VOL. 14 No. 11, pp. 313-344 MAY 1953

Philips Technical Review

DEALING WITH TECHNICAL PROBLEMS
RELATING TO THE PRODUCTS, PROCESSES AND INVESTIGATIONS OF
THE PHILIPS INDUSTRIES

EDITED BY THE RESEARCH LABORATORY OF N.V. PHILIPS' GLOEILAMPENFABRIEKEN, EINDHOVEN, NETHERLANDS

A DECADE COUNTER TUBE FOR HIGH COUNTING RATES

by A. J. W. M. VAN OVERBEEK, J. L. H. JONKER and K. RODENHUIS.

621.385.832: 621.318.57

Mechanical, electromagnetically operated counting devices which count the applied number of electrical pulses, have been known for a long time. In recent years there has been an ever increasing demand for counting devices which operate at a much higher speed. This demand exists both in telecommunication and for modern computers, for measuring frequencies and for carrying out nuclear measurements. It is only by electronic means that a solution is offered in these cases.

A new electronic tube, the E1T, which has been specially designed for counting purposes, can count pulses at a very high rate. The number of counts can be read directly on the tubes themselves.

There are various types of mechanical counting devices which are operated by an electromagnet under the influence of electrical pulses. With some of these the number of pulses can be read in figures, such as with counters for telephone calls; with others a switch lever is moved a number of steps equal to the number of pulses received, so that a given connection is established, as in the case with selectors in a telephone exchange. Due to the delay in build-up and die-away of a magnetic field and the inertia of the moving parts, the counting rate of such electromechanical counters is not very high. For computers which must make thousands of additions per second, for the pulse code systems used in telecommunication, etc., this rate is quite insufficient.

Electronic tubes have, of course, been widely used for counting purposes. With valves of the conventional type, however, fairly large numbers of valves are required. A further problem is to render the counted number visible.

Reports on the development work carried out by Philips in the field of electronic valves designed for switching have been published both in this review [1]) and elsewhere [2]). One of the tubes which has resulted from this research work is the decade counter tube. This tube has already been mentioned in the publications referred to in footnote [2]); a description of this tube is now given and a new circuit is discussed.

Description of the decade counter tube

The counter tube is provided with an electron gun which emits an electron beam towards the envelope of the tube. A deflecting device with a feedback system, which is to be discussed later, ensures that the beam can occupy ten discrete positions. The envelope is lined with fluorescent material which fluoresces at a different place for each of the positions, so that the position of the beam can be read from the figures 0, 1, 2,......9 placed opposite the fluorescing marks (*fig. 1*). Before counting starts, the beam occupies position 0, after the first pulse it is advanced to position 1, after the second pulse to position 2, etc., until position 9 is reached. At the tenth pulse the beam is reset to position 0, and at the same time a pulse is fed to a second counter tube, as a result of which its beam is moved from position 0 to position 1.

1) J. L. H. Jonker and Z. van Gelder, New electronic tubes employed as switches in communication engineering, Philips tech. Rev. 13, 49-54 and 82-89, 1951/52 (Nos 3 and 4).

2) J. L. H. Jonker, Valves with a ribbon-shaped electron beam: contact valve; switch valve; selector valve; counting valve, Philips Res. Rep. 5, 6-22, 1950. J. L. H. Jonker, A. J. W. M. van Overbeek and P. H. de Beurs, A decade counter valve for high counting rates, Philips Res. Rep. 7, 81-111, 1952 (No. 2).

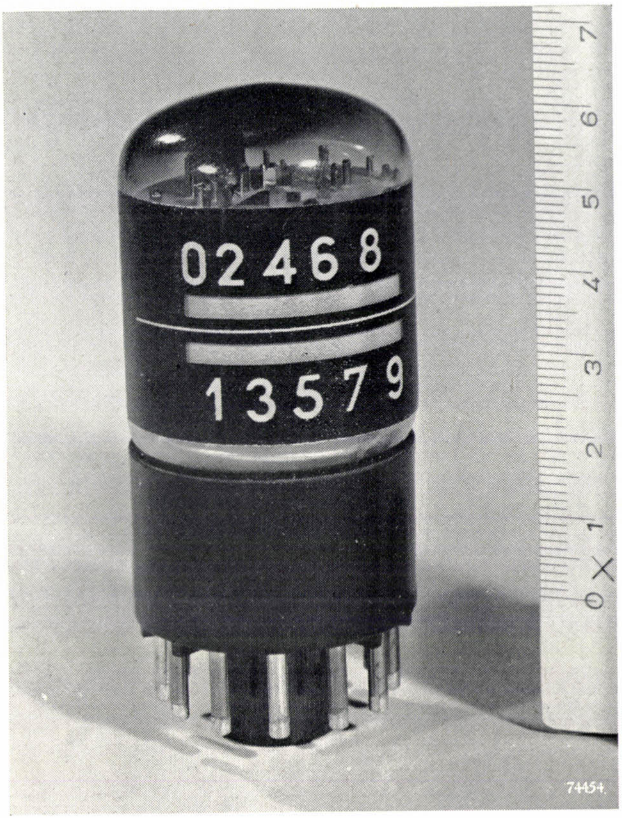

Fig. 1. The E1T decade counter tube. A blue fluorescent mark indicates the figure which corresponds to the position of the electron beam in the counter tube, i.e. to the number of pulses counted.

This second tube therefore counts the decades. A third tube can be added which counts the hundreds, a fourth which counts the thousands, etc. (*fig. 2*). With n tubes in cascade it is thus possible to count up to $10^n - 1$ ($\approx 10^n$) pulses.

Fig. 3a shows a cross-section of the decade counter tube, whilst fig. 3*b* shows the diagrammatic representation which will be used in circuit diagrams. The cathode is of the conventional type as used in receiving valves, apart from the fact that it emits electrons from one side only of its rectangular cross-section. A control grid (g_1), four rod-shaped focusing electrodes (p_1, p_2) and an accelerating electrode (g_2), together with the cathode, form the electron gun. This has been so designed that the cross-section of the electron beam thus obtained is not circular but ribbon-shaped. As shown elsewhere [1,2]), a ribbon-shaped electron beam has the following advantages:

1) It is easy to obtain a fairly strong beam current at a relatively low voltage, for example 1 mA at 300 V.
2) The dimensions of the tube can be kept small, roughly as those of a normal receiving valve. The E1T counter tube (fig. 1) has a maximum diameter of 37 mm and a maximum height of 83 mm.
3) It is necessary to align the electrodes, which are fixed between two mica discs as in the technique used for manufacturing receiving valves, in one dimension only, namely in the direction normal to the plane of the beam; with a beam having a circular cross-section it would on the other hand be necessary to align the electrodes in two directions, which would render manufacture much more difficult.

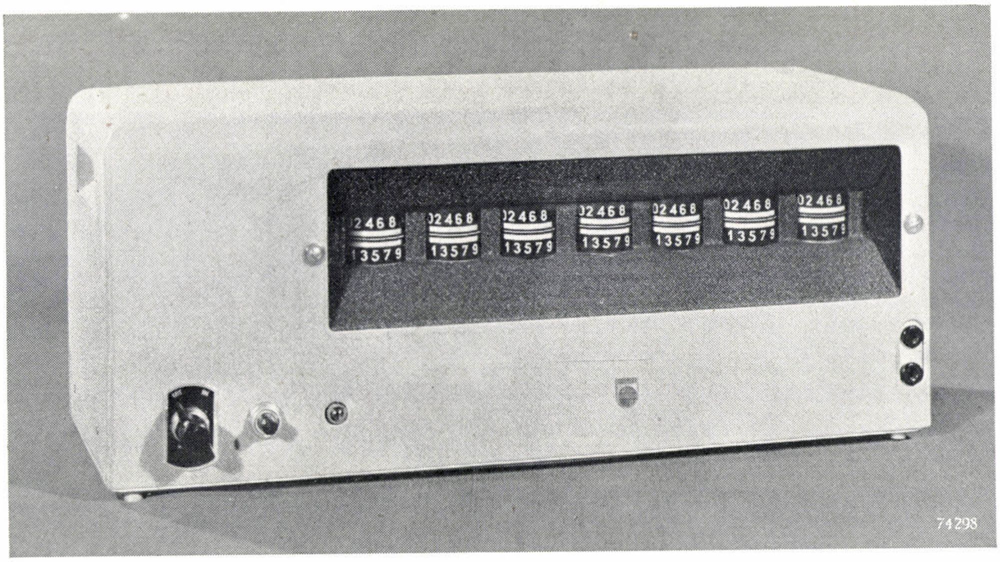

Fig. 2. Decade counter with seven decade counter tubes E1T connected in cascade, suitable for counting up to ($10^7 - 1$) at a speed of 30,000 pulses per second. From left to right the millions, the hundred thousands, the ten thousands, etc. can be read on the tubes themselves.
Bottom left: mains switch, push-button switch with which all counter tubes can be reset to zero before counting starts, and pilot lamp.
Bottom right: input terminals.

The importance of the advantages mentioned under (1) and (2) can be stated as follows. The advantage of a strong current in the case of a counter tube is related to the counting rate. Generally speaking, the time required for an "electronic event" is proportional to VC/I, where V is the potential difference traversed by the electrons, I the current intensity and C the inter-electrode capacitance. In order to keep this time short, it is thus favourable that V is kept small, I being given a large value. The ribbon shape of the beam is advantageous in both respects. Since C is proportional to the linear dimensions of the electrode system, attempts must moreover be made to keep this system small, i.e. to apply the technique used for receiving valves. It will be clear that the resulting small external dimensions of the tube are welcome also with a view to saving space.

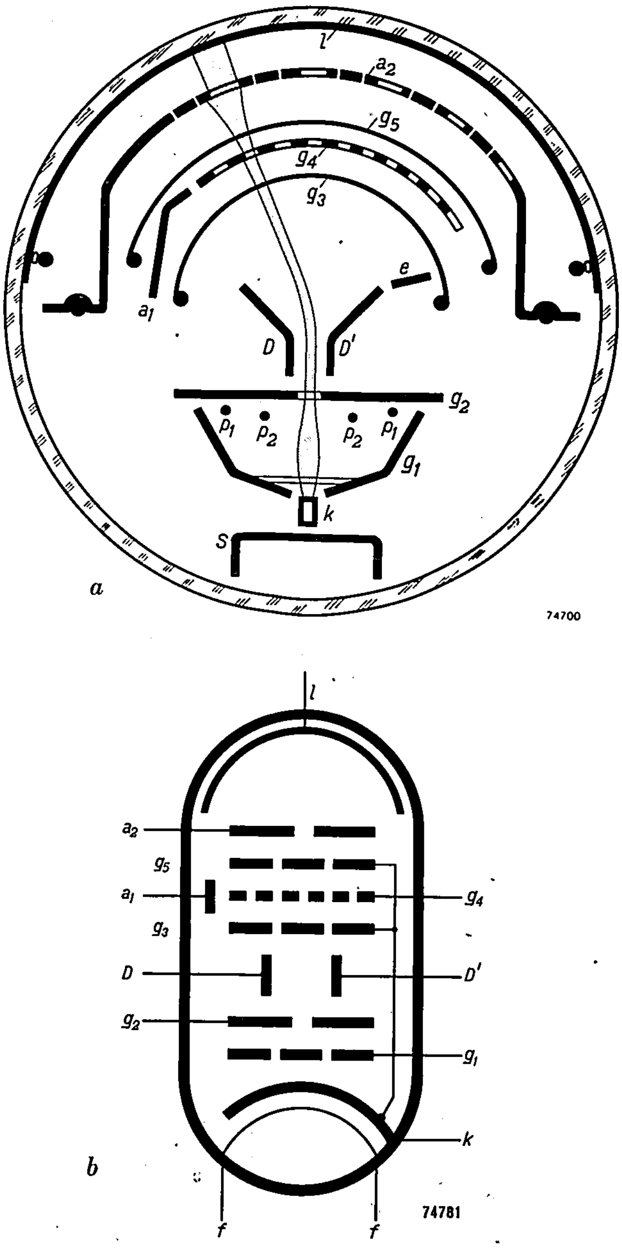

Fig. 3. (*a*) Cross section and (*b*) diagrammatic representation of the decade counter tube. The cathode k (with heater f), the control grid g_1, the four internally connected focusing electrodes p_1 and p_2 and the accelerating electrode g_2 form the electron gun, which produces a ribbon-shaped electron beam (the width of the ribbon is normal to the plane of the drawing). D, D' deflection electrodes. g_3, g_5 suppressor grids. a_1 reset anode. g_4 electrode with ten slots. a_2 anode. l fluorescent layer applied to a conductive layer. Screen s (internally connected to k) prevents primary electrons from impinging on the envelope. Auxiliary anode e (internally connected to g_2) captures secondary electrons.

The ribbon-shaped beam thus obtained proceeds between two deflection electrodes (D, D', fig. 3). These have been so positioned that the beam almost touches one of these electrodes in each of its extreme positions, deflection sensitivity thus being at a maximum.

At given values of the deflection, the beam passes through one of the ten vertical slots in the slotted electrode (g_4), which is at a positive voltage. It will be shown later how a special circuit ensures that the beam can occupy only one of these ten positions. Some of the electrons passing through a slot impinge on the anode (a_2) placed behind the slotted electrode; the remainder pass through an aperture in this anode and impinge on the envelope. The part of the envelope situated behind the anode is lined with fluorescent material, so that a fluorescing mark is produced behind the opening in the anode through which electrons pass. The number (fig. 1) opposite this mark thus indicates the position of the beam.

When the beam passes through slot *9*, it has not yet reached its extreme position, but can be deflected slightly further under the influence of a following pulse. When this occurs, it impinges on the so-called reset anode (a_1). The impinging of the beam on the reset anode initiates the resetting to position 0. Before discussing this, it will be shown how the beam is fixed at well-defined positions.

Step-wise deflection of the beam

Fig. 4a gives a schematic representation of an imaginary cathode-ray tube, containing an electron gun, a set of deflection electrodes and an anode. When the potential v_D of the one deflection electrode is kept constant and the potential $v_{D'}$ of the other is varied, the electron beam will move along the anode, but the anode current i_a remains constant (line *I* in fig. 4*b*). When the deflection electrode D' is connected to the anode and these two electrodes are fed via a common resistor R_a from a battery with voltage V_B (fig. 4*c*), the following equation, however, applies:

$$v_{a2} = v_{D'} = V_B - i_a R_a . \quad \quad (1)$$

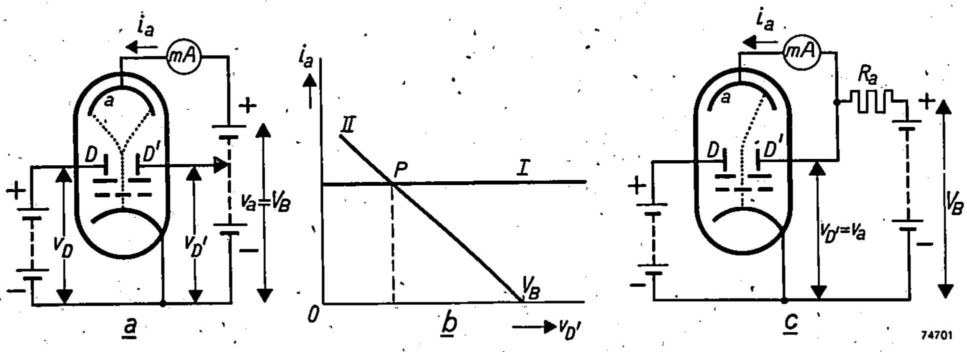

Fig. 4. (*a*) Imaginary cathode-ray tube with an electron gun, deflection electrodes *D*, *D'* and an anode *a*. At v_a and v_D = constant, the electron beam can be given any position between the extreme positions (dotted lines) by varying $v_{D'}$. In doing so the anode current i_a remains constant, see *I* in (*b*).

(*c*) When *D'* and *a* are connected to the positive terminal of a battery with voltage V_B via a common resistor R_a, eq. (1) is applicable (represented by the line *II* in (*b*). The beam can now occupy one position only, determined by the abscissa of the point of intersection *P*.

This relation is represented by the line *II* in fig. 4*b*. The point of intersection *P* of the lines *I* and *II* gives the state of equilibrium; the electrode *D'* then assumes a potential which corresponds to the abscissa of *P*, and according to this given potential the beam occupies a well-defined position.

Advantage is taken of this principle for fixing the positions of the beam in the counter tube. In this case too, the anode a_2 and the deflection electrode *D'* (i.e. the one nearest to the figure 0) are connected to a direct voltage source V_B via a common resistor R_{a2} (*fig.* 5); the potential of *D* and a_2 is denoted by $v_{D',a2}$. The straight line *I* of fig. 4*b* is now, however, replaced by the undulated curve *I* of *fig. 6*; the way in which this is obtained will be shown presently. This curve *I* is intersected 19 times by the resistance line *II*. Each of these points of intersection corresponds to a condition of equilibrium — although only the ten points of intersection numbered from *0* to *9* represent stable positions. From this it may be seen that the position of the beam indicated diagrammatically in fig. 3*a* is one of its stable positions, i.e., passing partly through a slot and impinging partly on the

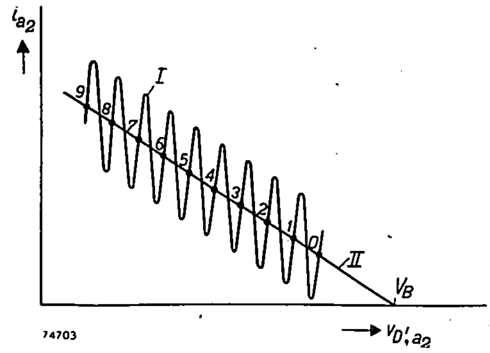

Fig. 6. The $i_{a2} = f(v_{D',a_2})$ characteristic of the decade counter tube has the form of the undulated curve *I*. The straight line *II* represents the resistance line according to eq. (1). Only the points of intersection of *I* and *II* numbered from *0* to *9* represent stable positions of the beam; the other points of intersection correspond to unstable positions. V_B is only slightly larger than the abcissa of the point of intersection *0*.

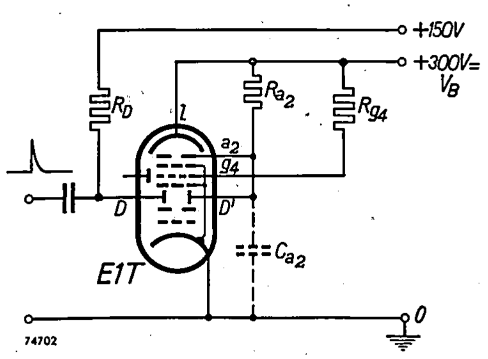

Fig. 5. E1T counter tube of which the anode a_2 and the deflection electrode *D'* are fed via a common resistor R_{a2}, similar to the tube shown in fig. 4*c*. The beam has now the same number of stable positions as the number of slots in the electrode g_4 (see also fig. 6). By applying positive pulses to *D*, the beam can be advanced in steps (see later). C_{a2} represents the stray capacitance.

metal at the left of this slot: in fact, when the beam is deflected further to the left the current i_a initially decreases, in accordance with the characteristic *I* near the points of intersection *0...9* (*fig. 6*).

How the characteristic $i_{a2} = f(v_{D',a_2})$ *is obtained*

In *fig. 7a* a slotted electrode and an anode have been drawn as flat planes. It is assumed that the ten slots have the same dimensions and are equidistant and that the thickness of the ribbon-shaped beam exceeds the width of the slots and is less than the width of the spaces between the slots.

When the beam is now made to move from slot *0* to slot *9* by (continuously) lowering the voltage v_{D',a_2}, it might be expected at first sight that a characteristic $i_a = f(v_{D',a_2})$ as shown by curve *I* of fig. 7*b* is obtained: each time the beam is directed on a slot, i_{a2} reaches a maximum (which has the same value for all slots), and each time the beam points to the centre between the slots, i_{a2} drops back to zero.

Assuming for the time being that the characteristic had this form, it would be possible to proceed according to fig. 5, and to give V_B and R_{a2} such values that the line *II*, which represents eq.(1) graphically, intersects all waves of *I* (fig. 7*b*). In practice, however, with a slotted electrode according to fig. 7*a*, the characteristic $i_a = \mathrm{f}(v_{D',a_2})$ will not assume the form *I* of fig. 7*b*, but that of fig. 7c. The disadvantages of the latter form are that the magnitude of R_{a2} (the slope of line *II*) must remain within very narrow limits and that V_B must be given a much higher value to prevent one or several points of intersection from being obliterated at the left-hand side. The form of *I* as shown in fig. 7*c* is a result of the asymmetry in the deflection (v_D constant, $v_{D'}$ variable).

It is in fact due to this asymmetry that the focusing of the beam on the slotted electrode deteriorates and that the beam thus becomes wider as it is displaced further to the left. Consequently, the number of electrons per second passing through the slots having high numbers is smaller than that passing through the slots with low numbers, i.e. the peaks of i_{a2} become lower as the beam travels from the right to the left. The influence of the defocusing on the minima is even more serious because the beam soon becomes so wide when it is deflected that it is wider than the space between the slots. Consequently, as the beam moves towards the left, the current minima become less pronounced, i.e. the amplitude of curve *I* decreases towards the left.

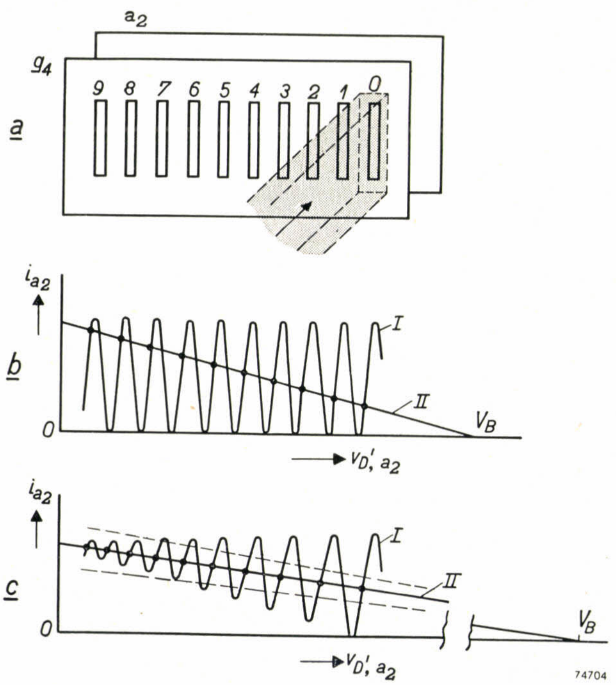

Fig. 7. (*a*) a_2 anode and g_4 slotted electrode of a (primitive) decade counter tube, both drawn as flat planes. The ten slots have been drawn as being of the same size and equidistant. (*b*) Curve $I: i_{a2} = \mathrm{f}(v_{D',a_2})$ characteristic which might be expected in the case (*a*). *II* again represents the resistance line. (*c*) Due to the defocusing of the beam as it is deflected to the left, the $i_{a2} = \mathrm{f}(v_{D',a_2})$ characteristic actually assumes the form represented by *I*. At small variations of R_{a2} (corresponding to the broken lines) some of the points of intersection at the left are lost. V_B must, moreover, largely exceed the value of v_{D',a_2} corresponding to the point of intersection *0*.

In order to obtain the much more favourable characteristic *I* of fig. 6, the slotted electrode has been provided with a d d i t i o n a l a p e r t u r e s, which are also scanned by the beam, so that an additional current is passed which increases as the beam proceeds further to the left.

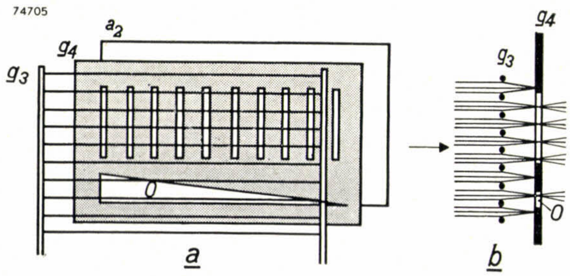

Fig. 8. (*a*) In order to obtain the characteristic *I* of fig. 6, the electrode g_4 might be provided with an additional triangular aperture *O* through which an additional current passes which increases as the beam is deflected further to the left. Due to the action of the suppressor grid g_3 (see the cross-section *b*), the magnitude of the additional current, however, depends too much on the location of g_3 with respect to the aperture *O*.

The most obvious solution is to make a triangular aperture in the slotted electrode (*O* in *fig. 8*). It would nevertheless be very difficult to obtain the desired improvement in this way. This is due to the presence of a suppressor grid (g_3) in front of the slotted electrode. The horizontal wires which constitute this grid give rise to a vertical variation of the current density of the beam with minima behind the grid wires and maxima behind the spaces of the wires (see fig. 8*b*). The "ribbon" might thus be imagined to be sliced into a number of threads situated above each other. The positions of the grid wires with respect to the narrow triangular aperture largely determine the way in which the current flowing through this aperture varies as a function of the deflection angle. This leads to difficulties in manufacture.

For this reason the idea of a narrow triangular aperture was abandoned in favour of rectangular apertures whose positions with respect to the grid wires are less critical. As shown in *fig. 9*, part of the beam passes through an aperture O_1 from slot 5 onwards. In positions 8 and 9 a second aperture moreover becomes operative (O_2).

A second measure applied to obtain a rising characteristic consists in making each slot slightly larger than its predecessor: starting from *2* to *9* the width gradually increases, whilst *1* is slightly lower than *2....9*. Slot *0*, which is made particularly wide, forms an exception, the reason of which will be shown later. To prevent the beam from bending around the edge of this wide opening — which might result in the figure 1 being indicated — slot *0* is covered with gauze.

By these measures the characteristic assumes the form as depicted [3]) in *fig. 10*. Due to the rising characteristic, V_B need not be much higher than the value of v_{D',a_2} at which the beam occupies position 0. A value of $V_B = 300$ V suffices; as will be seen from a circuit diagram to be discussed later, all other direct voltages the tube requires can be derived from the same source. The value of R_{a2} should be approximately equal to the average slope of the characteristic, which amounts to about 1 MΩ, but owing to the large amplitude of the waves there is a reasonable play in the magnitude of R_{a2}, although it remains desirable to keep the deviation within 1% for other reasons.

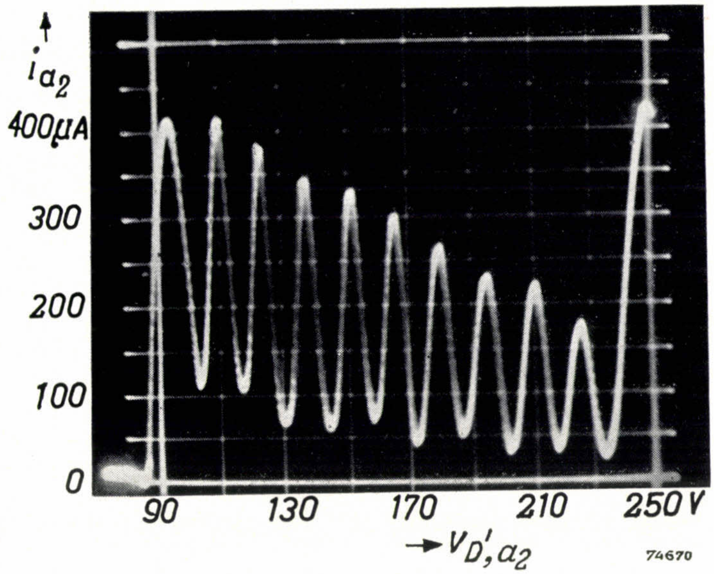

Fig. 10. Oscillographically [3]) plotted $i_{a_2} = f(v_{D',a_2})$ characteristic of the E1T counter tube. Cf. curve *I* shown in fig. 6. The oscillogram displays one peak more than the theoretical curve shown in fig. 6. This is due to the fact that in practice a peak — the one the extreme left — also occurs when the beam passes between the slotted electrode and the reset anode. This peak is of no consequence for the operation of the tube.

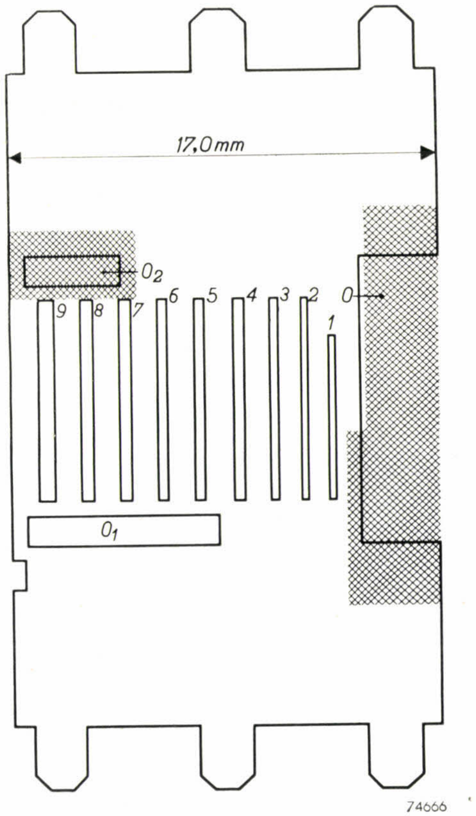

Fig. 9. Actual form of the apertures in the slotted electrode g_1 (drawn as a flat plane). The slots become larger and their distances from centre to centre increase in the sequence from *1* to *9*. An additional current passes through the two apertures O_1 and O_2 of which the upper one, like slot *O*, is covered with gauze.

Suppressor grids, anode and fluorescent screen

The previously mentioned suppressor grid g_3 (fig. 8) serves for rejecting secondary electrons which are emitted by the slotted electrode and would otherwise proceed mainly towards the deflection electrodes. A small proportion of these electrons, however, still passes through the suppressor grid, which is particularly troublesome when the beam is in position 0 or 1. For this reason an auxiliary anode has been incorporated at the right-hand side (*e* in fig. 3*a*); a voltage of 300 V is applied to this auxiliary anode, so that it captures these electrons. The screen *s*, which is mounted behind and connected to the cathode, prevents primary electrons from impinging on the envelope.

A second suppressor grid (g_5, fig. 3) is mounted between the slotted electrode and the anode and decelerates secondary electrons originating from the anode. It moreover "reassembles" the beam of primary electrons, which was sliced into threads by the first suppressor grid (fig. 8*b*), so that the ribbon-shaped beam again becomes homogeneous once it has passed the second suppressor grid [4]) (*fig. 11*). If this were not the case, the electrons which

[3]) Plotted with an apparatus as decribed in Philips tech. Rev. **12**, 283-292, 1950/51.

[4]) J. L. H. Jonker and B. D. H. Tellegen, Philips Res. Rep. **1**, 12-19, 1945.

pass through one of the ten slots of the anode would no longer give rise to a uniformly luminescing spot, but would produce a less distinct, "crumbly" spot.

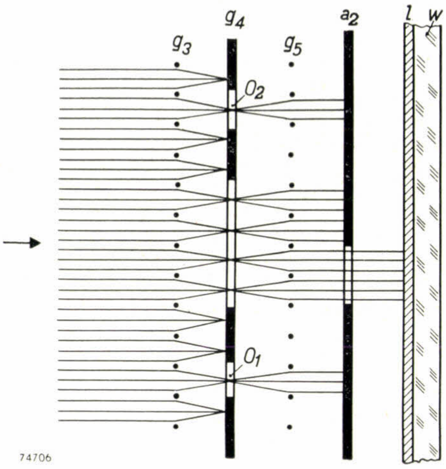

Fig. 11. Cross-section through the first suppressor grid g_3, the slotted electrode g_4, the second suppressor grid g_5, the anode a_2, the fluorescent layer l and the glass envelope w. By giving g_5 the correct pitch and position, a homogeneous beam is restored behind g_5.

By giving the grid g_5 the same pitch as g_3 and positioning it so that its wires are situated in the same horizontal planes as those of g_3, the beam will once again be homogeneous (fig. 11).

The fluorescing layer consists of a specially prepared type of zinc oxide with blue fluorescence and a very long life. It is applied to a conducting layer, which, during operation, is at a potential of 300 V.

In order to facilitate reading of the figures, they are placed in two rows above each other: 0....8 and 1....9 (fig. 1). The apertures in the anode are placed at corresponding positions; see *fig. 12,* in which the various parts of the tube are shown.

Mechanism of the displacement of the beam from 0 to 9

The positive-going voltage pulses to be counted are applied to the left deflection electrode D via a blocking capacitor, as shown in fig. 5.

In order to understand how the beam is shifted to a following position at each pulse, it should be recognized that the characteristic I shown in fig. 6 is applicable to a constant voltage v_D at the left deflection electrode, and that the angle of deflection is a function of $v_{D'} - v_D$. An increase of v_D by an amount V_i therefore corresponds to the line I being shifted to the right over a distance corresponding to V_i (*fig. 13*).

As a starting point it is assumed that the beam occupies one of its stable positions, for example

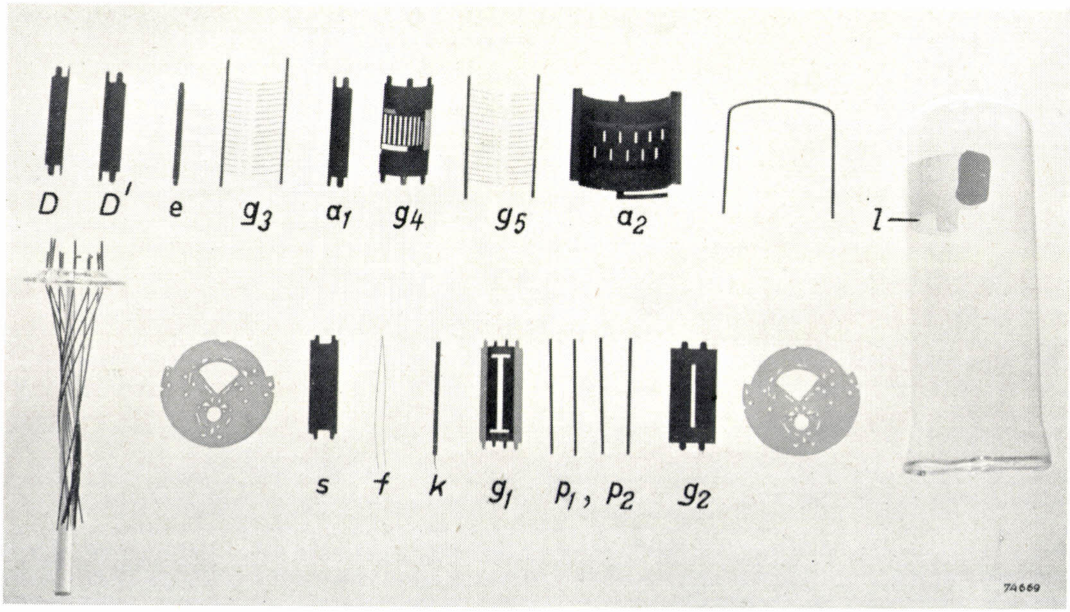

Fig. 12. Component parts of the E1T counter tube. The references have the same meaning as in fig. 3.

Lower row from left to right: glass base with pumping stem, mica support, screen (s), heater (f), cathode (k), control grid (g_1), four focusing electrodes (p_1, p_2), accelerating electrode (g_2), second mica support.

Upper row, from left to right: the two deflection electrodes (D, D'), auxiliary anode (e), first suppressor grid (g_3), reset anode (a_1), slotted electrode (g_4), second suppressor grid (g_5), anode (a_2), resilient bracket (to establish contact with the conductive layer on the envelope), envelope with fluorescent layer (l).

position 0. If a positive pulse is now applied to the left deflection electrode, so that v_D is temporarily increased, the beam will tend to move to the left (fig. 3a); the number of electrons passing through

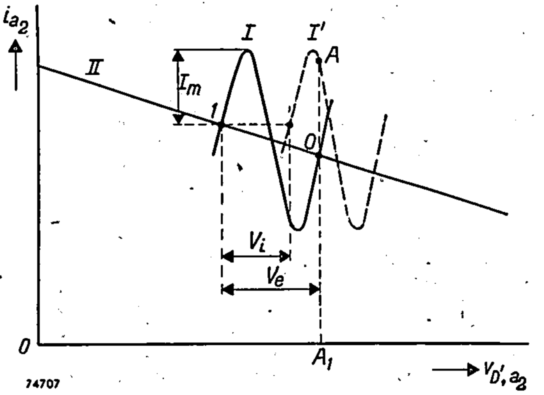

Fig. 13. $i_{a_2} = f(v_{D',a_2})$ characteristic I of the counter tube for a given voltage v_D on the left deflection electrode; I' the same characteristic for a voltage $v_D + V_i$ on the left deflection electrode. II resistance line. I_m amplitude of the waves. V_e horizontal distance between two adjacent stable points of intersection.

slot *0* then decreases, i.e. the anode current i_{a2} is reduced. If no stray capacitances were present, the decrease of i_{a2} would result in a rise of the potential of the anode and of the right deflection electrode connected to it, and this increase of v_{D',a_2} would counteract the deflection to the left, so that the beam would be retained at position 0.

In practice, however, the stray capacitance to earth of the electrodes a_2 and D' and their wiring, represented by C_{a2} in fig. 5, is shunted across R_{a2} and impedes sudden changes of the potential of a_2 and D'. Provided the condition is satisfied that the leading edge of the pulse is sufficiently steep, the potential v_{D',a_2} may be considered constant during the rise time ϑ_1 of the pulse (*fig. 14*). This amounts to the line I of fig. 13 being shifted to the right (I') over a distance equal to the amplitude V_i of the pulse, the anode current thus assuming the value A_1A. This differs from the original value, whereas the current flowing through R_{a2} still has its original value; the difference is supplied by the capacitance C_{a2}.

Provided the second condition is also satisfied, namely that the decay time ϑ_2, during which the pulse decays from V_i to zero, is sufficiently long, the characteristic I' will gradually return to I, and A will be shifted to the adjacent stable point of intersection between I and II, i.e. point *1*. In order to ensure that the beam is shifted just one step to the left, a third condition must be imposed to the beam, namely that the amplitude V_i should be roughly equal to the voltage difference V_e which corresponds to the horizontal distance between two adjacent stable points of intersection and amounts to approximately 14 V; it will be clear that at too small an amplitude the beam will return to its original position, whereas at too large an amplitude it will be advanced two or more steps.

As a result of the deflection being asymmetrical, the average potential in the space between the deflection electrodes drops each time the beam is shifted a step further to the left, since v_{D',a_2} decreases and v_D remains constant. As a consequence the deflection sensitivity increases, i.e. the reduction of $v_{D'}$ corresponding to a given increase of the deflection is smaller at the left than at the right. In the case of the primitive slotted electrode shown in fig. 7a, with equidistant slots, this means that the distances between the points of intersection of I and II become smaller in the direction from the right to the left (see fig. 7c), hence that V_e decreases from the right to the left. This is undesirable as it decreases the tolerance in the amplitude V_i of the pulses. This objection has been met with by increasing the distances between the centres of the slots in the direction from 0 to 9 in such a way that the gradually increasing deflection sensitivity is exactly compensated.

In practice the conditions imposed on the pulse may be formulated as follows:

$$\text{Interval } \vartheta_1: \quad \frac{dv_i}{dt} \geqq 3\,\frac{I_m}{C_{a2}}, \quad \ldots\ldots \quad (2)$$

$$\text{Interval } \vartheta_2: \quad -\frac{dv_i}{dt} \leqq 0.3\,\frac{I_m}{C_{a2}}, \quad \ldots\ldots \quad (3)$$

where v_i denotes the instantaneous value of the pulse amplitude and t the time. Theoretically, it might be expected that the amplitude of V_i may assume a value between $\frac{1}{2}V_e$ and $\frac{3}{2}V_e$, but the margin becomes smaller due to several causes. In fact, the following condition is valid:

$$\left.\begin{array}{l} 11.5\text{ V} < V_i < 16\text{ V} \\ \text{or} \quad V_i = 13.6\text{ V} \pm 18\,\%. \end{array}\right\} \quad \ldots\ldots \quad (4)$$

When it is assumed that $I_m = 0.1$ mA and $C_{a2} = 15$ pF, it can be calculated that v_i must

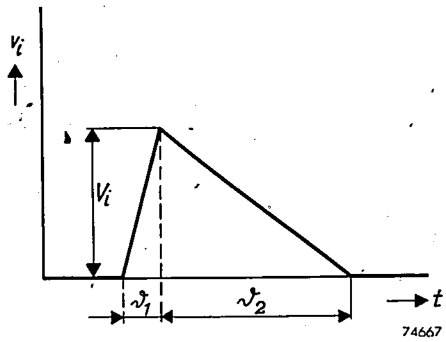

Fig. 14. Pulse voltage v_i as a function of the time t. V_i denotes the amplitude, ϑ_1 the rise time, ϑ_2 the decay time.

increase not slower than 20 V/μsec and subsequently decrease not faster than 2 V/μsec. At these extreme values of the slopes and $V_i = 14$ V, $\vartheta_1 = 0.7$ μsec and $\vartheta_2 = 7$ μsec.

If the counting pulses do not satisfy the imposed conditions they must be applied to a pulse shaper, i.e. a device which produces a pulse of the required form and amplitude for each pulse applied. Such a device will be referred to later.

Circuit for counting rates up to 30,000 per second

As previously shown, each tenth pulse applied to a counter tube should have two consequences: firstly the beam in the tube considered should be reset from position 9 to position 0, and secondly a pulse should be fed to the following counter tube to advance its beam one step. Both events are initiated by the fact that every tenth pulse initially deflects the beam occupying position 9 still further to the left, so that it leaves the slotted electrode and impinges on the reset anode.

The reset anode is connected to the + 300 V line via a resistor, so that its potential (v_{a1}) depends on i_{a1}, i.e. on the extent to which it is struck by the beam. The variations of v_{a1} are now used for initiating the resetting and for ensuring that a pulse is passed to the following counter tube.

Several circuits have been designed for this purpose. On closer investigation some of these circuits appeared to have the disadvantage of being suitable only for fairly low counting rates, whilst others produce faulty counts when the resistors or capacitors deviate very slightly from the rated values or when a counter tube is replaced.

These objections are not applicable to the carefully investigated counter circuit described below; a practical example of a decade counter built on these lines is shown in fig. 2. This circuit is characterized by the fact that each counter tube is followed by a pulse shaper, which feeds a resetting pulse to the preceding counter tube and a counting pulse to the following tube. The first counter tube is, moreover, preceded by a pulse shaper (of a slightly different type) which is commonly used in counter circuits and serves for converting the initial pulses into pulses of the required form and amplitude. Both types of pulse shaper incorporate a double triode (E90CC), so that for n counter tubes $(n+1)$ E90CC tubes are required (see *fig. 15*).

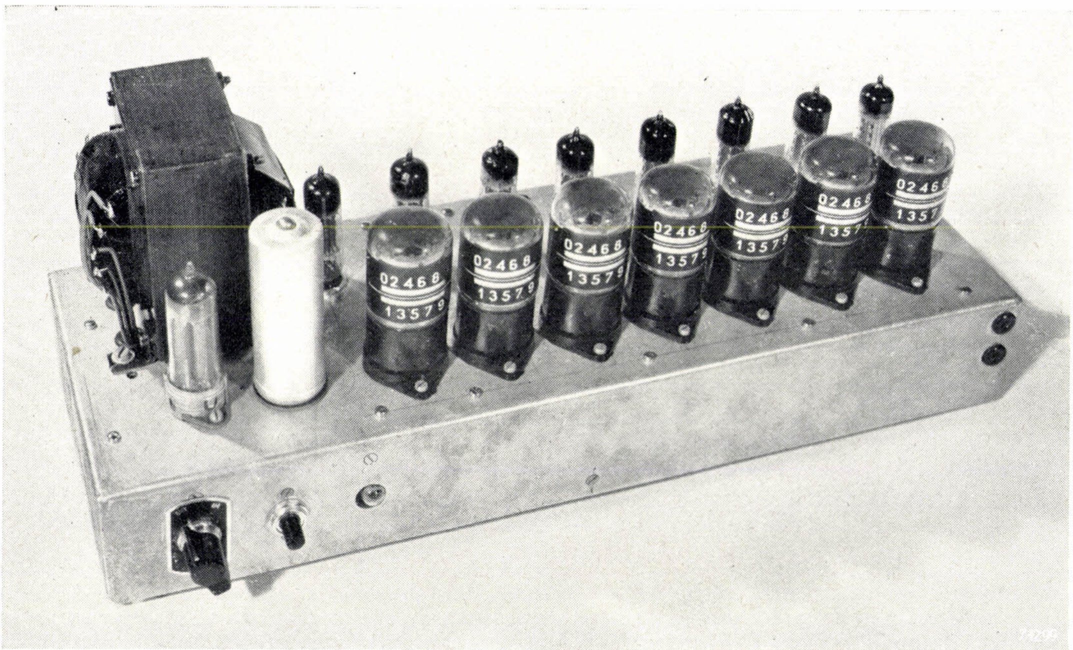

Fig. 15. The decade counter depicted in fig. 2 with the cover removed. Behind the seven E1T counter tubes the eight double triodes E90CC, which act as pulse shapers, can be seen. At the left is the rectifier valve AZ 41 which provides the direct current for the entire apparatus (300 V, approximately 50 mA).

The two types of pulse shaper will now be discussed separately.

Interstage pulse shaper

The pulse shaper which follows each counter tube is triggered each time it receives a pulse from the reset anode of the preceding counter tube. It then feeds a counting pulse of the required form and amplitude to the following counter tube and, moreover, ensures that the current in the preceding tube is temporarily suppressed during a sufficient length of time to allow the anode voltage of this tube to rise to the value corresponding to position 0, after which the beam is restored.

Further details follow from the circuit shown in *fig. 16,* in which one stage (counter tube and accessory double triode) is represented. The E90CC, in combination with a number of resistors and capacitors, forms a monostable ("one-shot") multivibrator, i.e. a multivibrator with one stable and one quasi-stable condition. The stable condition is that in which only triode section T passes current. When a negative voltage pulse is applied to the grid of T, this section is cut off and the other section, T', becomes conducting. From this quasi-stable condition the multivibrator automatically returns to the initial condition.

The operation of the monostable multivibrator may be explained as follows. The current which flows through T produces in the part R_1 of the cathode resistor $(R_1+R_2+R_3)$, a voltage drop which acts as negative grid bias for T' and ensures that this section is cut off. The anodes and the grids of T and T' will be denoted by a and a', and g and g' respectively. When the current flowing through T is decreased by a negative pulse on g, the potential of a and thus also that of g' rises, since g' is coupled to a via a capacitor (C_2). Due to the potential rise of g', current starts to flow through T', and since the anode resistor of T' has a much smaller value than that of T (R_a' = 3300 Ω, R_a = 39,000 Ω), this current largely exceeds that which flowed through T. As a result of this larger current, the cathode potential rises to such an extent that T is completely cut off.

Meanwhile the coupling capacitor C_2 is charged. The charging current flows through the resistor R_4, thus producing a voltage drop which acts as a positive grid bias for T'. The charging current decreases exponentially, and so does the potential of g'. The cathode potential follows that of g' and after some time — depending on $(R_a + R_4)\ C_2$ — reaches the value at which T again becomes conducting. The potential of a then drops and so does that of g'. Section T' is cut off and C_2 is discharged via T, the stable condition thus being re-established.

The negative pulse which triggers the multivibrator is derived from the reset anode via a coupling capacitor (C_1). The potential of this anode obviously drops when it is struck by the beam.

The sudden voltage drop which occurs at the anode of T' when current starts to flow through T', is used for temporarily suppressing the beam in the counter tube (in this way also terminating the negative pulse by which the multivibrator was triggered). This is achieved by coupling the anode of T' via a capacitor (C_3) to the control grid (g_1) of the counter tube. This grid has normally a voltage of +12 V with respect to earth, derived from a voltage divider (R_5-R_6-R_7) between the +300 V line and 0. By reducing the voltage on g_1 to —15 V or

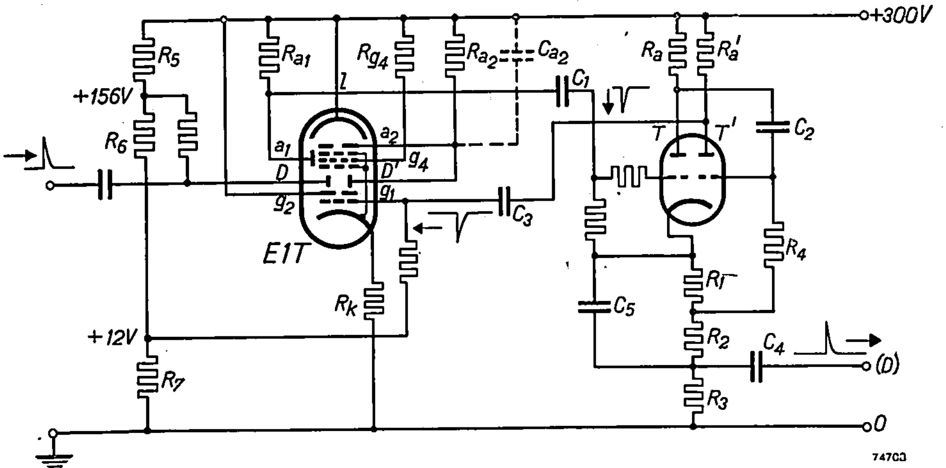

Fig. 16. Circuit of a counter tube and the following pulse shaper. The latter is a monostable (one-shot) multivibrator (flip-flop) incorporating a double triode T-T' (type E 90 CC).
At each tenth pulse applied to D the beam is advanced to a_1, which results in a negative pulse being fed to the grid of T via C_1. The multivibrator is thus triggered and brought from the stable condition (T conducting, T' cut off) into the quasi-stable condition (T' conducting, T cut off), but after a short interval it returns to the stable condition. During this operation two pulses are supplied: across R_3 a positive pulse is produced, which is fed to the following counter tube, whilst at the anode of T' a negative pulse is produced which is fed to the control grid (g_1) of the preceding counter tube; its beam is thereby temporarily suppressed and occupies position 0 after being restored.
R_a is the load resistor of T (39,000 Ω), R_a' is the load resistor of T' (3300 Ω).

an even lower value, the beam is suppressed.

While the beam still occupies position 9 (anode current $= I_{a9}$), the anode potential of the counter tube is $V_{a9} = V_B - I_{a9}R_{a2}$. Now V_{a9} is the lowest of the various potentials $V_{a0} \ldots V_{a9}$ that the anode assumes in the positions 0...9 — as shown by the oscillograms of *figs 17a* and *b* — since I_{a9} is the largest anode current. As the resistor R_{a2}, shunted by the stray capacitance C_{a2}, is connected between the anode and the +300 V line, the anode potential v_{D',a_2} rises exponentially as soon as the anode current has become zero (as a result of the beam having been advanced to the reset anode and subsequently having been suppressed). The beam must be suppressed during such a length of time that V_{D',a_2} has sufficient opportunity to rise to a value which exceeds $V_{a0} = V_B - I_{a0}R_{a2}$, where V_{a0} and I_{a0} denote the anode voltage and anode current at position 0 of the beam. When the beam is now restored after the negative pulse on the control grid has ceased, the anode and the right deflection electrode have reached a potential which exceeds the potential corresponding to position 0. As a consequence the beam is deflected to the extreme right and from this position it automatically travels to the adjacent stable position, i.e. position 0. The resetting is thus completed.

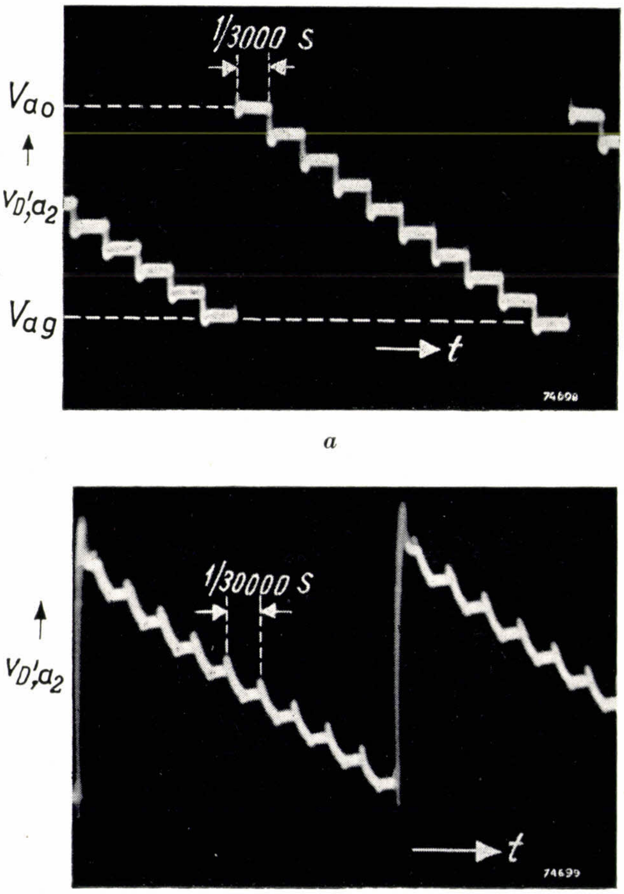

Fig. 17. Oscillograms of the anode voltage v_{D',a_2} of the counter tube shown in fig. 16, as a function of the time t. (a) has been registered at 3000 and (b) at 30,000 pulses per second. In position 0: $v_{D',a_2} = V_{a0} = 240$ V; in position 9: $v_{D',a_2} = V_{a9} = 95$ V. Between 9 and 0 the beam is suppressed and v_{D',a_2} rises exponentially.

The same principle is used for resetting all counter tubes to zero before counting starts. By means of a press-button switch (fig. 2) a negative voltage is applied to all control grids g_1, as a result of which the beams are suppressed and occupy position 0 when they are restored. The circuit required for this purpose has been omitted in fig. 16.

Finally, the pulse which should be fed to the following counter tube will be dealt with. For this purpose the voltage drop is used which is produced across the part R_3 of the cathode resistor of T-T' when, owing to the multivibrator being triggered, a larger current starts to flow through T' than previously flowed through T. The pulse is applied to the left deflection electrode of the following counter tube via a coupling capacitor (C_4).

The slope of the leading edge of this pulse depends on the speed with which the multivibrator changes from the stable to the quasi-stable condition. If the capacitor C_5 were absent, the strong negative feedback caused by the presence of the cathode resistor ($R_1+R_2+R_3$) would delay the triggering of the multivibrator to such an extent that the pulse would not be steep enough. Large negative feedback is, however, necessary to ensure good stability (insensitivity to changes of the valve characteristic, etc.). To solve this difficulty, R_1+R_2 is by-passed by the capacitor C_5, the capacitance of which is so chosen that only the cathode resistor R_3 is operative for "rapid" changes, whereas the complete resistor ($R_1+R_2+R_3$) is operative for slow changes.

The cathode resistor (R_k) of the counter tube also serves for increasing the stability.

The circuit of fig. 16 occurs seven times in the decade counter depicted in fig. 15. This circuit may be built as a separate unit which can be plugged into a tube holder. In this way counters can easily be assembled. *Fig. 18* shows an example of such a unit [5]).

Amplitude and duration of the pulses; counting rate

The positive pulse supplied by the pulse shaper must satisfy the conditions (2), (3) and (4) formulated above: sufficiently high slope of the leading edge, sufficiently low slope of the trailing edge, and an amplitude of 13.6 V ± 18%. The negative pulse, see *fig. 19*, must be sufficiently large to suppress the beam during at least the time τ that is required by v_{D',a_2} to rise from the value V_{a9} to

[5]) This unit is not in production.

V_{a0}, but its duration should, on the other hand, not exceed τ considerably, since this would affect the counting rate.

The time τ is given by the following equation:

$$V_B - V_{a0} = (V_B - V_{a9})\ e^{-\tau/R_{a2}C_{a2}}.$$

By substituting $V_B = 300$ V, $V_{a0} = 240$ V, $V_{a9} = 95$ V, $R_{a2} = 1.05$ MΩ and $C_{a2} = 16$ pF in this equation, τ is found to be 21.3 μsec. Making allowance for a safety margin, the condition is imposed that the pulse must not be shorter than 23 μsec. Taking the same tolerance (±18%) for the pulse duration as for the amplitude, an average duration of 27.2 μsec is obtained, the extreme values being 23 and 32 μsec. Allowing another 1.3 μsec as a margin, the longest pulse duration corresponds to a maximum repetition frequency of $10^6/(32 + 1.3) =$ 30,000 pulses per second.

Fig. 18. A decade counter tube with its accessory pulse shaper connected according to the circuit of fig. 16, in the form of a unit [5]) to be inserted in a tube holder.

The conditions regarding the form, amplitude and duration of the pulse can be met by a suitable choice of the component values. The question remains, however, whether these conditions are still satisfied when these values are subject to slight changes. In the circuit of fig. 16, by way of experiment, all resistances were changed simultaneously by 2% and all capacitances by 5%; the sign of each change was such that the influence on the final result was a maximum. The change of the pulse duration proved to be 7.5% and that of the amplitude appeared to be 8%; both changes thus remain well within the tolerance of 18%.

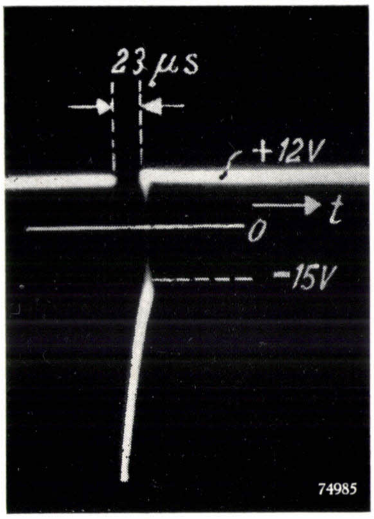

Fig. 19. Oscillogram of the negative pulse with which the pulse shaper (fig. 16) temporarily suppresses the beam of the corresponding counter tube.

Input pulse shaper

As the original pulses which are to be counted do not, as a rule, satisfy the imposed conditions, the first counter tube must be preceded by a pulse shaper. It might be expected that the previously discussed multivibrator can be used for this purpose, but a closer investigation reveals that it is necessary to extend this circuit.

The interstage pulse shapers are triggered by negative pulses which are derived from the preceding counter tube (fig. 16); the duration of these pulses is but a fraction of 1 μsec, that is, much shorter than the duration of the output pulses (23-32 μsec). The pulse shaper at the input, on the other hand, is triggered by the original pulses, the duration of which may be considerably longer than 23 μsec, particularly so at low counting rates. For reliable operation a multivibrator requires triggering pulses of shorter duration than the pulses delivered.

This difficulty has been overcome by differentiating the original pulses by means of a capacitor C_d and a resistor R_d (*fig. 20*). If the form of the original pulse is, for example, as drawn in *fig. 21a*, a voltage will be produced across R_d, which — provided R_dC_d has been chosen small enough — approximates the form depicted in fig. 21*b*, remaining negative during a shorter length of time than the original pulse. The negative voltage is now, however, followed by a positive voltage which suddenly drops to zero at $t = t_2$. This sudden variation might trigger the pulse shaper again and give rise to a faulty count. This is why R_d is shunted by a germanium diode (fig. 20), which prevents the voltage across R_d from becoming positive.

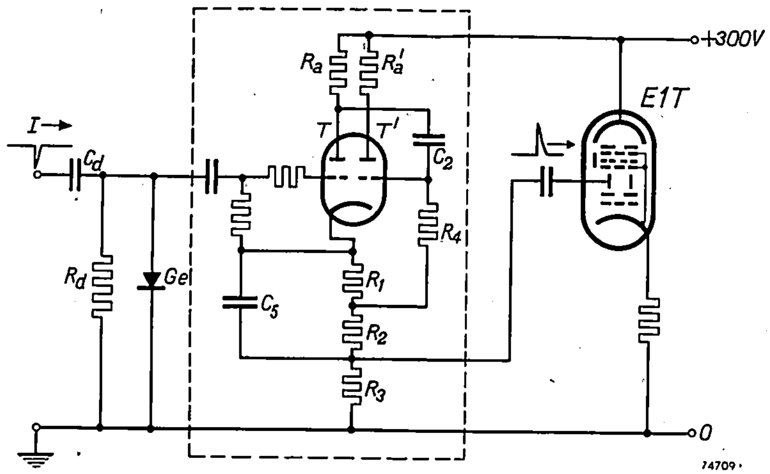

Fig. 20. Circuit of the input pulse shaper. *I* applied negative-going counting pulses. C_d-R_d differentiating network. *Ge* germanium diode (type OA 55), which prevents a positive voltage occurring across R_d. The circuit within the rectangle corresponds to that shown in fig. 16 of the other pulse shapers. At the right of this circuit is the first counter tube.

The input pulse shaper need supply pulses for operating the first counter tube only. The condition that the pulse duration must be greater than τ is not applicable to these pulses, so that it was possible to reduce the duration of these output pulses to 13.5 μsec.

It would lead too far to discuss the other (small) differences between this pulse shaper and the others, and it will suffice to quote the conditions which must be imposed to the original pulses (assuming these to have roughly a square wave-form):

Amplitude	20 V to 50 V,
Leading-edge duration	< 13.5 μsec,
Interval between end of one pulse and beginning of next	$\geqq 10$ μsec.

These conditions can as a rule easily be satisfied, and provided the values of the circuit components remain within certain tolerances, a counting rate of 30,000 pulses per second can be obtained with certainty.

All E1T tubes are tested at this counting rate; during these tests the pulse amplitude and the anode resistor are varied in order to guarantee reliable operation of the tubes in the circuit discussed at 30,000 pulses per second. This counting rate is however by no means the highest rate obtainable with the tube. In the laboratory it has proved possible to obtain counting rates of the order of 100,000 pulses per second and, by using a triode-hexode and a secondary-emission valve as

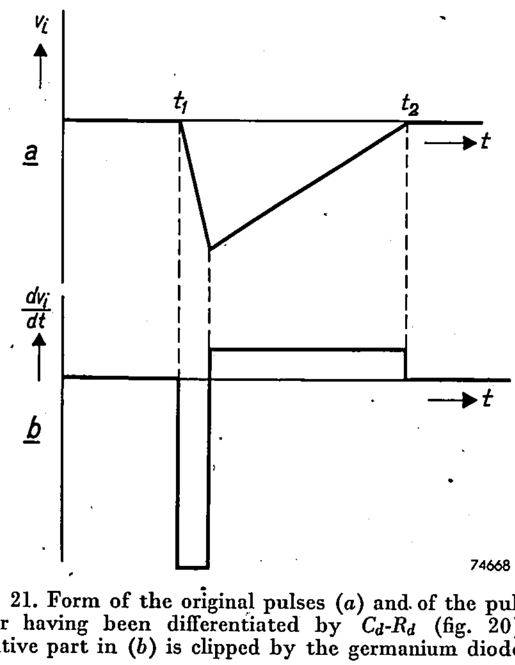

Fig. 21. Form of the original pulses (*a*) and of the pulses (*b*) after having been differentiated by C_d-R_d (fig. 20). The positive part in (*b*) is clipped by the germanium diode.

auxiliary valves, counting rates of millions of pulses per second have even been obtained [6]). For achieving these record performances the circuit parameters were adjusted to suit the individual tubes. On the other hand, the standard circuit discussed above will count up to 30,000 pulses per second without any special adjustment being made to allow for the unavoidable differences between production tubes.

[6]) See the second article quoted in footnote [2]).

Summary. A decade counter tube (E1T) has been designed which gives visual indication of the counts on the tube itself. The E1T is a cathode-ray tube — roughly the size of a receiving valve — whose electron gun produces a ribbon-shaped electron beam with a current of approximately 1 mA. A supply voltage of 300 V suffices for this tube. The beam impinges on an electrode with ten slots, behind which there is an anode with ten apertures. When the beam passes through a slot and an aperture, it impinges on a fluorescent layer with which the envelope is lined; at this spot a luminescent mark is produced adjacent to the corresponding figure (0......9).

On its way from the gun to the slotted electrode the beam passes between two deflection electrodes. The slots and some auxiliary apertures in the slotted electrode are so dimensioned that the anode current as a function of the deflection voltage assumes a number of maxima and minima which increase as the beam is further deflected from 0 to 9. By feeding the anode and the one deflection electrode (that nearest to the figure 0) via a common resistor of suitable value, the beam is given ten stable positions of equilibrium, corresponding to the figures 0......9. The beam is advanced to the following position by applying a positive pulse to the other deflection electrode.

At each tenth pulse the beam impinges on the reset anode. A suitable circuit ensures that the resulting voltage surge at this anode rapidly resets the beam to position 0, and, moreover, that a pulse is fed to the following counter tube, thus advancing its beam one step. The second tube thus counts the decades, and proceeding in this way, a third tube can be made to count the hundreds, a fourth tube the thousands, etc.

The slope and amplitude conditions which the pulses must satisfy are discussed. A circuit is outlined by means of which 30,000 pulses per second can be counted. In this circuit pulse shapers are used; the input pulse shaper converts the initiating pulses into pulses of the required form and amplitude, whilst the interstage pulse shapers initiate the resetting and feed a pulse to the following counter tube. All E1T counter tubes are tested at 30,000 pulses per second.