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High-Pressure Behaviour of an X-Ray Preionized Discharge Pumped XeCl Laser

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Abstract. The output characteristics are described of an X-ray preionized discharge pumped XeCl laser, fed by a low-impedance pulse forming line (PFL), at pressures up to 12 bar. The influence of a multichannel rail gap placed between the PFL and the laser head on the output energy was studied. We found an increase of output energy with increasing pressure up to 8 bar. At higher pressures a saturation behaviour was found. The maximum output energy per unit volume was 6.5 J/l.

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High-efficiency operation in a self-sustained avalanche discharge XeCl laser can be achieved when the laser is operated at high buffer gas pressures. This has been shown by Ernst et al. [1] in a corona preionized system for pressures up to 10 bar.

When operating at high pressures and large apertures, the use of X-rays for preionizing the gas is advantageous over UV from, for instance, a corona discharge or an array of spark discharges because of the higher mass penetration depth of X-rays. Besides this, gas contamination caused by sparks or a corona discharge does not occur in X-ray preionized systems. This is especially important when the system is operated at a high repetition rate. Special attention should be paid to the construction of the window which separates the X-ray source from the laser chamber at high pressures; this window should be strong enough to withstand high pressures and as thin as possible to let the low energy X-rays penetrate the laser medium fairly unhampered.

In order to obtain a highly efficient operation of the laser it is important to keep the inductance of the circuit low so that the current rise time becomes very short and energy can be delivered to the gas medium rapidly. To lower the current rise time a multichannel rail gap is often used. An optimization study was performed for the use of such a gap. Although numerous studies on large aperture X-ray preionized XeCl lasers were performed at moderate gas pressures (up to about 5 bar) [2–4] little information exists on XeCl operation at higher pressures. Recently operation up to 10 bar in this type of laser with comparable dimensions was described by Steyer and Voges [5]. In their laser system, however, discharge voltage and current, which have an important influence on the output energy, were limited because a thyratron was used for switching the main discharge. In the system described below the main discharge is fed by a water-filled, low-impedance pulse forming line (PFL). A self-triggered multichannel rail gap (MCRG) could be mounted between the PFL and the laser head. In this way a higher discharge voltage and current could be obtained. For the high pressure regime we found an output behaviour partially different from others [5, 6], as will be discussed below.

In this paper we describe the successful operation of a high pressure X-ray preionized XeCl laser. Details of the operation characteristics of the MCRG are given.

1. Description of the System

The construction of the system is schematically shown in Fig. 1. The laser chamber consists of a rectangular

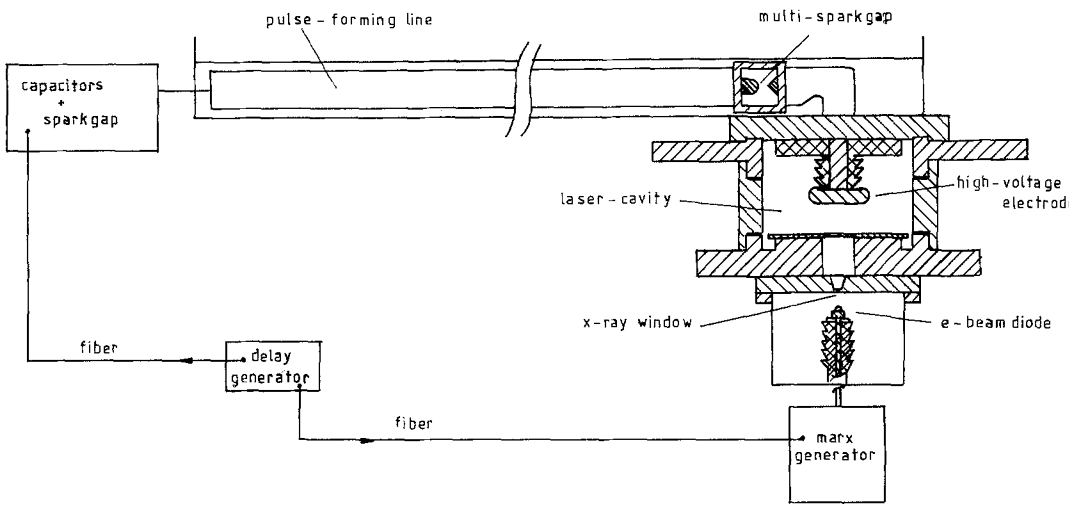


Fig. 1. Schematics of the high pressure X-ray preionized discharge pumped XeCl laser

stainless steel vessel designed for gas pressures up to 15 atm. The uniform-field high-voltage electrode, which has a shape as described by Ernst [7], is designed for a space between the electrodes of 1.5 cm with $k_0 = 0.02$. The length of the flat region is 60 cm. To prevent corrosion by HCl, this aluminium electrode is Ni-coated. The earth electrode is made of a flat stainless steel plate which is milled down to a thickness of 1 mm in the centre. This milled-down area was perforated with grooves so that the X-rays could penetrate the discharge region unhampered.

The X-rays are produced by decelerating electrons, produced by a cold cathode, in a 10 µm thick Ta foil. The cathode is made of carbon felt and has an area of 60×1 cm^2. The Ta foil serves as anode and is placed at a distance of 2 cm from the cathode. The Ta foil is attached to an aluminium plate which separates the vacuum and high-pressure chambers. In the centre, this plate is also milled down to a thickness of 1 mm in order to create a window for the X-rays. At the high-pressure side this plate is Ni-coated to prevent corrosion from HCl.

The e-beam diode is fed by a two-stage Marx generator equipped with two 20 nF capacitors, each charged to about 45 kV. The X-ray source generates about 7 mR/shot between the laser electrodes as measured with a pen dosimeter. The laser discharge is driven by a water filled PFL having a characteristic impedance of 0.65 Ω and a capacitance of 140 nF. The double transit time is 180 ns. In a part of the experiments described below, a nitrogen filled self-triggered rail gap followed by a short part of the PFL formes the connection between the pulse forming network and the laser head. The PFL is pulse charged by a low-inductance capacitor-bank having a capacitance of 160 or 280 nF through a conventional spark gap.

The time delay between the X-ray pulse and the main discharge can be varied electronically, where the delay is defined as the time difference between the onset of the e-beam voltage and that of the voltage of the main discharge. It turned out that this delay could be varied between about 50 and 700 ns without having a significant influence on the output energy of the laser.

Voltage and current measurements of the laser discharge were performed using a voltage divider and a low resistant shunt respectively. The voltage divider is constructed of hot-molded resistors, which have a very low inductance. The rise time of this divider is less than 10 ns. Output energy is measured using a GenTec ED500 and the output pulse is recorded by an EG & G photodiode type FND 100/Q. The optical cavity consists of a flat highly reflective dielectric mirror and a plane parallel uncoated quarz window for outcoupling.

The cavity was not optimized with respect to mirror parameters. However the use of an uncoated outcoupling mirror is attractive because of the sensitivity of dielectric coatings for high power densities and agressive gases like HCl.

2. Experimental Results

2.1. Operation Without a Multichannel Rail Gap

Experiments were first carried out using the system with a PFL having a length of 3 m and without a multichannel rail gap.

The measurements were performed in a HCl–Xe–Ne based mixture. We kept the HCl and Xe pressures at a constant value and used the buffer gas pressure as a parameter. Preliminary experiments performed at 4 bar showed that a partial HCl pressure of about 2.5 mbar was a good choice. Xe pressure was kept at about 22 mbar. As the output power is only slightly dependent on the Xe pressure we did not try to optimize this value.

Output power was measured at Ne pressures up to 10 bar. The shot-to-shot reproducibility of the system is very good and remains within a few percent. Between different fillings however, changes in output energy of about 10% may occur. This may be caused by the building up of impurities.

The output energy per pulse as a function of the load voltage of the sustainer power supply is presented in Fig. 2 for pressures up to 8 bar. The sustainer had a capacitance of 160 nF. At 9 and 10 bar the output energy did not significantly differ from the measurements at 8 bar. However, this is different from the measurements of Steyer and Voges [5] who found a maximum output energy at 7 bar and a significant decrease of output energy at higher pressures. Their results are supported by Lo and Zheng [6] who measured a rapid decrease of gain at pressures higher than 7 bar. Of course this decrease of gain will result in a decrease of output energy per pulse. They attribute the measured decrease in particular to the formation of

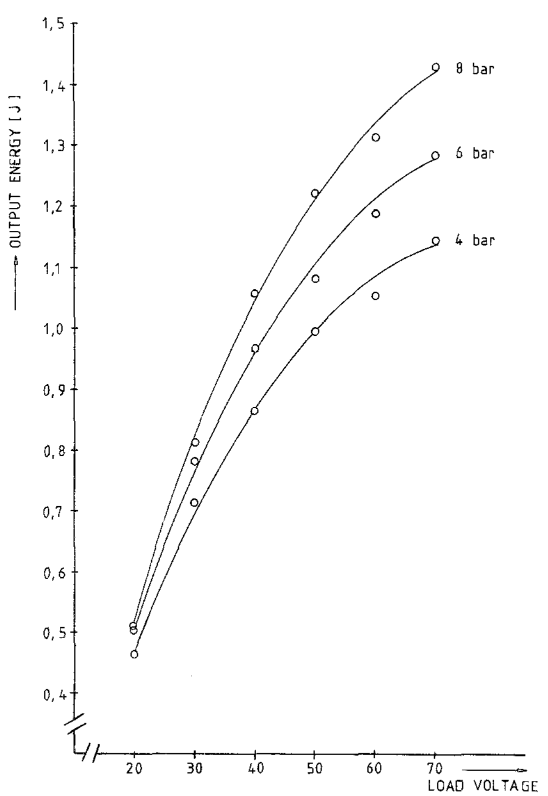


Fig. 2. The output energy as a function of the load voltage of the sustainer supply. The total gas pressure is used as a parameter. The multispark gap was not used

Xe_2^+, Xe_2^*, and Xe_2Cl^* which possess large ultraviolet absorption cross-sections. These absorbers are created primarily in a 3-body reaction which is favourable in a high-pressure Xe-rich mixture.

In our experiments a lean mixture of HCl and Xe was used. Probably the lower amount of Xe decreases the formation of UV absorbing species and the lower amount of HCl (which has a strong attachment for electrons) can delay the collapse of the homogeneous discharge.

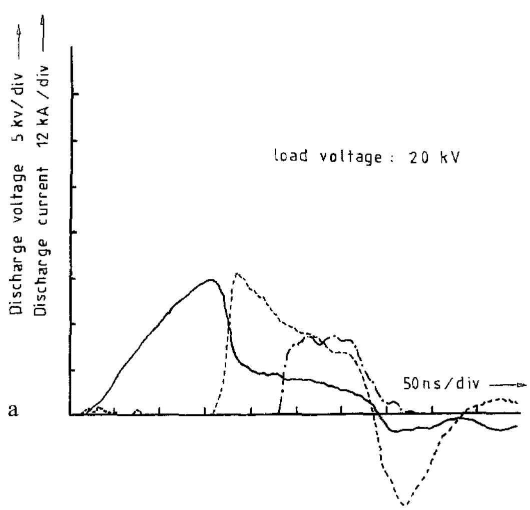
We believe that this sudden cessation of the increase in output energy is mainly due to the fact that at very high pressures part of the energy is not deposited in the active volume of the laser, but is lost along the walls of the laser chamber. At increasing gas pressure the breakdown and steady-state voltage of the gas mixture itself increases proportionally, whereas the surface breakdown voltage of the isolated feed-through on which the high-voltage electrode is mounted, is only slightly dependent on the gas pressure.

The steep slope of the curves for increasing load voltages of the sustainer is partly caused by the increasing width of the laser beam as observed from burn patterns. The width of the laser beam is determined by the divergence of the X-ray preionization source and the current of the main discharge. At higher currents a larger part of the discharge medium can achieve laser threshold. The width of the beam varies from about 17 mm at 20 kV to about 30 mm at 70 kV sustainer load voltage. So at 70 kV we achieved an active volume of $3 \times 1.5 \times 60 = 270\ \text{cm}^3$ resulting in an output energy of about 5.3 J/l in an 8 bar mixture. The higher efficiencies were obtained at low voltages; in the 8 bar mixture the efficiency at 20 kV was about $\frac{0.51}{32} = 1.6\%$.

Increasing the capacitance of the sustainer from 160 to 280 nF did not show a significant increase of output power except at low load voltages, (20 and 30 kV), where an increase of about 15% was observed. This was due to a somewhat higher current at the later part of the laser pulse. At higher load voltages no difference between the voltage characteristics at 160 and 240 nF sustainer capacitances could be observed. Typical characteristics obtained using a Tektronix R7912 transient digitizer are presented in Fig. 3.

As can be seen from these characteristics, the breakdown voltage is dependent on its rise time. This is due to the fact that the current needs some time to build up. The optical pulse length is about 90 ns.

After these experiments, we changed the plate which separated the laser chamber from the X-ray source. The new plate had a narrower X-ray window which resulted in a decrease of the beam width by about 20%.



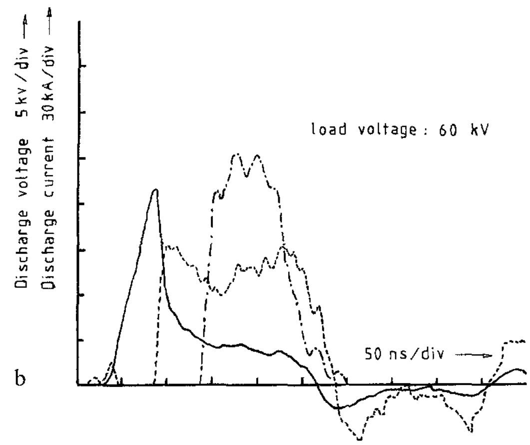


Fig. 3a, b. The time dependence of the discharge voltage (drawn line), laser current (– – – –) and optical output pulse (–·–·–) measured in an 8 bar mixture. The sustainer capacitance is 160 nF. The supply load voltages are 20 kV (a) and 60 kV (b), respectively. The multispark gap was not used

2.2. *Operation with a Multichannel Rail Gap*

In the experiments described in the previous section, the shape of the voltage across the laser electrodes is determined by the time for charging of the PFL and the gas pressure.

It can be concluded from Fig. 3 that a higher breakdown voltage, resulting in a higher current gives more output energy. It is obvious that only the energy delivered by the PFL during the double transit time of the PFL, effectively contributes to the formation of XeCl*. Energy that is delivered later is lost as the discharge collapses quickly into arcs and streamers.

In the experiments described below, higher breakdown voltages resulting in more energy being stored in the PFL, could be achieved by mounting a self-triggered multichannel rail gap (MCRG) between the PFL and the laser head. A disadvantage of a MCRG, however, is that it absorbes energy and contributes to the self-inductance of the system.

The MCRG consisted of a brass rod and a brass knife placed in a perspex box, which was filled with nitrogen. The pressure could be varied from 1 to 2.5 bar absolute. The distance between the sharpened edge of the knife and the rod could be varied between 5 and 20 mm.

The MCRG was mounted in the waterline leaving a distance of about 30 cm between the MCRG and the laser head which acted as a peaking capacitor. The sustainer was operated with a capacitance of 280 nF.

The dependence of the knife-rod distance of the multispark gap and the gas pressure inside it on the output energy of the laser is not obvious. We investigated this dependence for a 6 bar mixture. The results are shown in Fig. 4.

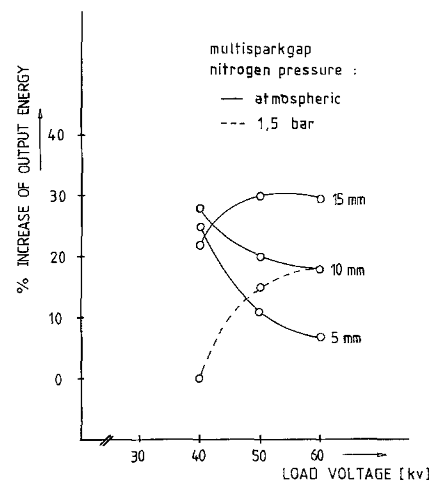


Fig. 4. Percentual increase of output energy compared to the system without the multispark gap as a function of the load voltage of the sustainer supply. Drawn lines represent measurements at atmospheric pressure for the multispark gap, the dashed line represents 1.5 bar nitrogen pressure. The rod-knife distance and the pressure of the multispark gap have been used as a parameter. The laser mixture contained 2.4 mbar HCl, 22 mbar Xe and 6 bar Ne

An increase in output energy with increasing knife-rod distances has been observed. At a knife-rod distance of 5 mm the output energy was hardly influenced by the gas pressure in the rail gap with a slightly higher output energy (about 4%) for the higher gas pressure. At larger knife-rod distances however the output energy decreased considerably at higher nitrogen pressures indicating that a considerable amount of energy was dissipated within the multispark gap. The best performance was obtained with a sustainer capacitance of 280 nF.

At a 15 mm knife-rod distance increasing nitrogen pressure caused electrical breakdown in the PFL. At knife-rod distances larger than 15 mm the rail gap did not operate properly because of arcing at the edges of the knife and rod. The best performance was obtained with a knife-rod distance of 15 mm by which, in a 6 bar mixture, a maximum increase of output energy was observed of about 30%. This increase was caused by an increase of the beam width by about the same amount. It can be concluded from the measurements with a 15 mm gap and atmospheric pressure and those with a 10 mm gap and 1.5 bar pressure that, although for both cases the same breakdown voltage can be obtained, the best results are found using the multispark gap at low pressures and a large knife-rod distance. The reason may be that at higher nitrogen pressures a smaller number of conducting channels is formed, leading to a higher self-inductance. Also the energy dissipation within the multispark gap may be larger at higher nitrogen pressures. Probably improvement of the output energy can be obtained by using larger knife-rod distances and operating under atmospheric pressures. Typical voltage-current-laser pulse characteristics when the laser is operated with an MCRG are shown in Fig. 5. Comparing the characteristics with those of Fig. 3 it can be concluded that the use of an MCRG leads to a shorter voltage rise time and a higher break-down voltage and current. After the determination of the optimal knife-rod distance and pressure we investigated the dependence of the output power on the gas pressure. For both 4 and 8 bar we found an optimum HCl pressure of about 4.5 mbar, which is considerably higher compared with the 2.4 mbar for the case without multispark gap. In this way an increase of output energy of about 30% could be obtained in an 8 bar mixture. Doubling the Xe pressure to about 50 mbar gave a reduction of output energy of about 15%. In Fig. 6 the output power is plotted as a function of the sustainer load voltage with the total gas pressure as a parameter. It was concluded from burn patterns that the width of the laser beam increased from about 29 mm at 40 kV sustainer load voltage to about 32 mm at 60 kV, whereas it did not depend on the total gas pressure. The steep slope of the curves is mainly caused by the increase of current at increasing sustainer load voltage as the voltage characteristics were hardly dependent on the sustainer load voltage. Again measurements performed at 10 and 12 bar gave no significant difference in output energy compared with the 8 bar measurements. This is clearly illustrated in Fig. 7.

By mounting the MCRG as close to the laser head as possible, which reduces the peaking capacitance, a slightly higher breakdown voltage and therefore an output energy increase by about 10% is observed. In this way in a 12 bar mixture we obtained an output energy per pulse of 2 J at 60 kV load voltage. As the active volume in this case was $3.4 \times 1.5 \times 60 = 306\ \mathrm{cm}^3$, the output energy per unit volume was 6.5 J/l.

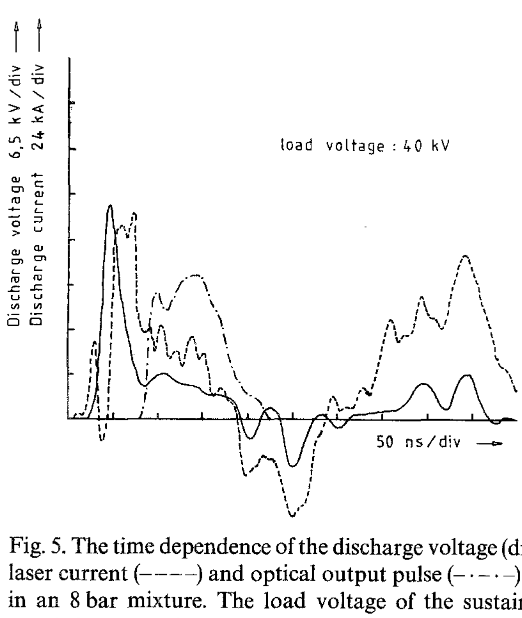


Fig. 5. The time dependence of the discharge voltage (drawn line), laser current (– – – –) and optical output pulse (– · – · –) measured in an 8 bar mixture. The load voltage of the sustainer power supply is 40 kV. The multispark gap was operated at atmospheric pressure and a knife-rod distance of 15 mm

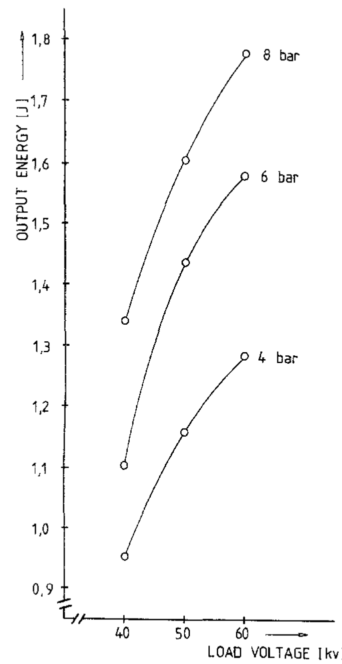


Fig. 6. The output energy per pulse as a function of the load voltage of the sustainer power supply. The multispark gap had a knife-rod distance of 15 mm and was operated at atmospheric pressure. The laser mixture contained 4.5 mbar HCl, and 22 mbar Xe. The total gas pressure is used as a parameter

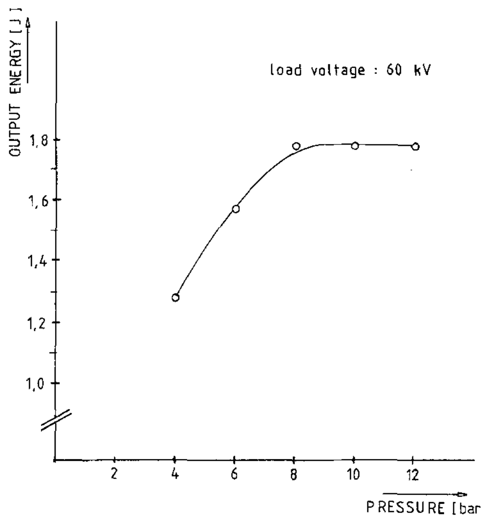


Fig. 7. The output energy per pulse as a function of the total gas pressure. The load voltage was 60 kV. The laser mixture contained 4.5 mbar HCl and 22 mbar Xe

3. Conclusion

An X-ray preionized discharge pumped XeCl laser was successfully operated at pressures up to 12 bar. At pressures of more than 8 bar the output energy did not further increase. This might be due to energy leaking along the walls of the laser chamber. In that case enlargement of the distance from the high voltage electrode to the wall may result in more output energy at pressures higher than 8 bar.

An important improvement of output energy could be obtained if a multichannel rail gap were mounted between the low-impedance pulse forming network and the laser head. Optimized operation conditions for the multichannel rail gap were determined.

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