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Electric-discharge XeCl laser emitting 10-J, 300-ns pulses

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***Abstract*.** **The development of a long-pulse electric-discharge XeCl laser with the 9 × 6 × 100 cm active volume is reported. Laser is excited by using a double circuit with a pulsed charged storage capacitor consisting of paper-oil capacitors forming the pulse-shaping line. The storage capacitor is switched by a multichannel extended gap. The laser mixture was preionised by X-rays. The laser generated the 10-J output pulses with the FWHM of 300 ns, and a uniform intensity distribution over the exit aperture.**

Keywords: *excimer laser, pulse-shaping lines, extended gap, preionisation, X-rays.*

1. Introduction

The applications of electric-discharge excimer lasers as high-power UV radiation sources in nonlinear optics, in material processing, and in physical experiments stimulate the development of excimer lasers with a large volume of the active region and a uniform energy distribution over the aperture [1 – 7]. The wide-aperture electric-discharge XeCl lasers developed in [4 – 6] emit 10-J pulses with the FWHM (full width at half-maximum width) from 85 to 180 ns. At the same time, it is possible in principle to obtain laser pulses of duration up to 1 μs [8]. A further increase in the laser pulse duration in such lasers may result in an increase in the output pulse energy and can simplify the problem of forming high-quality radiation [7]. Note that wide-aperture lasers with a long output pulse duration may be employed as amplifiers in high-power laser systems.

The main problem encountered by experimenters in the development of long-pulse lasers is to provide the uniformity of the volume discharge in the active region during the pump pulse. In this case, it is necessary to retain the optimal pump conditions and provide efficient energy input into the active medium. The main requirements imposed on the laser excitation system involve producing a uniform preionisation of the working gas mixture and a uniform electric field in the discharge gap. It is also necessary to form rapidly the volume discharge and then maintain the optimal current density in the volume discharge and the optimal electric field intensity in the plasma during the laser pump pulse. All these requirements are rather hard to satisfy in a real experiment, but it is the degree of their realisation that mainly determines the output pulse duration of the excimer laser.

The aim of our work was to investigate the possibility of increasing the duration of the radiation pulse of a wide-aperture electric-discharge XeCl laser and to build the laser emitting 10-J, 300-ns pulses.

2. Experimental

This work was carried out in two stages. At the first stage, we investigated an electric-discharge XeCl laser with an aperture of 7 × 4 cm, which had previously been employed to obtain the output pulse up to 150 ns in duration [6]. During these investigations, we increased the laser pulse duration to 200 ns by increasing the capacitance of the storage capacitor and determined the factors which could prevent the further increase in the output pulse duration. First of all, these are the degree and uniformity of X-ray preionisation.

At the second stage, taking into account the obtained results we designed, built, and investigated the setup whose appearance is shown in Fig. 1. The laser consists of three main units, which include the gas-discharge chamber with a pump generator and electric and pneumatic control systems. The gas-discharge chamber was made of stainless steel. It measured 41 cm in diameter and 140 cm in length. The chamber accommodated the vacuum diode of a soft X-ray source, the electrodes forming the discharge gap, and the insulator of the high-voltage lead.

The electrodes were made of stainless steel and were specially profiled to ensure the uniformity of the electric field in the discharge gap. The interelectrode distance was 9 cm. The electrode dimensions provided the discharge burning in the 6 × 9 × 100 cm volume. The electrode used as the cathode was attached in the discharge gap directly to the housing of the vacuum diode of the X-ray source. The electrode has a window of size 5 × 100 cm covered with an 80-μm thick titanium foil for the extraction of X-ray radiation to the discharge gap. The anode of the discharge gap is connected to the pump generator, which is located on the outside of the chamber, with the help of metal pins via an insulator. The elements connecting the generator to the anode and the inverse current-carrying conductors were designed to minimise the inductance of the discharge circuit.

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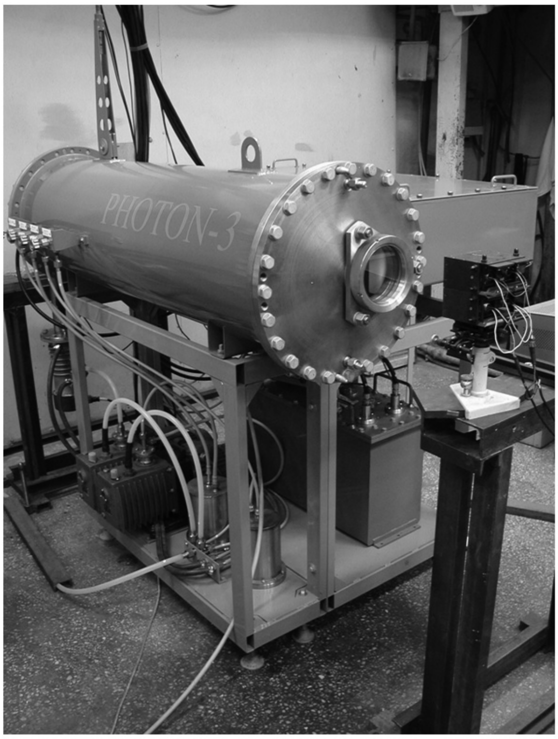


Figure 1. Experimental view of the laser setup.

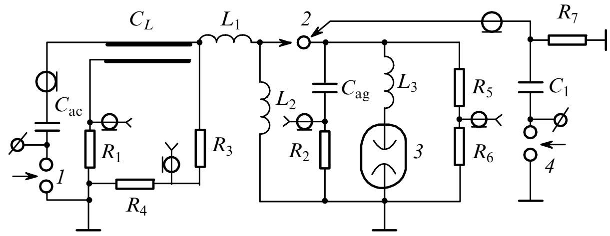


Figure 2. Principal electric circuit for laser excitation: (*1*, *4*) controllable gaps; (*2*) extended gap; (*3*) laser chamber; (R_1, R_2) current shunts; (R_3 and R_4), (R_5 and R_6) ohmic voltage dividers; (R_7) charging resistance; $L_1 = L_3 = 20$ nH, $L_2 = 250$ nH, $C_{ac} = 560$ nF, $C_L = 450$ nF, $C_{ag} = 7$ nF, $C_1 = 6.6$ nF.

The vacuum diode of the X-ray source has a cylindrical housing, which accommodates the anode and the cold cathode operating in the regime of explosive electron emission. The cathode consists of three strips of 0.5-mm thick foil-clad glass fibre laminate 1000 mm in length. The comb-configured strips were fixed on a separating mesh covered with a 40-μm thick titanium foil for sealing the vacuum diode and extracting the X-ray radiation from it. Tantalum foil was employed as the anode of the vacuum diode. The cathode – anode gap could be varied between 17 and 23 mm. The vacuum diode was evacuated with a diffusion pump to a pressure of $\sim 10^{-4}$ Torr.

The vacuum diode was fed from a three-stage Arkad'ev – Marx generator with a 15-nF total capacitance. The generator was connected to the vacuum diode with a KVI-120 high-voltage cable. A positive-polarity voltage was applied to the anode. The uniformity of current distribution over the diode length was achieved by connecting the anode and the diode-body lead-in with the aid of a set of equally long wire segments with a high-voltage insulation. The charging voltage of the generator could be varied between 20 and 30 kV.

Plane – parallel plates of fused quartz 140 mm in diameter served as the windows of the laser chamber. The laser resonator was formed by an external dielectric mirror with a reflectivity of 97 % at a wavelength of 308 nm and the window of the laser chamber. An Ne – Xe – HCl mixture was employed as the active medium. The working mixture pressure was 3.5 – 4 atm.

The main elements of the laser pump generator are the storage capacitor, the switch, and the peaking capacitor. The schematic electric circuit of the generator is presented in Fig. 2. The storage capacitor C_L consists of three parallel lines of FL-300 capacitors with paper-oil film insulation. Each line has a capacitance of 150 nF and a wave resistance of 1 Ω, making it possible to obtain 300-ns electric pulses. The pulsed charging of the lines is performed from an IK-100 kV – 0.56 μF C_{ac} capacitor connected to these lines via a KVI-120 cable. The capacitor C_{ac} was normally charged to a voltage of 60 – 65 kV. The peaking capacitor $C_{ag} = 7$ nF responsible for the formation of a volume discharge in the laser chamber was assembled of 20-kV, 680-pF KVI-3 ceramic capacitors.

A multichannel gap with a strongly inhomogeneous field at the anode was used as a low-inductance switch (2) [9]. The electrodes of the gap were made of stainless steel. The anode was a 1-mm thick plate and the cathode was a rod 15 mm in diameter. The electrode lengths were 100 cm and interelectrode gap was 6 mm. The triggering electrode, which consisted of separate lobes, was located near the cathode along its full length. The gap housing was made of a dielectric tube with an outer diameter of 65 mm. In the operating regime, the gap was filled with dry air at a pressure of 6.6 atm. The gap was triggered with a voltage pulse formed in the discharge of a C_1 capacitor via controllable spark gap (*4*). This pulse was applied to the cathode via spark gaps near the cathode; their radiation was an aid in providing the initiation stability and the multichannel nature of the breakdown of extended gap (*2*).

All spark gaps of the laser were triggered with the help of a high-voltage pulse generator made on the basis of a TGI-1-1000/25 thyratron. Artificial radio delay lines of the synchronisation system provide sequential actuation of the pump generator and the X-ray radiation source.

The operation principle of laser excitation scheme consists in the following. After charging of the capacitor C_{ac} from a constant voltage source, gap (*1*) is actuated to perform pulsed charging of the storage capacitor line C_L. When the voltage maximum is achieved, gap (*2*) is actuated, the peaking capacitor C_{ag} is charged, and a breakdown occurs in the discharge gap of the laser chamber. After this, the energy stored in the capacitor C_L is transferred to the discharge plasma.

The voltage pulses across the storage line C_L and the peaking capacitor C_{ag} were recorded with the help of voltage dividers $R_3 - R_4$ and $R_5 - R_6$. The discharge current of the storage lines was measured with a shunt R_1 consisting of TVO-0.5 resistors with a resistance of 1 Ω. The temporal and energy characteristics of laser pulses were measured with a FEK-22 photodetector and TPI-7 and IKT-2N calorimeters. The signals under study were recorded with a TDS-3014 oscilloscope. The soft X-ray exposure in the active medium of the laser was measured with KDT-02M and KID-1 dosimeters specially calibrated for these purposes.

3. Experimental results and discussion

Because preionisation is of special significance to the initiation of a long-duration volume discharge we investigated the X-ray source parameters. It was shown [10, 11] that the optimal voltage across the diode was 30 – 50 kV. This is due to the fact that the absorption of X-rays in the gaseous laser mixture decreases at accelerating voltages above 50 kV, resulting in a decrease in the initial electron concentration in the active region of the laser. When the voltage across the diode is below 30 kV, the losses of X-ray radiation in the foil, which normally separates the X-ray source from the gas-discharge gap of the laser chamber, increase. For this reason, we attempted to realise the operating mode of the X-ray source in which the main current through the diode corresponds to this accelerating voltage range.

At the last stage of the investigation of the X-ray source, we varied the charging voltage of the pulse generator and the anode – cathode gap in the diode. For a gap of length $d = 23$ mm and a charging generator voltage $U = 28$ kV, the duration of accelerated-electron current pulse achieved 700 ns and the current amplitude achieved 3 kA. The highest voltage across the diode was ~ 55 kV (Fig. 3). Lowering the charging voltage of the pulse generator resulted in a decrease in the X-ray radiation dose, while increasing the charging voltage resulted in an instability development at the end of a diode voltage pulse. When the gap was narrowed to 17 mm, the diode current amplitude increased to 4 kA and the maximum voltage across the diode decreased to 45 kV. We selected the operating regime of the X-ray source occurring for $d = 23$ mm and $U = 28$ kV. The nonuniformity of X-ray radiation dose distribution over the exit window aperture revealed that it was measured to be 10 % – 20 %. After passing through the titanium foils which covered the windows in the vacuum diode and the profiled electrode, the radiation exposure in the active region of the laser was ~ 30 mR. The initial electron density produced by this X-ray radiation dose in the gaseous laser mixture is estimated at $(5 - 10) \times 10^8$ cm^{-3}.

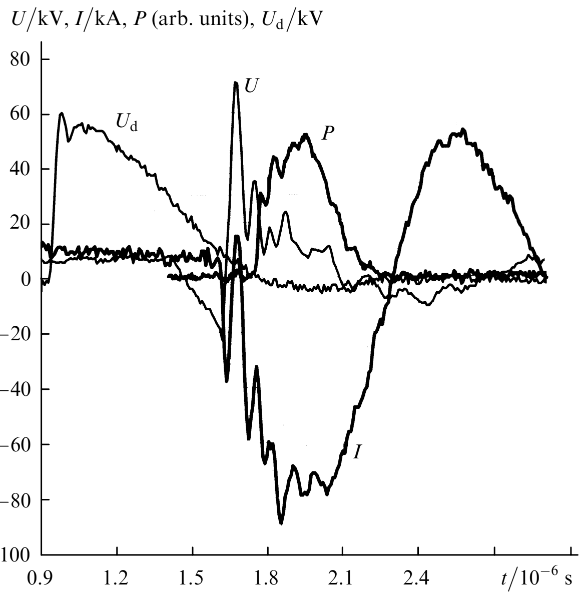


Figure 3. Oscilloscope traces of the voltage U across the peaking capacitor C_{ag}, the discharge current I of the storage capacitor C_L, the laser radiation power P, and the voltage U_d across the vacuum diode of the X-ray source. The Ne : Xe : HCl = 3200 : 10 : 1 mixture was used at a pressure of 4 atm, and the maximum voltage across the capacitor C_{ac} was 63 kV.

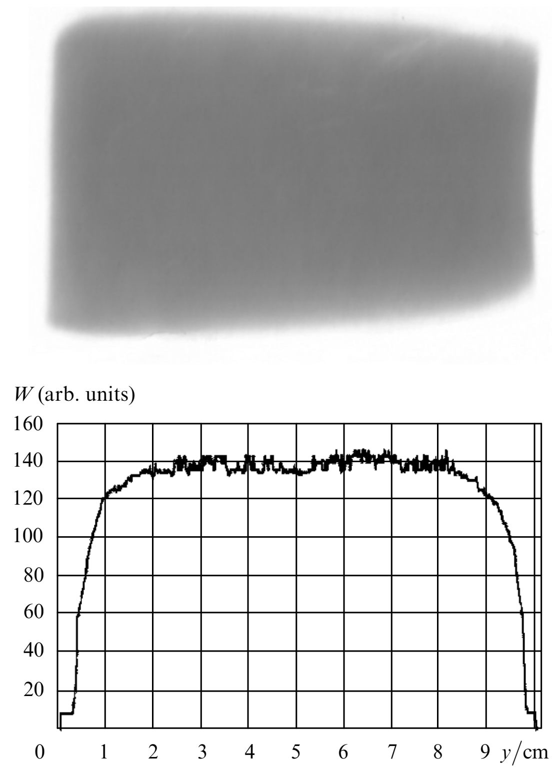
Figure 3 shows the oscilloscope traces of voltage, current, and radiation pulses which characterise the typical laser operation regime. In the experiments conducted, the pulsed charging of the storage line capacitor C_L from the capacitor C_{ac} to a voltage of 63 kV was performed for ~ 2.8 μs. The X-ray radiation source was actuated 700 ns prior to the cessation of lines charging. The optimal delay time between the triggering pulse applied to extended gap (*2*) and the onset of the pulse of accelerating voltage across the X-ray source was equal to 380 ns. After breakdown of the multichannel gap, the voltage across the peaking capacitor C_{ag} increased with a rate of $\sim 10^{12}$ V s^{-1}. This provided the charging of the peaking capacitor to 70 kV and the formation of a homogeneous volume discharge in the laser gap during its discharge. During the buildup of current through the discharge gap of the laser, the oscillating current of the peaking capacitor also passed through multichannel gap to maintain the conductivity in the channels and their uniform distribution over the length of discharge switch electrodes. The maximum discharge current of the storage lines was as high as 80 kA and the reduced voltage across the plasma of the volume discharge was ~ 0.3 kV cm^{-1} atm^{-1} at this instant. Lasing developed with a delay of ~ 100 ns relative to the onset of laser pumping and persisted for ~ 500 ns up to completion of the first half-period of the discharge current. The FWHM of the laser pulse was 310 ns.

The near-field imprints of laser radiation produced on photographic paper and the energy distribution over the laser-beam cross section with a power meter showed that the radiation was distributed rather uniformly over the 6×9 cm area (Fig. 4). For a mixture pressure of 3.5 – 4 atm and a variation of Ne content [Ne : Xe : HCl = (2000 – 3200) : 10 : 1], the output pulse energy varied only slightly and was ~ 10 J. Upon dilution of the mixture with a neon buffer gas, the duration of output radiation pulses increased from 250 to 310 ns. The highest output energy in our experiments was 10.8 J for a voltage across the storage capacitor of 64 kV for the Ne : Xe : HCl = 2800 : 10 : 1 mixture at a pressure of 3.5 atm.

The lasing efficiency relative to the energy deposited in the gas during the first half-period of discharge current was 3.5 %. The study of the energy losses in the pump generator showed that active losses in the extended gap and the dielectric losses in the FL-300 lines amounted to ~ 60 % of the energy stored in the lines. In addition, upon excitation of the laser there was no perfect matching between the impedance of discharge current and the resistance of laser gap plasma because of the use of a mixture with a reduced content of HCl required to obtain a long pulse. As a result, the working laser efficiency in our experiments did not exceed 1.2 %.

4. Conclusions

We have shown that the duration of 10-J pulses from a wide-aperture XeCl laser can be increased up to 310 ns. This result was achieved by using X-ray preionisation and a



a

b

Figure 4. Near-field imprint of a laser pulse (a) and output energy distribution W over the laser-beam cross section (b).

simple two-circuit excitation scheme with a pulsed charging of the storage capacitor. Paper-oil pulse-shaping lines were used for energy storage and an extended multichannel gap served as a high-current switch. Our experimental data have shown that to obtain 300-ns pulses from the XeCl-laser, the following conditions should be fulfilled:

(i) The discharge current density should be ~ 150 A cm^{-2} and the specific pump power ~ 150 kW cm^{-3};

(ii) the uniformity of preionisation in the active region should be better than 10 % – 20 % and the produced initial electron density no less than 5×10^8 cm^{-3};

(iii) the laser mixture should have reduced contents of xenon and HCl [Ne : Xe : HCl = (2000 – 3200) : 10 : 1].

This laser is intended for use as a preamplifier in a laser facility with a final amplifier based on an electron-beam pumped XeCl laser module [12] developed at the Institute of High-Current Electronics, Siberian Branch of the Russian Academy of Sciences, for the production of high-power UV radiation with a nearly diffraction-limited divergence.

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