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Effect of the prepulse electron density and population of the lower laser level on the pulse repetition rate achievable in a copper vapour laser

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***Abstract*.** **Factors are considered which restrict the limiting pulse repetition rate in a copper vapour laser. The existence of a critical prepulse electron density discussed in a paper of S.I.Yakovlenko [*Quantum Electronics*, 30, 501 (2000)] and new arguments in favour of the existence of the critical electron density reported in a paper of A.M. Boichenko and S.I.Yakovlenko [*Quantum Electronics*, 32, 172 (2002)] are analysed. The conclusion is made that the new arguments do not prove the existence of the critical electron density as well.**

Keywords: *copper vapour laser, restrictions imposed on the pulse repetition rate.*

1. Introduction

The question of factors restricting the pulse repetition rate in copper vapour lasers (CVLs) has a long history (see, for example, [1, 2]). This problem has been again actively discussed recently. In particular, S.I.Yakovlenko [3] studied the effect of the prepulse electron density N_{e0} and proposed a concept of the critical prepulse electron density $N_{e\,cr}$ above which lasing is impossible. In our paper [4], the existence of $N_{e\,cr}$ was questioned and it was concluded that the approach used in paper [3] cannot prove the existence of $N_{e\,cr}$. A.M.Boichenko and S.I.Yakovlenko presented in paper [5] new arguments in favour of the existence of $N_{e\,cr}$. This paper is devoted to their analysis.

First of all it is necessary to make clear the subject of discussion. In our papers, including papers [1, 2, 4] and detailed discussions mentioned in the introduction of paper [3], the question of the limiting pulse repetition rate $f_{\lim}$ was considered, i.e., of the rate that is limited by fundamental physical restrictions rather than by technical problems such as an imperfect design of gas-discharge tubes and pulsed power supplies and an inappropriate operating regime.

Several factors were pointed out which can restrict the pulse repetition rate f, among them the overheating of an active medium and an excess specific input power. When these factors are eliminated, the restrictions caused by a high prepulse population N_{m0} of the lower (metastable) levels and a high prepulse electron density N_{e0} can play a dominant role. The relative contributions of these two factors depend on the design of a gas-discharge tube (GDT), the parameters of a power supply, and the operating regime.

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2. Formula for $N_{e\,cr}$

In our paper [4], criticism was expressed concerning the derivation of a formula for $N_{e\,cr}$ presented in paper [3]. Because a new paper [4] does not contain in essence the answer to our criticism, whereas the same formula for $N_{e\,cr}$ was used, it is necessary to discuss this question again. The equation for $N_{e\,cr}$ was obtained in paper [3] by equating the power input to the medium at the peak current density $j_{\max}$ to the power spent for ionisation of copper at the critical temperature $T_{e\,cr}$:

$$\frac{j^2_{\max}}{\sigma(T_{e\,cr})} = \frac{j^2_{\max} m_e}{e^2 N_{e\,cr}} [k_{Ne}(T_{e\,cr}) N_{Ne} + 2k_{ei}(T_{e\,cr}) N_{e\,cr}]$$
$$= J_{i\,Cu} k_{i\,Cu}(T_{e\,cr}) N_{e\,cr} N_{Cu}\,, \tag{1}$$

This gives

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

where

$$N_{e\,cr0} = \frac{j_{\max}}{e}\left[\frac{m_e k_{Ne}(T_{e\,cr}) N_{Ne}}{J_{i\,Cu} k_{i\,Cu}(T_{e\,cr}) N_{Cu}}\right]^{1/2} \tag{3}$$

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

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

is the dimensionless quantity; σ is the plasma conductivity; k_{Ne}, k_{ei} are the rate constants of elastic collisions of electrons with neon atoms and copper ions; N_{Ne}, N_{Cu} are the densities of neon and copper atoms; $J_{i\,Cu}$ is the ionisation potential of copper (7.73 eV); and $k_{i\,Cu}$ is the rate constant of ionisation of copper by electrons (see [3]).

It is assumed that $j_{\max}^2/\sigma(T_{\rm e\,cr})$ is the maximum power density input to the medium. However, at the instant when $j = j_{\max}$, the temperature $T_{\rm e}$ is usually noticeably lower than the maximum temperature, i.e., generally speaking, it is not equal to $T_{\rm e\,cr}$, so that the density $j_{\max}^2/\sigma(T_{\rm e\,cr})$ does not related to any certain instant of time. In addition, at the instant when $j = j_{\max}$, as follows from experiments, the input power is not maximal. This is disputed in paper [5] by referring to the Joule–Lenz law. What actually happens is that the maximum of the input power density corresponds to the maximum of j^2/σ rather than to the maximum of j. The value of σ simply increases with j, so that the input power density reaches a maximum earlier than the current density j does. In addition, the lasing terminates, as a rule, when j reaches a maximum, so that the power input at this instant cannot directly affect lasing.

Therefore, it is most likely that the expression $j_{\max}^2/\sigma(T_{\rm e\,cr})$ gives the understated value of the input power. On the other hand, the ionisation losses are overstated because during lasing the ionisation is not direct, and excitation of levels mainly occurs. The authors of paper [5] point out that the ionisation losses are overstated no more than twice. However, taking into account that inversion in a CVL is often achieved only because of the difference in the statistical weights of the operating levels, which corresponds for the green emission line to the ratio of populations of the levels equal only to 1.5 (considering the statistical weights), it is unlikely that the assumptions used in the derivation of the formula for $N_{\rm e\,cr}$, in particular, the error in the estimate of the losses of about 2, can provide an accuracy sufficient for obtaining reliable results.

Finally, as was pointed out in paper [4], the derivation of expression (2) is also incorrect because the shape of the current pulse and, in particular, its amplitude depend on $N_{\rm e\,0}$. This was observed in many experiments. By the way, comparison of Figs 2a and 3a from paper [5] shows that the calculation of the authors [5] themselves leads to the same conclusion. Therefore, in deriving expression (2) one should use the quantity $j_{\max}(N_{\rm e\,0})$ instead of $j_{\max}$, and in this case the expression for $N_{\rm e\,cr}$ should change. It follows from the above discussion that expression (2) cannot reliably describe the effect of concentration $N_{\rm e\,0}$ on the limiting pulse repetition rate.

Unlike paper [3], in our paper [4] the input power density is expressed in terms of the field E in a plasma rather than in terms of the current density j, i.e., the quantity σE^2 is used instead of j^2/σ. In our opinion, this does not change the physical model because $j^2/\sigma = \sigma E^2$. However, it is more convenient to express the power density in terms of the field to study how electrons can be heated up to the required temperature $T_{\rm e}$. The field E in the active medium is determined by the voltage applied to a GDT minus the cathode and anode voltage drops and the voltage across cold ends of the GDT, where there are no copper vapours. All these parameters can be varied to a certain extent by an experimenter. The voltage applied to the GDT is determined by a pulsed power supply, while the voltage drop across external (with respect to the active region) parts of the GDT is determined by the GDT design and materials used.

Therefore, the question of whether the desired electron temperature $T_{\rm e}$ and, hence, inversion and lasing can be obtained in the active medium is reduced to the construction of a power supply providing the desired dependence of the voltage $U(t)$ across the GDT taking into account processes occurring at electrodes and the GDT ends. If the pulsed power supply provides an increase in the voltage across the GDT up to the value corresponding to $T_{\rm e} > T_{\rm e\,cr}$ for a short time during which $N_{\rm e}$ does not change noticeably, then the time of predominant population of metastable levels will be short and their population will be negligible, which allows the inversion and lasing to be achieved if $N_{\rm m\,0}$ is not large.

The authors of paper [5] do not consider the possibility of improving a power supply, however, they write: 'At the same time, having expressed j in terms of E, the author of paper [6] (G.G.Petrash) passed to another physical model. Within the framework of his model, a pump source can have arbitrarily high power. Indeed, the input power density $\sigma E^2 \propto N_{\rm e} E^2$ for a given value of E is arbitrarily high if $N_{\rm e}$ is arbitrarily high'.

However, to obtain the population inversion, it is necessary in any case to input into the active medium a sufficient power for a finite time, irrespective of the type of expression describing the power. The statement itself about the necessity of an arbitrarily high power is based, in our opinion, on a misunderstanding because there is no sense to deal with an arbitrarily high $N_{\rm e}$. It is obvious that it is useless to employ the value of $N_{\rm e}$ exceeding the initial density of copper atoms because under normal operating conditions only copper is ionised in the active medium; and when copper is completely ionised, the pulse repetition rate f is simply limited by slow recombination, as was pointed out in our papers (see, for example, [1, 2]).

On the other hand, it is known that real repetitively pulsed CVLs operate in the limited range of the copper density. Finally, by choosing favourable conditions for obtaining the limiting pulse repetition rate f, there is no need to operate at high copper densities. On the contrary, the limiting pulse repetition rate can be more easily obtained at a moderate copper density.

Therefore, no 'arbitrarily high' power is required from a power supply. A voltage pulse across the GDT should have a sufficiently steep leading edge in order to maintain the relation $T_{\rm e} > T_{\rm e\,cr}$ for a certain time, the preferable value of $T_{\rm e}$ being 3–3.5 eV. To prove the existence of $N_{\rm e\,cr}$, one should prove that there exist physical rather than technical factors which do not allow the construction of such power supplies. In addition, as was mentioned in papers [1, 2, 4], the requirements impose on the leading edge of a voltage pulse applied to the GDT can be alleviated by appropriately organising processes at the electrodes and in cold regions of the GDT (see, for example, [1, 2]).

Another requirement for a power supply is the minimisation of the energy input into the active medium immediately after the termination of lasing. This energy causes the additional heating of gas, additional ionisation, and additional population of metastable levels. This in turn results in an increase in $N_{\rm m\,0}$ and $N_{\rm e\,0}$, i.e., hinders lasing during the next pulse and prevents an increase in f and in the lasing efficiency, so that the optimisation of the power supply should include measures for reducing the energy input after the termination of lasing.

3. Simulation of the CVL kinetics and the substantiation of the existence of $N_{\rm e\,cr}$

The results of simulation of a CVL, which are also used for the substantiation of the existence of $N_{\rm e\,cr}$, are presented in papers [3, 5, 6–8]. The calculations were performed for different GDTs and pulsed power supplies with a thyratron. Here, we consider the results of simulation described in paper [5]. The authors [5] considered a three-contour electric circuit (see details in [5]) with some fixed values of capacitances and inductances. The choice of the circuit, of its elements, and the operating regime is not substantiated. The kinetics of processes was calculated for different values of N_{e0}, however, it is difficult to understand for what pulse repetition rate these calculations were performed.

Estimates show that for a charging voltage of 14 kV, already for $f = 10$ kHz, when the limitations related to N_{e0} or N_{m0} are not revealed yet, the average power taken from capacitors is 2.4 kW. For a GDT of length 40 cm, this power is already close to the power that cause the overheating of the active medium, so that it is the overheating, i.e., an increase in the equilibrium concentration N_m that will prevent an increase in f in this case. It is unlikely that this example can give any information on the effect of N_{e0} on the limiting pulse repetition rate.

Note in general that the simulation of a particular GDT with a particular power supply cannot give the answer to the question about the limiting parameters of lasing, in particular, about the limiting pulse repetition rate f_{lim} because one should prove that the variant under study exhausts all possible improvements of the GDT and the power supply matched to it. When the pulse repetition rate is increased, the average power supplied to the active medium should be kept approximately constant to avoid the overheating of the medium. This means that the input pulse energy should be decreased with increasing f, for example, by decreasing the working capacity, which results in a change in the kinetics and prepulse values of N_{e0} and N_m. Such calculations have not been performed unfortunately, whereas the calculations described in paper [5] do not elucidate the question about the limiting pulse repetition rate f_{lim}.

In addition, in paper [5], as in some other papers, the dependence of the laser output energy on N_{e0} or N_{m0} was calculated, the second parameter of this pair being fixed. We have already pointed out several times (see, for example, [1, 2]) that such calculations do not correspond to the real situation in a CVL because the quantities $T_e(t)$, $N_e(t)$ and $N_m(t)$ are interrelated in the process of three-body recombination due to the properties of the latter. The presence of three-body recombination in a CVL has never been doubted. An arbitrary independent variation of the above quantities means the deviation from a self-consistent solution, so that the results of such calculations should be treated with care because they can lead to great errors and only confuse a reader. This question will be discussed in more detail elsewhere because it concerns not only paper [5] but also some other papers.

In the conclusion of paper [5], the authors write: 'The results of calculations confirm the conclusion of paper [2] ([3], *in this paper* – G. P.) that for a given pump system there exists a critical initial electron density above which lasing in a CVL ceases. The results of calculations agree with estimates made in paper [2]. The calculations also showed that a critical initial density of metastable states also exists. The restrictions imposed by high initial densities of electrons and metastable states are interrelated and can compete with each other.'

Therefore, the case in point is already not a limiting pulse repetition rate but a situation concerning a *given pump system*. However, such a conclusion is of small interest. It is obvious that one can always imagine a pump system that is incapable of heating electrons with a given density up to the required temperature T_e (this was also mentioned in our paper [4]). This occurs when the rate of energy input into an active medium is low, which can be easily achieved by choosing the appropriate parameters of the system elements, a slow commuting element, and a low initial voltage. The agreement with almost any estimate of $N_{e\,cr}$ can be obtained by choosing an appropriate pump system.

As for expressions (2) and (3), they claim to a greater generality than that pointed out in paper [3]. These expressions were derived without indicating the parameters of a given pump system. They do not contain the parameters of the pump system, which determine the rate of energy input at the pulse onset. The only parameter in these expressions that depends on the pump system is j_{max}.

However, as was mentioned many times, lasing occurs typically at the leading edge of the current pulse and it terminates when the current achieves a maximum, so that the rate of energy input at the maximum current cannot affect lasing during this pump pulse and can affect lasing only during next pulses. It is also known that I_{max} can be increased easily by increasing, for example, a charging capacity, which results in an increase in the current amplitude and a shift of the current maximum to longer times. However, this does not improve lasing conditions but, on the contrary, deteriorates them due to a strong heating of the medium and increasing N_{e0} and N_{m0}. Therefore, expressions (2) and (3) only confuse the researchers developing pump systems.

Another conclusion of the authors of paper [5] is that there exists the critical initial density of metastable states, and the restrictions caused by high initial densities of electrons and metastable states are interrelated and can compete with each other. In our opinion, this is a step in a proper direction. However, if this is acknowledged, then the question remains of the factors that really limit the pulse repetition rate. In this case, the statement that N_{e0} restricts the maximum pulse repetition rate even for the zero density of metastable states is not correct because it does not correspond to the real situation in a CVL. Since the restrictions are interrelated, they should be analysed together, taking into account their interrelation.

4. Conclusions

It follows from the above discussion that both new calculations and arguments presented in paper [5] do not prove the existence of the critical electron density if we deal with a limiting pulse repetition rate and the choice of pulsed power supplies is not limited. However, it is this problem that is of interest and that has been the subject of long discussions mentioned in the introduction of paper [3].

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