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The Cathode Ray Oscillograph *

By J. B. JOHNSON

The cathode ray oscillograph, since its invention by Braun, has developed along three lines. The major types of tubes are the high voltage tubes with a fluorescent screen, the high voltage tubes with internal photographic equipment, and the low voltage tubes. This paper follows the structural development of commercial tubes. The operation of the tubes is discussed, from the standpoint of both theory and practice, with particular reference to the low voltage type of tube. Numerous examples are given of the applications of the tubes to problems in science and engineering.

IN our complicated life, we find that we need a great many aids to our primary sense organs. The processes of the modern world demand that we make correct estimates of things that are too large or too small, too intense or too feeble, for our poor senses. We have balances to give us the weight of masses too heavy for us to lift or too small to be felt. Telescopes enable us to see far-off objects, microscopes very small objects. Our ears are supplemented by telephones that put us within earshot of almost all the civilized world. For electric currents we have ammeters to measure currents so large as to destroy us in a second, and galvanometers that measure currents far too small for us to feel as a shock. Taste and smell have not yet been supplied with artificial aids, but that may come some day.

For recording long times we have clocks and calendars; for making a record of happenings that take place in a time too short for us to think of, we use oscillographs.

There are a number of different types of oscillographs in use, all of them electrical in nature. The kind I am going to discuss involves a stream of cathode rays and it is therefore called the cathode ray oscillograph. The principle of its operation is quite simple. We have two electrodes in an elongated, evacuated glass tube as in Fig. 1; one of them may be a heated filament, the other a plate with a small hole in it. When a potential is applied between the electrodes, making the filament cathode and the plate anode, the electrons emitted by the hot filament are drawn to the anode. Some of them pass through the fine hole in the anode and continue as a thin pencil of electrons, a cathode

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* Presented at Franklin Inst. mtg., Dec. 4, 1930. *Jour. Franklin Inst.*, December, 1931.

ray, down the length of the tube. At the end of the tube is a screen of fluorescent materials, which shines brightly at the point where the ray strikes it. We can therefore see where the ray ends on the screen. Another pair of electrodes in the form of two plates P and P_1 is introduced so that the cathode ray passes between them (Fig. 2). Now, by a battery or otherwise, we apply a voltage between the plates, so that one is positive with respect to the other. The electrons of the ray, being negative charges, are during their passage between the plates drawn toward the positive plate and emerge in a different direction because of the applied voltage. Similarly, a magnetic field applied by the magnet N-S, across the path of the ray and in the plane of the paper, as in Fig. 3, makes the ray emerge in a direction out from the page. The amount of the deflection is a measure of the strength of the applied magnetic or electric field. We have, then, in this cathode ray a pointer which tells the magnitude of the field that deflects it. It is, furthermore, a pointer that is almost without mass and sluggishness; it is almost not a material pointer. It can therefore follow variations in the applied field that are very rapid, as we shall see presently. Because of this property the instrument has been used extensively for studying the electrical phenomena of such a range of subjects as power machinery, telephone apparatus, radio transmission and electric surges.

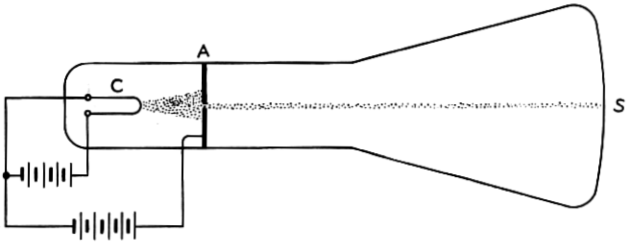

Fig. 1—Schematic of cathode ray tube.

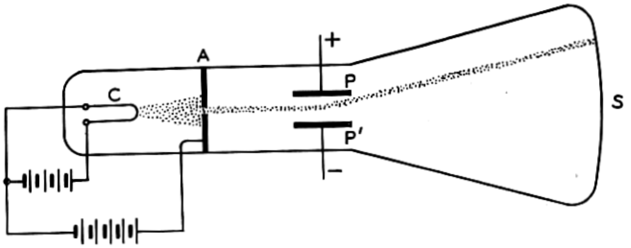

Fig. 2—Tube with electrostatic deflection.

One of the more dramatic recent applications has been the investigation of lightning, probably the most important work on lightning since its electrical nature was discovered by Benjamin Franklin one hundred eighty years ago.

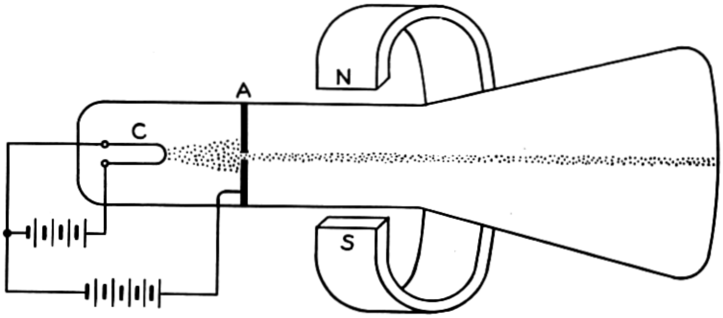

Fig. 3—Tube with magnetic deflection.

Let us examine the operation of the tube more closely. The speed of the electrons as they emerge from the aperture in the anode can be determined from the energy equation,

$$\tfrac{1}{2}mv^2 = eV,$$

the energy of motion equaling the total work done on the electron by the field between cathode and anode. V is the potential between cathode and anode, e the electric charge constituting the electron, m its mass and v its speed. Solving for the speed we have the relation between the speed and the driving voltage,

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

The value of e/m is known to be 1.77×10^7 e.m.u., the volt is 10^8 e.m.u. and the velocity of the electrons is thus

$$v = 5.95 \times 10^7\sqrt{V}\text{ cm./sec.}$$

If the driving potential is 300 volts, then the speed of the electrons is given as roughly 1×10^9 cm./sec. or 6000 miles per second. For a tube 20 cm. long an electron travels from the deflector plates to the screen in $20/10^9 = 1/50{,}000{,}000$ sec. If the applied voltage is 30,000 volts the speed is very nearly ten times as great as with 300 volts; it is ⅓ the velocity of light. A change of direction of the ray induced at the deflector plates is therefore transmitted to the end of the ray in a very short time, and the ray can follow faithfully potential variations at the plates that are very rapid.

Let us see how the ray responds to voltage applied to the plates. The ray normally travels with a speed v along the tube. Referring to Fig. 4, the ray now passes between two plates of length l and separation d, between which a potential difference V' is maintained. While the ray is passing between the plates the electrons are subject to an acceleration,

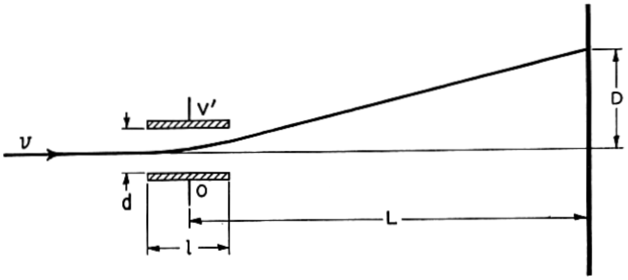

Fig. 4—Electrostatic deflection.

$$a = \frac{e}{m} E = \frac{e}{m} \frac{V'}{d}.$$

This continues during the time $t = l/v$. The transverse velocity acquired is therefore

$$v' = at = \frac{e}{m} \frac{V'}{d} \frac{l}{v}.$$

The ray then travels on in a straight line to the screen which it meets at a distance D from the normal position. The deflection D bears the same relation to the length of the beam, from the center of the deflecting plates, as the transverse velocity bears to the longitudinal.

$$\frac{D}{L} = \frac{v'}{v} = \frac{e}{m} \frac{V'}{d} \frac{l}{2\frac{e}{m} V} = \tfrac{1}{2} \frac{l}{d} \frac{V'}{V},$$

$$D = \tfrac{1}{2} \frac{lL}{d} \frac{V'}{V}.$$

This brings out an interesting point in connection with the design of the deflector plates. For high sensitivity the plates should be long and close together but the plates must not cut the path of the deflected ray. If we want to get a certain maximum deflection D with a tube of a certain length L, then the relation of spacing to length of the plates must be

$$\frac{d}{l}=\frac{D}{L},$$

as can easily be seen from Fig. 4. When this condition is satisfied it makes little difference in the sensitivity whether the plates are large and far apart or small and close together.

The magnetic sensitivity of the tube is more uncertain only because the boundaries of the magnetic field are usually less well defined than those of the electric field. One form of the derivation will be given here. If the ray generated by the driving voltage V passes for a distance l (Fig. 5) through a region in which there is a transverse magnetic field of strength H, the path of the beam is an arc of a circle whose radius is

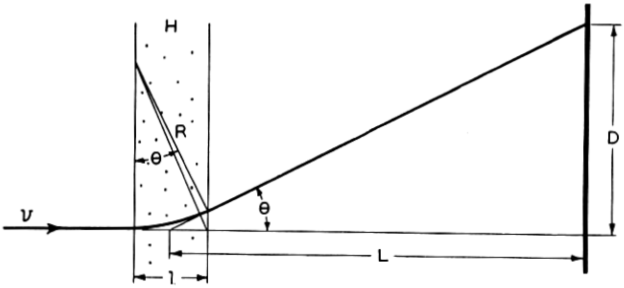

Fig. 5—Magnetic deflection.

$$R=\frac{mv}{eH}=\frac{1}{H}\sqrt{\frac{2mV}{e}}.$$

When the ray leaves the magnetic region it proceeds in a straight line to the screen, where the total deflection from the normal is D. If the angular deflection θ is not great then we have, very nearly,

$$\tan\theta=\frac{D}{L}\doteq\frac{l}{R}=lH\sqrt{\frac{e}{2mV}}$$

and hence

$$D\doteq lLH\sqrt{\frac{e}{2mV}}.$$

In practical units instead of electromagnetic the expression becomes

$$D\doteq .3lLH/\sqrt{V}.$$

Having now described in an elementary way how the cathode ray oscillograph works, let me turn to the story of the development of the tube.[1] The first reference I have seen to the idea that a cathode ray might be used to indicate magnetic field dates to 1894, when Hess,[2] in France, suggested the use of such a tube as a curve tracer. The first application of the idea, however, was made by Ferdinand Braun [3] in 1897, and after him the instruments have been called Braun tubes.

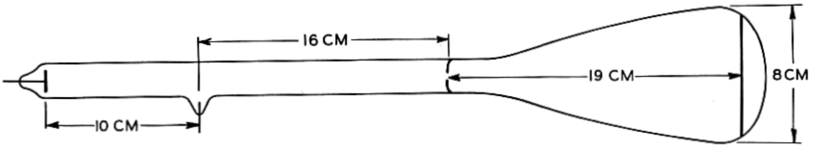

Fig. 6—The first cathode ray oscillograph, F. Braun, 1897.

The tube of Braun was quite simple (Fig. 6). It had a flat disc cathode, a wire in a side tube as anode, a pierced diaphragm to limit the beam and a fluorescent screen of zinc sulphide. It contained air at low pressure. Current from an electrostatic machine produced a discharge in the residual gas in the tube, from which emanated the cathode rays through the aperture in the diaphragm.

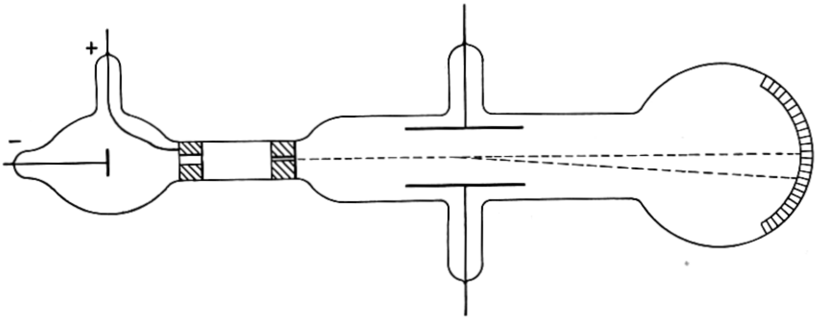

Fig. 7—Tube for measuring *e/m*, J. J. Thomson, 1897.

It is of interest that the invention of the tube took place before the nature of cathode rays was understood. It was in the same year that J. J. Thomson in England and W. Kauffmann in Germany, each using a tube that was almost identical with the Braun tube, deter-

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[1] More detailed chronicles of the development of the tube have been made by H. Hausrath, "Apparatus and Technique for Producing and Recording Curves of Alternating Currents and Electrical Oscillations," *Helios*, 1912; and by MacGregor-Morris and Mines, "Measurements in Electrical Engineering by Means of Cathode Rays," *Jl. Inst. El. Eng.*, **63**, p. 1056, 1925.

[2] Hess, A., *Compt. Rend.*, **119**, p. 57, 1894.

[3] Braun, Ferdinand, *Wied. Ann.*, **60**, p. 552, 1897.

mined that cathode rays have mass as well as charge. Thomson's tube [4] is shown in Fig. 7.

The Braun tube immediately found many applications. One of the most fruitful fields for it was its use by Professor Zenneck in studying radio circuits and the transmission of radio waves. From Professor Zenneck and his school there are still papers coming out on work done by means of the Braun tube. The tube was introduced in this country very early. Professor H. J. Ryan, then at Cornell, in 1903 described measurements on high voltage power circuits, and similar work has appeared occasionally ever since from Professor Ryan's hand.

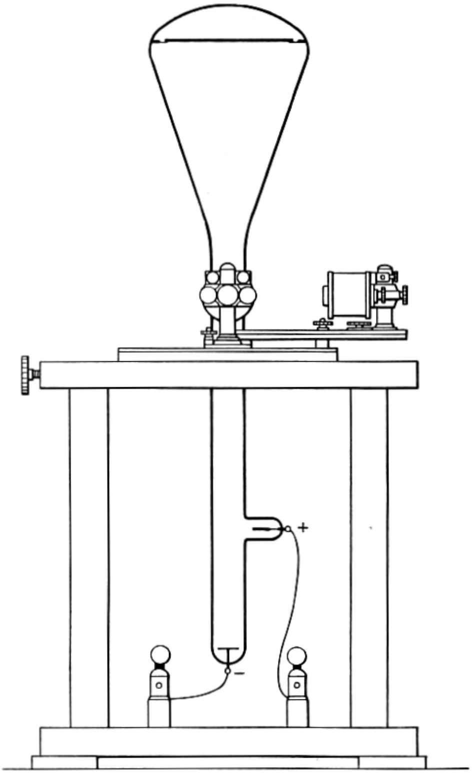

Fig. 8—Ebert and Hoffmann, 1898—tube by Geissler.[5]

After the invention of the tube there were a number of improvements that made it more convenient and its operation more reliable. Figures 8–12 show some of the many designs of tubes of this time.

[4] Thomson, J. J., *Phil. Mag.*, **44**, p. 293, 1897.
[5] Ebert and Hoffmann, *E. T. Z.*, **19**, p. 405, 1898.

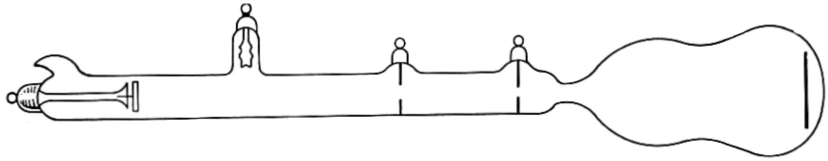

Fig. 9—MacGregor-Morris, 1902—tube by Cossor.[6]

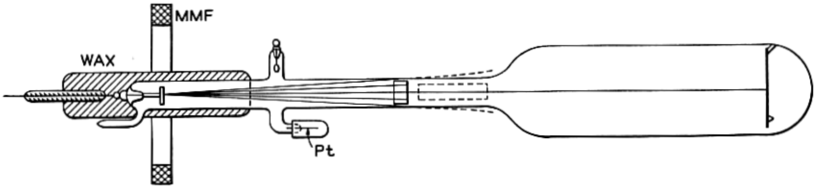

Fig. 10—Ryan, 1903—tube by Muller-Uri.[7]

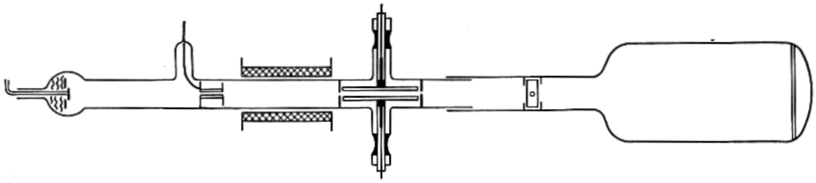

Fig. 11—Roschansky, 1911.[8]

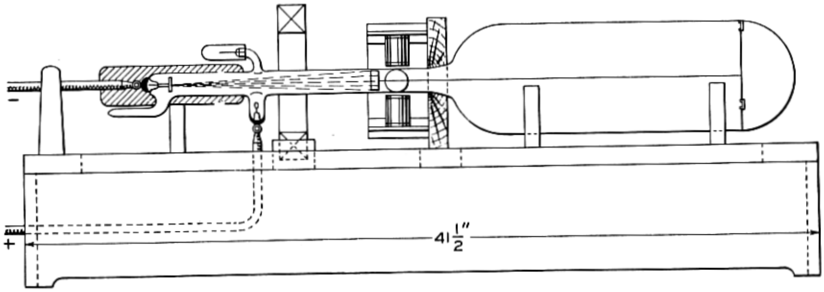

Fig. 12—Broughton, 1913—tube by Max Kohl.[9]

[6] MacGregor-Morris, *Engineering*, 1902, **73**, p. 754.
[7] Ryan, H. J., *Am. Inst. El. Eng., Trans.*, **22**, p. 539, 1903.
[8] Roschansky, D., *Ann. d. Phys.*, **36**, p. 281, 1911.
[9] Broughton, H. H., *Electrician*, **72**, p. 171, 1913.

In 1905 Wehnelt [10] suggested the use of a hot, lime coated filament, which he had found a couple of years earlier to be a strong emitter of electrons and which was the basis of the present day oxide coated filaments in vacuum tubes. Wehnelt made up such a tube (Fig. 13) which he could operate on the 220 volt power circuit. This was probably the first practical application of the oxide coated filament. A number of experimental tubes were made up with hot filaments in the years following, but almost twenty years were to elapse before a really successful tube with hot cathode and low voltage was developed. This was the Western Electric 224 tube,[11] to be discussed in greater detail presently.

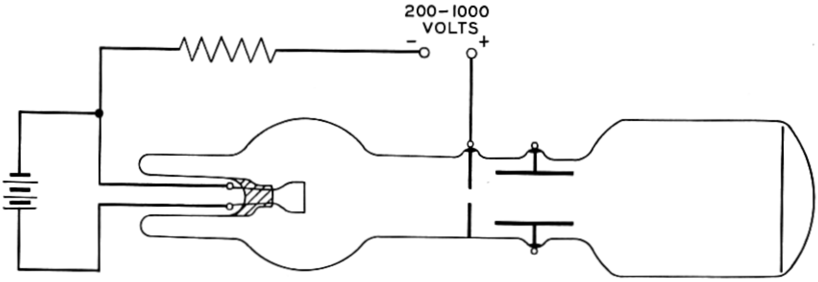

Fig. 13—Wehnelt, 1905.

Another tube of this type, by von Ardenne and Hartel,[12] is illustrated in Fig. 14.

After Braun and Wehnelt, the most notable change in structure was made by A. Dufour [13] in France in 1914. Up to that time permanent records of the pattern on the fluorescent screen were made by means of a camera. This usually meant that the pattern for a rapid phenomenon had to be repeated many times before the photographic plate was exposed enough. Dufour omitted the fluorescent screen and instead placed the photographic plate inside the tube so that the cathode ray could play directly on it. When the cathode rays strike the photographic emulsion directly a record can be traced in a much shorter time than when the intermediary light from a fluorescent screen is focused by a lens on the photographic plate. Placing the photographic plates internally of course involved a number of complications, such as mechanism for moving the plates inside the evacuated tube, means for inserting and taking out the plates, and pumps for producing and maintaining the vacuum. The old glass structure

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[10] Wehnelt, A., *Phys. Zeit.*, **6**, p. 732, 1905.
[11] Johnson, J. B., *Jl. Am. Opt. Soc. & R. S. I.*, **6**, p. 701, 1922.
[12] Hartel, H. von, *Zeit. f. Hochfr. Techn.*, **34**, p. 227, 1929.
[13] Dufour, A., *Compte Rend.*, **158**, p. 1339, 1914.

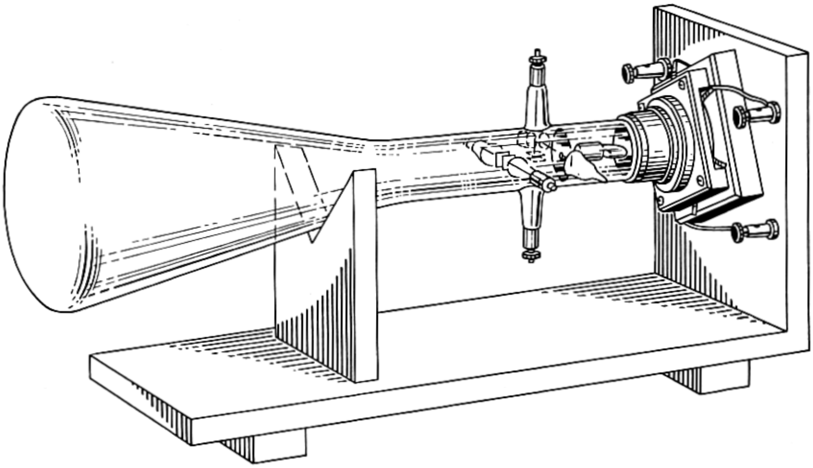

Fig. 14—von Ardenne-Hartel, 1930—tube by Leybold's Nachfolger.

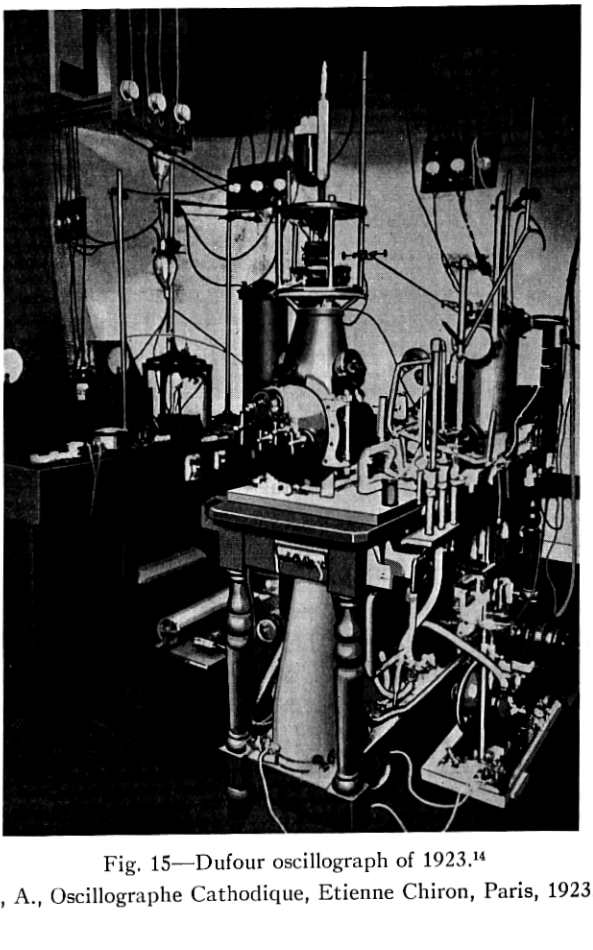

Fig. 15—Dufour oscillograph of 1923.[14]

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[14] Dufour, A., Oscillographe Cathodique, Etienne Chiron, Paris, 1923.

is largely abandoned in these tubes, and metal is substituted. The applied voltage is very high, of the order of 50,000 volts. This makes a rather formidable piece of apparatus (Fig. 15), but quite a useful one.

In the last few years several different tubes of this type have been developed. Aside from Dufour's tube, there are those of Rogowski in Germany, Wood in England, Berger in Switzerland, Norinder in Sweden, The Westinghouse Co. and the General Electric Co. in this country (Figs. 16–18, 21). All of them involve complicated tubes and control circuits. Some tubes are made to operate during a single peak of a 60 cycle wave. With others there are ingenious switching devices that start the tube operating at the very beginning of the electrical impulse to be studied, and the tube then proceeds to record the rest of the impulse. When we consider that the impulse may be a stroke of lightning on a transmission line, we realize that there are some things that are "faster than greased lightning."

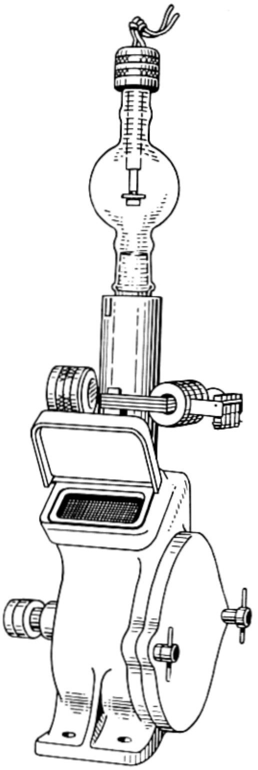

Fig. 16—Wood, 1923.[15]

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[15] Wood, A. B., *Phys. Soc. Lond. Proc.*, **35–2**, p. 109, 1923.

In the last couple of years a further step has been made by Max Knoll.[16] He seems to have simplified the operation of the tube considerably by attaching on the end of his tube a thin window in the manner of Dr. Coolidge's cathode ray tube. In this way the photographic plate on the outside of the tube is exposed to the pencil of cathode rays that has come through the thin window of metal or of cellophane.

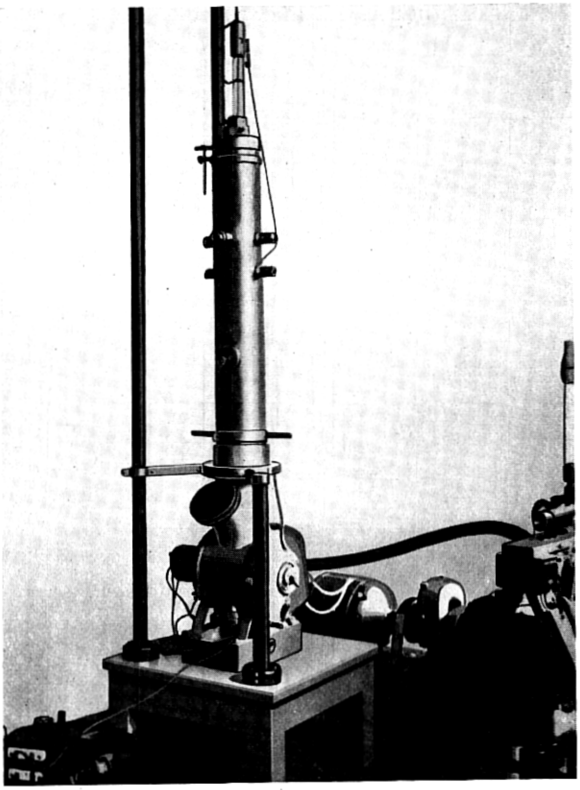

Fig. 17—Westinghouse-Norinder, 1928.[17]

We have, then, three general classes of cathode ray oscillographs: First those that resemble the original Braun tube, still in limited use, comprising a glass tube with a fluorescent screen, and a relatively high operating voltage; second the tubes of the Dufour type that I have just described, with direct recording on the photographic plate or

[16] Knoll, Max, *Zeits. f. tech. Phys.*, **10**, p. 28, 1929.
[17] Norinder, H., *A. I. E. E. Trans.*, **47**, p. 446, 1928.

film; and third, tubes with a hot cathode, with a relatively low operating voltage.

Of this last type is the Western Electric No. 224 Cathode Ray Oscillograph. Since this is the tube with which I have had more direct contact I wish to discuss some problems of its development and operation.

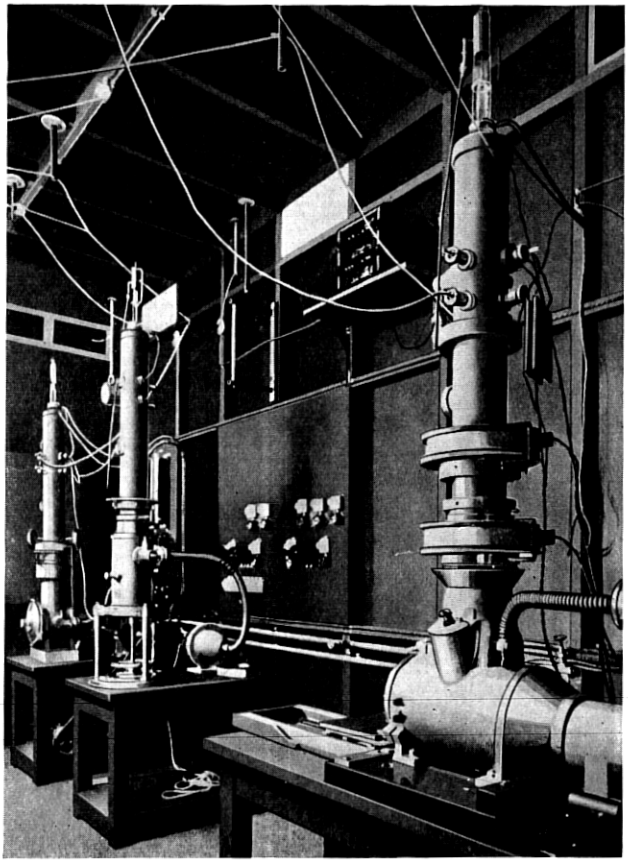

Fig. 18—Norinder, 1930—group of oscillographs.[18]

The design of the tube shown in Fig. 19 is now fairly familiar,* and

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[18] Norinder, H., *Zeits. f. Phys.*, **63**, p. 672, 1930.

* Since the paper was read the tube has been altered in certain respects. The glass enclosure for the filament has been replaced by one of metal, and the anode and deflector plates are supported on machined insulating blocks. These changes make the structure more rugged and insure more nearly perfect alignment of the parts. The end of the bulb has been changed so as to present a cylindrical surface instead of a spherical one, thus permitting more intimate contact between the fluorescent screen and a photographic film when contact photographs are made.

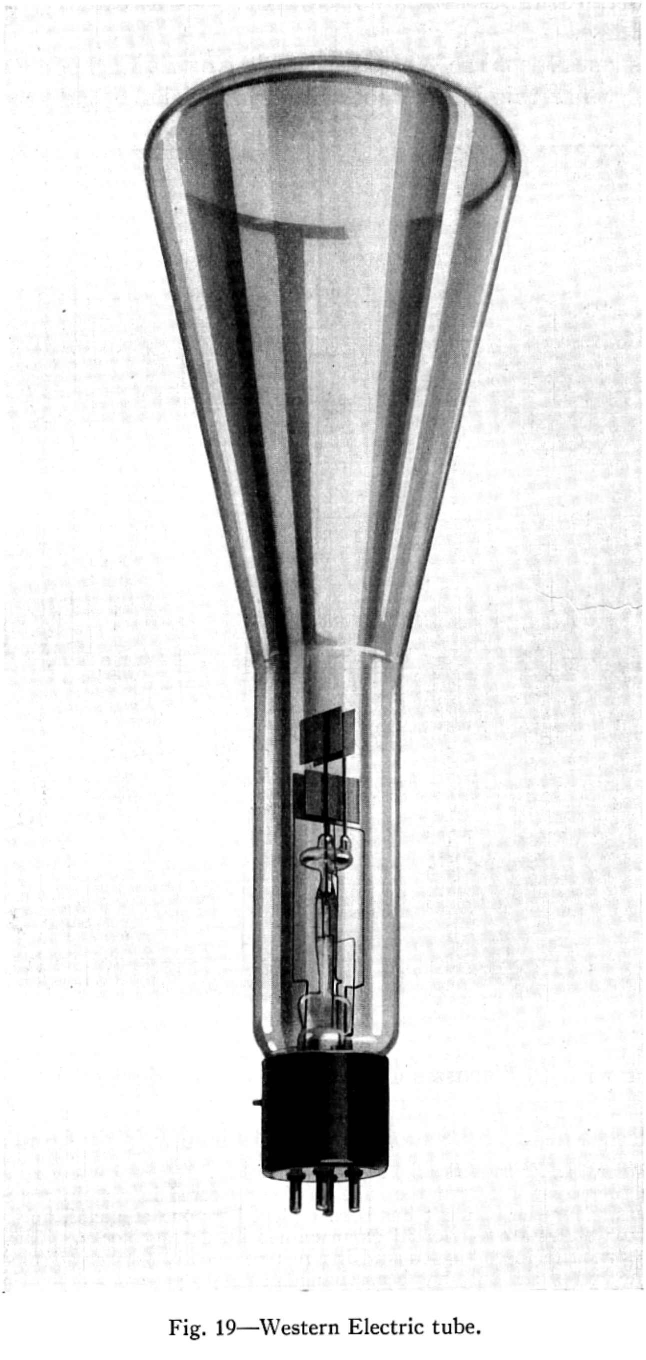

Fig. 19—Western Electric tube.

I shall describe it only as I describe the reason for the various features.

First we wanted a convenient tube to operate on the batteries of an ordinary vacuum tube. The thermionic filament cathode was therefore required. The anode is a metal tube placed a short distance from the cathode and between them is a metal disc with a perforation through which the electrons pass to the anode. These electrodes are represented respectively by the letters *C*, *A* and *D* in Fig. 20.

The electrons flow from the cathode to the inside of the anode and some of them pass through and form the electron beam. Now, for reasons to be mentioned presently, there is some gas in the tube and this puts two requirements on the structure of the electron gun. First, the gas would permit considerable ionization in the tube if the electrons were permitted to pass into it. Most of the current would go around the disc and to the outside of the anode. The cathode and anode are therefore enclosed in a small tube, having dimensions less than the mean free path of electrons in the gas so that no appreciable ionization can build up. There is some ionization, however, in the space between the cathode and anode, and the positive ions produced tend to bombard the filament. If the filament is directly exposed to this bombardment the oxide coating is worn off, as in a sand blast, in a matter of two or three hours. The filament is therefore wound in the shape of a helix which is mounted coaxially with the anode and the perforation in the disc so as to be out of the direct path of the ions. In this way the filament is made to last several hundred hours of operation.

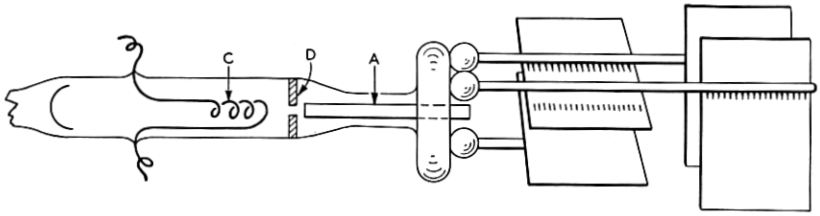

Fig. 20—Diagram of electron gun.

This completes the internal parts of the electron gun. Externally it has mounted on it two pairs of deflector plates that control the direction of the electrons after they leave the gun. In order to prevent any large difference of potential between the anode and deflector plates, one plate of each pair is connected directly to the anode, and only the other plate has the variable potential impressed on it. As for size and separation, the plates are designed to give maximum sensitivity for a given full deflection. The sensitivity is about 1 mm.

deflection for each volt applied to the deflector plates, or 1 mm. for each ampere turn in a pair of small coils placed outside of the tube. These figures are for the normal driving potential of 300 volts.

The flattened end of the bulb, on which the electron beam impinges, is covered with a fluorescent material. The powder is a mixture of zinc orthosilicate and calcium tungstate, both specially prepared for fluorescence. The zinc silicate produces a green light of high visibility and the tungstate a blue light of high photographic activity, so that with the mixture the same tubes can be used efficiently for both visual and photographic observations.

As said before, there is some gas in the tube. One purpose of the gas is to produce a small amount of ionization in the tube which prevents any unduly large charges from accumulating on the glass walls and screen. Electrons deposited on the glass are neutralized by positive ions produced in the gas. An electron current equal to the current in the beam drifts back through the gas to the anode. The chief result of this drift of electrons is that a negative space charge is formed in the tube which decreases the speed of the electrons before they strike the screen as if the driving potential had been lowered by about 50 volts.

The other and more important purpose of the gas is to bring the electrons of the beam to a sharper focus at the screen. The beam is diffuse for two reasons, first because it is originally divergent, and secondly because of the natural electrostatic repulsion that tends to force the electrons apart. The gas serves to overcome these actions in the following way: As the beam of electrons travels down the length of the tube, some electrons collide with atoms of the gas and separate the atom into an electron and a positive ion. The impact of the electron does little to displace the massive positive ion from the position it temporarily occupies while two electrons are immediately shot out of the path. The result is a column of positive ionization down the length of the beam, with a negative space charge surrounding it. This produces a radial electrostatic field which tends to bend the path of the outer electrons of the beam inward toward the centre. The magnitude of this action depends on the degree of the differential ionization. This, again, is the greater the higher the gas pressure and the greater the current in the beam. The gas pressure must be low enough so that the larger fraction of the electrons reach the screen, and then the current in the beam must be such as to produce the desired focusing action. The heavier the ions the lower can the pressure be. The condition for a focus then involves the kind and pressure of gas, the speed of the electrons, the current in the beam and the length of the tube. In the 224 tube, with argon at the pressure of .01 mm. the focusing occurs at about 20 microamperes in the beam. Less current makes a large unfocused spot; more current produces a focus before the screen is reached, with consequent spreading of the spot again. Hence it is that the spot on the fluorescent screen is focused by adjusting the heating current of the cathode.

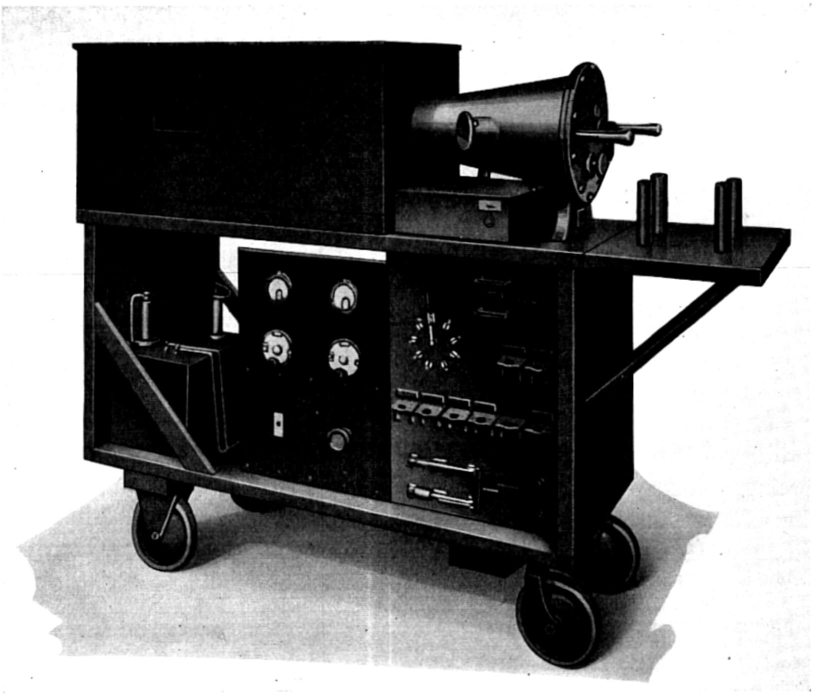

Fig. 21—General Electric, 1928.[19]

Besides focusing the electrons and preventing the accumulation of charges in the tube, the gas plays various other roles. One very curious effect of the gas is that it decreases the sensitivity of the tube at small deflecting voltages. When uniformly varying voltage is applied to a pair of deflector plates so as to move the spot across the screen, the spot seems to hesitate for an instant at the centre of the screen, appearing to be brighter there. The effect has always been observed but particular attention has recently been given to it by Professor Bedell.[20] The explanation has to do with space charge be-

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[19] Lee, E. S., *G. E. Rev.*, **31**, p. 404, 1928.

[20] Bedell, F. & Kuhn, J., *Phys. Rev.* **36**, p. 993, 1930.

tween the deflector plates. The beam of electrons produces slowly moving positive ions and electrons in the gas along its path between the plates. When a voltage is applied to the plates, the positive ions travel from the beam toward the negative plate and an equal number of the electrons travel toward the positive plate. The space charge set up by the electrons and ions produces an electric field opposing that created by the applied voltage. The greatest space charge occurs near the negative plate where the sluggish positive ions flow. The space midway between the plates remains nearly field free and there is little deflection of the beam until the voltage is greater than that at which all of the ions produced are drawn to the plate. Calculation agrees with observation that this voltage is 2 to 3 volts on either side of zero.

Having now described the operation and structure of some of the oscillographs, I should like to say something more about their uses.

The cathode ray oscillograph is essentially a curve tracer that plots out in rectangular coordinates the relation between two quantities represented by the fields between the deflector plates. Often one of these quantities is time, as in the ordinary moving mirror oscillograph, while the other is some electrical quantity. We then say that we plot a wave shape. We must then have a way of making the spot move at a uniform rate. One of the simplest and most reliable ways of producing a linear time axis,[21] at least for low voltage tubes, employs two thermionic tubes to control the charge in a condenser as shown in Fig. 22. One tube, a simple two-electrode tube T_1, limits the charging current of the condenser C so that the voltage across the condenser rises linearly with time according to the equation $V = Cit$. The second tube T_2 is filled with gas and has the property of passing current only when the voltage across it reaches a certain value, which in turn is controlled by the grid potential. When the condenser volt-

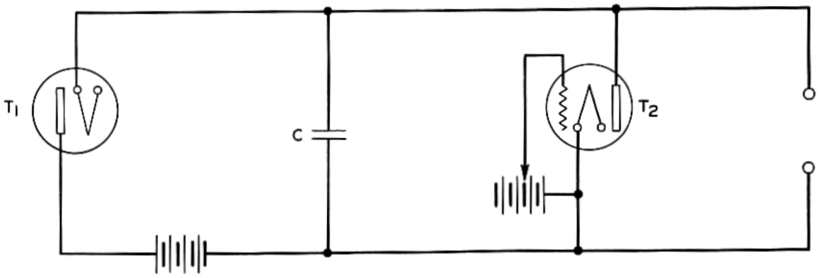

Fig. 22—Thermionic tube "sweep circuit."

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[21] A. L. Samuel, *Rev. Sci. Inst.*, **2**, p. 532, 1931.

age reaches this value the tube operates to discharge the condenser suddenly, and then the uniform charging process begins over again. The condenser voltage applied to one pair of plates of the oscillograph tube makes the spot travel over the screen at a uniform rate in one direction, returning much faster in the other direction. This process may be repeated once a second, or many thousand times a second, depending on the frequency of the wave that is being studied.

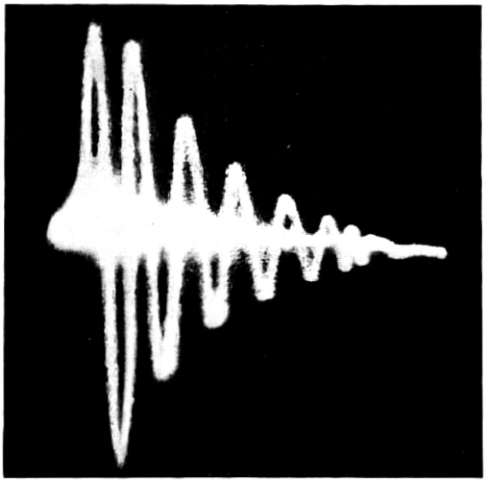

Fig. 23—Discharge of condenser through inductance.

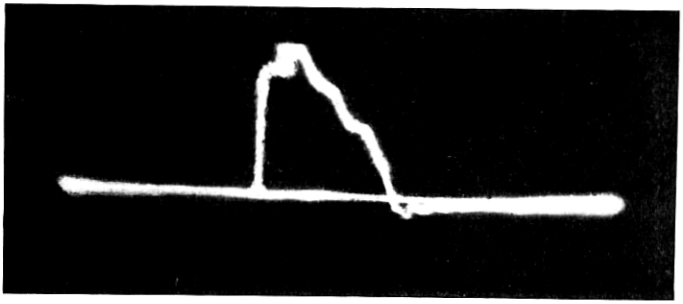

Fig. 24—Discharge of condenser through chattering contact.

In Figs. 23–29 are shown a number of records plotted on a time basis. Figs. 23–25 were made with the Western Electric tube, Figs. 26–27 with the Dufour oscillograph, and Figs. 28–29 on an oscillograph of the type of Rogowski.

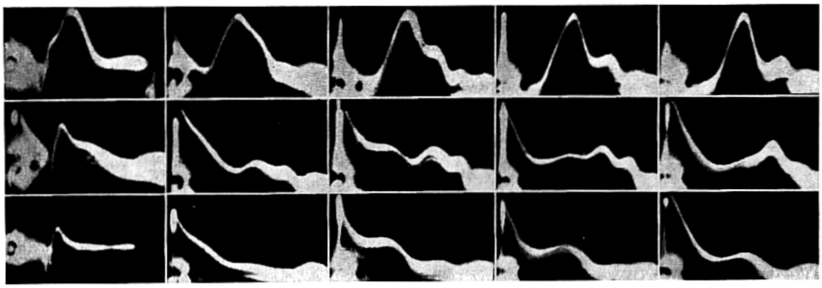

Fig. 25—Action current of a stimulated frog-nerve.[22]

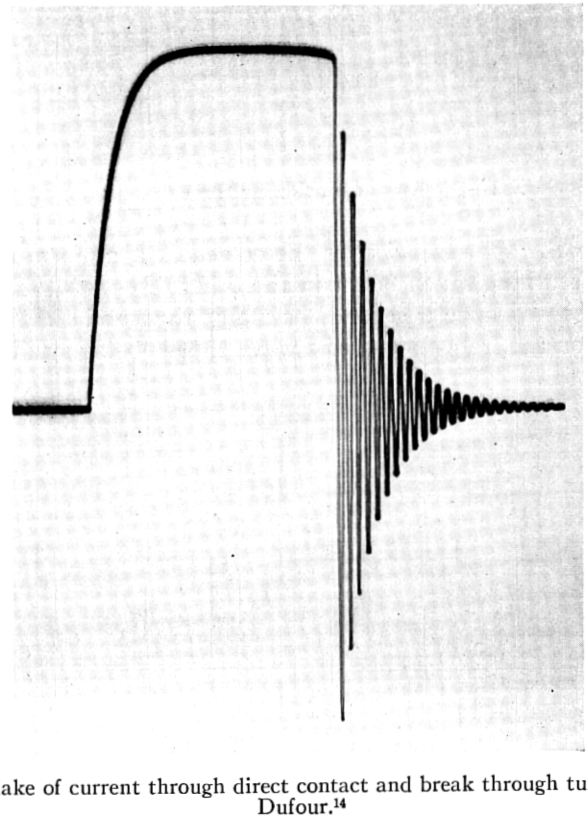

Fig. 26—Make of current through direct contact and break through tuned circuit—Dufour.[14]

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[22] Gasser and Erlanger, *Am. Jl. Physiol.*, **73**, p. 613, 1925.

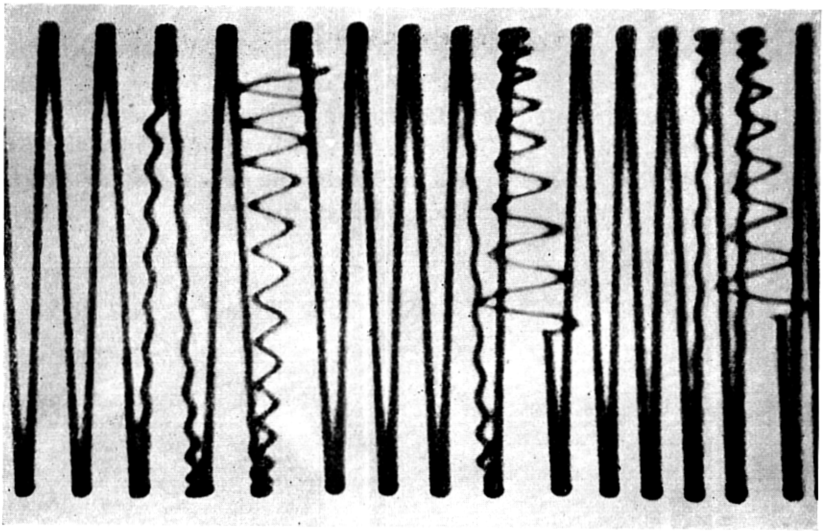

Fig. 27—Wave shape at 8,500,000 cycles—Dufour.[14]

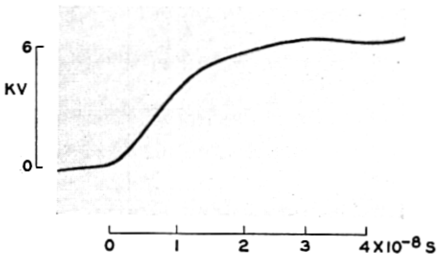

Fig. 28—Front of a voltage wave traveling on a conductor.[23]

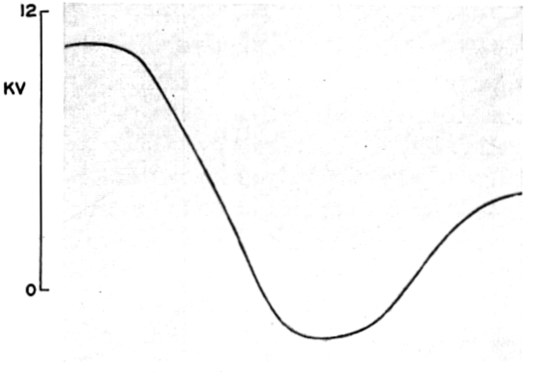

Fig. 29—Initiation of spark in a gas.[24]

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[23] Krug, W., *E. T. Z.*, **51**, p. 605, 1930.
[24] Krug, W., *Zeits. f. techn. Phys.*, **11**, p. 153, 1930.

Another way to use the tube is to have it plot the relation between two quantities irrespective of time. As a simple case we may take the current *vs.* voltage curve of a resistance through which an alternating current is flowing. The spot travels back and forth along a straight line, the slope of which measures the reciprocal of the resistance (Fig. 30a). If inductance is added to the resistance the spot does not come down on the same line it went up; an ellipse results, the spread of which tells us the amount of the inductive impedance (Fig. 30b). This method of operation has a wide variety of applications. Instead of the resistance, for instance, we may have a gas discharge device of which we want to know the properties. One of the applications of this method is the production of hysteresis curves of the ferromagnetic materials [25] (Fig. 31). Fig. 32 illustrates the application of the method to the study of distortion in an amplifier.

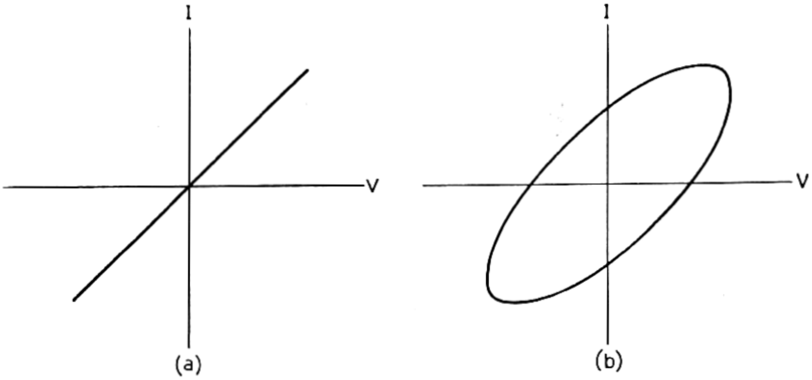

Fig. 30—Diagrams of current voltage curves.

Suppose we apply to each pair of deflector plates a voltage from each of two different oscillators. If the oscillators make exactly the same number of vibrations per second, then the pattern on the tube remains stationary, but if the frequency of the oscillators differ ever so little the pattern goes through gradual changes according to the different phase relations. This is one of the most sensitive means we have for comparing and calibrating accurate oscillators, and we may call it the Lissajous figure method. Fig. 33 shows the appearance of some of these stationary Lissajous patterns.

Another method of comparing the frequency of oscillators has been called the gear-wheel method. In this method the voltage from the low frequency source is split into two equal components 90° apart in

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[25] Johnson, J. B., *Bell System Technical Jl.*, **8**, p. 286, 1929.

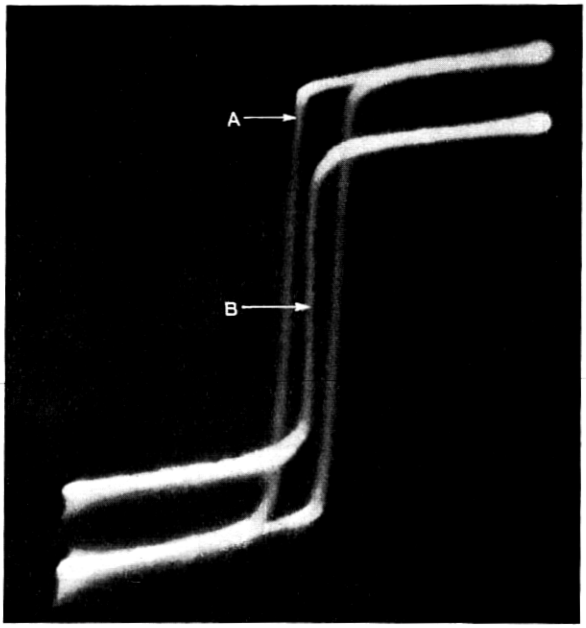

Fig. 31—Hysteresis curves (*a*) of iron, (*b*) of permalloy.

phase. These two voltages are applied to the deflector plates, producing a stationary circle on the screen. The voltage from the oscillator of higher frequency is introduced in the circuit between the cathode and anode of the tube so that the sensitivity of the tube is varied in accordance with the higher frequency. The circle is distorted into a gear-wheel shape as shown in Fig. 34, provided that the

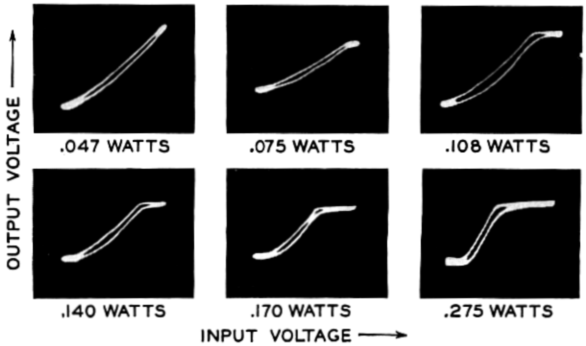

Fig. 32—Distortion in vacuum tube amplifier.[26]

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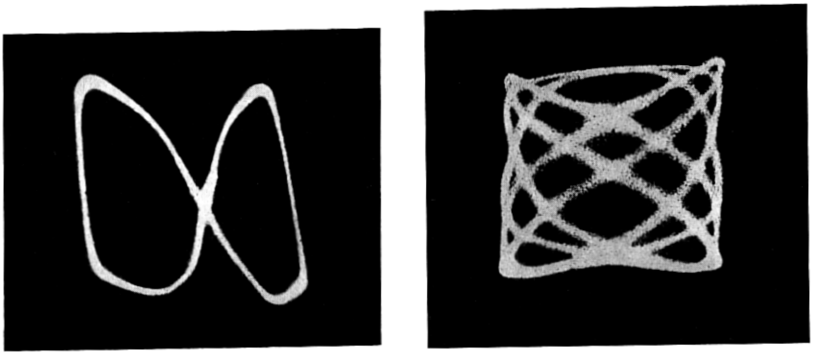
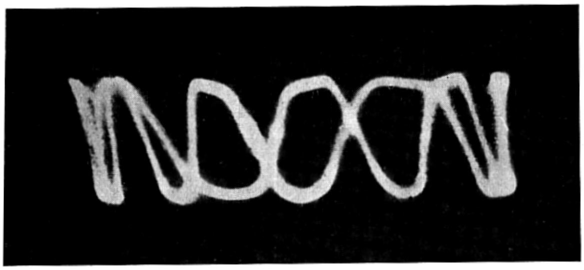
[26] Willis and Melhuish, *Bell System Technical Jl.*, **5**, p. 573, 1926.



(*a*) Ratio 2 : 1.

(*b*) Ratio 5 : 4.



(*c*) Ratio 8 : 1.

Fig. 33—Frequency comparison.

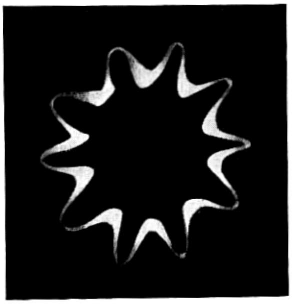


Fig. 34—"Gear wheel" frequency comparison, ratio 10 : 1.

higher frequency is an exact multiple of the lower. If the frequency ratio is not a rational number the gear-wheel rotates, showing the amount of the lack of synchronization.

Two interesting applications to the study of radio telephony are illustrated in Figs. 35 and 36. Fig. 35 shows two characteristics of a transatlantic radio channel, the tube plotting the amplitude of the received signal at a number of modulating frequencies. In Fig. 36 are plotted the magnitude and direction of static crashes as they were shown on the screen of the oscillograph tube.

For demonstration purposes the tube may be used to determine the value of the ratio of charge to mass of the electron, designated by e/m. The classical method is obvious from the derivation of the sensitivity of the tube given above. Especially is this so if we can assume the two fundamental relations $\frac{1}{2}mv^2 = eV$; $mv = eHR$. The method is subject to some error because the extent of the deflecting fields cannot be exactly determined, and because of the space charges in the tube.

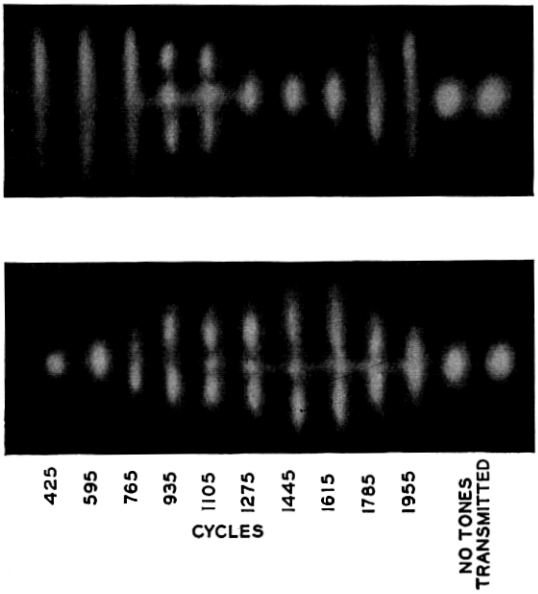


Fig. 35—Transmission characteristic of transatlantic short-wave radio channel.[27]

A more accurate method of arriving at the value of e/m is due to H. Busch.[28] A long solenoid carrying constant current creates a uniform magnetic field in the tube parallel to its axis. The electrons travel in spirals in this field in such a way that when the field has one of a series of values the electrons are focused on the screen. These critical values of the magnetic field are given by the equation

$$H = \frac{2\pi}{L}\sqrt{\frac{2m}{e}}\,V\,;$$

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[27] Potter, R. K., *Inst. Radio Eng.*, **18**, p. 581, 1930.

[28] Busch, H., *Phys. Zeits.*, **23**, p. 438, 1922.

where $n = 1, 2, 3$.—etc., L is the length of the beam and V the driving potential.

In this method there is less disturbance from gas focusing and space charge if the filament current is made as low as will give a still visible spot with the magnetic focusing.

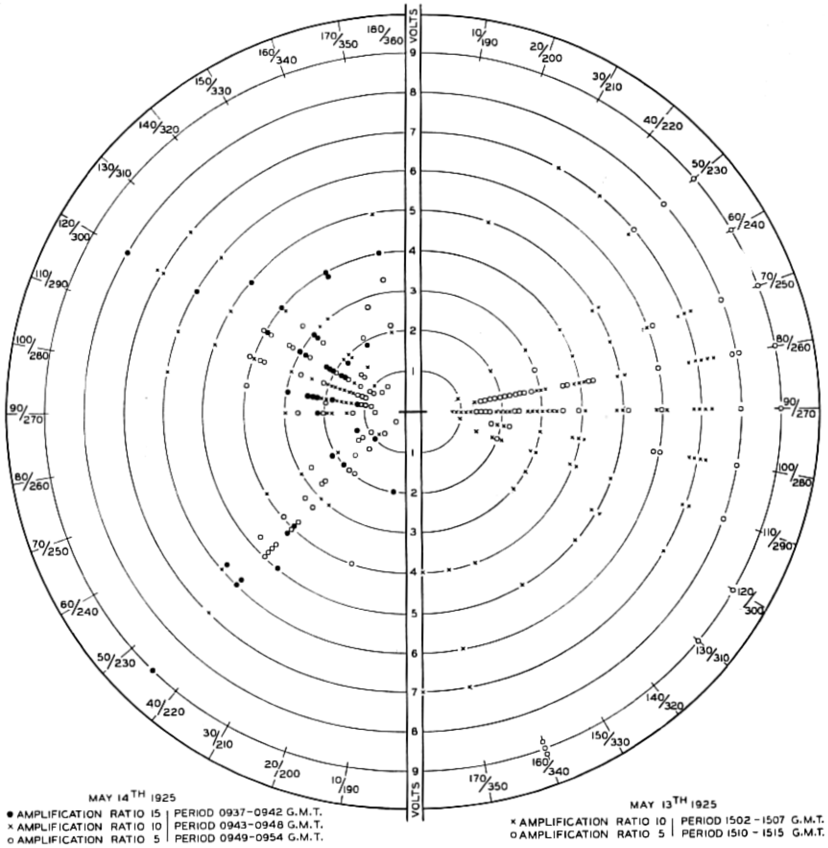

Fig. 36—Azimuthal distribution of atmospherics.[29]

From the beginning the cathode ray oscillograph was recognized as a tool of great promise. Its use was limited, however, by the difficulties of maintaining a constant degree of vacuum and of providing a suitable source of high voltage, as well as by the general bulk and clumsiness of the apparatus. We have seen that in the nearly thirty-five years since the first invention of the tube, many improvements have been made both in the structure of the tube and in the methods

[29] Watson Watt and Herd, *Jl. I. E. E.*, **64**, p. 611, 1926.

of operation so that the handicaps under which the early apparatus was used have been very largely eliminated. The introduction of the low voltage, high sensitivity tube of moderate cost expanded the use of cathode ray oscillographs rapidly, until now they are used in almost every laboratory where high frequency measurements are made. In the Bell System alone more than a hundred of these instruments are in constant use for research and for the control and calibration of manufactured products. Originally an intractable and little used device, the cathode ray oscillograph has become an almost universal scientific and industrial tool.