Chapter Four

Experimental Results

4.1 : Discharge voltage waveform

The inductance, current and other parameters of the plasma during discharge may be deduced from the discharge voltage waveform. The voltage waveform of the discharge at one of the isolated electrodes is recorded. Figure 4.1 and Figure 4.2 show the discharge voltage waveforms with 5nF and 2nF peaking capacitors respectively. For the experiment where the peaking capacitors used are 5nf, the storage capacitance used is 300nF. The voltage waveforms across both peaking and storage capacitor are shown in Figure 4.1. The ratio of Cs to Cp is approximately 1:1.

From the voltage waveform shown in Figure 4.1, it is found that the discharge time of the storage capacitor is about 620ns while the charging time for the peaking capacitor is 180ns before the laser channel breakdown. The breakdown voltage of the laser channel is only 7 kV. The laser output energy is only between 70μJ – 80μJ. When a higher charging voltage is applied, the breakdown voltage is still around 7 kV and thus the optical output energy does not increase much. The laser channel breakdown although the energy stored in the storage capacitor has not been fully transferred to the peaking capacitors. This is due to the storage capacitor took too long time (620ns) to transfer the energy stored to the peaking capacitors.

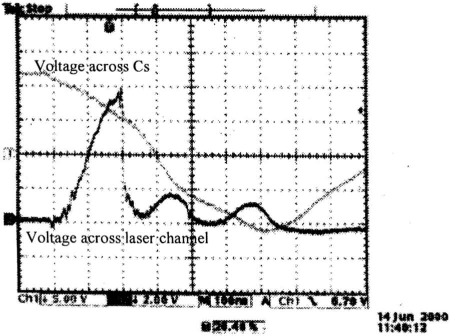

Figure 4.1: Voltage waveform of 300nF storage capacitor (Channel 1) and 5nF peaking capacitor. The electrode profile is M3 screw. Time base is 100 ns.

In order to overcome this problem, the capacitance of the storage capacitor has been reduced to 100nF instead of 300nF. Lower capacitance will provide a faster discharge. Therefore, the peaking capacitors used are 2nF while 100nF storage capacitor has been used. The ratio of Cs to Cp is still roughly 1:1. The rest of the experiments are carried out with 2nF peaking capacitors and 100nF as the storage capacitor. The voltage waveform of the storage and peaking capacitors are shown in Figure 4.2.

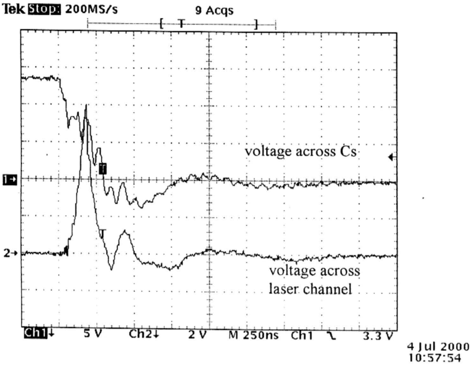

Figure 4.2 : Voltage waveforms of 100nF storage capacitor (CH1) and 2nF peaking capacitor with M3 screws as electrodes. Time base is 250ns.

The voltage waveform of the 2nF peaking capacitor is shown in Figure 4.2. The breakdown voltage of the laser channel is only 8 kV and the charging time is still around 180 ns before the channel breakdown. This does not help much in increasing the output energy. The laser channel breakdown before the peaking capacitors can be charged up to higher voltage. The sharp ends of the electrodes cause this early breakdown of the channel. The electrodes used are M3 screws. The corona caused by the sharp edges makes the laser channel to breakdown after 180ns. Therefore, flat cylinder electrode profiles have been machined. Moreover, the discharge time of the storage capacitor is 500ns, which is just 120ns shorter than the earlier experiment. This long discharge time of the storage capacitor reduces the efficiency of the laser system. A lot of energy stored in the storage capacitor does not contribute to the discharge. High inductance of the discharge loop is the main factor that makes the slow discharge. Therefore, all the wires are put close to the ground plate (as shown in Figure 3.2) to provide lower inductance.

Figure 4.3 shows the discharge waveform with the flat cylinder electrodes and when all the wires are put close to the ground plate. The voltage now can hold up to around 10 kV while the charging voltage is 15 kV. The laser channel breakdown is again 180ns after the spark gap is triggered.

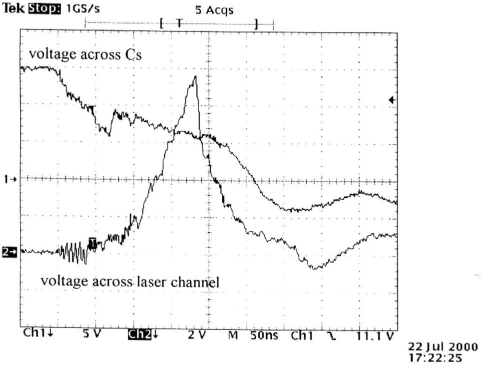

Figure 4.3: Discharge voltage waveform with flat cylinder electrodes. CH 1 is the voltage waveform at 100nF storage capacitor while the peaking capacitor is 2nF. CH2 is the voltage waveform at one of the electrodes.

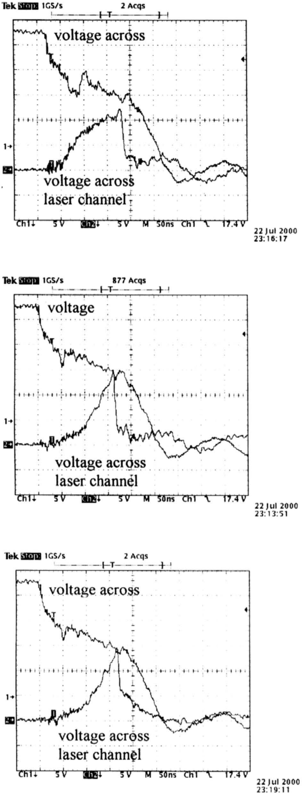

Figure 4.4: Voltage waveform measured across the electrode around the center of the laser channel (top figure) and at both ends (center and lowest figure). CH1 is the voltage across storage capacitor and CH2 is the voltage across the laser channel. Flat electrodes are used in this experiment.

On the other hand, the voltage waveform for the storage capacitor (refer to Figure 4.3) shows that the discharge of the storage capacitor slows down 20ns after the voltage drops. It then takes about 170ns for the voltage to drop 5kV. This is due to the charging time of each of the isolated peaking capacitors are different.

To further investigate on the charging and discharge of the peaking capacitors, measurements of the voltage across the laser channel for three different electrodes along the channel have been carried out. The electrodes are flat in profile. The results are as shown in Figure 4.4.

Figure 4.4 shows that the laser channel breakdown at about 180ns after the spark gap is triggered. The three waveforms are collected from three electrodes at three different positions along the laser channel. The voltage across the electrode at the center portion along the laser channel increase faster at the beginning. But, 100ns later, the increment of voltage starts to slow down (as shown in Figure 4.4a). On the other hand, the peaking capacitors at both ends of the laser channel start to be charged up a bit later (10ns-20ns) after the storage capacitor is discharged. This is because the peaking capacitors at both ends are further away from the spark gap, which is the common switch for all the isolated peaking capacitors. The schematic drawing shown in Figure 4.5 shows the arrangement of the peaking capacitors. The peaking capacitors at both ends are further away from the spark gap than the peaking capacitors at the center. Thus, the electrode at the center portion is being charged up faster.

However, from the three waveforms, they show that all the electrodes in the laser channel breakdown at about the same time at 180ns after spark gap breakdown.

In other words, all the isolated electrodes fire simultaneously. Synchronization of each discharge is important for laser amplification.

For the peaking capacitors located on the same row but at different distances from the spark gap (as shown in Figure 4.5), the charging and discharging time of the capacitors as labeled with numerals 1, 2, 3, 4, 5 and 6 are more or less the same. This is because all the wires are placed close to the ground plate and has created the same inductance for these different discharge loops. As a result, these isolated electrodes discharge almost simultaneously.

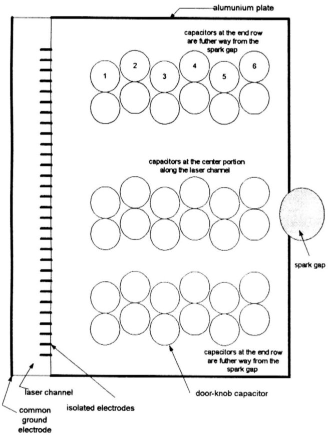

Figure 4.5 : The drawing shows measurement of the voltage across laser channel at different points along the laser channel. Capacitor 1 to 6 are at the same row.

The experiment is then carried out by using the cylindrical electrodes (refer Figure 3.6c) screwed onto their curved side. The discharge voltage waveforms are shown in Figure 4.6. The breakdown voltage for the laser channel is 180ns after the spark gap is fired. However, the voltage now holds up to 15 kV when the charging voltage is 24 kV. These three waveforms again show that the isolated electrodes are firing simultaneously. The voltage waveform for both the storage and peaking capacitors are not much different from the voltage waveforms with the flat electrodes.

The voltage drops very slowly for a period of 150ns too. The 'choking' phenomenon for the transfer of energy from the storage to the peaking capacitors still occurs in this case. This limitation has advantages and disadvantages for the laser system. The 'choking' of energy transfer will make sure that all the isolated electrodes discharge simultaneously. However, this has limited the rate of energy transfer to the peaking capacitors. The 'C-to-C' circuit may not efficiently transfer the energy from the storage to the peaking capacitors. This delay is due to the circuit inductance.

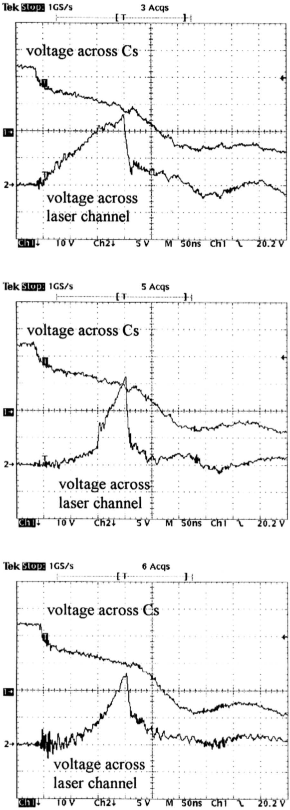

Figure 4.6: Voltage waveforms measured across center electrode (top figure) and both ends (center and lowest figure). CH1 is voltage across storage capacitor and CH2 is voltage across laser channel. Cylindrical electrodes are used in this experiment.

4.2 : Laser output energy

Output pulses have been detected. The wavelength of the output pulses is 337.1nm. This wavelength is measured using the PTI spectrometer. Laser output energy has been measured with a joule-meter for different pressures and different charging voltages. Figure 4.7 shows that the nitrogen laser output energy versus pressures at various charging voltages (with the flat electrode). From the results, they show clearly that the optimum pressure for this laser system is around 50mbar – 60 mbar. The output energy starts to decrease after the pressure is increased beyond this range. In addition, higher charging voltages give rise to higher output energy. In this experiment, the highest charging voltage that has been applied is 24 kV. The maximum output is 1.70 ±0.01mJ at 60 mbar. However, since this is a pulse laser, the energy recorded is the average output energy of five to six laser pulses.

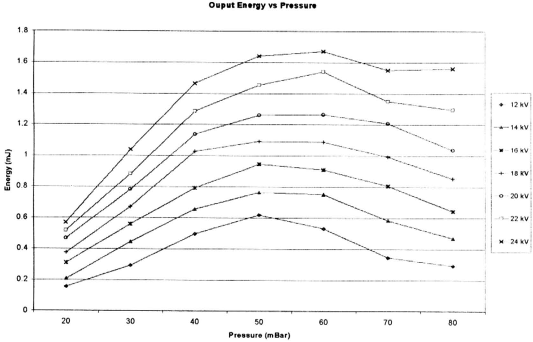

Figure 4.7: Output energy verses pressure at different voltage. Flat electrodes have been employed in this experiment.

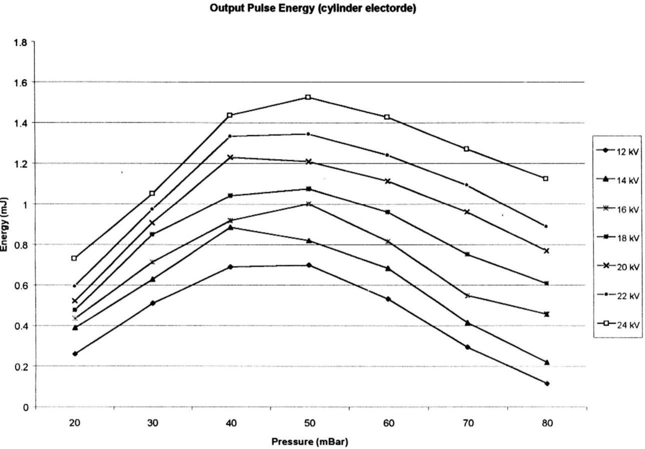

Figure 4.8: Output energy verses pressure at different voltage. Cylindrical electrodes are employed in this experiment.

Experiment is also carried out by employing the cylindrical electrodes. The laser output energy at various pressures and charging voltages are shown in Figure 4.8. The optimum pressure is more or less the same as the previous experiment. 50 mbar is the optimum pressure and the maximum laser output energy is 1.55 ± 0.01mJ. Higher charging voltage will give higher output energy too. In this experiment, the output energy is a bit lower than the previous one although the voltage waveforms are almost the same. This may be caused by impurity of gases in the laser channel. The vacuum for this system deteriorates after a few changes of the electrodes. The vacuum can only hold up to 5mbar instead of 2mbar in the previous experiment.

4.3 : Results of current measurements

Current pulse has been measured using the calibrated Rogowski coil and is shown in Figure 4.9. The voltage waveform in CH1 is measured across one of the electrode. The measurement of current pulse carried out is as shown in Figure 3.11 and the current pulse measured at that particular electrode is recorded in Channel 2. The electrode profile used in this experiment is the flat electrode. Ch2 shows the waveform for the current during the discharge indicating fairly large of noise pick-up.

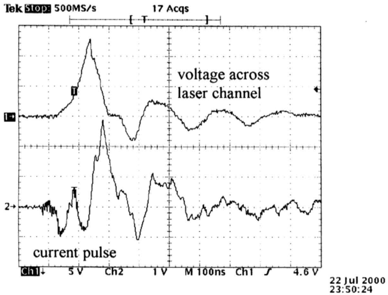

Figure 4.9: Voltage measured across laser channel (CH1) and current measured with Rogowski coil (CH2). Flat electrodes are used in this experiment.

Nevertheless, the current waveform shows that the current peak occurs 40ns after the laser channel breakdown. The Rogowski coil has been calibrated and the factor is 0.85±0.01kA/V. From the current pulse, it is measured that the peak current is 2.38±0.01 kA. The current pulse width for FWHM is 60±10 ns.

In the following experiment, the flat electrode is changed to the cylindrical electrode and the experiment of measuring current pulse is carried out. The waveform is recorded in Figure 4.10. CH1 is the voltage waveform across one of the electrodes while CH2 is the current waveform measured with the Rogowski coil at that loop.

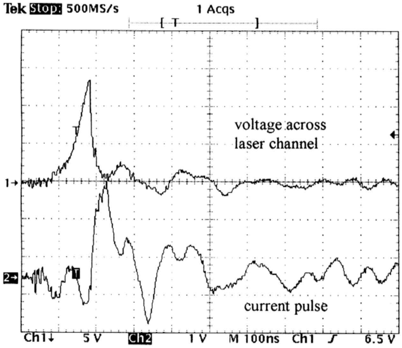

Figure 4.10: Voltage measured across laser channel (CH1) and current measured with Rogowski coil (CH2). Cylindrical electrodes are used in this experiment.

The current waveform is roughly the same as in the previous experiment. The current peak occurs 50 ns after the laser channel breakdown. The current pulse width for FWHM is 60±10ns too. The peak current measured is 2.13±0.01 kA.

Both the current and the voltage waveforms are measured at the same electrode for two different electrode profiles. Comparisons have been made and it is found that the two different electrode profiles did not make any significant differences for the discharge parameters. The laser output energies show basically no significant differences too.

4.4 : The optical pulse detected

An EG&G FND 100 with 1ns rise-time photodiode has been used to detect the optical pulse from the laser. The result of optical pulse with flat electrodes is shown in Figure 4.11. CH2 shows the optical pulse detected while CH1 is the voltage waveform across one of the laser electrodes.

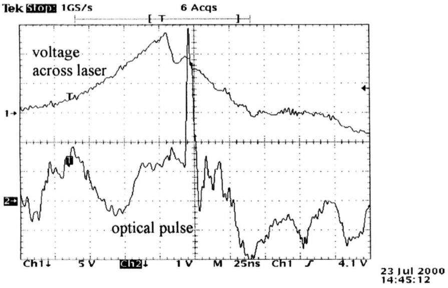

Figure 4.11: Voltage measured across laser channel (CH1) and optical pulse detected (CH2). Flat electrodes are used in this experiment.

The peak of the optical pulse occurs 16.0$\pm$2.5 ns after the laser channel breakdown. The optical pulse width is 5ns. This shows that the laser lase after the voltage of the peaking capacitor drops by 5kV. The current when the laser lases is 0.85$\pm$0.01 kA at the rising edge of the current pulse (refer to Figure 4.9).

The optical pulse of the laser with the cylindrical electrodes is detected and is shown in Figure 4.12. The peak of the optical pulse occurs 20$\pm$2.5ns after the laser channel starts to discharge. The pulse width is 5 ns too. However, the voltage of the peaking capacitor drops by 8 kV before the laser lases. The current at the moment the laser lase is 1.53$\pm$0.01kA.

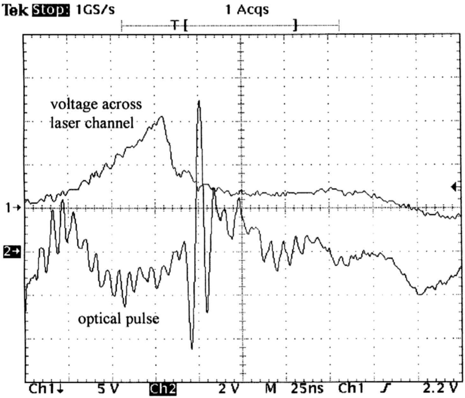

Figure 4.12: Voltage measured across laser channel (CH1) and optical pulse detected (CH2). Cylindrical electrodes are used in this experiment.

4.5 : Output energy with various number of arcs

Since the laser consists of an arc array, the number of arc will determine the output energy of the laser. Table 4.1 shows the results of the experiment.

Number of electrodes	Output energy E ($\pm 1 \mu J$)	ln(E)
52	50	3.91
42	41	3.71
32	32	3.47
22	14	2.64
12	5	1.61

Table 4.1: The output energy and ln(E) with various numbers of electrodes.

Figure 4.13 shows the graph of ln(E) versus the number of arcs. From the graph, it shows that it has a nonlinear gain. When the graph is extrapolated (as shown in dotted line), it seems that the graph is similar to the graph plotted by Rocca for Ne-like Ar laser [13]. Ne-like Ar which emits at 46.9nm wavelength achieves gain saturation at 15cm. From the graph plotted, the gain saturation is at around 30 arcs. Since the separation of the arcs is 1cm, therefore, the length of 30 arcs is roughly 30cm long. The gain of the discharge of N_2 gas can be calculated theoretically.

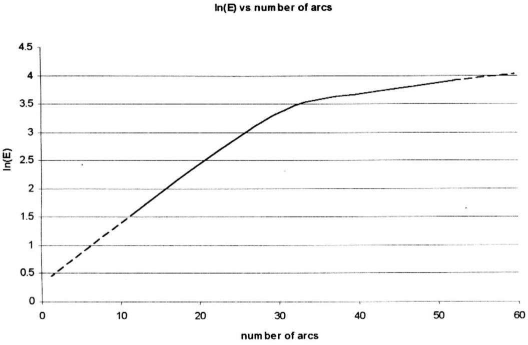

Figure 4.13 : The ln(E) vs number of arcs.

The output energy of laser is proportional to e^{gl} where g is the gain factor and the l is the length. Therefore, the slope of the graph of ln(E) versus length gives the gain factor. From Figure 4.13, there seems to have two slopes and the gain calculated up to 30 arcs is around 0.1cm^{-1}. An exact gain coefficient can be calculated from the Linford formula [33]. Saturation of intensity is observed at gain length product (gl) of about 3. This gain length product estimated is reasonable since nitrogen laser is a high gain laser.