DISTANT-FOCUS X-RAY TUBES
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There exists a comprehensive literature of theoretical and experimental investigations concerning the focusing of the electron beam in cathode-ray tubes, but little has yet been published on the analogous problem in X-ray tubes. The article below is a contribution to this subject. It describes a development the results of which have been applied for some years now by C. H. F. Müller A.G. and by Philips. Although this development refers to a special case, the considerations discussed here are perhaps of more general interest.

The focusing problem in cathode-ray tubes and X-ray tubes

X-ray images being shadow images, the smallest possible source of radiation and the most uniform possible brightness are necessary to produce sharp definition. The electrons emitted by the cathode in an X-ray tube, and which, upon striking the anode, give up their energy largely in heat and partly in the generation of X-rays, must therefore converge on the anode to a focus of a certain specified size. Upon arrival at this focus the electrons should be as uniformly distributed as possible. (Their density may, however, permissibly be somewhat greater at the edges, where the heat is more readily dissipated; otherwise, with an entirely uniform electron distribution, all parts of the anode material would not reach the rated maximum temperature.)

The focusing problem in cathode-ray tubes is more familiar in connection with cathode-ray tubes. In such tubes the electrons are accelerated by a constant voltage. Focusing problems arise because of the long trajectories which the electrons must describe before impinging on the fluorescent screen, and because the beam current is variable. In addition, there is the deflection of the beam to consider. To obtain the required narrow beam in these tubes, use is made of systems with auxiliary electrodes operated at different potential, some adjustable 1); in some cases, too, focusing magnetic fields are used 2).

With an X-ray tube it is necessary — without affecting the size of the focus — to be able to vary not only the beam current but also, as a rule, the accelerating voltage. For example, the current in diagnostic tubes must be capable of being varied by a factor of 500 and the voltage by a factor of 5. Normally, however, the electrons in X-ray tubes have only a short distance to travel from cathode to target, e.g. 10 to 20 mm, or, in the case of tubes operated at 200 or 300 kV, up to 50 or 100 mm. For normal X-ray tubes, therefore, a much simpler focusing system suffices than for cathode-ray tubes: the focusing system consists merely of a metal cathode block provided on the side facing the anode with a round, cup-shaped or oblong recess. Fitted inside this recess is an appropriately shaped filament, electrically connected with the cathode block. The cathode block and the anode constitute an electro-optical system of only two electrodes (fig. 1), the focusing properties of which are determined mainly by the shape of the cathode assembly. In practice, such a system is very desirable, since the voltages for the X-ray tube, which is enclosed in an earthed shield, have to be led in through high-tension cables, and a two-electrode system requires the fewest cables.

There is another reason why a two-electrode system is unsuitable for television picture-tubes and other cathode-ray tubes, namely the necessity for inertialess control of the beam current, with the accelerating voltage kept constant. For this purpose an extra electrode is used in the form of a circular or cylindrical diaphragm, to which a control voltage is applied for modulating the beam current. In general, then, only a fraction of the available electron emission is used; the filament operates in the space-charge region. In the case of X-ray tubes, inertialess control of the tube current is not necessary; on the other hand not merely the current but the voltage, too, must be capable of adjustment, and both independently of each other. For this reason the cathode in X-ray tubes is generally operated at saturation emission 3). The current is

1) For one of the most recent developments in this field, see J. C. Francken, J. de Gier and W. F. Nienhuis, A pentode gun for television picture-tubes, Philips tech. Rev. 18, 73-81, 1956/57.
3) Exceptions to this are certain small, special equipments for which control of the voltage is deemed unnecessary; see e.g. Philips tech. Rev. 6, 229, 1941, and 10, 224 et seq., 1943/49. It should be noted that variation of the current by means of a control voltage slightly alters the position of the beam cross-over and hence the size of the focus.
then adjusted to the required value by regulating the cathode temperature (filament current control).

In the case of certain types of X-ray tube used for therapeutic purposes and for the industrial examination of materials, the situation is somewhat different from that in normal X-ray tubes in that the electrons do not describe such short trajectories as described above. The focus in their case is formed at the end of a long, hollow rod, which can be introduced into body cavities for irradiating deep-seated lesions, or into boilers, pipes, etc. for taking radiographs of not readily accessible parts. In such X-ray tubes the electrons must travel through the hollow rod as a narrow beam, in some cases a distance of 700 mm or more. Good focusing is necessary here not only to obtain sharply defined shadow images and to make efficient use of the tube output, but also to prevent the undesirable generation of heat and X-rays at places such as the rod wall and the diaphragms.

Where such long trajectories are required of the electrons, the simple two-electrode system does not seem at first sight very promising. In the past magnetic means of focusing have therefore been resorted to in certain special cases 4) and also for series-produced X-ray tubes with “rod anodes”. Use was made of small permanent magnets or a focusing coil, which were slid over the rod anode and acted as a lens for converging the divergent electron beam. Any variation in tube voltage then calls for an adjustment of the magnetic field, i.e. of the magnetic lens, in order to keep the beam properly focused, and this is an undesirable complication. The difficulty is aggravated if the tube operates on a pulsating voltage, since the magnetic field must also be pulsed in the correct phase.

If we look more closely into the electron optics of the two-electrode system, however, we find that it is certainly possible (within certain limits, of course) to produce long and narrow electron beams with this system. We shall briefly review here the considerations that have led to this conclusion, and describe a number of X-ray tubes whose design, completed some years ago, is based on the principles evolved 5).

Electron-optical considerations

We base our considerations on the above-mentioned fundamental fact that the filament in an X-ray tube is operated in the saturation region, so that all emitted electrons contribute to the formation of the focus. The cathode required is therefore the classical, directly heated type, consisting of a coiled or spiraled tungsten wire. Oxide cathodes are quite unsuited for our purpose since, having regard to their life under continuous loading, they cannot be allowed to deliver more than 1/100 of their saturation current. Other types of cathode, such as the L type, are excluded because of barium evaporation, amongst other things. We thus arrive at a cathode system which, in its simplest form, is as shown in fig. 2. The system contains a closely coiled filament, which can be treated to a first approximation as a simple cylinder, situated in a slot in the cathode block. The cylindrical shape corresponds to a line focus, as required for most X-ray tubes. Disregarding the boundary effects at the ends of the cylinder, we can regard the potential field between cathode and anode as purely two-dimen-

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5) The writer read a paper on this subject to the International Congress on X-rays at Copenhagen in 1953, which has since appeared in the journal published by C. H. F. Müller A.G., “Röntgenstrahlen: Geschichte und Gegenwart”, 1956. The most important results and their application in endotherapy tubes are described briefly in Philips tech. Rev. 13, 77 et seq., 1951/52.
sional. This is represented in fig. 2 by equipotential lines (lines of intersection of equipotential surfaces with the plane of the drawing). The paths described by the electrons emitted from the filament can be most simply determined by experiment with a rubber membrane model of the potential field, on which small balls are rolled 6. Some characteristic trajectories found in this way are also shown in fig. 2. If we look at the situation at some distance from the cathode, we see that there are three principal beams, one originating from the foremost third of the filament and two from the two thirds at the rear of the filament. The rays of each of the two latter beams are reflected from the sides of the slot and cross each other. In the region at the height of the arrow the distribution of the electrons is approximately uniform over the cross-section of the beam. If the target surface is situated at this position, the desired focus with an approximately uniform distribution of electron bombardment and of X-ray emission is obtained. Since the equipotential surfaces in this region are virtually parallel and have a constant gradient, the potential pattern is not essentially altered if the target is introduced here slightly above or below the point indicated by the arrow. However, both above and below this region the electron density is non-uniform and will not produce a good focus. By proportionately changing all distances and also the dimensions of the cathode slot and filament, the focus obtained can be given the requisite size.

If the filament is moved somewhat towards the top of the slot, as shown in fig. 3, the three electron beams run more parallel and the region of uniform electron density is shifted farther outwards. At the same time, however, the total cross-section of the beam at that point is widened, so that this simple measure does not achieve the object, which is to produce the same focus at a greater distance. With continued displacement of the filament upwards we finally reach a situation where, as shown in fig. 4,

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The rubber membrane has been used for investigating the cathode system of X-ray tubes also by A. R. Lang and D. A. C. Broad, Electron optics of X-ray tubes and the design of unbiased sharply-focusing cathodes, Brit. J. appl. Phys. 7, 221-226, 1956. No long-distance focusing is involved here, however.
there is no longer any region in the anode space in which all three beams intersect each other. Even with this situation, however, focusing is still possible if the cathode system is given a somewhat more complicated shape while retaining a two-electrode structure. An additional, broader recess, or cup, fixed to the front of the original cathode system of slot and filament modifies the potential field near the cathode in the manner shown in fig. 5.

Fig. 5. By introducing a cathode cup in front of the configuration in fig. 4 an “auxiliary lens” is formed (extending from the substantially flat equipotential surface x-x upward; see brace), which again produces a focus, but now at a greater distance from the cathode.

As the illustrated electron trajectories show, a focus is again obtained which is now at a greater distance from the cathode.

Since the addition of such a cathode cup increases the number of design parameters by two at least (depth and breadth of the cup), it is now virtually impracticable to investigate all the possibilities by experiment, or by calculation. Nevertheless, it is possible by simple reasoning to gain enough insight to provide guidance on the design of practical systems.

In the close proximity of the filament, thought of as a cylinder, the equipotential surfaces closely follow the curvature of the cylinder. At the level of the mouth of the cup, however, they will evidently have the opposite curvature, so that between them there will always be an equipotential surface which will be flat within a certain range. Clearly, the potential field between this “flat” equipotential surface and the anode may be regarded as constituting an electrostatic lens (accelerating lens) situated in front of the electron-optical system of filament and slot. This auxiliary lens can be characterized by two parameters, namely by the power of the lens and the distance to the filament-slot system. It would seem at first sight difficult to say anything about the focusing brought about by the two electron-optical systems in combination, because of the complex situation near the filament. However, if the electron trajectories as far as the flat equipotential surface, where the auxiliary lens begins, have been determined by experiment with the rubber membrane analogue, we can for the present purpose replace the electron trajectories simply by their tangents at the points where they intersect this equipotential surface (fig. 6). We need then no longer be concerned with the complicated situation near the filament. These tangents can be constructed with satisfactory accuracy, since, as can be seen in fig. 6, the electron trajectories are not very strongly curved at the places where they cross the flat equipotential surface.

If the tangents of all electron trajectories be traced backwards (fig. 6), we see that these “virtual
paths (which the electrons can be imagined to describe in the total absence of any field in the entire space behind the flat equipotential surface) again form our three beams, but now they intersect in a minimum cross-section behind the filament at the plane \( A \). This zone of intersection may be regarded as a virtual image of the filament, produced by the filament-slot electron-optical system. (It is not actually a true virtual image, for in every "image" point there converge rays from different points of the filament.) We must now design our auxiliary lens so as to obtain on the target a focus that is the real image, approximately free from aberration, of the plane \( A \), or possibly of the plane \( B \), where the intersecting tangents are rather more uniformly distributed (see the "electron density" distribution in these planes as sketched in the figure). The virtual electron distribution in plane \( A \) — or in plane \( B \) if the auxiliary lens be so adjusted — acts as the virtual object.

What we must do to solve the problem posed at the outset, i.e. to produce a small focus at a long distance from the cathode, can now be inferred from the optical analogy. Taking the virtual object and its position as given, we need an auxiliary lens of low power and situated at a long distance from the object (see fig. 7a and b). In our case this implies the use of a cathode cup of considerable diameter and depth. Since we have two geometrical parameters available, it is fairly evident that the flat equipotential surface can be made to remain at approximately the same place; in this way we satisfy the condition that the virtual object and its position should not be significantly affected by the change in the dimensions of the cup. On the other hand, the shaping of the filament and its immediate surroundings still makes it possible within certain limits to exert some influence on the virtual object to be imaged by the auxiliary lens, both as to its position.

![Optical analogy diagram](image)

Fig. 7. Optical analogy.

a) A slightly magnified image \( B \) of the object \( G \), situated at a distance \( g_1 \) from the thin lens \( L_1 \) (focal length \( f_1 \)) is produced at a distance \( b_1 \).

b) To produce a \( k \) times more distant but no larger image of the same object, a weaker lens is required (focal length \( f_2 = k f_1 \)) which must be situated at a distance \( k \) times greater than \( g_1 \) from \( G \).

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7) The combined action of the two parts of the potential field must of course lead to a result which is independent of the equipotential surface one may choose as the boundary. Provided image aberrations may be disregarded, tangents can in fact be constructed for any given boundary plane, but any other choice than that described here may reduce the accuracy and make it more difficult to define the "auxiliary lens". See also the part of this section in small print.

It should be noted that, for the case of a point source in fig. 6, it can be demonstrated by a simple calculation that in the paraxial approximation the tangents constructed on the electron trajectories, where they intersect an arbitrary plane perpendicular to the axis, all intersect exactly in one point on the axis behind the point source.

![Cross-section diagram](image)

Fig. 8. Simplified cross-section of the electrode system of a distant-focus X-ray tube. \( W \) filament, \( K \) cathode cup, \( F \) focus. Some of the equipotential surfaces and electron paths are shown.
and size and as to the distribution of the electron density. In this way, and by suitably dimensioning the cup, varying requirements can be fulfilled with regard to the size and distance of the focus, and to the distribution of the load on the focus.

Depending on the requisite distance of the focus, the dimensions of the cathode cup can be quite considerable. Fig. 8 shows schematically the electrode system in one of the distant-focus X-ray tubes which we have developed on this principle and which are all characterized by their exceptionally large cathode cup. The focus of this tube is situated on the end of the tubular anode. The figure also shows the electron beam and a number of equipotential surfaces. The electrode system illustrated is that of the industrial X-ray tube shown in fig. 12, in which a 0.4 mm focus is produced, with the electrons travelling a distance of 200 mm.

The optical analogy should not be applied without reservation, since both the "auxiliary lens" and the filament-slot lens in the X-ray tube are entirely different in a certain respect from optical lenses: the rays move in a space of continuously changing refractive index, corresponding to the continuously increasing velocity of the electrons on their way to the target. Because we have chosen the "flat" equipotential surface, however, for dividing up the field into two lenses, we have a virtual object at a fairly considerable distance from the auxiliary lens, and the image (the focus) is also produced, as intended, at a considerable distance away. The variation in the refractive index is thus compressed in a relatively limited space. Hence the accelerating potential field can reasonably be taken as equivalent to a thin lens. On the other hand, a given lens has a longer focal length in a medium the higher the refractive index of that medium. In the anode space this index is much higher than in the cathode space (owing to the greater velocity of the electrons), and therefore in this case the discrepancy between the electron-optical case and the optical case works in favour of the former when long focal lengths are required.

However this may be, as a heuristic principle the optical analogy has served well, as is demonstrated by the successful design of a range of distant-focus X-ray tubes.

Some practical types of distant-focus X-ray tubes

Fig. 9 shows an endotherapy tube the construction of which was described some years ago in this journal (see article 3). The tube has an extended anode in the form of a hollow rod having an inside diameter of only 9 mm, the target of gold-plated copper being mounted at the end. The electrons travel a total distance of 250 mm to the target; for reasons of heat dissipation the focus diameter is fairly large, being 6 mm. Because of the small inside diameter of the rod-anode its overall thickness, including a cooling-water jacket, is no more than 15 mm, which makes the tube eminently suitable for the kind of irradiation required in gynaecological treatments.

The tube shown in fig. 10 is a special type designed for industrial radiography; it operates on 150 kV with earthed anode. The long, tubular anode makes it possible to introduce the source of radiation up to a depth of about 65 cm into narrow pipes, boilers or other hollow bodies. The tube has a round focus, so that the rays emerge with rotational
symmetry. When an X-ray film is placed around the part of a pipe to be examined, a single exposure suffices to obtain a radiograph of the whole 360° periphery of the pipe wall. The electrons in this tube have a trajectory of 800 mm and the focus produced at the end of the rod-anode is only 5 mm in diameter. The cathode cup in this tube has a large diameter as may be seen in the photograph. To produce the round focus required for the applications envisaged, the filament is not of cylindrical form but is wound to form a segment of a sphere (see fig. 11). A cylindrical shield is fitted close to the filament to prevent a halo being produced around the focus by electrons escaping backwards. As appears from fig. 11, the virtual object of this system is again the region where the tangents of the electron trajectories, projected backwards, intersect. The general situation, particularly as regards the function of the accelerating lens, corresponds entirely to that already discussed.

It can also be seen from fig. 11 that the smallest obtainable cross-section of the beam formed by the projected tangents is determined by the filament structure, since the latter governs the directions in

![Diagram](image)

Fig. 10. A 150 kV earthed-anode X-ray tube for the examination of materials. At the end of the rod-anode a round focus of 5 mm diameter is produced; electron trajectory 800 mm long.

![Diagram](image)

Fig. 11. The filament \( W \) of the tube shown in fig. 10 is wound to form a segment of a sphere. With an "auxiliary lens" of suitable power, taken as beginning at the plane \( x-x \), the narrowest cross-section \( F' \) of the pencil of tangents to the electron trajectories is projected as the focal spot on the target.
which the electrons are emitted. With a smooth cathode surface it should be possible in principle to reduce this cross-section considerably, and hence the focus too. However, the fact that X-ray tubes operate in the saturation region of the cathode makes it desirable to use tungsten filament wire, and for a cathode of tungsten wire there are only two constructions stable enough for practical purposes, viz. the helix and the flat spiral.

It may be remarked at this point that, although in the cathode systems so far described an accelerating lens produces an image of a virtual object lying behind the cathode, it is also possible in principle for the virtual object to lie in front of the cathode. For a line focus, the filament would then have to be mounted deeper inside the cathode slot in the system shown in fig. 2; for a round focus as in fig. 11 the spherical segment would have to be inverted, so that its concave side faces the target. Furthermore, the accelerating lens would have to be shifted correspondingly forwards, which can be done by making the cathode cup quite a lot deeper. In general this has the drawback, however, of resulting in a very low field-strength at the cathode. With heavy currents and low voltages the tube then no longer operates in the saturation region but in the space-charge region, one consequence of which is that the tube current and voltage have an undesirable effect on the dimensions of the focus.

Within the permissible range of currents and voltages, this drawback does not attach to systems in which the virtual object is behind the cathode, and therefore such systems are to be preferred.

In fig. 10 a number of parallel bands can be seen encircling the glass envelope. These are thin, equally spaced layers of metal applied to the inside wall of the envelope. Their purpose is to ensure that charges built up on the glass, which are unavoidable with the high tensions involved, will not alter the rotational symmetry of the potential field in the tube. There is thus no risk of the focus being shifted by radial potential differences. Evidently, a tube with the long electron trajectories here employed is particularly sensitive to such shifts. The metal rings have the further advantage of evening-out the potential drop in the axial direction, thereby precluding the occurrence of excessively steep potential gradients anywhere on the glass envelope.

Finally, fig. 12 shows a double-focus X-ray tube, again intended for industrial radiography. The two foci, either of which can be used according to requirements, are line foci with widths of 2.5 and 0.4 mm. Although the electron trajectories are here only 200 mm, the production of the very small focus of 0.4 mm called for a large cathode cup, as can be seen in the photograph and also in the cross-section given in fig. 8.

Summary. Whereas the electron beam in cathode-ray tubes is focused by means of several electrodes or with the aid of magnetic fields, a two-electrode system is normally sufficient for focusing the electrons in an X-ray tube. This article shows that a two-electrode system still serves where the electrons have to describe long trajectories, as in rod-anode X-ray tubes. For this purpose a cup-shaped body is fixed in front of the normal cathode system, basically a coiled filament situated in a slot in the cathode block. The cup has the same potential as the cathode. This arrangement constitutes an “auxiliary lens”. The electrons from the filament can be imagined to originate from a virtual object behind the cathode (or in front, with certain electrode configurations), i.e. a virtual “image” produced by the slot-filament electron-optical system and having a fairly uniform electron distribution. The auxiliary lens produces an image of this virtual object on the target. The position, size and electron density distribution of the virtual object depend on the design of the cathode system; these parameters have been obtained from experiments, for a series of cases, using a rubber membrane analogue. From the optical analogy of the problem it can be concluded that a distant focus calls for an auxiliary lens of low power, i.e. a wide and deep cathode cup. Various types of X-ray tube have been designed on this principle and are briefly described in this article. In one of these tubes a focus of 5 mm diameter is produced at the end of a tubular anode on a target 800 mm from the filament.