George R. Town

HAZELTINE SERVICE CORPORATION

(A SUBSIDIARY OF HAZELTINE CORPORATION)

NEW YORK LABORATORY:
333 West 52nd Street
COlumbus 5-0793

CHICAGO LABORATORY:
325 West Huron Street
Superior 0790

BAYSIDE LABORATORY:
Bayside, Long Island.
FLushing 7-5300

Report No. 1932

TITLE THE PICTURE TUBE - PART II
(TELEVISION PRINCIPLES - CHAPTER 10)

DATE *March 29, 1939.*

MFR. *General.*

Approved W. A. MacDonald

THE PICTURE TUBE - PART II

(TELEVISION PRINCIPLES - CHAPTER 10)

C. E. Dean
Editor

TABLE OF CONTENTS

CONSTANTS AND UNITS RELATED TO CHAPTERS 9 AND 10

Electron Charge -

$e = 1.59 \times 10^{-20}$ e.m.u.

$= 4.77 \times 10^{-10}$ e.s.u.

$= 1.59 \times 10^{-19}$ coulomb.

Electron Mass -

$m = 9.04 \times 10^{-28}$ gram (for electron at rest or slow speed in comparison with speed of light).

Ratio of Electron Charge to Mass -

$e/m = 1.77 \times 10^{7}$ e.m.u. $= 5.28 \times 10^{17}$ e.s.u.

$m/e = 5.65 \times 10^{-8}$ e.m.u. $= 1.89 \times 10^{-18}$ e.s.u.

Units in Present Chapter -

Most of the equations of the present chapter are followed by letters in parentheses to indicate the system of units for which the formula applies; the introduction of a suitable constant factor would in general be necessary with other units. The letters "e.m.u." indicate c-g-s electromagnetic units, the letters "e.s.u." c-g-s electrostatic units, and the letter "p" practical units such as the volt and ampere. The unit of length is the centimeter in all equations.

* ~~The e.m.u. of flux density and the practical unit are the same, namely the gauss; similarly with field strength, the unit being the oersted. In both these systems the permeability μ of vacuum or air is unity. The oersted is also called the gilbert per centimeter.~~

* However, for magnetic quantities, the c.g.s. electromagnetic units are used thruout, and suitable constants are introduced where necessary. These units include the gilbert of magnetomotive force, the oersted (or gilbert per cm) of magnetic intensity, the maxwell of total flux and the gauss of flux density.

Certain Conversion Constants -

1 joule = 10^{7} ergs.

1 e.m.u. of current = 10 amperes.

1 e.s.u. of potential = 300 volts.

1 amp. turn = 1.257 gilberts

* * * * * *

1 weber = 10^{8} maxwells

THE PICTURE TUBE - PART II
(TELEVISION PRINCIPLES - CHAPTER 10)

INTRODUCTION

In the preceding chapter a description is given of the essential qualities of the television image produced on the screen of the picture tube. A description of various types of distortion of this image is also presented. In addition, the electrical and electron-optical characteristics of the electrostatically focused and magnetically scanned picture tube are described in detail.

It is the purpose of the present chapter to extend the discussion of the picture tube with a treatment of the following subjects:

The electrical and electron-optical characteristics of the magnetically focused picture tube;

The picture-tube voltage-supply circuit for both electrostatically and magnetically focused tubes;

Magnetic and electrostatic deflection methods; and

The relation between the maximum deflection angle and the requirements of the deflection system, including consideration of the bulb geometry.

THE MAGNETICALLY FOCUSED TUBE

Figure 1 shows a cross-section of a particular design of magnetically focused and magnetically scanned tube. The electron gun consists of a cathode, grid, and anode, which can be regarded as a triode structure in contrast to the pentode structure of the electrostatically focused tube. The cathode and grid are similar to the corresponding electrodes of the electrostatically focused tube. The anode is adjacent to the grid as shown in Figure 1. The electric field produced in the space between anode, cathode, and grid constitutes an electric electron lens. The performance of this lens is very similar to that of the first lens of the electrostatically focused tube described in the preceding chapter. An important difference between the two is that in the magnetically focused tube the electron beam receives its entire acceleration in the first lens so that the diameter of the cross-over is smaller and the angle of divergence of the cone of electrons leaving the first lens is smaller than in the case of the first lens of the electrostatically focused tube.

As a rule, with the magnetically focused tube no apertures are required to limit the size of the electron beam entering the region of the second lens. This lens consists of a magnetic field produced by a short solenoid, or its equivalent, which is coaxial with the electron-optical axis of the tube. The resultant magnetic field acts as an electron lens which focuses the electron cross-over on the fluorescent screen.

THE MAGNETIC ELECTRON LENS

When a conductor carrying an electric current is placed in a magnetic field, the conductor is acted on by a force <u>F</u> which acts at right angles to both the current and the magnetic field. When an electron beam in a vacuum tube passes thru a magnetic field, a force similarly acts on the individual electrons in a direction at right angles to the direction of their motion and to the direction of the magnetic field. This force produces a change in the direction of the electrons. The value of the force on a single electron is given by the following equation:

$$F = Bev \sin \theta \; . \; . \; . \; . \; . \; . \; (1) \; (\text{e.m.u.})$$

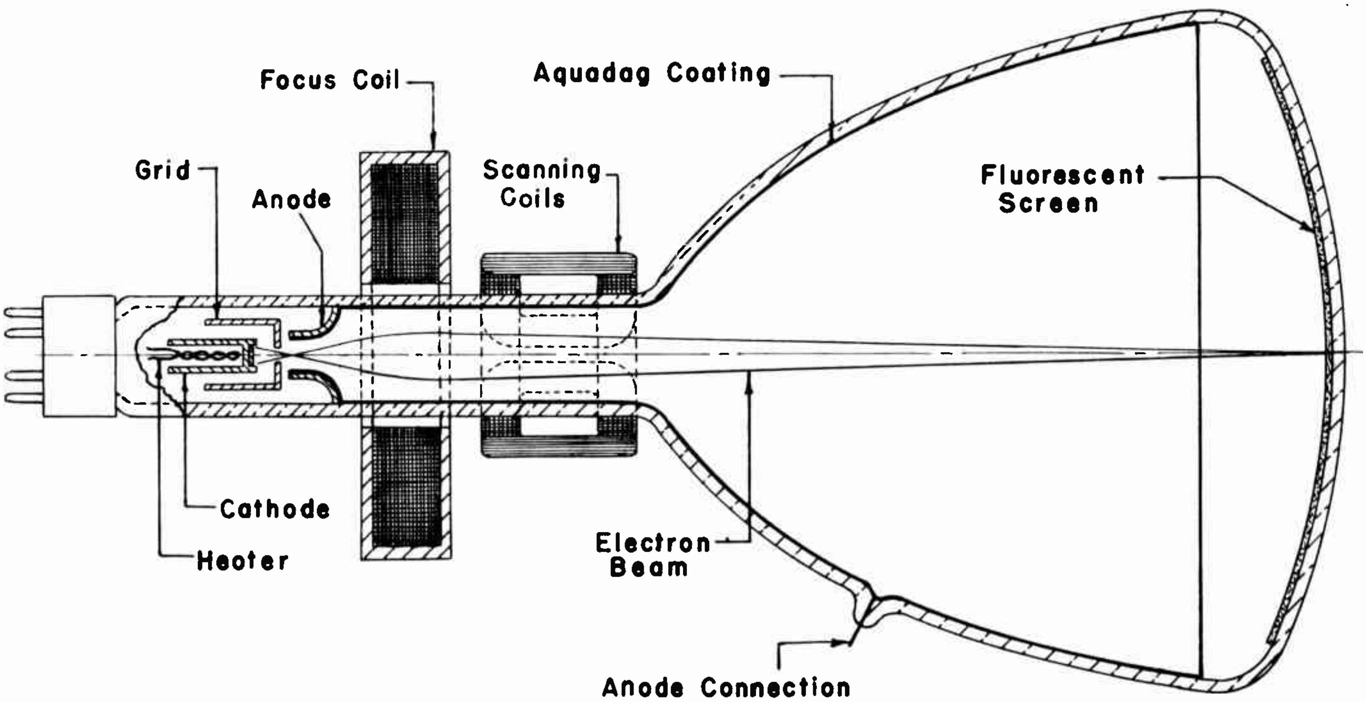


Fig. 1. Cross-Section of Picture Tube with Magnetic Focusing and Deflection.

where
- B = magnetic flux density,
- e = charge of electron,
- v = velocity of electron, and
- θ = angle between direction of motion of electron and direction of magnetic field.

For this and various following equations the letters (e.m.u.) beyond the equation number designate the use of absolute electromagnetic c-g-s units, the letters (e.s.u.) absolute electrostatic c-g-s units, and the letter (p) practical electric units. Metric units of length are used throughout.

Since the force produced by a magnetic field on a moving electron is always perpendicular to the direction of motion of the electron, this force cannot change the speed of the electron but can only change its direction of motion. The magnitude of this force depends, however, upon the velocity of the electron. We see therefore that the behavior of electrons in passing thru a magnetic electron lens is entirely different from that of electrons passing thru an electrostatic lens since, in the latter case, the force acting on the electron does change the speed of the electron and the magnitude of this force is independent of the velocity of the electron.

Action of Uniform Magnetic Field

A uniform magnetic field has properties which cause it to be often regarded as a lens. An introductory account of these properties is included in Chapter 7, Report 1894, pages 145-147, in connection with the magnetically focused image producer.

As a result of the magnetic field altering the direction but not the speed of the electron, the path takes the form of a helix whose axis is in the direction of the magnetic field. To investigate this, the velocity $\underline{v}$ may advantageously be resolved into a component v_1 in the direction of the field, and a component v_2 at right angles to the field. Applying equation (1) to component v_1, the angle θ is zero, whence the sine of θ is zero; therefore, as far as this component is concerned, the field produces no force on the electron, and has no effect on the motion. The progress of the electron in the direction of the field

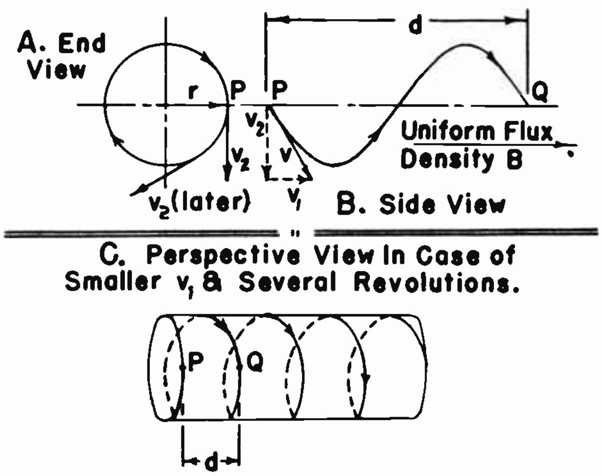


Fig. 2. Helical Path of Electron in Uniform Magnetic Field.

therefore continues as though the field were not present.

Applying equation (1) to component v_2, which is perpendicular to the field, the value of the sine of θ is unity, whence we have the force,

$$F = Bev_2, \quad . \; . \; . \; (2) \text{ (e.m.u.)}$$

which acts to vary the direction but not the amount of the component v_2. As regards this component of velocity, the electron moves in a circle; this circle is of course the end view of the helix. In Figure 2-A this is shown, P representing the initial position of the electron. The velocity v_2 initially, and also this velocity at a later time, are shown.

In Figure 2-B a side view of the helical path of the electron is represented, and the point Q is marked; here the electron has completed one revolution and crosses the element of the cylinder which passes thru P. In Figure 2-C a perspective view of the motion is shown for a smaller v_1 so that there is room for several revolutions. However, one revolution is all that is ordinarily employed.

The electron is acted upon by a centrifugal force due to the circular motion of its own mass, and this force just balances the force produced by the magnetic field; the centrifugal force in dynes is

$$F_c = m\omega^2 r, \quad . \; . \; . \; . \; . \; . \; . \; . \; . (3)$$

where m = mass of electron in grams,
ω = angular velocity in radians per second, and
r = radius of circular motion in centimeters.

Calling the force due to the magnetic field F_m, we have from equation (2),

$$F_m = Bev_2,$$

$$\text{or} \quad F_m = Be\omega r. \quad . \; . \; . \; (4) \text{ (e.m.u.)}$$

Now of necessity,

$$F_c = F_m,$$

$$\text{whence} \quad m\omega^2 r = Be\omega r.$$

$$\text{Therefore} \quad m\omega = Be,$$

$$\text{or} \quad \omega = B\frac{e}{m}. \quad . \; . \; . \; (5) \text{ (e.m.u.)}$$

We see therefore that the angular velocity of the electron in the circular path is independent of its velocity v_2; that is, the time required for the electron to traverse exactly once around its circular path is independent of the velocity v_2. This means that an electron passing thru point P with a velocity component v_1 in the direction of the magnetic field, will pass thru the particular point Q regardless of the direction in which it passes thru P. Thus if the point P is an electron object, the magnetic field produces an electron image of this at point Q.

The uniform magnetic field thus acts as a magnetic electron lens. The magnification of this lens is unity and the image which it produces is upright instead of inverted as is the case with an optical lens, or an electric electron lens. The separation d of object and image produced by this lens equals the distance $\overline{PQ}$ which may be computed as follows:

$$\overline{PQ} = d = v_1 t, \quad . \; . \; . \; . \; . \; . \; (6)$$

where d = distance between electron object and electron image, and
t = time required for the electron to go from P to Q.

In the time t, the electron makes one complete revolution in its circular orbit, as seen end-on. In equation (5), ω is the angular velocity in radians per second. There $1/\omega$ is the time required to turn one radian, and $2\pi/\omega$ the time required to make exactly one traversal of the circular orbit.

Therefore

$$t = \frac{2\pi}{\omega}, \text{ or } \omega = \frac{2\pi}{t}. \quad . . . (7)$$

Substituting this in (5) we get

$$\frac{2\pi}{t} = B\frac{e}{m},$$

whence

$$t = \frac{2\pi}{B}\frac{m}{e}. \quad . . . . (8) \text{ (e.m.u.)}$$

Substituting (8) in (6) we get

$$d = v_1 \frac{2\pi}{B}\frac{m}{e}. \quad . . . (9) \text{ (e.m.u.)}$$

Short Solenoid as Lens

A type of magnetic electron lens which finds a much wider application in picture tubes than the uniform magnetic field is that consisting of a short magnetic solenoid. The complete theory of this lens is beyond the scope of this chapter, but a brief description of its action and the very useful formulas which result from the theory are presented in the following paragraphs.

In this lens the electron-optical axis is the axis of the short solenoid. It is assumed that no electrostatic field is present. An electron approaching the lens on the electron-optical axis finds at all points that the field is in the direction of its own motion, whence it continues undeflected along the electron-optical axis and strikes the screen, having completed its entire course in a straight line. An electron originating at the same point in the object as the electron just considered, but traveling at an angle to the electron-optical axis, experiences a turning force so that it emerges from the field of the solenoid in such a direction as to be brought to focus on the screen at the electron-optical axis. In this way electrons going in various directions from the point of the object where the electron-optical axis intersects it are focused on the screen at the point where the electron-optical axis intersects the screen.

Electrons originating at some other point of the object, not on the electron-optical axis, and proceeding in various directions are similarly brought to focus on the screen; for very thin solenoids this point on the screen is almost exactly on the opposite side of the electron-optical axis. For fairly thick solenoids there is a substantial angle ψ by which the position of the image point differs from a location just on the opposite side of the electron-optical axis.

It is of interest to notice that a paraxial electron leaving such an object point (that is, an electron leaving a point which is not on the electron-optical axis, and proceeding parallel to the electron-optical axis) first undergoes deflection by the fringing field of the solenoid so that while traveling thru the central uniform field of the solenoid, it undergoes further deflection, and is finally brought to focus at the proper point in the general region on the opposite side of the electron-optical axis. In other words, the fringing field gives the electron velocity a radial component (v_2 in Figure 2), so that the central uniform field has this as "something to work on", and produces a helical path; the electron then undergoes further deflection in the other fringing field, after which it proceeds in a straight line to the focus point on the screen. In this case, if the fringing fields were not present, the paraxial electron would continue in a straight line and strike the screen on the same side of the electron-optical axis as it originated, corresponding to the action of paraxial electrons in the uniform field considered in the preceding section.

If therefore we consider an object plane perpendicular to the electron-optical axis, then points in this plane are brought to a focus at corresponding points in an image plane, which in practice is the fluorescent screen.

It should be noted that the focusing action now discussed is separate from any magnetic field used for scanning deflection, such as shown with the tube of Figure 1. The function of the focusing solenoid is accomplished if a sharp focus at the center of the fluorescent screen is obtained. The action of sweeping this spot over the screen is performed of course by the scanning elements.

The behavior of the short magnetic lens is like that of the optical lens or the electrostatic electron lens except that the inverted image is turned thru an angle ψ. This turning of the image does not affect its quality, however. The direction of this angle of turn depends upon the sense of the magnetic field and therefore upon the direction of current thru the solenoid. As the width of the region of the magnetic field is decreased relative to the distance between object and image, this angle of turn from exact inversion decreases. As the width of the magnetic-field region is increased, this angle increases, reaching a value of π (thus giving an upright image) for the case of a uniform magnetic field extending the entire distance from object to image; this extreme is of course the uniform field discussed in the preceding section.

In Figure 3-A a magnetically focused tube is shown in cross-section. The electron gun produces a small cross-over near the grid. The electrons emerge from this cross-over in a small cone with uniform velocity. The short solenoid, which constitutes a short magnetic electron lens, is coaxial with the electron-optical axis of the electron gun, and focuses the cross-over (which is the electron object) into the electron spot on the fluorescent screen (which is the electron image).

The theory of the short magnetic electron lens leads to certain quantitative relationships. The solenoid has a focal length $\underline{f}$ which depends on its magnetic flux density and the velocity or equivalent fall of potential of the electrons in the beam. Let B(z) be the magnetic flux density along the electron-optical axis, $\underline{z}$ representing distance along this axis with the origin at the point where the mid-plane of the solenoid intersects the axis. A plot of B(z) as a function of $\underline{z}$ is given in Figure 3-B. The focal length $\underline{f}$ may be obtained from the equation,

$$\frac{1}{f} = \frac{e}{8mE}\int_{-a}^{+b} B(z)^2\,dz, \quad . . (10)\,(\text{e.m.u})$$

where e = charge of electron,
m = mass of electron,
E = potential drop of beam, and
B(z) = magnetic flux density on z-axis, as already defined.

Integration from -a to +b is of course more than sufficient to include all the region in which there is appreciable flux density.

If we substitute the numerical values of $\underline{e}$ and $\underline{m}$, and express $\underline{E}$ in volts, leaving $\underline{B}$ in gausses and $\underline{f}$ in centimeters, we get

$$\frac{1}{f} = \frac{0.022}{E}\int_{-a}^{+b} B(z)^2\,dz. \quad . . (11)\ (p)$$

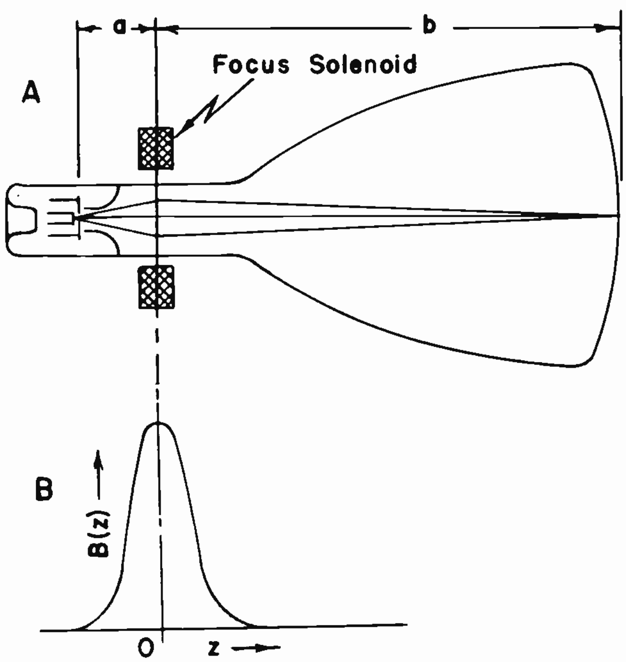


Fig. 3. Characteristics of Short Magnetic Lens Used With Picture Tube.

The relation between the focal length *f* and the object and image distances *a* and *b* respectively is identical with that pertaining to an optical lens, namely

$$\frac{1}{f} = \frac{1}{a} + \frac{1}{b}, \quad \ldots\ldots\ldots(12)$$

where a = object distance to lens, and
b = image distance to lens.

The magnification of the lens, which is the ratio of image size to object size, if given by the optical-lens formula,

$$m = \frac{b}{a}. \quad \ldots\ldots\ldots\ldots(13)$$

Equations (11), (12), and (13) can be seen to give all the information which is required to predict the behavior of the short magnetic electron lens.

The angle ψ thru which the electron image is turned is given quantitatively by

$$\psi = \sqrt{\frac{e}{8mE}} \int_{-a}^{+b} B(z)\, dz, \quad \ldots(14)\text{(e.m.u)}$$

where *e*, *m*, *E*, and B(z) have the same meanings as in equation (10).

If we substitute the values of *e* and *m* in this equation, and express *E* in volts, *B* remaining in gausses and *z* in centimeters, we obtain the angle of turn, still in radians, as follows:

$$\psi = \frac{0.15}{\sqrt{E}} \int_{-a}^{+b} B(z)\, dz. \quad \ldots (15)\ \text{(p)}$$

An examination of equations (10) and (11) reveals that the magnetic lens differs from the electrostatic lens, discussed in the previous chapter, in that the focal length is:

(1) Directly proportional to the voltage of the cathode-ray beam;

(2) Directly proportional to m/e; this means that the lens is ineffective for positive ions since these have masses which are of the order of ten thousand times the electron mass;

(3) Inversely proportional to the square of the magnetic flux density, which is to say the square of the current thru the solenoid when the entire field is produced by a solenoid;

(4) Independent of the sign of *B*, which means that it is independent of the sense of the magnetic flux and therefore of the direction of the current thru the solenoid;

(5) Dependent upon the distribution of the magnetic flux density along the axis, becoming shorter as a given total flux is crowded into a shorter region; and

(6) Always positive, which means that the magnetic electron lens is always a converging lens.

The magnetic flux density produced on the z-axis by a short solenoid with no magnetic material in the vicinity is given approximately by

$$B(z) = \frac{2\pi r^2 ni}{(z^2 + r^2)^{3/2}}, \quad \ldots(16)\text{(e.m.u.)}$$

where r = average radius of solenoid,
n = total number of turns,
i = current, and
z = distance along axis measured from the mid-plane of the solenoid.

This solenoid is shown by the number 1 in Figure 4-A, and the above relation is plotted in Figure 4-B as curve 1. If the outside of this solenoid is covered with a channel of iron as shown at 2 in Figure 4-A, the flux is crowded into a narrower region and increased in intensity at the point z = 0, as shown in curve 2 of Figure 4-B. This result is desirable since it improves the efficiency of the solenoid, requiring less current to produce a given focal length; also the lens can be placed closer to the scanning field without causing distortion by the overlapping of the focusing and scanning fields.

It is possible to cover a still greater portion of the focus coil with iron as shown at 3 in Figure 4-A, making the field still narrower as shown in curve 3 of Figure 4-B. However, the gap in the iron sheath around the focus coil may not be made too narrow. The magnetic flux at the axis may be thought of as the leakage across this gap. As the gap is reduced beyond a certain size, the flux at the axis becomes weaker.

Plots of the square of the flux density are given in Figure 4-C. While the first power is integrated for the angle ψ, the square is integrated in the determination of the focal length.

It is possible to use a permanent magnet for producing the magnetic field of a magnetic electron lens. Such a magnet may have various shapes including those of the iron sheaths surrounding the magnetic focus coils designated 2 and 3 in Figure 4-A.

Although the permanent magnet has an advantage over the solenoid in that it uses no power for its operation, it has the limitation that the flux density is not readily adjustable. With the solenoid, variation of the current gives a convenient control of the focal length, permitting a sharp focus of the electron spot to be obtained on the fluorescent screen. With the permanent-magnet lens, that is in the absence of a flux-density adjustment, two means of focusing remain. Since the focal length depends on the voltage of the cathode-ray beam, the lens can be focused by adjusting the anode voltage of the tube. Also it can be focused by adjusting the position of the lens (that is, the magnet) between the electron gun and the fluorescent screen, but such a method is not convenient. A compromise may be made by supplying a part of the field from a solenoid and the remainder from a permanent magnet, so that convenient and sensitive focus control may be had by controlling the solenoid current. In order to prevent defocusing due to change of second-anode voltage accompanying line-voltage

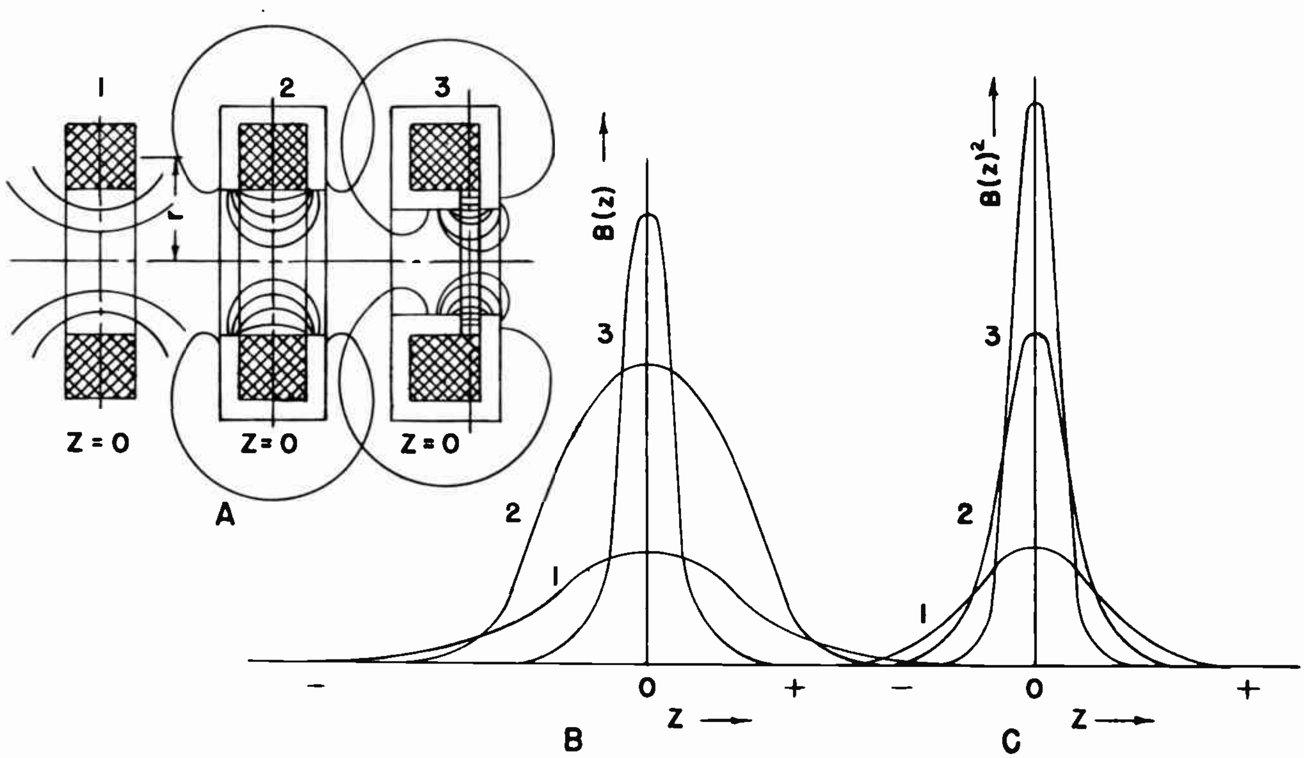


Fig. 4. Characteristics of Plain and Iron-Clad Solenoids as Short Magnetic Electron Lenses.

fluctuation, it is necessary to have either a readily accessible manual focusing control or means for automatic maintenance of focus.

ANODE-VOLTAGE SUPPLY FOR MAGNETICALLY FOCUSED TUBES

The half-wave rectifier circuit is commonly used for obtaining the anode voltage for picture tubes. Figure 5 shows various circuits used for this purpose. Figure 5-A shows the most elementary circuit; this is frequently used for magnetically focused tubes by the provision of a suitably large filter capacitor C. This circuit is not sufficient for electrostatically focused tubes because these require different voltages for the second anode, the first anode, and the screen grid.

The circuits of Figures 5-B and 5-C may be used for either magnetically focused or electrostatically focused tubes. In the case of electrostatic focusing, the first-anode and screen-grid voltages may be obtained from the taps shown on resistor R.

Effect of Ripple in Anode Voltage of Magnetically Focused Tubes

The focal length of the short magnetic electron lens has already been stated above in equation (11) on page 223 to be given by the relation,

$$\frac{1}{f} = \frac{0.022}{E}\int_{-a}^{+b} B(z)^2\,dz. \quad . . (17)\ (p)$$

If we assume that the magnetic flux density of the focus coils remains constant with time but the second-anode voltage does not, we can write this equation as

$$\frac{1}{f} = \frac{k}{E}, \quad . . . . . . (18)\ (p)$$

where k = a constant.

We also have from equation (12) that

$$\frac{1}{f} = \frac{1}{a} + \frac{1}{b}, \quad . . . . (19)$$

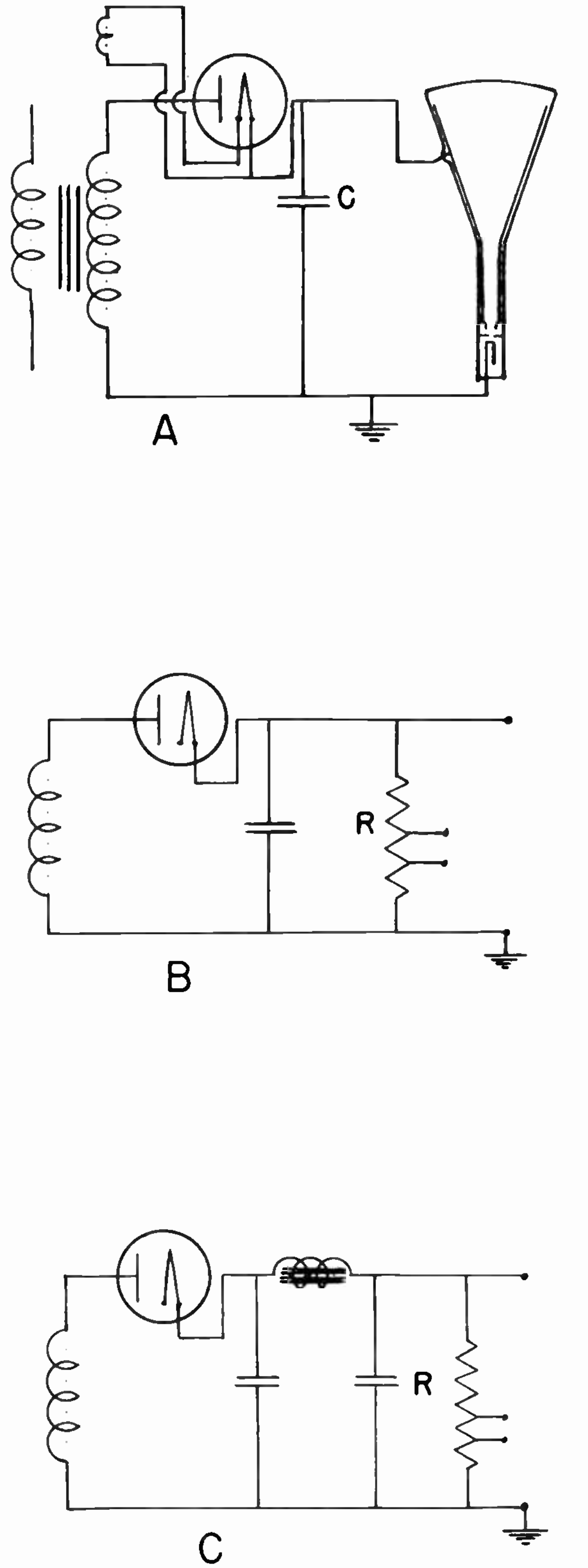


Fig. 5. Circuits Used to Supply High Voltage for Picture-Tube Operation.

where a = distance from lens to electron object, and

b = distance from lens to electron image.

Equating the two expressions for $1/f$ in (18) and (19) there results

$$\frac{k}{E} = \frac{1}{a} + \frac{1}{b}. \quad \ldots\ldots .(20)\ (p)$$

If $\underline{a}$ is kept constant while $\underline{E}$ is varied, $\underline{b}$ will vary in a manner which may be determined by differentiation of (20), as follows:

$$-\frac{k}{E^2}\, dE = -\frac{1}{b^2}\, db,$$

or $$\frac{k}{E}\frac{dE}{E} = \frac{1}{b^2}\, db.$$

Substituting now for k/E from (20), we get

$$\frac{a+b}{ab}\,\frac{dE}{E} = \frac{1}{b^2}\, db,$$

or upon solving for the differential of $\underline{b}$ and substituting increments,

$$\Delta b = \frac{b}{a}(a+b)\frac{\Delta E}{E}, \quad (21)\ (p)$$

where ΔE = a small change in $\underline{E}$, the beam potential, and

Δb = resultant change in $\underline{b}$, the image distance.

However, we see from Figure 6 that if a point electron object is imaged at a distance Δb in front of the fluorescent screen, the resulting image on the screen has a diameter Δs which is given by

$$\frac{\Delta s}{\Delta b} = \frac{U}{b}, \quad \ldots\ldots\ldots .(22)$$

where U = diameter of electron beam at center of lens.

This means that if the electron spot has a diameter $\underline{s}$ when focused, the diameter will increase to $(s + \Delta s)$ when the focus is moved to a distance Δb in front of the screen. The fractional change in spot diameter is $\Delta s/s$. Solving (22) for Δb and substituting this in (21) gives

$$\frac{b \cdot \Delta s}{U} = \frac{b}{a}(a+b)\frac{\Delta E}{E},$$

whence $$\Delta s = \frac{U}{b}\frac{b}{a}(a+b)\frac{\Delta E}{E},$$

or $$\frac{\Delta s}{s} = \frac{U}{sa}(a+b)\frac{\Delta E}{E}. \quad \ldots\ldots .(23)$$

This equation holds with any units since essentially only ratios of distances and a ratio of voltages are involved.

Since the factor $(U/sa)(a + b)$ is quite large (about 100 for a typical 9-inch tube), we see that for magnetically focused tubes the percentage variation of spot diameter is much larger than the corresponding percentage variation of anode voltage. This requires the anode voltage to be well filtered, since otherwise the ripple voltage will cause serious defocusing. The electrostatically focused tube on the other hand will tolerate a relatively large ripple voltage, since the focus is affected very little by the anode voltage and the ripple-voltage tolerance is set by the variation of deflection sensitivity with beam voltage, as described in the preceding chapter, Report 1924, page 206.

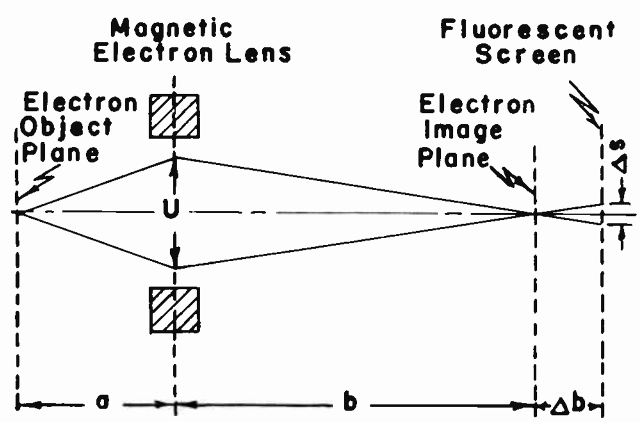


Fig. 6. Enlargement of Scanning Spot in Case of Focus at Distance from Screen.

EFFECT OF RIPPLE IN FOCUSING CURRENT

The above discussion is on the basis that the magnetic focusing flux is maintained constant, which means that if it is produced by a solenoid, the current thru the solenoid remains constant. Actually in most cases this current will have some ripple in it due to being supplied by a rectifier circuit. We now compute the effect of this ripple component.

Returning again to the equation for the focal length of a short magnetic electron lens, we have from page 223

$$\frac{1}{f} = \frac{0.022}{E}\int_{-a}^{+b} B(z)^2\,dz. \quad \ldots (24)(p)$$

If we assume that the magnetic flux density along the axis, $B(z)$, is directly proportional to the current i thru the focusing coil, then for a given coil and a constant beam voltage we can rewrite equation (24) as follows:

$$\frac{1}{f} = K i^2, \quad \ldots\ldots\ (25)$$

where K = a constant, and
i = current thru focusing coil.

Equating this with the value of $1/f$ from equation (12), there is obtained

$$K i^2 = \frac{1}{a} + \frac{1}{b}. \quad \ldots\ldots\ldots (26)$$

If a is kept constant while i is varied, b will vary in a certain way. To determine this let us differentiate (26), getting

$$2Ki\,di = -\frac{1}{b^2}\,db.$$

Solving (26) for K and substituting here gives

$$\frac{2\cdot(a+b)}{ab}\,\frac{di}{i} = -\frac{1}{b^2}\,db, \quad \ldots (27)$$

whence in terms of increments,

$$\Delta b = -2\frac{b}{a}(a+b)\frac{\Delta i}{i}, \quad \ldots (28)$$

where Δi = a small change in the focusing current i, and

Δb = resultant change in the image distance b.

However, as we have seen in the previous section from Figure 6 and equation (22),

$$\Delta b = \frac{b}{U}\,\Delta s,$$

where Δs = change in spot size s resulting from change Δb in image distance.

Equating this expression for Δb to that in equation (28) and solving for Δs gives

$$\Delta s = -2\frac{U}{b}\frac{b}{a}(a+b)\frac{\Delta i}{i},$$

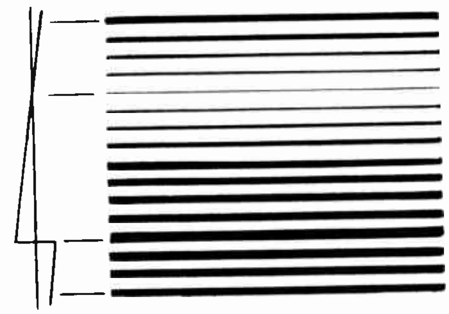
or

$$\frac{\Delta s}{s} = -2\frac{U(a+b)}{s\,a}\,\frac{\Delta i}{i}. \quad \ldots (29)$$

This formula is dimensionless in that only ratios of lengths and currents are involved; it therefore holds for any unit of length and any unit of current.

Comparing this result with equation (23) of the previous section, we see that a given percentage variation in the focusing current causes twice as large a percentage variation in the spot diameter as does the same percentage variation in beam voltage. Moreover, from equation (24) an increase in beam voltage increases the focal length, whereas from equation (25) an increase in focusing current decreases the focal length.

The distortion of the raster due to anode-voltage ripple, which comes about because of the variation of deflection sensitivity with anode voltage, is discussed in the preceding chapter. This effect is negligible with the magnetically focused tube since good voltage regulation is necessary to prevent large variations in spot size. Should the regulation be insufficient, the spot will be in focus for certain lines of the raster and out of focus for other lines, as shown in Figure 7 in a diagrammatic manner.



(Luminous intensity per line is constant, wider lines having less brightness.)

Fig. 7. Variation of Line Width of Magnetically Focused Tube Due to Anode-Voltage Ripple.

MAGNETIC DEFLECTION

The discussion of magnetic electron lenses earlier in this chapter includes the subject of the force acting on an electron moving in a magnetic field. The theory of the deflection of an electron beam by a magnetic field to produce scanning is much simpler, and we now consider this.

Figure 8 shows the path of an electron thru a magnetic deflecting field. It is assumed that no electrostatic field is present. The electron is proceeding in the plane of the paper with a velocity v, and passes thru a magnetic field of flux density B which is uniform and has a direction normal to the surface of the paper. We assume that this magnetic flux is confined between the planes 1 and 2 which are normal to the direction of the initial velocity v, although in practice the edge of the magnetic field cannot be so abrupt; the plot of the deflecting flux density in the lower sketch of Figure 8 shows this difference. For the sake of simplicity the effect of the

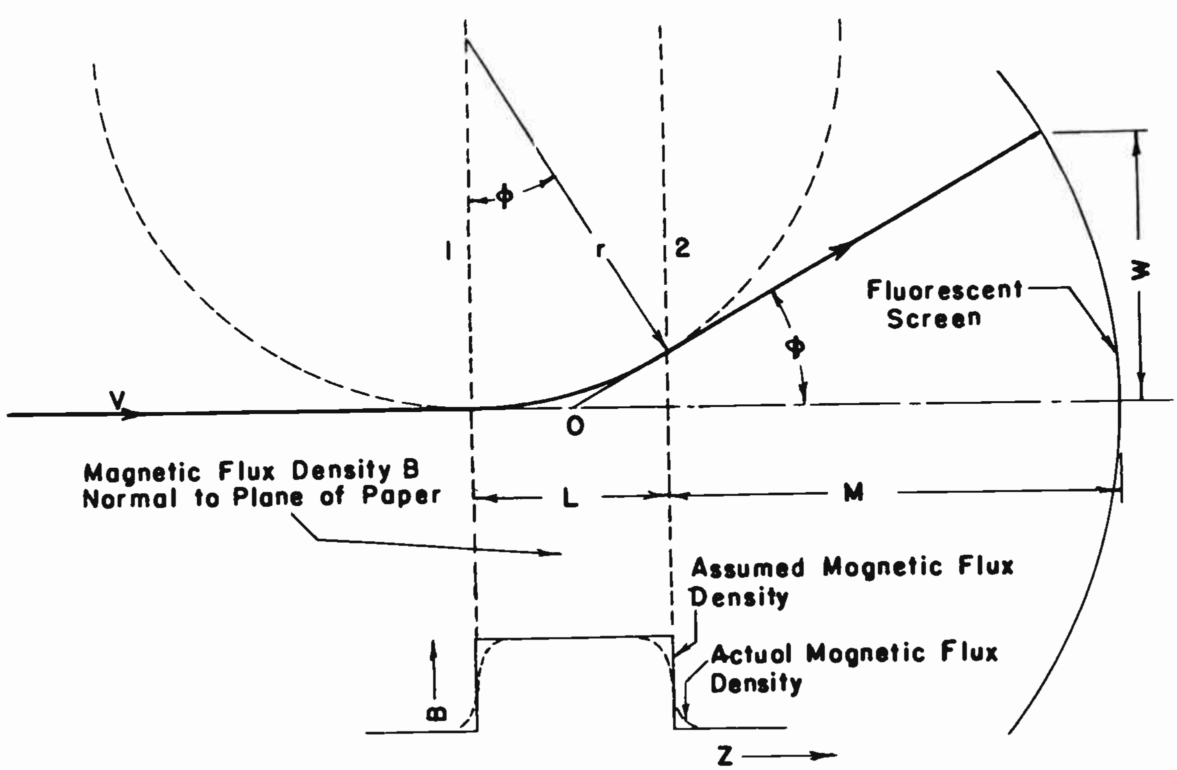


Fig. 8. Deflection of Electron Beam by Magnetic Scanning Field.

fringing field is neglected in the present discussion.

The general expression for the force on the electron after it enters the field is given above as equation (1) on page 219, and is as follows:

$$F = Bev \sin \theta.$$

In the present case this becomes

$$F = Bev, \quad . \; . \; . \; . (30) \text{ (e.m.u.)}$$

since $\theta = \frac{\pi}{2}$, whence $\sin \theta = 1$.

It can be seen that there is no velocity component parallel to the field, whence no motion in this direction; therefore the helix of the general theory degenerates into a circle. This circle lies in the plane of the paper in Figure 8 and has as tangents the straight paths of the electron outside the field. The angular velocity of the electron in its circular path is given by equation (5) from page 221 as follows:

$$\omega = B\frac{e}{m},$$

where B = magnetic flux density,
e = electron charge, and
m = electron mass.

However, $r\omega = v$,

where r = radius of circle, and
v = speed of electron.

The speed of the electron v remains constant when the electron is acted on solely by a magnetic field, as in the earlier discussion. Eliminating ω between the last two equations, there results

$$\frac{v}{r} = B\frac{e}{m}. \quad . \; . \; . \; . \; . (31) \text{ (e.m.u.)}$$

The electron enters the field normal to the plane 1 in Figure 8, and leaves the plane 2 in a straight line, having been deflected thru an angle ϕ relative to its initial direction. The center of the circular orbit which the electron travels between planes 1 and 2 must lie in plane 1, and we see from Figure 8 that the angle subtended by the curved path between these planes equals the angle of deflection ϕ. Moreover, if the distance between planes 1 and 2, which is the axial length of the deflecting field, is L, we see from Figure 8 that

$$\frac{L}{r} = \sin \phi.$$

Solving this equation for r and substituting in (31),

$$\frac{v}{L} \sin \phi = B\frac{e}{m},$$

or $$\sin \phi = \frac{L}{v} B\frac{e}{m}. \quad . \; . \; . \; . (32) \text{(e.m.u.)}$$

The speed of the electron can be expressed in terms of the fall of potential by which it has been accelerated in the electron gun, which is referred to as the beam potential. Thus

$$Ee = 1/2\, mv^2, \quad . \; . \; . \; . \text{(e.m.u.)}$$

where E = beam potential,

giving $v = \sqrt{2E\frac{e}{m}}$.

Substituting this value of v in (32), we get

$$\sin \phi = \frac{BL}{\sqrt{2E}}\sqrt{\frac{e}{m}}. \quad (33) \text{ (e.m.u.)}$$

This equation is valid for values of ϕ smaller than 90 degrees, which is of course ample for considering deflection. We see from the last equation that magnetic deflection is characterized by the fact that the sine of the angle of deflection is:

(1) Proportional to the magnetic deflecting flux B;

(2) Proportional to the length L of the magnetic field;

(3) Inversely proportional to the square root of the beam potential;

(4) Proportional to the square root of the ratio of charge to mass of the deflected particle; this makes the deflection of an ion only a fraction of a percent of the deflection which an

electron experiences on passing thru the same field; and

(5) Of opposite sign when the direction of the magnetic field is reversed.

If in equation (33) we express B in gausses and E in volts, leaving L in centimeters, and insert the value of e/m for an electron, we get for the sine of the angle of deflection,

$$\sin \phi = 0.30 \frac{BL}{\sqrt{E}} \cdot \quad \ldots (34)\ (p)$$

In Figure 9 the relation between the angle of deflection ϕ and the deflecting flux B is plotted over the range in which equation (34) is valid, namely for values of ϕ up to 90 degrees. The range used in practical tubes extends to about $\pm$ 30 degrees, and a range of $\pm$ 25 degrees is shown in a solid line, the rest of the curve being dotted. The variation of the angle of deflection with magnetic flux is practically linear over the range of interest.

Equation (33) can be expressed in terms of the amount of deflection W at the fluorescent screen and the distance M from the screen to the edge of the scanning zone. To do this note that the deflected beam when projected backward in Figure 8 meets the axis of the tube at a point O which is nearly midway between

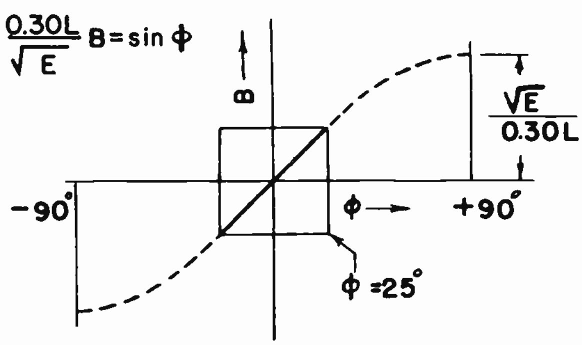


Fig. 9. Flux Density Necessary to Deflect Beam to Various Angles, According to Equation (34).

planes 1 and 2. (This becomes more exact as ϕ is smaller). The distance from O to the fluorescent screen is thus approximately M + L/2. From Figure 8 we see that if the center of curvature of the screen is at O we can write

$$\sin \phi \approx \frac{W}{M + L/2}.$$

Equating this with (33), we obtain

$$\frac{W}{M + L/2} \approx \frac{BL}{\sqrt{2E}} \sqrt{\frac{e}{m}},$$

or
$$W \approx \frac{B\sqrt{\frac{e}{m}}}{\sqrt{2E}} \left(\frac{L^2}{2} + LM\right). \quad (35)\ (\text{e.m.u.})$$

If we express B in gausses and E in volts, and substitute the numerical value of e/m, leaving lengths in centimeters, we obtain the deflection as

$$W \approx 0.30 \frac{B}{\sqrt{E}} \left(\frac{L^2}{2} + LM\right), \quad \ldots (36)(p)$$

where
- B = magnetic deflecting flux in gausses,
- E = beam potential in volts,
- L = length of scanning zone in centimeters, and
- M = distance from deflecting field to screen in centimeters.

WIDE-ANGLE MAGNETICALLY SCANNED TUBES

Wide-angle tubes are of special interest because they permit a shortening of the overall length, and thereby allow the installation of fairly large tubes for direct viewing where otherwise the less satisfactory method of viewing with a mirror would be necessary. The present section discusses for magnetically scanned tubes the relation of the maximum scanning angle to various design quantities. The scanning angle, represented by ϕ in the preceding section, is a variable which may have any value from zero to the largest possible deflection from the normal or undeflected position of the beam. In the present discussion the corresponding capital letter Φ is used to indicate the maximum deflection which is possible in particular tube designs.

Figure 10 shows a magnetically scanned tube indicating a number of important design quantities. The electron gun may have either magnetic or electric focus, and is not shown. The diameter $\underline{S}$ of the screen represents approximately the diagonal of the rectangular television picture whose corners touch the edge of the screen. The effective internal neck diameter $\underline{A}$, in combination with the bulb length $\underline{M}$ and the diameter $\underline{S}$, determines the maximum angle of deflection Φ which the cathode-ray beam must experience to scan a picture of diagonal $\underline{S}$. If the center of curvature of the screen is at the center of scanning $\underline{O}$, we see from Figure 10 that

$$\sin \Phi \approx \frac{S - A}{2M}, \quad \ldots\ldots\ldots(37)$$

where Φ = maximum angle of scanning deflection,

S = screen diameter,

A = effective internal neck diameter, and

M = bulb length.

We see, therefore, that for a given screen diameter $\underline{S}$ and neck diameter $\underline{A}$, the maximum angle of deflection Φ increases as the bulb length $\underline{M}$ is decreased. A decrease in $\underline{M}$ shortens the overall length of the tube; it also reduces the size of the spot on the screen, since it brings the screen closer to the electron lens, reducing the magnification. On the other hand, increase of Φ means that a larger magnetic scanning field is required, and in addition the length of the scanning zone $\underline{L}$ must be decreased. We now show the relation between $\underline{L}$ and other design quantities.

It is evident from Figure 10 that

$$\frac{A}{2q} = \tan \Phi, \quad \ldots\ldots\ldots(38)$$

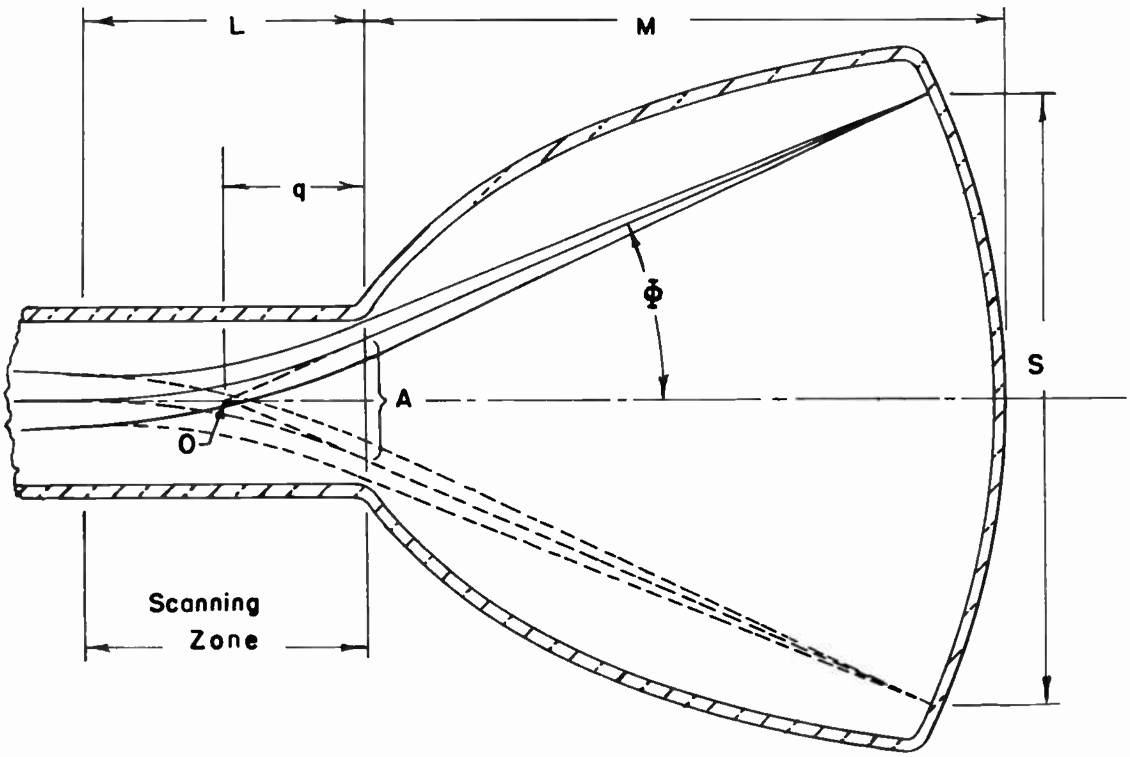


Fig. 10. Diagram Illustrating Quantities of Interest in Design of Short, Wide-Angle Tubes for Magnetic Deflection.

where q = distance from center of scanning to the screen end of scanning zone.

For small values of Φ, the distance q is nearly equal to $L/2$. This relation when substituted in (38) gives

$$L \approx A \cot \Phi. \quad \ldots\ldots (39)$$

The accurate expression for this relation can be shown to be

$$L = \frac{A}{2} \cot \frac{\Phi}{2},$$

or

$$\frac{A}{L} = 2 \tan \frac{\Phi}{2}. \quad \ldots\ldots (40)$$

These expressions indicate the maximum length of scanning zone $\underline{L}$ which can be used with a given maximum scanning angle Φ and a given effective internal neck $\underline{A}$. A shorter length of scanning zone can be used, but it would be uneconomical to do so. Equation (40) is plotted in Figure 11 for a range of Φ between zero and 90 degrees. The value of A/L for a typical tube of 25 degrees maximum deflection angle (from the normal undeflected position) is shown on the curve.

From equation (34) of the previous section we see that as the maximum angle of deflection Φ is increased, the maximum value of $\underline{B}$, which we shall designate as B_{max}, must be increased. Thus

$$\sin \Phi = 0.30 \frac{B_{max} L}{\sqrt{E}}. \quad \ldots (41)\ (p)$$

The plot of equation (34) in Figure 9 is with $\underline{L}$ taken as a fixed arbitrary quantity. We may, however, use equation (40), which gives the maximum value $\underline{L}$ can have for the corresponding value of Φ, and substitute this in (41); this gives

$$\sin \Phi = 0.30 \frac{B_{max}}{\sqrt{E}} \; \frac{A}{2 \tan (\Phi/2)}.$$

Expressing $\sin \Phi$ in terms of the half angle and solving for B_{max}, there is obtained

$$B_{max} = \frac{13.3\sqrt{E}}{A} \sin^2 (\Phi/2). \quad (42)(p)$$

The values of $[A/(13.3\sqrt{E})]\, B_{max}$ given by this formula for various values of Φ are plotted in Figure 12.

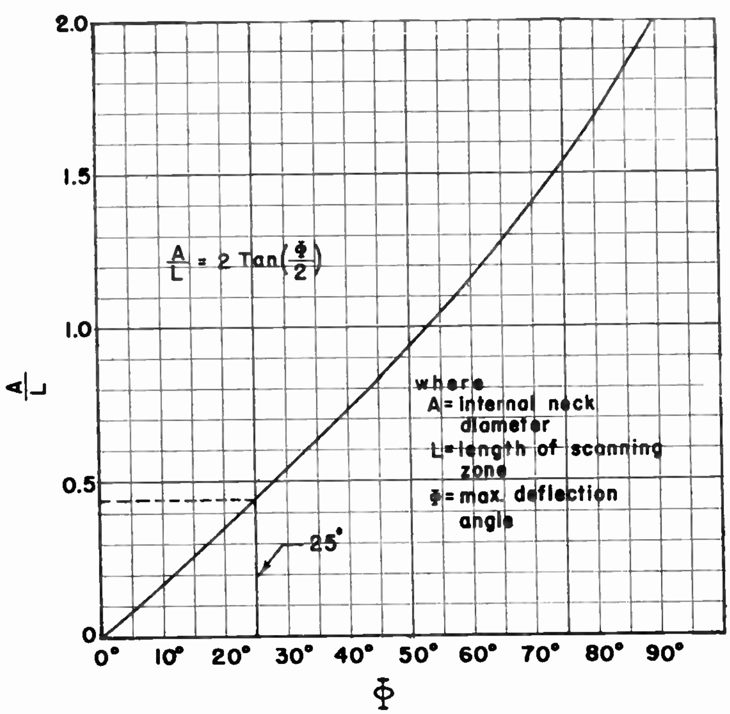


Fig. 11. Necessary Value of Ratio of Neck Diameter to Length of Scanning Zone for Various Maximum Angles of Deflection, According to Equation (40).

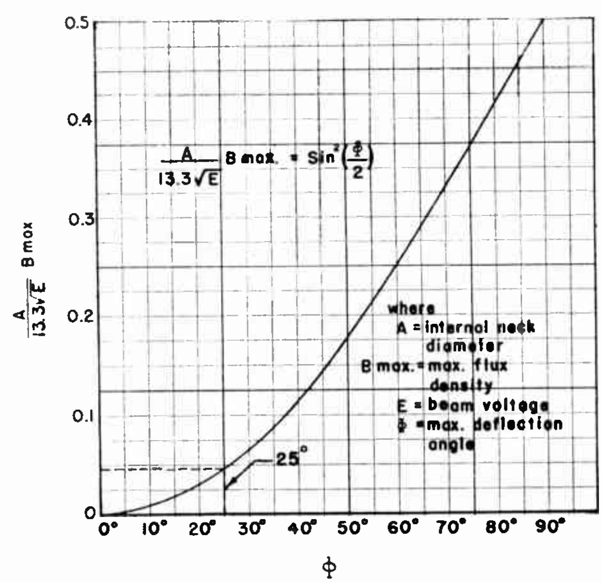


Fig. 12. Necessary Relation of Flux, Neck Diameter, and Beam Voltage, for Various Maximum Angles of Deflection, According to Equation (42).

The total instantaneous quantity of energy in the magnetic scanning field is $(1/2)LI^2$, where L is the inductance of the winding and I is the current. The maximum value of I, corresponding to full deflection for the particular direction of scanning, is the value of chief interest, and of course gives the maximum instantaneous total energy in the field for this component direction of scanning. If L is in henries and I is in amperes, the energy $(1/2)LI^2$ is in joules.

The total energy in the field may be approximated roughly from the energy in the scanning zone, the latter being computed on the assumption of uniform flux density. The approximation involves multiplying by a factor, which must of course be greater than unity, and whose value depends on the degree of concentration of the field.

The energy density in any magnetic field is given by

$$w = \frac{BH}{8\pi} = \frac{B(B/\mu)}{8\pi}, \quad . \; . \; .(\text{e.m.u.})$$

the value of w being in ergs per cubic centimeter. Since vacuum is the medium in the scanning zone, the value of μ is unity, giving

$$w = \frac{B^2}{8\pi} \quad . \; . \; . \; . \; .(43)(\text{e.m.u.})$$

On the basis of a uniform flux density throughout the scanning zone, the total magnetic energy W is the product of the energy density w and the volume V of the zone. That is,

$$W = wV. \quad . \; . \; . \; . \; . \; . \; . \; . \; .(44)$$

If A_1 is the diameter of the scanning zone, and L is the length of the scanning zone, then we have for the volume

$$V = \frac{\pi}{4} A_1^2 L. \quad . \; . \; . \; . \; . \; (45)$$

Substituting (43) and (45) in (44), we get

$$W = \left(\frac{B^2}{8\pi}\right)\left(\frac{\pi}{4} A_1^2 L\right),$$

or $$W = 0.031 A_1^2 B^2 L. \quad . \; . \; .(46)(\text{e.m.u.})$$

The energy in the scanning zone at the maximum deflection Φ can be determined from equation (46) by substituting for B the value of B_{max} given by equation (42), and for L the corresponding maximum value from equation (40). Making these substitutions we get

$$W_{max} = 0.031 A_1^2 \left[\frac{13.3\sqrt{E}}{A} \sin^2(\Phi/2)\right]^2 \frac{A}{2\tan(\Phi/2)},$$

which can be simplified to

$$W_{max} = 1.37 \frac{A_1^2 E}{A} \sin\Phi \sin^2(\Phi/2). \; (47)(\text{p})$$

The value of $[A/(1.37 A_1^2 E)] W_{max}$ from this equation is plotted in Figure 13 for various values of Φ. For practical purposes the value of Φ for each component direction of scanning, rather than that for the picture diagonal, is of most interest; the curve can be used to get W_{max} for each direction.

The magnetic flux density, which is directly proportional to the current flowing thru the scanning coil, varies with time in a sawtooth manner to produce the scanning action. On each cycle the field does a very small amount of work on the electron beam in producing the deflection. The amount of energy used in this way is negligible, so that the establishment and collapse of the field represents practically equal passages of energy from and to the scanning circuit. This equality of the energy supplied by the circuit and that received back gives a condition of wattless power, not counting the copper loss in the winding. It is therefore chiefly wattless power which must be supplied by the scanning circuit to the scanning coil.

ELECTROSTATIC DEFLECTION

When a positively charged particle is in an electrostatic field, it is acted on by a force which has the same direction as the field and which is proportional to the product of the field strength and the amount of the charge.

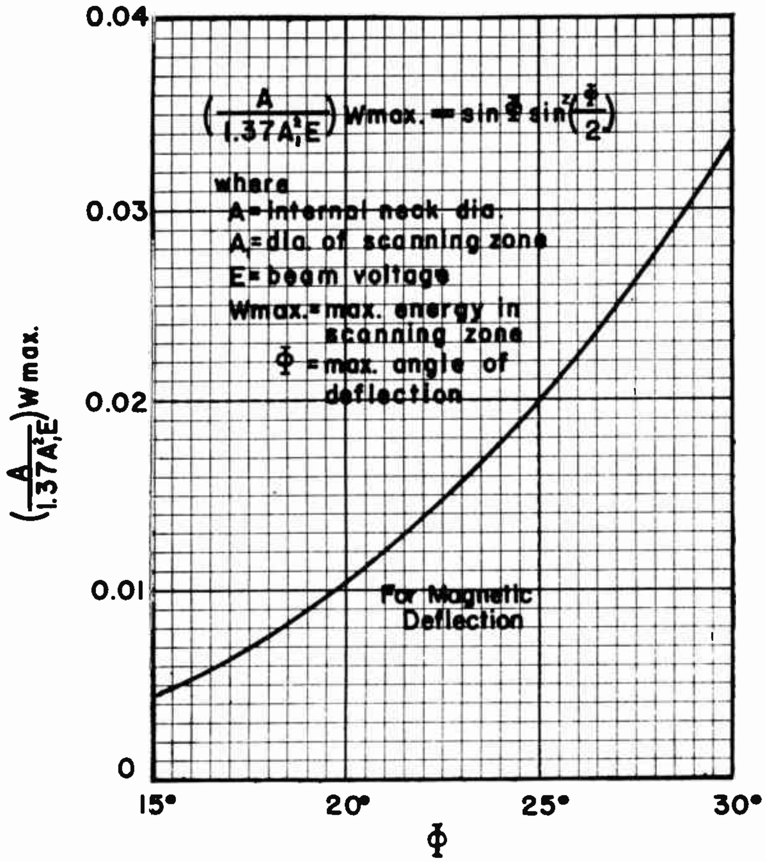


Fig. 13. Necessary Energy in Scanning Zone in Terms of Neck Diameter, Zone Diameter, and Beam Voltage, for Various Maximum Deflection Angles, According to Equation (47).

The force on an electron or negatively charged particle is in the opposite direction. The force on an electron is therefore given by

$$F = fe, \quad . \; . \; . \; . \; . (48)(\text{e.s.u.})$$

where F = force,

f = field strength, and

e = charge on the electron.

This force is independent of the velocity of the electron; it acts in a direction opposite to that of the field, and gives the electron an increase of velocity in the direction of the force.

In Figure 14 there is shown in cross-section a pair of plane parallel electrodes of length $\underline{L}$ separated by a distance $\underline{h}$, which are provided for electrostatic scanning deflection. These plates have a width dimension which is normal to the plane of the paper and can be thought of as being of the same order as $\underline{h}$, but this does not enter in the present discussion.

Let us assume that these deflecting plates are charged to potentials of $E + E'/2$ and $E - E'/2$ respectively, so that the potential difference between them is E'. Let us also assume that the field produced by this potential is uniform and is confined between the planes 1 and 2; these planes are defined by the edges of the deflecting plates and, according to the assumption, are boundaries of the field. Actually the field is not uniform in the regions near these planes, and the lines of force "fringe" or bulge outwards from the edges of the deflecting plates, but the assumption of a uniform field greatly simplifies the discussion and yields formulas which are sufficiently accurate to be of practical utility. On the basis of this assumption, the field between planes 1 and 2 is at all points normal to the deflecting plates, and its magnitude is

$$f = \frac{E'}{h} \quad . \; . \; . \; . \; . (49)(\text{e.s.u.})$$

In Figure 14 an electron is shown entering the field midway between the deflecting plates with a velocity $\underline{v}$ (equivalent to potential drop $\underline{E}$) in a direction perpendicular to the deflecting field. The motion of the electron thru the field can be conveniently described in rectangular coordinates taking as origin the point where the path of the electron enters the deflecting field. Let us take as the x-axis the direction of the initial velocity of the electron, and as the y-axis the perpendicular direction lying also in the plane of the paper. The deflecting force is then either in the y-direction or just opposite, depending on the polarity of the deflecting voltage. Let the electron pass the plane 1 at time $t = 0$, and leave the plane 2 at time t_1 which we shall call the "transit time". The component of the electron velocity in the x-direction remains constant and is equal to the initial velocity $\underline{v}$. The transit time is therefore given by

$$t_1 = \frac{L}{v} \quad . \; . \; . \; . \; . \; (50)$$

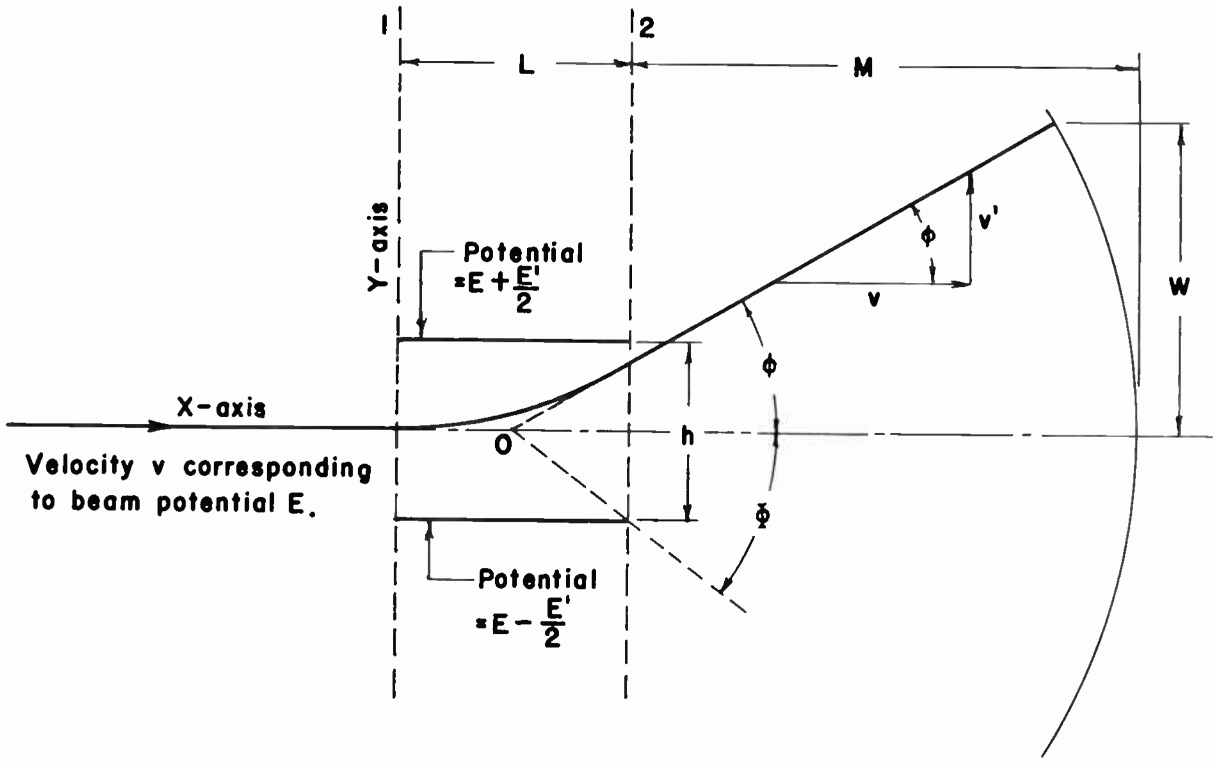


Fig. 14. Deflection of Electron Beam by Electrostatic Scanning Field.

During the transit time, the electron is acted on by a force along the y-direction, which from equations (48) and (49) is found to be as follows:

$$F_y = \frac{E'}{h} e. \quad . \; . \; . \; (51)(\text{e.s.u.})$$

The resulting motion of the electron is obtainable from the equation expressing force as the product of mass times acceleration, as follows:

$$F_y = m \frac{dv_y}{dt} .$$

Equating this and (51), we get

$$\frac{dv_y}{dt} = \frac{E'}{h} \frac{e}{m} \quad . \; . \; .(52)(\text{e.s.u.})$$

Integrating (52) over the transit-time period gives the velocity component in the y-direction when the electron passes plane 2,

$$v' = \frac{E'}{h} \frac{e}{m} t_1 . \quad . \; . \; .(53)(\text{e.s.u.})$$

The constant of integration here is zero since the electron has zero y-component of velocity when entering the field at plane 1. Substituting (50) in (53), we get

$$v' = \frac{E'}{h} \frac{e}{m} \frac{L}{v} ,$$

or $$v' = \frac{E' L}{v h} \frac{e}{m} . \quad . \; . \; . \; . \; (54)(\text{e.s.u.})$$

Since it is assumed that the field strength is zero to the right of plane 2, the electron when leaving this plane will continue in the same direction with which it leaves. The angle ϕ by which the path of the electron has been deflected from its initial direction is seen from the vector diagram in Figure 14 to be given by

$$\tan \phi = \frac{v'}{v} .$$

Combining this with equation (54) gives

$$\tan \phi = \frac{E' L}{v^2 h} \frac{e}{m} . \quad . \; . \; . \; (55)(\text{e.s.u.})$$

However, since E is the equivalent fall of potential corresponding to the initial electron velocity v, we can write

$$\frac{1}{2} mv^2 = Ee.$$

Solving this for e/m and substituting in (55) gives

$$\tan \phi = \frac{L}{2h}\left(\frac{E'}{E}\right). \quad \ldots : .(56)$$

Any unit of length and any unit of potential can be used in this formula because only ratios enter.

This equation is quite accurate for small values of ϕ, and is sufficiently accurate for practical purposes for angles up to 30 degrees; however, it begins to fail rapidly as ϕ approaches 90 degrees. We see that within these restrictions, the electrostatic deflection between plane parallel electrodes has the properties that the tangent of the angle of deflection is:

(1) Proportional to the deflecting potential E', but opposite to the direction of the electrostatic field;

(2) Proportional to the length L of the deflecting plates in the direction of the beam;

(3) Inversely proportional to the separation h of the deflecting plates;

(4) Inversely proportional to the beam potential E; and

(5) Independent of the charge or mass of the deflected particle; this means that ions receive the same amount of deflection as electrons.

It is of interest to note that the point O, which is the center of scanning and the point where the direction of the electrostatically deflected electron intersects the initial direction, is located midway between the ends of the deflecting plates for all values of ϕ.

This can be shown by solving the preceding equation of motion for the shape of the trajectory, which is found to be a parabola with its apex at the point where the electron beam enters the deflecting field, that is, at the origin of the chosen coordinate system.

Figure 15 gives a plot of equation (56) over a range of positive values of ϕ up to 40 degrees; negative values of course give numerically equal but negative ordinates. The value for a ϕ of 25 degrees is shown, and it is seen that the angle of deflection is practically proportional to the deflecting voltage over the range up to this value.

Equation (56) can be expressed in terms of the amount of deflection W at the fluorescent screen and the distance M from the screen to the edge of the scanning zone. It is evident from Figure 14 that

$$\sin \phi = \frac{W}{M + L/2}.$$

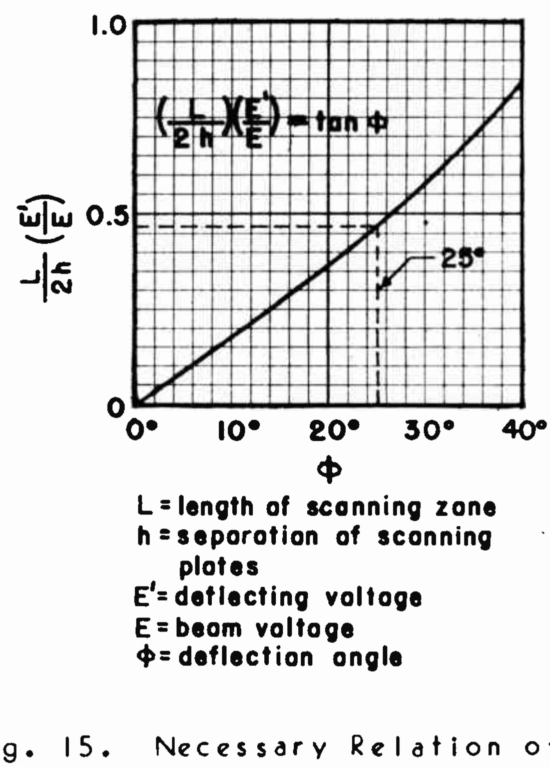


Fig. 15. Necessary Relation of Electrostatic Deflecting Voltage to Length and Separation of Plates for Various Angles of Deflection According to Equation (56).

For small angles of ϕ we can regard the sine and tangent as approximately equal. The foregoing value of the sine may therefore be equated approximately to the tangent of equation (56) giving

$$\frac{L}{2h}\left(\frac{E'}{E}\right)\approx\frac{W}{M+L/2},$$

$$\text{or} \quad W\approx\frac{1}{2h}\left(LM+\frac{L^2}{2}\right)\left(\frac{E'}{E}\right). \quad \ldots (57)$$

WIDE-ANGLE ELECTROSTATICALLY SCANNED TUBES

A drawing of an electrostatically scanned tube is shown in Figure 16. The electron gun may have either electrostatic or magnetic focus. The two pairs of deflecting plates are separated along the axis of the tube. This separation is necessary since the deflecting plates are necessarily conductors, and a conductor brought near the field produced by one pair of plates would seriously distort the field so that it would no longer be uniform. This condition does not obtain in the case of magnetic scanning fields, so that it is general practice with magnetic scanning to use a common center of scanning for the two deflecting fields. When separate centers of scanning are used, a given formula can be applied independently for each center.

In the discussion of wide-angle magnetically scanned tubes given above on pages 231-234 there is included a statement of the necessary geometrical relations to prevent the electrons from striking the neck of the tube at the junction of the neck and the bulb. From the standpoint of the deflection sensitivity of such tubes, a neck of small diameter is preferred, so that it is made only as large as necessary. A common center of scanning can be used with these tubes, and also in the case of magnetic scanning

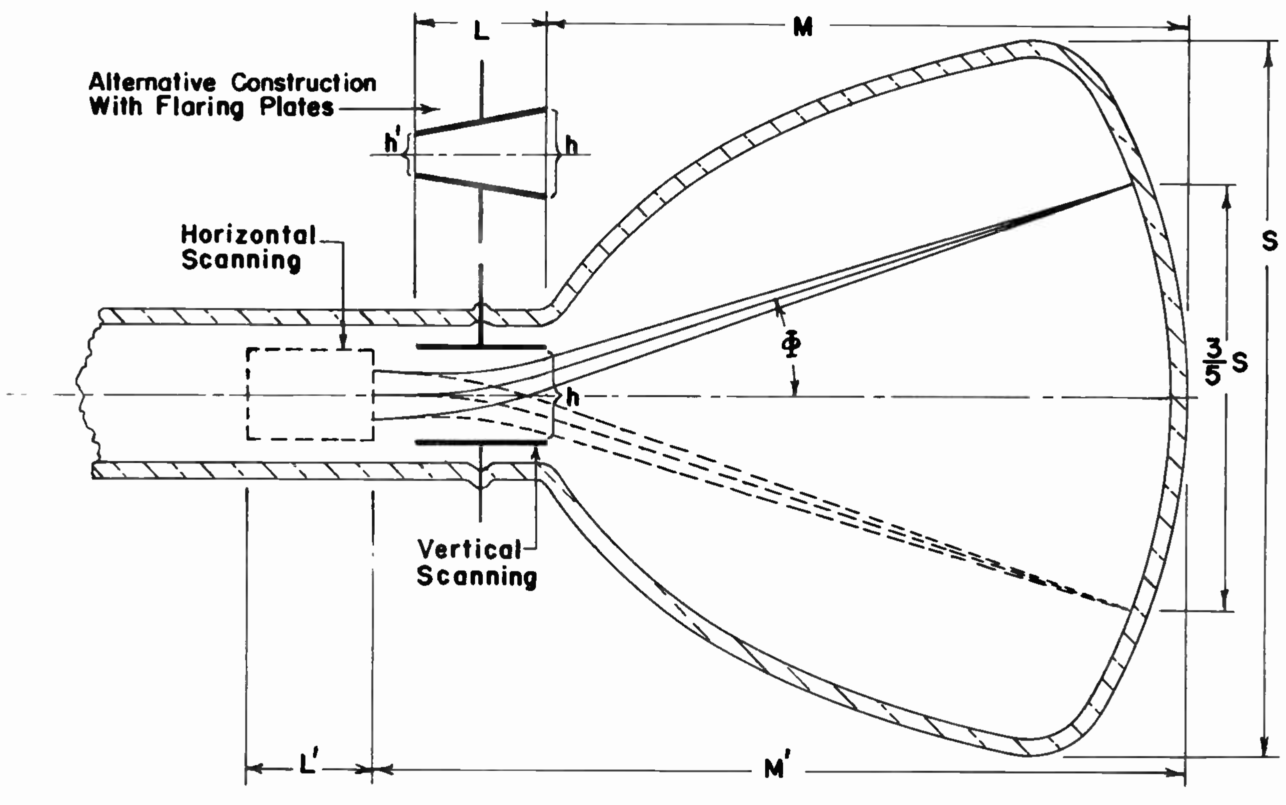


Fig. 16. Geometry of an Electrostatically Scanned Tube.

for one direction and electrostatic for the other.

In tubes for electrostatic scanning in both directions, a larger neck is used, so that the limitation in scanning is to prevent the beam from striking the deflecting plates, or coming so close to them as to impair the focusing. Whenever, as in this case, there are separate centers of scanning, it is necessary to consider individually each of the two component directions of scanning.

For a particular pair of deflecting plates, there exists a maximum usable value of ϕ beyond which the cathode-ray beam will strike the deflecting plate. If we call this maximum value Φ, we can say from Figure 14 that

$$\tan \Phi = \frac{h/2}{L/2} = \frac{h}{L}.$$

And from equation (56) we can write

$$\tan \Phi = \frac{L}{2h}\left(\frac{E'}{E}\right)_{max},$$

where Φ = maximum angle of deflection, and

$\left(\frac{E'}{E}\right)_{max}$ = maximum ratio of deflecting voltage to beam voltage.

Multiplying together the last two equations gives

$$\tan^2 \Phi = \frac{1}{2}\left(\frac{E'}{E}\right)_{max} \quad . \; . \; . (58) \text{ (e.s.u.)}$$

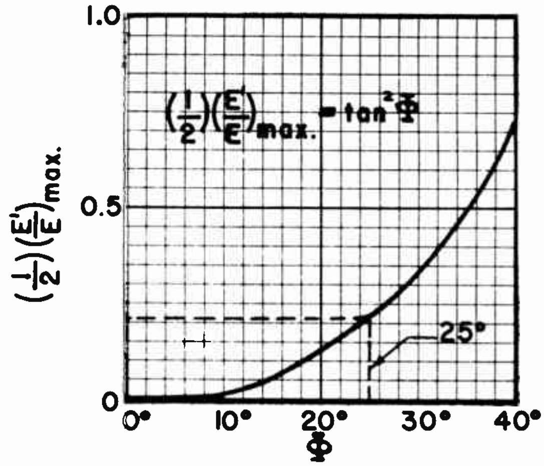
This relation is plotted in Figure 17.

We see from Figure 16 that for the vertical scanning,

$$\sin \Phi = \frac{(3/5)S-h}{2M}, \quad . \; . \; . \; . \; . \; . \; . \; (59)$$

and for the horizontal scanning,

$$\sin \Phi' = \frac{(4/5)S-h_1}{2M'}, \quad . \; . \; . \; . \; . \; . \; (60)$$



E' = electrostatic deflecting voltage
E = beam voltage
Φ = max. deflection angle

Fig. 17. Necessary Deflecting Voltage in Terms of Beam Voltage for Various Maximum Deflection Angles According to Equation (58).

where Φ = maximum deflection angle of vertical scanning from the undeflected position,

Φ' = maximum deflection angle of horizontal scanning from the undeflected position,

S = screen diameter,

h = separation of plates for vertical scanning,

h_1 = separation of plates for horizontal scanning,

M = distance from screen to the screen end of plates for vertical scanning, and

M' = distance from screen to the screen end of plates for horizontal scanning.

In practical design, consideration has to be given also to the finite width of the beam at the screen edge of the deflecting plates. This obviously increases the required spacing <u>h</u> between the plates.

The deflection sensitivity, that is the ratio of deflection <u>W</u> to deflecting potential <u>E'</u>, can be increased by the use of flared plates; an illustration of this is shown in dotted lines at the top of Figure 16. The factor which limits the deflection is the separation of the plates where the beam leaves. The separation where the beam enters may be reduced so that the beam just clears the plates. The plates may be plane or curved. In the case of the plane type illustrated in Figure 16, where <u>h'</u> is the separation at the entrance and <u>h</u> the separation at the exit, the deflection produced on the screen is given by the formula,

$$W = \frac{1}{2}\left[\frac{h' L^2}{(h-h')^2}\left(\frac{h}{h'}\log_e\frac{h}{h'} - \frac{h}{h'} + 1\right) + \frac{LM}{h-h'}\log_e\frac{h}{h'}\right]\left[\frac{E'}{E}\right]. \quad \ldots . (61)$$

This equation reduces to (57) in the case where <u>h</u> and <u>h'</u> are equal, that is, for parallel deflecting plates. This special case may be checked by substituting a series for the logarithm; this procedure avoids the infinite value of <u>W</u> otherwise resulting from h - h' being zero in the denominators.

SHARPNESS OF FOCUS WITH WIDE-ANGLE TUBES

Effect of Fringing of Scanning Field

In the foregoing discussion of magnetic deflection, the assumption is made that the scanning field is ideal, which is to say, that the field-intensity distribution is uniform throughout the scanning zone and that there is no bulging of the lines of force at the edges of the scanning zone. The formulas for the deflection of the beam which are derived on the basis of this assumption are in quite good agreement with values measured on actual tubes.

However, it should be noted that in an actual tube the cross-section of the cathode-ray beam in the scanning zone occupies an appreciable fraction of the diameter of the zone. Consequently if there is a variation in the magnetic field strength across the diameter of the beam, different parts of the electron beam encounter slightly different fields during their journeys thru the deflecting field and will therefore be deflected by slightly different amounts. This means that the angle at which the electron beam converges will change as the angle of deflection is increased. This change in the angle of convergence means a change in the distance at which the focus occurs, so that there is a defocusing effect which increases with the angle of deflection.

It is of course necessary to keep this defocusing effect sufficiently small in order that the picture detail may not be too greatly impaired. This defocusing effect is in general astigmatic so that it cannot be entirely corrected by focal-length adjustment. The amount of this effect is proportional to the angle of convergence of the cathode-ray beam and to the square of the angle of deflection. Since it depends upon the nature of the fringing field, with a given tube the amount of this effect depends upon the design of the scanning coil which is used with the tube. Due to being proportional to the square of the deflection angle, it is much more serious for wide-angle than for narrow-angle tubes.

A similar situation exists in the case of electrostatic scanning fields. The deflection equations developed on the assumption of an ideal scanning field (no fringing) are in good agreement with values measured on an actual tube. With regard to focus, the fringing field produces, as with magnetic deflection, an astigmatic defocusing effect which is proportional to the angle of convergence of the electron beam, proportional to the square of the angle of deflection, and dependent on the nature of the fringing field.

Defocusing Effect Due to Curvature of Cathode-Ray Screen

The glass end of the cathode-ray tube, on which the fluorescent screen is deposited, has a spherical curvature to give the bulb mechanical strength to resist the inward force of the atmosphere. For narrow-angle tubes, the radius of curvature of the screen can conveniently be made equal to the distance from the center of the scanning zone to the screen, so that the total path length along the beam is approximately the same for all angles of deflection; in this case the electron spot remains focused on the screen, assuming a negligible defocusing effect of the scanning field. The picture is thus produced on a spherical surface, and consequently has some geometrical distortion; however, this effect is not serious with typical narrow-angle tubes of less than 20 degrees.

If the same principle is applied to a tube having a wide angle of scanning, say 30 degrees, it is found that the curvature of the screen produces an objectionable geometrical distortion. To avoid this distortion, the screen curvature of a tube for a 30-degree scanning angle is made about the same as for a 20-degree angle, with the result that the center of curvature of the screen no longer lies at the center of the scanning zone, but is displaced toward the cathode. As a consequence of this construction, the path length along the beam to the fluorescent screen increases with the angle of deflection. This effect makes the focus fall short of the fluorescent screen by a distance which is proportional to the deflection angle. This effect is added to the defocusing action of the fringing field since the latter is always in such a direction as to make the focus fall short of the fluorescent screen.

Conclusion on Focusing in Wide-Angle Tubes

Summarizing the differences in focus characteristics of the long and short tubes, we may state that with the short tube:

(1) The reduced magnification tends to increase the sharpness of the focus;

(2) The wider deflection angle tends to defocus the spot in the outer portion of the picture due to the fringing field with either electrostatic or magnetic scanning; and

(3) The difference between the center of scanning and the center of curvature of the screen also tends to impair the focus in the outer portion of the picture.

As a result of these three effects the short tubes can usually be made to give sharp focus in the center of the picture, but the sharpness decreases as the deflection angle is increased, so that the margins of the picture become blurred.

In some tubes the difference in the radius of the screen curvature and the radius of scanning is the predominant factor with regard to focus. In such cases it is possible to adjust the focus so that a large broad ring, about the size of the picture, is sharply focused and the center is blurred. The usual adjustment of course is to focus the center of the picture as sharply as possible, and in cases where the fringing field has a large effect, this is the only region which can be sharply focused.

COMPARISON BETWEEN ENERGIES IN DEFLECTING FIELDS FOR ELECTROSTATIC AND MAGNETIC DEFLECTION

The energy density in the electrostatic and magnetic fields may be expressed in terms of the electrostatic and magnetic field strengths; if these field strengths are then replaced by the deflection angles which they produce, a relation can be obtained giving the ratio of the energy density in the electrostatic case to that in the magnetic case for equal deflection angles. Numerical computations from this relation give the result that at 1000 volts the energy density required for magnetic deflection is 250 times that required for electrostatic deflection, the ratio declining to 25 at 10,000 volts. This indicates an important factor favoring electrostatic deflection for the lower voltages. Before drawing any further conclusions, however, it is well to note that with either type of field the required energy is almost wattless, and that the expense of providing satisfactory scanning circuits is in practice the chief factor which determines the choice between electrostatic or magnetic deflection. There is a tendency to use electrostatic scanning for the lower beam voltages, say up to 3000 volts, and magnetic scanning for higher voltages.

SUPPLEMENTARY REFERENCES

The references in the preceding chapter, Report 1924, pages 213-215, were intended to cover the subject matter of both that chapter and the present one. However, a few additional references may be of interest, as follows:

"Braunsche Kathodenstrahlröhren und ihre Anwendung" ("Braun Cathode-Ray Tubes and their Use"), by E. Alberti, published by Julius Springer, Berlin, 1932; a volume of 214 pages with 158 figures, selling bound at 22.2 reichmarks.

"Die Kathodenstrahlröhre und ihre Anwendung in der Schwachstromtechnik" ("Cathode-Ray Tubes and Their Use in Communication Engineering"), by Manfred von Ardenne, published by Julius Springer, Berlin, 1933; a volume of 398 pages, 432 figures, and numerous references, the treatment of the tube itself occupying the first 118 pages.

"High Quality Radio Broadcast Transmission and Reception", Stuart Ballantine, PROCEEDINGS OF THE INSTITUTE OF RADIO ENGINEERS, May 1934, pages 564-629; a discussion of the gamma of electrical circuits is given on pages 612-616.

"Cathode Ray Oscillography", J. T. MacGregor-Morris and J. A. Henley, the former being University Professor of Electrical Engineering, University of London, published by Instruments Publishing Company, Pittsburgh, Pennsylvania, 1936; This is a volume of 249 pages and 151 illustrations, and includes a good deal of material fundamental to both oscilloscopic and television tubes.

"Fernsehen: Die neuere Entwicklung inbesondere der deutschen Fernsehtechnik" ("Television: The Recent Development, Especially of German Television Practice"), edited by Fritz Schröter, published by Julius Springer, Berlin, 1937; Chapter IV by E. Brüche is on geometrical electron optics, and Chapter V by M. Knoll on cathode-ray tubes in television.

"Television Optics: An Introduction", Second Edition, L. M. Myers, Marconi's Wireless Telegraph Company, Ltd., published by Sir Isaac Pitman and Sons, Ltd., London, 1938, at 30 shillings.

"Rasterformen bei doppeltmagnetischer Ablenkung des Elektronenstrahles in Weitwinkel-Kathodenstrahlröhren", ("Raster Forms with Double Magnetic Deflection of the Electron Beam in Wide-Angle Cathode-Ray Tubes"), Johannes Günther in FERNSEH A.G., the house organ of Fernseh Aktiengesellschaft, Berlin, April 1939, pages 88-94.

"Über die elektrostatische Ablenkung in Kathodenstrahlröhren mit nicht ebene Ablenkplatten", ("Concerning Electrostatic Deflection in Cathode-Ray Tubes with Non-Planar Deflecting Plates"), Werner Flechsig in FERNSEH A.G., the house organ of Fernseh Aktiengesellschaft, Berlin, April 1939, pages 94-97.

* * * * * * *