Chapter 4

Experimental Results

4.1 Experimental Approach

The main aim of the experiment is to optimise the performance of the electrical circuitry of a transverse arc array laser. Therefore, the roles of inductance and capacitance were studied in details in order to understand how they affect the electrical behavior of the laser.

The purpose of the research is to realize an effective pumping method for a short wavelength laser. In order to achieve this, we must have ways and means to obtain a fast and synchronised discharge. The amount of energy to be pumped in is also critical for the creation of high temperature plasma.

Various configurations and setups of the system had been tested to obtain the best discharge conditions. This included some earlier efforts to realise the practical implementation of the arc array concept. Results of these works were reported in the M.Sc thesis of K.S. Goh [2]. The inductance of the circuit plays a major role and has to be reduced. Different sets of capacitors had been tested to see how they will affect the current of the discharge. Optical pulse has also been taken for the purpose of gaining more insight into the laser behavior.
4.2 Diagnostic Methods

The most important diagnostic device used in this experiment is a fast digital storage oscilloscope. The oscilloscope is used to obtain the discharge waveforms of the laser, which contain a lot of information regarding the behavior of the laser. The voltage measurements were taken using a high voltage probe with a 1000X attenuation, whereas the current measurements employed a calibrated RC integrated Rogowski coil with a calibration factor of 1.3 ± 0.1 kA/V. The waveforms obtained in the experiment are then stored in floppy disks for further analyses.

Voltage probes have to be placed with the tips directly touching the point of measurement, connection using extra wires and cables should be avoided to reduce the reception of unnecessary rf noise. The Rogowski coil is placed around a connecting cable between one of the peaking capacitors and the discharge electrode. Extra cares had to be taken to ensure the coil is properly shielded and positioned to minimise the noise from the electromagnetic interference.

Laser energy was measured using power meter. The temporal behavior of the laser pulse was measured using a fast photodiode, FND 100, which has a rise time of 1 ns. The photodiode has to be used with a 50Ω terminator for minimum noise and input of the photodiode has to be attenuated to avoid saturation of the diode output. The wavelength of the optical output is determined using a spectrometer.
4.3 Experimental Results: 2 nF capacitors

First, the experiment starts off with capacitors of 2 nF x 48 capacitance manufactured by Murata with 40 kV rating. The same ceramic capacitors are used for both the storage and the peaking capacitors. These made the total storage capacitance and total peaking capacitance each to be 96 nF. The spark gap used is a conventional triggered spark gap.

Voltage measurements were taken across the spark gap which represent the charging voltages. Laser output energies were also measured. A graph is plotted using the data tabulated in figure 4.1.

<table>
<thead>
<tr>
<th>Voltage (kV)</th>
<th>Laser Energy (±1 μJ) With Different Operating Pressure (±2.5 mbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td>±0.5 kV</td>
<td>30</td>
</tr>
<tr>
<td>16 kV</td>
<td>244</td>
</tr>
<tr>
<td>18 kV</td>
<td>316</td>
</tr>
<tr>
<td>20 kV</td>
<td>489</td>
</tr>
<tr>
<td>22 kV</td>
<td>592</td>
</tr>
<tr>
<td>24 kV</td>
<td>723</td>
</tr>
</tbody>
</table>

From the graph plotted, there is a general trend for the laser output power. Initially, when the operating pressure is low, the output is small. As the pressure increases, the output increases as well. However, there is a maximum after which the power starts to decline. The graph also revealed that laser output energy increases with the charging voltage. The higher the voltage, the more intense the beam gets.

The optimum operating condition for this set of configuration is 70 mbar of nitrogen gas pressure, whereby at 24.0 ± 0.5 kV charging voltage, a 1.44 ± 0.01 mJ of laser radiation is produced.
Fig 4.2 Laser energy vs. pressure for different charging voltages using 2 nF capacitors.
The discharge waveforms of the above experiment were taken. In Fig. 4.3 below, Channel 1 denotes the discharge waveform across the spark gap which is holding $20.0 \pm 0.5$ kV, the half period of the storage capacitor discharge was measured to be $180 \pm 10$ ns. Channel 2 denotes the voltage waveform of the peaking capacitors, the capacitors start to charge up moments after the spark gap breakdown, the capacitor reach its peak at the same instant the storage capacitor reaches its minimum. The peak voltage of the peaking capacitor reaches a level of $25.0 \pm 0.5$ kV in $160 \pm 10$ ns duration. The peaking capacitors then discharge rapidly with a half period of $80 \pm 10$ ns. From the figure below, it is clear that the electrical circuit had managed to transfer charges from the storage capacitors to the peaking capacitors effectively. The system also breakdown at higher voltage due to the faster transfer time. However, it is noted that the peaking capacitors were charged to a higher voltage compared to the storage capacitor. In the peaking capacitor's waveform, it is also noticed that there are two discharge voltage slopes indicating two discharge conditions had occurred.

![Voltage waveform across spark gap (Chn 1) and voltage waveform across laser channel (Chn 2).](image)
From the enlarged time-scale waveform of Channel 2, we can see that the peaking capacitor discharges at a faster rate initially, and then slows down considerably towards the end of the discharge. One can estimate the discharge time of the first slope by extrapolating the curve extending further down. With this method, one obtains a discharge half period of $8 \pm 2$ ns. The second slope starts from approximately at half of the peak voltage, one can estimate that the discharge half period of the second slope to be about $80 \pm 2$ ns.

The abnormality of the above discharge waveform indicated that an unknown parameter was present in the discharge of the peaking capacitor. This requires further investigations. One will have to examine the current waveform for additional information. The relation of the voltage and current in the discharge circuit was obtained.
Fig 4.5 Discharge voltage (Chn 1) and current (Chn 2) waveform across the laser channel.

Fig 4.6 Discharge voltage waveform (Chn 1) and optical pulse (Chn 2) across the laser channel.
In Fig. 4.5, it is shown that Channel 1 denotes the voltage waveform across the peaking capacitor, whereas Channel 2 denotes the discharge current waveform across the laser channel. The voltage waveform serves as a timing reference for the current waveform.

The peak current detected with the 2 nF capacitor configuration is about 2.6 ± 0.1 kA. From the waveforms, one can see that the current started to rise right after the laser channel breakdown. The risetime of the current pulse is estimated at about 40 ns. However, the current peaked only towards the end of the voltage pulse. The current pulse has a full width half maximum (FWHM) of 60 ± 10 ns. Noticed also that the current also rises at two different rate as in the voltage waveform. One can see that the current pulse detected actually consists of two current pulses superimposed together. A prepulse of less than 10 ns risetime is present before the main current pulse. This is in correspondence with the observed voltage waveform.

In another waveform obtained as shown in Fig. 4.6, an optical pulse was detected using a fast photodiode. Channel 1 again denotes the peaking capacitor waveform which serves as a timing reference for Channel 2 which is the output of the photodiode. The output from the photodiode shows the temporal behavior of the laser pulse.

The optical pulse is a sharp and narrow pulse indicating laser output. From figure 4.7, the laser is emitted after about 14 ± 1 ns from the breakdown of the laser channel. When the discharge waveforms in figure 4.5 and figure 4.6 are compared, with the voltage waveforms as reference, one gains a lot of insight of the laser
behavior. The optical pulse peaked at the end of the first sharper discharge voltage pulse of the peaking capacitor, which corresponded to the peak of the first current pulse. The system already lases before the peak of the second current pulse arrives indicating a lot of energy is not converting into laser output.

Fig 4.7 Expanded view of the optical pulse together with the discharge waveform.

In figure 4.7 above, which is captured at 10 ns time-scale, the optical pulse is measured to have full width half maximum (FWHM) of only 5 ± 1 ns, a characteristic of fast, superadiant laser pulse. To further confirm the laser pulse is indeed the nitrogen 337.1 nm line, the laser pulse is channeled into a spectrometer.

The spectrometer employed the 0.25m Czerny-Turner configuration, the laser pulse passed through a collimating slit into the spectrometer, reflected upon hitting the optics and the grating and exit in another slit, in which a white printing paper is
placed for detecting the fluorescence effect of the laser beam. As a result, the laser output is confirmed to be at the wavelength of 337.1 nm.

4.4 Experimental Results: 5 nF capacitors

In order to understand how the capacitance of both the storage and peaking capacitors will affect the performance of the laser, the experimental setup is then reconfigured, the 2 nF capacitors are replaced by ceramic capacitors from Matroc with capacitance of 5 nF each and a voltage rating of 30 kV. The rest of the circuitry remained the same.

The same measuring approach is taken, whereby the voltage waveforms across the spark gap and laser channel were obtained. Laser power was also measured. Peak discharge current was measured. The relation of the charging voltage with the laser output was investigated, and the relation is plotted as a graph with different operating pressure.

<table>
<thead>
<tr>
<th>Voltage</th>
<th>Laser Energy (μJ) With Different Operating Pressure (mbar)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>40</td>
</tr>
<tr>
<td>16 kV</td>
<td>286</td>
</tr>
<tr>
<td>17 kV</td>
<td>380</td>
</tr>
<tr>
<td>18 kV</td>
<td>459</td>
</tr>
<tr>
<td>19 kV</td>
<td>564</td>
</tr>
<tr>
<td>20 kV</td>
<td>457</td>
</tr>
</tbody>
</table>

Fig 4.8 Table showing the laser energy variation with different charging voltages and operating pressures using 5 nF capacitors.
The graph revealed a similar pattern as in the previous configuration. The optimum operating pressure of this configuration is 60 mbar, in which the output is at its peak. The maximum output obtained in this configuration, when the system is charged at 20.0 ± 0.5 kV, laser output power obtained was 1.17 ± 0.01 mJ. One has to take note that the laser power is marginally higher compared to previous configuration, comparing at 20 kV, the 2 nF setup only gives 1.08 ± 0.01 mJ.
Fig 4.9 Laser energy vs. pressure for different charging voltages using 5 nF capacitors.
Fig 4.10 Voltage waveforms across the spark gap (Chn 1) and across the laser channel (Chn 2) for the 5 nF experiment.

Fig 4.11 Discharge's voltage waveform and current waveform across the laser channel in the 5 nF experiment.
Figure 4.11 shows the discharge voltage waveforms of the 5 nF configuration. The system retains more or less the same discharge characteristics with the exception of the discharge duration. The discharge duration is longer, as is expected since the capacitance of storage and peaking capacitors had increased from 96 nF to 240 nF each.

The trace of Channel 1 which denotes the storage capacitor voltage indicated that the charging voltage is 18.0 ± 0.5 kV and the spark gap discharge at a half period of 280 ± 10 ns, this is considerably slower compared to the earlier configuration. Despite the longer duration, the peaking capacitor, represented by Channel 2, still managed to charge up to 23 ± 0.5 kV when the storage capacitor swing to its minimum. The peaking capacitor then discharge through the laser channel with a half period of about 120 ± 10 ns. The discharge waveform of the peaking capacitor also showed two different discharge slopes as in the previous experiment, indicating the presence of an inherent constraint of the electrical circuit.

The current waveform was captured as figure 4.11. From the waveform, one can deduce that the peak current had indeed increased to 5.0 ± 0.1 kA. Although the current waveform contains a lot of noise due to the strong discharge, one can observe a clear current trace. The risetime of the current pulse is approximately 40 ± 10 ns whereas the current pulse had its full width half maximum of 60 ± 10ns.
4.5 Experimental Result: Multi Pin Spark Gap

![Graph showing voltage waveforms across the multi pins spark gap (Chn 1) and across the laser channel (Chn 2).]

Fig 4.12 Voltage waveforms across the multi pins spark gap (Chn 1) and across the laser channel (Chn 2).

It is impossible to further reduce the circuit inductance from the aspect of geometrical layout of the system. However, it is still possible to reduce the transfer loop inductance, if one considers the characteristic of the spark gap. The inductance derived from the spark gap is proportional to the rate of change of the magnetic flux induced by the current that is going through the spark gap. Therefore, if one manages to divert the current to flow in a wider channel, we may further reduce the inductance.

In order to validate the above statements, a multi pin spark gap was designed. The purpose of the new spark gap is to allow the breakdown of the gap to take place, instead of at one point, to as many pins as possible. This will effectively reduce the current density of each breakdown point, thus enabling lower spark gap inductance.
From the experimental data obtained as shown in figure 4.12 above, the charging voltage was limited as the pin gap does not allow high holding voltage, the system fired at only $15.0 \pm 0.5$ kV. From the oscilloscope traces, one can see that the discharge half period of spark gap is still around $250 \pm 10$ ns. However, spiking along the slope may indicate that more pins breakdown subsequently. The peaking capacitor only starts to charge up at about 100 ns later, and it only takes $150 \pm 10$ ns to reach its peak. This happened when the storage capacitors are at the end of their discharge. Therefore, the peaking capacitor had managed to charge up in a faster duration, indicating that the transfer loop inductance had been reduced.