Study of Electron Impact Excitation Rate Coefficients of laser states in the He-Cd$^+$ laser discharge as a function of electron temperature.

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Abstract : In the present work electron impact excitation rate coefficients of laser states by the processes like electron impact excitation, Penning excitation, Duffenduck reaction are obtained as a function of electron temperature. The electron impact excitation rate coefficient of the laser states of CdII from the ground state of CdI and CdII are obtained by considering the equation of electron The Penning excitation and Duffenduck reaction rate both increase as the gas temperature is increased. The rate coefficients of both processes are proportional to the square root of gas temperature. Gas temperature determines the collision frequency and hence the rate coefficient.

***Key Words* - Electron impact excitation, Penning excitation, Duffenduck excitation, Direct excitation, stepwise excitation**

I. INTRODUCTION

It has been found that the energy states are populated by the processes of collisions with the metastable states [1, 2, 3] and ions [4, 5] and by the process of electron collisions [6, 7]. In addition to this the energy states are found to be populated by the process of recombination. The energy states can be depopulated by collision with slow electrons. The electrons passing through the discharge transfers their energies to the gas particle by two types of collisions 1) Elastic collision and 2) Inelastic collision

In the elastic collision, the transfer of kinetic energy of the electron into kinetic energy of the gas particle takes place. The kinetic energy of the colliding particle is conserved and this type of collision process causes the heating of the gas particle to some extent. In second type of collision, kinetic energy of the electron is converted into potential energy of colliding gas particle and gas particle gets excited. This type of collision is called as Inelastic collision. The particles in the excited states either transfer back their energy to low energy electrons or they undergo a transition giving radiative emission. The rate of transfer of energy from the discharge electron to the gas particles may be written as

$$\frac{dE}{dt} = N_g N_e C_e + \sum_j N_{gj} N_e C_{in} E_j - \sum_j N_{gj} N_e C_{dex} E_i \qquad 1$$

Where, N_g is number of gas particles
C_e is coefficient of elastic collision
C_{in} is coefficient of inelastic collision
E_j is energy of j^{th} state excited by elastic collision
C_{dex} is de-excitation rate coefficient
E_i is energy of excited particle, which transfer the energy to the electron.

The processes which can populate and depopulate the states are excitation and de-excitation; only dominant processes are to be discussed in detail. The densities of the states $5s^2\,{}^2D_{5/2}$, $5s^2\,{}^2D_{3/2}$, $5p\,{}^2P_{3/2}$, $5p\,{}^2P_{1/2}$ plays important role in the determination of laser power at 4416 A° and at 3250 A°. When helium cadmium laser is operated at 4416 A° or at 3250 A° wavelength in the CW mode, the discharge is in steady state. Under steady state conditions the rate of change of population densities may be equated to zero. This balances the rate of population and the rate of depopulation of the energy states.

Excitation Rates And Rate Coefficient

The energy state of $5s^2\,{}^2D_{5/2}$, $5s^2\,{}^2D_{3/2}$, $5p\,{}^2P_{3/2}$, $5p\,{}^2P_{1/2}$ of cadmium ions are respectively populated with the rates as

$$(N_{Cd}^{+} R_{u1} + N_{Cd} D_{u1}) N_e + N_{Cd} N_m P_{u1} + N_{Cd} N_{He}^{+} T_{u1} + \sum A_{ju1} N_j \qquad 2$$

$$(N_{Cd}^{+} R_{l1} + N_{Cd} D_{l1}) N_e + N_{Cd} N_m P_{l1} + N_{Cd} N_{He}^{+} T_{l1} + \sum A_{jl1} N_j + S_{4416}(N_{u1} - N_{l1}) \qquad 3$$

$$(N_{Cd}^{+} R_{u2} + N_{Cd} D_{u2}) N_e + N_{Cd} N_m P_{u2} + N_{Cd} N_{He}^{+} T_{u2} + \sum A_{ju2} N_j \qquad 4$$

$$(N_{Cd}^{+} R_{l2} + N_{Cd} D_{l2}) N_e + N_{Cd} N_m P_{l2} + N_{Cd} N_{He}^{+} T_{l2} + \sum A_{jl2} N_j + S_{3250}(N_{u2} - N_{l2}) \qquad 5$$

The energy states which take part in producing laser beam at 4416 A° or at 3250 A° are populated by

1. Electron impact excitation from the ground state of CdI (i.e. Direct excitation)
2. Electron impact excitation from the ground state of CdII (i.e. Stepwise excitation)
3. Transfer of energy from helium metastable atoms to the cadmium atoms (i.e. Penning excitation)
4. Transfer of energy from helium ions to the cadmium atoms (i.e. Duffenduck excitation)
5. Cascading processes i.e. radiative decay of the states lies energetically above the states involved in the laser transitions.
6. Recombination of CdIII ions into the laser states (i.e. Cascading processes)

Electron Impact Excitation

In the electron impact excitation, the energy from a high energy electron is transferred to the colliding atom or ion. When an electron having energy more than the excitation energy of an electron rotating about an atom or ion, collides with an atom or ion, may transfer its energy to the system and this may result in the excitation of rotating electron to the higher energy orbit. The probability of excitation depends upon the energy of an excited electron and the cross-section of excitation at that particular energy. The excitation rate depends upon the excitation cross-section and number of effective collisions made by electron. The number of effective collisions is a function of electron velocity, which in turn is a function of electron temperature.

The discharge plasma consists of atoms, ions and electrons. There can be two types of electron impact excitation processes depending upon whether the colliding particle cadmium atom is in the ground state or in the ground state. Accordingly these electron impact excitation rate coefficients are defined as Direct Excitation and Stepwise Excitation respectively. The electron impact excitation rate coefficient is expressed in terms of excitation cross-section σ and electron velocity v_e as $<\sigma v_e>$. Now for two types of electron impact excitation, we can write

$$R = <\sigma_s v_e> \qquad 6$$

$$D = <\sigma_d v_e> \qquad 7$$

Where, R is the electron impact excitation rate coefficient due to Stepwise excitation
D is the electron impact excitation rate coefficient due to direct excitation
σ_s is the Electron impact excitation cross-section for the states from the ground state of CdII ion
σ_d is the Electron impact excitation cross-section for the states from the ground state of CdI atom

The velocity of an electron is a function of its energy and it is related to its energy E by the relation

$$v = 5.9 * 10^7 * \left(E^{1/2}\right) \qquad 8$$

The number dN of electrons having energy between E and E+dE is given by the Maxwellian distribution function as

$$dN = N\left[\frac{2}{kT}\left(E^{1/2}/_{\pi kT^{1/2}}\right) exp\left(-E/_{kT}\right)\right] dE \qquad 9$$

Thus the rate of excitation of the energy levels by the stepwise and direct excitation is expressed as

$$dR = N\left[\frac{2}{kT}\left(E^{1/2}/_{\pi kT^{1/2}}\right) \sigma_s\, exp\left(-E/_{kT}\right)\right] dE \qquad 10$$

$$dD = N\left[\frac{2}{kT}\left(E^{1/2}/_{\pi kT^{1/2}}\right) \sigma_d\, exp\left(-E/_{kT}\right)\right] dE \qquad 11$$

If T, E and dE are expressed in eV and all the cross-section values are in cm^2, the equations 10 and 11 become

$$R = \frac{6.7*10^7}{T^{3/2}} \int_{E_s}^{\infty} \sigma_s E\, exp\left(-E/_{kT}\right) dE \;\; cm^3/sec \qquad 12$$

$$D = \frac{6.7*10^7}{T^{3/2}} \int_{E_s}^{\infty} \sigma_d E\, exp\left(-E/_{kT}\right) dE \;\; cm^3/sec \qquad 13$$

When an electron having some energy is incident on the atom (ion), the electron transfers its energy to an electron rotating about an 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 excitation of the energy levels of the ions, energy of the incident electron is divided into three parts (1) a part of the energy is utilized in ionizing the atom (2) another part is utilized in exciting the produced ion and (3) the remaining part is kept by the incident electron itself. When energy states of an atom (ion) are to be excited, energy of the incident electron is divided into two parts (1) a part is given to the electron rotating about an atom (ion) and (2) the remaining amount of energy is kept by the incident electron itself. The former process may contribute towards the process of ionization and may indirectly excite the laser states via the process of recombination. Obviously, the contribution of the former process is negligibly small.

Penning Excitation

The excitation energy can be exchanged between neutral atoms. In general, an excited atom can get ionized by the virtue of its excitation energy, if the latter is larger than the required ionization energy. Such a process is made probable if the excited atom is in the metastable state and thus has longer life time during which the particle may undergo an effective collision. When the helium atom is in the metastable state, collides with a cadmium atom then there is a probability of ionizing cadmium atoms and getting excited to upper and lower laser states. This process is referred as Penning excitation.

The Penning excitation rate coefficient of the upper laser states and lower laser states are represented by third terms in the equations 2 through 5 and they are written as $N_{Cd} N_m P_{u1}$, N_{Cd}, $N_m P_{l1}$, $N_{Cd} N_m P_{u2}$, and $N_{Cd} N_m P_{l2}$. The laser states involved in the transitions 4416 A° and 3250 A° are 5s^2 ^{2}D$_{5/2}$, 5p ^{2}P$_{3/2}$, 5s^2 ^{2}D$_{3/2}$ and 5p ^{2}P$_{1/2}$ respectively. The excitation rates of the laser states by Penning process are determined by the fractional abundance of CdI, density of HeI metastable states and Penning transfer cross-section of the individual state of CdII and the gas temperature in the discharge. In the Penning process, energy of the excited electron of helium is transferred to cadmium atoms that results in ionization and excitation of CdI. As this process involves many sub processes, the cross-section is very small. The process of Penning excitation of cadmium i.e. cadmium atom to singly ionized cadmium ions in the excited states can be considered as same process as that of Penning ionization. The Penning ionization rate coefficient in He-Cd$^+$ can be termed as Penning excitation rate coefficient and it is expressed by the equation

$$P = <\sigma_p vHe> \qquad 14$$

where σ_p is Penning excitation cross section

vHe is velocity of helium atoms relative to cadmium atom which can be determined by temperature.

The velocity of helium gas follows Maxwellian distribution as the density of helium atoms is about 10^{16} cm^{-3}. Thus for the Maxwellian velocity distribution, the total Penning excitation rate coefficient can be expressed as

$$P = \frac{6.7*10^7}{86(\theta^{3/2})}\int_0^\infty \sigma_p E\, exp\left(-E/_\theta\right) dE \;\; cm^3/sec \qquad 15$$

where θ is the gas temperature and the factor 86 comes because of the helium mass (4 amu). The gas temperature has been expressed in terms of eV. But it is more convenient to express gas temperature in degree Kelvin. Then total Penning transfer rate coefficient reduces to

$$P = 7.79 * 10^5\left(\theta^{1/2}\right) \qquad 16$$

The total Penning transfer rate coefficient has been calculated by using the values of total excitation cross-section measured by Shearer and Padovani [9]. In order to make it more convenient to obtain the excitation of the individual states Inaba et al [8] has measured Penning excitation cross-section of the individual levels of 4416 A° and 3250 A° laser transition by the crossed beam method. The total Penning transfer rate coefficient is obtained by putting $\sigma_p = 4.5*10^{-15}$ cm^{-2} in equation 16 and results are plotted in the figure 1. The Penning excitation rate coefficient for the individual CdII state may be obtained from total rate coefficient by multiplying by the appropriate factor obtained from the table for excitation of the individual states of cadmium ions [8].

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

$$\frac{dN_m}{dt} = N_{He}N_eR_0 - N_{Cd}^{+}N_mP - N_mN_eD_0 \qquad 17$$

where R_0= electron impact excitation rate coefficient for the helium metastable state from the ground state of the helium atoms and D_0 electron impact de-excitation rate coefficient. When steady state is reached, the rate of excitation and rate of de-excitation balances each other i.e.

$$N_{He}N_eR_0 = N_{Cd}^{+}N_mP + N_mN_eD_0 \qquad 18$$

In the pure helium discharge the metastable density N_{He} is about 10^{13} cm-^{3}. When cadmium is mixed in the discharge the density reduces to 5x10^{12}cm^{-3}. The density of cadmium in the discharge is about 10^{13} cm^{-3} when the tube temperature is in between 600 °K to 1500 °K. For the above mentioned range of gas temperature, the value of Penning excitation rate coefficient P varies from 3.65x10^{-10} to 8.15x10-^{10} cm^3/sec. The product of metastable helium density, cadmium density and Penning excitation rate coefficient is of the order of 10^{16} cm^3/sec.

The electron impact excitation coefficient due to the Stepwise excitation is determined by the term $N_eN_{CdII}R$. The electron density N_e is of the order of 10^{13} cm^{-3}, the Stepwise excitation rate coefficient R is of the order of 10^{-6} cm^3/sec. The density of CdII is low at the low electron temperatures and it increases with the temperature. If the electron temperature is further increased then the density of CdII increases and the density of CdI starts to decrease which indicate that the Penning excitation rate coefficient is less than the Stepwise excitation rate coefficient by at least 5 orders of magnitude.

Duffenduck Excitation Rate Coefficient

The discharge plasma in the tube consists of mixture of atoms, electrons and ions. There is a possibility of collision among these species and with the walls of the discharge tube also. The process in which an ion of the buffer gas when collides with the atoms of active material and results in the formation of an ion of the active material and the atoms of the buffer gas, is known as Charge transfer process which is also known as Duffenduck reaction. In this process charge from an ion is transferred to the other ion. In He-Cd discharge, the excitation process in which the helium ion in the ground state when collides with the cadmium atom in the ground state, transfers its energy to the cadmium atoms and the cadmium gets ionized. When the energy is transferred from HeII to CdI, the ionized cadmium may be in the ground state or in the excited state. This process of ionization and excitation of cadmium atoms is known as Duffenduck excitation. The term $N_{Cd}N_{He+}T_{u1}$, $N_{Cd}N_{He+}T_{u2}$, $N_{Cd}N_{He+}T_{l1}$, $N_{Cd}N_{He+}T_{l2}$ are Duffenduck excitation rates for the states $5s^2\,^2D_{3/2}$, $5p\,^2P_{3/2}$, $5s^2\,^2D_{3/2}$ and $5p\,^2P_{1/2}$ respectively. The Duffenduck reaction rate coefficient is expressed in the same way as the Penning excitation rate coefficient as

$$T = < \sigma_T v He > \tag{19}$$

where σ_T is cross section of the Duffenduck reaction

Assuming the Maxwellian distribution for the helium metastable state and applying the same logic as in the charge transfer, the ultimate equation for the Duffenduck excitation rate coefficient has been obtained from the above equation as

$$T = 7.79 * 10^5 \left(\theta^{1/2}\right)(\sigma_T) \tag{20}$$

In the Penning reaction the helium atoms in the metastable state transfer its energy to the CdI to produce CdII ions in one of the six energy levels ($5s^2\,^2D_{5/2}$, $5p\,^2P_{3/2}$, $5s^2\,^2D_{3/2}$ and $5p\,^2P_{1/2}$, $5s\,^2S_{1/2}$, and $6s\,^2S_{1/2}$) and in the Duffenduck process the CdII ions are produced in one of the fifty energy levels. Hence the rate coefficient of the Duffenduck process to the individual level must be about a factor of 10 less than the rate coefficient of the Penning process to the individual level although the two cross-section are identical to each other.

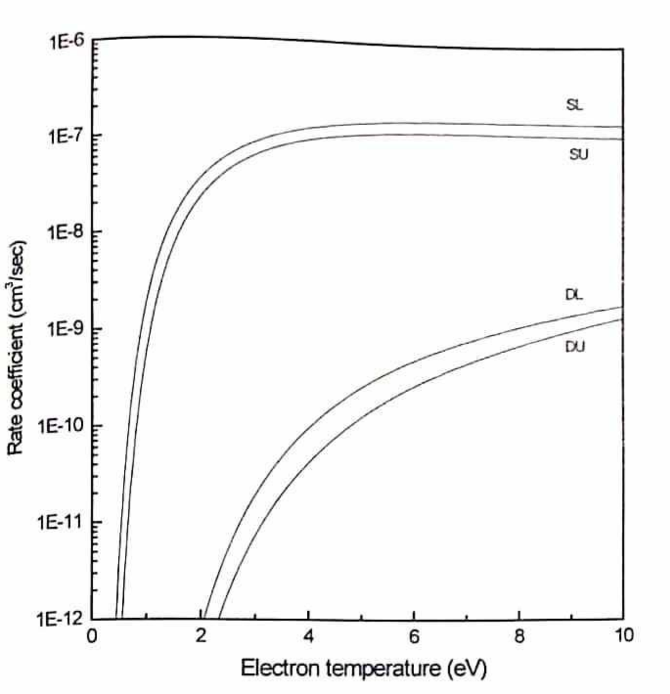
Further the data [10, 11], the energy difference between the ionization potential of HeI and ionization potential of CdII is 7.68 eV and there exist 50 energy levels having energy less than this energy difference which means that total Duffenduck excitation cross-section may be shared by 50 energy states of the cadmium ions. The effective values of the Duffenduck excitation cross-section for a particular energy state would be about 1/50th of the values obtained by using equation (18). The comparison of the rate coefficient shows that the electron impact excitation with the Stepwise excitation is the most dominant process when compared with the another processes of the excitation. Therefore for the calculations we have considered only stepwise excitation process.

II. RESULTS AND DISCUSSION

We have calculated electron impact excitation rate coefficient using equation 12 and 13 for the electron temperature between 1 through 10 eV. The stepwise and direct excitation rate coefficient for the states of 4416 A° and 3250A° transitions are displayed in the figures 1 and 2 respectively. In the temperature region between 1-3 eV, the stepwise excitation rate coefficient is about 4 orders of magnitude more than direct excitation rate coefficient. At higher temperatures also the stepwise excitation rate coefficient is about 2 orders of magnitude more than direct excitation rate coefficient. The fractional abundance of CdI and CdII are such that the differences in the excitation rate coefficients are further increased. Hence the excitation rates of the laser states by direct excitation in comparison to the excitation rates by the stepwise excitation are negligibly small which can be neglected. The comparison of the two rate coefficients shows that at all the temperatures the stepwise excitation rate coefficient is more than direct excitation rate coefficient.

The factors which influences the stepwise excitation rate coefficient are the electron velocity, energy of the exciting electron, cross-section of the exciting electron, electron temperature etc. The electron density N_e and the cadmium ion density N_{Cd+} are the functions of electron temperature and temperature of the furnace of the discharge tube. The laser power generated at 4416 A° and 3250 A° by the process of the Stepwise excitation are obtained for different values of N_e and N_{Cd+} as a as the function of electron temperature. The electron impact excitation rate coefficient R_u is assumed to be proportional to square root of the electron temperature. The magnitude of R_u is assumed to be same that of magnitude of electron impact excitation cross-section of the cadmium ions. The power generated by electron impact excitation of the laser states at the wavelengths 4416 A° and 3250 A° are as shown in the figure 3 and 4 respectively. The curves are obtained for different values of the product $N_{Cd+}N_e$ ranging from 10^{23} to 10^{29} cm^{-3} (curves 1 to 7 respectively). The observation of figures 3 and4 shows that laser power increases if the electron density is increased. For $N_e = 10^{11} cm^{-3}$ and $N_{Cd+} = 10^{12} cm^{-3}$, the maximum power generate is about 0.2 mW/cc at 4416 A° and it is about 5 mW/cc at 3250 A°. For $N_e = 10^{12} cm^{-3}$ and $N_{Cd+} = 10^{13} cm^{-3}$ the maximum power generated is about 20 mW/cc and 70 mW/cc at 4416 A° and 3250 A° respectively.

At the operating conditions the electron density is $10^{13} cm^{-3}$ and the cadmium density is $10^{13} cm^{-3}$. The product of $N_e * N_{Cd}$ is 10^{26} cm^{-3}. At this particular density the maximum laser power generated is about 100 mW/cc of the discharge volume. This indicates that electron impact excitation can alone generate the laser power observed in several experiments. The total density of the cadmium species is determined by the temperature of the side cups. The density of cadmium determines the value of the electron temperature. It has been observed experimentally that increase in the total density of the cadmium species decreases the electron temperature [12]. This is because of the low ionization potential of the metals and high spectral loss of the discharge in presence of the metals. Thus increase in the electron temperature of the side cups may not help in increasing the laser output power.



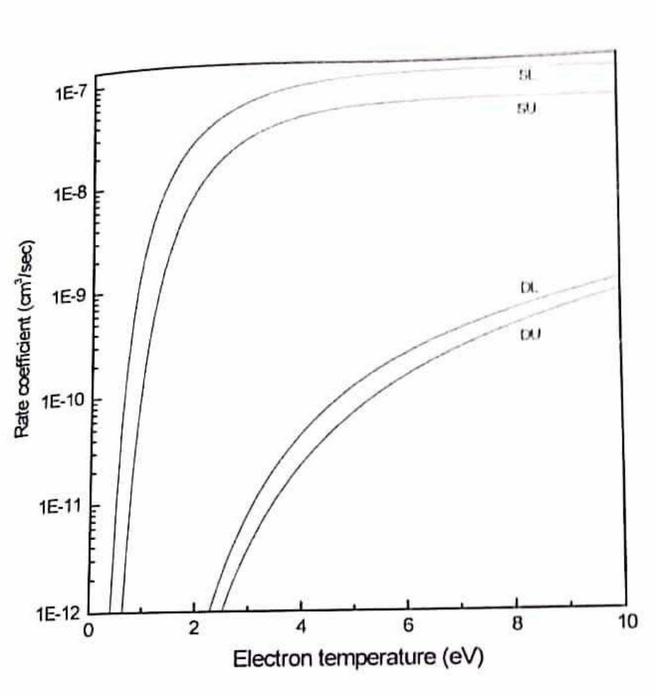
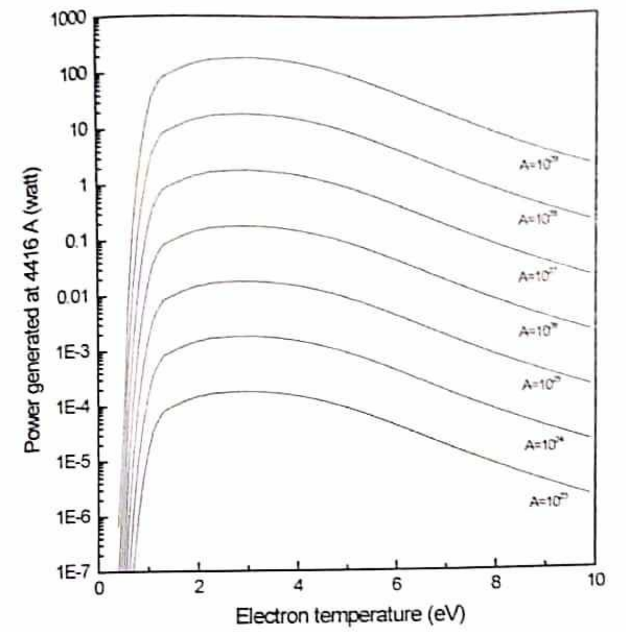


Fig.1. EIE rate coefficient of the laser states of the transition delivering 4416 A laser beam (S-Stepwise, D-Direct)

Fig2.EIE rate coefficient of the laser states of the transition delivering 3250 A laser beam (S-Stepwise, D-Direct)



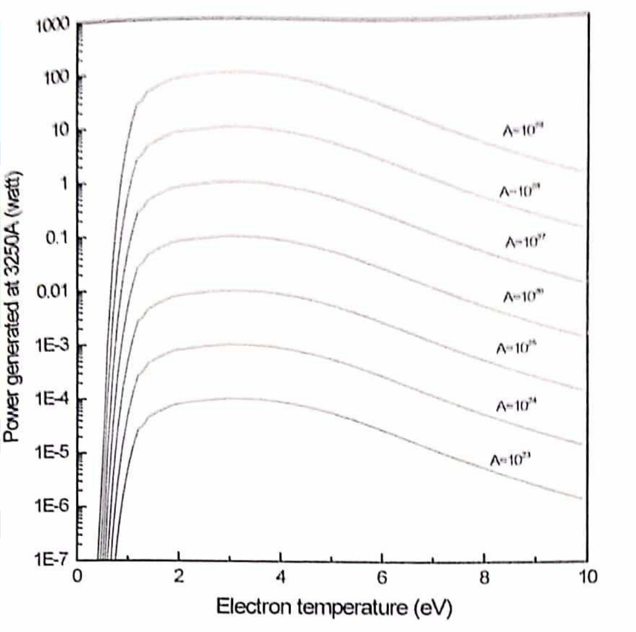


Fig3. Laser power generated at 4416A by Stepwise excitation for different values Of the product A= N_eN_{Cd}

Fig3. Laser power generated at 3250A by Stepwise excitation for different values Of the product A= N_eN_{Cd}

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