X-ray radiation source for discharge preionization in gas lasers

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We present some experimental results on the X-ray sources for preionization of lasing gas mixtures in wide-aperture electric-discharge excimer lasers. X-ray pulse was formed in a thermionic diode of the inverted type at deceleration of the accelerated electrons in the tantalum foil. It is shown that the use of a metal–dielectric cathode enables one to obtain the X-ray radiation with uniform intensity distribution, accurate to 10%, at the quanta energy up to 55 keV and exposure dose up to 160 mR.

Introduction

Use of X-ray radiation for preionization of the gas mixtures in gas lasers allows one to provide high uniformity of the initial electron concentration and thereby exciting gas in big volumes at high pressure. As shown[1–3] the highest efficiency of converting the pump energy into the energy of laser radiation and the best uniformity of output energy distribution of the excimer lasers are achieved if using X-ray radiation. Soft X-ray radiation with the quanta energy of ~30 to 50 keV has allowed obtaining the pulses of laser radiation with the energy of tens of joules.[4,5]

Generation of X-ray radiation in the source occurs, as a rule, in the thermionic diode at the bombardment of a target made from metal with large atomic number by accelerated electrons. As known,[6] the bremsstrahlung radiation is known to have a continuous spectrum with the maximum of the quantum energy distribution at about the half of the accelerating voltage. For the effective gas ionization, X-ray radiation should satisfy some specific requirements to the radiation energy spectrum, particularly to its intensity and distribution uniformity at the exit from thermionic diode.

As shown in Refs. 7 and 8, the optimum working range of the accelerating voltages of the thermionic diode is within the limits from 30 to 50 kV. The upper limit is caused by the reduction of absorbed radiation dose in the laser active area due to the reduction of mass attenuation factor of X-ray radiation in gas at X-ray quantum energy above 35 keV. Besides, in the electro-discharge XeCl laser, in the mixture of Ne–Xe–HCl gases, up to 90% of the exposure dose quanta with the energy about 34 keV, can be re-emitted in the K-series of the Xe fluorescence, that practically doesn't contribute to gas ionization. The lower limit usually occurring at the voltage at the diode below 25 kV, is caused by significant growth of the X-ray losses in foils shielding the exit window for radiation coming from the thermionic diode and one of the electrodes of laser gas-discharge chamber.

For obtaining high level of X-ray radiation in the thermionic diode, a cold explosion–emission cathode is usually used. The main problems in operation of such a diode are poor stability and uniformity of the explosive electron emission from the cathode due to the relatively low accelerating voltage in the diode.[9] In Ref. 10 one can find a description of the design and experimental results of the source of soft X-rays with the exit window of 5×100 cm in size, developed earlier. A thermionic diode of the inverted type was used in the source. Investigation of this source has shown, that instability limiting the amount of X-ray dose develops in the thermionic diode if the storage capacitance exceeds 5 nF. Besides, the radiation distribution across the cross section of an output window was insufficiently uniform.

In this paper, we investigate similar X-ray source in order to try to increase the intensity and uniformity of the output radiation.

Instrumentation and measurement procedure

The investigations have been carried out using X-ray sources with the output windows of up to 5×100 cm in size. The electrical schematic diagram of the sources is presented in Fig. 1.

A thermionic diode of the inverted type was used in the sources. The pulsed power supply of the diode was provided by the storage capacitor C charged up to 60 kV which was switched by spark gap *1*, or from the three-stage Arkadiev–Marx generator (PVG) with the shock capacitance C equal to 15 nF and internal inductance of ~1 μH. The capacitance C varied from 3.3 up to 25 nF. In all cases, a high voltage pulse of positive polarity was applied to the diode with the help of the cable KVI-120 *2*, whose length varied from 2.5 up to 13.5 m. High voltage

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was applied to the anode *4* with the help of several conductors *3* of equal length inside the diode. Various types of the cathode *5* were investigated in the course of the experiments. In one case, 25-μm thick staggered strips of tantalum foil served the cathode. In the second case, the cathode was made from foil-clad substrate from fiber-glass plastic of 0.5-mm thickness. In the third case copper wires pasted on the fiberglass strips made the cathode. The gap between the anode and the cathode varied from 14 to 23 mm. To bring the X-ray out from the diode, a window covered with a 50-μm thick titanium foil was placed behind the cathode. A pulse of electric current through the diode was recorded using a shunt R_1, while the voltage applied to the diode was recorded using the divider formed by the resistors R_2 and R_3.

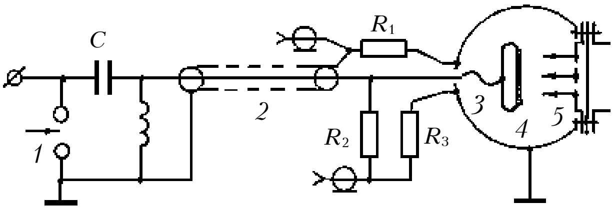

Fig. 1. The electrical schematic diagram of X-ray sources: the regulated spark gap *1*; the lead coaxial conductor *2*; the electric conductors *3*; the anode *4*; the cathode *5*. L_1 = 10 μH, R_1 = 0.02 Ω, R_2 = 10 kΩ, R_3 = 50 Ω.

In the experiments, the oscilloscope TDS-3014 recorded the pulses of the electric current and voltage. Measurements of the X-ray exposure dose behind the foil and its distribution over the output window of the diode were carried out by means of KDT-02M and KID-1 dosimeters that we specially modified for measurements of soft X-ray radiation. Besides, distribution of radiation intensity was recorded on the RF-3 film.

Results and discussion

The primary attention in our investigations has been paid to the seeking conditions favorable for forming a uniform e-beam in the thermionic diode, as it is just this diode that determines the parameters of X-ray radiation. In its turn, uniformity of the e-beam is known to be determined both by the properties of the cathode, and by the parameters of power supply of the thermionic diode.

First, we have carried out our experiments with the use of the cathode made from tantalum foil. In this case, the power was supplied to the diode from the capacitor C. Investigations have shown that the diode parameters strongly depend on the length of cable connecting the capacitor and the diode. Figure 2 presents oscillograms of the voltage at the capacitor and of the current through the diode for cables with the length of 3.5 and 13.5 m.

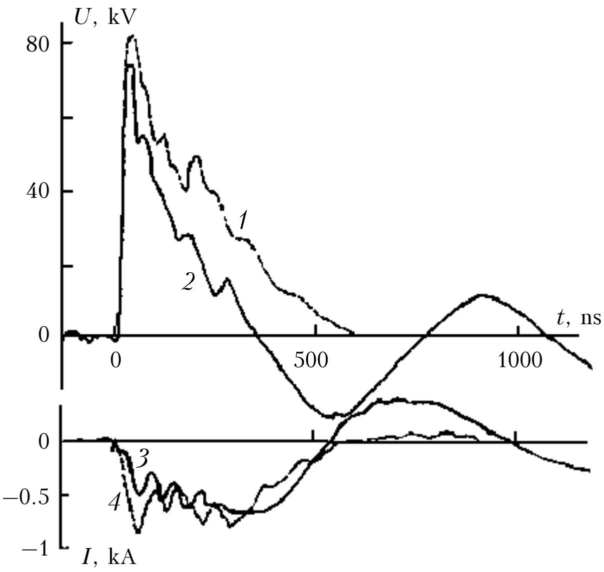

Fig. 2. Oscillograms of voltage U applied to the capacitor and the current I through the diode with the cathode from tantalum foil and C = 3.3 nF. The charging voltage U_0 was equal to 60 kV, the length of the lead cable was 3.5 (*2*, *3*) and 13.5 m (*1*, *4*).

It is seen, that voltage pulse is shorter at a short cable than the current pulse, and voltage falls down much faster, than in the case with a long cable. This fact and the reverse current polarity points to the development of instability in the diode in the first half-period of the current pulse and, hence, to the contraction of the X-ray pulse. Duration of the voltage pulse at a long cable almost coincides with the duration of the electric current pulse and no reverse polarity of the current occurs. In this case, we recorded higher dose of the output X-ray radiation.

In analyzing voltage pulses, one can notice that the maximum voltage in both cases exceeds the supply voltage of 60 kV. This is connected with the voltage jump on the constructional capacitance of the diode electrodes. This jump of voltage also points to the presence of a certain time lag between the pulse from the power supply and the start of the diode operation. High voltage facilitates the thermionic diode operation with a point cathode. In view of this, the higher voltage at a long cable allows the generation of the cathode plasma to start faster and, hence, to make its development more uniform and to make up the current of a higher amplitude in the diode during the same time. In our opinion, it is just this circumstance that has allowed us to realize more stable operation of the thermionic diode with a long cable. It is quite probable that under such conditions quite a uniform e-beam has been formed that lasted during the entire pulse of voltage applied to the diode.

To increase the X-ray exposure dose, we have increased the capacitance, supplying the thermionic diode, and the accelerating voltage applied to it. Thus, for a convenience of operation with high voltage, we applied PVG instead of the storage capacitor at charging voltages from 20 to 30 kV. The researches have been carried out using the same diode with the tantalum cathode at various length of the lead cable. In this case, the length of the lead cable in the diode operation did not play such an important role any more, as in the case with the low-inductance storage capacitor (Fig. 2). Therefore, in then we used the 2.5-m long lead cable.

From the oscillograms shown in Fig. 3, it is seen that in all the cases an instability develops in the diode that makes the electric current to oscillate.

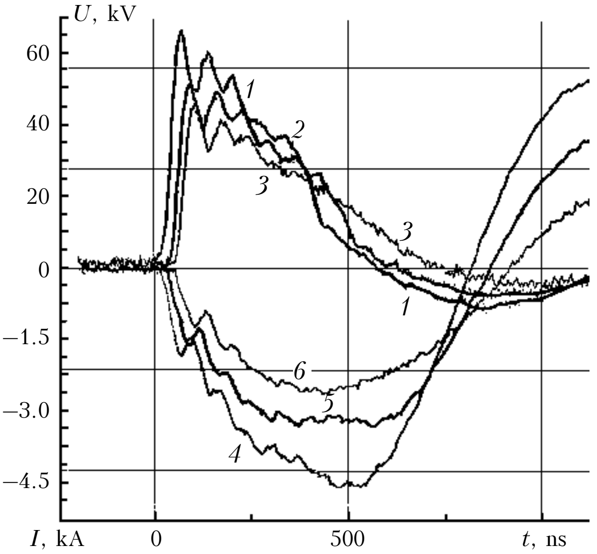

Fig. 3. Oscillograms of voltage pulses at the input to the diode and diode current for the diode cathode from tantalum foil and C = 15 nF. U_0 = 30 (*1*, *4*), 25 (*2*, *5*), and 20 kV (*3*, *6*). The length of the lead cable is 2.5 m.

The most favorable situation was observed at charging voltage of 20 kV when the e-beam existed practically through the entire voltage pulse length and instability developed only in its end.

The presence of instability in the diode with the tantalum cathode points to insufficient uniformity of the cathode plasma. To improve its uniformity, a metal point cathode has been replaced by the metal-dielectric (foil-clad fiberglass) one since it is known, that a metal–dielectric cathode allows facilitating the plasma formation and generating its more uniform distribution over the cathode surface.[11] The operation of such a diode was investigated at various distances between the anode and the cathode, and at various amplitudes of pulsed voltage. The change of anode–cathode distance from 17 up to 23 mm has shown that the optimum value is close to 19 mm. Thus, the diode works steadily at the charging voltage of PVG up to 28 kV. The oscillograms of the voltage and current pulses for this case are shown in Fig. 4. The diode current amplitude reached 3.5 kA at the pulse duration of 700 ns; the accelerating voltage at the current maximum was 50–55 kV.

If comparing these oscillograms with the oscillograms obtained in the case of metal cathode (see Fig. 3), the smaller amplitude of voltage pulse and the higher speed of current rise should be noted at the same values of the charging voltage from the PVG. Therefore, time of the electric current maximum has decreased from 350 down to 220 ns. It indicates that the metal–dielectric cathode starts working at smaller voltages applied the diode as compared with the metal ones and plasma appears faster on its surface. More stable operation of the diode and better uniformity of the e-beam density over the working area of the thermionic diode are the consequences of this circumstance. The X-ray exposure dose in the air for all operation modes of this diode with the size of the output window of 5×100 cm was about 80–100 mR at a sufficiently uniform distribution of the radiation intensity.

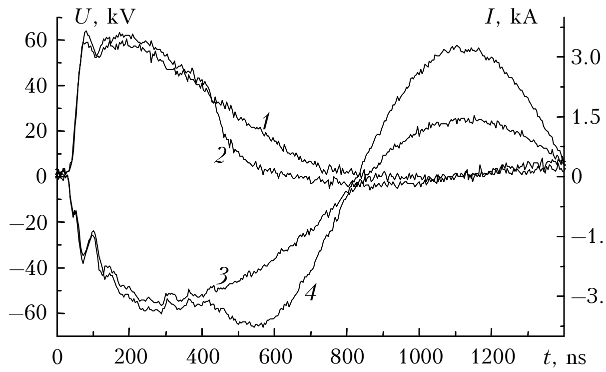

Fig. 4. Oscillograms of the voltage pulses at the diode (*1*, *3*) and diode current (*2*, *4*) for the case of the cathode from the foil-clad fiberglass. C = 15 nF, U_0 = 28 (*1*, *2*) and 30 kV (*3*, *4*).

We have carried out a detailed investigation of the radiation uniformity for various cathodes using the source with the size of the output window of 4×80 cm and the charging voltages from the PVG of 25–30 kV. The distance between the anode and the cathode of the thermionic diode in these experiments was 18 mm. The X-ray dose distribution over the central part of the output window along its length is shown in Fig. 5.

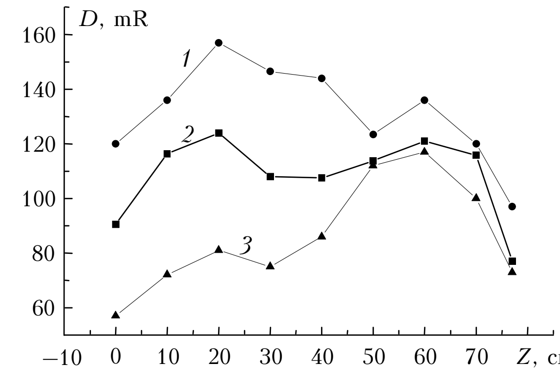

Fig. 5. Experimental dose distribution of X-ray radiation along the length of the output window of 80×4 cm in size. The cathode made from copper wires on the fiberglass, U_0 = 30 kV (*1*); the cathode from foil-clad fiberglass, U_0 = 25 kV (*2*); the cathode made from tantalum foil, U_0 = 25 kV (*3*).

The value of each point was averaged over 8 cycles of the source operation. As seen from Fig. 5, the uniformity of the dose distribution is much better in the case with metal–dielectric cathode. The quantitative estimation of non-uniformity without the account of extreme points for the cathode of a tantalum foil and the foil-clad fiberglass gives 37 and 10%, respectively.

In order to estimate the electron concentration in the lasing gas mixture and the influence of quantum energy of X-ray radiation on the gas ionization degree, we have performed computations of the linear coefficient of X-ray attenuation in the gas mixtures of Ne–Xe–HCl and a fraction of X-ray radiation exiting through the window of the X-ray source, covered by titanium foil (Fig. 6).

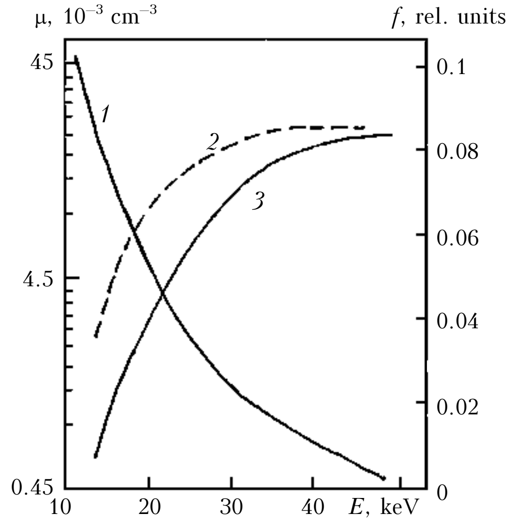

Fig. 6. Dependence of the linear attenuation coefficient of X-ray radiation μ in the 1000:10:1 gas mixture of Ne:Xe:HCl (*1*) and a fraction of X-ray radiation *f*, exiting through the window of a source covered by titanium foil of 50 (*2*) and 130 μm thickness (*3*), on the X-ray quantum energy.

Let us note that mainly xenon and neon absorb X-ray radiation in such a mixture. The X-ray quantum energy distribution was computed for various values of the accelerating voltage. Taking into account a solid angle of the useful part of the generated X-ray beam and energy losses owing to radiation scattering by the separation grid, the transmission coefficient of an output window for the investigated design of the diode was taken 0.09. The Ne:Xe:HCl gas mixture of the 2000:2.5:1 proportion was at the pressure of 4 atm.

Figure 6 demonstrates that output X-ray fraction depends on thickness of the output foil, whose transmission approaches the unity at the quantum energy above 50 keV. The low-energy component of X-ray radiation with the quantum energy of 15–25 keV significantly contributes to the gas mixture ionization in the active lasing region. However, the electrons experience significant losses at passage through the titanium foil.

Estimation of the conversion efficiency of the energy of accelerated electrons into the bremsstrahlung X-ray radiation, X-ray flux attenuation at passage through the titanium foil, and interaction of radiation with the Ne:Xe:HCl = 1000:10:1 gas mixture has shown that electron concentration in the mixture under the pulse action of X-ray radiation should reach $(5\text{–}10) \cdot 10^8$ cm^{-3}.

Conclusion

Research of soft X-ray strip source with a thermionic diode of the inverted type and a cold explosion–emission cathode has shown the possibility of forming sufficiently intense and uniform radiation. In a gas mixture of the excimer laser, this radiation can provide the initial electron concentration, sufficient for its effective operation. For the thermionic diode supply of X-ray source, the PVG with shock capacitance of 15 nF was used. Thus obtained X-ray radiation has pulse duration of 700 ns and provides the exposure dose up to 160 mR. Non-uniformity of X-ray intensity distribution over the aperture of the output window of the diode makes ~10%. High uniformity of X-ray intensity has been obtained due to the use of a metal–dielectric cathode.

The source described here has been used successfully for preionization of gas mixture in a discharge gap of a wide-aperture XeCl laser with the radiation energy of 10.8 J and pulse duration (FWHM) of 300 ns.[12]

Acknowledgments

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