CHAPTER V

COLD-CATHODE TUBES

Introduction

The gas-discharge tubes treated in the last two chapters contain a cathode which can be heated to incandescence by means of a separate voltage supply, and which then emits electrons. The various types of discharges which can then be produced belong to the class of non-self-sustaining discharges.

As we have already seen in Chapter I, a cathode can also emit electrons in the cold state, in a glow discharge and a corona discharge. Such discharges are self-sustaining. Here no separate source of energy is needed to heat up the cathode, and there is thus no heating-up time necessary for the cathode. It is therefore possible for the discharge to be ignited without any delay.

Whereas the discharge current in hot-cathode tubes can amount to many amperes, that in most cold-cathode tubes is restricted to some tens of milliamperes. If the current becomes much more than this, the cathode temperature rises so much that thermionic emission begins and the discharge can turn into a self-sustaining arc discharge.

As regards the number of electrodes, the simplest form of cold-cathode tube is the diode just as with the hot-cathode tubes, while we will also meet triodes and tetrodes, in which the current through the tube can be controlled. The way in which the current is controlled differs however from what we have met in hot-cathode tubes.

V-a **Diodes; voltage-stabilizing tubes, reference tubes**

There are several types of cold-cathode diodes, each with its own function to perform.

In the course of the treatment of the demands made on *voltage-stabilizing tubes,* we will find an opportunity to learn several of the problems and peculiarities which are also connected with other glow-discharge diodes. Moreover, this type of tube plays an important role in modern electronic apparatus. We will therefore discuss it first.

V-a-1 THE VOLTAGE-STABILIZING TUBE

In many applications of electronics, it is necessary to keep a DC voltage constant irrespective of variations in the mains voltage, the load, etc. Voltage stabilization is often needed in amplifiers, control circuits, generators, etc., in order to be able to comply with the demands made on the constancy of the quantity to be supplied (e.g. current, pulse, frequency).

Since the tube current in the glow-discharge tubes used for this purpose may not exceed some tens of milliamps with the available models, in connection with the maximum permissible cathode load of some mA per cm^2 of cathode surface, the glow-discharge stabilizing tube only comes into consideration for circuits in which the current is low.

The applied tube voltage must exceed the burning voltage V_{br} for the discharge to be ignited. It is useful if the ignition voltage V_{ign} is only slightly more than the burning voltage, so that the supply voltage can also be kept low. In any case, the difference between the supply voltage and V_{br} must be taken up by a resistor in series with the tube.

The gas mixture neon$+1\%$ argon is normally used, if this is compatible with the other demands made on the tube, in order to make the difference between V_{ign} and V_{br} as small as possible. We have already seen (I-d-3) that the rather high breakdown voltage of neon is considerably lowered by the addition of a little argon.

When a tube is completely screened off from the light, ignition is often found to be delayed somewhat; this delay may amount to as much as a few seconds. The tube should therefore in general be illuminated to a certain extent in order to prevent this delay. An increase in the supply voltage can also have the same effect. A little radioactive material is sometimes placed in the tube for the same reason.

The discharge in a voltage-stabilizing tube corresponds to a point on the horizontal part of the current-voltage characteristic of a gas discharge (cf. I-g-1 and Fig. 14). This is the glow-discharge region with normal cathode fall. In other words, the voltage V_{br} across the tube remains practically constant while the current varies within wide limits. The cathode fall of the various types of tubes has a value of between 60 and 160 V. If the pressure in the tube is high and the distance between the electrodes large, *anode fall* amounting to 10 or 20 V may also be present. In such cases, a luminous film or ball will be seen at the anode. The burning voltage is then no longer equal to the cathode fall, but to the cathode fall plus the anode fall.

It should be mentioned that the presence of an anode fall sometimes gives rise to undesired oscillations of the burning voltage.

The potential distribution between the cathode and anode of a stabilizing tube is sketched in Fig. 101. The potential difference between the cathode

k and the glow gl (the cathode fall V_k) is nearly equal to the tube voltage. If the current is increased, the glow spreads out over the surface of the cathode, and the tube voltage remains practically constant until the whole surface of the cathode is covered by the glow. The voltage then increases strongly, as shown by the current-voltage characteristic of Fig. 102 [20].

We have various means at our disposal to obtain a given value of V_{br}: we can choose the composition of the gas and of the cathode material, and we can choose the shape of the electrodes. Table V in section II-c-2-b showed values of the cathode fall for various gases and cathode materials.

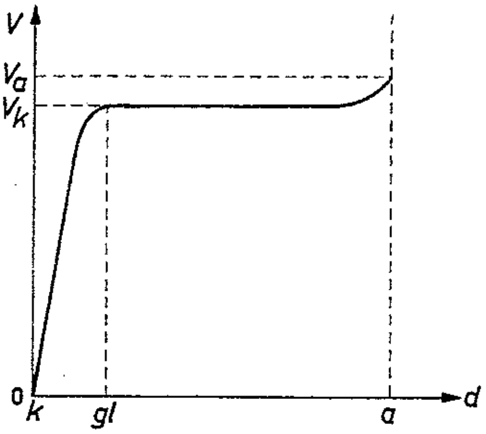

Fig. 101

Potential distribution between the anode k and the anode a of a voltage-stabilizing tube. Most of the tube voltage (the cathode fall V_k) lies between k and the glow gl. V_a is the tube voltage.

A very low tube voltage, e.g. 60 V, can be obtained with a nickel cathode coated with a layer of barium oxide. Another metal which can be used for the cathode is zirconium, with $V_k = 75$ V, and a third is molydenum ($V_k = 85$ V). As we shall see below, molybdenum has some very attractive properties when it is a question of obtaining a very constant burning voltage, if it is treated carefully during the manufacture of the tube. In some tubes, the cathode is made of iron coated with barium or magnesium. V_k then amounts to about 100 V (see Table X in section V-a-2).

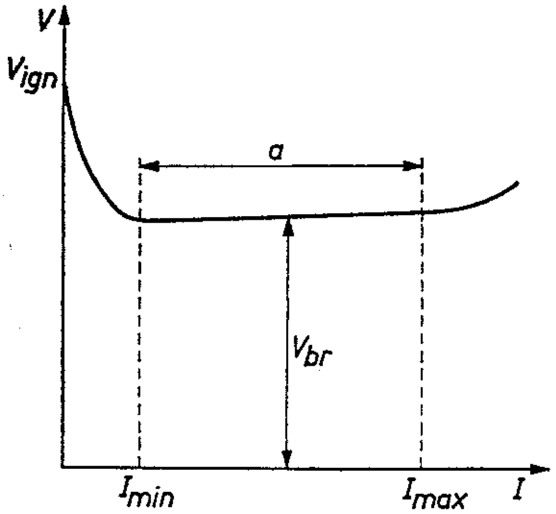

Fig. 102

Current-voltage characteristic of a voltage-stabilizing tube. a is the region of normal glow discharge.

If the stabilizing tube is to do what is expected of it, V_{br} should remain as good as constant while the current increases in the region of normal cathode fall. In other words, it is of prime importance that the impedance or AC resistance R_i of the discharge (i.e. the differential resistance dV_{br}/dI) should be small. This entails that the surface of the cathode should be very clean, since impurities can change the value of φ. If the glow discharge spreads out over such a dirty spot, a relatively large change in V_{br} will be produced. This variation of V_{br} usually takes place in jumps rather than continuously as the current varies. A clean cathode results in a low R_i. Moreover, a carefully prepared cathode may be expected to give a V_{br} which remains constant during the life of the tube and which varies little from tube to tube.

This is especially so for *reference tubes.*

V-a-2 REFERENCE TUBES

Reference tubes are voltage-stabilizing tubes which are used to provide a constant comparison voltage; they are thus rather like standard cells, and are made much use of in control circuits. While care must be taken in the use of standard cells that they do not pass any current, and it is also usual to keep them in a thermostat, the operating conditions for a reference tube are not so strict. On the other hand, the voltage across the latter is only accurate to about 0.1 %, while that of a standard cell is accurate to 0.01 to 0.001 %.

An example of this type of tube is the Philips reference tube type 85 A 2 (1 to 10 mA, 85 V). Fig. 103 shows a sketch of the inside of type 85 A 1, a precursor of the 85 A 2, in which the arrangement of the electrodes can be clearly seen (sealed-off tube, not yet sputtered). The cathode consists of a molybdenum plate, whose surface is cleaned by a special treatment (sputtering). During the cathode sputtering, the walls of the tube become covered with a layer of finely divided molybdenum, which plays an important role in the operation of the tube: not only does it take up impurities which are present in the gas, but it hinders gaseous impurities from being desorbed from the walls.

This molybdenum-sputtering technique enables tubes to be made with a burning voltage which does not vary by more than 0.1 V in 1000 hours of operation. The tubes as manufactured may however show a rather higher variation: the value published in the tube data is a few tenths of a volt. The spread in the value of V_{br} between different specimens of the same type is ± 1 V to ± 2 V. Tubes made in other ways may be expected to show a variation of the burning voltage during the life of the tube of about 10 V; the spread in V_{br} will have about the same value. These variations in V_{br} are due not only to impurities in the gas and on the surface of the cathode but also to the polycrystalline structure of the cathode. Recent experiments with monocrystalline cathodes [55] have shown that the spread in V_{br} can be reduced to a few tenths of a volt in this way.

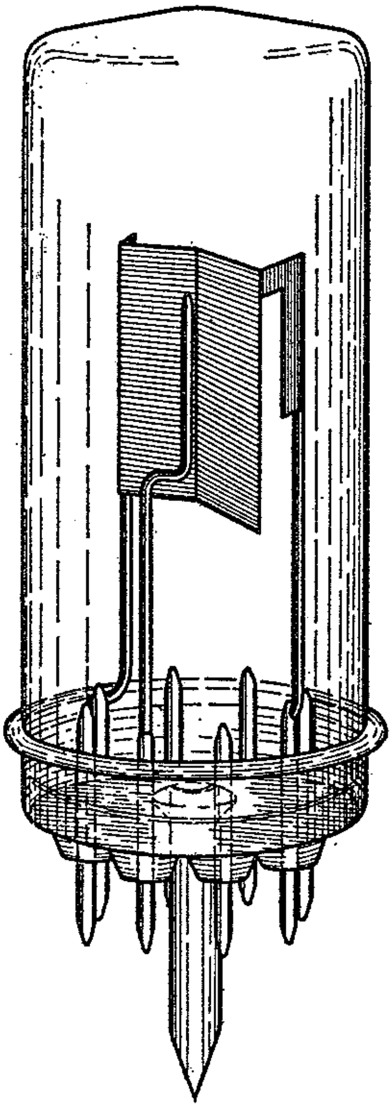

Fig. 103

Electrode arrangement of the (obsolete) Philips reference tube type 85 A 1. The rod -shaped anode is placed near the molybdenum cathode plate. Cathode sputtering has not yet taken place (the envelope is still transparent). Sputtering cleans the surface of the cathode and covers the wall of the tube, with an opaque layer of finely divided molybdenum, which acts as a getter for the gas [19].

Since the sputtering technique makes for a pure gas, the variation of V_{br} with the ambient temperature is also reduced in these tubes. While other stabilizing tubes are quoted as having variations of 20 to 30 mV per degree centigrade, a temperature coefficient of $-$ 4 mV/°C can be reckoned with for the 85 A 2. (The temperature coefficient is negative in tubes where the anode fall is absent.)

It was originally thought that the value of the normal cathode fall was to a first approximation independent of the density of the gas, and thus of the ambient temperature. More accurate investigations of ten years ago have however shown that this is not so [19]. It has however been shown that tubes with molybdenum cathodes can have a very constant and reversible value of the temperature coefficient, which makes it possible to compensate for the variation of V_{br} with the temperature by suitable additions to the circuit.

Fig. 104 shows the miniature model of the 85 A 2. The interior of the tube is in fact hardly visible because of the deposit of molybdenum on the walls.

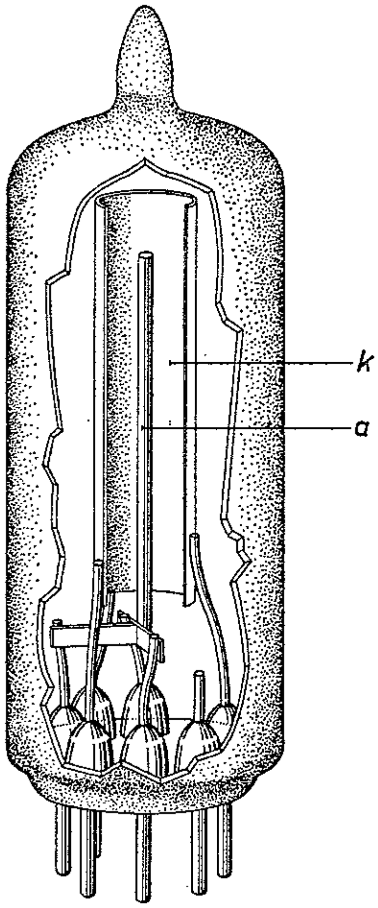

Fig. 104
Cut-away view of the modern reference tube type 85 A 2 with anode rod and coaxial cylindrical cathode.

Another example of a voltage-stabilizing tube is the Philips type 100 E 1, with a nominal voltage of 100 V. This tube is filled with a mixture of helium and argon. The extreme values of V_{br}, as published in the tube data, are 90 and 105 V; but the actual value found for a given tube will usually be much nearer 100 V than this. The current may be from 50 to 200 mA. This relatively high value is made possible by the large surface area of the electrodes (see Fig. 105). The cylindrical coated cathode is surrounded by an anode cylinder on the inside as well as on the outside. The cathode is thus covered with a glow on both sides, giving a low internal resistance.

It may be seen from the figure that the anode cylinders are not coaxial with the cathode. This ensures that the discharge always begins at the same spot, which gives a constant ignition voltage. Moreover, as the current increases the glow spreads evenly across the surface of the cathode, and always in the same way. The probability of voltage jumps is thus reduced.

The internal resistance of a voltage-stabilizing tube is governed by the walls of the tube, among other things. If these are too close to the glow, V_k and R_i may be increased owing to the recombination of positive and negative charge carriers on the walls. This effect is not found with the 100 E 1, because of the screened anode construction.

We may finally mention that there are tubes on the market with burning voltages of up to about 150 V (see table X on p. 148).

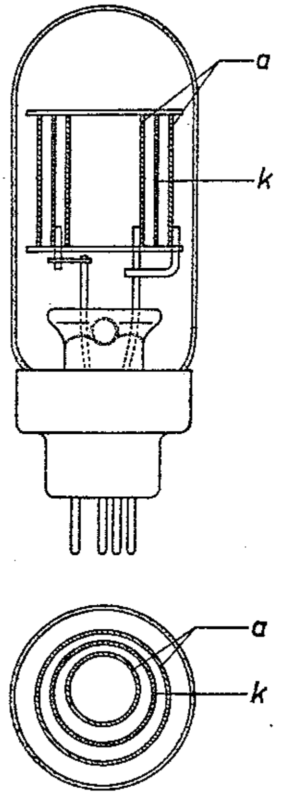

Fig. 105
Voltage-stabilizing tube type 100 E1. The voltage at which tube is stabilized is 100 V, the range of currents from 50 to 200 mA. The cathode cylinder is placed excentrically between the two anode cylinders, so that as the current increases the glow discharge spreads over the cathode in an orderly manner.

Circuits using stabilizing tubes

The principle of the design of a voltage-stabilizing circuit is illustrated in Fig. 106, which shows the simplest circuit of this kind. The voltage V_{aa} feeds both the stabilizing tube B and the load resistance R_o via the series resistance R_s. If e.g. the total current I alters as a result of changes in V_{aa}, the difference current ΔI will flow through B at constant voltage as long as the cathode is not completely covered by the glow. The variation in the voltage, $\Delta V_{aa} = \Delta I \times R_s$, is taken up by R_s.

Under normal conditions R_s is chosen so that the current has the value which corresponds to the middle of the horizontal part of the current-voltage characteristic.

Parallel combination of stabilizing tubes is not possible. The current will always pass through only one of the tubes, because of the negative current-voltage characteristic. If the tube current happens to be so large that it falls outside the stabilization region, a sturdier type of tube must be used.

Series combination is however possible. One example of this is shown in Fig. 107. If it is wished to have a stabilized voltage of 300 V, this can be achieved by three 100-volt tubes, or a suitable combination of tubes with different nominal voltages, in series with the ballast resistance R_s. In order to ensure the ignition of the individual tubes, one or possibly two of the tubes must be provided with a shunt resistance R_{sh} of e.g. 0.5 M Ω. The tube without shunt resistance ignites first, and the remaining voltage is then able to ignite the others.

Table X shows the data of a number of glow-discharge stabilizing tubes.

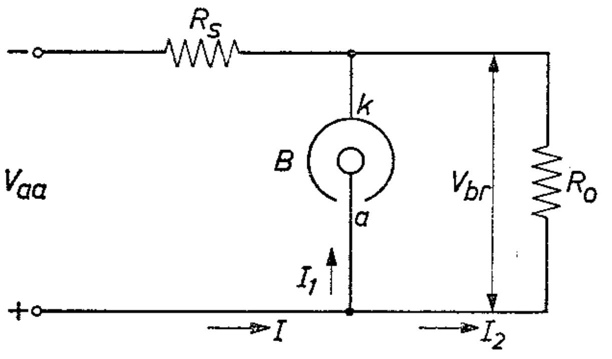

Fig. 106

Circuit for stabilizing the voltage across the load resistance R_o. The difference between the varying supply voltage V_{aa} and the constant tube voltage V_{br} is taken up by the ballast resistance R_s.

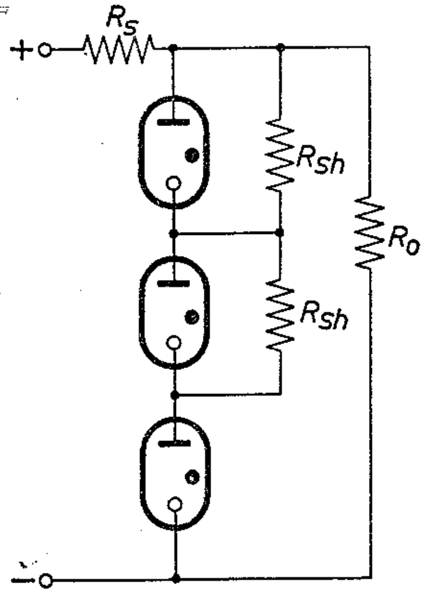

Fig. 107

Stabilizing circuit as in Fig. 106, but for higher voltages. Three tubes are used in series, with one or two shunt resistances R_{sh} (of e.g. 0.5 Mohm) to ensure reliable ignition.

TABLE X

OPERATING DATA OF SOME VOLTAGE-STABILIZING TUBES

TUBE TYPE	85A2 *)	90C1	100E1	OB2	150B2	OA2
nominal burning voltage (volt)	85	90	100	108	150	150
limits of the burning voltage 1) (volt)	83–87	86–94	90-105	106–111	146–154	144–164
recommended quiescent current (mA)	6	20	125	17.5	10	17.5
max. ignition voltage, in light/in darkness 2) (volt)	125/160	125/160	125/–	133/210	180/225	180/225
max. internal resistance (ohm)	450	350	30	140	500	240
range of currents (mA)	1–10	1–40	50–200	5–30	5–15	5–30
maximum variation in burning voltage 3) (volt)	4	14	4	3.5	5	6
max. variation in burning voltage (%) in first 1000 hours at the rated current	0.2 to 0.3 (5.5mA)	± 1 (20mA)	—	± 2 (17.5mA)	± 1 (10mA)	± 2 (17.5mA)
Ambient temperature (°C)	-55/+90	-55/+90	—	-55/+90	-55/+90	-55/+90
Temperature coefficient (mV/°C)	-2.7	—	—	—	10	—

V-a-3 CORONA STABILIZING TUBES

The corona stabilizing tube is very suitable for the stabilization of voltages higher than a few hundred volts at currents of less than 1 mA. Such loads are found e.g. in the control of the intensity of the cathode ray or of the accelerating voltage in oscilloscopes. Much use is also made of such tubes for obtaining a constant voltage in the range from 350 to 700 V at currents of 10 to 100 μA in equipment for measuring radioactivity.

Such a tube consists of a thin anode wire *a* of diameter $Ø_a$ (e.g. some

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*) reference tube

1) spread in the burning voltage from tube to tube at the rated operating current

2) during the life of the tube

3) over the whole range of currents

tenths of a millimetre) arranged along the axis of a cylindrical cathode k of length l and diameter $\varnothing_k$ (see Fig. 108). It can be shown that if $\varnothing_k/\varnothing_a$ and $l/\varnothing_k$ are given suitable values, a favourable control characteristic and a low differential resistance R_i (low for corona discharges, that is) can be obtained [67, 85]. The value obtained for R_i may be about 0.2 megohm.

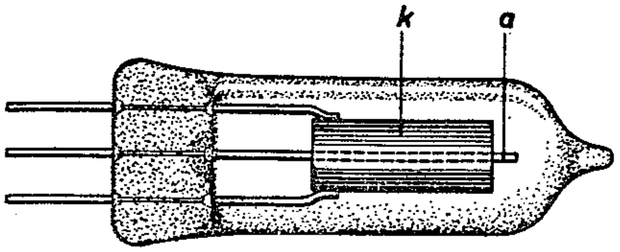

Fig. 108

Corona stabilizing tube. The control region depends on the relative dimensions of the anode wire a and the cathode cylinder k.

The gas filling often consists of hydrogen or a mixture of hydrogen and helium, with a pressure of about 50 mm Hg. As an example, Fig. 109 shows the current-voltage characteristic of an experimental corona stabilizing tube which is filled with hydrogen. The curve usually shifts to somewhat lower voltages during the life of the tube. Under favourable conditions, the voltage decrease is only a few percent in 1000 hours.

V-a-4 HOLLOW-CATHODE STABILIZING TUBE

Another possible basis for the production of a stabilizing tube is the hollow-cathode discharge [68]. A cylindrical hole is bored in a metal block which acts as the cathode. The anode is placed opposite this hole (see

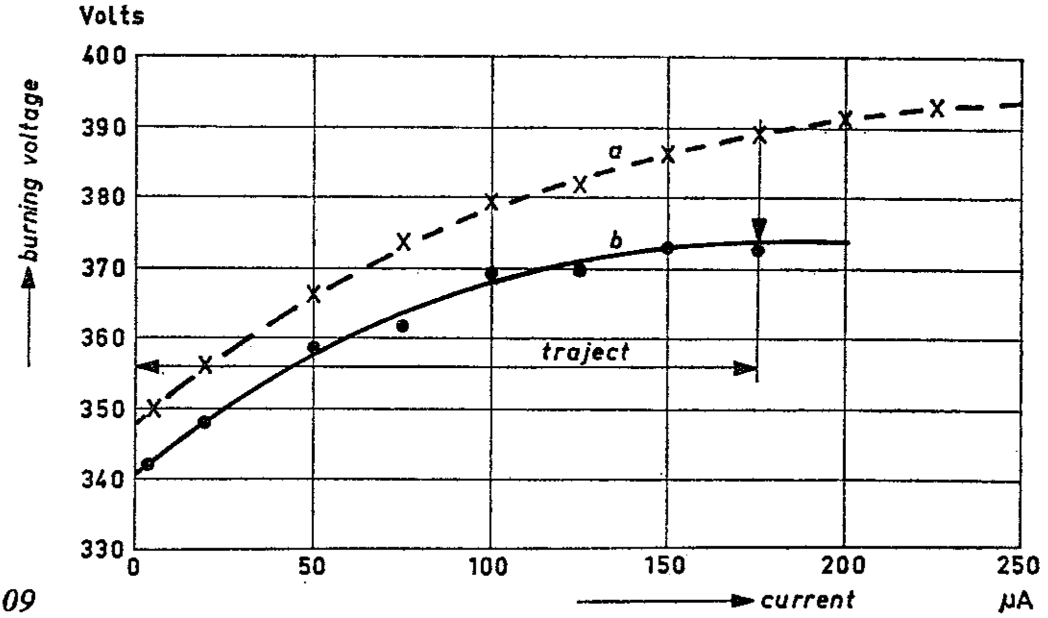

Fig. 109

Current-voltage characteristic of an experimental, hydrogen-filled corona stabilizing tube.
curve a at 0 hours
curve b after 350 hours
"traject" = region between $I = 0$ and I at maximum burning voltage.

Fig. 110 and 111). If the dimensions of the electrodes and the value of the gas pressure are suitably chosen, when a voltage is applied between the anode and the cathode the discharge produced will burn inside the hole, which will gradually change from a cylindrical to a spherical shape as a result of sputtering. The material which is removed from the wall of the hole in some places, causing a widening of the hole, is deposited on other parts of the inner wall. Once the hole becomes spherical, it does not change its shape any more. Gas is absorbed during sputtering. Once the spherical shape has been reached, the gas pressure remains stationary, and the discharge is stable as long as the operating point lies on the horizontal part of the current-voltage characteristic (Fig. 14). This set-up is thus perfectly suitable for use as a voltage-stabilizing tube or reference tube.

The current density can be much higher than at a flat cathode: a current of 50 mA can be obtained inside a spherical hole of about ½ mm radius. Apart from applications in telecommunication, hollow-cathode discharges are widely used for experimental work. For example, the very bright light emitted by the discharge during sputtering is characteristic of the metal used for the cathode, and can be used in spectroscopy.

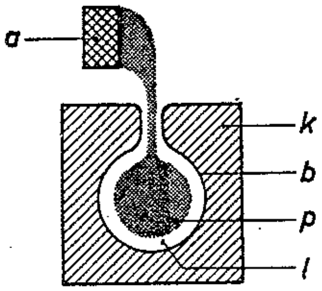

Fig. 110
Principle of the discharge in a hollow-cathode stabilizing tube. a = anode, k = cathode, b = spherical hole, p = plasma, l = ion space-charge layer [68].

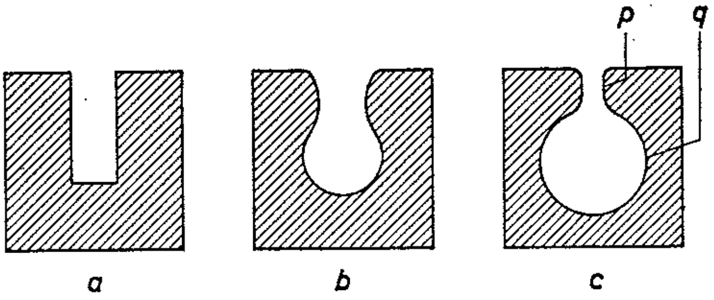

Fig. 111
Formation of the spherical discharge space.
a. Original state with cylindrical bore hole.
b. Intermediate state: the hole is widened by the discharge both at its mouth and in the middle of the cathode block.
c. Stable final state: the mouth of the hole has become narrower, owing to deposition of material removed from the sperical central space [68].

A construction in which this discharge can be approximated to makes use of a cathode consisting of plate bent into the shape of a U (Fig. 112). If the distance d is less than twice the thickness of the glow, the emitted electrons can be efficiently used for the ionization [67]. The fact that the hole is not entirely spherical means however that the cathode material will be attacked, so that sooner or later a hole will appear in it.

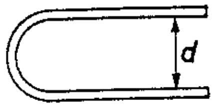

Fig. 112
Construction which gives an approximation to a hollow cathode: a U-shaped cathode plate is used, the distance *d* between the two limbs of the U being less than twice the thickness of the glow layer.

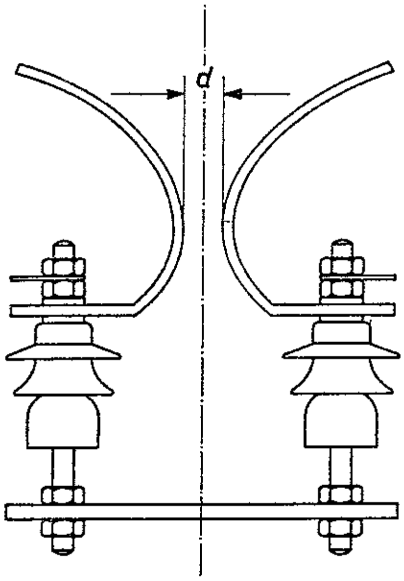

Fig. 113
A spark gap as an example of a conventional surge arrester; this type is known as a "horn arrester".
The shortest distance *d* between the horns determines the voltage at which the surge energy passes as a spark from one horn to the other.
The arc thus formed between the horns tends to rise because of the heat developed and because of the magnetic field due to the arc current itself; the arc thus becomes longer, and is finally extinguished.

V-b **Surge arresters**

Electrical equipment and mains must be protected against too high voltages or voltage pulses. The insulation between conductors can be broken down by voltage pulses caused by switching operations or atmospheric discharges. Among the classical means of limiting such overvoltages or of leading the excess energy to earth is the spark gap, with or without *horn arresters* for quenching the discharge (see Fig. 113). This does not however work as well as could be wished under some circumstances, e.g. at low voltages. Gas-discharge tubes, usually filled with rare gas, are also used for this purpose. Such tubes are called *surge arresters* [21] or *rare gas cartridges.*

The most important property which such a tube must possess is the ability to ignite with the minimum delay when the voltage exceeds the permissible value. Once it becomes conducting, it must conduct the excess charge away rapidly; and when the voltage falls again to a permissible value, the discharge must be quenched. These properties must not be appreciably altered by the passage of a charge which would be harmful to the equipment which the surge arrester is used to protect, because the arrester must be able to work properly when the next overvoltage comes along. This means, among other things, that the heat capacity of the electrodes is of importance.

Ignition

The *dynamic* ignition voltage of a surge arrester is often more important than the *static* ignition voltage (Fig. 114). A voltage surge is characterized by the duration of its leading and trailing edges, usually expressed in microseconds. The total voltage increase divided by the duration of the leading edge is approximately equal to the *slope of the leading edge* (expressed in kV/μsec), and this quantity determines the dynamic ignition voltage. We have already seen (I-e-1) that a certain time is needed for the discharge to build up between the electrodes of a gas-discharge tube; the dynamic ignition voltage will thus always be greater than the static.

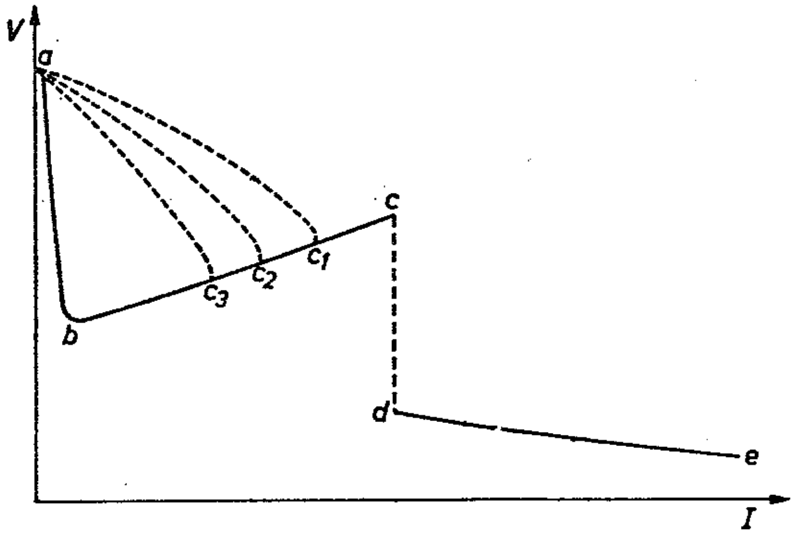

Fig. 114

Current-voltage characteristic of a surge arrester. After breakdown (point *a*), the tube voltage drops to the value corresponding to the point *b*. As the current increases, the positive glow-discharge region *b-c* is traversed. At *c* the discharge changes into an arc with a much lower burning voltage (*d-e*). If the current never reaches value *c*, the discharge will be quenched when the current has decreased to *b* again. In fact, in the very short time during which a discharge is produced, the relationship between current and voltage will not follow the static characteristic *a-b-c*, but one of the dynamic characteristics ac_1b, ac_2b, ac_3b, etc.

However, the breakdown of the insulation material to be protected also requires a certain time. What really matters therefore is that the dynamic ignition voltage of the surge arrester should be less than the dynamic breakdown voltage of the insulation material in parallel with it.

Now all sorts of overvoltages occur in nature, each with its characteristic form. A *standard wave* has therefore been defined, which can be produced by a pulse generator and used to test surge arresters. The form of this artificial voltage surge is shown in Fig. 115, together with the definitions of the quantities which characterize it. It may be mentioned that in atmospheric discharges, which are much more common than direct hits by lightning, the leading edge lasts 1 to 10 μsec., and the trailing edge 5 to 100 μsec. The current-voltage characteristic of the surge arrester is determined with the aid of the pulse generator and an oscilloscope, and the dynamic ignition voltage read off from this curve.

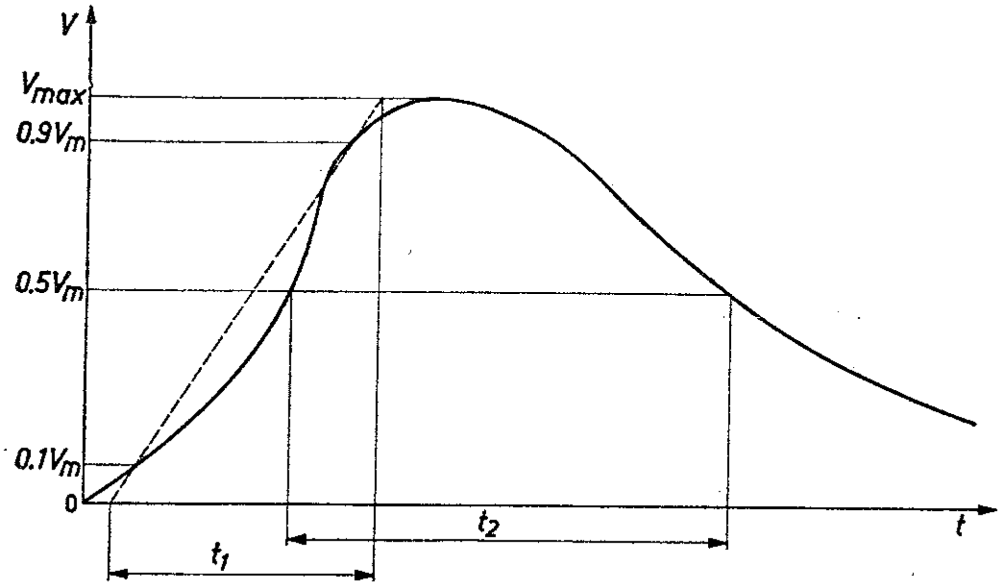

Fig. 115

Form of a "standard wave" (surge-voltage wave) for testing inert-gas surge arresters. The definitions of the front length, t_1, the front slope, V_m/t_1, and the rear length t_2 are made clear in the figure.

The behaviour of a surge arrester during a test is illustrated by the oscillogram of Fig. 116 [22]. The delay in ignition which can be seen here must be made as small as possible. Illumination of the surge arrester with weak daylight or artificial light is usually sufficient to ensure this; sometimes a small amount of some radioactive substance is placed in the tube for the same purpose. The electrodes are usually coated with a layer of material with a low φ, e.g. a calcium compound, in order to give a low ignition voltage.

Quenching

The discharge must cease at a voltage which is sufficiently far above the voltage of the mains to be protected, and the discharge must be quenched quickly. The composition and pressure of the gas in the tube are of importance in this respect; e.g. nitrogen at high pressure may be used. A special series resistance is often made use of too, to make certain that the discharge will be quenched properly. This resistance must not be ohmic, as it would then hinder the rapid removal of the energy of the

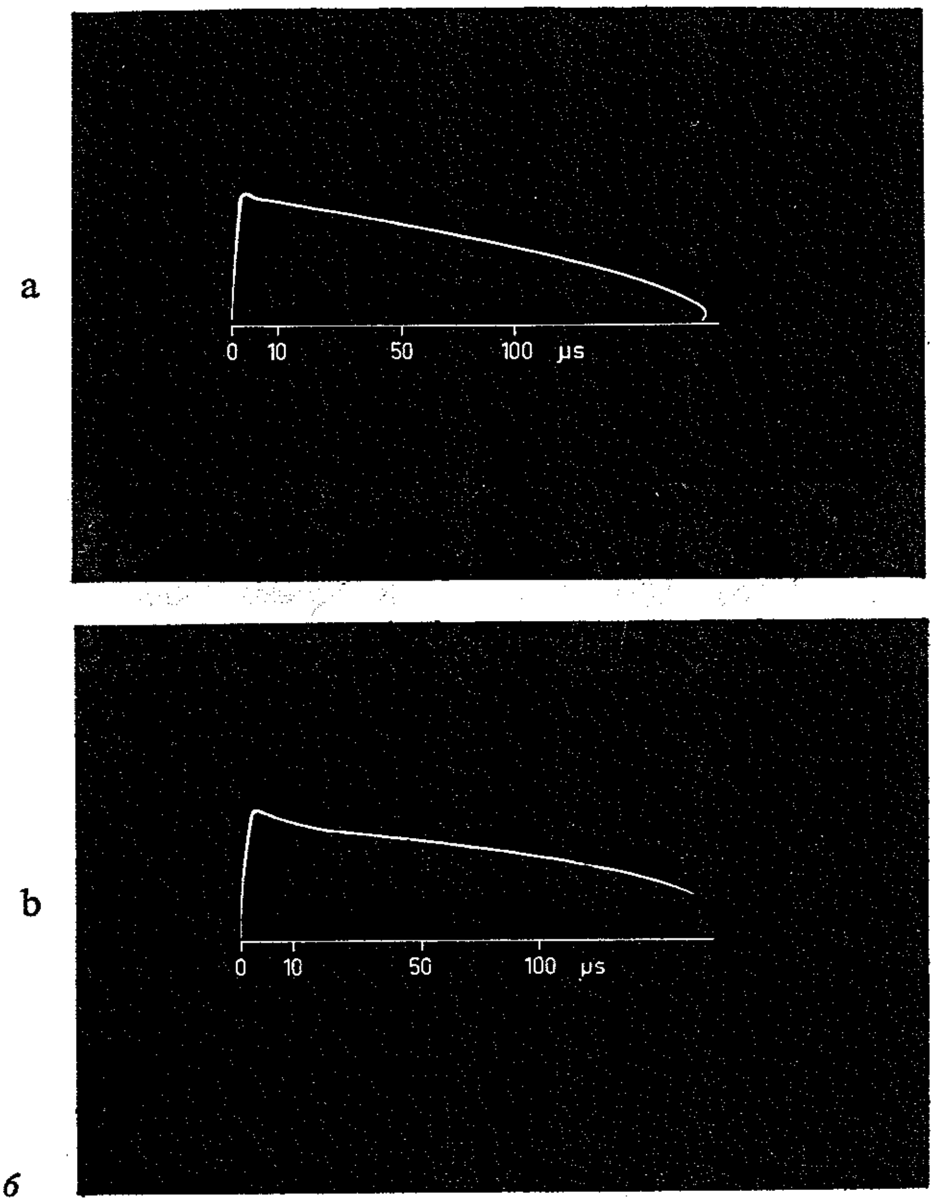

Fig. 116
a current, *b* voltage of a Philips surge arrester type 4394 as a function of time for an overload surge of 300 A. The maximum current is 300 A, the maximum voltage 1320 V. The front slope of the surge is 30 kV/µsec [22].

voltage surge. Voltage-dependent resistors (VDR) are used for this purpose; they are made of a sort of semiconducting material like silicon carbide. The relation between the voltage and the current for such a resistor has the form

$$V = C \cdot I^{\beta}$$

where $\beta = \tan \varphi$ is the slope of the approximately straight part of the voltage-current characteristic (Fig. 117) and C is the voltage at which $I = 1$ amp.

It is clear that the removal of the energy at high voltage is little hindered, but that the current through the surge arrester will decrease as soon as the surge has passed, which makes for rapid quenching. The resistor is usually included in the tube to exclude atmospheric effects on it.

Loadability

If the surge arrester is to continue to meet the demands made on it after a current has passed through it, the load to which it is subjected must not exceed a certain value. This load is expressed in watt-seconds. The sturdier type of Fig. 118 can stand 500 Wsec, and the type of Fig. 119 and 120 10 Wsec.

Typical application

Equipment such as kWh-meters which are attached to a high-current

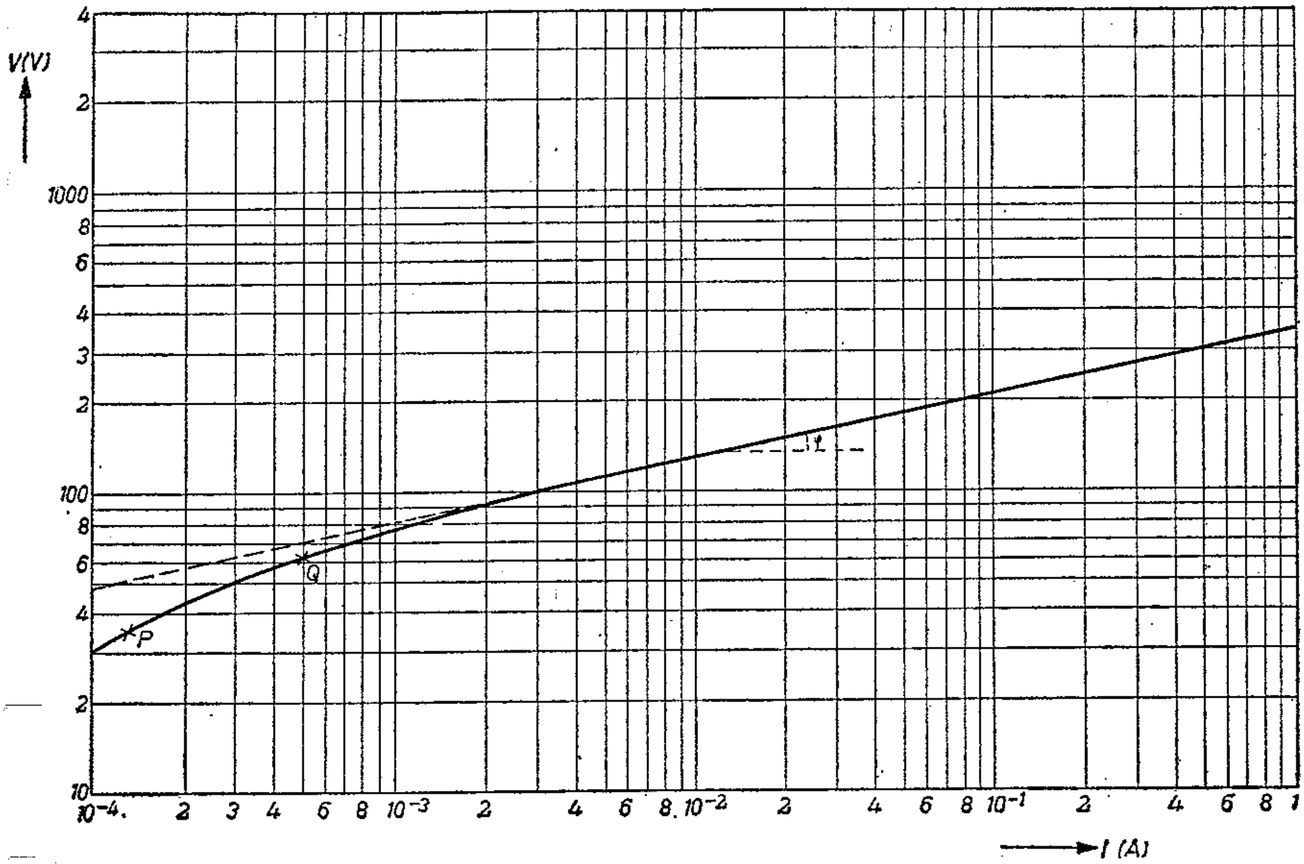

Fig. 117

Voltage-current characteristic of a VDR resistor plotted on a logarithmic scale. $C = 340$; $\beta = 0.21$.

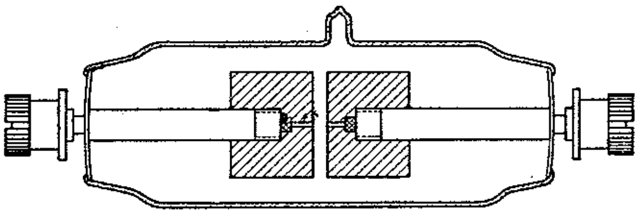

Fig. 118

Philips inert-gas surge arrester type 4390 in section. In the electrodes may be seen the cavities containing an alkali salt. A little of this compound evaporates at each discharge, and is deposited on the surface of the electrodes, among other places. This reduces the work function of the electrodes and thus the ignition voltage. The electrode leads pass through chrome-iron discs which are sealed into the glass envelopes. A large current surge can thus pass through the tube without danger of the glass breaking near the seal. Overall length 95 mm.

power transmission line for low voltages must be protected against breakdown as a result of overvoltages. If we assume that the line has a rms voltage of 220 V with respect to earth, the Philips tube type 4390 can be used for protecting it (see Fig. 118). The two electrodes are identical, as in most surge arresters, so it can be used with alternating current. The circuit is shown in Fig. 121.

The electrical data of this tube (and two similar ones) are given in the table below.

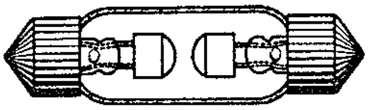

Fig. 119

Philips inert-gas surge arrester type 4371. The electrodes, made of a special alloy, are mounted on pinch seals. The tube with its two terminal caps can simply be pressed in place between two contact springs. Overall length 50 mm.

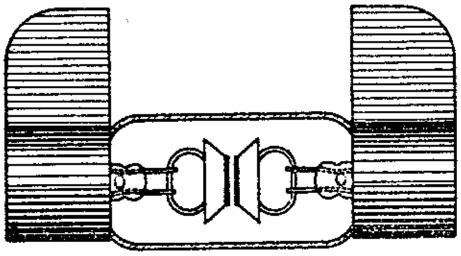

Fig. 120

Philips inert-gas surge arrester type 4372, with knife contacts. Length 62 mm.

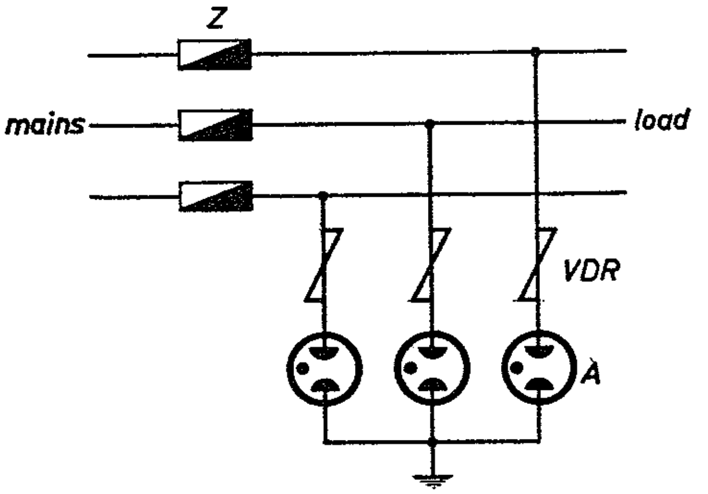

Fig. 121

Circuit with three surge arresters *A* and three VDR resistors for protecting a load connected to the 3-phase mains against overvoltages. Z = fuse.

TABLE XI

PHILIPS SURGE ARRESTER TYPE	4390 Fig. 118	4371 Fig. 119	4372 Fig. 120
static ignition voltage	700—910 V	150—200 V	280—350 V
min. quenching voltage	200 V	110 V	250 V
max. instantaneous peak current permissible for	25A/3 sec	5A/3 sec	2.5A/1 sec
fuse in series with surge arrester	25A	6A	6A
max. capacitive discharge (repeatedly permissible)	500 Wsec	10 Wsec	10 Wsec
max. mains voltage	175 V⎓ 300 V_{rms}	70 V⎓ 75 V_{rms}	200 V⎓ 180 V_{rms}
overall length	92.5—98 mm	49—52 mm	60—65 mm
diameter	max. 26.5 mm	max. 14.5 mm	max. 19.5 mm

The ignition voltage given above was determined with 50 c/sec AC. The dynamic ignition voltage is considerably higher: measurements with a standard voltage surge gave values of 1500 to 3500 V. A suitable voltage-dependent resistor is included in series with each surge arrester, which ensures quick quenching when the normal operating conditions are regained. A normal fuse is also placed in each lead as an additional precaution.

V-c **Ionization tubes**

Introduction

Various methods are available for the measurement of gas pressures below about 10^{-3} torr *) with measuring instruments which give a continuous indication of the (possibly variable) pressure. Some of these methods involve the measurement of the pressure itself; others are based on properties of the gas which depend on the pressure. In this section we shall only consider those pressure gauges based on gas discharges:

1. the ionization gauge, for pressures from 10^{-3} to 10^{-12} torr;
2. the Penning gauge; the range of pressures may be 10^{-3} to 10^{-6} torr or 10^{-3} to 10^{-9} torr, depending on the type of gauge;
3. the Hobson-Redhead gauges, which can still be used at pressures of 10^{-12} or 10^{-13} torr.

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*) 1 torr = 1 mm Hg

V-c-1 IONIZATION GAUGES *)

A heated filament emits electrons, which are accelerated in an electric field and used to ionize atoms of the gas whose pressure is to be measured. Measurement of the ion current allows the gas pressure to be determined. We are thus dealing with a non-self-sustaining discharge in the gas in question.

The pressure must be less thans about 10^{-3} torr, because above this pressure there is a risk that the discharge will become self-sustaining and destroy the gauge.

This gauge can be made as a triode or as a tetrode. The triode consists of a cathode filament, an anode grid for the acceleration of the emitted electrons, and an ion collector. The tetrode has, in addition to these three, a stabilizing grid in order to keep the electron current constant during the measurement.

An extra filament is sometimes also included as a spare, but this is not essential for the operation of the tube. In our further discussion of the ionization gauge we will restrict ourselves to the triode model.

At the low pressures for which this gauge is used (10^{-6} to 10^{-12} torr), the number of ionizations per electron is directly proportional to the pressure. Since the mean free path of the electrons at these pressures is large compared to the distance between the anode and the cathode, the probability of ionization by an electron moving from the cathode to the anode is small. If the path of the electrons can be increased in some way, the number of ionizations will increase in proportion, and the ion current at a given pressure will be greater, i.e. the sensitivity of the gauge will be greater. We will now describe how this is done.

In the triode ionization gauge shown in Fig. 122, the central filament f provides the primary electrons. These electrons are made capable of ionization by the anode a (accelerating electrode) which is arranged concentric with f. The distance between f and a is small compared with the mean free path of the electrons. Since a is made in the form of a grid, electrons can pass through it into the space between it and the third electrode, the ion collector Cl, which is made a few volts negative with respect to f. The electrons will then travel several times to and fro between f and Cl and will thus have more chance of ionizing an atom or a molecule. Experiments have shown that with most gases the ionization is maximum when the electron energy is about 100 eV (cf. I-d-3). The sensitivity of

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*) Though these gauges do not contain a cold cathode we will mention them as a suitable introduction.

the instrument is thus large if a is made about 100 V positive with respect to f.

The pressure is proportional to the ratio I^+/I^-, where I^+ is the measured ion current at *Cl*. The electron current I^- from the cathode is set to a relatively high value, e.g. 10 mA, so that the small ion current which goes to f does not have any effect on the value of I^-. The ion current is dependent on the nature of the gas, since the ionization probability depends on the gas involved; this means that the pressure of an unknown gas or mixture of gases cannot be determined accurately in this way. Pressures of down to 10^{-8} torr can be determined with the gauge shown in Fig. 122. Special models can measure down to 10^{-12} torr.

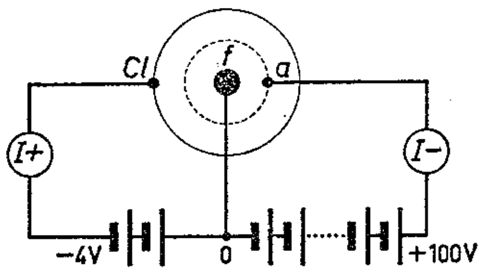


Fig. 122

Ionization manometer for measurement of pressures down to about 10^{-8} torr. A part of the electrons coming from the heater f pass through the meshes of the anode grid a and ionize the gas in the space between a and the ion collector *Cl*. The ratio of the ion current I^+ to the electron current I^- is a measure of the pressure.

One of the reasons for the above-mentioned lower limit for the pressure which can be measured is that soft X-rays are produced by the collision of the electrons with the accelerating electrode. This radiation frees photoelectrons from the ion collector, which add to the ion current to be measured and thus interfere with the result. Bayard and Alpert [59] designed another electrode arrangement which does not suffer so much from this trouble. They used a thin wire as the ion collector, with an anode cylinder round it and the hot cathode outside that. An arrangement of this type is shown in Photo 8. The chance of electron emission by the ion collector is much reduced, so that pressures down to 10^{-12} torr can be measured with this gauge.

Such an instrument is also sometimes used as a vacuum pump at low pressures [60]. If the potential of the wall and of certain electrodes is chosen properly, the ions are trapped. This effect can be a nuisance when the tube is used as a vacuum meter, since the pressure changes during the measurement.

If it is possible to increase the path of the electrons even further, the ionization will be amplified too. This possibility is realized in the Penning gauge, which we will now discuss.

V-c-2 PENNING GAUGE

The Penning gauge makes use of a self-sustaining discharge [23, 24]. If a DC voltage or a low-frequency AC voltage of about 1000 V is applied between the cold electrodes of a gas-filled tube, it has been found to be impossible to maintain a self-sustaining discharge if the gas pressure falls below 10^{-3} torr. However, if the shape and arrangement of the electrodes is properly chosen and a magnetic field is used, the discharge can be maintained down to pressures of 10^{-7} torr or even less.

There are two types of Penning gauge: a sensitive one and a less sensitive. Fig. 123 shows the arrangement of the electrodes and the magnet of the less sensitive type, for pressures between 10^{-3} and 10^{-5} torr. The cathode consists of the two plates P_1 and P_2, with the frame-shaped anode a in between. A magnetic field H is applied in the direction P_2—P_1. If this field were not there, electrons leaving P_2 or P_1 would go directly to a. In the presence of a sufficiently strong magnetic field, however, electrons coming from P_1 move along narrow spiral paths in the direction of P_2. After passing through a, the electrons find themselves in an electric field of the opposite sign and are decelerated. Just in front of P_2 they reverse direction and return towards P_1 along spiral paths. This process may be repeated several times before the electrons finally reach a. Thanks to the considerable increase in the distance travelled by the electrons, the

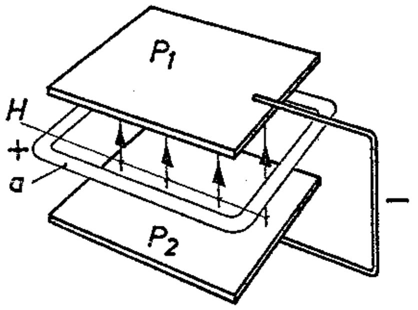


Fig. 123

Principle of the operation of a Penning gauge. A frame-shaped anode a is placed between two (cold) cathode plates P_1 and P_2

The electrons coming from P_1 and P_2 move along spiral paths because of the magnetic field H applied between P_1 and P_2, and pass to and fro several times before finally landing on a. The ionization probability is thus considerably increased, so that pressures down to 10^{-5} torr can be measured.

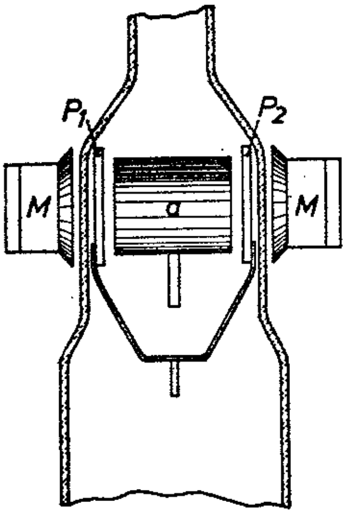


Fig. 124

Improved Penning gauge, with a cylindrical anode a placed between two cathode plates P_1 and P_2. The magnet M provides a magnetic field along the axis of a. The range of measurable pressures extends down to 10^{-9} torr.

ionization probability increases so that even at very low pressures enough collisions with gas molecules occur to maintain a self-sustaining discharge.

The construction of the more sensitive type, for pressures down to 10^{-9} torr, is shown in Fig. 124. The cylindrical anode a is placed between the two disc-shaped cathodes, P_1 and P_2, while the field of the permanent magnet M is parallel with the axis of a. It has been found that zirconium is a suitable material for the cathode. The magnetic field has a strength of $3 \times 10^5/4\pi$ to $4 \times 10^5/4\pi$ A/m. The gauge can be made less sensitive, i.e. suitable for the measurement of higher pressures, by removing the magnetic field or by changing the polarity of the electrodes.

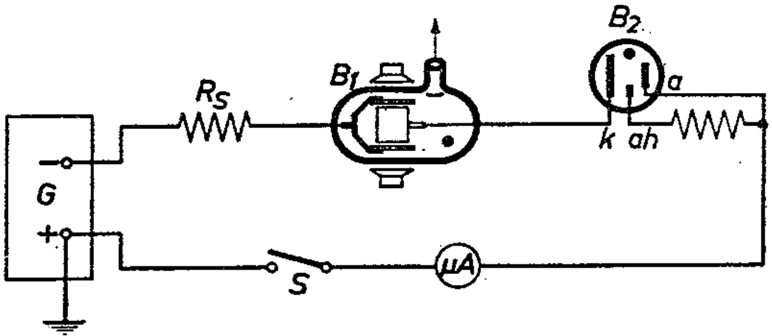


Fig. 125

Measuring circuit for a Penning gauge B_1. The magnitudes of the electron current and ion current can be read off from a μA meter or indicated by a tuning tube B_2 (cf. V-e-2). G is the DC voltage source, R_s a current-limiting resistance.

The measuring circuit shown in Fig. 125 consists of the Penning gauge B_1 in series with a microammeter and a limiting resistance R_s of 1 megohm. A tuning tube B_2 (see V-e-2) is often used to give a rough indication of the magnitude of the current. The supply voltage of 2000 V is supplied by the rectifier G. The variation of the current with the pressure for nitrogen, air and helium is shown in Fig. 126. In contrast with the well known McLeod gauge, the Penning gauge can also be used for condensible vapours.

This instrument is suitable not only for the continuous recording of pressures but also for the indication and detection of small leaks in vacuum equipment [24].

Like the ionization gauge, the Penning gauge can also be used as a vacuum pump at low pressures [24]. This must be borne in mind when it is used as a pressure gauge, as it will cause the pressure to change during the measurement.

Difficulties crop up if the Penning gauge is used to measure pressures below about 10^{-9} torr. In the first place, the discharge may fail to ignite at these low pressures, but the use of a Tesla coil usually solves this problem. Apart from this, the lowest measurable pressure is determined by the occurrance of field emission from the cathode plates at places where the field is high. The modification suggested by Hobson and Redhead brings about a great improvement in this respect.

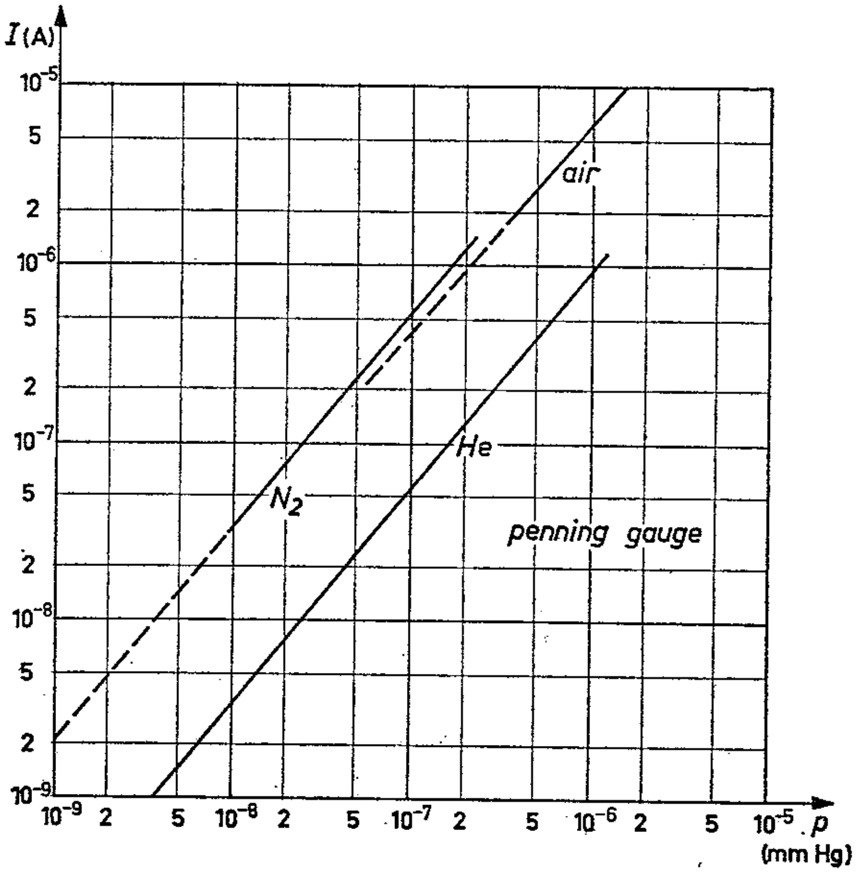


Fig. 126

Tube current as a function of pressure for nitrogen, helium and air, for the Penning gauge of Fig. 124.

V-c-3 HOBSON-REDHEAD GAUGES

In 1958 Hobson and Redhead suggested a number of designs, more or less based on the Penning gauge, in which the current due to field emission is kept separate from that due to ionization alone. Their "inverted magnetron gauge" (Fig. 127) has an anode wire placed in the direction of the magnetic lines of force, surrounded by the cylindrical box *Cl* which acts as the ion collector. The outer cylinder Cl_h is used as an auxiliary cathode, and shields the anode electrostatically from *Cl* by means of the tubes *d* connected to it. The ion current to *Cl* is measured separately. It is claimed that this pressure gauge can be used down to a pressure of 2×10^{-12} torr [61]. Their later design, the "magnetron gauge" (Fig. 128), is even more sensitive; it can be used down to 10^{-13} torr [62]. In this model, the magnetic field is parallel to the cylindrical anode *a*, which is placed between two collector plates *Cl* which are connected to each other. The edges of *a* are shielded by the two auxiliary cathodes Cl_h.

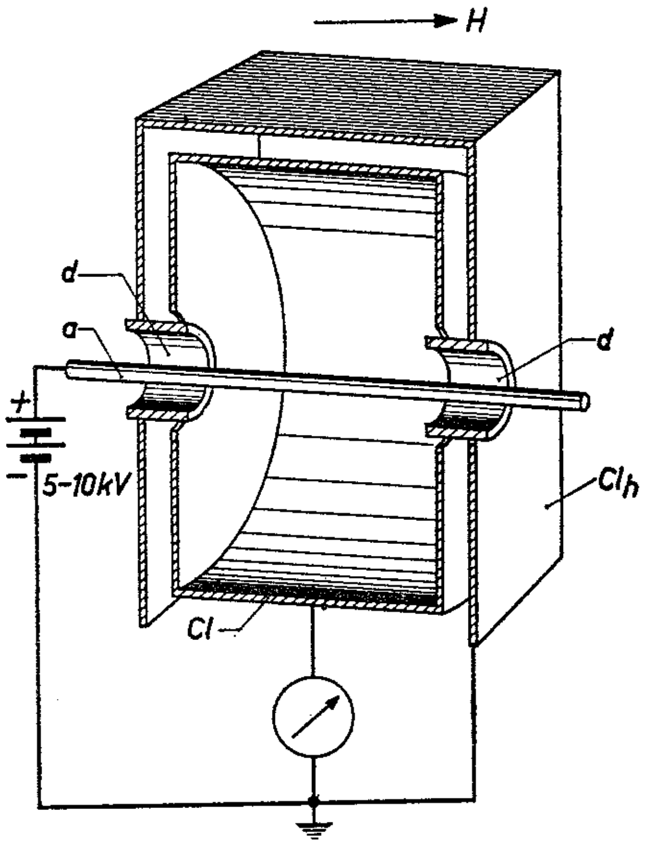


Fig. 127

Hobson-Redhead "inverted magnetron gauge". The outer mantle Cl_h screens the anode *a* from the collector *Cl*. The field-emission current is thus kept separate from the ion current. The lowest measurable pressure is about 2×10^{-12} torr [61].

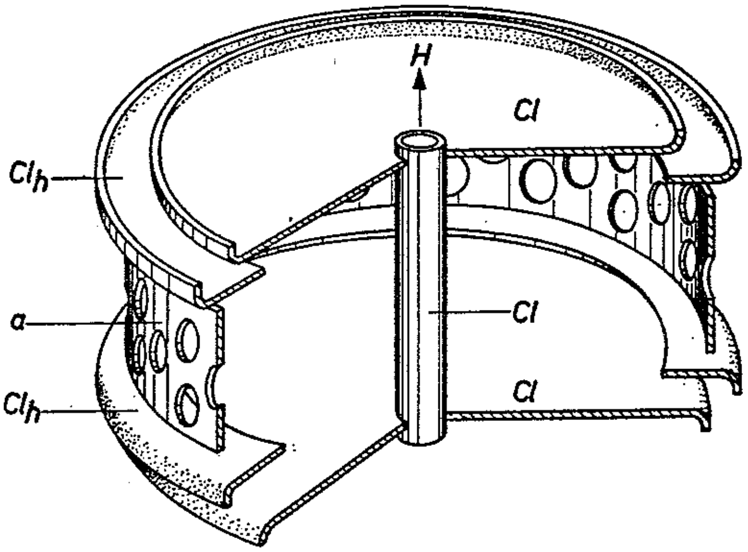


Fig. 128

Hobson-Redhead magnetron gauge. The flanges Cl_h screen the anode *a* from the ion collector *Cl*. Lowest measurable pressure about 10^{-13} torr [62].

V-d **Radiation counter tubes** [69, 84, 93]

V-d-1 INTRODUCTION

The phenomenon of radioactivity and the transmutation of the elements have been known for many years, but recently they have gained the attention of investigators outside the field of nuclear physics. The applications of radioactivity, nuclear fission and the interaction of radiation with matter have increased very considerably of recent years. Among these applications we may mention:

chemical investigations using tracers,
generation of energy by means of nuclear fission,
measurement of thickness with the aid of radioactive radiation.

In all these problems the detection, i.e. the observation, of the radioactive radiation plays an important part. Gas-filled detectors, in particular counter tubes, were the first devices to be used for this purpose.

The operation of a radiation detector is based on the principle that the kinetic energy of the incident particle or the quantum energy of the γ radiation is transformed into an electrical current pulse. This pulse is amplified if necessary and then measured or recorded with the aid of fairly simple equipment. The construction of the detector depends on the nature of the particles which must be detected: there are different types of detectors for α particles (doubly ionized helium atoms), β particles (electrons and positrons) and γ rays (electromagnetic radiation similar to X-rays).

V-d-2 RADIOACTIVITY

The phenomenon of radioactivity consists in the spontaneous disintegration of atomic nuclei with the emission of α particles, β particles and/or γ rays. Following on this disintegration, X-rays may also be emitted as a result of the rearrangement of the electronic shells. Nuclei may be divided into two sorts: radioactive, or unstable, and stable. Radioactive nuclei can be further divided into two groups: naturally occurring ones, which are to be found as such in the earth's crust, and artificial ones which are made in particle accelerators and reactors.

The nucleus of an atom is thought to consist of protons and neutrons. The chemical nature of an element appears to be determined by the number of protons only. A given chemical element may thus have several different kinds of nuclei, all with the same number of protons but with different numbers of neutrons. These different sorts of nuclei belonging to one element are called isotopes. Most elements have both stable and unstable isotopes. For example, hydrogen has two stable isotopes, H^1 and H^2, and one unstable one, H^3, these three isotopes contain 0, 1 and 2 neutrons per nucleus respectively. The unstable isotopes are known as radio-isotopes. Well known natural radio-isotopes are uranium and radium, and well known artificial ones e.g. sulphur (S^{35}), phosphorus (P^{32}) and carbon (C^{14}).

The α and β particles are both electrically charged particles, and as a result of their rapid motion they will ionize gases which they pass through, forming ion pairs consisting of an electron and a positive ion. Electromagnetic radiation such as X-rays or γ rays can not ionize gases in a direct way. But they can produce secondary electrons (or positrons) in matter, and each of these "secondary" charge carriers can give rise to a large number of ionizations in the gas because of the large energy it acquires from the radiaton.

α and β particles can be characterized by the following quantities:

electrical charge,
mass,
velocity and
kinetic energy.

The kinetic energy is expressed in keV or MeV (= 10^3 eV and 10^6 eV respectively). Electromagnetic energy is characterized by its wavelength or quantum energy; these two quantities are related by Planck's law

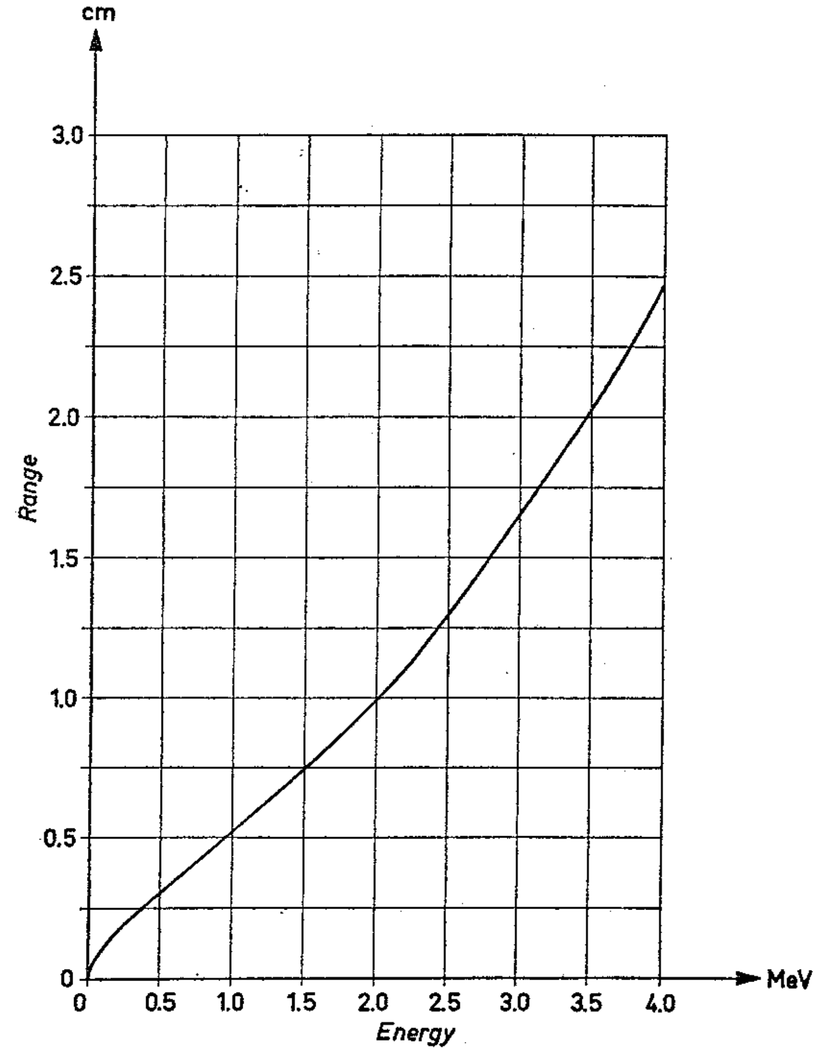


Fig. 129

Range-energy curve for alpha-particles in air (15 °C, 760 mm). Energy range 0 to 4.0 MeV [93].

($eV = h\nu$). The quantum energy is also expressed in keV or MeV. Other quantities which are characteristic for α and β particles and γ rays are their *penetrative power* and their *absorption coefficient,* and with α and β particles their *range,* i.e. the maximum distance they can penetrate into the material in question. The range is usually expressed in mg/cm^2, sometimes however in cm (Fig. 129).

V-d-3 DETECTION OF ELEMENTARY PARTICLES AND RADIATION WITH THE AID OF GAS-FILLED DETECTORS

The detection of radiation with the aid of these detectors is based on the fact that fast-moving charged particles ionize a gas in passing through it. This phenomenon is called *primary ionization,* in contrast to secondary ionization, which is discussed below. (The term primary ionization is used to represent not only the process of ionization, but also the magnitude and sign of the charge produced). The gas-filled space of the detector contains two electrodes. This may be seen in Photo 9, where the wire acts as the anode and the outer cylinder as cathode. If the voltage between these two electrodes is increased from zero, a series of different phenomena will be observed. In our discussion of these, we will assume that the position of the source of radiation with respect to the detector does not alter while the voltage is being increased, and that the radiation from the radioactive sample does not alter in the period in question. Fig. 130 shows the magnitude of the current pulses as a function of the voltage between the electrodes under these conditions. The lower curve refers to an experiment where the primary ionization was produced by electrons; the upper curve refers to α particles. It is clear from these curves that the primary ionization produced by α particles is considerably greater than that produced by electrons. If we plot the logarithm of the magnitude of the current pulses against the voltage, we see that the current first increases from zero to a certain value, and then remains constant over a certain range of voltages. If the voltage is increased further, the logarithm of the magnitude of the pulses increases linearly with the voltage. Finally the curve levels off again, and we see that at a certain voltage V_s the magnitude of the pulses produced by β particles is equal to that for α particles. This is called the start of the Geiger region.

The region in which the current through the tube is independent of the tube voltage is called the saturation region (*B*). All the charges landing on the electrodes come from the primary ionization caused by the incoming particles. There is no loss of charge due to recombination or diffusion, and neither is there a multiplication process which increases the number of charge carriers. To the left of the saturation region, we see a region in which charge is lost by recombination and diffusion (*A*). The higher the voltage, the less effect these two processes have. This region is of little importance for the use of the tube as detector.

Detectors which are designed for use in the saturation region are called ionization chambers.

The proportional region (*C*) lies to the right of the saturation region; here the current increases approximately exponentially with the tube voltage, so that the logarithm of the current is a linear function of the voltage. In this region we find a new phenomenon: gas amplification due to ionization by collision.

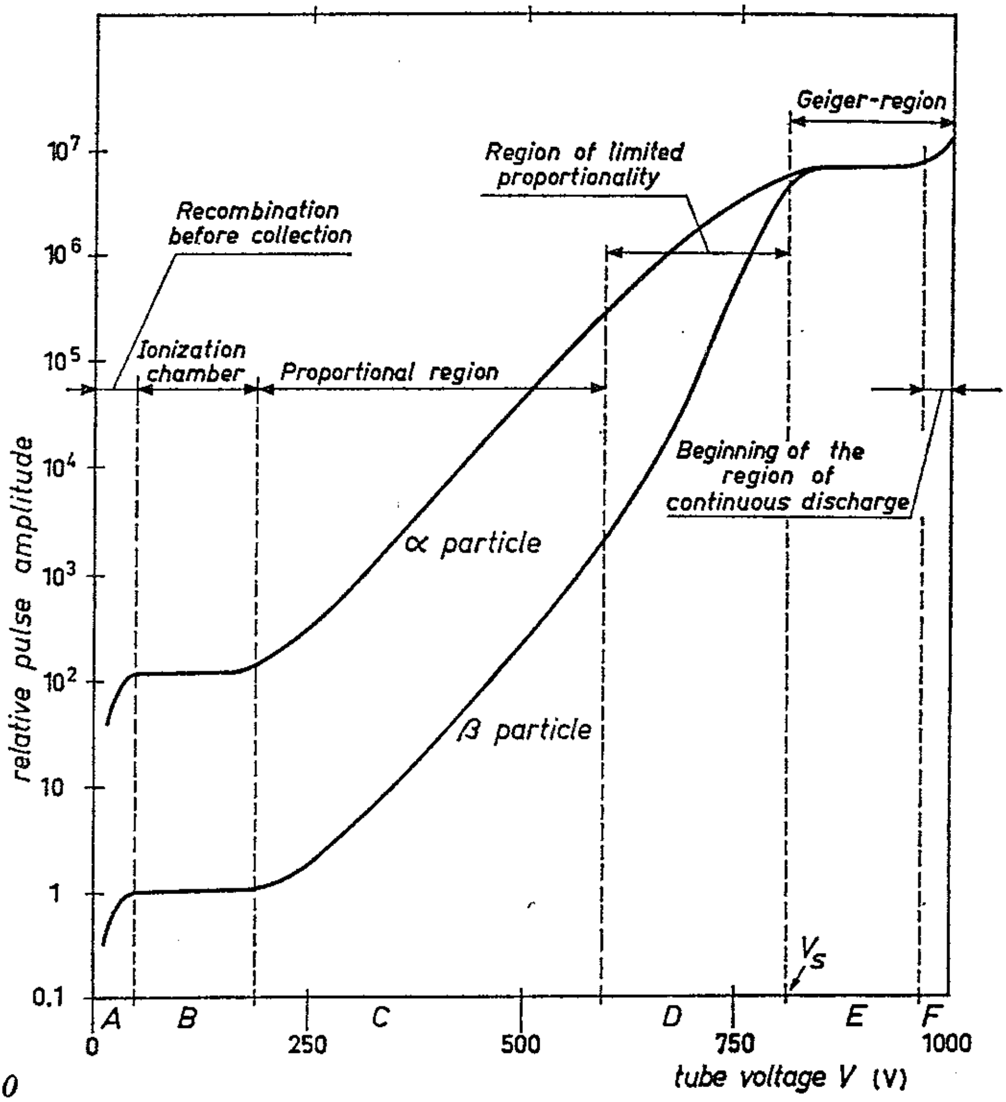


Fig. 130

Pulse amplitude as a function of tube voltage for ionization, proportional and Geiger regions of operation.

A = region with recombination and diffusion
B = saturation region
C = proportional region
D = region of limited proportionality
E = Geiger region
F = spurious-discharge region

The primary electrons move towards the (thin) anode, and where the electric field is strong enough they will give rise to ionization. The electrons produced in this way will cause further ionizations in their turn, so that the current will be considerably amplified (avalanche effect). The *gas-amplification factor* is defined as the ratio of the total charge which reaches the anode to the primary ionization.

If the composition of the gas and the shape of the electrodes are chosen properly, gas-amplification factors of up to 10^6 can be obtained before the system starts to be complicated by e.g. avalanche formation by photons (cf. V-d-6). The ionization is restricted to the immediate vicinity of the track of the incoming particles, and the current pulse is proportional to the primary ionization.

The Geiger region (E) is characterized by the fact that the size of the charge arriving at the anode is independent of the magnitude of the primary ionization. Thus, the current pulses due to α and β particles are the same size as each other, even though the primary ionization due to an α particle may be a factor 10^5 more than that due to a β particle. The lower limit of the Geiger region is sometimes called the Geiger threshold voltage (V_s). In the Geiger region, the magnitude of the current is independent of the primary ionization, but increases linearly with the voltage between the electrodes i.e. in proportion to the difference between the working voltage and the ignition voltage. The Geiger region usually extends over several hundred volts. It is bounded at high voltages by the spurious-discharge region (F) in which each particle to be counted may give rise to more than one current pulse. At slightly higher voltages, the tube goes over to a continuous discharge.

The proportional region and the Geiger region are separated by the region of *limited proportionality* (D). The charge produced per particle is here no longer proportional to the number of primary ionizations, but there is still some difference between the current pulses produced by α particles and those produced by β particles. The ratio of the charge pulses of α particles to those of β particles is lower than the ratio of the primary ionizations. This is due to space-charge effects: the first avalanche produces such a large positive space charge that the last avalanche reaches the wire at the moment when the electric field is already reduced by the space charge, so that the gas amplification is decreased.

V-d-4 THE IONIZATION CHAMBER

The ionization chamber operates in the saturation region, and it can be used either to count the integrated number of particles or to count the particles individually.

If the gas filling is chosen properly, an α particle can give rise to 10^5 ion pairs in the tube. If the ionization chamber is designed with a low capacitance, the voltage pulses due to the individual α particles may be large enough to stand out above the noise due to the amplifier. The range of a β particle in air is of the order of one metre. An electron will thus be able to lose only a small part of its kinetic energy by ionization within an ionization chamber of the normal size. The primary ionization caused by the electron will then in general not exceed 100 ion-electron pairs. This means that the individual voltage pulses caused by the β particles will not generally be detectable above the noise of the electronic amplifier. (The noise of a good amplifier is equivalent to 500 ion-electron pairs.) This means that electrons, and thus also γ quanta, cannot be counted individually with the aid of an ionization chamber; although if the intensity of the radiation is high enough it is of course possible to measure the mean current produced in the ionization chamber. In other words, the integrated intensity of α, β and γ radiation can be measured, but only α particles can be counted individually.

V-d-5 PROPORTIONAL COUNTER TUBES

The operating voltage of proportional counter tubes is so high that gas amplification due to ionization by collision is produced. A typical value for the amplification factor N is 10^4. The Philips tube type 18511 (Fig. 131) is a typical example of such tubes. This tube is filled with a mixture of xenon and methane. The cathode cylinder has a diameter of about 20 mm, while the diameter of the anode is only 0.1 mm. Under these conditions, ionization by collision will only occur in the immediate neighbourhood of the anode, in a region about 0.5 mm in diameter, called the *active volume*. If now an X-ray quantum enters the tube through the mica window (see under non-self-quenching counter tubes, V-d-6, II), its energy

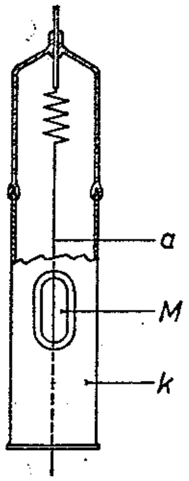


Fig. 131
Schematic view of proportional counting tube Philips type 18511 with mica side-window *M*.

can be completely absorbed by the xenon. The primary ionization thus occurs in the part of the gas where no ionization by collision is possible (the *passive volume*). Only in this way can the voltage pulse on the anode be made independent of the place where the X-ray quantum is absorbed by the gas. The amplitude of the pulse is proportional to the energy of the quantum, because the number of primary ionizations is. The magnitude of the pulses is only a few millivolts, so a good linear amplifier is needed to measure them.

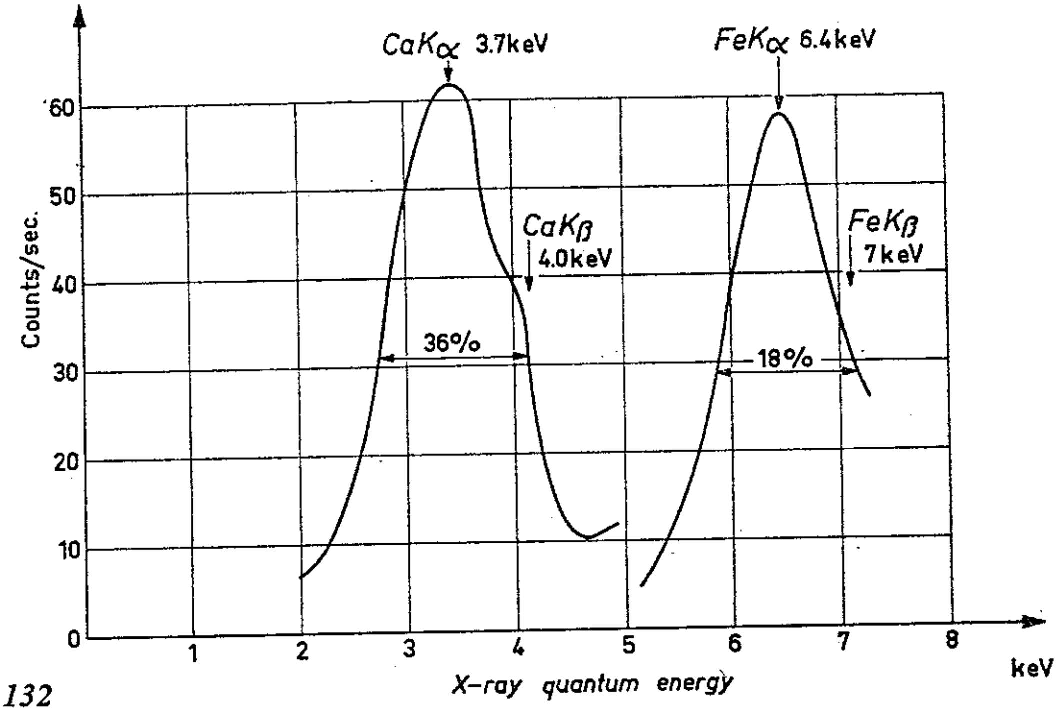


Fig. 132

Distribution of the amplitudes of the pulses of the proportional counter by irradiation with the *Ca* K_α and *Fe* K_α radiation.
(X- radiation with quantum energy of 3.7 and 6.4 keV respectively).

In Fig. 132 is shown the distribution of the amplitudes of the pulses at the output of the amplifier when the proportional counter is irradiated with mono-energetic X-rays (i.e. X-rays in which all the quanta have exactly the same energy). It will be seen that not all the voltage pulses have the same amplitude, but that fluctuations of 10—20 % occur. These fluctuations are mainly due to fluctuations in the primary ionizations. It may also be seen from this figure that the pulse amplitude corresponding to the peak of the distribution curve is proportional to the quantum energy of the radiation.

If in a given case an average of N ion-electron pairs are formed per X-ray quantum arriving in the tube, the standard deviation of the number of ion-electron pairs about this mean will be of the order of magnitude of $\sqrt{N}$, and the relative spread is thus $1/\sqrt{N}$. The relative spread will thus be less as the quantum energy of the X-rays increases. In practice the width of the distribution curve half-way up is taken as a measure of this spread (see Fig. 132). This quantity is called the resolution of the counter tube.

One interesting application of proportional counter tubes is the detection of neutrons. For this purpose, the tube must be filled with boron trifluoride gas. Slow neutrons will be trapped in the B^{10} nuclei and give rise to the reaction:

$$B^{10} + n \rightarrow He^4 + Li^7 + 2.2\ \text{MeV}$$

The energy produced is divided as kinetic energy between the He and the Li nuclei, which will move in diametrically opposite directions. Both particles will cause ionizations along their path, so the kinetic energy of the boron will again be transformed into primary ionizations. When the tracks of both particles fall completely within the tube, the primary ionization due to one neutron will produce about 70 000 charge carriers. This is enough to allow measurement without gas amplification, but even so gas

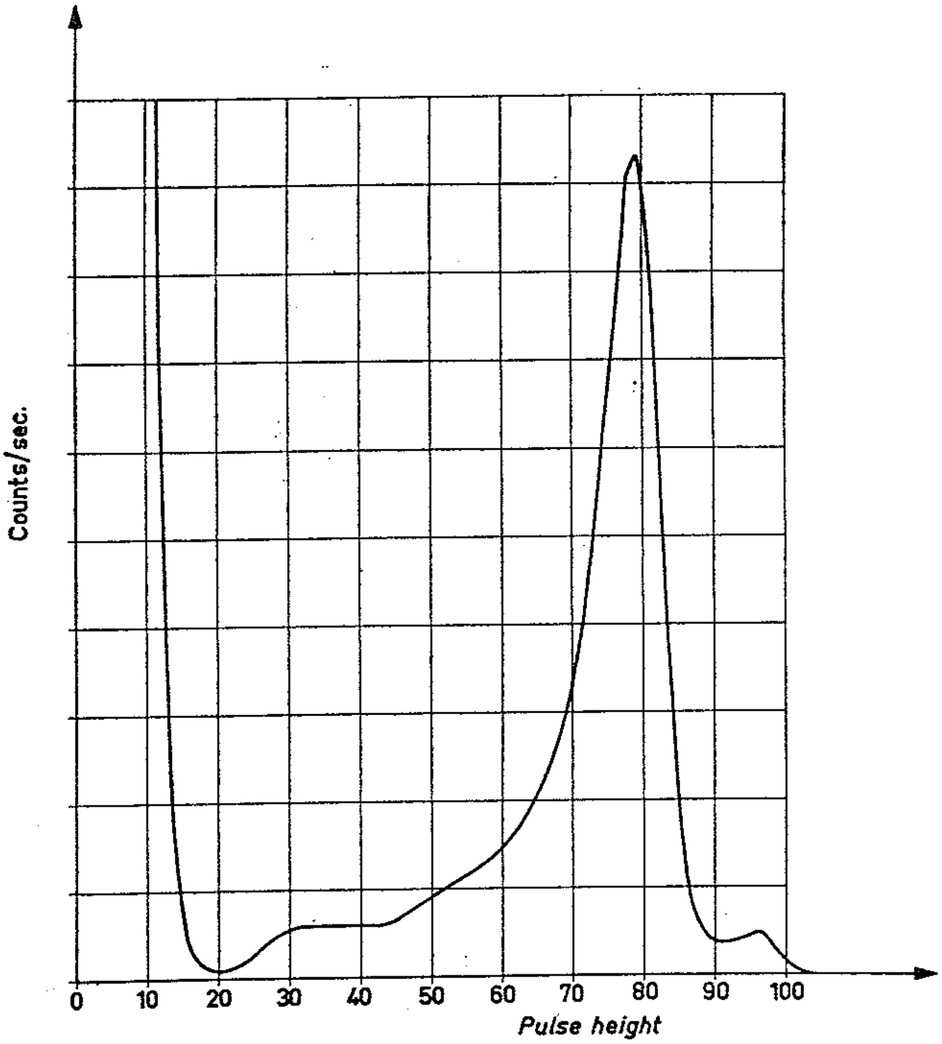


Fig. 133

Distribution of the amplitudes of the pulses of a borontrifluoride counting tube by irradiation with slow neutrons.

amplification will be used in a proportional counter tube because this simplifies the electronics. Fig. 133 shows the pulse-amplitude distribution curve for a BF$_3$ counter tube.

V-d-6 GEIGER COUNTERS

In 1908 Rutherford and Geiger published details of the first detector to work on this principle (Fig. 134). In 1928, Geiger and Müller described an improved model. The great difference between the detector designed by Rutherford and Geiger and that designed by Geiger and Müller is that the first was only able to detect α particles which passed close to the wire, while the latter could also detect electrons, even if they passed a considerable distance from the wire. In other words, the sensitive volume of the Geiger-Müller counter is nearly equal to that of the whole tube, while that of the Rutherford-Geiger counter only consists of the immediate neighbourhood of the anode filament. Moreover, the Rutherford-Geiger counter can only detect α particles, which naturally give rise to a considerable primary ionization, while the Geiger-Müller tube can also detect particles which produce very slight primary ionization (e.g. β particles).

These counter tubes can be divided into two groups:

I. Self-quenching tubes.

This group includes the well known argon-alcohol counter tubes, which have a filling of 90 mm argon and 10 mm ethyl alcohol. Other combinations of gases can be used for the filling, e.g. helium-isobutane.

II. Non-self-quenching counter tubes.

Many different gases and gas mixtures were formerly used for the filling of these tubes, e.g. hydrogen, argon-hydrogen and nitrogen. None of these

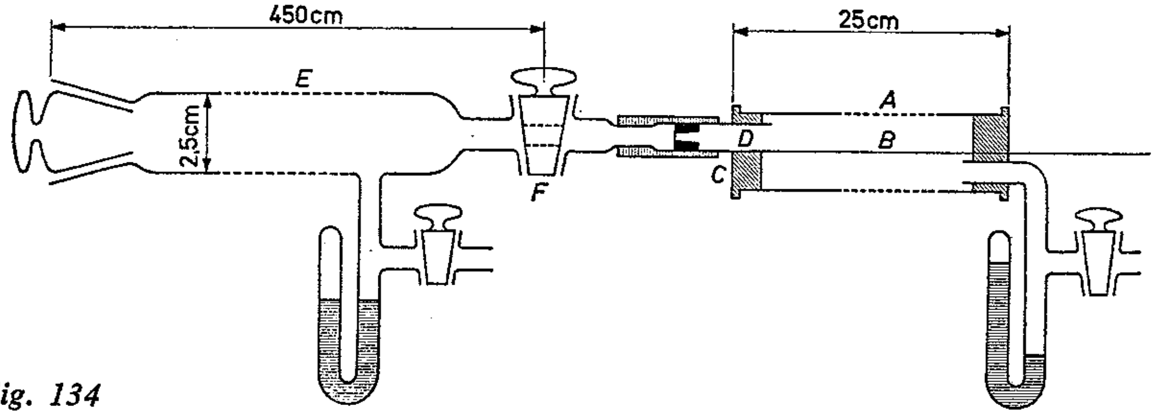


Fig. 134

Experimental design of an apparatus for magnifying the primary ionisation effect caused by the transfer of α-particles through a gas (according to Rutherford and Geiger, Phys. Z. 10/1909/1). Gas pressure 2 to 5 cm Hg.

A = ionisation room
B = wire 0.45 mm
C = rubber tube
D = glass tube
E = glass tube
F = tap with wide aperture

fillings are used any more: all such tubes now contain inert gases, with a small amount of halogen (at most a few tenths of a vol. percent).

V-d-6, I *Self-quenching counter tubes, containing a mixture of an inert gas and some organic vapour or gas.*

In self-quenching counter tubes, the discharge is always propagated along the anode filament. If for example an electron which enters a tube causes a primary ionization in the middle of it, the electrons which are produced move towards the anode, giving rise to an avalanche in the neighbourhood of this electrode. Also produced in this avalanche are UV photons, which will in their turn be able to produce ionizations at points some distance from their point of origin and thus give rise to new avalanches. This process repeats itself until the discharge has reached both ends of the anode filament. The velocity of propagation of the discharge is of the order of 10^5 m/sec., while the velocity of the positive ions is of the order of 10^2 m/sec. This means that the positive ions will have moved a negligible distance towards the cathode by the time that the discharge has reached the ends of the anode. There will thus be a high concentration of positive ions along the anode at this moment. These ions will give rise to a positive space charge which will weaken the original field of the anode and thus oppose the formation of further avalanches.

In the next phase of the discharge process, the positive ions will move to the wall of the tube (i.e. the cathode) in a period of e.g. 200 microseconds. The inert-gas ions wil undergo repeated collisions with molecules of the organic vapour on their way to the cathode, and since the ionization potential of the inert gas is greater than that of the organic vapour, all the inert-gas ions will have transferred their charge to organic molecules before they reach the wall. Only organic ions end up at the cathode, therefore, and these are not able to give rise to secondary emission. Secondary emission would however occur if inert-gas ions could reach the cathode, and the secondary electrons thus formed would be capable of starting new discharges. This is clearly undesirable, since then the discharge would not be quenched. The organic molecules thus play an essential role in the quenching process.

It follows from the above that the quenching of the discharge may be regarded as consisting of two separate phases:

a. the reduction of the electric field around the anode by the positive space charge,

b. the elimination of secondary emission from the cathode surface.

These tubes are called self-quenching because the discharge stops after a certain time, even though the voltage between the anode and the cathode does not alter appreciably.

A characteristic feature of such tubes is that the charge per pulse is independent of the external circuit. If we use the counter-tube circuit of Fig. 135, we find that the magnitude of the charge per pulse is not affected by variation of the series resistance R_s—R'_s or by an increase in the capacitance C_p in parallel with the counter tube.

The organic ions which reach the cathode are there neutralized, and dissociate to give H_2O, CO, CH_4 and unsaturated hydrocarbons. After a certain number of pulses, usually of the order of 10^8, so many of the molecules of the organic vapour have dissociated that the counter tube no longer works. There are of course still some undissociated organic molecules left, but not many.

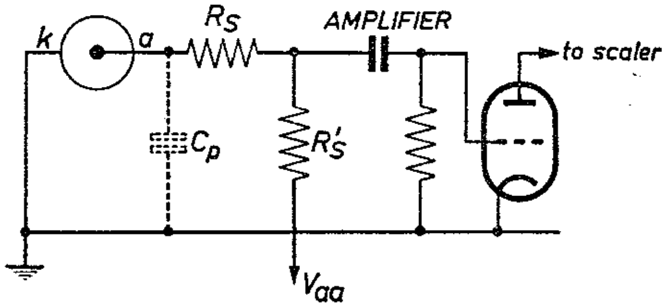


Fig. 135

Simplified circuit of a radiation counting tube and subsequent amplifier stage.
C_p = (parasitic) parallel capacitance,
R_s - R_s' = series resistance.

V-d-6, II *Non-self-quenching halogen counter tubes* [50]

In the non-self-quenching counter tubes, as their name suggests, the discharge is not automatically quenched after a certain time; the anode voltage of these tubes must definitely decrease during the discharge, and remain low for a sufficiently long period. This can be ensured by means of the Neher-Harper circuit (Fig. 136). Another method which was used previously consisted in placing a large resistance (about 10^9 ohm) in series with the tube. As in the self-quenching tubes, the quenching of the discharge occurs in two phases. The formation of avalanches is stopped by the combined effect of the positive space charge and the reduced anode voltage. The charge per pulse in tubes of this kind is about a factor 100 greater than in self-quenching tubes, and so therefore is the space charge. The halogen in the gas filling (usually Cl_2 or Br_2) has the same function as the organic vapour in the self-quenching tubes. The inert-gas ions transfer their charge to the halogens, and the halogen ions are neutralized at the cathode and dissociate immediately. In contrast to the organic molecules, however, the halogen molecules dissociate reversibly; after a certain time the halogen atoms will combine to reform molecules, which means that the life of these tubes is much longer than that of the previous type (at least a factor 1000 better).

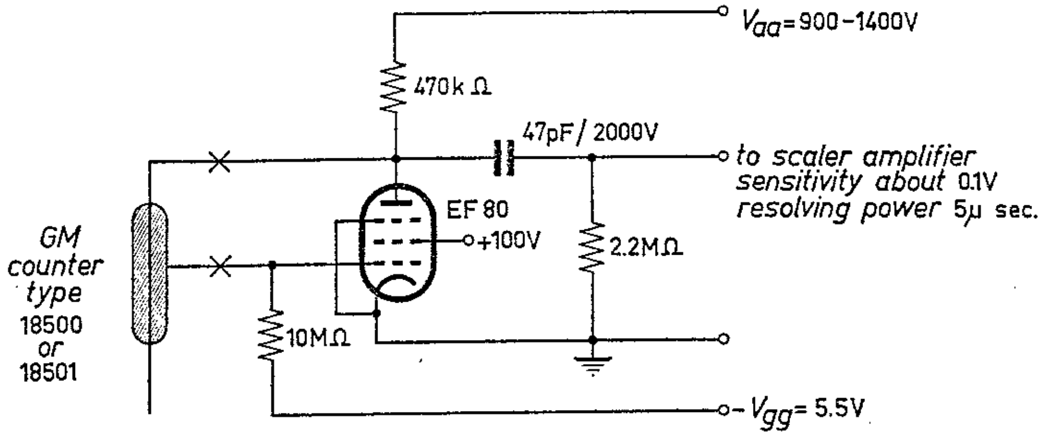


Fig. 136

Neher-Harper circuit to be used with non-self-quenching counting tubes.

The charge per pulse in the halogen counter tubes is dependent on the value of the capacitance C_p in parallel with the tube (Fig. 135): the larger this capacitance, the larger the charge. The charge per pulse also varies slightly with the value of the series resistance R_s, but as may be seen from Fig. 137 the influence of the latter is slight.

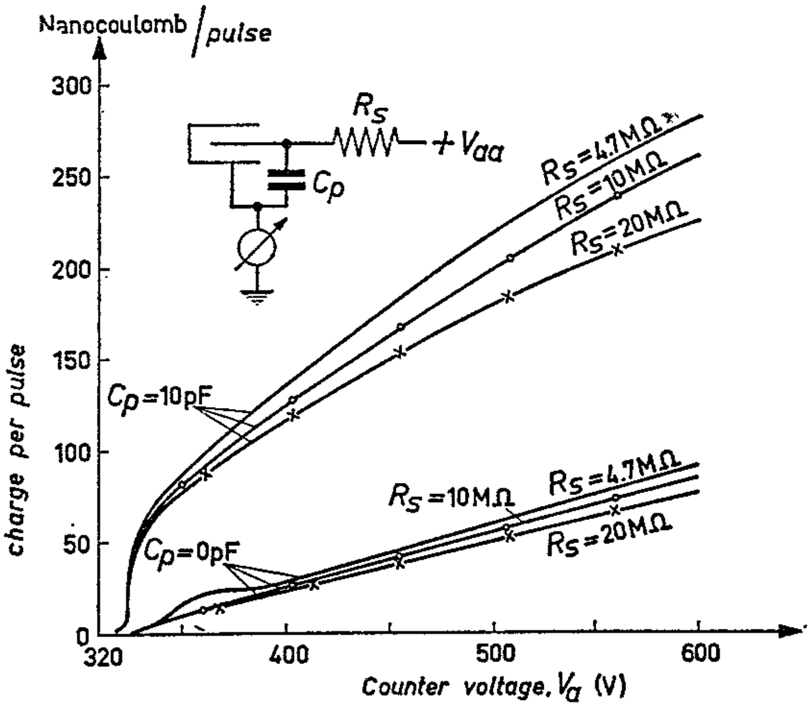


Fig. 137

Charge per pulse with a halogen counting tube as a function of the counter voltage V_a for various values of the parallel capacitance C_p and of the series resistance R_s.

The manufacturing technique for halogen counter tubes is much more complicated than for organic-vapour counter tubes. This is because the amount of halogen to be added to the gas is very small, of the order of 0.1 vol. %. A larger halogen concentration would lead to electrons attaching to the halogen molecules, and thus to a loss of primary electrons. The *sensitivity* (efficiency) of the tube is thus lowered, i.e. there is less chance that a particle entering the tube will cause a discharge. In a good counter tube, the sensitivity for electrons may amount to e.g. 98 %. If the partial pressure of halogen vapour rises to e.g. 1 mm Hg, the sensitivity can fall to 30 %. It is this necessity of restricting the halogen content of the gas to about 1/10 vol. % that complicates the manufacturing technique: halogens are chemically reactive, and special measures must be taken to prevent an appreciable part of the halogen from reacting with various parts of the tube. If the halogen content could be higher, this would naturally not present so much of a problem.

A typical construction for such a tube is shown in Photo 9, which represents the Philips counter tube type 18504. A thin metal wire which acts as the anode is placed along the axis of a thin-walled metal cylinder. This cylinder serves as the cathode and at the same time as the outer wall of the tube. This tube can be used for the detection of γ radiation. In order to make it suitable for the detection of electrons too, one end of the cathode cylinder is provided with a very thin mica window. The thickness of the metal wall or the mica window is usually specified in mg/cm^2. The mica window of the 18504 is 2-3 mg/cm^2, i.e. about 10 μ thick.

V-d-7 THE DEAD TIME AND THE RECOVERY TIME

It follows from what we have said above that a particle which enters the counter tube during the time that the electric field around the anode is weak will not be counted. The smallest time interval between two particles which still give two separate pulses in the counter tube is known as the *dead time*. We have seen that in the alcohol counter tubes after the discharge has reached the ends of the anode wire, which takes a fraction of a microsecond, the layer of positive ions moves towards the cathode. The field around the anode begins to recover as soon as this process begins. At a certain moment, the tube has recovered sufficiently to allow the next discharge to occur along the anode. However, pulses produced just after the end of the dead time will not be as large as normal ones, although the particles producing these pulses will at any rate be counted. The minimum time between the arrival of two particles each of which produces a pulse of the normal height is called the *recovery time*. For a self-quenching tube, the recovery time is precisely equal to the time the ions take to reach the cathode.

In the non-self-quenching halogen counter tubes, the situation is rather more complicated. This may be clearly seen from Fig. 138, which shows the anode voltage of the counter tube as a function of time. The dead time is indicated in this figure, and the time taken by the ions to reach the cathode is indicated by the break in the curve. It will be seen that the tube voltage has not yet returned to its original value by the time that all the positive ions have reached the cathode. Voltage pulses produced by particles which enter the tube just after this moment are thus not as large as normal. The recovery time for these tubes is larger than the transit time of the ions, in other words, it is partly determined by the value of the series resistance and the parallel capacitance, since these influence the

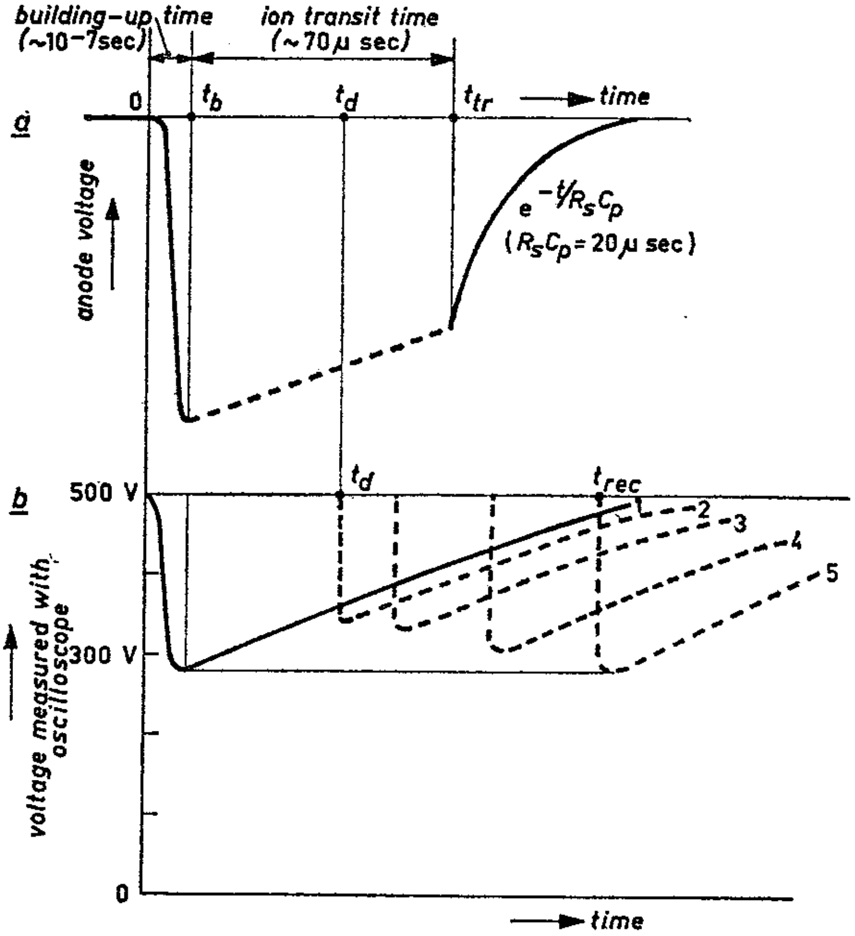


Fig. 138

a. Anode voltage of a non-self-quenching counter tube as a function of time.
b. Curves 1—5 represent pulses of different size.
Curve 1 is the pulse with normal height, curves 2, 3 and 4 are less high. At the time t_{rec} curve 5 again has obtained the normal height.
t_b = electron transit time (building-up time)
t_{tr} = ion transit time
t_d = dead time
t_{rec} = recovery time

time it takes for the tube voltage to regain is original value. It may be said in general that both the dead time and the recovery time of such counter tubes are determined by the transit time of the positive ions, and the value of the series resistance and the parallel capacitance. The relationship between these quantities is very complicated, since in this case the transit time itself will be a rather complicated function of the other two variables. A number of characteristics of the Philips counter tube 18506 (Fig. 139) show how the dead time depends on the tube voltage, the series resistance R_s and the parallel capacitance C_p. It may be clearly seen from these curves that the dead time increases with the values of the last two variables.

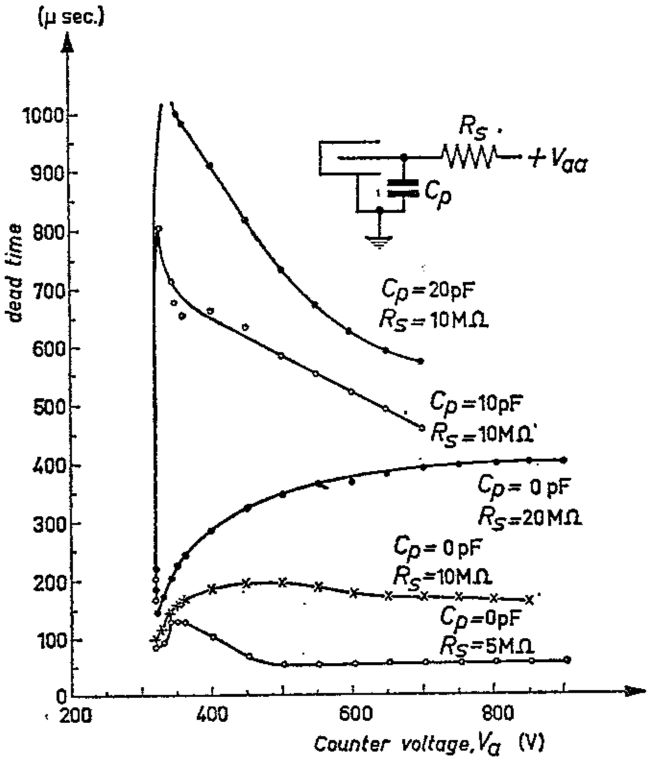


Fig. 139

Dead time as a function of the counter voltage V_a for various values of the series resistance R_S and the parallel capacitance C_p for a non-self-quenching halogen counter. (Philips counting tube type 18506). Anode diameter 8 mm, cathode diameter 28 mm.

V-d-8 THE COUNTING CHARACTERISTIC AND THE PLATEAU

One of the most important characteristics of a Geiger counter is the counting characteristic (Fig. 140). This curve shows the number of counts per second as a function of the tube voltage at constant irradiation. The counting characteristic consists essentially of three parts:

a. the initial region;
b. the plateau;
c. the spurious-discharge region.

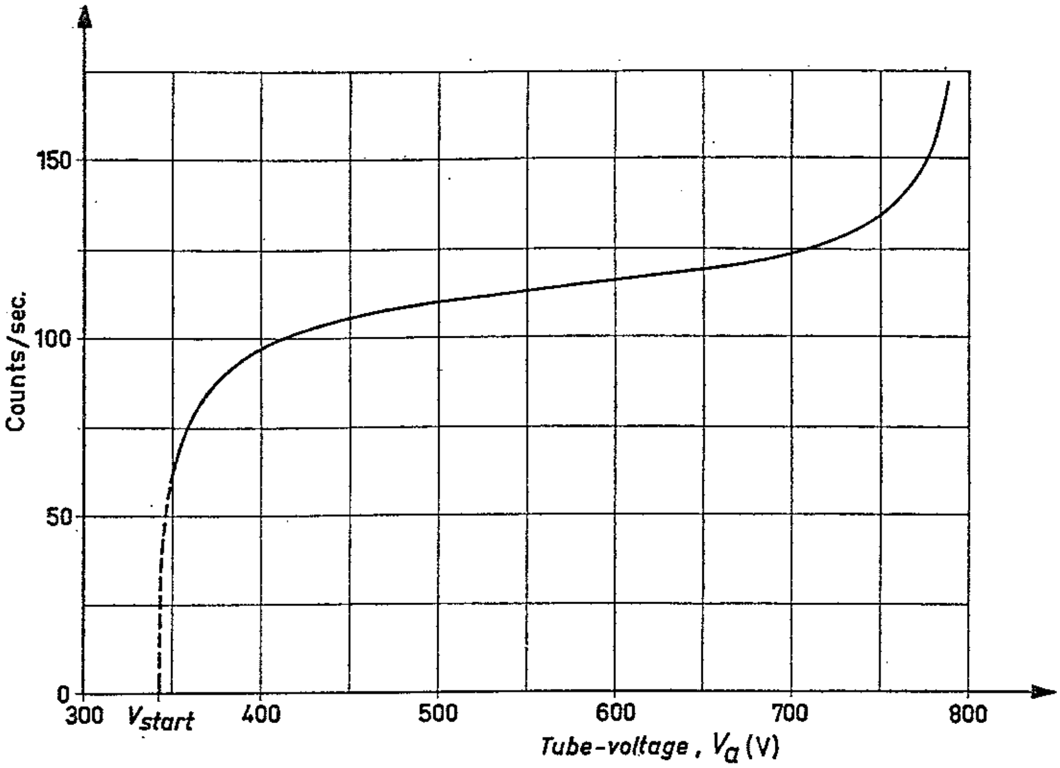


Fig. 140

Plateau curve of Philips counting tube type 18510.
This curve may be divided into three parts:
the initial region (curved part to the left),
the plateau (flat part) and
the spurious-discharge region (curved part to the right).

a. *The initial region*

Not all the incoming particles are counted at tube voltages in this region. It may be that the particles do give rise to a voltage pulse, but that this pulse is not large enough to be counted by the electronic counting equipment. It may be, on the other hand, that some of the incoming particles do not cause a Geiger discharge at all. One possible reason for this is that all the electrons of the primary discharge are captured by halogen atoms; another possibility is that the chain of avalanches is broken off for lack of secondary electrons.

b. *The plateau*

The plateau is the most important part of the counting characteristic (see Fig. 140). In this region, the number of particles registered increases only very slightly with an increase in the tube voltage. In an "ideal" counter tube, all incoming particles would give rise to one pulse — no more, no less — which could be counted by the counting equipment. In such a case, the plateau would be perfectly flat. In practice, however, it always has a slight slope; but in a good counter tube this slope amounts to only a few percent per hundred volts. In some special counter tubes, it is not possible to make the slope smaller than 10—15 % per 100 V. The value of the slope is determined by the construction of the tube, the geometry of the electrodes, the gas filling, the partial pressure of halogen vapour, etc.

Several reasons may be given for the existence of this slope. In the first place, it may be due to an increase in the active volume as the tube voltage is increased. The electric field at the ends of the anode is naturally weaker than in the middle, with the result that the ends of the anode only become active at higher voltages. This drawback can be considerably reduced by proper design of the tube, but it can never be eliminated completely [50].

A second reason for the increase in the number of particles counted is connected with the dead time. As we have seen (Fig. 139), the dead time varies very considerably with the tube voltage. As a result of this, up to 30 % of the incoming particles may not be counted at the beginning of the plateau, because they fall within the dead time of the preceding particle. At the end of the plateau, this counting loss may be reduced to 10 %. It is thus quite possible that the plateau has a slope of 30 % per 100 V all over the length at high counting rates, for this reason alone. This effect is naturally not found at low counting rates, the slope of the plateau is therefore usually specified at a definite counting rate; e.g. 100 counts/sec.

A third reason for the increase in the number of particles counted at higher tube voltages is the occurrance of double pulses. The above-mentioned quenching mechanism does not work so well at high tube voltages, and double or triple pulses occur. This is usually a statistical phenomenon: only a small fraction of the pulses are double, and an even smaller fraction are triple. The extent to which this effect plays a part is highly dependent on the values of the shunt capacitance and the series resistance.

As we have mentioned above, the slope of the plateau in a good counter tube is only 2—3 % per 100 V. This is of great importance for the designer of the electronic equipment, because it means that the supply voltage of the counter need not be stabilized very accurately. In fact, however, the slope in percent per 100 V is not so important to the designer as the quantity

$$\frac{\Delta N}{N} : \frac{\Delta V}{V}$$

It is very important that this should be low, which means that the tube voltage must also be low. The permissible variation in the supply voltage for a given accuracy can be simply calculated from the published data for the counter tube, making use of this expression.

c. *The spurious-discharge region*

As has been mentioned above, double and triple pulses can occur throughout the whole plateau, especially near the end. The sharp increase in the number of particles counted at the end of the plateau indicates that many pulses must be double or triple in this region. When the voltage is increased still further, the quenching mechanism fails altogether and the tube changes over to a continuous discharge which is no longer influenced by the presence of radioactive radiation.

In the self-quenching counter tubes filled with organic vapour, the re-ignition of the tube and thus also the occurrence of double and triple pulses is not affected by the series resistance and the shunt capacitance. The occurrence of spurious discharges in such tubes is therefore not influenced by the circuit. At counting rates below e.g. 100 counts/minute,

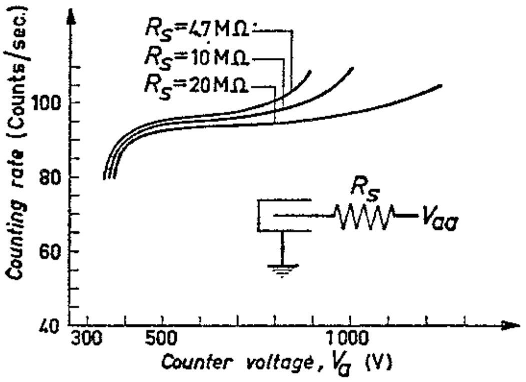


Fig. 141

Plateau characteristics for Philips tube 18506 for various values of the series resistance R_s.

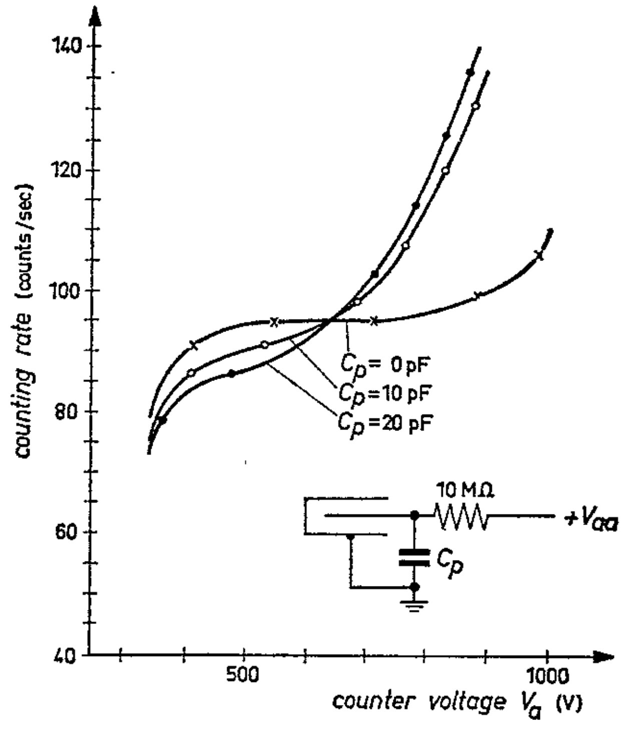


Fig. 142

Plateau characteristics for Philips tube 18506 for various values of the parallel capacitance C_p. The series resistance was 10 megohm in all cases.

the slope and length of the plateau are independent of the magnitude of the series resistance and the shunt capacitance.

In halogen counter tubes, which are non-self-quenching, the spontaneous re-ignition of the tube and the occurrence of spurious discharges *are* dependent on the two above-mentioned variables, and so therefore are the slope and length of the plateau. If the resistance is high (e.g. 10—30 Mohm), the plateau may be 600 V long (Fig. 141); but here we have the disavantage that the dead time is also very large (Fig. 139). In practice, the value of the resistance is always chosen so that the length of the plateau is about 200 V. If the length of the plateau is not so important and a very short dead time is desirable, the value of the resistance may be chosen lower than given in the published tube data.

An increase in the shunt capacitance has in general only unfavourable effects: the plateau becomes shorter and steeper, and the dead time increases (Fig. 142). Care must therefore always be taken that parasitic parallel capacitances are kept as low as possible.

V-d-9 THE BACKGROUND

Even if all radioactive substances are removed from the neighbourhood of the counter tube, a number of pulses will still appear. This is known as the background count, and is due to various different causes:

a. All materials, including those used to build laboratories, contain radioactive substances such as uranium, thorium, radium and also K^{40}. It is therefore necessary to screen the counter tube from its surroundings with a material which contains as little radioactivity as possible. Iron is a good choice; and lead is often used, because it allows a very compact and efficient screen to be made. Unfortunately, lead is by no means ideal for this purpose, because even when carefully refined it still contains radioactive lead isotopes. The half-life of the most important lead isotopes is 22 years, so lead which is a century or so old will be practically free of radioactivity. Mercury is practically as good as lead for screening purposes, but the use of mercury has a number of disadvantages in practice.

b. If the thickness of the screening is increased beyond a certain value, e.g. 10—20 cm of lead, it is found that the background does not decrease appreciably. This is because nearly all the pulses are now due to cosmic radiation, which is so powerfully penetrating that the lead offers practically no protection against it: 100 m of earth or water is needed to cut off this radiation. In principle, therefore, it should be possible to eliminate the cosmic rays by working at the bottom of a mine. A more elegant method will be discussed later in this chapter.

c. Finally, the radioactive impurities in the materials used in making the counter tube are also of importance. Radioactivity which is present in the tube itself will have even more effect than radioactivity in the screening material. In the first place, the tube material emits electrons, which are detected with an efficiency of nearly 100 %; and in the second place the solid angle over which the radiation is detected is practically 2π. It follows that the materials used for making the counter tubes must be chosen even more carefully than the screening materials.

V-d-10 CONSTRUCTION OF HALOGEN COUNTER TUBES

We shall now describe a number of different types of counter tubes, and some typical applications. The Philips counter tubes may be divided into:

end-window counter tubes,
cylindrical counter tubes,
hollow-anode counter tubes.

a. End-window counter tubes

The classical end-window counter tubes have a cylindrical cathode, with a thin window at one end and the anode lead at the other. The old counter tubes such as the 18505 (Fig. 143a) have a thin coaxial anode, and the mica window is insulating. The electric field at the point where the β radiation to be measured enters the tube is rather weak, while surface charges can build up on the insulating mica surface.

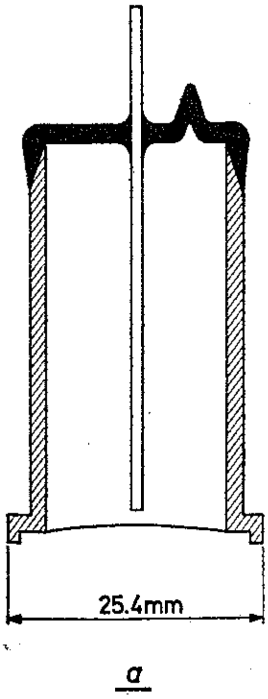


Fig. 143a

Schematic view of the electrode configuration of a conventional end-window beta-counter (Philips type 18505).

These handicaps are removed in the new types such as the 18515 and the 18516 (Fig. 143b). The anode is spherical with a diameter equal to about a third of that of the cathode, and the inside of the window has been made conducting. One advantage of this new construction is that ionization by collision can occur near the cathode, so that the risk of electrons attaching on to electronegative gas molecules (bromine or chlorine) is eliminated. This means that the sensitivity is high. Incidental advantages of this new construction are a lower sensitivity for γ radiation, a low background and a shorter dead time.

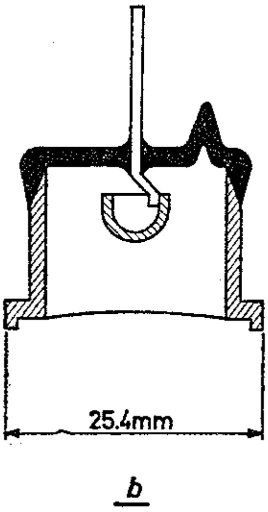


Fig. 143b

Schematic view of the electrode configuration for an end-window beta-counter with hemispherical anode and conducting window (Philips type 18515).

b. *Cylindrical counter tubes*

The original Geiger counter tubes had this design, which is still used for the detection of β and γ rays. Philips tubes 18550 and 18552 can be used for the first purpose, and the 18503 and 18522 for γ radiation. Cylindrical counter tubes are normally used where a large active surface is needed.

c. *Hollow-anode counter tubes*

Philips was the first firm to put hollow-anode halogen counter tubes on

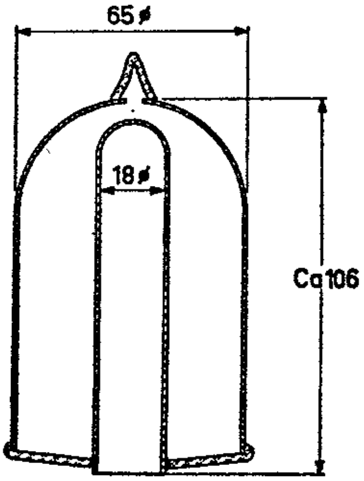


Fig. 144

Schematic view of Philips halogen counting tube with hollow anode type 18508 for γ-radiation in a 4π geometry.

the market. A typical example is the 18508, which can be used to measure the γ radiation over a solid angle of 4 π (Fig. 144). The radioactive sample is placed right at the bottom in the anode, so that all the radiation emitted by the sample is received by the counter tube. The effective solid angle is therefore very large, so samples of weak radioactivity can be counted. A second advantage is that the counting rate hardly depends on the position of the sample, as long as it is deep enough in the hollow anode. This is very useful if it is desired to compare radioactive samples of different shapes without having to correct for the difference in geometry.

Another interesting application of the hollow anode is found in the guard counter tubes 18517 and 18518. A combination of a cosmic ray guard counter tube and an end-window counter tube is shown in Fig. 145. The guard counter tube consists of two large concentric spherical electrodes, each with coaxial cylindrical parts. The end-window tube is placed inside the hollow anode of the guard counter tube. This ensures that all

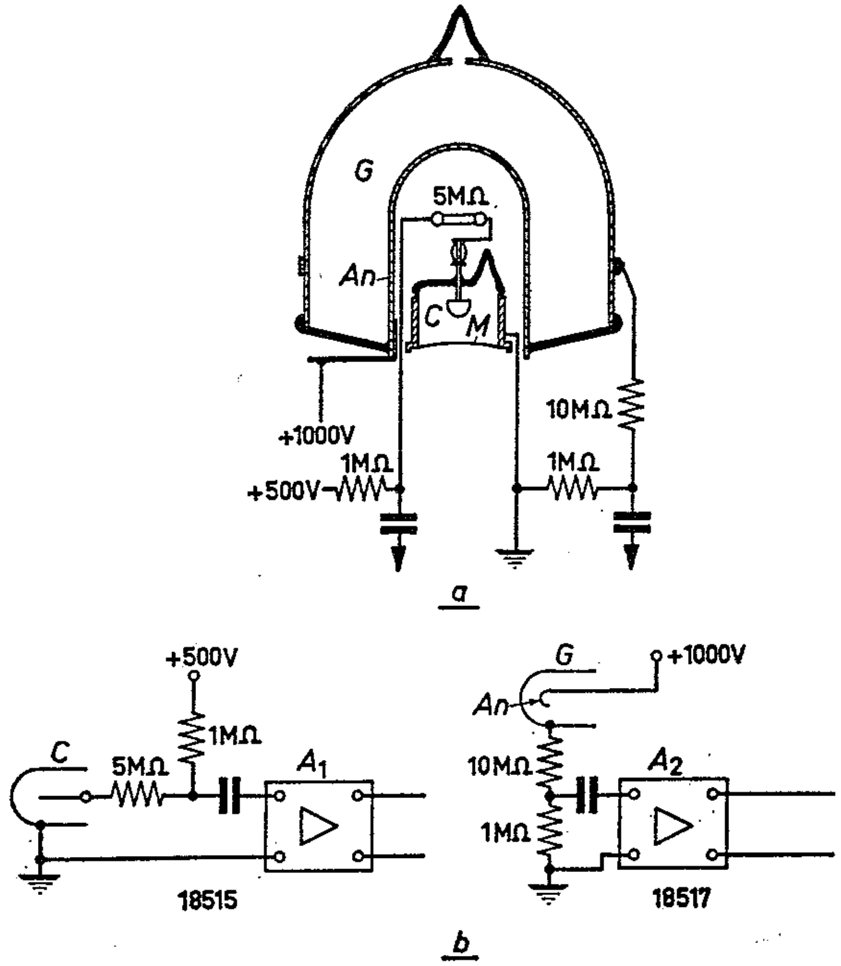


Fig. 145

a: Schematic view of the combination of the end-window beta-counter type 18515 (*C*) with mica window *M* and the cosmic ray guard counter type 18517 (*G*) with anode *An*.

b: circuits for the use of the combination given in *a*. A_1 and A_2 are amplifiers.

the mesons from the cosmic radiation which reach the end-window tube have passed through the guard counter tube first. (The penetrating power of mesons is so large that the stopping power of the counter-tube material is negligible). The electrical pulses from the two counter tubes are fed to an anti-coincidence circuit [77], which is adjusted so that the output pulse of the end-window tube is only counted when there is no simultaneous pulse from the outer counter tube. In this way all the mesons which strike the end-window tube (and which thus also excite the outer tube) are eliminated. The background of the 18516 end window counter can thus be reduced to less than 1 count/minute by use with the anti-coincidence arrangement, while use of the 18516 with the lead screening alone cannot reduce the background to less than about 7 counts/minute. This very low background is very important for counting very weak samples as in tracer work, and for radiation monitoring.

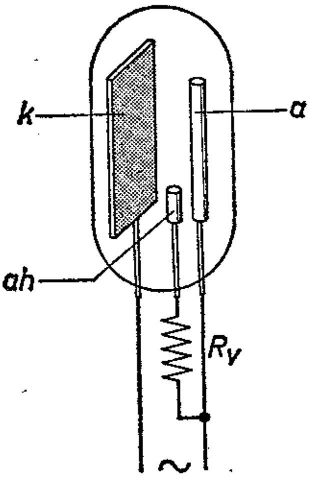


Fig. 146
Glow-discharge rectifier tube. When the cathode k is negative and the anode a positive, a preliminary discharge occurs between the auxiliary anode a_h and k, after which the main discharge between a and k ignites. If the polarity of the tube is reversed, no discharge can occur between k and a.

V-e **Some other non-controlled glow-discharge tubes**

V-e-1 THE GLOW-DISCHARGE RECTIFIER TUBE

We shall describe the operation of the glow-discharge rectifier tube with reference to the sketch of Fig. 146. There are two main electrodes, k and a, and an auxiliary electrode a_h. Suitable construction ensures that ignition can occur when k is negative with respect to a, and not *vice versa*; k thus acts as the cathode and a as the anode. In the half-period during which k is negative and a positive, ignition first occurs between a_h and k at a relatively low voltage; a small current flows in this auxiliary discharge, which is followed by ignition of the main discharge between k and a. If the voltage is reversed, the auxiliary discharge between k and a_h is not able to ignite the main discharge. The ignition voltage of the main discharge is made higher in the latter case (inverse phase) by the following means:

TABLE XII

DATA OF SOME RADIATION COUNTING TUBES

	proportional counter side-window 18511
use	x-ray
window:	
thickness (mg/cm²)	2.0—2.5
eff. diam. (mm)	7 × 18
material	mica
wall:	
thickness (mg/cm² or mm)	—
eff. length (mm)	67
outside diam. (mm)	—
material	Cr Fe
tube dimensions:	
max. diam. (mm)	27.5
max. overall length (mm)	141
gas filling	Xe(org)
Geiger threshold (V)	>1900
operating voltage (V)	1500—1850
do for pulse ampl. of 1 mV	1525 ± 25
do for pulse ampl. of 100 mV	1730 ± 40
energy resolution Mn, K_α at 5.9 keV (%)	<22
background (Mn, $K\alpha$) (c/min)	about 15 6)
tube capacity (pF)	2
weight (g)	85
ambient temp. (°C)	–50 to+75

	end-window counting tubes	18505	18506	18515	18516
a	use	α, β, γ	β, γ	α, β	β
b	*window:*				
	thickness (mg/cm²)	1.5—2	2.5—3.5	1.5—2	10
	eff. diam (mm)	19.8	27.8	19.8	27.8
	material	mica	mica	mica	CrFe
c	*wall:*				
	thickness (mg/cm² or mm)	1.2 mm	1.3 mm	1.2 mm	1.2 mm
	eff. length (mm)	37	37	13	18
	outside diam. (mm)	22	30.5	22	30.5
	material	CrFe	CrFe	CrFe	CrFe
d	*tube dimensions:*				
	max. diam. (mm)	25.9	34	26	34
	max. overall length (mm)	57	57	30	34
e	gas filling	Ne-A(halog)	Ne-A(halog)	Ne-A(halog)	Ne-A(halog)
f	max. starting voltage (V)	350	375	350	375
	plateau (V)	450—700 1)	450—750 1)	500—700 1)	500—750 1)
	max. slope (%/100 V)	2 1)	2 1)	3 1)	3 1)
	max. dead time (μsec)	160 1)	180 1)	70 1)	70 1)
	max. background (c/min)	15 2)	25 2)	5 3)	9 3)
g	recomm. resist. (MΩ)	>2	>2	>2	>5
h	tube capacity (pF)	2.5	3.5	1.5	1.3
	weight (g)	40	50	15	27
	ambient temp. (°C)	–55 to+75	–50 to+75	–50 to+75	–50 to+75

(continued on next page)

TABLE XII (continued)

	cylindrical counting tubes 18550	 18552	 18503	 18522	hollow-anode counting tubes 18508	 18517	 18518
a	$\beta > 0.25$MeV γ	$\beta > 0.3$MeV γ	γ	cosmic ray γ	4π γ liquid	in anti- coincidence with 18515	in anti- coincidence with 18516 or 18536
b							
c	36±4 mg/cm^2 28 8 Cr Fe	50±10 mg/cm^2 75 15.5 Cr Fe	250 mg/cm^2 40 15 Cr Fe	0,5 mm 400 39 Cr Fe	1 mm 90 mm 18 mm (inside) Cr Fe	1 mm — 78 Cr Fe	1 mm — 78 Cr Fe
d	10 52	18 146	17 55	41 460	69 125	80 90	80 90
e	Ne-A(halog)	Ne-A(halog)	Ne-A(halog)	Ne-A(halog)	Ne-A(halog)	Ne-A(halog)	Ne-A(halog)
f	380 500—650 7) 4 7) 50 7) 4 2)	400 450—800 5) 2 5) 70 5) 30 2)	325 425—650 1) 2 1) 100 1) 10 2)	600 700—1000 1) 3 1) 500 1) 110 4)	450 800—1100 4 1) — 200 2)	650 800—1200 8) 3 8) 1000 8) 75 3)	650 800—1200 8) 3 8) 1000 8) 75 3)
g	>2	>1	10	10	10	10	10
h	1.1 1.2 –50 to+75	4 8 –50 to+75	2 7 –55 to+75	15 200 –50 to+75	6.5 210 –50 to+75	5.5 175 –50 to+75	8 190 –50 to+75

Note 1) measured at 100c/s and $R = 10$ MΩ
Note 2) shielded with 5 cm Pb and 3 mm Al
Note 3) shielded with 10 cm Fe and 5 cm Hg (Fe outside)
Note 4) shielded with 5 cm Pb and 10 cm Fe (Fe outside)
Note 5) measured at 100c/s and $R = 2$ MΩ
Note 6) integrated background for pulses > 50 % of the pulse amplitude for Mn, K_α radiation; unshielded.
Note 7) measured at 100c/s and $R = 5$ MΩ
Note 8) measured at 50c/s and $R = 10$ MΩ

1. choosing a material for *k* with a lower work function than that for *a*;
2. suitable positioning of the electrodes;
3. the cathode fall still has to be formed when *a* is negative, while when *k* is negative the cathode fall is already present at *k* thanks to the auxiliary discharge.

Since the burning voltage will be at least 60 V, use of a glow-discharge rectifier is indicated at high operating voltages. This tube was once quite widely used, but has now largely been replaced by semiconductor diodes.

The glow-discharge diode still has advantages for certain applications, however; it gives a visible indication that current is flowing; and the inverse current is low, or even zero e.g. if the voltage supply on the primary of the rectifier transformer is cut off while charging batteries.

For these and other reasons, these tubes are sometimes still used, e.g. for charging the small batteries for hearing aids and for maintaining the voltage of buffer batteries.

V-e-2 TUNING TUBE

This glow-discharge tube owes its name to the use to which it was previously put as indicator for tuning a radio receiver on to a particular station. However, it was first used for oscillograph measurements with

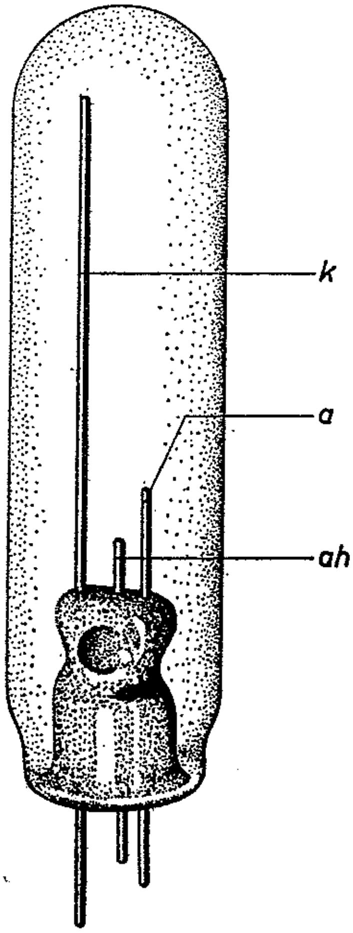


Fig. 147

Philips tuning tube type 4662. Ignition as for the tube of Fig. 146. The length of the part of *k* covered by the glow discharge is a measure of the glow-discharge current.

a rotating mirror. It contains a long rod-shaped cathode, a short rod-shaped anode, and an even shorter wire between the two which acts as an auxiliary anode (Fig. 147). The tube is filled with argon mixed with a little mercury. The ignition mechanism is similar to that of the glow-discharge rectifier tube (V-e-1). The tube is fed by a DC voltage, a permanent auxiliary discharge being maintained between k and the auxiliary anode a_h to prevent possible interruption of the main discharge if the current should suddenly decrease for some reason. As the current increases, to a maximum value of 1 mA, the length of the part of k covered by the glow also increases. With the construction described here, the length of the glow increases roughly logarithmically with the current; while if the anode is as long as the cathode and parallel to it, the length of the glow is roughly a linear function of the current. Among other things, this tube is still used to give a quantitative indication of the pressure in an evacuated space, in conjunction with a Penning gauge (see V-c-2). The circuit for this application has already been given in Fig. 125.

V-e-3 TUBES WITH EXTERNAL ELECTRODES

If a high-frequency voltage is applied to a neon-filled tube with two electrodes, a gas discharge will be initiated if the voltage is high enough. If the frequency is of the order of 1 Mc/sec, the ions will only move a very short distance to and fro each period, because of their large mass, and may be regarded as stationary. The only motion possible to them is a slow diffusion to the wall. The much more mobile electrons can cover much larger distances, and even at such high frequencies as 10^4 Mc/sec they can take up enough energy from the electric field for ionization, the displacement of the electrons at these frequencies is, however, also small compared to the dimensions of the tube.

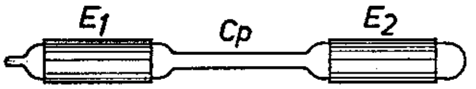


Fig. 148

Geissler tube with external electrodes E_1 and E_2 between which the discharge energy can be transferred at high frequencies. In the capillary middle part Cp of the tube, the discharge becomes a positive column, with a strong luminous effect.

Because the charge carriers move such short distances, there is no need to introduce the electrodes into the tube. At very high frequencies a discharge can even be obtained simply by placing a sealed tube filled with neon or neon-argon (pressure 1 mm) in the HF-radiation field. Such tubes are used in laboratory experiments to give a rough indication of the strength of the radiation field. For frequencies of the order of 1 Mc/sec, used e.g. in RF heating equipment, external electrodes in the form of cylindrical sheaths around the tube are used (see Fig. 148). The RF energy is transferred capacitively to the discharge. The tube is narrowed to a capillary in the middle, which increases the luminous intensity of the discharge, because under such conditions a positive column is produced (see I-g-2). Such tubes are known as Geissler tubes because they have the same shape as the original tubes of the same name; the original tubes had, however, internal electrodes.

Geissler tubes are used to indicate the presence of HF fields. It may be mentioned that at high frequencies (above 0.01—0.1 Mc/sec) the discharge is ignited if only the peak voltage is high enough (some kV), since the state of the plasma does not alter during the rest of the period. This also means that if the discharge is once ignited, e.g. with the aid of a Tesla coil, a peak voltage of a few hundred volts may be enough to maintain the discharge. This is not the case e.g. at 50 c/sec, where ignition occurs anew each period. It is, however, still possible to use Geissler tubes as indicators of high-voltage fields of 50 c/s.

V-f Glow-discharge relay tubes

V-f-1 INTRODUCTION

Just as in a thyratron the introduction of a third electrode between the anode and the cathode makes it possible to control the discharge, so can use be made of a switching electrode in glow-discharge tubes, to ignite the discharge at the desired instant. The ignition mechanism of the discharge is, however, different in the two different cases, as will be shown in the next section. Fig. 149 shows the Philips trigger tube type Z 50 T as an example. The switching electrode *t*, called the trigger (or starter) in this

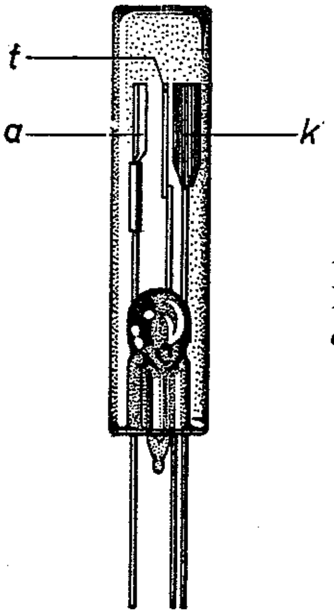


Fig. 149

Philips glow-discharge relay tube type Z 50 T. *t* = trigger. *a* = anode, *k* = cathode.

case, controls the moment of ignition of the discharge between the cathode and the anode. Here too, the trigger no longer has any control over the discharge as soon as the latter has been ignited. In order to be able to make use of the trigger again, the discharge must first be quenched by reducing the voltage between the cathode and the anode to less than the burning voltage. These trigger tubes, or cold-cathode relay tubes, have a lower tube current and a higher burning voltage than thyratrons. Among the advantages of trigger tubes we may mention the following: the cathode does not need to be heated, so the discharge can be ignited immediately after switching on (no warming-up time); the triggering power needed is low; since the tube current is low, so is the dissipation of energy in the tube, and the tube may safely be made small. Like the thyratron, the trigger tube is an electronic "on-off" switch, with only two stable states. It is used in time-switches, counting circuits, as a sensitive relay, etc. In such applications, the ignition and its build-up time and the quenching of the discharge play an important role. We shall now discuss these points, after which we shall describe the various types of tube.

V-f-2 IGNITION

The main discharge should be initiated by an auxiliarly discharge between the trigger and the cathode. The auxiliary discharge gives rise to a cathode fall with glow. A plasma is also produced, with more or less the trigger potential, from which the anode can extract charge carriers when the anode is positive with respect to the plasma. By means of these effects, the auxiliary discharge reduces the ignition voltage between cathode and anode. The amount by which the ignition voltage is reduced depends on the auxiliary-discharge current, or trigger current, as shown in Fig. 150. Thanks to this reduction of the ignition voltage, the anode voltage can be chosen so that ignition occurs when the trigger discharge is present, but not when it is absent. The trigger current in cold-cathode tubes need not be more than a few tens of microamps. Moreover, it is sufficient to let the trigger current flow for a short time; it is thus possible to feed the trigger discharge from a small capacitor, as we shall see below.

The main discharge cannot be formed until the trigger current is flowing. In this respect, the ignition mechanism differs from that of thyratrons, where in general ignition can occur as soon as the grid-cathode voltage reaches a suitable value, since the hot cathode emits electrons before the discharge is produced. To begin with, therefore, there will be no grid current at all in a thyratron, which is thus said to have a voltage characteristic or field characteristic.

The voltages at which glow discharges can be produced may be controlled within certain limits by suitable choice of the materials of the various electrodes and their geometry, and also of the composition and pressure of the gas filling. In connection with the demands made on the switching circuit (see e.g. Fig. 151), it is preferable to keep the ignition voltage of the auxiliary discharge low, which may be achieved by working near the minimum in the Paschen curve.

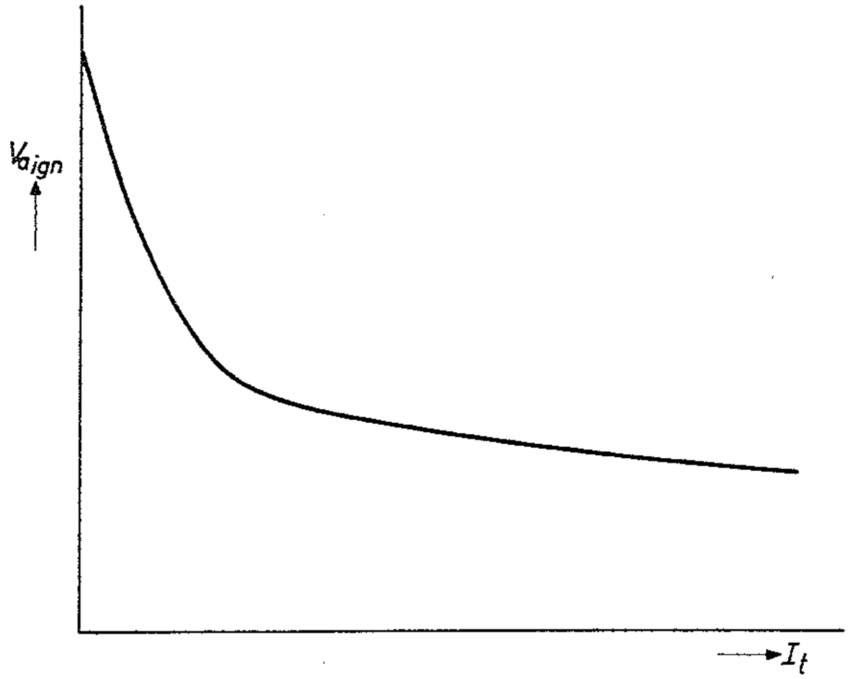


Fig. 150

Typical breakdown characteristic for the space between anode and cathode as a function of the trigger current I_t which is required for obtaining transition from trigger-cathode discharge to anode-cathode discharge.

If the trigger tube has an AC supply, care must be taken when the polarity of the voltage changes, that no discharge occurs between the negative anode and the positive cathode. Let us investigate in this connection how the ignition depends on the instantaneous anode and trigger voltages V_a and V_t, with reference to the ignition characteristic of the tube type 5823, shown in Fig. 152. This is a tube for 117 V AC, to be used as a rectifier for a mean current of 25 mA and with the trigger positive with respect to the cathode.

The area within the closed curve is divided into four quadrants. These represent the regions within which *no* ignition can occur between two given electrodes. The shaded area Ia to the right of quadrant I is the normal operating region for the tube as a rectifier. Here both the anode and the trigger voltages are positive with respect to the cathode, so that first the auxiliary discharge $k - t$ and then the main discharge $k - a$ is ignited. The ignition characteristic $V_a = f(V_t)$ corresponding to a given value of the resistance R_t in the trigger circuit will have more or less the form indicated by the broken line. Thus, as $+V_t$ is steadily increased to the right of the point S, the anode voltage needed for the ignition of the main discharge will gradually decrease, since the V_a required for ignition is determined by the value of the product of the trigger *current* $I_t \times R_t$ (cf. the curve of Fig. 150).

In the regions IIa, IIIa and IVa, outside the quadrants II, III and IV

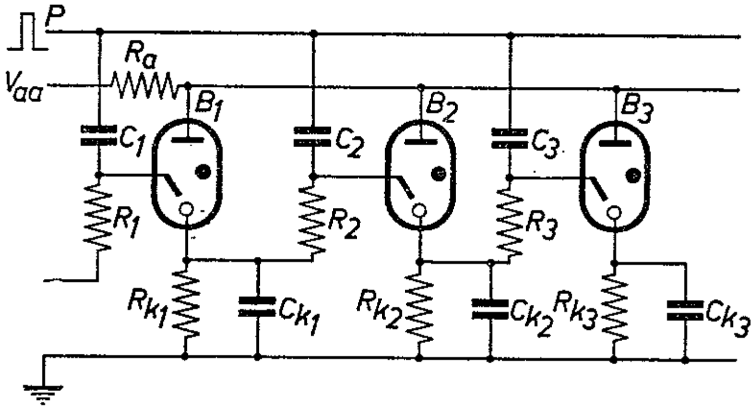


Fig. 151

Example of a counting circuit with three counting tubes (see text).

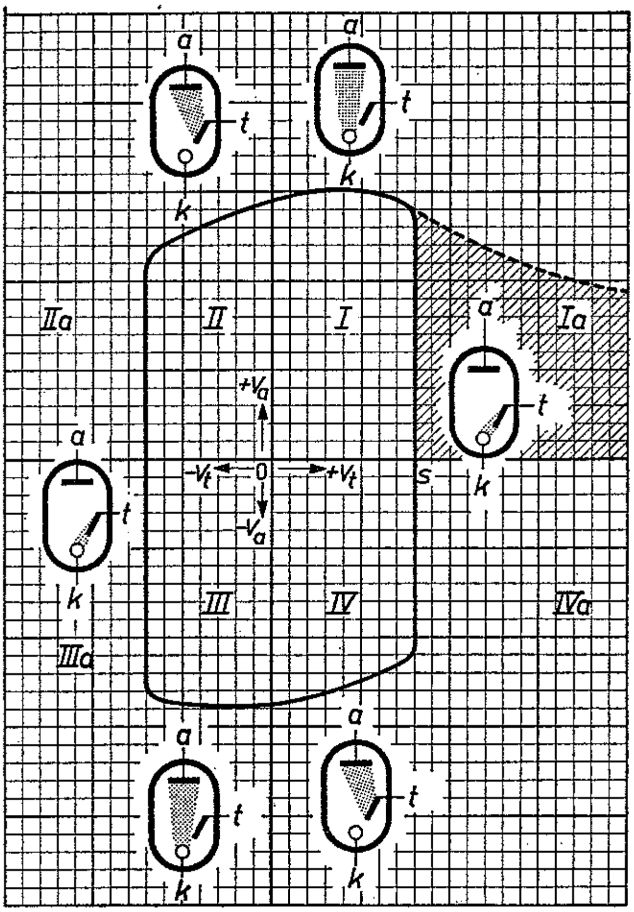
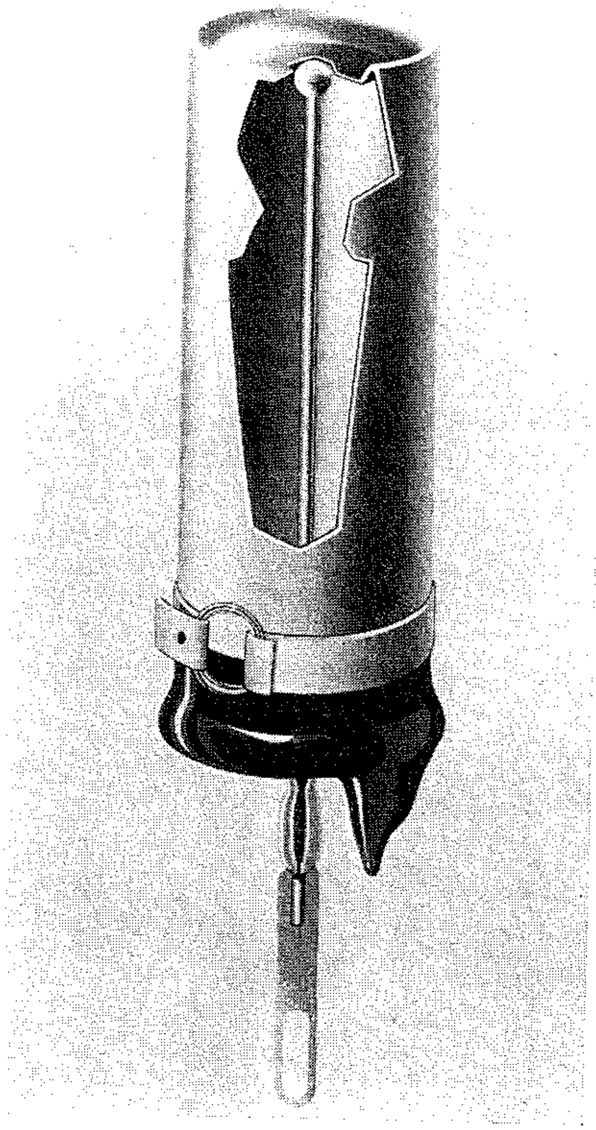


Fig. 152

Ignition characteristic of the trigger tube type 5823. The different sections of the loop refer to a discharge between the electrodes as indicated schematically.

Photo 9

Cut-away view of an (obsolete) radiation counting tube Philips type 18504 with mica end window. The metal strip around the tube serves as a cathode connection.



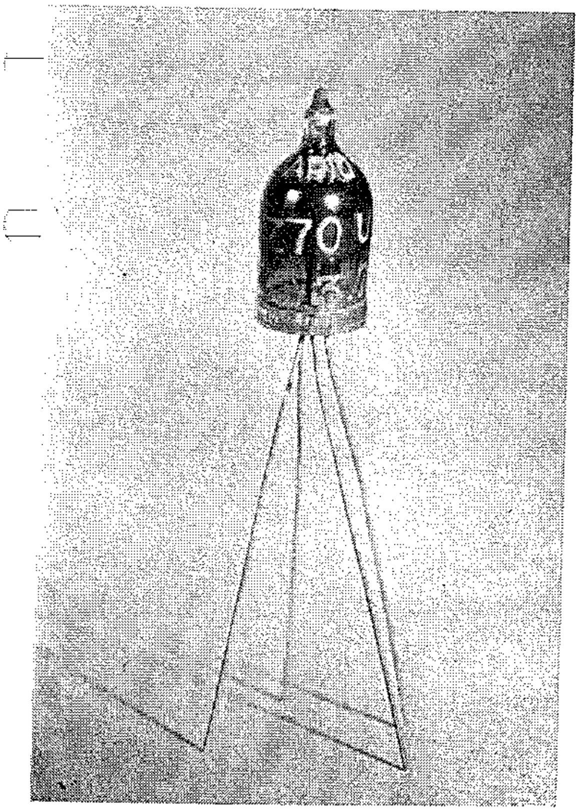


Photo 10

Photograph of a small trigger tube, Philips type Z 70 U, actual size.

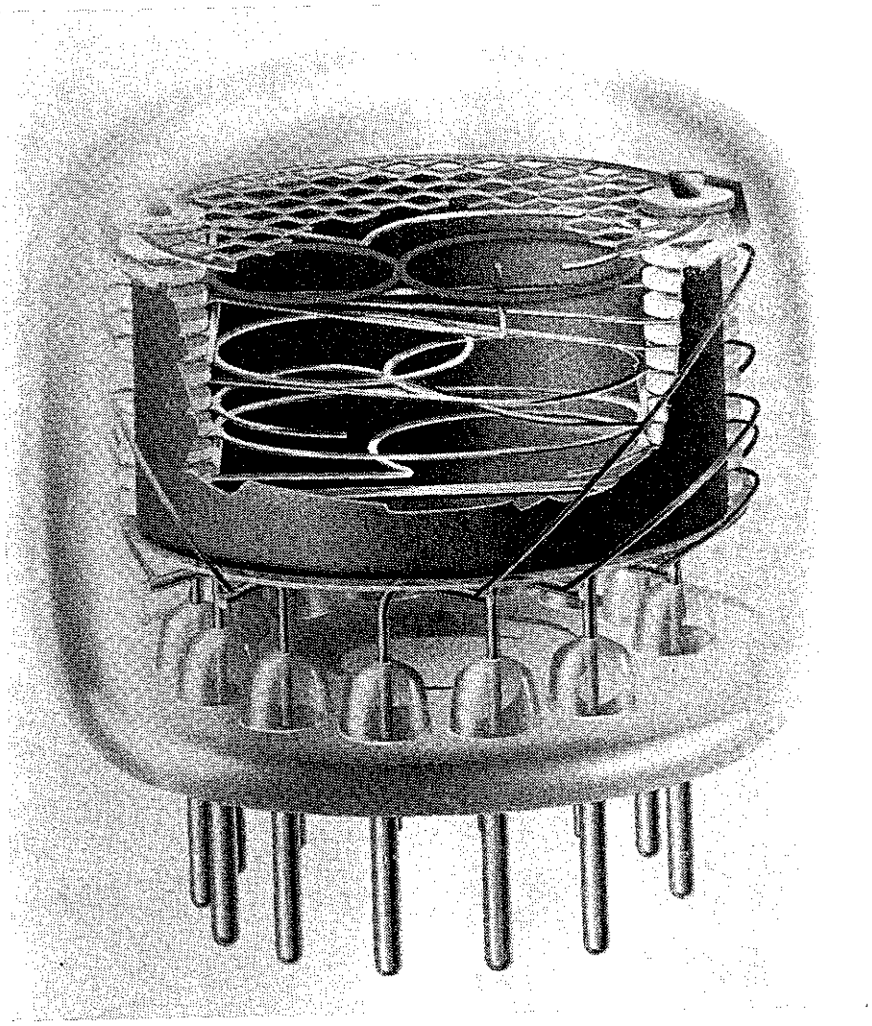


Photo 11

Cut-away photograph of the Philips indicator tube type Z 510 M.

respectively, undesired ignition can take place between the electrodes indicated in the figures. We should like to mention in particular the dangerous situation which can arise in region IVa, bottom right: when V_t is positive and V_a negative, an undesired ignition can occur between *t* and *a*. This situation, of which there is always some risk when an AC anode supply is used, can be made less critical, e.g. by ensuring that as long as the anode voltage is negative, V_t is scarcely positive (or even negative), so that the voltage between *t* and *a* is sufficiently low. This can be achieved by suitable design of the control circuit for the trigger. The situation for normal ignition, i.e. during the positive phase of V_a, can be achieved with the aid of the circuit shown in Fig. 153, which is open to modification in various ways. $+ V_{aa}$ is chosen so that no discharge can occur between *a* and *k* unless the value of $+ V_{tt}$ is sufficiently high. The trigger current is limited in the first place by the series resistance R_t; but it is often advantageous to use a small capacitor C_t to give an extra current pulse of short duration, with a peak value considerably greater than that determined by R_t. The ignition voltage is thus made less critical, so that the slope of the broken line in Fig. 152 becomes much greater: the first part of this curve can indeed become almost vertical. A value of 100—00 pF for C_t is sufficient for this purpose.

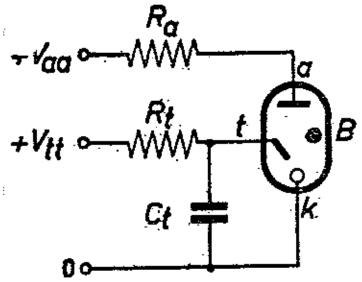


Fig. 153
Typical control circuit for a trigger tube with positive trigger voltage. The small capacitor C_t causes an extra trigger current pulse of short duration which makes the ignition of the main discharge less critical.

The cathode of the 5823 is coated with an alkaline-earth oxide in order to obtain a lower trigger ignition voltage and trigger burning voltage (70—90 V and about 60 V, respectively). While this tube has an auxiliary discharge with positive trigger, other tubes such as the Philips type Z 804 U work with a *negative ignition pulse*: when the voltage between the negative trigger and the cathode is high enough, the auxiliary discharge is produced between *t* and *a*, whereafter the main discharge between *a* and *k* can follow. The advantage of the negative trigger is that the plasma of the auxiliary discharge is then practically at cathode potential, so that the voltage needed between cathode and anode for the ignition of the main discharge is lower than with a positive trigger. Alternatively, instead of a lower anode voltage and a normal trigger current, we can choose to ignite the main discharge with a normal anode voltage and a lower trigger current. If the anode is fed with AC, the voltage between *a* and *t* during the negative phase of the anode (assuming that the trigger is permanently biased) is less than with positive trigger ignition (or trigger bias) as in tubes like the 5823. The risk of current flowing between anode and cathode in this interval is thus less, which is another advantage of these tubes.

Trigger tubes with special properties can be obtained by the addition of extra electrodes. For example, there are tubes with a fourth electrode which acts as an auxiliary cathode [63]. The "Cerberus", type GR 16, has an anode which is screened by an insulated metal cylinder (Fig. 154) so as to give a high inverse ignition voltage. This tube can be used on the 220-V AC mains and works with a positive starting pulse. The maximum cathode current is 20 mA. This tube also has a "priming" electrode *pr*. A continuous discharge is maintained between *pr* and the cathode, at a sufficient distance from the main discharge to ensure that the ignition voltages are not affected. This priming discharge ensures that there are always enough charge carriers in the gas, so that retardation of the ignition is prevented.

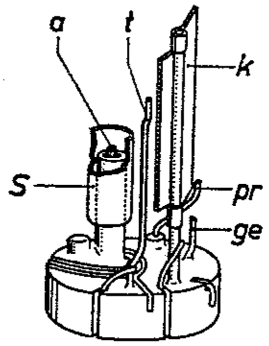


Fig. 154

Electrode arrangement of trigger tube GR16 for AC voltage. The anode *a* is screened by a metal cylinder *S*, resulting in a high inverse ignition voltage (*a* negative, *k* positive). *t* = *trigger*, *pr* = priming electrode, *ge* = getter.

V-f-3 RETARDATION OF IGNITION

The ignition of the main discharge will be retarded by a certain time, which may be resolved into the *statistical retardation* (see I-e-1) and the *take-over time*. The statistical retardation, due to the fact that the formation of the first charge carriers in the gas is a random process, holds up the formation of the trigger discharge by a shorter or longer time. A very small quantity of radio-active material is sometimes placed in the tube in order to remove this delay, or a small proportion of a radio-active gas may be added to the normal filling. Another solution is irradiation with ultraviolet light. Where the tube envelope absorbs ultraviolet, or if the tube is used in the dark, or if the cathode it not coated with barium, a permanent auxiliary discharge of a few μA may be maintained between a "waker" electrode (or "primer" electrode) and the anode to provide the initial ionization.

If steps are taken to ensure this initial ionization, the trigger discharge will always ignite sufficiently rapidly (max. retardation about 100 μ sec.).

After the trigger discharge has once been produced, a second period of retardation follows, during which the main discharge is built up; this is called the *build-up time* or *take-over time*. If we allow the trigger current I_t to increase uniformly, then for each value of I_t a corresponding anode voltage can be found at which the main discharge is ignited. The build-up time of the main discharge is short, about 10 μ sec.

Under favourable circumstances, the total retardation time may be expected to be a few tens of microseconds.

V-f-4 QUENCHING (DE-IONIZATION, RECOVERY TIME) [25]

Just as with the thyratron, the switching electrode of a trigger tube cannot be used to quench a discharge once ignited between anode and cathode. Here too, the tube voltage must be lowered below the burning voltage V_{br}, for long enough to ensure that the discharge is not re-ignited when the tube voltage is increased again, before the trigger discharge is ignited. During this time, the de-ionization time, the ions and electrons must be given the chance to recombine.

As we have seen in IV-b-4, this time is not constant, but depends on the nature and pressure of the gas, the magnitude of the tube current just before quenching and the tube voltage during the de-ionization. It is also mentioned there that these factors depend on the values of the components used in the external circuit.

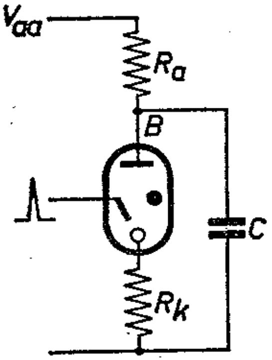
It is therefore more accurate and more practical to speak of the recovery time (see IV-b-4). This is the time, for a given circuit, after which the anode voltage can be applied again with the assurance that the main discharge will not re-ignite unless the trigger discharge is present.

The importance of the recovery time e.g. for the counting circuit of Fig. 151 is brought out during the discussion of the maximum possible counting frequency (see V-g-2). Here too, we see how in a series of tubes a given tube can be quenched with the aid of the following one.

Self-quenching

There is another method of quenching, which does not involve the co-operation of a second tube. In the circuit of Fig. 155, the tube is quenched after the passage of a current pulse. While the tube is cut off, the capacitor C is charged in series with R_a. If the tube then receives a trigger pulse, C is immediately discharged rapidly via the tube B and the cathode resistance R_k, after which the discharge breaks off because of the high value of R_a, which ensures that the continuous current through the tube is too low to maintain a discharge. C is then charged again. To each value of C corresponds a minimum value of R_a which ensures that B will be quenched reliably; $R_{a\ min}$ is of the order of 1—10 megohm.

A tube constructed like the Mullard type Z 801 U (cf. V-g-2) still quenches at relatively low values of R_a [63]. R_k, on the other hand, must not be too large so as to give a short RC time; the inductive properties of the tube, always present to a certain extent, and the self-inductance of the wiring aid the quenching.



Typical circuit for a self-quenching trigger tube.
Fig. 155

V-g **Counting tubes**

V-g-1 INTRODUCTION

The application of controlled cold-cathode tubes has not remained restricted to relay circuits, time switches and amplifiers for very low currents. They have proved very useful in the "electronification" of all sorts of industrial processes; but of recent years they have also proved their usefulness in electronic counting and calculating systems. They have established a place for themselves in this field, alongside vacuum counting tubes (the Philips E1T, the Ericsson trochotron with electrostatic and magnetic deflection of an electron beam), transistors and the like. The ever-increasing demands made on the counting speed have driven mechanical calculating machines, whose speed is limited because of the relatively high inertia of their moving parts, into the background [27, 28, 29]. When very high counting rates are not needed, glow-discharge trigger tubes come into consideration. As we have seen above, these tubes can give counting rates of up to a few thousand a second. Their "on-off" character (two stable states) makes them suitable for use in *digital* counting systems, i.e. systems in which numbers are represented by discrete stable states of the system.

Among the factors which must be taken into consideration when deciding whether a trigger tube can be used for a given application, we may mention the maximum counting rate, the power consumption (also of the trigger circuit), the supply voltage needed, how the final result is to be displayed, the life and volume of the counter.

V-g-2 TRIODES AND TETRODES (counting tubes with one cathode)

We have already seen in V-f-4 that not only the tube but also the external circuit has an effect on the counting rate. The power is of minor importance, and should preferably be kept small. Anode currents of tens of milliamperes need not be delivered provided that the result of the counting process is to be indicated by the discharge state of the tubes used. The simplest form of such indication is where the tube itself gives a visual indication of whether it is passing current or not. If a tube gives a discharge which is invisible or hardly visible, its state can be indicated by e.g. placing a neon glow-discharge tube in parallel with its series resistance. A typical example of a counting tube which itself gives an indication of its state is the sub-miniature Philips trigger tube type Z 70 U, whose electrode arrangement is shown in Fig. 156. With a current of 1—3 mA, the discharge is seen through the base of the tube as a clearly visible red glow.

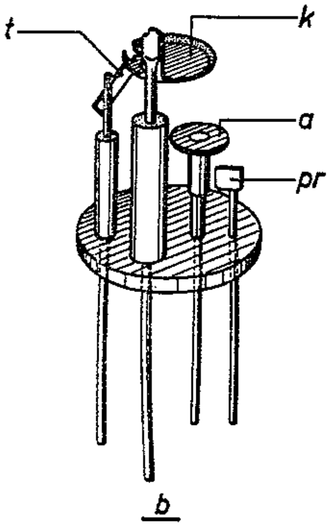


Fig. 156

Electrode arrangement of a small trigger tube, Philips type Z 70 U.

Trigger electrode *t* is placed quite near the cathode *k*. A continuous priming discharge is maintained between the negative primer *pr* and anode *a*.

The electrical properties of this tube are very constant, thanks to the molybdenum cathode which is treated by sputtering methods (cf. V-a-2).

The small dimensions (diameter 10 mm, length max. 25 mm, Photo 10) and the very low power make is possible to build a 1.2-W decade counter, including the necessary resistors and capacitors, on a printed wiring board measuring about 10 × 10 cm². The tube is simply soldered on to the wiring by its projecting lead wires.

The low power needed for the counting pulses applied to the trigger can be seen from the fact that a trigger current of as little as 20 μA (the transfer current) is enough to enable the anode to take over the trigger discharge. This tube also has an extra primer electrode which acts as an auxiliary cathode and passes a permanent current of about 1—10 μA. The task of this electrode is to maintain a slight preliminary ionization, to prevent retardation of the ignition. Ten of these tubes are needed for a decade counter. We shall mention some details of the external circuit during the discussion of the counting rate at the end of this section.

The tube type Z 70 W offers more possibilities. This is a modification of the Z 70 U, containing a second trigger electrode. The need for two triggers is felt for electronic addition and subtraction. One trigger is used for addition, and the other for subtraction. The counting circuit therefore contains two pulse lines, each of which supplies a series of corresponding triggers from a group of counting tubes.

The Mullard tube type Z 801 U is a tetrode whose fourth electrode is an auxiliary cathode. This tube was originally intended for use with positive trigger-voltage pulses [63].

The principle of a circuit using these tubes for counting high-frequency pulses, with a self-quenching discharge, is shown in Fig. 157. The trigger t is connected directly to the anode supply via the resistance R_t, so that the quiescent voltage on t is near the breakdown value for a discharge between t and k. The slightest positive pulse delivered via C_t, will thus ignite the trigger discharge. The fourth electrode is not in principle necessary for this purpose, but its addition does improve the recovery time (separation of the functions of ignition and quenching) and thus increases the possible counting rate. The main discharge, which follows the production of the auxiliary discharge, is first formed between a and the auxiliary cathode k_h, after which the potential of k_h rises owing to the presence of R_{kh} and C_{kh}. When it has risen sufficiently, the main cathode k takes over the discharge, C_a then discharges and the discharge is quenched. Since k_h does not immediately return to cathode potential, ignition of a discharge between k_h and a is not so easy; the recovery time is partly determined by the values of R_{kh} and C_{kh}.

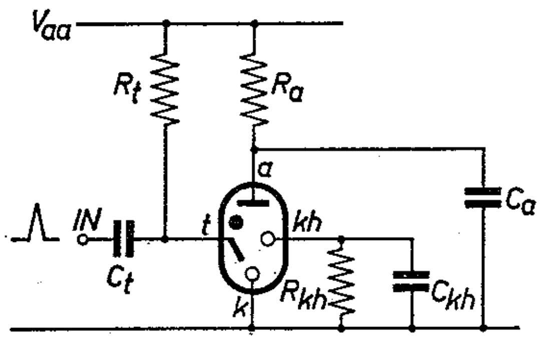


Fig. 157

Self-quenching circuit for measuring counting rates, using a cold-cathode tube with four electrodes and positive trigger pulses. The fourth electrode makes it possible to separate the functions of ignition and quenching, which can be useful for counting radiation in conjunction with Geiger-Müller tubes (counting rates up to 10 kc/s). Typical values of the circuit components are:
$R_t = 100\ \text{M}\Omega$,
$Ct = 50\ \text{pF}, R_a = 200\ \text{k}\Omega,\ C_a = 0{,}01\ \mu\text{F}$,
$R_{kh} = 1\ \text{M}\Omega$ and $C_{kh} = 50\ \text{pF}$.

This tube can however be used to better effect with negative pulses. This is desirable when the tube is used as an amplifier in conjunction with Geiger-Müller radiation counter tubes. Since the cathode of the latter tubes is normally at earth potential, negative pulses are produced in the series resistance. The ignition cycle of the Z 801 U when used for this purpose (see Fig. 158) is as follows. First a preliminary discharge is produced between k_h and t by the negative voltage pulse on k_h; the auxiliary discharge between t and k then takes over, and finally the main discharge a-k. Used in such a set-up, the tube has a very high sensitivity; an input charge of 3×10^{-11} C is enough to trigger the discharge, as against 5×10^{-10} C when positive pulses are used. This method permits counting rates of the order of 1000 c/s. Moreover, the pulse energy is found to be constant over a fairly wide range of anode supply voltages.

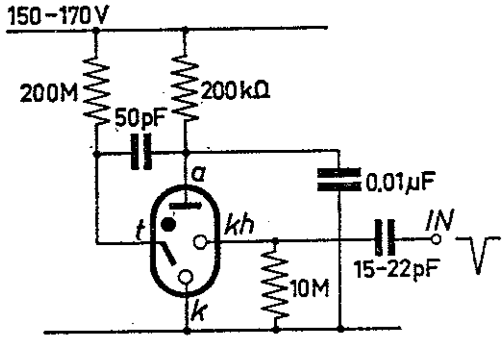


Fig. 158

Self-quenching circuit for a counting-rate meter for negative pulses and high count rates. This circuit, using the tetrode counting tube type Z 801 U, has a high input sensitivity.

Counting frequency

We shall now examine how counting actually takes place, with reference to Fig. 151, which shows a circuit with three counting tubes, B_1, B_2 and B_3. V_{aa} is the DC anode supply voltage, and periodic positive pulses are applied to the line P. If B_1 passes a current I, the voltage across the cathode resistance R_{k1} (of magnitude $R_{k1} \times I$) acts as trigger bias for B_2; the values of R_{k1} and the common anode resistance R_a are so chosen that this trigger bias is slightly less than the triggering voltage of B_2.

The next (positive) pulse applied to the pulse line P makes the trigger voltage high enough for a brief period for B_2 to be triggered. As a result of the passage of current by B_2, the voltage drop across R_a increases somewhat, as a result of which the voltage across B_1 falls below the burning voltage and the tube is quenched. The details of this process are as follows: the capacitor C_{k2} in parallel with R_{k2} acts as a short-circuit across the latter during the build-up of the current through B_2, because of its low impedance. The voltage across R_a during the ignition will thus remain practically equal to $V_{aa}-V_{br}$, where V_{br} is the burning voltage of the tube. The voltage across B_1 is therefore equal to $V_{aa}-IR_{k1}-(V_{aa}-V_{br})$ $= V_{br}-IR_{k1}$, i.e. less than V_{br}, during this period.

After B_1 is quenched, the initial situation has shifted along one place: B_2 is now burning and provides trigger bias for B_3, so that the next pulse on P will ignite B_3 and quench B_2, and so on.

The frequency with which the counting can proceed without disturbance depends mainly on the RC time constants in question. The charging time of C_{k2} is determined by $R_{k2} \cdot R_a \cdot C_{b2}/ R_{k2}+R_a)$ during the ignition of B_2, and $R_{k1}\, C_{k1}$ determines the discharge time of C_{k1} during the quenching of B_1. Together, these two determine the time which must pass before the voltage across R_{k1} is again practically zero, so that the voltage across B_1 is once again greater than the burning voltage. If in the meantime the de-ionization process in B_1 has proceeded far enough, in other words if the tube has recovered sufficiently, it will not reignite.

The chance of complete recovery thus also depends on the frequency of the pulses on P, because a high frequency demands short RC times (R and/or C small), and the shorter the RC time the less chance the tubes have to recover. Trigger tubes in general cannot give counting rates of more than a few thousand per second.

Data of a number of trigger tubes are given in Table XIII.

While triode and tetrode trigger tubes can be used in many control circuits, special multi-cathode glow-discharge counting tubes have been developed for calculating purposes; we shall discuss these in the next section.

V-g-3 RING COUNTING TUBES (multi-cathode) [26]

We have seen above that a decade counting circuit can be made by combination of ten tubes, each with one anode and one cathode. In such a circuit, the tubes are connected by RC links, and on receipt of a control pulse the discharge is transferred from one tube to the next one, while the first is quenched.

Much work has been done in an attempt to combine such a set of counting tubes into one. These attempts have led to the development of glow-discharge tubes with one anode and many cathodes in the same discharge space. The cathodes with their auxiliary electrodes ("guides") are arranged in a ring round the anode, so that application of control pulses to the guides causes the discharge to jump from one cathode to the next one. In these *ring counting tubes,* the visible glow on a certain cathode (which may be given a special shape), indicates the number of pulses applied. If a decimal ring counting tube (i.e. one with ten cathodes) is combined with a second one, it is possible to count up to 99; with three tubes one can count to 999, etc.

TABLE XIII

OPERATING DATA OF SOME TRIGGER TUBES

TUBE TYPE	5823/ Z900T	Z50T	Z70U	Z801U	Z804U	GR16
Anode supply (DC or AC)	DC or AC	DC	DC	DC	DC or AC	DC or AC
Max. anode voltage, or $V_{a\,rms} \times \sqrt{2}$ (V)	200	175	310	170	400	360
Burning voltage between anode and cathode (V)	nom. 62 max. 85 ($I_a = 25$mA)	nom. 61 max. 67 ($I_a = 2$-6mA)	nom. 118 max. 121 ($I_a = 3$mA)	nom. 105 ($I_a = 2$mA)	min. 108 max. 115 ($I_a = 15$mA)	nom. 110 max. 115 ($I_a = 20$mA)
Typical ignition voltage between trigger and cathode *) (V)	80	71	145	—	-125	130
Minimum ignition voltage between trigger and cathode *) (V)	73	66	139	—	-119	120
Maximum ignition voltage between trigger and cathode *) (V)	105	90	151	—	-131	140
Burning voltage between trigger and cathode (V)	61 ($I_a = 25$mA)	—	—	—	—	—
Necessary trigger current (I) (μA)	nom. 50 max. 400 ($V_a = 140$V)	nom. 50 max. 100 ($V_a = 130$V)	nom. 20 ($V_a = 250$V)	—	—	nom. 5
Necessary trigger current (II) (μA)	max. 160 ($V_a = 175$V)	—	—	—	—	—
Typical/maximum primer current (μA)	—	—	3/5	0.4/0.6	—	—
Minimum voltage between primer and anode (V)	—	—	210	—	—	—
Maximum mean cathode current (mA)	25 ($t_{av} =$ 15 sec. max.)	6	3 ($t_{av} =$ 1 sec. max.)	2.5 ($t_{av} =$ 15 sec. max.)	40	20
Maximum peak cathode current (mA)	100	24	12	10	—	40
Maximum mean auxiliary-cathode current (mA)	—	—	—	1.0	—	—
Maximum peak auxiliary-cathode current (mA)	—	—	—	4.0	—	—
Ionization time *) (μsec)	20	50	—	—	—	—
De-ionization time (μsec)	500	200	—	—	—	—

*) When the tube is illuminated.

Various manufacturers have succeeded in making useful ring counting tubes. Some of these have two guides per cathode, and need a double pulse to make the discharge jump from one cathode to the other. Other tubes work with a single square-wave pulse of short duration, or with sinusoidal pulses and three guides per cathode. A number of types can count in both directions [30].

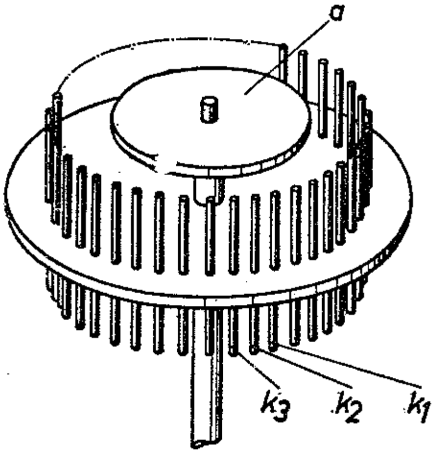


Fig. 159

The 10 × 3 electrode rods of the decimal ring counting tube type GS10C. If k_1 is a main cathode, k_2 and k_3 are "guide cathodes". *a* is the anode.

We shall now describe one two-pulse tube with its ancillary circuit, to give a clearer idea of how these ring counting tubes work.

The tube we shall choose for this purpose is the dekatron counting tube type GS 10 C (made by Ericsson), whose electrode configuration is sketched in Fig. 159. Fig. 160 shows how the electrodes are connected within the tube. Three times ten cathode rods are arranged round the disc-shaped anode. All thirty lie on one circle, but they can have one of three different functions. We distinguish the main cathodes and the take-over cathodes or guides.

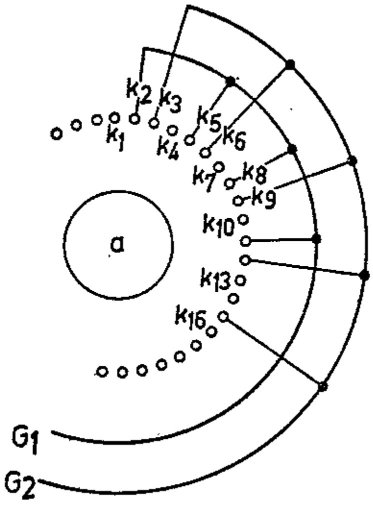


Fig. 160

Sketch of the internal connections between the various electrode rods of the ring counting tube type GS 10 C. The main cathodes k_1, k_4, k_7 ... are not connected. The other electrodes are connected in two guide groups, G_1 and G_2.

The main cathodes k_1, k_4 etc. are not connected within the tube, but the two sets of guides, k_2, k^5.... and k^3, k^6.... are. The letter S (for "selector") in the type number of this tube means that all the main cathodes have leads which pass through the envelope, so that they can be selectively connected to the external circuit. For the rest, there is one anode lead and one lead for each of the sets of guides: 13 pins in all.

Fig. 161 shows the GS 10 C in a counting circuit. A double negative control pulse can transfer the discharge from one main cathode to the next, as follows. The two sets of guides have a constant bias, slightly positive with respect to the main cathodes. This ensures that the discharge will always tend to remain on one of the main cathodes. Let us suppose that in a quiescent state k_1 is covered by the glow discharge. If now the neighbouring guide electrode k_2 is made sufficiently more negative than k_1 (peak pulse voltage greater than positive bias), the glow discharge will jump from k_1 to k_2, and k_1 will be quenched. If then the set of guides containing k_3 is made more negative than k_2, k_3 will begin to glow and k_2 will be quenched. When the second negative pulse has passed, the neighbouring main cathode k_4 is more negative than k_3, so the discharge will jump to k_4 and remain there until the next pair of pulses comes along.

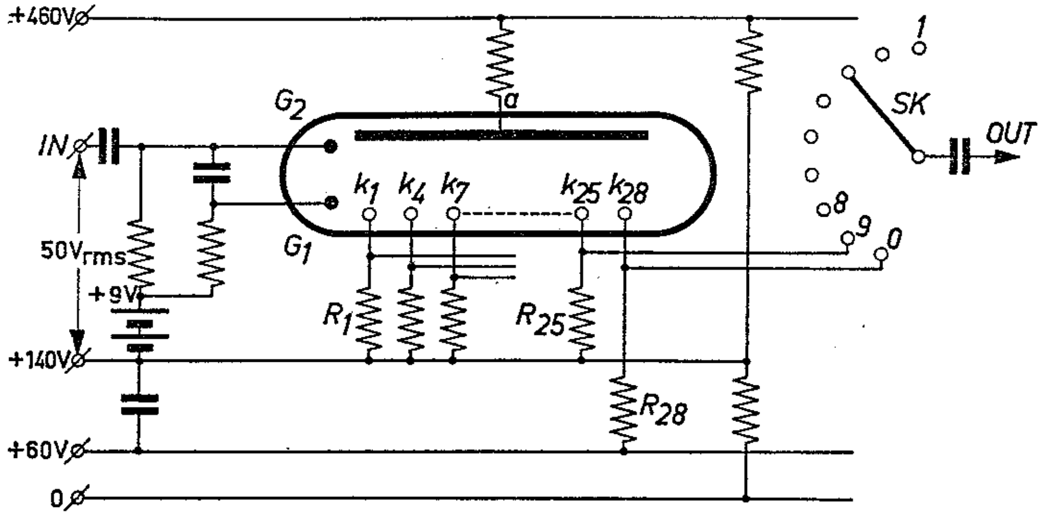


Fig. 161

Example of a counting circuit for a ring counting tube type GS 10 C. The guides G_1 and G_2 receive pulses from an AC voltage source of 50 V_{rms}. The guide circuit shown in the figure makes double pulses from these, with a phase difference between the voltages on G_1 and G_2. As soon as one of the main cathodes k_1, k_4, k_7 etc. ignites, a voltage jump is produced on the corresponding cathode resistance. The position of the switch *SK* determines which voltage jump will be delivered at the output.

The discharge will have no tendency to jump back from k_3 to k_1, because the voltage difference needed for this has been found to be five times as much as that for the jump from k_3 to k_4. One double control pulse thus causes the originally stable glow discharge on the main cathode

k_1 to jump to a stable position on main cathode k_4. A second pulse pair takes the discharge to the next main cathode, and so on. By reversing the order of the pulse pair, the tube can be made to count in the opposite direction (subtract). The selector switch *SK* can be connected to any one of the resistances R_1–R_{28} in series with the main cathodes; as soon as the corresponding cathode has taken over the discharge, a voltage pulse can be delivered via *SK* to a following decimal counter tube.

The maximum counting rate is 4000 c/s. Further data are given in Table XIV.

TABLE XIV

OPERATING DATA OF THE DEKATRON GS 10 C

Maximum counting rate, sinusoidal or square-wave pulse	4000 c/s
maximum anode current	550 μA
minimum anode current	250 μA
minimum anode-cathode voltage	400 V
maximum voltage difference between guides and cathodes	140 V
nominal anode current	325 μA ± 20 %
burning voltage ($I_a = 325\mu A$)	192 V
cathode series resistance	0—270 kΩ
amplitude of output pulses	0—45 V

V-h **Indicator tubes**

When use is made of the tubes mentioned in the previous section, the number which is the result of a given counting operation must be "read off" (one might even say "translated") from the position of the lit-up tube in a decade, or from the position of the glowing cathode rod in a ring counting tube — assuming that the discharge is visible. It is however possible to display the result directly in numbers with the aid of an *indicator tube,* which does not take part in the counting operation. The glow discharge has also proved useful in realizing such tubes.

A cathode made in the shape of a number will give the required visual indication as long as the cathode current is so high that the whole surface is covered by the glow discharge. This principle is made use of in the Philips indicator tube type Z 510 M.

The numbers from 0 to 9 made out of thin wire are placed one right behind the other in a glass envelope filled with a gas mixture consisting mainly of neon. All ten electrodes are connected to pins in the base of the tube. Each electrode can be chosen as the cathode, while the other nine act together as the anode (Photo 11).

The wire figures are so thin that even the rear one can be clearly seen through the other nine when it is covered by the glow discharge. The choice of which electrode is to light up is made by the selector switch *S* (Fig. 162). Several variations of this type of indicator tube are available.

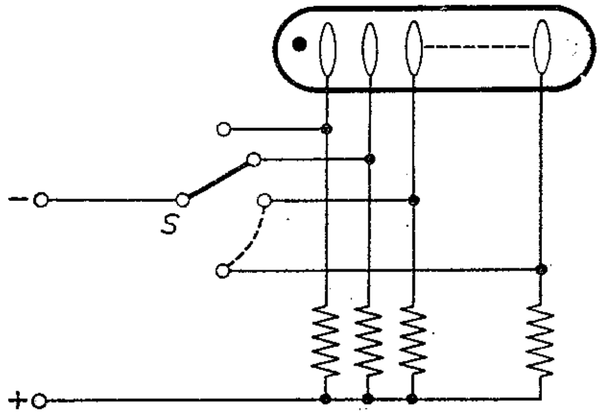


Fig. 162
Circuit for indicator tube type Z510M. The position of the switch *S* determines which cathode will light up.

The tube current naturally depends on the size of the figures, but is always a matter of milliamperes. It is thus possible to include these tubes in the electronic counting circuit.

Is must be remembered however that in this case the current and the voltage (some tens of volts) for the indicator tube must be supplied by the electronic circuit. It is therefore not possible to place such tubes directly behind e.g. a transistorized circuit. We shall now describe a construction for an indicator tube which makes this possible.

Decimal ring indicator tube

Transistorized counting circuits can be constructed with a resolution as high as that of circuits using radio tubes. The indication of the results must occur separately, as transistors cannot do this themselves. If it is wished to use a glow-discharge indicator tube for this purpose, the difficulty arises that the output signal produced by a transistor is too small to ignite normal indicator tubes. Moreover, the relatively large glow-discharge current needed to make the figures visible can cause errors in the counting. The tube we shall now describe presents an answer to these problems [58].

The photograph of the electrode system shown in Photo 12 shows an annular cathode plate made of molybdenum, divided into twenty sectors. Ten of these (the narrow ones) are covered with an insulating layer; the other ten can each act as the cathode *k*. They can be marked with the numbers 0 to 9, e.g. with the aid of a number plate placed round the cathode ring inside the envelope. A circular nickel-wire anode *a* is placed above the cathodes. A trigger *t* is arranged between *a* and each of the cathodes. The gas filling consists of about 15 cm neon, mixed with 0.1 % argon. The argon is added for the following reason. It may be seen from the Paschen curve (see Fig. 12) for this gas mixture that the ignition voltage varies very little with $p \times d$ in a wide range near the minimum of the curve. In other words, at a given pressure the distance between the electrodes has very little effect on the ignition voltage. This makes it possible to simplify the construction of the indicator tube.

We shall explain the operation of the tube with reference to the simplified circuit diagram of Fig. 163. The tube is fed with rectified AC voltage (e.g. 50 c/s). Before ignition, the triggers and the anode all have the same voltage with respect to the cathodes. When there is no control signal, ignition can always occur between one or other of the triggers and the corresponding cathode, or between the anode and one of the cathodes. If however a triggering control voltage V_t is applied to one of the trigger circuits, the trigger in question will ignite first. V_t has a value of a few volts, and is delivered by the voltage source X_i, i.e. one of the positions in the transistorized counting circuit. The value of the supply voltage is not critical, since it is the same for all triggers. What matters is which trigger first reaches the trigger ignition voltage as a result of the extra voltage V_t. After the auxiliary discharge of about 50 μA has been formed between a given *t* and *k*, the main discharge *a*-*k* will also ignite. The main discharge

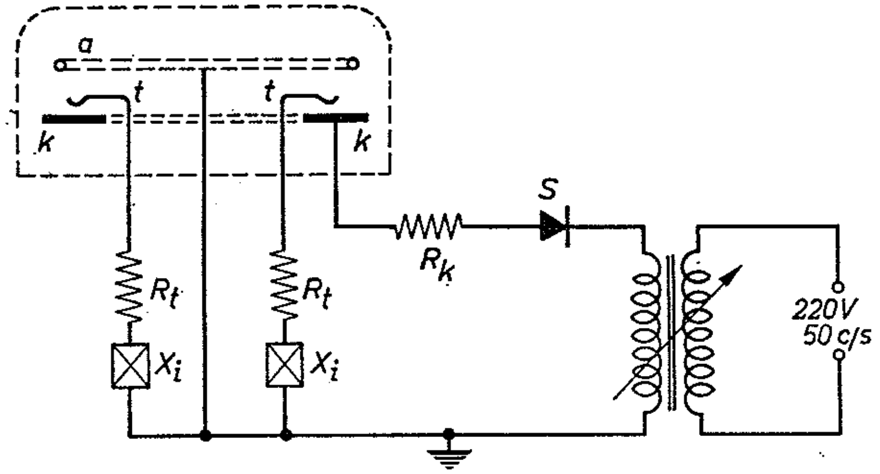


Fig. 163

Circuit for the indicator tube of Photo 12, *a* anode (earthed), *k* cathodes, *t* triggers, X_i voltage source which delivers the control signal. The current of the main discharge is limited by the resistances R_k, that of the auxiliary discharge by R_k together with one of the resistances R_t. The tube is fed with AC rectified bij *S* [58].

with a current of several mA is thus fed from the mains. The discharge is periodically quenched because of the sinusoidal voltage used, but will always be reignited on the same cathode as long as V_t remains applied to the corresponding trigger. As the counting proceeds further, V_t will move to another trigger, and the discharge will then be ignited on the cathode belonging to that trigger. The rate at which V_t moves, i.e. the counting rate of the transistorized counter, does not matter here; it may even be so great that the indicator tube cannot follow it. This tube only needs to display the final result of the counting, when the counter has stopped.

This indicator tube will not disturb the counting circuit, as the trigger current is low.

A tube has been built on this principle which can be controlled by a signal of not more than 5V with 50 μA, while the glow discharge gives a clear indication of the number in question.