CATHODE-RAY TUBE DISPLAYS

The invention of the cathode ray tube (CRT) is generally ascribed to Karl Ferdinand Braun in 1897. His tube was the first combining the basic functions of today's CRTs: electron source, focusing, deflection, acceleration, phosphor screen, and a sealed mechanical structure (1).

The invention was followed by a period where the CRT progressed from being a laboratory curiosity, through the appli-

J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*.

cation stages of oscillograph, radar, and black and white television, to the major modern applications that have helped shape the world and have become a part of our everyday lives: color television and information displays.

CRT BASICS

Figure 1 shows the basic components of a CRT used for color displays: electron gun, deflection yoke, phosphor screen, shadow mask, and glass bulb. References 1–7 provide good overall information about CRTs.

The electron gun is the source of electrons. This component, located at the rear of the CRT, contains (1) three cathodes which generate electrons by thermionic emission and (2) a series of electrodes at various electrical potentials to accelerate, modulate, and focus the electron beams. The gun's configuration determines the relationship between the incoming signal and the beam current. It also plays a significant role in determining the size and shape of the picture elements and, hence, sharpness. Three electron beams leave the gun from slightly different positions. These separate beams carry the red, green, and blue video information.

The deflection yoke creates the magnetic fields that deflect the electron beams. This component contains two formed coils: one to deflect the beams horizontally and one to deflect them vertically. It is located between the electron gun and the screen. The yoke provides the precise electron beam scanning which is a key aspect of television picture reproduction.

The phosphor screen, comprised of phosphor elements which provide red, green, and blue light, converts the energy in the electron beams to visible light through cathodoluminescence. In addition, the screen typically contains black elements which improve contrast by reducing reflection of ambient light. The screen is located at the front of the CRT on the inside of the glass panel.

The glass bulb encloses the internal components and supports the external components. The enclosure is airtight allowing a vacuum to be created on the inside. The bulb consists primarily of the panel at the front of the CRT and the funnel at the back. The neck, a cylindrical glass tube, is located at the rear of the funnel and provides support for the electron gun and the deflection yoke.

The shadow mask governs the operation of nearly all of today's color CRTs. H. B. Law of RCA developed the shadow mask principal of operation in the 1950s. The shadow mask is typically a curved metal sheet 0.10 mm to 0.25 mm thick, approximately the size of the screen and containing small apertures or slots. The three electron beams approach the screen at slightly different angles. The apertures in the mask combined with the proper geometry allow the appropriate electrons to pass while the solid space between openings blocks or shadows other electron beams from striking undesired colors.

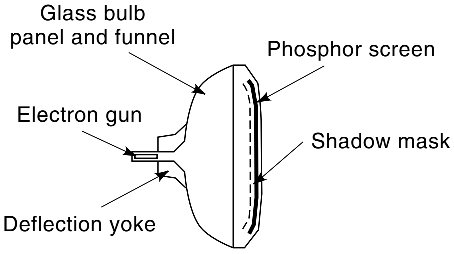


Figure 1. Basic parts of the color CRT: panel, funnel, shadow mask, phosphor screen, electron gun, and deflection yoke.

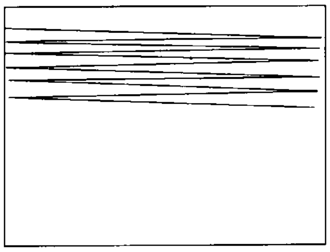


Figure 2. The raster is created by vertical and horizontal deflection of the electron beam. The vertical scan occurs at a much slower rate than the horizontal scan, thereby causing the slight tilt in the lines. The nearly horizontal retrace lines occur at a very high rate.

The raster is the pattern of scanned lines created by deflecting the electron beams horizontally and vertically with the deflection yoke (see Fig. 2). The electron beam currents are modulated during the scan to provide the proper luminance and chromance for each portion of the picture.

The screen is typically at a potential of about 30 kV. Thus, it acts as the anode and attracts the electrons emitted from the cathode, which is near ground potential.

The funnel is coated with conducting layers on the inside and outside. The capacitance between these two layers filters the high voltage generated by the raster scan circuit, thus providing an acceptable anode voltage source and the energy storage necessary to produce high peak currents. The capability to supply this instantaneous high power provides the CRT with outstanding highlight brightness.

PERFORMANCE BASICS

There are many performance measures that can be used to characterize the quality of CRT displays. In this section we will describe some of the more important parameters and quantify the performance levels typically obtained in color television applications (see Refs. 6–10).

Resolution/Sharpness

Probably the item first thought of when asked to describe the performance of a CRT display system is its sharpness or focus quality. The resolution of the display is one of the most important, and probably the most difficult, of the performance parameters to quantify. In describing the resolution of a display, you have to determine not only what pieces of information can be seen, but how well they can be seen. This involves the physical parameters of the display device itself, as well as psychophysical properties of the human vision system (see Refs. 11–29).

Resolution Versus Addressability. Display monitors and television sets are often described as being able to display a certain number of pixels, or lines of resolution. Oftentimes the number of addressable elements (pixels) of a system is confused with its actual resolution. The number of scan lines and

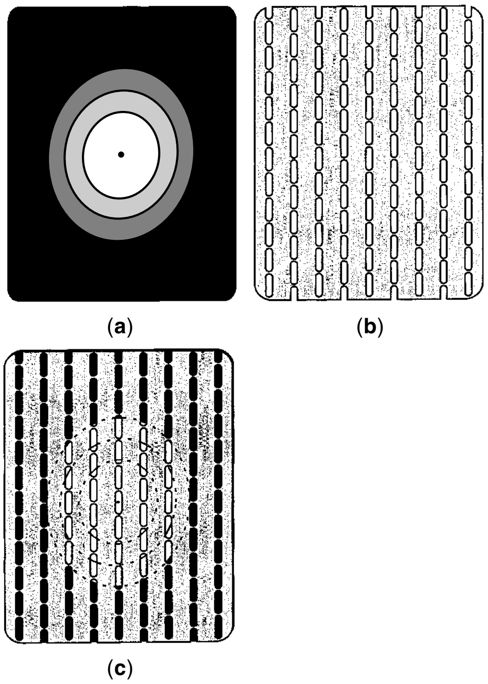


Figure 3. Representation of the projection of the electron beam through the shadow mask onto the screen, illustrating the difficulty of measuring the actual electron beam distribution. It consists of (a) a representation of the electron beam density as it strikes the shadow mask, (b) the shadow mask, and (c) the projection of the electron beam through the shadow mask apertures.

number of pixels are, in general, addressability issues related to the input signal and the electrical characteristics of the display monitor or TV set and are not related to the CRT itself. A 600 × 800 pixel specification on a monitor describes only the electrical characteristics of the monitor and does not tell how well the pixels are resolved by the CRT display. The actual resolution of a color CRT display is determined not only by the input signal and monitor performance, but also by the characteristics of the CRT itself. The important CRT characteristics are (1) the size and shape of the electron beam as it strikes the screen, (2) the size of the CRT color selection elements, and (3) the convergence of the three electron beams.

Electron Beam Spot Size and Shape. The electron spot characteristics are determined by the design of the electron gun and deflection yoke, as well as many of the basic CRT parameters: tube size, deflection angle, and anode voltage. The size and shape of the electron spot is a complicated function and requires special care to measure and analyze.

At a given screen location and peak beam current, the electron beam distribution can be characterized as the distribution of a static spot fixed in time. Because much of the spot is hidden by the shadow mask and screen structure, it is difficult to obtain a good measure of the actual spot distribution (see Fig. 3). Specialized measurement equipment has been developed to "see" the distribution of the electrons within the electron beam behind the mask. The resolution is generally evaluated separately in the horizontal and vertical directions by doing the appropriate integration of the two-dimensional electron spot. The resulting "line-spread profiles" are representative of the electron distribution across horizontal and vertical crosshatch lines.

These line-spread profiles are roughly Gaussian in distribution at low currents but can deviate significantly from Gaussian at high peak currents. A common descriptor of the spot size is the width of these profiles in millimeters at a given percentage (usually 5%) of the spot height as shown in Fig. 4.

The spot sizes vary greatly with tube size, beam current, and screen location. Figure 5 shows the 5% spot size of an A90 (36 in. visual screen diagonal) color television CRT as a function of the beam current at both the center and the corners of the visible screen.

While the 5% spot size is a measure of the CRT's resolution capability, it does not consider the input signal to be reproduced. A better descriptor of how well the image is reproduced is the modulation transfer function (MTF). The MTF describes the response of the display system as a function of the frequency of the input signal. In broad terms, it is the ratio of the output (light intensity or electron beam density) to a sinusoidal input video signal as a function of the signal frequency, normalized such that the ratio goes to one as the frequency approaches zero. The MTF can be measured directly, but more often it is calculated by taking the Fourier transform of the line spread profile distribution of the electron spot. Specifically, the MTF is

$$\mathrm{MTF} = M(\nu) = \int_{-\infty}^{\infty} l(x) e^{-2\pi i \nu x}\, dx \tag{1}$$

where $l(x)$ is the line spread profile and ν is the frequency of the input signal.

Using fast Fourier transforms common in computer mathematical programs, the MTF can be numerically calculated from the measured line-spread profile. For cases where the electron beam distribution is Gaussian, the MTF can be calculated in closed form:

$$M(\nu) = e^{\pi^2 d^2 \nu^2/12} \tag{2}$$

where d equals the 5% spot size in millimeters and ν represents the spatial frequency of the display in cycles per millimeter. Figure 6 shows the horizontal direction MTF for an

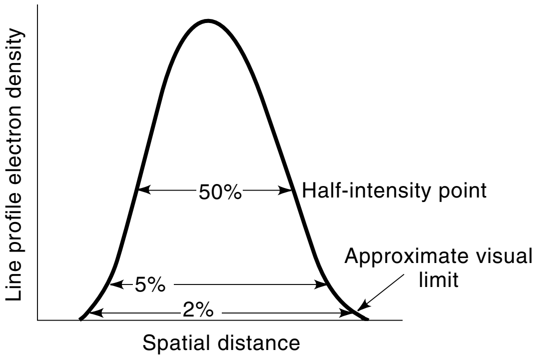


Figure 4. Line profile distribution of the electron beam as it strikes the shadow mask. This represents the electron density perpendicular to a single crosshatch line.

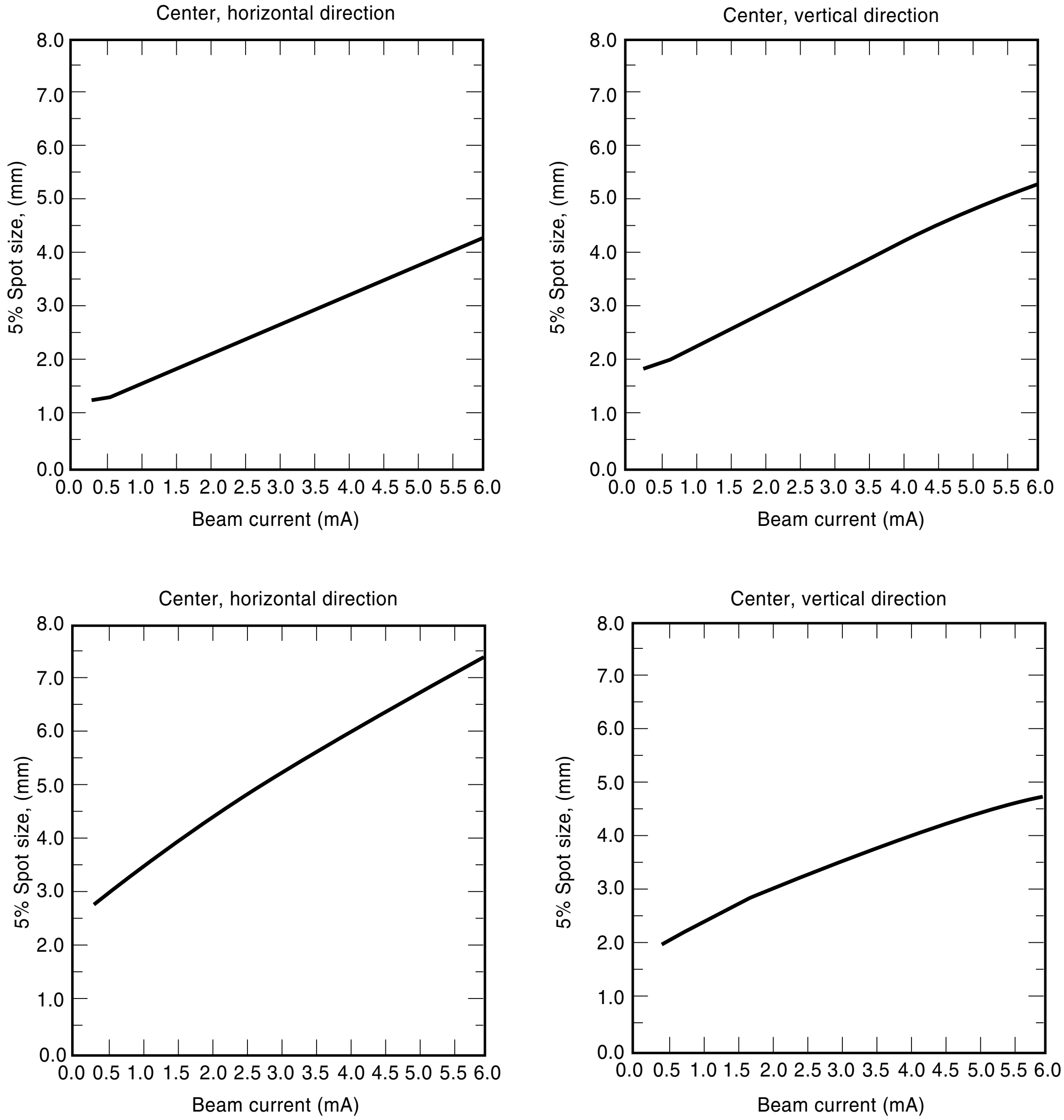


Figure 5. Plots of the 5% spot size as a function of beam current for a typical 36V CRT. Both horizontal and vertical direction and center and corner data are shown.

A90 CRT for various Gaussian spot sizes. Some common signal frequencies (NTSC, VGA, SVGA, and XGA) are indicated.

Typical values of MTF at the pixel frequency for television receivers showing television pictures or for desktop display monitors showing appropriate VGA or SVGA signals are in the 40% to 70% range at the screen center and are in the 20% to 50% in the corners. However, MTFs as low as 10% still give resolvable images.

Convergence. The electron beams from the three guns should land at the same position when scanned to any area of the screen so that a white spot comprised of red, green, and blue primary colors can be formed. If the beams are not coincident, the composite spot will be larger than the individual beams, thereby degrading the resolution and possibly causing color “fringing” at the edge of the white lines. The distance that the three beams are separated from each other is called misconvergence. Misconvergence is generally observed by looking at a crosshatch pattern consisting of narrow horizontal and vertical white lines, and it is determined by the distance from the center of one color to another at a given location on these lines. Since each of the three electron beams typically covers multiple screen elements, care must be taken to determine the centroids of the light from each of the three colors. The misconvergence is then defined as the distance between the centroid of each of these colors. The misconvergence of self-converging systems is generally greatest near the edge of the screen. Typical maximum misconvergence values are 0.3 mm to 0.5 mm for desktop data display monitors, 1.5 mm to 2.0 mm for 27V CRTs, and 2.0 mm to 2.4 mm for 36V CRT direct view systems.

Screen Structure Size. The resolution capability of a color CRT is related to the spacing of adjacent trios (screen pitch), and an excessively large screen pitch will inhibit the ability to resolve fine details. However, it is secondary to the electron beam spot size and convergence. The pitch needs to be small enough so that the structure is not visible to the viewer at typical viewing distances, and so that it does not significantly interfere with the viewer's perception of the size and brightness of a single pixel electron spot. In general, this means that the spacing between screen elements of the same color should be no larger than about one-half the size of the electron spot.

Brightness/Contrast

Other very visible and important characteristics of the quality of the CRT display are the brightness and contrast. Brightness is a perceptual sensation: The measurable parameter from the CRT is light output or, more properly, "luminance." Luminance is the normalized luminance flux emitted from the CRT surface and is measured in candela per square meter (preferred) or in footlamberts (1 fL = 3.43 cd/m^2). The light output from the CRT is linear with the electron gun beam current except at very high currents, where phosphor saturation occurs. Typical luminance values for a 27 in. television set are an average value of 100 cd/m^2 and a small area peak light value of 600 cd/m^2.

It makes little sense to talk about light output of a CRT without also considering the contrast or, more specifically, the contrast ratio. To make a more readily visible image under high ambient lighting effects, the CRT panel glass contains neutral density darkening agents that enhance the contrast at the expense of basic light output. The contrast ratio is defined by TEPAC Publication No.105-10 (29) as the ratio of the luminance from the excited area of the CRT phosphor screen to that of an unexcited area of the screen. It is calculated by measuring the luminance at the center of a fully excited screen and then changing the pattern to include a 1 in. wide vertical unexcited area (black bar), remeasuring the luminance, and taking the ratio of the two readings:

$$\mathrm{CR} = \frac{L_1}{L_2} \tag{3}$$

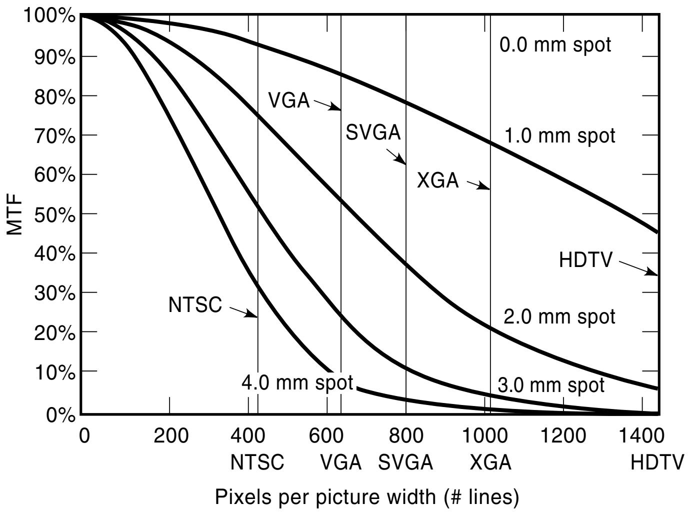
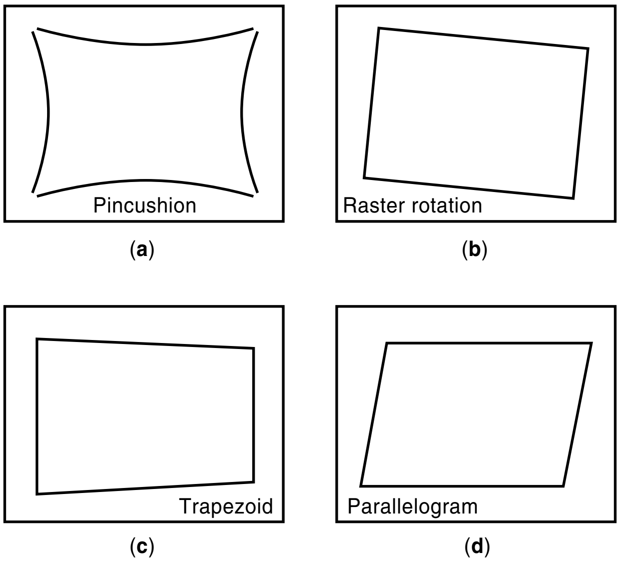


Figure 6. Horizontal direction modulation transfer function as a function of input signal frequency (pixels per picture width) for various-sized Gaussian spots. Some common television and computer resolutions are also indicated.



(a) (b)

(c) (d)

Figure 7. Raster geometry deviations from rectangular illustrating the shape of some common distortions. (a) Pincushion, (b) raster rotation, (c) trapezoid, (d) parallelogram.

The contrast ratio is affected by the luminance that the system is driven to, internal light reflections falling on unexcited areas, the unexcited area being excited by internally scattered electrons, and the ambient light being reflected from the CRT screen.

The contrast ratio is normally measured under ambient lighting conditions approximating a normal user environment. An ambient value typically used is 215 lux (20 footcandles).

White Uniformity/Color Fidelity

The color display should have the proper colors over the entire screen and not exhibit distorted colors caused by the electrons striking the wrong phosphors. This is called color purity and is usually determined by utilizing signals, which energize only one of the three guns at a time, and observing for pure red, green, or blue fields over the entire CRT. There should be no visible discoloration at normal brightness with the CRT facing in any direction. Because of the earth's magnetic field effects on the electron beam, every time the CRT direction is changed it must be properly demagnetized. In addition when all three guns are energized in the proper ratios to make the desired white field, the white field should be smooth and uniform without any rapid changes in color or intensity. A gradual change in luminance from the center to the corner of the screen such that the corner luminance is about 50% of that of the center is normal and typical for TV applications.

Raster Geometry

Deviations in the display of what would normally be a rectangle with perfectly straight lines is called raster geometry distortions, as shown in Fig. 7. Typical geometry errors are (1) pincushion, (2) raster rotation, (3) trapezoid, and (4) parallelo-

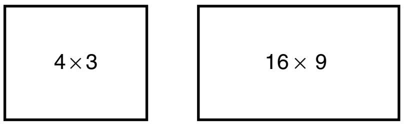


Figure 8. Illustration of the 4 × 3 and 16 × 9 aspect ratios. The height of both rectangles have been set equal.

gram. All of these can be controlled in the signal and scan circuitry of the monitor or TV set; but in typical modern TV sets, only the side pincushion correction and the raster rotation (for large size TV sets) are controlled electronically. The other items—top and bottom pincushion, trapezoid, and parallelogram—are controlled in the design, manufacture, and setup of the deflection yoke and CRT. Since the CRT panel surface is not flat, the apparent shape of the raster lines depends on the location of the viewer. A typical measurement location is from a point along the axis of the tube at five times the picture height from the center face, as described in IEC Publication 107-1960. Another method is to measure just the *X* and *Y* coordinates of the location independent of the screen curvature, which is equivalent to viewing the screen from infinity. In discussing raster geometry errors, one must be careful to understand which method is being used.

DESIGN CONSIDERATIONS

The design of a CRT typically starts with the selection of several basic parameters: screen size, deflection angle, and panel contour. These parameters are usually established by engineering and sales and allow a workable and manufacturable product to be delivered to the customer market.

CRTs for commercial television applications have screen diagonals ranging up to about 40 in., deflection angles from 90° to 110°, and panel contours that are slightly curved to flat.

An understanding of basic performance issues is needed to understand the design space available in selecting tradeoffs.

Tube Size and Deflecton Angle

The size of entertainment television sets in the United States is designated by the viewable screen diagonal in inches such as 19 in., 27 in., and 36 in. The corresponding CRTs are identified as 19V, 27V, and 36V, where V indicates the preceding number is the viewable screen diagonal in inches. The aspect ratio, the screen width divided by the screen height, must also be specified for a complete description. The common format in use is a 4 × 3 aspect ratio. CRTs for high-definition television will use a wider aspect ratio, 16 × 9 (see Fig. 8).

The screen size is measured from the outside of the CRT and is the chord distance between the apparent location of diagonally opposite screen corners as seen from infinity (i.e., measured parallel to the center axis of the tube). The actual screen on the inside of the panel is slightly smaller because of the optical refraction caused by the sloped surfaces of the panel (see Fig. 9).

In general, larger screen sizes imply more difficult design and manufacture, and they result in larger, more expensive, and heavier tubes and TV sets.

The deflection angle is the angle formed between straight lines originating at the deflection center of the yoke and ending at diagonally opposite corners of the screen on the inside of the panel (see Fig. 10).

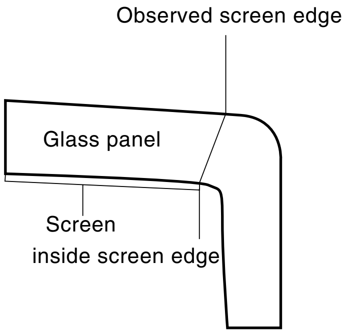


Figure 9. The observed screen edge is larger than the actual screen on the panel inside. The measurement is made parallel to the tube centerline and refracts through the glass as shown.

The tradeoffs involved in selecting the deflection angle are the overall length of the tube, deflection power, geometric distortion, convergence, technical difficulty, and cost.

Panel Design Considerations

The panel contour is also a tradeoff. Flatter is better for styling and aesthetic purposes. However, weight, technical difficulty, and cost are increased. In the industry, panels are often associated with descriptions such as 1R, 1.5R, and 2R. These identifications characterize the flatness of the panel. The reference is an early 25V tube having a spherical contour with approximately a 1 m radius. It became known as the 1R contour. A 36V 1R contour would have a radius scaled by the ratio of the screen sizes: 1 m × $\frac{36}{25}$ or 1.44 m. A 2R contour for a 25V screen would be flatter and have a radius of 2 m. A 36V 2R contour would have a radius of 2.88 m.

Some panels have an aspheric curvature. In these panels the radius of curvature is a function of position. For example, if only the center point and the corner point are considered, a particular panel may be 2R. If only the center and the top are considered, the same panel might be 1.5R.

As the contour becomes flatter, thickness of the faceplate typically increases to reduce the glass stress introduced by atmospheric pressure. The path length differences between beams traveling to the center of the screen and to the edge become larger and require more complex gun and yoke designs. In addition, as will be seen later, the shadow mask becomes flatter, which increases local thermal distortions.

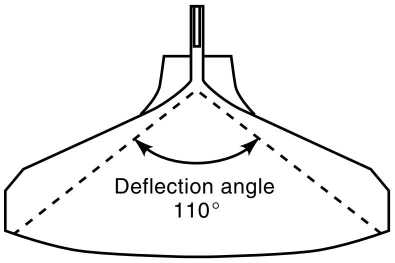


Figure 10. The deflection angle is the angle between the beam path connecting the deflection center with diagonally opposite corners of the screen.

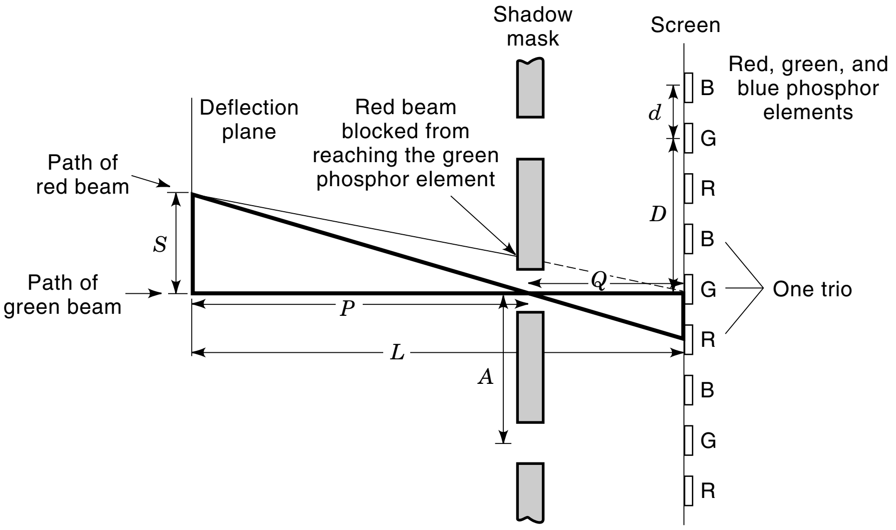


Figure 11. Geometry showing similar triangles relating S and P to Q and d, which is necessary for the derivation of $Q = LA/3S$.

Basic Shadow Mask Geometry

A detailed understanding of several key performance aspects begins with understanding the shadow mask principle.

The three beams leave the electron gun with a slight separation, approximately 5.8 mm. Most tubes today utilize the in-line geometry wherein the three beams leave the gun in a horizontal plane. The two outer beams are angled slightly inward to achieve convergence at the screen.

Figure 11 shows that proper positioning of the shadow mask allows only the correct beam to reach the red, green, or blue phosphor. If the screen consists of regularly spaced vertical stripes of red, green, and blue phosphor (a trio) for each mask aperture, and if the trios are contiguous across the screen, then

$$Q = LA/3S \tag{4}$$

where A is the spacing between mask apertures, Q is the distance between the mask and the screen, S is the spacing between beams in the deflection plane, and L is the distance between the deflection plane and the screen. The screen trio pitch, D, is the projection of the mask aperture pitch, A, onto the screen ($A \times L/P$). Proper meshing of the individual phosphor stripes occurs when the spacing between adjacent colors, d, is one-third of D.

This fundamental equation plays a key role in determining the geometry aspects of the shadow mask. It should be noted that during the manufacturing process, the phosphor elements are optically printed using a photosensitive resist. Optical lenses are used during the printing process together with the shadow mask assembly and panel combination that will be made into the final tube to properly place the screen elements.

Screen Register Tolerances

Figure 12 shows a close up of the screen structure and the electron beam pattern passed by the shadow mask. The electron pattern, called a beamlet, is smaller than the electron beam emitted from the gun. It is formed by a single mask aperture and is wider than the visible phosphor stripe. The red, green, and blue phosphors stripes are separated by black stripes. This geometry allows the beamlet to misregister with the visible phosphor line and still provide nearly full illumination. The amount of misregister possible without striking the wrong color phosphor is called clipping tolerance and the amount of misregister that can occur before the white uniformity is affected is called leaving tolerance. While the actual tolerance calculations take into account the Gaussian distribution of electrons across the beamlet and, if needed, the impact of adjacent beams, a simplified version is shown in Fig. 13.

Older CRTs used a different geometry: The phosphor stripes were contiguous (no black stripes) and the tolerance was obtained by having the beamlet smaller than the phosphor stripe. This construction was eventually replaced by the black matrix construction of today's screens which allow higher glass transmission and hence higher picture brightness while maintaining good contrast because of the nonreflective black stripes.

Mask to Screen Alignment Issues

After the tube is completed, anything causing motion of the shadow mask or anything perturbing the electron path will

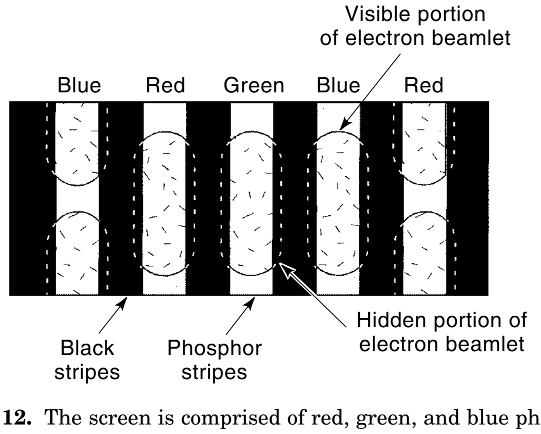


Figure 12. The screen is comprised of red, green, and blue phosphor stripes with a black material between the colors. The beamlets formed by individual mask apertures are wider than the phosphor stripes. Their edges are hidden behind the black material.

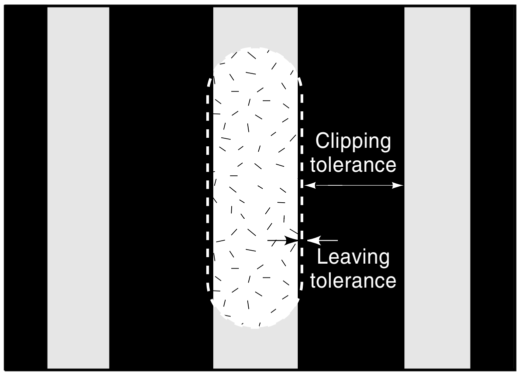


Figure 13. The distance between the edge of the electron beamlet and the edge of the adjacent phosphor stripe is the clipping tolerance and is a measure of how much the beamlet can move before it clips the wrong color and causes color impurity in the picture. The distance between the edge of the beamlet and the edge of its own phosphor stripe is the leaving tolerance and is a measure of how much the beamlet can move before the phosphor stripe is not fully illuminated.

disturb the correct alignment of the electron beamlet with the phosphor element. This important fact is the reason why several performance items—thermal (warpage, doming, blister), mechanical shock, and magnetic shielding—are key issues for CRT performance.

During operation, the shadow mask intercepts about 80% of the electrons emitted by the gun. Typical TV sets can produce an average steady-state beam current of about 2 mA at 30 kV. The total power is then 60 W. The mask intercepts about 48 W, which in turn raises the temperature of the mask and, by radiation, the temperature of the metal structure supporting the mask. After an hour or two a thermal equilibrium is reached. However, both the mask and the supporting frame have expanded. The expansion across the surface of the mask is a function of the thermal expansion coefficient of the mask and the temperature change. For example, a mask of aluminum-killed (AK) steel has an expansion coefficient of about 12.0×10^{-6} mm/mm°C, and a 700 mm length will expand approximately 0.4 mm when heated 50°C. This expansion moves the mask apertures from their desired location. Compensation for this expansion is obtained by moving the entire mask/frame assembly forward through the use of bimetal mounting elements. Invar material has a lower expansion coefficient, about 1.5×10^{-6} mm/mm°C in the range of interest and practically eliminates the expansion of the mask. It is used in many higher-performance CRTs because of its better thermal characteristics.

A second thermal performance issue is doming. It occurs during the time the mask (a thin sheet) is hot but the supporting structure (much more massive) is still relatively cool. Thus the mask expands but is constrained at the edge. As a consequence, the domed portion of the mask moves forward as seen in Fig. 14.

Doming is controlled through a combination of techniques that cool the mask (coatings increasing the electron backscatter or coatings increasing the radiation to nearby structures), and proper positioning of the beams and phosphor elements to allow misregister to occur without loss of performance, or use of Invar material.

A third thermal performance issue is blister (or local doming). It occurs when a small portion of the mask becomes very hot compared to the surrounding areas. Such conditions occur in pictures having small areas of very high brightness such as specular reflections. Under these conditions, temperature differences of 50°C between different areas on the mask can occur. Again, the heated area expands and domes forward. However, since only a small area is affected, a bubble or blister forms in the heated area of the mask. This movement of the mask causes large misregister which can affect performance—notably color field purity and the color uniformity of a white picture area. The solution for blister is the same as the solution for doming.

Magnetics

Electron beams are very sensitive to magnetic fields. The force on an electron traversing a magnetic field is given by the product of the charge, the velocity, and the magnetic field flux density. This force causes a perturbation of the electron trajectory.

This phenomena occurs in CRTs primarily because of the earth's magnetic field. A TV set may be operated facing in any direction—north, south, east, west, or in between—where it interacts with the horizontal component of the earth's field. Horizontal components of 200 mG to 400 mG are typical. In addition, the vertical component of the earth's field varies strongly with latitude. It can range from +500 mG in Canada to −500 mG in Australia.

Beamlet motions of several hundred micrometers and unacceptable performance would occur without magnetic shielding.

The shielding is accomplished by a magnetic shield inside the CRT. The internal magnetic shield, together with the shadow mask and its supporting structure and to some degree the deflection yoke, provides the complete shielding system. Shielding the entire tube would be desirable but impractical. The screen must not be obstructed for the viewer, and the electrons must pass through the shield to reach the screen.

Another important component of the shielding system is an external degaussing coil placed on the funnel body. During the degaussing process, alternating current is applied to the coil then reduced to zero in less than a second. The magnetic domains in the shielding system are reoriented to align more precisely with the magnetic field lines, thereby bucking or canceling the external magnetic field. The shielding system successfully reduces the magnetic field inside the CRT, but does not eliminate it.

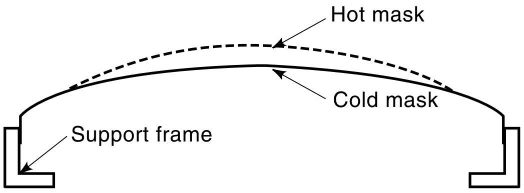


Figure 14. Doming of the mask occurs as it is heated and expands while the mask edge is constrained by the cooler support frame.

The typical misregister shifts occurring in different magnetic fields are of interest and are shown in Fig. 15.

Moiré

A moiré or beat or interference pattern can be produced by the horizontal scan lines comprising the scanned raster interacting with the periodic placement of the mask aperture. The frequency of the moiré pattern is a function of the vertical pitch of the mask apertures and the vertical pitch of the scan lines. The vertical pitch of the apertures is chosen to minimize moiré at the number of scan lines used in the intended application. The intensity of the moiré pattern is a function of the amount of the height of the horizontal bars (tie bars) vertically separating the mask apertures and the height of the scanned line which is in turn a function of the vertical spot size. Conventional shadow mask tubes have adjacent columns of apertures shifted by half the vertical pitch to minimize moiré. Tubes with tension masks due to the scan lines do not have moiré because of their particular mask structure.

Safety

CRTs meet strict federal and regulatory agency standards for safety. Two critical aspects of safety are protection against X rays and protection against implosions.

X rays are generated as the electron beam strikes the internal components of the tube. The resulting X rays are absorbed and attenuated primarily by the glass envelope (panel and funnel) which contains X-ray absorbing materials. The glass thickness and material composition provide the necessary attenuation characteristics.

As the tube nears the end of the construction process, it is evacuated to provide a proper environment for the cathodes. Thus, the glass envelope is stressed by atmospheric pressure. If the envelope failed mechanically, the tube would implode. Events such as a hammer strike or a gunshot can trigger a failure. The common means for providing protection is a metal band on the outside of the side walls of the panel. The band is in tension and supplies a compressive force to the panel side walls. This force, in addition to the proper distribution of internal stress by design of the panel and funnel, ensures that the glass is safely contained in the rare event of an implosion.

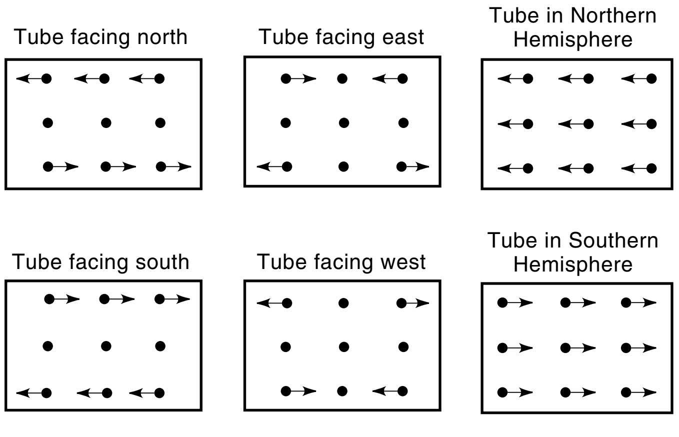


Figure 15. The beamlet motions over the whole screen when the tube is facing north, south, east, or west and experiences a horizontal field as well as the tube is in the Northern Hemisphere and Southern Hemisphere and experiences a vertical field.

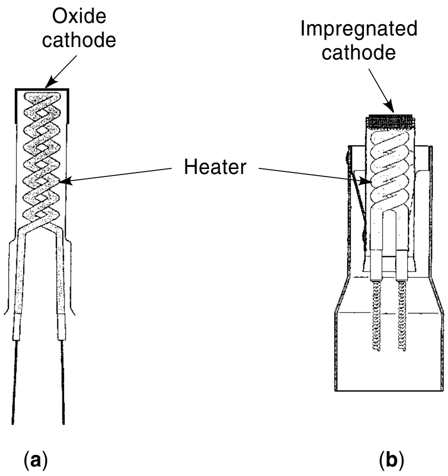


Figure 16. Drawings of typical heater/cathode assemblies showing (a) oxide cathodes used in most television tubes and (b) impregnated or dispenser cathodes used where high current density is required.

ELECTRON GUN

Essentially all of today's direct view color CRTs use tricolor electron guns, which generate three electron beams, one to illuminate each of the primary phosphor colors. These generally use common grids for the three guns in which each of the grids have three apertures, one for each of the three electron beams. The cathodes are separated so that each of the three beams can be electrically modulated (see Refs. 31–38).

Heater and Cathode

The sources of the electrons used to create the image on the screen are thermionic cathodes near the socket end of the electron gun. These cathodes are raised to emitting temperature by standard resistance-type wire-wound heaters. The vast majority of the CRTs in use today use oxide cathodes, while a few high-end products use impregnated (or dispenser) cathodes (Fig. 16). The long-term electron generating capability of the oxide cathodes is limited to about 2 A/cm^2, while the impregnated cathodes can operate up to 10 A/cm^2. Impregnated cathodes are used in some very large tubes, which require high beam current, and in some high-end display tubes with very small apertures, where the current density from the cathodes is also high.

Basic Gun Construction

The simplest of the electron guns in use today incorporate cathodes G_1, G_2, G_3, and G_4 grids, as shown in Fig. 17(a). This is a standard bipotential focus-type gun. The cathodes, G_1, G_2, and G_3 bottom comprise the beam-forming region (BFR) in which the electron cloud from the cathode is accelerated and focused into a crossover at about the level of the G_2 grid. This crossover becomes the image of the beam, which is eventually focused on the CRT screen. This electron beam is focused on the screen by the main focusing lens, generated by the potential difference between the G_3 and the G_4, where the

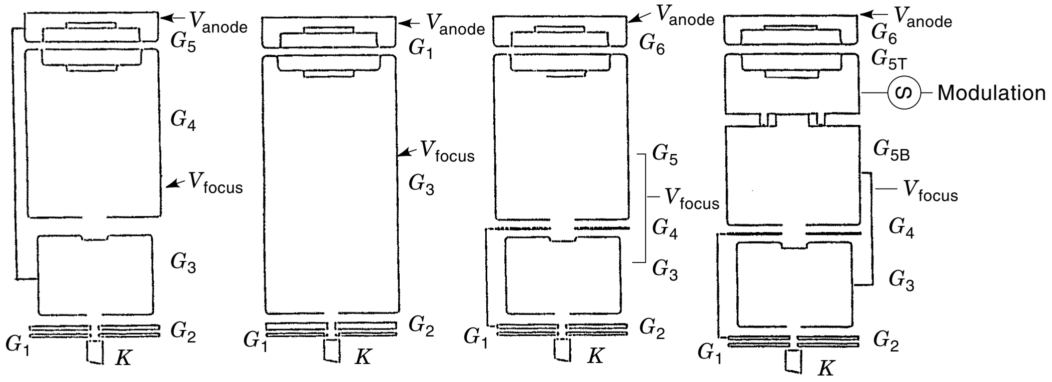


Figure 17. Representations of various electron gun configurations showing the location and interconnections of the various grids. Gun types illustrated are (a) unipotential, (b) bipotential, (c) uni-bipotential, and (d) uni-bipotential with dynamic correction.

G_3 is at an adjustable focus potential while the G_4 is at the CRT anode potential. This focus lens is a simple bipotential lens, utilizing two voltages,: focus and anode. Another basic type of focus lens is the unipotential, or Einsel lens, shown in Fig. 17(b). In this lens there are equal voltages, usually anode, on either side of the focus electrode. Unipotential focus lenses generally have better high-current performance than bipotential lenses but poor low-current focus performance and increased high-voltage stability problems by having the anode voltage further down the neck of the gun, closer to the BFR.

As a general rule, the electron guns used in today's CRTs use a combination of bipotential and unipotential lenses to achieve the best spot performance. One of the most common is the uni-bipotential lens shown in Fig. 17(c). In this type of gun there is a unipotential lens formed by the G_3, G_4, and G_5, where the G_3 and G_5 are at focus potential while the G_4 is connected to the G_2. A bipotential lens then follows this between the G_5 and the G_6, with the G6 being connected to the anode.

Optimized Main Lens Designs

The gun design characteristics primarily affecting the spot size performance of the electron beam on the screen are the magnification (related mostly to the gun length and focus voltage), the mutual repulsion of the electrons in the beam (space charge), and the aberrations of the focusing lens. In general, for minimum spot size on the screen, one would want to have as large a beam as possible in the main lens. However, the effects of spherical aberrations of the main lens become large as the beam approaches the extremities of the focus lens, limiting the spot performance. Consequently, it is advantageous to have the physical size of the focus lens as large as possible. In the BFR portion of the gun (G_1, G_2, G_3 bottom), individual apertures are used for each of the three beams. However, for the main focussing lens, modern electron guns use lenses with a single oval opening encompassing all three beams as shown in Fig. 18. These lenses are limited in size by the CRT neck and the glass beads that hold the electron gun parts together. Since the three electron beams go through different portions of this lens, which have slightly different focusing effects, some means is needed to trim the different focusing effect between the three beams. This is generally done with plates and/or apertures near the individual beams a few millimeters remote from the main focus lens gap.

Trinitron® Gun

A variation on the construction described above is the electron gun used in the Trinitron® tube (Fig. 19). There are still three cathodes and three separate electron beams, but they cross each other in the main focus lens region. Beyond the main focus lens, the diverging outer beams then need to be deflected to again converge on the center beam at the center of the tube. This is done electrostatically by parallel plates in the upper end of the gun operating at a voltage about 500 V lower than the anode voltage. This configuration allows a large-diameter single-aperture focusing lens where the three beams cross, but it adds complications and cost to reconverge the outer beams with the second anode voltage.

Dynamic Astigmatism

The self-converging in-line system inherently causes a strong overfocus of the beam in the vertical direction, while maintaining focus in the horizontal direction at the corners of the screen. In small size tubes and/or low-end systems, this effect

Figure 18. Photograph of grids creating the low-voltage side of the main focus lens illustrating the expanded lens type of grid on the left and showing a conventional three-lens type of grid on the right.

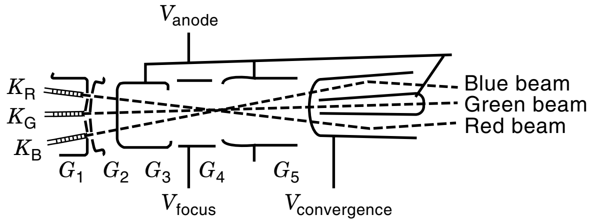


Figure 19. Representation of a Trinitron® type of electron gun illustrating the crossover of the three beams at the main focus lens and showing the location of convergence plates.

is tolerated and results in some amount of overfocus or flare of the beam in the corners in the vertical direction. In high-performance systems, the use of a special gun [Fig. 17(d)] and dynamic focus modulation generated by scanning waveforms can compensate for this effect. The principle behind this operation is to add special grids in which the individual electron beams can be underfocused in the vertical direction and overfocused in the horizontal direction. This can be done with opposing orthogonal rectangular apertures or with interdigitized plates, as shown in Fig. 20. In either case, applying a voltage differential between the two grids causes underfocus in the vertical direction and overfocus in the horizontal direction. If a dynamic focus voltage is applied to these grids and at the same time also applied to the main focus lens such that the beam is underfocused in both the horizontal and vertical direction, the result is a strong underfocusing action in the vertical direction and essentially no effect on the horizontal focus of the beam. This then corrects the overfocusing action of the self-convergence system in the vertical direction without affecting the good focus already obtained in the horizontal direction. Using the interdigit approach, waveforms required are about 800 V at the horizontal rate and 300 V at the vertical rate for approximately 1100 V in the corners of the CRT screen.

Electron Gun Drive Characteristics

The electron gun is a nonlinear device, and the resultant picture performance is very dependent on the gun operating characteristics of the TV set. The TV set or monitor designer must decide at what cutoff voltage to operate the gun. This is the voltage between cathode and G1, at which the electron beam is just cut off. It is obtained by applying this direct-current (dc) voltage between the cathode and G_1 (generally 150 V to 190 V with cathode positive) and then increasing the G_2 voltage until the electrons are at the verge of being accelerated to the screen. From this point the video signal is applied to the cathode (driving it closer to the G_1). Higher operating cutoff generally gives better spot performance, but it requires a higher drive voltage to obtain the same beam current and resulting light output. The resulting beam current is described by the equation

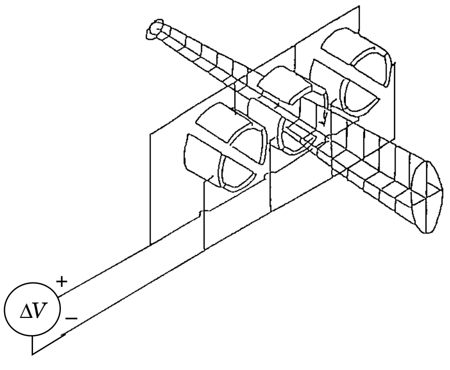


Figure 20. Representation of the interdigital grids method of obtaining dynamic astigmatism correction by applying a voltage differential between the two interdigital grids.

$$I = k(V_{\text{d}})^{\gamma} \tag{5}$$

where V_{d} is the video drive voltage, k is a constant, depending on the gun design and the operating cutoff, and γ is approximately 2.7. Gamma (γ) is relatively constant for all CRTs and is already anticipated in the TV signals transmitted; that is, a display with this gamma is expected in order to give the proper reproduction of the image seen by the TV camera. See the tube data bulletins of any CRT manufacturer for more information on electron gun operating characteristics.

DEFLECTION YOKES

The deflection yoke is a wire wound electromagnetic device located around the outside of the CRT neck whose primary function is to deflect the electron beam to any location on the CRT screen. The basic yoke consists of two sets of orthogonal coils to provide horizontal and vertical direction deflection, along with a ferrite core to provide a low reluctance return path for the magnetic flux. For NTSC television operation the vertical direction scan is at a relatively slow rate of about 60 Hz, and the horizontal direction is scanned at 15,750 Hz. This scanning of the electron beams is synchronized with the video signals applied to the electron gun, to “paint” the proper image on the screen. These frequencies are for normal NTSC broadcast television, which has 525 scan lines, of which 483 contain active video information. Computer display monitors and digital HDTV systems have more scan lines and operate at higher frequencies to provide reduced flicker and higher resolution.

In addition to deflecting the electron beams, the distribution and shape of the magnetic field generated by the deflection yoke has a very strong influence on many of the performance parameters—particularly geometry and convergence. With the self-converging inline system used in nearly all modern television receivers, the deflection yoke magnetic fields need to have a very strong but precisely controlled nonuniformity. This is done by careful control of the distribution of the wires within each of the coils.

Saddle Versus Toroidal Deflection Coils

There are two basic types of coil constructions used in television deflection yokes: saddle and toroidal. In saddle coils the wires are wound into a shaped cavity and then bonded together to maintain that shape. In this case the shape of the cavity determines the distribution of the wires and the magnetic field. Two similar coils are located opposite each other on the tube neck, and a ferrite core is placed around the out-

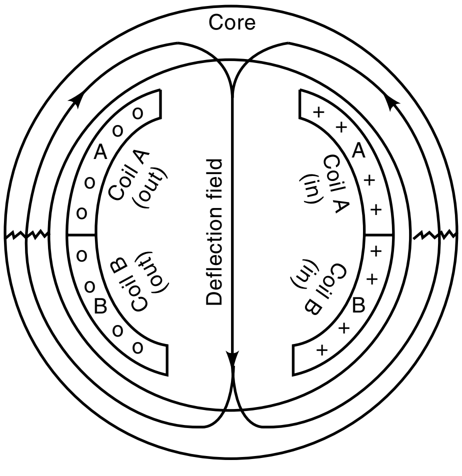


Figure 21. Schematic representation of a saddle-type coil and ferrite core showing the wire location and the main magnetic flux lines.

side to provide a magnetic return path (Fig. 21). In toroidal coils the wires are wound in toroidal fashion around the core itself. The two toroidal coils are wound on opposite sides of the cylindrical core, and they are connected so that the fields "buck" each other and the deflection is accomplished by the "leakage flux" across the middle of the cylinder, as shown in Fig. 22. There is more versatility in designing different magnetic field configurations with saddle coils than with toroidal coils.

In television applications the horizontal deflection coils are of the saddle type, but the vertical deflection coils may be either toroidal or saddle. Most television applications use the S–T (saddle horizontal, toroidal vertical) type because they are less expensive to manufacture than the S–S (saddle horizontal, saddle vertical) type of deflection yoke. However, many data display desktop monitor applications and HDTV and high-end television applications use the S–S yoke because the additional design flexibility can give better electron optics performance. The S–S yoke also has less leakage flux, which can be important in monitor applications. Figure 23 shows photographs of S–S and S–T yokes.

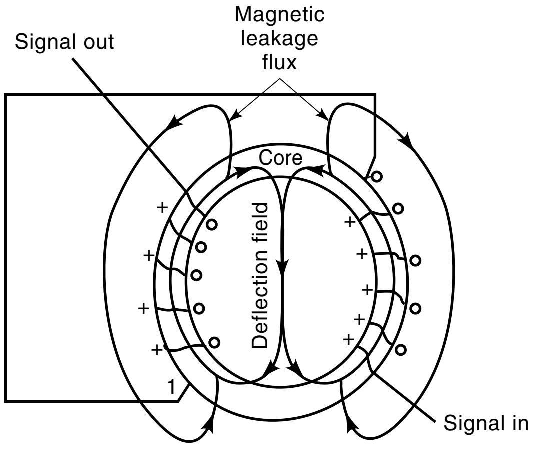
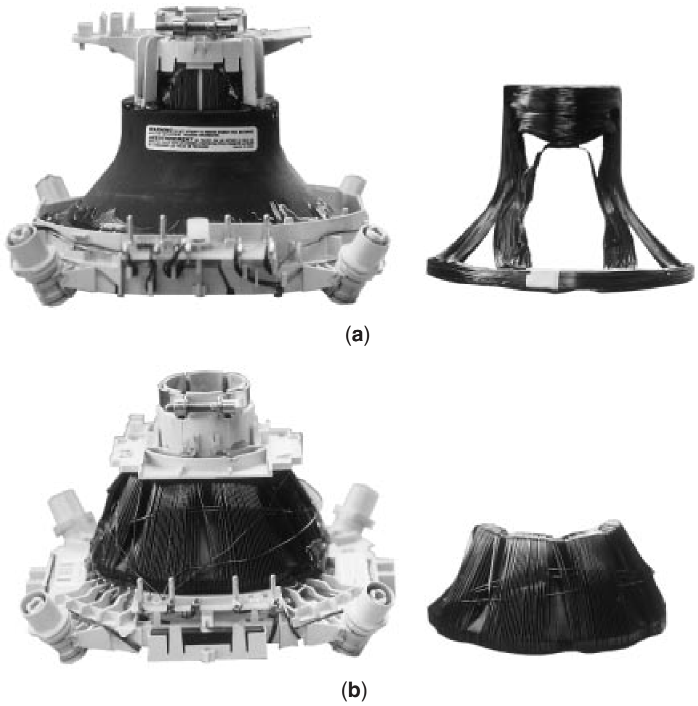


Figure 22. Schematic representation of a toroidal type of coil and ferrite core showing the wire location and the magnetic flux lines.


(**a**)

(**b**)

Figure 23. Photographs of (a) saddle/saddle yoke and typical saddle coil and (b) a saddle/toroidal yoke and typical toroidal coil and core assembly.

Deflection Power

The deflection yoke is an inductive device, and the power to drive it consists of (1) the resistive losses in the coils and deflection circuitry and (2) the inductive reactance to the rapid changes in deflection current necessary to scan the beam to various parts of the screen. The vertical direction deflection is at a relatively slow 60 Hz, and the resistive losses predominate. Consequently, the vertical sensitivity is normally expressed in peak watts required to deflect the beam to the top or bottom of the CRT screen. However, for the horizontal deflection, the inductive reactance predominates and the horizontal deflection sensitivity is better characterized by the stored energy, which needs to be switched to retrace the beams from the right side of the screen to the left.

$$\text{Vertical power} = (I_\mathrm{p})^2R \tag{6}$$

$$\text{Horizontal stored energy} = \tfrac{1}{2}L(I_\mathrm{p})^2 \tag{7}$$

where I_p is the peak vertical or horizontal scan current.

The stored energy is a basic parameter of the yoke and CRT mechanical configuration and is not strongly affected by the impedance (number of turns of wire) of the yoke itself. It is, however, highly dependent on the anode voltage (directly proportional) and the deflection angle of the system. Typical stored energy values for 90° systems are about 2 mJ, while for 110° systems the stored energy increases by about two and one-half times to 5 mJ.

Raster Geometry—Pincushion

The deflection angle of the CRT, the flatness of the CRT screen, and the basic design of the deflection yoke largely determine the outline shape of the deflected raster (pincushion distortion). Wider deflection angles and flatter screens cause greater pincushion-type distortion. With self-converging inline systems, some of this distortion can be corrected in the design of the deflection yoke, and some must be corrected by appropriate modulation of the scanning signals. In particular, the design of the deflection yoke can correct the pincushion distortion at the top and bottom of the screen. For 90° deflection systems and some 110° systems, the pincushion at the sides of the picture is also correctable in the yoke design. However, with flatter panels and 110° deflection, circuit correction is required to correct the pincushion distortion at the sides of the raster.

SUMMARY

For nearly 40 years, direct view color CRTs have been the primary display device for television and many computer and industrial displays. As we move into the age of digital television signals, the requirements on the display performance will become even greater. The higher resolution and less noisy digital television signals will create a demand for better resolution and higher brightness displays that give more realistic natural-appearing images. CRTs are continuing to improve to meet these challenges with larger sizes, new aspect ratios, better resolution, and higher brightness images.

At the same time, alternative display technologies are appearing which may threaten the CRT dominance in certain areas. In the small sizes, liquid crystal displays can give very good computer-generated images, and they do indeed dominate the laptop display market. However, they are much more expensive than CRTs, particularly as the size increases, and nearly all nonportable desktop computer displays above 13 in. are CRT. For the very large sizes greater than 40 in., the displays are mostly projection, both CRT-based and light valve-based (e.g., liquid crystal) projectors. Large plasma displays (greater than 40 in.) are also becoming available on the market, although still at a very high price. CRT projectors are quite bright, but are very directional due to their special screen structure to obtain the light output gain; and they also lack the sharpness of a direct view CRT display. Liquid crystal projectors and plasma displays are much dimmer and much more expensive than CRT displays. In the predominant television market of 15 in. through 40 in. screen sizes, none of the alternate technologies have the performance or the cost to match direct view CRTs. Consequently, CRTs will remain the dominate display for television applications for many years to come.

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ROBERT L. BARBIN
ANTHONY S. POULOS
Thomson Consumer Electronics