0-D MODEL OF A Xe-Cl LASER. PROBLEM ON THE DISCHARGE-PUMPING OPTIMIZATION

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We present in this paper some results of 0-D-modeling of a Xe-Cl *laser. The values of the laser output energy calculated theoretically are in a good agreement with the experimentally measured ones. It is shown that approximately* 10 HCl *molecules, from the gas mixture of* Ne:Xe:HCl = 1000:10:1, *are consumed to produce one laser photon. Maximum energy density for this gas mixture is* 1.6 J/l×[HCl, mbar]. *With the increase of* HCl *partial pressure the rate of* HCl *molecules consumption per one photon delivered increases. Thus in the same gas mixture at the proportions of* 1000:10:2 12.2 HCl *molecules are consumed per photon produced and the limiting output energy density is* 1.2 J/l×[HCl, mbar]. *The possibility of achieving a significant increase in the energy output is shown owing to an increase of* HCl *content in the gas mixture provided the high uniformity of the pumping is maintained.*

1. INTRODUCTION

In recent years many investigations have been being carried out aimed at achieving maximum power characteristics of the Xe-Cl laser radiation. However, the question on its limiting power characteristics is still to be addressed. As the electric circuitry of a power supply and the laser head design improve, the higher output power and efficiency of lasing are being achieved in the experiments. Use of a photon-induced initiation of the pump electric discharge enabled a significant enhancement of the laser performance characteristics to be achieved. In the studies of that kind high efficiency, 4% (Ref. 1), high specific energy output, 6 J/l (Ref. 2), and high mean power, 500 W (Ref. 3), have been obtained. Moreover, the pulse energy of 15 J has been demonstrated in Ref. 4 in the experiments with a wide-aperture laser.

The maximum energy output of 7.6 J/l with the efficiency of 3.5% has been reported in Ref. 5, where it is shown, for the first time, that high energy of lasing is reached at an enhanced content of HCl in the gas mixture of Ne:Xe:HCl at the proportions of 1000:5:1.7.

Numerical simulation of the physical processes in a laser is an effective and almost the only way to study the kinetic processes in the lasing media and to seek ways for optimizing and predicting Xe-Cl laser performance characteristics.

But, the 0-D modeling does not allow for the inhomogeneities occurring in the pump discharge. This circumstance creates certain difficulties for making a comparison between the calculated and measured data.

In this paper we present a comparison made between the experimental data and the results of theoretical modeling. The problems of optimizing parameters and seeking possible ways to increase the energy output are also considered in this paper.

2. MODEL OF Xe-Cl LASER

The model used involves the Boltzmann equation for the electron energy distribution function (EDF), kinetic equations for electrons and heavy particles, equations for external electric circuit, and equations for calculating the laser radiation fluxes Φ^+ and Φ^-.

The kinetic model takes into account 33 types of particles and more than 300 reactions. Data on the constants needed are taken mostly from Ref. 5. The number of kinetic processes to be involved in calculations in any particular case could be essentially reduced without a significant loss of the calculation accuracy. However, the matter is that the basic kinetic processes are different in each particular case and the reduction of the number of kinetic processes to be involved every time must be justified separately. That is why we use the kinetic model that is applicable in the entire range of the initial conditions considered.

The Boltzmann equation is solved using the method of weighted discrepancies by the Galerkin method (see Ref. 6).

The metastable and resonance atoms of neon Ne*, Ne** and Xe–Xe*, Xe**, Xe***, and atomic Ne^+, Xe^+ and molecular Ne_2^+, Xe_2^+, $NeXe^+$, HCl^+ ions are considered in this model besides the electrons. Since the constant of dissociative capture of electrons by HCl molecules increases with increasing number of the vibrational level, we take into account, in this model, the ground $HCl_{v=0}$ level and 3 vibrational levels, $HCl_{v=1}$, $HCl_{v=2}$, and $HCl_{v=3}$. Even if the level $HCl_{v=4}$

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is also involved in calculations no significant improvement in the calculation accuracy is achieved.

As known the Ne and Xe do not provide for equilibrium distribution of XeCl molecules over the vibrational states, as well as over the states XeCl(B) and XeCl(C). Therefore in our model we allow for the XeCl(B) and XeCl(C) states. Among the levels of the $XeCl(B_0)$ state we isolate the level with $\nu = 0$. All other levels with $\nu > 0$ are represented as a single level XeCl(B)*. The levels $\nu = 0$ and $\nu = 1$ are united into one level denoted as $XeCl(C_0)$, the rest levels being represented as the XeCl(C)* level. The states XeCl(B)* and XeCl(C)* appear due to the vibrational relaxation of XeCl** in the fractions of 0.77 to 0.23%, respectively. The analysis made shows the 0-D model of the cavity to lead to a significant error in the energy of output laser radiation, under the external conditions accepted in this paper. Therefore we use a one-dimensional model (Ref. 7) where the laser radiation inside the cavity is represented as two counter directed fluxes of laser photons Φ^+ and Φ^-.

The model has been tested by comparing the theoretical data to the experimental ones from Ref. 8. The comparison made showed that the model works quite well in the entire range of boundary conditions.

3. COMPARISON BETWEEN THE THEORETICAL AND EXPERIMENTAL DATA

The experimental data we use for making the comparison have been obtained by M.K. Makarov on the DENEB installation, where many investigations have been carried out on optimizing the pump discharge.

The electric circuitry of the power supply operates in the regime of the discharge initiation with *X*-rays and comprises a capacitor with $C = 123$ nF, inductance $L = 18.5$ nH, and the discharge plasma. The capacitor is charged in a pulse mode during a 500-ns time interval to the voltage U_0. The dose of *X*-ray radiation used to initiate the discharge was equal to $1.5\cdot10^{-3}$ R. The discharge gap in this laser head is 5.3 cm high, 3 cm wide and 40 cm long. Thus, the volume of the active medium equaled 0.636 liter.

The experimental (solid lines) and theoretical (dotted lines) dependences of the specific energy output on the ratio E_0/P, where $E_0 = U_0/d$ at different pressures of the gas mixture are shown in Fig. 1. Figure 2 presents the lasing efficiency, the ratio between the output laser radiation energy and the energy stored in the capacitor, as a function of the E_0/P ratio. The gas mixture composition is Ne:Xe:HCl in the proportion of 1000:8:0.8.

From the comparison between the experimental and theoretical data (see Fig. 1) it follows that in the range of small E_0/P values the experimentally measured radiation energy is higher than the calculated one. On the contrary, in the range of large E_0/P values the theoretical energy is higher than the experimental one.

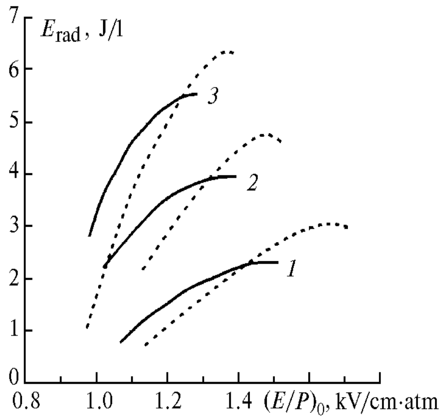

FIG. 1. Dependence of the laser radiation energy on the ratio E_0/P at different pressures of the gas mixture. Experiment (solid curve); calculations (dotted curve). Gas mixture composition is Ne:Xe:HCl = 1000:8:0.8. *Total pressure of the mixture in the cases presented by curves 1, 2, and 3 was* 3, 4, *and* 5 atm, *respectively*.

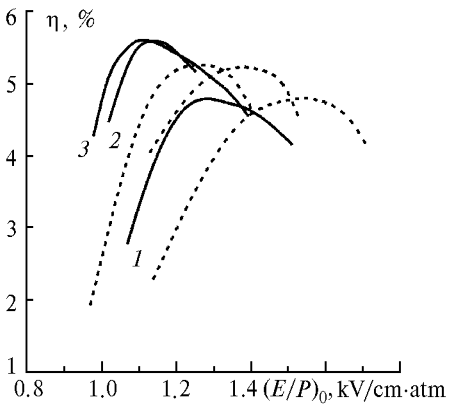

FIG. 2. Dependence of the lasing efficiency, regarding the energy stored in the capacitor on the E_0/P ratio. Conditions are the same as those in the case presented in Fig. 1.

The experimental and theoretical oscilloscopic traces of the discharge current and output power pulse are shown in Figs. 3*a* and 3*b*. The traces correspond to $E_0/P = 1.12$ kV/cm·atm and the gas mixture pressure of 5 atm. Under these conditions $E_{rad}^{exp} = 4.7$ J/l and $E_{rad}^{th} = 3.7$ J/l. The difference appears to be quite a significant.

It is characteristic of the theoretical curves that electric current flows only during the first half of the period. Besides, only 60% of the initial number of HCl molecules have worked.

On the contrary, high amplitude of the current in the second half of the period is typical for the experimentally observed traces. High current values in the second half-period could only occur if in the first one almost complete burning out of HCl molecules happened.

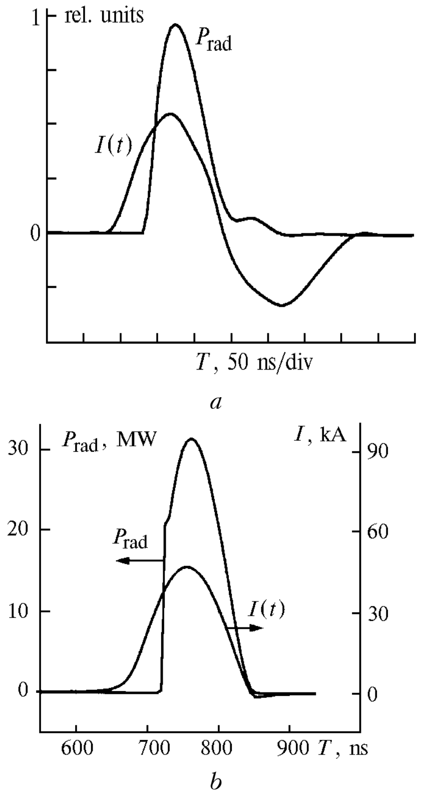

FIG. 3. Oscilloscopic traces of the discharge current and output laser power pulse at E_0/P *of* 1.12 kV/cm·atm *for experiment (a) and theory (b).*

These data allowed us to come to a conclusion that in the experiment there occurred completely the burning out of HCl molecules in the central part of the gas-discharge volume and most likely along the entire length of the electrodes. This complete burning of HCl in a part of the volume higher than the partial burning predicted by theoretical calculations. It is just this fact that explains the higher values of the experimentally obtained energy as compared to theoretical one. Such a conclusion is confirmed by the fact that the discharge prints on the electrodes are more dense in their central parts than near the edges, along the entire length of the electrodes.

The main cause of the discharge instability is that the plasma contracts to the discharge regions where the electron density is higher. In the example considered the current contracted relatively smoothly from the electrode edges towards their central part. If our conclusion is true to life this situation clearly demonstrates that even under unstable discharge regime it is possible to achieve high power of the output laser radiation.

4. DEPENDENCE OF THE OUTPUT LASER ENERGY AND LASING EFFICIENCY ON THE PARTIAL PRESSURE OF HCl

Theoretical dependences of the output radiation energy and lasing efficiency on the initial voltage U_0 at different partial pressures of HCl are depicted in Figs. 4 and 5. The total pressure of the mixture in this case was 5 atm. The dependence *1* presents data acquired at the gas mixture composition of 1000:10:1, while in the cases shown by the dependences *2* and *3* the HCl fraction has been increased by 1.5 and 2 times, respectively, others parameters being unchanged.

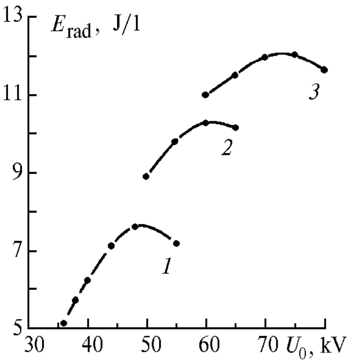

FIG. 4. Calculated dependences of the output radiation energy on the ratio E_0/P *at different pressures. Total pressure of the gas mixture for the dependences 1, 2, and 3 is* 3, 4, *and* 5 atm.

With an increase in the HCl content E_{rad} also increases. In each mixture the maximum energy is achieved at ~ 90% burning out of HCl molecules from its initial amount. At a two-time increase in the HCl content the radiation energy increases by a factor of 1.5, while the lasing efficiency falls from 5 to 4%.

The sequence of reactions converting the HCl molecules into the photons is shown in Table I. Figures in the lines are the numbers of the corresponding particles necessary for producing one photon of the output laser emission. Figures above the arrows show the number of particles lost during the reaction. The data from Table I correspond to the maximum values of energy on the curves depicted in Fig. 5.

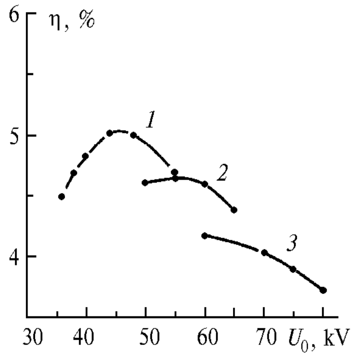

FIG. 5. Calculated dependences of the lasing efficiency on the ratio E_0/P *at different pressure. Other data being the same as in the case presented in Fig. 4.*

From Table I it is seen that with the increasing HCl concentration the loss of HCl molecules and the number of photons in the cavity significantly increase.

Therefore, the total number of molecules that are necessary for producing one photon also increases.

TABLE I.

Gas mixture Ne:Xe:HCl	Reactions $HCl \rightarrow Cl^- \rightarrow XeCl^* \rightarrow h\nu_{res} \rightarrow h\nu_{rad}$
1000:10:1	$9.1 \xrightarrow{4.83} 4.3 \xrightarrow{0.3} 4.0 \xrightarrow{1.8} 2.2 \xrightarrow{1.2} 1$
1000:10:1.5	$10.1 \xrightarrow{5.75} 4.4 \xrightarrow{0.4} 4.0 \xrightarrow{1.6} 2.4 \xrightarrow{1.4} 1$
1000:10:2	$12.2 \xrightarrow{7.2} 5.0 \xrightarrow{0.4} 4.5 \xrightarrow{1.8} 2.7 \xrightarrow{1.7} 1$

Thus, at a two-time increase of the HCl partial pressure the number of HCl molecules that are necessary for generation of a single laser photon increases by a factor of 1.3. Therefore a two-time increase in the HCl concentration leads to approximately 1.5-time increase in the output energy.

The output radiation energy E_{rad} as a function of the HCl partial pressure is given in Table II. The fourth column of the table gives the values of specific energy of radiation, E^1_{rad}, reduced to 1 mbar partial pressure. The value E^1_{rad} decreases with the increase of HCl partial pressure. This decrease occurs due to an increase in the number of HCl molecules to be burnt out to produce a single photon of laser radiation, according to data given in Table I. The parameter E^1_{rad} is a suitable indicator of the utilization of HCl in a particular discharge pumping regime.

TABLE II.

	Gas mixture Ne:Xe:HCl	Hq l^0, mbar	e_{rad}, J/l	e^1_{rad}, J/(l× ×[HCl,mbar])	Efficiency, %
Experi-ment	1000:8:0.8	4	5.6	1.4	5.1
Calcula-tion	1000:8:0.8	4	6.4	1.6	5.0
	1000:10:1	5	7.7	1.54	5.0
	1000:10:1.5	7.5	10.3	1.37	4.6
	1000:10:2	10	12.1	1.2	3.9

When making calculations we did not vary the resonator Q-factor, therefore it seems that one may decrease the loss of photons in the cavity by optimizing its parameters.

Data given in Table I are the values integrated over the discharge pump pulse, so it is clear that a smaller number of HCl molecules are burnt per one laser photon at the moment when current reaches its maximum, while increasing at the stage of the current growth and fall off. So, the choice of a proper pulse shape allows one to increase, to a certain degree, the utilization of HCl molecules.

The calculations presented show that kinetic processes of creating the inversion and extraction of radiation from the cavity allow an increase in the HCl concentration, at least by several times as compared to that in the standard mixture composition of 1000:10:1.

However, the increase of HCl content inevitably leads to a decrease in the discharge stability and can deteriorate homogeneity of the pump discharge. To achieve the limiting performance characteristics of the gas mixture with an enhanced HCl content some other and more efficient ways of the pump discharge formation are needed. In Ref. 5 one may find an example of high energy output, up to 7.6 J/l, obtained from a laser that was operated in the gas mixture of Ne:Xe:HCl (1000:5:1.7) with enhanced content of HCl at the total pressure of 6 atm. However, the reduced energy output of 0.75 J/l·[mbar of HCl] is quite small. Actually, this gas mixture can produce higher energy output of the laser radiation.

5. DISCUSSION OF THE RESULTS

As follows from Table II the experimentally obtained energy, E_{rad}, of 5.6 J/l differs from the theoretical only by 15%. We think that in this experiment the almost full limiting potentialities of the gas mixture composition of 1000:8:0.8 proportions have been achieved. It is also obvious that achieving limiting potentialities of the gas mixture of the proportion 1000:10:1 is the matter of certain modification of the experimental installation.

The results of modeling presented allow us to state that the problem of XeCl laser optimization, aimed at increasing the radiation energy output, is in the necessity to increase the partial pressure of HCl in the working gas mixture while choosing other parameters such that the generation of a single laser photon costs a minimum number of HCl molecules.

The increase of partial pressure HCl can be performed in two ways. One of the ways has practically been realized, it is in the increase of the total pressure of the mixture at its composition being constant. In this case the technical difficulties may appear because the laser chamber becomes a high-pressure vessel.

The second way is to increase partial pressure of HCl at a reasonably high (3–5 atm) total pressure of the mixture. In this case it is necessary to solve the problem of a temporal and spatial uniformity of an active medium.

With the increase of partial pressure of HCl the discharge stability inevitably deteriorates. However, even if the discharge is unstable this does not necessarily mean that it is nonuniform. The instability is the discharge property that may or may not manifest itself in full measure, or partly. Therefore the problem is that in a certainly unstable discharge one must obtain its uniformity such that it is sufficient for achieving the limiting potentiality of a gas mixture.

The stability and uniformity of the discharge make an independent subject for a discussion that is beyond the scope of this paper.

6. CONCLUSIONS

1. It is shown that the radiation energy output of 5.6 J/l and the efficiency of 5.1% obtained experimentally are, actually, the limiting ones for the gas mixture Ne:Xe:HCl (1000:8:0.8.).

2. The possibility is shown of arranging such a discharge regime that at the stage of its unstable burning the smooth contraction of the discharge plasma from the electrode edges towards the center occurs, while keeping its sufficient uniformity along the electrodes.

3. From analysis of the modeling results it follows that in the gas mixture of the composition 1000:10:1 approximately 10 molecules of HCl are necessary to produce one photon of the output laser emission, therefore the limiting radiation energy output is ~1.6 J/l·[HCl, mbar]. That value of the energy output is possible if the uniformity of the pump discharge is sufficient for complete burning out of the HCl molecules.

4. The principle possibility of increasing the radiation energy output further is in an increase of the HCl content in the gas mixture and while providing the uniformity of the pump discharge to make the HCl burning out within the active volume complete.

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