The Magnetically Focused Radial Beam Vacuum Tube

By A. M. SKELLETT

A new type of vacuum tube is described in which a flat radial beam of electrons in a cylindrical structure may be made to rotate about the axis. Features of the tube are its absence of an internal focusing structure and resultant simplicity of design, its small size, its low voltages, and its high beam currents. The focusing of the beams and their directional control are accomplished by the magnetic fields in small polyphase motor stators. A time division multiplex signaling system for 30 channels using these tubes is briefly described.

IT HAS long been recognized that the substitution of electron beams for mechanical moving parts would offer decided advantages in many applications in the field of communications. The high voltages required for the usual cathode-ray type of tube and the very low currents obtainable therefrom prevent their use in most such proposals; their complicated guns and their large sizes are also undesirable features. The kind of tube described herein has no focusing structure, is small in size, requires only low voltages, utilizes the cathode power efficiently, and produces beam currents of the same order of magnitude as the space currents of ordinary vacuum tubes.

Figure 1 shows the elementary tube structure. It consists, in the simplest case, of a cylindrical cathode of the sort in common use in vacuum tubes, surrounded by a cylindrical anode structure. When this structure is made positive with respect to the cathode and there is no magnetic field in the tube, the electrons flow to the anode structure in all directions around the axis. When a uniform magnetic field is applied with its direction at right angles to the axis, the electrons are focused into two diametrically opposite beams as shown. The beams are parallel to the lines of force of the magnetic field so that if the field is rotated the beams move around with it. Thus the magnetic field serves both to focus the electrons and to direct the resulting beams to different elements of the anode structure.

If ordinary commercial cathodes are used with anode structures an inch or two in diameter, 100 volts or less on the anode will draw the full space current for which the cathode was designed. The application of the magnetic field will then focus from 85 to 90 per cent of this electron current into the two beams, the remaining 10 or 15 per cent being lost at the cathode due to an increase in the space charge which the magnetic field produces. Some of the smaller tubes produce beam currents of more than 5 milliamperes with only 50 volts on the anode structure, and in some of the tubes with larger cathodes beam currents of 50 milliamperes or more are easily obtainable. The magnetic field strengths range from 50 to 300 gauss.

For some applications it is desirable to eliminate one of the two beams and this may be accomplished by substituting a uniform electrical field in the tube for the cylindrical one described above. The uniform field may be obtained by applying to the anode elements a series of potentials that vary according to the sine of the angle taken around the axis. The line joining the maximum potentials (+ and −) is maintained parallel to the magnetic field so that on one side of the cathode the potentials are all negative and the

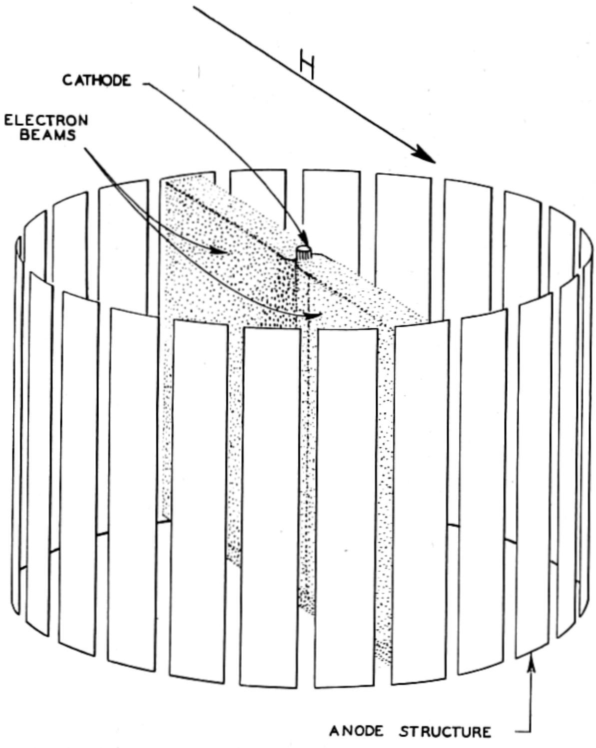


Fig. 1.—Elementary tube structure showing focused beams.

beam on that side is suppressed. The remaining beam will have somewhat less current than the corresponding one in the cylindrical field but the magnetic field-strength required for focus is reduced.

Cylindrical Electrical Field

For the case of the cylindrical electric field the focus is obtained by applying a magnetic field that is strong enough to reduce the radius of curvature of the spiral electron trajectories to a small value. There is not obtained an electron optical image of the cathode in the usual sense that for each point on the cathode there is a corresponding point on the image. The sharpness of the image may be increased by increasing the strength of the magnetic field and the field required for any degree of focus is not sharply critical.

Figure 2 shows a series of drawings of the various electron images that were obtained as the magnetic field-strength was increased in a tube having

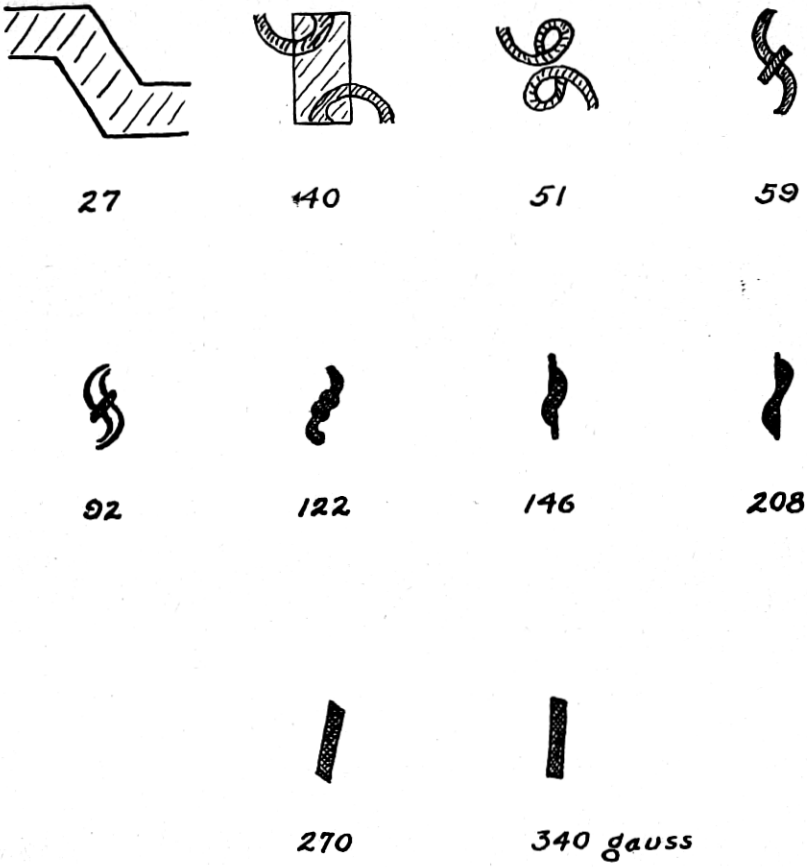
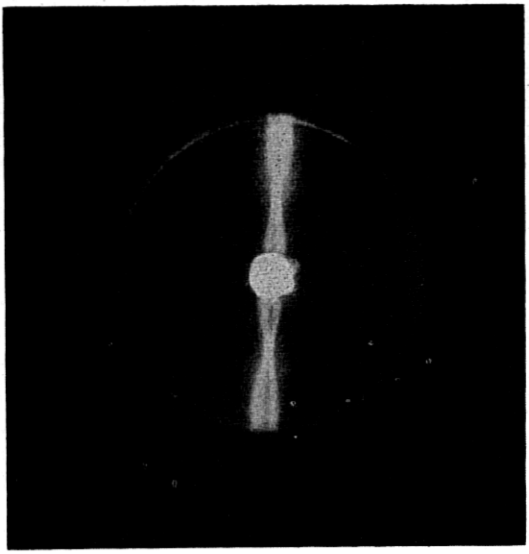
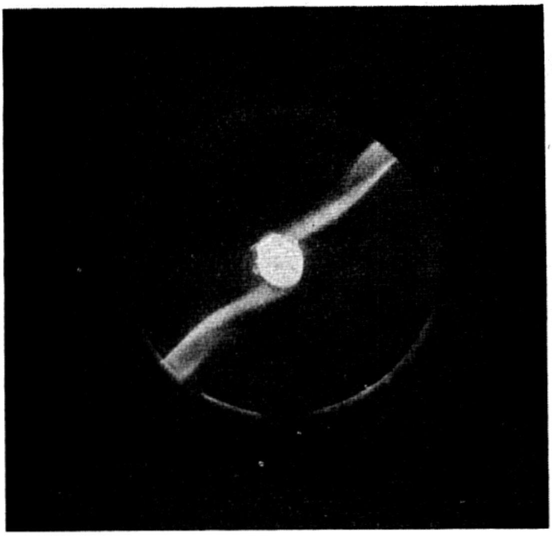


Fig. 2.—Drawings of the patterns obtained with a fluorescent coating on the inside of the anode when the magnetic field strength is increased from zero to the focus values.

a fluorescent coating on the inside cylinder. The cathode and anode diameters were 0.0625 and 2.5 inches, respectively, and the axial length was 2 inches. The anode was held at 150 volts. Only one-half inch of the cathode length, located centrally along the axis, was coated to emit electrons. The image at 340 gauss appeared to be one-half inch long. In attempting to interpret these patterns it should be remembered that on the two sides of the cathode at right angles to the plane of the beam the electrons follow



A



B

Fig. 3.—Electron trajectories made visible with a small amount of gas. A.—Magnetic field lined up with active spots on the cathode. B.—Magnetic field at 45° with respect to the active spots.

cycloid-like paths along the cathode, moving up on one side and down on the other.

The photographs of Fig. 3 showing the trajectories were obtained by introducing argon at a pressure of about a micron into the tube. The electrons are emitted from only two spots of active material located at the opposite ends of a diameter on the cathode sleeve. In Fig. 3a the line joining the spots is lined up with the magnetic field and in 3b this line is at an angle of about 45° with respect to the field. This arrangement does not reproduce exactly the space charge conditions in the tube as actually used but does serve to give a picture of the electron paths in a qualitative sort of way.

As shown by the patterns of Fig. 2 above a minimum strength of magnetic field the shape of the focus does not change greatly. An approximate equation may be derived for the beam width in terms of the magnetic field above this minimum value that is useful for predicting the performance of new designs. The electrons that leave the cathode at right angles to the beam require the strongest magnetic field to keep them in focus. Now because of the cylindrical structure the electric field is concentrated near the cathode and we will assume that after leaving the vicinity of the cathode the velocity does not change appreciably. Setting v equal to the component of this velocity at right angles to the magnetic field we have that the radius r of the spiral path is given by the relation

$$r = \frac{mv}{eH}$$

where H is the magnetic field-strength and m and e are the mass and charge of an electron.

We also write

$$v = \sqrt{\frac{2eKV}{m}}$$

where K is the fraction of the anode voltage corresponding to v.

The width of the focus A is approximately equal to the cathode diameter D plus twice the maximum radius of curvature of the spiral paths

$$A \doteqdot D + \frac{6.7\sqrt{KV}}{H}$$

where A and D are in centimeters and V is in practical volts. By substitution in this formula we have found that the empirical constant K is about 0.7 for the tubes that have been made to date. A minimum value for H is obtained, again approximately, by setting the last term in the equation equal to D.

Uniform Electric Field

As mentioned above the uniform field is obtained by imposing potentials around the anode periphery varying as the sine of the angle. The cathode is at a point of zero potential. In this case a real electron optical image of the cathode is obtained.

Neglecting the distortion of the field in the vinicity of the cathode, the force equation for the electrons is

$$m \frac{d^2 x}{dt^2} = e \frac{V}{R}$$

where V is the maximum anode potential, R is the radius of the anode structure and x is measured in the direction of the fields. Since the acceleration is uniform the transit time t, neglecting space charge effects, may be obtained from the expression

$$\frac{1}{2}\left(\frac{d^2 x}{dt^2}\right) t^2 = R$$

Combining these equations we get

$$t = \frac{R}{\sqrt{\frac{Ve}{2m}}}$$

The condition for focus is that the electrons make one revolution around the lines of force in time t. The angular velocity of the electrons is given by the well-known expression

$$\omega = \frac{He}{m}$$

Setting $\omega t = 2\pi$ we get

$$H = \frac{2\pi}{R}\sqrt{\frac{m}{2e}V}$$

or in practical units

$$H = \frac{10.6\sqrt{V}}{R}$$

Since the effect of the magnetic field on the space charge has not been evaluated, we can only estimate the order of magnitude of the increase of transit time due to the space charge. On the assumption that this increase introduces a factor of 3/2* the above expression with space charge is

$$H = \frac{7.1\sqrt{V}}{R}$$

This formula has been found to check well experimentally.

* The factor of 3/2 is the ratio of the transit times in a plane parallel diode with and without space charge. See for example Millman and Seely, "Electronics," Chapt. 7, p. 231.

These last two formulae are for the first focus. Focii will also be obtained for values of H equal to nH where n is an integer and equal to the number of electronic revolutions. Actually as the field is increased beyond that necessary for the first focus the beam does not get very badly out of focus because the radius of curvature of the spiral path is small and for still higher fields the beam remains in approximate focus for all values of H.

In applications where the beam is rotated by means of a rotating magnetic field this electrostatic field is made to turn by separating the anode structure into four or six elements (or groups thereof) and applying either two- or three-phase alternating potentials to them.

Magnetic Field Supply

The stator of a two-pole polyphase alterating-current motor furnishes an excellent magnetic field for use with these tubes. The tube is inserted in place of the armature and when the polyphase currents are applied the beams are formed and rotate at the cyclic frequency. For applications where the beams are not rotated continuously, a two-phase stator may be used in which the currents through the two windings are adjusted to be proportional to the sine and cosine of the desired direction angle of the beam. Permanent magnets of the horseshoe design have also been found to be suitable.

The power consumed by a stator depends on its size and the strength of the field it produces and on the cyclic frequency if it is used to rotate the beam. At low frequencies, e.g., 20 or 60 cycles, the power consumed is primarily that due to the copper loss. At higher frequencies the losses in the core material become important. For some of the smaller tubes operating at a low frequency, the power consumed by the stator is less than three watts. This stator has the regular motor windings which do not completely fill the slots.

Since a polyphase source of power is not always readily available, it is sometimes advantageous to split single-phase power in the stator itself to produce the rotating field. This may be done by inserting a condenser in series with each winding so that the current through one phase winding lags by 45° and that through the other leads by an equal angle. Polyphase potentials for producing a rotating electrostatic field in the tube may then be taken from the windings of the stator if desired.

Tube Design

The particular design of tube depends on its application. The simple design shown in Fig. 1 has been found adequate for some purposes but more elaborate designs which increase the versatility of the tube are also needed.

Figure 4 shows a tube with 30 anodes that incorporates various auxiliary elements. This tube is 2.25 inches in diameter. Figure 5 shows the internal arrangement of the elements. Closely surrounding the cathode is a control grid that may be used for modulating the current density of the electron beams. Farther out is a cylindrical element with 30 windows that is maintained positive and which by virtue of its similarity in position to the third element of a tetrode is called a screen. Immediately behind each window there is a pair of paraxial wires which because of its similarity in function to the fourth element of a pentode is called a suppressor grid. In back of each suppressor grid there is an anode. In this particular tube there are pro-

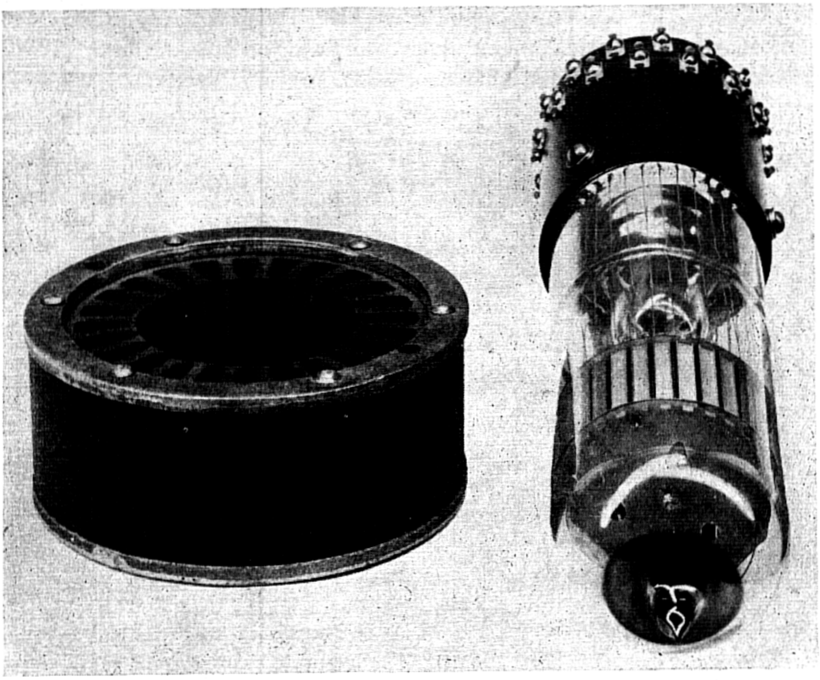


Fig. 4.—Radial beam tube with 30 anodes and unwound stator used with it.

jections like gear teeth on the back of the screen element to prevent electrons, destined for one anode, from reaching an adjacent one.

The control grid that is close to the cathode is biased negatively and controls the electron current in the same way that it would if the magnetic field were not present. The space current vs. grid potential curve is nearly identical for the two cases: with and without the magnetic field. The slight difference is due to the fact that the presence of the magnetic field increases the space charge near the cathode. Thus the tube may be used for amplification in the usual way when the electrons are focused. The presence of this grid has no appreciable effect on the focusing of the electrons.

Since the screen element is in one piece there will be present two beams out to it. One of these may be suppressed after it has passed through the screen by the suppressor grids or by the anodes in the manner described below.

These suppressor grids are generally operated at cathode potential or at a potential that is negative with respect to the cathode. They may be used for three purposes: to suppress secondaries from the anodes, to modulate the beam current to their particular anode, and to suppress one of the two beams. For the first of these functions they are biased at cathode potential. For the second they are biased negatively and have a modulation curve similar to that of the suppressor grid in a pentode. Curve A of Fig. 6 shows the variation of beam current to one anode when the potential of the suppressor grid in front of it is varied. This curve is for a grid similar to the two paraxial

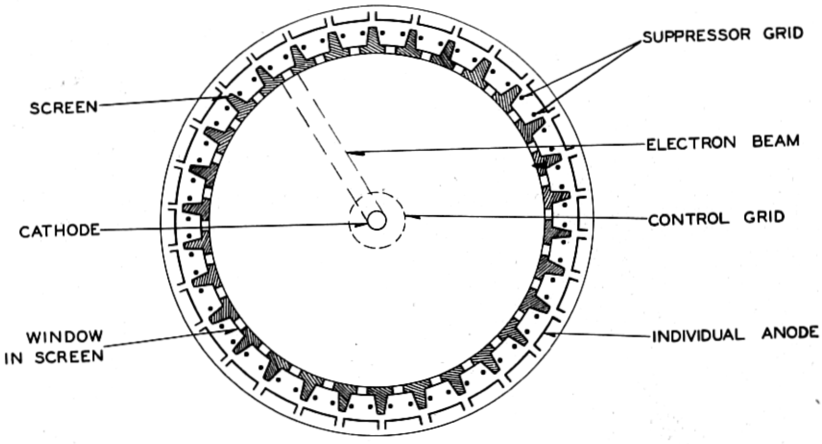


Fig. 5.—Arrangement of elements in the tube shown in Figure 4. Only the operating beam is shown.

wires in the tube shown in Fig. 5. For some applications a higher suppressor-anode transconductance or a lower cut-off is desirable and these may be obtained by welding lateral wires across this grid window to make the grid action more effective. Curve B of Fig. 6 was taken with the same size window across which laterals were welded. The table below gives the data for this suppressor grid with and without the lateral cross wires.

	Without Laterals	With Laterals
Transconductance (mho)	100	250
Anode Resistance (ohms)	30,000	64,000
Amplification Factor	3.5	16.0
Cut-Off Voltage	−80	−20

It is apparent from these data that amplification of the signals applied to the individual suppressors may be readily obtained.

If the screen element is split to give a uniform electrostatic field to suppress one beam, the beam current is only about half that of one beam of the cylindrical field case. This is because with the uniform electrostatic field the potential gradient at the cathode decreases with azimuthal angle away from the beam axis. If the unwanted beam is rejected by the suppressor grids, however, the beam current for the cylindrical case is obtained since the screen in this latter case supplies a cylindrical electrostatic field at the cathode and the unwanted beam is rejected between the screen and suppressor grids.

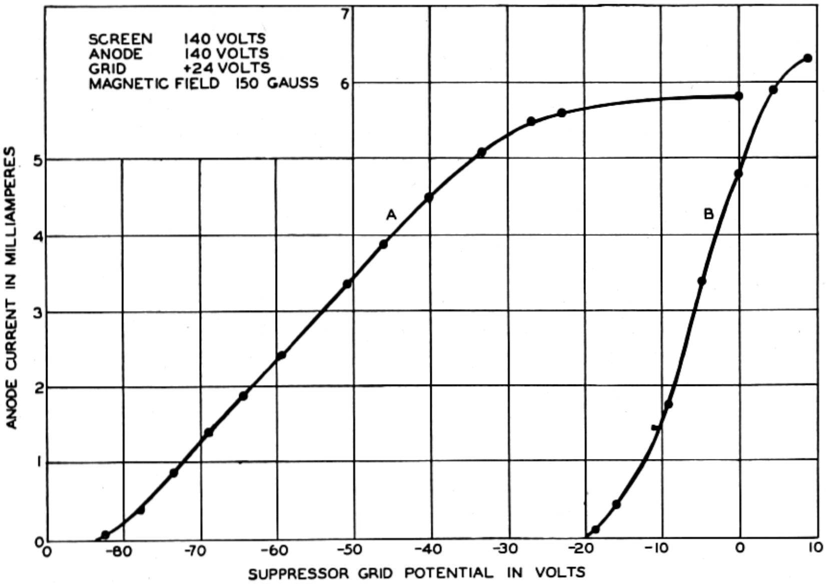


Fig. 6.—Suppressor grid characteristics. A.—Without lateral wires. B.—With lateral wires.

For this case the screen is maintained at the same positive potential required for the two-beam condition and the suppressors are so biased that they are beyond cut-off on one side of the tube and at or near cathode potential on the other side. If the beam is rotated the suppressors are connected to the polyphase supply in groups in the same way that the screen elements would be connected except that the d-c. bias above and below which the a-c. potentials swing is made negative at a value near cut-off for the suppressors.

When one beam is suppressed either by splitting the screen or by grouping the suppressors, the currents to the different anodes are not all exactly the same. For instance, maximum current will be received by an anode back of the center of one of the screen elements or one of the suppressor groups and a minimum current will be received by an anode back of the junction of two such elements or groups. If two-phase supply is used (4 elements or groups) the ratio of maximum to minimum anode current will be 0.707 and for three-phase supply this ratio will be 0.866. There will be 4 or 6 maxima, respectively, around the tube. This variation may be effectively eliminated by varying the individual anode load impedances or in other ways.

The anode characteristics are similar to those of a pentode if suppressor grids are used and to that of a tetrode if these grids are not used.

There is still another method of effectively eliminating one beam. This consists in using an odd number of anodes so that when one beam is focused on an anode the opposite one falls on the screen in between two anode positions. With this type of tube the effective rotational frequency is twice the cyclic frequency of the rotating field, that is, all of the anodes are contacted twice (once for each beam) per revolution of the field.

Applications

The many possible combinations of the tube elements just described permit a variety of applications. One of the simplest and most obvious is that of an electronic commutator which has the advantages over the corresponding mechanical device of speed and freedom from contact trouble. There is, however, a practical limitation to the speed of this electronic commutator that is set primarily by the alternating-current losses in the stator. This is estimated to be in the neighborhood of 10,000 cycles per second for ordinary stator and tube designs. The highest cyclic speed for a stator that has been used to date was 600 cycles per second which with utilization of both beams gave an effective cyclic frequency of 1200 cps.

One of the earliest systems of multiplex telegraphy was based on time division using mechanical rotating commutators. A small portion of the time of one cycle of the moving brush was allotted to each channel. The usefulness of this system is limited because of the faults of the mechanical commutators. The substitution of these electronic commutators eliminates these difficulties and puts the time division system on a more practical basis. It has an advantage over the frequency division multiplex system (carrier system) in that the elaborate filters of the latter are not required.

A 30-channel multiplex system for signaling using two of the 30 anode tubes described above has been successfully tested over short distances in the metropolitan area in New York City. The tube at the transmitter had all of the anodes tied together and the signal from them was sent over the line. The 30 input channels terminated on the suppressor grids of this tube. At the receiver, the input was fed to the negative grid surrounding the cathode and each of the anodes was connected in series with a small neon lamp for an indicator. A signal on any one or signals on any group of the 30 input channels would actuate the corresponding lamp or lamps at the receiver. No amplification other than that provided by the receiver tube was needed.

A single beam was used in each tube, the other one being rendered ineffective in the transmitter by means of two-phase potentials applied to the

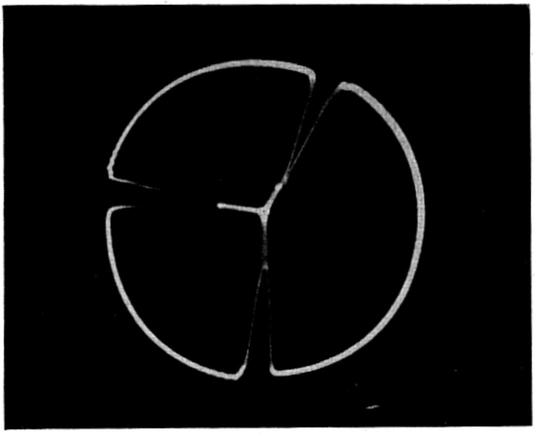


Fig. 7.—Circular trace oscillograph of transmitted signal when 3 out of 30 channels are in operation.

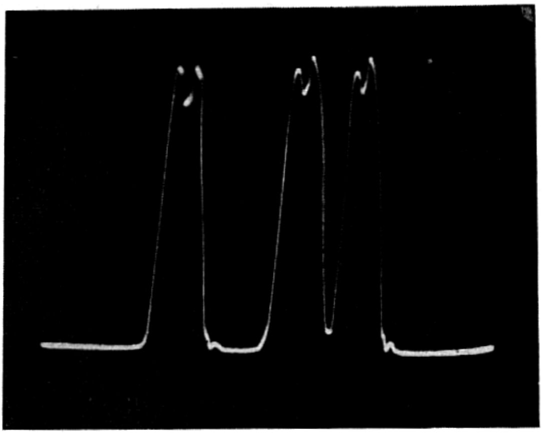


Fig. 8.—Linear trace oscillograph showing transmitted signal with 3 channels in operation 2 of which are adjacent.

suppressors in the manner described above and in the receiver by means of a combination of d-c. and two-phase a-c. potentials applied to the individual anodes. The potential of an anode was zero when the unwanted beam arrived and at or near 200 volts at the time of passage of the operating beam. The rotational frequency of the beam was sixty cycles and since both stators were tied into the same source of power, no separate synchronizing means was necessary.

Figure 7 is a photograph of the cathode ray trace of the output of the transmitter tube when signals were being sent over three channels. A circular sweep circuit was used which distorted the signals somewhat. The shape of the pulses is shown better in Fig. 8 for which a linear sweep was employed. Signals were put on three channels, two of which were adjacent. The double-humped top of the pulse is caused by the window in the screen being slightly narrower than the beam width so that as the beam crosses the window, the greater densities in the edges relative to the center give this shape. A flat-topped pulse may be obtained by making the windows wider than the beam.

In conclusion the writer wishes to acknowledge his indebtedness to a number of his colleagues in the Laboratories for aid in the development of the tube. The 30-channel multiplex system was set up with the aid of Mr. W. H. T. Holden.