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T. Arai, Y. Mori, Y. Imai, K. Sugino, M. Obara, et al.. CW X-RAY PREIONIZED PULSED GAS LASERS. Journal de Physique Colloques, 1980, 41 (C9), pp.C9-237-C9-242. 10.1051/jphyscol:1980931 . jpa-00220585

HAL Id: jpa-00220585

<https://hal.science/jpa-00220585>

Submitted on 1 Jan 1980

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CW X-RAY PREIONIZED PULSED GAS LASERS

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Abstract.— We have successfully demonstrated that the cw x-ray generator can work as a preionization source for a pulsed HF laser. The preionization effect of cw x radiation was revealed by a comparative study of with and without applying x-ray photons to the HF laser. Since dose rate of the cw x-ray generator is easily controllable, the laser output could be measured as a function of initial electron number density produced. The cw x-ray preionizer has many advantages for actual gas laser systems compared with other preionizers. There are attributable to its high-energy photons and its characteristics of the cw x-ray generator. Applicability of the cw x-ray preionizer for actual laser systems, especially for high-repetition-rate pulsed laser systems is discussed.

I. INTRODUCTION

We have first used a cw x-ray generator as a preionizer for pulsed-discharge gas lasers. The preionization by cw x radiation has a potential similar to that by the flash x-ray preionization for high pressure gas lasers. Since x-ray photons penetrate longer distance than uv photons, the x-ray preionization scheme is scalable against gas pressure and discharge volume. In addition, the cw x-ray generator has a long operation lifetime (>1000 hours) which is being utilized for industrial application, and it gives a purely continuous preionization so that it can be used for ultra-high-repetition-rate (<10⁵ Hz) operation. The x-ray flash preionizers have been successfully operated in a high pressure KrF laser, which was reported by Sumida et al.¹ and Lin et al.² By using the x-ray flash preionizers, many advantages have been found for high-pressure pulsed-discharge gas lasers. Although the x-ray

flash preionizer did not have sufficient durability (<1000 shots)³ due to its anode evaporation by high current density, the cw x-ray generator has a long operating lifetime as a preionizer. Here, we want to report the preionization effect of cw x radiation on a pulsed-discharge initiated HF chemical laser.

II. EXPERIMENTAL SETUP

An industrial cw x-ray tube (Hitachi SIO-100-5/Be), about 50-mm in diameter and 220-mm in length, was used as the cw x-ray generator. This cw x-ray tube consisted of a 1×1 mm² target on Cu anode, a hot cathode, and an x-ray exit window of Be of 1-mm thickness which allows low energy x-ray photons less than 5 keV to be transmitted to provide high x-ray dose. Using a Victreen model 660-3 survey meter, an x-ray dose rate of 125 R/min. was measured at 30 cm away from the cw x-ray exit window, under conditions where cw x-ray

tube voltage and current were 50 kV and 2 mA, respectively. Since this x-ray survey meter can not detect photons less than 10 keV due to the transmission characteristics of its incident window, practical dose rate is larger than the measured value. This cw x-ray tube was immersed in a insulation oil bath for high voltage insulation and cooling. The cw x-ray beam emitted from the tube was spread out with a half angle of 20 degrees. This angle is mainly determined by the arrangement between the x-ray target and the x-ray exit window. The maximum input power into the tube was 500 W (100 kV, 5 mA). We used it at a tube voltage less than 60 kV and a tube current less than 4 mA. Under such a low input power condition, the lifetime of this cw x-ray tube would be over 3×10^3 hours, and even under the maximum rated conditions the nominal lifetime is longer than 10^3 hours.⁴ A dc high voltage power supply was used as a acceleration potential of the cw x-ray tube.

FIG. 1. Schematic drawing showing cross-sectional view of the laser chamber and discharge circuit.

The cross-sectional view of the laser chamber and the electrical circuitry for

main discharge are illustrated in Fig. 1. The laser chamber envelope was made of Lucite plates, and both ends of the laser chamber were sealed with CaF_2 windows. A 350- μm Polyester film was used as a x-ray incident window allowing soft x-ray photons to be transmitted. The x-ray photons irradiated from the cw x-ray tube was transmitted through the air to the laser chamber. In order to uniformly illuminate the entire discharge volume transversely, the laser chamber was placed 35 cm away from cw x-ray tube. The discharge electrodes, 3-mm thick and 280-mm long, were rounded on both corners to reduce field enhancement, and separated by a 10-mm interelectrode gap. The main discharge was driven by a L-C inversion circuit, consisting of low-inductance capacitors (1 nF each), and a pressurized N_2 spark gap. The laser discharge was fired once every 4 seconds because of the replenishment of the laser gas mixture during shot to shot intervals and due to the removal of influence of the afterglow of the previous shot. The laser gases (C_4H_{10} and SF_6) were premixed and flowed into the laser chamber. The arrangement of the laser chamber and the cw x-ray generator is shown in Fig. 2. The laser cavity comprised an Au concave reflector and a flat CaF_2 output coupler. The laser energy was measured by a Gen-Tec ED-200 joule-meter.

III. EXPERIMENTAL RESULTS AND DISCUSSION

The effect of the cw x-ray preionization on HF laser energy is shown in Fig.

3. The mixture of $\text{C}_4\text{H}_{10}/\text{SF}_6 = 7/73$ was

used, which gave the maximum laser energy.

FIG. 2. Arrangement of the laser chamber and the cw x-ray preionizer.

FIG. 3. Effect of cw x radiation on C_4H_{10}/SF_6 laser energy. O: with cw x radiation, Δ : without cw x radiation (i.e. without any pre-ionizers). cw x-ray tube voltage, 50 kV; cw x-ray tube current, 3 mA; charging voltage, 16 kV. The pressure ratio of C_4H_{10}/SF_6 is 7/73.

As shown in Fig. 3, since the main discharge was unsettled without any pre-ionization, the laser output energy was weak (<5 mJ), and lasing pressure was less than 100 Torr due to the onset of arcing. When applying cw x radiation, however, the maximum laser energy was

increased about 3 times larger than without applying cw x radiation and the total pressure producing the maximum laser energy was 120 Torr. The uniform glow discharge could be obtained at pressures less than 300 Torr with x-ray illumination. Similar preionization effect was also observed in an N_2 laser.⁵ Thus, the illumination of cw x-ray seems to be capable of establishing arc-free discharge, so that this illumination can work as a pre-ionizer of gas discharge lasers.

Since the dose rate of the cw x-ray generator is easily controllable, the

FIG. 4. Graphs of C_4H_{10}/SF_6 laser energy versus x-ray tube voltage for various total pressures. cw x-ray tube current, 2 mA; charging voltage, 16 kV. The pressure ratio of C_4H_{10}/SF_6 is 7/73. Total pressure, ∇ : 40 Torr; Δ : 120 Torr; O: 200 Torr.

laser output energy from HF laser was measured as a function of its dose rate, corresponding to the initial preionization number density. The initial electron number density was estimated from the ele-

electron-ion kinetic equations.⁵ In the case of HF ($\text{C}_4\text{H}_{10}/\text{SF}_6$) laser, the existence of electronegative SF_6 gas induced the electron-ion kinetic equations to be complicated and then it is impossible to estimate the initial electron number density due to appearance of the unknown electron-ion loss coefficient for SF_6 . However, since the electron-ion production rate is in proportion to x-ray tube voltage, it is reasonable that the initial electron number density produced by cw x-ray irradiation increases with increasing the x-ray tube voltage.⁶ The HF laser energy versus the cw x-ray tube voltage against various mixture pressures are plotted in Fig. 4. This experiment was carried out under conditions where the energy stored in the discharge circuit was kept constant. On the curves of total pressures of 40 Torr and 120 Torr, the laser energy tends to saturate at tube voltages in excess of 20 kV. On the curve of 200 Torr, however, the laser energy increases almost linearly with increasing the cw x-ray tube voltage. This behavior indicates that the high pressure gas requires a sufficient preionization electron number density to create volumetrically-uniform avalanche-discharge. Then, the cw x-ray preionizer is found to control the laser output, and/or minimize the input power into the preionizer for maximization of system efficiency of the laser device.

Since x-ray photons have a characteristic of long penetration, the cw x-ray preionizer has many advantages for gas

FIG. 5. The rough estimation of the penetration distance of photons and electrons for various energies. The particle energies are normalized by 1 at distance equal to 0. N_2 gas (1 atm, 0 °C) is used in this estimation.

laser systems. The rough estimation of the penetration distance of photons and electrons for various energy transmitting through N_2 gas is shown in Fig. 5. The ordinate is the normalized particle energy. In this estimation, it is assumed that the absorption cross section of electrons and photons against the gas remain constant with transmitting through the gas. Then, the calculated penetration distance of electron and x-ray photons except uv photons is over estimated. However, by comparing the penetration distance and the deposit energy delivered for ionization of these particles, this estimation is available. As can be seen in Fig. 5, it is clear that the 20-keV photons (i.e. x-ray photons) transmit longer distance than the same energy electrons and uv photons (130 nm = 9.4 eV).^{7,8,9} At the same time, fraction of the deposit energy for gas ionization by x-ray photons per unit penetration distance is smaller than that of electrons and uv photons. Thus, on the assumption that the incident energy from various preionizers to

laser gas is kept constant, it is impossible to satisfy simultaneously long penetration of preionization and the large deposited energy delivered for preionization. However, we observed $5 \times 10^7 \text{ cm}^{-3}$ of the electron number density in N_2 gas of 50 Torr produced by the cw x-ray photons at 35 cm apart from the x-ray generator with 150 W (50 kV, 3 mA) of cw x-ray generator input.⁵ This number density is large enough to precondition the gas discharge for the high-pressure lasers.¹⁰ Accordingly, the cw x-ray preionizer has a potential of long penetration depth together with sufficient preionization establishing the uniform glow discharge.

Since the cw x-ray preionizer has long mass penetration, this makes it possible to separate spatially the preionizer from the laser chamber by an appropriate x-ray window. Therefore, the problem of gas contamination and degradation induced by the preionizer put together with discharge region in the laser gas (e.g. uv flash preionizer) can be solved, which became serious in the H.R.R. closed-cycle laser. Moreover, the long penetration also provides high scalability. For instance, the cw x-ray preionizer used in these experiments is expected to be capable of preionizing large-scale lasers with their discharge dimensions in excess of $30 \times 30 \times 100 \text{ cm}^3$ (90 l). When this preionizer is used for such a large-scale laser, the input power of the cw x-ray generator is negligible in comparison with the average input power of H.R.R. main discharge. The cw x-ray preionizer can be adaptable for

huge-volume preionization (>90 l) by means of the use of several cw x-ray generators.

The long lifetime of the cw x-ray generator is suitable for the practical H.R.R. lasers, moreover, the repetition rate of laser action is not limited up to 10^5 PPS by this preionizer.

The use of the cw preionization source, such as a cw x radiation for a pulsed-discharge laser has never been reported.

This type of preionization allows elimination of the adjustment of the time delay between pulsed preionization and main discharge. For such lasers in which electronegative gases are contained, as rate-gas halide lasers, and/or for high-pressure gas lasers, the disappearance rate of initial electrons produced by a pulsed preionization source is extremely rapid, so that in these lasers troublesome optimization of these delay time may become very sensitive. Therefore, the use of a continuous-wave preionization source for these lasers has the advantage of being delay-time adjustment-free.

IV. SUMMARY

In summary, we have revealed experimentally the effect of preionization by cw x radiation on an HF laser and have concluded that cw x-ray preionizer is very suitable for large-scale H.R.R. closed-cycle gas lasers^{11,12} and especially for high-pressure lasers and/or those containing electronegative gases, such as high-pressure rare-gas halide excimer lasers.

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