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Electron Guns for Television Application

G. A. Morton
RCA Laboratories Division, Princeton, New Jersey

CATHODE-RAY beams are required in the terminal tubes of both the receiver and transmitter, in almost all modern television systems. The means for generating the cathode-ray beams or fine stream of electrons, are commonly designated as electron guns. These guns consist of a primary source of electrons usually in the form of a thermionic cathode, and an electron-optical system for collimating the emitted electrons into a narrow thread. They also, in most cases include a control element or control grid for varying the current in the beam.

At the viewing tube the stream of electrons is made to scan a phosphor screen, exciting luminescence from it in proportion to the current in the beam. The scanning of the beam is synchronized with the corresponding deflection at the pick-up device and the current is controlled by a signal received from the transmitter in such a way that there is reconstructed on the fluorescent screen of the viewing tube a luminous reproduction of the scene being televised.

Television receivers can be broadly subdivided into direct-viewing receivers and projection receivers. The former employs a cathode-ray tube or kinescope, where the reproduced image is seen directly on the fluorescent screen on the end of the tube. The latter uses a cathode-ray tube which produces a small, very bright image that is projected by means of a suitable optical system onto a viewing screen.

The two types of kinescopes impose different requirements on the cathode-ray beams used in them, and therefore the guns employed, though similar in principle, differ in their design. The gun in the direct viewing kinescope (Fig. 1) must produce a relatively high current beam at moderate voltages (5 to 15 kv). Since the viewing screen is large, the spot size or beam diameter at the screen does not have to be extremely small. In the projection kinescope the gun operates at a much higher voltage and must produce a spot which is considerably smaller in diameter. The voltages required in this application range from 25 kv to over 100 kv. As will become apparent as the discussion proceeds, the higher voltage, while increasing difficulties of insulation, leakage, and cold discharge, makes it easier to obtain a small spot.

There are at present four principal types of electronic pick-up tubes used in television broadcasting. These are, in order of their sensitivity, the image orthicon, the orthicon, the iconoscope, and the dissector tube. The following will indicate roughly the magnitude of sensitivity obtained with these devices: If employed in cameras with approximately equivalent optics such that the image orthicon requires a scene brightness of 1 footlambert for a minimum usable picture, the orthicon will require 20 footlamberts, the iconoscope 100 footlamberts, and the dissector tube several thousand footlamberts. With a similar lens and an exposure equal to the television frame time (i.e., 1/30 sec.) a camera using XX super panchromatic film will require 5 to 8 footlamberts.

The three first-mentioned pick-up tubes employ cathode-ray scanning beams for their operation and therefore require electron guns. The dissector tube, however, operates on an entirely different principle which makes an electron gun unnecessary, and is, therefore, outside the scope of this paper.

The principal components of the iconoscope and their arrangement in the tube are shown schematically in Fig. 2. The light-sensitive element is a photo-emissive target or mosaic consisting of a dielectric layer (e.g., a thin sheet of mica) covered on one side with a metallic conducting film and on the other with minute silver

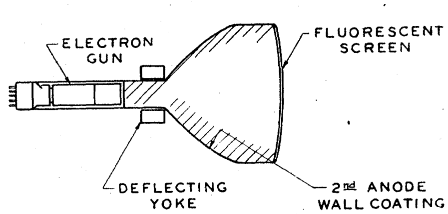

FIG. 1. Kinescope.

elements, which are photo-sensitized with oxygen and caesium. The elements are electrically separate from one another and each forms a tiny condenser with the metallized back plate so that it is capable of storing an electrical charge. An electron gun, which is mounted in the neck of the tube, produces a fine electron beam having a velocity corresponding to about 1000 volts and carrying a fraction of a microampere of current. This beam is made to scan the mosaic in a series of straight parallel lines by means of a magnetic deflecting yoke. When the mosaic is in darkness the scanning beam drives the elements to an equilibrium potential. This is determined by secondary electrons emitted by the mosaic some of which go to a collecting electrode and some of which are scattered or redistributed over the mosaic surface. If light falls on a portion of the mosaic the illuminated elements emit electrons and become positively charged with respect to their neighbors. When the scanning beam returns these elements to equilibrium the released charge causes a current to flow in the signal lead connected to the conductive backing of the mosaic. It should be noted that the photo-emission occurs during the entire time the element is illuminated, so that the charge released by the beam from an element is equal to its net emitted current integrated over the scanning frame period.

There are two principal causes of loss of efficiency in the iconoscope type of pick-up tube. The average field aiding the escape of photoelectrons from the elements is small so that the effective photo-emission is low. Furthermore, scattered electrons from the point where the beam impinges on the mosaic tend to be collected by elements which are being charged positive by photo-emission. The non-uniform redistribution of scattered electrons over the mosaic produces another undesirable effect. It is responsible for a spurious video signal which is reproduced as an irregular shading over the kinescope screen.

Both the photoelectric inefficiency and the redistribution of electrons is overcome in the orthicon type of pick-up tube. This tube employs a photoelectric mosaic target similar in principle to that used in the iconoscope. The scanning beam, however, instead of striking the target with a velocity corresponding to about 1000 volts as in the case of the iconoscope, reaches the target with a very low velocity. The beam velocity is so low that the secondary emission ratio of the elements is less than unity. Consequently when the target is scanned in darkness the elements go negative until they are slightly below cathode potential and the beam can no longer strike the target. In this type of operation the element equilibrium is determined by the cathode potential and initial velocities, rather

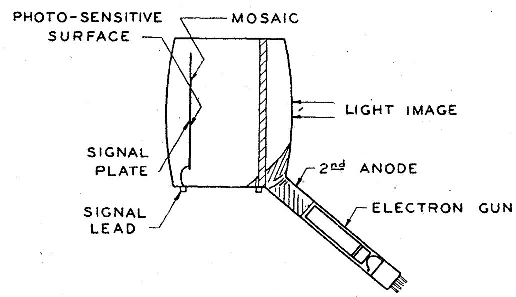

FIG. 2. Iconoscope.

than by the potential of a collector in the vicinity of the mosaic as in the iconoscope. When a portion of the orthicon target is illuminated the elements emit photoelectrons and become positively charged. As the beam scans over these positively charged elements it returns them to cathode potential. The storage principle described for the iconoscope, applies here also: The elements emit photoelectrons the entire time they are illuminated, storing the charge thus emitted until the scanning beam returns to them.

Since the element equilibrium potential is determined by the cathode potential, a positive photoelectron collector can be placed near the target making it possible to obtain high photoelectric efficiency. Furthermore, the target secondary emission is low and any secondary electrons which might be emitted are collected by the positive electrode. This completely eliminates the loss of efficiency and spurious signal due to redistribution which exists in the iconoscope.

The image orthicon employs a low velocity beam and a target whose equilibrium is determined by the gun cathode potential. The video signal is not, however, obtained from a signal plate on the target as in the case of the two previously described pick-up tubes but instead is obtained from the returning electrons of the scanning beam. This returning electron current carries exactly the same signal as does the signal lead from the ordinary target except that it is opposite in polarity. When the target is in darkness, all of the electrons are returned. As portions of the target are made positive by light incident on them some of the beam electrons remain on the target to neutralize the positive charge. Thus

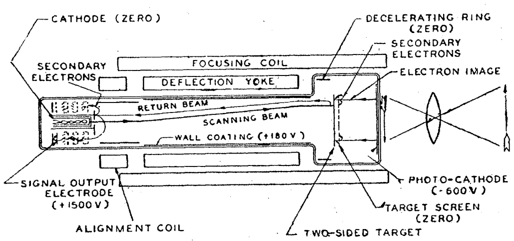

FIG. 3. Image orthicon.

the returning electron current is reduced as the beam scans these areas. The advantage of obtaining the signal from the returning electrons over taking the signal off the signal plate is that these electrons can be directed into a multiplier. Here the video signal can be intensified sufficiently so that the fluctuation noise of the coupling resistor and first stage of the video amplifier is below the shot noise of the scanning beam. This results in a considerable increase in the low light sensitivity of the tube.

The charge image stored on the target is not the result of photo-emission of elements on the target as it is for the iconoscope and orthicon. Instead the optical image of the scene being televised is focused on a separate semi-transparent photo-cathode. The electron image formed from electrons leaving the cathode is focused onto the back of the target. The target is treated so that large numbers of secondary electrons are emitted where the image electrons strike it, and therefore an intensified positive charge image is stored, corresponding to illuminated portions of the scene. It will be noted that the electron image falls on one side of the target, while the scanning beam strikes the opposite side. In order to obtain the conductivity through the target required to enable the beam to neutralize the stored charge, the target is made of very thin conducting glass. The resistance of the glass is so chosen that it is high enough to prevent appreciable transverse leakage of charge during a frame period, yet low enough to permit the required flow of current through the glass. A schematic diagram of this type of pick-up tube is shown in Fig. 3.

The two-lens electron guns employed in both the direct viewing and projection picture tubes and in the iconoscope are similar in principle. Therefore, these guns can be considered as a group, the design differences required to meet the various applications becoming apparent as the discussion proceeds.

A very different type of gun must be used to produce the low velocity beams necessary in the operation of the orthicon and image orthicon. These guns and the problems associated with them will be treated in a separate section.

I. THE TWO-LENS ELECTRON GUN

Basically, the two-lens electron gun is composed of three principal elements. The first element is the cathode which is the primary source of electrons for the beam. The cathode may be flat or shaped depending upon the gun design. The area of the cathode and the degree to which it is restricted is also a function of design. The cathode is followed by the first lens section, which contains, in addition to the electron optical system which produces the "crossover" (to be defined later), a control element for governing the current in the beam. Finally there is the second lens system which in most instances images the "crossover" onto the fluorescent screen. In practice the first lens system is almost always electrostatic, while the second lens may be either electrostatic or magnetic. Figure 4A is a diagram showing an idealized two-lens electron gun, while Fig. 4B illustrates electron ray paths through the gun. Electrons emitted from the cathode are accelerated through the control element and first lens and converged towards the axis of the gun. Those electrons which leave the cathode with zero initial velocity constitute the "principal rays" of the system and cross the axis at a point close to the second focal point of the first lens system. At this point other electrons having radial initial velocities will be separated from the axis by a small radial distance which depends upon their initial velocity. The point where the principal electron rays cross the axis is known as the "crossover." The "crossover" should not be confused with the image of the cathode, nor, as has sometimes been stated in the literature, should it be considered as being a region where electrons have random motion as in a virtual cathode. Actually the "crossover" corresponds to the optical "exit pupil" of the first lens system. Beyond the "crossover" the electron ray bundles from each point on the cathode may converge into a real image of the source, or they may diverge from a virtual image behind the cathode. However, this image can never coincide with the "crossover" itself.

The second lens in general images the "crossover" onto the fluorescent screen or mosaic. Unless the cathode area is very restricted the maximum current density is obtained under these conditions. Special guns with very small emitting areas on the cathode may operate by imaging the cathode on the screen, but such guns rarely, if ever, have television application.

With an electrostatic or combined electrostatic and magnetic second lens, the major part of the acceleration of the electron beam usually occurs in this lens. However, with a purely magnetic second lens the acceleration is in the first lens system.

II. LIMITING PERFORMANCE OF THE ELECTRON GUN

Certain aspects of the limiting performance of beam-forming systems can be derived without reference to the type of gun employed. This is done by employing the electron-optical analog of the Helmholtz-Lagrange relation giving the maximum light intensity in an optical system, and making use of the Maxwellian velocity distribution of the electrons emitted from a cathode to determine the appropriate indices of refraction at the object.

In any optical system the maximum brightness B_2 which can be obtained at any point in terms of the source brightness B_0 is

$$B_2=B_0\alpha^2(\mu_2^2/\mu_0^2), \tag{1}$$

where α is the aperture angle at the image, and μ_0 and μ_2 are the indices of refraction at the source and image, respectively.

Similarly, in electron optics:

$$\rho_2=\rho_0\alpha^2(\phi_2/\phi_0), \tag{2}$$

where ρ_0 and ρ_2 are the current density at the source and image, ϕ_2 the potential at the image, and ϕ_0 the effective potential of the source. Although the cathode is commonly assumed to be at zero potential, electrons are emitted from it with various initial velocities. These initial velocities determine the effective index of refraction at the source. If $e\phi_0$ is the energy of emission in electron volts of an electron under examination its index μ_0 is $(\phi_0)^{\frac{1}{2}}$, and thus proportional to its initial velocity.

If now the total current from the source at potential ϕ_0 is I_T this current can, from Eq. (1), be converged into a spot whose radius r is:

$$r=(I_T/\rho_2\pi)^{\frac{1}{2}}=(I_T\phi_0/\rho_0\pi\alpha^2\phi_2)^{\frac{1}{2}}. \tag{3}$$

As higher and higher initial velocities are examined the current density is found to decrease and the minimum radius to increase.

Where, as in the case of a real cathode, the current from the source is made up of electrons having a range of velocities, the current density at any given distance from the center of the spot can be found by summing over those electrons

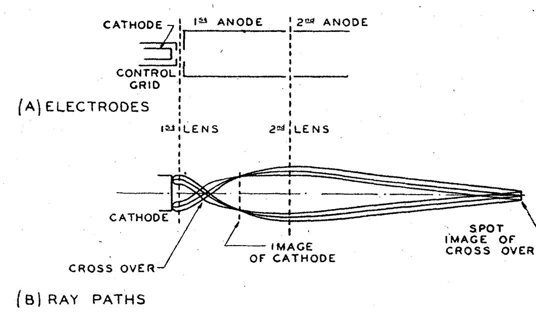

FIG. 4. Elements of two-lens gun.

which have high enough initial velocities to contribute current at this distance from the center.

For a cathode at a temperature T (absolute) the number of electrons having an initial velocity ϕ_0 will, according to the Maxwellian distribution law, be:

$$n(\phi_0)d\phi_0=(e/kT)^2\exp(-e\phi_0/kT)\phi_0 d\phi_0. \tag{4}$$

Hence the current density at the point r_s from

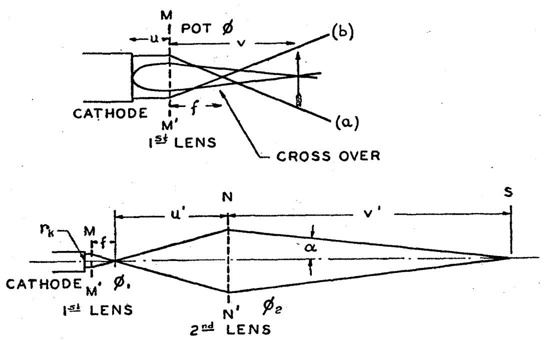

FIG. 5. Electron rays in idealized gun.

the center of the spot will be:

$$\rho(r_s)=I_T\int\frac{n(\phi_0)d\phi_0}{\pi r_{\phi_0}^2}=\rho_0\alpha^2\phi_2\left(\frac{e}{kT}\right)^2\times\int_{(\pi r_s^2\rho_0/I_T)\alpha^2\phi_2}^{\infty}\exp\left[-\frac{e\phi_0}{kT}\right]d\phi_0$$
$$=\rho_0\alpha^2(e\phi_2/kT)\times\exp\left[-\pi(\rho_0/I_T)\alpha^2 r_s^2(e\phi_2/kT)\right]. \quad (5)$$

It will be seen from this expression that the current density at the center of the spot is, for a given aperture angle, specific emissivity of the cathode, and temperature, dependent only on the final voltage, and is not influenced by the distribution of potentials in the intervening region. The density at the center of the spot is:

$$\rho(r=0)=\rho_0\alpha^2(e\phi_2/kT). \quad (6)$$

Furthermore, if the spot is small and the total emission from the cathode large the density is essentially constant. Therefore, the total current in a spot of radius r_s will be:

$$I_s\cong\pi r_s^2\rho(0)=\pi r_s^2\rho_0\alpha^2(e\phi_2/kT). \quad (7)$$

Finally if the spot size or aperture angle is large and the total emission small the current density will decrease exponentially with the square of the radius.

Further information can be obtained from these limiting relationships when they are applied to an idealized two-lens gun. Figure 5 illustrates this gun and the ray paths through it. The first lens, with the control grid omitted, is assumed to be aberration free and for convenience it is considered as a thin lens a distance u from the cathode and of focal length f. In the region between the cathode and the first lens there exists a uniform accelerating field while beyond the first lens, up to the second lens the entire space is field free. The second lens is again taken as a short lens which accelerates the electrons to their final velocity ϕ_2.

Paths a and b in Fig. 5 represent the trajectories of electrons leaving the edges of the cathode with zero initial velocities. These rays are principal rays of the system. Since they enter the first lens MM' essentially parallel to the axis of the gun they will cross the axis at the second focal point of the lens. This point will be, by definition, the crossover of the gun. From the crossover the principal rays diverge until they enter the second lens NN'. Inasmuch as the second lens is adjusted to image the crossover on the screen S the principal rays are deflected by the second lens and meet the axis at the screen. From the geometry of the figure it will be seen that the cone of rays through the second lens, and therefore the aperture angle α, is essentially determined by the radius of the cathode. Thus if the cathode has a radius r_k and the second lens an object and image distance U' and V', respectively, it is evident that

$$\alpha=(U'r_k/V'f).$$

Furthermore, the total current I_T and the current density ρ_0 from the cathode are related by:

$$\rho_0=I_T/\pi r_k^2.$$

Therefore, substituting these values in Eq. (5), it is found that the current density distribution at the spot is:

$$\rho_s(r)=\frac{I_T}{\pi(V'/U')^2f^2}\frac{e\phi_2}{kT}\times\exp\left[-\frac{r^2}{(V'/U')^2f^2}\frac{e\phi_2}{kT}\right]. \quad (8)$$

Also by integration the total current in a spot of radius r_s becomes:

$$I_S=I_T\left(1-\exp-\frac{r_s^2}{(V'/U')^2f^2}\frac{e\phi_2}{kT}\right). \quad (9)$$

Before discussing the significance of these equations, let us further examine the behavior of the electrons at the crossover. As has already been pointed out, electrons leaving the cathode with zero initial velocities cross the axis at the crossover. If, however, an electron leaves the cathode with a radial component of velocity it no longer crosses the axis at this point. Instead, if the initial radial component of velocity of an electron $(2e\phi_r/m)^{\frac{1}{2}}$ its radial distance from the axis will be, for the type of first lens system postulated, $r_c=(\phi_r/\phi_1)^{\frac{1}{2}}f$, where ϕ_1 is the potential at the crossover and f the focal length. Again taking into account the Maxwellian distribution of radial initial velocities the current distribution at the crossover can be shown to be:

$$\rho_c(r)=\frac{I_T}{\pi f^2}\frac{e\phi_1}{kT}\exp\left[-\frac{r^2}{f^2}\frac{e\phi_1}{kT}\right], \tag{10}$$

where r is measured at the crossover.

This of course is exactly the distribution which would have been obtained simply by considering the final spot and crossover as optical conjugates with the magnification of

$$\frac{V'}{U'}(\phi_1/\phi_2)^{\frac{1}{2}}$$

due to the second lens.

Although the assumptions and simplifications in the model of the gun used in deriving the above relations make it necessary to use a certain amount of caution in their interpretation, nevertheless they indicate the limiting performance that can be obtained with any gun and allow a number of important conclusions to be drawn regarding the commonly used two-lens gun.

A frequently used concept in considering gun performance is that of spot size. Since, as is evident from Eq. (5), the spot does not have a sharp boundary but rather the current density decreases exponentially with the square of the distance from the center, it is necessary to formulate an arbitrary definition for the boundary of the spot. One practical definition of spot size is the radius at which the current density falls below a certain preassigned fraction of the density at the center of the spot. This definition is useful because of its operational significance. The effective widths of scanning lines, both in the pick-up tube and viewing tube can be expressed in this way, and the line width can in turn be related to the resolution in the over-all reproduced image.

If K is the ratio of density defining the radius R_s of the spot it can readily be seen from Eqs. (5) and (8) that

$$R_s=\frac{r_k}{\alpha}\left(-\frac{kT}{e\phi_2}\ln K\right)^{\frac{1}{2}}, \tag{11}$$

or for the two-lens gun

$$R_s=f\left(\frac{V'}{U'}\right)\left(-\frac{kT}{e\phi_2}\ln K\right)^{\frac{1}{2}}. \tag{12}$$

Furthermore, the fraction of the total current which falls within the area of the spot is:

$$I_s=I_T(1-K). \tag{13}$$

Thus it is seen that the radius R_s of the spot does not depend upon the voltage distribution in the gun but only on the over-all voltage, and the optical parameters of the first and second lenses. It will also be noticed that the spot size is independent of the cathode area. This corresponds to an electron optical arrangement for which the radius of the cathode r_k and the aperture angle α are proportional and is characteristic of imaging the crossover on the screen. If, on the other hand, the cathode is imaged on the screen, the angle α is independent of the cathode radius, and the spot size is proportional to the size of the cathode. Guns operating in this way are rarely used in television cathode-ray tubes.

The physical gun actually used to produce the cathode-ray beams in television tubes are of course much more complicated than the idealized gun discussed above. A control element must be provided to govern the beam current. This, in general, takes the form of an apertured disk near the cathode, which determines the field strength in the immediate vicinity of the emitter. Such a control element is thus part of the first lens system and as such has an effect on its cardinal points. Furthermore, the lenses, which have heretofore been considered as aberration-free thin lenses, are actually thick lenses formed between cylinders or apertures, for which the aberrations cannot be neglected. Finally, the

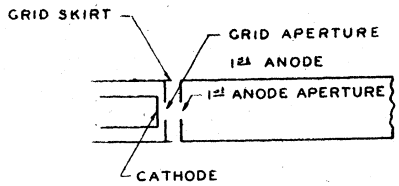

FIG. 6. First lens system.

current density in the high current guns used in viewing tubes is sufficient so that space charge has a considerable effect on the optics of the first lens system.

A simple form of first lens system is shown in Fig. 6. While, for reasons which will be discussed, a somewhat more elaborate first lens is generally used in practice, the system shown will give a sharp high current spot with fair control characteristics. This structure is selected for the initial discussion of first lens systems because it has been analyzed in detail by Maloff and Epstein.

III. THE FIRST LENS SYSTEM

The source of electrons is an oxide-coated cathode which is indirectly heated by a tungsten twist insulated from the cathode cup with a refractory ceramic. The emitting barium and strontium oxide coats the disk which closes the cathode cylinder. Such a cathode is capable of emission densities of $\rho_0 = 0.2$ to 0.5 ampere/cm^2 at normal operating temperatures.

The control grid is in the form of an apertured disk inside a short length of cylinder. The cylinder proper serves only as a shield and surrounds the cathode cylinder. The apertured disk which is the control element, is spaced a few thousandths of an inch from the emitting surface. A short length of cylinder extends beyond the apertured disk and is known as the grid skirt. This grid skirt may have a marked effect upon the control characteristics of the grid. The first anode, which forms the second part of the first lens, is also a cylinder closed with an apertured disk mounted so that it is coaxial with the cathode and grid cylinders.

In operation, the grid potential varies between -30 volt and 0 volt with 1000 volts applied to the first anode. This variation has some effect on the imaging characteristics of the first lens system. However, the primary effect of the grid voltage is to influence the field strength in the immediate vicinity of the cathode and, thus, to control the emission from it. The action of the grid is twofold. First, it reduces the diameter of the emitting area by preventing emission from the peripheral area of the cathode. Second, near the center of the cathode, it produces a space-charge barrier which restricts the net current from the cathode in a manner similar to a conventional control grid.

The cardinal points of this lens system, which describe its first-order imaging properties are located by first determining the potential distribution through the system and then tracing the paths of two paraxial rays. Equipotential maps of the first lens system illustrated in Fig. 6 are shown in Fig. 7. The upper diagram is for a grid potential of 0 volt and the lower for -30 volt. While potential distributions of this type can be computed by numerical approximations, they can be determined much more readily by means of a model of the electrode structure and an electrolytic plotting tank. This method was used to obtain the distributions illustrated. With the aid of these equipotential maps, the axial potential distribution and its derivatives can be determined.

The differential equation describing the path of paraxial electron rays has the following form:

$$\frac{d^2r}{dz^2}+\frac{\phi'}{2\phi}\frac{dr}{dz}+\frac{\phi''}{4\phi}r=0, \qquad (14)$$

where z is the distance along the axis, r the radial displacement of the ray, and ϕ, ϕ', ϕ'' the potential along the axis and its first and second derivatives, respectively.

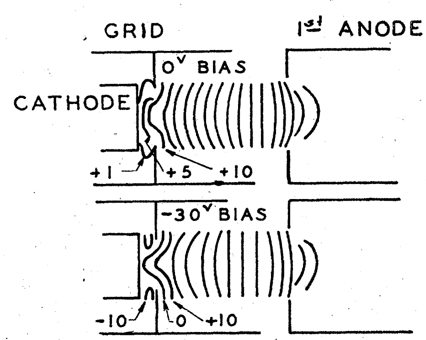

FIG. 7. Potential distribution in first lens.

Using the values obtained from the potential distribution, Eq. (14) may be integrated by one of a number of graphical or numerical methods. Where the method used requires the second derivative of the potential, it can be obtained with fair accuracy from the equipotential map by measuring the radius of curvature τ of the equipotential lines and using the relation:

$$\phi''(z) = 2\phi'(z)/\tau.$$

If one carries out the indicated integration, the positions of the cardinal points for the lens system are found to be as shown in Fig. 8. These determinations were made for electrons having 0.2-volt initial velocity. In accordance with Maxwellian distribution of initial velocities the majority of electrons have initial velocities lower than 0.2-volt. The effect of decreasing initial velocities is to reduce the first focal length and move the first principal point closer to the source. In the limiting case of zero initial velocity, the first focal length becomes zero and the first principal point lies at the source. This range of velocities has only very slight effect on the second focal length and the position of the second principal point. Thus the position of the crossover is not very much affected by the initial velocities in this range.

The equipotential maps shown in Fig. 7, from which the positions of the cardinal points of the first lens were determined, are the potential distribution in the absence of space charge. The effect of space charge upon the behavior of the first lens was examined and it was found that it could by no means be neglected under conditions of high beam current. The method used in this computation was one of successive approximations. Starting with the potential distribution in the absence of space charge, the envelope of the beam is determined. From the initial velocities and the field configuration, the electron velocities along the beam are computed. This, together with current in the beam, makes it possible to calculate the charge density at all points. With a knowledge of the charge distribution, the charges induced on the electrodes and the new potential distribution can be computed. A better approximation can be obtained by repeating the procedure using the new potential distribution. Figure 9 shows the effect of space charge on the potential distribution in the vicinity of the cathode and grid. The effects found to be produced by the existence of space charge can be summarized as follows:

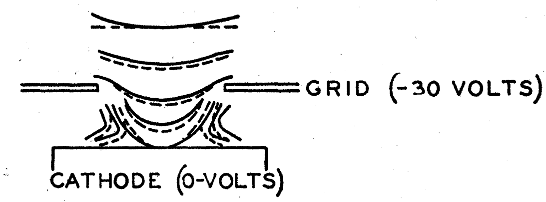

FIG. 9. Potential distribution in the presence of space charge. Dashed line, equipotential lines corrected for space charge; solid line, uncorrected.

1. The field strength in the neighborhood of the cathode is decreased.
2. The effective emitting area of the cathode is slightly decreased.
3. The first and second focal lengths of the first lens are increased and the principal points displaced.
4. The size of the crossover is increased (the increase is found to be in the neighborhood of 15 to 20 percent for normal beam currents).

The net result is a decrease in the current which can be obtained in the beam and a slight increase in spot size due to the increase in the crossover diameter.

In practice, the first lens systems used in television tubes include a number of modifications which, while they do not alter the basic principle of operation, nevertheless result in improved performance. Where an extremely small sharply defined spot is required together with modest current demands, as in the iconoscope, a small defining aperture is placed at the crossover. This aperture may be circular or may take the form of a rectangle with its narrow dimension in the direction of horizontal scanning. The schematic drawing of the gun used in the RCA 1850A iconoscope shown in Fig. 18 illustrates

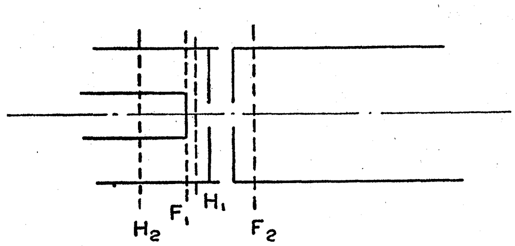

FIG. 8. Cardinal points of first lens.

the use of a crossover aperture. In order to reduce interaction between first anode focusing and beam current, an electrode is frequently inserted between the grid and first anode. The specific design of the grid and grid skirt may vary considerably between tubes. This is done to obtain the most favorable beam current control characteristics for the particular application of the tube. Where the fluorescent screen is not protected by a metalized layer which also serves to increase the efficiency of the screen it may be advisable to provide means for preventing the bombardment of the phosphor by negative ions. One way of accomplishing this is by an ion trap in the gun. An interesting form of ion trap is illustrated in connection with the 7DP4 gun shown in Fig. 16. Here the electrons are deflected by the magnetic flux from the small permanent magnet, while the ions are relatively undeflected. The electrons are again deflected by the tilted electrostatic lens B back into a path parallel to their original trajectories. The ions, which enter the tilted lens along the axis of the gun are deflected out of the beam and are absorbed by the walls of the gun.

IV. THE SECOND LENS

The final step in the formation of the required high current-density spot is the imaging of the crossover onto the fluorescent screen or mosaic. This is accomplished, as has already been pointed out, by means of another electron-optical system, the second lens. The size of the final spot, once the crossover diameter has been fixed, is determined by the magnification of the second lens, and by its spherical aberration.

In general, the second lens system is much simpler than that required for forming the crossover. For an electrostatic gun, it is based essentially on the lens formed between two coaxial cylinders. Various departures from the simple cylinder lens have been studied and some are in use in practical tubes. These modifications are dictated by the following considerations: (a) reduction of spherical aberration; (b) ability to withstand high voltages (particularly in viewing tubes); (c) ease in construction and alignment; and (d) circuit considerations.

For all or most electrostatically focused viewing tubes and pick-up tubes, the diameter of the glass neck of the tube envelope determines the maximum diameter that the electrodes of second lens can have. Under these circumstances, it can be shown that the minimum spherical aberration is obtained when the lens is in the form of a pair of cylinders having this maximum diameter. Any shaping of the lens elements can only be effected by reducing the diameter of the lens and this reduction in diameter more than offsets the improvement in spherical aberration resulting from the shaping. The same thing is true of making one lens cylinder different in diameter from the other.

A two-cylinder electrostatic lens of the type just discussed is illustrated in Fig. 10. The axial potential distribution of this configuration is given, to a close approximation, by the following relation:

$$\phi(Z)=\frac{\phi_1+\phi_2}{2}+\frac{\phi_2-\phi_1}{2}\tanh\frac{2.630}{D}Z.$$

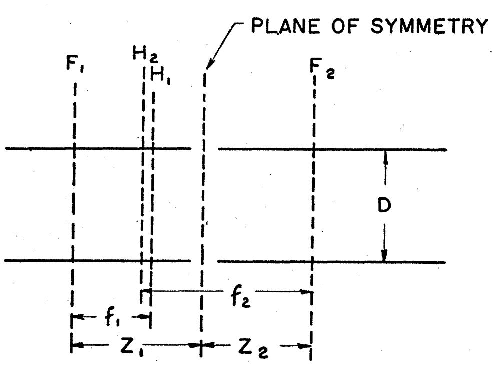

FIG. 10. Two-cylinder second lens.

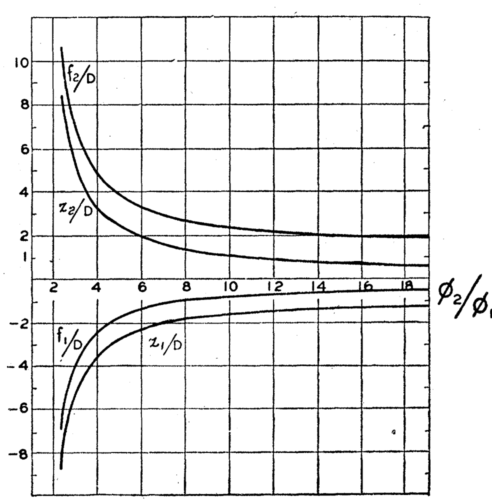

FIG. 11. Focusing properties of two-cylinder lens.

Here D is the diameter of the cylinders, Z the distance along the axis, and ϕ_1 and ϕ_2 are the potentials of the first and second cylinders, respectively. With the aid of this expression for the potential distribution the ray equation can be integrated permitting a determination of the distances Z_1 and Z_2 of the first and second focal points from the plane of symmetry of the lens, and the values of the focal lengths f_1 and f_2. These focal properties are shown in Fig. 11. The four curves shown suffice to determine completely the first-order imaging properties of the lens, so that for any preassigned values of crossover to lens and lens to screen distance the voltage ratio required to form a sharp Gaussian image can be obtained.

In determining the position of the second lens, a number of considerations are involved. These include practical features of tube design (e.g., the position of the deflection yoke, the maximum permissible tube length, etc.), the total current required, and the amount of space charge that can be tolerated in the first lens.

As the position of the second lens is changed, the current density at the center of the spot remains nearly constant because the distance between the second lens and screen is large compared with that between lens and crossover, and a constant fraction of the second lens, as determined by a limiting aperture, is filled by the electron stream. However, both the spot size and the total current in the spot increase with decreasing distance between the second lens and crossover. The current and spot size for a given first lens system is therefore one of the factors determining second lens position.

Also, as the lens is moved towards the crossover, it is necessary to increase the strength of the second lens. Since usually the over-all voltage is fixed by the operating requirements, and the diameter of the lens electrodes cannot be reduced because of spherical aberration considerations, this means reducing the first lens voltage. Because of space charge effects, etc., a low first lens voltage is not desirable. Therefore, even when a crossover aperture is employed to limit the size of the spot, the second lens should not be too close to the crossover. In practice a voltage ratio ϕ_1/ϕ_2 in the neighborhood of $\frac{1}{4}$ to $\frac{1}{5}$ is found to yield satisfactory results.

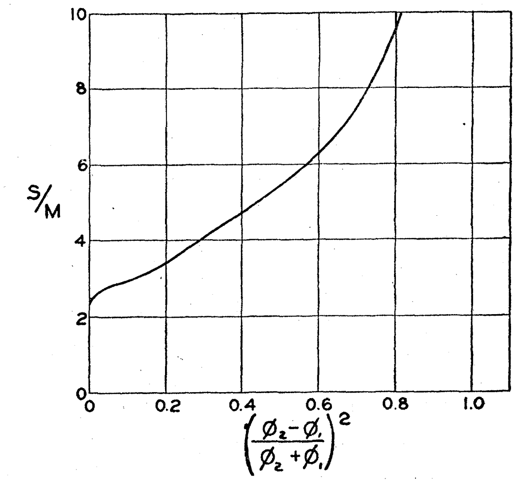

FIG. 12. Spherical aberration of two-cylinder lens.

The spherical aberration of this type of lens can be computed from the potential distribution. The separation Δr from the axis at the Gaussian image plane of a ray which originates from an axial object point and passes through the aperture of the lens at a distance r_a from the axis is given by:

$$\Delta r_s = S r_a^3, \tag{15}$$

where S is an aberration constant of the system.

If then r_s is the radius of the Gaussian image of the spot and r_a that of the aperture gun, the actual radius of the spot will be $r_s+\Delta r_s$. It is, however, more convenient to refer the increase in size back to the crossover so that the size increase can be determined independently of the first order magnification. Expressed in this way Eq. (15) becomes:

$$\Delta r_c = (S/M) r_a^3, \tag{16}$$

where Δr_c is the increase in radius of the crossover r_c which would in the absence of aberration give a spot of the same size as the actual spot. The aberration constant S/M is shown as a function of $(\phi_2-\phi_1)/(\phi_2+\phi_1)$ for an equidiameter, two-cylinder lens in Fig. 12.

To illustrate the application of Figs. 11 and 12 to the general problem of gun design, consider the case of the two-cylinder lens illustrated in Fig. 10. Here the lens is assumed to consist of two cylinders 0.8 inch in diameter with a voltage ratio of 5. From Fig. 11, the values of the first and second focal lengths and the positions from the center of symmetry of the lens are:

$$f_1 = 1.32'', \quad Z_1 = -2.25'',$$
$$f_2 = 2.95'', \quad Z_2 = 1.92''.$$

Assuming a throw of $14\frac{1}{2}''$ from the center of the gun to the fluorescent screen, the position of the object (i.e., the crossover) will be 2.6 inches from the center as can be readily calculated from the positions of the cardinal points. Furthermore, the magnification of the system is found to be 4.3.

If now the tube requirements dictate that the diameter of the final spot be 0.08 inch, and the minimum practical diameter of the crossover, produced by the first lens selected, is 0.01 inch, the maximum fraction of the second lens which can be utilized can be readily determined.

Since from the above: $r_s = M(r_c + \Delta r_c)$ where, $r_s = 0.04''$, the spot radius, $r_c = 0.005''$, the crossover radius and $M = 4.3$, the magnification it follows that Δr_c, the increase in radius referred back to the crossover, is 0.0043 inch.

An inspection of the curve given in Fig. 12 indicates that the spherical aberration coefficient S/M for the voltage ratio $\phi_2/\phi_1 = 5$ (i.e., $(\phi_2 - \phi_1)/(\phi_2 + \phi_1) = 0.67$) is 5 diam.$^{-2}$. Consequently, the maximum aperture permissible, which is given by:

$$\Delta r_c = S/Mr_a^3$$

will be $2r_a = 0.16$ inch at the first principal plane.

Since the first principal plane is 1.0 inch from the center of the lens and the electron rays follow nearly straight lines to the lens the actual fraction of the lens diameter utilized will be:

$$f = \frac{0.16}{0.8} \times \frac{2.6}{1.6} = 0.3.$$

Therefore, an aperture must be placed in the system so as to limit the portion of the lens accessible to the electron beam to 30 percent of the lens diameter. Such an aperture would, in general be located in the first anode, far enough from the lens not to influence the lens field distribution. The cathode area would also be restricted to prevent excessive collection of electrons by the first anode and first anode aperture. Actually, the spot size would be slightly less than is indicated by the above calculation, because the second lens would not be focused for a true Gaussian image of the crossover, but rather to yield the minimum spherical aberration figure. This would lead to perhaps a 30 percent reduction in spot size.

It will be noticed that the limiting aperture is placed at the second lens, rather than relying on a restricted cathode to define the beam. The equations for the ideal gun indicate that the current distribution should be essentially constant over the aperture angle defined by the cathode area, with fairly sharply defined edges. However, due to the aberrations of the first lens the actual distribution is more nearly an error curve. Therefore, if the aperture angle is limited at the cathode, the mean electron density through the lens would be greatly reduced. Consequently it is necessary to limit the angle at the lens by an aperture in spite of the fact that this aperture collects considerable current.

Where an extremely small, sharp spot is required, as in the pick-up tube, it is general practice to use a very much smaller fraction of the second lens, which is accomplished by employing a very small masking aperture.

Frequently, for reasons related to practical design and construction considerations, the second lens differs considerably from the equidiameter, two-cylinder lens discussed above. For example, the second anode often takes the form of a wall coating on the neck of the tube, while the first anode will be a cylinder of somewhat smaller diameter. Such an arrangement introduces slightly more spherical aberration, but its practical advantages much more than outweigh this disadvantage. The same is true of the unipotential lens which is sometimes employed.

A magnetic lens is frequently used as part of the second lens system in television cathode-ray tubes. The lens takes the form of a short coil around the neck of the tube. This coil may be encased in a high permeability yoke with a suitably shaped air gap in order to concentrate the flux.

In some instances when a magnetic lens coil is used, the actual imaging of the crossover is accomplished by the combined effect of the magnetic lens and the electrostatic lens formed between a first and second anode. However, frequently the magnetic lens alone serves as the second lens.

An important advantage gained by using a magnetic lens is that the lens diameter is not limited by the inside diameter of the glass neck of the tube as an electrostatic lens. Thus a given diameter of the beam represents a smaller fraction of the lens diameter for a magnetic lens than for an electrostatic lens, resulting in less spherical aberration in the former case.

V. LOW VELOCITY BEAMS

The gun required for a low velocity beam pick-up device, such as the orthicon and image orthicon, presents a somewhat different problem. Here the electrons are accelerated away from the cathode, move down the tube at velocities corresponding to the range from 50 to 200 volts and are then slowed down to virtually zero velocity at the target.

The spot formed by the intersection of the beam with the target must be small but the beam current needed is also very small so that, in general, it is not difficult to obtain sufficient beam current. However, an additional demand is placed on the means for producing the beam which is not required of any of the guns discussed above. This is that it forms a beam in which the velocity component normal to the target of the electrons is as nearly uniform as possible. To do this, the gun should not introduce a larger range in direction of motion of the electrons than necessary.

Magnetic fields are used to focus the low velocity electron beam on the target in the orthicon and image orthicon. Electrostatically focused, low velocity beam guns have to date only been employed in experimental tubes. The present discussion, however, will deal primarily with magnetically focused beams.

The simplest low velocity gun consists of a small emitting source, with a uniform magnetic field forming an image of the source on the target. A relatively weak electric field accelerates the electrons away from the cathode, and a retarding field brings the electron velocity down to a low value again in the vicinity of the target. The image so formed will be erect and have unity magnification. If the target potential is equal to that of the emitting surface of the cathode (due account being taken of contact potential) and aberrations introduced by the magnetic focusing field are neglected, the current density in the spot will be equal to the emission density of the cathode. As the target is made negative with respect to the cathode, the current density becomes:

$$\rho = \int_{\phi_T}^{\infty} \rho_0 (e/kT) \exp[-e\phi_0/kT] d\phi_0$$
$$= \rho_0 \exp[-e\phi_T/kT], \qquad (17)$$

where ρ_0 is the emission density and ϕ_T the potential between cathode and target.

When a low velocity, pick-up tube is operated in darkness, the target assumes a potential which is sufficiently negative so that the beam current which reaches it just equals the current lost by the target due to electrical leakage and positive ion bombardment. When a portion of the target is illuminated, this area becomes more positive and consequently, in accordance with Eq. (17) the current to it increases. Excessive illumination will cause the target to require more current than can be supplied by the beam. Instability will then result and the target will continue to become increasingly positive until the secondary emission ratio of the electrons bombarding it is greater than unity, the beam no longer tends to drive the target to equilibrium. (Note: In the image orthicon, this form of instability is avoided by applying only a small positive potential to the electrode which collects the image electrons emitted by the target.)

There are a number of objections to this type of gun which makes it impractical for existing pick-up tubes. In the first place, it contains no provision for controlling the current in the beam, except through the temperature of the cathode. This makes it difficult to adjust to optimum beam current for the immediate operational requirement and also does not permit cutting off the beam during the return time of the scanning pattern. In the second place, the maximum beam current which can be obtained, when the spot is small enough to give high definition, is not always sufficient to discharge the target for an optimum charge image. (By optimum charge image is meant one which will yield a signal-to-noise ratio high enough so that the pick-up device does not limit the picture quality of the system.) The

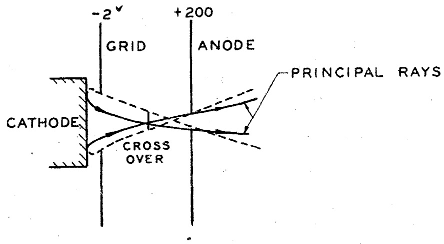

FIG. 13. Low velocity gun.

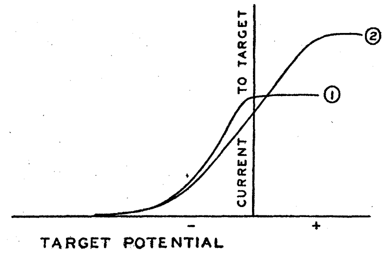

FIG. 14. Current to target from low velocity gun. (1) point cathode gun; (2) focused gun.

current limitation is particularly objectionable in the case of the orthicon.

A gun which overcomes both of the above mentioned objections is shown in Fig. 13. This gun consists of a cathode with a fairly large emitting area, a control grid close to the cathode, and a small defining aperture spaced a distance from the cathode equal to four or five times the cathode grid spacing. A magnetic field extends from the cathode to the target and focuses the beam electrons.

As operated, the grid cathode structure forms a crossover which lies on the cathode side of the small defining aperture. In a typical electrode assembly of this kind, the crossover will be about 5 mils in diameter. Its position depends upon the grid potential. For smallest spot, the magnetic field is adjusted to approximately focus the small defining aperture on the target. If there were no lens aberrations, the magnetic focusing field would be adjusted to form a Gaussian image of the aperture on the target; the actual adjustment is made so as to give a minimum aberration figure.

The current obtained from a gun of this type is greater, for a given spot size, than where a small cathode is imaged on the target. However, the range of electron velocities is also greater. In general it is not possible to obtain a greater current density of electrons in any small velocity range than that corresponding to the maximum current density in an equal velocity range in the low velocity gun first described. Figure 14 illustrates the current reaching the target as a function of target potential for the two types of guns. The practical voltage range for the directly imaged cathode is less than 0.2 volt whereas for a large cathode crossover gun the range may be 1 to 1.5 volts.

The velocity range in the large cathode crossover gun is dependent upon the bias voltage applied to the control grid. As the grid is made more negative, the crossover moves back towards the cathode and electrons from a smaller area of the cathode enter the beam. Since the components of the beam having low axial velocities consist of electrons coming from the outer portions of the cathode, to which the lens action of the grid-cathode system have imparted transverse velocities at the expense of longitudinal velocities, the more negative grid potential tends to remove these components, and decrease the velocity range.

For the orthicon, in which the signal is removed by means of a signal plate on the back of the target, a large beam current with considerable velocity range is not undesirable as long as a sharp spot can be maintained. Here, when the light level is very low and the charges accumulated on the target small, the low velocity components of the beam simply do not reach the target. As the light is increased, the low velocity electrons become available for discharging the target.

Conditions in the image orthicon are however such that the beam current should be as small as possible. This is because the signal is obtained from a multiplier as a modulation of the beam returning from the target. A beam current in excess of that required to completely discharge the brightest areas of the target simply contributes to the noise output of the multiplier without adding to the signal. Therefore, the image orthicon should be operated with a beam having the smallest velocity range and total current compatible with the illumination of the scene so that a high percentage modulation of the beam is obtained. The application of the principles outlined above can best be illustrated by a description of some of the guns used in a number of practical television pick-up and viewing tubes.

VI. ILLUSTRATIVE ELECTRON GUN TYPES

The gun in the projection kinescope Type 5TP4 is an excellent example of a typical high voltage gun. This tube has an aluminum backed fluorescent screen 5 inches in diameter, and gives a black and white picture which is bright enough so that it can be projected onto a large viewing screen by means of a Schmidt optical system. In order to obtain the required brightness the gun must operate at a high voltage and be capable of delivering a large beam current. At the same time, the spot size must be very small in order to produce a high definition picture.

To satisfy these conditions, the gun is operated with an over-all voltage of 27,000 volts and can deliver a maximum beam current of several hundred microamperes. The spot diameter is about 0.006 inch under normal operation. The gun employed in this tube is illustrated in Fig. 15. An oxide coated cathode serves as the source for the beam electrons. The control grid, in the form of an apertured cap, surrounds the cathode cylinder, with the control aperture spaced only a few mils from the cathode. The grid is followed by a shield electrode which is operated at approximately 200 volts and then a first anode at 4900 volts. The shield electrode serves to make the beam current independent of the focus of the second lens, and also, by the adjustment of its voltage to control the cut-off voltage of the control grid. Nominally the cut-off voltage is -70 volt, but it may vary from tube to tube due to small differences in grid-cathode spacing. The adjustment mentioned above makes it possible to set the cut-off voltage arbitrarily to the correct value of -70 volt.

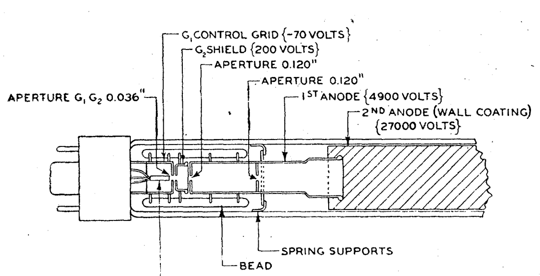

FIG. 15. Schematic diagram of high voltage gun of RCA 5TP4 projection kinescope.

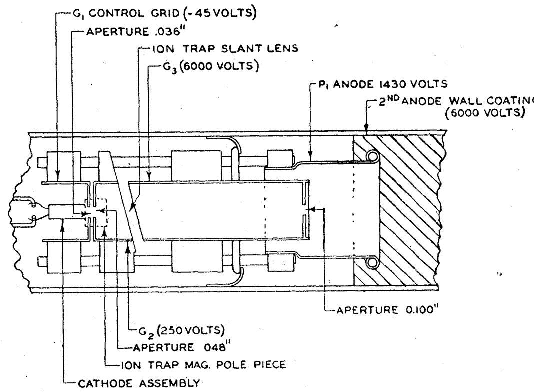

FIG. 16. Schematic diagram of gun of RCA 7DP4 kinescope.

The lens formed between the shield electrode and the first anode has a relatively short focal length, its first focal point being a small distance behind the crossover. This lens forms a virtual image of the crossover, lying behind the real crossover. As a result, the principle rays through the crossover are to some extent collimated, which reduces the amount of current intercepted by the limiting aperture of the second lens.

The second lens is formed between the first anode and the wall coating on the neck of the tube which serves as second anode. Since the field strength is quite high at the end of the first anode cylinder, the mouth of this electrode is carefully rounded and freed from points and roughness to avoid cold emission. For similar reasons the end of the shield electrode facing the first anode is also carefully smoothed and rounded.

It might be pointed out that no ion trap is required in this gun inasmuch as the aluminum backing on the fluorescent screen completely eliminates the destructive effect of the bombardment of the phosphor by high velocity ions.

Figure 16 illustrates the gun employed in the Type 7DP4 direct-viewing kinescope. This tube has a 7-inch uncoated white phosphor screen and operates with an over-all voltage of 6000 volts. The grid-cathode arrangement of the gun is similar to that in the type 5TP4 but has a slightly different grid-cathode spacing. The shield electrode, located next to the grid, also forms the first portion of the tilted lens which serves as the

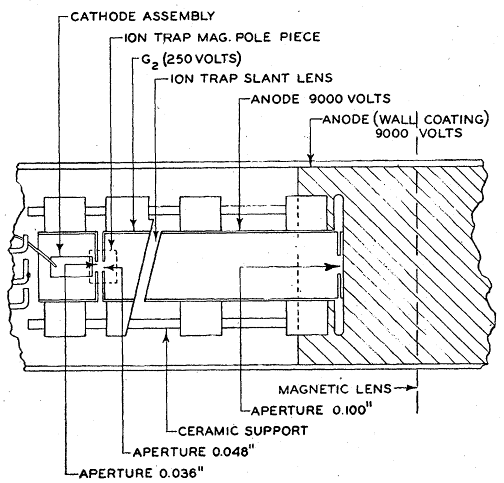

FIG. 17. Schematic diagram of gun of type 10BP4 kinescope.

ion trap. A cylinder, operated at the full over-all voltage (second anode voltage) of the tube, forms the second element of the slant lens.

The second lens is a unipotential lens. The two positive elements of this lens are the cylinder which forms the second half of the ion trap and the wall coating of the tube which is also operated at the full over-all voltage of the tube. The center element of the lens is a cylinder operated at a considerably lower voltage. The masking apertures which limit the diameter of the beam through the lens are located in the first of the three cylinders making up the unipotential lens.

The reasons for using an unipotential lens as second lens are purely practical ones, but they more than off-set the disadvantage of the inherently greater spherical aberration of this type of lens. The masking aperture of necessity intercepts a considerable fraction of the electrons going through the lens and therefore the electrode containing the aperture collects a fairly large current. Furthermore, the magnitude of this current depends upon the instantaneous beam current. In general the potential for the low voltage electrode is obtained by a resistance divider between the high voltage terminal and the cathode. If the low voltage electrode has a large variable current flowing to it a low resistance voltage divider must be used, to avoid excessive variation of spot size with beam current. By placing the masking apertures in the high voltage electrode, this difficulty is overcome.

An example of a magnetically focused kinescope gun is found in the Type 10BP4, viewing the tube shown in Fig. 17. This is a direct viewing kinescope with a white screen which operates at about 10,000 volts. The cathode, first lens system is, as can be seen from the figure, very similar to that in the 7DP4. However, instead of the unipotential electrostatic second lens of the latter, the second lens is formed by a coil around the neck of the tube, located close to the end of the high potential cylinder which follows the ion trap. The coil is surrounded by an iron yoke having an iron cap arranged to concentrate the magnetic field into the lens region.

It will be noticed that the entire acceleration of the beam occurs in the first lens-ion trap region. The entire second lens focusing is magnetic inasmuch as there are no accelerating fields in the second lens region.

The gun in question has a nominal grid cut-off voltage of -45 volt. Where necessary, the voltage applied to electrode G2 can be adjusted to correct the cut-off voltage for differences due to constructional variations. A maximum current of several hundred microamperes can be supplied to the spot and is sufficient to give a screen brightness of 40 or 50 footlamberts without appreciable defocusing of the spot.

The gun illustrated in Fig. 18 is the type used in the RCA 1850A iconoscope. This gun is a two-lens gun similar in principle to those used in the viewing tubes. However, it operates with an over-all voltage of only 1000 to 1200 volts. In spite of this rather low voltage, it is required to produce a spot which is considerably smaller than

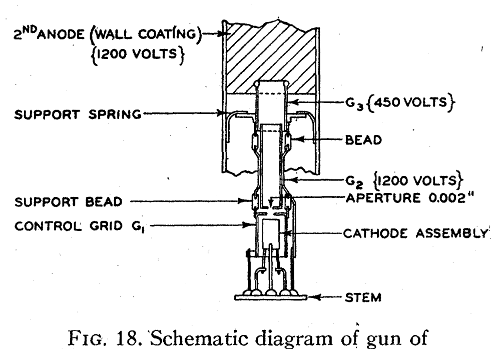

FIG. 18. Schematic diagram of gun of RCA 1850A iconoscope.

that from a viewing tube gun. This is only possible because of the very small current required in the beam. Instead of currents of the order of a hundred microamperes, less than a microampere is all that is needed.

The first lens system consists of the cathode, grid and high voltage electrode assembly. In order to form a small sharply defined spot, a 0.002-inch aperture near the crossover is employed. This aperture serves in part to limit the crossover and in part to restrict the angular aperture of the beam.

The second lens is an unipotential lens. Since only a small fraction of its diameter is used, its spherical aberration is not serious. On the other hand, this type of lens has many constructional and alignment advantages and also makes the beam current and crossover convergence independent of focusing voltages on the first anode.

The guns described so far have all been for the production of high velocity beams. The guns illustrated in Figs. 19 and 20 are guns producing low velocity beams. That shown in Fig. 19 is used in the Type 1840 orthicon. The beam in this tube is magnetically focused by means of a long coil producing an axial magnetic field of 70 gauss extending nearly uniformly from cathode to target. Deflection of the beam in the horizontal direction is produced by a pair of shaped electrostatic plates whose field in combination with the longitudinal magnetic field causes a lateral motion of the beam. Vertical deflection is accomplished by a varying magnetic field at right angles to the axis of the tube and in the desired direction of deflection. The vertical deflecting coil is located between the ends of the horizontal deflecting plates and the target.

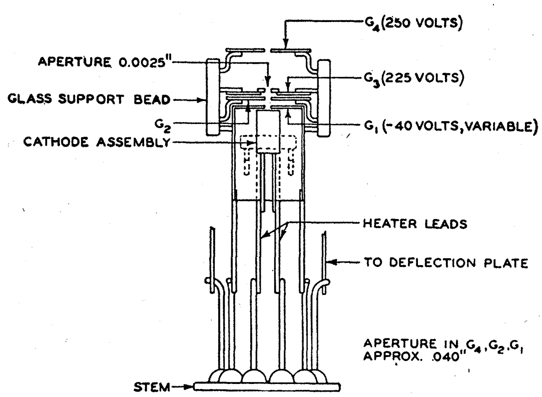

FIG. 19. Schematic diagram of gun for RCA 1840 orthicon.

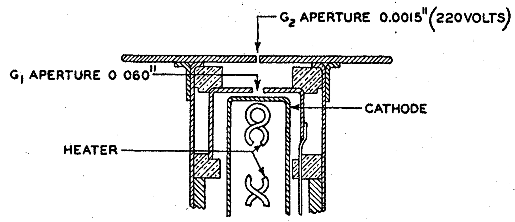

FIG. 20. Schematic diagram of gun of RCA 2P23 image orthicon.

The gun illustrated has a grid-cathode configuration which produces a crossover close to the fine aperture in electrode G_3. An additional aperture about a quarter of an inch beyond the small crossover aperture, in electrode G_4 serves to limit the angle of beam. This electrode also serves as an additional focusing means and as an electrostatic shield between the crossover region and the electrostatic deflecting fields.

The magnetic field focuses the fine crossover aperture onto the target. This focus is a rather high order focus inasmuch as the separation between points of sharp image is only 2 to 4 centimeters over most of the length of the tube.

The second low velocity gun illustrated is that used in the image orthicon Type 2P23. This gun is essentially the same as the crossover gun described earlier, in the discussion of low velocity beam formation. The tube in which it is employed is magnetically focused with a long coil extending from the target and image section almost to the gun. However, it is arranged that the magnetic field strength in the gun itself is lower by a factor of two or three than the field strength in the main body of the tube. Both horizontal and vertical deflections are accomplished by magnetic fields perpendicular to the axis of the tube.

The reasons for using this form of gun, instead, for example, a small cathode of the size of the required spot, in this type of tube is based entirely on practical considerations. These include the ease of activation and reliability of the cathode, the superior control of the beam current and the shielding of the photo-sensitive elements from the light from the thermionic cathode.

On the other hand, this gun causes a greater spread of electron velocities, as has already been pointed out. However, in practice this spread in velocities has not been found to interfere seriously with the operation of the tube and the advantages of this gun far outweigh its disadvantages.

The electron guns selected as illustrations were not chosen because of possible superiority to other guns of similar type but rather as representing the practical application of some of the design principles under discussion.

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