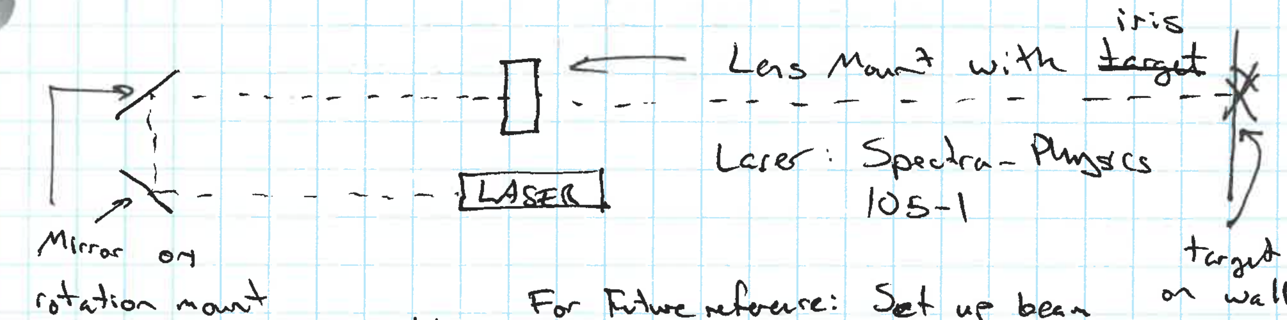
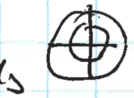
Gaussian Laser Beams Lab

Bjorn Sumner — 16 Jan
Ben Crane



Note: For Future reference: Set up beam ~~Set~~ path away from ~~manual~~ work area: Prevent blocking beam with hands

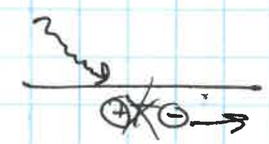


Q3b

When the beam propogation is unchanged after inserting a lens into the above setup, the beam passes through the center of the lens.

Q4a

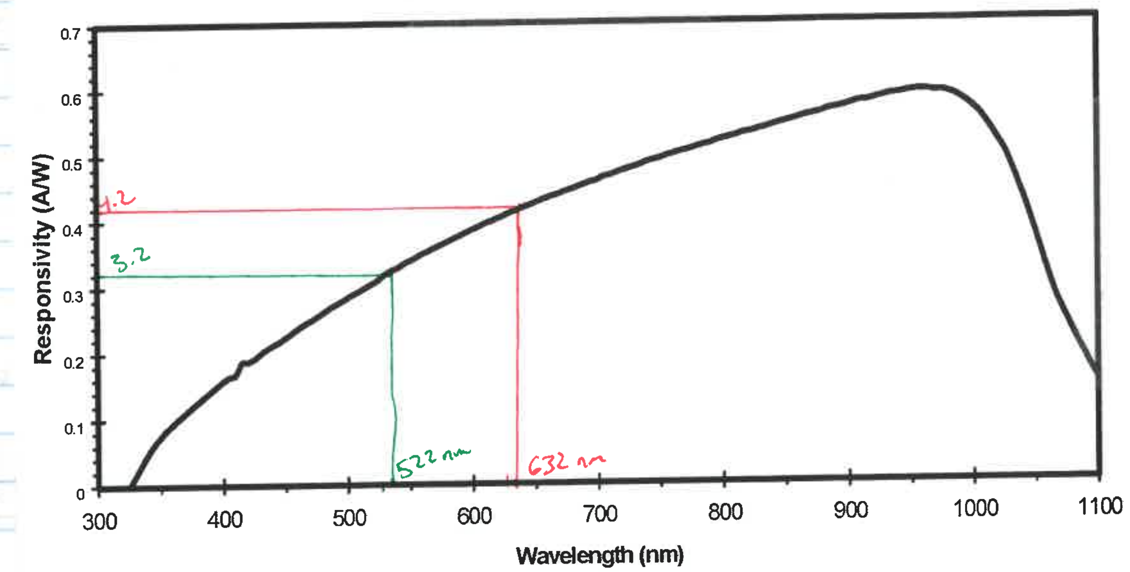
A photodetector works by taking advantage of the photoelectric effect. As ~~an~~ a photon interacts with the metal, an electron is ejected with kinetic energy given by



$KE = \phi - \hbar f$ where ϕ is work function of metal
f is frequency of incoming light

In the photo diode, those ~~ejected~~ ~~photo~~ electrons set up a potential across a pn junction. This voltage is measured by the PDA36A

Figure 1 – PDA36A Spectral Responsivity



Q4b Conversion of Watts of light to Amps of Current

(a) To convert, use figure 1: PDA36A Spectral Resistivity

Use wavelength of light λ to find Responsivity $\mathcal{R}$ as given by plot of Spectral Resistivity

For HeNe laser:

$$\boxed{\lambda = 632.8\text{ nm} \qquad \mathcal{R} \simeq \cancel{0.418}\ 0.42\ \text{A/W}}$$

Nd:YAG laser

$$\boxed{\lambda = 532\text{ nm} \qquad \mathcal{R} = 0.32\ \text{A/W}}$$

(i) $$\frac{\text{electrons}}{\text{photon}} = \frac{\text{electrons/sec}}{\text{photons/sec}} = \frac{I/e}{P/hf} = \frac{I \cdot \frac{hc}{\lambda}}{Pe} = \frac{I}{P} \cdot \frac{hc}{\lambda e}$$

$$\Rightarrow \boxed{\frac{\text{electrons}}{\text{photon}} = \mathcal{R} \cdot \frac{hc}{\lambda e}} \simeq \frac{\mathcal{R}}{\lambda} \cdot \left(1240\ \frac{\text{W}\cdot\text{nm}}{\text{A}}\right)$$

(ii) $$\boxed{\left(\frac{e}{\gamma}\right)_{HeNe} = \frac{0.42 \frac{A}{\cancel{W}}}{632.8\ \cancel{nm}} \cdot 1240\ \frac{\cancel{W}\cdot\cancel{nm}}{\cancel{A}} \simeq 0.82}$$ HeNe

$$\boxed{\left(\frac{e}{\gamma}\right)_{Nd:YAG} = \frac{0.32\ A/W}{532\ nm}\left(1240\ \frac{W\cdot nm}{A}\right) \simeq 0.75}$$ Nd:YAG

Q4b

(iii) These numbers are less than 1. This number tells us that the photodiode is not perfectly efficient. While the photoelectric effect guarantees one electron will be released for every photon above a minimum energy, ~~This~~ This electron may be reabsorbed within the depletion region of the photodiode and may not contribute to the induced voltage measured by the photodetector.

Q5a

(a) Defn of Power: $P = IV$
Joules Law : $V = IR \Rightarrow I = \frac{V}{R}$

$$\Rightarrow P = \frac{V^2}{R}$$

$$\boxed{\text{Gain} = 10 \cdot \log\left(\frac{P_{out}}{P_{in}}\right) = 20 \log\left(\frac{V_{out}}{V_{in}}\right)} = 10 \cdot \log\left(\frac{V_{out}^2/\cancel{R}}{V_{in}^2/\cancel{R}}\right) = 10 \cdot \log\left[\left(\frac{V_{out}}{V_{in}}\right)^2\right]$$

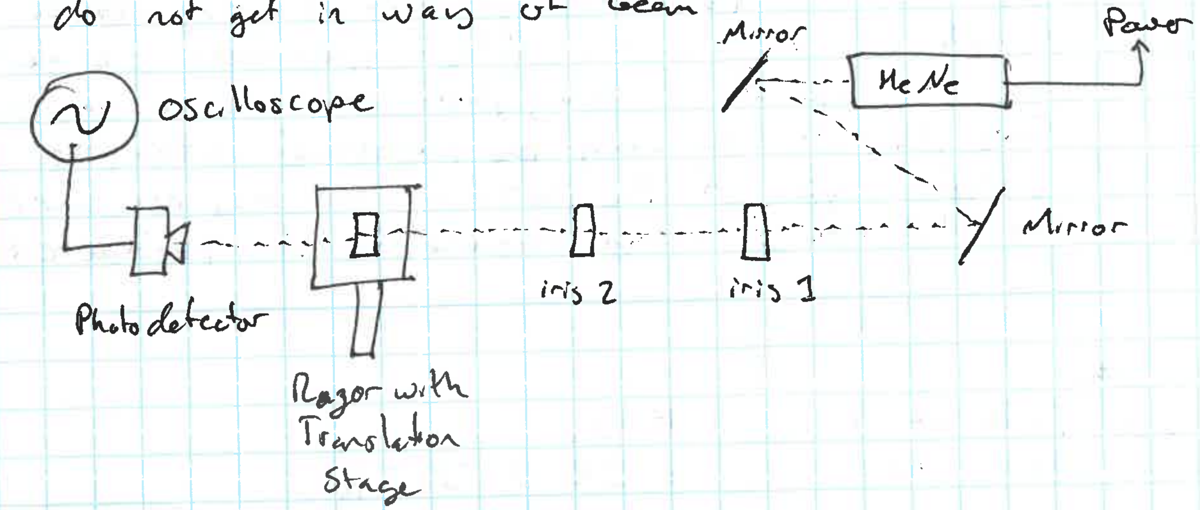
Since we are measuring across same resistor.

Calibrating Offset of Oscilloscope:

- Check offset of Oscilloscope:
- Make sure proper probe settings / impedance matching

17 Jan

Readjusted Table for simplicity of use. Now, hands do not get in way of beam



Q5

b) Photodetector Calibration

i, ii) See table below
~~Some~~ The measured offset for each gain setting is ~~within the~~ below the specified maximum, although the measured value tends to be close to th maximum.

Offset Measurement

	Gain Setting	Measured Offset (mV)	Spec Offset (mV)	% Diff Offset	Day to Day % Diff
16 Jan	0	8.05	5	61.0%	
	10	11.5	6	91.7%	
	20	11.75	6	95.8%	
	30	12.3	8	53.8%	
	40	13.9	10	39.0%	
	50	18.4	15	22.7%	
	60	30.5	20	52.5%	
	70	68.5	40	71.3%	
17 Jan	0	8.35	5	67.0%	3.7%
	10	11.9	6	98.3%	3.4%
	20	12.1	6	101.7%	2.9%
	30	12.5	8	56.3%	1.6%
	40	14.1	10	41.0%	1.4%
	50	18.7	15	24.7%	1.6%
	60	31	20	55.0%	1.6%
	70	70	40	75.0%	2.2%

Q5

b) iii) We ensured the photodetector was covered by an electrical tape-wrapped ~~tap~~ razor blade. At higher gain settings, we noticed our measurements tended to vary significantly, so we turned off the lights and shut the door. We then remeasured the offsets for all gain settings. We noticed a drop in voltage readings across all settings, as well as improved stability in each reading.

19 Jan

- After remeasuring offsets on the oscilloscope to ~~con~~ test stability of photodetector, we took two runs of data

- On oscilloscope: Used position toggle to bring "down" data, and used cursors to ~~bring~~ measure the midpoint of the data.

Q5

c) i) It is not possible to measure V/A gain for each setting. We are trying to characterize the gain of the transimpedance amplifier within the PDA36A, and to get an absolute measure of this quantity would require knowing the current going into the amplifier (or at least the power entering the photodetector). Therefore, we can only measure the relative gain as we change settings.

ii) See runs 1 + 2 for data collected. We set up the experiment by first adjusting the position of the razor blade so the intensity of the laser light on the diode does not exceed the maximum voltage output of the PDA36A (10 V) at the highest gain setting while still being detectable at the lowest gain setting.
We identify the 2 largest sources of systematic error as:
1) Possible time variation in the power output of the laser.
   - We address this by ~~taking~~ measurements by adjusting the gain non-sequentially. This means a change in the laser power will manifest itself as greater uncertainty, rather than looking in a general trend.

<continued>

Q5

c) ii) cont.

2) When toggling the gain dial on the PDA 36A, it is possible that we changed the angle of the detector relative to the incoming light.

- To address this, we ensured the post with the photodetector was firmly in place, and rotated the gain dial in the direction of tightening the PDA 36A on the post to minimize any travel.

iii) See data for runs 1 & 2 below

Spec Sheet Gain (Hi-Z) (V	Gain rel 0 (dB)	Multimeter Run 1 (V)	Data-offset	Gain rel 0	% Error rel 0
1.51E+03	0	0.011	0.00236	0	
4.75E+03	10.0	0.02	0.0081	10.7	7.61%
1.50E+04	19.9	0.039	0.0268	21.1	5.83%
4.75E+04	30.0	0.098	0.0852	31.2	3.99%
1.51E+05	40.0	0.284	0.2695	41.2	2.88%
4.75E+05	50.0	0.88	0.8606	51.2	2.57%
1.50E+06	59.9	2.66	2.6267	60.9	1.65%
4.75E+06	70.0	8.52	8.4436	71.1	1.60%

[When using the multimeter on Run 1 we noticed the voltage reading decreasing several 100 mV over the course of 30 sec.]

Oscilloscope Run 2 (V)	Data-offset (V	Vgain rel 0.	% Error Gain
0.0115	0.00286	0	
0.0214	0.0095	10.4	4.75%
0.0425	0.0303	20.5	2.80%
0.109	0.0962	30.5	1.94%
0.324	0.3095	40.7	1.71%
0.968	0.9486	50.4	0.92%
2.98	2.9467	60.3	0.53%
9.47	9.3936	70.3	0.54%

~~Tab~~ iii) ctd: I believe our results provide a <u>more</u> accurate estimate of the photodetector gain than the data sheet, as we are working with the detector as-is. The specification sheet for the detector was generated using multiple different detectors, whereas we are obtaining results from a specific composite device at this time. However, it is encouraging to note that the data we obtained mostly conforms with the margins of error given by the specification sheet (2%)

Q5

iv) To measure the output of our laser, we must try to collect as much of the light from the laser as possible. To this end, we moved the photodetector directly in front of the laser. This required a ~~setting~~ gain setting of 0dB, as any higher setting resulted in a voltage exceeding the specified maximum output.

Output Voltage:	Spectral Resistivity $\mathcal{R}(\lambda)$	Transimpedance Gain (0dB) (Hi-Z)
3.68 V	0.42 A/W	1.51×10^3 V/A

$R_{Load} = 1\,M\Omega$ (Oscilloscope impedance input)

Using Equation E.g.3 in the spec sheet, we get

$$P_{meas} = \frac{V_{out} - \text{Offset (0dB)}}{\mathcal{R}(\lambda) \cdot \text{Gain}_{X\text{imped}} \cdot \text{Scale}} = \frac{(3.68\,V) - (0.00864\,V)}{(0.42\,A/W)(1.51 \times 10^3\,V/A) \cdot (1)}$$

$$\boxed{P_{meas} = 5.67\ mW}$$

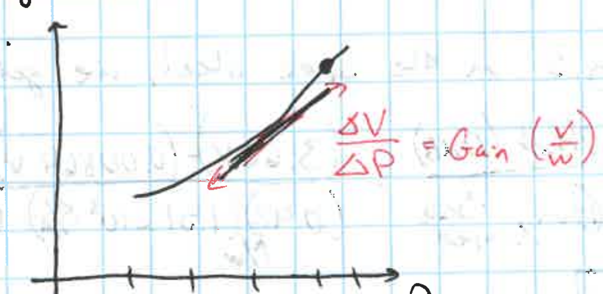
We measure the output voltage from the photodetector and divide this by the product given in the output of eq. E.g.3 in the specification sheet of the PDA36A manual. Since we are using a high impedance oscilloscope ($1M\Omega$) with a short coax cable, the scale factor is ≈ 1, ~~and use the 0dB specs~~ and using 0dB setting we use eliminates the need for converting gain.

We were unable to find a specification sheet (online or in the lab) for the Spectra-Physics 105-1 Laser, but the 10 mW safety placard suggests that it ~~is~~ operates below 10mW power. This certainly agrees with our result, but lacks confidence since this is only an upper bound.

We also note that we observed significant reflection of the laser from the (glass?) protector covering the actual photodiode. This may be a significant source of loss in measured power.

Q5

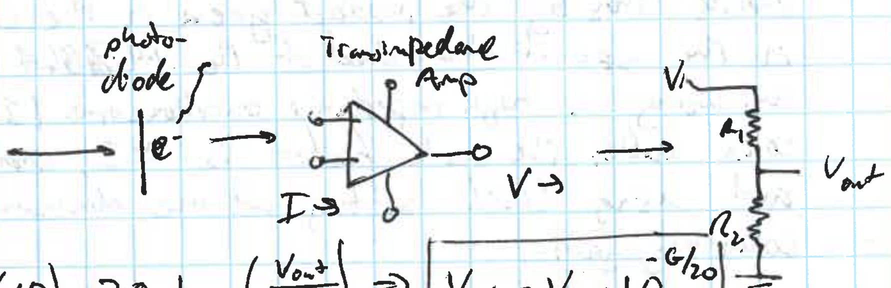
c) v) To measure the absolute gain, we would require a known source of power that we could vary. For each gain setting, we would vary the power of the laser across this range and measure the output voltage from the detector. By then plotting V_{out} against P_{in}, we could obtain the gain from the slope of the plot in units of V/W. This is different from the V/A given in the specification sheet, as we are unable to ~~determine the~~ measure the current coming from the diode. However, if we trust the values given by the manual for spectral responsivity, we could deduce the Transimpedance gain by dividing our measured gain $\left(\frac{V}{W}\right)$ by $\mathcal{R}(\lambda)$ to get this value:



@ 0dB

example of how to obtain absolute gain.

Q6



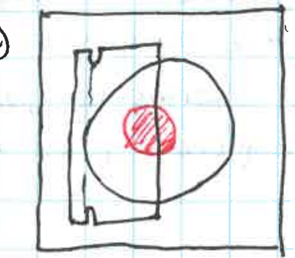
$$\text{Gain}^{G}\,(dB) = 20 \log_{10}\left(\frac{V_{out}}{V_{in}}\right) \Rightarrow \boxed{V_{out} = V_{in} \cdot 10^{-G/20}}$$

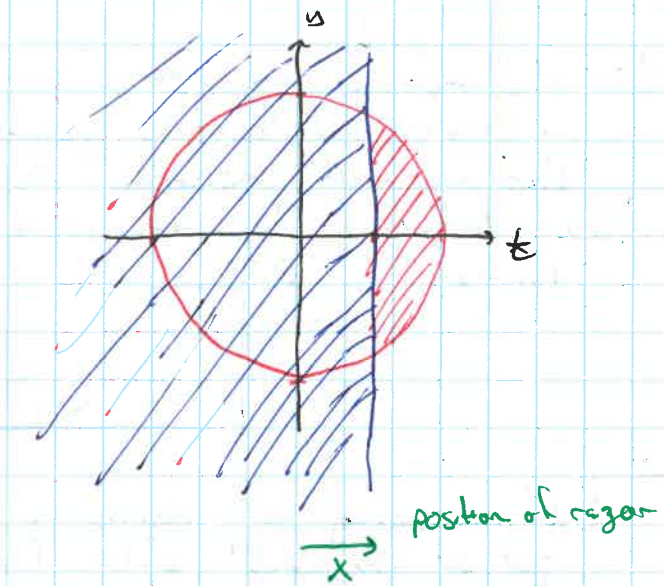
~~V_{out} =~~

$$\boxed{\begin{aligned} V_{out} &= P_{in} \cdot \mathcal{R}(\lambda) \cdot (\text{Transimpedance}) \cdot \left(10^{-\text{Gain}/20}\right) \cdot (\text{Scale Factor}) \\ P_{in} &= \frac{V_{out} \times 10^{\text{Gain}/20}}{\mathcal{R}(\lambda) \times (\text{Transimpedance})(\text{Scale Factor})} \end{aligned}}$$

Q7

a)





$$I(t,y) = I_{max} \exp\left(-2(t^2+y^2)/\omega^2\right)$$

$$P(x) = \int I \, dA$$

b) $$P(x) = \iint I(t,y)\, dA$$

$$= I_{max} \int_{-\infty}^{\infty} \int_{x}^{\infty} \exp(-2t^2/\omega^2) \exp(-2y^2/\omega^2)\, dt\, dy$$

$$= I_{max} \underbrace{\int_{-\infty}^{\infty} \exp(-2y^2/\omega^2)\, dy}_{\sqrt{\frac{\pi}{2/\omega^2}} = \omega\sqrt{\frac{\pi}{2}}} \underbrace{\int_{x}^{\infty} \exp(-2t^2/\omega^2)\, dt}$$

$u^2 = 2t^2/\omega^2$ $\quad u = \frac{\sqrt{2}}{\omega} t$

$du = \frac{\sqrt{2}}{\omega} dt$ $\quad dt = \frac{\omega}{\sqrt{2}} du$

$$= I_{max}\, \omega \sqrt{\frac{\pi}{2}} \int_{\frac{\sqrt{2}}{w}x}^{\infty} \exp(-u^2) \frac{\omega}{\sqrt{2}}\, du$$

$$= \frac{I_{max}\, w^2 \sqrt{\pi}}{2} \underbrace{\int_{\frac{\sqrt{2}}{w}x}^{\infty} \exp(-u^2)\, du}$$

$\operatorname{erfc}(x) = \frac{2}{\sqrt{\pi}} \int_x^{\infty} e^{-t^2} dt$

$\Rightarrow \int_x^{\infty} e^{-t^2} dt = \frac{\sqrt{\pi}}{2} \operatorname{erfc}(x)$

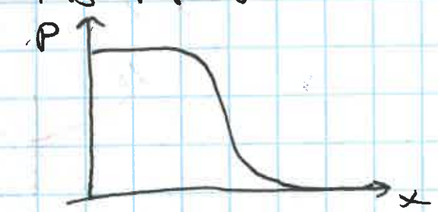
$$\boxed{P(x) = \frac{\pi w^2 I_{max}}{4} \operatorname{erfc}\left(\frac{\sqrt{2}\,x}{w}\right)}$$ Complementary Error Function

$$\boxed{P(x) = \frac{\pi w^2 I_{max}}{4} \left(1 - \operatorname{erf}\left(\frac{\sqrt{2}\,x}{w}\right)\right)}$$ Error Function

b) c+d Assumptions are inherent in the statement of the intensity: Intensity is gaussian + time independent.

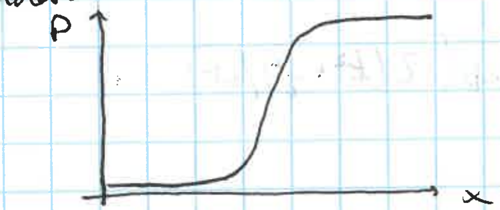
razor covers light with increasing x

Also assumed increasing x means decreasing power on detector. This results in a Complementary Error Function:



razor uncovers light with increasing x

If increasing x results in increased power, we will get a "standard" Error Function shape:



This is not a problem, as one process is just the reverse of the other, so we expect an invariance ~~~~ in the direction of coverage.

8 a) Though we derived the expected ~~intensity~~ power from a given intensity, this was a derivation of power without taking into account experimental/measurement factors.

Fit Function:

$$\boxed{Power(x) = \frac{\pi w^2 I_{max}}{4} Erf\left(\frac{\sqrt{2}}{w}(x-c)\right) + d}$$

b) Nonlinear, since our fitting function is a nonlinear function of the independent variable (position of razor blade, x)

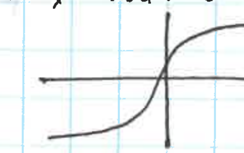
c) w and I_{max} come from our mathematical derivation of power. They characterize the shape of our fit.

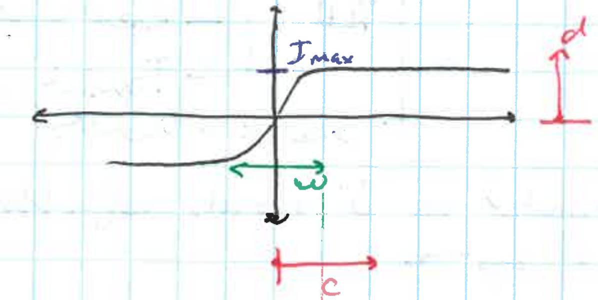
c & d come from measurement realities. c shifts the fit left or right, since it is not practical to set the razor blade to $x=0$ when it cuts the beam in half.

<continued>

8 c ctd

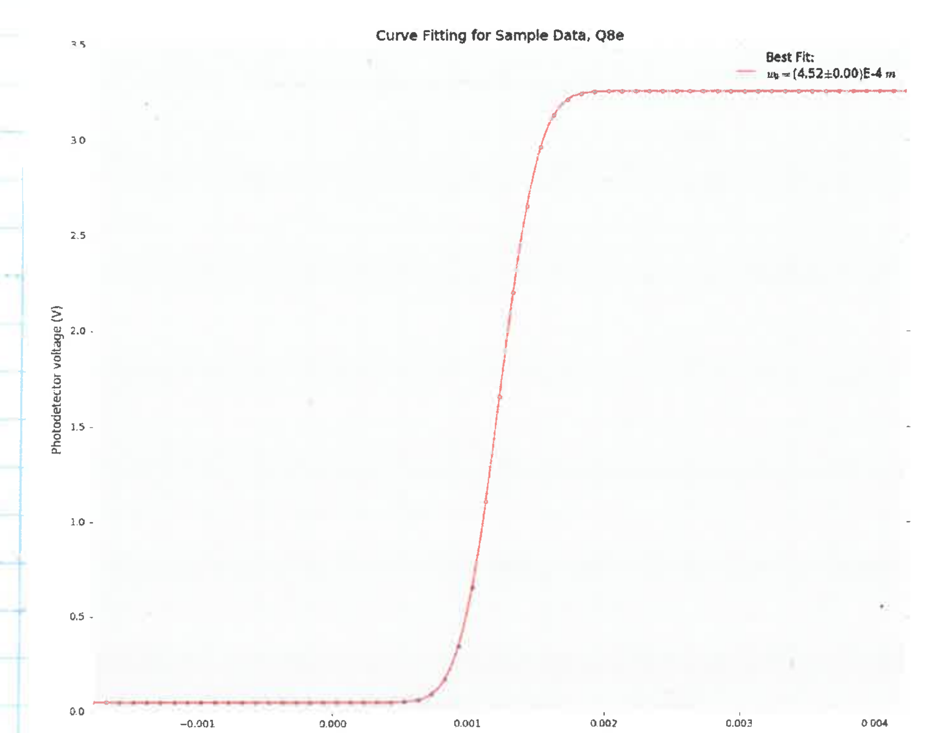
d adjusts the fit vertically, and takes into account that we will not measure a power less than zero, ~~Furthermore,~~ as would be expected from $Erf(x)$





d) Instead of the chosen fit (as guided by theory), I could have chosen $P = a\,Erf(b(x-c)) + d$ and we would then compare to Theory to determine beam width can be found from $\omega = \frac{\sqrt{2}}{b}$

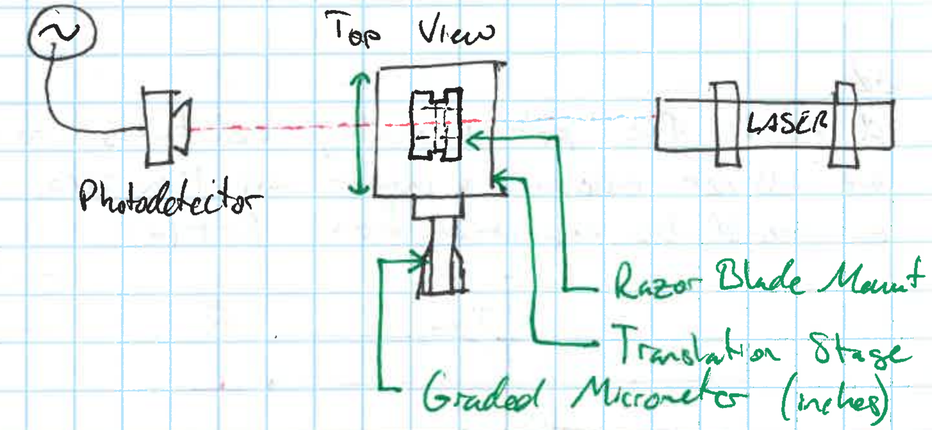
e) This data came in the form of $V(x)$, rather than $P(x)$. As such, we can characterize the width of the beam, but the I_{max} will be unreliable unless we know the behavior of the detector used to obtain this data

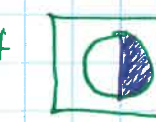


$W_0 = 4.52 \pm 0.00\,E{-4}\ m$

$u_{1c} = 1.72\times10^{-19}$

Q9 a)





All systems mounted on 3" Thorlabs adjustable posts to ensure proper height of systems.

b) We can tell if the experiment is working by traversing the translation stage across its range & watching the output voltage on the oscilloscope. We are probably in good shape if we read a maximum voltage ($\approx 3V$) when the razor is not blocking any light, sharply decreases as it enters the beam, and then approaches the offset voltage when the razor is completely blocking the light.

c) We are going to use an oscilloscope, since we can explore how the measured voltage changes at different time scales (and voltage scales) This will lead to greater confidence in our data.

d) We have to convert measured voltage to power. This has been done in question 6, and this result is incorporated in the code used to obtain the below plots. Additionally, the micrometer is graded in inches, so we must convert from inches to meters. Also done in code

See next page for data

Q10 a) Random Uncertainty Sources ~~include~~ of photodetector voltage include the noise mentioned in the specification sheet (530 μV @ 0 dB) and the noise ~~~~ created by random fluctuations of light incident on the photodetector generating oscillations in observed voltage.

b) We can estimate the uncertainty by measuring the $\Delta V = V_{high} - V_{low}$ when the detector is exposed to "constant" light.

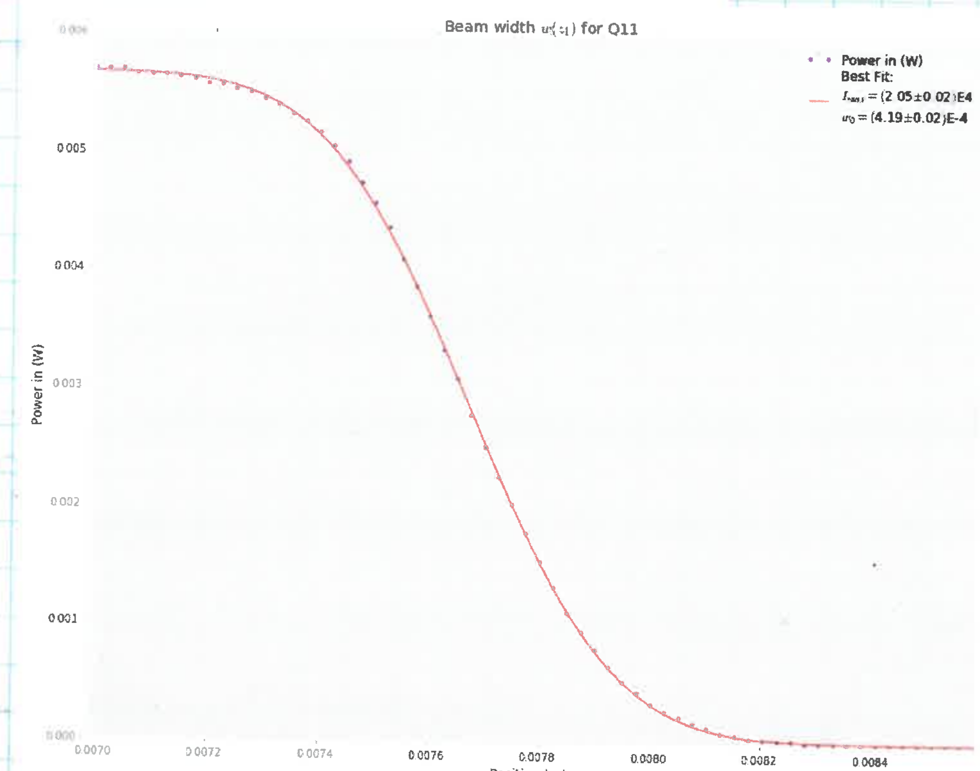
Q10 c) The ~~lar~~ largest sources of uncertainty ~~are~~ is random uncertainty in reading voltages. The spread in values is larger than that for any other measured variable. ~~When compared with the amplifier / detector noise, and~~

Q11

Razor Position (in)	Razor Position (m)	Vout (V)	Vout – offset	Power in (W)
0.275	0.00699	3.62	3.612	0.00570
0.276	0.00701	3.62	3.612	0.00570
0.277	0.00704	3.62	3.612	0.00570
0.278	0.00706	3.6	3.592	0.00568
0.279	0.00709	3.59	3.582	0.00565
0.28	0.00711	3.59	3.582	0.00565
0.281	0.00714	3.58	3.572	0.00563
0.282	0.00716	3.57	3.562	0.00562
0.283	0.00719	3.55	3.542	0.00558
0.284	0.00721	3.54	3.532	0.00557
0.285	0.00724	3.52	3.512	0.00554
0.286	0.00726	3.5	3.492	0.00551
0.287	0.00729	3.47	3.462	0.00546
0.288	0.00732	3.44	3.432	0.00541
0.289	0.00734	3.39	3.382	0.00533
0.29	0.00737	3.35	3.342	0.00527
0.291	0.00739	3.29	3.282	0.00518
0.292	0.00742	3.22	3.212	0.00506
0.293	0.00744	3.13	3.122	0.00492
0.294	0.00747	3.02	3.012	0.00475
0.295	0.00749	2.91	2.902	0.00458
0.296	0.00752	2.78	2.772	0.00437
0.297	0.00754	2.61	2.602	0.00410
0.298	0.00757	2.46	2.452	0.00387
0.299	0.00759	2.3	2.292	0.00361
0.3	0.00762	2.12	2.112	0.00333
0.301	0.00765	1.97	1.962	0.00309
0.302	0.00767	1.77	1.762	0.00278
0.303	0.00770	1.6	1.592	0.00251
0.304	0.00772	1.44	1.432	0.00226
0.305	0.00775	1.29	1.282	0.00202
0.306	0.00777	1.14	1.132	0.00178
0.307	0.00780	0.984	0.976	0.00154
0.308	0.00782	0.848	0.84	0.00132
0.309	0.00785	0.712	0.704	0.00111
0.31	0.00787	0.608	0.6	0.00095
0.311	0.00790	0.512	0.504	0.00079
0.312	0.00792	0.424	0.416	0.00066
0.313	0.00795	0.344	0.336	0.00053
0.314	0.00798	0.288	0.28	0.00044
0.315	0.00800	0.224	0.216	0.00034
0.316	0.00803	0.184	0.176	0.00028
0.317	0.00805	0.152	0.144	0.00023
0.318	0.00808	0.12	0.112	0.00018
0.319	0.00810	0.096	0.088	0.00014
0.32	0.00813	0.072	0.064	0.00010
0.321	0.00815	0.056	0.048	0.00008
0.322	0.00818	0.04	0.032	0.00005
0.323	0.00820	0.035	0.027	0.00004
0.324	0.00823	0.029	0.021	0.00003
0.325	0.00826	0.027	0.019	0.00003
0.326	0.00828	0.021	0.013	0.00002
0.327	0.00831	0.017	0.009	0.00001
0.328	0.00833	0.016	0.008	0.00001
0.329	0.00836	0.015	0.007	0.00001
0.33	0.00838	0.014	0.006	0.00001
0.331	0.00841	0.013	0.005	0.00001
0.332	0.00843	0.011	0.003	0.00000
0.333	0.00846	0.01	0.002	0.00000
0.334	0.00848	0.01	0.002	0.00000
0.335	0.00851	0.009	0.001	0.00000
0.336	0.00853	0.009	0.001	0.00000
0.337	0.00856	0.009	0.001	0.00000
0.338	0.00859	0.009	0.001	0.00000

Data from Q9d

Q11



Q12

a) Yes, if a beam starts out Gaussian, it will remain so provided it does not encounter any fields or matter that could change it.

b) A lens acts as a fourier transform for incoming waves. If the incoming wave is gaussian, the fourier transform is also a gaussian, ~~and~~ so will the beam exiting the lens.

c) A gaussian beam reflecting will retain its gaussian properties, though the wave may have a phase shift afterwords.

d) The beam will reach a minimum spot size at the focus of the lens. However, it will not be a point. Because light is fundamentally wave-like, the smallest it can really get is on the order of its wavelength.

Q13

a) $I(x,y) \propto |E|^2 = E^*E$

$$= |E_0|^2 \frac{\omega_0}{\omega(z)} \exp\left(-2\frac{x^2+y^3}{(\omega(z))^2}\right)$$

since all complex exponentials disappear when multiplied by their conjugates.

If we take a measurement at a specific point z along propogation axis, call its width ω and set $I_{max} \propto |E_0|^2 \omega_0$, we get

$$I(x,y) = I_{max} \exp\left(-2\frac{x^2+y^2}{\omega^2}\right),$$

consistant with eq. 8.

Q14

a) All equations would be modified by the substitution $z \to z - z_w$

$$\vec{E}(x,y,z,t) = \vec{E}_0 \frac{\omega_0}{\omega(z)} \exp\left(-\frac{x^2+y^2}{\omega^2(z)}\right) \exp\left(ik\frac{x^2+y^2}{2R(z)}\right) e^{-i\zeta(z)} e^{i(k(z-z_w)-\omega t)}$$

$$\omega(z) = \omega_0\sqrt{1+\left(\frac{\lambda(z-z_w)}{\pi\omega_0^2}\right)^2} \qquad R(z) = (z-z_w)\left(1+\left(\frac{\pi\omega_0^2}{\lambda(z-z_w)}\right)^2\right)$$

$$\zeta(z) = \mathrm{ArcTan}\left(\frac{\pi\omega_0^2}{(z-z_w)\lambda}\right)$$

Which all ~~conver~~ become their original forms when $z_w = 0$

Q15

a) i) We expect something like equation 9:

$$w(z) = w_0\sqrt{1 + \left[\left(\frac{(632.8\times10^{-9}m)}{\pi w_0^2}\right)(z - z_w)\right]^2}$$

ii) There are only two parameters here: w_0 and z_w

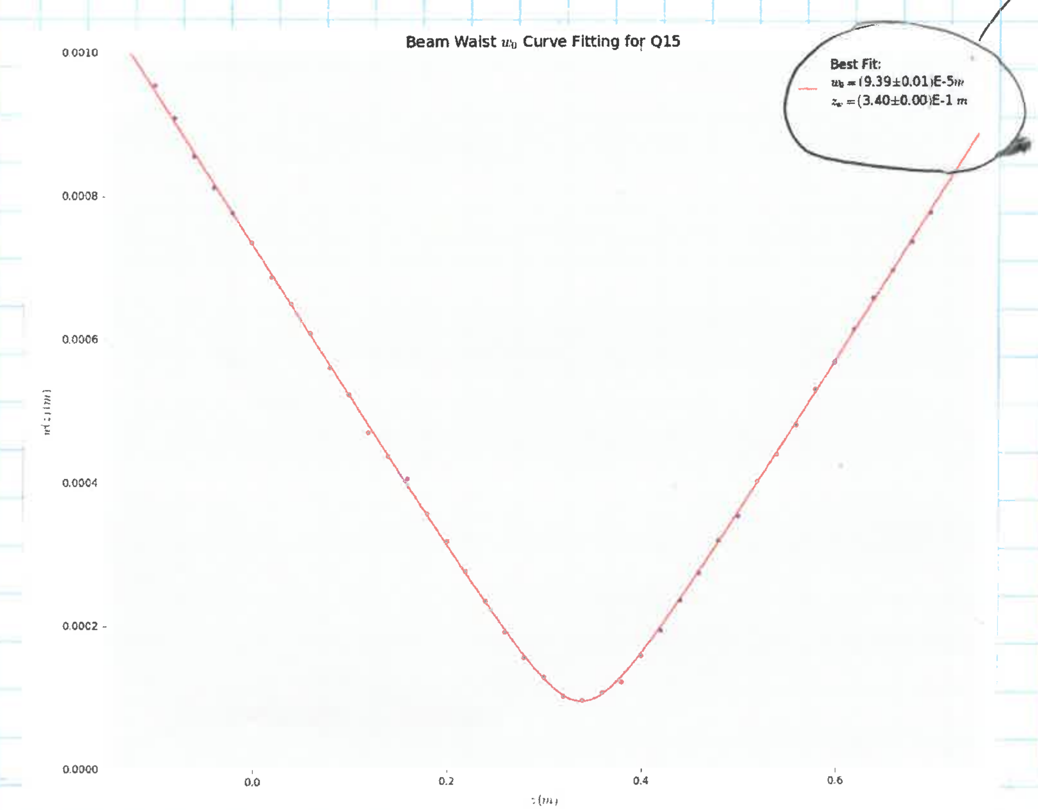
w_0 scales the fit to the minimum beam width

z_w shifts the position of the minimum beam waist along z

iii) This is again a nonlinear fit, as $w(z)$ is a nonlinear function of z

b) See plot below

Agrees with stated values



Q16

a) ≈ 10 minutes per measurement.

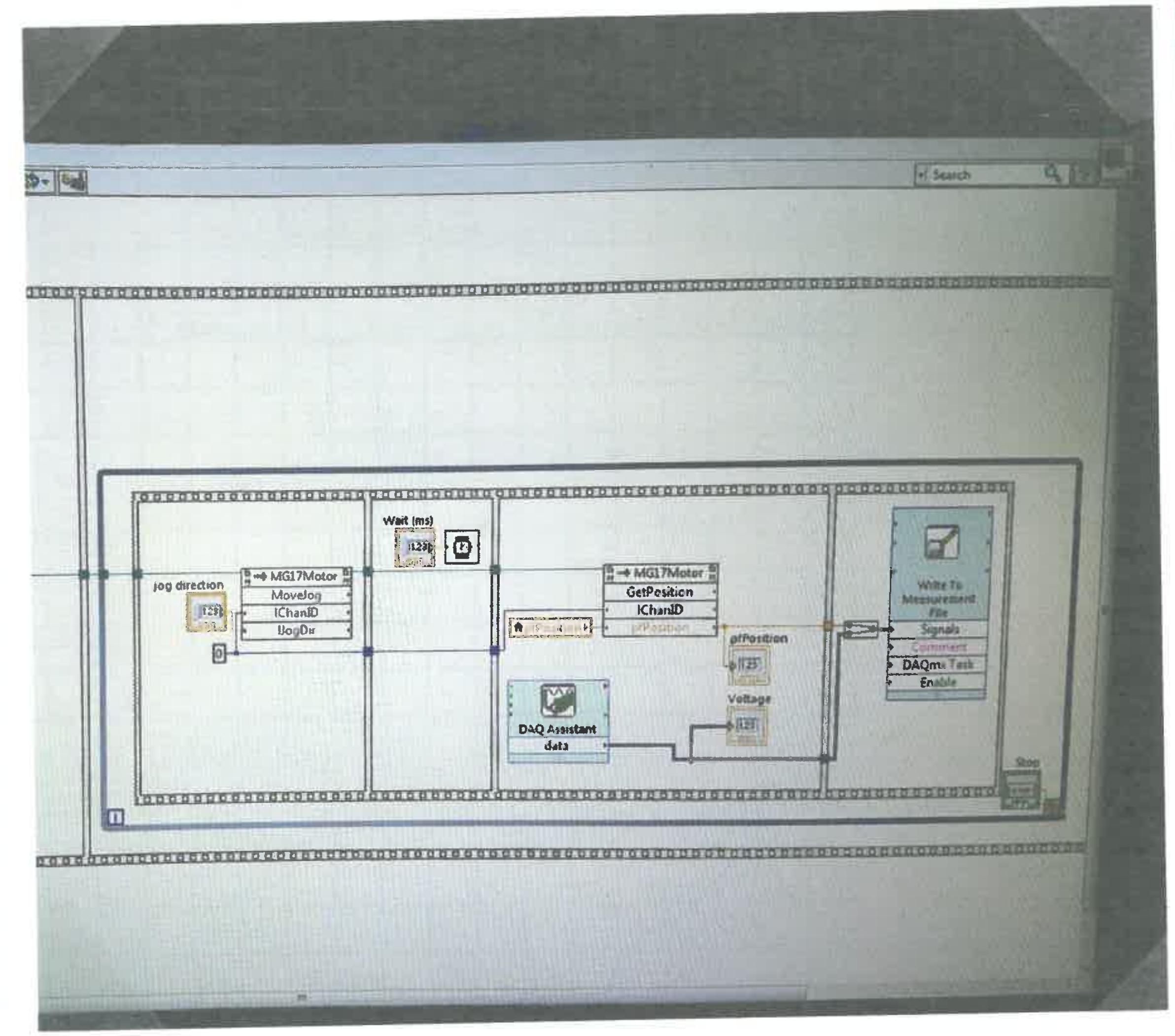
b) ≈ 3-5 hours Yuck.

c) The most time consuming portions are adjusting the translation stage and reading the voltage. These would benefit the most from automation, as they are repetitive operations requiring precision & accuracy.

Q17

a) ✓

b)



Q18

a) We had to disassemble the translation stage between taking
b) data manually e completing automation with Labview, so we
cannot compare directly the values taken by hand with those
taken automatically. However, data collected afterwards suggests
our process is accurate e faithful in reproducing the same results.

c) Upon automating the process, it now takes ≈ 3 minutes per
run. We choose a longer run time to ensure stability in
the measurement process

Q19

a) With our equipment, we can only test ~~the~~ equation (9): $w(z)$

- We cannot test the Electric field of (8) since our detector only measures the intensity $|\vec{E}|^2 \times$ area (Power). In fact, we can only sample this at a given frequency, and it is unlikely we can measure the power on the timescales of the optical frequency $f = \frac{c}{\lambda} \simeq 400\,\text{THz}$

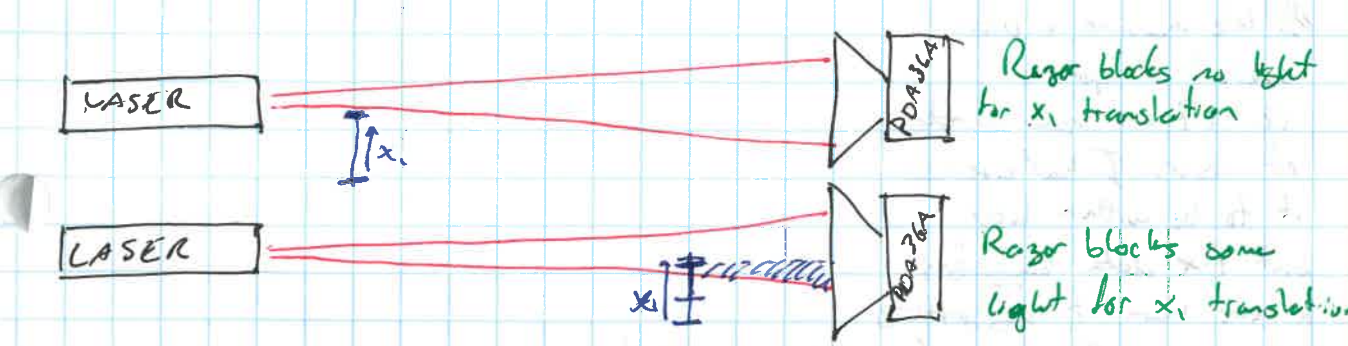
- We can measure the beam width ~~and~~ at various points along the direction of propagation, so we can test eq. (9)

- To measure the radius of curvature ($R(z)$), we need ~~to~~ to know where the phase of the beam is constant. We could choose a pickoff and compare the phase at various positions within the wave, but we would need to construct an interferometer and ~~to~~ ensure a constant phase at the imaging point of the beam pickoff (splitter). So with our equipment we cannot test $R(z)$ eq (10)

- For similar reasons, we cannot directly measure the phase of the beam, and so we can't test (eq 11).

However, once we obtain ω_0 and z_{w_0}, we can deduce the values for all of these features and put them together. ~~for tests of~~

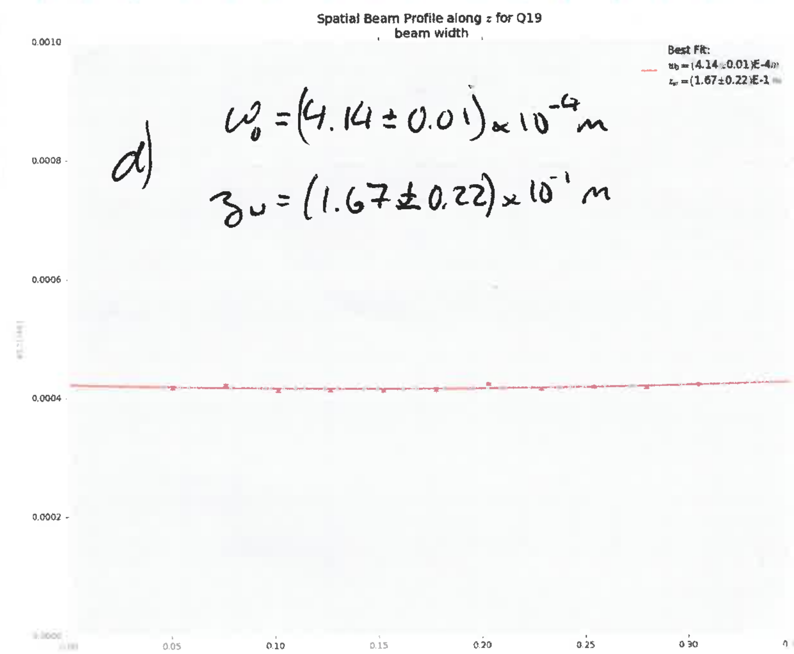
b) We are trying to obtain a measurement of the beam width as a function of distance from the aperture. We want to keep the laser and detector in the same locations, but move the razor along the propogation axis. ~~At~~ At different points along the axis, ~~we~~ a given translation ~~along the~~ of the razor edge will block out different amounts of the laser, resulting in different amounts of power incident on the detector. See below for visual explanation:



Q19 ctd

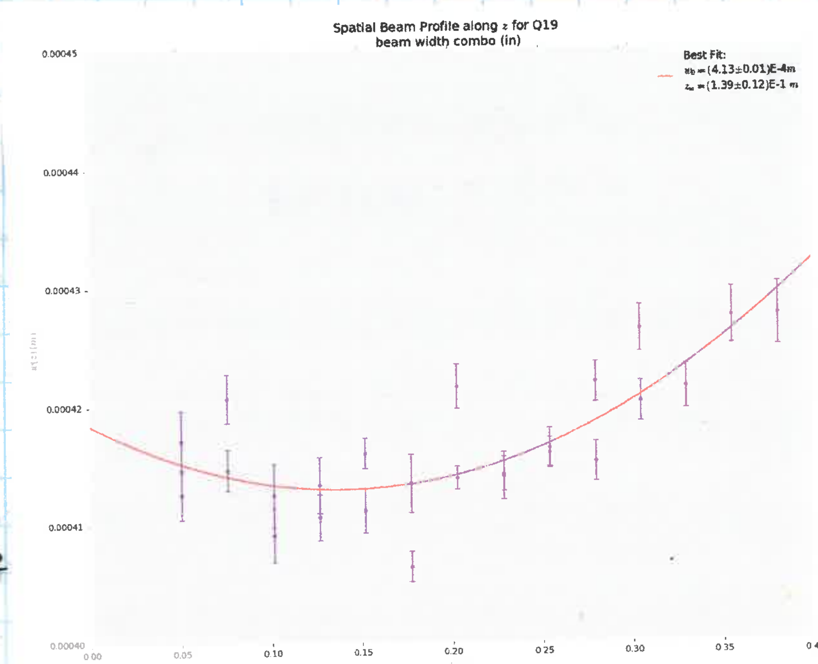
b) ctd: We tried to get a reasonable sampling of the beam; so we moved the stage ~~at~~ to each drilled hole between the laser and the detector. This has the benefit of ensuring equal z-spacings between measurements.

c) We performed two seperate profile experiments and obtained the two plots below.



d) $w_0 = (4.14 \pm 0.01) \times 10^{-4}$ m

$z_R = (1.67 \pm 0.22) \times 10^{-1}$ m

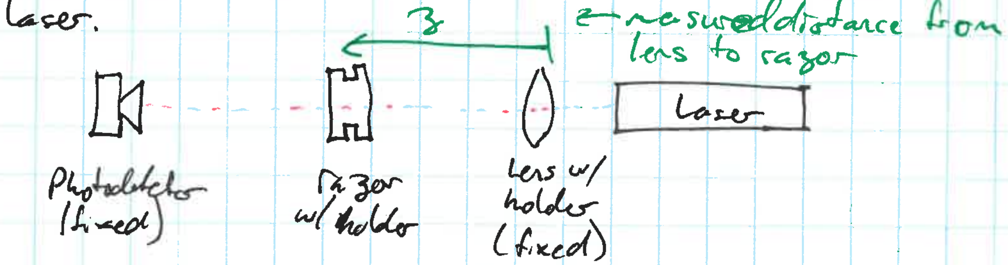


We note that ~~those~~ ~~to~~ while the ~~beam~~ waist minimum agree well, the location of this minimum differs significantly ~~be~~ between the two runs. We attribute this to the limited ~~values~~ range of values of z we took data over. The data nor the fits show ~~a~~ a very clear "spreading" we saw in the sample data. We could improve this by using mirrors to extend the beam path from laser to detector & measuring ~~the~~ along this greater range.

d) We measure a beam waist at ~~approx~~ 12-17 cm from aperature of laser. I had expected it to be within laser, but the data suggests a more linear fit, suggesting we are well away from beam waist.

Q20

- We performed this part of the experiment with a 100 mm lens and a 150 mm lens.
- We used the same setup as in Q19, but inserted the lens near the laser.



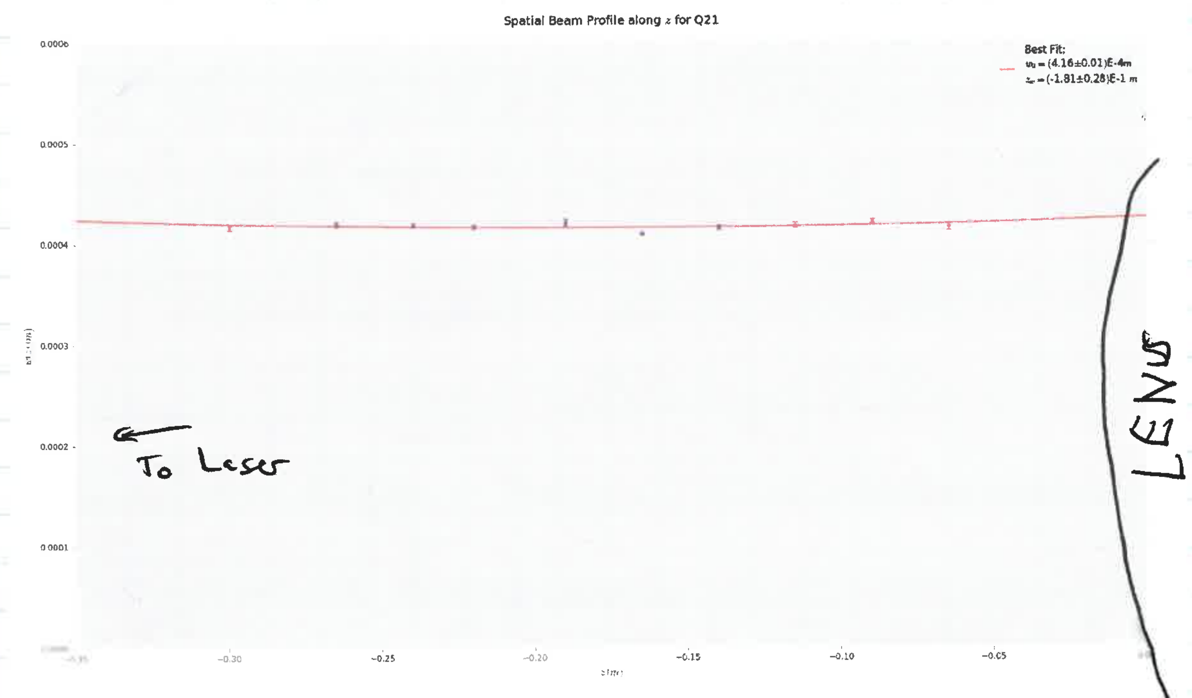
- The beam without the lens appeared to exhibit little spreading (the data was nearly linear in the previous part) outside the laser, and so we placed the lens several centimeters away from the laser where we expect little spreading of the beam.
This means that we expect the beam leaving the ~~laser~~ lens to have a new waist near the focus of the lens.
We took data at several locations around this focus to get as good a fit for the data as possible.

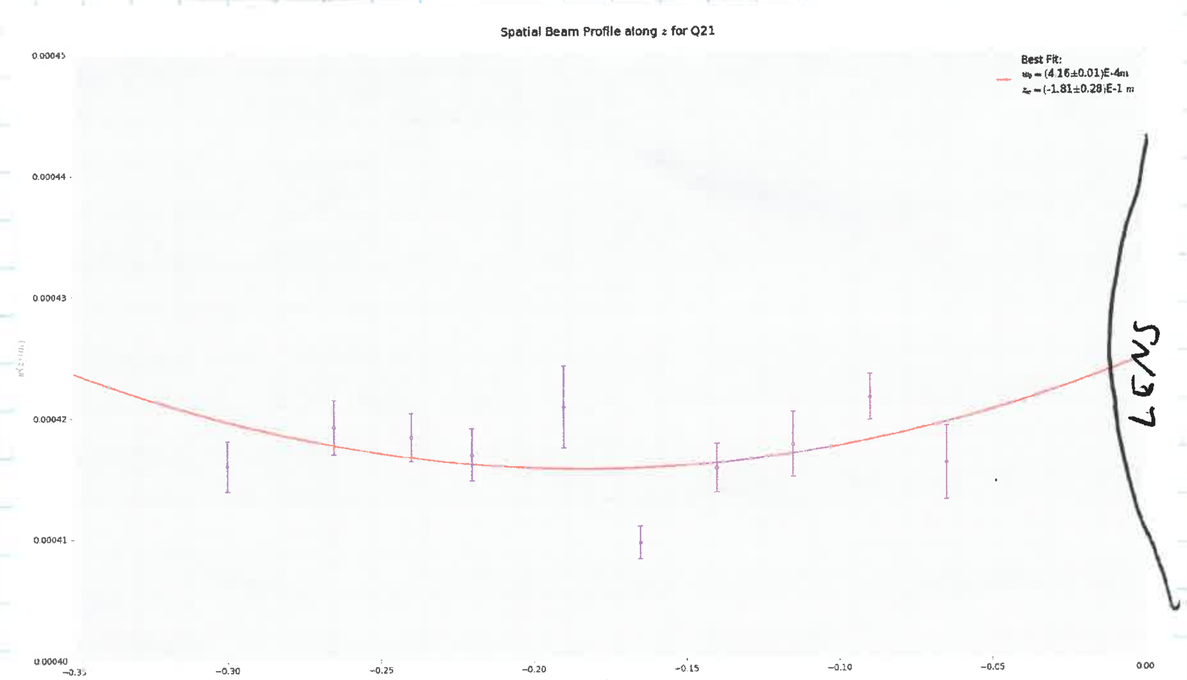
a) It appears our hypothesis was correct. The beam has a waist very near the focus for both the 100 mm and 150 mm lenses, ~~in c~~ conforming with the behavior of a Gaussian beam.

b) We measured the distance (z) from the lens to the razor, and the waist occurred near the focus of the lens under consideration. See plots of data below.

c) The beam profile is affected by the beam "spread" going into the lens: if the ~~beam is~~ beam's wavefronts are not ~~parallel~~ planar, the location of the waist on the far side of the lens will ~~differ~~ differ from the location of the focus.
Also, the power of the lens $(P = \frac{1}{f})$ will affect where this waist occurs

$\omega(z)$ before lens

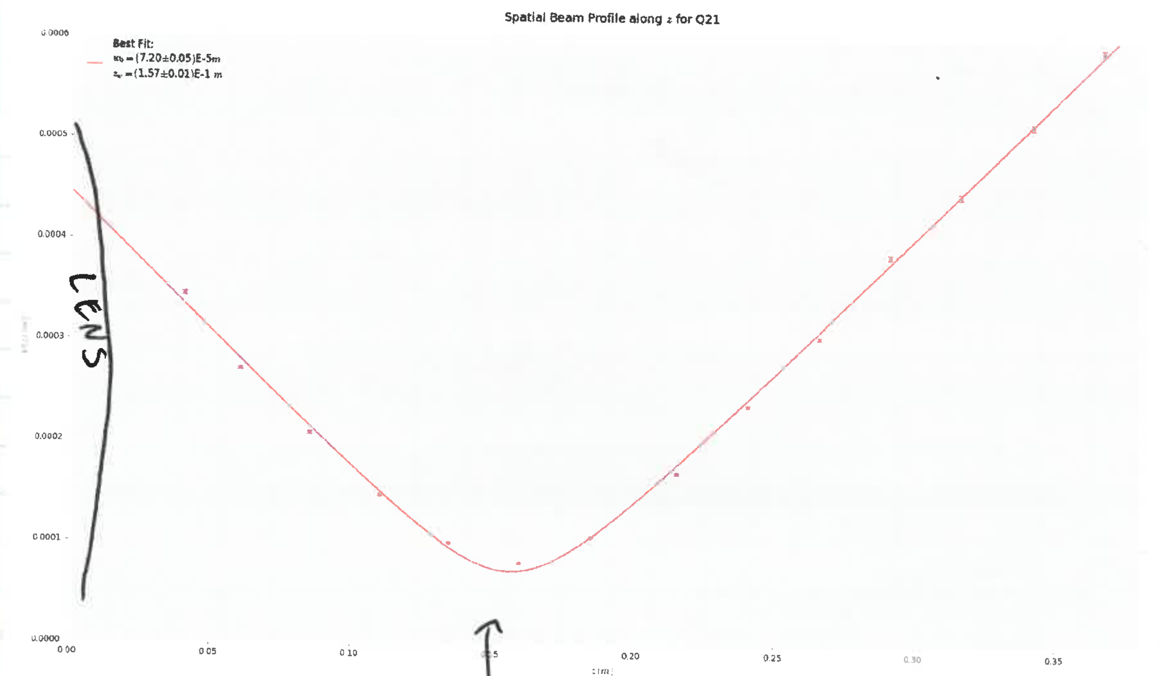




Two plots of the measured width of the laser beam prior to interacting with the ~~beam~~ lens. The top is plotted on the same scale as the plot on the next page of the beam width after going through the lens.

The bottom plot is zoomed so as to see error bars.

$w(z)$ after lens.



focal length of lens (150 mm)

Q20.

d) The measured beam coming out of the lens fits the $w(z)$ of equation very nicely. The error bars are almost to small to see on this scale, but the data follows the expected shape closely.

Note: The beam width becomes approximately linear in the limit of $|z| \gg z_w$:

$$\lim_{|z|\to\infty} w(z) = \lim_{|z|\to\infty} w_0 \sqrt{1 + \left(\frac{\lambda(z - z_w)}{\pi w_0^2}\right)^2}$$

$$\simeq w_0 \sqrt{\left(\frac{\lambda(z - z_w)}{\pi w_0^2}\right)^2}$$

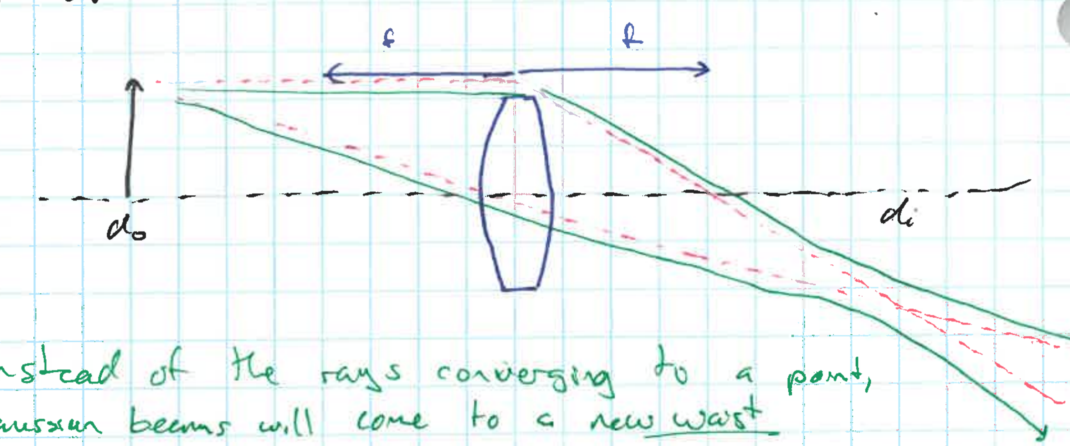
$$\simeq \frac{\lambda}{\pi w_0}(z - z_w) \quad \text{is linear in } z$$

- This corresponds to the nearly linear behavior we see in the plot above as we get away from the waist. Furthermore, it explains the "linear" behavior of the data on the previous page. If the beam is far from the waist ($w_0^2 \ll z - z_w$) the "envelope" will be approximately linear.

- I believe the fitting of the all plots on the 2 earlier pages are an example of over fitting.

Q21 $\frac{1}{d_o} + \frac{1}{d_i} = \frac{1}{f}$

a)



Instead of the rays converging to a point, gaussian beams will come to a new waist

- These new waists will occur at the image location. If the wavefronts are parallel at the lens, then the waist will be at the focus of the lens.

- By considering an object at the image location we see that we should expect another beam waist at the location of the objects ~~which makes sense. a~~

- The power of the lens ($P = \frac{1}{f}$) determines the width of the waist. A more powerful lens (shorter focus) will result in a smaller waist

b) We expect our lens equation to ~~represent~~ work as well, but instead of measuring objects, we will use d_o and d_i as the location of the beam waists. ~~on the object side and~~ ~~Waz~~ In our previous fittings, we found $S_o = 0.181\,m$ $S_i = 0.157\,m$

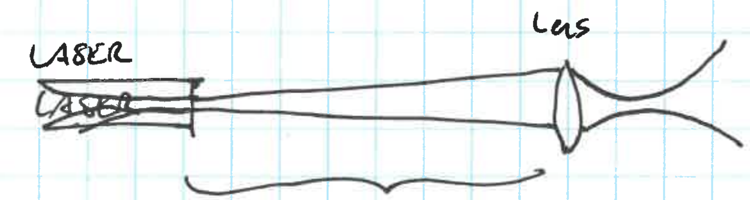
With these numbers, we expect a focal length

$$f = \frac{1}{\frac{1}{S_o} + \frac{1}{S_i}} = 0.084\,m = 84\,mm.$$

However, we used (and confirmed by measuring focal length) a 150 mm lens. Clearly there is a discrepancy.

b) ctd. I do not feel the beam waist location is a reliable figure. We do not seem to have a minimum within the data. In fact, we expect the beam waist to be within the laser tube, and so all our measurements ~~should be~~ upstream of the lens should indicate a growing beam width until it hits the lens.

Expectation:



In this region, we expect a constantly (~linear) growing width. So for this reason, I believe our waist location is suspect.

- So if we trust our beam waist after the lens and we trust our focal length, we can ~~estimate our the~~ calculate the location of the beam waist from the lens equation:

$$S_o = \frac{1}{\frac{1}{f} - \frac{1}{S_i}} = \frac{1}{\frac{1}{.150\,m} - \frac{1}{.157\,m}} = 3.36\ m$$

- This number is still not what we would expect, as the laser is ≈ 1 m from the lens. I believe the primary source is uncertainty in the location of the waist relative to the focus. If we change our mean value of S_i to .156 m, we get $S_o = 3.9$ m.

So a slight change in any of our values can have a massive effect on our outcome.

c) Systematic Errors: The lens equation is most valid where light is ray-like. We chose to "image" the beam waists, and the ~~region wh~~ beam at the location of the lens is very nearly ray-like. To get better agreement, ~~we~~ we would need to be very precise with our values for the reasons mentioned in (b).