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Electrical investigation of the transverse discharge of U.V. nitrogen gas laser

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Résumé. — Des mesures simultanées et résolues temporellement des paramètres électriques et de la densité de puissance d'un laser à azote à excitation transversale sont présentées et analysées. Les mesures expérimentales sont réalisées sur un laser à courte cavité (380 mm de longueur active) fonctionnant à basse pression (40 torr) et délivrant jusqu'à 150 kW de puissance crête à la longueur d'onde 3 371 Å. Certaines corrélations entre les évolutions temporelles du courant de décharge, de la tension et de la densité de puissance laser sont montrées.

Abstract. — Simultaneous time-resolved measurements of electrical parameters and laser power density of a transversely excited nitrogen gas laser are analysed. The experimental results were obtained from a short cavity laser device (380 mm active length) operating at low pressure (40 torr) and producing up to 150 kW peak power at a wavelength of 3 371 Å. Correlations between temporal behaviours of discharge current, voltage and laser power density are shown.

1. Introduction.

Since 1963 [1], the lasing system in nitrogen from the electronic transition in the second positive band has given rise to numerous experimental [2-5] and theoretical works [6].

Basing ourselves on these previous studies and on the commercial availability of nitrogen lasers as U.V. sources for pumping tunable dye lasers, for use in spectroscopy, a compact laser device has been developed in our laboratory.

In this paper, a low cost nitrogen laser structure is described. Time resolved measurements of electrical laser discharge parameters and laser power density are carried out. In particular, the main purpose of this study is to analyse the behaviour of the current discharge across the laser channel and to correlate this with the laser pulse.

2. Experimental arrangement.

The experimental device schematically shown in figure 1 is described below.

2.1 NITROGEN LASER DEVICE.

2.1.1 General description and mechanical construction. — The laser channel (Fig. 2) is basically formed

Fig. 1. — Experimental set up.

1) Nitrogen laser ; 2) High power supply ; 3) Trigger generator ; 4) Manochromator ; 5) Programmable digitiser Tektronix 7912 AD ; 6) Microcomputer HP 87 ; 7) Powermeter or UV photon-drag ; 8) HV probe ; 9) Rogovsky probe.

by a hollow and a screw cap made out of one piece of polyvinyl den fluoride (PVDF). The PVDF was

Fig. 2. — Schematic design of the nitrogen laser (side view).

1) PVDF shell ; 2) PVDF cap ; 3) PVDF mirror and window mounts ; 4) Current connexions ; 6) Grounded plate ; 7) Capacitor banks ; 8) System of adjustment of the electrode position ; 9) Spark gap ; 10) Gas inlet ; 11) Gas outlet.

chosen because this is a UV and temperature proof insulating material.

The top (screw cap) and lower sides of the apparatus support brass bar electrodes and their electrical connexions. The electrodes are 360 mm in length and have elliptical profiles of small radius of curvature. The gap between them is adjustable from 10 mm up to 40 mm.

Two axial holes have been made in the PVDF to screw mount the mirror and the window. The mirror is a 38 mm diameter suprasil coated flat with 99 % of maximum reflectivity at the wave length of 3 371 Å. The output window is an 38 mm diameter uncoated suprasil flat of which the 4 % normal reflectivity yields enough prelasing feedback.

The 10 mm diameter gas inlet and the 25 mm diameter gas outlet are at each end on one side of the laser channel, allowing the gas to flow axially. Hermetic sealing is ensured by silicone gaskets for the screw cap and O ring silicon seals for the optical mounts. The pressure is controlled by a needle valve and measured at the outlet.

Thus, the laser cavity can be pumped down to less than 10^{-2} Torr and can operate up to gas pressures of 5 bars. In our experiment the most adequate cooling is obtained with a 4.5 liter/s flow rate at nitrogen gas operating pressure of 40 torr.

Three holes corresponding to air-tight windows

are made along one side for observation of the electrical discharge and the transversal fluorescence light.

2.1.2 Electrical circuit. — It is wellknown that the laser action in nitrogen at 3 371 Å requires a population inversion between the $C^3\Pi_u$ and $B^3\Pi_g$ levels of N_2 such that the excitation time is shorter than the 40 ns natural life time of the $C^3\Pi_u$ level [7].

Consequently, the circuitry of the pulsed nitrogen laser which is shown in figure 3 must be able to achieve a very fast population inversion. The principle of the circuitry is based on the discrete Blumlein pulse generator design [3, 8, 9].

Fig. 3. — Electrical schematic of the nitrogen laser based on the discrete Blumlein generator design [3].

A positive 20 kV power supply (Universal Volttronics Corporation) charges two parallel 2.82 nF low inductance capacitor banks C_1 and C_2 and an atmospheric spark gap through a current limiting resistor R_c (392 kΩ/25 W). Each capacitor bank consists of six 470 pF low inductance (< 30 nH) capacitors (LCC HTX 330) connected between a grounded common copper plate and each of electrode connexion plates. The spark-gap switch which triggers the fast discharge breakdown is fixed in parallel with the capacitor banks by the side of the high voltage supply. The resistance $R = 470 \Omega/45$ W which is along the outside of the laser cavity keeps the voltage of the laser channel at zero during the charging of C_1 and C_2 .

2.2 ELECTRICAL MEASUREMENTS AND ACQUISITIONS. — The charging and discharging of the capacitor banks is observed with a Tektronix P 6015 fast high voltage probe (5 ns rise time). Whereas a Rogowsky probe permits the analysis of the current across the spark gap giving a voltage with a sensitivity 2.025×10^3 V/A, a rise time of 8 ns and a delay time of 20 ns as following [10] :

$$V [V] = 2.025 \times 10^{-3} I [A] \exp(-t[s]/8 \times 10^9). (1)$$

2.3 OPTICAL MEASUREMENTS. — The shape and time position of the UV laser pulse are observed for

each shot with a fast photon drag RTC UV HC 20 (200 ps rise time and 20 ns delay time) connected to a Tektronix 2213 high pass frequency oscilloscope with a $50\ \Omega$ input impedance. The laser power density is reduced by using a 35 dB calibrated U.V. optical attenuator.

The fluorescence light is focused on the slit of a 600 mm Jobin-Yvon grating spectrometer, and analysed by a fast Photomultiplier RTC 56 D.U.V.P. (3.5 ns rise time and 38 ns delay time) connected to the previous oscilloscope.

The laser energy is measured with a fast calibrated powermeter (Laser Precision Corporation RJ 7100).

2.4 ACQUISITION. — All the signals can be digitized with a programmable digitiser Tektronix 7912 AD connected to a HP 87 for numerical treatment. The acquisition is performed in the single shot mode.

3. Experimental results.

The experimental results which are reported in this section are obtained for an applied high voltage $V_0 = 7.5\text{ kV}$ with a 5 Hz repetition rate for a 40 torr nitrogen gas pressure.

Thus the UV laser pulse measured with the RTC UV HC 20 photon-drag has roughly a Gaussian shape of 6 ns full width at high maximum (FWHM) and contains an energy of $0.7 \pm 0.02\text{ mJ}$ (Fig. 4). However, by studying the pressure dependence of the pulse duration, we observed that this can be shortened to $5.5 \pm 0.5\text{ ns}$ FWHM for 50 torr.

Fig. 4. — Experimental recording of the laser pulse for a typical settings $V_0 = 7.5\text{ kV}$ and $p = 40\text{ torr}$. (Scale = 15 V/div ; time base = 5 ns/div.)

On the other hand, the time duration of the transversely observed fluorescence light at $3\,371\text{ Å}$ is nearly 20 ns. This value can be compared with the pressure dependence of $C^3\Pi_u$ lifetime given by Wagner [11] :

$$\tau_3 = 36 / \left(1 + \frac{p}{58} \right) \quad (2)$$

which gives for $p = 50\text{ torr}$, $\tau_3 = 19.3\text{ ns}$.

The fluorescence light is shown in figure 5 for a lower gas pressure $p = 17\text{ torr}$ where the 28 ns duration is in accordance with equation (2).

Figure 6 shows the oscillogram of the voltage $V_1(t)$ across the capacitor bank C_1 and referred to the grounded plate. $V_1(t)$ starts from 9.5 kV, attains the nul value in about 40 ns and oscillates because of the inductance of the circuit.

Fig. 5. — Experimental recording of fluorescence light at $3\,371\text{ Å}$ for $V_0 = 7.5\text{ kV}$ and $p = 17\text{ torr}$. (Scale = 200 mV/div ; time base = 10 ns/div.)

Fig. 6. — Experimental recording of the voltage $V_1(t)$ (see Fig. 3) for typical settings $V_0 = 7.5\text{ kV}$ and $p = 40\text{ torr}$. (Scale = 2 kV/div ; time base = 20 ns/div.)

The voltage $V_2(t)$ with respect ground across the capacitor bank drops rapidly when the breakdown voltage across the laser channel is obtained. It drops to the zero voltage at the end of about 25 ns with a change of slopes at 15 ns (Fig. 7). However, an over voltage of 2 or 3 kV is observed on the first humps of

Fig. 7. — Experimental recording of the voltage $V_2(t)$ (see Fig. 3) for typical settings $V_0 = 7.5$ kV and $p = 40$ torr. R_p corresponds to the change of slopes in the drop. (Scale = 2 kV/div ; time base = 20 ns/div.)

the voltages $V_1(t)$ and $V_2(t)$ corresponding to the respective values of 9.5 kV and 11 kV, while the supply voltage V_0 is only of 7.5 kV.

This over voltage is due to residual oscillations produced by the spark-gap breakdown as has been experimentally observed.

It was assumed that more accuracy could be obtained if the contributions of this over voltage were carried off for the analysis of the signals $V_1(t)$ and $V_2(t)$.

Nevertheless, it can be possible to remove this over voltage by adjusting the separation between the trigger pin and the spark gap electrode, and thus reducing the trigger voltage ; however a more important jitter occurs.

Actually, use of high power thyatron is recommended, because they can be triggered by a smaller

Fig. 8. — Experimental recording of the spark gap current $I_L(t)$ for typical settings $V_0 = 7.5$ kV and $p = 40$ torr. The duration AB corresponds to the charging and discharging of the first capacitor bank C_1 . The lowering of the top of the first hump is attributed to micro breakdowns in the Rogowsky probe. (Scale = 2 V/div ; time base = 20 ns/div.).

voltage pulse, provide a greater reliability and have a relative stable shot to shot low inductance which minimizes output fluctuations due to the impedance variations.

The corresponding spark-gap current $I_L(t)$ is shown in figure 8. The first oscillation is the charging and discharging of the first capacitor bank C_1 through the spark-gap. When the voltage $V_1(t)$ is zero, the current reaches its maximum value and then drops until breakdown is achieved in the laser channel. Then the current grows during 20 ns with the discharging of the second capacitor bank C_2 through the laser channel.

The oscillograms 9, 10, 11 show the simultaneous recordings of voltages $V_1(t)$ and $V_2(t)$ spark gap

Fig. 9. — Simultaneous recordings of the voltage $V_1(t)$ and the laser pulse for typical settings $V_0 = 7.5$ kV and $p = 40$ torr. C indicates the hyperfrequency noise resulting from the laser breakdown and the amplification of the stimulated emission. The 20 ns delay time between the noise and the laser pulse result from the transit time in the UV photon-drag. (Voltage scale = 2 kV/div ; laser pulse scale = 15 V/div ; time base = 20 ns/div.)

Fig. 10. — Simultaneous recordings of the voltage $V_2(t)$ and the laser pulse for typical settings $V_0 = 7.5$ kV and $p = 40$ torr. For the point C, there are the same comments as in figure 9 (voltage scale = 2 V/div ; time base = 20 ns/div).

Fig. 11. — Simultaneous recordings of the spark gap current $I_L(t)$ and laser pulse for typical settings $V_0 = 7.5$ kV and $p = 40$ torr. For AB, there are the same comments as in figure 8. We observe that the current and the laser pulse are correctly time positioned because the Rogowsky probe and the UV photon-drag have the same 20 ns transit time. (Current scale = 2 V/div ; laser pulse scale = 15 V/div ; time base = 20 ns/div).

current $I(t)$ and laser pulse $P_L(t)$, taking into account the respective delay times of the different probes, of the UV photon-drag and the coaxial connexion (5 ns/m). The different above mentioned signals are digitalized and time-correlated (Fig. 12).

At first, the contributions of weak oscillations of the voltage across the spark gap switch were removed from the voltages $V_1(t)$ and $V_2(t)$. Then the origin of time was chosen as the time where the spark gap current is maximum whereas the voltage $V_1(t)$ is zero.

But subsequently, the V_2 potential was displaced so that its drop corresponds to the spark-gap current rise.

Finally, the laser pulse and fluorescence light

Fig. 12. — Digitalized time correlated recordings of the spark gap current, $I_L(t)$, voltages $V_1(t)$, $V_2(t)$, laser pulse and fluorescence light.

linked to the current behaviour were displaced so that they start to grow at the beginning of current rise.

The voltage across the laser channel $V_L(t)$ is obtained by subtracting, point by point, $V_1(t)$ from $V_2(t)$ (Fig. 13). Thus we obtained, at the maximum of $V_L(t) = V_2(t) - V_1(t)$, an over voltage of 10 kV with in the drop a noticeable change of slopes of which the first slope corresponds to the peak power of the stimulated emission. These experimental results are in good agreement with the Schwab's simulations [12].

Fig. 13. — Correlated curves of the voltage through the laser channel $V_L(t)$ and the laser pulse. We observe that the laser pulse occurs during the first part (first slope) of the voltage drop.

4. Determination of discharge parameters.

From these experimental results we can estimate the values of the discharge parameters : E/p the reduced electric field, α/p the reduced Townsend ionization coefficient, T_e the electron temperature and n_e the electron density.

The convenient time scale for the microscopic properties of a nitrogen gas laser discharge is of the order of a few nanoseconds as one has previously seen. It is correct to consider that the molecular collisions and ions recombinations do not affect this discharge regime in such a time scale. It is convenient to take into account only the ionization and excitation by electron collisions with N_2 molecules [13]. Furthermore it has been demonstrated that when the E/p ratio exceeds 30 or 40 V/cm.torr, the electron velocity distribution can be considered as a Maxwellian distribution. Thus the electron temperature can be evaluated by equating Townsend's ionization rate with the rate which results from a kinetic model for electron motion [14].

$$\alpha v_d = [N_2] \int_0^\infty f(T_e, v) \sigma_i(v) 4 \pi v^3 dv \quad (3)$$

where

- α is Townsend ionization coefficient
- v_d the electron drift velocity
- $[N_2]$ ground-state nitrogen molecule density
- $f(T_e, v)$ normalized Maxwell-Boltzmann distribution
- $\sigma_i(v)$ ionization cross-section for the nitrogen molecule.

In fact, α/p and v_d are given in literature with a very good approximation.

Thus, Bayle gives [15] :

$$\alpha/p [T_d] = 1.17 \times 10^{-4} (E/p - 32.2)^2 \quad (4)$$

for $44 \leq E/p \leq 176$ V/cm.torr and Felsenthal gives [16] :

$$v_d [\text{cm/s}] = 2.9 \times 10^5 E/P [\text{V/cm.torr}] \quad (5)$$

Since the ionization cross section for N_2 is well known [17], the above equation (3) can be resolved point by point and the results can be correctly approximated by the following expression [18] :

$$KT_e = 0.11 (E/p)^{0.8} \quad (6)$$

The electron density n_e can be obtained from the current density j_e , so that :

$$j_e = n_e e v_d = \frac{I_L}{S} \quad (7)$$

where e is the electron charge, I_L the total current across the laser channel and S the emissive area of electrodes.

Hence :

$$n_e = \frac{I_L}{e v_d S} \quad (8)$$

Thus we can evaluate the macroscopic discharge parameters from the experimental values of $V_L(t)$ and $I(t)$ and the geometrical characteristics of the discharge.

The maximum voltage across the laser channel is 10 kV for a gas pressure of 40 torr and a 1 cm separation between electrodes as one can be seen in figure 13. This corresponds to $(E/p)_{\text{Max}} = 250$ V/cm.torr. However we observe that the maximum of the laser pulse corresponds to $V_L(t) = 6$ kV (Fig. 13) and $I_L(t) = 3$ kA (Fig. 12) across the laser channel which leads to a reduced field, labeled « effective reduced field » $(E/p)_{\text{eff}} = 150$ V/cm.torr.

Under these conditions we obtained :

$$\begin{aligned} \alpha/p &= 1.62 \text{ Td} \\ v_d &= 4.35 \times 10^7 \text{ cm/s} \\ KT_e &= 6.06 \text{ eV} \\ n_e &= 1.13 \times 10^{14} \text{ cm}^{-3} \end{aligned}$$

for $S = 3.8 \text{ cm}^2$ which corresponds to a width of

about 1 mm of the effective emissive area of electrodes.

These results are in a good enough agreement with the values of the discharge parameters given by Fitzsimmons *et al.* [13].

As Girardeau-Montaut *et al.* [19] and A. W. Ali [20] show, delay time of few nanoseconds still remains between the maximum of electron temperature and the maximum of laser power density. Thus, for the maximum of actual voltage $V_L(t) \geq 10$ kV across the laser channel, we can consider that an electron temperature $KT_e \sim 11$ eV is achieved. That is just sufficient to ensure an electronic excitation of the laser level $C^3\Pi_u$. This result is in agreement with the nearest case (number 4) of reference [19].

Furthermore, at the maximum of laser power density, few nanoseconds later, it is noticing that the electron temperature is higher than 4 eV ($KT_e \sim 6$ eV) and sufficient to hold the efficiency of the laser system. Thus, the energy loss by electrons into the excitation of the ground state vibrational levels is reduced [20]. However, the efficiency of electron excitation of the state $C^3\Pi_u$ can be improved by decreasing the inductance of the switch by using a thyatron switch, that will reduce the current rise time and increase the electron density.

The peak power is about 120 kW for a laser pulse of 6 ns FWHM ; this corresponds to an electrical conversion efficiency of 0.7 % through the laser channel with a correct reliability of about 1-3 %.

The most suitable nitrogen gas operating pressure is ($P = 40$ torr) as indicated in figure 14, where the peak power is plotted *versus* the gas pressure. We observed that beyond 40 torr, the peak power drops because of the collisional quenching of the laser state $C^3\Pi_u$ which reduces its life time. Gas operating

Fig. 14. — Laser peak power *versus* gas pressure.

pressure is a few higher than usual operating pressure of low pressure nitrogen gas laser 30 torr. However, some improvements can be made by very carefully adjusting the pressure and electrode separation simultaneously for increasing the electron density, and electron temperature.

5. Summary.

The electrical properties of a pulsed nitrogen gas

laser discharge have been investigated. The time resolved measurements of the electrical characteristics have permitted evaluation of the macroscopic parameters of the laser discharge, in particular the mean value of the electron density.

This pulsed nitrogen gas laser can be used as a UV source for pumping a tunable dye laser for spectroscopy experiments in the photochemical framework.

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