

# **Experiment II: Gaussian Wave Optics**

**PHY 555: Optics Lab**

**Dr. Streletzky**

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**Group  $\alpha$ :**

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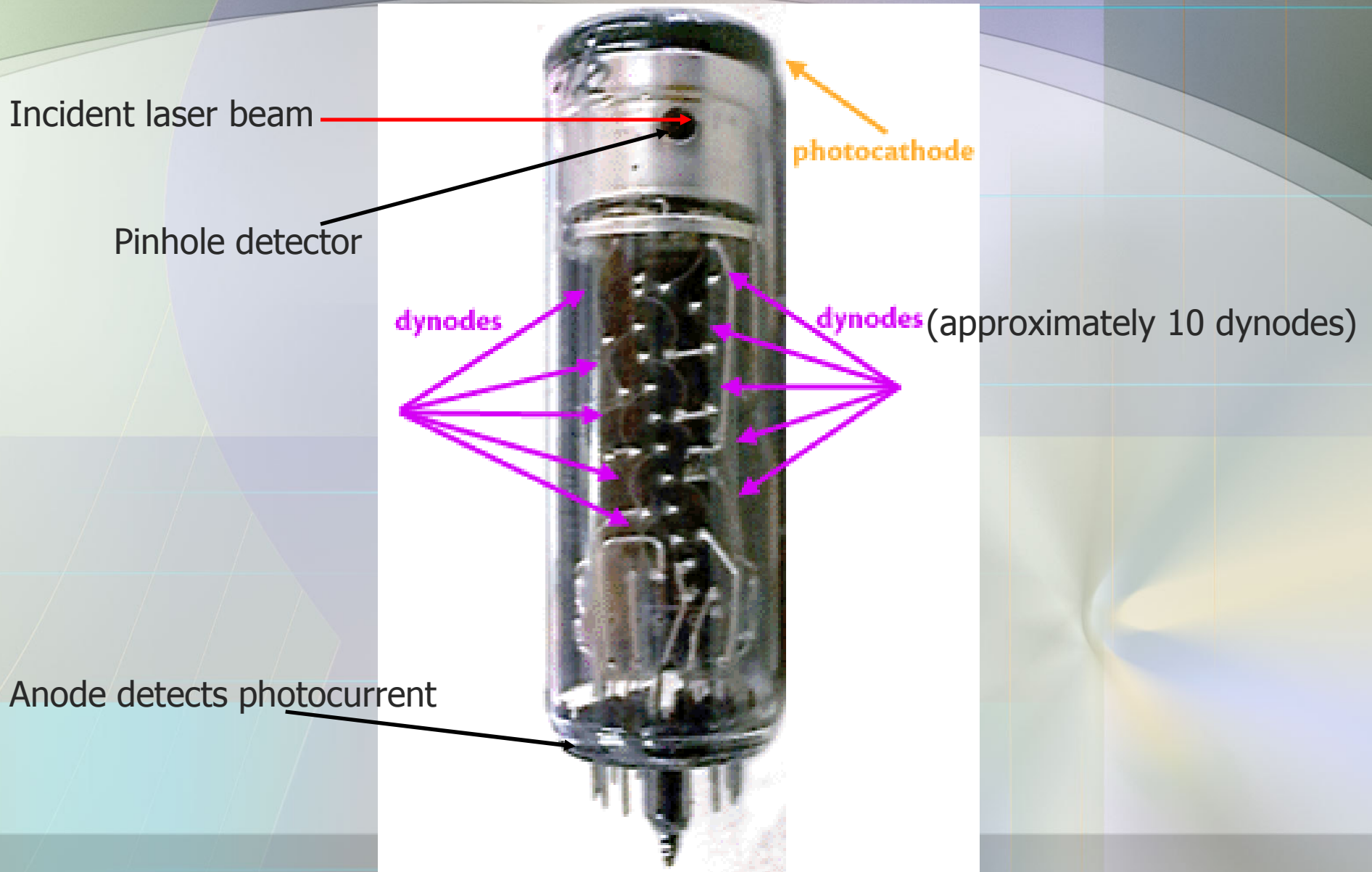
# Objective

- **Focus the HeNe laser's Gaussian beam with a lens**
- **Measure the waist of the beam at several locations along the beam profile**
- **From recorded data, calculate the radius of the beam waist**

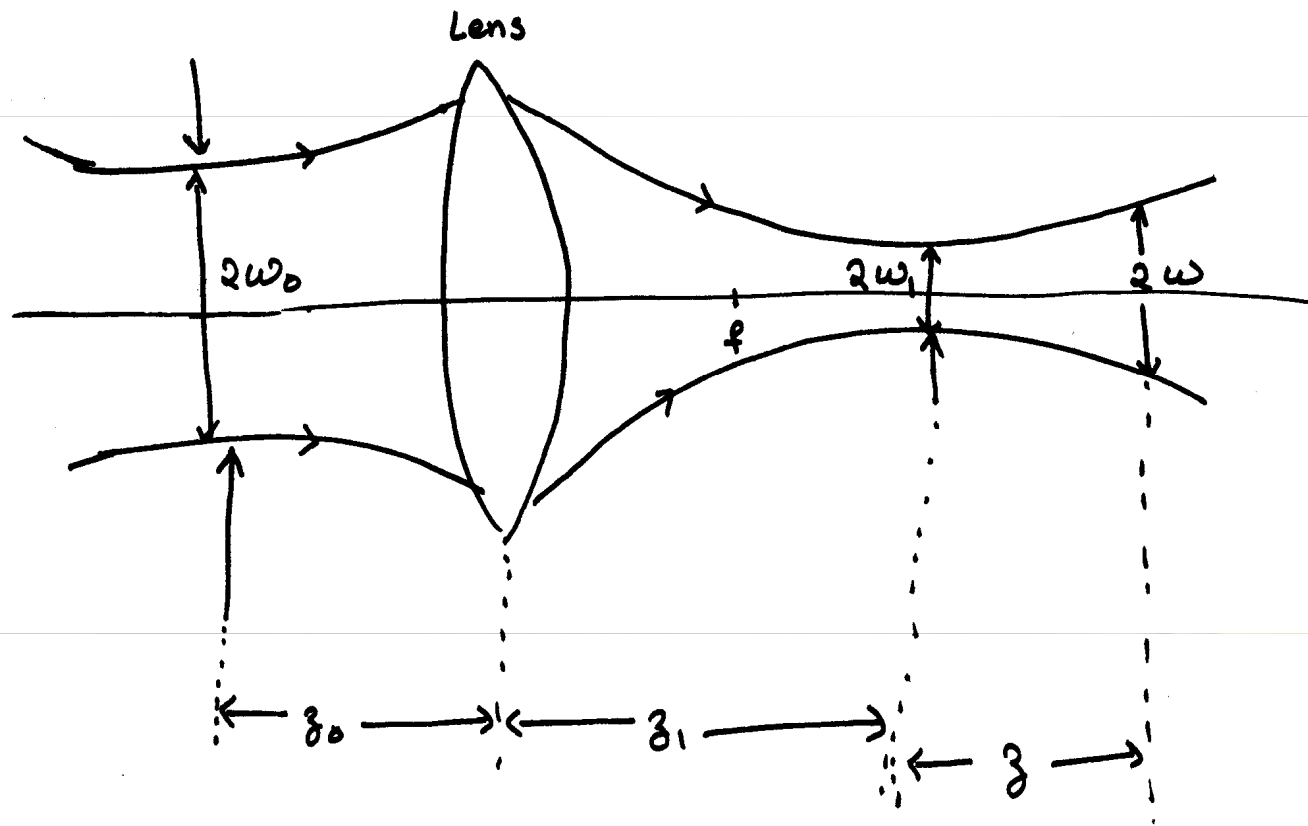
# Background: Photomultiplier Tube

- **Invented from a need to improve (increase sensitivity) of television video cameras, around 1934 by RCA**
- **Oriel PMT, model #77346, detects 185-850nm, HeNe laser used is 633nm**
- **Very light sensitive, especially in the presence of bias voltage**
- **Principle of operation: photoelectric effect**
- **Photocathode, charged surface that emits electrons when struck with photons**
- **Detection requires multiple electrons, series of dynodes located inside PMT**
- **Dynodes coated in photosensitive material, when initial electron strikes each dynode, secondary electrons are emitted**
- **Due to a potential difference between the dynodes, the electrons increase in kinetic energy as they strike each subsequent electrode**
- **Electrons with higher potential energy emit a greater amount of secondary electrons when they strike the dynodes**
- **The emission of secondary electrons allows for the detection of the photocurrent, since detection of a single electron would be difficult**
- **Emitted electrons gather on the anode, which detects that the photocathode has been struck by an incident beam**

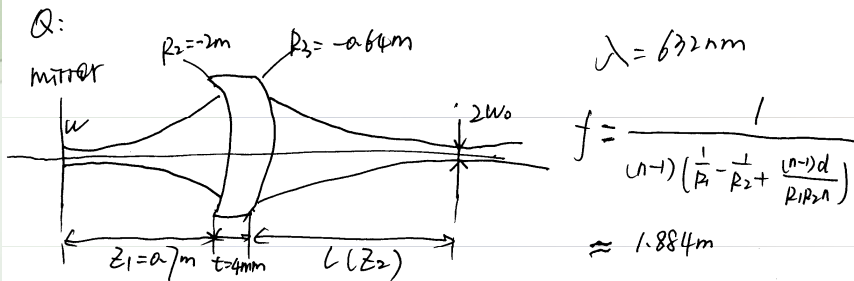
# Background: Photomultiplier Tube



# Background: Gaussian Beam Profile



# Background: Gaussian Beam Profile



$$\frac{1}{q_2} = \frac{1}{q_1} - \frac{1}{f} \quad \frac{1}{q(z)} = \frac{1}{R(z)} + i \frac{\alpha}{\pi w^2(z)}$$

$$q_1 = z + i b_0 = z + i \frac{\pi w_0^2}{\alpha}$$

$$q_2 = \frac{a_1 f}{f - q_1} = -\frac{q_1}{f + 1} \Rightarrow \begin{bmatrix} A & B \\ C & D \end{bmatrix} = \begin{bmatrix} 1 & 0 \\ -\frac{1}{f} & 1 \end{bmatrix}$$

$$= \frac{(z + i \frac{\pi w_0^2}{\alpha}) f}{f - z - i \frac{\pi w^2}{\alpha}}$$

$$= \frac{(z + i \frac{\pi w_0^2}{\alpha}) f \cdot [(f - z) + i \frac{\pi w_0^2}{\alpha}]}{(f - z)^2 - i^2 \left(\frac{\pi w_0^2}{\alpha}\right)^2}$$

$$= \frac{f(f - z)(z + i \frac{\pi w_0^2}{\alpha}) + i \frac{\pi w_0^2}{\alpha} \cdot f(z + i \frac{\pi w_0^2}{\alpha})}{(f - z)^2 + \left(\frac{\pi w_0^2}{\alpha}\right)^2}$$

$$= \frac{f z_1 (f - z) + f(f - z) \frac{\pi w_0^2}{\alpha} i + f z_2 \frac{\pi w^2}{\alpha} i + i^2 f \left(\frac{\pi w_0^2}{\alpha}\right)^2}{(f - z)^2 + \left(\frac{\pi w_0^2}{\alpha}\right)^2}$$

$$= \frac{f z_1 (f - z) - f \left(\frac{\pi w_0^2}{\alpha}\right)^2 + [f(f - z) + f z_2] \frac{\pi w^2}{\alpha} i}{(f - z)^2 + \left(\frac{\pi w_0^2}{\alpha}\right)^2}$$

$$q_2 = \frac{f z_1 (f - z) - \left(\frac{\pi w_0^2}{\alpha}\right)^2}{(f - z)^2 + \left(\frac{\pi w_0^2}{\alpha}\right)^2} + \frac{f^2 \left(\frac{\pi w_0^2}{\alpha}\right)}{(f - z)^2 + \left(\frac{\pi w_0^2}{\alpha}\right)^2} i$$

$$q_2 = z_2 + i \frac{\pi w_0^2}{\alpha}$$

$$\Rightarrow z_2 = \frac{f z_1 (f - z) - \left(\frac{\pi w_0^2}{\alpha}\right)^2}{(f - z)^2 + \left(\frac{\pi w_0^2}{\alpha}\right)^2}$$

$$\frac{\pi w_0^2}{\alpha} = \frac{f^2 \left(\frac{\pi w_0^2}{\alpha}\right)}{(f - z)^2 + \left(\frac{\pi w_0^2}{\alpha}\right)^2} \Rightarrow w_0 = \frac{f w}{\sqrt{(f - z)^2 + \left(\frac{\pi w_0^2}{\alpha}\right)^2}}$$

$$R = z \left[ 1 + z \left( \frac{\pi w_0^2}{\alpha z} \right)^2 \right]$$

$$\Rightarrow W = \left[ \frac{(R - z) \alpha^2 z}{\pi^2} \right]^{\frac{1}{4}} \quad \left. \begin{array}{l} \alpha = 632.8\text{nm} \\ R = 2\text{m} \\ z = 0.7\text{m} \end{array} \right\} \Rightarrow W = 4.381 \times 10^{-4}\text{m} \approx 0.44\text{mm}$$

# Background: Gaussian Beam Profile

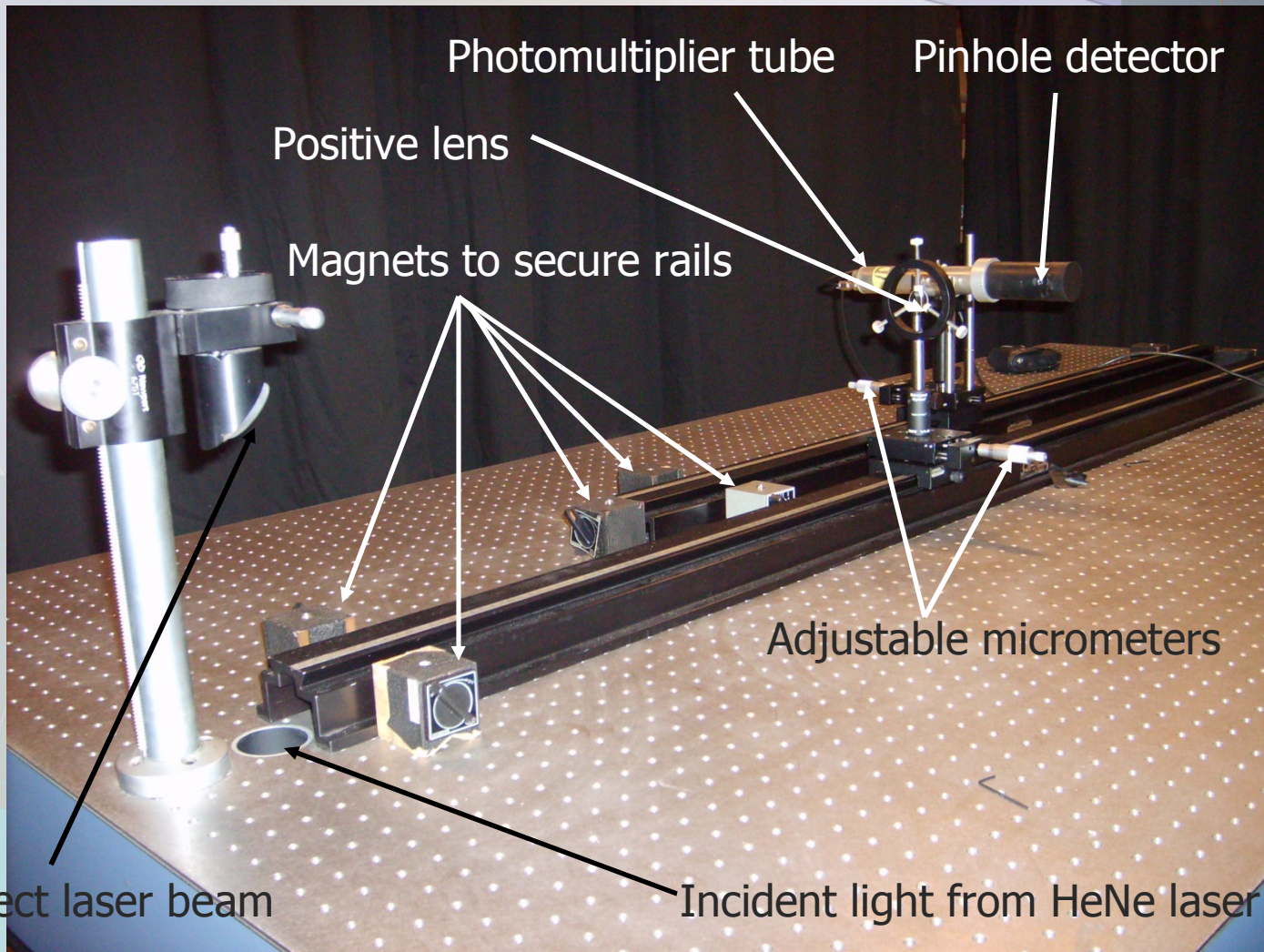
$$z_z = \frac{f z_1 (f - z_1) - \left(\frac{\pi w^2}{\lambda}\right)^2}{(f - z_1)^2 + \left(\frac{\pi w^2}{\lambda}\right)^2} = \boxed{0.282 \text{ m}}$$

(1)

$$w_0 = \frac{f w}{\sqrt{(f - z_1)^2 + \left(\frac{\pi w^2}{\lambda}\right)^2}} = 5.428 \times 10^{-4} \text{ m}$$

$\approx \boxed{0.54 \text{ mm}}$

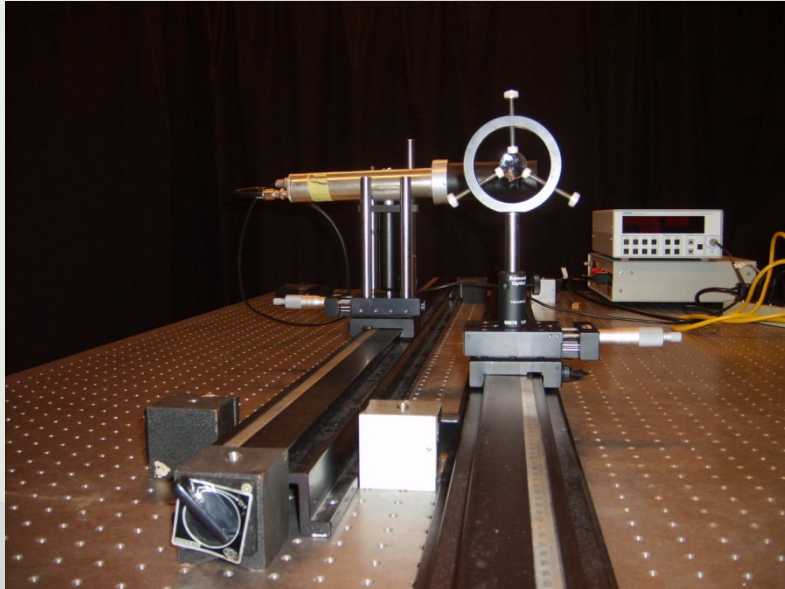
# Experiment Setup



# Procedure

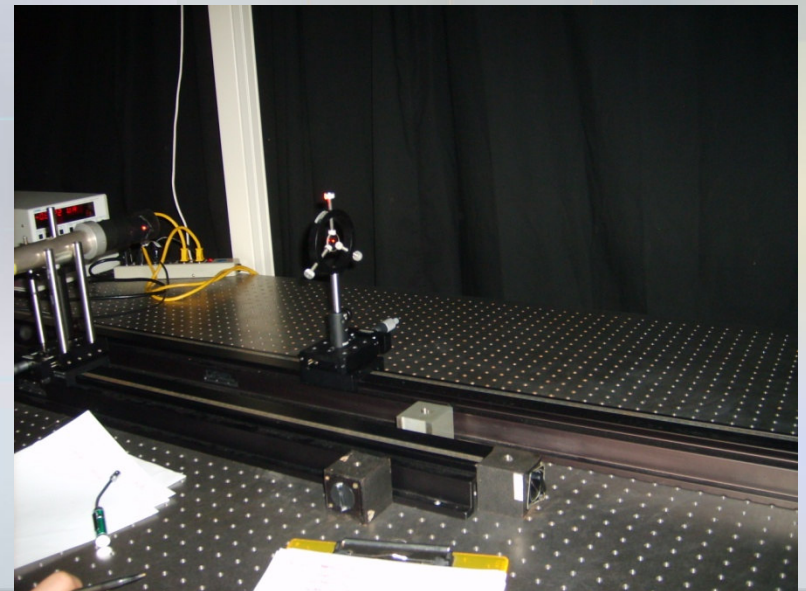
- **Securely mount the PMT and lens on movable rails**
- **Secure the rails to the optical table**
- **Align the pinhole detector along the plane of the table, proved difficult**
- **Using the fine tuning screws, align the laser with the pinhole aperture, using the current reading as a guide. This alignment also involved moving the pinhole detector to allow a maximum reading.**
- **Position the lens and PMT at the focal point**
- **Using the fine tuning micrometers that the lens and the PMT are mounted on, locate the center point of the Gaussian beam profile, the location of the greatest photocurrent reading**
- **Mark that position as the central point, then scan significantly to either side of the center point to best approximate the beam profile, taking five readings at each point. Points separated by .001 inches for focal point.**
- **Repeat steps for 2 positions, 10cm and 15cm, outside of the focal point.**
- **Note: took longer to adjust mirrors and lens to take measurements outside of the focal point**

# Procedure



Securing the PMT

Aligning the laser with the lens and pinhole





# Equations used for Calculations

From lab manual, equations (3), (4), (5) rewritten

$$z_1(w_0) := \left[ \frac{(z_0 - f) \cdot f^2}{(z_0 - f)^2 + \left( \frac{\pi \cdot w_0^2}{\lambda} \right)^2} + f \right]$$
$$z(w_0) := (L - z_1(w_0))$$
$$w_1(w_0) := \left[ \left[ 1 - \left( \frac{z_0}{f} \right)^2 \right] \cdot \left( \frac{1}{w_0^2} \right) + \left( \frac{\pi \cdot w_0}{\lambda \cdot f} \right)^2 \right]^{\frac{-1}{2}}$$
$$w(w_0) := \left[ (w_1(w_0))^2 \cdot \left[ 1 + \left[ \frac{\lambda \cdot z(w_0)}{\pi (w_1(w_0))^2} \right]^2 \right] \right]^{\frac{1}{2}}$$

$$\lambda := 633 \cdot \text{nm} = 6.33 \times 10^{-7} \text{ m}$$

$$f := 250 \cdot \text{mm} = 0.25 \text{ m}$$

$$w := 2.286 \times 10^{-4} \text{ m}$$

$$z_0 := 80 \cdot \text{cm} = 0.8 \text{ m}$$

$$L := 35 \cdot \text{cm} = 0.35 \text{ m}$$

# Results at focal point, 25cm from lens

$$r_{125_{1avg}} := r_{125_1}^{(0)} \qquad r_{125_{2avg}} := r_{125_2}^{(0)}$$

$$r_{125_{1normavg}} := r_{125_1}^{(1)} \qquad r_{125_{2normavg}} := r_{125_2}^{(1)}$$

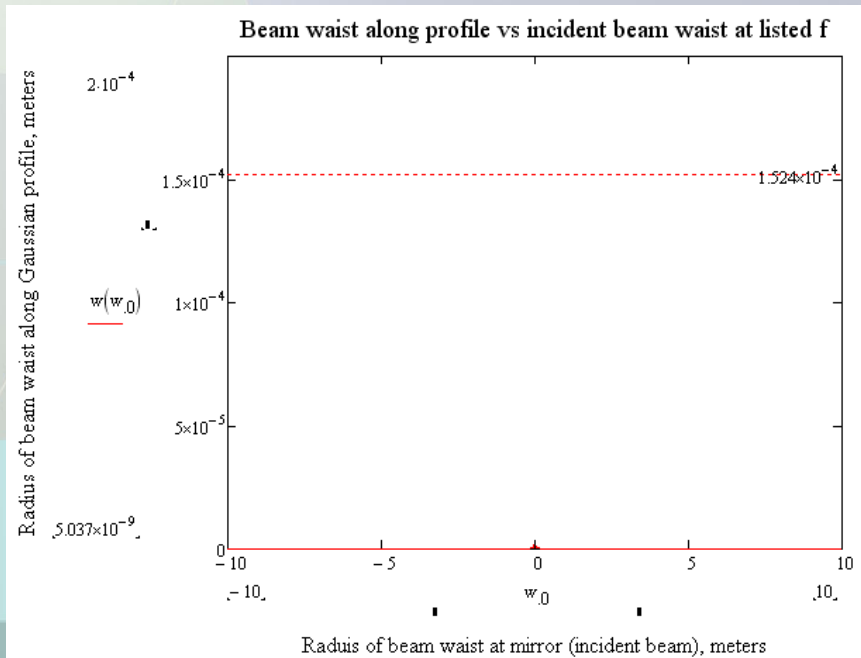
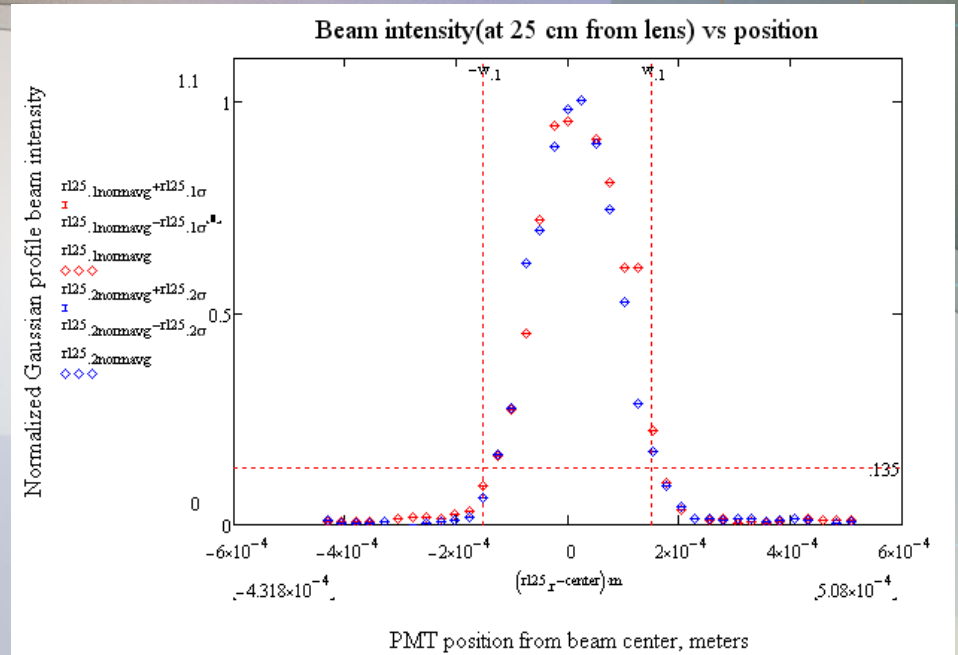
$$r_{125_{1\sigma}} := r_{125_1}^{(2)} \qquad r_{125_{2\sigma}} := r_{125_2}^{(2)}$$
  

$$center := .440 \text{ in} = 0.011 \text{ m}$$

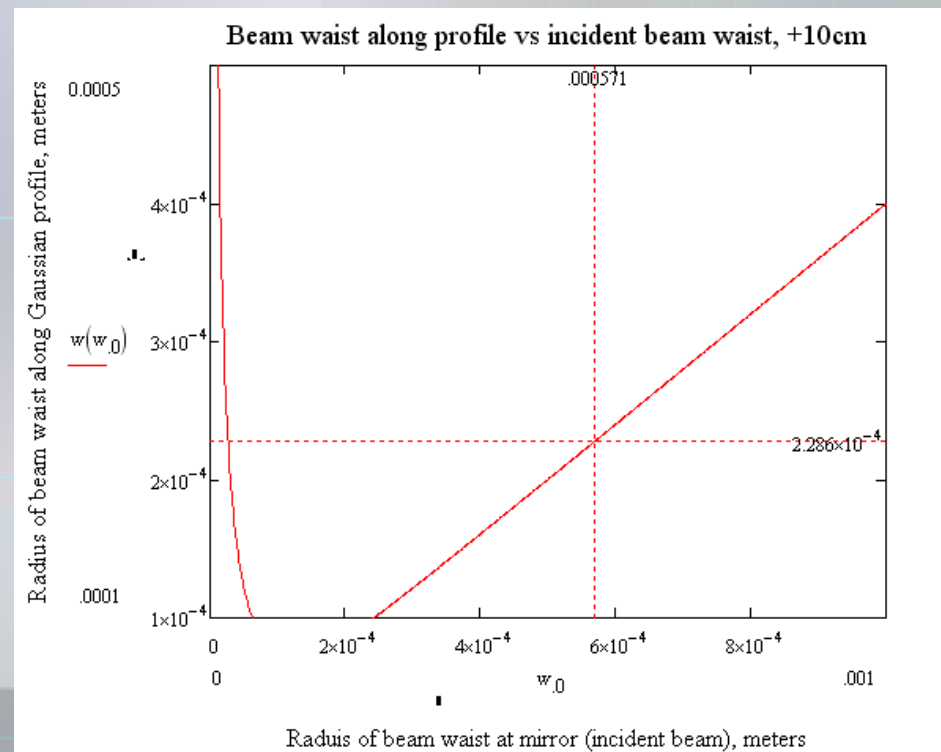
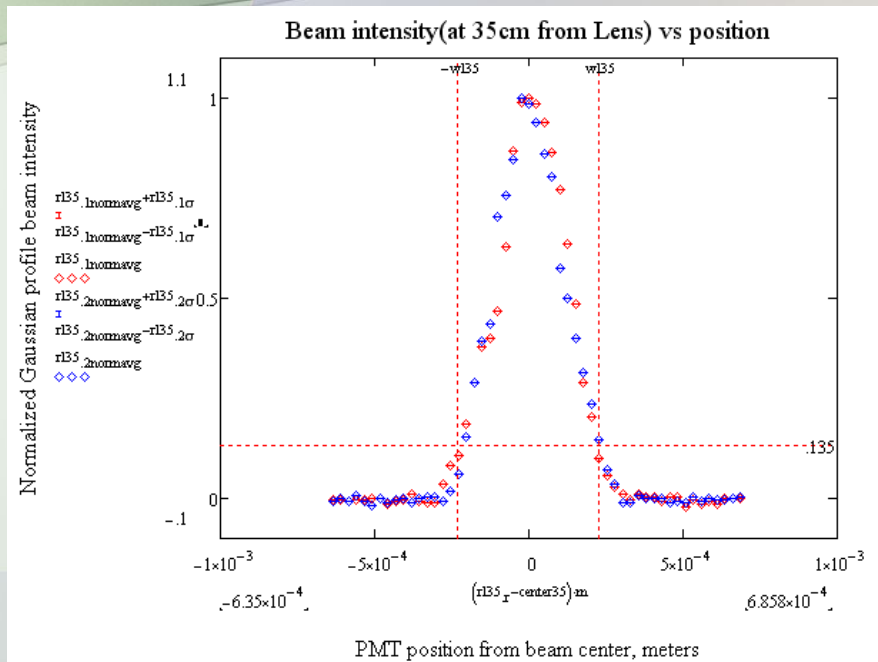
$$beamrad_2 := .447 \text{ in} - center = 1.778 \times 10^{-4} \text{ m}$$

$$beamrad_1 := .435 \text{ in} - center = -1.27 \times 10^{-4} \text{ m}$$

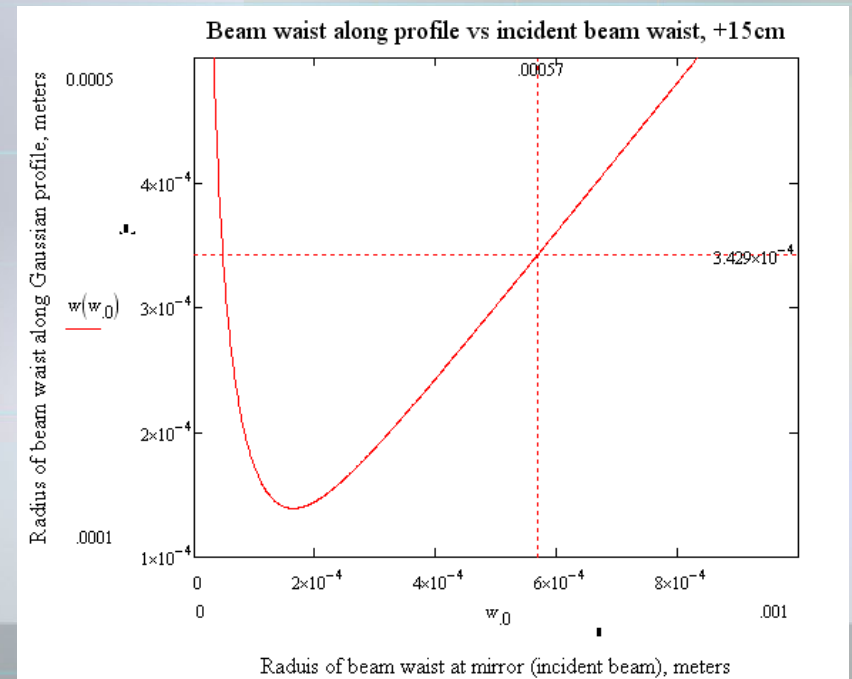
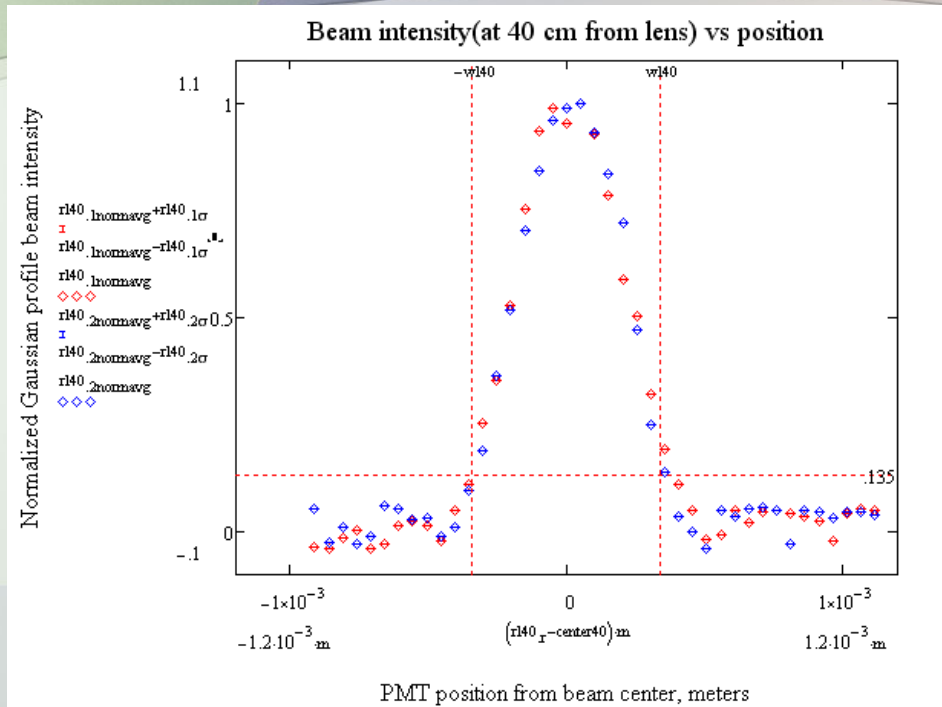
$$w_1 := \frac{beamrad_2 - beamrad_1}{2} = 1.524 \times 10^{-4} \text{ m}$$



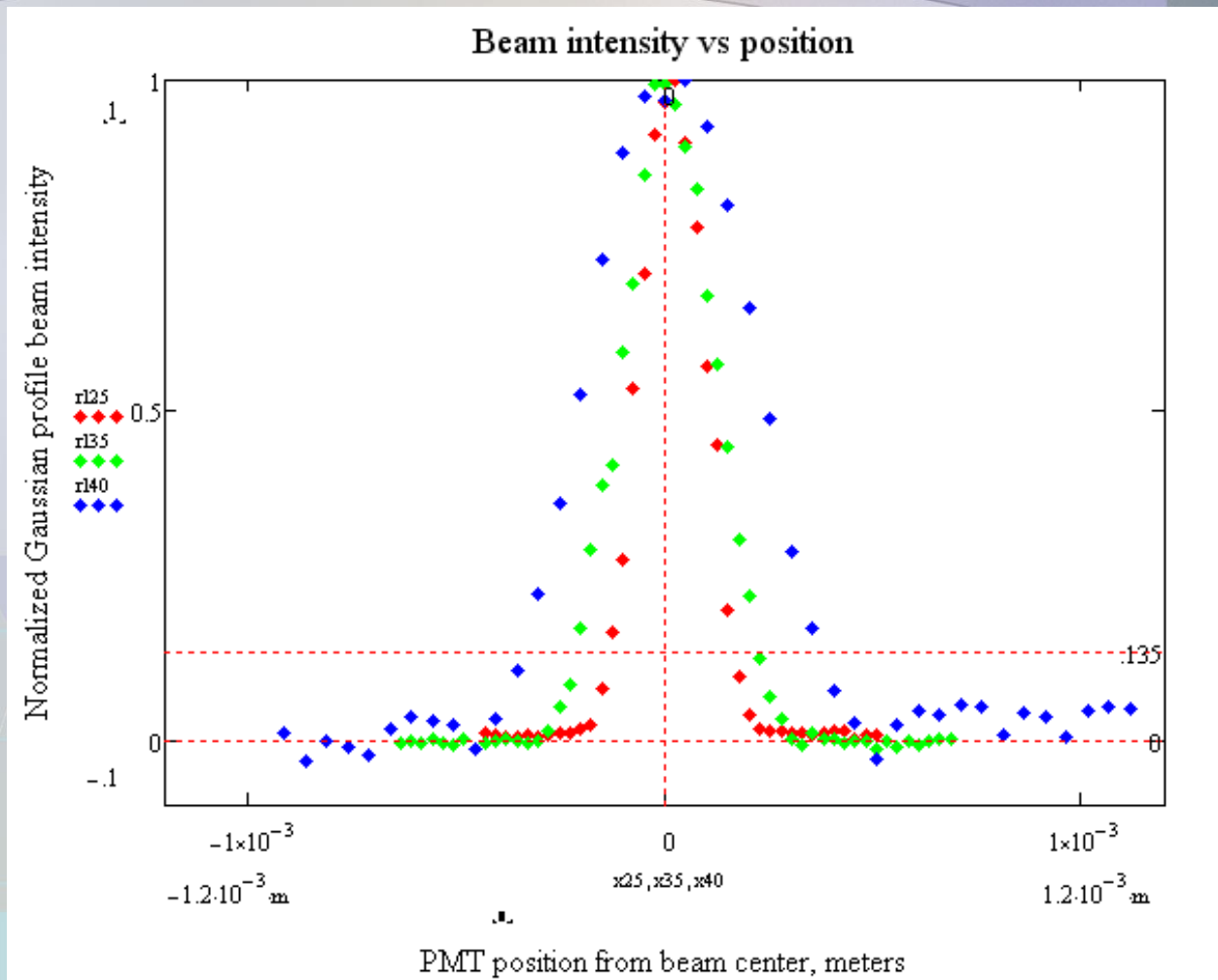
# Results at 35cm from lens



# Results at 40cm from lens



# Results



## Conclusions/Observations

- **The radius of the beam waist of the laser that we found, .57mm, was approximately 6.5% off from the expected value of .61mm**
- **Focal point of the beam calculated to be 26.2cm instead of listed  $f$  of 25cm**
- **Difficulties in finding center of beam at all positions, took much fine tuning of mirror and lens positions**

# **Error Analysis**

## **Sources of system error:**

- 1. Alignment of the optical system was not accurate.**
- 2. Human parallax in reading the micrometer and the scale of the rail.**
- 3. The pinhole didn't work properly; tape interfered with readings and very difficult to align.**

## **Sources of random error:**

- 1. Environmental effect. (room light and particles in air)**
- 2. The "pinhole" program crashed randomly.**
- 3. The PMT fluctuated, causing intensity readings to vary (boiling noise)**

# Error Analysis



# **Physics in the Real World: PMT Applications**

- **Photomultipliers used for measuring quantum dots**
- **Used in space for star mapping**
- **Particle accelerators, neutrino detection**
- **Medical applications include detection of diabetes and HIV in blood samples**
- **Environmental applications include pollution detection**

# Reference Sources

- **PHY 555 Lab Manual and Appendix D**
- **Wikipedia**
- **Thorlabs.com**
- **Newport.com**
- **<http://quarknet.fnal.gov/projects/pmt/student/dynodes.shtml>**