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IMAGE DISSECTOR TUBE

by

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The first television camera tube, the image dissector, was invented and developed by Philo T. Farnsworth of the Farnsworth Electronics Company in 1934. It was the first successful non-mechanical system of scanning to be in operation.

The features of the Farnsworth image dissector are shown in Figure 1. Essentially, the tube consists of a translucent cathode, the surface of which is coated with photo-sensitive material, and upon which is projected the optical image of the scene to be transmitted. This optical image causes a photo-emission of electrons which are distributed in space with a density at each part of the cathode plane proportional to the light intensity of that particular part of the picture. The electron-optical image is then propelled from the cathode to the anode by means of an electrical field. Proper focusing is achieved with the aid of a uniform axial magnetic field. The distribution of electrons at the anode plane corresponds to the distribution of light intensity upon the cathode, thus giving at the anode what might be termed an electron image of the scene being reproduced. The anode is perforated in the center by a tiny aperture behind which is an electrode which collects the electrons passing through the aperture. This electrode, the first dynode, receives an electron current proportional to the light intensity of the corresponding part of the optical image. The picture is scanned by displacing the electron image at the anode with respect to the aperture so that the part of the image that supplies electrons to the first dynode is continuously changing in a systematic manner so as to measure the light intensity of each elemental part of the entire projected scene. This is achieved by deflecting the whole electron image in two directions at right angles to each other with the aid of two magnetic fields which are produced by two pairs of coils as shown in Figure 2. The electron current received by the first dynode through the aperture has an instantaneous value equal to the photocurrent from a single element of the cathode. It has been calculated that under ordinary conditions a bright outdoor scene gives only a few hundred electrons from an elemental cathode area equal to the aperture area as it is scanned. This amount of signal current is so small that, if it were amplified, thermal-agitation voltages in the input circuit of the first tube would be comparable to the signal.

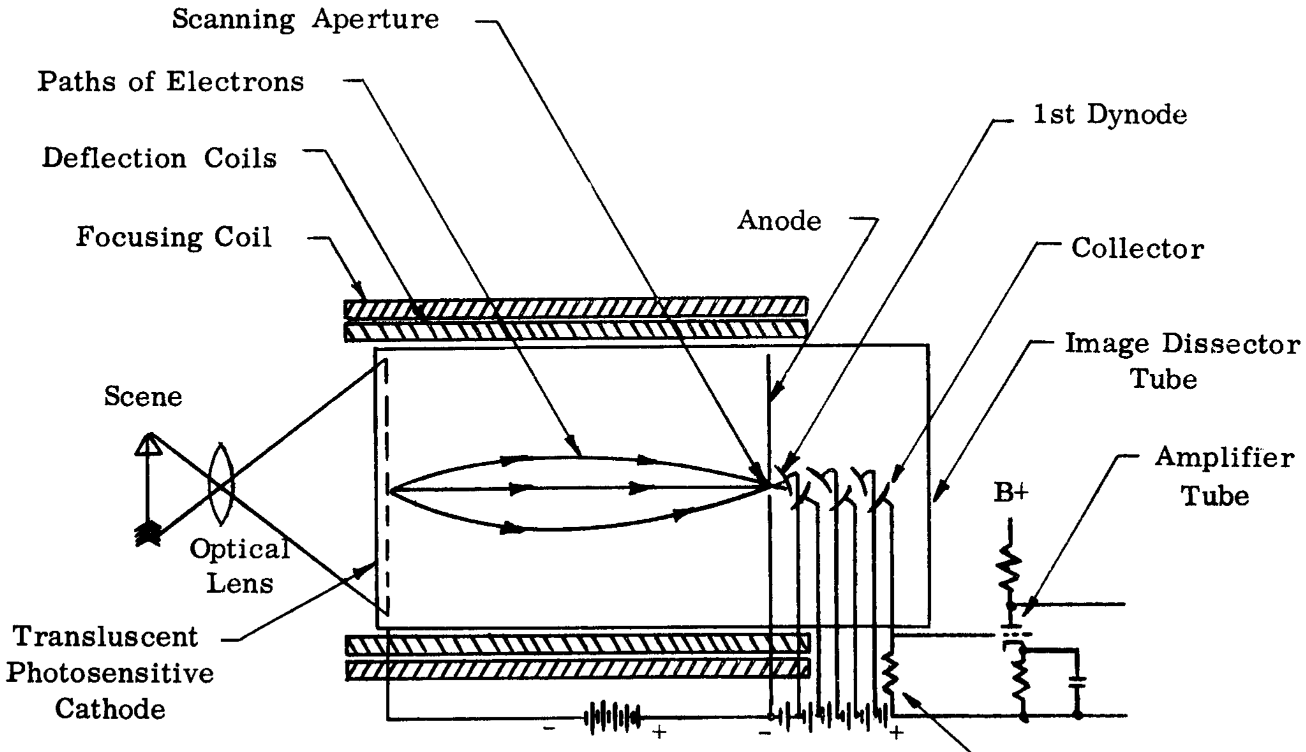

Figure 1 Features of Image Dissector Tube

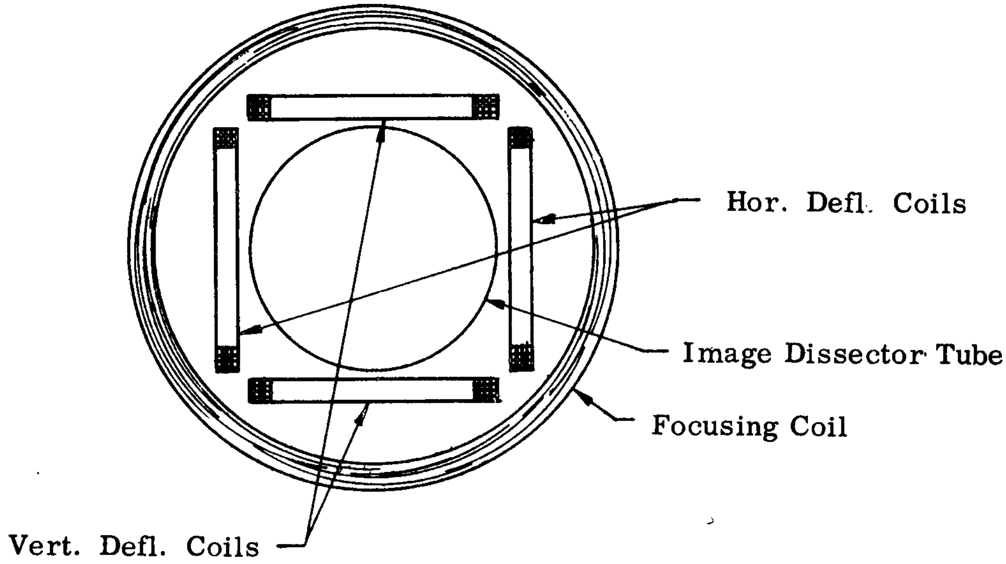

Figure 2 Focusing and Deflection Coils (End View)

This limitation has been overcome by making use of secondary emission to multiply the number of electrons that the scanning tube develops. Several dynodes are incorporated in the multiplier section to build up the small signal current to a value that can be made distinguishable. The result is a reproduced picture of higher contrast.

In order to account for the experimental facts observed in connection with the phenomenon of photoemission, it is necessary to make use of the quantum theory of radiation, as well as the quantum mechanical picture of metals. This paper is too brief to include an adequate discussion of this subject. There are several good books which cover this subject thoroughly, and as a starter, reference is made to Television by Zworykin and Morton, pp. 22-28.

Various physical phenomena occur when electrons are in the vicinity of an electric and/or a magnetic field. The rest of this paper will be a discussion of the various influences by these fields on the electrons in the image dissector tube from the time they are released at the photocathode until they are removed from the multiplier output as a video signal.

In order to understand just how the axial magnetic field influences the moving electrons for proper focusing, the orbit of a charged particle in a magnetic field must be understood. Let a negatively-charged particle at point 0 in a uniform magnetic field of flux density B be given a velocity v in a direction at right angles to the field. (See Figure 3.) An upward force F, equal to Rev, is exerted on the particle at this point. Since the force is at right angles to the velocity, it will not affect the magnitude of this velocity but will merely alter its direction. At points such as P and Q the directions of force and velocity will have changed as shown, the magnitude of the force remaining constant. The particle therefore moves under the influence of a force whose magnitude is constant but whose direction is always at right angles to the velocity of the particle. The orbit of the particle is therefore a circle described with constant tangential speed v, with force F being the centripetal force. Since

$$\text{centripetal acceleration} = \frac{v^2}{r}$$

we have from Newton's second law,

$$Bev = \frac{m v^2}{r}$$

and the radius of the circular orbit is

$$r = \frac{m v}{e B}$$

Notice from the above equation that the radius of this circle is smaller the greater the strength of the magnetic field and the more slowly the electron is moving through the field.

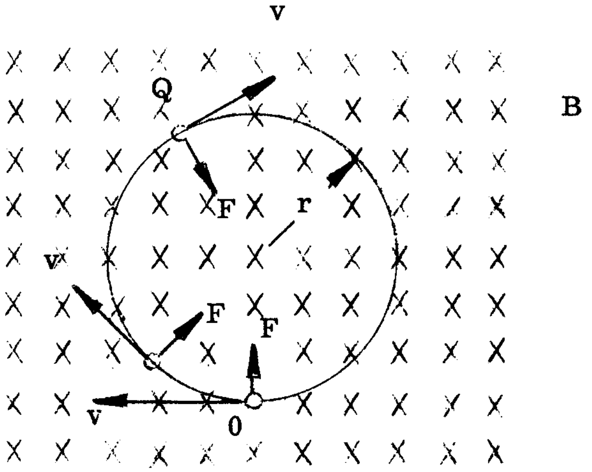

Figure 3 Circular Orbit of an Electron in a Uniform Magnetic Field

If the direction of the initial velocity is not perpendicular to the field but at some angle to it, the particle moves in a helical path. When an electron moves exactly parallel to the direction of the lines of induction of a magnetic field, no force is exerted upon it and it continues unchecked in its course. But, if there is the slightest difference in direction, the velocity v of the electron may be considered to be split up in a direction parallel to the lines of induction and in a direction perpendicular to those lines. The perpendicular component is affected by the magnetic field as though the axial component were non-existent. If the angle made by the path of the electron with the lines of induction when entering the magnetic field is x, the axial component is $v_1 = v \cos x$ and the radial component $v_2 = v \sin x$. As a result of this radial component, the projection of the electron on a plane perpendicular to the lines of induction will be a circle with radius:

$$r = \frac{m v_2}{e B} = \frac{m v}{e B} \sin x.$$

The path of the particle is therefore a spiral line on a cylinder with its axis parallel to the lines of magnetic induction. If, therefore, a number of electrons coming from a point P on the cathode enter the axial magnetic field at different angles, all the particles will describe helical paths according to the above equation, but each path will have a different radius. Since the line of induction through the point P on the cathode is a common denominative of the cylinders forming the surrounds of the spirals described by the electrons as shown in Figure 4, the electron is more or less compelled to follow the lines of induction; the greater the magnetic induction, the closer they follow the lines.

The transit time T for one revolution round the cylinder is

$$T = \frac{2\pi r}{v_2},$$

and since

$$v_2 = \frac{eBr}{m},$$

after substitution it follows that:

$$T = \frac{2\pi m}{eB}.$$

In other words: in the same interval of time and regardless of the angle x, each electron will describe a complete circle, of which the radius is a function of x. In that time the distance travelled by the electron in the direction of the field is:

$$T v_1 = \frac{2\pi m}{eB} v \cos x.$$

If, therefore, the electrons contained in an electron beam leave a common point at the same speed v but at small angles to the direction of the lines of magnetic induction of the uniform field, the axial distance travelled will be the same for all the particles as long as the angle x is so small that it may be assumed, with sufficient accuracy, that $\cos x = 1$. Although the separate particles leaving point P of the cathode describe spirals on cylindrical planes with different radii, they all converge

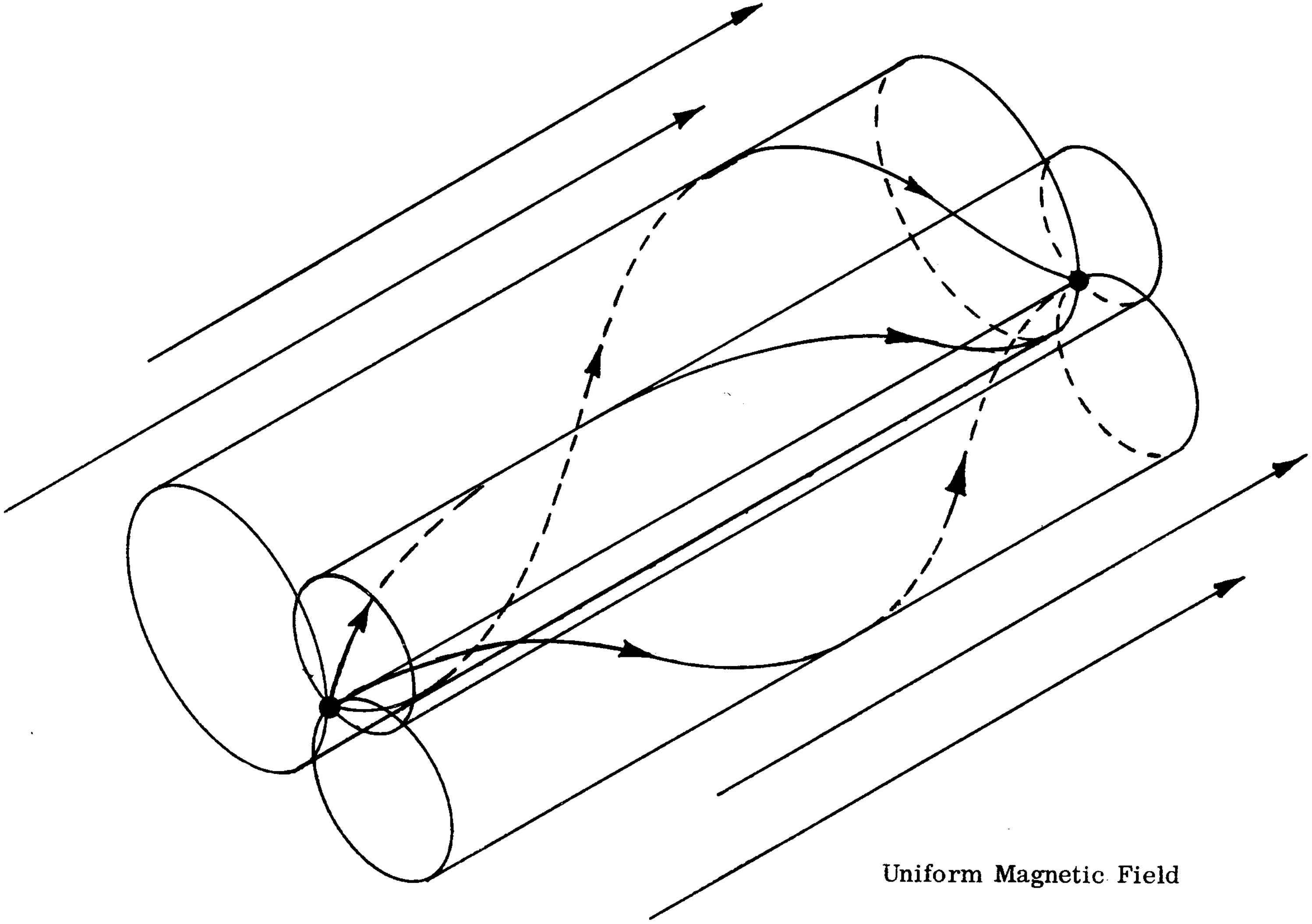

Figure 4 Helical Paths of Electrons in a Uniform Magnetic Field

upon one point P^1 of the anode. Thus, it can be seen, by changing the magnetic induction B, the diverging electron beam described can be concentrated at point P^1 of the anode by adjusting the magnetic induction B for proper focusing.

It can be described briefly, in light of the previous paragraphs, what happens when a magnetic field is introduced with an induction B_z in an axial direction and with its lines of induction running parallel to the direction of motion of the electron, while locally a uniform magnetic field with an induction B_y is introduced perpendicular to the direction of motion. The magnetic induction of this resultant field is equal to:

$$B_r = \sqrt{B_z^2 + B_y^2}$$

while the angle between B_r and B_z is given by

$$\tan y = \frac{B_y}{B_z}$$

If the velocity v is again resolved into a component $v_1 = v \cos y$ along B_r and a radial component $v_2 = v \sin y$, it is found that the latter will cause a spiral movement as before, but this time round a cylinder of which the axial direction is equal to the direction of B_r. This is so because, as already described, when an electron is moving exactly parallel to the lines of induction, it will not be subjected to any deflecting force and will be able to continue its way undisturbed at a rate of v. Hence, it can be shown that a combination of two magnetic fields, one in the axial direction of the dissector tube and the other at right angles to it, can be used to direct the photoemitted electrons from any point on a line on the cathode to the aperture of the anode. Also, a combination of three magnetic fields, one in the axial direction of the tube and the other two at right angles to it and at right angles to each other, can be used to direct the photoemitted electrons from any point on the entire cathode to the aperture of the anode. The three magnetic fields discussed can be produced by a focus coil and two sets of deflection coils as shown in Figures 1 and 2.

It has been assumed in the above discussions, for theoretical understanding only, that all the electrons are emitted from the photocathode with a velocity v and that they remain at that same velocity throughout their course until they arrive at the anode. Actually, during the operation of an image dissector tube, the electrons are emitted from the photocathode with almost a zero velocity but they are accelerated to higher velocities by means of an electric field between cathode and anode.

The following paragraph discusses the axial velocity that the accelerated electron achieves upon reaching the anode.

Assume that an electron is released from a photoemission cathode C with an initial velocity almost equal to zero (see Figure 5) and that a distance L from that surface, there is an anode A at a positive potential V with respect to C. The electron will be accelerated by the action of the field between cathode and anode. If the gradient of the potential between the plates C-A is defined by E, then

$$E = \frac{V}{L} \quad \text{(volts/meter)},$$

and the force F acting upon the electron is

$$F = eE \quad \text{(Newton's)},$$

where e is the charge of the electron in coulombs. When, as a result of that force, the electron has traveled the distance L (in meters), the amount of energy is

$$FL = eV \quad \text{(Newton - meters)}.$$

This must be equal to the kinetic energy $1/2mv^2$ which the electron has received upon reaching the anode, so that:

$$\frac{1}{2} mv^2 = eV$$

from which it follows that:

$$v = \sqrt{\frac{2eV}{m}} \quad \text{(meters/sec.)}.$$

now

$$\frac{e}{m} = 1.77 \times 10^{11} \text{ coulombs}/_{\text{kg}},$$

so that:

$$v = 5.95 \times 10^5 \sqrt{V} \text{ (meters/sec.);}$$

or in other words: the velocity of an electron is proportional to the square root of the potential difference traversed. Further, from the above equation, it is seen that, after traversing a potential difference of 1 volt, a stationary electron obtains a velocity of 595 km/sec. This is briefly referred to as one-volt electron, and it is also said that this electron has a kinetic energy of one electron-volt. When this electron, after having been accelerated to a velocity v in the electric field between cathode and anode, emerges through an opening into a space where there is no field, it will not suffer any further changes in velocity and will continue at a uniform speed. For voltages greater than 25 kilovolts, at which the electron obtains a velocity greater than one-third the speed of light, the equation no longer applies. since the mass m of the electron was assumed to be a constant. From Einstein's theory of relativity, it follows that at high velocities the mass m increases, this increase being greater the closer the speed of light is approached. For a more thorough discussion of this, reference is made to Television by Kerkoff and Werner, pp. 21-22.

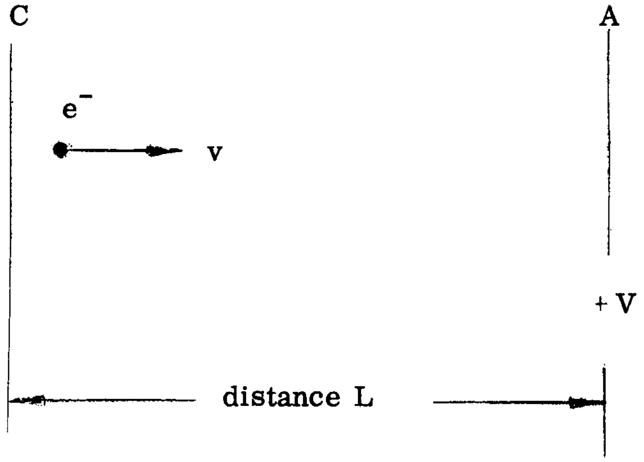

Figure 5

The following is a derivation of the relationship between the accelerating potential used and the magnetic induction required for proper focusing of electrons. The axial force on the electron is

$$F = m \frac{d^2 l}{dt^2} = E e$$

Integrating:

$$m\frac{dl}{dt} = Eet + C_1$$

Integrating again:

$$ml = \frac{Eet^2}{2} + \cancelto{0}{C_1 t} + \cancelto{0}{C_2}$$

Inserting limits of integration

$$ml\Big|_0^L = \frac{Eet^2}{2}\Big|_0^T$$

$$mL = \frac{Eet^2}{2}$$

$$T = \sqrt{\frac{2mL}{eE}} = L\sqrt{\frac{2m}{eV}} \quad \text{(sec.)}$$

Now it already has been shown that the period of a circular orbit of an electron traveling with a component of velocity at right angles to a magnetic field in which it is traveling is equal to:

$$T \equiv \frac{2\pi m}{eB} \quad \text{(sec.)}$$

Hence, setting the time of travel of electron from cathode to anode equal to the period of a circular orbit,

$$L\sqrt{\frac{2m}{eV}} = \frac{2\pi m}{eB}$$

$$B = \frac{\sqrt{2}\,\pi}{\left(\frac{e}{m}\right)^{1/2}} \times \frac{V^{1/2}}{L} = 0.108 \times 10^{-4}\,\frac{V^{1/2}}{L} \text{ webers/meter}^2$$

$$\text{or } B \approx 0.1 \times \frac{V^{1/2}}{L} \text{ gauss.}$$

where V is in volts, and L in meters. Notice from the above equation that the magnetic induction necessary for proper focusing is proportional to the square root of the accelerating potential. If L, the distance between the cathode and anode, is fixed, proper focusing may be achieved by either changing the accelerating potential V, or by changing the magnetic flux density B. But from the equation it can be seen that less change in B is required, percentagewise, than in V for proper focusing. Also, it is usually much easier to adjust the current in a focus coil than it is to vary a high voltage. Hence, this is the manner in which proper focusing is normally achieved.

Thus far in the analysis of the motion of an electron in an electric and/or a magnetic field some assumptions had to be made. In the first place we studied the motion of an electron which had a constant velocity v with a direction at some small angle to the direction of the lines of induction of a uniform magnetic field. Here the resultant motion was a helical path, the radius of which was constant as long as the velocity did not change.

Next we studied the spiral path (not truly a helical path) that an electron takes as it leaves the cathode with a low initial velocity at some angle to the lines of induction of a uniform axial magnetic field and as it is accelerated toward the anode by an axial electric field. Although the axial velocity changes, the circular velocity remains the same throughout the electron's journey from cathode to anode. A mathematical expression was derived showing the relationship between the accelerating potential and the magnetic induction required for proper focusing.

Now if a uniform magnetic field with its lines of induction running perpendicular to the axis of the dissector tube is introduced along with a uniform axial magnetic field and an accelerating potential between cathode and anode, the electron path is not as clearly defined as before. The combination of the two magnetic fields which are at right angles to each other forms a resultant magnetic field whose lines of induction run at some angle to the axis of the dissector tube. In this case, as the electrons are being accelerated toward the anodes, the velocity component perpendicular to the lines of induction of the resultant magnetic field is changing as well as the velocity component parallel to those lines. Knowing that the radius of the circular orbit is proportional to the velocity which is at right angles to the lines of induction of a magnetic field, we see that the spiral is expanding as it approaches the anode.

In order to avoid a complicated and lengthy mathematical description of the true electron path, let us suffice to say that the electron travels a path which is almost a true helix.

Experimental evidence shows that an optical image projected onto a photocathode is reproduced as an electron image at the anode with some degree of rotation. Mullard Limited has carried out some investigation of this phenomenon and has found that the amount or rotation increases as the diameter of the focus coil is made smaller. It is believed, from this evidence, that the curvature of the lines of induction of the magnetic field away from the region of the center of the focus coil cause this observed rotation to exist. A truly homogeneous magnetic field, theoretically, causes no rotation of the image.

Now that the electrons have passed through the aperture, secondary emission multiplication is used to provide amplification of the weak electron current. (See Figure 6.)

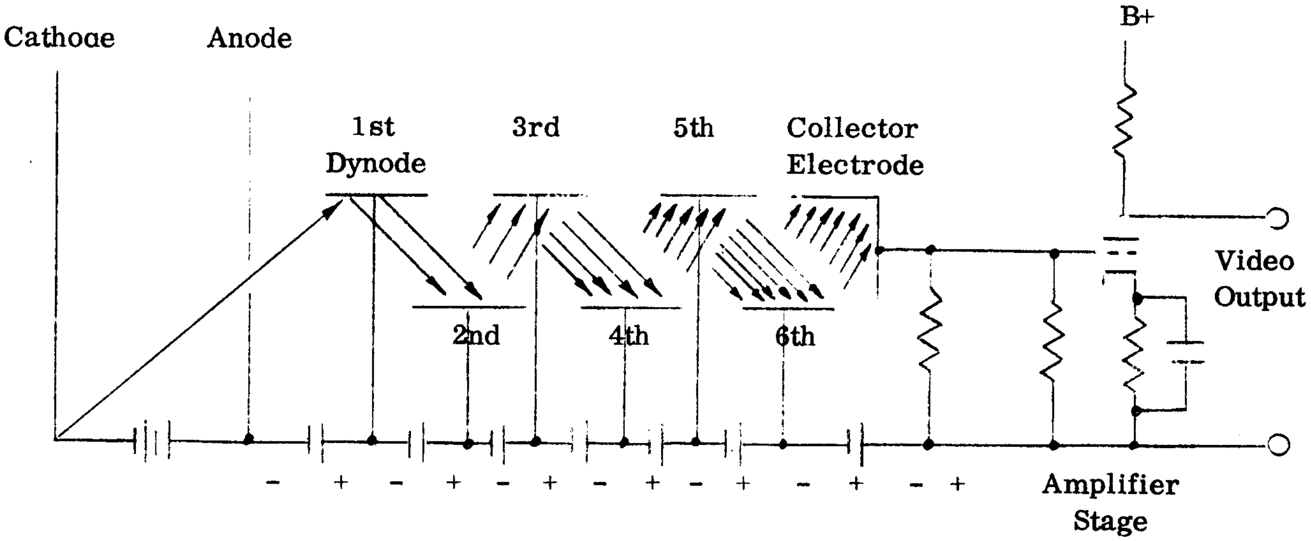

Figure 6 Secondary Emission Multiplier

This is necessary because of the relatively small number of electrons which are emitted from a photocathode that is subjected to light intensity equivalent to a bright outdoor scene. After acceleration of the electrons to a velocity at the anode equivalent to V volts (the potential between cathode and anode), and after passing through the aperture, they bombard an electrode which is called the first dynode.

Depending upon the nature of the surface bombarded and upon conditions of bombardment, a number of electrons, called secondary electrons, are re-emitted from the dynode surface. Usually the number of electrons released are greater than the number of electrons bombarding the surface by a factor of from two to five. An electric field must be provided near the dynode surface to accelerate these electrons away from the metal.

These accelerated secondary electrons now become the primary electrons which bombard the second dynode. This second dynode, in turn, re-emits more electrons. This process is continued through several stages of multiplication until the number of electrons is at least 1000 times as great as the original ones. By proper selection of operating voltages of the dynodes, a stable output current may be obtained that is proportional to the number of primary electrons originally passing through the aperture. This instantaneous output current is analog representation of the magnitude of light intensity falling upon a particular element of the photocathode surface of the image dissector.

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