June 6, 1961 L. WEGMANN 2,987,641
IRRADIATION SYSTEM FOR AN ELECTRON BEAM APPARATUS WITH COLD CATHODE
Filed Jan. 27, 1958 4 Sheets-Sheet 1

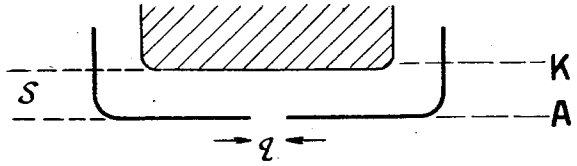


Fig. 1

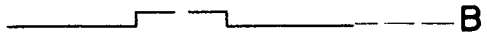
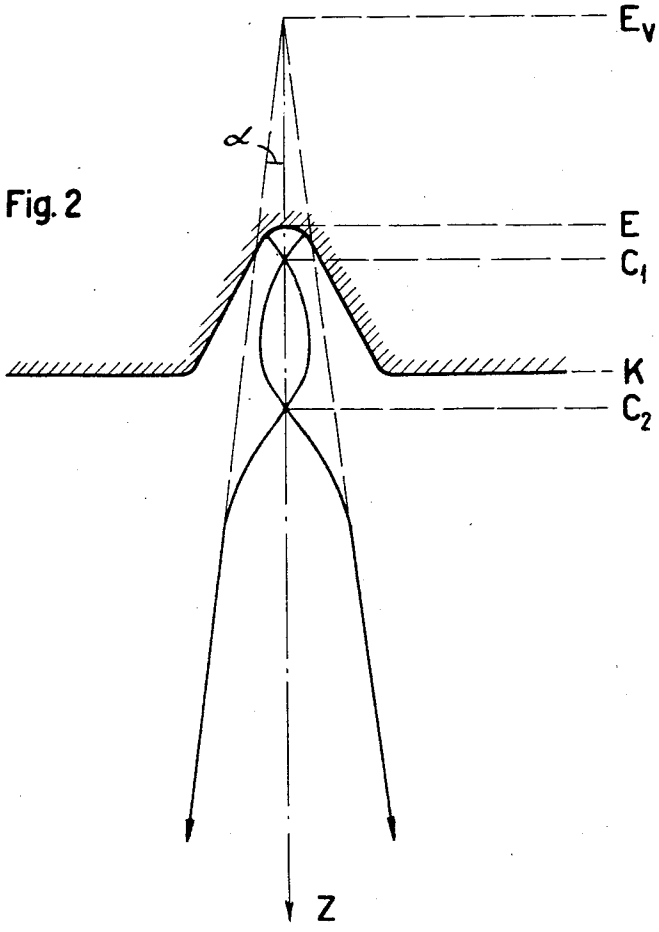


Fig. 2



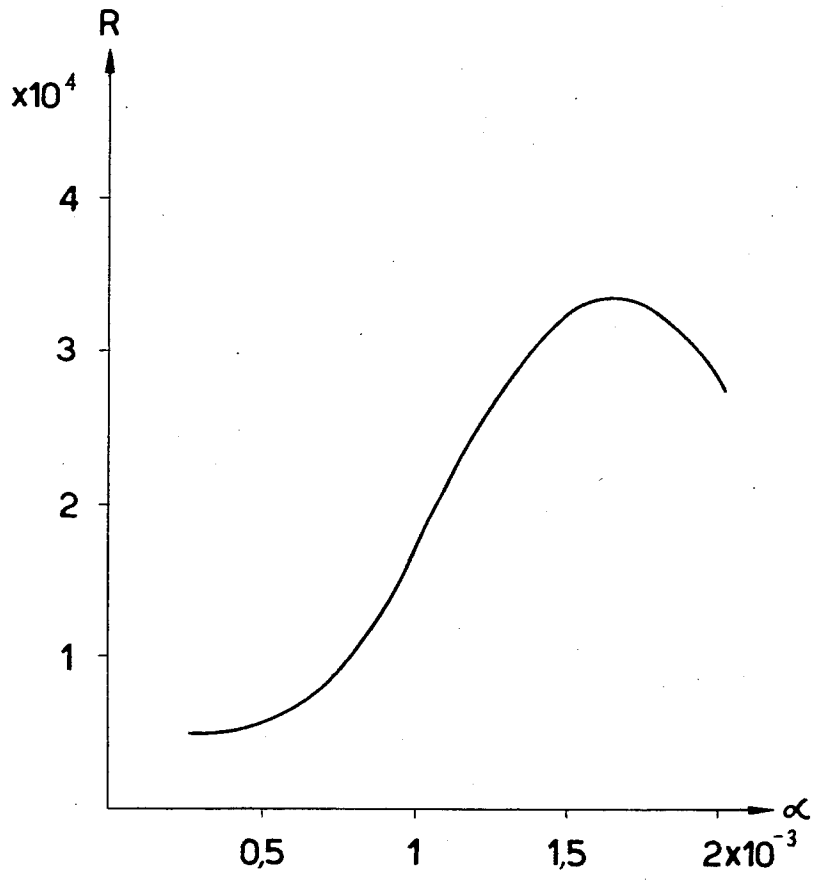


Fig. 3

Fig. 4

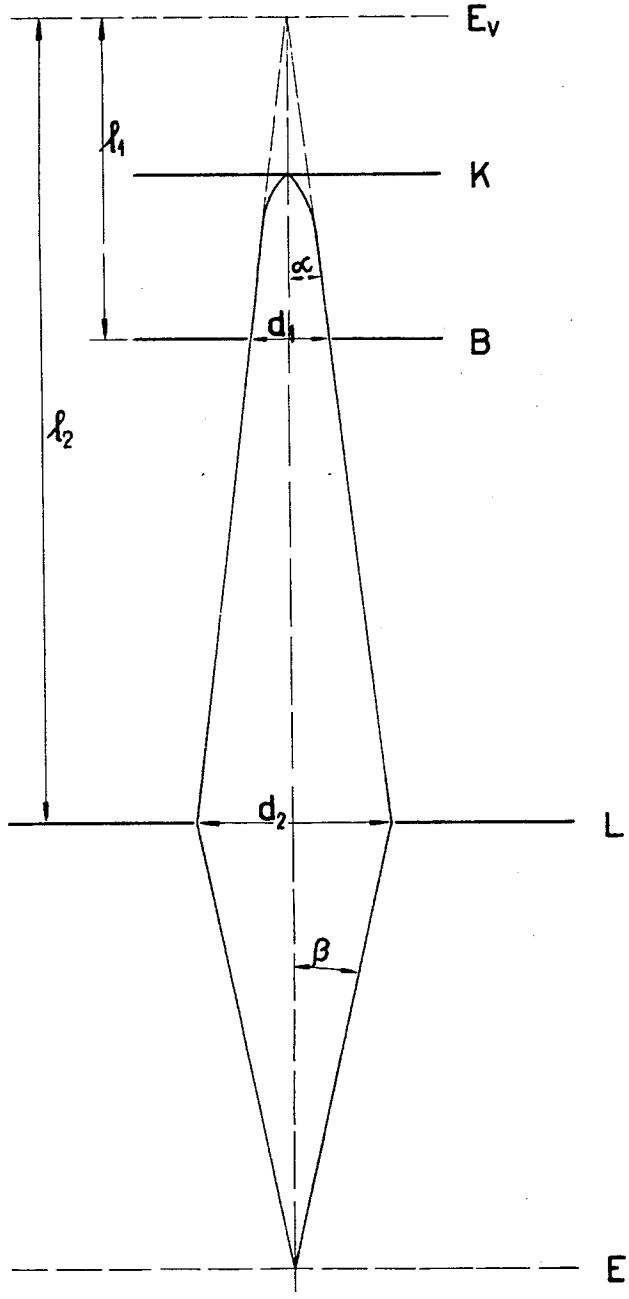


Fig. 5

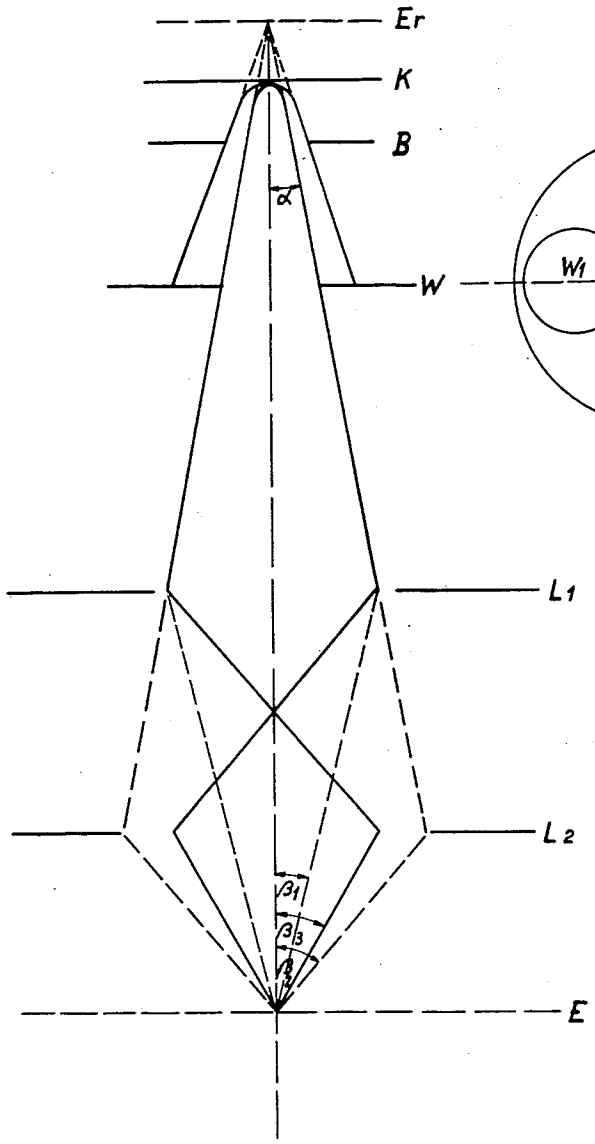
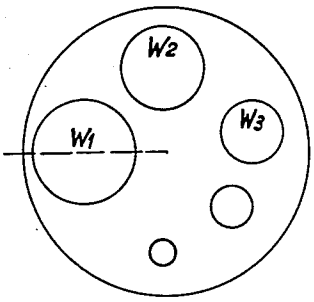


Fig. 6



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2,987,641

IRRADIATION SYSTEM FOR AN ELECTRON BEAM APPARATUS WITH COLD CATHODE

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1 Claim. (Cl. 313—214)

The present invention relates to an illuminating system for an electron-beam apparatus with a cold cathode.

Several principles and arrangements for the production of electron beams have become known, in which the electrons are emitted by secondary emission processes which are effected by ion bombardment of the cathode. These arrangements are called "cold cathodes" in contradistinction to electron sources with thermal electron emission.

The disadvantage of the cold cathode is the small and changing intensity of the electron beam emitted. With the use of known illuminating arrangements having the cold cathode the intensity of the electron beam used in the electron beam apparatus after the first switching of the cathode voltage is yet comparable with that of arrangements with thermal emission; it declines however continuously during the initial minutes or hours of the burning period—depending on the cathode material used—to about one third to one sixth of the initial value. At this reduced value the intensity remains for the rest of the lifetime of the emission spot. The intensity of the cold cathode available over a prolonged time lies accordingly by factors of 5 to 20 below the values attainable with thermal cathodes at the same accelerating voltage.

For this decline in intensity mainly two reasons have been given:

On the one hand by the ion bombardment a change of material may take place at the point of the emission spot. This may be a contributory cause with a few metals having a pronounced oxide skin, but in general such a change cannot be held to be the main factor responsible for the decline in intensity. The fact that the emission is very largely independent of the cathode metal used, is a strong argument against such assumption. The main reason for the decline in intensity is the formation of a crater caused by the ion bombardment. At the place of the emission spot after a certain burning time an erosion crater is formed which gains in depth with continued time of burning and, depending on the resistance of the cathode material and on the average emission current, may reach after several hundred or thousand hours a depth of one centimetre or more. The lifetime of a cathode is accordingly limited also by the fact that at a certain depth of the crater the focussing properties of the ion optics are changed and the intensity is thereby further reduced, or that the whole depth of the cathode material is pierced, whereby a so called molecular cathode is formed which also has a lower intensity of emission than a cold cathode.

That this crater formation is responsible for the disturbing decline in intensity, has been recognized before, and there was accordingly no lack in attempts of improvements, all of which aimed at obviating the crater or at changing the location of the burning spot before the formation of a crater has progressed to a certain extent. In principle, this was mostly the question of embodiments with a rotatable or continuously rotating cathode; in some embodiments the solid cathode material has also been replaced by a liquid metal which automatically restores the material at the emission spot. Apart from the technical insufficiency of the last solution, all these proposals have the disadvantage that on the one hand they complicate the simple arrangement of the cold cathode and thereby affect also the stability of emission, and that on the other hand the pointshape of the cold emission is not assured before the formation of a crater. It is in fact the crater which helps to form the "pointshaped" emission spot for the electrons. It is therefore undesirable to obviate the crater formation altogether.

The present invention has the main object of providing a system which provides in an electron beam apparatus an electron beam of sufficient intensity with a burnt-in crater, and accordingly with a point-shaped spot of emission. It is another aspect of this object to investigate the reasons why the intensity prevailing before the crater formation disappears to its greater part after the formation of the crater, and to provide means for restoring this intensity in the electron beam apparatus for a prolonged burning time. For this purpose detailed investigations and measurements have been made.

The advantages of the cathode which is the subject of this invention, which in the literature is often called an Induni cathode, are as follows: owing to the short distance between the cathode and an anode placed to cover the cathode, with an appropriately dimensioned hole in the anode, the ions passing the hole are focussed on to the cathode so that a very small emission spot of a few hundredths of a millimetre in diameter only is formed. This well point-shaped source has a life period of several hundred to several thousand hours, which is very long in comparison to that of thermal cathodes. On the other hand the stability in operation of the Induni cathode is very high as compared with other cold cathodes, which have no holed anode at a smaller distance from the cathode than the mean free length of path and its intensity is easily and continuously adjustable within a wide range i.e. of about 1:100 by the gas pressure, without affecting the stability of the discharge.

The invention is illustrated in the accompanying drawings, in which FIG. 1 is a diagrammatic illustration of one embodiment of the invention including a cathode, an apertured anode and a second apertured anode, all suitably related and spaced;

FIG. 2 diagrammatically shows a cathode surface with a burnt-in crater and the trajectories of the electron emission;

FIG. 3 is a curve showing the functional relationship between the directional beam angle and the brightness of the beam;

FIG. 4 is a diagrammatical representation of a device for ascertaining the correct dimensions of a cold cathode system comprising a cathode, an anode diaphragm and an electron lens;

FIG. 5 is a diagrammatical representation of a similar device, two lenses being shown; and

FIG. 6 illustrates a diaphragm, for use with a device as shown in FIG. 5, with apertures of different sizes.

FIG. 1 illustrates one embodiment of cold cathode system which has proved to be particularly successful. Here, the cathode K, which is normally charged at a high negative voltage is in juxtaposition firstly to a holed anode A and then to a further anode B which contains the anode diaphragm. The two anodes A and B are generally kept at earth potential or close thereto. It is, however, essential only that between K and A a high voltage difference is present, and between A and B a small one. The described arrangement functions correctly when the gas pressure in the discharge chamber is so adjusted that the mean free length of path of the molecules or ions is larger than the distance between the cathode K and holed anode A, and smaller than the distance between the cathode K and anode diaphragm B. The ions are then sucked from the gas space between the anodes A and B towards the cathode K where

they are focussed at the same time, and there release the electrons which are accelerated in a fine beam towards B, and fall through the anode diaphragm B into the electron beam apparatus proper, for example an electron microscope, an electron diffractograph or an electron oscillograph.

The results of the aforementioned researches will now be described with reference to FIGS. 2 to 4 of the accompanying drawings, and on the basis of these results an illuminating system will be disclosed fulfilling these requirements, as well as a method leading to the correct dimensioning of this irradiation system.

From these researches follow the below-stated important and partly quite new realizations:

(1) With the burnt-in crater at least two cross-overs are formed in the trajectory of the electrons in or immediately in front of the crater. An example of such a trajectory of the beam is diagrammatically illustrated in Fig. 2, however with largely overdimensioned angular aperture. In the cathode K a crater has formed itself, at the bottom of which there is now located the emission spot E. The criterion for the crater or emission spot to be "burnt-in" is the necessity of a point shape of the source of emission E, which may be controlled by dimensioning and adjusting of the electron beam apparatus. As long as the burning-in of the crater is not complete, the emission spot projected is large (about 1 mm. in diameter). With the crater increasing in depth it is reduced in diameter, and then attains a diameter of 3×10^{-2} millimetres which apparently corresponds to that part of the crater bottom which, viewed optically, emits in the direction of the anode diaphragm. The crater walls which also, but likewise weakly, emit in the direction of the anode diaphragm will be disregarded hereinbelow, since the intensity of their radiation is 100 to 1000 times lower.

The field between anode and cathode penetrating into the crater forms a lens which forces the emitted rays to deviate slightly laterally from the Z-axis on which the emission spot is located (paraxial rays) to pass at least two cross-overs C_1 and C_2. The trajectory is apparently influenced on the one hand by the lens effect of the crater and on the other hand by the geometrical form of the emitting bottom of the crater.

(2) As with most electron beam emitters with high beam brightness, the trajectory of the rays in an Induni cathode with crater is also such that a virtual spot may be assumed present behind the cathode. The position of the virtual spot is accurately defined by the ratio of the tangential initial velocity of the electrons to the accelerating voltage. This point may be found approximately also as the point of intersection of the asymptotes of the trajectories drawn in FIG. 2, forming thereby the virtual apex of the emission cone. The error made by this approximative determination is equal to the radius of the virtual emission spot E_v divided by the angular aperture α. The angular aperture α may be referred to as the cathode-side aperture. This magnitude is small as compared with the distance between the virtual emission spot and the first projecting lens of the electron beam apparatus, and may accordingly be disregarded.

(3) The measurement of the intensity distribution of the emission of such an Induni cathode with a crater shows that a "hollow beam" is present. This hollow beam is defined by that the maximum of the integral beam brightness does not coincide with the zero aperture angle. The value R of the beam brightness is defined as the electron current emitted per area unit at the respective aperture angle. When the emission cone is spread out symmetrically to the Z-axis, the integral beam brightness is thereby defined. A hollow beam then means that the beam brightness plotted as a function of the aperture angle does not decrease continuously in the manner of a Gauss's distribution or of a bell-curve from maximum at zero aperture angle, but increases first from its value for zero aperture angle towards wider angles, and then drops again after having reached a maximum.

Such a measured curve is plotted in FIG. 3. It has been measured on an Induni cathode at 56 kv. The beam brightness R is plotted in amps. per $cm.^2\times radians^2$ as a function of the angular aperture α. The graph shows that the measured Induni cathode with burnt-in spot has for example a maximum of beam brightness for an angular aperture of about 1.6×10^{-3}, and that this value is six times higher than the beam brightness for small apertures.

An idea on the formation of this hollow beam can be obtained with the aid of FIG. 2. It is sufficient for the formation of a hollow beam that the bottom of the crater has a shape at which the radius of curvature continuously increases from the centre on the Z-axis outward. This shape of the crater bottom cannot be controlled by reason of the small dimensions of the crater. Whether or not this hypothesis is correct, is not of decisive importance, since emphasis is placed only on the presence of a hollow beam, and not on the cause of its formation.

(4) With a suitable dimensioning of the Induni cathode its intensity distribution remains unaltered over a long period.

This result is by no means self evident. It may be assumed that on the one hand the field in the crater varies with the depth of the crater, and that accordingly the lens effect of this penetration varies. On the other hand the bottom of the crater may also vary its shape with increasing depth, and the maximum of the beam brightness may thereby be shifted to a different angular aperture. This is in fact the case with arbitrary dimensioning, and the irradiation system then maintains its optimal properties only during a relatively short time. With increasing depth of the crater it does not work any more under optimal conditions, and loses accordingly in intensity. Since the lifetime is defined in that the obtainable intensity does not substantially vary during this period, this lifetime is comparatively short with wrong dimensioning and may drop to less than 100 hours even for a suitable cathode material.

On the other hand, it can be ascertained experimentally that with correct dimensioning the intensity and the distribution thereof does not vary over a long period after the effective burning-in of the spot, i.e. over several hundred hours, provided a suitable cathode material, for example chromium steel, is used. This is the case when the diameter of the hole of the holed anode A is equal to or little smaller than the distance between the cathode K and the anode A. The diameter is to be considered "little smaller," if the difference does not exceed 25%. A further but known condition is that the distance between the holed anode A and the anode diaphragm B must be larger than two and a half times the distance between the holed anode A and the cathode K.

Taking into consideration these new discoveries, an illuminating system with an Induni cathode will now be so dimensioned that the electron beam apparatus is supplied by it with the maximum possible yield in electron radiation. In most cases the essential point is to generate at a certain place in the apparatus a maximum area density of the electron beam; for example in an electron microscope at the location of the preparation in order to achieve maximum luminosity of the largely magnified image on the luminous screen; or in an electron oscillograph so as to obtain on the luminous screen or on the photographic layer a radiation or blackening of the highest possible intensity, respectively. In all these cases important is not the overall intensity of the electron radiation in the plane in question, but the area density of the electron beam. In most cases additional limitations intervene for the aperture angle under which the electron trajectories hit this plane so that the magnitude decisive for the quality of the illuminating system must be defined as the electron

current per area unit at the respective angle aperture, measured in a plane on which the electron beam is focussed for a certain purpose. The same magnitude, defined in the plane of emission, will be called the beam brightness R. Denoting j the electron current per area at the respective angle aperture measured in amp./cm.^{2}.radians^2 in a predetermined plane of the apparatus, and β the aperture angle measured in radians, under which the electron rays are allowed to enter into this plane (FIG. 4), the equation is:

$$j=\pi.R(\alpha).\beta^2 \tag{1}$$

In this equation R (α) is the beam brightness of the Induni cathode for example plotted in FIG. 3. The Equation 1 shows that the essential value j reaches a maximum where R has a maximum.

An illuminating system according to the invention can accordingly be dimensioned as follows:

(a) According to point 4 of the above description the Induni cathode has to be so dimensioned that the diameter q of the hole in the holed anode is equal to or little smaller than the distance S between cathode and holed anode. For example, if the distance between cathode and holed anode is 1 cm., the diameter of the hole will be between 7.5 and 10 mm.

(b) This cathode has to be operated at a gas pressure at which the mean free length of path of the ions is larger than the distance between cathode and holed anode. For example for a distance of 10 mm. a pressure better than $\frac{1}{100}$ Tor is appropriate.

(c) The cathode is kept in operation until a crater according to point 1 is burned-in.

(d) With the aid of a diaphragm (for example B in FIG. 4) of variable diameter and of a receiver placed in the beam unaffected by the said diaphragm the electron current (amp.) i_1 is measured in dependance on the diameter d_1 of the diaphragm hole.

(e) The same measurement is repeated with a diaphragm with varying hole diameters in another plane (for example in the plane of the lens L). This gives the electron current i_2 as a function of the diameter of the diaphragm hole d_2.

(f) From these two measured curves the beam brightness of the cathode used is calculated as follows:

$$R(\alpha)=\frac{i}{\frac{\pi D^2}{4}\cdot\pi\alpha^2} \tag{2}$$

wherein D is the diameter of the emission spot in the location of the virtual emission spot E_v. In FIG. 4 the crater and the two cross overs C_1 and C_2 of FIG. 2 could not be represented since the whole crater at the scale of FIG. 4 is too small therefor. The structure of the emission spot on K and the structure of the beam in its vicinity is, however, the same as illustrated in FIG. 2. FIG. 4 has been laid out for geometrical considerations for which the knowledge of the distance $K-E_v$ is sufficient. The aperture angle α to be inserted is yet unknown and must still be determined. Since according to FIG. 4 α is defined by

$$\frac{1}{2}\frac{d}{l}$$

wherein l is the actual distance of the diaphragm from the virtual emission spot E_v,

$$R(\alpha)=\frac{i_n}{\frac{\pi D^2}{4}\cdot\pi\frac{d_n^2}{4l_n^2}} \tag{3}$$

wherein the indices 1 and 2 of the measurements carried out are to be inserted for n. Moreover the two measurements performed must of course yield the same value R(α) so that:

$$i_1\frac{\pi D}{4}\pi\frac{d_2^2}{4l_2^2}=i_2^2\frac{\pi D^2}{4}\pi\frac{d_1^2}{4l_1^2} \tag{4}$$

wherefrom a value for the magnitude

$$\frac{l_1}{l_2}$$

results. Since from FIG. 4 also the magnitude l_2-l_1 is known, l_1 and l_2 can be computed therefrom.

(g) In this manner the distance of the virtual emission spot E_v from the cathode K is found.

(h) Now by means of one or more lenses (for example L), the emission spot is projected onto a plane E and its diameter D_E is measured there. From the distances $L-E$ and $L-E_v$ results the enlargement or reduction, and hence the diameter D of the virtual emission spot E_v.

(i) With the measured magnitudes d and i and the calculated magnitudes D and l it is now possible to calculate from Equation 3 the beam brightness for each measured point, and to plot the graph of R(α) as in the Fig. 3.

(k) According to point 3, this graph has a maximum at a certain value α_0 of α.

(l) A diagram limiting the aperture angle on the cathode side is so dimensioned that the quotient of the radius of the diaphragm hole by the distance of this diaphragm from the virtual emission spot (E_v) is equal to α_0. This diaphragm may lie anywhere between the anode diaphragm B and the lens diaphragm L, including the location of both these diaphragms. However, it must be the only diaphragm limiting the aperture angle on the cathode side.

An illuminating system demensioned in the manner yields according to Equation l the optimum radiation in a predetermined plane. When for example the aperture-limiting diaphragm is inserted into the lens L, the further step is that with predetermined planes of L and E the diameter d_2 is so selected that a predetermined focussing aperture β results. Then by d_2 and α a distance l_2 is detemined which determines likewise the distance of the cathode K from the lens L. The dimensioning according to the invention lies in this case substantially in the selection of the correct distance between cathode and lens. When the aperture limitation lies closer to B, same procedure is applied accordingly.

The Equation 1 determines only the maximum area density in the plane E. Smaller densities can be attained by variation of the focal length of the lens or lenses L or by exchanging the diaphragm for one having a hole of smaller diameter.

Likewise by the dimensioning according to the invention the diameter of the image of the emission spot is given for the maximum luminosity. By the choice of two or more lenses L for the dimensioning according to the invention of the illuminating system it can be attained that by withdrawing or adding one or more lenses a variation of the image diameter can be attained even in a focussed condition, however always by sacrificing part of the area density.

It suffices however for fulfilling the requirements to the system according to the invention if the conditions are satisfied for one certain set of diaphragms and of focal lengths of the lenses.

A system with two lenses according to the present invention is illustrated in FIG. 5. The anode diaphragm B does not here limit the aperture, neither does so one of the two lenses L_1 and L_2. The aperture-limiting diaphragm is arranged separately, namely in such a manner that diaphragm W_1, W_2, W_3 etc. of different size (FIG. 6) can be brought into the path of the beam.

According to the invention the diaphragm W_1 is to be for example so dimensioned that the aperture angle related to the virtual emission spot corresponds to the maxi-

mum of the beam brightness. In this case the luminosity j at the respective angle aperture reaches the maximum possible value for any angular aperture β realised in the image plane, according to the Equation 1 $j=\pi.R.\beta_1^2$ in the case of the lens L_1 alone being inserted, or $j=\pi.R.\beta^2$ when only the lens L_2 is inserted. R is then always the maximum attainable, since α has been chosen appropriately. In both cases, however, the luminosity is different, and also the illumination aperture β and likewise the size of the illuminated area. The diameter of the latter is defined by

$$Q=D.\frac{\alpha}{\beta} \qquad (5)$$

wherein D denotes as before the spot diameter of the virtual emission spot E_v. The same Equations 1 and 5 apply to the case that both lenses L_1 and L_2 are inserted, and the emission spot is again projected onto the plane E. Then β_3 may vary between β_1 and β_2 depending on the focal length of the lenses L_1 and L_2.

All these possibilities concern the maximum luminosity. When the latter is to be reduced, this is effected by varying the focal length of one of the lenses L_1 or L_2; the projection of the emission spot then no longer occurs in the plane E. In this plane accordingly β and at the same time j diminish.

When, however, the luminosity is to be reduced while the aperture angle β remains constant, the focal lengths of the lenses are left unaltered, and one of the diaphragms W_2, W_3 etc. is swung into the path of the beam, whereby the effective aperture angle α is reduced. Accordingly in the Equation 1 a smaller value $R(\alpha)$ of the beam brightness becomes effective.

Somewhat more complicated, but still soluble with the explanations given, are the conditions, when the aperture-limiting diaphragm lies between L_1 and L_2, or in L_2. According to the invention then the effective aperture diaphragm must at least at one certain combination of the focal lengths of L_1 and L_2, limit such a bundle of rays, that its boundary constitutes the optimum aperture α in the space above L_1.

The arrangement described hereinabove is suitable for the greatest variety of electronic appliances; the plane E constitutes for example the object plane in an electron microscope, the object diaphragm or luminous screen plane in a diffraction apparatus, the luminous screen plane in a cathode ray oscillograph, or the anti-cathode in an X-ray tube.

Depending on the type of apparatus, various additional electron-optical elements may be inserted between those of the illumination system, for example between the lens L_1 and the cathode or between the lenses L_1 and L_2 a diaphragm in a cathode ray oscillograph, or between the lenses and the plane E some deflection systems in an oscillograph or object holders in a diffractograph.

While I have described herein and illustrated in the accompanying drawings what may be considered a typical and particularly useful embodiment of my said invention I wish it to be understood that I do not limit myself to the details and dimensions described and illustrated, for obvious modifications will occur to a person skilled in the art.

What is claimed is:

An electron beam producing apparatus for a cathode ray tube comprising a cold cathode, an anode spaced from said cathode having an aperture therein of a diameter smaller than the distance between said cathode and said anode, an anode diaphragm spaced from said anode on the side thereof opposite to said cathode by a distance of at least 2.5 times the distance between said cathode and said anode, and a gas applied in the apparatus between said cathode and said anode diaphragm at a pressure whereby the mean free length of path of the ions in the gas is greater than the distance between said cathode and said anode and smaller than the distance between said cathode and said anode diaphragm.

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