CHAPTER VIII

SPECIAL TUBES

VIII-a **Noise tubes**

The sensitivity of a receiver for radio signals is limited by its internal noise. To measure the noise quantitatively, one must have a noise standard, i.e. a set-up which provides an accurately known amount of noise and with which other noise sources can be compared. A saturated vacuum diode may be used for this purpose, as the fluctuation of the tube current is theoretically known [94]. However, such a diode can only be used up to a frequency of about 1000 Mc/sec. For measurements at higher frequencies, i.e. in the UHF region, the column discharge in a gas-filled "noise tube" can be used as a noise standard.

As has already been mentioned (I-f), the elastic collisions undergone by the electrons in a gas discharge give these electrons velocities whose distribution corresponds with that for free electrons in a gas which has been heated to a very high temperature. These electrons emit electromagnetic radiation which is similar to that emitted by a thermal radiator of the same temperature, and which is picked up by a receiver as HF noise [76, 89, 90].

The noise temperature is expressed in decibels above 290 °K, that is about room temperature. (The concept decibel (dB) will be discussed below.) For neon, the noise temperature is about 40 times room temperature, so the noise power of such a thermal noise source is about 10 log 40 = 16 times greater than that of a resistance at room temperature. (The noise power is proportional to the noise temperature expressed in dB.)

As we have already seen in I-g-2, various phenomena in the column discharges are dependent on the nature of the gas, the pressure p_o and the radius r of the column. The electron temperature T_e in the column, and thus the noise, is also dependent on these factors — and on the current: at high currents, the gas is ionized stepwise, via the excited state, as well as directly, and this affects the electron temperature [88].

The column discharge in the long neck of a noise tube is the real source of the noise. The variation of T_e as a function of $p_o \,.\, r$ for this discharge in neon has been measured by Druyvesteyn and de Groot [73, 74], and is shown in Fig. 203. The electron temperature can thus be read off from this graph for a given pressure and a given column diameter.

It is no simple matter to calibrate the noise temperature of the tube, but this may be done by e.g. measuring the probe characteristic of the discharge. A thermally heated wedge-shaped ceramic resistor is often used as a noise standard for absolute measurements of the noise temperature [95].

Under certain circumstances, however, the influence of the current on the electron temperature is slight over a wide range (see Fig. 204 [88]. The gas pressure must be at least several mm, and the conductance of the column discharge must not be too small. The tube current is usually of the order of 100 mA. Such a tube can be used in a wide frequency range; only transit-time effects limit the frequency. The matching of the noise tube with the other equipment is only difficult if the pressure is high.

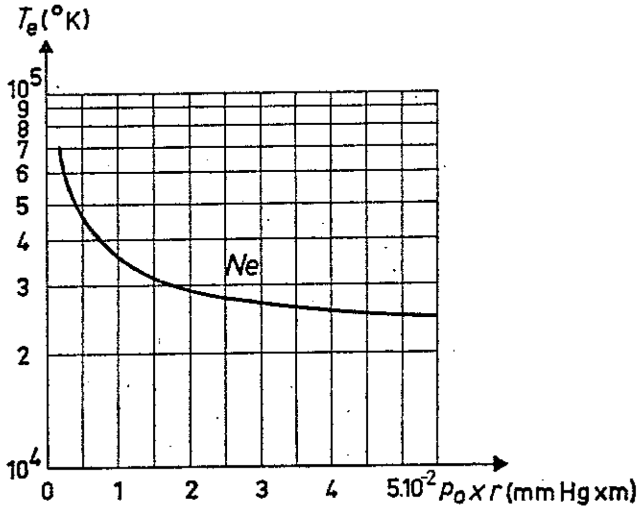


Fig. 203

Theoretical relation between electron temperature T_e and product of gas pressure $_0$ for neon and radius r of discharge tube [74].

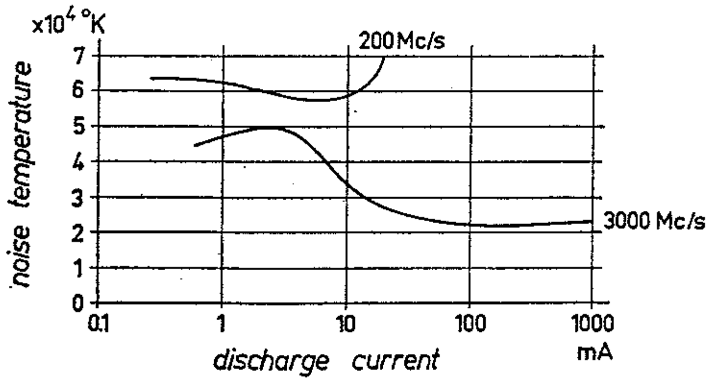


Fig. 204

Example of measurements of effective noise temperature of discharge for $P_0 = 2.80$ mm Hg [88].

Originally, it was found by Mumford that a fluorescent lamp is suitable for noise measurements [75]. Such lamps are still used, but as the filling contains mercury the pressure in these tubes depends on the ambient temperature. A calibration curve is therefore needed to give the relationship between the ambient temperature and the noise temperature. Later, special tubes have been developed by e.g. Bendix, Bell, the Kay Electric Co. and Philips (Photo 15).

ARRANGEMENT OF THE TUBE

When a noise tube is used in a waveguide, the plasma in the tube must be matched with the waveguide, i.e. all the available noise power must be able to disappear in the waveguide. The tube must be made long and thin, to obtain a positive column discharge of the required temperature. It is possible to arrange such a tube in several ways with respect to the waveguide. One way is to stick the tube through the waveguide at a certain angle (Fig. 205). Another method is to place the tube inside a helix, so that coaxial measuring equipment can be used, especially at low frequencies [91]. We shall now consider the first method in somewhat more detail.

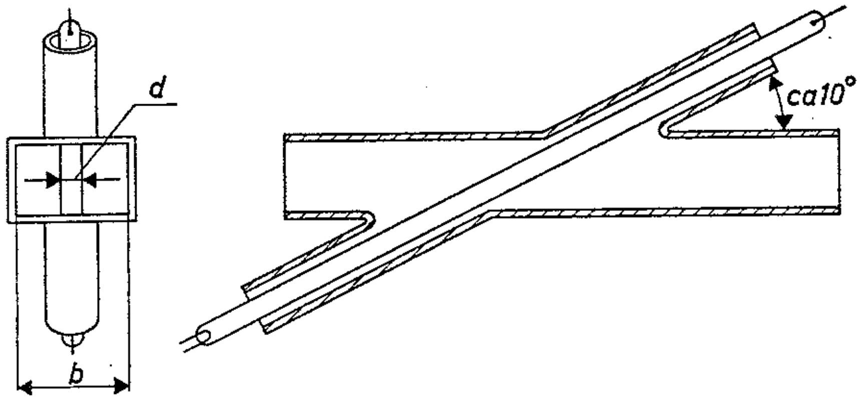


Fig. 205

Example of a noise-tube set-up. The tube passes at an angle through a waveguide. The precise value of the angle depends on the type of tube used. The ratio of the two diameters *d* and *b* is important in this connection.

The angle between the axis of the tube and that of the waveguide is important for proper matching of the terminal impedance with the characteristic impedance of the waveguide. This matching is never perfect. The *voltage standing-wave ratio* is a measure of the deviation from complete matching. When matching is not perfect, the travelling wave in the waveguide is accompanied by reflections, which gives rise to standing waves and to places where the field strength is maximum and minimum (F_{max} and F_{min}). The ratio F_{min}/F_{max} is called the voltage standing-wave ratio, and tends to unity as perfect matching is approached.

The tube should further be placed with the anode at the receiver end, since this makes for the best matching. Finally, attention must be paid to the relation between the diameter of the tube and that of the waveguide.

Example

Let us take as an example the Philips noise tube type K50A (Photo 15), whose operating data are given in table XXI. This is a neon-filled diode which can be used in waveguide systems for the 3-cm waveband. The noise power is practically independent of the ambient temperature and the operating temperature. Within certain limits, it also depends very little on the tube current (see Fig. 206). Because of the long narrow neck in which the discharge occurs, the ignition voltage is several thousand volts. The supply voltage of 500 V is thus insufficient to ignite the tube, and the ignition circuit of Fig. 207 is used.

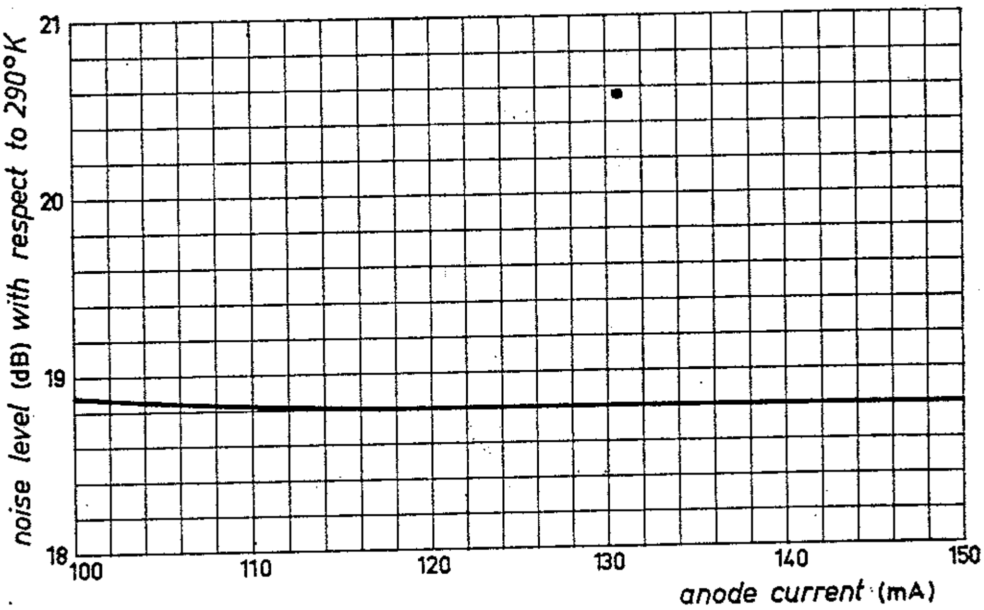


Fig. 206
Noise level of the Philips diode K50A as a function of the tube current.

The available noise power of the discharge may be assumed to be $kT\Delta f$, where Δf is the bandwidth of the equipment used and k is Boltzmann's constant. The noise voltage is given by Nyquist's equation

$$\overline{VV^*} = 4\,k\,.\,T_e\,.\,R_e\,.\,\Delta f$$

where R_e is the ohmic terminal resistance at the input side of the waveguide, which is equal to the impedance of the noise source. (Fig. 208.) This resistance (which is usually wedge-shaped) is only used when the tube is not burning.

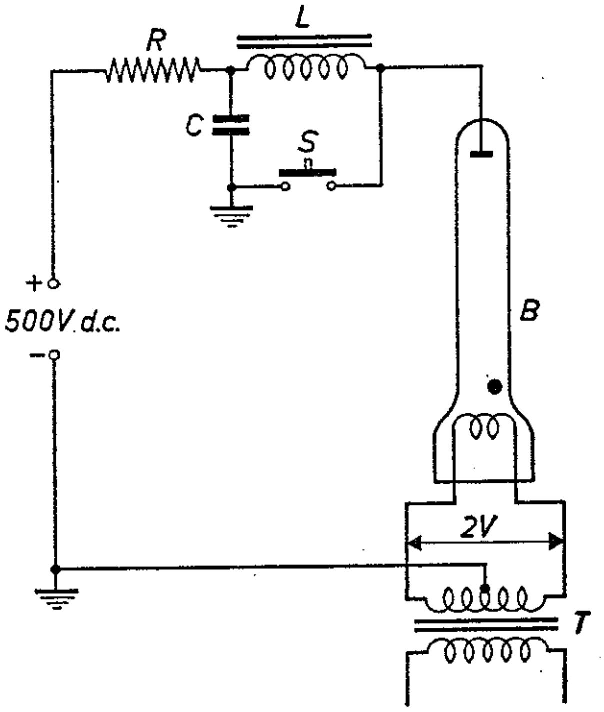


Fig. 207

Ignition circuit for the Philips diode K50A. The discharge of C if S is closed causes a high voltage on L.
$C = 0.01\ \mu\text{F}$, $L = 8$ henry, $R = 2700$ ohms.

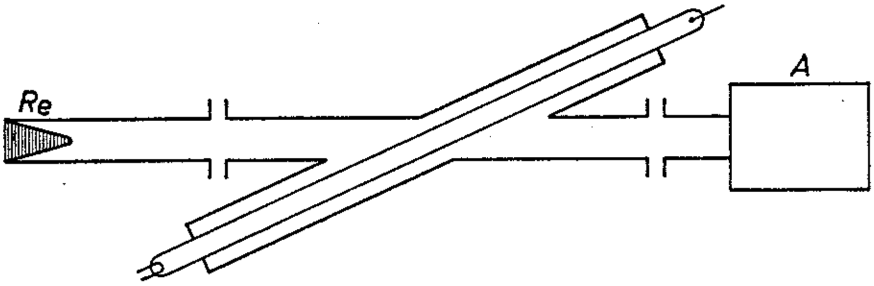


Fig. 208

Waveguide with noise tube preceded by the wedge-shaped terminal resistance R_e and followed by the amplifier A.

The noise figure N of the receiver is given by

$$N = \frac{T_e/T_o - 1}{P_e/P_o - 1}$$

This is determined by measuring the noise power delivered by the receiver for two temperatures T_e and T_o of the resistance of the noise generator. When the tube is ignited (T_e), we can write for the power delivered:

$$P_e = G \,.\, k \,.\, T_e \,.\, \Delta f + P_i$$

and when the tube is quenched:

$$P_o = G \,.\, k \,.\, T_o \,.\, \Delta f + P_i$$

where the internal noise of the receiver is denoted by P_i and G is the amplification factor.

It is only necessary to measure P_e and P_o to determine N for the set-up, since T_e and T_o are known. T_o is usually taken as 290 °K, since this is more or less room temperature.

According to the operating data, the noise level of the K50A is 18.8 dB. This follows from $T_o = 290$ °K and $T_e = 22\,330$ °K, since $10\,{}^{10}\log\,(T_e/T_o - 1) = 18.8$.

The noise factor of a good receiver for e.g. 3000 Mc/s is less than 4 dB.

THE DECIBEL

The *decibel* is frequently used in pure and applied physics as a means of comparing two quantities. In amplification technique, for example, the amplification factor is expressed in these units to give the relationship between the input and output power of an amplifier or attenuator, or between its input and output voltages.

In this chapter, the decibel is used to express the noise figure of a radio receiver. In order to avoid the large numbers involved in such measurements, it is convenient to compare the logarithms of the quantities in question. Another good reason for doing this is that sense impressions and physiological effects, which are sometimes involved in such measurements, follow logarithmic laws.

The "bel" was originally used as a unit of amplification: the number of bels is by definition the logarithm to base ten of the ratio of the two powers P_1 and P_2:

$$\text{number of bels} = {}^{10}\log P_2/P_1.$$

The bel is however rather too big for a practical unit, and therefore the tenth part of a bel, the *decibel*, is now used as a unit:

$$\text{number of decibels} = 10\,{}^{10}\log P_2/P_1.$$

The decibel is sometimes also used to express the ratio of two voltages or currents. Since voltages (or currents) occur squared in the formulae for electrical power, it follows that

$$\text{number of decibels} = 20\,{}^{10}\log V_2/V_1 \text{ (or } 20\,{}^{10}\log I_2/I_1\text{)}.$$

A power amplification of 2000 thus corresponds to 33 dB, and a voltage amplification of 100 to 40 dB.

The decibel is thus not a unit of absolute power (or some other quantity) but of relative power. In other words, the power in question must always be compared with a certain reference value. In some fields, a standard reference level has been chosen, e.g. a power of 1 mW in telephony and microwave receivers. Values expressed in decibels thus only mean something if the reference value is also given. It may be seen from the literature that different workers often choose different reference levels.

Another similar unit, used especially in German technical literature, is the *neper*. The number of nepers is equal to the natural logarithm of the ratio of two amplitudes, currents or voltages. It thus follows that 1 neper = 8.68 dB.

TABLE XXI

OPERATING DATA FOR THE PHILIPS NOISE TUBES TYPES K 50 A AND K 51 A

	K 50 A	K 51 A
	for 3 cm waveband	for 10 cm waveband
Heater voltage V_f (volt)	2	2
Heater current I_f (amp.)	2	3,5
Heating time t_w min. (sec)	15	15
Ignition voltage V_{ign} (volt)	6000	6000
Anode voltage V_a (volt)	approx. 165	approx. 140
Anode current I_a (mA)	125	200
Min. Anode current $I_{a\ min}$ (mA)	50	100
Max. anode current $I_{a\ max}$ (mA)	150	300
Ambient temperature t_{amb} min. (°C)	—55	—55
max. (°C)	+75	+75
Noise level in test amount with respect to 290 °K (dB)	18,8	19,1

VIII-b **The plasmatron** [86]

CONSTRUCTION AND OPERATION

We have seen that the thyratron is a switching tube for large currents. It is not however possible to obtain continuous and reversible control with a thyratron, as it is with a vacuum tube. This is however possible with a plasmatron, which moreover does not have the inconveniently high impedance of the vacuum tube.

This gas-discharge tube, which is filled e.g. with about 1 mm of helium, contains a plasma with a high concentration of electrons and an equal concentration of positive ions, which is used as a conductor. This plasma is found between an anode and a hot cathode which acts as the main cathode; it is however *formed* between a second hot cathode (the auxiliary cathode) and the two above-mentioned electrodes, both of which acts as an anode with respect to the auxiliary cathode.

The two functions of the electrons in such a tube, to form a very conductive plasma by ionization of the gas and to carry the largest part of the active tube current, are thus carried out by electrons from two separate thermally emitting cathodes in the plasmatron, while in the thyratron all the electrons come from a single cathode.

Fig. 209 shows a sketch of the tube in its simplest form. These is an ionization or generator compartment and a conducting or operating compartment. The auxiliary cathode k_h is placed in the former, with a sort of cylindrical screen g_c (the "garrote") around it. This screen is usually connected to the cathode, and has one (or more) small apertures in it. No ionization is possible within the garrote, but the relatively few electrons which emerge from it in the direction of the main cathode k are able to produce sufficient ionization to form a very dense plasma when a sufficiently high voltage V_1 is applied between k_h and k.

The field is concentrated on the garrote.

The plasma thus formed has a high conductivity, of the order of 1 ohm-cm, and makes it possible for a relatively large current to flow in the operating compartment, that is between the main cathode k and the anode a. Under these conditions, the voltage V_2 between these electrodes can be low, and is always less than the ionization voltage of the gas (cf. [67] p. 148).

The variation of the main current I with the anode voltage V_a for various values of the auxiliary current I_h is sketched in Fig. 210.

It will be seen that it is possible to vary the main current continuously over a considerable range by means of a relatively small variation in I_h, which causes a variation in the density and conductivity of the plasma. This can be achieved e.g. by varying the internal resistance of a vacuum triode which is placed as a modulator in the auxiliary-current circuit (Fig. 209). The current can be regulated continuously and reversibly in this case because the voltage between the anode and the main cathode is less than the ionization voltage of the gas. If the anode is fed with AC, the back current of positive ions while the anode is negative is very small, only a few mA.

Another way of controlling the current is to place a grid in the operating compartment. The construction of the tube then becomes as shown in Fig. 211; it is then no longer necessary to use a vacuum triode as a control element. Changing the density of the ion layer round the more or less negative grid causes a variation in the effective cross- section of the plasma region, and thus alters the conductivity of the plasma [87].

The curves of Fig. 212 give an impression of the current-voltage characteristic for various values of the grid voltage V_g, at constant auxiliary current.

The modulation frequency characteristic is better if the modulation is performed with the aid of a grid than if a vacuum triode in the auxiliary circuit is used. In the latter case, the density of the whole volume of plasma is controlled, while in the first case only that part of it near the grid is affected. Even with grid modulation, however, the frequency

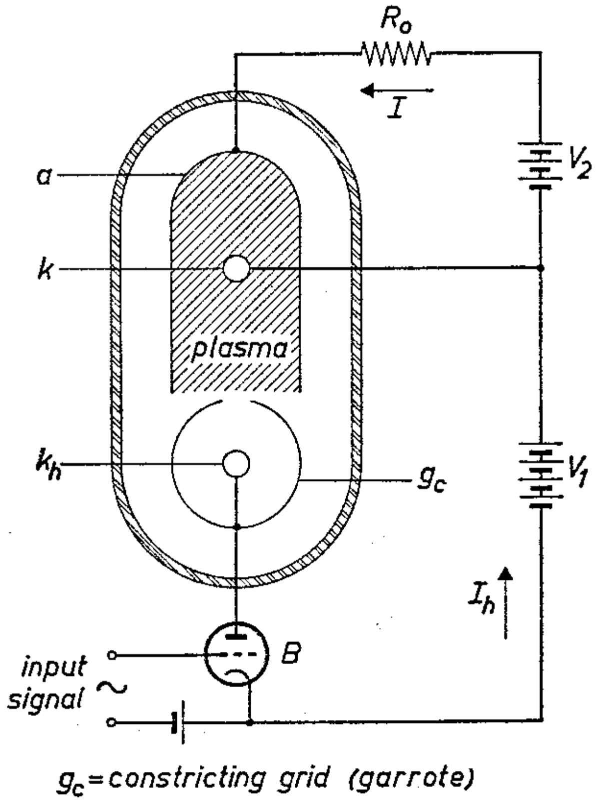


Fig. 209

Circuit arrangement for diode operation of a plasmatron. Generator compartment between k_h and k, operating compartment between k and a. B = modulator tube. R_o = load.

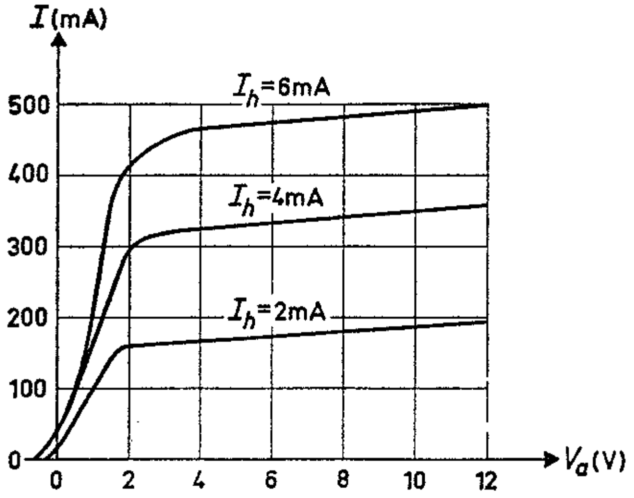


Fig. 210

Main current I of a plasmatron used as a diode, as a function of the anode voltage V_a for various values of the auxiliary current I_h.

characteristic begins to flatten off above 10 kc/s (Fig. 213). This is because of the much slower motion of the ions compared to that of the electrons during the de-ionization (cf. VII-d).

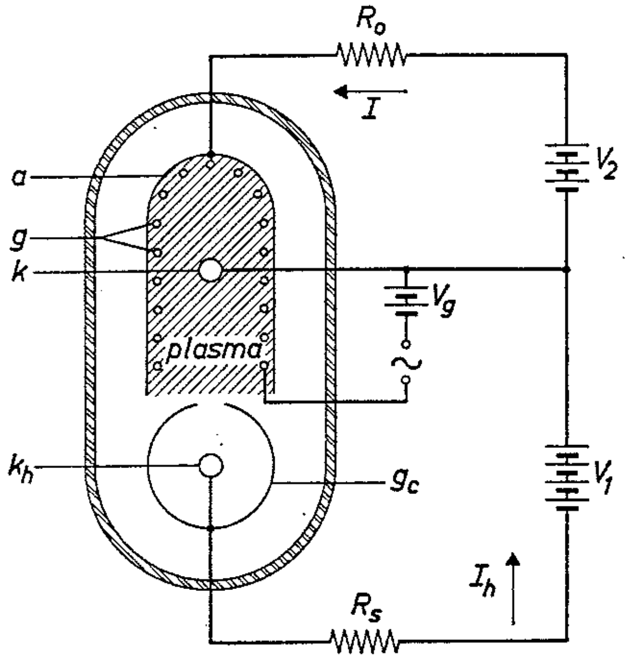


Fig. 211
The triode plasmatron. The grid *g* replaces the vacuum triode *B* of Fig. 209 as regulating element. R_S = current-limiting resistor. R_O = load.

Application

The high amplification and relatively high power which can be obtained with these tubes (power amplifications of 17 dB and more have been mentioned) makes them very suitable as output tubes in AF amplifiers; the AF transformer would then no longer be necessary. Plasmatrons should be suitable in car radios and for controlling motors. Very little is known however about these and other applications: potential users are not yet very interested because the life of the tubes is still unsatisfactory.

Plasmatrons are put on the market by Bendix, among others.

VIII-c **Neutron generators**

Introduction

A neutron source is necessary for certain experiments in the fields of fundamental physics, biology, chemistry and the medical sciences [96, 105]. Neutrons are uncharged particles with a mass approximately equal to that of the proton (the positively charged nucleus of a hydrogen atom). They can be produced by nuclear reactions, e.g. by bombarding the nuclei of certain elements with helium nuclei (α particles), which are emitted by certain naturally radioactive elements, e.g. radium. As a result of this bombardment, the element emits radiation with a great penetrative power, which can be detected e.g. with the aid of the radiation counter tubes described in Chapter V. At the same time, neutrons are released from the nucleus. These neutrons can be used e.g. to make many other elements radio-active in their turn.

Now the yield of nuclear reactions carried out with the aid of radium is not high. For example, the amount of radium needed to produce 1.7×10^6 neutrons per second from the element beryllium under optimal conditions of mixing is about 100 mg. Considering the scarcity of radium, this is an expensive way of producing neutrons, especially as for most purposes a neutron yield of at least 10^7—10^8 per second is desirable.

A much better way of producing neutrons has been known since about 1932 (Cockcroft and Walton), based on giving gas ions a high energy artificially with the aid of particle accelerators. The most suitable gas to use for this purpose is deuterium (symbol D) i.e. hydrogen whose nucleus consists of a proton and a neutron instead of just a proton, otherwise known as heavy hydrogen. The advantage of this hydrogen isotope is that its nucleus (i.e. its ion) can easily penetrate into the nucleus of the element to be bombarded, because of its low electric charge and mass. In this method, deuterium ions or deuterons (symbol d) are first made in a gas discharge, and are then given a high velocity in a strong electric field. The deuterons accelerated in this way are capable of releasing neutrons from a disc of a suitabel material placed in their path.

Although such "accelerator neutron sources" are much more complicated and unwieldy than neutron sources using naturally radioactive substances, they are much more effective and also have other advantages. For example,

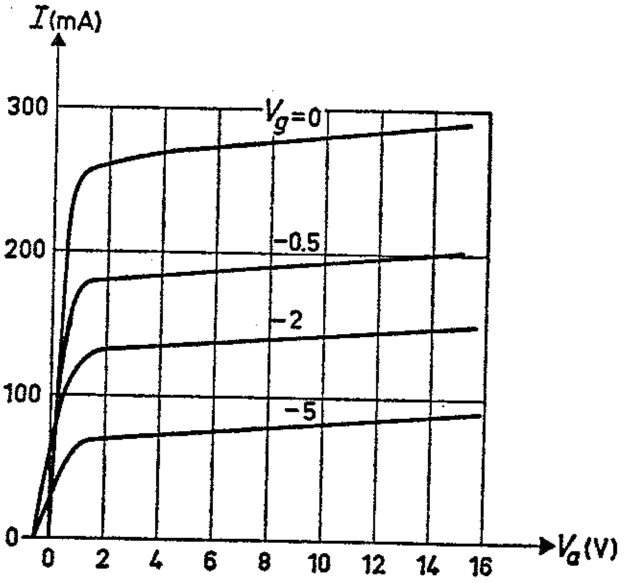


Fig. 212

Current-voltage characteristics of a triode plasmatron for various values of the grid voltage V_g and a constant auxiliary current $I_h = 10$ mA.

the number of neutrons produced can easily be made much larger, and they have a higher energy. Mono-energetic neutrons can be produced in this way, and the production can be controlled. We may mention as an example that 6.3×10^{15} deuterons per second, which corresponds to a current of 1 mA, accelerated by a voltage of 1 MV, can lead to the production of 7×10^9 neutrons per second if they bombard a target of "heavy ice" (solid D_2O). This is much more than could be produced by the α particles from 100 mg of radium.

We shall now go into somewhat greater details about how the deuterons are produced, and how they are used to produce neutrons.

VIII-c-1 THE CONSTRUCTION OF A NEUTRON GENERATOR

A neutron generator always contains the following three components:

an ion source,
an ion-accelerating system and
a "target".

Ion sources

The ions needed in a neutron generator are formed in a gas discharge [103, 104]. The gas pressure must in general lie in the region from 10^{-1} to 10^{-2} mm Hg; on the one hand the mean free path of the electrons as regards collisions with gas molecules must be less than the dimensions of the discharge space, to make ionization possible; while on the other hand the pressure must be kept as low as possible so that the necessary extraction voltage of several kilovolts can be applied between the electrodes without giving rise to undesirable secondary discharge phenomena and so that the gas consumption can be kept low (see below).

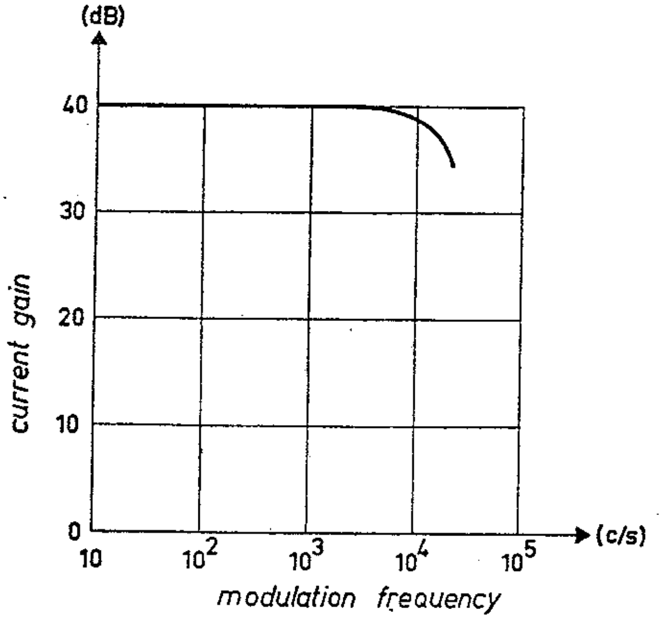


Fig. 213

Modulation characteristic of a triode plasmatron at an anode voltage of 6 volts.

If a hydrogen isotope is used as the gas, both atomic ions and molecular ions can be formed. It is generally desirable to have atomic ions, because they produce more neutrons (cf. Fig. 219). However, molecular ions are naturally formed first in the discharge; atomic ions can only be formed after some atomic hydrogen has been produced by collision of the molecules with electrons:

$$H_2 + e \rightarrow H + H + e.$$

A good ion source is expected to deliver a high ion current without using much gas. Gas is used up not only by clean-up (see II-b-2) but also in an other way, as we shall see presently.

Some of the fast ions, produced in the discharge, pass through a narrow channel into a second space, where they are given a much higher velocity. Various suggestions are made in the literature about the form which this channel should have in order to ensure that a large part of the ions will be able to get through it, and that the ion beam emerging from it should be sharply focused [103].

The energy of the ions emerging from the channel should be as homogeneous as possible.

Of the various types of ion sources which exist, we will only mention the Penning ion source and the ion source with HF discharge. The Penning source will be treated below, in the discussion of an easily transportable sealed-off neutron generator, so here we shall only describe some details of the second, more modern type.

Ion source with HF discharge

In this ion source, the electrons get the energy they need for ionization from a HF alternating field, which can e.g. be applied between two electrodes placed outside the discharge space [104]. An even simpler and in some respects better solution is to place the discharge space in a coil through which a HF alternating current flows. The discharge vessel can then be made of an insulator with a low recombination coefficient for atomic ions, e.g. Pyrex glass. A high percentage of atomic ions, in some cases amounting to 90 %, can then be produced. The plasma is kept at a positive potential by means of a suitable electrode.

An extraction probe is used to get the ions out of the plasma. The maximum ion current is obtained with a certain probe voltage. Various improvements have been made to the probe and the channel in the course of time, to increase the ion current and to decrease the gas consumption. This gas consumption is mainly caused by the pressure difference necessary between the discharge space and the neighbouring acceleration space. It is now posible to obtain a continuous ion current of 10 mA, and a gas consumption of 40 cm^3 (at normal temperature and pressure) per hour. The inhomogeneity of the ions coming from the channel is estimated at some hundreds of electron-volts, which is acceptable for most experiments in nuclear physics.

The accelerating space

The ions coming from the channel must be accelerated in one or more stages through a voltage of hundreds or thousands of kilovolts, so that they will hit the target with enough energy to release fast neutrons from it. The ion accelerator is usually built up of several stages, to avoid field emission.

The voltage between the electrodes of a single stage is usually not more than 200 kV.

The electrode system of the accelerator has rotational symmetry, and thus also acts as an electric lens. If the electrodes are given a suitable shape, the ions are focussed into a narrow beam.

Because of the high voltage between the electrodes, the gas pressure in the accelerating space must be much less than in the discharge space where the ions are produced: in the accelerating space, the mean free path of the ions for collisions with gas molecules must be long, to prevent breakdown occurring as a result of the ignition of an independent discharge.

In order to meet these requirements, the distance between the electrodes must be about 1 or 2 cm.

Fig. 214 shows as an example an accelerating space in five stages for 1 MeV, with the preceding HF ion source [108].

The target

The DD and DT reactions are usually used for the production of neutrons. In order to bring about these reactions, deuterons (deuterium ions) which have been accelerated through a high voltage are allowed to fall on a target which must contain as much deuterium or tritium (T) as possible. Titanium and zirconium are very suitable materials for the target, because they can absorb large amounts of hydrogen and its isotopes. These metals are evaporated in an extremely thin layer on to a support, e.g. a silver disc, and are then saturated with the hydrogen isotope [101].

Titanium is to be preferred to zirconium because it can stand higher temperatures (200 °C) and gives a higher neutron yield. Under favourable conditions, an ion beam of 1 μA and 200 kV falling on a titanium-tritium target can produce about 10^8 neutrons/sec.

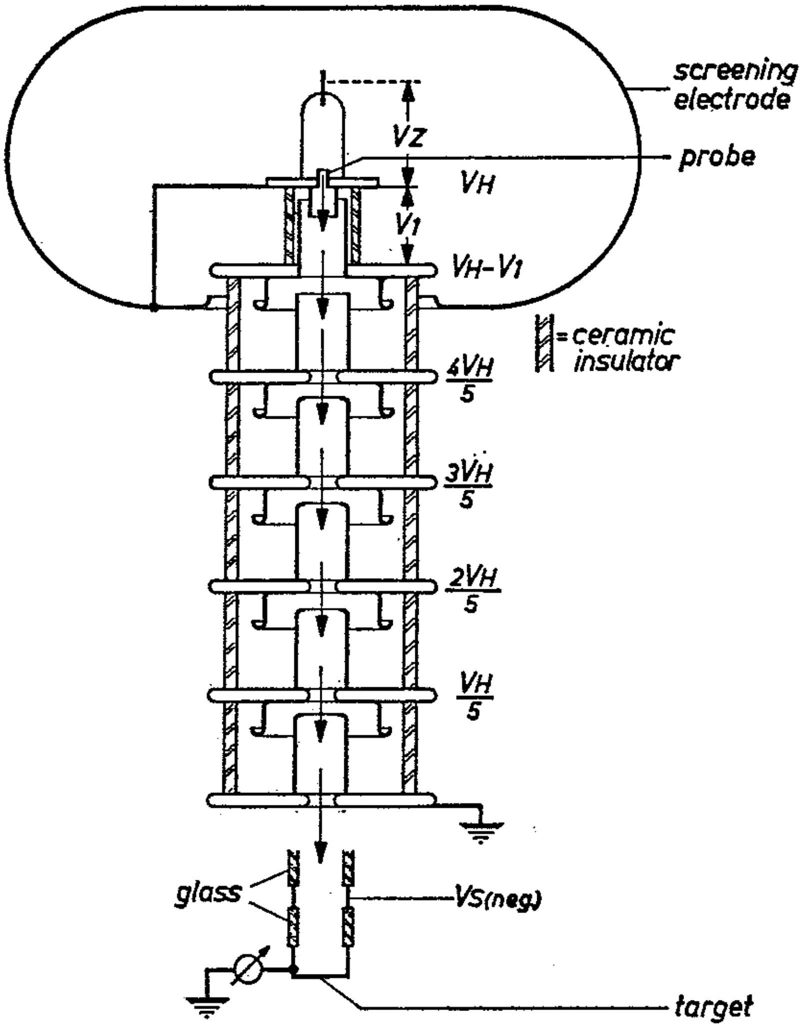


Fig. 214

Sketch of a Thonemann *HF* ion source with five-stage accelerating system for 1 MeV [108].

V_z = "Suction voltage" with respect to the probe.

V_1 = voltage across the first accelerator lens.

V_H = high tension of the cascade generator.

The probe is connected to the screen electrode, and thus has the voltage V_H. The ions leave the tube with a voltage $V_H + V_Z$. An electrode with a negative voltage V_S of a few hundred volts is situated above the target to reduce the emission of secondary electrons.

VIII-c-2 A SEALED-OFF TUBE AS NEUTRON GENERATOR

The increasing importance of neutron physics in science and industry has brought about a demand for suitable neutron sources. Those containing radioactive substances, e.g. Ra-Be and Po-Be generators, are simple in construction and easy to use, but they produce a complex neutron spectrum which often has a strong gamma background. Moreover, the intensity of the neutrons is limited and cannot be controlled.

The other types of neutron generators described above are rather elaborate, mainly because, as we have seen, a pressure difference must be maintained between the ion-source compartment and the accelerating space. The gas removed by pumping from the accelerating space must be continually made up for near the ion source. A controllable gas supply and a vacuum pump are therefore indispensible as auxiliary equipment, and this makes the whole installation rather difficult to move about.

Various attempts have been made to make this equipment more compact and if possible mobile. One important step in this direction would be getting rid of the vacuum pump, so that the generator could take the form of a sealed-off tube. As long ago as 1937, Penning showed in principle how this could be done [98]. The life of the Penning neutron generator was limited, as a result of gas clean-up in the electric discharge, and the neutron yield was not very large (about 10^5 per second), so the tube was never put to any practical use.

Of recent years, Reifenschweiler has carried out fundamental investigations in this field, which have led to the production of a tube which Philips has now put on the market and which we shall now proceed to describe.

Fundamental demands made on the construction

The gas pressure in all parts of a sealed-off neutron tube must naturally be the same. The arrangement of the electrodes in the ion source and the ion accelerator, and the voltages applied to them, must therefore be specially adapted to work at this pressure. The gas consumption in a sealed-off tube must be small or must be compensated for, so that the pressure remains within certain limits during the life of the tube.

The life is among other things determined by the durability of the target, which cannot be replaced when it is worn out in a tube of this sort.

We shall notice how these demands are met in the description of the various parts of the tube, given below.

The ion source

A good ion source for a sealed-off neutron tube should fulfil the following demands:

1. low gas pressure,
2. high ion current,
3. low gas clean-up,
4. large proportion of atomic ions,
5. low power,
6. reliability in continuous use,
7. long life,
8. simple and robust construction,
9. simple maintenance.

An improvement of the Penning ion source and of the accelerating system, combined with a gas reservoir (replenisher) which moreover allows the pressure to be adjusted, has led to a tube which satisfies nearly all these conditions [97]. The only condition which is not fulfilled is the fourth: only 5 % of the ions are atomic ions. In view of the fact that all the other conditions *are* fulfilled, however, this disadvantage has proved to be acceptable.

A small permanent magnet (Fig. 215a) is included in the tube. The magnetic field is parallel to and concentric with the axis of the tube. This field makes it possible to maintain a glow discharge at the low gas pressure in the tube (about 10^{-4}—10^{-2} mm Hg) with an electrode voltage of a few kilovolts. The gas pressure used is usually about 10^{-3} mm Hg. The anode consists of a hollow cylinder which is placed between the two sections of the cathode. The ignition voltage is about 1 kV.

One of the cathodes has the form of a soft-iron cup which encloses most of the discharge space. The bottom of this cup contains a hole or channel through which a large proportion of the ions can pass into the accelerating space.

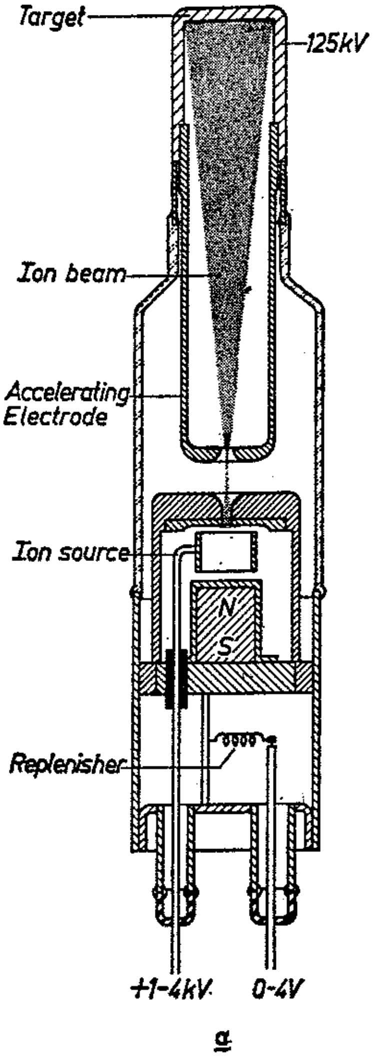
The magnetic lines of force pass through the soft-iron wall. This prevents a part of the magnetic field from continuing into the neighbouring accelerating space, where it might give rise to breakdown. Fig. 216 shows how the magnetic field strength decreases along the channel through the cathode, and that the accelerating space is completely free from magnetic lines of force.

The gas pressure can be controlled within wide limits by varying the current through a replenisher coil. This coil consists of a zirconium wire saturated with deuterium and tritium, wound round a tungsten support (cf. IV-b-5); it is placed behind the ion space. This wire gives off gas or absorbs it according to the voltage applied to it, in a way which has been described earlier; see Fig. 217 [97].

The gas pressure can be simply stabilized by allowing the ion-source current to control the replenisher voltage.

The accelerating space

After leaving the channel and having been accelerated, the ions enter the field-free space of the long accelerating electrode in the form of a narrow, slightly divergent beam of angle about 0.1 radian (Fig. 215a). The shape of the beam and the distance from the opening in the accelerating electrode to the target can be chosen so that the whole surface of the target is bombarded by ions. This is why the chrome-iron accelerating electrode is



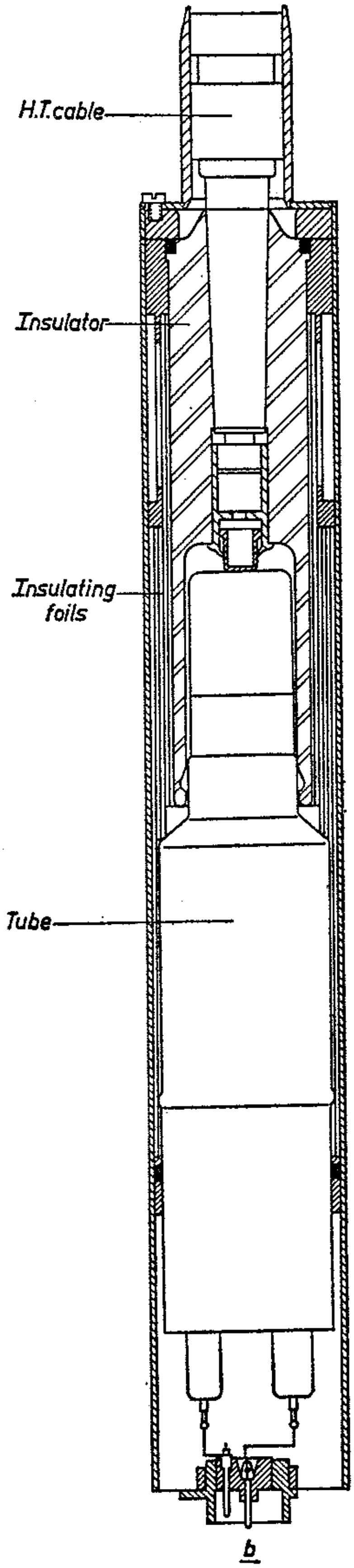


Fig. 215a

Cross-section of a sealed-off neutron-generator tube. *N-S* = permanent magnet which enables the ionization to be maintained at the very low gas pressure used in the tube. After having been accelerated, the ions enter the field-free space of the accelerating electrode as a divergent beam which strikes the target. The gas pressure can be controlled by means of the heater current of the replenisher.

Fig. 215b

hollow, while the shortest distance from it to the channel is only about 1 cm. Accelerating voltages of up to 200 kV are permissible in the gap with this construction, which also ensures that electrons produced from the target cannot get to the accelerating gap. The whole tube is enclosed in a metal sheath (Fig. 215b). Layers of plastic foil with oil are used as insulation between the tube and the metal sheath.

The target

Tritium targets which can be used in conventional neutron generators are on the market [101]. They consist of a silver disc about 0.2 mm thick, with a thin film of titanium or zirconium about 1 μ thick evaporated on to it. This film is then saturated with tritium.

The target should emit as many neutrons as possible when bombarded by the accelerated ions. The neutron yield is mainly determined by the accelerating voltage and the ion current. Since the temperature of the target may not exceed a certain limit (200 °C for Ti-T targets), care must be taken that the ions bombard the whole surface of the target; this also makes the loadability maximum. The special construction of the accelerating system takes care of this, as we have seen.

If only part of the target is bombarded, the temperature increases too much there, and the neutron yield drops.

Titanium targets have been found to be more temperature-resistant than zirconium ones. At a temperature of 200 °C, tritium is still not lost from a titanium target. Moreover, titanium produces relatively more neutrons than zirconium, because it captures the deuterons better.

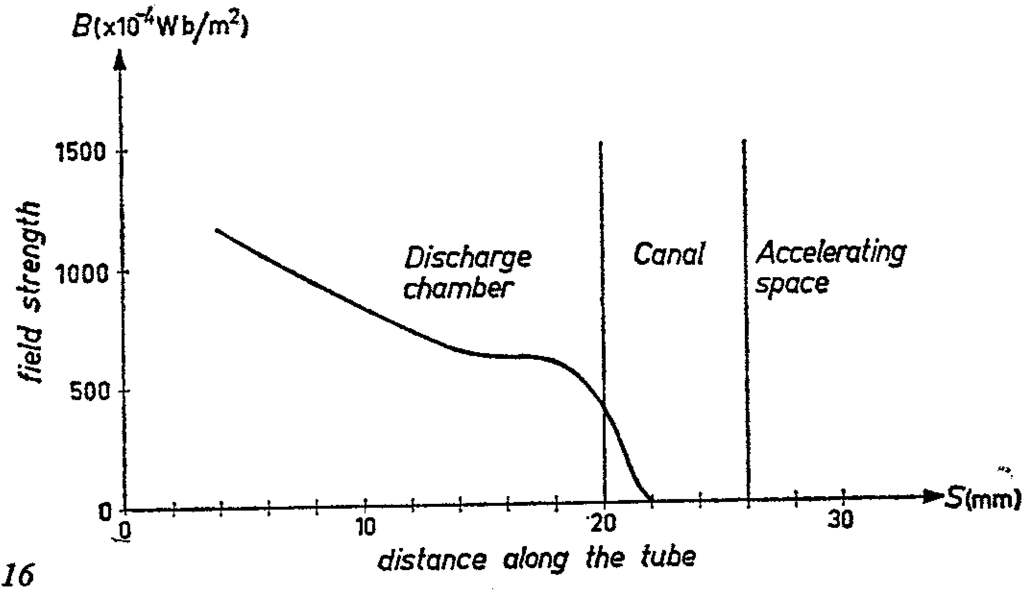


Fig. 216

Configuration of the magnetic field caused by the permanent magnet of Fig. 215a. The field is attenuated in the channel, and the accelerating space is completely field-free, as a result of which breakdown in the gas there is prevented.

If it was possible to make titanium targets which were able to make up their own loss of tritium, this would be a great step in the direction of a long life for the tube. Such a self-replenishing target for the DD reaction, the "drive-in target", has been thoroughly investigated by e.g. Fiebiger [102].

If a metal disc with a sufficiently low diffusion coefficient for hydrogen is bombarded with deuterons for long enough, it can be made into a deuterium target: the deuterons penetrate into the metal and spread by diffusion. If the deuteron bombardment continues, neutrons are produced by the DD reaction:

$$_1H^2 + {_1H^2} \rightarrow {_2He^3} + {_0n^1} + 3.265\ \text{MeV}.$$

If the bombardment is continued even further, the neutron production increases until a state of saturation is reached, when as many deuterons leave the target as reach it. Fiebiger found that gold gives the highest neutron yield under these circumstances, four times as much as titanium.

Following on from this, the conclusion was reached that if the tube was filled with half deuterium and half tritium, a simple self-replenishing target for the DT reaction

$$_1H^2 + {_1H^3} \rightarrow {_2He^4} + {_0n^1} + 17.6\ \text{MeV}$$

should be realizable, with a considerably higher yield than with the DD

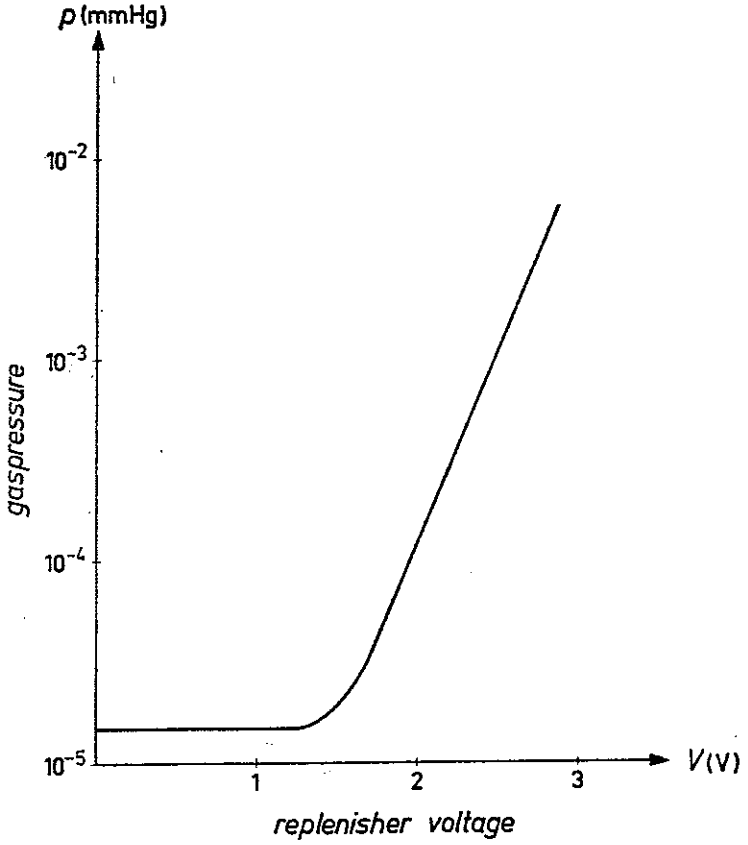


Fig. 217

Variation of the gas pressure as a function of the replenisher voltage in the tube of Fig. 215a.

reaction [97]. Once such a target was saturated, it should be able to keep working for the whole life of the tube; and the neutron production need not fall, as long as the replenisher compensates for the gas clean-up in the ion source.

It can be calculated that with the usual accelerating voltage the neutron yield of such a target will only be a third of that with a target of the same metal saturated with tritium and bombarded with deuterons. The advantages of long life and constant production more than compensate for this, however.

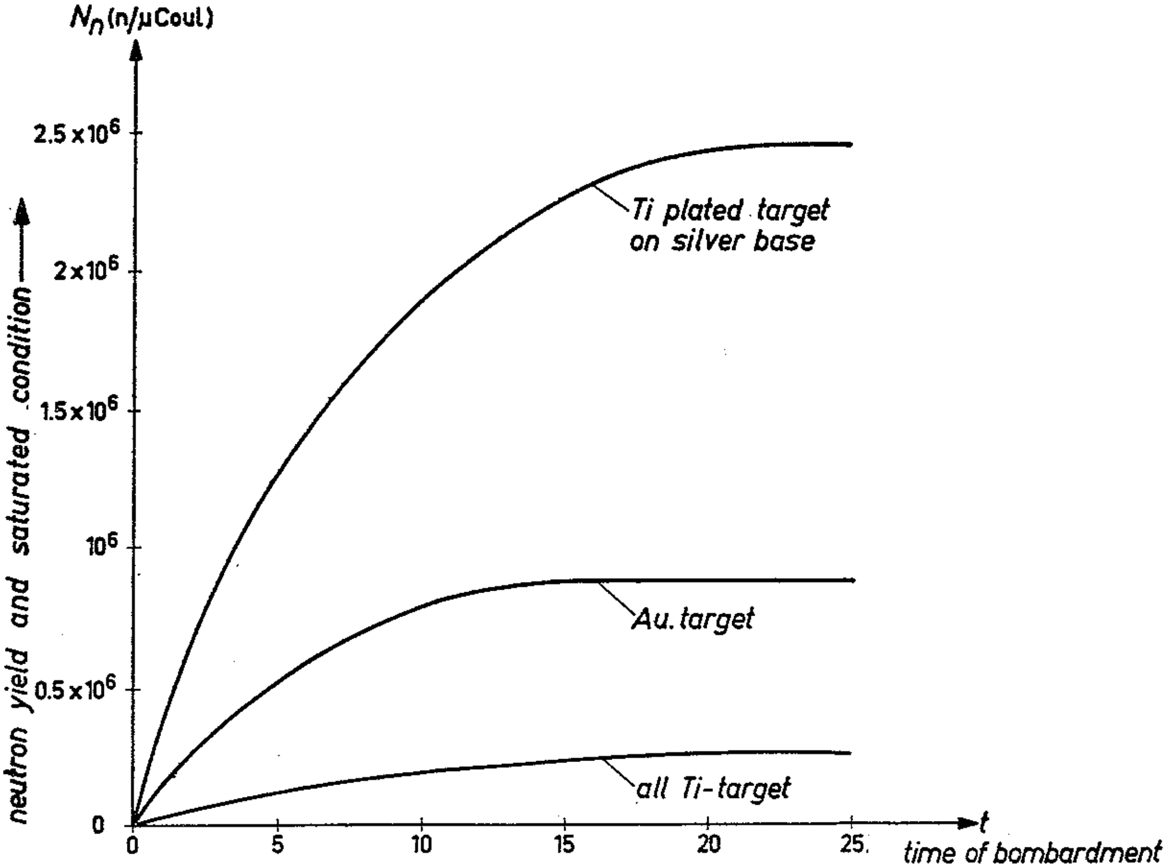


Fig. 218
Neutron yield N_n in neutrons per microcoulomb of some drive-in targets as a function of the time of bombardement.

The neutron yield of a gold disc in the saturated state was 8×10^7 n/sec with an ion current of 100 μA and an accelaration voltage of 125 kV.

A much better method is to use a thin film of material with a high diffusion coefficient for hydrogen and which can at the same time absorb hydrogen strongly, on a support with a low diffusion coefficient for hydrogen so that the hydrogen atoms cannot diffuse away. Titanium and zirconium are suitable for the top film. Since they have a lower atomic stopping power than gold, titanium-coated drive-in targets should give a higher neutron yield than gold ones with the same atomic ratio. A silver disc with a film of titanium about 1 μ thick on top was found to give a good yield. Fig. 218 shows the neutron yield of a titanium-coated silver target, a gold one and an all-titanium one, under the same conditions, as a function of the bombardment time.

Apart from the advantage of a higher neutron yield, self-replenishing titanium-coated targets can stand high temperatures better than plain gold ones: they can stand 200 °C, while the neutron yield of a gold target already falls of considerably at 150° C. Pumping the tube out at the normal temperature of 400—450 °C does a drive-in target no harm, because the bombardment needed to saturate it is not carried out until after the tube is sealed off.

The neutrons emitted by this target in all directions can pass through the walls almost without hindrance, and have an energy of about 14 MeV under the above-mentioned conditions.

The self-replenishing target goes on producing neutrons as long as there is gas in the tube, so that the life of the tube now depends largely on the replenisher.

Results

The neutron yield is determined from measurements on activated copper with the aid of Geiger-Müller counters. The experimental and calculated values for various accelerating voltages are shown in Fig. 219.

Curve 1 shows the calculated yield of a titanium/tritium target with an atomic ratio of 1 : 1, for bombardment with deuterons.

Curve 2 shows the calculated yield if the beam consists of molecular ions instead of atomic ions. At an accelerating voltage of 100 kV, the yield is about a third of that obtained with atomic ions (deuterons).

Curve 3 shows the calculated yield of a DT mixture in a titanium-coated self-replenishing target bombarded with molecular ions. Here again, the yield is about a third of that obtained with an "all-tritium" target bombarded with pure deuterium (molecular ions).

Curve 4 shows the measured yield of a conventional tritium target in a tube filled with pure deuterium.

Curve 5 shows the measured yield of a self-replenishing titanium-covered target in a tube filled with a DT mixture. It will be noted that the actual yield of such a target is nearer to the calculated value than for commercial targets. Targets of this sort give 2.4 — 3 × 10^8 neutrons per second at an accelerating voltage of 125 kV and an ion current of 100 μA, under which conditions the operation of the tube is very stable.

The generator described is capable of pulse operation if the ion-source voltage is applied pulse-wise. Pulses with a minimum duration of 5 microseconds can be produced in this way. With a duty cycle of 1 %, a maximum neutron yield of 3×10^{10} n/sec can be achieved during the pulse [106].

Applications

The sealed-off neutron generator described above enables the research worker to make radioactive isotopes of nearly all the elements of the periodic table, for use e.g. in biology and the medical sciences. Because of the short half life of many of these substances, it is a great advantage if they can be made on the spot. The mobility of the generator is useful here.

It can also be used in all sorts of fundamental work in nuclear physics, where a yield of 10^8 n/sec is sufficient. It is also useful for chemical analyses (activation analysis, geological investigations). It is especially useful for "oil-well logging" [99, 100], where it is used as follows: it is

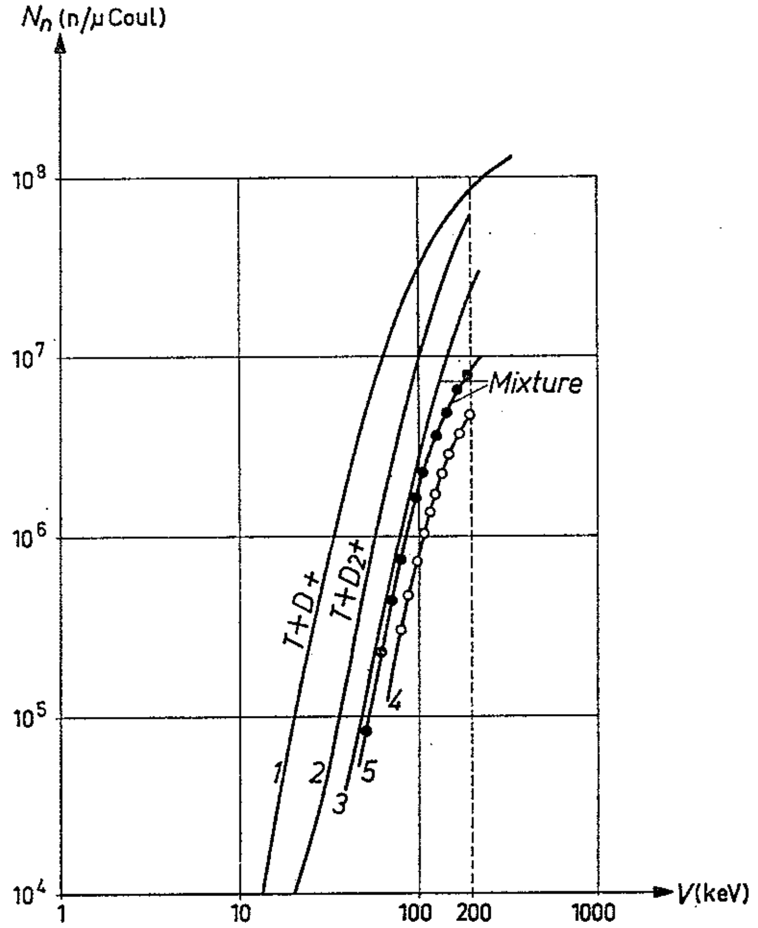


Fig. 219

Neutron yield N_n in neutrons per microcoulomb as a function of accelerating voltage V for some titanium targets. For further explication see text.

lowered down the borehole together with a radiation detector. Analysis of the scattered neutrons or of the gamma-radiation excited can show whether oil or natural gas is present.

We may also mention the important field of reactor physics, especially when it is used in pulse operation for the investigation of screening materials for neutrons. Finally, it is of great use in training neutron physicists.

The above list certainly does not exhaust all the possibilities, and many more uses will doubtless be found as these tubes are developed further.

PHYSICAL CONSTANTS

e = charge of an electron (1.6×10^{-19} coulombs)

h = Planck's constant (6.625×10^{-34} watt.second^2)

k = Boltzmann's constant (1.38×10^{-23} joule/°K)

SYMBOLS

a = anode
a_h = auxiliary anode

C_{ag} = anode-grid capacitance
C_{gk} = grid-cathode capacitance
C_{kh} = auxiliary cathode capacitor
C_p = parallel capacitance
C_t = triggering capacitor

$E(or\ F)$ = electric field strength

f = frequency or filament (heater)
$F(or\ E)$ = electric field strength
F_c = commutation factor
F_r = arc back factor

g = grid
ge = getter

i_{ahp} = peak current of auxiliary anode
i_{am} = crest value of sinusoidal alternating current
i_{ap} = instantaneous peak value of an alternating current
i_{ignp} = peak value of ignition current
i_{surge} = surge current
$i_{surge\ p}$ = peak value of a surge current
I_{ahav} = average current of auxiliary anode
I_{av} = average current
$I_{av\ max}$ = maximum average current
I_e = emission current
I_f = heater current or photo-electric current
I_g = grid current
I_{gem} = grid emission current
I_{gl} = glow current

I_h = auxiliary current
I_o = DC output current
I_{pr} = current through primary transformer winding
I_{rms} = *rms*-value of AC current
I_s = electron current density
I_{sat} = saturation current
I_t = trigger current

j = current density

k = cathode
k_h = auxiliary cathode

m = mass (electron)
M = mass (atom)

p = pressure of a gas
p_o = gas pressure reduced to O °C
p_r = priming electrode (primer)

q = multiplication factor (secondary electrons)

R_a = series resistance of the anode
$R_{a\ min}$ = minimum value of R_a
R_g = series resistance of the grid
R_I = resistance of ignition rod
R_k = series resistance of the cathode
R_{kh} = series resistance of the auxiliary cathode
R_o = ohmic load resistance
R_{prim} = resistance of primary transformer winding
R_s = series resistance
R_{sec} = resistance of secondary transformer winding
R_{sh} = shunt resistance
R_t = total ohmic resistance in the circuit or series resistance of the trigger
R_v = ballast resistance

$\left.\begin{matrix}S\\S_c\end{matrix}\right]$ = screen

t = time or temperature or triggering electrode (trigger)
t_{amb} = ambient temperature
t_{av} = averaging or integration time

$t_{de\ ion}$ = de-ionization or recovery time
t_f = preheating time of filament
t_{Hg} = temperature of mercury condensate
i_{ion} = ionization time
$torr$ = mm Hg
t_s = duration of surge current
t_w = warming up time

T = one period of an alternating voltage (current) or absolute temperature (in degrees Kelvin, $273 + {}^\circ C$)
T_e = electron temperature in $^\circ K$
T_o = room temperature in $^\circ K$
T_w = true temperature in $^\circ K$

v = velocity
$v_{ahp\ forw}$ = forward peak auxiliary anode voltage
$v_{ahp\ inv}$ = inversed peak auxiliary anode voltage
v_{am} = crest value of sinusoidal alternating anode voltage
$v_{ap\ forw}$ = forward peak anode voltage
$v_{ap\ inv}$ = inversed peak anode voltage
v_{gp} = peak value of grid voltage
v_m = most probable velocity of a gas

V_a = voltage at the anode or excitation voltage of atoms
V_a' = excitation voltage of metastable atoms
V_{aa} = DC anode supply voltage
V_{agl} = anode glow voltage
V_{arc} = arc voltage
V_{arms} = sinusoidal alternating anode voltage
V_b = battery voltage, counter voltage
V_{br} = burning voltage
V_d = breakdown voltage
V_f = filament voltage, heater voltage
$V_{f\ rms}$ = sinusoidal alternating filament voltage
V_g = voltage at the grid
V_{gcrit} = critical grid voltage
V_{gg} = DC grid supply voltage
V_{go} = quiescent value of grid voltage (zero excitation)
$V_{g\ rms}$ = sinusoidal alternating grid voltage
V_i(or V_{ion}) = ionization voltage
V_{ign} = ignition voltage
V_{ion}(or V_i) = ionization voltage

V_k = cathode fall
V_L = choke voltage
V_o = *DC* output voltage
$V_{p\,forw}$ = forward peak voltage
$V_{p\,inv}$ = inversed peak voltage
V_{pr} = voltage on primary transformer winding
V_{rms} = *rms*-value of *AC* voltage
V_s = (Geiger) threshold voltage
V_{sec} = voltage on secondary transformer winding
V_t = trigger voltage
V_{tt} = *DC* trigger supply voltage
V_z = ohmic and inductive voltage drop
$V_{=}$ = *DC* voltage

W_{arc} = energy losses in the arc
W_f = filament (heater) losses
W_g = power of grid circuit
W_{ign} = power of ignitor circuit
W_m = mean kinetic energy of gas particles
W_o = *DC* output power

X_L = inductive resistance of the choke

Z_a = anode impedance

α = Townsend's ionization coefficient ($= \eta \times F$) or ignition angle
γ = ionization coefficient (gamma effect)
ε = base of the natural logarithms (≈ 2.718)
η = ionization coefficient (per volt)
λ_e = mean free path of the electrons
μ = control ratio of a thyratron
ν = frequency (light or radiation)
φ = work function

AN ABSTRACT OF: THE TRON FAMILY

A dictionary of many well-known and not so well-known tubes and other electronic devices having a common suffix ‘tron’.
Compiled by W. C. White, General Electric Company,
Electronic Industries, Jan. 1946, p. 80-83 and p. 130-136,
completed with some other ‘tron’-tubes.

Gas-filled tubes

*) Excitron	A type of mercury pool tube containing a holding anode and a special form of starting electrode. *Excitron Mercury Arc Rectifiers*, O. K. Marti. Transactions AIEE, 1940; V. **59,** p. 927.
Gusetron	Sometimes called Gausitron. A mercury-arc pool tube. An insulated probe type electrode dips into the mercury pool to provide cyclic ignition. *A new form of Ignitor of Mercury Pool Tubes*, K. J. Germeshausen. Phys. Rev. Jan. 15, 1939, p. 228.
*) Ignitron	A pool tube with a single main anode in which an ignitor is used to initiate an arc spot on the cathode before each conducting period. *New Method of starting an arc*, J. Slepian, and L. R. Ludwig. Electrical Engineering, Sept. 1933; V. **52,** p. 605.
Kathetron (Cathetron)	A gas-content thermionic cathode triode having the grid external to the envelope. *The Kathetron – A control Tube with External Grid*, Palmer H. Craig. Electronics, March 1933; V. **6,** p. 70.
Neotron	A gas-filled tube designed particularly as a pulse generator. *Gas-filled Tubes as pulse generators*, F. J. G. van den Bosch. Electronic Engineering, April 1945, p. 474.
Permatron	A gas or vapor-content thermionic cathode diode. Cyclic anode current flow is initiated by a magnetic field change. *The Permatron and its application in Industry*, W. P. Overbeck. Electronics, April 1939; V. **12,** p. 25.
*) Phanotron	A hot cathode, gas or vapor content diode in which no means are provided for controlling the current flow. It is essentially a rectifying device. *Gas-filled Thermionic Tubes*, A. W. Hull, Transactions A.I.E.E., July 1928; V. **47,** p. 753.

Plomatron	A name suggested for the grid-controlled, mercury-arc rectifier. London Electrician. December 18, 1942, p. 669.
Pulsatron	A double-cathode, gas-filled triode. *Gas-filled Tubes as Pulse Generators*, F. J. G. van den Bosch, Electronic Engineering, April 1945, p. 474.
*) Sendytron	Japanese designation for a mercury-pool tube in which the arc is initiated by a high-voltage probe electrode. Electro-Technical Journal of Japan, August 1938; V. **2** No. 8, p. 180. See also Wireless Engineer; Nov. 1938, p. 641, No. 4609.
Strobotron	A cold-cathode discharge tube with control electrode designed to pass heavy currents for very short periods of time. Used for high-speed photography. *A cold-cathode arc discharge Tube*, K. J. Germeshausen and H. E. Edgerton. Electrical Engineering, July 1936, p. 790.
Takktron	A gas-filled, cold-cathode diode designed for the rectification of low-currents at high voltage. *A Portable Instrument for Measuring Insulation Resistance at High Voltage*, F. W. Atkinson and R. B. Taylor. Electrical Engineering, April 1945; V. **64**, p. 164. *Industrial Testing with High Voltage*, Electronic Industries, Nov. 1945, p. 106.
*) Thyratron	A hot-cathode, gas-content tube in which one or more control electrodes initiate, but do not limit, the anode-current except under certain operating conditions. *Hot Cathode Thyratrons*, A. W. Hull. Gen. Electric. Rev. April 1929; V. **32**, p. 213.
Trignitron	A trade name for a mercury-pool type of tube used in a welding control device sold by the Electronic Power Co., Inc., Electronics, July 1944, p. 58.
Alphatron	A particular form of ionisation tube used for measuring the degree of vacuum.
Capacitron	One form of pool cathode tube.
Cathetron	(See Kathetron).
*) Dekatron	A cold cathode gas-discharge counter tube.
*) Plasmatron	A thermionic gas-filled tube in which continuous control is exercised over the anode current.
Tacitron	A form of low-noise thyratron having a grid of special design so that the tube current can be interrupted by grid action.

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*) = discussed in this book.

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