Cathode Ray Tubes:

Getting Down to Basics

FORWARD

This book was written to serve three major purposes:

1. To understand the interaction and interdependence between the CRT and electronic circuitry in measurement devices having CRTs. The cathode-ray tube (CRT), as the output or display section of oscilloscopes, graphics terminals and other measurement devices, requires understanding in isolating a malfunctioning electronic circuit, the design of circuitry that interfaces with the CRT is dependent upon the requirements of the CRT and before these circuits can be fully analyzed the requirements of the CRT must be known. The proper operation of the various controls and adjustments directly associated with the display requires an understanding of the probable effect upon the CRT.

2. To understand the basic theory or principles of CRT design and operation. In today's world of solid-state devices the principles of operation of vacuum devices is relatively unknown. This book is an attempt to give the engineer, technician or other reader a basic understanding of CRT operation.

3. To consolidate previous CRT-technical documents under one cover. Over the past 30 years there have been a number of CRT theory booklets and technical reports written by Tektronix covering CRT design and theory of operation; some were published and now are out-of-date and no longer in print, others were never published.

I wish to acknowledge those whose publications have been used in this book and whose efforts continue to advance the performance of cathode-ray tubes.

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THE DEFLECTION SYSTEM

The purpose of the CRT deflection system is to deflect the electron beam vertically and horizontally with minimum deflection factor and minimum distortion. (Minimum deflection factor is the same as maximum deflection sensitivity.) The system must be mechanically and electrically compatible with the other parts of the instrument.

Figure 5-1 shows the second anode of the focus lens and a set of vertical deflection plates. (Several assumptions will be made in the following presentation to simplify the subject.) Notice that the potential on the two plates is equal and that they are approximately equal to the second anode potential. An electron's path is shown. After passing the deflection plates no other forces affect the direction or acceleration of the electron. The electron travels in a straight line and strikes the screen near the center.

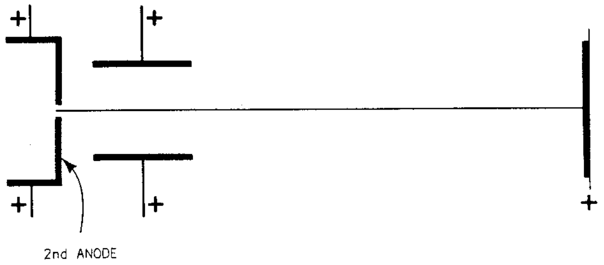


Figure 5-1

The electrical center of a CRT is the point that the beam strikes on the screen when the two deflection plates are at the same potential. The plates are operated at some DC potential near the second anode voltage. When checking a CRT for its electrical center, the plates should be shorted together (NOT TO GROUND) with a well insulated tool.

The deflection above the axis (Y) is directly proportional to the deflection voltage (Vd), the plate length (l), and the distance from the plates to the screen or throw (L). Y is inversely proportional to the distance between the plates (D) and the average deflection plate voltage (V). The formula is:

$$V \approx \frac{Y_d l L}{2DV}$$

This relationship is shown in Figure 5-2.

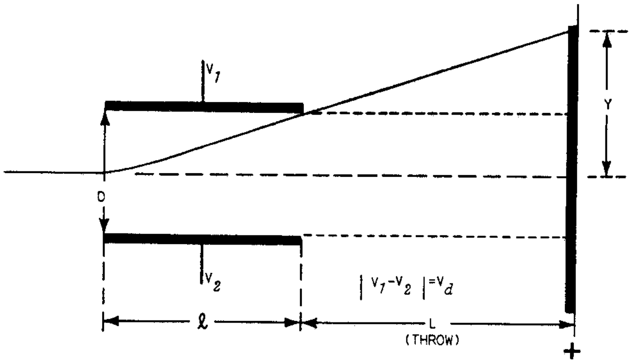


Figure 5-2

The deflection factor (DF) of a CRT is the voltage required for one division of deflection. Volts/cm usually expresses deflection factor. The deflection sensitivity (DS) is the number of divisions of deflection per volt difference between deflection plates. The ratio cm's/volt commonly expresses deflection sensitivity.

$$DF \approx \frac{1}{DS}$$

Both terms are in general use. However, Tektronix has standardized on the term deflection factor. A high deflection sensitivity and a low deflection factor is desired.

Taking the formula $Y \approx \frac{V_d IL}{2DV}$

we see that the deflection sensitivity is equal to

$$\frac{Y}{Vd} \approx \frac{IL}{2DV}$$

and the deflection factor is equal to $\frac{Vd}{Y} \approx \frac{2DV}{IL}$

Figure 5-3 shows a deflection system with parallel plates. The maximum deflection or scan before the beam strikes the plate for a given plate length is shown. The scan could be increased by decreasing the plate length but this would increase the deflection factor or the number of volts per cm of deflecting voltage. The scan could also be increased by increasing the plate spacing but this would also increase the deflection factor. Scan could also be increased by increasing the distance between the end of the deflection plates and the screen, but this would require a longer tube.

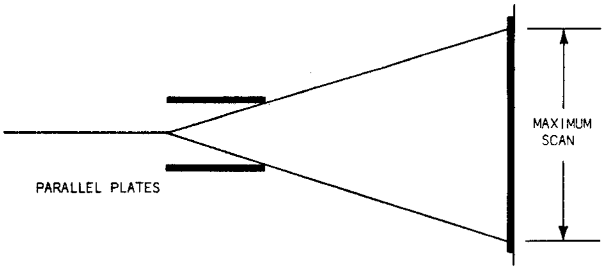


Figure 5-3

Bent plates as shown in Figure 5-4 would increase the scan while holding most other factors constant. The actual section of the plates act in the same way as has been previously described. The bent section acts like sections of parallel plates with increasing plate spacing and therefore increasing deflection factor. The increased deflection factor can be overcome by an increase in plate length. In actual construction the plates may be segmented for ease of construction. (Figure 5-5).

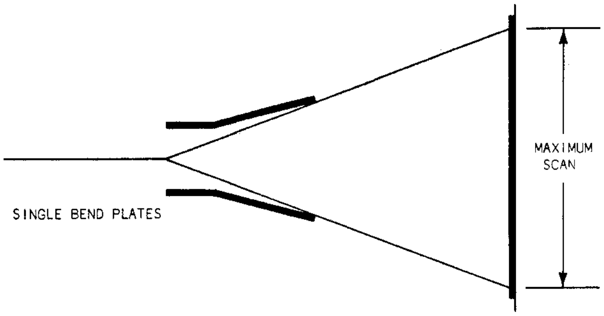


Figure 5-4

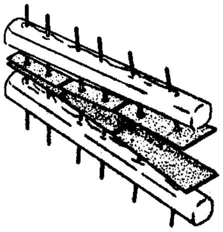


Figure 5-5

The first set of deflection plates after the focus lens is denoted D3-D4 and usually deflects the beam vertically. The next set of plates is denoted D1-D2 and usually deflects the beam horizontally. In some tubes horizontal deflection is done prior to vertical deflection but the notation is the same. (D3-D4 near the focus lens, D1-D2 nearer the screen.)

The capacitive load on the amplifier driving a set of deflection plates may be reduced by using distributed deflection. A segmented plate configuration is used with the segments connected by small sections of delay line. The load is now the Zo of the delay line and not the total capacitance of the plates. The load is now a constant of about 900 ohms as compared to a regular deflection system where the capacitance is typically 12-15 pf and the load varies with frequency. Distributed deflection may be used in a CRT when it is to be operated at 100 MHz and above.

When conventional deflection is used in a CRT, transit-time effect may reduce deflection at higher signal frequencies. If an electron beam is between a set of plates for 2 units of time and the signal on the plates during this time changes from zero volts to ten volts and back to zero volts, the net effect on the beam is less than the ten volts applied. Distributed deflection may be used to reduce this effect by matching the propagation velocity of the delay line to the velocity of the electron beam between the plates. This matching increases the deflection obtained at higher frequencies because an electron passing between the plates is affected by the same signal for the entire transit time.

Consider both propagation velocity and electron beam velocity in a distributed deflection CRT. For optimum performance the electron velocity (Ve) and the signal velocity (Vs) match. The difference in potential between the vertical deflection assembly and the cathode determines electron velocity independant of frequency considerations. Conversely, deflection assembly fixes signal propagation velocity as a function of frequency. Signal velocity diminishes with frequency.

Figure 5-6 charts the effects of electron beam velocity and signal velocity upon deflection. For both curves:

(1) Ve greater than low-frequency Vs;

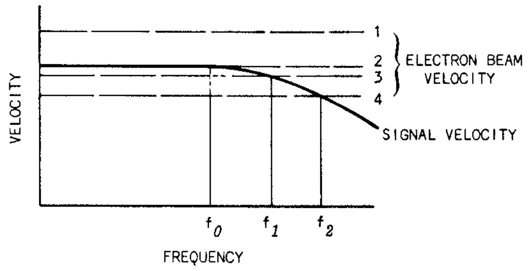
(2) Ve equal to low-frequency Vs;

(3) Ve slightly less then low-frequency Vs;

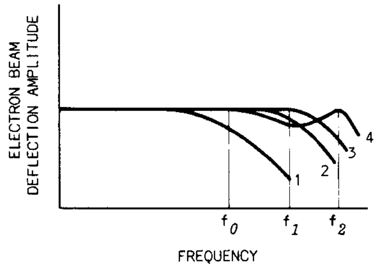
(4) Ve much less than low-frequency Vs.

Figure 5-6 A plots intercept points where electron beam velocity (Ve) and signal velocity (Vs) match. From these curves on plots Figure 5-6B.

Curve 1:	Ve exceeds Vs. A velocity mismatch occurs over the entire frequency spectrum. Electron beam deflection attenuation begins at a low frequency.
Curve 2:	Ve and Vs equal. The mismatch begins at fo as the signal velocity curve rolls off.
Curve 3:	Ve a little slower than Vs. Velocity match occurs at a higher frequency, f1. Consider electron beam deflection on this curve equal from DC to f1. Neglect the attenuation between fo and f1. (Figure 5-6A shows this attenuation more clearly than Figure 5-6B.)



(A) VELOCITY VS. FREQUENCY



(B) AMPLITUDE VS. FREQUENCY

Figure 5-6

Curve 4: Ve much slower than Vs. Velocities match at a much higher frequency, f2. However, beam deflection attenuates at frequencies both above and below f2.

Figure 5-7 schematically represents the distributed deflection assembly. Push-pull signal voltage, applied across R1 and R2, travels down the transmission line at a velocity determined by lumped L and C values. Signal energy dissipates in forward terminators R3 and R4. At some upper frequency limit, signal velocity becomes less than electron beam velocity, reducing deflection sensitivity.

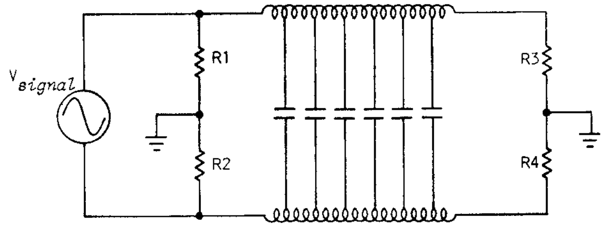


Figure 5-7

A CRT capable of vertical response in the gigahertz range (0.35 nanosecond risetime) connects directly to the signal source of interest. Further, CRT construction allows only single-ended deflection. The generally preferred push-pull deflection is preempted by the high frequency response required. Most circuit measurements are taken single-ended. Circuitry, such as a vertical amplifier, then converts the single-ended input signal into push-pull CRT drive. Current state-of-the-art amplifiers do not extend to fractional nanosecond risetime response.

Figure 5-8 schematically illustrates the single-ended distributed deflection system. Input signals transit the transmission line to dissipate in the forward termination, represented by R2. R1 and R2 must equal the characteristic impedance of the transmission line. The transmission line consists of a tapped inductance and parallel capacitance at each tap. Adjustable portions of C2 parallel the upper vertical deflection plate segments.

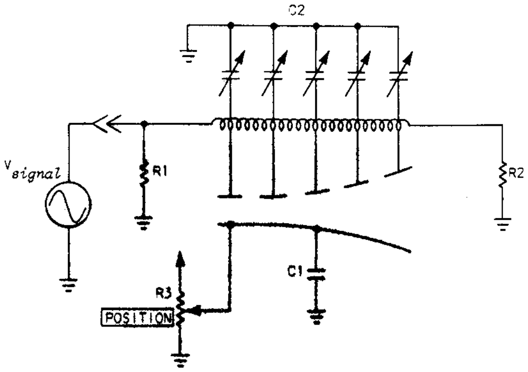


Figure 5-8

The lower deflection plate is a single plate. C1 bypasses the lower plate to ground, allowing application of positional voltages and the entire lower deflection plate surface to represent signal ground.

C2 provides the capability of calibrating the vertical deflection system. At the frequencies involved, stray reactances become an appreciable portion of the lumped-component transmission line, and capacitance between deflection plates changes from electron beam entrance and exit. At the point of beam entry the deflection plates are quite close. Deflection plate coupling then dominates transmission line capacitance. At the beam exit point, the widely separated plates constitute a minor capacitive component. Many upper deflection plate segments, more than shown, occur between electron beam entrance and exit. Each segment and associated inductance make up a short section of transmission line. Each line section must match all other sections. One adjusts C2 for optimum display of known input waveforms. In practice one tunes the deflection assembly then encloses it in the CRT envelope.

Figure 5-9 shows a cutaway drawing of this vertical deflection assembly. The upper vertical deflection plate and transmission line consists of a continuous, "S" shaped metal strip called a stripline (1). Stripline shape creates inductance and mechanical strength. Capacitive coupling occurs between the lower deflection plate and the stripline surface. The tuning screws also capacitively couple to the stripline surface, paralleling deflection plate capacitance.

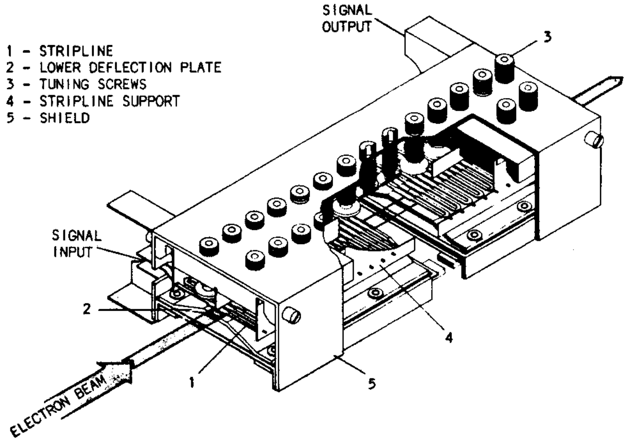


Figure 5-9

In Figure 5-10 single-ended drive is shown with 6 volts on one plate and 0 volts on the other plate. An electron passing through the second anode aperture is accelerated by the +3 volt equipotential line before entering the deflection region. The electrons axial velocity is increased and it gains some radial velocity as it passes through the deflection system and strikes the screen; for example, 2 divisions above center.

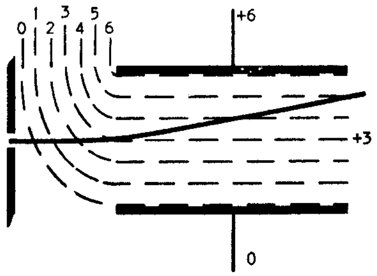


Figure 5-10

Figure 5-11 shows the top plate at −6 volts and the lower plate still at zero. An electron passing through the 2nd anode aperture is decelerated by the −3 volt equipotential line before it enters the deflection region and picks up some radial velocity striking the screen; for example 3 divisions below center. This nonlinearity is unacceptable in oscilloscopes and push-pull drive is used to insure linear deflection.

Most oscilloscopes have push-pull drive to both D1-D2 and D3-D4 because of the nonlinearity of single plate drive. Figure 5-12 shows a push-pull drive, the voltage between the plates being 6 volts. An electron passing through the second anode aperture sees an equipotential line about equal to the anode voltage. The electron is not accelerated before passing through the deflection system where it gains some amount of deflection (3 volts worth). The beam has been deflected up, say 3 divisions, above center. If the upper plate voltage is changed to −3 volts and the lower plate to +3 volts, the beam will be deflected down 3 divisions.

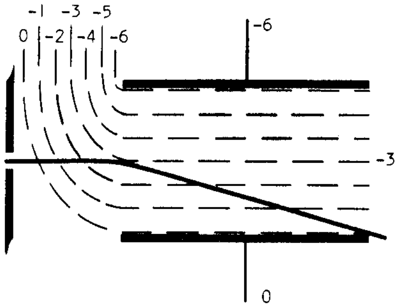


Figure 5-11

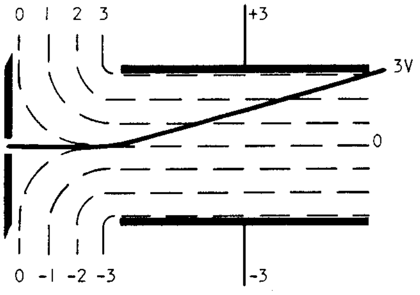


Figure 5-12

The graphs in Figure 5-13 show the deflection-linearity characteristics or change in deflection factor for three different CRT's with push-pull drive. The graphs show the percent difference in voltage required to deflect the beam one centimeter at any point on the screen, compared to that required to deflect the beam one centimer at the axis. Notice that the T5470 has compression while the other two have expansion.

Figure 5-14 plots single-ended vertical deflection linearity of the T5470. Compare this graph to the T5470 plot of Figure 5-13. One sees the linearity contrast between push-pull and single-ended deflection.

When an electron beam is deflected near a deflection plate, some of the beam electrons are intercepted by the plate. This results in lower beam current reaching the screen and therefore a slight decrease in intensity. The percentage of beam current intercept is different for the vertical and horizontal so each axis must be measured.

%Ib to screen (100%-% horizontal intercept) (100%-% vertical intercept) 0.01.

A T5030's beam located 4cm to the left and 3cm up from center for a Tektronix 503 would have 15% horizontal intercept and 5% vertical intercept or approximately 81% total beam current reaching the screen. Because of other factors, a 20% intercept does not yield a 20% decrease in visual intensity. The formula is less accurate as the percentage of both intercepts increases. The least accurate calculation would be for a beam located near the corner of the screen.

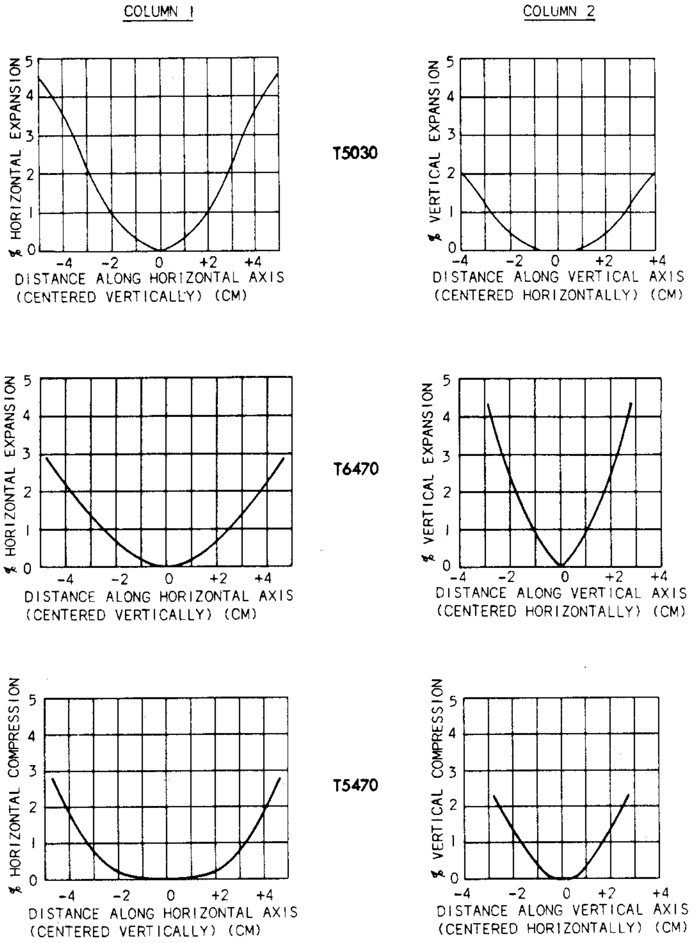


Figure 5-13

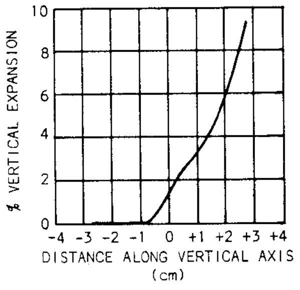


Figure 5-14

There are two causes of defocusing associated with the deflection plates. Geometric defocusing occurs when the beam is focused in the center of the screen. It is focused for some distance and when the beam is deflected the distance to the screen increases but focus distance remains the same. The result is a defocusing of the spot. The size of the spot is larger at the top, bottom, and on the sides of the screen than it is at the center of the screen (see Figure 5-15).

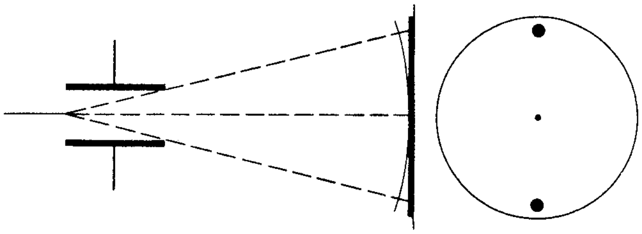


Figure 5-15

Deflection defocusing is greater (by a factor of about 10) than geometric defocusing. An electron beam has a finite thickness and when it passes close to a deflection plate the electrons nearer the plate are accelerated more than those further from the plate. The end product of this effect is defocusing of the beam when it is deflected off center (Figure 5-16). Deflection defocusing changes the shape of the spot making it oblong vertically when deflected close to a vertical plate and oblong horizontally when deflected close to a horizontal plate.

Consider the upper section of the beam. These electrons pass through an accelerating field, increase in velocity, and are then deflected. Their velocity is V + Vd. The electrons on the lower side of the beam pass through a decelerating field, decrease in velocity (V−Vd), and are then deflected. The slower electrons are between the deflection plates for a longer period of time and are therefore more affected by the deflecting field.

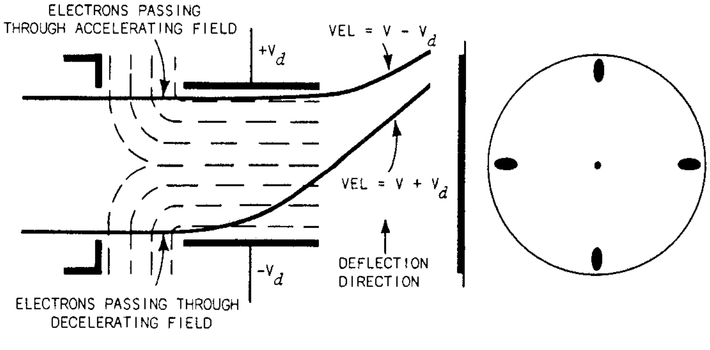


Figure 5-16

The pattern distortion shown in Figure 5-17 is caused by fringing fields between the deflection plates and the band of conducting Aquadag on the glass envelope of the tube in the region of the D1-D2 plates. The geometry control sets the voltage on this neck Aquadag and on the isolation shield. (In some tubes the geometry control also sets the voltage on the deflection plate shields which are indicated on the sides of the D1-D2 plates. See Figure 5-18.) The geometry control is adjusted for an unbowed display.

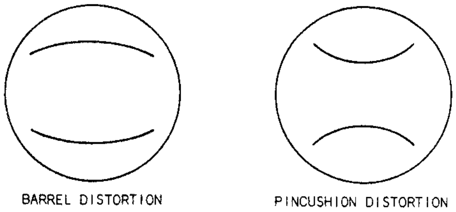


Figure 5-17

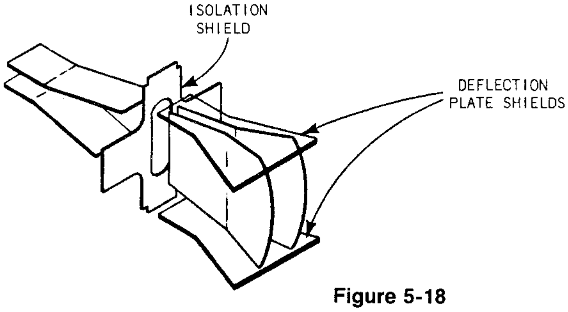


Figure 5-18

The beam may be deflected prior to passing between the D1-D2 plates. The path length within the plates for a deflected beam is different than for an undeflected beam and if the shape of the plate is not altered, a geometric distortion results. With correction, a deflected beam is affected the same as an undeflected beam.

Recall that the deflection of an electron beam above or below the axis is a function of, among other things, the distance from the deflection plates to the screen. If the tube length must be short, the angle of deflection must be larger to yield a given scan.

When an electron beam must be deflected through a wide angle, electrostatic deflection has limitations. These limitations are linearity and edge defocussing. These problems may be overcome by using magnetic deflection but the trade off of lower bandwidth is necessary.

Figure 5-19 shows the deflection yoke used in one of Tektronix's monitors. The horizontal deflection coils are wound around the core. The vertical deflection coils are fitted inside the core. Magnetic deflection is used in this instrument to give the maximum amount of deflection with the shortest tube in length.

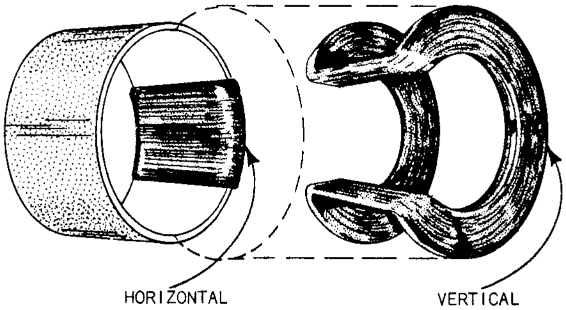


Figure 5-19

The yoke is positioned around the neck of the CRT as shown in Figure 5-20.

The magnetic fields created when current is passed through these deflection coils is shown in Figure 5-21.

If an electron is propelled through a magnetic field such as shown in Figure 5-21, the electron will feel a force that is normal to the direction of the field. This force causes the deflection. The direction of the field determines the direction of deflection and the strength of the field determines the amount of deflection. The strength of the field is a function of the amount of current in the deflection coils, the number of turns in the coil, and the physical dimensions and location of the yoke. The direction of the field is a function of the direction of the current through the coils.

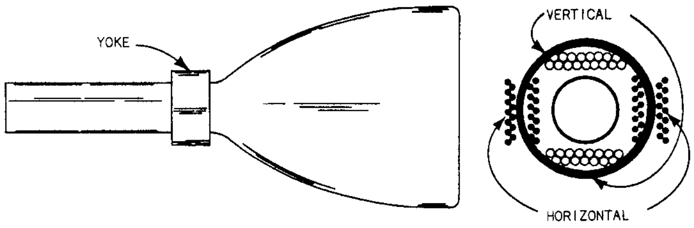
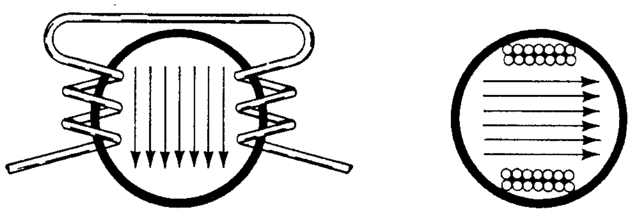


Figure 5-20



HORIZONTAL

VERTICAL

Figure 5-21

Occasionally an oscilloscope user monitors signals by connecting circuits of interest to vertical deflection plates through a simple coupling network. He does this to extend his frequency measurement capabilities. Tektronix CRT vertical frequency response curves follow the general shape of Figure 5-22.

The coupling network included allows predictable displays. Coupling capacitors C1 and C2 block DC since source voltage usually fails to match average deflection plate voltage.

Disturbing average deflection plate voltage creates geometry problems. Additionally, maximum voltage ratings between electrodes must be observed. Each type CRT has design maximum value ratings and the excerpt below is an example:

Average deflection plate voltage, 2000 volts DC maximum.

Astigmatism electrode voltage, 2000 volts DC maximum.

Peak voltage between astigmatism and/or any other deflection electrode, 500 volts DC maximum.

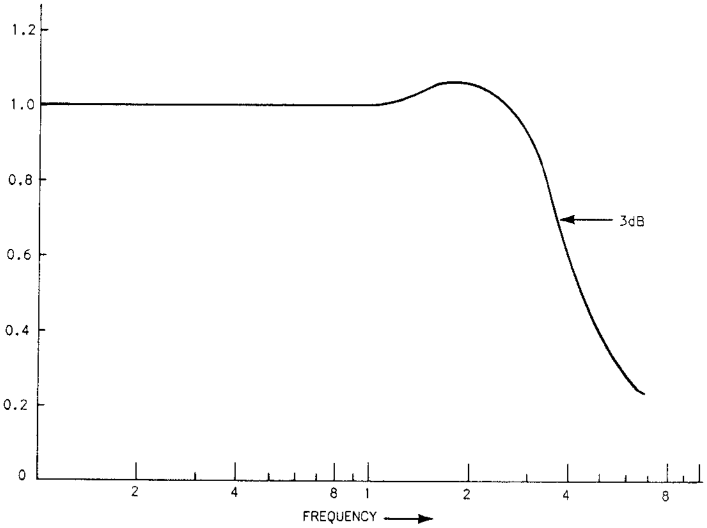


Figure 5-22

Notice the circuit of Figure 5-23 indicates push-pull drive. Many measurements are single-ended, therefore not related to the response curve shown.

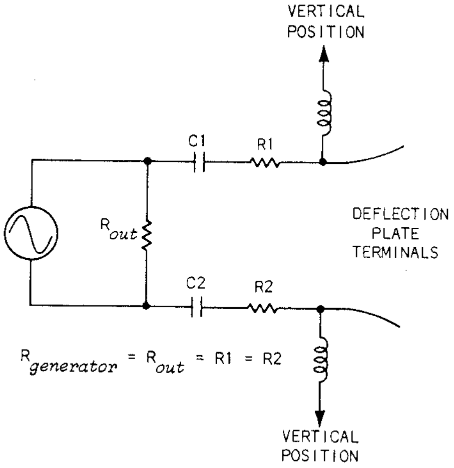


Figure 5-23