Lab 2: The Oscilloscope - motion of free electrons in an electric field

1 Introduction

The oscilloscope is a very versatile instrument that is used almost universally for data acquisition, and as a diagnostic tool. Its principle of operation is relatively easy to understand. However, students usually react with alarm and confusion when confronted with the numerous buttons and switches on the front panel of the device. This laboratory will hopefully assist you in overcoming any hesitation in using this device.

An analogue oscilloscope consists of an electron gun encased in an evacuated narrow glass tube. The tube has a wide end face (coated with a phosphor) on which signals are displayed. In many ways, its construction resembles that of a television tube. Electrostatic focusing plates and electron beam deflection plates are enclosed within the narrow tube and connected to the outside via feed-through elements. This lab will allow students to understand the principles of such an oscilloscope.

An electron beam is produced by electrically heating a metal foil (or filament). Electrons in the foil acquire sufficient kinetic energy to escape the foil. A large electric potential difference between the foil and a ring electrode accelerates the electrons. The focusing plates shape the cross section of the electron beam. The electron beam can be deflected by uniform electric fields between the deflection plates before hitting the phosphor screen. These electric fields are produced by applying a (voltage) signal to the inputs of the oscilloscope. When the electron beam strikes the phosphor screen, excited atoms in the phosphor convert the kinetic energy of the electron beam into light, producing a characteristic glow.

A digital oscilloscope does not have an electron beam tube. The input waveform is digitized and displayed on the screen.

You will first use a stripped down electron tube to learn how electrons are deflected in a uniform electric field. **For the rest of this report, we will refer to this oscilloscope as the cathode ray tube or CRT.** The CRT is built so that the deflection plates and other electrodes are clearly visible. The experiments will allow you to measure the axial speed of the electron beam. Subsequently, you will learn how a simple waveform can be displayed on the screen. Finally, you will work with a standard laboratory oscilloscope, learn how to trigger the scope, and display waveforms.

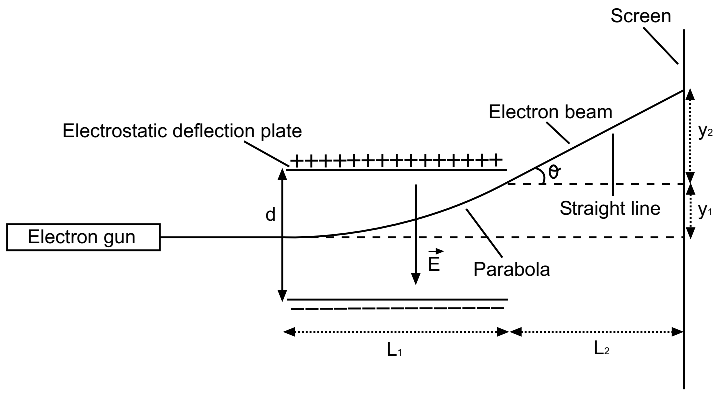

Figure 1: Electron beam deflection. **NOTE:** $L_2 \gg L_1$.

EXERCISES 1 AND 8A PERTAIN TO THE BACKGROUND CONCEPTS AND EXERCISES 2-7 AND 8B-11 PERTAIN TO THE EXPERIMENTAL SECTIONS.

2 Background

The basic principle of the oscilloscope is electrostatic deflection. When the electron beam shown in figure 1 travels through a uniform electric field $\vec{E}$ between the deflection plates, it experiences a force $\vec{F}$ along the vertical direction given by,

$$\vec{F} = q\vec{E}. \tag{1}$$

The corresponding acceleration $\vec{a}$ in the region between the plates is given by,

$$\vec{a} = \frac{q\vec{E}}{m} \tag{2}$$

where, q and m are the charge and mass of the electron respectively.

The relationship between the magnitude of the uniform electric field and the electric potential difference V between the plates is expressed by the equation,

$$E = \frac{V}{d} \tag{3}$$

where, d is the distance between the plates. The direction of the electric field is shown in figure 1.

In the absence of an electric field between the deflection plates, the electron beam travels straight from the gun and strikes the phosphor screen. When a voltage is applied between the plates, the deflected spot moves along a line perpendicular to the deflection plates. Using two mutually perpendicular pairs of deflection plates, a laboratory oscilloscope is able to deflect the beam to any point on the screen. The CRT has only one set of deflection plates. Therefore, we will use a magnetic field produced by a current carrying coil to produce the deflection associated with the second pair of plates.

The force due to the electric field responsible for the deflection of the beam is experienced only when the electrons are between the plates. Assume that the electron beam is moving with an initial speed v_x in the horizontal direction when it enters the region between the plates. The time spent between the plates (of length L_1) is given by,

$$t_1 = \frac{L_1}{v_x} \tag{4}$$

When the beam leaves the region between the plates, the horizontal component of its velocity is unchanged. The vertical component of its velocity is given by $v_y = at_1$. Using equation 2 and equation 4 we can write,

$$v_y = (\frac{q\overrightarrow{E}}{m})(\frac{L_1}{v_x}) \tag{5}$$

It is easy to see that the angle of deflection of the beam Θ can be expressed as,

$$\tan\Theta = \frac{v_y}{v_x} \tag{6}$$

Exercise 1a: Using the results of equations 5 and 3 in equation 6, show that

$$\tan\Theta = \frac{qVL_1}{md{v_x}^2} \tag{7}$$

Exercise 1b: What is the time taken by the electron beam to travel the distance L_2?

Exercise 1c: Find expressions for the deflections y_1 and y_2 shown in figure 1. Hence show that the total deflection $y = y_1 + y_2$ in terms of L_1 and L_2 is,

$$y = \frac{qVL_1}{md{v_x}^2}(\frac{1}{2}L_1 + L_2) \tag{8}$$

Exercise 1d: With the aid of figure 1, and your expression for the deflection y_2, derive an expression for $\tan\Theta$ and show that this expression agrees with equation 7.

3 Suggested Reading

Refer to the chapters on Capacitors and the Magnetic Field,

R. Wolfson and J. Pasachoff, **Physics with Modern Physics** (3rd Edition, Addison-Wesley Longman, Don Mills ON, 1999)

D. Halliday, R. Resnick and K. S. Krane, **Physics** (Volume 2, 5th Edition, John Wiley, 2002)

4 Apparatus

Refer to Appendix E for photos of the apparatus

- Cathode Ray Tube or CRT with Magnetic Coil attachment
- Oscilloscope
- 100-300V DC Power Supply
- 0-120V DC Power Supply (Hewlett Packard 6212A)
- 6.5V DC Power Supply (Hammond)
- 0-30V DC Power Supply (Lodestar PS-305)
- Function Generator
- Magnetic Field Coil
- Banana Wires
- BNC cables
- Adapter box with connectors (to connect deflection plates to HP 6212A Power Supply)

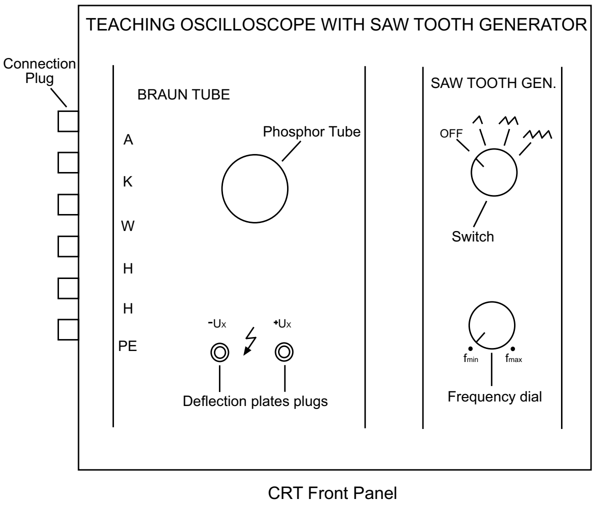

Figure 2: CRT front panel

5 Setting up the experiment

You will be using several power supplies during the experiment. Therefore, it is necessary that you carefully connect the devices in use. Study the diagrams below carefully.

Figure 2 is a sketch of the front panel of the CRT. Notice where the vacuum tube is located, labeled phosphor tube. It has been removed from the sketch in order to provide a clearer view of the panel. The connecting plugs found on the left side of the panel are used to supply the CRT with power. Plug 'A' is connected to the anode while 'K' is connected to the cathode. This setup is required to accelerate the electrons down the tube. The two 'H' plugs are used for supplying power to the filament that is heated to emit electrons.

The Saw Tooth Generator on the CRT panel has two knobs, one to turn it on and change the nature of the waveform and the other to adjust the frequency of the chosen waveform. The two plugs labeled U_x supply power to the deflecting plates in the tube. The potential difference between these plates deflects the electron beam.

Figure 3 shows the top view and the side view of the Cathode Ray Tube. Notice the CRT's panel plugs in each of these figures. The anode and cathode are held and connected to the panel using separate metal wires. The cathode contains the filament (metal foil) that is the source of electrons. The anode has a small hole in the middle that focuses the electron beam. The horizontal electrostatic plates are connected to the deflection plugs.

The magnetic field coil that is visible in the side view diagram of the CRT is attached on a circular ring that has been omitted for the sake of simplicity. The ring surrounds the CRT around the area of the deflection plates. As mentioned previously, the magnetic field coil is used instead of a set of vertical deflection plates.

CAUTION: THIS EXPERIMENT USES HIGH VOLTAGES. MAKE SURE THAT ALL CONNECTING CABLES ARE PLUGGED INTO THE APPROPRIATE CONNECTORS BEFORE YOU TURN ON ANY OF THE EQUIPMENT.

CAUTION: THE CRT HAS A FAIRLY LIMITED LIFETIME. PLEASE TURN OFF THE ELECTRON GUN WHEN IT IS NOT IN USE.

The filament (cathode) in the electron gun is heated by the Hammond 6.5V DC source. The red plug on the power source should be connected to the green plug on the CRT controller labeled 'H'. The black plug on the power source should be connected to the black plug on the CRT controller labeled 'H'.

The accelerating ring electrode is maintained at +175V using the 100-300V DC power source. The red connector on this power source is connected to the red plug labeled 'A' on the CRT controller. The black plug on the source must be connected to the black plug on the CRT controller labeled 'K'. The 'W' plug on the CRT controller must also be connected to the 'K' connector. Verify the source voltage is set to 250V using a voltmeter.

When the power supplies are turned on, a green fluorescent dot should appear on the phosphor screen within 30 seconds. If the dot is not observed, please consult the TA. A round magnet on the support arm of the CRT can be adjusted to move the dot around and center it on the phosphor screen.

CAUTION: KEEP THE POWER SUPPLIES AS FAR AWAY FROM THE CRT AS POSSIBLE. MAGNETIC FIELDS FROM THE POWER SUPPLIES CAN AFFECT THE ELECTRON BEAM.

6 Experiment I: Electrostatic deflection

To apply a DC voltage to the deflection plates, first disconnect the (red and blue) deflection plate cables from the CRT controller. Connect these cables to the + and − outlets of the Hewlett Packard 6212A power supply. An adapter box with suitable connectors is provided to connect the deflection plates to the power supply.

When the power supply voltage is turned on, you will notice that the fluorescent dot on the phosphor screen becomes very dim. You may want to turn off the room lights for this portion of the experiment. Adjust the round magnet on the support arm of the CRT so that the dot moves along a horizontal line when the power supply voltage to the deflection plates is increased. The round magnet is necessary to cancel out the effect of the Earth's magnetic field at the location of the plates.

Exercise 2: Now measure the displacement of the fluorescent dot by varying the voltage to the deflection plates in steps of 5-10 volts (up to $\sim$ 50V). For each voltage setting, measure the power supply voltage with a digital voltmeter. Tabulate your results.

Exercise 3: Based on the results of exercise 1, figure out a way of plotting your data and extracting the speed of the electron beam v_x from your graph. **NOTE:** The deflection plates have dimensions 12 mm x 20 mm. They are spaced 12 mm apart.

Exercise 4: From your answer to exercise 3, estimate the time it takes an electron to reach the phosphor screen from the time it leaves the filament. Neglect the acceleration due to the ring electrode. Estimate the deflection of the electron beam due to gravity in the time that it arrives at the phosphor screen.

7 Experiment II: Deflection due to a magnetic field

Magnetic fields can also cause the deflection of an electron beam. A particle with charge q that is moving with a velocity $\overrightarrow{v}$ in a uniform magnetic field $\overrightarrow{B}$ will experience a force $\overrightarrow{F}$ given by,

$$\overrightarrow{F} = q(\overrightarrow{v} \times \overrightarrow{B}) \tag{9}$$

Connect the + and − outlets of the LODESTAR PS-305 power supply to the green and yellow plugs of the magnetic field coil respectively. Adjust the voltage between 0 V and 3 V using the fine adjust knob.

Exercise 5: What happens to the dot when the power supply voltage is adjusted? Observe and record the direction in which the dot moves. Use equation 9 to deduce the direction of the magnetic field. Draw a diagram indicating the position of the coil, the direction of deflection and the direction of the initial velocity of the electron beam.

Exercise 6: Calculate the deflection of the electron beam due to the magnetic field of the earth ($\sim$ 1 Gauss, with a downward angle of inclination of $\sim 71^o$ with respect to the horizontal along the S-N direction). To verify your calculation, first turn off all the deflecting electric fields. Adjust the round magnet on the support arm of the CRT to center the electron beam on the phosphor screen. Then move the magnet far away from the apparatus. Is the deflection of the electron beam in the earth's field consistent with your calculation?

Exercise 7: Use the round magnet to center the electron beam on the phosphor screen. Connect the magnetic field coil to the function generator. Set the frequency to its lowest setting. Gradually increase the frequency to $\sim$ 100 kHz. Observe the spot on the screen. Draw a sketch of what you observe at low frequencies and at high frequencies.

The inductance of the magnetic field coils poses severe limitations at high frequencies. This is why most laboratory oscilloscopes use two pairs of electrostatic plates to deflect the electron beam (and avoid using magnetic field coils).

8 Experiment III: Adding a time base to the CRT

The CRT contains a built in saw tooth generator. The output of this generator is a time dependent saw tooth voltage.

Exercise 8a: Sketch a saw tooth voltage as a function of time and show the period of the waveform on the sketch. When this voltage is connected to the deflection plates, predict the motion of the electron beam on the phosphor screen. Explain your prediction qualitatively. Also explain what you would expect if the frequency of the saw tooth waveform is increased (i.e. the waveform period is decreased)

Exercise 8b: Connect the red and blue cables attached to the deflection plates to the CRT controller. Turn on the saw tooth generator on the CRT controller. The saw tooth voltage is now applied to the deflection plates. Record your observations. What happens when the frequency of the saw tooth generator is increased? Are your results consistent with your predictions?

Exercise 9: Connect the deflection plates to the saw tooth generator and the function generator to the magnetic field coil. The dial on the saw tooth generator can be adjusted to change the frequency of the saw tooth waveform. This is the "sweep frequency" of the electron beam. Now turn on the function generator and fix the oscillation frequency at $\sim$ 1 kHz. You should be able to see a "steady" pattern on the screen when you vary the frequency of the saw tooth waveform. Draw a sketch showing this pattern.

An oscilloscope is usually used to record a time dependent signal. Since the electron beam can be "swept" at high speeds using an appropriate saw tooth voltage, the oscilloscope can be used to record extremely short transient signals.

Exercise 10: During the previous exercise, you would have observed that the output of the oscillator appeared nearly "steady" on the screen when the sweep frequency is set to certain discrete values. Explain why this is the case (note that the saw tooth oscillator and the function generator are not correlated).

NOTE: PLEASE TURN OFF THE ELECTRON GUN OF THE CRT.

9 Experiment IV: Triggering

You can now experiment with a standard laboratory analogue oscilloscope. Such a scope will have two channels (two electron beams). These beams are controlled by a single set of horizontal deflection plates. Each electron beam is also controlled with a set of vertical deflection plates.

Connect the function generator to channel 1 of the oscilloscope. Set the trigger mode to normal mode, and the trigger source to channel 1.

Locate the gain controls (labeled volts/div) and the time base control (labeled sec/div) knobs. Adjust the time base knob to control the sweep frequency of the electron beam. The sweep voltage is supplied to the horizontal deflection plates of the oscilloscope. Adjust the gain control knob to amplify the signal so that it nearly fills the display screen. The gain control knob controls the gain of an amplifier so that a small signal can be enhanced. The amplifier controls the voltage applied to the vertical deflection plates. You can also use the vertical and horizontal position control knobs to center the signal on the display screen (these knobs shift the position of the electron beam).

In normal trigger mode, the sweep will occur only when the voltage on channel 1 increases above a threshold, set by the trigger level knob. On the other hand if auto trigger mode is used, the electron beam begins a new sweep automatically after the end of a sweep. The signal displayed on the screen will slide across the field of view. To observe the effects of triggering, adjust the threshold voltage by adjusting the trigger level knob until the output of the function generator is clearly displayed. Note that the signal no longer slides across the field of view. You have now successfully triggered the oscilloscope!

Exercise 11: Record the frequency and amplitude of the triggered waveform. Draw an accurate representation of the signal. Indicate the period and amplitude of the waveform.

Now change the frequency of the function generator and observe the signal. Practice triggering signals of various amplitudes and frequencies. Most oscilloscopes also have an external trigger mode and a line trigger mode. Discuss how these modes work with the TA. Refer to Lab 0 for details.

Your lab report should include:

Answers to exercises 1-11 along with relevant data tables, graphs, figures and qualitative comments. Refer to Appendix D for Maple worksheets.

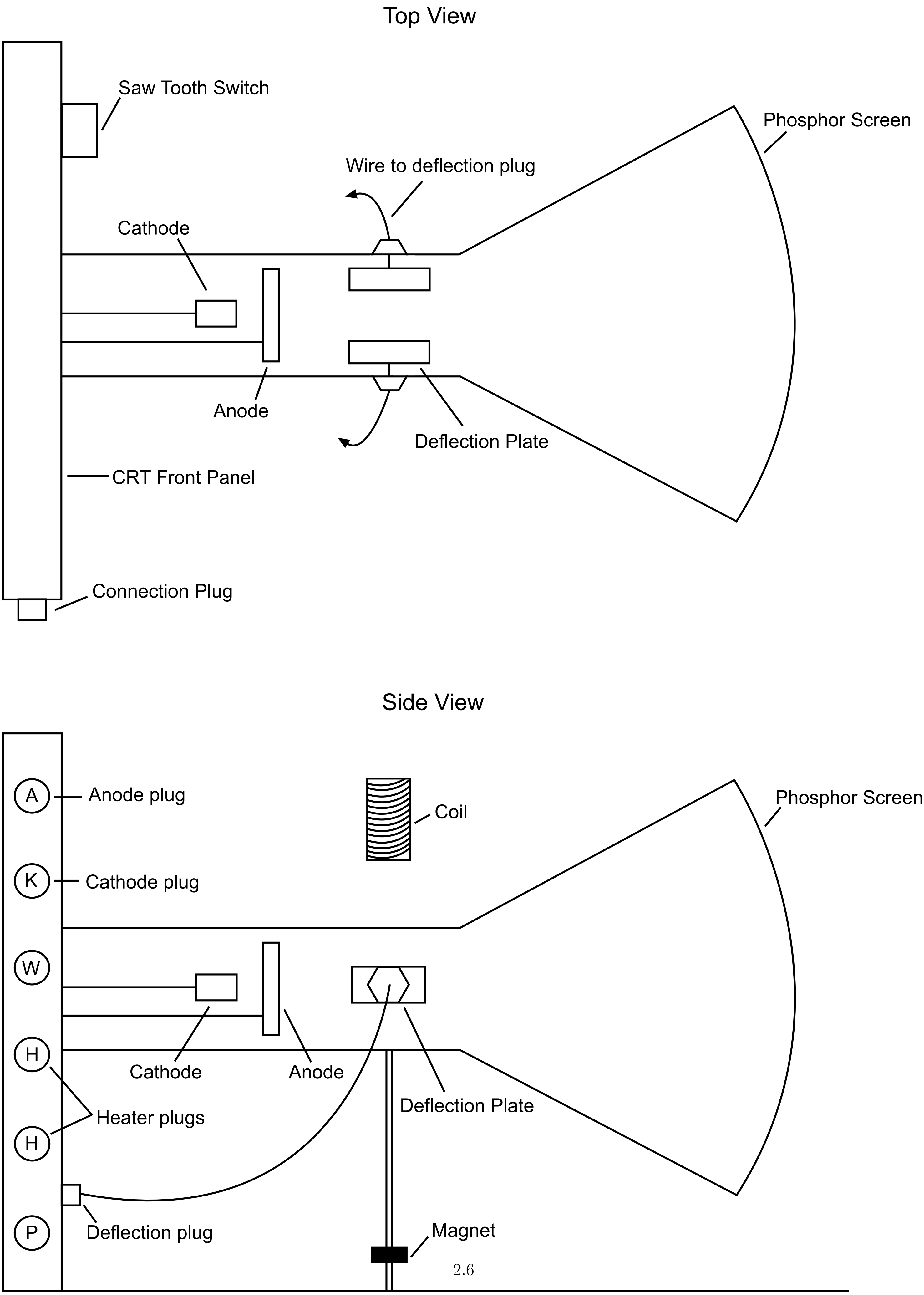

Figure 3: CRT, Cathode Ray Tube