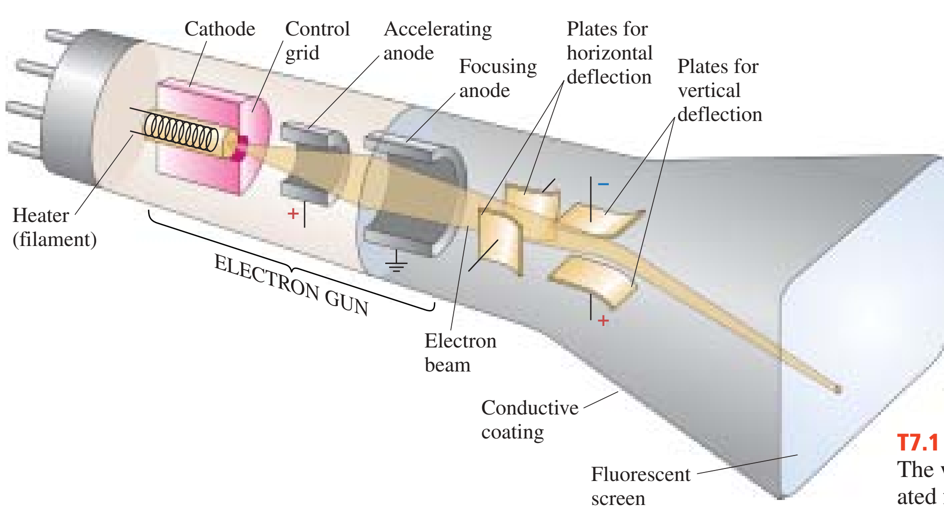
Topic 7 | The Cathode-Ray Tube

Let's look at how the concept of potential is applied to an important class of devices called **cathode-ray tubes,** or "CRTs" for short. Cathode-ray tubes are found in oscilloscopes, and similar devices are used in TV picture tubes and computer displays. The name goes back to the early 1900s. Cathode-ray tubes use an electron beam; before the basic nature of the beam was understood, it was called a cathode ray because it emanated from the cathode (negative electrode) of a vacuum tube.

Figure T7.1 is a schematic diagram of the principal elements of a cathode-ray tube. The interior of the tube is a very good vacuum, with a pressure of around 0.01 Pa (10^{-7} atm) or less. At any greater pressure, collisions of electrons with air molecules would scatter the electron beam excessively. The *cathode,* at the left end in the figure, is raised to a high temperature by the *heater,* and electrons evaporate from the surface of the cathode. The *accelerating anode,* with a small hole at its center, is maintained at a high positive potential V_1, of the order of 1 to 20 kV, relative to the cathode. This potential difference gives rise to an electric field directed from right to left in the region between the accelerating anode and the cathode. Electrons passing through the hole in the anode form a narrow beam and travel with constant horizontal velocity from the anode to the *fluorescent screen.* The area where the electrons strike the screen glows brightly.

The *control grid* regulates the number of electrons that reach the anode and hence the brightness of the spot on the screen. The *focusing anode* ensures that electrons leaving the cathode in slightly different directions are focused down to a narrow beam and all arrive at the same spot on the screen. We won't need to worry about the control grid or focusing anode in the following analysis. The assembly of cathode, control grid, focusing anode, and accelerating electrode is called the *electron gun.*

The beam of electrons passes between two pairs of *deflecting plates.* An electric field between the first pair of plates deflects the electrons horizontally, and an electric field between the second pair deflects them vertically. If no deflecting fields are present, the electrons travel in a straight line from the hole in the accelerating anode to the center of the screen, where they produce a bright spot.



T7.1 Basic elements of a cathode-ray tube. The width of the electron beam is exaggerated for clarity.

To analyze the electron motion, let's first calculate the speed v of the electrons as they leave the electron gun. The initial speeds at which the electrons are emitted from the cathode are very small in comparison to their final speeds, so we assume that the initial speeds are zero. Then the speed v_x of the electrons as they leave the electron gun is given by

$$v_x = \sqrt{\frac{2eV_1}{m}} \tag{T7.1}$$

The kinetic energy of an electron leaving the anode depends only on the *potential difference* between anode and cathode, not on the details of the fields or the electron trajectories within the electron gun. As a numerical example, if $V_1 = 2000$ V,

$$v_x = \sqrt{\frac{2(1.60 \times 10^{-19}\,\mathrm{C})(2.00 \times 10^3\,\mathrm{V})}{9.11 \times 10^{-31}\ \mathrm{kg}}} = 2.65 \times 10^7\ \mathrm{m/s}$$

This is about 9% of the speed of light in a vacuum.

If there is no electric field between the horizontal-deflection plates, the electrons enter the region between the vertical-deflection plates (shown in Fig. T7.2) with speed v_x. If there is a potential difference (voltage) V_2 between these plates, with the upper plate at higher potential, there is a *downward* electric field with magnitude $E = V_2/d$ between the plates. A constant upward force with magnitude eE then acts on the electrons, and their upward (y-component) acceleration is

$$a_y = \frac{eE}{m} = \frac{eV_2}{md} \tag{T7.2}$$

The *horizontal* component of velocity v_x is constant. The path of the electrons in the region between the plates is a parabolic trajectory. A particle moves with constant x-velocity and constant y-acceleration. After the electrons emerge from this region, their paths again become straight lines, and they strike the screen at a point a distance y above its center. We are going to prove that this distance is *directly proportional* to the deflecting potential difference V_2.

We first note that the time t required for the electrons to travel the length L of the plates is

$$t = \frac{L}{v_x} \tag{T7.3}$$

During this time, they acquire an upward velocity component v_y given by

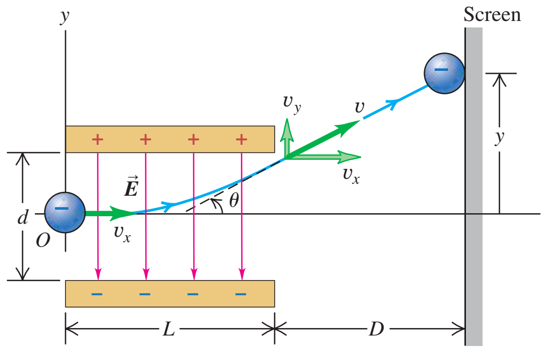
$$v_y = a_y t \tag{T7.4}$$

Combining Eqs. (T7.2), (T7.3), and (T7.4), we find

$$v_y = \frac{eV_2}{md}\frac{L}{v_x} \tag{T7.5}$$

When the electrons emerge from the deflecting field, their velocity $\vec{v}$ makes an angle θ with the x-axis given by

$$\tan\theta = \frac{v_y}{v_x} \tag{T7.6}$$



T7.2 Electrostatic deflection of an electron beam in a cathode-ray tube.

Ordinarily, the length L of the deflection plates is much smaller than the distance D from the plates to the screen. In this case the angle θ is also given approximately by $\tan\theta = y/D$. Combining this with Eq. (T7.6), we find

$$\frac{y}{D} = \frac{v_y}{v_x} \tag{T7.7}$$

or, using Eq. (T7.5) to eliminate v_y, we get

$$y = \frac{DeV_2L}{mdv_x{}^2} \tag{T7.8}$$

Finally, we substitute the expression for v_x given by Eq. (T7.1) into Eq. (T7.8); the result is

$$y = \left(\frac{LD}{2d}\right)\frac{V_2}{V_1} \tag{T7.9}$$

The factor in parentheses depends only on the dimensions of the system, which are all constants. So we have proved that the deflection y is proportional to the *deflecting* voltage V_2, as claimed. It is also *inversely* proportional to the *accelerating* voltage V_1. This isn't surprising; the faster the electrons are going, the less they are deflected by the deflecting voltage.

If there is also a field between the *horizontal* deflecting plates, the beam is also deflected in the horizontal direction, perpendicular to the plane of Fig. T7.2. The coordinates of the luminous spot on the screen are then proportional to the horizontal and vertical deflecting voltages, respectively. This is the principle of the cathode-ray oscilloscope. If the horizontal deflection voltage sweeps the beam from left to right at a uniform rate, the beam traces out a graph of the vertical voltage as a function of time. Oscilloscopes are extremely useful laboratory instruments in many areas of pure and applied science.

The picture tube in a television set is similar, but the beam is deflected by *magnetic* fields rather than electric fields. In the system currently used in the United States and Canada, the electron beam traces out the area of the picture 30 times per second in an array of 525 horizontal lines, and the intensity of the beam is varied to make bright and dark areas on the screen. (In a color set, the screen is an array of dots of phosphors with three different colors.) The accelerating voltage in TV picture tubes (V_1 in the above discussion) is typically about 20 kV. Computer displays and monitors operate on the same principle, using a magnetically deflected electron beam to trace out images on a fluorescent screen. In this context the device is called a CRT display or a VDT (video display terminal). (Flat screen monitors and TVs use an entirely different technology.)