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Critical electron density in a self-contained a copper vapour laser in the restricted pulse repetition rate

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Abstract. One of the mechanisms of the inversion breaking in copper vapour lasers caused by a high prepulse electron density is considered. The inversion breaking occurs at a critical electron density $N_{\rm e\,cr}$. If the prepulse electron density exceeds $N_{\rm e\,cr}$, the electron temperature $T_{\rm e\,cr}$ cannot achieve during a plasma heating pulse, a temperature of ~ 2 eV required for lasing. A simple estimate of $N_{\rm e\,cr}$ is made.

1. Introduction

A vast number of papers have been devoted to the study of copper vapour lasers (see references in reviews and books [1 – 4]). However, the fundamental question of factors that restrict the pulse repetition rate in self-contained copper lasers is still raising debates among researchers involved in the studies of these lasers for dozens of years. Petrash et al. [5 – 7] explained the restriction of the repetition rate by the residual (remained after a previous pulse) population of the lower metastable operating state of an atom. Bokhan et al. [8 – 13] believe that the repetition rate is restricted due to a large residual electron density, which, in their opinion, prevents a fast heating of electrons and increases the rate of population of metastable levels during a pulse. The results of calculations [14] also suggest that a large prepulse electron density can affect the efficiency of copper vapour lasers.

The study of the problem of restriction of the pumping pulse repetition rate in copper vapour lasers was recently reviewed by Petrash [15]. This review contains corresponding references, and the author notes, in particular, that the restriction mechanism itself related to a high initial electron density has still not been developed in detail (see p. 19 in [15]). This paper is devoted to the development of this mechanism.

Of course, the factors that restrict the repetition rate can be studied using a detailed self-consistent computer model of a copper vapour laser. Such models have been developed in papers [14, 17 – 19]. They are intended for a comparatively complete analysis of both kinetic processes in a laser tube and variations in currents and voltages in an electric circuit. However, these models are not only complicated but also include necessarily some parameters of a discharge that are not adequately known. Because we would like to demonstrate the nature of the restrictions in an explicit form, the factors restricting the initial electron density are analysed below using simple kinetic models, which are directly based on the experimental time dependences of the current density. This allows us to estimate the critical electron density in a simple way. The known restriction on the electron temperature from below is used as a necessary condition for producing the population inversion.

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2. Kinetic models

Because the characteristic pumping time is three orders of magnitude shorter than the time between pulses, it makes sense to consider two models of the time behaviour of properties of the copper vapour laser plasma. One model describes the development of the plasma ionisation under the action of a heating pulse, and another model describes the plasma afterglow. Results of calculations performed within the framework of these models allow one to find the initial conditions for each of them.

2.1. Plasma ionisation during pumping

Basic equations. The kinetic model of ionisation of a mixture of copper vapours by a heating pulse includes equations for the density of ions of copper and inert gas, $N_{\rm i\,Cu}$ and $N_{\rm i\,Ne}$, and also the thermal balance equation for the electron temperature $T_{\rm e}$:

$$\frac{{\rm d}N_{\rm i\,Cu}}{{\rm d}t} = k_{\rm i\,Cu}N_{\rm e}(N_{\rm Cu} - N_{\rm i\,Cu}),$$

$$\frac{{\rm d}N_{\rm i\,Ne}}{{\rm d}t} = k_{\rm i\,Ne}N_{\rm e}(N_{\rm Ne} - N_{\rm i\,Ne}), \qquad (1)$$

$$\frac{\rm d}{{\rm d}t}\left(\frac{3}{2}N_{\rm e}T_{\rm e}\right) = -Q_{\rm i\,Cu} - Q_{\rm i\,Ne} - Q_{\Delta T} + \frac{1}{\sigma}j^2(t).$$

Here, $N_{\rm e} = N_{\rm i\,Cu} + N_{\rm i\,Ne}$ is the electron density, $k_{\rm i\,Cu}$ and $k_{\rm i\,Ne}$ (in cm^3 c^{-1}) are the ionisation rates of copper and neon atoms, respectively (hereafter, the rate $k_{\rm X}$ of the binary process X represents a product of the cross section $\sigma_{\rm X}$ for this process by the velocity $k_{\rm X} = \langle\sigma_{\rm X}v\rangle$) of the relative motion of the particles averaged over the Maxwell distribution); $N_{\rm Cu}$ and $N_{\rm Ne}$ are densities of heavy particles (ions and neutral atoms) of copper and neon;

$$Q_{\rm i\,Cu} = J_{\rm i\,Cu}k_{\rm i\,Cu}N_{\rm e}(N_{\rm Cu} - N_{\rm i\,Cu}),$$
$$Q_{\rm i\,Ne} = J_{\rm i\,Ne}k_{\rm i\,Ne}N_{\rm e}(N_{\rm Ne} - N_{\rm i\,Ne}) \qquad (2)$$

is the power density spent to ionise copper and neon; $J_{\mathrm{i\,Cu}} = 7.73$ eV and $J_{\mathrm{i\,Ne}} = 21.6$ eV are the ionisation energies of copper and neon;

$$Q_{\Delta T} = 2\left(\frac{m_{\mathrm{e}}}{m_{\mathrm{Ne}}} k_{\mathrm{Ne}} N_{\mathrm{Ne}} + \frac{m_{\mathrm{e}}}{m_{\mathrm{Cu}}} k_{\mathrm{ei}} N_{\mathrm{e}}\right) N_{\mathrm{e}} (T_{\mathrm{e}} - T_{\mathrm{g}}) \tag{3}$$

is the power density spent to cool electrons in elastic collisions with neon atoms and copper ions; k_{Ne} and k_{e} are the rates of elastic collisions of electrons with neon atoms and copper ions; m_{e} is the electron mass; m_{Ne} and m_{Cu} are masses of neon and copper atoms; T_{g} is the gas temperature; and

$$\sigma = \frac{e^2 N_{\mathrm{e}}}{m_{\mathrm{e}}} (k_{\mathrm{Ne}} N_{\mathrm{Ne}} + 1.96 k_{\mathrm{ei}} N_{\mathrm{e}})^{-1} \tag{4}$$

is the plasma conductivity. The factor in the second term in parentheses is approximately equal to two because a small group of conduction electrons collide not only with ions but also with many other electrons. The value 1.96 is given, for example, in Ref. [20].

The last term in the right-hand side of the thermal balance equation for electrons describes the Joule heating, which is proportional to the square of the current density. Below, we will take the time dependence of the current density $j(t)$ from the experimental data.

The reaction rates used. The elastic collision rates are described by the expressions

$$k_{\mathrm{Ne}} = (T_{\mathrm{e}}/1\,\mathrm{eV})^{1/2} 8.9 \times 10^{-9}\,\mathrm{cm}^3\ \mathrm{s}^{-1},$$
$$k_{\mathrm{ei}} = \frac{4\sqrt{\pi}\, e^4 \Lambda}{3\, T_{\mathrm{e}}^2} \left(\frac{2T_{\mathrm{e}}}{m_{\mathrm{e}}}\right)^{1/2}, \quad \Lambda = \frac{1}{2} \ln\left(1 + \frac{T_{\mathrm{e}}^3}{2e^6 N_{\mathrm{e}}}\right). \tag{5}$$

The cross section σ_{Ne} for the elastic scattering of an electron with the neon atom was assumed equal to 1.5×10^{-16} cm^{-2}, and the known expressions from Refs [20, 21] were used for Coulomb collisions.

The ionisation rates of copper and neon are described by the expressions

$$k_{\mathrm{i\,Cu}} = 2 \times 10^{-7} F(E^*_{\mathrm{Cu}}/T_{\mathrm{e}})\,\mathrm{cm}^3\ \mathrm{s}^{-1},$$
$$k_{\mathrm{i\,Ne}} = 4 \times 10^{-10} F(E^*_{\mathrm{Ne}}/T_{\mathrm{e}})\,\mathrm{cm}^3\ \mathrm{s}^{-1},\ F(x) = 0.5\mathrm{e}^{-x}/x^{1/2}, \tag{6}$$

where $E^*_{\mathrm{Cu}} = 3.8$ eV and $E^*_{\mathrm{Ne}} = 16.6$ eV. The ionisation rates of copper and neon were assumed equal to the excitation rate of the resonance states. This is true for the quasi-stationary ionisation when each excitation event is accompanied by the excited-state ionisation event (see details in [21, 22]). The fitting function $F(x)$ well describes the dependence of the excitation rate of the $^2P_{3/2}$ resonance state on the electron temperature [18, 26].

2.2. Afterglow

The kinetic model of the afterglow is quite simple and it was well studied upon analysis of the kinetics of plasma lasers [22]. This model includes the equations for the electron density and temperature:

$$\frac{\mathrm{d}N_{\mathrm{e}}}{\mathrm{d}t} = C_{\mathrm{r}} T_{\mathrm{e}}^{-9/2} N_{\mathrm{e}}^3,$$
$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{3}{2} N_{\mathrm{e}} T_{\mathrm{e}}\right) = E_{\mathrm{r}} C_{\mathrm{r}} T_{\mathrm{e}}^{-9/2} N_{\mathrm{e}}^3 - Q_{\Delta T}. \tag{7}$$

Here,

$$C_{\mathrm{r}} = \frac{4}{5} \frac{2^{5/2}\pi^{3/2}}{9} \frac{e^{10}}{\sqrt{m_{\mathrm{e}}}} \Lambda = 5.8 \times 10^{-26}\,\mathrm{eV}^{9/2}\,\mathrm{cm}^6\ \mathrm{s}^{-1} \tag{8}$$

is a constant characterising the triple recombination rate [22–24] and $E_{\mathrm{r}} \approx J_{\mathrm{i\,Cu}} = 7.73$ eV is the energy released per recombination event.

3. Analysis of experiments

3.1. The choice of initial data

Some plasma parameters. The mechanism of the inversion breaking will be illustrated using the plasma parameters that are close to the parameters observed in detailed experiments [6] (see also [4, 15, 16]). In these experiments, a commercial laser tube with an inner diameter $d = 20$ mm and length $l = 40$ cm was used, which operated at a neon pressure of 300 Torr and a pulse repetition rate of 10 kHz. The mean excitation power was 2 kW. The time dependences of the current and voltage were measured (the peak value of the current was 300 A). The role of metastable levels was studied by the method of paired pulses [5]. The populations of metastable and resonance levels were measured by the method of resonance absorption for various delays Δt of the second pulse with respect to the main pulse. For short delays ($\Delta t < 15$ μs), the amplification was absent because the population of the metastable state during the pulse action was higher than that of the resonance level (Fig. 1).

Among the parameters specified, there is no direct experimental data on the gas temperature and the initial electron density. Consider these questions.

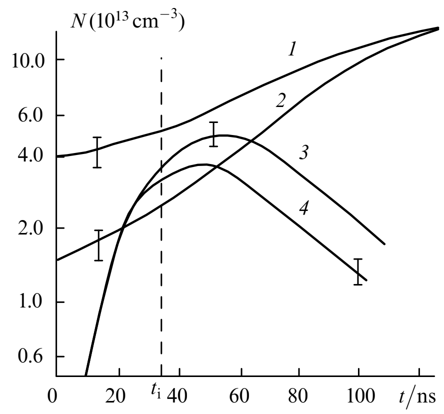

Figure 1. Time dependences of populations of the $^2D_{5/2}$ metastable level (*1*, *2*) and the $^2P_{3/2}$ resonance level (*3*, *4*) of a copper vapour laser during pulsed excitation for delays $\Delta t = 15$ (*1*, *4*) and 70 μs (*2*, *3*). The data are taken from review [15].

The gas temperature. The distribution of the gas temperature over the radius r of a long tube is commonly described by the expression [15]

$$T_{\mathrm{g}}(r) = \left[T_{\mathrm{w}}^{b+1} + \left(1 + \frac{4r^2}{d^2}\right) \frac{W_{\mathrm{d}}(b+1)}{4\pi A}\right]^{1/(b+1)}. \tag{9}$$

Here, the gas thermal conductivity is approximated by the expression $\kappa = A T_{\mathrm{g}}^b$ (for neon, $A = 8.96 \times 10^{-6}$ W cm^{-1} K$^{1.683}$

and $b = 0.683$ [4]), T_w is the wall temperature; d is the tube diameter; and W_d is the mean linear power (the input power per tube unit length.) It is assumed that the total input power is spent on gas heating.

For the linear power $W_d = 2$ kW/40 cm and the wall temperature $T_w = 1590$ °C $= 0.161$ eV, the ratio of the temperature on the tube axis to the wall temperature is $T_g(0)/T_w = 2$. In calculations, the mean gas temperature $T_g = 1.5T_w$ was used.

Density of copper vapours. The populations N_m of the metastable levels, in particular, at the initial moment are reported in Refs [4, 6, 15, 16]. Assuming that the population of the metastable level is related to the ground-state population by the Boltzmann distribution, we obtain for the density of copper vapours

$$N_{Cu} = N_m(2/6)\exp(1.389\,\mathrm{eV}/T_{e0}) \approx 4\times10^{15}\ \mathrm{cm}^{-3}, \quad (10)$$

where $T_{e0} \approx 1.22T$ is the initial electron temperature (see below); $N_m \sim 10^{13}$ cm^{-3} is the prepulse population of metastable levels. Based on the experimental data, we used in our calculations a somewhat lower value $N_{Cu} = 2\times10^{15}$ cm^{-3}.

The initial electron density and temperature. The initial electron density N_{e0} and temperature T_{e0} in the problem of plasma ionisation were taken from calculations of the afterglow. For calculations of the afterglow, these parameters were taken from the solution of the problem of plasma ionisation. To make the initial and final electron densities and temperatures involved in these problems consistent, the iteration calculations were performed. As a result, the following values were obtained for the initial electron density and temperature before pulses following with a period of 100 μs: $N_{e0} \approx 2.3\times10^{13}$ cm^{-3} and $T_{e0} = 1.22T$ for the initial conditions of the ionisation problem; and $N_{e0} \approx 3.3\times10^{14}$ cm^{-3} and $T_{e0} \sim 1$ eV for the initial conditions of the afterglow problem. The electron temperature and density for other moments of the afterglow are presented in Fig. 2.

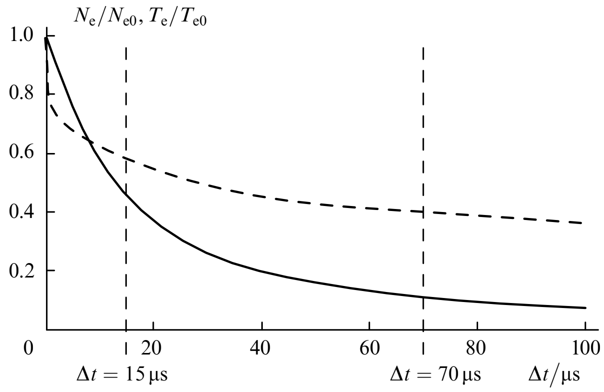

Figure 2. Time dependences of the electron density (solid curve) and electron temperature (dashed curve) in the afterglow for $N_{e0} = 3.3\times10^{14}$ cm^{-3} and $T_{e0} = 1$ eV.

3.2. Results of calculations

Figs 3 and 4 present the results of calculations for different initial electron densities. These densities correspond approximately to moments $\Delta t = 70$ and 15 μs in the afterglow of the previous pumping pulse in experiments [4, 6, 15, 16]. The parameters required for calculations are listed below.

The neon density . . . . $N_{Ne} = 1.5\times10^{18}$ cm^{-3}
The copper vapour density . . . . $N_{Cu} = 2\times10^{15}$ cm^{-3}
The gas temperature . . . . $T_g = 2800$ K
The length and diameter of a plasma column . . . . $L = 40$ cm, $d = 2$ cm
The peak current and peak current density . . . . $J_{max} = 300$ A, $j_{max} = 95.5$ A cm^{-2}
The initial electron density and temperature in the afterglow . . . . $N_{e0} = 3.2\times10^{14}$ cm^{-3}, $T_{e0} = 0.8$ eV
The prepulse electron density in the afterglow for delays 100, 70, and 15 μs, respectively . . . . $N_{e0} = 2.6\times10^{13}$, 3.7×10^{13} and 1.5×10^{13} cm^{-3}

One can see from Figs 3b and 4b that a major part of the power supplied to the medium by Joule heating is spent on the copper ionisation. Only a small fraction of the input power is

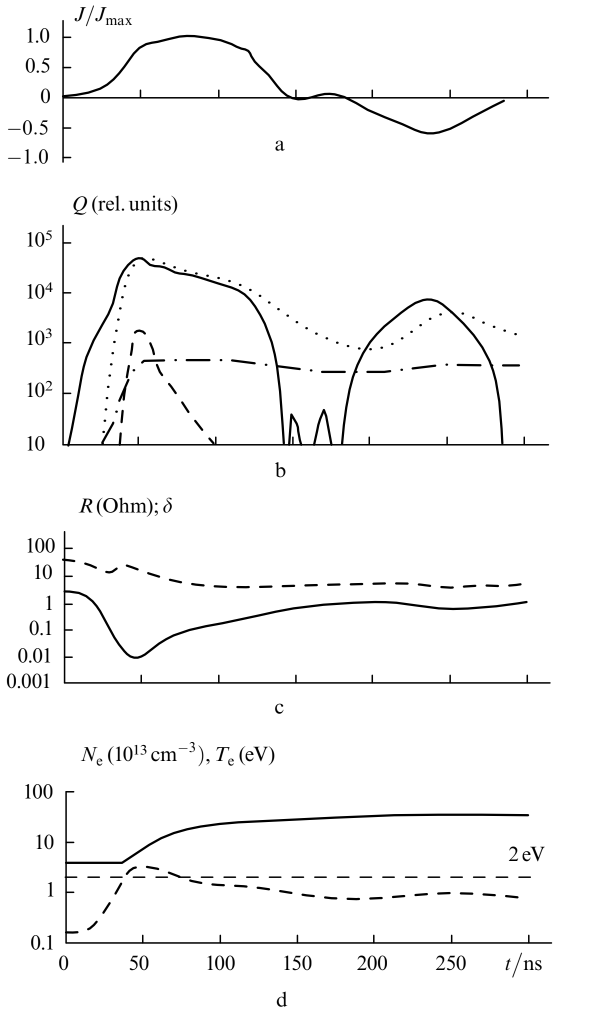

Figure 3. Time dependences of the current and characteristics of a plasma during the heating pulse for the initial electron density $N_{e0} = 3.7\times10^{13}$ cm^{-3}, which approximately corresponds to $\Delta t = 70$ ns for the afterglow (Figs 1 and 2):
(a) current $J(t)$ passing through a tube (experiments [4, 6, 15, 16]); (b) power supplied to the medium (Joule heating $j^2(t)/\sigma$) (solid curve); power Q_{iCu} spent for ionisation of copper (dashed curve); power Q_{iNe} spent for ionisation of neon (dashed curve) and power $Q_{\Delta T}$ spent for gas heating in elastic collisions (dashed-dotted curve); (c) ratio of the contribution from Coulomb collisions to the plasma conductivity to the contribution from elastic collisions with neon $\delta = k_{Ne}(T_e)N_{Ne}/2k_{ei}(T_e)N_e$ (solid curve) and the plasma column resistance R (dashed curve); (d) $N_e(t)$ (solid curve) and $T_e(t)$ (dashed curve).

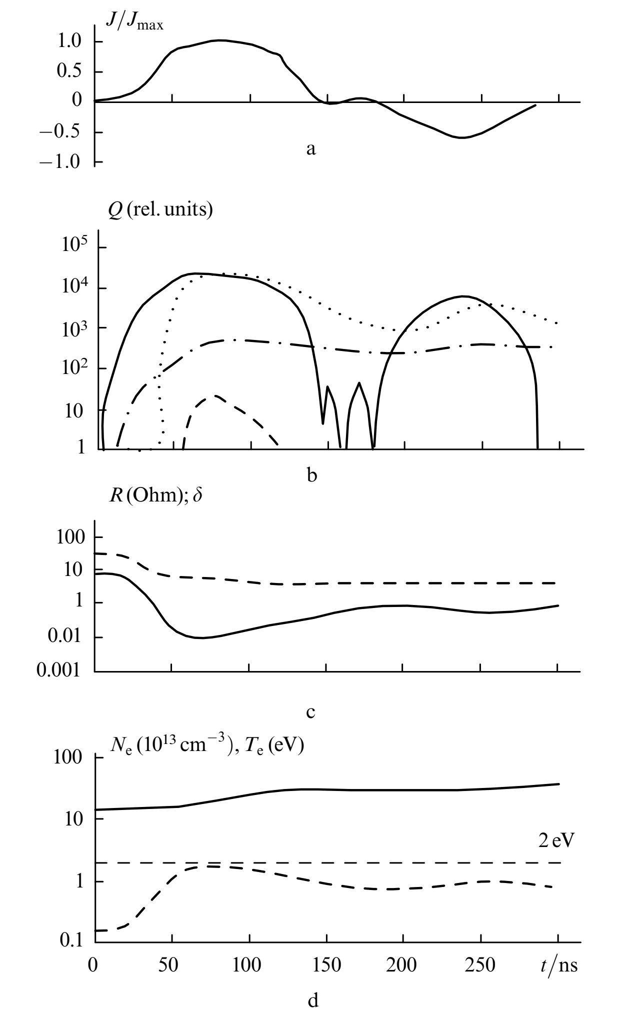

Figure 4. The same as in Fig. 3, but for the initial electron density $N_{e0} = 1.5 \times 10^{14}$ cm^{-3}, which approximately corresponds to $\Delta t = 15$ μs **for the afterglow (Figs 1 and 2).**

spent on gas heating due to elastic collisions and to the neon ionisation. The electron temperature reaches a maximum at the moment when the power supplied to the medium becomes equal to the power spent to the ionisation. This occurs already at the interval where the beam current increases. The presence of the maximum of the electron temperature is a very important condition for the achievement of lasing (see below).

In the case of a high neon density under study, elastic collisions with neon atoms dominate over Coulomb collisions with electrons and ions at all stages of the ionisation; i.e., the plasma resistance is mainly determined by collisions with neon atoms. The calculations show that, in the case of a low neon density, the Coulomb collisions dominate during a much longer period of time and determine the plasma resistance at the initial time, which was pointed out in Ref [25].

4. Critical electron density

It is known that to produce the inverse population of operating levels in a copper laser, the electron temperature should exceed a critical temperature $T_{e\,cr} \approx 2$ eV. For $T_e < T_{e\,cr}$, metastable states are excited by electrons more efficiently than resonance levels so that the inversion does not appear [15, 16]. At the same time, as was already mentioned, the electron temperature reaches a maximum already at the interval of the current growth. If the maximum temperature proves to be lower than the critical temperature $T_{e\,cr}$, lasing is impossible. In turn, the possibility of achieving high electron temperature is substantially limited by the initial electron density. Consider this question in more detail.

The power supplied to a medium is proportional to the plasma resistance; i.e., it is inversely proportional to the electron density. At the same time, the power spent for ionisation is proportional to the electron density (see (1)). Therefore, there exists the critical electron density for a given current density and a given electron temperature beginning from which the power supplied to the medium will be lower than the power spent for ionisation.

The equation for the critical electron density $N_{e\,cr}$ can be obtained by equating the power supplied to the medium at the peak current density j_{max} to the power spent for ionisation of copper at the critical electron temperature:

$$\frac{j_{max}^2 m_e}{e^2 N_{e\,cr}} \left[k_{Ne}(T_{e\,cr}) N_{Ne} + 2k_{ei}(T_{e\,cr}) N_{e\,cr}\right]$$

$$= J_{i\,Cu} k_{i\,Cu}(T_{e\,cr}) N_{e\,cr} N_{Cu}. \qquad (11)$$

From here, we obtain the following expression for the critical electron density

$$N_{e\,cr} = N_{e\,cr0}\left[a + (a^2 + 1)^{1/2}\right], \qquad (12)$$

where

$$N_{e\,cr0} = \frac{j_{max}}{e}\left(\frac{m_e k_{Ne}(T_{cr}) N_{Cu}}{J_{Cu} k_{i\,cr} N_{Ne}}\right)^{1/2} \qquad (13)$$

is the critical density for the case when the conductivity is determined by collisions with neutral particles: $k_{Ne}(T_{e\,cr}) N_{Ne} \gg k_{ei}(T_{e\,cr}) N_{e\,cr}$;

$$a = \frac{k_{ei}(T_{e\,cr}) N_{e\,cr0}}{k_{Ne}(T_{e\,cr}) N_{Ne}} \qquad (14)$$

is a dimensionless quantity, which is substantial in the cases when Coulomb collisions make an appreciable contribution to the conductivity.

The boundary degree of ionisation at which the contributions from Coulomb collisions and collisions with neutral particles become equal ($a = 1$) is determined by the expression

$$\frac{N_{e\,cr0}}{N_{Ne}} = \frac{K_{Ne}(T_{e\,cr})}{k_{ei}(T_{e\,cr})} \approx 5 \times 10^{-4}. \qquad (15)$$

When the initial electron density exceeds the critical one ($N_e > N_{e\,cr}$), the lasing is impossible in principle, even if the prepulse population of the metastable levels will be negligibly small for some reasons. This does not mean, of course, that lasing necessarily occurs when $N_e < N_{e\,cr}$.

A simple estimate presented above can be confirmed by direct calculations. For example, for $T_{e\,cr} = 2$ eV, $j_{max} =$ 95 A cm^{-2}, and $N_{Cu} = 2 \times 10^{15}$ cm^{-3}, the critical electron density $N_{e\,cr} = 1.6 \times 10^{14}$ cm^{-3}. The calculated initial electron density $N_{e0} = 1.5 \times 10^{14}$ cm^{-3} (Fig. 4) shows that the electron temperature is indeed insufficient for lasing.

According to the above calculations of the afterglow (see Fig. 2) related to the experiments [4, 6, 15, 16], the electron density N_{e0} within 15 μs after the pulse end is 1.5×10^{14} cm^{-3}, being close to the critical electron density. The experiments with paired pulses (Fig. 1) showed that when the second pumping pulse was supplied within 15 μs after the first pulse end, the population of the resonance level was lower than that of the metastable level during the entire pumping pulse. If the second pulse was supplied within 70 μs after the first pulse end, the initial electron density $N_{e0} = 3.7 \times 10^{13}$ cm^{-3} was lower than the critical electron density.

This does not mean that the high initial electron density is the only reason for the generation breaking upon a small delay of the paired pulse in experiments [4, 6, 15, 16]. The high initial population of the metastable levels also impedes the inversion conditions. Nevertheless, it is clear that even when the population of metastable levels is zero, the inversion can be broken because of a high residual electron density.

5. Conclusions

Consider briefly two basic mechanisms resulting in the inversion breaking.

Concerning the restrictions caused by the prepulse density of metastable levels, note the following. Under the conditions being discussed, the relaxation time of metastable levels caused by collisions with electrons is far shorter than the time between pumping pulses. A high prepulse density of the metastable levels is explained not by the fact that they have no time to decay before the arrival of the next pulse but by a comparatively high prepulse electron temperature, which provides the population of these levels due to electronic excitation from the ground state. Therefore, the restrictions related to the prepulse density of metastable levels are caused not by the residual density of the latter but by the relaxation time of the electron temperature and a high gas temperature. The difference between the gas and electron temperature can be reduced by various methods, for example, by increasing the buffer gas density and replacing neon by helium, and also by using small molecular additions. It is possible that a high density of copper vapours at low gas temperatures can be achieved by using pulsed evaporation.

The restriction of the prepulse electron density should be reduced in another way. The electron density decreases between pulses significantly slower than the electron temperature. Even at the electron temperature equal to the gas temperature, the recombination time can substantially restrict the pulse repetition rate. To increase the repetition rate, the peak current density should be increased and the power supplied to a plasma should be decreased by simultaneously increasing the buffer gas density. The consideration of specific methods for achieving these goals, in particular, analysis of the kinetics of molecular mixtures is beyond the scope of this paper.

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