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On limitation of the pulse repetition rate in copper vapour laser associated with prepulse electron density

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***Abstract*. Limitations imposed on the pulse repetition rate due to the presence of the prepulse electron density are considered. The existence of the critical prepulse electron density formulated by S I Yakovlenko [*Quantum Electron.* v. 30, No. 6, p. 501 (2000)] is analysed. It is shown that the approach adopted in this paper does not prove the existence of critical density.**

Keywords: *copper vapour laser, limitation of the pulse repetition rate.*

1. Introduction

The factors limiting the pulse repetition rate in a laser on transitions from resonance to metastable levels (r – m transitions) in a copper atom are of prime importance for this laser, as well as for other lasers of this class. For this reason, these factors have been discussed by many authors right from the moment of creation of such lasers. In fact, we are speaking of the processes determining the attainable lasing parameters. The history of this problem and the corresponding literature are presented in Refs [1 – 3]. In particular, the limitations imposed on the pulse repetition rate by the prepulse electron density remaining after an incomplete recombination of plasma in the time period between pulses have been considered by many authors (mainly on qualitative level).

In a recent publication [4], Yakovlenko made an attempt to clarify the origin of limitations of the pulse repetition rate using simple kinetic models. Such attempts are commendable since the conclusions concerning the effect of the prepulse electron density on laser action were drawn exclusively from qualitative considerations (see Refs [2, 3]). Yakovlenko [4] suggested the existence of a critical prepulse electron density at which population inversion is ruled out in principle. However, in our opinion, the results obtained in this work were based on too simplified models and approaches leading to dubious estimates and conclusions. The present work is devoted to an analysis of these models and conclusions and estimates based on them.

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2. Kinetic models

The kinetic models used in Ref. [4] are based on the equations for ionisation of copper and the buffer gas as well as the heat balance equation for the electron temperature:

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

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

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

where $N_{\mathrm{e}} = N_{\mathrm{i\,Cu}} + N_{\mathrm{i\,Ne}}$ is the electron density; $k_{\mathrm{i\,Cu}}$, and $k_{\mathrm{i\,Ne}}$ are the ionisation rates for Cu and Ne atoms (in cm^3 s^{-3}); $N_{\mathrm{i\,Cu}}$ and $N_{\mathrm{i\,Ne}}$ are the densities of copper and neon ions; $j^2(t)/\sigma$ is the density of the power supplied to the medium;

$$\begin{aligned} Q_{\mathrm{i\,Cu}} &= J_{\mathrm{i\,Cu}} k_{\mathrm{i\,Cu}} N_{\mathrm{e}} (N_{\mathrm{Cu}} - N_{\mathrm{i\,Cu}}), \\ Q_{\mathrm{i\,Ne}} &= J_{\mathrm{i\,Ne}} k_{\mathrm{i\,Ne}} N_{\mathrm{e}} (N_{\mathrm{Ne}} - N_{\mathrm{i\,Ne}}) \end{aligned} \tag{2}$$

are the densities of the power spent for ionising copper and neon; $J_{\mathrm{i\,Cu}} = 7.73$ eV, $J_{\mathrm{i\,Ne}} = 21.6$ eV are the ionisation energies for 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 density of power spent for cooling electrons due to elastic collisions with Ne atoms and Cu ions; m_{Ne}, m_{Cu} are the masses of Ne and Cu atoms; T_{e} is the electron temperature; T_{g} is the gas temperature; k_{Ne}, k_{ei} are the rate constants for elastic collisions of electrons with Ne atoms and Cu ions; m_{e} is the electron mass;

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

is the plasma conductivity. Here, we have used the notation adopted in Ref. [4].

The following dependence of the rate constant on T_{e} was used in calculations: $k_{\mathrm{Ne}} = (T_{\mathrm{e}}/1\,\mathrm{eV})^{1/2} 8.9 \times 10^{-9}$ cm^3 s^{-1}; i. e., it was assumed that the transport cross section for neon is constant and equal to 1.5×10^{-16} cm^2. For Coulomb collisions, the familiar expressions were used [5, 6]. The ionisation rate constants for copper and neon (in cm^3 s^{-1}) were described by the formulas

$$k_{\mathrm{i\,Cu}} = 2{\cdot}10^{-7}F\left(\frac{E^*_{\mathrm{Cu}}}{T_{\mathrm{e}}}\right), \quad k_{\mathrm{i\,Ne}} = 4{\cdot}10^{-10}F\left(\frac{E^*_{\mathrm{Ne}}}{T_{\mathrm{e}}}\right), \qquad (5)$$

where $F(x) = 0.5\,\mathrm{e}^{-x}/x^{1/2}$; $E^*_{\mathrm{Cu}} = 3.8$ eV, $E^*_{\mathrm{Ne}} = 16.6$ eV are the energies of the resonance states of copper and neon. Thus, the ionisation rates for copper and neon were assumed to be equal to the excitation rate of resonance states, which corresponds to instantaneous ionisation of these states, when each excitation event is accompanied by an instantaneous ionisation event. This means that we consider the maximum possible ionisation rate, because the excitation rates for resonance levels exceed the rates of direct ionisation and excitation of other levels under conditions typical of the copper vapour laser (CVL).

The processes occurring in the periods between pulses were described by the three-body recombination equations:

$$\frac{\mathrm{d}N_{\mathrm{e}}}{\mathrm{d}t} = C_{\mathrm{r}}T_{\mathrm{e}}^{-9/2}N_{\mathrm{e}}^3,$$
$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{3}{2}N_{\mathrm{e}}T_{\mathrm{e}}\right) = E_{\mathrm{r}}C_{\mathrm{r}}T_{\mathrm{e}}^{-9/2}N_{\mathrm{e}}^3 - Q_{\Delta T}. \qquad (6)$$

Here, $C_{\mathrm{r}} = 5.8\times10^{-26}$ eV$^{9/2}$ cm^6 s is the three-body recombination rate constant and $E_{\mathrm{r}} = 7.73$ eV is the energy released during a recombination act; i.e., it was assumed that the entire energy released during recombination is spent for heating electrons, while their cooling occurs during elastic collisions with neon atoms and ions. As a matter of fact, a fraction of energy is also carried away by plasma radiation and due to diffusion of ions and metastable atoms to the walls. The estimates of the fraction of energy carried away by each of these processes from the total amount of energy introduced into the medium are given for a specific CVL in Ref. [7].

3. Critical electron density

Consider first the most fundamental question concerning the existence of critical prepulse electron density. Yakovlenko proceeded from the fact that there exists an electron temperature $T_{\mathrm{e\,cr}}$ below which electrons predominantly populate the metastable (lower) levels rather than the resonance (upper) levels. Consequently, no population inversion is created if we always have $T_{\mathrm{e}} < T_{\mathrm{e\,cr}}$ in the process of excitation. Further, since the power density j^2/σ introduced into the medium is inversely proportional to N_{e} in accordance with (1), while the power losses for ionisation are directly proportional to N_{e}, Yakovlenko [4] draws the following conclusion: 'Consequently for a given current density and a given electron temperature, there exists a critical density of electrons starting from which the power introduced into the medium is lower than the power spent for ionisation.' This means that electrons will not be heated to the required temperature.

The equation for the critical electron number density $N_{\mathrm{e\,cr}}$ is derived in Ref. [4] by equating the power introduced into the medium for the peak current density $j_{\max}$ to the power spent for the ionisation of copper at the critical electron temperature:

$$\frac{j^2_{\max}}{\sigma(T_{\mathrm{e\,cr}})} = \frac{j^2_{\max}m_{\mathrm{e}}}{e^2N_{\mathrm{e\,cr}}}\left[k_{\mathrm{Ne}}(T_{\mathrm{e\,cr}})N_{\mathrm{Ne}} + 2k_{\mathrm{ei}}(T_{\mathrm{e\,cr}})N_{\mathrm{e\,cr}}\right]$$
$$= J_{\mathrm{i\,Cu}}k_{\mathrm{i\,Cu}}(T_{\mathrm{e\,cr}})N_{\mathrm{e\,cr}}N_{\mathrm{Cu}}\,, \qquad (7)$$

whence

$$N_{\mathrm{e\,cr}} = N_{\mathrm{e\,cr0}}\left[a + (a^2+1)^{1/2}\right], \qquad (8)$$

where

$$N_{\mathrm{e\,cr0}} = \frac{j_{\max}}{e}\left[\frac{m_{\mathrm{e}}k_{\mathrm{Ne}}(T_{\mathrm{e\,cr}})N_{\mathrm{Ne}}}{J_{\mathrm{i\,Cu}}k_{\mathrm{i\,Cu}}(T_{\mathrm{e\,cr}})N_{\mathrm{Cu}}}\right]^{1/2} \qquad (9)$$

is the critical electron density in the case when the conduction is determined by collisions with neutral particles; i.e., for $k_{\mathrm{Ne}}(T_{\mathrm{e\,cr}})N_{\mathrm{Ne}} \gg 2k_{\mathrm{ei}}(T_{\mathrm{e\,cr}})N_{\mathrm{e\,cr}}$;

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

is the dimensionless parameter. [Note that in formula (13) for $N_{\mathrm{e\,cr0}}$ in Ref. [4], N_{Cu} and N_{Ne} are erroneously interchanged (probably, because of unlucky number of the formula).]

On the basis of the above estimate, the following conclusion is drawn: 'If the initial density of electrons is higher than the critical density ($N_{\mathrm{e}} > N_{\mathrm{e\,cr}}$), the generation is impossible in principle even if the prepulse population of metastable energy levels becomes negligible for some reason'.

However, this conclusion and the formula for $N_{\mathrm{e\,cr}}$ given above are doubtful. The fact is that formulas (7)–(9) contain j, which is itself a function of N_{e}, including the prepulse electron density $N_{\mathrm{e}}(0)$, since it is well known that the value of $j_{\max}$ and the current front steepness $\mathrm{d}J/\mathrm{d}t$ increase with $N_{\mathrm{e}}(0)$ (see, for example, Refs [8, 9]) and the kinetics of discharge evolution naturally changes somehow on the whole. Since an increase in $N_{\mathrm{e}}(0)$ leads to an increase in $j_{\max}$ and in the power introduced, it cannot be ruled out that the increase in the latter quantity may compensate the energy expenditures for electron heating (especially at the beginning of the excitation pulse) since the value of $\mathrm{d}J/\mathrm{d}t$ also increases. Consequently, the value of $N_{\mathrm{e\,cr}}$ cannot be estimated correctly from an expression containing a quantity which is a function of N_{e} and $N_{\mathrm{e}}(0)$.

Note also that in the above formulas, it is apparently assumed that the quantity $j^2_{\max}/\sigma(T_{\mathrm{e\,cr}})$ is the maximum power introduced into the medium over the excitation pulse duration. However, the peak of the current does not correspond at all to the peak of the power introduced under typical operation conditions for CVL (see, for example, the oscillograms for current, voltage and introduced power pulses in Refs [9–11]). The substitution of $\sigma(T_{\mathrm{e\,cr}})$ for σ corresponding to the peak current generally does not guarantee the maximum introduced power.

Actually, all the plasma parameters, including $j(t)$, $N_{\mathrm{e}}(t)$, and $T_{\mathrm{e}}(t)$, are determined by the field $E(t)$ applied to it, which is an extrinsic parameter that can be varied over a wide range in experiments. Consequently, it would be more appropriate to estimate the electron heating and the effect of $N_{\mathrm{e}}(0)$ by expressing the introduced power in terms of E rather than in terms of j. It is well known that the power introduced in the medium is equal to $jE = j^2/\sigma = \sigma E^2$. Let us estimate the value of $N_{\mathrm{e\,cr}\,0}$ by using formula (9); i.e., we use the same model of kinetics, but express the power introduced through E, which allows us to take into account the dependence of power on N_{e}. For simplicity, we assume that $a \ll 1$ since it does not change the situation and will not affect the subsequent analysis. In this case, we obtain the following expressions instead of (7):

$$\sigma E_{\max}^2 = \frac{eE_{\max}^2 N_{\mathrm{e\,cr}}}{m_{\mathrm{e}} k_{\mathrm{Ne}}(T_{\mathrm{e\,cr}}) N_{\mathrm{Ne}}} = J_{\mathrm{i\,Cu}} k_{\mathrm{i\,Cu}}(T_{\mathrm{e\,cr}}) N_{\mathrm{e\,cr}} N_{\mathrm{Cu}}\,, \quad (10)$$

whence

$$eE_{\max}^2 = [J_{\mathrm{i\,Cu}} k_{\mathrm{i\,Cu}}(T_{\mathrm{e\,cr}}) N_{\mathrm{Cu}}][m_{\mathrm{e}} k_{\mathrm{Ne}}(T_{\mathrm{e\,cr}}) N_{\mathrm{Ne}}]. \quad (11)$$

One can see that Eqn (11) does not contain $N_{\mathrm{e\,cr}}$ at all and this equation can be written for any instant of time. This means that in the model adopted by us, the power introduced for any N_{e} may exceed the ionisation loss as well as any other losses proportional to N_{e} for an appropriate choice of E, which in turn indicates that $N_{\mathrm{e\,cr}}$ does not exist and inversion may be obtained for any value of $N_{\mathrm{e}}(0)$. Thus, without changing the approach, we arrive at the opposite conclusion concerning $N_{\mathrm{e\,cr}}$ taking into account the dependence of j on N_{e} and expressing the introduced power in terms of an extrinsic parameter.

Although the conclusion drawn above is more substantiated, it should not be overrated since the above analysis is based on a too rough simplification. The expression for energy losses adopted in Ref. [4] and used by us so far cannot provide an adequate description of the energy losses and the kinetics of excitation and ionisation in CVL since it presumes instantaneous ionisation from the resonance level. This means that an atom excited to the resonance level immediately goes to a higher energy level; for this reason, the population of the resonance level cannot be appreciable, and we cannot speak of a population inversion.

It follows from an analysis of kinetics [10] and detailed calculation [11] as well as from general considerations that in actual practice the ionisation of copper under the standard conditions is stepwise and there exists a time period at the beginning of an excitation pulse during which the population of resonance levels increases rapidly. In other words, the rate of pumping $k_{0\mathrm{r}} N_0 N_{\mathrm{e}}$to the resonance level is much higher than the rate $k_{\mathrm{ri}} N_{\mathrm{r}} N_{\mathrm{e}}$ of transitions to upper levels [here, N_0 and N_{r} are the populations of the ground and resonance states and $k_{0\mathrm{r}}$ and k_{ri} are the rate constants for the excitation from the ground level to the resonance level and from the resonance level to higher levels (inverse processes are disregarded in this case)].

During this period, the rates of transition from the ground state and of copper ionisation are still low, and the population inversion takes place just in this period. The instant when these rates become equal upon a decrease in N_0, increase in N_{r}, and a variation of T_{e} approximately corresponds to the maximum of N_{r} and to the end of inversion, because the population of metastable levels increases during the excitation pulse.

Thus, the model used in Ref. [4] overestimates losses and ionisation rate during the time period corresponding to the existence of population inversion and, hence, lowers the attainable electron temperature. In addition, since the ionisation is mainly indirect, its rate is not necessarily proportional to N_{e}, and the dependence of the ionisation rate on N_{e} may change during the excitation pulse. In this connection, an analysis based on formulas (1) and (2) does not guarantee an adequate description of the effect of prepulse electron density.

It should also be noted that some difficulties are encountered in maintaining the required value of $E(t)$. In particular, it is not always possible to ensure a rapid increase in voltage in the discharge gap at the initial stages of the excitation pulse. This is determined to a considerable extent by the operation speed of the commutator and is predominantly a technical problem which can be solved in various ways, for example, using peaking capacitances, magnetic compression cells, and faster commutators such as vacuum tubes. An analysis of pulsed power supply systems ensuring the required time dependence of voltage across the discharge gap is beyond the scope of this paper.

It should be pointed out, however, that the value of $E(t)$ in the active zone of the discharge depends not only on the power supply system, but also on the processes at the electrodes and in the cold regions near the electrodes, which are free of metal vapours. This problem was considered in our previous publications [2, 3, 12, 13], where it was proved that the improvement of the $E(t)$ front under certain conditions in the active medium is possible as a result of rapid redistribution of voltage between the cathode and electrode regions and the active discharge zone.

In the case when a fairly steep wave front of the increase in $E(t)$ cannot be ensured in the active zone, the existence of a high prepulse electron density may indeed considerably deteriorate, and even disrupt, the generation since there exists a long period during which metastable levels are populated predominantly even if the value of T_{e} is rather high over a certain period during the excitation pulse and $j_{\max}$ may attain high values. It follows hence that a correct description of the effect of $N_{\mathrm{e}}(0)$ must take into account the temporal change in the field in the active zone which just determines the evolution of the discharge and the kinetics of population and decay of energy levels. It is necessary to find out what changes of kinetics are induced by a variation of $N_{\mathrm{e}}(0)$.

4. Analysis of experiments with double pulses

Let us analyse the calculations of the CVL kinetics made in Ref. [4]. These calculations were made for a specific laser and cannot substantiate the existence of $N_{\mathrm{e\,cr}}$ in the general case, but it is expedient to consider these calculations since they are used as an example confirming the existence of $N_{\mathrm{e\,cr}}$.

Calculations were made for the laser described in Ref. [8]. This publication presents the results of measurements of the dependence of populations of resonance $\left({}^2P^{\mathrm{o}}_{3/2}\right)$ and metastable $\left({}^2D_{3/2}\right)$ energy levels for a copper atom on the time delay Δt of an excitation pulse relative to the main pulse (double pulse mode). The measurements were made under optimal lasing conditions at the tube wall temperature 1570 °C. The experimental conditions are described in detail in Ref. [8].

Fig. 1 borrowed from [8] and presented also in Ref. [4] shows the results of these measurements for $\Delta t = 15$ and 70 μs. For $\Delta t = 70$ μs, the effect of the previous pulse was weak, and the amplification in the second pulse is close to the amplification in regular pulses with a repetition rate of 10 kHz. The amplification decreased with Δt and vanished for $\Delta t = 15$ μs. The current pulse amplitude $J_{\max}$ and its steepness $\mathrm{d}J/\mathrm{d}t$ increased upon a decrease in Δt, while the amplitude $U_{\max}$ of the voltage pulse decreased, thus indicating the effect of residual prepulse electron density on the discharge evolution kinetics. The time variation of the populations of the ground and metastable energy levels of copper in the afterglow was also measured. Oscillograms of current and voltage pulses are not presented in this paper.

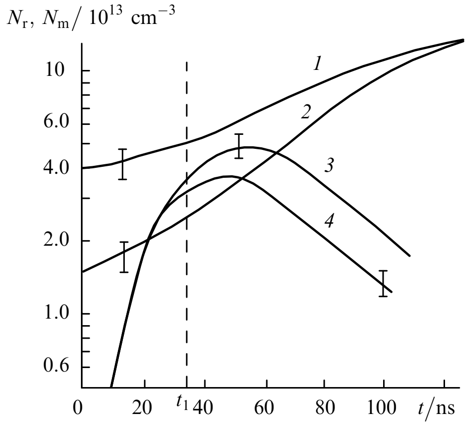

Figure 1. Kinetics of population of the working levels of a CVL at the discharge axis during the excitation pulse: populations N_m of the metastable energy level $^2D_{5/2}$ (*1*, *2*) and N_r of the resonance level $^2P^o_{3/2}$ (*3*, *4*) for $\Delta t = 15$ (*1*, *4*) and 70 μs (*2*, *3*); t_1 is the instant of maximum gain.

Yakovlenko [4] presented the results of calculations of the power introduced into the medium, the power spent for the ionisation of copper and neon and for gas heating, the resistance of plasma column, and also $N_e(t)$ and $T_e(t)$ for $\Delta t = 15$ and 70 μs. In these calculations, the oscillograms of current pulses from [10] but not from [8] were used. The laser described in Ref. [10] was nominally the same as in Ref. [8], but operated in the regular pulse mode and rather than with double pulses. In order to make the presentation simpler, we present in Fig. 2 only the results of calculation of $N_e(t)$ and $T_e(t)$ for $\Delta t = 15$ μs (Fig. 4d from Ref. [4]).

One can see from Fig. 2 that, according to the calculations, the temperature $T_e < 2$ eV during the entire excitation pulse for $\Delta t = 15$ μs. This led to the conclusion that 'the high initial electron density (amounting to 1.5×10^{14} cm^{-3}, according to calculations made in Ref. [4], which is close to the value of $N_{e\,cr}$ calculated by Yakovlenko [4] *– remark by G Petrash*) is the only cause of generation disrupt in experiments [8] for a small delay of the double pulse'. This conclusion is drawn to confirm the existence of $N_{e\,cr}$. Note that it is in direct contradiction to the conclusions drawn in Ref. [8].

Analysing the results of these calculations, we must note above all that they were made for some arbitrary conditions differing from the experimental conditions in Ref. [8]. The measurements in Ref. [8] were made for the axial region of the discharge of diameter 2 mm for the wall temperature 1570°C and the density $N_{\mathrm{Cu}} = 10^{15}$ cm^{-3}. In particular, the prepulse density N_{Cu} decreases with decreasing Δf, by 30 % for $\Delta t = 15$ μs. The value of $N_{\mathrm{Cu}} = 2 \times 10^{15}$ cm^{-3} used in Ref. [4] increases the losses for copper ionisation nearly by a factor of three.

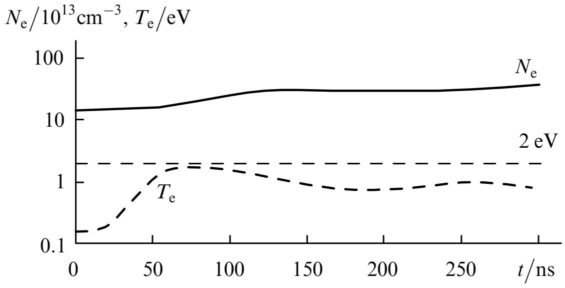

Figure 2. Time dependences of N_e and T_e calculated in Ref. [4] for $\Delta t = 15$ μs for $N_e(0) = 1.5 \times 10^{14}$ cm^{-3}.

The oscillogram of the current pulse in Ref. [4] is taken from another experiment with regular pulses; i.e., this oscillogram does not correspond at all to a delayed pulse, while the graph presented in Refs [2, 8] demonstrates that the amplitude of the current pulse and its steepness increase upon a decrease in the delay time. In addition, the current density on the axis of the tube is higher than the density averaged over the cross section used in Ref. [4]. Thus, the power introduced into the medium was noticeably underrated in Ref. [4], and its time dependence did not correspond to the actual dependence for $\Delta t = 15$ μs. There are also some other differences between the computational and experimental conditions, which will not be enumerated here. Consequently, for actual experimental conditions, the calculated value of temperature T_e for $\Delta t = 15$ μs should be noticeably higher than 2 eV. However, even for temperature T_e slightly lower than 2 eV which was obtained in Ref. [4], one can hardly speak of the absence of inversion since the rate of pumping to the upper level starts exceeding the pumping rate to the lower level for $T_e \approx 1.7$ eV, the value of $T_{e\,cr}$ being still lower due to the difference in the statistical weights of the levels.

Finally, if we substitute into the formula for $N_{e\,cr}$ the value of $N_{\mathrm{Cu}} = 7 \times 10^{14}$ cm^{-3} which appears as realistic for $\Delta t = 15$ μs, as well as the actual value of $j_{\max}$ which, according to the estimates, is at least 1.5 times higher than that used in Ref. [4], we obtain $N_{e\,cr} \approx 4.2 \times 10^{14}$ cm^{-3}, which noticeably exceeds the value of $N_e(0) = 1.5 \times 10^{14}$ cm^{-3} calculated in Ref. [4].

Moreover, the experimental results obtained in Ref. [8] directly contradict the conclusion drawn in Ref. [4]. Indeed, a decrease in the value of T_e for a higher initial electron density must lead to a decrease in the population of the resonance level and to an increase population of a metastable level during the excitation pulse. However, this was not observed in experiments (see Fig. 1). For the delay times under investigation, the dependences $N_r(t)$ at the beginning of the pulse virtually coincide, while the value of N_r at the peak of amplification for $\Delta t = 15$ μs is just 12 % lower than for $\Delta t = 70$ μs. At the same time, an increase in the population N_m of the metastable level from the initial value to the population corresponding to the maximum gain is the same for the two values of delay time to within the errors of measurements. On the contrary, the prepulse population $N_m(0)$ increases significantly (from 1.5×10^{13} cm^{-3} to 4×10^{13} cm^{-3}), which disrupted generation under the given experimental conditions. It should be noted that the population inversion taking into account the statistical weights of the levels for $\Delta t = 15$ μs was close to zero, and the inversion for this value of delay time would be just 12 % lower than for $\Delta t = 70$ μs, were it not for the increase in $N_m(0)$.

Thus, under the given experimental conditions, the disrupt of generation in a delayed pulse upon a decrease in the delay time to 15 μs can by no means be attributed to the effect of the prepulse electron density.

A number of misprints in Ref. [4] should also be noted: in Fig. 4, the delay time is erroneously indicated as 15 ns instead of 15 μs; in the figure caption to Fig. 3, read 70 μs instead of 70 ns and 3.7×10^{13} cm^{-3} instead of 3.7×10^{14}.

5. Conclusions

Thus, the analysis of limitations imposed on the pulse repetition rate in a pulsed CVL, which are associated with the effect of the prepulse electron density, based on the simplified models adopted in Ref. [4] does not prove the existence of a critical electron density. In this connection, it is expedient to continue the theoretical analysis of this problem on the basis of more complex self-consistent models correctly describing the kinetics of the evolution of a pulsed discharge and the kinetic of population and decay of energy levels associated with it.

In particular, it is necessary to describe the field variation in the plasma, i.e., to take into account the actual characteristics of commutating elements and the entire system of pulsed power supply as well as the processes occurring in the electrodes and cold regions near the electrodes. Only such an analysis may provide a reliable answer to the question concerning the effect of the prepulse electron number density on laser parameters. It is also expedient to take into account in theoretical models the dependence of the parameters of plasma and population of energy levels on the radius since the electron density (including the prepulse density) as well as other characteristics of the medium are inhomogeneous over the cross section so that generation may exist, for example, in the form of a ring. It should also be noted that the variation of the values of N_e and N_m in CVL are interrelated; consequently, attempts to change one of these parameters and calculate further the CVL kinetics may lead to erroneous results.

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