Duke University

Cathode Ray Tube

From the birth to the demise

Yida Chen
Dr. Hubert Bray
Math 190s: Mathematics of the Universe
25 July 2017

Introduction

As the LCD and plasma displays develop, thousands of CRT displays are discarded by the people. It seems that the usage of cathode ray tube could only be find in history books in few years. The scientists have spent more than fifty years to devise the cathode ray tube. Ten years ago, consumers still believed that the LCD could not beat the CRT. The efforts that inventors spent also make us be confident with the future of the CRT. However, the development is unstoppable, and the demise of the CRT is irremediable. Before the cathode ray tube is really forgotten by the people, we need to make a specific research on this amazing device. Below, I will lay out the ingenious design of the cathode ray tube and give mathematical explanations for the operation principle of the cathode ray tube. At last I will explain the limitations of the cathode ray tube.

Cathode Ray

For having a better understanding of the cathode ray tube, the definition of the cathode ray should be clearly stated at first. According to the Encyclopedia Britannica," Cathode ray, stream of electrons leaving the negative electrode (cathode) in a discharge tube containing a gas at low pressure, or electrons emitted by a heated filament in certain electron tubes."[1]

The cathode ray was first discovered by the German physicist Johann Hittorf in 1869.He found that the rays extended from a negative electrode in the tube, and

---

[1] Direct quote from "Cathode Ray." Encyclopædia Britannica. Encyclopædia Britannica.

they produced a fluorescence when they hit the tube`s glass wall. (https://en.wikipedia.org/wiki/Johann_Wilhelm_Hittorf)However,although Hittorf found the cathode rays, the scientists did not know the actual composition of the cathode rays until the British physicist J.J.Thomson found the electrons in the rays in 1897.

The electron is subatomic particle, whose mass is 9.10938356×10^{-31} kg and electric charge is -1.6021766208 C.[2]The nature of the cathode ray is a beam of electrons.

Crookes tube

The invention of the cathode ray tube did not keep pace with the discovery of cathode ray. Historically, the first cathode ray was generated by the Crookes tube, whose design is much simpler than the CRT and technically unreliable.

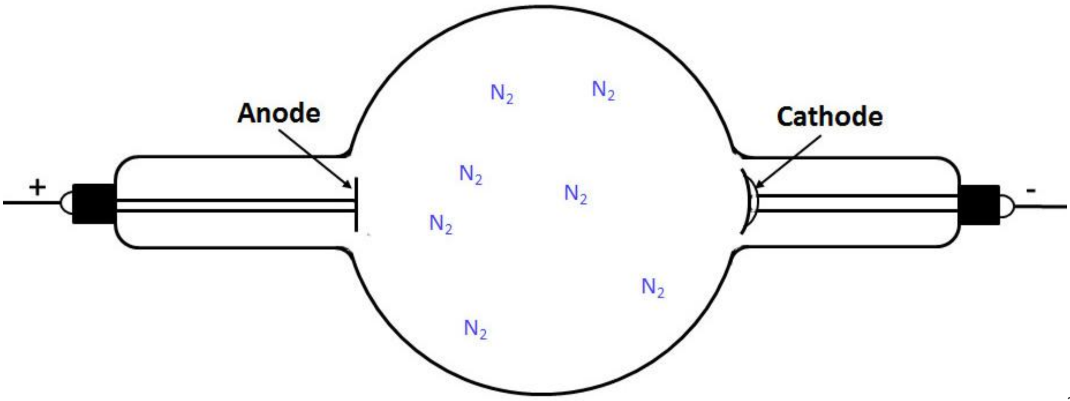
The operation principle of Crookes tube is totally different from that of the CRT, which uses the electron gun to generate cathode rays, whereas the Crookes tube use high DC voltage between the anode and cathode to ionize the rarefied gas in the tube.

Since the barometric pressure of the tube is lower than 10^{-6} Pa, the electrons of gas molecules have more space to

---

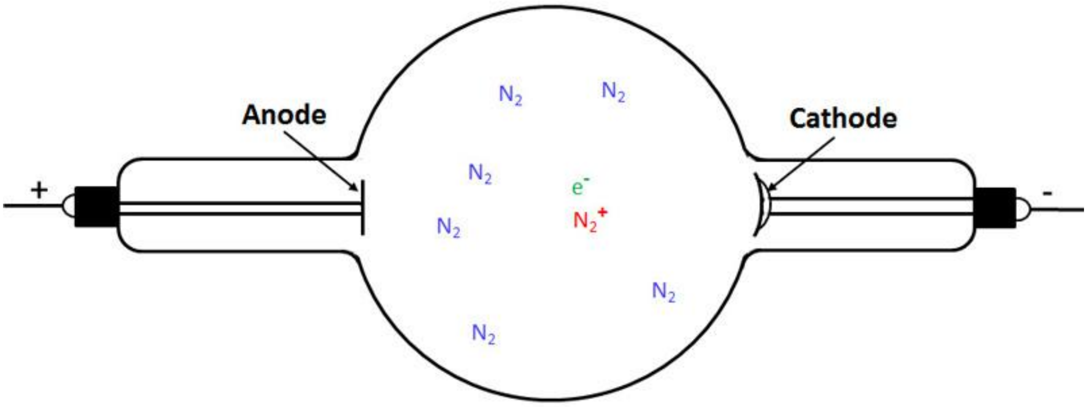
[2] The data were adapted from https://en.wikipedia.org/wiki/Electron.

escape.



[3]

When the strong electric field is generated by the high voltage between the electrodes, the electrons could readily get rid of the atoms and become the free electrons. (https://www.orau.org/ptp/collection/xraytubes/introduction.htm)

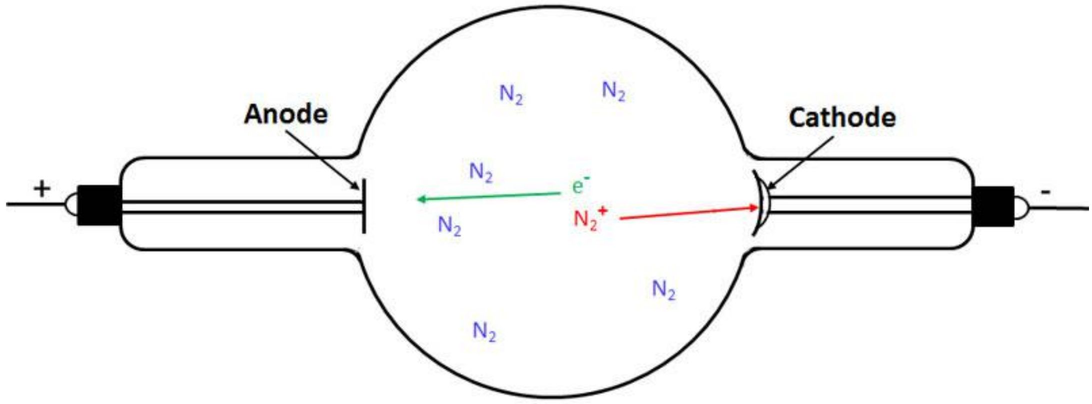


[4]

According to law of the Townsend discharge, the electrons will collide with air molecules and free more electrons from them. After a series of this chain reaction, there will be number of free electrons and positive ions. (https://www.orau.org/ptp/collection/xraytubes/introduction.htm)

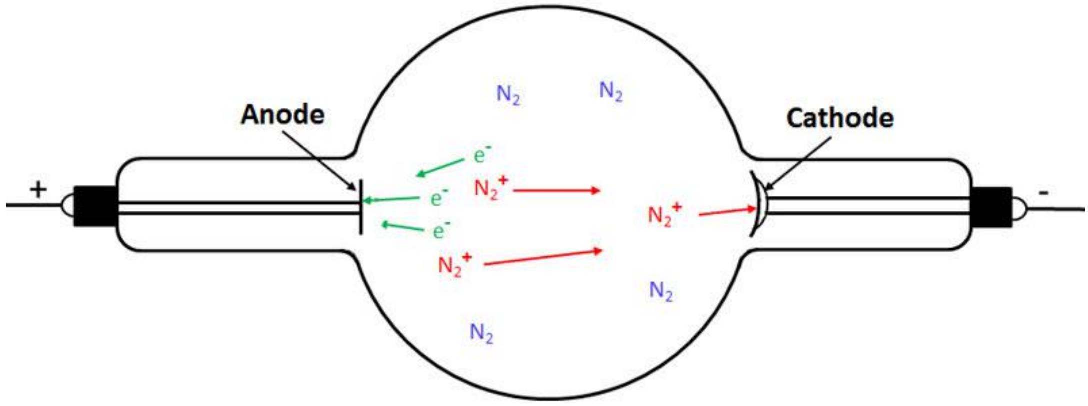
---

[3] The image was adapted from https://www.orau.org/ptp/collection/xraytubes/introduction.htm.
[4] The image was adapted from https://www.orau.org/ptp/collection/xraytubes/introduction.htm.



[5]

The electrons will be attracted by the anode and ions will be attracted by the cathode. Positive ions will strike the metal cathode, and electrons of the metal will be knock off at the same time. (https://www.orau.org/ptp/collection/xraytubes/introduction.htm)

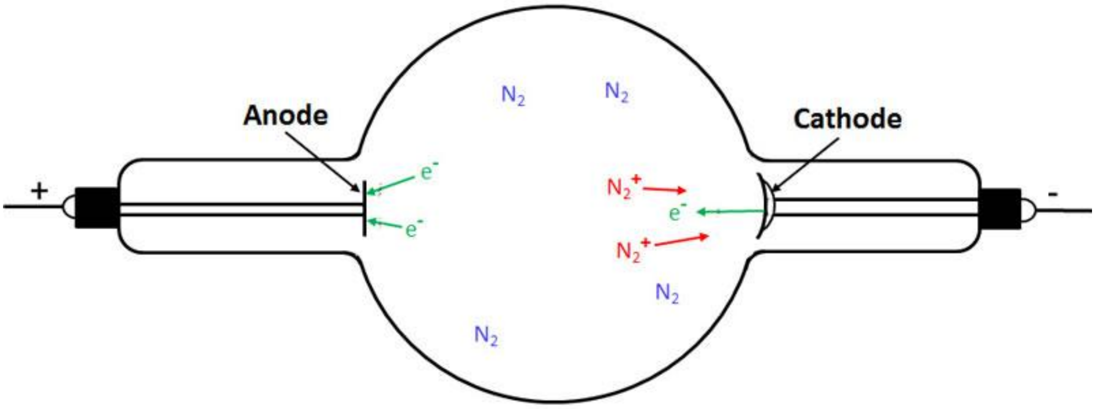


[6]

Then the electrons of the metal will be attracted by the anode and the cathode rays is formed. (https://www.orau.org/ptp/collection/xraytubes/introduction.htm)

---

[5] The image was adapted from https://www.orau.org/ptp/collection/xraytubes/introduction.htm.
[6] The image was adapted from https://www.orau.org/ptp/collection/xraytubes/introduction.htm.



[7]

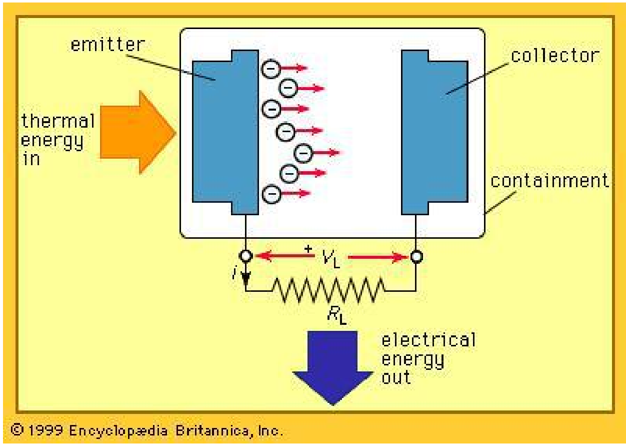
Improvement of the cold cathode

The disadvantage of the Crookes tube limits its usage, “over time these ions might damage the cathode when they strike it if the tube was operated at high enough currents and voltages. This damage involves ‘sputtering,’ a process whereby some of the atoms of a material are knocked free when struck by ions.” [8] Also, the Crookes tube`s requirement with the pressure of the air in the tube is very strict. That means the production of Crookes tubes is very difficult, since we need to make the pressure become lower so that the electrons have enough space to escape, but we also need to ensure that we leave enough air for gas ionization. The tubes cannot be reused for too many times either, because of the sputtering damage from the electrons.

To improve these disadvantages, the scientists change the way that we use to generate cathode ray. The Crookes tube uses the gas ionization to generate electron beams, which are also referred to the “cold cathode. “In contrast, the electron beams of the modern cathode ray tube are referred to the “hot cathode, “since they are generated by the thermionic emission.

[7] The image was adapted from https://www.orau.org/ptp/collection/xraytubes/introduction.htm.
[8] Direct quote from https://www.orau.org/ptp/collection/xraytubes/introduction.htm

In the modern cathode ray tube, the cathode is a heated filament, which is called thermionic power converter, since the heat can be transfer into the electricity directly by using this device. According to the Encyclopedia Britannica," A thermionic power converter has two electrodes. One of these is raised to a sufficiently high temperature to become a thermionic electron emitter, or 'hot plate.' The other electrode, called a collector because it receives the emitted electrons, is operated at a significantly lower temperature. The space between the electrodes is sometimes a vacuum but is normally filled with a vapor or gas at low pressure."[9]



[10]

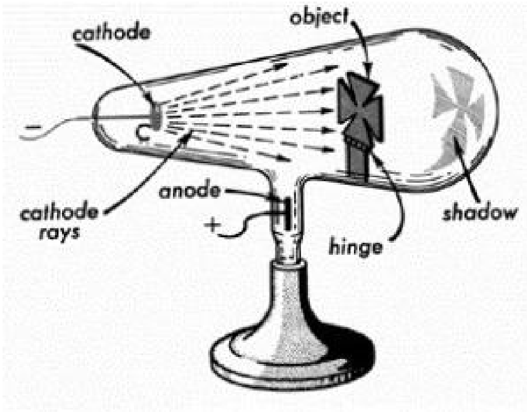
<u>The first attempt to take advantage of the cathode rays</u>

As the cathode rays become reliable, the next step of the development of tubes is trying to control the cathode rays by taking advantage of their properties. The cathode rays are composed of the electrons, so the cathode rays` properties are like those of the electrons. Thus, cathode rays can also be attracted by the positive terminals, be deflected by the magnetic field, and be accelerated by the electronic field. However, since there are so many electrons in the cathode rays, some properties of the cathode rays are more complicated than those of a single electron.

[9] Direct quote from https://www.britannica.com/technology/thermionic-power-converter.
[10] Image was adapted from https://www.britannica.com/technology/thermionic-power-converter.

For instance, the cathode rays consist of many electrons, and these electrons have similar charges, which can create repulsive forces between these electrons, so the cathode rays tend to diverge. In the Crookes tubes, the cathode rays are heavily diverged by the repulsive forces.

(https://en.wikipedia.org/wiki/Crookes_tube)

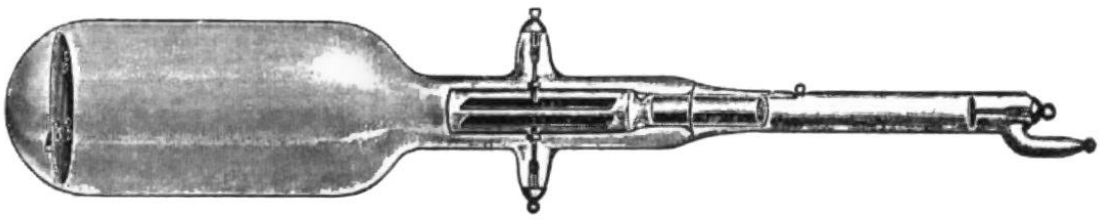


[11]

This kind of the cathode ray cannot be put into any practical use. To solve this problem, a new type of cathode ray tube was invented. The rays of this new tube could be focus by the narrow aperture, when they are passing through it. The tube also has a pair of deflecting plate. The plates can generate the electric field when a high voltage is applied between them, and the electron beams will be deflected by it. The electron beams can scan the screen according to the frequency of an incoming signal, and the tubes also have a chemically treatment on the its screen, so we can see the electronic signal when the beams strike the screen. This tube is oscilloscope, which was first invented by the German physicist Karl Ferdinand Braun.

(http://www.discoveriesinmedicine.com/Bar-Cod/Cathode-Ray-Tube-CRT.html)

[11] The image was adapted from http://www.worldofchemicals.com/311/chemistry-articles/william-crookes-discoverer-of-thallium.html



[12]

Fluorescent screen Deflecting plates anode cylinder cathode

Although the Braun tube still uses the cold cathode technique, it gives us a lot of significant insights about the design of modern cathode ray tubes.

Modern cathode ray tubes

The modern cathode ray tubes use the same design of the Braun tubes. However, they have more components and use the thermionic ionization technique.

In the modern cathode ray tubes, they use the electron gun to generate electron beams, and use a pair of anodes to accelerate the beams. The deflecting system can concentrate the beams into a narrow line and stir them to strike the correct dots. Different cathode ray tubes have different deflecting systems, and the main types of the deflecting system are electrostatic deflecting and magnetic deflecting system. The choices of the deflecting systems depend on the application of the cathode ray tubes. For example, the televisions always chose the magnetic deflecting system, but most of the oscilloscopes use the electrostatic deflecting system. These differences come from the different operation principles of the deflecting systems.

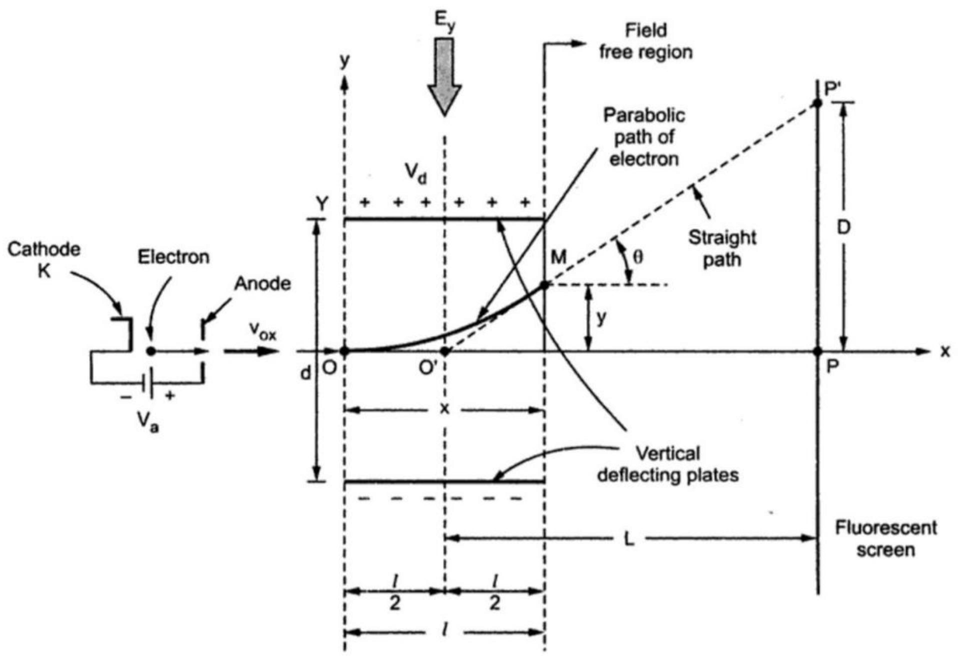
Below, I will lay out the differences between the designs of two types of the modern cathode ray tubes and give the mathematical explanation for these differences.

[12] The image was adapted from https://en.wikipedia.org/wiki/Cathode_ray_tube.

Electrostatic deflection design

Since the cathode rays are composed of the negative electrons, they can be deflected by the electric field and move toward the positive terminals. The electrostatic deflecting plates are like capacitors. One of them is negative and the other one is positive. The electric field is generated between two plates, and the electric field force exerting on the electron beam can change beam`s direction to strike the proper position of the screen. Below, I will make a mathematical explanation for this procedure.

If we want to measure the deflecting motion of the electron beams, the first thing we need to do is to measure the velocity of electrons.



[13]

We apply a voltage V_a between two electrodes, so the electrons will have electronic potential energy E_p, when they are emitted by the cathode. The electronic potential energy of electrons will transfer into the kinetic energy of electrons. Below, the

---

[13] The image was adapted from the Electronic Devices and Circuits.

equations could measure the final speed of the electrons. (Electronic Devices and Circuits)

$$E_p=qV_a$$

$$E_k=(mv_{ox}^2)/2$$

$$E_p=E_k$$

$$v_{ox} = \sqrt{\frac{2qV_a}{m}}$$ [14]

q is the charge of the electron, which is approximated to -1.6 C.

V_a is the voltage which is applied between the anode and the cathode.

m is the mass of the electron.

E_k is the kinetic energy of the electrons.

v_{ox} is the final velocity of the electrons, before they enter deflecting field.

We also apply a voltage V_d between the deflecting plates. The magnitude of the electric field between these plates is E_y.

$$E_y = \frac{V_d}{d}$$ [15]

d is the distance between the deflecting plates.

We need to measure the vertical acceleration a_y of the electrons, so that we can measure the degrees of their deflection.

$$F_e=E_yq$$

$$F_e=ma_y$$

$$a_y=(qE_y)/m=(qV_d)/(md)$$

---

[14] The equation was adapted from the Electronic Devices and Circuits.

[15] The equation was adapted from the Electronic Devices and Circuits.

F_e is the force of the electric field that exerts on the electrons.

The electrons move along the parabolic path. However, we can divide the motion of electrons into the vertical motion and horizontal motion. Since the acceleration of the electrons is perpendicular to their horizontal motion, the horizontal velocity does not change during the deflection, and we can use the horizontal velocity to measure the time t which is used for the deflection. (Electronic Devices and Circuits)

$$x = v_{ox} t$$ [16]

x is the horizontal length of the plates.

Finally, we can measure the distance of the vertical motion of the electrons. Namely, we can measure the deflection of the electron beams.

$$y=(at^2)/2$$

$$y=(qV_dx^2)/(2dmv_{ox}^2)$$

$$y=(V_dx^2)/(4V_ad)$$

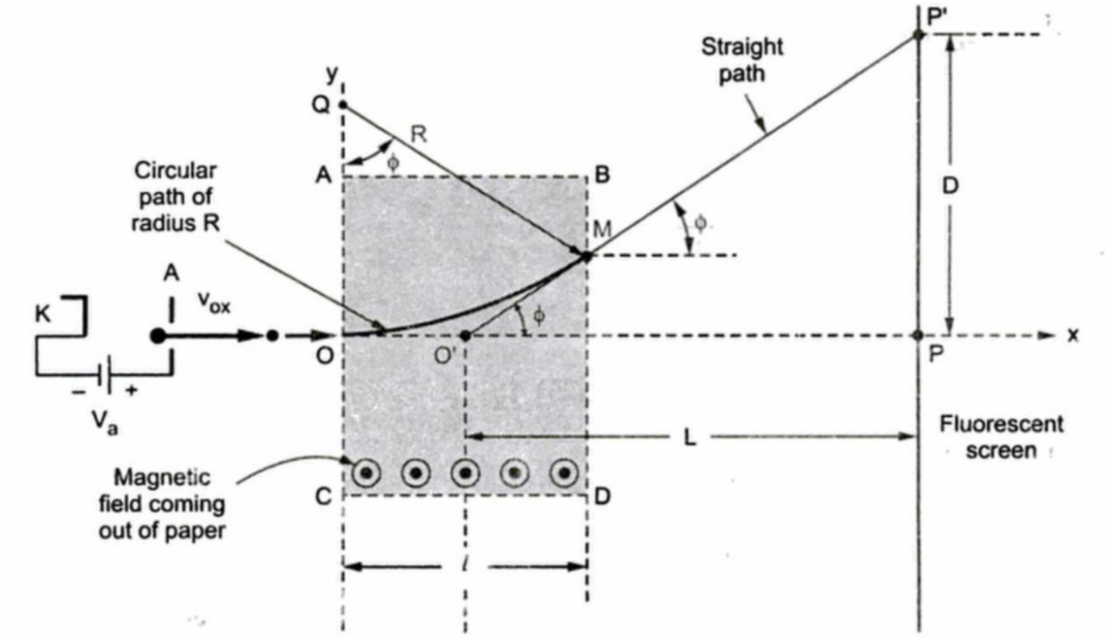
From the equation, we can make some observations. In each cathode ray tube with fixed accelerating voltage V_a, the deflection of the beams is directly proportional to the deflecting voltage V_d. According to the Bakshi and Godse," the cathode ray tube can be used as a liner voltage indicating device."[17]Namely, we can also transfer the signals into the different voltages of the deflecting plates, and the beams can scan the dots of screen orderly to represent the signals. (Electronic Devices and Circuits_

Magnetic deflection design

[16] The equation was adapted from the Electronic Devices and Circuits.

[17] Direct quote from the Electronic Devices and Circuits.

In the magnetic deflection system, tubes use the magnetic field to deflect the electrons.



[18]

We use the same device to generate the electron beams in the magnetic deflection design, so the velocity v_{ox} of the electrons can be measured by the same way which we use in the electrostatic deflection design.

$$v = v_{ox} = \sqrt{\frac{2\,q\,V_a}{m}}$$

[19]

In the magnetic field, “the force exerts on an electron is constant and is perpendicular to the velocity motion and the magnetic field. Due to this, path of the electron is circular in the uniform magnetic field.”[20]The radius R can be measured by the following equations.

---

[18] The image was adapted from the Electronic Devices and Circuits.
[19] The equation was adapted from the Electronic Devices and Circuits.
[20] Direct quote from the Electronic Devices and Circuits.

$$R = \frac{m v}{q B} \text{ m}$$

$$v = \text{Velocity of electron in m/s}$$

$$B = \text{Magnetic field intensity in Wb / m}^2$$ [21]

To make it easier for us to measure the deflection of the electrons, we can use deflecting angle θ to represent the degree of the deflection.

$$\phi = \frac{\text{arc length(OM)}}{R}$$

But for small deflection, arc length OM ≈ l.

$$\phi = \frac{l}{R}$$

$$\phi = \frac{l q B}{m v}$$ [22]

From the equations, we can observe that the deflection is directly proportional to the magnitude of the magnet field, since the length and the magnitude of velocity of the electrons are fixed in each cathode ray tubes, and the q/m is a constant.

Differences

The most important difference between the electrostatic deflection and magnetic deflection is the deflection sensitivity.

The definition of the electrostatic deflection sensitivity is "the deflection on the screen in meters per volt of the deflection voltage."[23]It can be measured by the following function.

$$S = \frac{D}{V_d} = \frac{l L}{2 d V_a} \quad \text{m/V}$$ [24]

---

[21] The equations were adapted from the Electronic Devices and Circuits.
[22] The equations were adapted from the Electronic Devices and Circuits.
[23] Direct quote from the Electronic Devices and Circuits.
[24] The equation was adapted from the Electronic Devices and Circuits.

S is the sensitivity.

D is the distance between the midpoint of the screen and the dot that is struck by the electron beams.

"It can be observed that decreasing the accelerating voltage, sensitivity can be increased. But this decrease the brightness of spot. On the other hand, high V_a values, produces a bright spot. But for high V_a, high V_d is required and such a beam which is highly accelerated is difficult to deflect."[25]

The definition of the magnetic deflection sensitivity is the "deflection on the screen in meters per Tesla."[26]It can be measured by the following function.

$$S = Ll \cdot \sqrt{\frac{q}{m}} \frac{1}{\sqrt{2 V_a}}$$ [27]

We can observe that the sensitivity is not affected greatly by the increasing voltage V_a, as it does in the electrostatic deflection. According to the Bakshi and Godse," magnetic scheme gives more brightness and resolution."[28]

Because of these differences, the magnetic deflection and electrostatic deflection have different applications.

To scan the same area, the shorter tubes are enough for the electromagnetic deflection, and we can obtain more brightness and resolution from magnetic deflection tubes, so the monitors always chose the electromagnetic deflection design for the tubes. But the general-purpose oscilloscopes chose the electrostatic

---

25 Direct quote from the Electronic Devices and Circuits.
26 Direct quote from the Electronic Devices and Circuits.
27 The equation was adapted from the Electronic Devices and Circuits.
28 Direct quote from the Electronic Devices and Circuits.

deflection system, since they need to represent the input electronic signal, which can be readily indicated by electrostatic deflection. (Electronic Devices and Circuits)

Limitations

However, even the most efficient magnetic deflection system has its own limitation, which was predicted by the scientists 80 years ago.

According to the David Langmuir, aberrations of the focusing system, the cathode current density, the temperature of the cathode, the final voltage, and the half angle subtended by the beam at the final spot limit the current density, which is significant for the cathode ray tube to represent signals. (Theoretical Limitations of Cathode-Ray Tubes)

The energy consumption is also a concern. To make larger monitors, the deflecting system need to have a larger deflecting range. However, the expense of the larger deflecting range is larger energy consumption, which is strictly prohibited now.

It is hard to shrink the size of the cathode ray tube as well. In an age when every square yard is so expensive, the enormous televisions are disappearing from our life.

We used to think the cathode ray tube would still dominate the manufacture of the electronic microscopes. However, as the LCD technique develops, the digital microscope is taking place of the electronic microscope.

Conclusion

The development of the cathode ray tube is circuitous. During this long journey, we make a lot of amazing inventions and make number of significant discovery. The discovery of the electrons opens the new age of the physics and the chemistry. The televisions, computers, radars, and microscopes all depend on the CRT to represent images. The developments of the LCD and plasma technique presage the demise of the cathode ray tubes. It is very upset to witness the disappearance of this amazing invention, but it is also very excited to watch the new technique maturing. Our knowledge is changing as amazingly as this world, and our techniques should follow our pace.

Work cited

"Cathode Ray." Encyclopædia Britannica. Encyclopædia Britannica, Inc., n.d. Web. 20 July 2017.

"Johann Wilhelm Hittorf." Wikipedia. Wikimedia Foundation, 11 July 2017. Web. 20 July 2017.

"Electron." Wikipedia. Wikimedia Foundation, n.d. Web. 20 July 2017.

"Crookes Tube." Wikipedia. Wikimedia Foundation, n.d. Web. 24 July 2017.

Introduction to Gas Discharge Tubes and Cold Cathode X-ray Tubes. N.p., n.d. Web. 24 July 2017.

"Thermionic Power Converter." Encyclopædia Britannica. Encyclopædia Britannica, Inc., n.d. Web. 24 July 2017.

"William Crookes – Discoverer of Thallium - World Of Chemicals." William Crookes British Chemist – Discovered Thallium Element Properties Invented Vacuum Tubes. N.p., n.d. Web. 24 July 2017.

Langmuir, D.b. "Theoretical Limitations of Cathode-Ray Tubes." Proceedings of the IRE 25.8 (1937): 977-91. Web.