A CATHODE RAY TUBE WITH POST-ACCELERATION

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In order to obtain a high scanning speed with a cathode ray tube it is desirable to raise the accelerating voltage for the electrons as high as possible. In the ordinary models this attempt is limited because of the fact that the dimensions of the tube would have to be increased with the voltage and the deflection sensitivity would decrease. These disadvantages are very much reduced when post-acceleration is applied i.e. when the electrons are accelerated anew with the help of an extra electrode after they have passed the deflection plates. By this means a considerably higher scanning speed can be attained without it being necessary to increase the dimensions of the tube, while in addition the sensitivity is not so unfavourably affected as when the electrons have already attained their final velocity before they pass the deflection system. In this article the post-acceleration tube DN 9-5 is described which has been developed from the cathode ray tube DN 9-3. The electrode for post-acceleration can be given a voltage of 5 000 volts with respect to the cathode. A maximum scanning speed of 24 km/s is hereby obtained. A detailed account is given of the way in which the post-acceleration electrode affects the deflection sensitivity of the cathode ray tube and of the way in which the distortions caused by the post-acceleration electrode are combated.

A very important quantity for the characterization of a performance of a cathode ray tube is the maximum scanning speed, i.e. the maximum speed at which the light spot may move on the screen of the cathode ray tube in the case of a phenomenon occurring only once, in order to be visible or to be recorded photographically. In an earlier article in this periodical 1) an account was given of the electrical tube properties and factors of the photographic process which determine the maximum scanning speed. As to the electrical tube properties, in order to obtain a high scanning speed, provision must be made for a high beam current, a small diameter of the spot and a high speed of the electrons which strike the fluorescent screen. In the photographic method, moreover, it is chiefly a question of a large relative aperture of the photographic objective and the greatest possible reduction in size of the photograph.

In order to illustrate the scanning speeds which can be obtained with ordinary types of cathode ray tubes, an investigation may serve which was carried out on the cathode ray tube DN 9-3 (a tube with a screen diameter of 9 cm, which is employed in the cathode ray oscillograph CM 3 152). The accelerating voltage in this case amounted to 1 000 volts, the current in the beam to 20 μA. The oscillogram was a reduction of the image in the ratio 1 : 4, while a lens with an aperture 1 : 2.2 was used, such as is found in many of the miniature cameras at the present time. The film used was Agfa Isopan. It was found that the greatest scanning speed with which an easily visible blackening of the film is obtained amounts to 850 m/s. This means that a phenomenon with a duration of $10^{-5}$ sec can be represented by a line of 8.5 mm arc length. In many technical applications this will be adequate, but for the investigation of breakdown phenomena, surge voltages, etc., where processes with a duration of $10^{-6}$ or $10^{-7}$ sec may occur, considerably higher scanning speeds are required.

The obvious method of solving the difficulties is by trying to increase the scanning speed by choosing more favourable values for the above-mentioned factors which determine the scanning speed. An increase in the scanning speed by a reduction in the diameter of the spot (0.8 mm) is, how-

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ever, practically impossible, since the constriction of the beam is limited by the mutual repulsion of the electrons. This repulsion is also the cause of the fact that no success is achieved by increasing the beam current; this would result in an increase in the diameter of the spot, which is undesired in connection with the sharpness of the oscillogram and, moreover, has an unfavourable effect on the scanning speed, which is inversely proportional to the spot diameter at a given light intensity.

It is indeed possible to obtain a very appreciable improvement by increasing the accelerating voltage. In the first place, with constant current more power is converted into light, and proportional to this power the maximum scanning speed also increases. In the second place the efficiency of the conversion also becomes greater (see fig. 1), so that the amount of light produced with an increase of the voltage from 1 000 to 5 000 volts, for instance, is not five times, but more than ten times as great. In the third place the mutual repulsion of the electrons becomes continually less effective with increasing velocity, so that the light spot on the screen can be reduced in size, which, as we have seen, means an increase in the scanning speed obtained. In the fourth place, in certain cases when there is no particular need of this reduction in spot diameter, it would be possible to increase the current with increasing voltage, whereby the power, and thus also the scanning speed, would increase still more. Practically, an increase of the voltage by a factor 5 means an increase in the maximum scanning speed by 25 or 30 times.

Any considerable increase in the accelerating voltage is, however, not immediately possible in cathode ray tubes of small dimensions such as are used in portable types of cathode ray oscillographs. The insulation of the leads in the tube DN 9-3 is calculated for potential differences of 1 000 or perhaps 1 200 volts. For 2 000 volts the base would have to have dimensions which cannot be considered for a portable instrument. Another, fundamental, objection to the increase in voltage is that the deflection sensitivity of the tube is hereby decreased, since the deflection of the cathode ray by a given deflection voltage is inversely proportional to the accelerating voltage. With an accelerating voltage of 1 000 volts the deflection sensitivity of the tube DN 9-3 is 0.4 mm/volt for the first set of plates and 0.3 mm/volt for the second, and these values must not be decreased too much by the increase in the accelerating voltage.

**Principle of the post-acceleration tube**

It is possible to overcome the above difficulties by making the acceleration take place in two stages instead of directly. The focussing system forms an electron beam with a velocity corresponding, for instance, to 1 000 volts. This beam passes successively the systems for vertical and horizontal deflection and then undergoes a second acceleration with the help of an electrode at a considerably higher potential, and at such a distance from the other electrodes that the insulation does not present insuperable difficulties. If, in addition, this second acceleration, the so-called post-acceleration of the electron beam, is made to take place in such a way that the direction of the beam remains unchanged, the second objection to the high voltage, decrease in sensitivity, is eliminated.

If we wish to accelerate the electrons which leave the deflection system without changing their direction, we must excite an electric field whose equipotential surfaces are perpendicular to the trajectories of the electrons.
space the desired character, it is sufficient to cause the potential at the boundaries of the tube to vary in the correct way. This can be done by covering the walls of the tube with ring-shaped conducting strips, corresponding to the lines of intersection of the equipotential surfaces and the wall of the tube, and bringing these strips to the desired values of the potential (see fig. 3). In practice it has been found that such a complicated structure is unnecessary; instead of a large number of narrow strips, two broad coatings can be used: one at 1 000 volts, i.e. the potential which determines the speed of the electrons in the deflecting system, and one at 5 000 volts, for instance, which determines the speed at which the electrons impinge on the fluorescent screen.

The principle of this arrangement is shown in fig. 4. As may be seen from the equipotential surfaces which hereby occur, the potential field has not exactly the desired character, and it is found that the post-accelerating field also deflects the electron trajectories, so that the sensitivity of the tube decreases slightly with increasing post-acceleration. We shall examine this phenomenon more closely because the attempt to combat it has had some influence on the construction of the new tube.

The lens action of the post-acceleration electrode 2)

In order to describe the motion of an electron in an electrostatic field qualitatively, use can often be made of an analogy between the trajectory of an electron in a potential field and the path of a light ray in a medium with an index of refraction which is in general variable. This analogy is as follows. If an electron at a point at zero potential has the velocity \( v_0 \) and if, to every point in space, an index of refraction given by the following is ascribed:

\[
 n = \sqrt{\frac{v_0^2 + \frac{2e}{m} V}{v_0^2}}
\]

where \( V \) is the potential at the point in question, then a light wave which is emitted in the same direction as the electron follows the same trajectory as the electron 3). If we apply this proposition to the space behind the deflection system of the post-acceleration tube, we see that, after passing the deflection system in fig. 4, the electron beam first passes through a number of less strongly negatively refracting planes. To make this clear, the optical system which is formed in this way is given in fig. 5b. In this figure the positive and negative refracting surfaces lying close together are indicated by a single surface.

The system already shows some similarity with an optical lens, with this difference, that the index of refraction is greater in the image space than in the lens itself. We may, however, adopt more normal relations by setting the index of refraction in the image space equal to unity once more, and at the same time changing the curvature of the last lens surface so that the refractive properties of the lens remain the same. The lens represented in fig. 5c is then obtained, with a convex and a concave surface. The vertical planes \( H \) and \( H' \) in fig. 5c indicate the main planes of the lens and show that the lens must be imagined somewhat closer to the deflection system than the middle of the open space.

3) The following considerations were first given by W. Rogowski and H. Thiele: Über die Nachbeschleunigung bei Braunschen Röhren, Arch. Elektrot. 33, 411, 1939.

2) This proposition can most easily be deduced from the analogy between the so-called principle of least action of Maupertuis:

\[
 \int \sqrt{T \ ds} \rightarrow \text{minimum for the trajectory actually described of a mass point (T kinetic energy, ds element of trajectory)}
\]

and the proposition of Fermat for optics:

\[
 \int n \ ds \rightarrow \text{minimum for the path chosen by the light (n index of refraction)}.
\]

The quantity under the radical sign in equation (1) is, except for a factor, nothing else than the kinetic energy, from which the analogy between electron trajectory and light ray immediately follows.
between the coatings. We shall use this optical picture further in the discussion of the influence of the post-acceleration on the deflection of the beam.

![Diagram of lens action of the post-acceleration field.](image)

Fig. 5. Lens action of the post-acceleration field.  
a) Form of the equipotential surfaces.  
b) Lens, which would have the same refracting effect on a light ray as the electric field on the electron trajectories.  
c) Lens, derived from b) by reversing for the second surface both the sign of the curvature and the sign of the change in index of refraction, so that the refraction of this surface remains the same. The optical analogy with the potential field thus obtained is a lens in air. \( H \) and \( H' \) are the main planes of the lens.

It is very important for the sensitivity of the cathode ray tube at what point this lens is situated and how strong it is. Figs. 6a-f make this clear. In cases a and b, which most closely approach the form actually chosen, the lens is quite weak, but still strong enough to cause the deflection of the beam to decrease appreciably. Fig. 6c represents a considerably stronger lens. The residual deflection of the beam now becomes very small. It is therefore clear that the decrease in sensitivity upon application of post-acceleration need by no means always be smaller than with a direct acceleration of the electron beam. It may even happen that no sensitivity at all remains (fig. 6d), or that the sign of the deflection is reversed by the post-acceleration lens (fig. 6e). In the last case it is even possible theoretically to increase the strength of the lens so much that the absolute value of the deflection becomes greater than the original deflection in the absence of post-acceleration (fig. 6f). In practical cases the possibilities offered by e and f cannot be used directly because a very strong deflection of the beam is always accompanied by distortions. We are thus concerned with cases a, b and c where the sensitivity is decreased by the action of the post-acceleration, and we can only try to choose

![Diagram of influence of the post-acceleration lens on the deflection of the electron beam by the deflection plates.](image)

Fig. 6. Influence of the post-acceleration lens on the deflection of the electron beam by the deflection plates.  
a) and b) Weak post-acceleration lens. The deflection of the electron beam is only slightly decreased.  
c) and d) Strong post-acceleration lens. The deflection of the electron beam is considerably diminished and disappears in the last case entirely.  
e) and f) Very strong post-acceleration lens. The deflection of the electron beam has a direction on the screen opposite to that caused by the deflection plates. In the last case the absolute value of the deflection caused by the presence of the post-acceleration lens is increased.
the conditions in such a way that this decrease is as slight as possible.

In the first place the lens itself must be made as weak as possible. The strength of the lens increases with increasing post-acceleration voltage, so that in practical cases this voltage will not be made higher than necessary for the particular phenomenon to be projected on the screen. The absolute value of the voltage is not actually the determining factor for the strength, but the relation between the voltages of the first and last coating. It might therefore be imagined that the lens could be made weaker by increasing the voltage of the first coating. In doing this, however, as already mentioned, one is limited to about 1000 volts in the case in question due to considerations of a structural nature.

When the voltages of the coatings are chosen, the strength of the lens can still be affected by suitable construction of the electrodes. To make the lens as weak as possible the diameter of the electrodes must be as large as possible. By constructing the electrodes in the form of wall coatings, this condition is satisfied, the diameter of the tube is naturally limited by the size of the oscillograph apparatus. Furthermore, the strength of the lens increases with increasing distance between the coatings and this should therefore be taken as small as possible. A practical limit is set to this by the requirement of sufficient insulation. This point will be considered further in the following.

Finally an attempt may be made to choose the position of the lens in the tube so that its deflecting effect is as small as possible. In this respect a certain amount of variation is found to be possible with a given strength of the lens.

If for a weak lens the magnitude of the deflection finally obtained is calculated as a function of the position of the lens, it is found that the deflection has a minimum when the lens is situated symmetrically with respect to the point halfway between the deflection plates and the point at the centre of the screen. Every displacement from this plane of symmetry thus improves the sense of the lens, for example it might for example be placed as close as possible to the screen. This displacement is, however, limited by the fact that, as we have seen, the lens is always further away from the screen than the open space between the coatings, which themselves must be applied at not too small a distance from the screen, since otherwise the potential does not attain the desired high value over the whole surface of the non-conducting screen. If one attempts, conversely, to displace the lens as far as possible towards the deflecting system that difficulty does not arise, but the equipotential surfaces of the post-acceleration field are then deformed by the presence of the field of the deflection plates, which is not rotation symmetrical, and the lens exhibits an astigmatism. This difficulty, however, is found not to be unconquerable, so that the second method is to be preferred. In the discussion of the practical construction we shall see how the astigmatism is corrected.

Construction of the post-acceleration tube

Fig. 7 is a photograph of the post-acceleration tube DN 9-5.
tube DN 9-5. Both the external dimensions and the internal electrode system correspond in the main to those of the tube DN 9-3 previously de-
scribed 4) of the cathode ray oscillograph GM 3 132. The most important difference is that the conducting coating on the inner wall of the tube is split into two coatings A and B, of which part A as in it was made possible for the voltage on electrode B to be raised to 5 000 volts without danger of flash-over between the two coatings.

The internal electrode system of the post-acceleration tube is shown diagrammatically in fig. 8 while fig. 9 is a photograph of the system. The electrons which leave the cathode k and pass the regulatory electrode g, then they are accelerated by the tubular anodes a1 and a2, the first of which is at an adjustable focussing voltage of about 275 volts and the second at the acceleration voltage of 1 000 volts.

The electron beam which leaves the focussing system passes the two sets of deflection plates D1 and D2 which serve for vertical and horizontal deflection, respectively, of the electron beam. The system D2 has two rods d which serve to eliminate the so-called trapezium distortion which occurs when a non-balanced voltage is applied to the second set of deflection plates 6).

Due to the post-acceleration two other types of distortion also occur, namely:
1) an astigmatism of the electron beam, which has already been mentioned in connection with the choice of position for the post-acceleration lens;
2) a barrel-shaped deformation of the oscillogram.

Both coatings consist mainly of a deposit of graphite on the inside of the glass. In order to make the edge of electrode A smoother in order to increase the flashover voltage, at the edge the graphite was replaced by platinum; in addition, in front of this edge lie several ring-shaped stripes of the platinum deposit which are not brought to a definite potential, but are free to become charged. These stripes influence the distribution of potential between the coatings in such a way that the breakdown potential becomes still higher. In this way when a non-balanced voltage is applied to the second set of deflection plates 6).

For this purpose the convenient supply apparatus GM 4 198 may be used, which gives an adjustable voltage of from 0 to 5 kV. This supply apparatus is adapted to the measuring apparatus provided with the post-acceleration tube, namely the cathode ray pressure indicator GM 3 154 and the cathode ray oscillograph GM 3 156.

Fig. 8. The internal cathode system of the cathode ray tube DN 9-5 with post-acceleration. k cathode, g regulatory electrode, a1, focalising anode with voltage of about 275 volts, a2 accelerating anode with voltage of 1000 volts, D1 and D2 deflection system, d rods for combating trapezium distortion, paddles for combating astigmatism and distortion due to the post-acceleration.

Fig. 9. Photograph of the internal system of the post-acceleration tube.

Fig. 10. The equipotential surfaces of the post-acceleration field are compressed, at it were, which leads to astigmatism.

4) J. D. Veegens, Philips techn. Rev. 4, 210, 1939.
5) In the customary application of the cathode ray tube the horizontal deflection is obtained with the help of a saw-tooth generator. In the case of the cathode ray oscillograph GM 3 152 this gives a non-balanced voltage, i.e. the potential of one terminal of the generator is constant, while that of the other varies. In order not to obtain trapezium distortion, the terminal which has a variable potential must be connected to the plate bearing the rods.
Both phenomena may be ascribed to the fact that the potential field of the post-acceleration electrode penetrates between the deflection plates and here undergoes a deformation like that sketched in fig. 10. The equipotential surfaces are more sharply curved by the set of plates $D_2$ in the plane of the drawing, thus in the horizontal plane, than in the vertical plane, which means in optical language that a cylindrical lens is placed in front of the actual post-acceleration lens.

Fig. 11. Action of an astigmatic lens (cylindrical lens). An originally rectangular beam is compressed in one direction and in addition given a barrel-shaped distortion.

This cylindrical lens strengthens the electron lens in the horizontal plane, so that the beam no longer has a focus point on the screen, but a focus line. Moreover, it deforms the oscillogram in the way shown in fig. 11: in the first place it decreases the sensitivity of the system in the direction of the time base, and in the second place it leads to a barrel-shaped distortion of the oscillogram.

The astigmatism and the consequent distortion can be combatted by providing a plate of set $D_2$ with paddle-shaped appendages (see fig. 9 and more clearly fig. 12). These paddles provide an extra focussing of the beam in a direction perpendicular to the extra focussing by the set of plates $D_2$, and thus combat the astigmatism. The paddles are made so large that the astigmatism is just eliminated, the barrel-shaped distortion is then also found to have disappeared.

Fig. 12. The second system of deflection plates ($D_2$) with rods $d$ and paddles $z$.

Properties of the post-acceleration tube

Focussing voltage

Fig. 13 shows the variation of the focussing voltage with the post-acceleration voltage. As has already been mentioned in the discussion of the astigmatism, the post-acceleration lens also has a focussing action on the beam. If the tube is switched on without post-acceleration, and then focussed, the focussing voltage of the electrode $a_1$ must be increased as soon as the post-acceleration is set in action. The strength of the lens $a_1$, $a_2$ is hereby made smaller, which is necessary to keep the sum of the lens strengths constant.

Deflection sensitivity

Fig. 14 shows the relation between the deflection sensitivity and the post-acceleration. The voltage of $a_2$ and the coating $A$ has been kept constant at 1 000 volts, while that of the second covering varies between 1 000 and 5 000 volts. The reduction in sensitivity is greater, the stronger the post-acceleration, as has already been shown.

With post-acceleration with a voltage of 5 000 volts with respect to the cathode the sensitivity amounts to one half of that without post-acceler-
If the same system were allowed to operate without post-acceleration with an anode voltage of 5 000 volts, the sensitivity would be 1/5 of that at 1 000 volts, so that the post-acceleration is 2.5 times more favourable than a direct acceleration of the electron beam, as far as the sensitivity is concerned.

Size of image and definition

The reduction in the deflection sensitivity with increasing post-acceleration is naturally accompanied by a decrease in the maximum size of the image which can be attained without the oscillogram being distorted or cut off by the deflection plates. In designing the tube the primary aim was to give the tube the same sensitivity at a voltage on the screen of 1 000 volts (thus without post-acceleration) as that possessed by the tube DN 9-3. The deflection plates then also have such appropriate dimensions that the whole screen can be covered at 1 000 volts.

With a maximum post-acceleration (5 000 volts with respect to the cathode) this is, however, no longer possible. The largest oscillogram which can be obtained without deformation has dimensions of 40 by 40 mm, while the screen itself has sufficient area for an image 65 by 65 mm. This reduction in size of the image by no means involves a loss of details, however, since the fluorescent spot becomes sharper with increasing voltage. With constant beam current the reduction in size of the spot with increasing voltage on the screen is found to be about as great as the reduction in size of the oscillogram due to the decreased deflection sensitivity.

Scanning speed

Extensive tests have been carried out to determine the maximum scanning speed. Use was here again made of a camera with a lens aperture 1 : 3,2 and Agfa Isopan roll film. If the post-acceleration electrode has a voltage of 5 000 volts with respect to the cathode, then with a fourfold reduction and a beam current of 20 μA the maximum recordable scanning speed is 24 km/s. At a voltage of 1 000 volts one obtains, under otherwise the same conditions, the scanning speed of 850 m/s already mentioned, so that there is a gain of a factor 25.

In laboratory measurements lenses with larger apertures, 1 : 1.5 for instance, will usually be available, and with such lenses a scanning speed of 100 km/s can be obtained.

In conclusion, here are a few practical hints for the use of the post-acceleration tube.

The post-acceleration voltage must not be connected to the screen as long as the fluorescent spot is stationary. Due to the high power the spot would immediately burn in, which means that at the spot where the screen is struck by electrons of too high energy the sensitivity of the screen for electrons of low energy decreases appreciably. A straight line, also, i.e. a deflection with one set of plates offers no security against burning in. If, however, an A.C. voltage acts on both deflection plates then, with a beam current of 5 μA, for instance, the image may be kept continuously on the screen without there being a chance of burning in even at the highest post-acceleration voltage. (This beam current of 5 μA is sufficient to cause an image to appear on the screen which can also easily be seen in a well-lighted room). With short exposures one may go as far as 20 μA. For very rapid phenomena the regulatory electrode will simply be connected to the cathode, whereby a beam current of about 50 μA is obtained. One must then, however, work very quickly in adjusting the definition and desired size of image, since in that extreme case the image may only remain on the screen for a few seconds.