due to walls. The portion
of plasma on the axis of the discharge tube is hottest and the plasma
electron temperature go on decreasing towards the walls. There is no
experimental data available on the measurement of the electron temperature
across the discharge tube. Therefore one has to assume a suitable radial
profile which would fulfill the above said boundary conditions. The
profile of electron temperature in the discharge tube can be considered to
be of two types given by equations

\[ T(R) = T_0 \left[ 1 - \left( \frac{R}{R_0} \right)^2 \right] \]

\[ T(R) = T_0 \left[ 1 - \left( \frac{R}{R_0} \right)^3 \right] \]

These two radial profiles are shown in figure 2.1. In the first profile the
rate of temperature decline is slow as one goes from axis to the walls.
The second profile shows fast rate of decline of temperature as one goes
from axis towards the walls. The choice of profile depends on experimental
system under consideration. Usually the first profile is considered as it is in good
agreement with the experimental observations.

During the period of discharge current pulse, the discharge electrons
get heated. After the current pulse is over the electrons are cooled down
by different processes. The electron temperature in the discharge tube lies
between 1 to 6 eV. The electron temperature is not same for the discharge tubes of different diameters.

2.1.3) The gas temperature:

The gas temperature determines the penning transfer rate coefficient, charge transfer rate coefficient and deexcitation rate of the metastable states. The gas particles also act as a sink for the hot discharge electrons. The average gas temperature is governed by the average discharge current, the material of the discharge tube, the enclosure of the discharge tube, etc. The partial pressure of the copper in the discharge tube depends upon the gas temperature. The operating temperature of CVL is high since high temperature is required to obtain desired partial pressure. It may be maintained by using proper insulation and by passing high average discharge current.

2.1.4) Resistivity of the plasma:

The resistivity of the plasma column is expressed as \((7,14)\)

\[
\eta = \frac{5.2 \times 10^3 \ln (\Lambda)}{(T_e)^{3/2}} \text{ ohm cm} \quad \text{(2.3)}
\]

where \(T_e\) is in eV

The logarithmic term \(\ln(\Lambda)\) is function of electron density and it is very slowly varying function. For the conditions in CVL discharge plasma...
the value of $\ln(\Lambda)$ is about 10 (15). Using this value of term $\ln(\Lambda)$ the expression for resistivity becomes

$$\eta = \frac{5.2 \times 10^{-2}}{(T_e)^{3/2}} \text{ ohm} \cdot \text{cm} ----- 2.4$$

The plasma electrons are cooled by the collisions with the walls of the discharge tube and heated by the electric current. The plasma on the axis is far away from the walls and least affected by cooling due to walls. The plasma near the walls is cold and the temperature goes on increasing towards the tube axis. This gives rise to high current density on the axis and low current density on the walls. Conversely the resistivity of the plasma is minimum on the axis and goes on increasing towards the walls. It is maximum near the walls. This behavior is also displayed in fig (1). This effect again adds up to non uniform distribution of the electron temperature across the discharge tube which leads to non uniform distribution of 1) The electron density, 2) The ion density, 3) The ion temperature, 4) The density of the laser upper state and 5) The density of the laser lower state.

**2.2 Densities:**

In absence of current pulse the density of electrons is low and it is of the order of $10^{13} / \text{cm}^3$ (8). Since the plasma segments are neutral, the ion density must be same as the electron density. The current pulse ionizes the gas particles and increases ion as well as electron density. The
typical value of the electron density for a set of operating conditions has been obtained by Kushner (8) and it is about $4 \times 10^{13} \text{ /cm}^3$.

The lower laser state is metastable having lifetime 700 nsec. The density of lower laser state plays vital role in the determination of pulse characteristics. The laser output power is reduced to large extent if atoms are accumulated in this state. The distribution of the metastable state is not uniform across the discharge tube (9-10). The radial distribution of the lower laser state is function of time.

The properties of laser output beam are determined by the factors like 1) The distance between the two electrodes, 2) Charging Voltage 3) The value of the capacitor which is discharged through the active medium, 4) The pulse repetition rate, 5) Total pressure and partial pressure in the discharge tube, 6) The kind of buffer gas that is used and 7) The impedance of the thyretron, when the thyretron is used as switching element and the impedance of the spark gap when spark gap is used as switching element.

The effect of the parameters on the quality of output laser beam is studied by Kushner and his group (11-13). They have solved the rate equations and obtained the solutions under variety of conditions. They concluded that the theory developed by them may be employed to study several experimental results. However they have not considered the concept of fractional abundance of different species. The exact solution to the rate
equations is impossible without some approximations to obtain the solutions in any way needs the knowledge of fractional abundance.

In the present work, I have introduced the concept of fractional abundance for the first time for obtaining the results in the branch of CVL discharge. The detailed rate equations have been obtained and rigorous treatment of the equations is discussed.

The rate equations are divided into three categories based on the quantities for which rates are expressed. Each category contains several rate equations.

2.3 The possible reactions in the discharge:

The electrons, atoms and ions in the discharge tube collide among themselves and with each other. In the collision particles may transfer KE or PE to other particles. This transferred energy may be converted in to KE or PE. Some reactions taking place in the discharge tube are listed below.

\[ e + m \rightarrow m^+ + e + e - \Delta E \] ionization
\[ e + m \rightarrow m^* + e - \Delta E \] excitation
\[ e + m^* \rightarrow m + e + \Delta E \] super elastic collision
\[ e + m^+ \rightarrow m^{**} \] collisional recombination
\[ e + e + m^+ \rightarrow m^{**} + e + \Delta E \] radiative recombination
\[ \text{He}^+ + \text{Cu} \rightarrow \text{Cu}^+ + \text{He} \] charge transfer
\[ \text{He}_m + \text{Cu}^* \rightarrow \text{Cu}^+ + \text{He} + e + \Delta E \] penning reaction
\[ m^* + m \rightarrow m + m \text{ collassional deactivation} \]

\[ M^* + \text{wall} \rightarrow M \text{ diffusion and deactivation} \]

The rate of the any above mentioned reaction depend upon the densities of the particles taking part in the reaction and the rate coefficients of the reaction.

2.4 Rate equations:

2.4.1 Rate equations governing the gas pressure:

Before firing of discharge pulse the gas temperature and pressure inside the discharge tube is constant. When the discharge pulse is fired the gas temperature suddenly increases, increasing the local pressure of the gases. The rate of change of buffer gas pressure \( P_g \) and laser gas pressure \( P_{cu} \) are expressed as

\[
\frac{dP_g}{dt} = \frac{dT_g}{dt} \frac{P_g}{T_g} - \frac{(P_g - P_{ex})}{L} 2V_s \quad \text{----- 2.5}
\]

\[
\frac{dP_{cu}}{dt} = \frac{dT_g}{dt} \frac{P_{cu}}{T_g} - \frac{(P_{cu} - P_{vp})}{R} V_d \quad \text{----- 2.6}
\]

where,

\( V_s \rightarrow \) is the speed of sound in the gas

\( V_d \rightarrow \) is the diffusion velocity of copper

\( P_{ex} \rightarrow \) is the external buffer gas pressure

\( P_{vp} \rightarrow \) is the vapor pressure of the copper based on the temperature of the wall.
\( L \rightarrow \) is the length of the discharge tube

\( R \rightarrow \) is the radius of the discharge tube.

The density of the copper atoms relaxes to the cold walls and buffer gas relaxes to the external pressure with the time rates \( V_d / R \) and \( \frac{1}{2} V_s \) respectively. The rate equations for corresponding densities may be written as

\[
\frac{dn_g}{dt} = \frac{n_g}{T_g} \frac{dT_g}{dt} + \frac{n_g}{P_g} \frac{dP_g}{dt} = -(P_g - P_{ex}) n_g \frac{2V_s}{LP_g} \quad \text{---- 2.7}
\]

\[
\frac{dn_{cu}}{dt} = \frac{n_{cu}}{T_{cu}} \frac{dT_{cu}}{dt} + \frac{n_{cu}}{P_{cu}} \frac{dP_{cu}}{dt} = -(P_{cu} - P_{vp}) n_{cu} \frac{V_d}{kP_{cu}} \quad \text{---- 2.8}
\]

where,

\( n_g \rightarrow \) is the density of buffer gas

\( n_{cu} \rightarrow \) is the density of copper atoms

The rate of change of the densities of the buffer gas and the copper may be studied during the laser discharge pulse.

2.4.2 Rate equations governing the currents and voltages:

The discharge circuits used for the excitation of the laser states are shown in figure 2.2. One circuit is for the ideal laser and another circuit
for the real laser. In this case the exciting field is axial. Before firing of exciting pulse the power supply charges the capacitor of the circuit with certain rate. The charged capacitor is discharged through the laser medium. The time rate of change of voltage across the capacitor is written as

\[
\frac{dV}{dt} = [f(T_s) V_0] - \frac{V}{R_d C} \quad ----2.9
\]

where,

\( f(T_s) \) → is the voltage turn on function

\( V_0 \) → is the maximum voltage on the capacitor

\( R_d \) → is the instantaneous discharge impedance

\[
R_d = \frac{L m_e v}{n_e A e^2} \quad ----2.10
\]

where,

\( L \) → is the distance between electrodes \( m_e \) → Mass of electron

\( v \) → is the electron collision frequency

\( n_e \) → is the density of electrons

\( A \) → is the effective cross sectional area of the discharge tube.

Another set of rate equations for circuit currents and voltages are written as

\[
\frac{dI_1}{dt} = \frac{(V_1 - V_2 + V_0 f(T_d))}{L_1} \quad ----2.11
\]
\[
\frac{dI_2}{dt} = \frac{(V_2 - V_d)}{L_2} \quad \text{--- 2.12}
\]

\[
\frac{dV_1}{dt} = -\frac{I_1}{C_1} \quad \text{--- 2.13}
\]

\[
\frac{dV_2}{dt} = \frac{I_1-I_2}{C_2} \quad \text{--- 2.14}
\]

where,

\(I_1\) → is the current flowing through \(L_1\)

\(V_1\) → is the Voltage across \(C_1\)

The voltage across the discharge tube is

\[
V_d = I_2 \frac{R_c R_d}{(R_c + R_d)} \quad \text{--- 2.15}
\]

While the current through the discharge is

\[
I_d = I_2 \frac{R_c}{(R_c + R_d)} \quad \text{--- 2.16}
\]

From the above equations voltages and currents in different parts of the circuit may be studied. The important parameter here are the impedance of the discharge tube. The current passing through the discharge tube heats the discharge electrons which in turn excites the laser medium. The impedance of the gas between the electrodes is time and space dependent. The impedance of the gas is almost infinity and no current passes through the gas when the gas is not in breakdown.
condition. When the voltage across the gas is increased, the gas between the electrodes breaks down, the impedance suddenly decreases causing heavy current to flow through the discharge. The current density across the discharge tube is not uniform as the electron temperature is not uniform across the discharge tube. At this stage the resistivity of the plasma is given by equation 2.3.

Near the walls the electron temperature is almost zero and the resistivity at the wall is infinity, since the electron density is very near to zero at the discharge tube walls. The resistivity of the discharge tube decreases towards the axis of the discharge tube. Thus more and more current would pass through the plasma segment in the direction of the axis and the current density goes on decreasing towards the walls. While talking about the resistivity of the discharge plasma it is to be divided into coaxial cylindrical shells of infinitesimal thickness. Since the parameters on which the resistivity depends are uniform, for the plasma in the cylindrical shell the resistivity of the plasma may be treated as constant for the shell. The equations written for the gas density must be modified for the spatial variations of the current density.

Kushner et al (13) studied the radial distribution of the electric field, electron temperature and the power deposited into the gas etc for small bore tubes and large bore tubes. They have shown that the electric field is more near to the wall than that on the axis for large bore tubes.
The energy deposited near the walls is more than that deposited on the axis. This is true for large bore tubes and for the leading edge of the laser pulse. As pulse advances the radial dependence of the electric field disappears. However Kushner and Warner in their theory have not taken into account the radial dependence of conductivity $\sigma$. The electrical conductivity is expressed by the equation

$$\sigma = (e^2 n_e)/(m_e v_m)$$

where,

$v_m \rightarrow$ is the electron heavy particle momentum transfer collision frequency

The conductivity $\sigma$ of the plasma varies from point to point in the discharge tube. While applying skin effect the radial dependence of $\sigma$ must be taken into account. After considering the radial dependence of $\sigma$, the electric field and the electron temperature should be calculated.

2.4.3] The rate equations for the densities of the laser states:

The pertinent partial energy level diagram of copper atom is shown in figure 2.3 which will be helpful to understand different processes. The current passing through the laser active medium heats the electrons by collisions between the electrons. These electrons ultimately heat the gas by collisions. The heated electrons colloid with copper atoms and atoms of the buffer gas and excite them into different states depending upon the corresponding cross section. The time rate of heating of electron is
\[
\frac{d(3/2\ kT_e)}{dt} = \frac{e^2 E^2}{m_e v} + \sum_i H_{m_i} N_{ij} r_{ij}^p \Delta E_{ij}^p \\
+ \sum_{(i,j,k)} N_{ij} \ r_{ijk}^S \Delta E_{ijk}^S - \sum_{(i,j,k)} N_{jk} \ r_{jk} \Delta E_{ijk}^p \\
- \frac{(3/2)}{D_a} \left( k T_e \right) / \left( \lambda^2 n_e \right) - \sum_{ij} N_{ij} \ r_{ij}^l \ (3/2) kT_e \\
- \frac{(3/2)}{k} \left( T_e - T_g \right) \sum_{ij} N_{ij} r_{ij}^g \frac{2m_e}{M_i} \quad \quad 2.18
\]

The terms in the equation are defined in the appendix A. The first three terms represent heating of plasma electrons by electric field, the penning ionization of species and the super elastic relaxation of the different states respectively. The discharge electrons loose their energy in following processes. 1) Excitation and ionization, 2) Diffusion to the walls, 3) Heating of the electrons produced in the ionization and 4) Heating of the gas atoms which are at relatively low temperature.

The discharge electrons derive their energy primarily from the applied electric field and secondly from the super elastic collisions. The discharge electrons excite the helium atoms to the state which in penning collision transfer energy to the electrons.

When the laser system is not put on the gas enclosed in the laser cavity contains no electrons although there are few, their density is very low. The

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firing of the spark gap for the first time produces electrons by acceleration of stray electrons and subsequent ionization by collisions with the gas particles. The electrons grow in number by process of avalanche. When the charge on the capacitor gets exhausted consequently there is no further acceleration of electrons. The discharge electrons start cooling through the processes mentioned above. The electron temperature as well as the electron density go on depleting depending upon the decay time. The laser medium may retain certain number of electrons till the second pulse comes. The firing of second pulse may experience more electron density than that experienced by the first pulse. The electron density present at the time of firing of the discharge go on increasing as the number of pulses are fired and the value of electron density may reach a saturation level. Furthermore the increase in the repetition rate increases the value of the electron density present at the time of the firing of the pulse. Running of the discharge for some time increases the overall temperature of the system. This increase in temperature enhances the average value of the electrons present in the discharge tube.

When the discharge is fired the electrons are produced by ionization of the atoms of buffer gas and copper and they are destroyed by process of recombination. The process of penning ionization also produces the electrons. Few electrons are lost due to the diffusion process. The net rate of production of electrons is

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\[ \frac{dn_e}{dt} = n_e \left[ \sum \frac{r_{ij}}{\lambda^2} N_{ij} - (D_a / \lambda^2) - \sum \frac{N^1_i}{\lambda^2} (r_{RR} + n_e r_{RR}) \right] + He_m \sum \frac{r_{pj}}{\lambda^2} N_{ij} ----2.19 \]

The energetic electrons when colloid with atoms either ionize them or excite the atoms (ions) to various levels depending upon the excitation cross section. The excited atoms (ions) loose their energies by several processes. The rate equation for the laser upper state and the lower state are written as

\[ \frac{d[Cu_m]}{dt} = n_e \left( r_{12} [Cu] + r_{32}^S [Cu^*] + r_{42}^S (Cu^{**}) - (r_{21}^S + r_{23} + r_{42} + r_{2}^j) [Cu_m] \right) + \left( Cu^*/T_{32} \right) + \left( Cu^{**}/T_{42} \right) - \left( r_{21,Cu}^C [Cu] + r_{21,He}^C [He] \right) \]

\[ - r^p [He_m] - r^{CE} [He^+] \right) [Cu_m] d\left( D_{cu}/\lambda^2 \right) [Cu_m] + JB ([Cu^*] - \left( g_3/g_2 \right) [Cu_m] \right) ----2.20 \]

and

\[ \frac{d[Cu^*]}{dt} = n_e \left( r_{12} [Cu] + r_{23} [Cu_m] + r_{43}^S [Cu^{**}] - (r_{31}^S + r_{32}^S + r_{34} + r_{3}^l) [Cu^*] \right) + \left( Cu^{**}/T_{43} \right) - \left( r_{32,Cu}^C [Cu] + r_{32,He}^C [He] - r^p [He_m] - r^{CE} [He^+] + D_{cu}/\lambda^2 \right) \]

\[ - 1/T_{32} + 1/T_{31} \left( [Cu^*] - JB ([Cu^*] - \left( g_3/g_2 \right) [Cu_m] \right) \right) ----2.21 \]

The electron impact excitation and de-excitation rates are denoted by 6 with corresponding subscript. The subscript S, C and I are used for the super elastic collisions, collision activation and ionization, respectively. The laser states are populated by the processes like 1) Electron impact excitation from the ground state and low lying energy state, 2) Super elastic collisions with high lying energy states, 3) Radiative decay of high lying energy states
and 4) Recombination of the ions into the state. The atoms in the laser state are destroyed by the processes like 1) Radiative decay of the state, 2) Super elastic collision of the atoms in the state and 3) Ionization of the atoms present in the state. Furthermore the atoms in the upper state are destroyed and the atoms in the lower state are produced by the process of stimulated emission. The time rate of change of the intensity of the laser beam is

\[
\frac{dI}{dt} = h\nu B(I([Cu^*] - \frac{g_3}{g_2}[Cu_m])) l_a/l_c - cI ([1 - R] / l_c + r) + h\nu A [Cu^*] \alpha = 2.22
\]

where,

- \(l_a\) → is the length of heated region
- \(l_c\) → is the length of optical cavity
- \(R\) → is the mirror reflectivity
- \(A\) → is the Einstein's coefficient

The first term is the rate of increase in intensity by process of stimulated emission and absorption. The second term represents the loss at output coupling mirror. The third term is the addition of the photons to the laser beam because of the spontaneous emission of the radiation.

2.5 Properties of copper ion laser:

The mixture of copper ions Cu\(^+\) and inert gas when excited by electric discharge produces laser action at wavelengths 237, 242, 248, 259, 270, 272 and 273 nm. The discharge tube is hollow cathode. The operating temperature is near 1500 \(^\circ\)C. The discharge is operated with neon or argon as buffer gas. The
buffer gas pressure is in the range 5.5 mbar to 31 mbar. The average current is about 80 amp. The laser power generated would be 90 mW.
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Fig. 2.1 Radial profiles of electron temperature ($T_e$) and resistivity ($n$) of the plasma column for $T_o = 5eV$
Fig. 2.2 Discharge circuits for the excitation of the laser states
\[ ^2P_{3/2} \rightarrow ^2D_{5/2} \quad \text{5106 Å Green} \quad ^2P_{1/2} \rightarrow ^2D_{3/2} \quad \text{5782 Å Yellow} \]

<table>
<thead>
<tr>
<th>Copper Ion</th>
<th>Energy</th>
<th>Neon Ion</th>
<th>Energy</th>
</tr>
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<td></td>
<td>7.7 eV</td>
<td>Pseudo State</td>
<td>21.6 eV</td>
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<tr>
<td></td>
<td></td>
<td>5.7 eV</td>
<td>18.5 eV</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Metable State</td>
<td></td>
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</table>

\[ ^2P \quad \begin{array}{c} 3/2 \\ 1/2 \end{array} \quad 3.8 eV \quad \begin{array}{c} 3/2 \\ 5/2 \end{array} \quad 1.4 eV \]

- Laser Radiation

| Copper Ground State | 0         | Neon Ground State | 0        |

Fig. 2.3 The energy level diagram for copper atom and buffer gas.