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Abstract

High potentiality leading to rapid cooling of a high temperature plasma is investigated in a gas contact cooling method in which the effect of finite time for mixing the plasma and the contact gas is considered. The calculation has shown that the cooling is much more rapid than the radiative loss cooling and that the gain per unit length of the HeII 164 nm is ~2cm^{-1} for the laser oscillation under an optimum condition. Possibility of realizing a shorter wavelength laser is also discussed in a plasma with higher charge number Z.

1. Introduction

Recently a considerable interest has been aroused in the amplification of XUV radiation in a rapidly cooling plasma [1-13]. Such a plasma is in a strong nonequilibrium state which usually occurs in rapidly expanding plasmas [1-8] and in decaying plasmas with strong radiation loss [9-13]. Expanding plasmas are accompanied with a decrease of plasma density and it is said that the cooling by the radiation loss is relatively slow. On the other hand, gas contact cooling has a high potentiality for the amplification of XUV radiation. This cooling is mainly caused by the inelastic collisions between electrons and the introduced gas atom, and has two advantages; it is more rapid than the radiation loss cooling, and it does not decrease the plasma density.

An example of mixing a plasma and a gas was presented using a magnetically confined stationary plasma with the TPD-I machine [14]. In a recombining helium plasma due to the interaction with a neutral helium gas not expanding, Sato and others observed a stationary population inversion between the lower lying levels of He^{+} ion, although the gain constant was too small for lasing [15]. This situation will be much more improved if the initial electron density n_{e0} and temperature T_{e0} are considerably increased and the electron temperature T_e is further lowered at a high cooling speed.

In previous papers [16,17] we have theoretically investigated the processes leading to the population inversion in a recombining hydrogen plasma which is interacting with neutral gases. Calculation has been made by using the rate equations on the basis of the collisional-radiative(CR) model under an assumption that the plasma and the gas are instantaneously mixed. In a real experiment, however, the mixing time for the plasma and the contact gas is more or less finite. Then it is very important to consider the influence of the mixing time for obtaining sufficiently strong population inversion.

The main purpose of this paper is to describe a numerical study of a rapid cooling rate and a relatively high gain of the lasing action by gas contact cooling under the consideration of the effect of the mixing time and to make clear the mechanism of electron energy transfer due to collisions between electrons and gas atoms. This will play an important role for promoting the experimental studies of the VUV laser oscillation in a recombining helium plasma (such as TPD-I plasma) in which we can easily control the plasma parameters. Numerical calculation is performed for HeII 164nm line (n = 3→2 transition) as a representative case. Also the effect of charge exchange process between He^{2+} ion and H atom is briefly discussed.

2. Basic Equation

We consider a stationary helium plasma flow in low temperature and high density gas of hydrogen atoms. The plasma is confined by a magnetic field. In this case, the particle confinement time is much longer than the electron temperature decay time. Only the neighbourhood of the center axis of the magnetically confined plasma column is considered. Let the plasma flow velocity along the center axis(z-axis) of the plasma column be constant v_0. We consider in a coodinate system fixed to the flow, i.e., $d/dt = \partial/\partial t + v_0 \, \partial/\partial z$.

The recombining plasma considered here is composed of hydrogen-like He^+ ions, fully stripped He^{2+} ions, He atoms, H^+ions, H atoms and electrons. The time derivative of the population density n_i(He)(cm^{-3}) of energy level i of He atoms is written as

$$\frac{dn_i(\mathrm{He})}{dt} = \sum_{j=1}^{49} a_{ij}(\mathrm{He})\; n_j(\mathrm{He}) + \delta_i(\mathrm{He}) \qquad 1 \le i \le 49. \qquad (1)$$

Here we consider all of the sublevels to be individual levels with different orbital angular momentum l for the principal quantum number $n \le 6$, except that levels with $l \ge 3$ are grouped together in a single level. For the levels $7 \le n \le 20$, all of the sublevels are grouped together. The total number of levels involved in the rate equations is 49. And a_{ij}(He) and δ_i(He) are given by the radiative transition probability (A_{ij}(He), $i<j$) and the optical escape factors Λ_{ij}, and by the rate coefficients for the electron collisional ionization C_{ii}(He) and recombination K_i(He), electron collisional excitation (C_{ij}(He), $i<j$) and deexcitation (C_{ji}(He), $i<j$) and radiative recombination β_i(He); i.e.,

$$a_{ij}(\mathrm{He}) = n_e \, C_{ji}(\mathrm{He}), \qquad j<i$$

$$a_{ii}(\mathrm{He}) = -n_e \sum_{j=1}^{49} C_{ij}(\mathrm{He}) - \sum_{j=1}^{i-1} \Lambda_{ji} A_{ji}(\mathrm{He}),$$

$$a_{ij}(\mathrm{He}) = \Lambda_{ij} A_{ij}(\mathrm{He}) + n_e\, C_{ji}(\mathrm{He}), \qquad j>i$$

$$\delta_i = n_e\, n_1(\mathrm{He}^+)\,[n_e\, K_i(\mathrm{He}) + \beta_i(\mathrm{He})],$$

where $n_1(\mathrm{He}^+)$ is the population density of the ground state of He^+ ion. These coefficients have been given by Fujimoto [18].

Similar equations are used for the population density $n_i(\mathrm{He}^+)$ of energy level i of He^+ ions:

$$\frac{dn_i(\mathrm{He}^+)}{dt} = \sum_{j=1}^{20} a_{ij}(\mathrm{He}^+)\; n_j(\mathrm{He}^+) + \delta_i(\mathrm{He}^+) \qquad 1 \le i \le 20, \quad (2)$$

where $a_{ij}(\mathrm{He}^+)$ and $\delta_i(\mathrm{He}^+)$ except for $a_{11}(\mathrm{He}^+)$ and $\delta_1(\mathrm{He}^+)$ are expressed in the same way as those for He atom by using the rate coefficients for the helium ions given by Johnson [19]. Because the ionization of He atom to the ground level of He^+ ion and the inverse process must be taken into account, $a_{11}(\mathrm{He}^+)$ and $\delta_1(\mathrm{He}^+)$ are complicated :

$$a_{11}(\mathrm{He}^+) = -n_e \sum_{j=1}^{20} C_{1j}(\mathrm{He}^+) - n_e \sum_{j=1}^{49} [K_j(\mathrm{He})\; n_e + \beta_j(\mathrm{He})],$$

$$\delta_1(\mathrm{He}^+) = n_e\, n(\mathrm{He}^{2+})\,[n_e\, K_1(\mathrm{He}^+) + \beta_1(\mathrm{He}^+)]$$

$$+ n_e \sum_{j=1}^{49} C_{jj}(\mathrm{He})\; n_j(\mathrm{He}),$$

where $n(\mathrm{He}^{2+})$ is the stripped helium ion density; the direct ionization-excitation process from the levels of He atom to the excited levels of He^+ ion and the inverse processes are neglected.

The rate equation for the population density $n_i(\mathrm{H})$ of energy level $i(\geq 2)$ of hydrogen atoms is given by

$$\frac{dn_i(H)}{dt} = \sum_{j=1}^{20} a_{ij}(H)\ n_j(H) + \delta_i(H) \qquad 2 \leq i \leq 20, \tag{3}$$

where $a_{ij}(H)$ and $\delta_i(H)$ are expressed in the same way as that of He atom by the rate coefficients for the hydrogen atoms given by Johnson.

We express the effect of the influx of the hydrogen gas by adding a source term to the right hand side of the equation for $dn_1(H)/dt$. It is assumed that the source term is a function of time as $2n_\tau(1/\tau_{mix} - t/\tau_{mix}^2)$ for $0 \leq t \leq \tau_{mix}$ and remains to be zero thereafter; τ_{mix} is the mixing time for the plasma and hydrogen gas and the value n_τ is the density of hydrogen gas at $t=\tau_{mix}$ which would be obtained without the He plasma. We have, therefore,

$$\frac{dn_1(H)}{dt} = \sum_{j=1}^{20} a_{1j}(H)\, n_j(H) + \delta_1(H) + 2.\, n_\tau\left(\frac{1}{\tau_{mix}} - \frac{t}{\tau_{mix}^2}\right),$$

for $0 \leq t \leq \tau_{mix}$. The last term drops for $t > \tau_{mix}$.

The plasma flow velocity is nearly $10^6 \sim 10^7$ cm sec^{-1}, and the mixing time τ_{mix} is assumed to be nearly 10^{-6} sec.

We consider the electron energy equation in the following:

$$\frac{d}{dt}\left(\frac{3}{2}n_e T_e\right) = R_e + Q_e, \tag{4}$$

where the terms of spatial divergence are neglected as in the rate equations; $3/2\ n_eT_e$ denotes the total thermal energy of electrons per unit volume; R_e and Q_e express the rate of increase of the total thermal energy of electrons due to the elastic collisions and the inelastic collisions, respectively. The energy transfer rate due to elastic collisions, R_e, is expressed as

$$R_e = \sum_k \frac{n_e}{\tau_{ek}}(T_k - T_e),$$

where τ_{ek} represents the collision time for the electron-k-species-particle encounters; k=1,2,3,4 and 5 correspond to He^{2+} ion, He^+ ion, H^+ ion, He atom, and H atom, respectively. These values are given by Spitzer for ions [20], and by Golden and Bandel for helium atoms [21], and by Duchs for hydrogen atoms [22].

We make the following assumptions for the transfer of energy between the various particles due to the inelastic collision and radiative processes:

1. In the excitation processes, the kinetic energy of the excited atom does not change before and after the reaction. The excitation energy is supplied by the electron.

2. In the ionization processes, the kinetic energy of the excited atom is transferred to that of the ion without any loss. The ionization energy is supplied by the electron. We neglect the kinetic energy of the released electrons.

3. The energy transfer accompanying the deexcitation

processes and the recombination processes are regarded as the inverse of the transfer in the excitation processes and in the ionization processes, respectively.

4. The energy released in the radiative deexcitation and the inelastic radiative recombination process are carried off by the photon.

Thus, the rate of increase of the thermal energy due to the inelastic collisions, Q_e, is expressed as

$$Q_e=-\sum_k[\sum_{i=2}^{l}\sum_{j=1}^{i-1}(E_j-E_i)(C_{ji}n_j-C_{ij}n_i)+\sum_{j=1}^{l}E_jC_{jj}n_j-n_e n_{ion}\sum_{j=1}^{l}E_jK_j$$

$$+\frac{3}{2}T_e n_{ion}\sum_{j=1}^{l}\beta_j]n_e,$$

where E_i is the ionization energy from level i, l=20,20,49 and k=1,2,3 correspond to the He^+ ion, hydrogen atom and helium atom.

We assume the electric neutrality as follows:

$$n_e = 2\ n(He^{2+}) + n(He^+) + n(H^+), \tag{5}$$

and also sum of the helium ions and atom density to be constant n_0:

$$n_0 = n(He^{2+}) + n(He^+) + n(He), \tag{6}$$

where $n(He^{2+})$, $n(He^+)$, $n(He)$ and $n(H^+)$ are the He^{2+} ion, He^+ ion ,He atom and H^+ ion densities, respectively.

Let the total density of the hydrogen atoms and ions increase at a rate of $2n_T(1/\tau_{mix}-t/\tau_{mix}^2)$ per unit time for $0 \leq t \leq \tau_{mix}$ and remain to be a constant n_T thereafter;

$$\frac{d}{dt}[n(H) + n(H^+)] = 2n_T(1/\tau_{mix} - t/\tau_{mix}^2), \qquad 0 \leq t \leq \tau_{mix},$$
$$= 0, \qquad t > \tau_{mix} \qquad (7)$$

where $n(H)$ is the H atom density.

The mean electron energy is derived from equation (4) by use of the conservation laws eqs.(5) (6) and eq.(7).

$$\frac{dT_e}{dt} = \frac{2}{3}\sum_k \frac{1}{\tau_{ek}}(T_k - T_e) - \frac{2}{3}\sum_k \sum_{i=2}^{l} \sum_{j=1}^{i-1} (E_j - E_i)(C_{ji}n_j - C_{ij}n_i)$$

$$-\frac{2}{3}\sum_k \sum_{j=1}^{l} (E_j + \frac{3}{2}T_e) C_{jj} n_j + \frac{2}{3} n_e n_{ion} \sum_k \sum_{j=1}^{l} (E_j + \frac{3}{2}T_e) K_j . \qquad (8)$$

The terms with factor $3T_e/2$ arise from the variation of n_e due to ionization and recombination processes. We assume that the plasma at $t=0$ is in a steady state with an electron density n_{e0} and temperature T_{e0}. We consider the case that the atom and ion temperature are 0.2eV, and the plasma is optically thin for the helium atom and He^+ ion. For the hydrogen atom, the optical escape factors for the Lyman series lines with the Doppler profile are caluculated simultaneously with eqs. (1) ~ (8) in the manner described in a previous paper [23]. All the other escape factors Λ_{ij} ($j>i\geq 2$) for the hydrogen atom are set to be unity, that is, the hydrogen atom is considered to be optically thin except for Lyman series.

We have made calculation for three cases shown in Table 1. Numerical results are given as a function of time, which were obtained by using a high speed method proposed by Tsuji et al [24]. The population densities of atoms and ions, the electron density and the electron temperature are obtained by integration with the rate equations and energy balance equations (1), (2), (3), (8) and with the differential equation derived from the conservation law (5) and (6) and eq.(7). Integration of the equations was performed by using the Runge-Kutta method.

3. Numerical Results and Discussion

The calculation has been carried out for three cases of the initial conditions listed in Table 1. We determined the initial values of $n_j(\mathrm{He})$ and $n_j(\mathrm{He}^+)$ at $t=0$ by solving eqs. (1) and (2) with the time derivatives set to zero and eq.(5) with zero $n(\mathrm{H}^+)$ for the given values of n_{e0} and T_{e0}=30eV. For case 1 with zero mixing time we have already investigated in the previous paper the behavior of the gas contact recombining hydrogen plasma [16]. However no examination has been presented on the effect of the finite mixing time τ_{mix} as given in cases 2 and 3. A strong over- population density may be produced in the initial plasma in case 3 because it has the optimum initial density as elucidated in the calculation of our preveous paper [25] in which it is assumed that T_e changes with finite decay time τ_E.

Figure 1 shows the assumed time history of the total density of the hydrogen atoms and ions; the ordinate represents $n_T[2t/\tau_{mix}-(t/\tau_{mix})^2]$ for $0\leq t\leq\tau_{mix}$, and n_T for $t>\tau_{mix}$. In the figure, "1", "2" and "3" denote cases 1, 2 and 3, respectively. Figure 2 shows the evolution of T_e in the recombining helium plasma which is interacting with hydrogen atoms. As shown in the figure, the relaxation time of the electron temperature, τ_E, in case 3 is about 10^{-7}sec. Figure 3 shows the evolution of the over-population density of He^+ ion $\Delta n_{32} = n_3/\omega_3 - n_2/\omega_2$, where ω_i is the statistical weight of level i of He^+ ion. It can be seen from the results in cases 1 and 2 that the maximum value of the over-population density $[\Delta n_{32}]_{max}$ with the finite mixing time is smaller than that in the instantaneous mixing but the decrement is very small, while the results of cases 2 and 3 show that the strongly growing of $[\Delta n_{32}]_{max}$ is produced by the recombining plasma with the optimum initial electron density.

Figure 4 shows the evolution of n_e, $n(He^{2+})$, $n(He^+)$ and $n(H^+)$ in case 3, which are shown in solid, dashed, dot-dashed and dot-dot-dashed curves, respectively. Figure 5 shows the evolution of n_i/ω_i (i=1,2,3) of He^+ and H in case 3 by dot-dashed, solid and dashed curves, respectively. The curves labeled "He^+" and "H" represent the reduced population density for He^+ ion and H atom. Up to $t\sim\tau_E$ = 10^{-7}sec these population densities continue to be almost constant and increase abruptly in low electron temperature phase of $t>10^{-7}$sec.

The electron density is raised with the development of mixing of the plasma and gas, He^{2+} ions start to be recombined strongly with growing electron density (Figs. 1, 4) and a large Δn_{32} is produced simultaneously (Figs. 3, 4). The relaxation time of the electron temperature, τ_E, is about 10^{-7}sec (Fig. 2), and the over population density Δn_{32} attains the maximum value $[\Delta n_{32}]_{max} = 5\times10^{12}cm^{-3}$ at $t\sim2\times10^{-7}$sec (Fig. 3). The plasma is cooled before the plasma electron density decreases and Δn_{32} is abruptly raised with a sudden decrease in $n(He^{2+})$. Note that the gas contact cooling is not accompanied with decrease of the plasma electron density in contrast to the case of the adiabatic expansion cooling.

In the following the mechanisms of electron energy transfer are mainly discussed for the optimum case 3 as an typical example. Figure 6 shows the evolution of the absolute value of the total electron energy loss rate $-dT_e/dt$ and the electron energy loss rates due to ionization, excitation and elastic collisional processes and the electron energy gain rates due to recombination and deexcitation processes. The dashed curve and solid curve show the absolute value of the energy outflux from and influx to electrons, respectively. The effect of ionization nearly compensates for that of the recombination, and most effects of the excitation and the deexcitation processes at $t>10^{-7}$sec compensate for each other. The cooling in the time range ($t>10^{-7}$sec) is mainly produced by the elastic collision between electrons and H^+ ion.

Figure 7 shows the absolute values of the sums of the third and fourth terms of the right hand side of eq.(8), which are sums of the electron energy loss rate due to all the ionization processes and of the electron energy gain rate due to all the three body recombination processes. Figure 8 shows the absolute value of a sum of the second term of the right hand side of eq.(8), which is a sum of the total electron energy loss rate due to all the excitation processes and of the total electron energy gain rate due to all the deexcitation processes. In the figures, the dashed section of the curve means that the energy loss exceeds the gain, and the solid section means that the energy gain is larger than the energy loss. "H", "He^+" and "He" denote the sums for hydrogen atom, for He^+ ion and for helium atom, respectively. Since the transferred energy due to single ionization or recombination process is the sum of the level energy and the kinetic energy of an electron as shown in eq.(8), in the high temperature plasma the transferred energy is larger than that due to single excitation or deexcitation process. Hence it is recognized that in very early time ,($t<5\times10^{-8}$sec), the energy loss of the plasma with high temperature is mainly due to the ionization of hydrogen atoms.

Figure 9 shows the evolution of the decay rate of T_e and of the electron energy transfer rate due to the ionization from the ground state of the hydrogen atom, which is labeled "$1\rightarrow C$"in the figure. The evolution of the sum of the electron energy transfer rate by ionization and recombination of the hydrogen atom and by elastic collisions is also shown. It can be seen from the figure that in very early time ($t<5\times10^{-8}$sec) the electron energy transfer is mainly caused by the ionization from the ground state of the hydrogen atom. After then, the energy transfer due to electron inelastic collisions yields an influx to electrons through strong recombination. But this influx energy transfer to electrons is overcomed by the cooling due to the elastic collision mainly between electrons and H^+ ions.

Since the energy loss of electrons is mainly due to the ionization of hydrogen atoms and the elastic collision between electrons and H^+ ions, it is recognized from eq.(8) that the cooling rate of T_e depends on the hydrogen atom density but not on the initial electron density. Therefore, at a recombining plasma with higher ionic charge numbers Z, a sufficiently large Δn_{32} will be obtained as shown by Bohn [26], if a plasma flow in a steady state of initial high temperature T_e ($n_e \sim Z^7 \times 10^{14} cm^{-3}$)) is contacted with the high density cold gas ($n(H) \sim n_e$).

Here, we show that the gas contact cooling is enough effective compared with radiation loss cooling. Since the radiation cooling is principally due to line radiations from ions and atoms, the cooling rate is given nearly by $\sim F\sum(n_i/n_e)A_{1i}h\nu_{i1}$, where h is Planck's constant, ν_{i1} is the frequency of the line radiated from levels i to the ground level of ions and atoms, and the factor $F \sim 3$ takes into account the radiation losses from the other levels of ions and atoms as shown by Suckewer [9]. At $t \sim \tau_E \sim 10^{-7}$sec (Fig. 5), the order of magnitude of the cooling rate is given by the line radiation from level 2 of He^+ ion, which is expressed by the large population density $n_2(He^+)$ and the large radiativ transition probability ($A_{11}(He^+)$) and the energy ($h\nu_{i1}(He^+)$), i.e., ~ ($(n_2(He^+)/n_e)A_{12}(He^+)h\nu_{21}(He^+)$). Since the population density $n_2(He^+)$ and the electron density are nearly $1.5\times10^{10}cm^{-3}$ (as shown in Fig.5) and $3.6\times10^{16}cm^{-3}$ (as shown in Fig.4), respectively, and the radiative transition probability A_{12} and the emitted photon energy $h\nu_{21}$ are $7.5\times10^{9}sec^{-1}$ and 41eV, respectively, the order of magnitude of the rate is $3\times10^{4}eVsec^{-1}$. The cooling due to the inelastic collision is mainly caused by the ionization process from the ground state of hydrogen atoms. The cooling rate is thus $n_1(H)C_{11}(H)(E_1+3T_e/2)$. At $t\sim\tau_E$, the ground state population density of hydrogen atoms $n_1(H)$, the ionization rate coefficient $C_{11}(H)$ and the value of the energy $E_1+3T_e/2$ are $1\times10^{14}cm^{-3}$, $2\times10^{-8}cm^{3}sec^{-1}$ and 45eV, respectively. Therefore, the cooling rate is $9\times10^{7}eVsec^{-1}$. Note that the gas contact cooling is very effective compared with the radiation loss cooling.

The gain per unit length of HeII 164nm line, κ, is expressed as $\kappa=\omega_3\sigma_{32}\Delta n_{32}$, where ω_3 is the statistical weight of level 3, σ_{32} is the cross section for stimulated emission with the line width broadend by the Stark effect taken into account [9]. Our calculation in case 3 shows the maximum value of Δn_{32} of about $\sim5\times10^{12}cm^{-3}$. We estimate κ to be about $2.cm^{-1}$ for the above recombining plasma with $\Delta n_{32}\sim5\times10^{12}cm^{-3}$. Since such high gain can be realized only in optically thin plasmas, let us consider a thin sheet plasma flow. If the sheet has a width of $l\geq5cm$, the total gain κl will be more than 10 in the transverse direction to the plasma flow. In this plasma, we can expect the laser oscillation of the 164nm line of HeII. Furthermore, stationary oscillation may be possible because of the steady plasma flow.

The charge exchange process

$$He^{2+} + H(1s) \rightarrow He^{+} + H^{+}$$

may be considered to destroy the population inversion between levels 2 and 3 of He^{+} because the charge exchange cross section has a resonance character for level 2 of He^{+} ion, and increases the population of level 2. The charge exchange cross section σ_{ex} for the above process is given by Fite et al [28]. For the particle with a velocity (~ the plasma flow velocity $v_0 \sim 10^6$cm/sec) relative to the contact gas the cross section σ_{ex} is $\sim 10^{-16}$cm^2 and the rate coefficient $\langle\sigma_{ex}v_0\rangle$ is nearly 10^{-10}cm^{3}sec^{-1}. At $t \sim \tau_E$, the relaxation time of the charge exchange process τ_{ex} is $(\langle\sigma_{ex}v_0\rangle n_1(H))^{-1} \sim 10^{-4}$sec since the ground state population density of hydrogen atoms is $\sim 10^{14}$cm^{-3}. On the other hand the decay time of the fully stripped ion He^{2+} by CR process is nearly 10^{-7}sec as shown in Fig. 4. Therefore, it can be said that the charge exchange process has no effect on the over-population density in the recombining helium plasma cooled by the hydrogen gas contact.

4. Conclusion

The gas contact cooling is very effective compared with the radiation loss cooling. That is, in the case of an optimum initial plasma condition as n_{e0}=3.53×10^{16}cm^{-3} and T_{e0}=30eV, a rapid cooling time τ_E of 10^{-7}sec is obtained for a contact hydrogen gas of density 3.53×10^{16}cm^{-3}, where the finite mixing time of the plasma and the contact gas is considered. The gain per unit length of the HeII 164nm line is ·stimated to be ~2.cm^{-1}. This indicates that the laser oscillation will be possible if a sheet plasma flow with a width of more than 5cm is produced.

Since the plasma is cooled before the plasma density decreases, a large Δn_{32} is obtaind owing to a fast recombination of a high density cooling plasma. Namely it merits attention that the cooling is not due to the decrease in plasma density in contrast to the adiabatic expansion.

The principal inelastic collision process which contributes to the cooling is the ionization from the ground state of the gas atom. The cooling speed depends generally on the gas pressure and does not on the plasma density. Therefore, the plasma with high charge number Z can be cooled rapidly by the gas contact method, and the laser oscillation is expected in the short wavelength.

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Figure Captions

Fig.1. Time history of the assumed total density of H atoms and H^- ions in cases 1, 2 and 3. The ordinate represents $n_T[2t/\tau_{mix}-(t/\tau_{mix})^2]$ for $0 \leq t \leq \tau_{mix}$, n_T for $t > \tau_{mix}$.

Fig.2. Time history of the electron temperature T_e. "1" means T_e in case 1.

Fig.3. Time history of the over population densities Δn_{32} of He^+ ion in cases 1, 2 and 3.

Fig.4. Time history of the densities in case 3; n_e (solid curve), $n(He^{2+})$ (dashed curve), $n(He^+)$ (dot-dashed curve) and $n(H^+)$ (dot-dot-dashed curve).

Fig.5. Reduced population densities in case 3: n_1/ω_1 (dot-dashed curve), n_2/ω_2 (solid curve) and n_3/ω_3 (dashed curve).

Fig.6. Total electron energy transfer rate and the electron energy transfer rate for the ionization, recombination, excitation, deexcitation and elastic collision processes in case 3. "ionization" means the absolute value of the electron energy loss rate due to ionization and "recombination" means the electron energy gain rate due to the total collisional recombination.

Fig.7. Sum of the electron energy transfer rate by ionization and collisional recombination for H, He, He^+ in case 3.

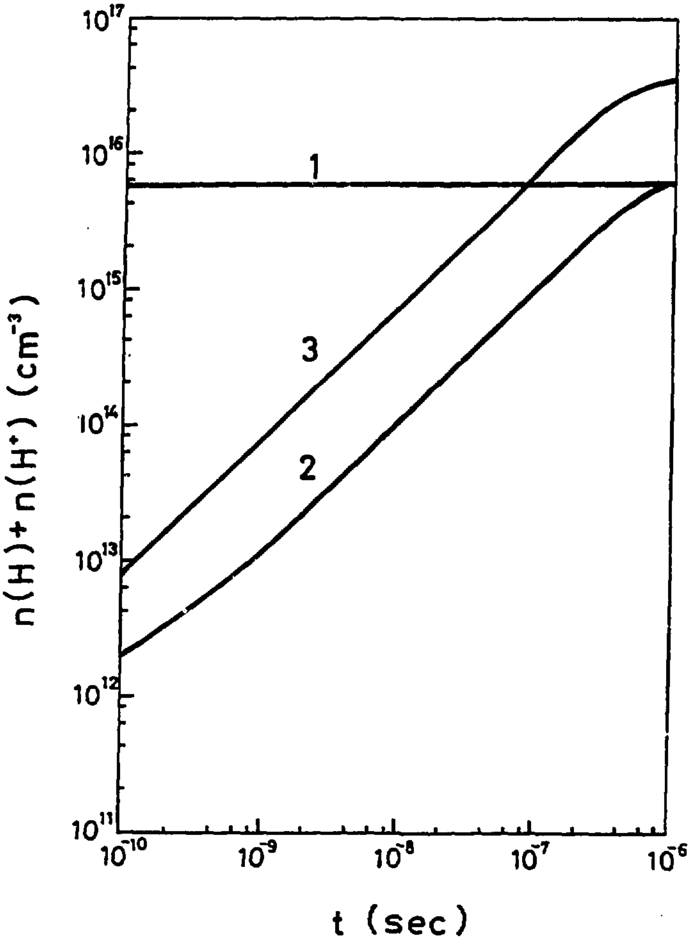
Fig.8. Sum of the electron energy transfer rate by excitation and collisional deexcitation for H,

He, and He^+ in case 3 vs.

Fig.9. Time history of the total electron energy transfer rate "$-\dot{T}_e$", the electron energy transfer rate by all elastic collision "elastic" ,the sum of electron energy transfer rate by ionization and recombination for H atom "ionization+recombination", the electron energy transfer rate due to the ionization from the ground state of H atom, "1→C" in case 3.

Table 1. Initial conditions

Case	n_{e0} (cm^{-3})	n_T (cm^{-3})	τ_{mix} (sec)
1	3.53×10^{15}	5.31×10^{15}	0
2	3.53×10^{15}	5.31×10^{15}	10^{-6}
3	3.53×10^{16}	3.53×10^{16}	10^{-6}



10^{17}
10^{16}
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
1
3
2
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
t (sec)
$n(H)+n(H^{+})$ (cm^{-3})

Fig. 1

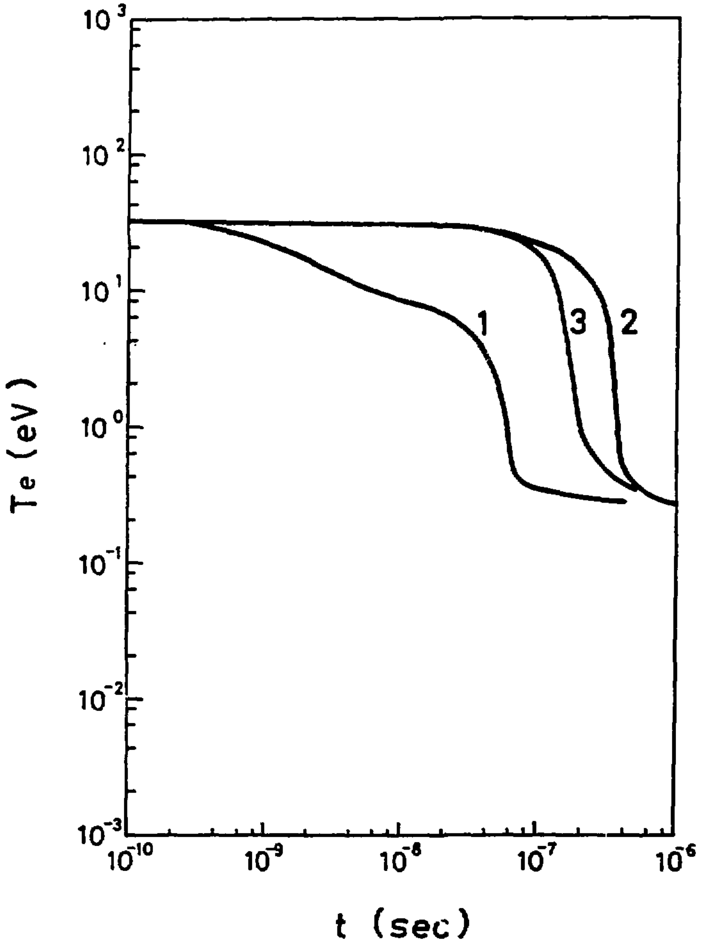
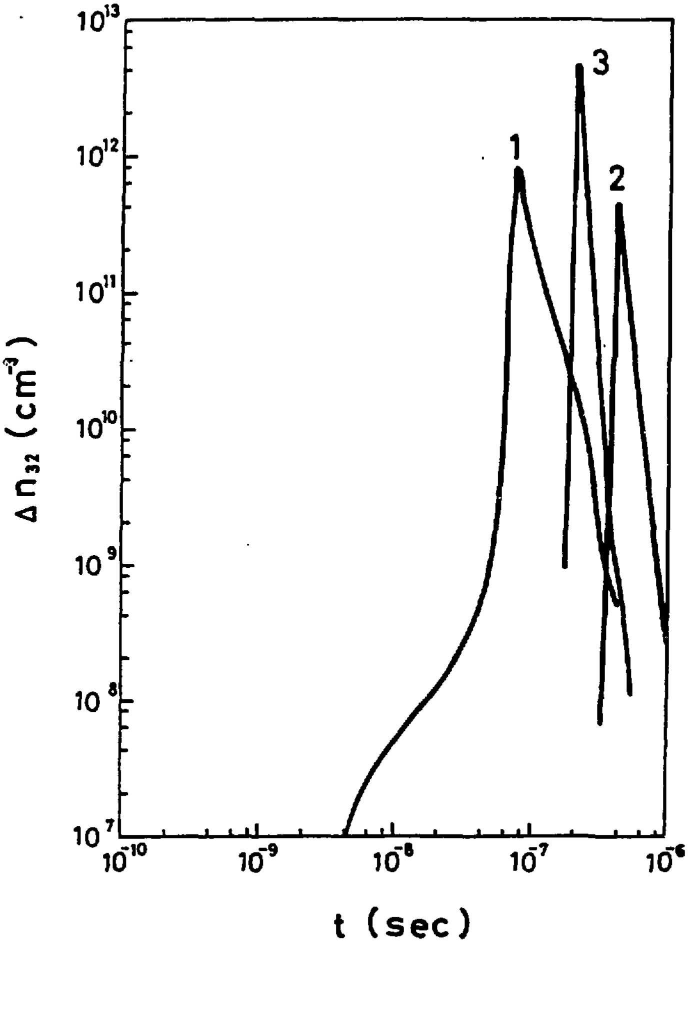


Fig. 2



Δn_{32} (cm^{-3})
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
t (sec)
1
2
3

Fig. 3

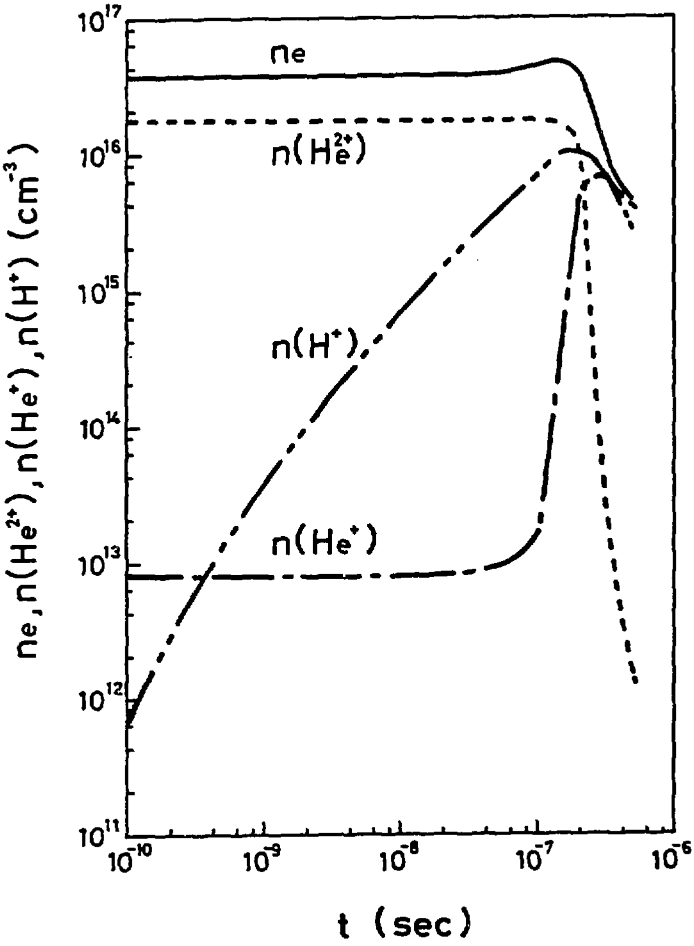
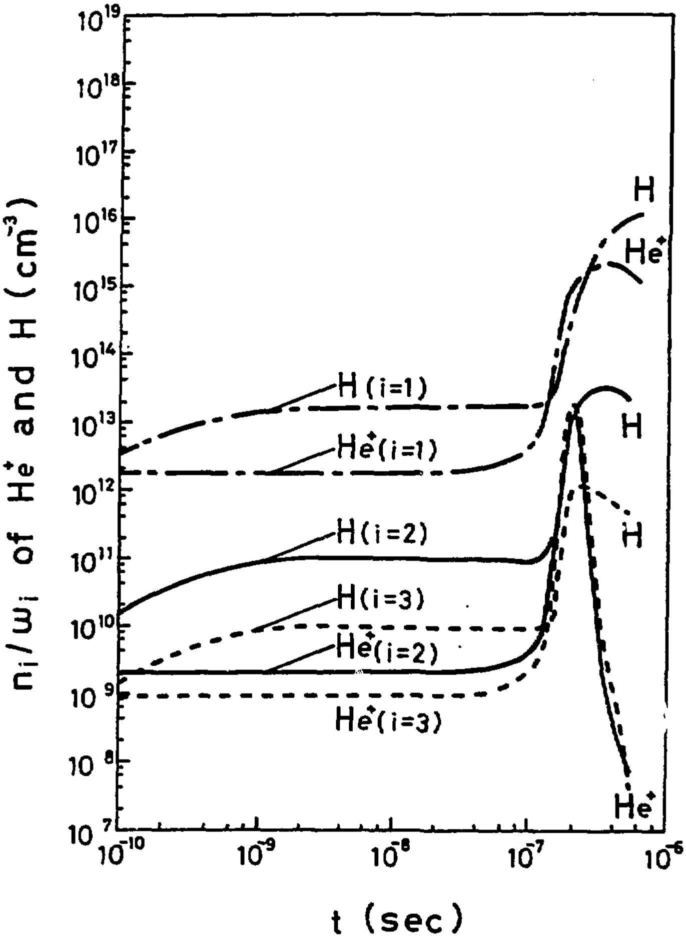

ne
n(He2+)
n(H+)
n(He+)
ne, n(He2+), n(He+), n(H+) (cm-3)
10^17
10^16
10^15
10^14
10^13
10^12
10^11
10^-10
10^-9
10^-8
10^-7
10^-6
t (sec)

Fig. 4



n_i/ω_i of He^+ and H (cm^{-3})
t (sec)
H (i=1)
He^+(i=1)
H (i=2)
H (i=3)
He^+(i=2)
He^+(i=3)
H
He^+
H
H
He^+

Fig. 5

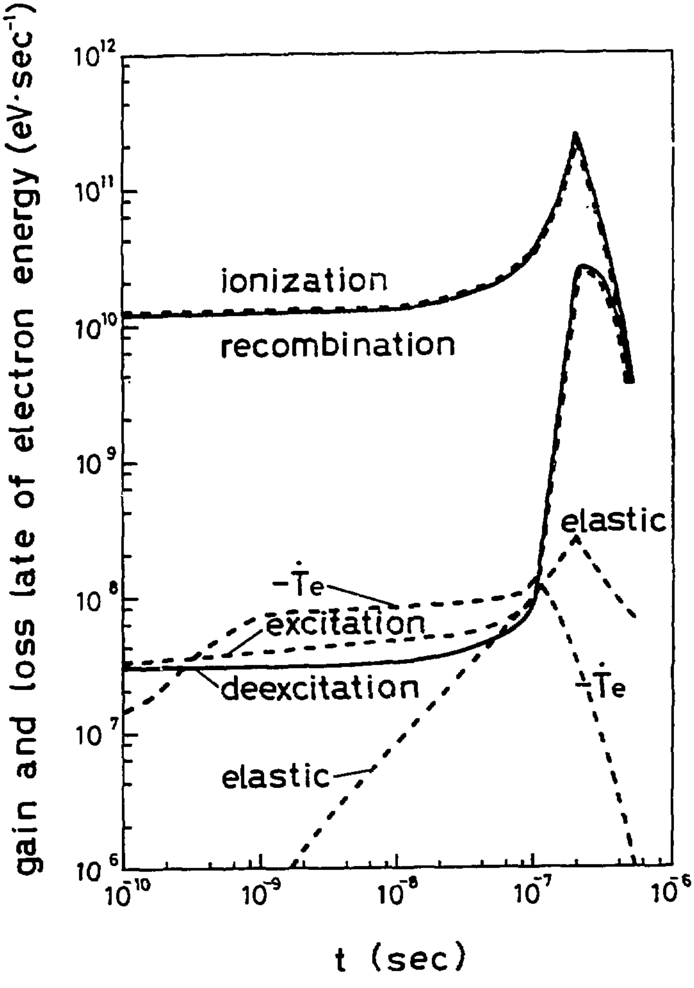

gain and loss late of electron energy (eV·sec⁻¹)
10^12
10^11
10^10
10^9
10^8
10^7
10^6
10^-10
10^-9
10^-8
10^-7
10^-6
t (sec)
ionization
recombination
elastic
−Ṫe
excitation
deexcitation
−Ṫe
elastic

Fig. 6

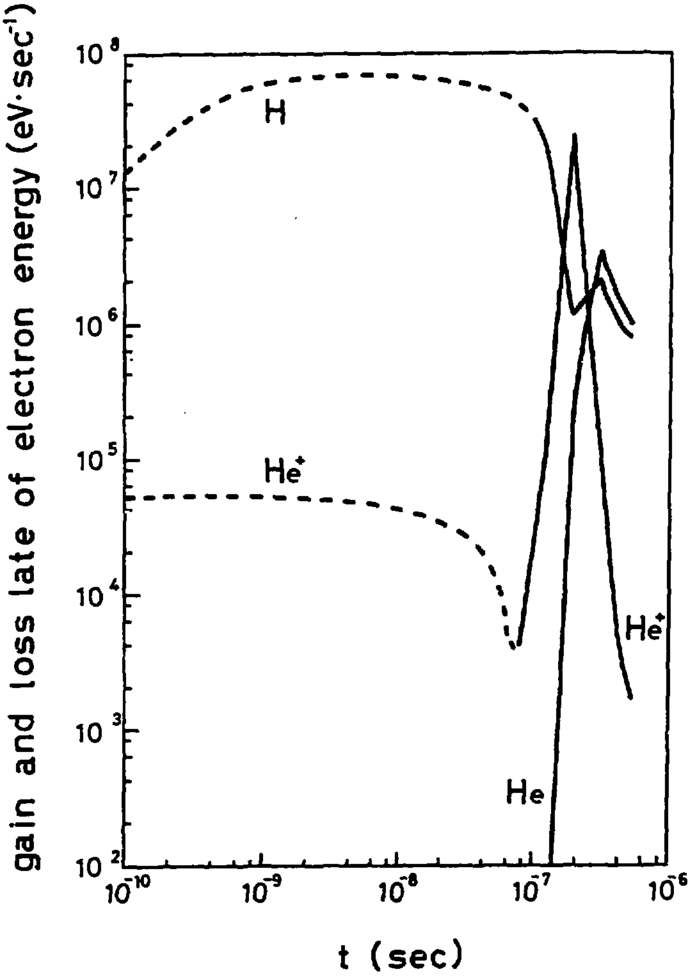

gain and loss late of electron energy (eV·sec⁻¹)
10 8
10 7
10 6
10 5
10 4
10 3
10 2
H
He+
He
He+
10-10
10-9
10-8
10-7
10-6
t (sec)

Fig. 7

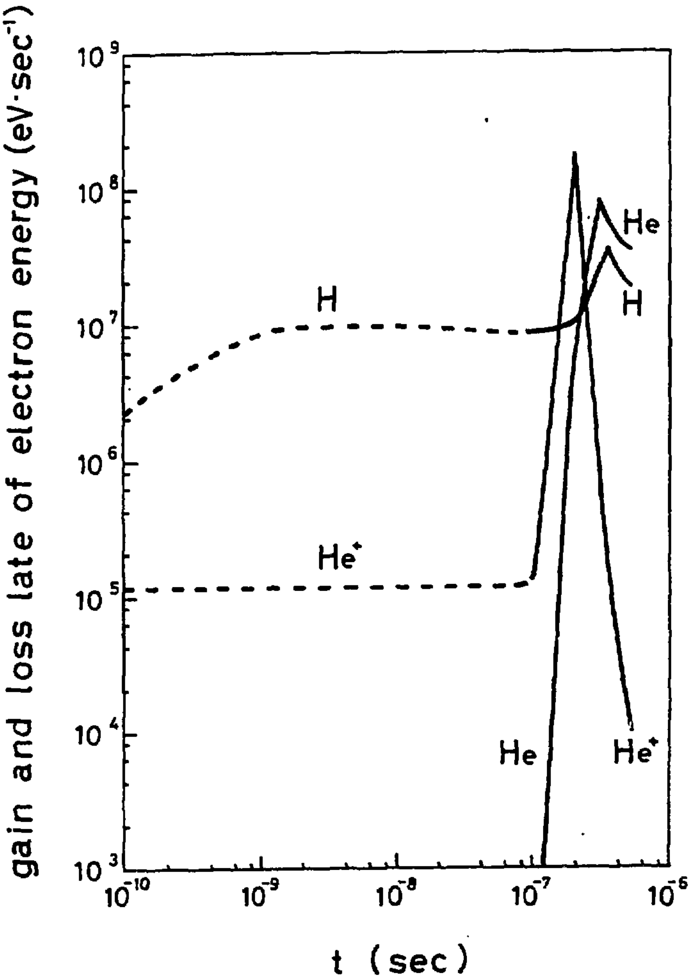
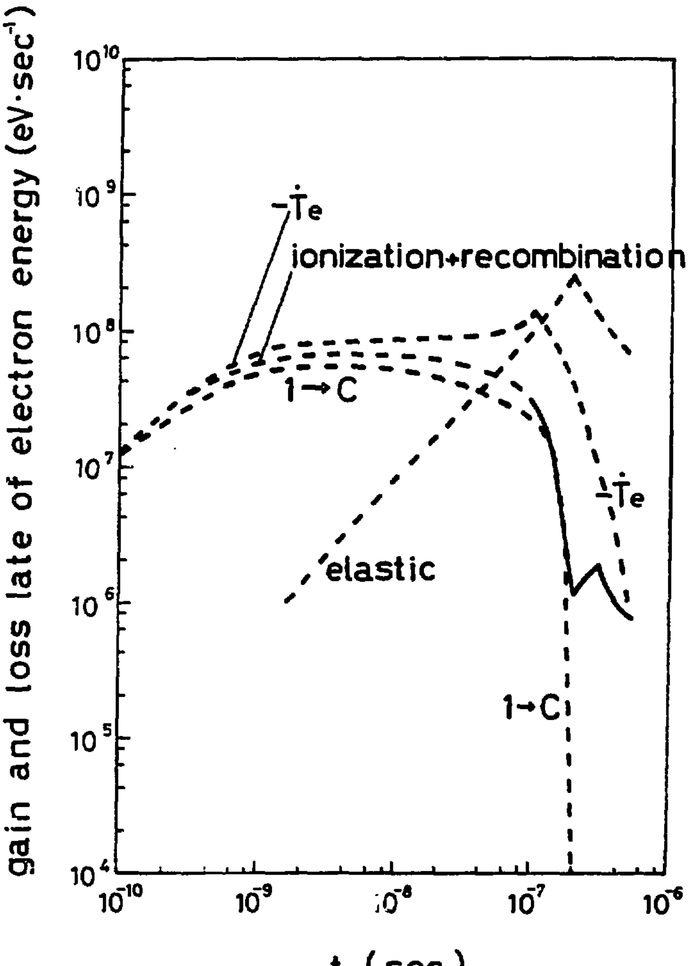

gain and loss late of electron energy (eV·sec-1)
10 9
10 8
10 7
10 6
10 5
10 4
10 3
10-10
10-9
10-8
10-7
10-6
t (sec)
H
He+
He
H
He
He+

Fig. 8



gain and loss late of electron energy (eV·sec⁻¹)
10¹⁰
10⁹
10⁸
10⁷
10⁶
10⁵
10⁴
-Ṫe
ionization+recombination
1→C
elastic
-Ṫe
1→C
10⁻¹⁰
10⁻⁹
10⁻⁸
10⁻⁷
10⁻⁶
t (sec)

Fig. 9