AMOP BEC 4 Summer Intern Report

Teddy Ong

Aug - Oct 2021

1 The Circuit

This section documents the components in the circuit, their effects and limitations.

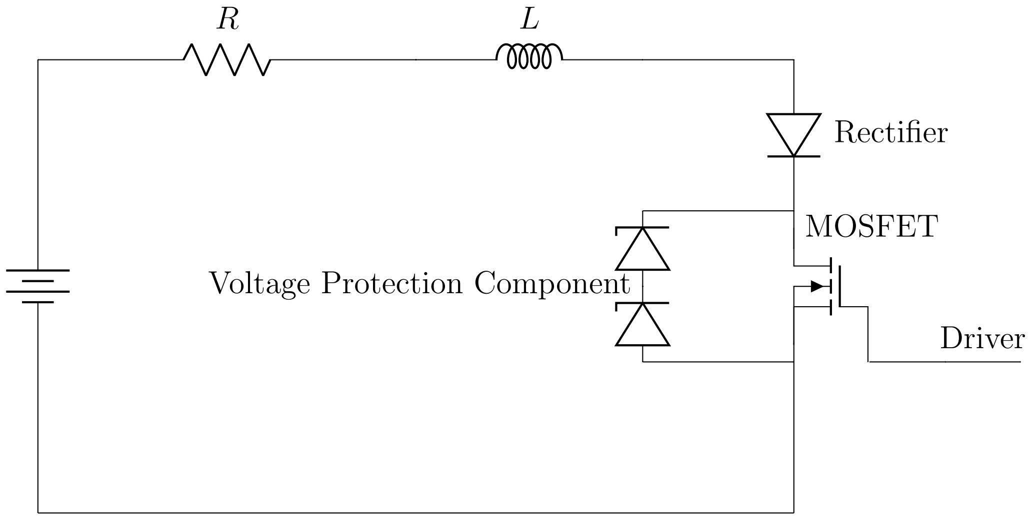


Figure 1: Diagram of Magnetic Coil Circuit

R: The effective resistance of the circuit, estimated to be 40 $m\Omega$
L: The inductance of the Electromagnet Coil
Voltage Protection Component: Either TVS Diodes or Varistors

All electrical components other than the magnetic coil are placed on a water-cooled aluminium block, arranged as follows.

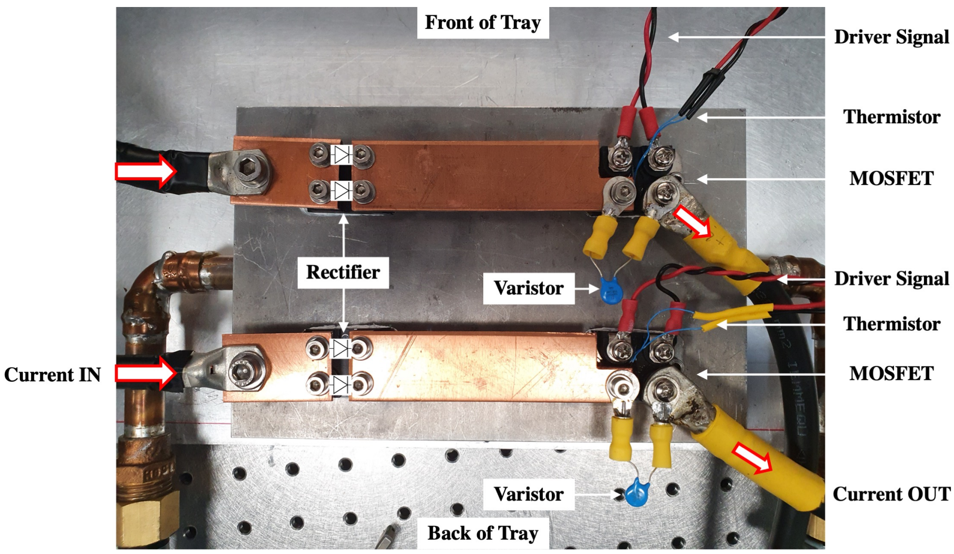


Figure 2: Water-cooled Aluminium Block with Circuit Components

When the circuit is closed, the current will increase as follows:

$$I = I_0\left(1 - e^{-\frac{R}{L}t}\right) \tag{1}$$

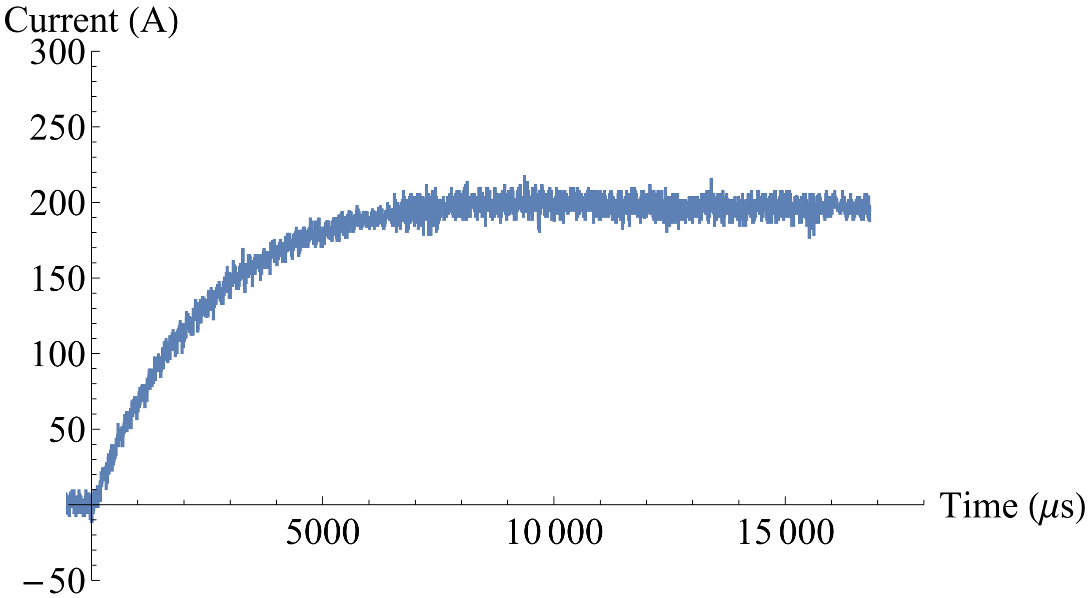


Figure 3: Graph of Current (A) against Time (μs)

The 10 - 90 rise time is about 4600 μs. Therefore the inductance can be estimated at $L = \frac{R\Delta t}{ln(9)} \approx 8.37 \times 10^{-5} H$.

1.1 Modification to MOSFET Driver

The MOSFET Driver is powered by a DC 5V power supply. Inside it, a wire connection is added between the "G" and the pin that would produce the $\pm 15\ V$output signal to the MOSFET. The box was designed to have the MOSFET mounted inside it, now the signal voltage on the "G" pin is sent out via the red wire.

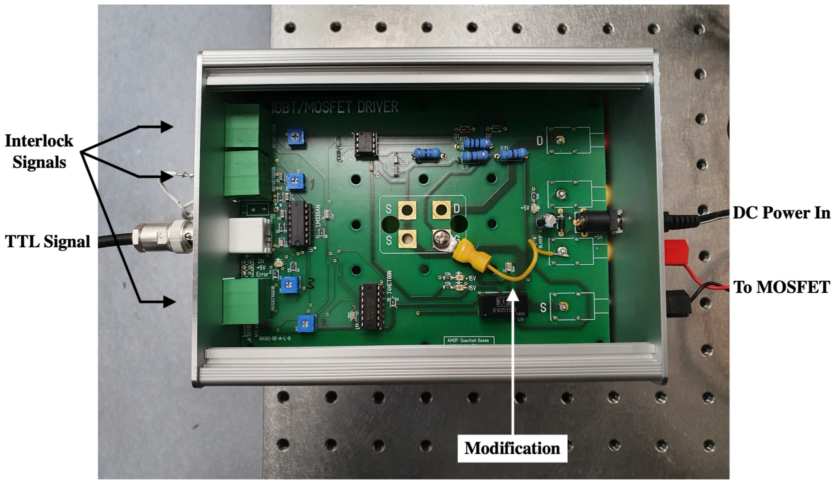


Figure 4: Labelled Picture of MOSFET Driver

1.2 Connections at MOSFET [1]

The MOSFET consists of 4 pins. Arranged vertically on the right are input signals from the MOSFET driver. A thermistor is also epoxy-ed to the MOSFET to monitor its temperature. On the left are the current carry cables, with direction of current labelled. The branch with TVS diodes is placed above them.

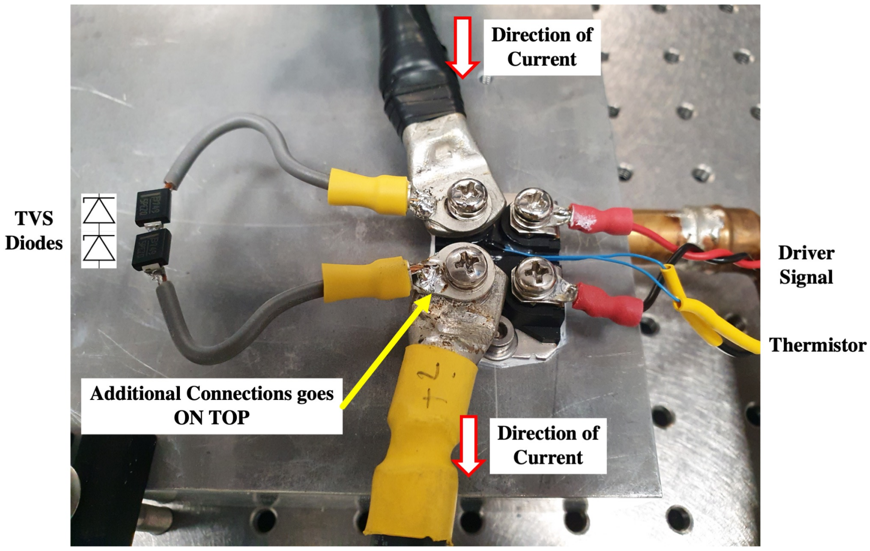


Figure 5: Labelled Picture of MOSFET

1.3 Interlock Signals for MOSFET Driver

The Driver compares each interlock signal with the reference voltage (it can be set, usually at 2.5V). If the interlock signal is lower, then it is deemed safe. If the interlock signal is higher, then the MOSFET will be opened and the experiment will be stopped.

1.3.1 Water Flow Detector

The water flow detector is mounted on the returning pipe (with arrow pointing upwards). When water is flowing, the mechanism inside it is pushed upwards and it conducts electricity with negligible measured resistance $R = 0.8\ \Omega$. If the water stops flowing, the mechanism drops and it does not conduct.

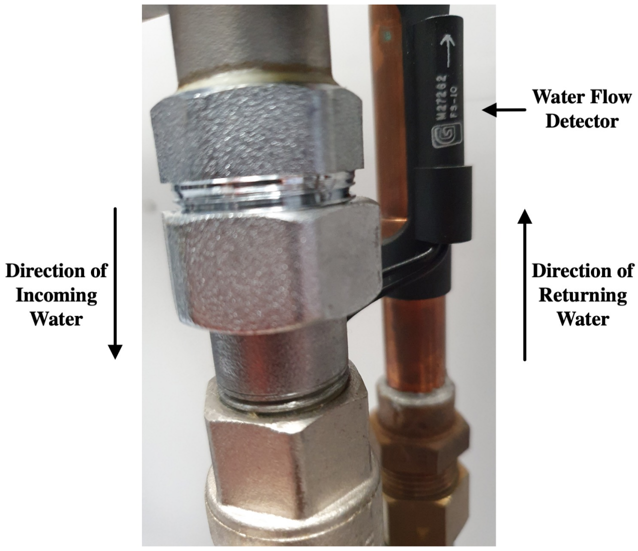


Figure 6: Labelled Picture of Water Flow Detector

For BEC4, the water for each coil is separate. There are 3 water flow detectors: 1 for each of the 2 coils, and 1 for the aluminium block. The following circuit is designed to duplicate the Water Flow interlock signal from the aluminium block to both MOSFET Drivers. By using an optocoupler [7], the resulting signals are electrically isolated. Furthermore, if the water supply for a coil fails but the water supply for the aluminium block is as normal, we do not want the signal duplication to be affected.

Choice of values for the circuit is determined as follows:

1. Determine R_0, r_0 by the current required to power the optocoupler
According to the datasheet [7], the optocoupler requires an input current of at least $I_1 > 1.6\ mA$ to turn on the LED inside. At this current, the Input Forward Voltage of the LED is $V_F \approx 1.1\ V$. For the output side, a current of $1.6\ mA \leq I_2 < 5\ mA$ is required. This means the input current to the optocoupler is:
2. Choose the other resistors
Therefore we want the resistances $R_2 >> R_1 >> R_0$ and $r_2 >> r_1 >> r_0$, so that their effect is negligible whether their respective components are on or off.
3. Choose an appropriate capacitor C_2, c_3
Using the formula $T = 2\pi R_2 C_2$.

Water Flow Detector for Coils 1 and 2	I_1	I_2
Normal	$\dfrac{5 - V_F}{R_0 \;//\; R_1}$	$\dfrac{5}{R_0 \;//\; R_1}$
Fail	$\dfrac{5 - V_F}{R_0}$	$\dfrac{5}{R_0}$

Table 1: Current to Optocoupler

Values that work: $R_0 = 3.3\ k\Omega$, $R_1 = 47\ k\Omega$, $C_1 = 22\ nF$. These give a characteristic timescale of $T = 2\pi R_1 C_1 = 6.50\ ms$.

To convert two or more of these to a 5V or 0V interlock signal, connect the detectors in series (so that if water stops flowing in one pipe, the whole circuit will be stopped), and the interlock circuit is designed as follows:

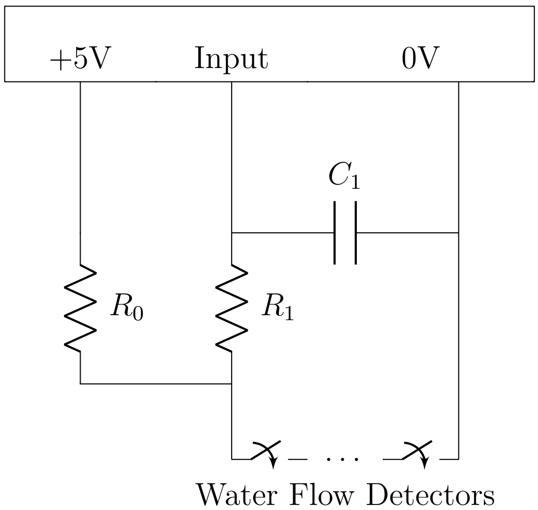


Figure 7: Diagram of Water Flow Interlock Signal with RC Filter

Choice of values for the circuit is determined as follows:

1. Determine the timescale of possible disruption
The large circuit current rises or falls in the timescale of $< 5\ ms$. As we do not want the interlock to be tripped by inductive effects in the circuit, we will choose a timescale of around $T = 10\ ms$.

2. Choose a convenient capacitor C_1 by availability

3. Choose an appropriate resistor R_1
Using the formula $T = 2\pi R_1 C_1$

4. Choose an appropriate resistor R_0
This resistor should be significant so that when the switch is closed, the current in the

circuit is small. In order for the capacitor charging and discharging behaviour to be roughly the same, we need $R_0 << R_1$. Hence we have chosen R_0 to be roughly one order of magnitude smaller than R_1.

Values that work: $R_0 = 3.3\ k\Omega$, $R_1 = 47\ k\Omega$, $C_1 = 22\ nF$. These give a characteristic timescale of $T = 2\pi R_1 C_1 = 6.50\ ms$.

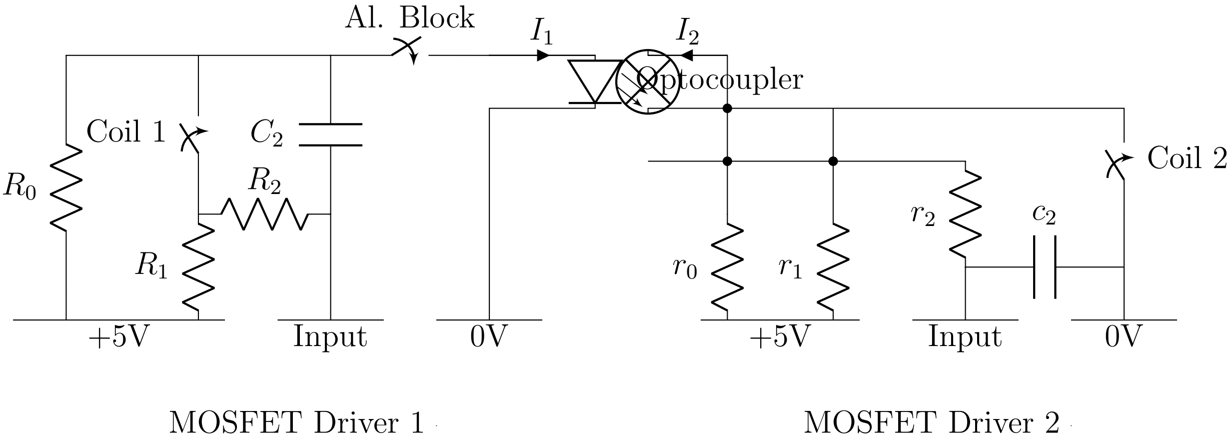


Figure 8: Diagram of **Proposed** Water Flow Interlock Signal for both MOSFET Drivers

1.3.2 Thermistor (10 $k\Omega$ $\pm 5\%$) [3]

Thermistors are used to measure the temperatures at the MOSFET and the Coil. As temperature increases, the resistance across the thermistor decreases. To convert this to an interlock signal, the following potential divider circuit is designed such that the input voltage is $> 2.5\ V$ if the temperature is too high.

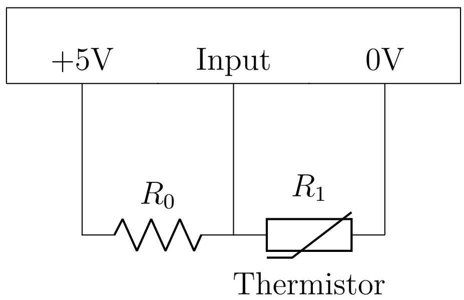


Figure 9: Diagram of Thermistor Interlock Signal

Choice of values for the circuit is determined as follows:

1. Run the experiment for a few hours

2. Measure the range of resistance of the Thermistor

I got $R_1 = 4.92 - 7.19\ k\Omega$. According to Data Sheet [3], $R_{25°C} = 10\ k\Omega$, this indicates the temperature is in the range $30 - 45°C$.

3. Choose R_0 to some amount lower than the lowest value of resistance (with reference to data sheet, if available)

1.4 Need for Voltage Protection and Rectifier

According to the MOSFET data sheet [1], it takes 142 ns for it to open the circuit. The current will decrease rapidly. The induced voltage can be estimated $V = L\frac{dI}{dt} \approx 1.18 \times 10^5\ V$. The MOSFET can handle only up to 150 V, so it needs to be protected from this voltage spike.

Note: Without using any voltage protection components, experience suggests the MOSFET will fail quickly, within 15 minutes.

1.4.1 TVS Diodes

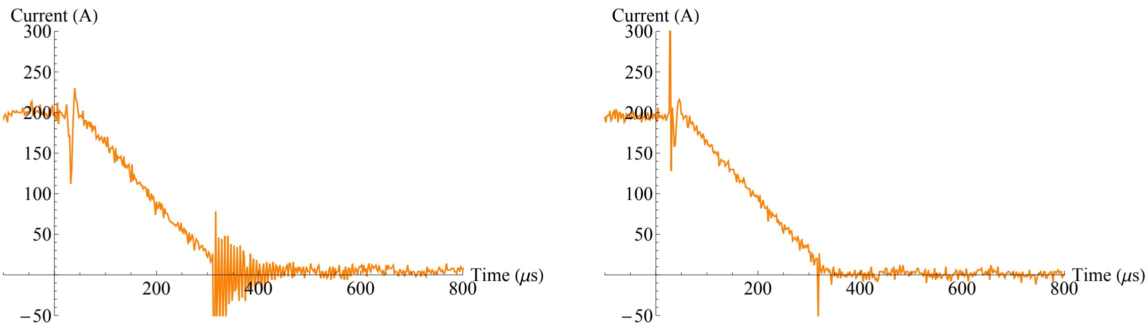
According to the TVS Diode data sheet [2], they break down in the range $26.7 - 29.5\ V$ and provide a maximum p.d. (i.e. Clamping Voltage) of $38.9\ V$. As they are connected in parallel with the MOSFET, this limits the voltage across the MOSFET and provides an alternate path for the current to flow. The TVS diodes then provide a power dissipation of $P = IV$ which helps to rapidly dissipate the energy $\frac{1}{2}LI^2$ in the coil. The maximum amount of TVS Diodes that can be connected in series is $\left\lfloor \frac{150}{38.9} \right\rfloor = 3$.

1.4.2 Varistors

We also tested the effect of two available Varistors. The Varistor is symmetrical in both directions of current flow, so it does not matter which way it is installed. The Varistors have a Clamping Voltage of 77 V [5] and 135 V [6], respectively.

1.4.3 Need for Rectifier [4]

When the potential difference drops below the breakdown voltage of the TVS diodes, they no longer conduct. The current will exhibit rapid oscillation as seen in Fig. 10a. This happens consistently at some critical current (indicated on the graph with dashed black line). To protect circuit components from this unintended reverse current a rectifier is used. The oscillation is clearly reduced significantly.



(a) Without Rectifier

(b) With Rectifier

Figure 10: Graph of Current (A) against Time (μs)

Note: the power supply voltage needs to be increased by about 1V when a rectifier is used, as it provides some voltage drop.

1.4.4 Comparison of TVS Diode and Varistor

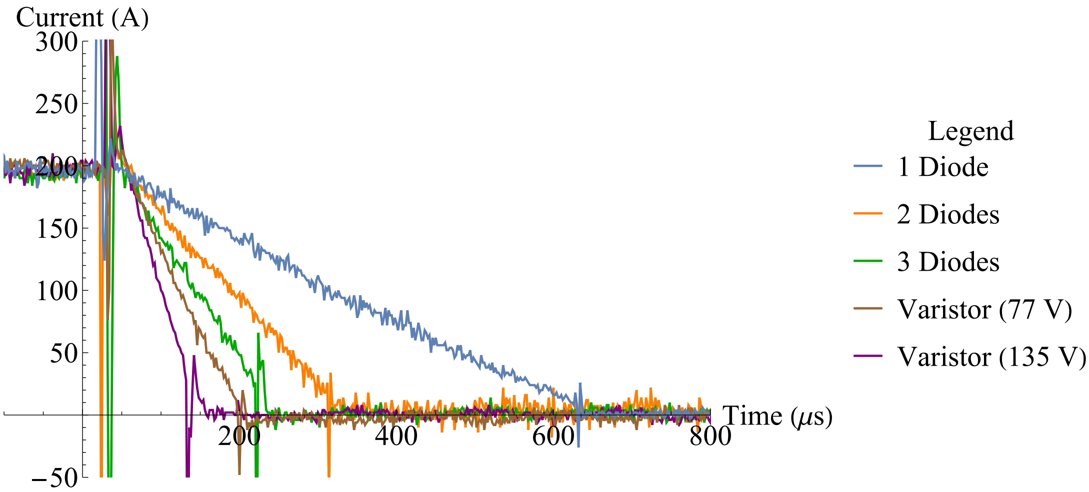


Figure 11: Graph of Current (A) against Time (μs)

Legend	Component	Clamping Voltage (V)	90 - 20 Fall Time (μs)	Approx Critical Current (A)
Blue	1 Diode	38.9	411	9
Orange	2 Diodes	77.8	199	20
Green	3 Diodes	116.7	139	25
Brown	Varistor (77 V)	77	104	11
Purple	Varistor (135 V)	135	65	28

Table 2: Data of Current Decay with 1 to 3 TVS Diodes

For safety, because the MOSFET breaks at 150V, we want to clamp at a much lower amount. From the above data, the 77V Varistor is the best choice, with a fast decay time and low amounts of oscillatory noise. The additional benefit of using a varistor is that it is bi-directional, so it cannot be accidentally connected the wrong way.

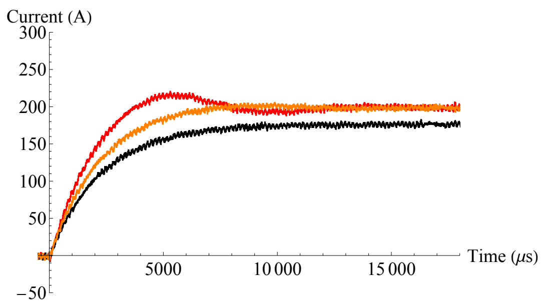
Note: It appears the critical current is non-linear with the breakdown voltage.

1.5 Effect of Power Supply [8] Voltage

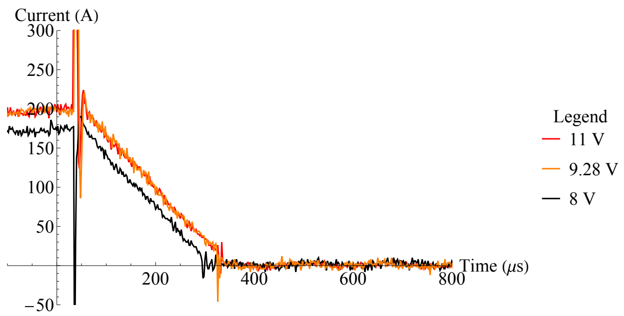
The power supply controls allow us to set the maximum limit on the voltage and current. It should always be on current-limited mode.

If the voltage limit on the power supply is too high, the current rises quickly and temporarily overshoots the desired level of 200A. When the circuit is opened, the decay is not affected.

If the voltage limit on the power supply is too low, the current is not able to reach the desired level of 200A. At this point, the power supply switches to voltage-limited mode. When the circuit is opened, the decay starts at a lower current and hence ends earlier.



(a) Rise



(b) Fall

Figure 12: Graph of Current (A) against Time (μs)

When the current is flowing, the voltage supplied by the power supply slowly drifts upwards. This is because as circuit components heat up, they increase in resistance, thus more potential difference is needed to maintain the same current.

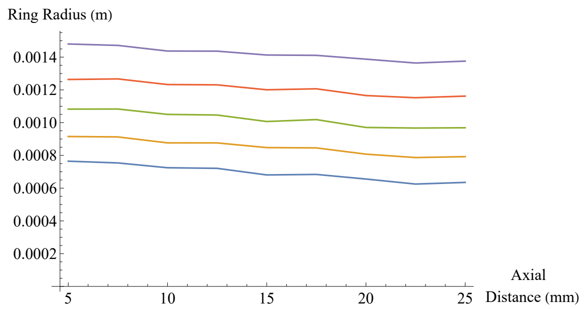
Therefore, in order to determine the optimal power supply voltage:
1. Set the voltage limit higher than required (e.g. 10V);
2. Let the system run for a few hours;
3. Record the maximum voltage of the power supply throughout one cycle;
4. Set the voltage limit slightly above that value.

2 Axicons

Finding the Imaging Plane

Axicon, +150mm collimating lens, 200 and -50 telescope, 2mm pinhole, 300mm and 400mm imaging telescope, variable telescope in between.

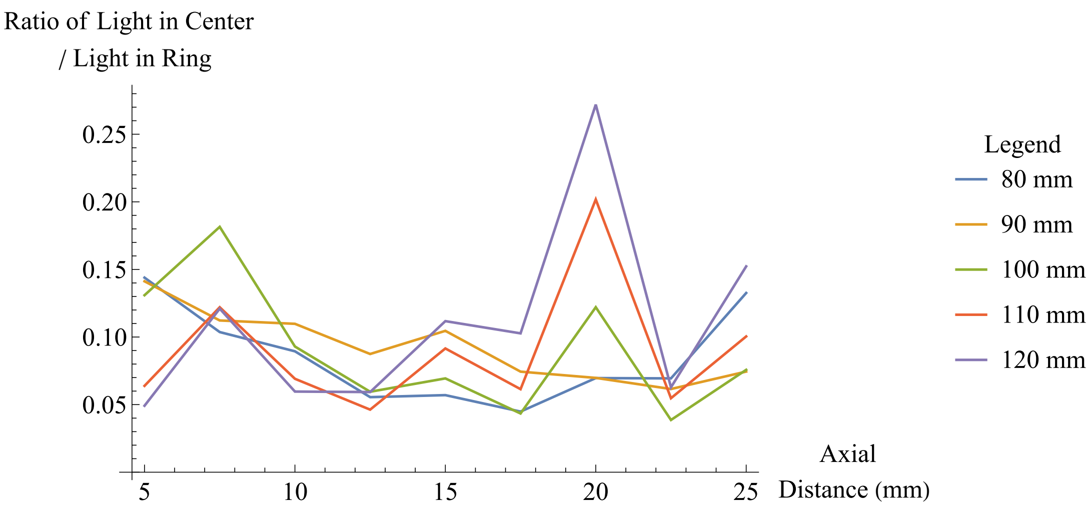
We observe that the ring radius and thickness decreases slightly - the ring goes in and out of focus slightly.



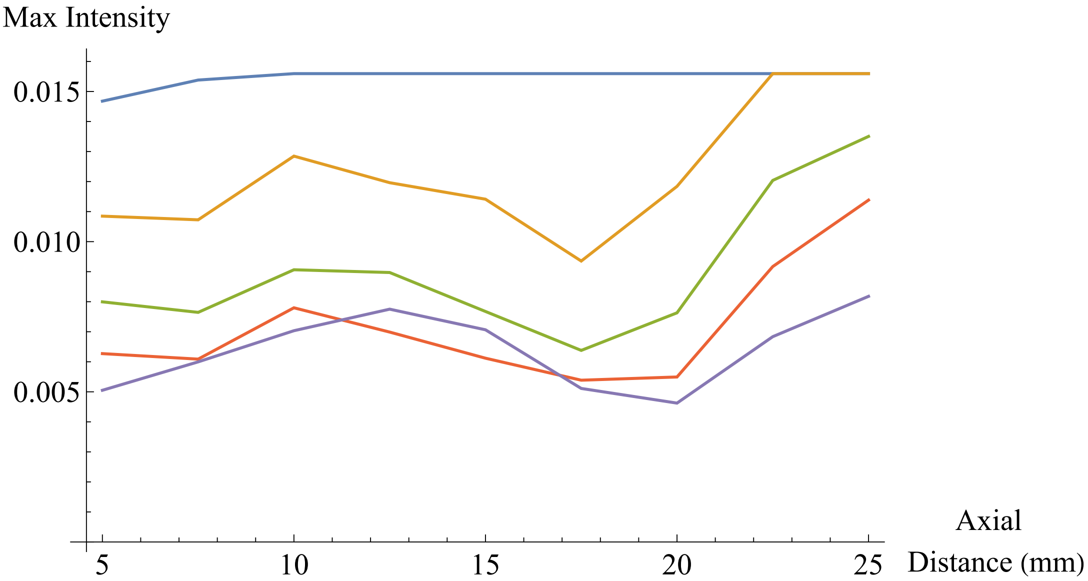
(a) Variation in Ring Radius (b) Variation in Ring Thickness

Figure 13: Variation of Ring radius and thickness

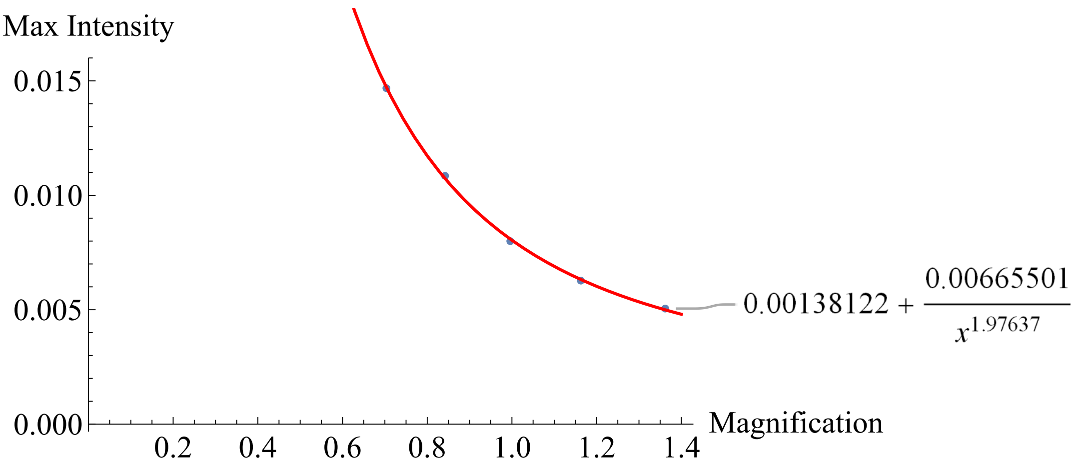
To find the imaging plane, we ask the computer to find the ratio of light in the center / light in the ring. We conclude that $x = 12.5\ mm$ is the center, which is also confirmed by our own judgement by eye. Although later on, I thought $x = 17.5\ mm$ is also the imaging plane (and indeed it seems to be another local minima).



Now we relate the maximum intensity to axial distance. Unfortunately, I let the intensity saturate, so the first dataset is useless. I also don't know why the red ($f_1 = 110\ mm$) and purple lines ($f_1 = 120\ mm$) swap order.



Taking data at $x = 5\ mm$, we see that it agrees well with the prediction of $\frac{1}{M'^2}$ scaling.



Here, the magnification refers to M', the magnification provided by the variable telescope. $M' = 1.0$ is given by an image where the Optotune lenses are disconnected and unpowered.

The overall magnification is MM', where $M = \frac{4}{3}$ is the magnification of the imaging telescope.

2.1 Experimental Set-up

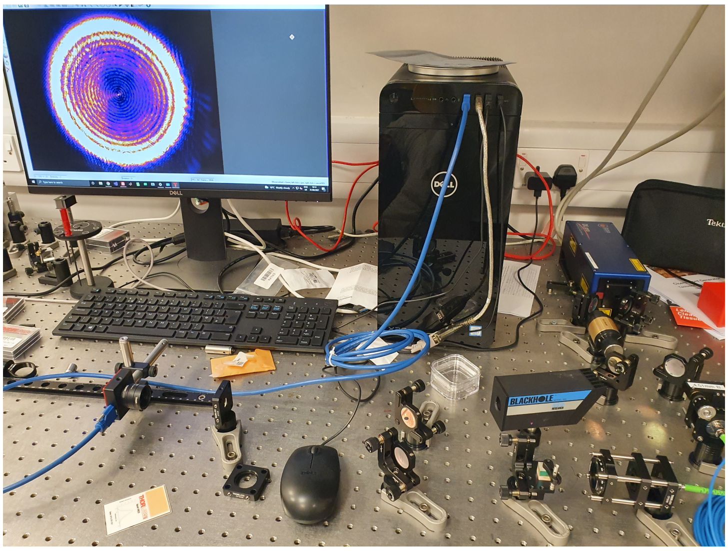


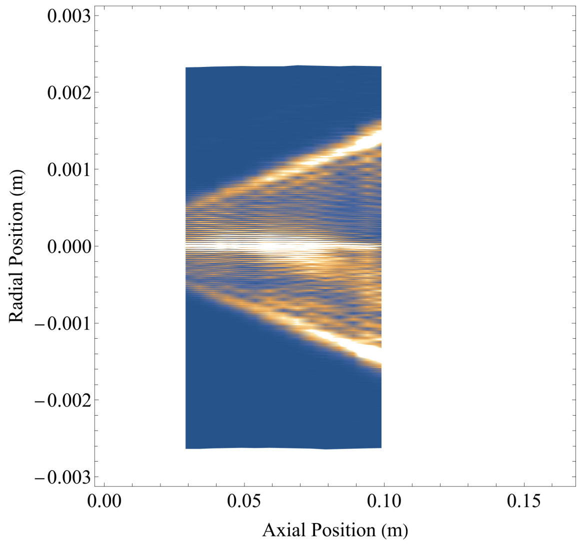
Figure 14: Experimental Set-up as of 31 Aug 2021

A 780 nm laser was coupled into a single mode, polarisation maintaining optical fibre. Upon exit, a collimating lens of $f = 6.24\ mm$ was used to create a beam of radius $R = 713\ \mu m$. The beam passes through a polariser and a beam splitter. Two mirrors are used to align the beam onto the center of a 2 Degree Axicon (AX122). A camera is mounted on a rail behind it to take images of the cross-sectional profile.

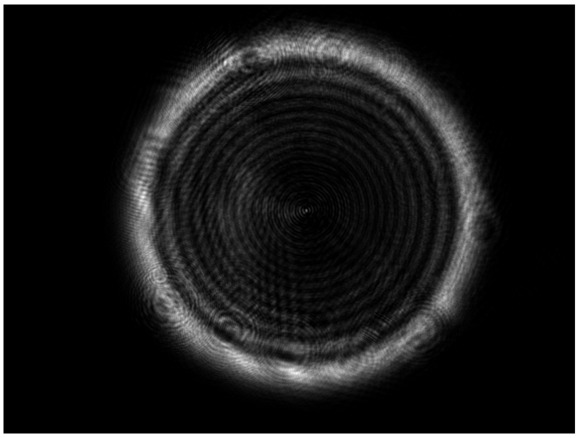
Figure 15: Experimental Set-up as of 1 Oct 2021

A fixed telescope is used to project the axicon image onto the shutter. A variable telescope consisting of two Optotune lenses are mounted behind the shutter (mounted right under the triangular pieces).

2.2 One Axicon with Beam Size $R = 713\ \mu m$



(a) Axial Cross Section

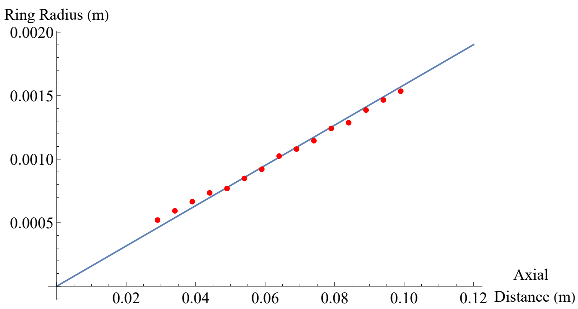


(b) Frontal Cross Section at $z = 0.10\ m$

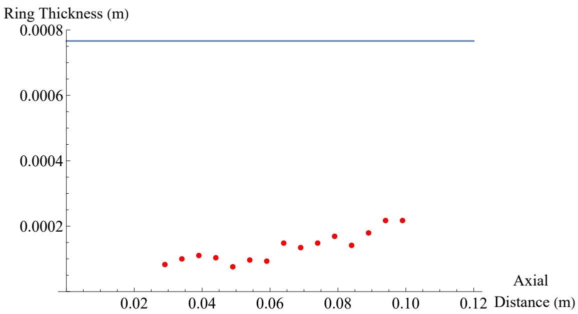
Figure 16: Cross Sections of Laser Intensity after Passing through Axicon

The bessel regime dominates the area of interest, hence this configuration is unsuitable.

The theoretical lines below are by Geometric Optics [9].



(a) Ring Radius



(b) Ring Thickness

Figure 17: Graph of Ring Thickness and Ring Radius (m) against Axial Distance (m)

We can see that the ring radius is well predicted by geometric optics. However the ring thickness is much less than predicted by geometric optics, and displays an increasing trend.

2.3 Effect of Shutter

The Depth-of-Field of the Bessel Regime is proportional to the beam radius. We used a shutter to adjust the beam radius:

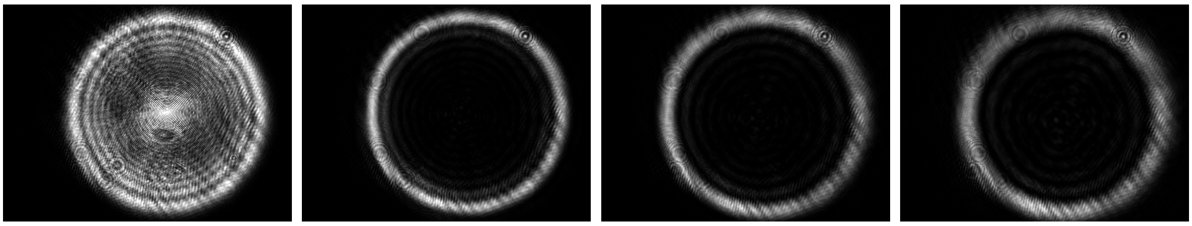


Figure 18: Frontal Cross Section as the Shutter is gradually closed

A program was made to add all the pixel values inside the ring, and on the ring. The bar graph below corresponds to picture above.

Bessel Region:

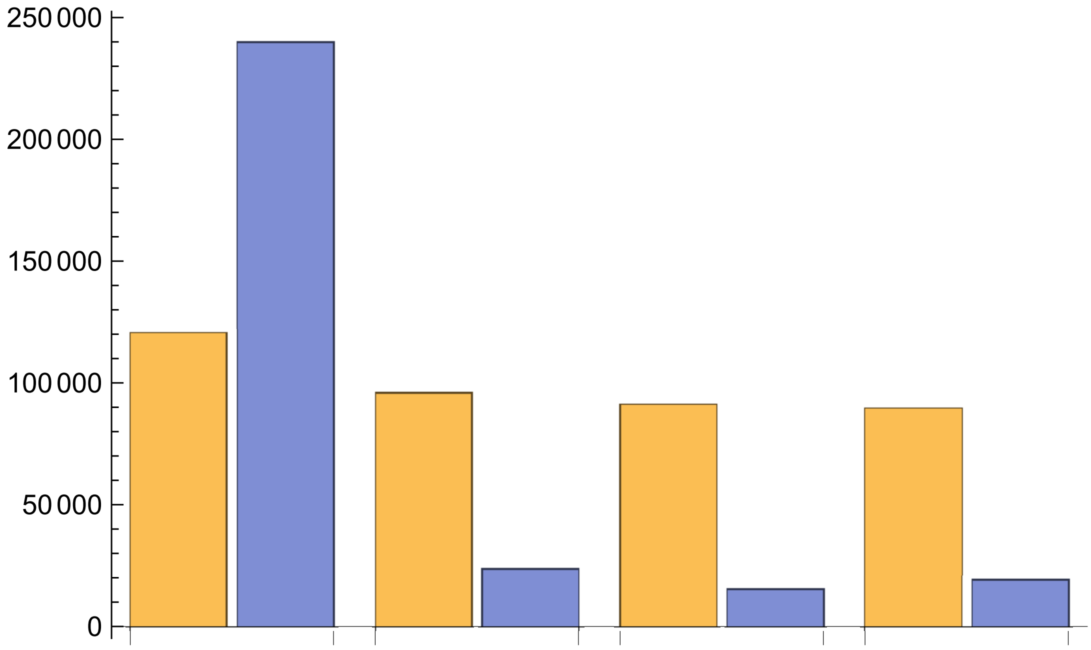


Figure 19: Bar Graph of Total Intensity in the ring (yellow) and the center (blue)

For the ring regime, we also tried: The laser was put through two lenses in a telescope configuration to double the beam radius. The shutter is then adjusted.

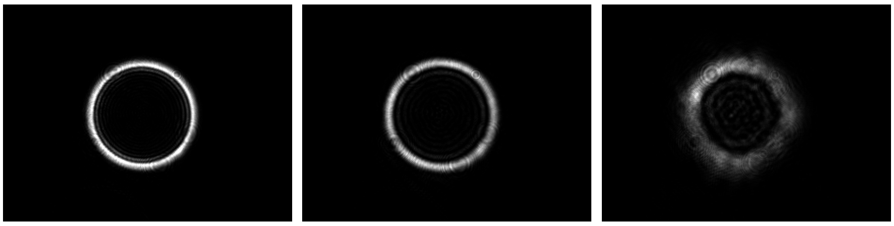


Figure 20: Frontal Cross Section as the Shutter is gradually closed

2.4 Effect of Beam Radius

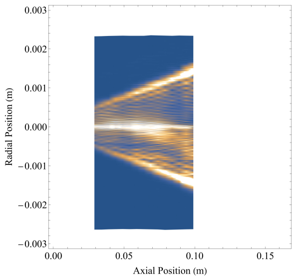
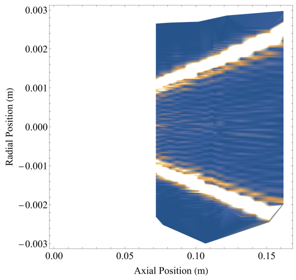
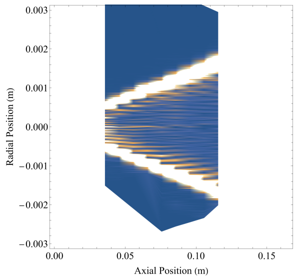
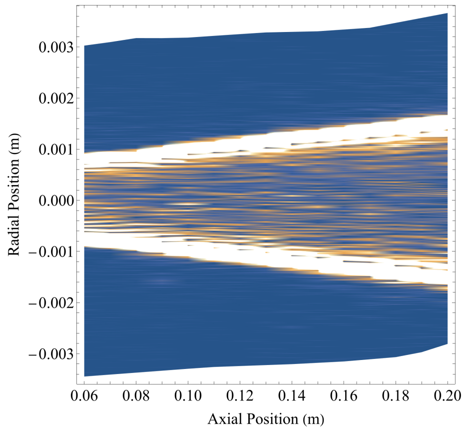
$R = 713\ \mu m$	$R = 581\ \mu m$	$R = 363\ \mu m$
		

Table 3: Beam Profile

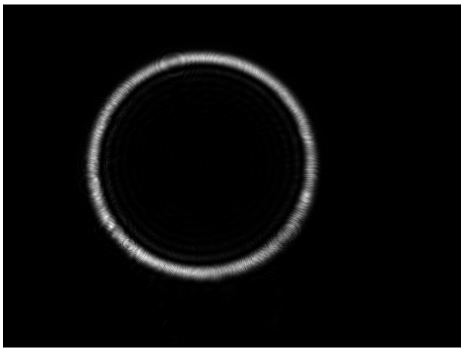
Note: the different sampling range for each subsequent experiment is due to the fact that data was only collected once the Bessel regime was observed to have ended.

2.5 Lens on Camera

This gives us an idea of converting data between using the camera and not.

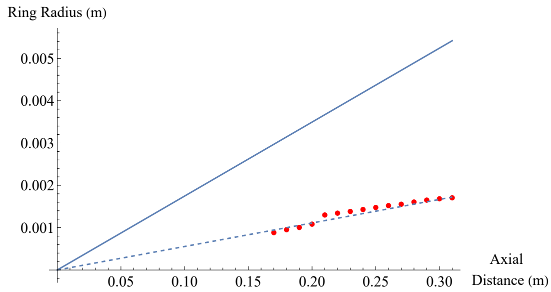


(a) Axial Cross Section

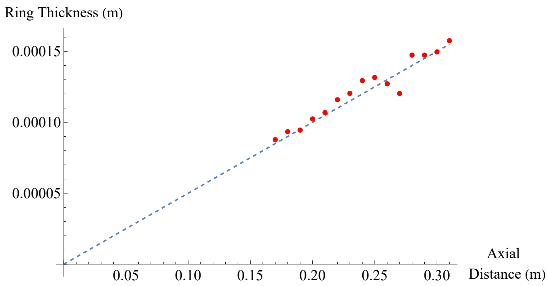


(b) Frontal Cross Section

Figure 21: Cross Sections of Laser Intensity after Passing through Axicon



(a) Ring Radius



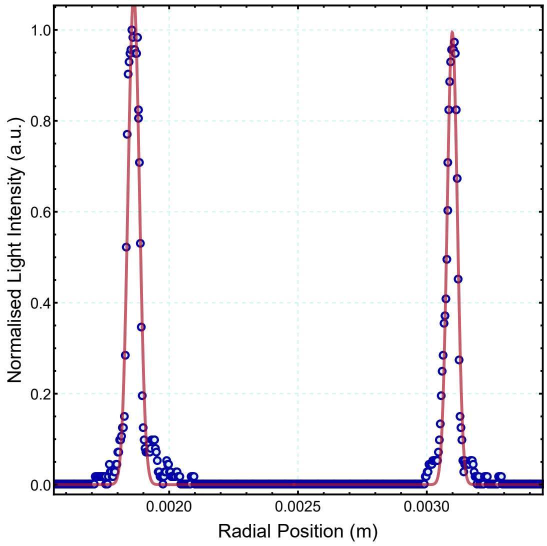
(b) Ring Thickness

Figure 22: Graph of Ring Thickness and Ring Radius (m) against Axial Distance (m)

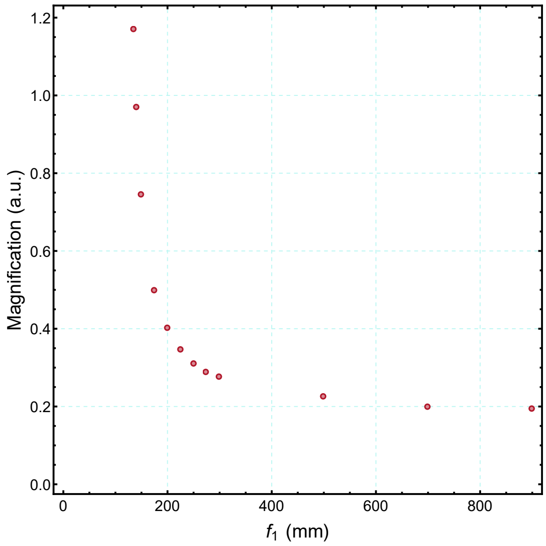
Solid line: from section 1. Dashed line: fitted linear function.

2.6 Characterising Steepness

For this section, a telescope with variable focal length lenses (Optotune) are placed behind the axicon. The focal length of the first lens f_1 is adjusted, and the second focal length is chosen to produce a focused image. The distance between the two lenses was 1m.



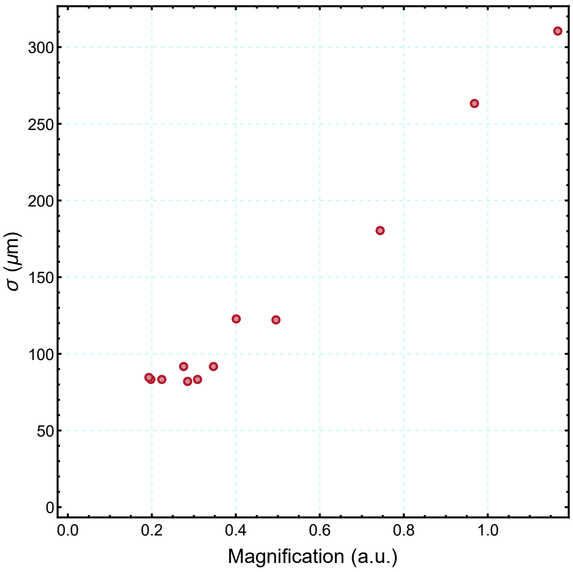
(a) Intensity Cross-section and Fitted Gaussian Profile at $f_1 = 225mm$



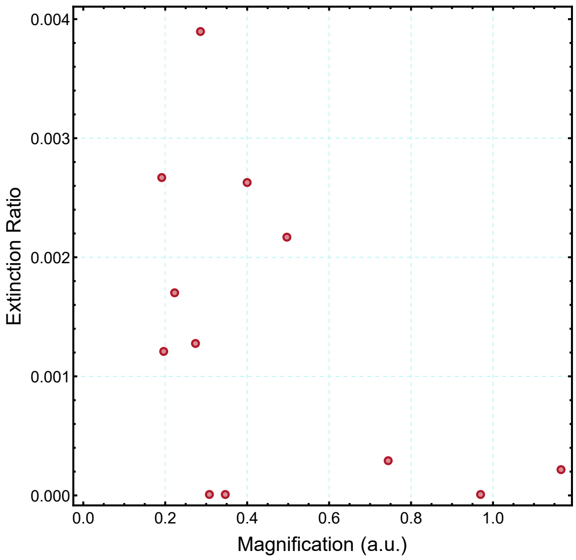
(b) Magnification against f_1

Figure 23: Characterising Telescope with Optotune Lenses

The thickness σ comes from the fitted variance for the gaussian profiles. The extinction ratio comes from pixel counting and comparing the total intensity in the dark vs bright parts of the ring. The extinction ratio is limited by the sensitivity of the camera, but overall tells us that there is little stray light in the center of the ring.



(a) Thickness

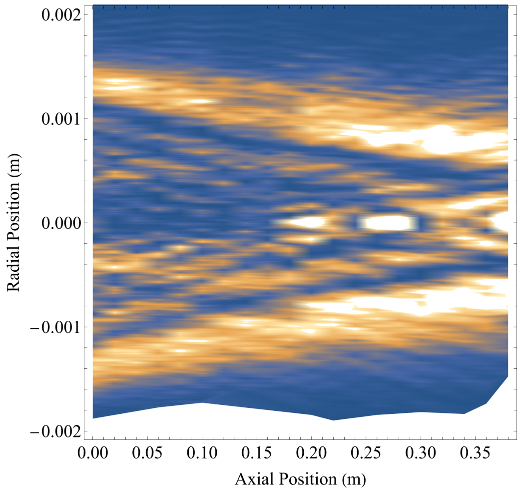


(b) Extinction Ratio

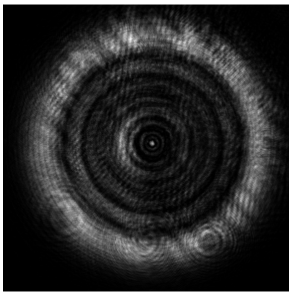
Figure 24: Features of the Ring

2.7 2 Axicon

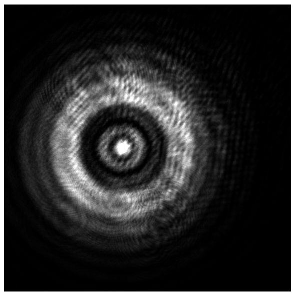
We tried to put 2 Axicons facing each other. While it can produce a small ring, the Bessel regime appeared, which is not desired.



(a) Axial Cross Section

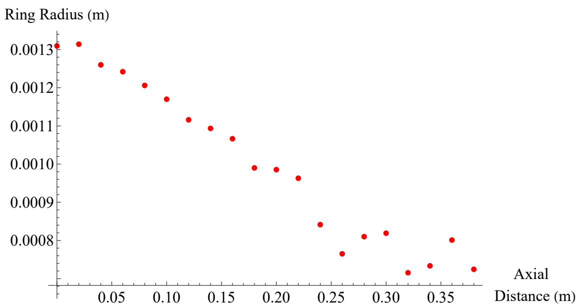


(b) Start

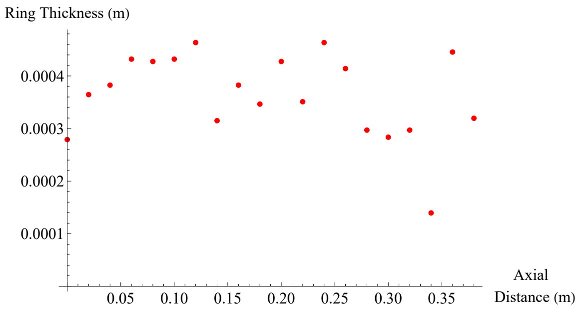


(c) End

Figure 25: Cross Sections of Laser Intensity after Passing through Axicon



(a) Ring Radius



(b) Ring Thickness

Figure 26: Graph of Ring Thickness and Ring Radius (m) against Axial Distance (m)

References

[1] MOSFET Data Sheet

[2] TVS Diode Data Sheet

[3] Thermistor Data Sheet

[4] Rectifier Data Sheet

[5] Varistor (77V) Data Sheet

[6] Varistor (135V) Data Sheet

[7] Optocoupler H11L1M Data Sheet

[8] Power Supply SM18-220 Data Sheet

[9] Axicon Geometric Optics Formula

Components and Specifications

1. MOSFET: (Farnell)
   Manufacturer Part No: VS-FC420SA15
   Order Code: 3513308
   Data Sheet [1]

2. TVS Diode: (Farnell)
   Manufacturer Part No: 5.0SMDJ24A-Q
   Order Code: 2908766
   Data Sheet [2]

3. Thermistor (10 $k\Omega$ $\pm 5\%$): (RS-Online)
   Manufacturer Part No: B57861S0103J040
   Stock Number 528-8536
   R/T Characteristic 8016
   Data Sheet [3]

4. Rectifier: (Farnell)
   Manufacturer Part No: VS-UFB280FA40
   Order Code: 2690159
   Data Sheet [4]

5. Varistor (77 V): (Farnell)
   Manufacturer Part No: 390KD07-TR
   Order Code: 3052480
   AC Breakdown Voltage: 25 V
   DC Breakdown Voltage: 31 V
   AC Breakdown Voltage: 77 V
   Data Sheet [5]

6. Varistor (135 V): (Farnell)
   Manufacturer Part No: 820KD07-TR
   Order Code: 3052493
   AC Breakdown Voltage: 50 V
   DC Breakdown Voltage: 65 V
   AC Breakdown Voltage: 135 V
   Data Sheet [6]

7. Optocoupler H11L1M: (Farnell)
   Manufacturer Part No: H11L1M
   Order Code: 1021127
   Data Sheet [7]

8. Power Supply SM18-220: (Delta)
   SM3300 Series
   Data Sheet [8]