CONSTRUCTION and INVESTIGATION of a SIMPLE NITROGEN LASER

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ABSTRACT

A simple transversely excited nitrogen laser has been constructed, powered by an easily made 6V battery power supply circuit. It provided bright ultraviolet (337nm) pulses at a rate of about 1Hz, operating at up to 20kV and 100torr optimum pressure. The laser theory is discussed, as well as the pressure and voltage dependences, which are also measured. The pulse energy was found to more than double by placing a mirror at one end, with the divergences halving. (45mrad to 20mrad horizontally and 5.5mrad to 2.5mrad vertically)

Construction and investigation of a simple Nitrogen laser.

Introduction.

Since the first observation of stimulated emission in nitrogen by Mathias and Parker (1963) and the first construction of a nitrogen laser by Heard (1963) much work has been done on transversely excited nitrogen ultraviolet (337nm) lasers. One of their most important uses is in the pumping of dye lasers, which have revolutionised spectroscopy over recent years.

Peak powers are frequently reported in the region of several megawatts, with 10ns to subnanosecond pulses. Devices have been made to operate at pressures from 1torr to several atmospheres. Recently Kagawa et al (1982) made an oscillator-amplifier system producing single transverse mode, polarised pulses of 400kW, 5ns duration and a beam divergence of 1mrad.

Our aim was to build completely from basic materials, a battery operated nitrogen laser and to investigate its divergence, wavelength and pressure and voltage dependence. The effect of a mirror at one end was also investigated. The design was an adaption of that used by Small (1974), with our own design of power supply.

Laser theory.

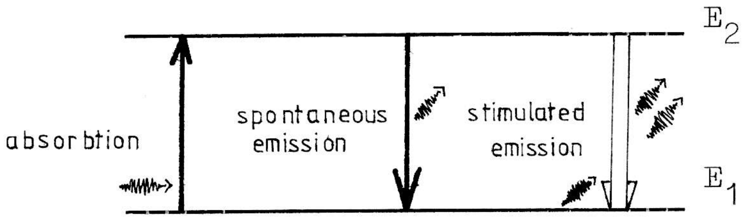


Figure 1.
Transition possibilities.

An atom in an excited state E_2 may spontaneously emit a photon of frequency ν given by

$$\nu = \frac{E_2 - E_1}{h}$$

h=Plank's constant

A gas with many spontaneously emitting atoms will emit light incoherently in all directions. Alternatively if a photon of frequency ν passes near the excited atom it may stimulate the emission of another photon with the same phase,polarisation and direction as the original.

The gas may also absorb these photons, if in the ground state E_1, the rate of absorbtion being:

$$R_a = N_1 B_{12} U_\nu$$

N_1= No. of atoms in E_1
B_{12}= Einstein coefficient of absorbtion.
U_ν = energy density of incident radiation of frequency

The rate of stimulated emission:

$$R_1 = N_1 B_{21} U_\nu$$

$B_{21} = B_{12} = B$

The rate of spontaneous emission:

$$R_s = N_2 A_{21}$$

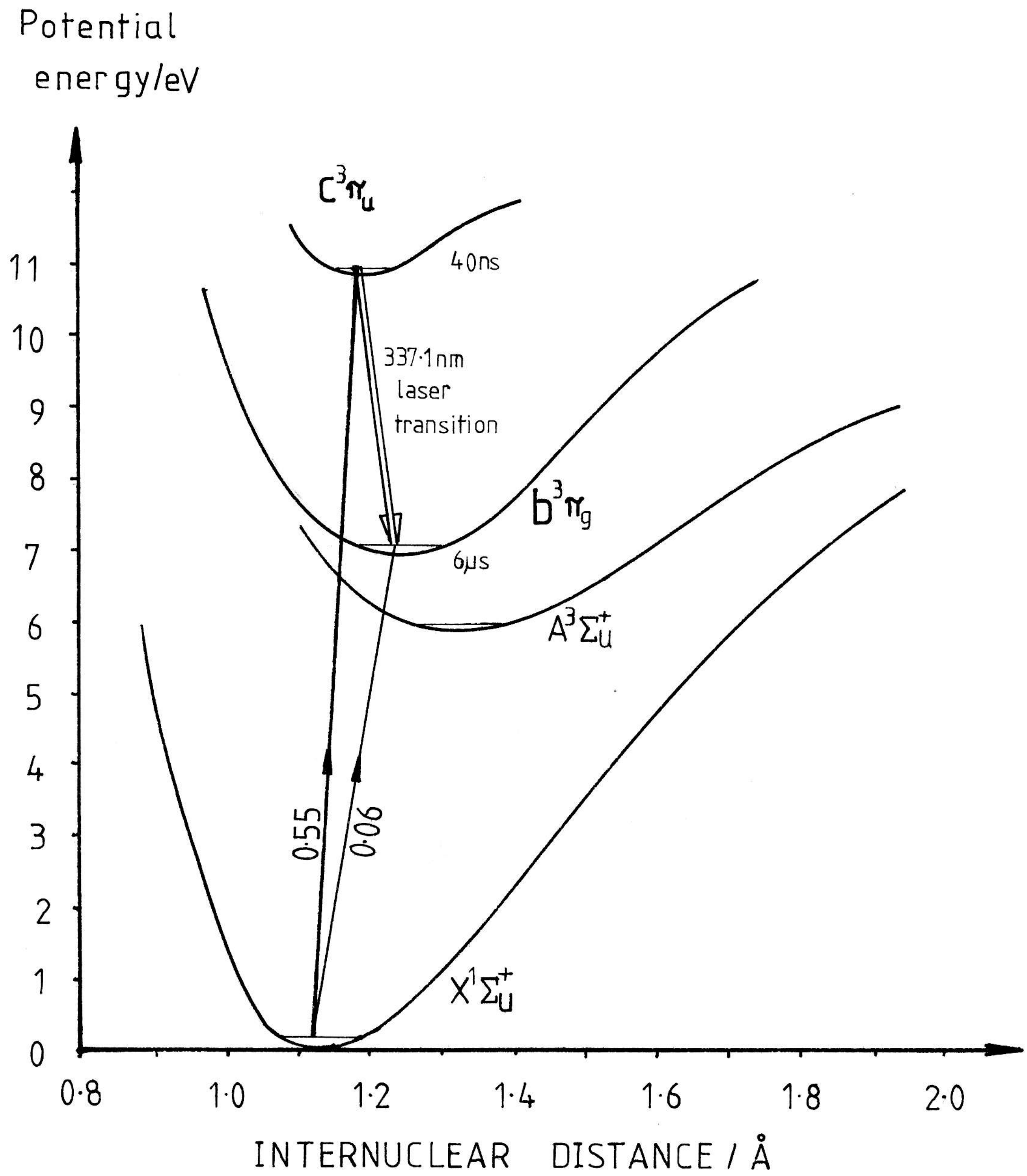
A_{12}= Einstein coefficient of spont. emission.
N_2 = No. of atoms in E_2

The ratio of the populations is:

$$\frac{N_2}{N_1} = \frac{e^{-E_2/kT}}{e^{-E_1/kT}}$$

k= Boltzmann's constant
T= Temperature

Figure 2,



Potential energy diagram for the nitrogen molecule. Franck-Condon factors are shown, as well as relevant radiative lifetimes.

(after Godard(1974) and Fitzsimmons et al(1976))

So

$$\frac{\text{Stimulated emission rate}}{\text{Absorbtion rate}} = \frac{N_2\ B\ U_\nu}{N_1\ B\ U_\nu} = \frac{N_2}{N_1} = e^{-(E_2-E_1)/kT}$$

So the stimulated emission rate cannot excede the absorbtion rate with direct excitation. Only if $N_2 > N_1$ is there more stimulated emission than absorbtion and the gas would amplify incoming photons of frequency ν . This is laser action; Light Amplification by Stimulated Emission of Radiation.

The net rate of emission of photons being:

$$N_2\ A_{21} + U_\nu B\ (N_2 - N_1)$$

So the gas emits coherent radiation and incoherent spontaneous radiation in all directions. To achieve this, a population inversion must be made. (ie: $N_2 > N_1$).

Laser action in nitrogen

The first four electronic energy levels of the nitrogen molecule are shown in figure 2. Electronic excitation leads to a change in the mean separation of the nitrogen atoms of the molecule, due to a change in bond strength, and so the Franck-Condon factors (related to transition probability) are different for each transition. This is because a fast electronic transition does not allow for sudden interatomic distance changes, so the transition with the least change in distance is favoured. Hence if nitrogen gas is excited with an electric discharge, the transition $X^1\Sigma_g^+ - C^3\pi_u$ is favoured, and the $C^3\pi_u$ state becomes more populated than the $B^3\pi_g$ state: a population inversion is created.

The population inversion must be created in a time shorter than the natural radiative lifetime of the $C^3\pi_u$ state (40ns) so that the inversion exists for some time and is not destroyed by spontaneous emission. Steady state

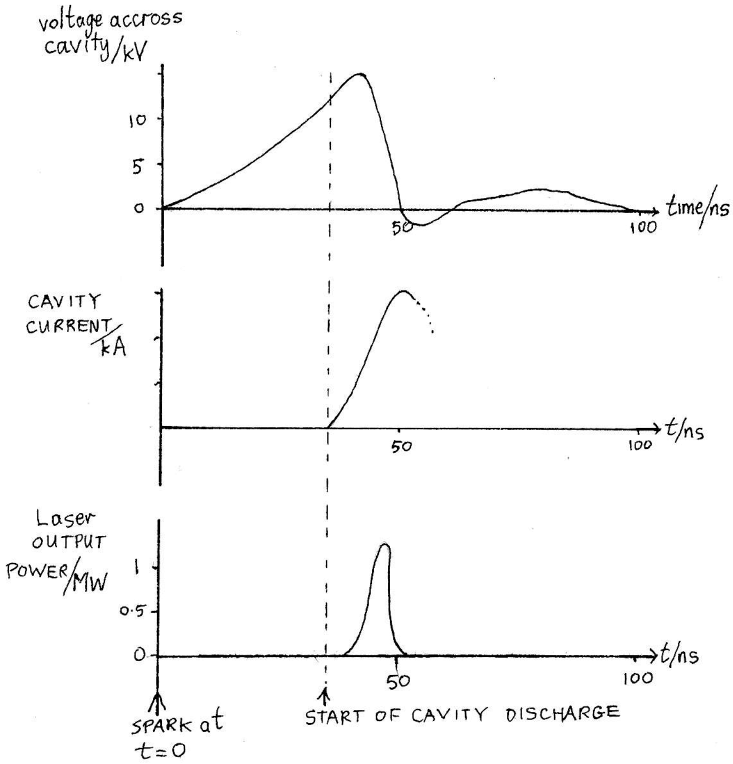
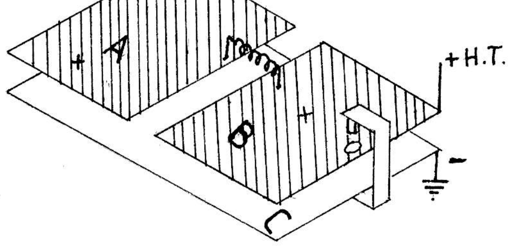


Figure 3,

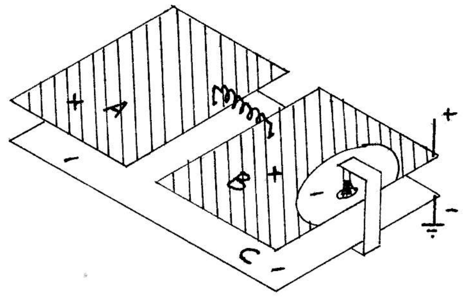
Cavity voltage, current and laser output measured by Schwab and Hollinger.(1976) (The current is a qualitative sketch)

Figure 4,

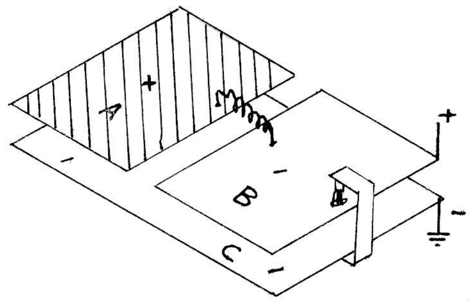
These schematic diagrams show the operation of the Blumlein switching.



Spark gap breaks down, and a wave of negative potential sweeps across plate B.



The inductor acts like an open circuit to such fast changes, so the full potental difference appears between A and B.



inversion cannot be achieved because the lifetime of the lower laser level ($B^3\pi_g$) is about 10μs and so it quickly fills up during laser action and terminates amplification when there is no longer a population inversion. This laser is thus self terminating and has to be pulsed. The emission stops after typically 8ns when the nitrogen becomes strongly absorbing to 337nm UV. The gain is so high that a resonant cavity, with precisely fixed mirrors,is unnecessary.

It can be shown (Godard(1974)) that the population inversion must be obtaned in a time t such that:

$$t < \frac{1}{(Y_{cb} + 1/\ {}_{cb})}$$

Where Y_{cb} is the collision deexcitation rate by electrons and τ_{cb} the natural radiative lifetime of the transition $C^3\pi_u$ to $B^3\pi_g$. Here $Y_{cb} \ll 1/\tau_{cb}$ usually so:

$$t < 1/\tau_{cb}$$

$$t < 40\text{ns}$$

This is not true when the electron density is greater than $6\times10^{14}\ \text{cm}^{-3}$ when $Y_{cb} > \tau_{cb}$ and the inversion duration is shortened. A fast switch was necessary to quickly build up a high energy discharge.

<u>The Blumlein switch</u>

A Blumlein switch was used to switch on the discharge since it can easily switch 20kV and thousands of amperes in about 10ns (see figure 3) Figure 4 shows how this switching is achieved. The top and bottom plates act as a capacitor, and charge up relatively slowly. The inductor maintains plates A and B at the same potential. At a certain voltage (set by the spark gap) the spark gap conducts (sparks)

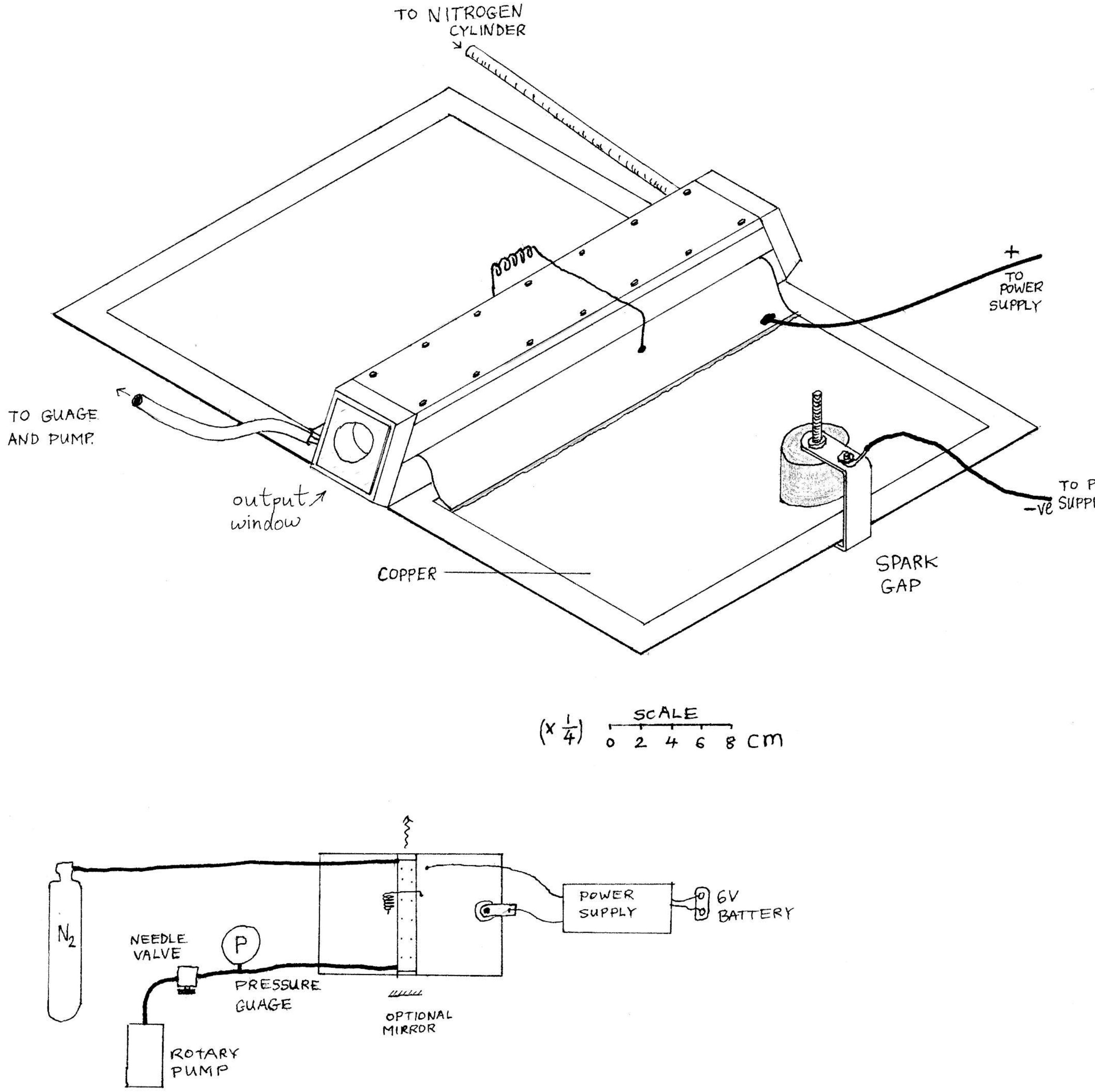


Figure 5,

Diagram of nitrogen laser, with schematic operation diagram. (the laser was encased in $\frac{1}{4}$" perspex for safety) and rapidly makes plate B negative. The inductor (a low value) prevents sudden charge flow between plates A and B so the full voltage appears between these two plates. The laser uses plates A and B as electrodes.

Experimental set up and construction details

A diagram of the laser can be seen in figure 5. The capacitors were made of 0.034" thick copperclad glass-epoxy circuit board measuring 30x45cm. A 6cm channel was etched down the middle of one side and 2cm of copper etched away around the edges to prevent sparking. This gave a total capacitance of 5nF. The laser box was made out of $\frac{1}{4}$" thick perspex 30x5x5cm (external dimensions) held together by 14 screws on the bottom and12 screws on top, as well as thick layers of silicone rubber cement (which allowed dismantling). This could withstand the lowest pressure possible using a rotary pump. The design used by Small (1974) without screws,could not cope with such low pressures (down to 10torr) and also flexed inwards at higher pressures thereby changing the electrode spacing. The end sections were $\frac{1}{2}$" thick perspex with 1mm thick glass plates covering the angled exit holes. The ends were mounted at 25° to minimise direct reflections back into the tube. Tubes attached to the end pieces connected the pump and nitrogen cylinder.

The electrodes were made of copper foil soldered onto the top capacitor plates and sealed into the laser tube with a separation of 1cm. This electrode separation was the optimum for maximum output for this type of design as found by Godard (1974) and Bergmann and Eberhardt (1973).

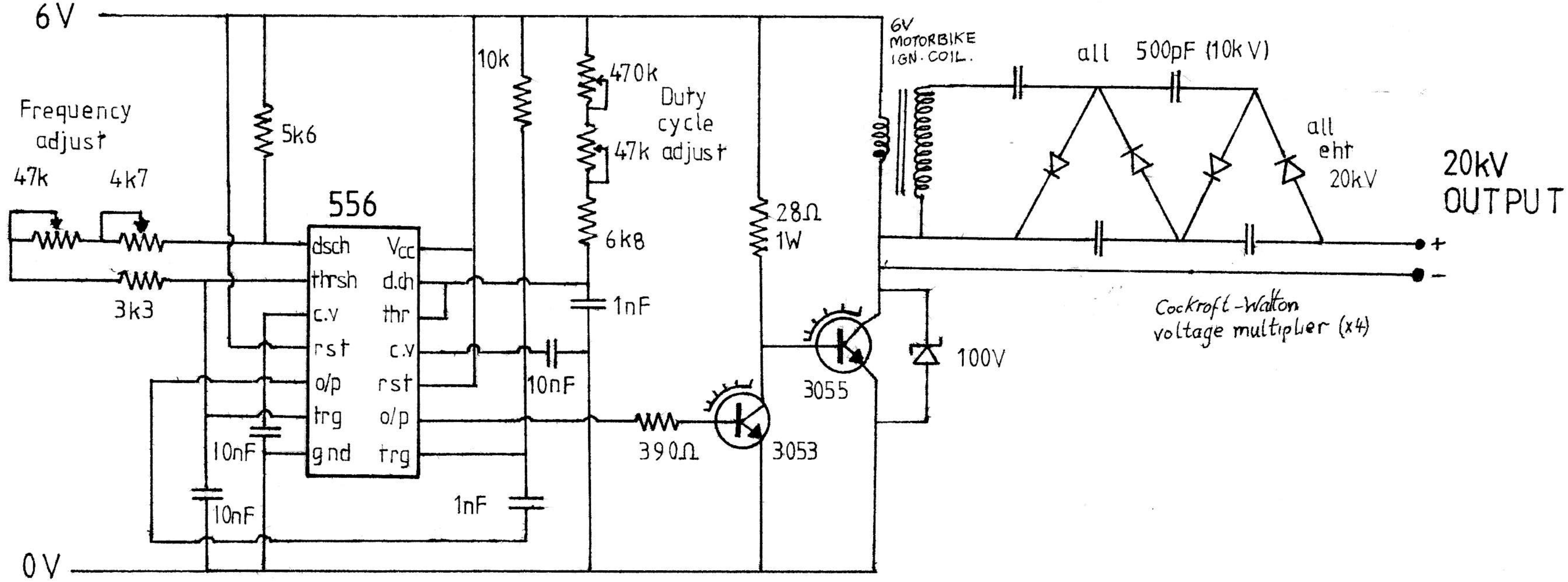


Figure 6, The Power Supply

The spark gap was made out of 2mm thick, 2cm wide copper with a 4mm brass screw threaded through a nut heavily soldered over a hole in the copper. This heavy design with thick metal was to reduce the inductance of the spark gap assembly; crucial in obtaining fast switching action, as shown by Fitzsimmons et al (1976). The slit in the screw head was filled with solder and rounded. Sharp edges were rounded where possible to avoid corona discharge. A brass disc was soldered to the capacitor plate to prevent spark damage. A PTFE cylinder covered in black insulating tape held the copper spark gap in position by spring action and also prevented spark light emission. A perspex rod was attached to the screw so that the gap and hence breakdown voltage, could be adjusted without having to ground everything first.

The inductor was made of 10 turns of 20 wire (2x6cm) as used by Small but the laser worked with 3-15 turns, so its value is not critical. Schmidt (1977) also came to this conclusion.

The power supply

The circuit diagram can be seen in figure 6. Only standard electronic components are used. A 6V motorbike ignition coil was pulsed by an adjustable square wave generator, using a power transistor as a switch. The coil output was then multiplied by a factor of about four and rectified by using a Cockroft Walton voltage multiplier circuit. The frequency and duty cycle of the square wave generator were adjusted to produce maximum output voltage. This corresponded to a very short coil off time (14 s) and frequency of 3200Hz. The output was 20kV measured with a ballbearing spark gap voltmeter (this was used for all

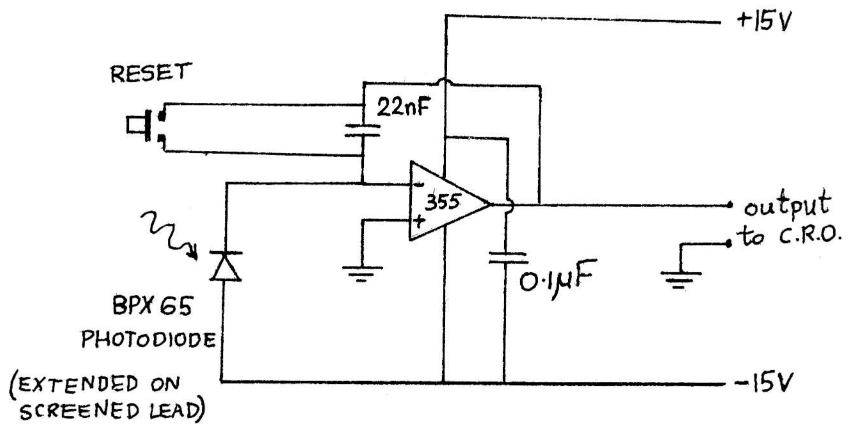


Figure 7,

The detector.

high voltage measurements). The circuit operated from a large 6V battery drawing 1.1A current. Power supply connections to the laser were made using 10A wire, to reduce their inductance, covered in rubber tube for safety. All solder joints were made rounded to reduce corona discharge at points.

Rough estimate of wavelength

The laser produced bright UV pulses which could be seen as bright flashes on white paper, fluorescent felt tips, fluorescene and Rhodamine 6G solution (used in dye lasers). A diffraction grating of 600lines/mm was placed directly at one output port with no slit or lens. A piece of paper covered in fluorescent felt tip was placed 76cm away and on each pulse beams corresponding to several orders of diffraction were seen. The first order beam was displaced 15cm so using

$$n\lambda = d \sin\theta \qquad \begin{aligned} d &= 1.67\times10^{-6}\text{m} \\ \theta &= \tan^{-1}(15/76)\text{ rad} \\ n &= 1 \end{aligned}$$

gives $\lambda = 323\text{nm} \pm 10\%$

which is very near, considering the method employed, to the expected value of 337.1nm.

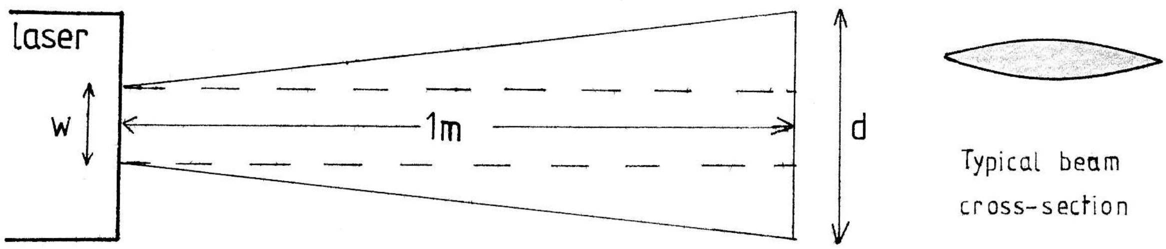
The detector

The circuit diagram is shown in figure 7. A simple current integrating amplifier was built using a fast op-amp and a photodiode as detector. The photodiode had a peak response at 850nm and so did not detect the ultraviolet well, so a drop of Rhodamine 6G dye was suspended on the end of the photodiode.

The dye provided yellow flashes to the photodiode, which it could easily detect. The circuit gave a steady output voltage (with a dark room and black cloth covering the set up) reading after each pulse, related to the pulse energy. These pulses were measured on a CRO. A manually operated switch reset the circuit after each pulse. This provided relative pulse energy readings in arbitrary units.

Beam Divergence and the effect of one mirror

The divergence of the beam was obtained by measuring the full beam width at a distance of 1m from the laser output port. A piece of paper covered in fluorescent felt tip was used to see the pulses. Readings were taken with and without a front silvered mirror placed at the other output port (and carefully adjusted for direct reflection).



$$\text{Divergence} = \theta = \tan^{-1}\left(\frac{d-w}{2l}\right) \text{ rad.}$$

The results are shown bellow:

Tube pressure= 95torr , applied Voltage= 15kV.

	Horizontal Divergence	Vertical Divergence
No mirror	45mrad	5.5mrad
With mirror	20mrad	2.5mrad

(all ± 5%)

These readings compare with those obtained from a 45cm long tube with mirror used by Bergmann and Eberhardt (1973) giving 25mrad vertically and 6.9 mrad horizontally.

The pulse energies were also measured with the photodiode with and without the mirror. The photodiode was placed in the centre of the beam and about 15cm away. The average pulse heights obtained were:

	pulse energy (arbitrary units)	standard deviation
No mirror	1.1	0.2
with mirror	2.3	0.2

Since the mirror was probably not 100% reflecting and may have been slightly misaligned , the value with mirror is probably an underestimate. Other workers (Godard(1974), Small(1974) and Schmidt(1977)) suggest a boosting of output by a factor of about three by using a mirror.

The divergence (without mirror) seems to relate to the discharge dimensions. The discharge was 26cm long and 1cm wide, so the maximum angle a photon could make to the axis by travelling end to end might be 1/26 = 38mrad (compare with 45mrad measured). Similarly if the discharge is about 1mm thick then 0.1/26 = 4mrad (compare with 5.5 measured). This explains the difference in vertical and horizontal divergences. The narrower the discharge, the lower is the range of angles of travel which pass through a substantial distance of gas in order to be amplified. A mirror, reflecting back the beam from one side effectivelly doubles the discharge length and hence roughly halves the divergences.

The effect on the output power is because the reflected

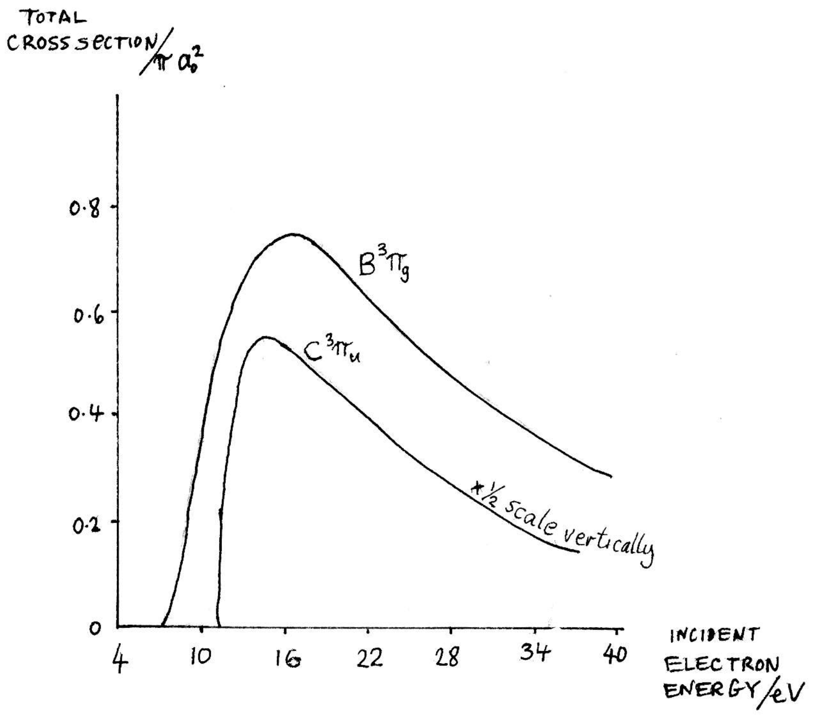


Figure 9

Total cross sections for excitation of the laser levels from the ground state, as a function of electron energy. (after Godard 1974) beam is further amplified by the still amplifying nitrogen. Thus the output is more than doubled, as our results show. The standard deviation is quoted as there was considerable fluctuation in pulse readings. This might be due to fluctuations in the spark gap breakdown voltage, as only a small gap distance change alters the voltage considerably. Pressurised nitrogen spark gaps are frequently used to increase reproducibility and decrease their inductance (Schwab and Hollinger 1976).

Von Bergmann and Penderis (1977) using an atmospheric pressure, 5cm long tube with one mirror, found they could double their output by using a 12% reflecting mirror at the output port also.

Pressure and voltage dependence

The nitrogen excitation is almost entirely due to electron collisions in the discharge. The electrons in the discharge may be considered to be in a steady state with the instantaneous electric field, since the Langevin relaxation time for their drift velocity is of the order of 10ps ($m_e v_d eE$), which is much less than the nanosecond times of the discharge. These discharge conditions allow the electron velocities to be described by a Maxwellian distribution (Judd 1976) The nitrogen plasma may be described by the electron temperature:

$$kT_e = 0.11 \left(\frac{E}{P}\right)^{0.8} \text{ eV} \qquad \text{Eqn 1.}$$

(Fitzsimmons et.al)
(E/P in V/cm.torr)

Cartwright (1970) calculated the total cross-sections for the excitations and showed that an electron energy of about 16eV provokes the highest possible population inversion. According to equation 1, with a voltageof 14kV, electrode separation of 1cm and pressure of 100 torr, the electron temperature is 5.7eV but the Maxwellian distribution will many electrons in the 16eV region in the high energy 'tail'.

At constant pressure, an increase in voltage increases the mean electron energy and raises the number of high energy electrons. (see figure 10)

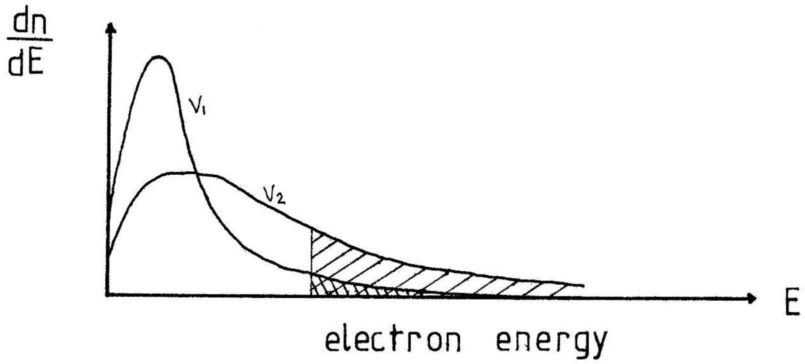


Figure 10, Maxwellian distributions. (at constant P.) $V_2 > V_1$

For the voltages we used, up to 20kV, the peak of the distribution would not reach 16eV, so the output would be expected to increase with voltage. (Capacitor energy is higher also)

This effect was measured, at a constant pressure of 90torr the voltages being preset by adjusting the spark gap with a ball bearing voltmeter parallel to it, until they both sparked at the same rate. The results can be seen in figure 11. Increasing the voltage increases the output but reduces the life of the capacitor board: our 0.034" board broke down after only about a thousand pulses along a ridge of high electric field. (where the central break in the copper was etched away)

From equation 1 it would appear that decreasing the pressure would increase the electron temperature and hence the output. But decreasing the nitrogen density by reducing the pressure reduces the gain, as there are less amplifying molecules there. But Eqn.1 predicts an electron temperature of 16eV at about 30torr.

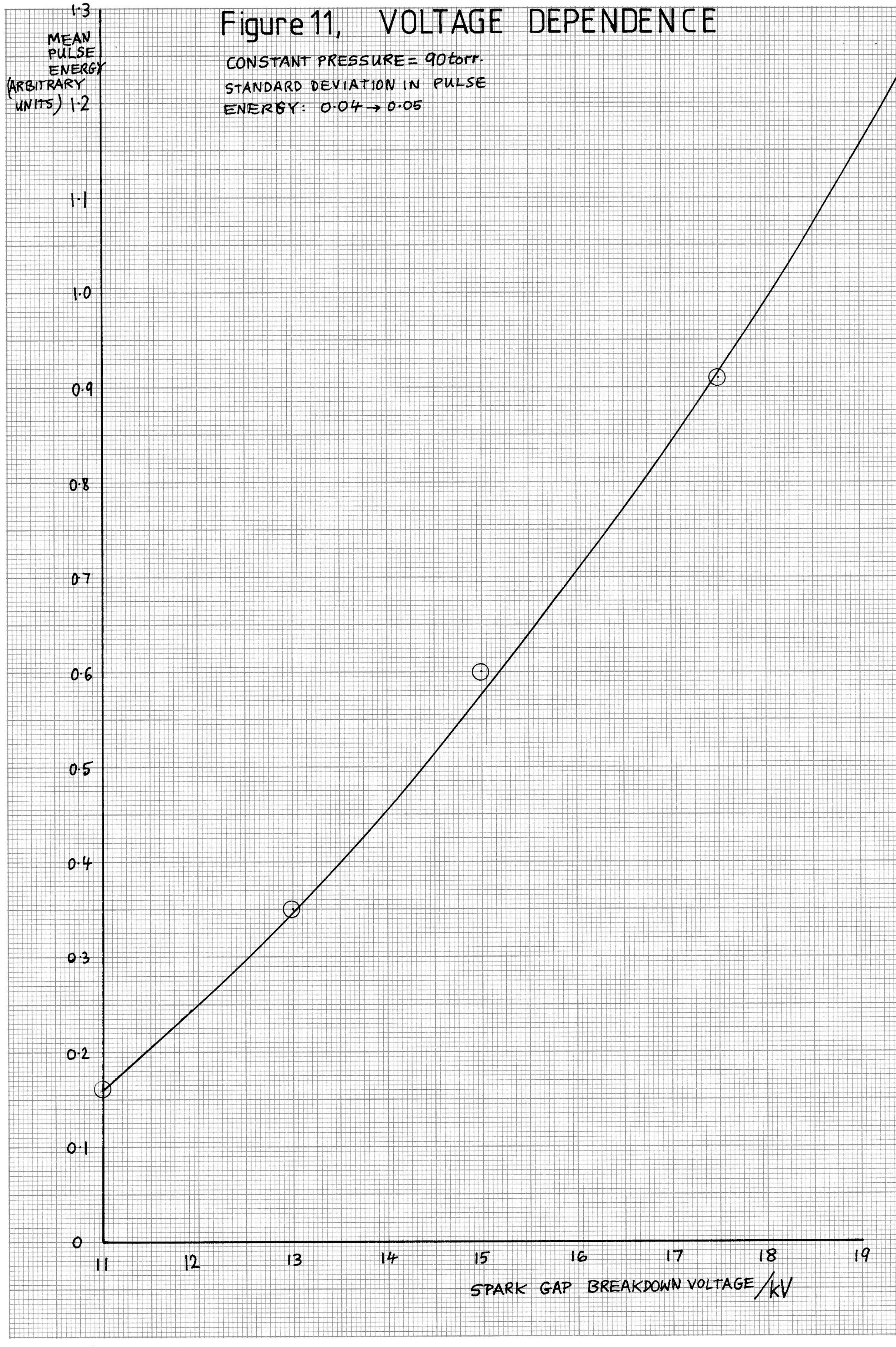
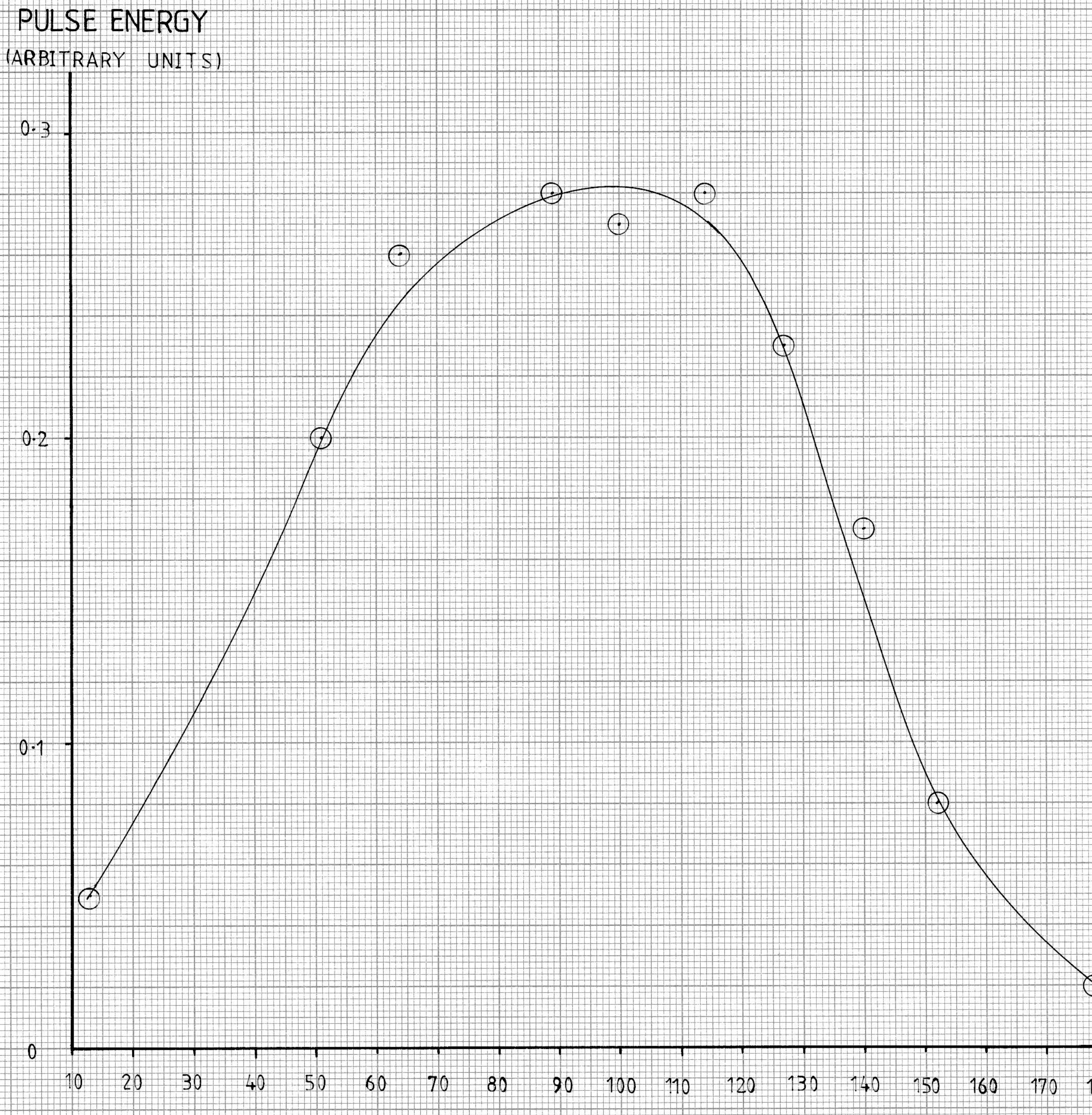


Figure 11, VOLTAGE DEPENDENCE
CONSTANT PRESSURE = 90 torr.
STANDARD DEVIATION IN PULSE
ENERGY: 0·04 → 0·05
MEAN PULSE ENERGY (ARBITRARY UNITS)
1·3
1·2
1·1
1·0
0·9
0·8
0·7
0·6
0·5
0·4
0·3
0·2
0·1
0
11
12
13
14
15
16
17
18
19
SPARK GAP BREAKDOWN VOLTAGE /kV

Figure 12, PRESSURE DEPENDENCE



Voltage = 14kV. Standard deviation in P from 0.01-0.05

Weak lasing was observed up to 200torr; at higher pressures the discharge degenerated into a few sparks.

The lower limit was about 20 torr; below that, a faint discharge filled the whole tube.(even at low voltages)

The result is an optimum pressure for a fixed voltage.

The pulse energies were measured for various tube pressures, by adjusting the nitrogen cylinder output, with a constant voltage of 14kV. The results can be seen in figure 12. The maximum output was obtained with the ratio E/P 140V/cm.torr. This compares with the value of 200v/cm.torr obtained by Leonard (1965) and Godard (1974). The graph is similar to those obtained by Bergmann and Eberhardt (1973) and many other researchers.

The experimental errors of the energy measurements were very low in comparison to the fluctuations between readings, although the pressure readings are not very accurate due to the guage used.

Nitrogen flow rate

Mean pulse energies were measured for maximum and no flow rate, with P=100torr, V=17.5kV constant. (the pump and nitrogen were throttled accordingly) A slight change in output was observed: 5.1units (sd=0.6) with maximum flow, and 6.2 units (sd=0.8)with no flow. This change is not very significant statistically, probably because at our repetition rate (1Hz) residual ionisation effects were negligible. (Fitzimmons et al reported that gas flow was particularly important at high pulse rates)

Problems

Capacitor breakdown was a serious problem: the dielectric should have been thicker, with larger plates if necessary. Electrical noise and interference was also very serious.

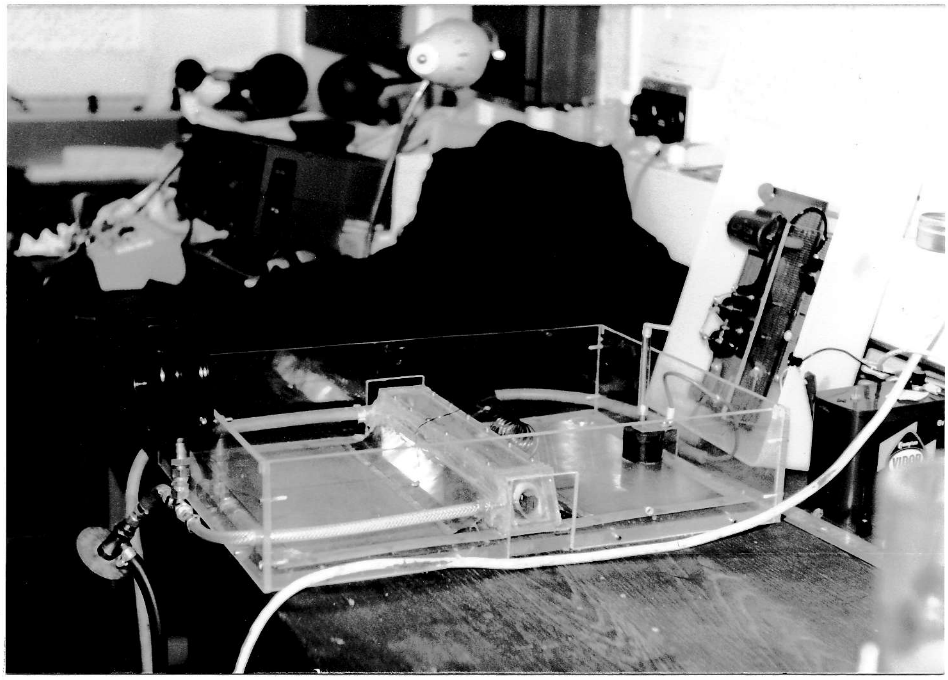


Figure 12. Photograph of laser.

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