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Pulsed CO_2 laser with an X-ray preioniser based on a high-voltage low-pressure glow discharge

V.F. Oreshkin, A.M. Seregin, V.V. Sinaiskii, A.R. Sorokin, T.A. Shchetinkina

***Abstract*. An X-ray preioniser with an electron beam energy density of 0.1 J cm^{-2} based on a high-voltage (20 – 40 kV) low-pressure glow discharge is developed for repetitively pulsed gas lasers. The electron concentration in the CO_2 – N_2 – He mixture as a function of the voltage across the preioniser is calculated for titanium and other foils. The preioniser can be operated both in a single-pulse regime and at pulse repetition rates ranging up to hundreds of Hertz. A specific energy yield of 51 J L^{-1} is achieved in the X-ray preionised pulsed CO_2 atmospheric-pressure laser. This preioniser was shown to be efficient for other active media (CO and excimer lasers), which opens up new opportunities for the development of repetitively pulsed gas lasers.**

Keywords: *gas lasers, preionisation, CO_2 laser.*

1. Introduction

The elaboration of an efficient preioniser is the key to the development of repetitively pulsed gas lasers. It is the preioniser that determines the type, the character, and the properties of the volume discharge and is of primary importance in determining all laser characteristics. In recent years, vigorous world-wide research has been pursued to improve X-ray preionisers and the lasers designed on their basis. The use of X-ray preionisation has made it possible to develop CO_2 lasers with a volume of the active medium of 280 L, a specific energy output of 40 J L^{-1}, and an efficiency of 20 % [1 – 4], excimer XeCl lasers with a specific energy output of 10 J L^{-1} and an efficiency of 5.3 % [5]. In this case, the preionisation electron density n_0 was 10^{10} – 10^{12} cm^{-3}.

In gas lasers, the chemical composition degradation of the active medium exposed to X-rays is significantly weaker than the degradation in the case of electron beams or spark UV preionisation sources. This allows a substantial reduction of the expenses for the renewal of the active medium and an increase in laser service life, obtaining in this case a nearly diffraction-limited divergence.

However, employing ultrahigh voltages (hundreds of kilovolts) in the preioniser [1 – 5] strongly hampers its application in repetitively pulsed gas lasers. It has been possible to reduce the voltage to 50 kV (the working voltage of the majority of switches operating at frequencies above 30 Hz) in X-ray preionisers in which vacuum diodes are used. Such a soft X-ray source was described in Ref. [6]. It can operate with a pulse repetition rate up to 35 Hz to produce preionisation with an electron density of $\sim 10^8$ cm^{-3} in CO_2 lasers and rare-gas halide lasers (the electron energy density in the beam is 0.01 J cm^{-2}). The authors of Ref. [6] point out the possibility of developing higher-power facilities with a pulse repetition rate up to several kilohertz.

Note that vacuum diodes based on explosive electron emission show poor performance in the repetitively pulsed regime. The typical service life of ordinary autoelectronic cathodes is $\sim 10^4$ pulses (for a current density of ~ 1 A cm^{-2}) [7]. The diode functions properly only at pressures below 10^{-4} Torr and requires a complex pump system for its operation in the repetitively pulsed regime.

Wide-aperture electron beams with average (10 – 70 keV) [8, 9] and higher [10, 11] energies can also be obtained in a low-pressure high-voltage glow discharge. In this case, the pulse repetition rate may achieve tens and hundreds of kilohertz and is limited only by the capacities of the switch and the thermal resistance of the foil [12].

The aim of our work was to develop an X-ray preioniser for repetitively pulsed lasers with an operating voltage below 50 keV and an electron beam energy density of 0.1 J cm^{-2} as well as a CO_2 laser on its basis.

2. Laser design

The laser design and the electric power supply circuit are presented in Fig. 1. The main discharge occurred between the cathode and the anode, which had the Ernst profile. The $\sim$ 80-mm wide and $\sim$ 180-mm long electrodes were spaced at 30 mm. The main discharge was switched with a TGI2-15000/50 thyratron (T_1). As an X-ray preioniser, we used a device in which the electron beam was produced in a low-pressure high-voltage glow discharge. The $\sim$ 160-mm × 70-mm × 50-mm preioniser housing was made of organic glass. The lower lid of an aluminium alloy served as the cathode and the upper aluminium lid, which was perforated to a transmittance of $\sim$ 80 %, served as a support grid for the foil and was the preioniser anode. The foil, which fulfilled the function of electron-to-X-ray energy converter,

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V.F. Oreshkin, A.M. Seregin, V.V. Sinaiskii, T.A. Shchetinkina 'Astrofizika' Research and Production Association, Volokolamskoe shosse 95, 125424 Moscow, Russia; e-mail: aphysica@aha.ru;
A.R. Sorokin Institute of Semiconductor Physics, Siberian Branch, Russian Academy of Sciences, prosp. akad. Lavrent'eva 13, 630090 Novosibirsk, Russia; e-mail: ifp@isp.nsc.ru

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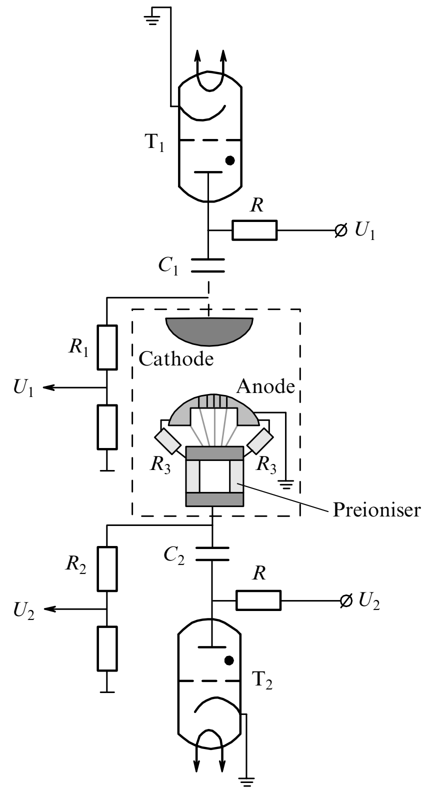

Figure 1. Scheme of the experimental setup: (U_1) voltage of the laser main discharge; (U_2) preioniser supply voltage; (R_3) preioniser shunt resistance.

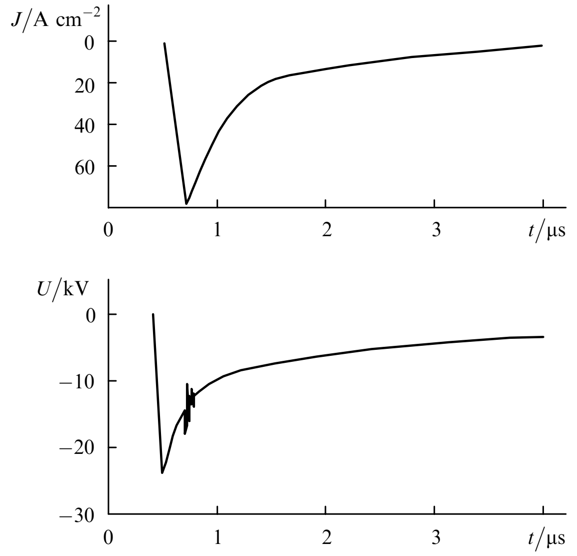

Figure 2. Typical oscilloscope traces of current density and voltage in the preioniser.

was vacuum-tight attached to the grid with a K-400 glue. The distance between the plane–parallel preioniser cathode and anode was equal to 35 mm. The electric preioniser parameters were monitored with the aid of a voltage divider and a current shunt of TVO resisters.

Figure 2 shows typical oscilloscope traces of voltage and current density in the preioniser. The energy density in the electron beam was calculated by integration over the voltage and current oscilloscope traces and was equal to 0.05–0.1 J cm^{-2} under operating conditions; the electron energy was neglected when it was below 20 keV. We note that the specific output energy of pulsed gas lasers increases logarithmically with initial electron density [13, 14], which in turn depends on the intensity of ionising radiation source $S_0 = n_0/t$, where t is the duration of an X-ray pulse. In accordance with Ref. [15],

$$S_0 = \frac{UJ\beta\mu f}{2W}, \qquad (1)$$

where U is the accelerating voltage; J is the density of electron beam current; β is the electron-to-X-ray conversion efficiency; W is the energy required to produce an electron–ion pair; μ is the X-ray absorption coefficient; and f is the geometrical factor which takes into account the solid angle of the useful fraction of the X-ray beam as well as the losses by absorption and scattering.

In Introduction we noted that the parameters of both CO_2 and excimer lasers improve significantly when $n_0 = 10^{10} - 10^{12}$ cm^{-3}. According to formula (1), this electron density can be obtained in the active medium when the energy density of the electron beam is $UJt \geqslant 0.1$ J cm^{-2}.

By varying the He pressure in the preioniser (from several Torrs to a fraction of a Torr), one can easily change the X-ray pulse duration from 30 ns to 30 μs. The preioniser electron gun produced electron beams with a maximum energy from 15 to 40 keV and an energy density of 0.1 J cm^{-2}, and could be operated both in a single-pulse regime and with a pulse repetition rate greater than 100 Hz. The form of oscilloscope traces of the current and the voltage across the preioniser did not vary in the repetitively pulsed regime (including repetition rates above 100 Hz). In our work, CO_2-laser experiments were performed in the single-pulse regime. The results of experiments staged in the repetitively pulsed regime will be outlined in subsequent papers.

The required pressure in the gun was attained by supplying He through a leak and pumping with a 2NVR-5D backing pump. The gas pressure at the preioniser output was monitored employing a PMT-4M thermocouple transducer and a VIT-2 meter. The electron beam with a cross section of 2 cm × 12 cm slowed down in the 12-μm thick titanium foil to generate X-rays and thereby produce preionisation in the main discharge due to the passage of soft X-rays through the openings in the perforated anode. The preioniser foil and the surface of the anode of the main discharge were spaced 2 cm apart.

The current in the preioniser was switched with a TGI2-15000/50 thyratron (T$_2$). The triggering system of the thyratrons of the main discharge and the preioniser allowed us to smoothly change the relative delay of thyratrons actuation, the jitter in actuation of the thyratrons relative to the initiating pulse not exceeding 10 ns. For storage capacitors we employed K15-10 ceramic capacitors with capacitances $C_1 = 20$ nF and $C_2 = 4.7$ nF. By now the preioniser has yielded 10^6 pulses with no change of its characteristics. The laser cavity was made up of a non-transmitting mirror with a radius of curvature of 6.2 m and a semitransparent mirror of KCl (or ZnSe) with a dielectric coating and a reflectivity of 90 % (or 80 %).

In this system we obtained a stable uniform discharge in mixtures with a high content of molecular gases. A mixture with the $CO_2 : N_2 : He = 1 : 2 : 4$ composition proved to be optimal under our experimental conditions. The output laser energy was equal to 2.6 J. The energy was measured with the aid of a TPI-2M radiation detector coupled to an F-30 voltammeter or an IMO-2M meter. The measurement data proved to be the same. The active medium measured 3 cm × 2 cm × 11 cm, and its radiation was stopped down with the barrel of the semitransparent mirror 28 mm in diameter. The imprints on thermosensitive paper and on carbon-paper measured 18 mm × 26 mm, which corresponded to a volume of the active medium of ~ 51.5 cm^3 and a specific energy output of 51 J L^{-1}. The radiant efficiency relative to the energy stored in the capacitor was higher than 10 %. The 51 J L^{-1} specific energy output was possible to obtain due to the high energy input into the laser medium with a high content of molecular gases due to the high and uniform initial electron density in the active CO_2-laser medium.

3. Preionisation regime and pulse duration

A significant feature of the preioniser elaborated in our work is that the duration of its X-ray emission is easy to control. The resultant pulse duration ranges from 10 ns to 30 μs. This range can be easily extended to milliseconds if use is made of artificial pulse-forming lines. The preioniser can also harness simply a continuous glow discharge.

For comparison we note that the duration of electron beams in vacuum accelerators is no greater than several microseconds for explosive-emission cathodes. Furthermore, the use of hot cathodes and plasma electron sources with a hollow cathode, which enables obtaining long-duration ribbon-shaped electron beams (including the continuous regime), complicates the facility to an extent that it is justified only in the special case of large and expensive facilities. A spark discharge commonly employed for preionisation in gas lasers has a high temperature required for efficient preionisation for only several tens or, at best, hundreds of nanoseconds. Subsequently, the spark discharge expands and cools down. Tubular quartz lamps exhibit a relatively low gas discharge temperature and can be efficient only when easily ionisable materials like tripropylamine etc. are added to the active laser medium.

In the regime of a long pulse (over 3 μs) it was possible to increase the e-beam energy density in the X-ray preioniser from 0.1 to 0.3 J cm^{-2}. The performance of the newly developed X-ray preioniser was demonstrated for CO lasers. A volume discharge with an energy input of ~ 500 J L^{-1} and a high visual uniformity was obtained with the $CO : N_2 : He = 1 : 9 : 10$ composition mixture at atmospheric pressure. In this case, no attempts were made to obtain lasing, because the active mixture was not cooled and was short in length (~ 11 cm).

4. Assessment of performance of different preioniser foil materials

A critical element of the preioniser, which affects the electron density n_0 in the active medium, is the e-beam-to-X-ray converter foil, for it determines the coefficient β in formula (1). Furthermore, the density n_0 depends on the composition and pressure of the active media of gas lasers.

Calculations of preionisation electron density for different active media and foil materials were performed in accordance with Ref. [16]. For a 12-μm thick titanium foil (Fig. 3), the electron density in the active medium with a composition $CO_2 : N_2 : He = 1 : 2 : 4$ is higher than 2×10^{10} cm^{-3}. It was assumed in the calculations that the e-beam energy density in the preioniser was 0.1 J cm^{-2} and the e-beam-to-X-ray energy conversion efficiency was 1 %. Account was taken of both the bremsstrahlung and the characteristic X-ray radiation, although the latter was found to make only an insignificant contribution under our conditions.

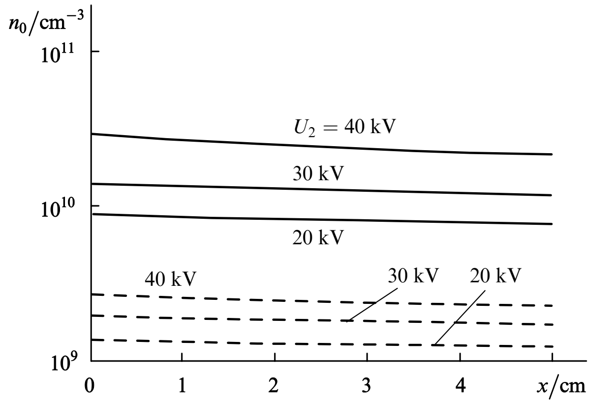

Figure 3. Initial preionisation electron density distributions in the active CO_2-laser medium with a composition $CO_2 : N_2 : He = 1 : 2 : 4$ when employing a 12-μm thick titanium foil (solid lines) and a 50-μm thick aluminium – beryllium foil (dashed lines) for different voltages across the preioniser.

Note that we restricted ourselves to computer calculations and did not perform direct measurements of the initial electron density. In our case, owing to the smallness of the surface area of main discharge electrodes (20 cm^2), the useful signal proved to be only slightly above the level of unavoidable noise [13], which hampered the pursuance of correct measurements. The calculations were experimentally checked by the authors of Refs [6, 16], and the calculated data were found to agree well with experiment.

The thermal load on the foil is significantly heavier in the repetitively pulsed regime. A 50-μm thick aluminium – beryllium foil (Al – 50 %, Be – 50 %) may prove to be well suited for the operation under these conditions. It is vacuum-tight and possesses a high strength and rigidity. The calculated data for the aluminium – beryllium foil are given in Fig. 3. One can see that the electron density distribution in the active medium is rather uniform, which has a beneficial effect on the quality of the pump discharge. When the 50-μm thick aluminium – beryllium foil was used, the preionisation electron density is an order of magnitude lower than with the use of a 12-μm thick titanium foil. In excimer lasers, however, rare gases with a high atomic number and a high density are used, in which X-rays are absorbed much stronger. According to our calculations, even with the aluminium – beryllium foil the preionisation electron density in the excimer medium is equal to $10^{10} - 10^{11}$ cm^{-3} and more (Fig. 4).

The output energy increases with initial density not only in CO_2 lasers, to a large measure this is true of excimer

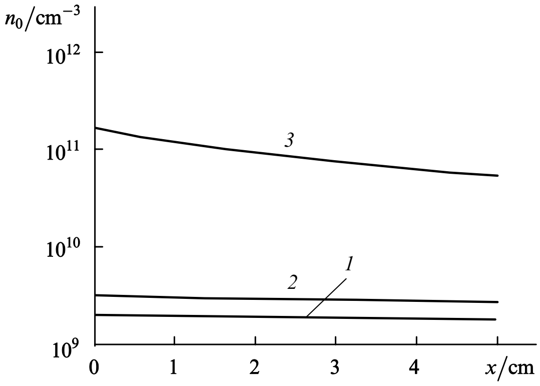

Figure 4. Preionisation electron density distributions in the active CO_2-laser medium for different media when employing a 50-μm thick aluminium–beryllium foil for a 30-kV voltage across the preioniser: (*1*) $CO_2 : N_2 : He = 1 : 2 : 4$ (1 atm); (*2*) $CO_2 : N_2 : He = 1 : 1 : 1$ (1 atm); (*3*) $HCl : Xe : Ne = 2.5 : 20 : 1000$ (4 atm).

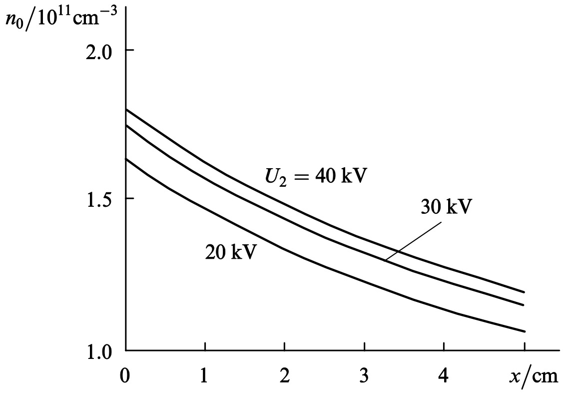

Figure 5. Preionisation electron density distributions in the active CO_2-laser medium with a composition $CO_2 : N_2 : He = 1 : 2 : 4$ when employing a 50-μm thick beryllium foil with a ~ 1-μm thick gold coating for different voltages across the preioniser.

lasers as well [17]. However, this dependence is slow (logarithmic).

Our experiment showed that lowering the voltage across the preioniser from 28 to 15 kV (see Fig. 1) resulted in the reduction of the output CO_2-laser energy by only 11 %, i.e. it is safe to suggest that the laser designed is scalable. Indeed, by lowering the energy density in the beam from 0.1 to 0.01 J cm^{-2} we can by an order of magnitude increase the cross-sectional area of the electron beam and hence the volume of the active laser medium. In doing so the output laser energy will rise by almost a factor of ten owing to an insignificant change of specific energy output.

5. Conclusions

Therefore, we report the implementation of an X-ray preioniser, which is convenient and simple in production and operation, intended for repetitively pulsed gas lasers with small weight and dimensions. The following was experimentally determined:

– the preioniser operates at voltages of 15–50 kV with standard thyratrons both in the single-pulse regime and with pulse repetition rates up to hundreds of Hertz and higher;

– the preioniser enables producing electron beams with a high current uniformity and an energy density of ~ 0.1 J cm^{-2}, which is an order of magnitude higher than the energy density in the best samples reported [6];

– a CO_2 laser harnessing the X-ray preioniser exhibits a specific energy output of 51 J L^{-1} and an efficiency of over 10 %; the output laser energy was 2.6 J;

– the CO_2 laser with the X-ray preioniser admits scaling, and its energy can be increased by at least an order of magnitude for an insignificant lowering of specific energy output and efficiency.

Our calculations show that the initial electron density in the active CO_2-laser medium with a composition $CO_2 : N_2 : He = 1 : 2 : 4$ at atmospheric pressure exceeds 2×10^{10} cm^{-3} when employing a 12-μm thick titanium foil. Under our experimental conditions it is equal to 5×10^{9} cm^{-3}.

By optimising the preioniser, in particular by going over to a pure beryllium foil with a gold coating (Fig. 5), the electron density can be raised to $10^{11} - 10^{12}$ cm^{-3} and higher, which will result in the improvement of the energy characteristics of different high-pressure gas lasers.

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