RADIANT ENERGY DISTRIBUTION OVER THE OUTPUT BEAM CROSS SECTION FOR WIDE-APERTURE LASERS EXCITED WITH A RADIALLY CONVERGENT BEAM OF ELECTRONS

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The results are presented of experimental and theoretical investigations of excitation and generation of the HF *laser pumped by nonchain chemical reaction initiated by a beam of electrons as well as of the* KrF *and* XeCl *lasers pumped by beams of electrons. The effect of the volume charge field on the distributions of energy over the cross section of a laser cell and of the radiant energy density over the cross section of an output laser beam in mixtures with different concentrations of halogen is analyzed. The output energy density distribution over the beam cross section for lasers excited by the radially convergent beam of electrons and the total pump energy are determined. The pump energy distribution over the laser cell cross section and the total pump energy in various gas mixtures are calculated.*

1. INTRODUCTION

In the present time laser systems on the basis of dense-gas pulsed lasers[1–6] are being developed. These laser systems are intended for shaping of high-power radiation pulses and are used for the investigation of interaction of high-power coherent radiation with matter including experiments on controllable thermonuclear synthesis. Amplifiers in these laser systems are, as a rule, wide-aperture lasers pumped by the electron beam. In the wide-aperture lasers,[1–12] uniform distribution of pumping over the active volume should be provided to form high-quality beams. Especially urgent is the problem of uniform pump energy distribution over the cross section of a wide-aperture laser cell for the chemical HF and DF lasers,[6–10] including those pumped by nonchain chemical reactions.[8–10] Thus, in Refs. 8–10 it was demonstrated that the volume charge in mixtures with SF_6 affected the size of the excited volume and radiant energy distribution over the output beam cross section of the HF laser (generating at wavelengths $\lambda \sim 2.6$–3.2 μm).

In the present paper, the results are presented of investigations of energy distribution over the output beam cross section for wide-aperture lasers and mixtures SF_6:H_2, Ar:Xe:HCl, and Ar:Kr:F_2 pumped by an electron beam as well as the results of calculation of pump energy distribution in different gases. These results were obtained for the wide-aperture lasers on mixtures with small (~ 0.1%) and large (~ 90%) halogen content pumped by the radially convergent electron beam.[9–12] In the investigated lasers the electron beam was injected simultaneously from four or six sides of the laser cell to achieve uniform pump energy distribution without magnetic field.

2. EXPERIMENTAL SYSTEMS AND PROCEDURES

In the experiments we used two systems. First system[5,9,10] comprised a compact laser[5,9,10] with an active volume of ~ 30 l. An electron accelerator with vacuum insulation forming the radially convergent electron beam from four cathodes made from velvet was described in detail in Ref. 12. In this experiment we used a modernized system.[9,10] The charging voltage of a ten-step pulsed voltage generator varied from 70 to 100 kV. The voltage on a vacuum diode was 300–600 kV, the beam current was 20–40 kA, and its pulse duration at half maximum was ~ 400 ns in the laser cell. The active volume of the laser cell had a length of ~ 100 cm and a diameter of 20 cm. Working mixtures comprising hydrogen and SF_6; argon, xenon, and HCl; or argon, krypton, and F_2 were prepared directly in the laser cell. The second system (with an accelerator described in detail in Ref. 12) comprised a wide-aperture laser with an active volume of 600 l, which was previously used to excite generation on atomic transitions of xenon[11] and the mixture[3] Ar:Xe:HCl. The laser was pumped from six sides of the laser cell. The laser cell had a diameter of 60 cm and an active length of 200 cm. For the accelerators of electrons of both lasers the electron energy and the beam current varied within the time over which the pumping pulse acted. In the e'xperiments for comparison of electrical conductance of mixture with

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different halogen concentrations, the LIDA electric-discharge laser was used.[3] Resonators of several types were used. Plane concave spherical Al mirrors and a plane mirror with gold coating were used as "nontransmitting" mirrors. Parallel-sided plates made from NaCl, KRS–5, and KRS–6 with reflection coefficients of 9, 33, and 27% at ~ 3 μm were used as output mirrors and parallel-sided plates made from quartz were used to extract the radiation with λ ~ 250 and 308 nm.

To measure the radiant energy, the TPI–2M calorimeters were used or two IMO–2 calorimeters placed at different points of the output laser beam. For the mixture SF_6:H_2 = 8:1, which was optimum, the radiant energy was measured after the first triggering of the accelerator. Temporal characteristics of the radiation pulse were registered by the FP–1 detector or by the FEK–22 photodiode. Signals from their outputs entered the S8–14 oscillograph.

3. PUMP ENERGY DETERMINATION FROM A PRESSURE JUMP IN WORKING MIXTURES

The energy put in a gas was calculated from a pressure jump in the cell on gas heating after the beam injection. To record the pressure jump, a mechanotron was used representing a sealed electronic device consisting of two vacuum diodes with a common cathode.[13] The anode of the first diode was immobile, and the diode current was independent of the gas pressure. The anode of the second diode was connected with the membrane and moved under changes of pressure in the cell resulting in a change of the diode current. Resonance frequency of a kinematic system of the mobile anode of the mechanotron was about 500 Hz. It was capable of recording pulses of pressure with small rise times.

When the released energy is distributed uniformly over the cell volume, the gas is not expanded, and energy losses from the volume are small, the pump energy ΔW and the pressure jump in the cell Δp are connected by the simple relation that follows from the ideal gas laws

$$\Delta W = 0.36\ \rho\ C_v\ V\ \Delta p. \qquad (1)$$

Here, p is the gas density at a temperature of 273 K and a pressure of 760 Torr, in g/l; V is the cell volume, in liters; C_v is the heat capacity at constant volume, in J/g·deg; ΔW and Δp are in J and Torr, respectively. It can be seen that the pressure jump is independent of the initial temperature and pressure. Because C_v depends weakly on the temperature and pressure, the pump energy ΔW is determined by the product ΔpV.

Estimates show that the pressure jump Δp is noncritical to the pump energy distribution over the cell volume. This permits us to use Eq. (1) to calculate the pump energy also when the excited gas volume V_E occupies only a part of the cell volume. In these cases Eq. (1) yields underestimated value of ΔW; however, the error is small. For a monoatomic gas when $V_E/V > 0.5$ and pressure jumps are not very large ($p/p_0 \le 1.5$, where p_0 and p are the initial and final pressures in the cell, respectively), the error does not exceed 8%. The error decreases with the increase of V_E/V and the decrease of p/p_0 and the adiabatic exponent, for example, when we go to molecular gases.

The pump energy ΔW for $V_E < V$ can be determined when we substitute the actual values of the excited volume V_E and the pressure jump in the excited volume Δp_1 into Eq. (1), if we succeed in recording them. The quantity Δp also can be calculated from the pressure jump Δp registered by the mechanotron with the help of the relation

$$(p_1)^{1/\gamma}\ V_E = (p)^{1/\gamma}\ V - (p_0)^{1/\gamma}\ (V - V_E), \qquad (2)$$

where p_1 is the pressure in the volume V_E just after the beam injection.

The 6MDX–1B and 6MDX–3B mechanotrons that differ by the working pressure ranges (0–0.5 and 0–10 atm) were used in the experiments. Signals from their anodes were applied at the S8–13 oscillograph or at a digital voltmeter.

4. CALCULATION OF THE ENERGY PUMPED BY THE ELECTRON BEAM IN THE WORKING MIXTURES

In case of measurements of the energy put in the gas by the beam of electrons with the help of the mechanotron, only total energy put in the working mixture is determined. The information about the pump energy distribution over the laser cell cross section is lacking. In addition, as the experiments[8] show, the electric field of the volume charge caused by one-side injection of electron beams in the gas mixtures SF_6–H_2 may significantly affect the absorbed energy distribution over the working volume of the laser. Thus, in Ref. 12 the significant decrease (~ twice) of the generation volume was observed for the HF laser pumped by a chain chemical reaction with the increase of the working mixture density from 3.4 to 3.6 g/l.

To estimate the effect of the volume charge electric field on the pump energy distribution for the laser pumped by the radially convergent electron beam, we calculated the absorbed energy distribution by the Monte Carlo method using the program described in Ref. 14. A comparison of the pump energy calculated ignoring the effect of the volume charge field with the experimental measurements of the radiant energy density distribution over the laser beam cross section in the mixtures with small and large halogen concentrations permits us to estimate the effect of the volume charge field.

5. RESULTS AND THEIR DISCUSSION

Figure 1 shows the radial distributions of the absorbed energy density calculated by the Monte Carlo method neglecting the effect of the volume charge for the mixtures $SF_6:H_2 = 8:1$ at different pressures and Ar:Xe = 9:1 at $p = 2.5$ atm as well as the experimentally measured radial distribution of the output laser radiation for the mixtures $SF_6:H_2 = 8:1$ at $p = 0.45$ atm (the HF laser), $Ar:Kr:F_2 = 970:60:1$ (the KrF laser), and Ar:Xe:HCl = 950:10:1 (the XeCl laser).

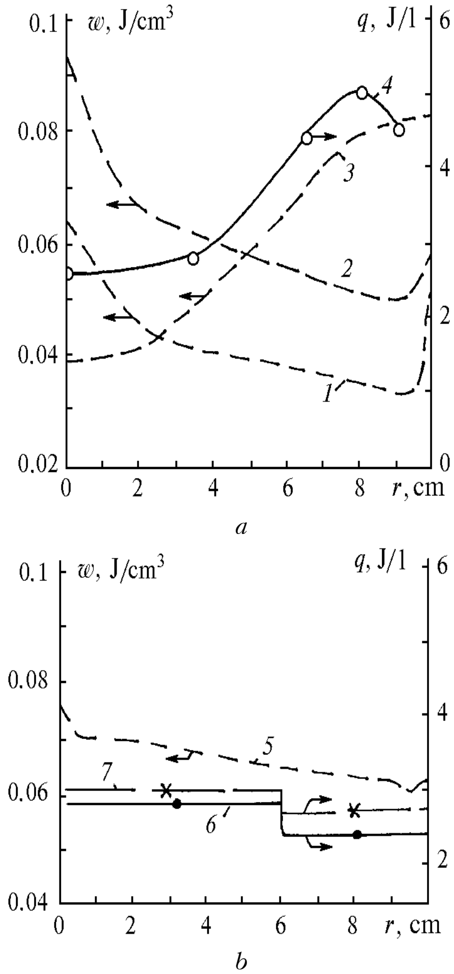

FIG. 1. Radial distributions of the absorbed energy density calculated by the Monte Carlo method neglecting the effect of volume charge for the mixtures $SF_6:H_2 = 8:1$ *at pressures* $p = 0.25$ *(1),* 0.45 *(2), and* 1.0 atm *(3) and for* Ar:Kr = 9:1 *at* $p = 2.5$ atm *(5) along with the experimental radial distributions of the output laser radiation for the mixtures* $SF_6:H_2 = 8:1$ *at* $p = 0.45$ atm *(4),* Ar:Xe:HCl = 950:10:1 *at* $p = 2.5$ atm *(6), and* $Ar:Kr:F_2 = 970:60:1$ *at* $p = 2$ atm *(7). System 1. Curves 1–6 are for* $U_0 = 80$ kV *and curve 7 is for* $U_0 = 100$ kV.

These results and our previous investigations[5–10] showed that the shapes of calculated and experimental radial distributions for mixtures in which the concentrations of electronegative gas components are small or they are absent agree well (curve *5* in Fig. 1 and experimental curves *6* and *7*). The type of the halogen carrier whose concentration is small (< 1%) affects only insignificantly the radiant energy distribution over the laser beam cross section. For the mixtures $SF_6:H_2$ (curves *1–3* and experimental curve *4*) with halogen concentrations in mixtures of ~ 90%, there is no such agreement. This is connected with the effect of the volume charge in mixtures with high concentrations of halogens, which decreases the energy pumped by electron beam at the center of the laser cell and leads to additional energy pumping in the near-wall zones due to the inverse current and hence to the decrease of the generation energy density at the center of the laser beam.

We note that the shape of the dependence of experimentally measured radial distributions of laser radiation for the mixture $SF_6:H_2$ at the pressure $p = 0.45$ atm agree qualitatively with the distributions calculated for this mixture at large pressures (curve *3*) when the energy losses of electrons per unit path length are higher. This circumstance also confirms a conclusion about the effect of volume charge on the radial energy distribution over the working volume of the laser cell whose electric field leads to the increase of the energy density losses of electrons per unit path length.

To obtain relatively uniform distribution of radiant energy density over the output beam cross section for a charging voltage of 80 kV (with a maximum voltage on the vacuum diode of ~ 400 kV), a working pressure of ~ 0.45 atm should be used in the working mixture in this system which provides a laser radiant energy of ~ 110 J for efficiency of 7%. For a pressure of the working mixture of 1 atm and essentially nonuniform radiant energy distribution over the output beam cross section the total laser energy was ~ 200 J with efficiency of ~ 10%.

A comparison of the electrical conductance of gas mixtures with large and small halogen concentrations for the electric discharge laser showed that their electrical resistance differed by more than two orders of magnitude under comparable conditions. Thus, in the mixture of SF_6 with propane in the 20:1 ratio with the discharge gap 3 cm long, a cross section of the discharge region of 60 cm^2, and a discharge voltage of 23 kV the minimum resistance recorded at the maximum current and a pressure of SF_6 of 30 Torr was 2Ω and at a pressure of 60 Torr it was 3.9 Ω. The increase of the charging voltage from 19 to 28 kV at a pressure of this mixture of 45 Torr led only to the insignificant decrease of the plasma resistance from 3 to 2.5 Ω. We note that when the discharge current decreases within the time over which the pumping pulse acts, the plasma resistance starts to increase in proportion.

Let us analyze possible distribution of the potential over the laser cell cross section with pumping by radially convergent beam of electrons. For relatively uniform pump energy the charge may accumulate near the cell center resulting in the formation of the electric field inhibiting the electron beam motion. The field strength depends on the halogen concentration and type, current beam density and energy of electrons in the working mixture, as well as on the laser cell size and geometry. The electric field causes the charging current flow from the region with enhanced negative potential to the laser cell walls through the working mixture ionized by the electron beam and produces additional pump energy. With the increase of halogen carrier pressure and laser cell transverse size or with the decrease of the beam electron energy, the zone with the enhanced potential approaches the laser cell walls thereby increasing the nonuniformity of the pump energy.

In Fig. 2*a*, the radial distributions are shown of the absorbed energy density for the laser with an active volume of 600 l calculated by the Monte Carlo method neglecting the effect of the volume charge for the mixture SF_6:H_2 = 8:1 at pressures of 0.25, 0.45, and 1 atm and in Fig. 2*b* – for the mixture Ar:Xe at p = 1, 1.5, and 2 atm along with the experimentally measured radial distributions of the output laser radiation for the mixture Ar:Xe:HCl = 750:10:1 at pressures of 1, 1.5, and 2 atm. Our results also demonstrate that calculated and experimental data on the radial energy distributions for the mixtures in which the electromagnetic gas components are small or absent agree well in their behavior (see Fig. 2*b*).

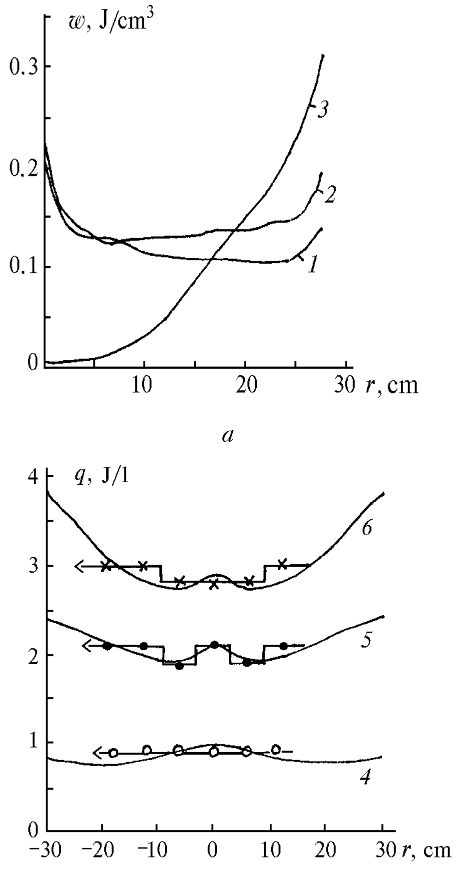

FIG. 2. Radial distributions of the absorbed energy density calculated by the Monte Carlo method neglecting the effect of the volume charge for the mixtures SF_6:H_2 = 8:1 *at pressures* p = 0.25 *(curve 1),* 0.45 *(2), and* 1.0 atm *(3) and* Ar:Xe = 9:1 *at* p = 1 *(4),* 1.5 *(5), and* 2 atm *(6) along with the experimental radial distributions of the output laser radiation for the mixture* Ar:Xe:HCl = 750:10:1 *at* p = 1 ( ), 1.5 (•), *and* 2 atm (×). *System 2 with* U_0 = 95 *(=)* and 85 kV *(b).*

In Fig. 3 the spatial distributions of the absorbed energy are shown for the second system calculated by the Monte Carlo method. It can be seen that at a pressure of 2 atm, pumping is fairly homogeneous. This is confirmed by uniform distribution of the radiant energy density over the beam cross section.

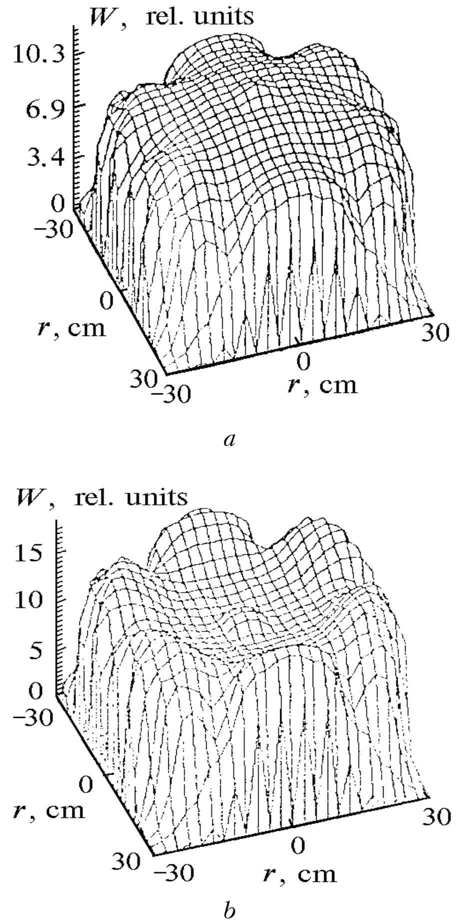

FIG. 3. Spatial distributions of the absorbed energy calculated by the Monte Carlo method for system 2 at pressures of argon p = 1 *(a) and* 2 atm *(b). The gas volume is pumped from six sides and the current pulse and the voltage correspond to the experimental conditions with* U_0 = 85 kV.

For the mixtures SF_6:H_2 (curves *1*, *2*, and *3* from Fig. 2), in which the halogen concentration is ~ 90% even neglecting the effect of the volume charge, the pump energy distribution at high pressures is significantly nonuniform. This is connected with the fact that specific weight of SF_6 is 3.7 time larger than that of argon. If we predict the parameters of this wide-aperture laser with an active volume of 600 l pumped by the radially convergent electron beam and operating in the IR spectral range on the mixtures SF_6:H_2(D_2), the radiant energy for a total energy pumped by the electron beam of ~ 60 kJ and fairly uniform radiant energy distribution over the beam cross section (the minimum radiant energy density at the beam center is halved) is ~ 1 kJ. The working pressure should be 0.2–0.3 atm. Dependence of the total pump energy on the pressure of SF_6 calculated for a charging voltage of 100 kV is shown in Fig. 4.

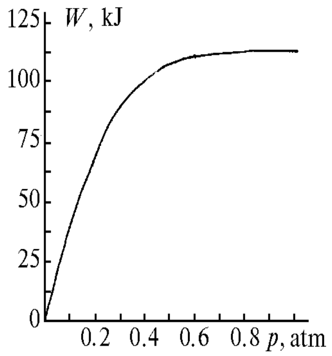

FIG. 4. Dependence of the total energy put in a gas at U_0 = 95 kV *on the pressure of* SF_6. *Calculations were done for the model neglecting the effect of the volume charge. System 2.*

The increase of the mixture pressure for the proper choice of the output mirror leads to the increase of the radiant energy, but the degree of uniformity of the energy density distribution over the output beam cross section deteriorates. As demonstrated above for the laser with an active volume of 30 l at a pressure of mixture of 0.45 atm, the radiant energy was ~ 110 J for efficiency of 7% and the difference between the radiant energy density at the center and near the foil did not exceed 50%. For this laser on the gas mixtures whose basic component is the gas SF_6, though we will observe stronger influence of spatial charge, nevertheless, at relatively low pressures of working mixture 0.2–0.3 atm resulting in the decrease of the efficiency 1.5–2 times with the increase of the charging voltage on the pulsed voltage generator up to 100 kV (~ 600 kV on the vacuum diode) we also can excite the high-power radiant energy at the center of the output beam.

Good agreement of the results of calculations made neglecting the volume charge field and experimental measurements of the total pump energy from the pressure jump should be noted. This is caused by the fact that all the energy spent on ionization of the medium and on the work against the electric field forces is dissipated in the heat energy and is recorded with the pressure gauge. Therefore, for efficient geometry of the electron beam injection used in the systems (radially convergent beam), the volume charge field affects only weakly the total energy absorbed in the volume.

6. CONCLUSION

Excitation and generation of the HF laser pumped by nonchain chemical reaction initiated by a beam of electrons as well as of the KrF and XeCl lasers pumped by a beam of electrons have been studied theoretically and experimentally. Distributions of the radiant energy density over the output laser beam cross section have been found for lasers excited by radially convergent electron beams. Total pump energy in different gas mixtures also has been calculated. The effect of the volume charge field on the distributions of the pump energy over the laser cell cross section and of the radiant energy density over the output laser beam cross section in the mixtures with large (~ 90%) halogen concentrations have been demonstrated.

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