CHAPTER 6

INTENSITY DISTRIBUTION ACROSS THE OUTPUT LASER BEAM

6.1 Increasing laser power:

In the first copper vapor laser invented in 1966 by Walter et al (1) average power of 20 mW at 660 Hz was obtained. The discharge tube of diameter 1 cm and length 80 cm was used since then number of workers in the field have put in their efforts to increase the laser power and quality of laser output (2-6). Consequently, the laser average power of 100 W at 5 kHz pulse repetition rate was obtained from 8 cm diameter tube. The increase in the laser power was due to 1) The increase in the pulse repetition rate, 2) The greater sophistication in the discharge circuit and thermo mechanical design and 3) Volumetric scaling of the discharge region. It was thought that power can be increased by increasing the volume of the laser medium. The volume of the laser medium can be either increased by increasing the length of discharge tube or by increasing the diameter of discharge tube. The length of discharge plasma can be easily increased by increasing the length of discharge tube but it is limited by the available high voltage pulse power technology and the inversion lifetime of the laser transition. Thus the length of the discharge tube must be optimum so that the laser radiation should come out before the inversion density is exhausted.
It is fact that the volumetric scaling can be done to some extent by increasing the length of discharge tube. The volume of the discharge plasma can also be increased by increasing the diameter of the discharge tube but this leads to the generation of the annular shape of the laser beam. Thus diameter of the discharge tube can not be increased above some optimum value. Due to above mentioned reasons the volume of the discharge tube has to be fixed to a certain optimum value. It should be mentioned here that the power output may be increased by increasing the density of the medium. The increase in density is limited by the voltages available for firing the discharge.

The average laser power can be increased above limit by increasing the pulse repetition rate. Increase in the pulse repetition rate decreases the time between two consecutive pulses as a result of this succeeding pulse sees high metastable state density left by the previous pulse. The increase in the metastable density decreases the pulse peak power and pulse energy as it acts as lower laser state.

The designs of discharge circuit have their impact on peak power and ultimately on the average power. The design of low impedance thyretrons give fast rising discharge pulse and efficient laser action. The output power of the laser would be proportional to the volume of laser medium provided that the density of the copper atoms, density of electrons and the electron temperature are uniform along and across the discharge tube. But several experimental studies have shown that the parameters

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responsible for the excitation of the laser states do not have uniform values across the discharge tube. As a result of this laser beam does not have uniform power across it. Several workers in the field have observed that the laser output is annular in shape. Kushner and Warner have studied the annular shape and they explained the origin of annular shape in the output of laser beam on the basis of skin effect. Hayashi et al (7) have studied the annular shape of the laser beam in detail. They used neon as buffer gas and they studied the effect of hydrogen on the annular shape of the output beam. At the charging voltage 20 kV the beam is less annular. As the voltage becomes 21 kV the beam becomes more annular and at 22 kV the beam becomes completely annular. The authors are of the opinion that the beam becomes more annular as the charging voltage is increased because of the increase in the metastable density. At 20 kV charging voltage the leading part of the pulse is more annular than the lagging part of the pulse. At 22 kV when hydrogen was added to the discharge the beam becomes less annular. The phenomenon of the annular shape was attributed to the high thermal conductivity of hydrogen. Because of high thermal conductivity of hydrogen the metastable density increases and the laser power increases.

Izawa et al (8) have measured the density of lower laser level \( ^2D_{5/2} \) as well as upper laser level \( ^2P_{3/2} \) after the discharge as a function of radial distance in the discharge tube of 2 cm diameter. They measured the density of copper atoms at different times after firing of discharge pulse.
They observed that after 15 and 20 μsec of firing of discharge pulse the density on the axis was minimum. The density increased very sharply as we move away from the axis.

For 30 and 50 μsec the density profile shows a dip on the axis. As we move away from the axis the density increases, attains its maximum value and then decreases. For 100, 150 and 200 μsec the density is maximum on the axis. As we move away from the axis initially the density decreases very slowly but after that it falls very rapidly. They attribute this behavior to the large non uniformity in the temperature.

6.2 Annular shape of the laser beam:

In order to study the annular shape of the output laser beam in detail we have studied radial profiles of spectral emission of the discharge at laser wavelength in detail.

The laser action in CVL is observed on the two transitions of the copper atom. Higher copper densities would be favored for getting high power form the laser medium. We have studied in the last chapter that the electron impact excitation of the laser states is the most dominant process of excitation. In the calculation of radial profiles of spectral emission of the discharge we have considered the contribution of only electron impact excitation. The excitation of a state by electron impact excitation process is equal to Cu* R_e n_e. 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 wavelength $\lambda$ would be proportional
to the factor $C u^{*} R_{u} n_{e}$. The study of the variation of these parameters give
the radial profile of spectral emission. The values of radial profiles are
evaluated by using the value of fractional abundance of CuI at a particular
electron temperature and corresponding electron impact excitation rate
coefficient value at that electron temperature. We have studied the radial profiles
of spectral emission for different axial temperatures and the results are
displayed in the figures 6.1, 6.2, 6.3 and 6.4.

We have studied radial profiles of spectral emission for various axial
temperatures on the axis. The results are displayed in respective figures. We
have considered a square array of 5 cm x 5 cm. At the center of array we
have considered the origin of the system. The axis of the discharge tube is also
supposed to be coinciding with origin. The distance of any point $x$ $(m,n)$
from the axis is calculated by drawing a radius vector $R$ from origin to that
point by formula $R = (m^2 + n^2)^{1/2}$. We have computed the intensity at
different points around the axis and the results are displayed in respective
figures.

The radial profiles of spectral emission for axial electron temperature
0.5 eV are displayed in fig 6.1. The intensity profiles show a peak on the axis. As
we move away from the axis the intensity decreases gradually and attains
zero value. This is because the fractional density of neutral copper atoms

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is reasonably high along the axis of discharge tube for low electron temperature like 0.5 eV and EIE rate coefficient is maximum. The fractional density of neutral copper atoms decreases as we move away from the axis. Thus the intensity profile shows a Gaussian shape for 0.5 eV electron temperature on the axis.

The radial profiles of spectral emissions for axial temperature 4 eV are displayed in fig 6.2. The intensity shows a dip on the axis with two side peaks. It is a well shaped structure. This is because the fractional density of neutral copper atoms on the axis of discharge tube becomes less. The neutral copper atoms get converted into the highly ionized species. The profiles of neutral copper shows well shaped structure at the electron temperature 4 eV on the axis (like fig 5.5). The fractional density of neutral copper atoms shift towards the walls of the discharge tube. Hence the spectral intensity profile shows annular shape.

The radial profiles of spectral emission for axial electron temperature 7 eV are displayed in fig 6.3. The intensity shows a dip on the axis with two side peaks. The dip on the axis is further deepened and the side peaks have shifted further more towards the walls of the discharge tube. Due to the reasons explained above the annular shape of output laser beam is more prominent in this case.

We have obtained an interesting profile of spectral emission for axial temperature 1 eV. The corresponding results are displayed in fig 6.4.
The intensity is maximum on the axis. As we move away from the axis, initially the intensity decreases slightly, becomes minimum and then it increases attains to certain maximum value, then further decreases gradually and attains the zero value. The computations show very good agreement with the experimental results of Izawa et al (8). The discharge pulse has fast rise time so the electron temperature also increases rapidly and then decreases slowly. Izawa et al have obtained the radial profiles at different times and we obtained the radial profiles at different temperatures. It is implied that the electron temperature is maximum when the discharge pulse is fired and as time advances the electron temperature goes on decreasing.

6.3 Power calculations:

The study of evaluation of the laser power output is not easier and straightforward because the parameters which influence the power output do not have uniform values along and across the discharge tube. The factors that influence the laser output power are electron temperature, electron density, copper atom density etc. The power delivered by different volume elements of the discharge plasma is not same. Thus our first job is to find the nature of the parameter variation across the tube and then to find out contributions of all such volume elements of the discharge column of which it is supposed to be consisting of. The total power output would then be summation of all such contributions.
As the discharge tube employed for operating discharges are cylindrical, the plasma column is cylindrical. The plasma column is supposed to have cylindrical symmetry i.e. in a hollow cylindrical shell of radius \( R \) and thickness \( dR \), the parameters responsible for the excitation of the laser states have uniform values. For the computation of total power delivered by the laser, we divide the laser medium of radius \( R_0 \) into hollow cylindrical shells of radius \( R \) and thickness \( dR \). We compute the laser power delivered by each shell and then take sum of all terms obtained by changing \( R \) from 0 through \( R_0 \) with the difference of \( dR \) (where \( R_0 \) is the radius of the discharge tube). The necessary diagram to be imagined in the process of calculations is shown in the figure 5.1. In the present work we have assumed radial profile of electron density and electron temperature to have the shape like zero order Basset's function of first kind with maximum on the axis of the discharge tube. The stimulating radiations traveling parallel to the laser axis and perpendicular to the mirror plane are the most effective because the radiation’s traveling in the other direction may be treated as oblique radiation and they escape the laser cavity after traveling certain distance through the plasma column. Thus the volume element parallel to the tube axis and perpendicular to the mirror plane is responsible for the intensity of the outcoming laser radiation’s at a particular position.

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6.4 The power delivered by volume element $dV$ of the discharge tube at laser wavelength:

The electron temperature is the important parameter in the determination of radial variation of EIE rate coefficient, fractional abundance, the electron density and hence the laser output power. It must be explored how electron temperature influences the laser output power and how it can be controlled so that the laser beam of high power at high efficiency can be extracted from plasma column. It has been shown in chapter 4 that the electron impact excitation is the most dominant process of excitation over other excitation process like Penning excitation, Duffenduck excitation and Cascading processes. Therefore the contribution of other processes to the generation of the laser power may be considered to be negligible. Thus the power delivered by laser discharge is obtained by taking into consideration electron impact excitation process only. Thus the power delivered by volume element $dV$ is expressed as

$$dp \propto C u^* n_e R_u \, dV \, h\nu \quad \text{6.1}$$

where,

$C u^*$ → is the density of copper atoms

$n_e$ → is the electron density

$R_u$ → is the electron impact excitation rate coefficient

$dV$ → is the volume of the volume element under consideration.
When the radiation density is sufficient all the photons emitted by the volume element at the laser wavelength are added to the laser beam. Thus the contribution of the volume element $dV$ to the laser power would be same as RHS of equation 6.1. The output power of the laser beam can be determined by the density of copper atoms $Cu^*$, the density of electrons $n_e$ and the electron impact excitation rate coefficient $R_u$. In addition to this $Cu^*$ depends upon the total density of copper in the discharge tube. The total density of copper is determined by the temperature of the discharge tube. Increase in the temperature of discharge tube increases the total density of copper species. However this increase in the copper density may decrease the electron temperature as has been observed in the metal vapor discharges (9-12). This leads to decrease in fractional abundance of copper atoms. Thus increasing the discharge tube temperature continuously will not help in increasing the value of $Cu^*$ but optimum value must be obtained. The electron density is not direct function of the electron temperature. The increase in electron temperature may increase the fractional density of ionized species and the detached electrons may increase the electron density. The factor $R_u$ increases approximately as the square root of electron temperature as shown in figure 4.1. Although the factor $R_u$ may be expressed in terms of electron temperature by some function, the product $R_u Cu^*$ cannot be described by a well defined function. Moreover the optimization of these parameters independently does not help as the parameters do not have
uniform values across the discharge tube. The total power delivered by the
discharge column must be optimized and not the individual factors Cu*, n_e
and R_w. Since the factors in the equation 6.1 are the functions of the electron
temperature and the electron temperature is not same for all the values of
R. The power delivered by a volume element having value dV(R) may
be rewritten as

\[ dp(R) = Cu^*(R) \, n_e(R) \, dV(R) \, R_w(R) \, hv \quad \text{---- 6.2} \]

All the parameters Cu*(R), n_e(R), dV(R) are the functions of the
distance of the point from the axis. Hence in actual practice the power
optimization may be done by obtaining total power as a function of the
temperature on the axis of the discharge tube.

6.5 Computation of total power delivered by the CVL discharge:

In order to calculate the total power delivered by the discharge
tube it is assumed that all the atoms which are excited to the upper
laser state contribute to the emission of radiation at laser wavelength. If the
discharge tube is perfectly aligned the discharge column in the tube has
cylindrical symmetry i.e. all the parameters like electron density n_e, electron
temperature T_e, the densities of copper atoms, the density of inert gas ions
and the densities of helium metastable state have same values inside a
thin hollow coaxial cylindrical shell of radius R and thickness dR. We can
approach more closer to the assumption by making the thickness of this
shell dR as small as possible. The cross section of the tube is shown in
fig 5.1. S is a coaxial cylindrical shell of radius $R$ and thickness $dR$. The contribution of this shell having unit length in the emission of laser power at the laser wavelength may be written as

$$dp = 2\pi R \, dR \, n_e(R) \, Cu^*(R) \, R_d(R) \, \nu$$

6.3

The value of radius $R$ of the shell ranges from 0 on the axis to $R_0$ at the wall of the discharge tube. Thus the total power delivered by the discharge tube is obtained by integrating equation 6.3 within the limits 0 and $R_0$ as follows

$$P = L \int_{0}^{R_0} 2\pi R \, dR \, n_e(R) \, Cu^*(R) \, R_d(R) \, \nu$$

6.4

where,

$L \rightarrow$ is length of the discharge tube.

As the functions $Cu^*(R)$ and $R_d(R)$ are not well defined functions of $R$ it is difficult to integrate equation 6.4. Thus the numerical computations can be used to evaluate the integral for different values of axial temperature $T_0$. Two sets of computations can be carried out; 1) For constant electron density across the discharge tube and 2) For electron density given by

$$n_e = N_e(0) \left[ 1 - \left( \frac{R}{R_0} \right)^2 \right]$$

6.5

For the first set of calculations the equations is modified as

$$P = 2\pi L \, n_e \, \nu \int_{0}^{R_0} R \, dR \, Cu^*(R) \, R_d(R)$$

6.6

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and for the second set of calculations the equation is modified as

\[
P = 2\pi L R \int_0^{R_o} h \nu C^\ast \left( \frac{R}{R_o} \right) R_o(R) N_e(0) \left[ 1 - \left( \frac{R}{R_o} \right)^2 \right] dR
\]

6.6 Results and conclusions:

We have computed the fractional abundance of neutral copper atoms Cu\(^\ast\), the electron impact excitation rate coefficient \( R_u \) and the product of the fractional abundance of copper atoms and the EIE rate coefficient Cu\(^\ast\) \( R_u \). The results are displayed in fig 6.5. The value of Cu\(^\ast\) \( R_u \) is maximum at the electron temperature of about 3 eV. The parameter Cu\(^\ast\) \( R_u \) goes on decreasing if the electron temperature is decreased or increased. The value of Cu\(^\ast\) \( R_u \) reduces by a factor 5 at the electron temperatures of about 1.2 eV and 5.5 eV. It is very difficult to maintain constant electron temperature across the discharge tube. In general the electron temperature is maximum on the axis of the discharge tube and minimum near the walls. The discharge must be operated at the conditions such that maximum volume of the discharge has favorable electron temperature.

For the calculation of total output power we have assumed that the electron temperature and electron density have radial profiles like zero order Bessel’s function. We have taken discharge tube of diameter 2.5 cm because many experimenters have utilized the tube of this bore size or very near to this bore size for exciting the mixture of the copper with the inert gas.
interval dR is taken to be 0.2 cm. The laser output power is a function of axial temperature $T_0$ has been obtained for laser transitions at wavelengths 5106 and 5782 Å and the results are displayed in the figures 6.6 and 6.7. From the fig. 6.6 it can be observed that initially the laser output power increases as electron temperature is increased. After the electron temperature on the axis reaches the value of 2.5 eV, the output plasma starts getting saturated. The output power becomes maximum at the electron temperature of about 3 eV. Further increase in the electron temperature results in decrease in the output power. Thus it may be stated that the electron temperature on the axis must be in the neighborhood of 3 eV. The electron temperature can not be maintained constant through out the discharge pulse but a pulse forming network can be designed so that we get electron temperature in the neighborhood of favorable region for maximum time interval. The behavior of output power with electron temperature on the axis at 5782 Å wavelength is similar to the behavior at 5106 Å wavelength. The initial increase in power as electron temperature increases is because of the increase in the electron impact excitation. After reaching maximum value the power decreases as electron temperature is increased. This may be due to decrease in the fractional density of CuI. If we imagine that the temperature axis is treated as the time axis, the curve displayed in 6.6 and 6.7 show very close agreement with experimental results (13,14). When the discharge pulse is fired the electron temperature starts increasing and reaches a peak value. After
some time the electron temperature goes on decreasing and reaches to zero. If the evaluation of electron temperature as a function of time is known exactly, the exact behavior of the laser output power may be studied.
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Fig. 6.1: Power distribution across the output laser beam at an event when temp=0.5 eV on the axis
Fig. 6.2: Power distribution across the output laser beam at an event when temp = 4 eV on the axis.
Fig. 6.3: Power distribution across the output laser beam at an event when temp = 7 eV on the axis
Fig. 6.4: Power distribution across the output laser beam at an event when temp = 1 eV on the axis.
Fig. 6.5 The fractional abundance of CuI (dotted curve), the electron impact excitation rate coefficient of $^{2}P_{3/2}$ state (solid curve) and the product of the two as a function of electron temperature (dash dot curve)
Fig. 6.6: Output power as function of the electron temperature on the axis of the discharge tube with i) constant $N_e$ and ii) $N_e$ varying, as Bessels function of zeroth order, across the discharge tube for 5106 Å transition of copper atom.
Fig. 6.7: Output power as function of the electron temperature on the axis of the discharge tube with i) constant $N_e$ and ii) $N_e$ varying, as Bessels function of zeroth order, across the discharge tube for 5782 Å transition of copper atom.