CHAPTER IV: EXPERIMENTAL FINDINGS, RESULTS AND DISCUSSION.
Experimental setup used during these investigations is described in detail in chapter 3. Nitrogen used was of commercial grade and high purity nitrogen has also been used. The laser peak output power was measured using a reverse biased PIN photodiode HP 5082-4220 with a rise time of less than 1 ns. The sensitivity of this photodiode is low at the wavelength of UV N₂ laser due to window transmission. However, even after undergoing divergence, after traversing enough distance, the laser output was intense enough to drive the PIN diode into saturation. Therefore, the laser output was attenuated using standard neutral density filters to bring down the incident intensity within the working range of the photo-diode.

The photodiode was mounted in a special holder of low inductance configuration in order to be able to faithfully reproduce the short duration pulse (5 ns) with a fast rise time. The signal cable was terminated into a 50 ohm load. This low inductance 50 ohm termination was obtained by parallelly connecting ten resistances (500 ohm 1/8 watt each) with short leads in a coaxial geometry. A mismatch between the cable and termination gives rise to reflections complicating the actual waveform.

Weak signals have been monitored after adequate attenuation using a fast response photomultiplier coupled
to a monochromater. This has been used particularly for confirming the wavelength of 357.7 nm line, when this was found to lase with addition of SF$_6$ to the nitrogen in the laser head.

All the measurements have been carried in the double shielded room, described elsewhere in this thesis. The bandwidth limited rise time of the detection system, both with PIN diode and fast photomultiplier with the 50 MHz Tektronics 466 storage oscilloscope, was about 5 ns. All the measurements of laser peak output power presented here have been averaged over more than twentyfive shots.

A typical laser pulse recorded, using PIN diode, by a storage oscilloscope is shown in fig.(1). This shows a FWHM of 5 ns and a bandwidth limited rise time of less than 5 ns. The pulse is transit time isolated from small reflections in the cable. We suspect the characteristic impedance of commercially available cables rated at 50 ohm to be a bit higher. The slow oscillations of the base line are due to noise.

The peak power estimated was about 200 KW under optimum conditions, this corresponds to an energy of about 1 mJ per pulse. The efficiency as calculated using
SWEEP: 10 ns/cm

FIG. 1
the energy stored in the line comes out to be 0.33%; an acceptable value. However, the efficiency can further be improved. In the present work no serious attempts have been made in this regard. The beam divergence without a cavity mirror was about 30 m rad, which reduced to less than 10 m rad with the cavity mirror.

Some simple experiments have successfully been done with this laser system, such as excitation of dye lasers in solutions and in PMMA films under various concentrations. The performance has been excellent due to very good beam homogenity.

The variation in peak output power as a function of line charging voltage is shown in fig.(2) at different nitrogen pressures in the laser head from 10 torr to 130 torr. Fig.(3) shows the same for laser head pressure in the range of 150 torr to 340 torr.

In lower operating pressure range, i.e. 10 torr to 130 torr, the peak output power is found to increase very slowly and uniformly. This is seen from the near straight line curves of fig.(2), showing a tendency towards saturation. At higher pressures, the trend shown is a relatively rapid increase in the laser peak output power with increasing line charging voltage, reaching saturation at relatively higher operating voltages.
FIG. 2
FIG. 3

- 150 TORR
- 220 TORR
- 290 TORR
- 340 TORR

PEAK POWER [Arb units]

VOLTAGE [KV]
Fig. (4) shows the dependence of laser peak output power on the nitrogen pressure in the laser head for line charging voltages of 15 kV and 20 kV. The laser peak power is found to increase with pressure initially, reaching a maximum around 130 torr and falling down again above this pressure. This corresponds to an optimum pressure of about 130 torr. It is seen from fig. (4) that for an increase in line charging voltage from 15 to 20 kV (which corresponds to an increase in energy stored by the PFL by a factor of two) laser peak power increases by about 10%. Therefore, marginal increase in power at higher operating voltages is not significant in terms of energy extraction efficiency.

From fig. (3), for the 130 torr curve, it is seen that stable laser output starts at about 15 kV, below which shot to shot variation is too large and in some shots there is no discharge in the laser head. Taking 15 kV as the voltage at the time of breakdown (which actually remain a bit lower than this value), the E/P value comes out to be about 200 volts/cm torr. For other curves working on similar lines the value of E/P is found to be in the range of 150 to 200 volts/cm torr. These values of E/P and optimum pressure are in agreement with those obtained by others. However, using efficient preionisation, lower values of optimum E/P can be achieved.
PEAK POWER (Arb units)

PRESSURE (Torr)

20 KV

15 KV

FIG. 4
It is worth noting that the line charging voltage here, is the peak voltage on the line when there is no breakdown in the head. Under given operating conditions of the laser head the static breakdown voltage is fixed, and in course of charging of the line, discharge starts when this limit is reached and discharge conditions govern the situation. The initial part of energy effectively contributes to lasing and rest is dissipated in arcing as late energy. However, a small amount over volting may arise due to statistical delay in firing of the main discharge. This effect can be more pronounced with a fast rising voltage pulse, allowing higher over volting that results in higher values of E/P favouring extraction of energy.

To improve upon the voltage rise time on the laser head for better overvolting of the laser channel a multichannel transfer gap was incorporated in series with the laser head. The multichannel operation was satisfactory, with more than about twenty channels opening at a time. However, the channels were not localised and were found to shift from shot to shot. The multichannel switch design was somewhat similar to that used by Sarjeant et al. /2/. With the use of transfer gap, peak output power was found to increase by about 20% with the threshold operating
voltage increased to a higher value as is seen in fig.(5). The shifting of threshold operating voltage to a higher value is due to the sharing of the PFL output by the switch (the transfer gap) and the laser head, at the initial voltages. The increase in peak output powers at higher operating voltage can be attributed to the fast rise time pulse allowing better overvolting of the laser discharge allowing higher E/P values.

With the transfer gap incorporated the voltage characteristics show an interesting trend, as seen from fig.(6). With increase in line charging voltage, the laser peak output power is found to increase initially reaching a maximum and further increase in voltage causes a decrease in output reaching a minimum, which increases again with further increase in voltage.

This perhaps can be explained on the basis of voltage and power sharing between the laser head and the switch and the energy transferred to the load under changing impedance conditions. The initial rise in power with voltage can be attributed to the reduction in transfer gap impedance at increased voltages with the maxima corresponding to the effective series impedance of switch and the laser head in nearly matched condition. The dip then can be explained as due to mismatch between line and load (series combination of transfer gap and head)
FIG. 5

- With out transfer gap
- With transfer gap
FIG. 6

PEAK POWER (Arb units)

VOLTAGE (KV)

N₂ PRESSURE (TORR)

A: 30
B: 37
C: 47
D: 62
E: 87
F: 147
causing decrease in energy transfer. The latter rapid rise is due to the domination of available energy at the laser head being proportional to square of voltage.

The change in laser output power as a function of nitrogen pressure in the laser discharge is shown in fig.(7) for various operating voltages. The curve for 22 KV is seen to remain below the rest of the curves for almost entire range of pressure in the laser head. This corresponds to the dip portion of fig.(6).

It is known that an initial preionisation favours energy extraction in this type of discharges. Among various approaches, one is to seed the discharge with low ionisation potential molecules. We have tried triethyl amine (TEA), which is found to have the lowest ionisation potential, in an experimental setup as shown in fig.(3 & 4) of chapter 3. The laser was operated in simple PFL mode without a transfer gap. The addition of triethyl amine was controlled and the partial pressure was monitored on a sensitive pressure gauge with digital readout.

The laser output power was monitored under changing conditions of pressure and line charging voltage, with a small amount of TEA added to the laser discharge.
FIG. 7
It was noticed that this substantially reduced the static breakdown voltage. This was evidenced by the appearance of discharge in the laser head under pressure and voltage conditions, where there was absolutely no discharge in the absence of TEA.

It has also been noticed that the discharge uniformity is affected, which manifested in degradation of the intensity distribution in the beam cross section. This intensity distribution was found to differ slightly from shot to shot. Addition of TEA has been found to decrease the peak output power substantially over a wide range of working conditions and intensity fluctuation from pulse to pulse very much increased. This is perhaps because of the early nucleation of localised discharge channels working against the buildup of a homogeneous glow discharge, at least in the early stage.

Interesting part of the systematic investigations is presented in fig.(8). This shows that, under optimum conditions, the laser output decreased due to addition of TEA in small amount. An attempt to see the effect of pressure revealed that for addition of TEA in small amounts causes reduction in output in the entire working pressure range whereas addition of TEA in excess showed a different behaviour, with a remarkable increase in
FIG. 8

Peak Power (Arb units) vs. Pressure [Torr]

- TEA in Excess
- Pure N₂
- Low TEA
- TEA - Tri Ethyl Amine
power for a narrow range of pressure near 60 torr (fig.8). For rest of the pressure range, the power remained substantially low compared to that without addition of TEA under identical conditions.

The laser performance with excess TEA added at this critical pressure of 60 torr at various operating voltages is presented in fig.(9). At low voltages a decrease in power is noticed. At higher voltages the power is found to increase with increasing voltages, with the increase approaching about 25 % at 20 kW. The increase in power at various voltages is also indicated by the vertical shaded bars (to the scale) at that voltage. The other two bars represent the standard deviation of the peak power for pure N₂ (blank bars) and that with excess TEA added (dotted bars). At higher voltages, the shot to shot variation has been found to be reduced in this pressure region; elsewhere it is much higher compared to that without TEA.

**SF₆:**

Addition of SF₆ to N₂ laser discharge is known to have strong influence on the laser output. This has been tested with the present laser system. The peak output power has been found to increase substantially with addition of SF₆. In the presence of SF₆ in the
discharge, the 357.7 nm line starts lasing. For low partial pressures of SF$_6$, this intensity is low. At lower intensities the line was detected after sufficient attenuation using a fast photo multiplier in conjunction with a monochromator which also helped to confirm the wavelength. At higher output powers, with higher partial pressures of SF$_6$, the output was sufficiently strong and was detected (using a quartz prism to separate the two lines 337.1 and 357.7 nm) on the PIN diode described previously. The intensity of 357.7 nm line was found to increase with SF$_6$ partial pressure in agreement with findings of others /3/.

The effect of addition of SF$_6$ to the N$_2$ discharge in different proportions is presented in fig.(10). This shows the peak output power of 337.1 nm line as a function of pressure in the discharge, for different partial pressures of SF$_6$. The curve for pure N$_2$ shows a maximum at a discharge pressure of about 120 torr. Addition of 2 torr of SF$_6$ to the discharge altogether changed this shape, indicating some increase in laser peak power in the low pressure range, and decrease on the high pressure side. For 5 torr partial pressure of SF$_6$, the increase in output is by a factor of about three (change from about 1 to 3), at a discharge pressure of 20 torr. The power was found to drop rapidly with increase in pressure. The curves corresponding to 10 and
FIG. 9

PEAK POWER [Arb units]

WITH TEA

PURE N₂

POWER INCREASE WITH TRI ETHYL AMINE (TEA)

SD IN POWER, PURE N₂

""" WITH TEA

VOLTAGE [KV]

10 12 14 16 18 20
FIG. 10

SF$_6$:
- 0 Torr.
- 2 "
- 5 "
- 10 "
- 20 "

PEAK POWER (Arb units)

N$_2$ PRESSURE (Torr)
20 torr partial pressures show similar trends indicating a continuous increase in power on the low pressure side, indicating that optimum working pressure is shifted to a lower value.

The general trend shown in fig.(10) is that in the partial pressure range (of SF$_6$) investigated, the power has been increased several fold at low total pressures, and at the pressure corresponding to the optimum pressure without SF$_6$, power always remains low; with fall in power (with increase in total pressure) becoming more and more rapid at increased SF$_6$ partial pressures.

Blumlein line mode of operation:

The pulse forming line has also been operated in Blumlein line mode and its performance studied. The performance of $N_2$ laser in Blumlein line mode was found to be very much similar to that in the simple PFL mode. However, for a given charging voltage, the peak output power in Blumlein line mode remained a bit low (20% low under optimum conditions) compared to that in the PFL mode. This was so, inspite of the fact that the energy stored in the Blumlein line mode is much greater than that in simple PFL mode, at a given charging voltage; as described in chapter (5). For comparison a typical set
of observations is presented in fig.(11), showing the laser peak output power as a function of laser head pressure (pure N₂) when both the modes of operation had the same Marx charging voltage (9kV). This corresponds to about 25 kV on 6.25 nF PFL and about 18 kV on Blumlein line (with more than twice energy stored in PFL). Also the output voltage of Blumlein line into a matched load is expected to be about 50% higher than that for PFL under these conditions.

A comparison of the two modes (simple PFL and Blumlein line) of operation showed that the laser system performs more efficiently in the simple PFL mode. This suggested that the ideal Blumlein line performance is not being achieved in the existing setup. Had it been so, this discrepancy would not have existed.

As is already pointed by others, the true transmission line effects in Blumlein line can be achieved with high output impedance lines with fast switches (having low inductance). Our Blumlein line switch was suspected and attempts were made to reduce the switch contribution. Multichannel surface gap switch and water dielectric switches were tried. The glass container housing the water gap was broken into pieces in a single shot when the gap fired, due to the pressure wave.
PEAK POWER [Arb units]

PRESSURE [TORR]

a: Simple PFL
b: Blumlein line

FIG. 11
generated. The arrangement was then changed to take care of this and the switch worked. However, with both the switches, no discernible change could be observed. This was so, perhaps, because of the contribution from switch leads (though reasonably short).

This indicated that for the system of the type used, with low impedance and short transit time the switch performance becomes a limiting factor. In addition the inductance that has to be connected across the laser head while charging plays its role by shunting the head when the line erects. This inductance is also a critical factor while charging with a short duration pulse. The reactance is to be carefully selected to remain low enough while charging, and high enough while discharging. Any optimised value, certainly starts contributing when switch rise times are high and become crucial when the transit time and the output pulse duration is small. So it is concluded that in the present system a simple PFL is a better and efficient configuration giving further improved performance with a multichannel transfer gap.

**Delay and Jitter:**

The delays assume importance when several events are synchronised with some standard. Delay is the time lapsed from initiation of an event to the appearance of
the effect. More important is the jitter, which is the mean standard deviation in the delay. The jitter becomes very critical while using laser amplifier system, where two events are to be precisely synchronised. For pulse durations of the order of 5 to 10 ns, the jitter must be still low.

The various delays and jitters present in the entire system has been studied. Delays encountered at various stages under a typical set of operating conditions are shown in fig.(11A). The figure shows the time correlation between various events such as the command trigger pulse and the firing of the SCR gate, its conduction, krytron firing, Marx firing and the time of appearance of the laser output pulse (the cable transit times are included). The delays associated with the Krytron trigger pulse generator are dependent upon the Krytron supply voltage, SCR supply voltage and the magnitude, risetime and duration of applied command signal. And so also the associated jitters.

The delays present in the laser system (simple PFL mode and without a transfer gap) i.e. the delay between firing of the Marx generator and the appearance of the laser signal is shown in fig.(12) as a function of line charging voltage under a given set of operating
conditions. The measurements are accurate upto not more than 10 ns. Obviously the delays are sensitive to the conditions prevailing at the laser head. Delays are found to increase with the pressure in the head, and show decreasing trend with increase in operating voltage. Unusually higher values of delays have been found arising from late breakdown in the laser head. Fig.(12A) showing the oscillogram of voltage across the laser head shows such an incident of late breakdown. The associated jitters in the above mentioned delays are plotted in fig.(13) as a function of line charging voltage for three different working pressures.
FIG. 12A

Sweep: 100ns/cm
REFERENCES

