A LOW-VOLTAGE HIGH SPEED CATHODE-RAY OSCILLOGRAPH

Thesis by

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SUMMARY

This thesis is a description of the development of a compact, continuously pumped, metal cathode-ray oscillograph. The design incorporates several features which it is hoped will prove to be a useful contribution to the subject. In particular, the design and operation of a discharge tube which is both simple and reliable is discussed. The tube operates at about 10,000 volts and the beam is sufficiently intense to permit a recording speed in excess of 10^8 centimeters per second. The principle of "pre-concentration", as suggested by Rogowski, has been utilized and seems to offer some advantage in increasing the efficiency of the discharge tube; in addition, it permits ready visual observation of the cathode surface by adjusting the two magnetic focusing coils to act as an electron microscope. Roll film mounted in the evacuated space is used to record phenomena by a means which seems to overcome some of the inherent difficulties of this method. Two circuits used in conjunction with this tube, one of which having some advantage over the more common types, are briefly discussed. The performance of the apparatus is illustrated by several records.

ACKNOWLEDGMENT

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A LOW-VOLTAGE HIGH SPEED CATHODE-RAY OSCILLOGRAPH

The general subject of high voltage cathode-ray oscillography is well developed and extensively covered in the literature. However, this is not true to the same degree for low voltage instruments capable of relatively high recording speeds, and it seemed to be desirable to extend the development in this field. In particular, it was proposed to construct a tube embodying principles which the author learned while working under Rogowski in Germany and which should operate at approximately 10,000 volts instead of the customary 50,000 to 100,000 volts. Obvious advantages would be increased safety, reliability, and compactness. This thesis will be an account of such a tube.

An important consideration was that conditions made it impossible to have the tube constructed by machinists, and consequently the design had to be within the limits of the author's mechanical ability. Although it was hoped that the tube would be capable of useful work, it was intended to serve primarily as a preliminary research model which could later be expanded into more convenient and useful form. Consequently, the design is not considered final but rather as a basis for further development. Continued use will undoubtedly suggest many improvements and additions.

General Considerations

The sensitivity of a photographic emulsion to a cathode beam is some function of the velocity of the electrons and the total charge deposited at a point. The exact function is not known as it depends in some complex manner upon the characteristics of the emulsion as well as upon those of the beam. However, it is in general true that the beam current and accelerating voltage are inversely related for a given recording speed. Consequently, for a constant speed, it is necessary to increase the beam current as the voltage is reduced. Moreover, computations by Wallraff(1) indicate that the beam must be as narrow as possible in order to reduce aberrations caused by electrostatic deflection; that is, the angle of divergence of the beam with respect to its axis must be limited. Furthermore, the electron-optical relations obtaining between the source and focal point of the beam require that the source be small for sharp definition. We are, then, led to consider the means for producing a relatively great electron current from as nearly a point source as is possible.

The general types of electron source for the purpose utilize either thermionic emission or a gaseous discharge, each of which has certain advantages and disadvantages. Thermionic emission did not seem to be as suitable for this application as a discharge, for a number of reasons. In the first place, since it was proposed to make the tube of metal, it would be necessary in any event to pump it continuously, thus nullifying one of the principal advantages of a thermionic source, - the ability to seal it into a vacuum system. Moreover, a thermionic source requires a rather complicated electrostatic accelerating and focusing device somewhat similar to those found in small glass tubes which would involve a complex method of nice voltage control at fairly high potentials. Finally, there is great, in fact hitherto insurmountable, difficulty, in obtaining high enough beam current from a small enough area. On the other hand, the alternative has a number of real advantages. Undoubtedly the most intense source of electrons is that from a hole drilled in the anode of a properly designed discharge tube. The emission at this point is limited largely by the construction of the tube and may become many times greater than that for the most intense simple thermionic emission. As it was proposed to operate at relatively low voltage, it was believed to be possible to reduce the dimensions of the normal discharge tube and correspondingly to increase the gas pressure within it, which should render the tube nearly insensitive to "bursts" of gas and slight irregularities in control. Thus it was hoped that the ease of control and reliability of a thermionic source could be equalled by a discharge tube.

These considerations, therefore, led to the choice of a cold cathode discharge tube as a source of the beam as opposed to a thermionic source.

Since the gas pressure within the discharge chamber must be relatively high while that in the body of the oscillograph must be as low as is possible, there is a continual leakage of gas from one to the other. This necessitates two further considerations: first, there must be some means for replenishing the gas (air) removed from the high pressure region; and, second, there must be sufficient pumping capacity to remove the gas from the low pressure region without permitting flash-over between the deflecting plates. The former requirement is satisfied by providing an adjustable leak to allow air to enter the discharge tube as fast as it is removed. The latter requirement becomes less stringent because of the necessity for a small anode hole (source) through which the gas diffuses.

The necessity for high beam current has two consequences which are especially important in this type of tube: one is that the decrease in beam current caused by the crater formed at the cathode spot requires frequent renewal of the cathode; the other is that the principle of "pre-concentration" first proposed by Rogowski(2) be used. Consequently, the cathode should be simple and easy to replace, and a "pre-concentration" coil must be provided to focus a beam of electrons from the cathode spot upon the anode hole. It seemed reasonable by careful design to fulfill the requirements outlined above, and it was hoped that the discharge tube would prove to be as reliable as a thermionic source within the limitations imposed by the two different principles of operation. It is believed that this hope has been realized in a satisfactory manner.

In many applications the oscillograph must be capable of recording phenomena at any arbitrary instant beyond the control of the operator. This means that there may be long periods during which the oscillograph is ready to function though no record is made.

Consequently if the discharge tube is to run continuously, some means for blocking the beam at will must be provided. One satisfactory method of accomplishing this is to use an electrostatic field to deflect the beam away from the axis of the tube and to the side of a metal diaphragm. A hole is drilled in the diaphragm at the axis of the tube to allow the beam to pass through when the deflecting field is removed. Several, generally at least two, such blocking sets are provided in order to block the beam completely. The control circuit is then so arranged that a deflecting field is applied at all times except during the instant when the beam is being swept across the film. Circuits to accomplish this are discussed in a later part of this thesis.

Some means for focusing the beam is necessary in order to record a fine trace. The so-called "magnetic lens" is frequently used for this purpose because it forms an image relatively free from aberrations, it can be located entirely outside the evacuated space, and it requires only a low voltage easily controllable direct current.

Two mutually perpendicular sets of deflection plates must be provided in order to deflect the beam parallel to two perpendicular axes on the film. Some means must be provided to alter the voltage sensitivity (deflection / deflection voltage) in order to cope with different types of problems. Also in order to permit high recording speeds the leads to all deflecting plates must have the lowest possible inductance and capacitance. This necessitates a simple lead-in design having straight, short conductors with wide clearances and little dielectric material between the lead-in and the body of the tube.

In order to make a record, it is necessary to allow the beam to act upon a photographic film. The methods which have been proposed may be grouped into two classes: those in which the film is outside the vacuum and is acted upon from within through some kind of window; and those in which the film is introduced into the vacuum. The former have the advantage of ease of operation as they do not require that the vacuum system be opened at frequent intervals. However, they have several important disadvantages among which are: the great difficulty of preparing and maintaining vacuum-tight windows which are sufficiently transparent either to electrons or to light, the loss in energy because of absorption in the window, and the loss of sharpness because of diffusion of either light or electrons. The latter objections become very important in low voltage tubes. It seemed probably that the increased efficiency and "cleanness" of internal recording would amply compensate for the disadvantage of opening the vacuum system at the end of each roll of film, if a reliable, tight joint could be made, and if the film could be easily operated.

Finally, an easily constructed body was desired which could readily be maintained vacuum tight. This made it desirable to use standard sizes of brass tubing having simple turned ends. Removable joints were to be avoided wherever possible and all permanent joints were to be soldered; and in the interest of mechanical strength, no butt joints were to be used where stress could occur.

In brief, these considerations led to the development of a low voltage cathode-ray oscillograph which it was hoped would prove to be a useful addition to the research equipment of this Institute, and represent a further development of an already highly developed instrument. A description of the solution of the above indicated problems of design and some records obtained with this tube will occupy the rest of this thesis. A cross-section of the tube is shown in Figure.1.

The Discharge Tube

The first question in designing the discharge tube was to determine the operating voltage. It seemed reasonable that if the electron beam were to impinge directly upon the film, it should have sufficient energy to penetrate at least to the bottom of the emulsion. Wood[3] has stated that about 10,000 volts is the minimum accelerating voltage to satisfy this condition. Previous experiments by Rogowski, Westermann and Malsch[4] at even lower potentials demonstrated that this voltage would be effective. Von Borries[5] has made measurements of the density of the trace as a function of accelerating voltage and charge deposited which show that although

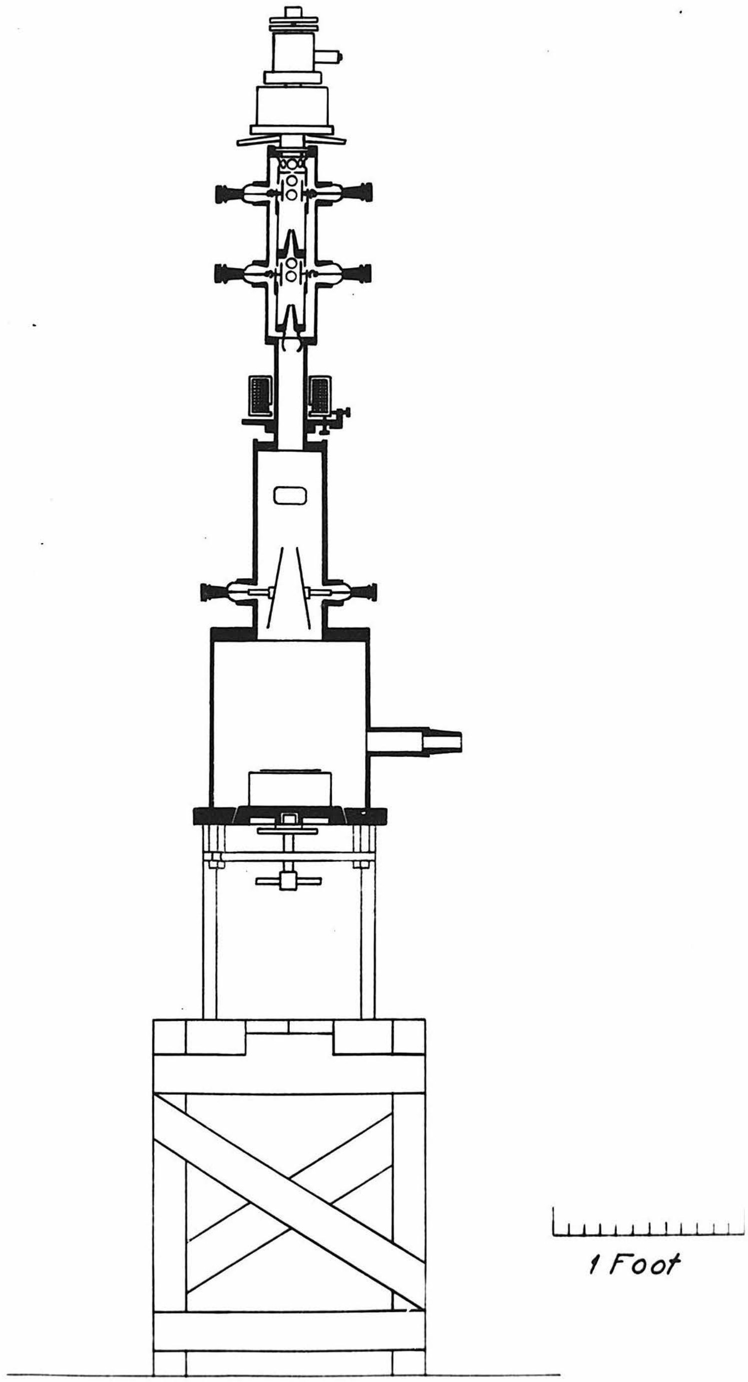


Figure 1
Cross-section of Tube

the sensitivity of the film decreased slowly with decreasing voltage, it is still satisfactory at 20,000 volts. This indicated that satisfactory operation would be likely at voltages of about 10,000 and, probably, that there would be little advantage in further decreasing it.

The metal tube for high voltage work described by Dodds(6), which seemed to be particularly rugged and efficient, was chosen as a model. The dimensions given by him for a tube which would operate satisfactorily at 25,000 volts (8 mm. cathode diameter, 10 mm. anode diameter) were reduced very approximately in the ratio of 10,000 to 25,000 to .118 inch (3 mm.) and 0.20 inch (5 mm.), respectively. Later, because of a tendency to spark over inside, the diameter of the anode tube was increased to 0.25 inch. Dodd's results indicated that the longest length of the discharge should amount to one inch or less. Malsch(7) has worked out the most efficient means for utilizing pre-concentration and it follows that a reduced image of the relatively large cathode spot upon the anode hole is desirable. From this and the dimensions of the discharge tube, it appears that the focal length of the pre-concentration lens must be short. Calculations of the necessary ampere turns and consideration of the available stock for its construction determined the external dimensions of the coil housing,which in turn determined the limits of length and over-all diameter of the discharge tube.

A cross-section of the discharge tube is shown in Figure 2. It will be noted that the bottom is closed by a turned piece in which the anode hole (#77 drill 0.018 inch diameter) is drilled. It is held and centered by a knurled screw which is screwed into the body of the tube. The tube is surrounded by the magnetic lens supported on a plate which may be lifted off. The upper end of the discharge region is closed by a conical greased joint which supports the upper structure. Since heat is liberated in the discharge region, some means for cooling the tube is necessary. It was hoped that a water jacket around the lower end would be sufficient to cool the whole by conduction; however, this was not successful and after a short period of use the joint became warm and leaked. The tube was then reconstructed to allow complete water jacketing and suitable baffles were provided to direct the flow of water up one side and down the other along the entire length of the discharge chamber. This overcame troubles caused by overheating and greatly increased the reliability of operation.

The problem of insulating the cathode from the anode structure becomes acute in a design of this type because of the small clearances permitted. It is not possible to increase the thickness of the insulation beyond the minimum anode-cathode distance without at the same time increasing the danger of flash-over across the insulator face since Poisson's law of sparking is used to control and direct the discharge. This law states that the sparking voltage

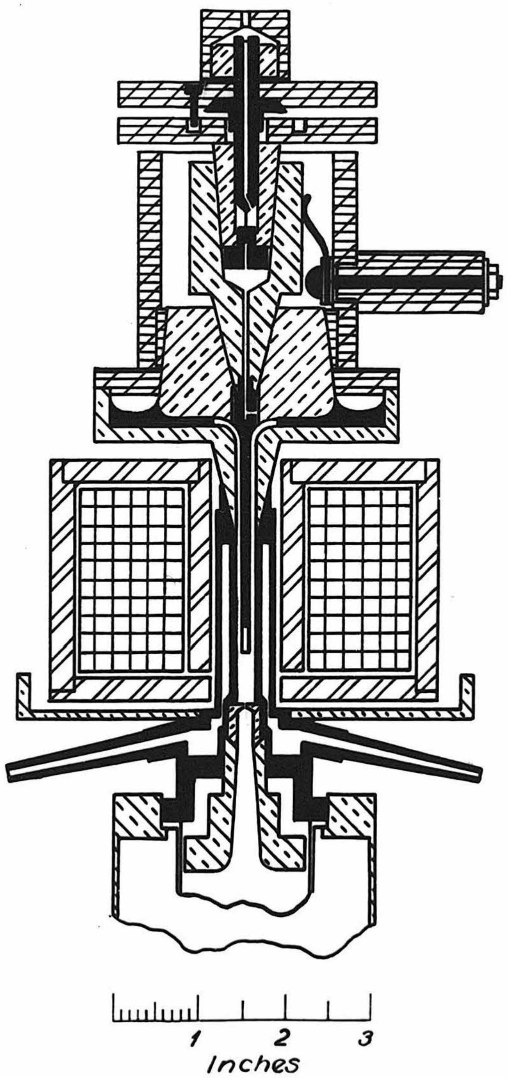


Figure 2
Discharge Tube

between two electrodes is a function of the amount of gas between them as well as of their geometrical configuration. It follows from this that if there is a great difference in the lengths of two discharge paths between two electrodes, the gas pressure may be adjusted so that, for a given applied voltage, a discharge can take place only over the longer path. It will also be true that as the shorter path length increases the difference in sparking voltage between it and the longer path will decrease. In order to make this difference great and thereby prevent a discharge between the sides of the cathode and anode, the separation at this point is made as small as is convenient; while, conversely, the distance between the face of the cathode and the anode is made relatively large. As the insulation is located in a region where no discharge is desired, its thickness must be small, in fact it should not exceed about 0.07 inch. In addition, it must not be in a region close to sharp corners which would cause high dielectric stress; it must be capable of centering the cathode support properly; and, it should be easily removed and replaced. The most obvious way of fulfilling these requirements is to shape the insulator in the form of a double cone. Several materials in this form were tried, including the common plastics, soapstone, and glass. Of these, only glass had sufficient dielectric strength, but it was so difficult to form and proved to be so fragile that it was abandoned. The design was changed a number of times and finally to the form shown in Figure 2. In it mica washers support a central brass body which supports the rest of the structure. This insulated body is centered by a bakelite ring which fits closely around it and presses against its conical sides. The whole is made gas-tight by a layer of Peceien wax. Because the surface of the bakelite ring has a tendency to flash-over occasionally, it may be removed after the wax has hardened.

Above the cathode support in the only remaining free space is located a valve to maintain proper pressure for the discharge. It consists of a fine sewing needle mounted in a threaded spindle which screws into the valve body and adjusts the position of the needle with respect to the brass plug in which it seats. In order to make the control sensitive, the threads are made fine (20 per cm.) and the needle is burnished into its seat until contact occurs along the slightly conical surface behind the point. This has been found to make a very satisfactory type of valve capable of controlling and maintaining the discharge current within close limits. The plug in which the needle seats is sealed to the valve body by means of hard wax or shellac. It is unnecessary and undesirable to grease the point of the needle, for, if properly made, it is vacuum tight and the grease is likely to cause unstable operation. As the valve is at cathode potential, it is insulated by two bakelite disks to permit manual adjustment. The upper disk drives the spindle by friction and consequently can be readily adjusted.

The lower disk is fastened to the valve body and serves to steady the operator's hand and to prevent rotation of the lower structure. A screw in the upper disk projects into a circular groove in the lower in which there is a stop to prevent forcing the needle too far into the seat. The proper adjustment can be determined by feel and must not be exceeded,as the needle can be broken or bent very easily. It is necessary to turn the valve screw forward a few degrees at infrequent intervals to compensate for wear.

It may be well to discuss some general considerations of this design. It has been found possible to operate it continuously literally for hours at a time with no more than a slight adjustment of the valve at intervals of about a half hour. This remarkably steady and reliable operation was, of course, very gratifying but care was necessary to achieve it. It was found to be necessary to keep all parts very clean. The slightest trace of grease or oil prevented satisfactory operation. For this reason great care had to be exercised at all times to avoid the excessive use of stopcock grease in any joint in the discharge tube, especially in the lowest one, and the parts were frequently washed in ether or some other solvent. With this precaution, very little trouble was experienced.

This design makes no provision for cooling the cathode except by conduction through the supporting stem and by radiation. Consequently, the power which can safely be dissipated in the discharge is strictly limited by the maximum allowable temperature of the cathode. The maximum safe power input to the tube is about 110 watts and a slight increase beyond this will raise the temperature above the melting point of the aluminum tip. There seems to be no disadvantage in operating close to the limit if desired, although ordinarily it is not necessary to exceed 30 to 50 watts input.

The design has some advantages which may be worthy of brief notice. In the first place, all parts may be removed from the body by simply lifting them off. This of course allows parts requiring frequent attention to be readily removed and disassembled. Also the ground joints are located in a region which is normally maintained at a relatively high pressure and, therefore, one in which slight leaks are of relatively little importance. Moreover, the small diameter of the anode hole prevents the immediate filling of the evacuated body below when it becomes necessary to open the tube. Thus by removing the top and inserting a plug which fits the ground joint, it is possible to replace the cathode and pump the tube down to a satisfactory vacuum without causing a delay of more than about ten minutes.

As has been mentioned, the intense positive ion bombardment at the center of the cathode results in the gradual formation of a crater in the surfacewhich causes the beam current to decrease. Experiments made by Ruhlemann[8] indicate that the most generally suitable metal for this purpose is aluminum, as it maintains itself at a higher average efficiency over a longer time than any metal except beryllium. The cathode is made in the form of a small tip of aluminum which screws into a brass shank in order that it may be readily removed and discarded when necessary. Preliminary experiments indicated that the efficiency of the tube was apparently greatly affected by the length of the discharge path and accordingly this question was studied. Freshly turned and cleaned aluminum cathodes of various lengths were prepared and tested in the tube. In order to form the same type of surface on each cathode, the tube was run at 5 milliamperes and 10,000 volts for 3 minutes, at which time the beam was properly focussed using both coils and directed into a Faraday cage. This consists of a cup which is supported by an insulated bushing in the door of the oscillograph through which a connection is made to a microammeter. The cup is completely shielded by a grounded case except for a 2 mm. hole in the top through which the beam is deflected. This may be seen to the right in Figure 7. The results, indicated in Figure 3b, show a remarkably sharp maximum for a discharge length of about 0.80 inches. The corresponding dimensions of the cathode are given in Figure 3a.

The effect of the formation of the crater upon the beam current, was also determined. A new cathode was used and the input to the tube maintained at 10,400 volts and 5 milliamperes. The manner in which the beam current varied during the first hour and a half is shown in Figure 3c. As may be seen, the current falls off rapidly during the first 15 minutes and thereafter at a decreasing rate

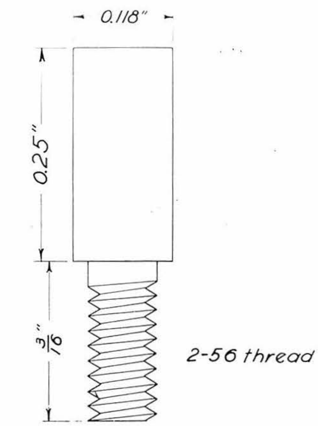


Figure 3-a

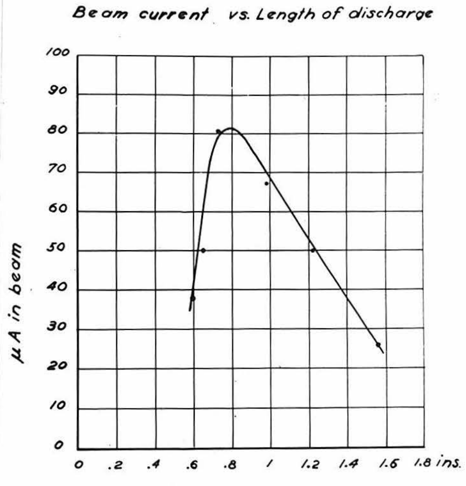


Figure 3b

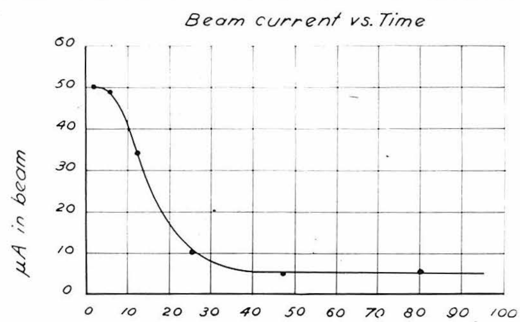
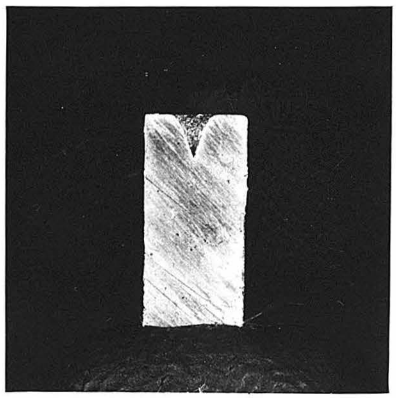


Figure 3-c



Cathode Crater
Figure 3-d

until after about 40 minutes it reaches a nearly steady value. From this time on during the next 6 to 10 hours the beam current decreases almost imperceptibly until it becomes necessary to renew the cathode. A cross-section of the cathode crater after about eight hours of use is shown in Figure 3d.

It is possible to adjust the two focussing coils so as to form a much enlarged electron image of the emitting surface upon the florescent screen. This is done by adjusting the current in the main coil to a maximum and that in the pre-concentration coil to give a satisfactory image. Though the image represents a magnification of possibly 150 diameters of the cathode surface, it appears to be quite distinct and free from aberrations. This makes it possible to follow readily the changes which the cathode surface undergoes during use. At the start, a new surface appears to be unevenly illuminated with bright patches centering around one spot in the cathode. The emission at this time is greatly influenced by surface irregularities, and tool marks and scratches can be easily seen. However, the relatively intense positive ion bombardment at the cathode soon causes appreciable erosion of the surface and this markedly changes the pattern of the emitting areas. The uneven patches widen into one another and form a brilliant circular area with indistinct edges roughly 1 mm. in diameter on the cathode. This corresponds to the beginning of the curve of Figure 3c. The bombardment of the surface is most intense at the center of the cathode spot and consequently the emission is greatest there, as is also the erosion, and scratches disappear after only a few minutes. As erosion proceeds the difference in brilliance between the center of the cathode spot and the surrounding area becomes increasingly greater, and at the same time the beam current decreases until after about a half-hour there is a very brilliant but small area enclosed by a nearly dark zone which in turn is surrounded by a fairly bright though narrow ring. The center, of course, represents the apex of the conical crater found by erosion and the electron image shows that most of the emission comes from it. The walls of the crater contribute very little to the beam, while the edge, as represented by the ring about the dark zone and brilliant center, contributes a little. If the beam is brought to a point focus, the most efficient adjustment of the pre-concentration coil can be readily found. This does not correspond exactly to the adjustment necessary for the best electron image but the difference is not great.

BLOCKING CHAMBER

It is the purpose of the blocking chamber to cut off the beam at all times except when it is required for a record. In order to secure sufficiently fast operation, it is necessary to use electrostatic means and to reduce the time constant of the circuit to a minimum; it should be possible to unblock the beam completely in a fraction of a microsecond. Blcoking is accomplished by means of two pairs of deflection plates located directly below the discharge tube. The center of the plates is about 2-3/4 inches above an inverted conical diaphragm having a small hole through which the undeflected beam passes. Both deflection plates and diaphragms are held in an easily demountable brass tube which is suspended from the same opening into which the base of the discharge tube fits. It is thus possible to provide means for readily removing the whole assembly without requiring an additional joint. The general appearance of the blocking chamber is shown in Figure 4, and a cross-section in Figure 1.

The plates are supported and insulated by strips of mica which are screwed to the supporting tube, as shown in Figure 4. Several other designs were tried but were abandoned in favor of this which has the advantages of simplicity and low capacitance. Contact to the plates is made by means of springs fastened to insulated conductors connected with the external circuit. The blocking chamber is removed by lifting it 1/2-inch to free the contact

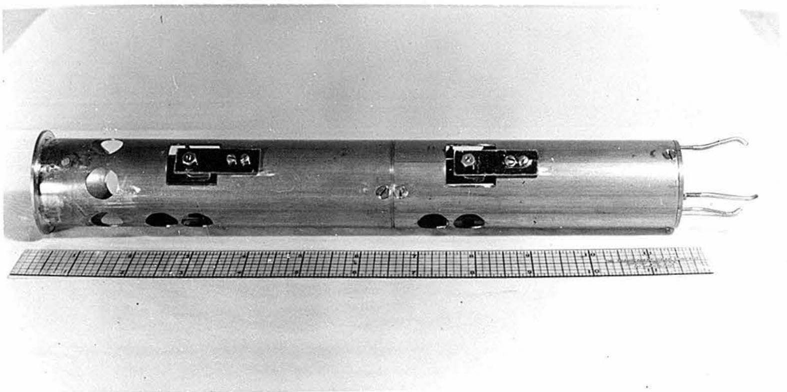


Figure 4
Blocking Chamber

springs, turning it through 90° and lifting it out. The diaphragms which block the deflected beam are made in the form of inverted cones in order to prevent the secondary electrons released by the deflected beam from getting through and fogging the film. The brass cones are fitted with aluminum caps through which the hole is drilled in order to reduce secondary emission from this point. Some fogging directly in line with axis of the tube does occur and is caused by heavy gas ions which are not completely blocked, and light from the discharge region. This can be seen in the oscillograms as a partly exposed circular spot slightly less than 1/2-inch in diameter. Except under extreme conditions, this does not appear to be objectionable and no attempt has been made to reduce it. The possibility of fogging, however, makes it desirable to avoid unnecessarily exposing the film except when a record is to be made.

Some difficulty was at first experienced because of a tendency to flash-over between plates. It is very important that the design provide for adequately large passageways to the pump in order to prevent too high gas pressure in this region. The continual flow of gas from the discharge tube and the great concentration of electrons in the beam make this critical. The attempt was first made to extend a 2-inch brass pipe the entire way from the central joint to the top but this prevented sufficiently high pumping speed and did not allow enough clearance around the plates. The construction was then changed to allow more space about the blocking structure, greater distance between plates and greater pumping speed. Under these conditions a separation of 1-1/4-inches between plates is sufficient to withstand potential difference of at least 4000 volts provided the beam does not strike the plates. To prevent this, to decrease the concentration of ions, and to block out all but the core of the beam, a diaphragm is placed above the top set of plates between them and the discharge tube. This has eliminated difficulties caused by discharges between plates.

A voltage of from 1500 to 1800 is required to block the beam using plates 1-1/4-inches long separated 1-1/4-inches. While this voltage could be reduced, this has not been necessary because the full sweep potential of 3000 to 4000 volts is applied directly to the blocking plates.

SOLENOIDS

The theory of focussing an electron beam by means of an axially symmetrical non-homogeneous magnetic field was first developed by Busch(9) and later put into more practicable form by Ruska and Knoll(10). The latter authors were able to derive an analytic expression for the focal length of a circular current loop from which the corresponding expression for a coil of rectangular cross-section can be approximated. Upon this basis the necessary ampere turns were calculated for focal lengths determined from the tube dimensions. A brass spool of a size which would permit a sufficient number of turns of wire with a low enough resistance for operation with a storage battery was made for each coil and filled with number 22 wire. It is necessary that the effective field of each coil be as concentrated as is possible. In the pre-concentration coil this is necessary in order to avoid a very material decrease in the efficiency of the discharge tube when the cathode is exposed to a strong magnetic field. Concentration is necessary for the main focussing coil in order to avoid spurious deflection and distortion which would be caused by a non-uniform magnetic field in the region through which the beam normally is swept by the deflection plates. This is accomplished by making the internal diameter of the coils as small as possible and by enclosing them completely in an iron case 1/4-inch thick except for a narrow slit inside. The case of the pre-concentration coil has an internal diameter of 7/8-inch and a slit 1/16-inch wide located normally about 0.52 inches below the cathode surface; the corresponding dimensions of the main focussing coil are 2-1/2-inches and 1/2-inch, respectively.

For minimum aberration, it is necessary that the coil and beam be coaxial in order that there be a symmetrical field distribution. This requires that some means be provided to adjust the position of the coils and to hold them in place. One of the simplest and most satisfactory mountings for this purpose is to support the coil on three equally spaced screws below and to clamp it in place by means of three screws bearing against the sides close to the base. This mounting has the advantage of allowing easy and quick adjustment with three degrees of freedom and of maintaining the adjustment permanently. The mounting of the principal focussing coil is also constructed so that it may be moved axially in order that the waxed joint directly below it be readily accessible.

Below the center of the tube are located two sets of mutually perpendicular biasing coils. Their purpose is primarily to make it possible to change the zero position of the beam as a whole with respect to the film. By this means it is readily possible to move the trace with respect to a system of coordinates on the fluorescent screen without requiring adjustment of the sweep circuit. This has proved to be a very useful feature and has made possible a simplification of the sweep circuit which will be described later. An additional coil is provided which extends around the entire tube, as shown in Figure 8. This is made necessary by reason of the horizontal component of the earth's field. It was found without neutralization of this field that the beam was deflected approximately two inches from the axis of the tube at the fluorescent screen.

The manner of adjusting the coils properly can best be learned by experience. It is, of course, true that if the coils and beam are co-axial changing the current in the coil will not change the position of the center of the spot on the fluorescent screen as the diameter changes. This is a convenient means of determining the proper position of both coils, at which time the trace will be most sharply focussed. Depending upon the condition of the cathode the pre-concentration coil will increase the beam current by a factor of 1.5 to 3, although at some sacrifice in sharpness of focus.

FLUORESCENT SCREEN AND FILM HOLDER

As was previously stated, in the interest of efficiency and "cleanness" of record, it is highly desirable to locate the film inside the tube. This, however, ordinarily leads to considerable difficulty in operation, as it requires that the tube be opened frequently. It is necessary that some form of door be used which is reliable and does not require special attention at frequent intervals. Moreover, there must be some simple means for exposing and winding the film ahead when necessary. It was felt that the usefulness of the tube would depend largely upon the success with which this could be accomplished, consequently great care was taken that the parts be simple and reliable.

The film holder and fluorescent screen are mounted directly upon the door which closes the bottom of the tube. The door is turned from a piece of brass and is 7-inches in diameter and 1-inch thick. The sides are slightly conical and are ground to fit into a 1-inch brass plate which forms the base of the tube. A kind of breach mechanism in the form of a screw and cross bar which fits into studs in the base of the tube is provided to seat the door firmly and to remove it; this may be seen in Figures 1 and 7. The joint has proved to be quite reliable and easy to maintain; stop cock grease need be applied only occasionally. Except that the large ground surfaces must be carefully protected from injury, the door is both easy to operate and reliable.

The film is held in a light-tight box with a hinged cover upon which the fluorescent screen is mounted. The screen is formed by dusting the fluorescent material upon a sheet of aluminum about 1/32-inch thick which has been painted with a tacky solution of sodium silicate. The aluminum sheet is held at opposite edges by slots milled in two brass straps upon which the cover hinges. It is necessary to provide a new fluorescent screen occasionally because of a tendency to "burn" when the sweep speed is low. Both willemite and zinc sulphide material supplied commercially for this purpose[11] appear to be well suited for fluorescent screens. Although the fluorescent material may be deposited more evenly by allowing it to settle down upon the plate out of a sodium silicate solution which is then drained off, the method of dusting a layer over a tacky surface is found to result in more efficient screens. In any event, it is desirable to reduce the amount of binding material to a minimum.

The general construction of the film holder is shown in Figures 5, 6, and 7, and it will be noticed that only one control requiring one additional joint is necessary to operate the cover and advance the film. This is accomplished by connecting the shaft supporting the cover and the film drive by gears and operating the cover by means of an over-running clutch, as indicated in Figure 5. The cover is connected to the shaft by means of a spring wound tightly about it. When the shaft turns in a direction to open

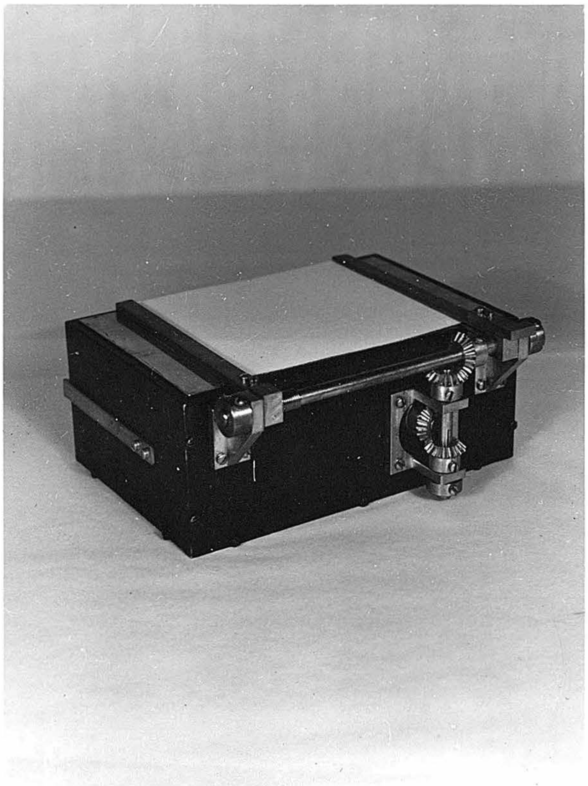


Figure 5
Film Holder

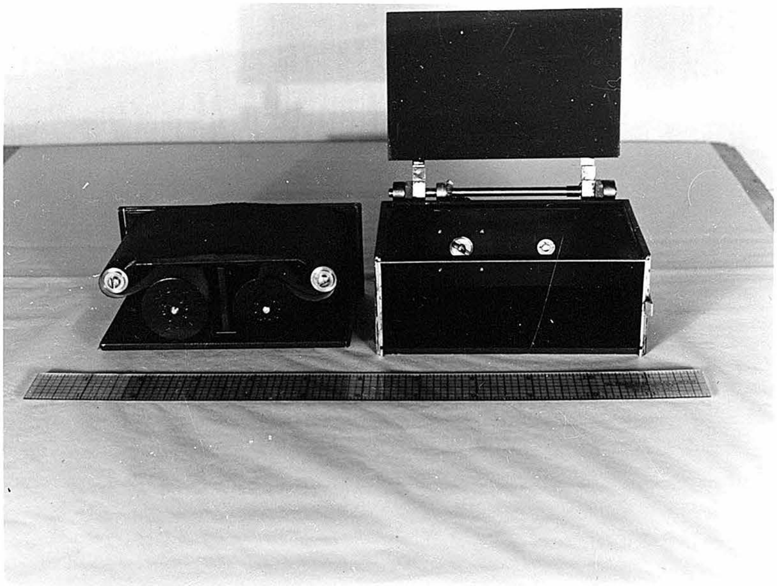


Figure 6

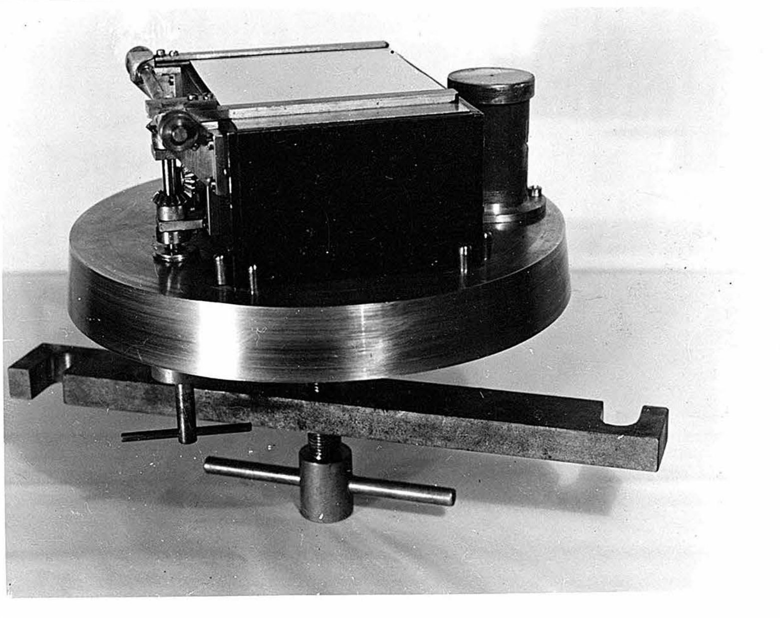


Figure 7
Film Holder Mounted on Door

the cover, the spring snubs about it and opens the lid; it is closed by the friction between the shaft and spring. If the shaft is turned in the same direction beyond the point where the cover is closed, the film is advanced. Thus a quarter turn of the handle to the right exposes the film and a quarter turn to the left covers it; 1-1/2 turns further to the left will advance the film about one frame. The box is held in position by two pins at each corner and is operated through a ground joint.

The manner of placing the film in the holder and the general construction can be seen in Figure 6. Standard roll film having reels 2-7/8-inches wide is used and 10 or 11 exposures are ordinarily possible in a regular 8 exposure film, the size of the opening being 2-5/8- by 3-inches. There seems to be no great degree of correlation between the sensitivity of the film to light and to the electron beam; the cheapest film appears to be satisfactory. It is possible with a little practice to insert or remove film either in the dark or in daylight without difficulty. Considerable trouble was at first experienced in pumping the tube out after a fresh film was inserted because of the water vapor which it releases. It was not found satisfactory to depend upon drying agents within the tube; the best solution is to keep the film in a sealed container connected to the fore pump and containing P_2O_5 until needed. After 24 hours or more of such treatment the film does not give off a noticeable quantity of water vapor.

GENERAL DESCRIPTION

The general construction of the body is sufficiently well indicated in Figures 1 and 8. This design seemed to offer the most reasonable compromise between ease of construction, simplicity, minimum number of joints, and accessibility. Two wax joints are provided to enable the tube to be disassembled, one at the base of the discharge tube, the other below the principal focussing coil. It is thus possible to remove the entire upper half of the tube including the discharge tube, blocking section, the control circuit, and focussing coil in a body by breaking only one joint. Connections to the deflection plates are made through glass insulators which fit into conical holes in brass bases soldered to the body. The outer end of the insulator is necked down and ground so as to fit a conical brass plug into which a rod supporting the deflection plates or spring contact is screwed. Both ground joints are sealed with wax. Unfortunately, it did not appear to be practicable to provide means for easily adjusting the main deflection plates; this is accomplished by softening the wax around the insulated plug and working from below through the door or from above by removing the top half of the tube. This is awkward but fortunately it need not be done frequently. Two windows about 2-3/8-inches in diameter are located at the top of the lower section for viewing the screen.

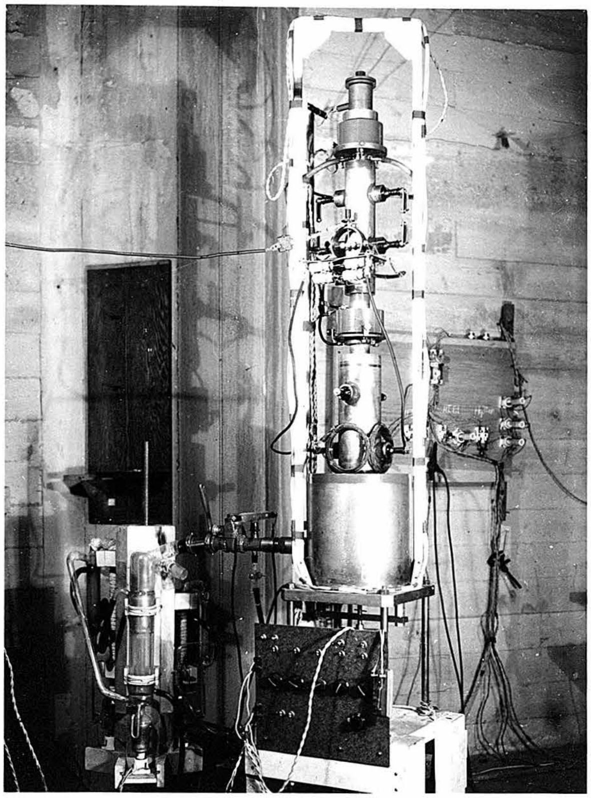


Figure 8
General View of the Tube

An indication of the size of the rectifier equipment necessary is given in Figure 9. As will be noticed, the entire equipment is located under one end of a table. Actually since it was assembled out of equipment at hand, it is larger than it need be. As the operating voltage of the tube never exceeds 15,000 volts, the maximum voltage required from the rectifier is about 25,000 including the potential drop in a protective resistance connected in series with the tube to allow ready control of the discharge. The maximum power required is about 350 watts.

Figures 8 and 10 show the metal connection to the pumps including a standard brass gate valve. This valve, in conjunction with a by-pass to the fore pump, makes it possible to isolate the mercury diffusion pumps from the system and to allow them to remain hot when the vacuum is broken, which results in a considerable saving in time. A discharge tube is also mounted on the connection to serve as a rough vacuum gauge; for ordinary operation it is merely necessary to reach a pressure sufficient to prevent a discharge in this tube. However, for very high frequencies of the order of 10^7 cycles per second and higher, it is necessary to reach a considerably lower pressure in order to prevent flash-over between deflection plates. A flexible connection between the glass pumps and the tube was found to be desirable; the most successful design is that shown in Figure 10. This consists of a syphon bellows which is prevented from collapsing by a gimbal ring at each end pivoted to the syphon structure and to two links in such a way that the ends are free to adjust themselves to any position within wide limits without axial motion. The three glass mercury diffusion pumps in series aided by a "Hyvac" fore pump reach a "black" vacuum in the gauge in about 18 minutes.

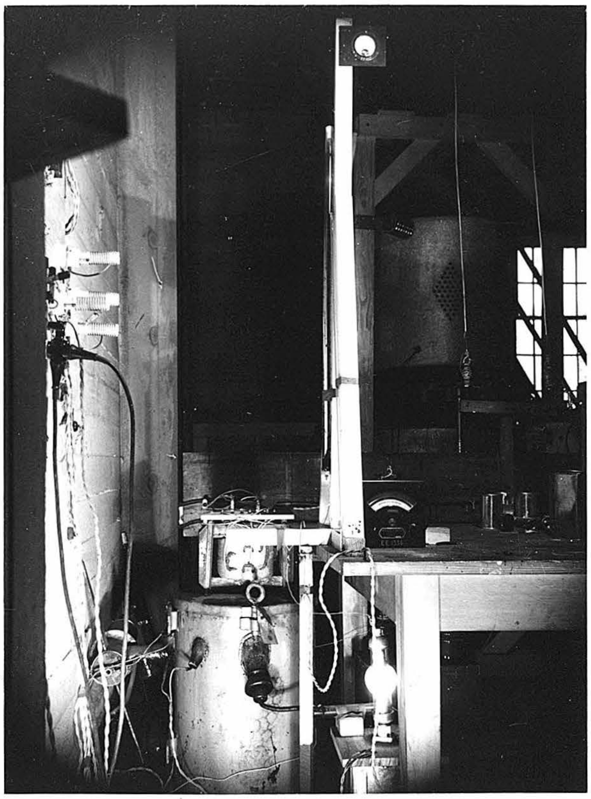


Figure 9
High Voltage Rectifier

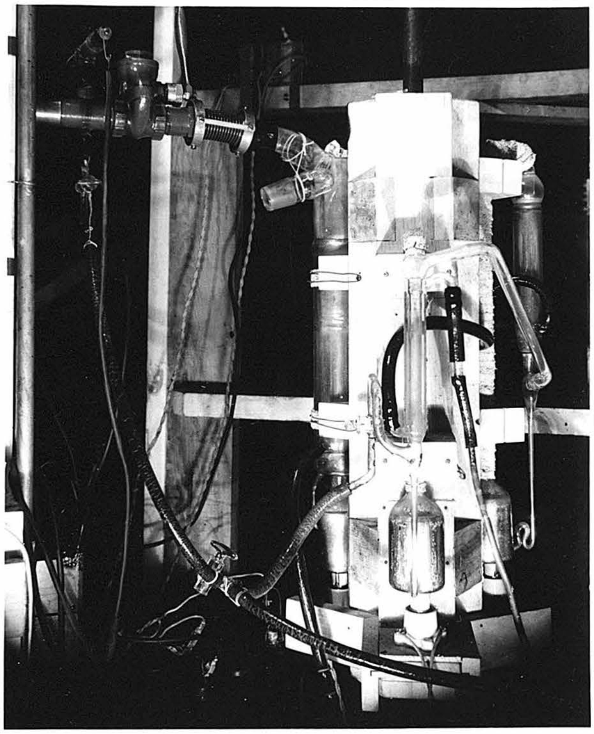


Figure 10
Pumps and Connection
to Tube

CIRCUITS AND PERFORMANCE

It is essential that the blocking and sweep circuits be simple and that the possibility of oscillation in the circuit elements be prevented. For this reason and to reduce stray capacitance all leads are made as short as possible and are provided with damping resistors (50 ohms). This makes it advantageous to mount the control circuit directly upon the tube and the necessity for a minimum time constant in the blocking circuit indicates that it be close to the blocking plates. Actually, as shown in Figure 8, the gap and auxiliary equipment was mounted directly upon the housing of the blocking section. Two circuits which were found to be satisfactory are those shown in Figures 11a and 11b. In both diagrams c 1-a and c 1-b are the condensers of two half-wave rectifiers capable of a maximum of 2000 volts D. C. each. In order to prevent these condensers from becoming completely discharged through the gap, sufficient resistance (several thousand ohms) is connected in series with them.

The rectifiers are connected so that the potential supplied to the circuit is symmetrical with respect to ground as shown. It will be noticed that the tripping mechanism is a spark. This was chosen because it is simple and, if properly cleaned and adjusted, fairly reliable. It has the advantage of a very small time lag and very low potential drop after tripping, both of which are necessary.

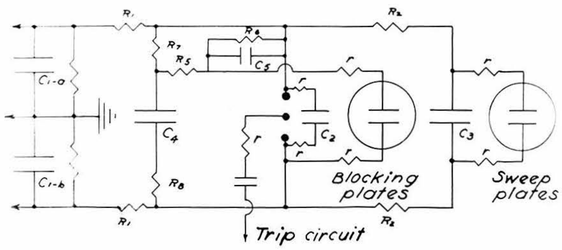


Figure 11-a

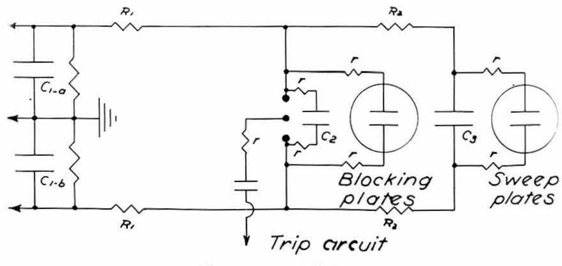


Figure 11-b

Many means of coupling the spark gap to an external circuit have been tried; one of the most common is to use a three-electrode gap, in which the potentials of the two outer electrodes are maintained symmetrically with respect to ground, while the central electrode is ordinarily maintained at or near ground potential. The electrodes are adjusted so that the gap between the central sphere and each of the others is the same and just long enough not to discharge. If then the potential of the central electrode is either raised or lowered with respect to ground, the voltage across one of the two gaps will increase, causing it to break down. This throws nearly the entire voltage across the other gap causing it to discharge immediately. Thus either a positive or negative surge of relatively low voltage is effective in tripping the gap. A coupling condenser and voltage divider is ordinarily used in order to control the strength of the tripping surge and prevent it from disturbing the rest of the circuit. It is also very desirable to shield the circuit as completely as possible from electrostatic fields.

The spark gap thus becomes essentially nothing more than a very quickly acting switch capable of shorting two electrodes normally at some potential difference with respect to each other. Since it is necessary to have a low voltage arc form between the electrodes, it is desirable to connect a so-called "heating" condenser in parallel with the gap. When the gap discharges, enough current flows from this condenser to assure the formation of a low voltage arc. A capacitance of 0.025 μf. in series with a damping resistance of about 5 ohms is sufficient for this purpose. This was found to increase the reliability of the gap to a noticeable degree. No study of electrode materials was made, but Westermann has stated to the author that experience has indicated that magnesium is the most generally satisfactory and reliable metal. Frequent cleaning of the surface with sand paper is desirable.

The purpose of the control circuit is, of course, to unblock the beam, sweep it across the screen and block it again before it is swept back in the opposite direction. There are a number of circuits capable of doing this(12), of which two were tried. In both, the principle is to make the time constant of the blocking circuit small as compared with the sweep circuit in order that when they are connected in parallel the blocking plates can discharge and charge in a fraction of the time required for the sweep circuit. Thus the beam is unblocked before the sweep circuit becomes discharged and later blocks before it becomes completely charged. Consequently, the beam is unblocked, swept across the screen and blocked before it can return. In order to assure flexibility and ease of adjustment of the blocking circuit, the circuit of 11-a was devised. Unfortunately, the principle was later found to have been described by Boekels(13), although in a somewhat modified form.

In this circuit it will be noticed that the blocking plates are connected to the gap through a condenser, C 5, in parallel with a resistance, R 6. C 4 is a condenser whose capacitance is large enough to make the time constant of the circuit from it through resistances R 7 and R 8 or R 5 and R 6 large as compared to the time during which the gap discharges. While a straight-forward analysis of the voltage at the blocking plates can readily be made, the result is so complicated that it tends to obscure the essential simplicity of the behavior and it is sufficient to discuss two limiting cases. Before the gap breaks down, the circuit is in equilibrium; i.e., no current flows and condenser C 5 is uncharged. As soon as the gap is tripped, the potential drop across it becomes very low and the equilibrium of the circuit is disturbed. If for a moment we consider only the condenser C 5 and the capacitance of the blocking plates C_b, it is seen that they are connected in series to the gap and consequently the voltage e_b at the blocking plates would be expressed by:-

$$e_b = E\left(\frac{C_b}{C_b + C_5} + \left[1 - \frac{C_b}{C_b + C_5}\right] \varepsilon^{-\frac{C_b + C_5}{2\, r\, C_b\, C_5} t}\right)$$

If the damping resistance 2r is as small as possible and C5 is much larger than C_b, the blocking voltage will fall very quickly to a value approaching $E\frac{C_b}{C_b + C_5}$.

Immediately, however, C5 begins to charge up through the resistance R5 and R8 and if we neglect the rest of the circuit the corresponding voltage will be given by:-

$$e'_b = E\left(\frac{R_6}{R_5 + R_8} + \left[\frac{C_b}{C_b + C_5} - \frac{R_6}{R_5 + R_8}\right] \varepsilon^{-\frac{t}{C_5(R_5 + R_8)}}\right)$$

Of course, these represent limiting cases which only approximate actual circuit behavior but since C6 $<<$ C5, and 2r $<< R_5 + R_8$, the error is not great. Thus, immediately upon tripping the gap, the blocking voltage falls from E to approximately $E \frac{C_b}{C_b + C_5}$ and at once begins to build up to the limit $E \frac{R_6}{R_5 + R_8}$. The fact that the voltage begins to increase before the spark is extinguished is an advantage because it reduces the likelihood of trouble caused by the beam "sweeping back" with slow sweep speeds. The interval of time during which the beam is unblocked is, of course, largely controlled by the time constant C5 $(R_5 + R_8)$ and the blocking voltage which should be substantially less than $E \frac{R_6}{R_5 + R_8}$. This circuit appears to have some promise because of the flexibility and control over the unblocking time which it permits without excessive complexity. However, for very fast sweeping speeds it appears to have no marked advantages over the much simpler circuit of Figure 11-b. Here both blocking and sweep circuits are connected in parallel to the gap. This, while being very simple and relatively free from trouble, does not allow very great control over the lateral bias as the blocking voltage builds up too slowly to prevent the beam being partly swept back before blocking. It hardly need be pointed out that the sweep speed is controlled by the time constant of the circuit comprising the gap, the two resistances R2 and the capacitance C3.

It will be noticed that no means is provided in either circuit to deflect the beam from one side of the screen to the other; as shown, neither circuit could sweep the beam beyond the center. This follows, of course, because the function of the gap is merely to remove the initial charge on the deflecting plates and therefore to eliminate the deflecting field; consequently unless some means is provided to give the beam a constant deflection or "bias", the beam will not traverse the entire width of the screen. To accomplish this, the beam is normally biased to one side with no voltage on the sweep plates and then deflected against this biasing field by the sweep circuit. Two methods of biasing may in general be used, either electrostatic, by applying a biasing voltage to the sweep plates, or magnetic, by means of a transverse uniform field. Magnetic biasing has the advantage of ease of adjustment and simplicity and therefore was used with these circuits.

Time did not permit an extensive study of the application of the tube to practical problems and an attempt was made simply to determine the maximum possible recording speed. Although the following illustrations are presented in that light only, they appear to be typical of the type of record which can be obtained.

No special technique was used to intensify the trace; both film and prints being treated by standard developers to obtain greatest contrast. Figure 12 shows the effect of oscillations in the sweep circuit, the oscillations being impressed upon a one megacycle wave. The frequency of the transient is roughly 42 megacycles and the maximum recording speed 6.3×10^7 centimeters per second. Figure 13 shows the transient oscillations set up in a short transmission line, (12) and (14), roughly 75 ft. long by suddenly shorting the charged line through a spark gap capacitively coupled to the trip gap of the tube which was tripped manually, the opposite end being directly connected to the deflection plates. The timing wave is one megacycle. Figure 14 shows the output of a vacuum tube oscillator operating at a frequency of about 84 megacycles. The corresponding recording speed is about 10^8 centimeters per second. Figure 15 appears to have reached the ultimate recording speed, and is the record of the oscillation set up in a circuit consisting of the deflection plates, a spark gap mounted as closely as possible to them, and short connections of resistance wire for damping about 3 inches long. The gap was connected through coupling condensers to the transmission line which acted as a delay circuit and which in turn was connected to the trip gap. The frequency is estimated to be about 90 megacycles and the corresponding maximum legible recording speed to be approximately 1.3×10^8 centimeters per second. It probably will not be possible to extend

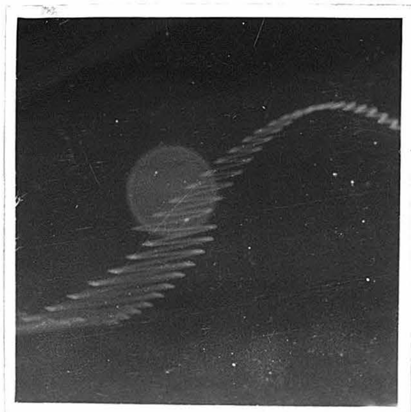


FIGURE 12

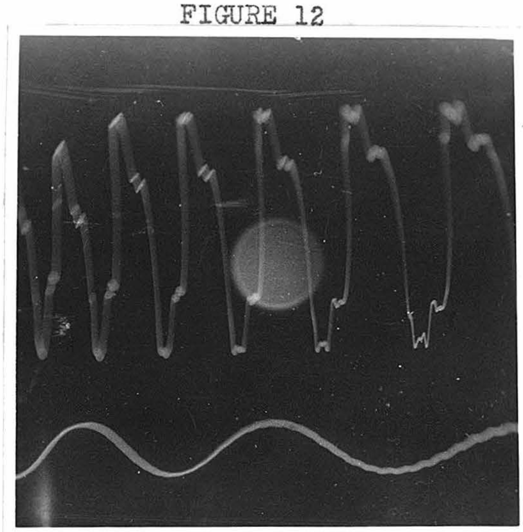


FIGURE 13

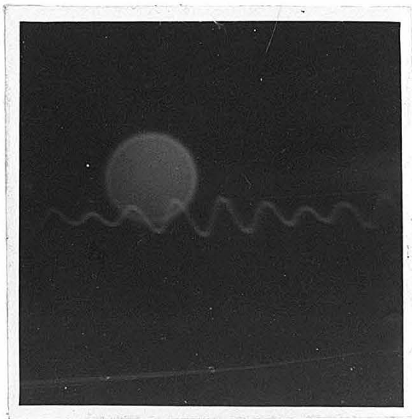


FIGURE 14

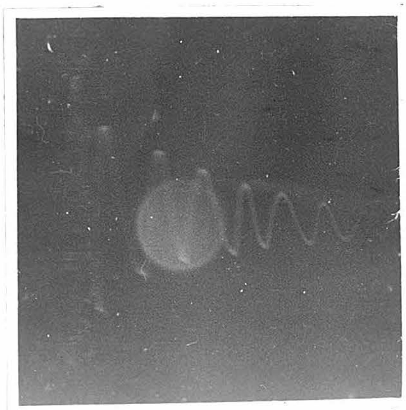


FIGURE 15

this speed appreciably without extraordinary care and special photographic technique.

It need not be emphasized that cathode-ray oscillography is in a constant state of flux and that the number of conflicting opinions of what constitutes the ideal type of equipment is limited only by the number of workers in this field. However, it seems reasonable to conclude that the apparatus described in this thesis contains some advantages of simplicity and compactness and some details of design which may be worthy of further consideration and development.

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