Spark Gap Pressure and Lasing Behaviour of a non-Blumlein type Nitrogen Laser

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The effect of the nitrogen or SF_6 pressure in a spark gap of a small rugged free running nitrogen laser (laser gap 2.4 mm, channel length 170 mm) is studied. No significant difference between nitrogen and SF_6 as spark gap chamber gases was found. With increase of the spark gap pressure from 1 to 3.5 bar the pulse energy increases from 30 to 70 µJ, at 10 kV, or from 90 to 130 µJ, at 14 kV. The maximum of the laser efficiency is found at lower breakdown voltages with higher spark gap pressures. Pre-ionization by UV light from the spark gap can be excluded, but not that from a corona discharge over the capacitor foil below the laser channel. It is shown that further effort to increase the laser output power must start from the design of a fast spark gap, well integrated into the whole discharge circuit.

Key words: Nitrogen laser; spark gap; UV laser; laser design.

1. Introduction

In [1] a small rugged nitrogen laser for instrumentation in analytical applications has been described. It was run under 1 bar nitrogen and was fired by a spark gap that lay open, above one of the laser electrodes which have been integrated into one of the laser capacitors. Some hint came from the performance of the laser that pressurization, and thus shorter rise times of the spark gap switch, should increase the output power as was already reported for a Blumlein type laser [2]. In order to study this effect on the present laser which does not comprise the Blumlein typical transmission line, the spark gap was kept at the same position but reconstructed in such a way that pressures up to 4 bar could be applied to the spark gap. The lasing behaviour will be discussed in terms of the pulse width limiting relaxation times involved.

2. Experimental

A cross section through the modified laser with the spark gap is shown in Figure 1. By using small o-rings around the spark gap electrodes the space between the electrodes was sealed into a transparent plexiglas cylinder (alternatively into a black nylon cylinder) and the pressurizing nitrogen was fed through the upper electrode, which for this, purpose was provided with a concentric boring of 1 mm internal diameter.

Following [1], a laser with 170 mm active length of the laser channel was constructed. The laser electrode distance was 2.4 mm in the experiments presented here, a value which was found to be superior to 1 or 3.4 mm for all laser properties. The spark gap was

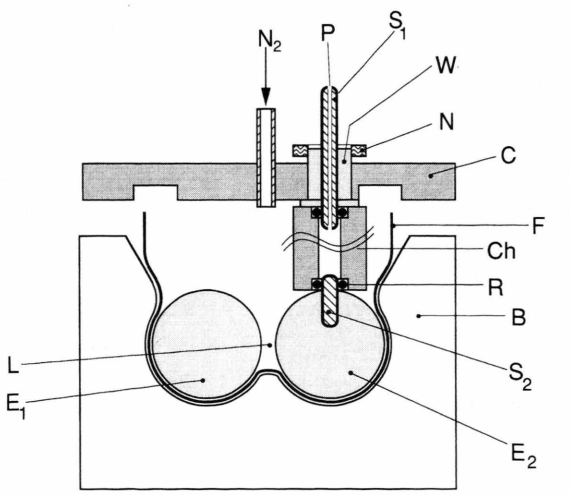

Fig. 1. Cross section of the investigated nitrogen laser. E_1 and E_2: laser electrodes (170 mm × 30 mm ∅); L: laser channel; S_1 and S_2: spark gap electrodes; P: pressure inlet to the spark gap chamber; Ch: spark gap chamber; R: o-ring; B: aluminum laser body; F: condenser foil; C: upper laser chamber cover; W: clamp screw; N: nut; N_2: nitrogen inlet.

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centered with respect to the laser axis. The purity of nitrogen was 99.9996% (Linde, Kostheim).

Pulse form measurements were performed using a silicon photodiode (Oriel type CD, 170 ps rise time, 370 ps pulse duration) and a sampling oscilloscope (Philips PM 3340/40, rise time 175 ps).

Absolute pulse energies were determined with a Joule meter (RK 3230, Laser Precision Corp.).

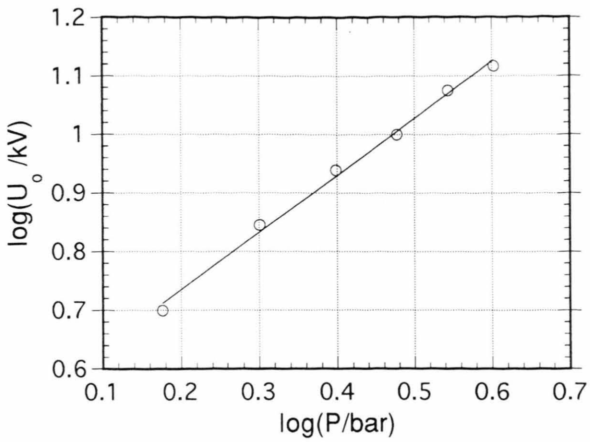

Fig. 3. Double logarithmic plot of the spark gap breakdown voltage U_0 versus the spark gap pressure p.

3. Effects on the Rise Time of a Spark Gap

It has already been discussed in [1] that the rise time of the firing switch in a normal pressure nitrogen laser must be very short in order to yield high population inversions within the life time of the upper $C\,^3\Pi_u$ state of around 2.5 ns [3, 4]. Also, the rise time of the spark gap must be short compared to the time necessary to build up the electric breakdown of the nitrogen in the laser channel. Weizel [5] has studied a spark from the theoretical point of view, using the LRC circuit Fig. 2, comprising a resistor R, inductor L and capacitor C in series to a cylindrical plasma P in the spark gap which is a good approximation for the laser spark gap discussed here.

He has shown quantitatively that is

$$\tau_s \sim (s/p)^{1/2}, \tag{1}$$

where τ_s is the decay of the (spark gap-) capacitor voltage, s the length of the gap and p the pressure,

$$U_0 \sim (p\,s)^{3/4}, \tag{2}$$

where U_0 is the firing voltage U_0 of the spark gap. Hence short spark gaps s and high pressures p yield short sparks.

He also has shown quantitatively for a spark gap that the capacity C, the ohmic resistance R and the inductance L of the discharge circuit must be as low as possible for short sparks. Thus, in order to avoid resistance and inductance of the connecting lines, the spark gap should at best be integrated into the capacitor (of course, this statement does not hold if a transmission line effect is to be incorporated; see discussion in [1]). As Fig. 1 shows, this was verified in the present laser.

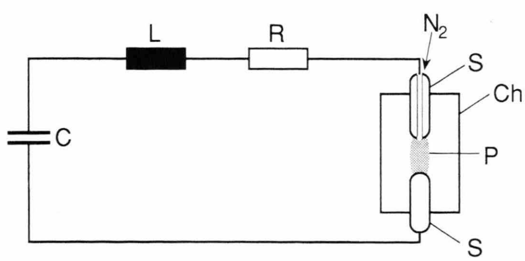

Fig. 2. Electric representation of a spark gap. L: inductivity; R: resistance; C: capacity; S: spark gap electrodes; Ch: spark gap chamber; N_2: gas inlet to the chamber; P: cylindrical plasma.

4. Results

Figure 3 shows the pressure dependence of the firing voltage U_0 at constant spark gap electrode distance s in nitrogen. According to (2), a plot of $\log U_0$ versus $\log p$ should give a straight line:

$$\log U_0 = \text{const} + \frac{3}{4}\log p. \tag{3}$$

Figure 3 shows that this linear relationship is confirmed in the range of $p = 1.5$ to 4 bar, but that the slope is roughly 1, a bit different from the theoretical slope of 0.75. This difference is not surprising since Weizel did his calculations for the circuit shown in Fig. 2, whereas in the spark gap fired laser circuit presented here the spark gap discharge will not be independent of the rest of the laser.

Figure 4 shows the dependence of the laser pulse energy on the spark gap pressure p. The spark gap distance has been adjusted with each pressure to give the same firing voltage $U_0 = 10$, 12 or 14 kV, respectively. Especially for low fixed firing voltages the laser

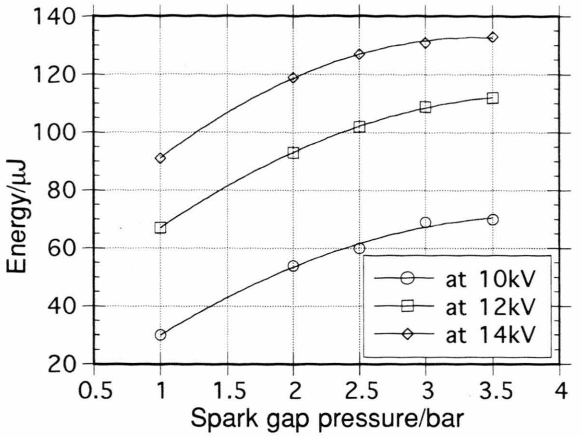

Fig. 4. Plot of the laser pulse energy versus the spark gap pressure p at three fixed breakdown voltages U_0.

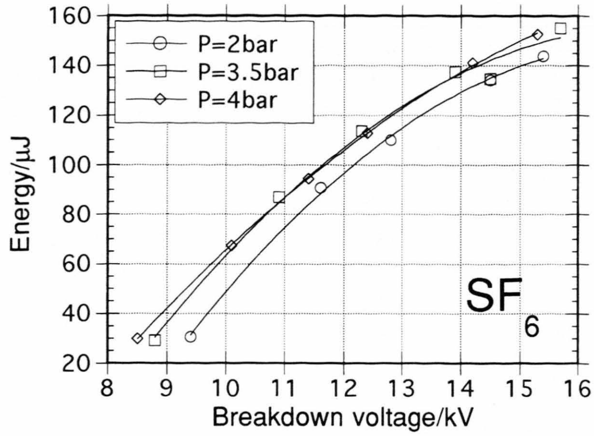

Fig. 6. Plot of the laser pulse energy versus the breakdown voltage U_0 at three fixed SF_6 pressures p in the spark gap.

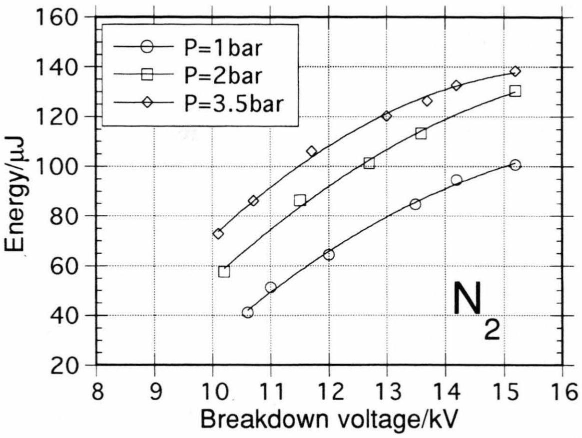

Fig. 5. Plot of the laser pulse energy versus the breakdown voltage U_0 at three fixed nitrogen pressures p in the spark gap.

pulse energy increases strongly with the spark gap pressure.

Figure 5 shows an example for the energy/voltage behaviour of this laser at different spark gap pressures. At 3.5 bar spark gap pressure, pulse energies of 100 µJ are achieved already at 11 kV – quite favourate for the capacitor foil life time – whereas about 15 kV are necessary for the same pulse energy at 1 bar. Of course, the threshold voltage also shifts considerably to lower voltages with higher spark gap pressures.

The same experiment was repeated using SF_6 as the gas in the spark gap. The results shown in Fig. 6 indicate that there is no advantage using SF_6 as a spark gap gas, at least not up to 120 µJ.

In the present laser, at least some pre-ionisation of the laser channel by the UV light of the spark in the spark gap is automatically present. In order to clarify whether this source of pre-ionisation plays an important role with respect to the laser pulse energy, the clear plexiglas housing of the spark gap was replaced by a black nylon one. Comparison of the laser pulse energy in both cases revealed that pre-ionisation by UV-light from the spark gap does not play any noticeable role, as was already mentioned in [1]. On the other hand, pre-ionization by corona discharge over the capacitor foil between the laser electrodes cannot be excluded; Bergmann and Hasson have positively used this effect already in 1978 [6].

5. Discussion

It has been mentioned before that the rise time τ_s of the spark gap must be shorter than the life time τ_c of the upper laser state $C\,^3\Pi_u$ of $\sim$2.5 ns. It also has been said that the rise time τ_s of the spark gap should be faster than the time τ_l required for the laser channel to break through. Otherwise, after firing the spark gap, the laser channel would break through already at a fraction of the applied voltage U_0 – only part of the supplied energy would be transferred to population inversion of the respective excited states. In other words, the overvoltage would be low, of the order of the static breakdown voltage. Hasson and von

Bergmann [7] have reported that the delay time τ_d between the voltage maximum across and the current pulse through the laser channel was ~ 2 ns with a small normal pressure Blumlein laser with 2 mm laser electrode distance and fired by a spark gap under 3 bar. Also, rise times τ_v of the voltage pulse across the laser channel before the laser channel breakdown took place have been reported in [2, 8] to be ~ 5 ns, using pressurized spark gaps. Obviously, it would be highly desirably to have τ_v much shorter than τ_l which might be roughly estimated by τ_d. With the present laser there is no pulse steepening effect to be expected since there is no transmission line. Hence, with the present laser τ_s should be expected to be short compared to τ_l (or τ_d).

From Figs. 4 and 5 follows after extrapolation that the threshold field strength for 2.4 mm laser electrode distance is around 4 kV/mm at 1 bar spark gap pressure, going down to roughly 3 kV/mm at 4 to 5 bar, which is not much higher than the static breakdown voltage between the laser electrodes determined in pure nitrogen to be 2.6 kV/mm. Since pressurization of the spark gap lowers the threshold voltage to a value only near but not below the static breakdown voltage of the laser gap, it must be concluded that the nitrogen laser presented here does not show an overvoltage at the moment of the laser channel breakdown (due to ringing of the circuit formed by the spark gap, storage capacitor, and laser gap). This holds especially for higher voltages U_0.

The observation that the laser output increases strongly with the spark gap pressure p at a given firing voltage U_0 can be discussed in terms of the spark gap rise time τ_s. (1) and (2) yields

$$\tau_s \sim U_0^{2/3}/p. \tag{4}$$

Now consider Figs. 5 and 6: at low voltages U_0 the laser output increases strongly with the spark gap pressure and to a lesser extent at high voltages. Since the proportionality between τ_s and $1/p$ holds independently of the spark gap voltage, the limited increase of the laser output at high U_0 values must be ascribed to the higher values of τ_s. On the other side, also τ_l is dependent on U_0. Lue [9], in his general design considerations, cites the work of Kassirov and Mesyats [10], who derived the delay time τ_{ds} between the current through and voltage across a spark gap

$$\tau_{ds} \sim k\, s^2\, p/U_0, \tag{5}$$

where k is a geometrical constant. Weizel [5] has calculated the decay time of the spark gap voltage to be

$$\tau_s \sim s^2\, p/U_0^2. \tag{6}$$

As a very rough estimate, (5) or (6) might also be used to understand the observed dependence of the laser channel break through time τ_l on U_0, which accordingly is expected to decrease strongly with increasing U_0.

Then it is to be assumed that with the present laser a change in the order of the involved decay times τ takes place, so that at low U_0 (larger τ_l) the order is $\tau_s < \tau_l < \tau_C$, but at high U_0 (lower τ_l) the order changes to $\tau_l < \tau_s < \tau_C$. With $\tau_C \approx 2.5$ ns this is not utopic, particularly not with the present very lumbed laser circuit, since even the half width of the current pulse ($\sim \tau_l$) of a Blumlein-type laser has been measured to be around 1 ns [11].

This behaviour also shows up in Fig. 7, where the overall efficiency (referred to the energy stored in *both* capacitors) is plotted against the breakdown voltage of the spark gap at three different spark gap pressures. Here not only the efficiency increases with increasing spark gap pressure but the maximum efficiency shifts to lower voltages. If the ratio of the breakdown field strength $E = U_0/2.4$ mm and the laser gas pressure p_L is calculated for the three spark gap pressures shown in Fig. 7, this value E/p_L shifts from 74 V cm^{-1} Torr^{-1}

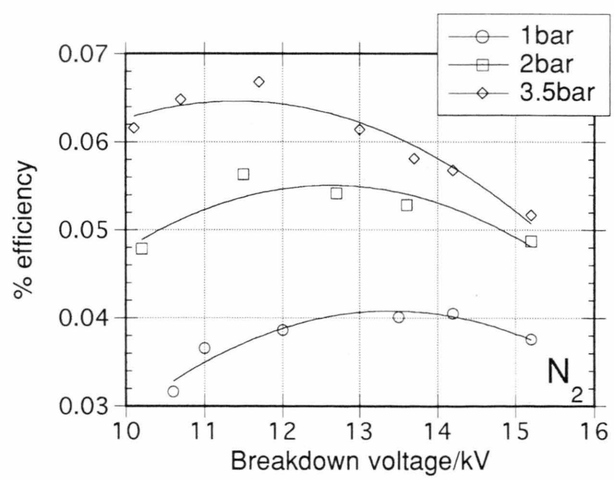

Fig. 7. Overall efficiency as a function of the spark gap breakdown voltage at three values of nitrogen pressure in the spark gap.

at 1 bar spark gap pressure to 62.5 $\mathrm{V\,cm^{-1}\,Torr^{-1}}$ at 3.5 bar spark gap pressure. A similar behaviour was reported recently for a quite different nitrogen laser [12]. The low values for E/p_L compared to Goddards theoretical estimate may also be due to a possible corona discharge over the capacitor foil below the laser channel, as mentioned above, which then would reduce the value of E/p_L considerably [13].

As a consequence, further effort to increase the output power of this laser at high firing voltages U_0 requires reduction of τ_l, which means complete changes in geometry, whereas the presented results indicate that at low firing voltages U_0, sealed high pressure spark gaps (which would reduce the spark gap discharge rise time τ_s) will increase the laser output power.

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