CHAPTER 5

EXCITATION AND DEEXCITATION OF LASER STATES

While discussing the rate equations we have listed all possible processes responsible for the excitation of the laser states. The laser power generated at a particular wavelength depends upon the excitation and deexcitation rates of the laser states and the radiation density at the laser wavelength. The energy states are populated by electron collisions and the collisions with the helium metastable states, collision with the helium ions. The energy states are depopulated by the collisions with slow electrons i.e. the super elastic collision. Besides, the states are also populated and depopulated by some radiative processes.

The electrons passing through the discharge transfer their energies to the gas particles and plasma electrons by two types of collisions. In the first type of collision the transfer of kinetic energy of electrons into the kinetic energy of gas particles takes place and the collisions are called as the elastic collisions. In this type of collision the kinetic energy of the colliding particles is conserved. The elastic collisions in the discharge heat the discharge electrons and the gas particles. In fact only the elastic collisions are responsible for the heating of the laser plasma. When heating of the laser plasma is to be
studied quantitatively the elastic collisions are to be considered in details. In the second type of collisions the kinetic energy of the electrons is converted into the potential energy of the gas particles i.e. the gas particles get excited. This type of collision is called as inelastic collision. The particles in the excited state either transfer back their energy to the low energy electrons or they undergo a transition emitting electromagnetic radiation. The rate of transfer of energy from the discharge electrons to the gas particles may be written as

\[
\frac{dE}{dt} = N_e n_e C_e E_e + \sum_j N_{gj} n_e C_{in} E_j - \sum_i N_{gi}^* n_e C_{dex} E_i
\]

where \( N_g \) is the number of gas particles, \( C_e \) is the rate coefficient of elastic collisions, \( E_e \) is energy transferred in elastic collision, \( C_{in} \) is the rate coefficient of the inelastic collisions, \( E_j \) is the energy of the \( j \)th state excited by elastic collision, \( C_{dex} \) is the deexcitation rate coefficient and \( E_i \) is the energy of excited particle, which transfers its energy to the electron. The sum runs over all possible states of the gas particles.

The gas discharge lose the energy through the radiative emission and the collisions of the particles with the walls.

The rate equations governing the population density
of the laser energy states are discussed in short in chapter 2. All the processes which can populate and depopulate the states are listed but out of them only the dominant ones are to be considered in details. In CVL the laser states are excited probably by the processes like: 1) electron impact excitation, 2) the Penning transfer, 3) the charge transfer and 4) the cascading processes.

In the work of Kushner and others all processes of excitation are considered and contribution of each process to the laser power is computed. However, the calculations do not consider the fractional abundances of the ions of the copper in the discharge. As it has been shown in the previous chapter the ion density may vary from 100% to less than 1% if the temperature is changed, it is essential to take into account the fractional abundance. In the following the rate of excitation of the laser states by various excitation processes are obtained by numerical calculations and the results are presented graphically. The influence of the fractional abundance is discussed wherever necessary.

5.1 EXCITATION RATES AND RATE COEFFICIENTS:

The copper vapour laser operates on two wavelengths 5106 A and 5782 A. The electronic states $^2P_{1/2}$, $^2P_{3/2}$, $^2D_{3/2}$ and $^2D_{5/2}$ are involved in the transitions. We have to study rates of the excitation of these states. We have written one rate equation for the two upper laser
states and one equation for the lower laser states. If the state is populated or depopulated by some other process it is discussed in details. The rate equations for the upper and lower states are

\[
\frac{dN_u}{dt} = Cu^* R_u n_e + Cu^* N_{he^*} P_u + Cu^* N_{he} T_u + \sum_j A_{ju} N_j \quad (5.1)
\]

\[
\frac{dN_1}{dt} = Cu^* R_1 n_e + Cu^* N_{he^*} P_1 + Cu^* N_{he} T_1 + \sum_j A_{j1} N_j + S (N_u - N_1) \quad (5.2)
\]

The exciting terms in the above equations come in picture due to the following processes.

1) The first terms in the equations (5.1) and (5.2) stand for the rate of excitation of the states by the electron impact excitation from the ground state of the CuI.

2) The transfer of energy from helium atoms in metastable states to the copper atoms in the ground state i.e. Penning reaction.

3) The transfer of energy from the helium ions to the copper atoms in the ground state i.e. Duffenduck reaction.

4) The cascading processes i.e. radiative decay of states which lie energetically above the state involved in the laser transition.

The excitation rate and the excitation cross
sections are entirely different from each other. When one particle is colliding with another particle there may be transfer of energy between them. The probability of transfer of energy in the collision is called as the transfer cross section. The total amount of energy transferred is governed by the number of effective collisions made by the species and the rate of transfer per second per particle is called as the transfer rate coefficient. In the following the transfer rate coefficients and the transfer cross sections are discussed in details.

5.2 ELECTRON IMPACT EXCITATION (EIE) :

When an electron having energy more than the excitation energy of an electron rotating about an atom(ion) collides with the atom(ion) transfers its energy to the system and excite the rotating electron to a higher orbit. The probability of excitation depends upon the energy of exciting electron and the cross-section of excitation at that particular energy. The excitation rate depends upon the excitation cross-section and the number of effective collisions made by the electron. The number of effective collisions is function of electron velocity, which in turn is function of electron temperature $T_e$. The electron impact excitation rate coefficient is expressed in terms of the excitation cross-section $\sigma_s$ and the electron velocity $v$ as,
\[ R = \langle \phi_{s}, v \rangle \] \hspace{1cm} (5.3)

where \( \phi_{s} \) is the electron impact excitation cross-section for the states from the ground state of copper atoms. The velocity of an electron is related to its energy \( E \) by the equation

\[ v = 5.9 \times 10^{7} \ (E)^{1/2} \] \hspace{1cm} (5.4)

The number of the electrons \( dN \) having energy between \( E \) and \( E+dE \) is given by Maxwellian distribution i.e.

\[ dN = N \frac{2}{kT_{e}} \frac{E^{1/2}}{\pi kT_{e}} \exp\left(-\frac{E}{kT_{e}}\right) \ dE \] \hspace{1cm} (5.5)

Thus, the rate of excitation of the energy levels by the collisions with the electrons having energy between \( E \) and \( E+dE \) is expressed as

\[ dR = \frac{2}{kT_{e}} \frac{E^{1/2}}{\pi kT_{e}} \phi_{s} \exp\left(-\frac{E}{kT_{s}}\right) \ dE \] \hspace{1cm} (5.6)

The total excitation rate coefficient is the integral of the equation 5.5 from 0 through \( \infty \). However, the excitation cross-section of an energy level is zero when the electron energy is less than the threshold energy \( E_{s} \). The lower integration limit may be taken as \( E_{s} \) instead of 0. The upper limit of the integration must be infinity but as we see the
excitation cross section becomes very small as the
electron energy is increased beyond certain limit and
the number of electrons having high energy also is
reduced making the value of the integration very small.
Furthermore, it is convenient to express the electron
temperature and electron energy in eV. If T, E and dE
are expressed in eV and the cross sections are
expressed in cm$^2$, the equation for the rate coefficient
become

$$R = 6.7 \times 10^7 \frac{1}{T_e^{3/2}} \int_{E_s}^{E_0} \frac{\epsilon_s E \exp(-E/T_e)}{E} \; dE \; \text{cm}^3\text{-sec}^{-1}$$

(5.7)

Drawin (1) in his paper gives the semiempirical
expressions for the electron impact excitation rate
coefficients of several kinds of the electronic
transitions. The careful observation of the equations
given by him shows that the electron impact excitation
rate coefficient is directly proportional to the square
root of the electron temperature for the forbidden
transitions and it is directly proportional to the cube
root of the electron temperature for the allowed
transitions. Furthermore, in the work for the helium
cadmium laser it is found that the electron impact rate
coefficient is very nearly proportional to the square
root of the electron temperature (2) for low electron
temperature. Since the transitions of the copper atoms
from the upper laser state and lower laser state to the ground state are almost forbidden, the electron impact excitation rate coefficient may be assumed to be is directly proportional to the square root of the electron temperature.

Drummond's semiempirical formula may be employed for the calculation of electron impact excitation rate coefficient when the excitation cross-section of the states of atom are not known. In the case of copper vapour laser the electron impact excitation cross-sections are measured by Trajmar et al (3). The experimental values of the integral cross-sections may be used and the excitation rate coefficient may be obtained. When an electron is incident on an atom (ion) electron transfers its energy to an electron rotating about the ion and the energy of the incident electron is shared by the incident electron and the electron rotating about the atom (ion). In the process of the excitation of the energy levels of ions energy of the incident electron is divided into three parts: 1) A part of the energy is utilised in ionising the atom, 2) Another part is utilised in exciting the produced ion to the laser state and 3) The remaining part is kept by the incident electron itself. When energy states of an atom are to be excited the energy of the incident electron is divided into two parts: 1) a part is given to the electron rotating about atom and 2) the remaining part is kept by the incident electron itself. The former
process may contribute towards the process of ionisation and may indirectly excite the laser states. Obviously, the contribution of the former process is negligibly small. It has been shown by the computations of the excitation rate coefficients for the cadmium species it is found that the two rate coefficients differ by four orders of magnitude (2). Thus in case of copper also the two rate coefficients must differ by four orders of magnitude. For further calculations the former process of excitation may not be taken into account. The EIE rate coefficients of the laser states of the copper atom are obtained as a function of the electron temperature from 0 to 10 eV and the results are displayed in the figures 5.1 and 5.2.

5.3 PENNING EXCITATION RATE COEFFICIENT:

The terms Cu\(^*\) \(N_{he}^*\) \(P_u\) and Cu\(^*\) \(N_{he}^*\) \(P_l\) in the equations 5.1 and 5.2 are the Penning excitation rates of the upper and lower laser states respectively. The excitation rates of the states by the Penning process are determined by the fractional abundance of CuI, the density of the helium atoms in the metastable states and the Penning transfer cross-section of the individual state of CuI. In the Penning transfer of the energy the excited electron of helium atom comes to the ground state and the energy is transferred to the copper atom resulting in the ionisation and excitation of the copper. As the process involves many subprocesses the
cross section is very small.

The Penning excitation rate coefficient may be obtained from the cross-section using the equation

\[ P = \langle \xi_p \cdot v_{he} \rangle \]  

--- (5.8)

Where \( \xi_p \) is the Penning excitation cross-section and \( v_{he} \) is the velocity of helium atoms relative to copper atoms. The velocity of the helium atom is determined by the gas temperature. The velocity of helium gas follows the Maxwellian distribution as the density of the helium atoms is about \( 10^{16} \) and the plasma is highly collisional one. Thus for Maxwellian velocity distribution, the Penning excitation rate coefficient may be expressed as

\[ P = \frac{6.7 \times 10^7}{86 \times (6^{3/2})} \int_0^\infty \xi_p E \exp(-E/\Theta) \, dE \]  

--- (5.9)

Where \( \Theta \) is the gas temperature and the factor 86 comes because of the helium mass (4amu). The gas temperature is expressed in terms of electron volts. However, it is more convenient to express the gas temperature in degrees Kelvin. Moreover, the Penning transfer cross-section does not depend upon the velocity of colliding helium atoms (4,5). Hence the Penning transfer rate coefficient reduces to

\[ P = 7.79 \times 10^5 \Theta^{1/2} \xi_p \]  

--- (5.10)
The total Penning transfer cross-section has been measured by Shearer and Padowani (6) for the mixture of helium and cadmium. The cross-section of the Penning transfer process in case of copper atoms is about $4 \times 10^{-15} \text{cm}^2$ (6). However, for obtaining the excitation rate coefficient of the individual level the Penning transfer cross-section to the individual level must be measured as has been measured for cadmium by Inaba et al (4). In case of copper atoms the Penning transfer process excites about 25 energy levels of the copper ion (7). The excitation of the individual level of copper ion by the Penning process must be smaller by factor of 25 than that for the copper ion as a whole. The ions then would recombine and form the copper atoms in the laser states. The cross-section of the direct excitation of the laser states by the Penning transfer would be very small. The total Penning transfer rate coefficient is obtained by putting $\gamma_p = 4.5 \times 10^{-15} \text{cm}^2$ in the equation 5.10 and the results are plotted in figure 5.3. The Penning excitation rate coefficient for the individual CuI state may be obtained from the total rate coefficient by multiplying by the appropriate factor obtained after few calculations. When the copper atom colloids with the helium atom in the metastable state it is excited to one of the 25 states of CuII or in one of the states of CuI. Thus the rate of excitation of a state by Penning transfer must be less than the total
Penning transfer rate coefficient of the copper by a factor of about 25.

The density of the metastable state of helium governs the Penning excitation rate and the electron temperature. The population density of the metastable state is controlled by several processes like electron impact excitation, the penning collision, the electron impact deexcitation etc. The rate equation for the metastable density is written as

\[
\frac{dN_m}{dt} = N_{he} n_e R_{he} - N_m \text{Cu}^* P - N_m n_e X \quad (5.11)
\]

Where \( R_{he} \) is the electron impact excitation rate coefficient of helium metastable state from the ground state, \( X \) is the electron impact deexcitation rate coefficient. When steady state is reached the rate of excitation and rate of deexcitation balance each other i.e.

\[
N_{he} n_e R_{he} = N_m \text{Cu}^* P + N_m n_e X \quad (5.12)
\]

The electron impact excitation rate coefficient \( R_{he} \) is computed as a function of the electron temperature and the results are plotted in the figure 5.4. For the calculations the electron impact excitation cross-section measured by Borst (8) and Lloyed (9,10) have been used. The results show that in the range of the electron temperature less than about 0.8 eV, where CuI has maximum abundance the EIR rate coefficient for the
triplet state has value between $10^{-16}$ to $10^{-18}$ cm$^3$ sec$^{-1}$. For the metastable density of $10^{12}$, the copper density of $10^{13}$ the excitation rate donot exceed $10^9$ sec$^{-1}$.

5.4 DUFFENDUCK EXCITATION RATE COEFFICIENT:

The terms $N_{He} Cu^* T_u$ and $N_{He} Cu^* T_l$ in the equations 5.1 and 5.2 are the Duffenduck excitation rates for upper and lower laser states respectively. In the Duffenduck reaction the helium ions in the ground state transfer their energy to the copper atoms in the ground state. The Duffenduck reaction rate coefficient is expressed in the same way as Penning excitation rate coefficient, as

$$T = \langle \ell_d \cdot v_{He} \rangle \quad \text{(5.13)}$$

Where $\ell_d$ is the cross-section for the duffenduck process. In the calculation of this rate coefficient the average is to be taken for the velocity of helium ions or atoms. For the Maxwellian velocity distribution the rate coefficient is written as

$$T = 7.79 \times 10^5 \ (\theta)^{1/2} \ \ell_d \quad \text{(5.14)}$$

In the calculation of McKenzie (11) for the He-Cd discharge it is assumed that the cross-section for the Duffenduck reaction is same as the cross-section for electron impact excitation. In fact the cross section of
the Duffenduck process must be same as the cross section of the Penning process because in one process atom in metastable state transfers energy and in another process helium ion transfers energy i.e. energy is transferred between atom and atom and atom and ion. In the present work we assume the cross-section of the Duffenduck reaction same as the cross-section of the Penning reaction. Thus the total Duffenduck transfer rate coefficient must be same as the total Penning transfer rate coefficient. However, there is difference in the excitation rates of the individual energy states.

In the Penning reaction the helium atom in metastable state transfers its energy to CuI to produce CuII ion in one of the 25 energy levels. And in the Duffenduck process the CuII ions are produced in one of the 125 energy levels. Hence the rate coefficient of the Duffenduck process to individual level of the copper ion must be about a factor of 5 less than the rate coefficient of the Penning process to the individual level of the copper ion. After formation of copper ions in different energy levels the atoms in the laser states are produced. This process further is less probable.

The relative behaviour of the total rate coefficient of the Duffenduck process with the gas temperature should be same as that shown in figure 5.1.

5.5 ELECTRON IMPACT DEEXCITATION:

As the elastic collisions excite the atoms they can
deexcite the atoms. This process is called as the superelastic collision (12). The deexcitation process may be expressed by the reaction

$$A^* + e \text{ (slow)} \rightarrow A + e \text{ (fast)} \quad \cdots \cdots \quad (5.15)$$

The extra energy of the excited atom is taken by the colloid electron and its energy increases. The atom(ion) which takes part in collision, is in higher excited state before collision and in the process of collision it makes transition to lower excited state or ground state. The rate of deexcitation of a level is mathematically written as

$$\frac{dN}{dt} = -N n_e X \quad \cdots \cdots \quad (5.16)$$

Where $X$ is the electron impact deexcitation rate coefficient, which is determined by the electron temperature. It may be mentioned here that the population density of the laser lower state, which is metastable states is affected by this process as the atoms remain in the state for longer time.

5.6 EXCITATION AND DEEXCITATION DUE TO THE CASCADING PROCESSES:

The radiative decay processes depopulate the upper states and populate the lower states involved in the radiative transition. The upper state is depopulated with the rate $N_u/\gamma_u$, where $N_u$ is the population of
the upper state and \( \tau_u \) is the radiative lifetime. When the copper in the upper state decays radiatively, it may make transition to one of the low lying states. The number of the copper atoms or ions undergoing typical transition depends upon the branching ratio of the transitions originating from the upper state. A state may decay by the collision with the other copper atom or ion or an electron. In this process extra energy is taken by the colloidating partner. The collisional depopulation is effective for the states having large value of the principal quantum number. Thus the higher states are not heavily populated and the decay rate from these states to the laser states is small. The effect of the cascading processes on the rate of population of the energy levels involved in laser transition can be considered to be negligible.

The population of the laser states and ultimately the rate of the power delivered by the laser discharge is not determined by only the excitation rate coefficient but by several other parameters. In fact, the excitation rates play vital role in the determination of the laser power. The excitation rates depend upon the excitation rate coefficient and the densities of the particles which take part in the process of excitation. We consider the role of the various densities and find the contribution of the processes to the laser power.
5.7 CONTRIBUTION OF DIFFERENT PROCESSES TO THE LASER POWER:

In last few articles the processes which can excite and deexcite the laser states have been considered in great details. The processes of deexcitation also are important in the study of the laser power that can be extracted from the laser discharge because the power which can be extracted from a laser discharge depends upon the rate at which the lower states are evacuated and the rates at which the upper states are filled.

When there is no stimulated emission the population of the upper laser states go on building up until there is balance between the excitation and deexcitation rates i.e.

\[ n_e \text{ Cu}^* R_u + \text{ Cu}^* N_{He+} T_u + \text{ Cu}^* N_m P_u \]
\[ = \frac{N_u}{T_u} + N_u X_u n_e \]

\[ \text{(5.17)} \]

\[ n_e \text{ Cu}^* R_l + \text{ Cu}^* N_{He+} T_l + \text{ Cu}^* N_m P_u \]
\[ = \frac{N_l}{T_l} + N_l X_l n_e \]

\[ \text{(5.18)} \]

The upper laser state has lifetime 40 nsec and the lower laser state has lifetime 700 nsec. The deexcitation rate by the super elastic collision must be more in case of lower laser state. The deexcitation rate because of the super elastic collision of the upper laser state may be neglected as the population of the
upper states are reduced considerably because of the onset of the process of the stimulated emission. Now the balance between exciting and deexciting processes may be expressed as

\[ n_e \text{Cu}^* \text{R}_u + \text{Cu}^* \text{N}_{\text{he}+\text{T}_u} + \text{Cu}^* \text{N}_{\text{M}_u} = (N_u - N_1) \ S \]

--- (5.19)

Thus as many photons are produced as the number of atoms are created in the upper states irrespective of what is the process of excitation if and only if the lower laser state is constantly exhausted and there is no more accumulation of atoms in the lower laser state. However, the lower laser state is metastable and there is accumulation of atoms in the state. As a result of this only less than half of the excited atoms would contribute to the laser power.

5.7.1 CONTRIBUTION OF THE PENNING PROCESS TO THE EXCITATION OF THE LASER STATES \((N_u \text{Cu}^* \text{P}_u \nu)\):

If all helium atoms excited to the metastable state transfer their energies to the copper atoms, the excitation rate of the energy states of the copper ions would be equal to the the EIE rate coefficient of the helium metastable state. Then the excitation rate of the state would be determined by the excitation cross section of the helium metastable state, electron density and the helium atom density or in other words we can say that the excitation rate of the copper is directly
proportional to the excitation rate of the helium metastable state.

The excitation rate of the states of CuI by the process of Penning transfer has been obtained as a function of the electron temperature for different values of the helium pressure from the rate coefficient shown in the figure 5.4. The excitation rate behaves relatively like the excitation rate coefficient.

The results show that as the electron temperature is increased from 0 to 2 eV, the excitation rate of the states increases rapidly. As the temperature is increased above 2 eV the increase in the excitation is slow and above 5 eV the excitation rate tends to saturate. In fact this excitation rate is high however, for getting this high excitation rate the metastable density should be built to exceedingly high values because of the small value of the Penning transfer rate coefficient. The excited metastable states are destroyed by the electron impact deexcitation, the collision between the metastable states and collisions with the tube walls. Furthermore, in order to obtain the actual value of the contribution of the Penning process to the excitation of the laser states one has to include the fractional abundance of CuI in the calculations. The inclusion of the fractional abundance of CuI further reduces the Penning excitation rate.

The process of Penning transfer ionises the copper atoms and the ionised copper atoms may recombine to form
the atom into the laser states. The Penning transfer may
directly excite the laser states but with very less
probability.

5.7.2 CONTRIBUTION OF DUFFENDUCK REACTION:

\( (\text{Cu}^* N_{\text{He}} T_{u y}) \):

The contribution of the Duffenduck process to the
laser power depends upon the density of the copper atoms
in ground state, the helium ions in the ground state
and the transfer rate coefficient. The transfer rate
coefficients have already been discussed in article 5.4.
The transfer rate coefficients for the Duffenduck
reaction to the individual energy levels are about 5
times less than the transfer rate coefficients of the
Penning reaction. The value of the Duffenduck reaction
rate coefficient may be assumed to be about \( 10^{-9} \ \text{cm}^3 \ \text{sec}^{-1} \). For obtaining the contribution of the Duffenduck
process to the laser power the term \( \text{Cu}^* N_m P_u \) of
the Penning process may be compared with the term \( \text{Cu}^* N_m T_u \) of the Duffenduck process. Thus the ratio of the
two terms is

\[
\text{Ratio} = \frac{\text{Cu}^* N_m P_u}{\text{Cu}^* N_{\text{He}} T_u} = \frac{5 N_m}{N_{\text{He}}}
\]

At the operating conditions the experimental value
of \( N_m \) is about \( 5 \times 10^{12} \). Hence, the ratio of the Penning transfer rate to the Duffenduck reaction rate has the
value around \( 4 \times 10^{13}/N_{\text{He+}} \). Thus if the values of \( N_{\text{He}} \) is
more than $4 \times 10^{13}$ the contribution of the Duffenduck process is more than the contribution of the Penning process otherwise it is less. As the experimental values of the electron density does not exceed $10^{13}$ the value of the sum of $N_{he}$ and $Cu^*$ should not exceed $10^{13}$. Hence the contribution of the Duffenduck process is always less than the contribution of the Penning process. And the Duffenduck process should not be the dominant process of excitation because the Penning process itself is very weak process of excitation.

5.7.3 CONTRIBUTION OF THE ELECTRON IMPACT EXCITATION:

The factors which influence the electron impact excitation rate have been discussed in last few chapters. The electron density $n_e$ and the density of copper atoms $Cu^*$ are the functions of electron temperature and the temperature of the gas discharge tube. The laser power generated at various wavelengths by the process of the electron impact excitation are obtained for the different values of $N_eCu^*$ as a function of the electron temperature. The power generated by the RIE of the states at the laser wavelength is shown in the figure 5.6. The curves are obtained for the different values of the product $Cu^*n_e$ ranging from $10^{22}$ to $10^{26}$ cm$^{-6}$ (curves 1 to 5 respectively). The observation of the figure shows that the laser power generated by the electron impact
excitation is quite high for \( n_e = 10^{13} \text{ cm}^{-3} \) and \( \text{Cu}^+ = 10^{13} \text{ cm}^{-3} \), the values which are very near to the actual experimental values. The maximum of about 200 mW power per cc of the discharge volume is generated. This indicates that the electron impact excitation alone can generate the laser power observed by the experiments.

The laser power delivered by the discharge at any other wavelength may be obtained from the results of the figure 5.6 by multiplying an appropriate factor. The laser power plotted in the figure 5.6 would be observed when the laser is oscillating on only one laser transition and there is no collisional mixing of the laser states. In case of CVL it has been observed experimentally that there is collision mixing between the energy levels \( ^2P_{3/2} \) and \( ^2P_{1/2} \) of the copper atom (13) and that may change the output power. It has been observed experimentally that the increase in the total density of metal in the discharge decreases the electron temperature (14). In case of the He-Cd\(^+\) and He-Se\(^+\) laser discharges the effect of the total cadmium and selenium density on the electron temperature has been experimentally observed (14), and it is shown that the electron temperature decreases as the metal density is increased. This is because of the low ionisation potential of the metals and high spectral loss of the discharge due to the presence of the metal.

It is expected in case of copper vapour laser that the increase in the temperature of the discharge tube
may increase the density of copper decreasing the electron temperature and hence the laser output power (15). In order to study the behaviour of the laser power generated at different values of the electron temperatures we compute the density Cu* as a function of T_e and display the results in the figure 5.5. We also compute the factor Cu* R_u and plot the results in the figure 5.6. The figures 5.5 and 5.6 show that the initial increase in the electron temperature increases the factor Cu* R_u and later the increase in the electron temperature decrease the factor. When the electron temperature is increased the density Cu of the copper atoms decreases continuously. Regarding copper atom density the low temperatures are favoured. But at lower electron temperatures the electron impact excitation is very less. The higher copper density needs lower temperatures and higher R_u needs high temperatures. Thus, the compromising value must be found out. This is possible from the figure 5.6. The most favourable electron temperature for the CVL operation at 5106 A wavelength is about 2 eV. Thus, we may conclude that the computed values show the quantitative agreement with the experimental results.
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Figure 5.1 EIR rate coefficients of $^2p$ energy level of copper atom.
Figure 5.2 EIE rate coefficients of copper \( ^{2}D_{5/2} \) and \( ^{2}D_{3/2} \) energy levels of copper atom.
Figure 5.3 Penning excitation rate coefficient $P$ as a function of the gas temperature $\Theta$. 
Figure 5.4 EIE rate coefficient of the metastable state of helium atom as a function of electron temperature.
Figure 5.5 Fractional abundance of copper atom as a function of electron temperature.
Figure 5.6 Laser power $P$ generated by EIE process as a function of electron temperature $T$. The curves 1-5 show power generated for the product $n_{CuRu}$ varying from $10^{22}$ to $10^{26}$. 