Cathode Ray Tube Deflection

Introduction

I am particularly interested in the motion of electrons in electric and magnetic fields. During an in-class demonstration, I watched the luminous spot on the Cathode Ray Tube's (CRT) phosphor screen move as I changed the accelerating voltage knob in the slightest way. I want to explore the underlying workings of electron beam deflection.

Background:

The cathode ray tube utilizes the fundamental concepts of energy conservation, electric fields, and magnetic fields, to accelerate and deflect electrons beams emitted from an electron gun. The general parts of a cathode ray tube are shown in Figure 1.

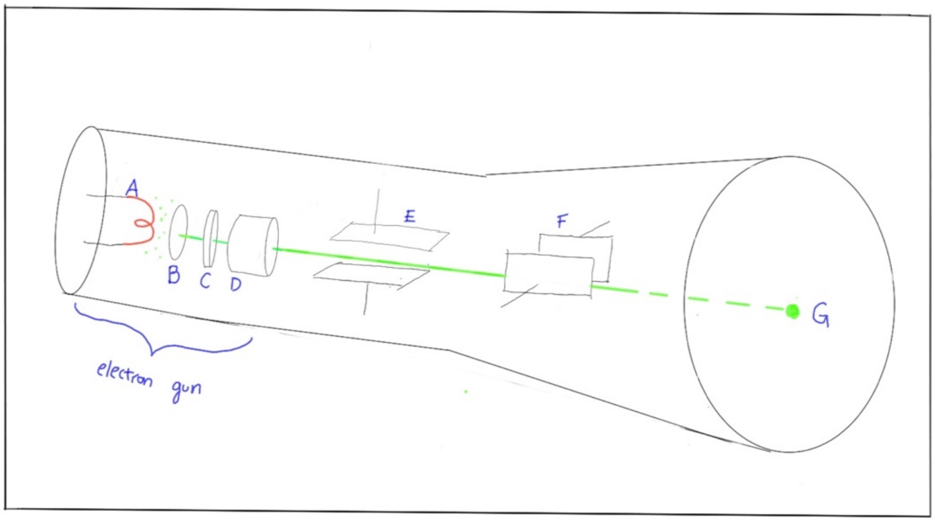

Fig. 1 General parts of Cathode Ray Tube

Through an effect called Thermionic emission, electrons are discharged from hot tungsten filament (A). These free electrons are then accelerated from the cathode (B), to the anode (D), gaining kinetic energy. In between the cathode and anode, the electrons pass through a grid (C), which controls the flow of electrons from the cathode. Some of these electrons pass through a hole in the anode and emerges as an electron beam all with the same speed. The electrons pass through two sets of horizontal plates: y-plates (E) and x-plates (F) and. By changing the potential difference between each set of plates, the beam is deflected up and down and side to side. The electron exits the horizontal plates in a line tangential to the point of exit. The beam eventually hits screen of the CRT. The phosphor coating absorbs the energy of the electrons and a spot of fluorescent light is produced where the beam hits. The path of the electron beam, and ultimately the deflection of the electron beam is dependent on both the accelerating voltage between the cathode and anode and the deflecting voltage between the x-plates and y-plates.

CRT technology was widely used in television and computer monitors. In modern times, they are utilized in the medical field to solve visual stimulation problems. They are used to test visual fields and visual sensitivity.[1]

Research question:

What is the relationship between the accelerating voltage and the deflection of an electron beam in a Cathode Ray Tube.

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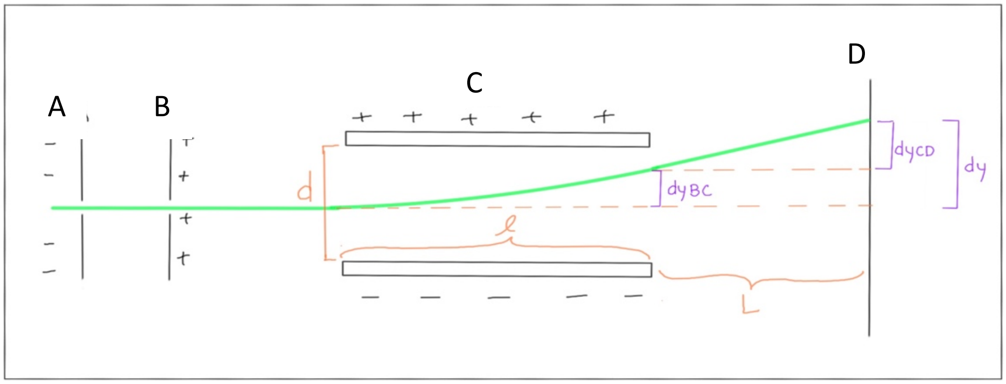
1. Vernier, Francoise, et al. "Application of Cathode-Ray Tube Technology to the Clinical Evaluation of Visual Functions." *NASA/ADS*, https://ui.adsabs.harvard.edu/abs/1988OptEn..27..123V/abstract.

Theory:

Fig. 2 Sketch of Electron Beam deflection



Part 1. Electron gun

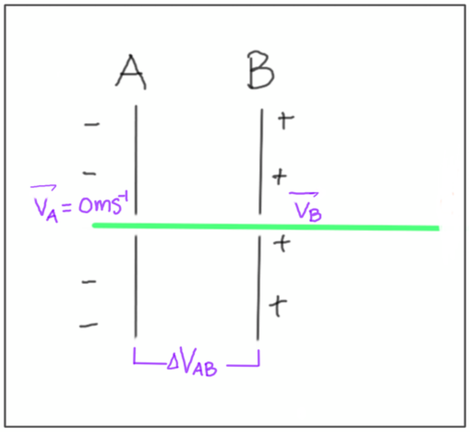


Fig. 3 Cathode and Anode

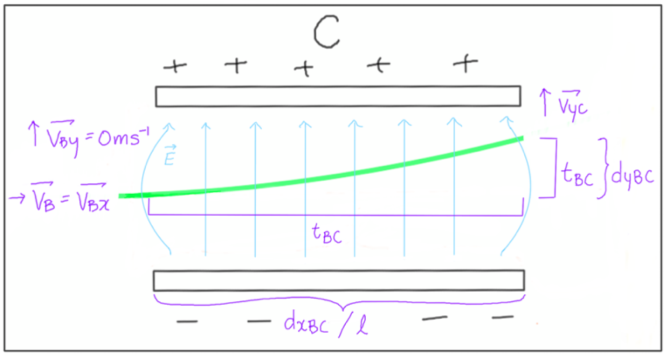
Variables and their signs

$\Delta E_{pAB} =$ *Potential Energy Change from A to B (J)*
$\Delta E_{kAB} =$ *Kinetic Energy Change from A to B (J)*
$q =$ *Charge of electron* $(-1.602 \times 10^{-19})\ C$
$m =$ *Mass of electron* $(\ 9.109 \times 10^{-31})\ kg$
$\Delta v =$ *Velocity Change between A and B* (ms^{-1})
$v_B =$ *Velocity at B* (ms^{-1})
$v_A =$ *Velocity at A* (ms^{-1})
$V_{AB} =$ *Accelerating Voltage (V)*

Conservation of energy states that:
$\Delta E_{pAB} = -\Delta E_{kAB}$, where $E_{pAB} = V_{AB} \times q$ and $E_{kAB} = \frac{1}{2} m\, v^2$ Thus, $\Delta V_{AB} \times q = -\frac{1}{2}\, m\, \Delta v^2 = -\frac{1}{2}\, m\, (\, v_B^2 \text{ - } v_A^2)$
$v_A = 0\ ms^{-1}$, as the electron starts at rest
Thus, $\Delta V_{AB} \times q = -\frac{1}{2} m v_B^2$
With some rearrangement, I get $Eq.1\ v_B^2 = \frac{-2\Delta V_{AB}\, q}{m}$
Electrons escape from the anode in a straight path at a speed of v_B and remains at this speed until they enter the x and y-plates. In this experiment, however, only the x-plates will have a potential difference. The y-plates are short circuited so there is no potential difference between them; the y-plates will not affect the deflection of the electrons.

Part 2. Deflecting Plates

Fig. 4 Cathode and Anode



Variables and their signs

F_e
$=$ *Electrostatic force exerted on electron*
by the uniform electric field (N)
$E =$ *Electric field* (Vm^{-1})
$\Delta V_d =$ *Deflecting Voltage (V)*
$d =$ *Distance between x − plates (m)*
$F_{net\ y} =$ *Net force acting on electron (N)*
$a_v =$ *Accleration in the vertical*

Vertical direction:

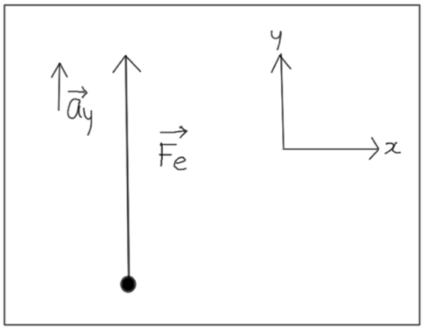


Fig. 5 Free Body diagram of electron inside electric field

As the electrons travel between the uniform field, the electric field exerts an electrostatic force on the electrons and deflects them towards the positive plate:

$F_e = E \times q$ where $E = \frac{\Delta V_d}{d}$. So, $Eq. 2\ F_e = \frac{\Delta V_d q}{d}$

F_e is the only force acting on the electrons so $F_{net\,y} = F_e$.

F_e accelerates the electrons in the vertical direction.

$$Eq. 3\ F_e = ma_y$$

Through combination and rearrangement of Eq. 2 and Eq. 3, a_y can be found.

$$Eq. 4\ a_y = \frac{\Delta V_d q}{dm}$$

The deflection of the electron in the y-direction can be found by utilizing the kinematic equation $d = v_i t + \frac{1}{2}at^2$, where d is displacement of object, v_i is initial velocity of object , a is the acceleration of object, t is elapsed time.

$$d_{yBC} = v_{By} t_{BC} + \frac{1}{2} a_y {t_{BC}}^2$$

$v_{By} = 0ms^{-1}$ as the electron has no velocity in the vertical direction when it just enters the x-plates.

$$Eq. 5\ d_{yBC} = \frac{1}{2} a_y {t_{BC}}^2$$

The vertical velocity of the electron as in exits the plates can be found by utilizing the kinematic equation $v_f = v_i + at$, where v_f is the final velocity of object.

$$v_{yc} = v_{By} + a_y t_{BC}$$

Plugging in Eq. 4 and $0ms^{-1}$ for v_{By} $Eq. 6\ v_{yc} = \frac{\Delta V_d q t_{BC}}{dm}$

Horizontal direction:

The velocity of the electron in the horizontal direction is constant. d_{xBC} can be substituted by l, the length of the x-plates.

$$d_{xBC} = l = v_B t_{BC}$$

$$Eq. 7\ t_{BC} = \frac{l}{v_B}$$

The deflection of the electron in the vertical direction between the x-plates can be found by substituting Eq. 4 and Eq. 7 into Eq. 5

$$Eq. 8\ d_{yBC} = \frac{\Delta V_d q l^2}{2dmv_B^2}$$

Part 3. Exiting deflection plates

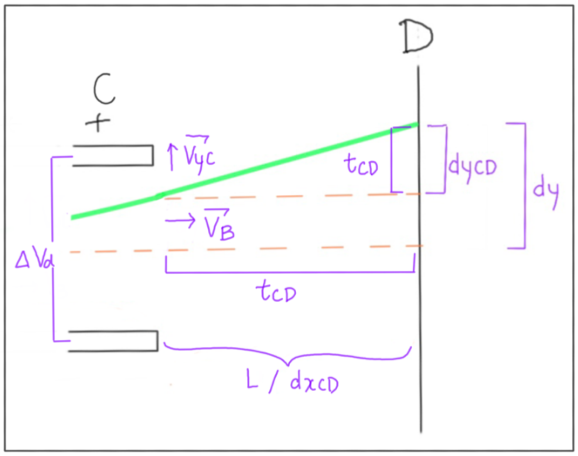


Fig. 6 Electron travelling to phosphor screen

The electron travels in a straight line tangential to the parabolic path it was already travelling in. The velocity in the horizontal and vertical direction is constant.

Vertical direction:

At constant velocity, the displacement of the electron in the vertical direction is shown below:

$$Eq. 9\ d_{yCD} = v_{yc} t_{CD}$$

Horizontal direction:

At constant velocity, the displacement of the electron in the horizontal direction is shown below. d_{xCD} can be replaced by L, the distance between the x-plates and the phosphor screen.

$$d_{xCD} = L = v_B t_{CD}, \text{ so } Eq. 10\ t_{CD} = \frac{L}{v_B}$$

The deflection in the vertical direction can be found by plugging $Eq. 10$ and $Eq. 6$ into $Eq. 9$.

$$Eq. 11\ d_{yCD} = \frac{\Delta V_d q l L}{d m v_B^2}$$

The total deflected distance of the electron in the vertical direction, d_y, is the sum of d_{yBC} and d_{yCD}:

$$d_y = d_{yBC} + d_{yCD}$$

$$d_y = \frac{\Delta V_d q l^2}{2 d m v_B^2} + \frac{\Delta V_d q l L}{d m v_B^2} = \frac{\Delta V_d q l\ (l + 2L)}{2 d m v_B^2}$$

Substituting in $Eq. 1\ v_B^2 = \frac{-2\Delta V_{AB}\, q}{m}$ I get $d_y = \frac{\Delta V_d \cancel{q} l\ (l+2L)}{2d\cancel{m} v_B^2} \times \frac{\cancel{m}}{-2\Delta V_{AB}\, \cancel{q}}$

$$Eq. 12\ d_y = \frac{-\Delta V_d l\ (l + 2L)}{4 d \Delta V_{AB}}$$

From this expression, the vertical deflected distance of the electrons is inversely proportional to the accelerating voltage between the cathode and anode and is proportional to the deflecting voltage between the x-plates. In this investigation, the independent variable is the accelerating voltage and the dependent variable is the electron beam's deflection in the vertical direction.

Controlled variables:

1.The voltage of the 9-volt battery is supposed to stay constant throughout the experiment. This was difficult to control as the CRT is constantly drawing current from the battery. To monitor the state of the battery and reduce errors due to changing deflecting voltage, new batteries were used and after every 6 data points, the voltage of the battery was checked using a multimeter. Two batteries were used during the entirety of the experiment: the first one was switched out when its voltage dropped from 9.47 V, before experiment, to 9.10, after running experiment for a while.

2.The experiment was conducted all at once at the same location. If Earth's magnetic field impacts the deflection, I wanted to make sure that the impact was at least consistent throughout the trials.

3.The focus and intensity knobs were taped down so that they remain constant throughout. Changing these settings alter the accelerating voltage.

Methodology

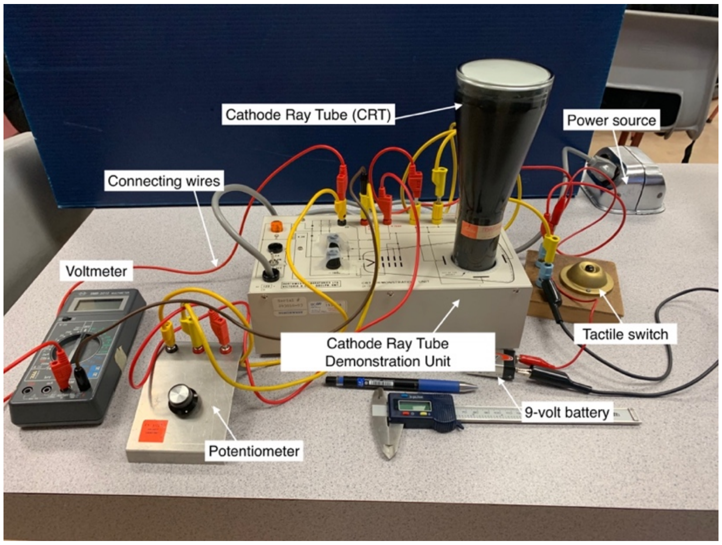


Fig. 7 = Full set up

Setup:

The cathode ray tube was inserted into the demonstration unit. After a few minutes, a green illuminated spot appears on the phosphor screen. To change the accelerating voltage, the CRT demonstration unit is connected to a potentiometer. To measure the accelerating voltage, a voltmeter was connected in parallel to the potentiometer.

The deflective voltage was kept constant throughout the trials. A tactile switch was connected to the x-plates and a new 9-volt battery was connected in parallel to the switch. No battery was connected to the y-plates as they will not be used during this experiment.

Pre-emptive measures:

Earth's magnetic field where the experiment was conducted measured and recorded using the magnetometer on the phyphox app. The possible effects of Earth's magnetic field are discussed in analysis.

Fig. 8 Inside of broken CRT and working CRT

Using a broken and working CRT of the same model, I was able to measure the dimensions of the screen diameter, the distance between the x-plates (d), the length of the x-plates (l), and the distance between the x-plates and the phosphor screen (L). These values can be found in Table 1. The absolute uncertainties in the measurements were chosen to be 0.8 mm instead of 0.5mm, half of the smallest increment on the ruler. Due to the broken pieces of CTR, it was difficult to measure so a greater uncertainty was chosen.

Table 1 CRT dimensions

Distance between x-plates (d)/m	Length of x-plates (l)/m	Distance between x-plates and screen (L)/m	Screen diameter/ m
5.00×10^{-3}	7.45×10^{-2}	1.54×10^{-1}	1.78×10^{-1}

Overview of data collection

The reference point when there is no deflecting voltage was marked. Then the potentiometer was turned to the lowest resistivity setting, allowing the most current through. This is when the accelerating voltage is the highest and the deflection of the electron is the lowest. The illuminated spot was marked, the polarity on the battery was switched, and the new illuminated spot was remarked, resulting in two different deflected points (Fig. 9). This was done because there is a chemical imbalance in the battery resulting the magnitude of electron deflection being slightly different when the polarity is reversed. The average of these two points will be taken. The resistance of the potentiometer was slightly decreased to change the accelerating voltage, and the value was measured using the voltmeter. The range of accelerating voltage the were least and greatest amount of voltage that could be used before the illuminated spot deflected off the screen and was no longer visible. 3 trials were taken at each accelerating voltage, and 18 different accelerating voltages was used, resulting in 54 data points altogether. Using tracker, an online analysis program, the distance between the reference point mark and the deflection marks were measured. (Fig. 10)

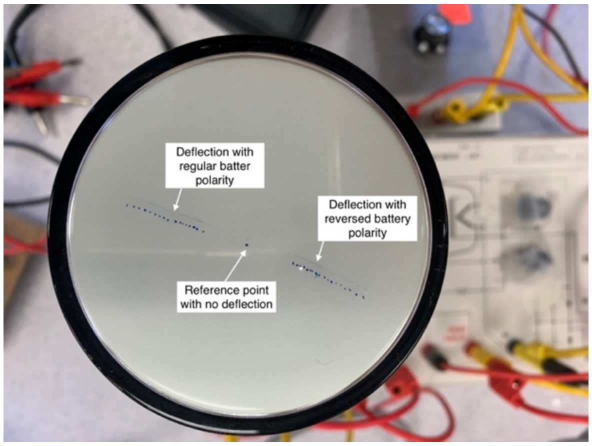


Fig. 9 Deflection pen markings

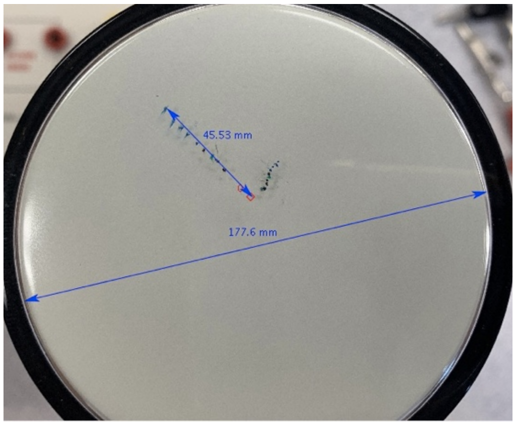


Fig. 10 Measuring deflection, Tracker

Safety concerns:

The CRT itself carries high voltages and can draw large currents. With many connection wires and connecting points, electrocution due to improper connection or CRT discharge could have been a danger to myself and to those around me. CRT's can also be hazardous if dropped; due to the large amounts of gas evacuated, the broken glass would fly outwards at fast speeds. Additionally, I was working with a broken CRT with exposed glass edges. Although the sharp pieces were already covered with tape, this equipment was fragile and could easily shatter in my hands. Utilizing spatial awareness and taking extra care with the electrical connecting points and sharp glass material, I conducted this experiment with caution.

Collected data:

At each accelerating voltage, there is two different deflected distance (due to polarity reversal of the battery). These two values are averaged. 3 trials were taken at each accelerating voltage, and 18 different accelerating voltages was used. The Raw Data table can be found in the appendix (p 15). The Processed Data Table with the average deflected distances is shown below. As seen in Table 2, the absolute uncertainty on the accelerating voltage, V_{AB}, is 5volts, despite the voltmeter being precise to the ones place. This is because when reading the voltmeter, the value on the screen fluctuated. Thus, a greater uncertainty was placed on the variable. The absolute uncertainty for the deflection is 0.8mm although on Tracker, the deflected value was precise to the hundredth place. The greater absolute error is to account for parallax error in the photo as it may not have been taken exactly 90° above the screen as well as for the uncertainties in markings due to pen smudges and thicker dots.

Table 2: Accelerating Voltage and Average Deflection

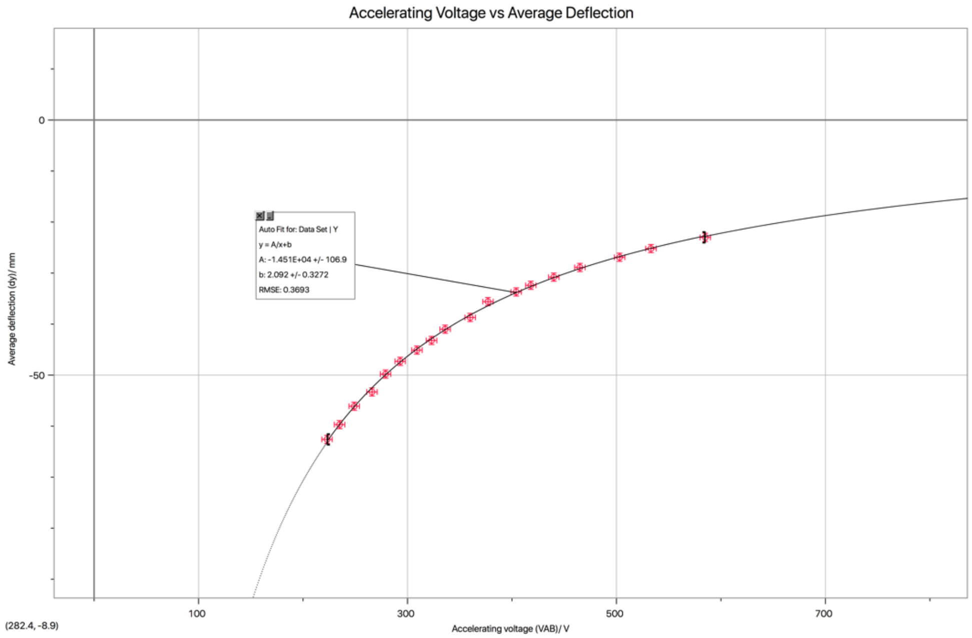
Data point number	Accelerating voltage $5V$	Average deflection d_{yave}/ mm $\pm 0.8mm$
1	585	-23.0
2	533	-25.2
3	503	-26.9
4	465	-28.9
5	440	-30.8
6	418	-32.4
7	404	-33.7
8	377	-35.6
9	360	-38.7
10	336	-41.0
11	323	-43.2
12	309	-45.1
13	293	-47.3
14	279	-49.8
15	266	-53.3
16	249	-56.1
17	235	-59.7
18	223	-62.6

Graphing the data from Table 1 will show a visual representation of the relationship between the accelerating voltage and the deflected distance.

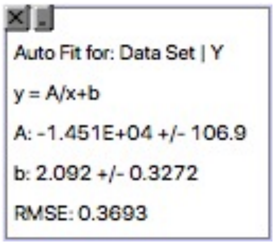
Sample calculation for d_{yave}

$$d_{yave} = \frac{d_{y1} + d_{y2} + d_{y3}}{3} = \frac{-24.5 + (-22.0) + (-22.6)}{3} =$$

-23.0mm



Graph 1 Average Deflection vs Accelerating Voltage


Auto Fit for: Data Set | Y

y = A/x+b

A: -1.451E+04 +/- 106.9

b: 2.092 +/- 0.3272

RMSE: 0.3693

Fig. 11 Zoom in on graph 1 details

From Graph 1, the relationship between the accelerating voltage and the average deflection was found to be inverse in the form of $y = \frac{A}{x} + b$. My mathematical model, however, shows an inversely proportional relationship in the form of $y = \frac{A}{x}$. The average deflection intercept of 2.092mm may signify a systematic error present in the experiment. The greater the intercept, the further the data points deviates from the theoretical inverse relationship and greater the systematic error present. Further discussion found later. All the deflection values are negative, although in data collection, the absolute deflected distance was recorded down. Qualitatively observing the graph, it is evident that the absolute deflection decreases drastically when the accelerating voltage is in the lower voltage range (from around 223V- 336V) whereas the deflection decreases less significantly as the accelerating voltage reaches its max range (465V-585V). As a result, the slope of the graph is steeper at the lower voltage range and starts to flatten out at the higher end. The best fit line crosses the error bars of every data point and the root-mean-square-error (RMSE) of 0.37 shown in Fig. 11 is relatively small. However, RMSE is scale-dependent and may not be a good measure of how accurate the relationship between the variables is.

Table 2: Inverse of Accelerating Voltage and Average Deflection

Data point number	Inverse of Accelerating voltage $(\frac{1}{V_{AB}}) / \frac{1}{V}$ $\pm 1.0 \times 10^{-5}\ V$	Average deflection d_{yave}/ mm $\pm 0.8mm$
1	0.00171	-23.0
2	0.00188	-25.2
3	0.00199	-26.9
4	0.00215	-28.9
5	0.00227	-30.8
6	0.00239	-32.4
7	0.00248	-33.7
8	0.00265	-35.6
9	0.00278	-38.7
10	0.00298	-41.0
11	0.00310	-43.2
12	0.00324	-45.1
13	0.00341	-47.3
14	0.00358	-49.8
15	0.00376	-53.3
16	0.00402	-56.1
17	0.00426	-59.7
18	0.00448	-62.6

To confirm the $y = \frac{A}{x} + b$ relationship suggested above, Graph 1 was linearized by plotting the inverse of accelerating voltage, $\frac{1}{v_{AB}}$, against the average deflected distance, d_{yave}. Graph 2 is the linearized graph.

Sample calculation for $\frac{1}{v_{AB1}}$ and $\Delta\frac{1}{v_{AB1}}$

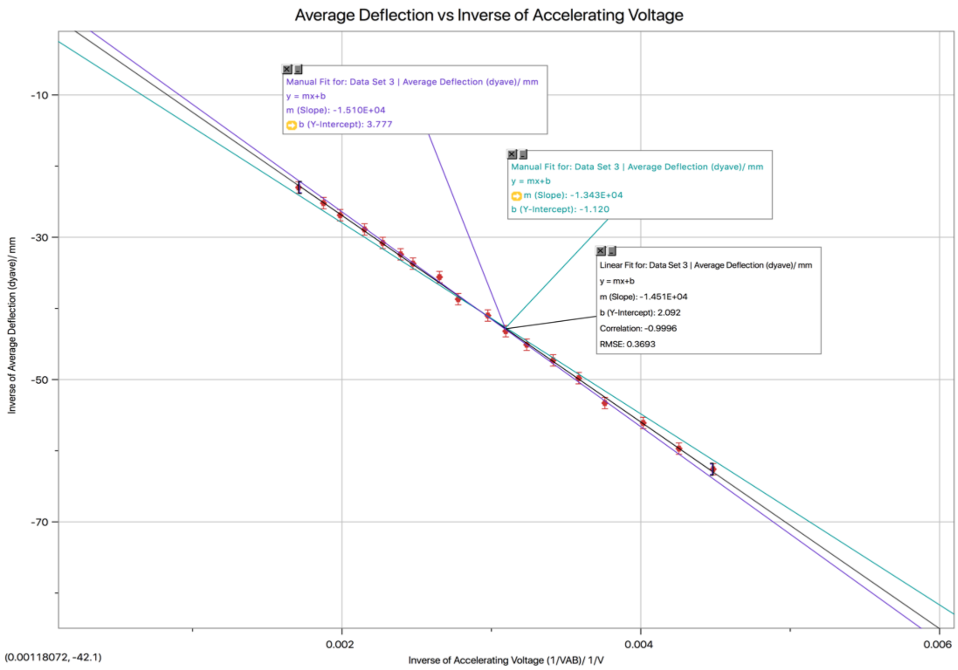
$$v_{AB1} \pm \Delta v_{AB1} = (585 \pm 5)V$$

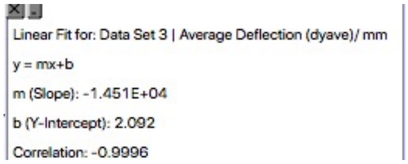
$$\frac{1}{v_{AB1}} = \frac{1}{585} = 0.00171\ V$$

$$\Delta\frac{1}{v_{AB1}} = \frac{\Delta v_{AB1}}{v_{AB1}} \times \left|\frac{1}{v_{AB1}}\right| = \frac{5V}{585V} \times 0.00171\ V$$

$$= 0.000012\ V \approx 0.00001\ V$$

$$\frac{1}{v_{AB1}} \pm \Delta\frac{1}{v_{AB1}} = (0.00171 \pm 0.00001)\ V$$





Linear Fit for: Data Set 3 | Average Deflection (dyave)/ mm

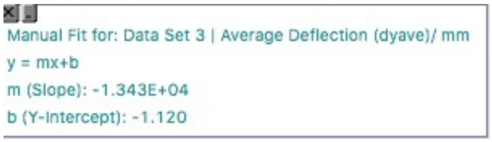
y = mx+b

m (Slope): -1.451E+04

b (Y-Intercept): 2.092

Correlation: -0.9996

Fig. 12 Zoom in on graph 2 details

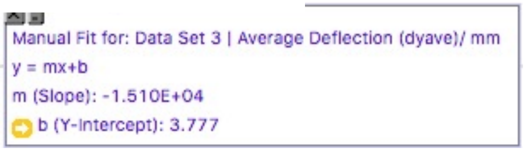


Manual Fit for: Data Set 3 | Average Deflection (dyave)/ mm

y = mx+b

m (Slope): -1.343E+04

b (Y-Intercept): -1.120



Manual Fit for: Data Set 3 | Average Deflection (dyave)/ mm

y = mx+b

m (Slope): -1.510E+04

b (Y-Intercept): 3.777

Observing Graph 2, it is evident that the relationship between the accelerating voltage and the inverse of average deflection is linear, also confirming the inverse relationship between the accelerating voltage and the average deflection. The best-fit line, minimum-steepness line and maximum-steepness line were all graphed. The correlation between the data points and the best-fit line was -0.9996, showing a very high negative correlation. The average deflection intercept from Graph 1 is still present here but is reduced from 2.092mm to 0.001mm. But this does not mean the systematic error got smaller; it is merely scale dependent.

The slope of the line and its theoretical value:

Eq. 12 $d_y = \frac{-\Delta V_d l\,(l+2L)}{4d\Delta V_{AB}}$, can be rearranged into the following expression: $d_y = \frac{-\Delta V_d l\,(l+2L)}{4d} \times \Delta V_{AB}{}^{-1}$

Here, it becomes obvious that the slope of a Deflection vs Accelerating Voltage graph represents $\frac{-\Delta V_d l\,(l+2L)}{4d}$.

The absolute uncertainty of the slope of the best-fit line can be calculated using the maximum-steepness and minimum- steepness lines from Graph 2. Using the same accelerating voltage, deflecting voltage and magnetic field values from the original data set, as well as measured CTR dimensions, the theoretical value of the slope, $m_{literature}$, can be calculated. CTR dimensions can also be found in Table 1.

m_{best}= -14500 mmV m_{max}= -15100 mmV m_{min}= -13400 mmV

$$\Delta m_{best} = \frac{|m_{max} - m_{min}|}{2} = \frac{|-15100\,mmV - (-13400 mmV)|}{2} = 850\,mmV$$

$m_{best} \pm \Delta m_{best}$= (-14500±800) mmV

ΔV_d= 9.5V $l = 7.45 \times 10^{-2} m = (74.0\ \pm 0.8)mm$ $L = 1.54 \times 10^{-1} m = (154.0\ \pm 0.8)mm$

d =5.00× $10^{-3}\ m\ = (5.0 \pm 0.8)mm$

$$m_{literature} = \frac{-\Delta V_d l\,(l+2L)}{4d} = \frac{-\Delta 9.5V \times 74.0mm \times\ (74.0 + 2 \times 154.0)mm}{4 \times 5.0\ mm} = -13105\ mmV$$

Here, it is evident that the $m_{literature}$ value is smaller than the m_{best} values. Since $m_{literature}$ was found using the same accelerating voltage as in m_{best}, the deviation is due to the amount of deflection. m_{best} values were greater, meaning the experimentally determined deflection was greater than the theoretically determined deflection. The systematic error is found by comparing the literature value of the slope, $m_{literature}$, to the measured value of the slope, m_{best}.

$Percentage\ error$

$$\frac{|measurement - literature\ value|}{literature\ value} \times (100\%) = \frac{m_{best} - m_{literature}|}{m_{literature}} \times (100\%) = \frac{|-14500\ mmV - (-13105\ mmV)|}{-13105\ mmV} \times (100\%)$$

$Percentage\ error$= 10.6%

$Random\ error$

$$\frac{absolute\ uncertainty}{measurement} \times (100\%) = \frac{\Delta m_{best}}{m_{best}} \times (100\%)$$

$$= \frac{800}{14500} \times (100\%)$$

$Random\ error$= 5.5%

$Systematic\ error$

$$|Random\ error - Percentage\ error| = |5.5\% - 10.6\%|$$

$$= 5.1\%$$

Analysis:

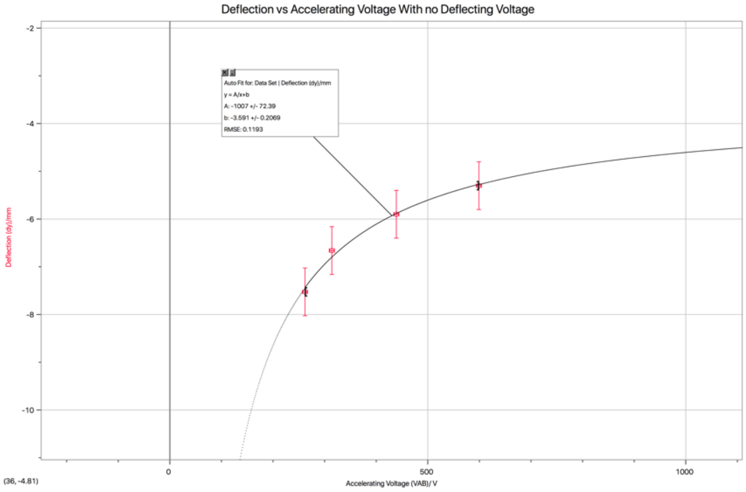
Many factors may have contributed to the 5.1 % systematic error and most are discussed later in Apparatus limitations and error analysis. However, I particularly wanted to investigate the influence of Earth's magnetic field on the deflection.

Earth's magnetic field:

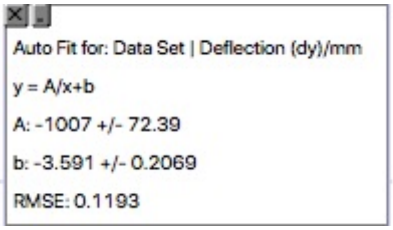
To test if the magnetic field was causing any unaccounted deflection, I short-circuited both and x-plates and y-plates, meaning the deflecting voltage was zero. Theoretical model indicates that when deflecting voltage is zero, there should be no deflection: $d_y = \frac{-\Delta V_d l\ (l+2L)}{4d\Delta V_{AB}}$, when $V_d = 0V, d_y = 0mm$. However, the electron beam was still deflected from its original position when I changed the accelerating voltage.

Table 3 Accelerating Voltage and Deflection with no battery

Data point number	Accelerating voltage $(V_{AB})/\ V$ $\pm 5V$	Deflection d_y/ mm $\pm 0.8mm$
1	599	-5.3
2	439	-5.9
3	314	-6.7
4	262	-7.5



Graph 3 Deflection vs Accelerating voltage with no Battery



Auto Fit for: Data Set | Deflection (dy)/mm

y = A/x+b

A: -1007 +/- 72.39

b: -3.591 +/- 0.2069

RMSE: 0.1193

Graph 3 shows the relationship between the deflection and the accelerating voltage. The $\frac{-\Delta V_d l\,(l+2L)}{4d}$ or A value on the graph is smaller than that of the original data set with a deflecting voltage of 9.4V, meaning that the deflection was greater when there was a deflecting voltage than when there was not. Nonetheless, there was still a deflection when accelerating was changed even with no deflecting voltage. This deflection may be due to Earth's magnetic field strength. To further test this theory, I compared the theoretical deflection to the experimental deflection.

$Theoretical\ deflection\ with\ Accelerating\ voltage\ of\ 559V\ and\ magnetic\ field\ of\ 49\ \mu T$

The following equation is used to calculate the deflection in the presence of a magnetic field. B is magnetic field strength (T): $Eq.13\ d_y = \frac{qBL^2}{2mV_B}$ where, $v_B = \sqrt{\frac{-2\Delta V_{AB}\,q}{m}}$ (rearranging Eq. 1)

$$v_B = \sqrt{\frac{-2\times 599V\times(-1.602\times10^{-19})\,C}{(9.109\times10^{-31})\,kg}} = 1.4\times 10^7$$

$$d_y = \frac{(-1.602\times10^{-19})\times4.9\times10^{-5}\times(1.54\times10^{-1})^2}{2\times(9.109\times10^{-31})\times1.4\times10^8} = \text{-0.007m} = \text{-7.0 mm}$$

Experimental value = -5.3mm

The close experimental and theoretical deflection values suggest that Earth's magnetic field is a major systematic error in this investigation.

Further analysis of apparatus and data collection process:

Apparatus: The limitations of the apparatus itself may have contributed to the random and systematic errors present in this investigation.

Residual voltage: Because the CRT was running for the entirety of the experiment while using high voltages, residual voltages may remain in the tube itself or in circuit containing the CRT. These residual voltages can build up and eventually cause electron deflection that are hard to accounted for. As discharging the CRT is extremely dangerous, this is not recommended. However, testing in increment of time and allowing the CRT the rest in between trials may lead to better results. The residual voltage may explain the deflection when deflecting voltage was zero, but this is only a speculation and no evidence was found to confirm this hypothesis.

Inconsistent spot sizes: As the accelerating voltage was decreased, the size of the illuminated dots increased and became fainter, making the deflection hard to mark. The dot sizes range from less than half a mm to almost 2 mm. The deflection may have been slightly skewed as I had difficulties deciding where to mark the spot. I tried to mark the centre of each dot to be consistent, but the spot itself was often not circular and the boundaries of the spot's outline were ambiguous. By finding the relationship between the size of the dot and the deflection, I can better understand where exactly to place my marking to best represent the deflection.

Data collection process:

I found Tracked to be quite reliable. With tracker I was able to zoom in extremely close to the markings and track the deflection with higher precision, accuracy, and confidence. Nonetheless, the process was not perfect. The pictures of the phosphor screen which were later analyzed in tracker were not taken directly above the screen, resulting in parallax errors. When analyzing the picture in tracker, the markings may have been slightly skewed. By using a tripod and inclinometer, these parallax errors can be reduced significantly.

Conclusion:

Through my investigation, I was able to answer the research question: "*What is the relationship between the accelerating voltage and the deflection of an electron beam in a Cathode Ray Tube".* Using a potentiometer to change the accelerating voltage and using tracker, an online analysis and modelling tool, I was able to collect data and visually represent them graphically. Average deflection was plotted against Accelerating voltage in Graph 1 and this Graph's best fit curve passed through all the error bars, indicating a strong correlation. An inverse relationship with an Average deflection- intercept of 2.092mm was found between the variables. Theoretically, the relationship should just be inverse, so the intercept found signifies that systematic errors are present. To confirm the relationship, graph 1 was linearized by plotting average deflection against the inverse of accelerating voltage in graph 2. Here, the best-fit line, maximum steepness-line, and minimum steepness line were graphed. From the mathematical model, it is evident that the slope of the best-fit line represents $\frac{-\Delta V_d l\ (l+2L)}{4d}$. $m_{best} \pm \Delta m_{best}$ was found to be (-14500$\pm$800) mmV and was compared to $m_{literature}$,$-13105\ mmV$. The systematic error is the difference between the random and percentage and was found to be 5.1%.

Uncertainties for the accelerating voltage and deflection was based on the precision of the equipment itself and how well I was able to use them. The voltmeter often fluctuated, so the uncertainty was 5V rather half of the smallest readable increment, which was 0.5V. Tracker, the tool I was using the measure deflection, gave lots of decimal points. However, I wanted to account for parallax errors that might have been present when taking the photo. From Eq. 12, it shows that when no deflecting voltage is used in the CRT, there should also be no deflection. However, this was not the case when I experimentally tested the CRT with no deflection voltage. Using Eq. 13, the theoretical deflection values were found and compared to experimental values. The results were very similar, leading to the conclusion that Earth's magnetic field was a significant systematic error. Even with random and systematic errors present in this investigation, the data collected and results are well supported by the mathematical model and theory.

Extension to investigation:

A possible extension to this investigation can be to further research the impacts of a magnetic field on the deflection of an electron beam. By conducting the experiment at a variety of locations with different magnetic field strengths, I can find relationship between changing magnetic field strengths and deflection. If the range of Earth's magnetic field strength is not significant, I can create a magnetic field using a solenoid to better control the range of magnetic field strength.

Works Cited:

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TV and Monitor CRT (Picture Tube) Information, http://repairfaq.cis.upenn.edu/sam/crtfaq.htm.

Appendix:

Table 4 Raw data table with 3 deflection trials

Data point number	Accelerating voltage (V_{AB})/ $V \pm 5V$	Deflection d_y/ mm $\pm 0.8mm$		
		T1	T2	T3
1	585	-24.5	-22.0	-23.0
2	533	-26.7	-25.4	-25.2
3	503	-28.2	-27.0	-26.9
4	465	-30.3	-29.3	-28.9
5	440	-32.1	-31.0	-30.8
6	418	-33.6	-32.8	-32.4
7	404	-34.5	-34.2	-33.7
8	377	-36.5	-36.5	-35.6
9	360	-38.5	-40.3	-38.7
10	336	-41.4	-42.7	-41.0
11	323	-43.2	-44.6	-43.2
12	309	-45.3	-47.0	-45.1
13	293	-47.7	-49.9	-47.3
14	279	-50.2	-52.3	-49.8
15	266	-52.9	-55.5	-53.3
16	249	-55.1	-58.3	-56.1
17	235	-59.2	-61.5	-59.7
18	223	-62.9	-63.9	-62.6