NEW LOW PRESSURE GAS SWITCHES

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DECLARATION

I, Clifford Robert Weatherup, hereby certify that this thesis has been composed by myself, that it is a record of my own work, and that it has not been accepted in partial or complete fulfilment of any other degree or professional qualification.

Signed...

CERTIFICATE

I hereby certify that the candidate has fulfilled the conditions of the Resolution and Regulations appropriate to the Degree of Ph.D.

Signed...

to

Rachel, Robbie and Stephen

AUTHOR'S CAREER

The author was born in Toronto, Canada in 1956. His family returned to Ulster in 1960 and he received his primary education in Gleno and his secondary education at Larne Grammar School. He was awarded an Honours degree in the Physical Sciences in 1978 from the New University of Ulster, Coleraine. He commenced work in 1979 for the Gas Tubes Division at EEV Limited, Chelmsford, where he was involved in the production and development of glow modulators, flashtubes and hydrogen thyratrons. In 1985 he began work on the study described here. The work was funded by EEV and was carried out in their facility at the Gas Tubes Division. The author continues to be employed in the Gas Tubes Division of EEV.

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ABSTRACT

This thesis describes an investigation the aim of which was the development of low pressure gas switches with the advantages of zero standby power consumption and instant readiness. Hydrogen thyratrons use a hollow anode to give the switch a convenient reverse conduction capability. The hollow anode structure has been shown to pass a 4 kA pulse current at 500 Hz for 10^{10} shots. The use of the hollow anode structure as a cold cathode for a low pressure switch is proposed and triggering of the structure by ions is demonstrated. Under conditions of low gas pressure and high discharge voltage, electrons make few collisions in the cathode dark space of a glow discharge and form extensive beams which travel many centimetres in the gas. Current/voltage characteristics of this 'electron beam' type of discharge are presented for deuterium at pressures between 0.2 and 1.0 torr. The electron beam discharge was found to be space–charge limited with $I \propto V^{3/2}$ at pressures below about 0.25 torr and $I \propto V^2$ at pressures above about 0.25 torr. It is proposed that the current in the electron beam discharge is limited by the flow of positive ions in the cathode dark space. Control of the emission area of a discharge in a hollow metal cylinder is demonstrated and is used as a triggering method for a new type of low pressure gas switch. Tests in a pulse modulator at repetition rates up to 1 kHz show that the switch operates satisfactorily. The triggering mechanism is shown to depend on the properties of the cold cathode glow discharge which, in certain circumstances, leads to the unusual phenomenon of post trigger–pulse firing of the switch. The phenomenon is shown to result from the interaction of the trigger discharge cathode dark space and the geometry of the switch. The glow discharge electron beam is successfully applied as a triggering method in several new low pressure gas switches. In one arrangement, the electron beam is used to pre–ionise the switch and subsidiary grids are used to trigger main conduction. In another arrangement, the electron beam is directed into the high voltage region to trigger conduction directly. The designs of these switches are discussed and their operation is demonstrated.

CHAPTER ONE

The low pressure gas switch.

CHAPTER TWO

Electron beams in the glow discharge.

CHAPTER THREE

Glow discharge electron beam guns.

CHAPTER FOUR

The triggered hollow cathode switch.

CHAPTER FIVE

The e–beam triggered switch.

APPENDICES

CHAPTER ONE

The low pressure gas switch.

1.1 Introduction.

A low pressure gas switch is designed to exploit the insulating properties of neutral gas in the 'off' state and the conducting properties of ionised gas in the 'on' state, with the gas at a pressure in the region of 0.5 torr. The work presented in this thesis describes developments in the art of low pressure gas switching and draws mainly on the physics and technology used in the manufacture of hydrogen thyratrons. The hydrogen thyratron is the low pressure gas switch *par excellence*, and an understanding of its application, design and mode of operation provides the background to this study. Hydrogen thyratrons are used almost exclusively as switches in pulse modulators, where they have a long demonstrated ability to hold off voltages of 30 kV or more and to conduct currents in excess of 1 kA at repetition rates up to tens of kHz. The upper limits to the present capability of thyratrons are about 200 kV; 100 kA; 100 kHz. Note that these limits are not achieved simultaneously in one switch design. In fact, EEV Ltd. manufacture in excess of 300 types of thyratron, yet, every week or so, a customer will require a thyratron to a specification outwith any of the 300. Photograph 1.1 shows a small selection of the hydrogen thyratrons manufactured by EEV. The motivation for the work presented in this thesis is the requirement for low pressure gas switches with low or zero standby power consumption and instant readiness for operation. Traditionally, thyratrons have used thermionic cathodes to provide reliable emission for operating periods up to 10,000 hours. The surface that provides the emission is inherently delicate so operating the thyratron at high cathode current densities, or at high average current, may seriously reduce the cathode's useful life. It is possible that a cold cathode with its robust and relatively simple surface could extend the capability of low pressure gas switches. The use of a thermionic cathode in thyratrons has two disadvantages, which may be critical in applications where energy supply is limited and immediate readiness is of prime concern *ie.*, mobile systems and space systems. Depending on the thyratron type, its thermionic cathode may consume in excess of 500 W continuously. The thermal mass associated with the cathode heater may also impose a prolonged warm–up time of 5 minutes, or more, to attain the necessary operating temperature. The glow discharge techniques to be described in this thesis offer the possibility of a low pressure gas switch with no standby power consumption and instant start capability. In order to provide a context for the low pressure gas switch, the rest of this chapter will describe the applications, design and principles of operation of hydrogen thyratrons. Methods whereby the technology may be extended to provide new low pressure gas switches will also be discussed.

1.2 The pulse modulator.

A pulse modulator is an electrical system which provides pulses of electrical energy. In the pulse modulator, energy is transferred at low peak power from a source to an energy store. In response to a trigger signal applied to a switch, the energy is released to a load at high peak power for delivery to a target (Figure 1.1). This general principle has been applied for thousands of years in devices such as the bow and arrow, the crossbow and the catapult. Today, radars, lithotripters, lasers and linear accelerators are examples of electrical systems which employ the 'pulse' principle to deliver very high peak powers for detecting aircraft, pulverising kidney stones, ablatively machining semiconductor chips and destroying tumours. All of these systems use a particular type of pulse modulator which is described in the following section.

1.2.1 The line–type modulator.

The pulse modulator systems that are of concern for gas discharge switches (Figure 1.2) use a voltage–fed, capacitative–inductive network (lumped–parameter, transmission–line) for energy storage and pulse shaping, a switch to transfer energy on demand from the store to the load and an isolating element to limit both the rate at which energy is transferred from the source to the store and the degree of interaction between the charging and discharging circuits (Glasoe & Lebacqz, 1948, pp 175, 355). The behaviour of the discharge circuit depends upon the degree of mismatch between the effective load impedance and the characteristic impedance of the network. The circuit of Figure 1.1 shows the components of a 'line–type modulator' using a thyratron as a switch. The circuit consists of a charging side and a discharging side and both perform their function as a result of firing the switch.

1.2.1.1 The discharge circuit.

During normal operation of the modulator, the DC power supply voltage is V and the pulse–forming network (PFN) is charged to $2V$. At a given time, a voltage pulse is applied to the thyratron grids to initiate thyratron conduction. The voltage across the thyratron drops to a low value (~100 V) in tens of nanoseconds and the current pulse, defined by the parameters of the PFN, passes through the load. At the end of the current pulse, the thyratron is filled with a conducting plasma which persists until current zero and beyond and the thyratron will only recover its voltage hold–off capability when the plasma decays. The voltages appearing at the switch anode after conduction depend on the degree of impedance matching between the PFN and the load. When their impedances are matched, all of the energy in the PFN is transferred to the load. If their impedances are not matched, some energy will remain on the PFN at the end of the normal pulse duration and this usually results in the appearance of a positive or negative voltage on the switch anode. If the voltage is positive, the plasma will be maintained and recovery of voltage hold–off will be delayed. If the voltage is greater than a few kilovolts negative, the switch may conduct in the reverse direction with consequent damage to its anode (high–voltage region). In practice, the impedance of the PFN is arranged to give a slight negative mismatch so that a small negative voltage appears on the thyratron anode. This initiates a period of zero current in the switch and the voltage hold–off capability recovers in a few tens of microseconds.

1.2.1.2 The charging circuit.

The design of the charging circuit is determined both by the need for the switch to recover voltage hold–off and by the pulse repetition frequency that is required from the system. In addition, the power losses in the charging circuit are usually required to be kept to a minimum. As a result, the PFN of capacitance C is charged from the power supply via a charging choke of inductance L. The charging choke and the capacitance of the PFN form a resonant circuit of frequency

$$f = \frac{1}{2\pi\sqrt{LC}} \quad . \qquad 1.1$$

Charging with this circuit is known as resonant charging. In practice, a diode is included in series with the choke to hold the voltage on the PFN once it is charged. The system repetition frequency can then be varied up to a maximum of twice the resonant frequency given by equation 1.1. The circuit operation can be described as follows. Immediately after the thyratron switches on, its anode voltage falls to approximately one hundred volts. The charging choke then has the DC supply voltage V across it. A current grows at a rate

$$\frac{dI}{dt} = \frac{V}{L} \quad . \qquad 1.2$$

and begins to charge the pulse–forming network. Since the current is initially small it takes tens of microseconds to remove the negative voltage left on the PFN at the end of the thyratron current pulse (see §1.2.1.1). In effect, the charging choke acts as an isolating element (Figure 1.2) which allows the thyratron time to de–ionise after conduction. As charging continues, the current through the choke reaches its peak when the PFN is charged to V. With 'perfect' matching, the current continues to flow until the PFN is charged to $2V$, where it is held by the diode until the thyratron is triggered again.

1.2.1.3 The switch.

The range of switch technologies that can be employed in a line–type modulator is very wide (Burkes *et al.*, 1979). However, most high–power applications are covered now by three gas discharge switches, the spark gap, the ignitron and the thyratron. In order to be of use in a pulse modulator, the switch must isolate the voltage on the PFN from the load until the energy transfer is required. In response to an applied trigger signal, the switch must initiate conduction rapidly and provide a low impedance connection so as to minimise power dissipation. After transfer, the switch must recover its isolating condition so that the PFN may be recharged. In summary, a switch is required to:

(i) insulate high voltages;

(ii) switch on with precise timing;

(iii) conduct with small power dissipation;

(iv) recover its high voltage insulating properties rapidly.

In implementing the above four requirements, we recognise that the essential elements in a gas discharge switch are a cathode, a gas, an anode, and a means of triggering. An insulating envelope is included to support the electrodes and contain the gas at the required pressure. The geometry of the electrodes, their spacing and the gas pressure are arranged to provide a high voltage hold–off until the switch is triggered into its conducting state. When the switch is conducting, a plasma connects the cathode to the anode. At the end of the current pulse, the plasma recombines and the gas recovers its insulating properties. Voltage may then be applied to recharge the energy store in preparation for the next pulse.

The description above can be applied to two different categories of gas discharge switch, the high pressure switch and the low pressure switch. Spark gaps are high pressure devices, used widely for applications which require very high voltage hold–off (up to 1 MV) and high rate of rise of current. They operate satisfactorily at low repetition rates and because of the high energies involved are rarely called upon to do otherwise. The thyratron is a low pressure switch which can be used at voltages up to 200 kV. It can accommodate moderate charge transfer at high rates of rise of current up to 10^{11} A/sec, and may be triggered precisely at repetition rates up to 100 kHz. With this performance and versatility, the hydrogen thyratron is the most widely used gas discharge switch in pulse modulators for commercial, scientific and operational military systems. The design considerations that govern its performance are described below.

1.3 Hydrogen thyratron design.

The variety in hydrogen thyratron design can be seen in Photograph 1.1. The first designs used a glass envelope with the electrodes and grids made of high purity nickel. The ceramic thyratron uses alumina cylinders as the envelope with grid and anode structures in copper, and cathodes in high purity nickel.

A further development which takes ceramic thyratrons to the highest powers uses an envelope which is mostly metal with alumina sections for the high voltage gaps.

1.3.1 Voltage design.

The design of a thyratron is governed primarily by the requirements of Paschen's law (Paschen, 1889), according to which, the breakdown voltage of an electrode/gas system is a function of the product of pressure p, and electrode separation d as described by

$$V = f(p\,d) \quad . \qquad 1.3$$

The graph of this relation is of the form shown in Figure 1.3(a) and the breakdown voltage has a minimum at the pd value designated pd_{min}. On each side of pd_{min}, the breakdown voltage rises fairly steeply and it is thus possible to find two values of pd which give the same breakdown voltage. The shape of the curve can be explained in terms of the electron mean free path between collisions. To the right hand side of pd_{min}, the mean free path is much shorter than the electrode separation d and an electron loses energy in the many collisions it makes as it traverses the gap. As pd increases, the breakdown voltage increases. In order to cause breakdown, the applied voltage must be high enough to give an electron sufficient energy over one free path to make an ionising collision. Once this point is reached, the ionisation can multiply exponentially and many ions are created. The ions return to the cathode where they release secondary electrons and the processes constituting breakdown are established. To the left hand side of pd_{min}, the mean free path is greater than the electrode separation d, so an electron makes few collisions in crossing the inter–electrode gap. If breakdown is to occur under these conditions of low rates of collisional ionisation, the ions returning to the cathode must generate enough electrons by secondary emission to make up the collisional deficit and so sustain conduction. Thus, as pd reduces, the breakdown voltage increases. In summary, to the right of pd_{min}, gas processes dominate in determining the breakdown voltage. To the left of pd_{min}, a combination of gas and electrode surface processes are important. Moving further left, we arrive at the region of vacuum breakdown, where surface processes dominate in determining the breakdown voltage. These considerations are incorporated in the designs of thyratrons and spark gaps as illustrated in Figure 1.3(b). In the thyratron, which is filled with hydrogen to a pressure of about 0.5 torr, the high voltage hold–off is provided by the small inter–electrode spacing of about 3 mm, marked *low pd* in the diagram. Such a gap can hold–off a voltage of about 30 kV. In order to minimise the trigger–voltage requirement, the cathode/trigger–grid spacing, marked pd_{min} in the diagram, is set at about 15 mm. The right hand side of the Paschen curve is applied to the design of the envelope of the thyratron, which is usually in atmospheric air, and the high voltage electrode must have a spacing of about 3" from other electrodes.

Although the high and low *pd* regimes both result in high voltage hold–off, they give rise to different behaviour when the discharge is triggered. The discharge behaviour is related to the ionisation coefficient η, whose variation with E/p is shown in Figure 1.4. Note that, in Figure 1.4, spark gaps operate to the left of the maximum and thyratrons operate to the right of the maximum. On the high pressure, left hand side of Figure 1.4, breakdown is initiated by electron avalanches which propagate across the high voltage gap (Raether, 1964; Williams & Peterkin, 1989). Further current conduction through the ionised path causes heating. Since the gas density reduces with temperature, E/p, and therefore η, increases and the discharge concentrates into a channel, with conduction taking place at high current density from a very small area of the cathode. The concentration of energy on a small area of the cathode causes cathode material to evaporate. The metal vapour usually has a lower ionisation potential than the gas, and so a metal vapour arc develops and is maintained throughout the discharge. On the right hand side of Figure 1.4, the discharge develops as a uniform glow rather than a discrete arc channel. Any localised heating tends to reduce the gas density in that area and E/p increases, leading to a decrease in η, which acts to oppose the concentration of current to a small area of the cathode. The glow therefore fills the inter–electrode gap and covers the cathode and anode surfaces so that the surface current densities are much less than is the case with arc conduction. The result is that evaporation of electrode material plays little part in the glow discharge conduction processes of the thyratron.

We have seen that gas discharge switches fall into two categories depending on how voltage hold–off is achieved. To the right of the Paschen minimum, where *pd* values are large, we find the region of the spark gap. Here the discharge takes place in the arc mode as described above. To the left of the Paschen minimum we have the region of the thyratron with conduction usually taking place in the glow mode.

1.3.2 Cathode design.

The cathode surface in a hydrogen thyratron forms the interface between metallic and gaseous conduction in the discharge circuit and the electrons of the main current pulse are emitted through it. Figure 1.5(a) reminds us of the electron energy distribution in a metal. The saturation current density, J_S, available from the cathode is given in A/cm^2 by,

$$J_S = 120\, T^2 e^{-\frac{11600\,\phi}{T}} \quad , \qquad 1.4$$

where ϕ is the work function in electron volts at the operating temperature, T. Because of the variation in ϕ with temperature it is customary to express it as

$$\phi = \phi_0 (1 + \alpha T) \quad , \qquad 1.5$$

where α is the temperature coefficient of the work function ϕ_0.

Equation 1.4 thus becomes

$$J_S = (120\, e^{-11600\,\alpha\,\phi_0})\, T^2\, e^{\frac{-11600\,\phi_0}{T}} \quad . \qquad 1.6$$

It is usual to calculate J_S by using ϕ_0 and the bracketed constant which is designated A. For tungsten at a temperature of 2520 K with $A = 80$ and $\phi_0 = 4.54$, the value obtained for J_S is 0.4 A/cm^2. For a thyratron cathode, this emission current density is too low and the operating temperature too high to be useful. In order to supply the currents demanded from a thyratron cathode at temperatures below 1500 K, it is necessary to find a 'low temperature' cathode with an emission density in excess of 10 A/cm^2. From equation 1.4, large increases in J_S can be obtained if the work function can be reduced. Methods for achieving a lower value of work function are discussed in the following paragraph.

Figure 1.5(b) shows the potential close to the surface of a clean metal in vacuum. The height of the potential barrier, and thus the effective work function, can be reduced by application of an external positive field. Unfortunately, in a practical cathode, it is not convenient to implement schemes where such a field could be applied. However, changes to the effective work function of the cathode surface may also occur as the result of the adsorption of a monolayer of foreign atoms or molecules. When the adsorbed layer is electropositive with respect to the substrate, its atoms become polarised with their positive charges outwards and the effective work function is reduced, as shown in Figure 1.5(c). The magnitude of the reduction in potential, V', depends on the charge separation, d and the number, n, of adsorbed particles so that,

$$V' = \frac{n\,e\,d}{\varepsilon_0} \quad . \tag{1.7}$$

For a typical value of $n = 10^{14}$ atoms/cm^2 and d of the order of the atomic radius, V' may be as much as 3 eV (Jenkins, 1969). The work function of various types of atomic layers on tungsten is given in Table 1.1. Before going on to describe practical thermionic cathodes as used in thyratrons, it is worth noting that the presence of an electronegative layer on the cathode surface can have precisely the opposite effect to that described above. In the electronegative case, Figure 1.5(d), the layer is polarised with the negative charges away from the cathode and the effective work function is increased by V'. In practice, electronegative contamination is likely to result from the chloride ions transferred in fingerprints. Other electronegative contaminants may be deposited from the residual atmosphere in the assembled device, with oxygen, water vapour and carbon dioxide being the possible sources.

Although Table 1.1 indicates that a large reduction in work function can be achieved by applying a layer of say, barium, to a tungsten surface, such an approach does not directly offer a useful cathode, since the layer can be disrupted by evaporation and ion bombardment. As a result, practical cathodes based on the monolayer principle described above, depend on an internal reservoir of the active material to replenish the surface monolayer. For thyratron use, these 'dispenser' cathodes take two forms, the impregnated cathode and the 'L' cathode. The widely used impregnated cathode consists of a porous tungsten cylinder with barium calcium aluminate in the pores. The tungsten cylinder is formed from milled powder, isostatically pressed to a density of about 70% and machined to size. The porous cylinder and the impregnant are heated to about 2000 K and the now molten impregnant is drawn into the tungsten matrix by capillary action. The impregnant is usually a 5:3:2 mix of barium, calcium and aluminium oxides. In order to release the barium and calcium, the cathode is 'activated' by heating under vacuum. After initial outgassing at about 700 K, the temperature is raised to about 1400 K and barium is produced in the matrix, probably by the reaction,

$$6(Ba\,O)_3Al_2O_3 + W \Rightarrow Ba_3WO_6 + 6(BaO)_2Al_2O_3 + 3Ba. \qquad 1.8$$

The production of free barium is also assisted by establishing a discharge to the cathode so that it receives a bombardment by hydrogen ions. The free barium is a vapour at the operating temperature of the cathode and it moves through the tungsten matrix by a process of Knudsen flow to coat the outer surface with a monolayer for which ϕ is about 2 eV. The process of replenishment of the monolayer continues through the life of the cathode. The 'L' cathode, named after its inventor Lemmens, has a porous tungsten shell in the form of a disc or cylinder, which covers a cavity in a molybdenum support structure. The cavity contains a mixture of the oxides of barium, strontium and calcium. If the carbonate is used, it must be decomposed to the oxide by careful heating while under vacuum. Activation in the 'L' cathode depends on the reaction,

$$6BaO + W \rightarrow Ba_3WO_6 + 3Ba. \qquad 1.9$$

The free barium flows through the tungsten cap and coats its surface as described earlier. The designs of both types of cathode, including the heater and heat shield arrangement are shown in Figure 1.6.

It remains now to describe the most widely used of all cathodes, the 'oxide' cathode. This type of cathode was developed by Wehnelt in 1903 and it consists of a matrix of barium, strontium and calcium oxides on a nickel substrate. Its surface can have a work function of about 1.5 eV at 1000 K and this gives it the advantage of producing an equivalent emission at a lower temperature than the dispenser cathode. In spite of the passage of almost 90 years since its discovery, the processes by which a successful oxide cathode operates are still not fully understood. However, the most probable explanation is that the oxide is an n–type semiconductor with barium as the donor. Thermionic emission would also follow a Richardson–Dushman equation (Jenkins, 1969). The oxide layer is laid on the surface of the cathode in a carbonate form and processing consists of outgassing, decomposition of the carbonate to oxide, and then reduction of some of the oxide to barium. In the thyratron case, this reduction is accomplished by bombardment of the cathode surface by hydrogen ions and activation thus proceeds from the surface inwards. The whole process involves a considerable degree of care since the decomposition and reduction products are water vapour, carbon dioxide and oxygen and the deleterious effect which these electronegative gases can have on the cathode surface has already been described. A further complication in processing any cathode heated by a tungsten filament, is that the incandescent filament, in the presence of water vapour, invariably suffers from progressive oxidation of the tungsten heater, since water vapour is decomposed on the filament, volatile tungsten oxide is evaporated, the tungsten oxide condenses on any nearby cooler surface and releases its oxygen, which then recombines with free hydrogen to complete the cycle. Tungsten heaters which are exposed to water vapour in this way can easily be reduced in diameter by 20% in a few hours and are rendered useless. A processing schedule for 'activating' cathodes is therefore designed to ensure that the partial pressure of water vapour is reduced to below 10^{-6} torr before the filament is allowed to reach its operating temperature.

The conditions under which a cathode must operate are somewhat different in the thyratron than in a vacuum device. In the thyratron, emission is required in short pulses, which tends to allow higher emission current densities than DC, but the main difference is that the thyratron cathode is required to operate in a gas discharge rather than in vacuum. The ions in the gas discharge are accelerated through several hundred volts across a thin sheath in front of the cathode surface when large current pulses are being conducted. The result of this ion bombardment is likely to be the removal of barium atoms from the surface monolayer and a degradation in the cathode emission. On the benefit side, the neutral gas atoms/molecules have the effect of reducing barium evaporation from the surface of the cathode, thereby prolonging its life as an active emitter. In addition, ions and photons from the glow cause a large increase in the effective cathode emission density compared with the value of J_S calculated from equation 1.6. In the oxide cathode, the hydrogen ion bombardment from the thyratron discharge creates dislocations in the oxide structure which also enhance the emission capability (Abroyan & Movnin, 1961). In order to make an estimate of the emission enhancement achieved in the thyratron, one further piece of information needs to be considered. Recent tests at EEV have established that the cathode heat shield structures of Figure 1.6 contribute up to about 50% of the total pulse current drawn from the cathode region. Assuming that 50% of the pulse current is emitted from the cathode, we can state that the emission current density achieved from an oxide cathode is about 100 A/cm^2 and from a dispenser cathode about 300 A/cm^2. If the cathode emission is non–uniform, these estimates could be exceeded by a factor of 3–5 on some of the cathode area.

1.3.3 Trigger design.

All gas discharge switches are triggered by the introduction of free charges into the voltage hold–off region. The charges are rapidly accelerated by the field in the high voltage gap, and collisions result in the growth of ionisation to provide a self–sustaining discharge between cathode and anode. The free charges introduced can be in the form of an electron or ion beam or a plasma. The usual method is to use plasma by creating a secondary discharge close to the high voltage region. Free charges can then diffuse into the high voltage gap through suitable apertures. Once the thyratron is conducting, the grid loses control since a negative–going pulse to the grid merely causes it to develop a larger positive ion sheath, thus cancelling the applied potential. The thyratron cannot, therefore, be switched off until the anode voltage has fallen below zero and the plasma has recombined. In a conventional thyratron (Figure 1.7), voltage hold–off is obtained by locating a baffle structure close to the anode. The baffle structure or part of it may be used as a trigger grid and it must also include apertures to allow the passage of main discharge current. Subsidiary trigger grids are often located just below the baffle apertures.

The first requirement in designing the grid region is to prevent the deposition of low work function cathode materials onto surfaces which are exposed to the field in the anode gap. This is accomplished by baffling the cathode so that any direct path to the grid apertures is obstructed. Preferably, the thyratron has two trigger grids (Figure 1.7), driven by seperate trigger voltages. The trigger voltage applied to grid 1 may be DC or pulsed, but must not initiate the main discharge current on its own. The trigger voltage applied to grid 2 must be in the form of a fast-rising pulse which creates sufficient ionisation so that electrons move into the anode field. At this point in the triggering cycle, the geometry of the aperture design becomes important (Menown, 1960). As Menown points out, a compromise must be struck between an open grid aperture and an obstructed grid aperture. The open aperture allows significant anode field penetration, and the longer path for electron acceleration in the anode field greatly assists the rapid initiation of conduction. The obstructed aperture has a shallow anode field penetration and deionisation in the grid slot rapidly isolates the anode from the post-conduction plasma in the cathode region, thus ensuring rapid recovery of voltage hold-off capability. Menown's preferred arrangement was an annular slot with staggered baffles beneath it, which gave an increase in the rate of anode voltage fall of about 30% compared with earlier designs. The recovery time of the annular slot design is improved by the addition of a negative bias voltage to the grid 2 and a recovery time close to 10 µsec can be achieved, which is adequate for most applications.

1.4 Hydrogen thyratron operation.

The electrode waveforms for a typical glass thyratron (Figure 1.7) operating in a radar modulator are shown in Figure 1.8. In the "off" state the thyratron has a voltage hold–off of up to 40 kV. In this case, conduction is initiated by pulsed discharges to grids 1 and 2, with voltage waveforms as shown in Figure 1.8. The grid 1 is fired first and creates a high current plasma in the cathode region. A few hundred nanoseconds later, a fast, high voltage pulse is applied to grid 2, and the plasma moves into the high voltage region. At this time a voltage spike appears at the grid and it is considered to mark the onset of anode conduction. The voltage on the anode falls while the current begins to rise in a period known as the commutation phase (Figure 1.8). The anode voltage reaches a low value in the region of 100 V and this level is maintained for the duration of the current pulse. At the end of the current pulse, the external circuit applies a small negative voltage to the thyratron anode and the post–conduction plasma begins to recombine. The thyratron can withstand the application of positive voltage as soon as the anode field penetration region has de–ionised and at this point the thyratron has recovered. The recovery period can be as short as 3 μsec, after which voltage can be applied to the PFN in preparation for the next pulse. Each modulator application imposes particular requirements on the performance of the thyratron. For example, the kicker magnets used to direct pulsed beams in particle accelerators must be driven with precise timing by a current pulse with a short rise–time (Fiander *et al.*, 1978). Thyratron performance parameters and the testing required to establish them, are defined in British Standard BS9014, extracts of which are reproduced in Appendix A. The timing parameters of the thyratron are briefly described below. The anode time delay, t_{ad}, is the interval between the application of the trigger pulse and the start of switch conduction. British Standard BS 9014 (Appendix A) defines t_{ad} more precisely as the interval between the 26% point on the unloaded grid waveform and the onset of anode conduction as indicated on the grid waveform by the presence of a fast oscillation called the grid spike (Glasoe & Lebacqz, 1948, p 352). In a conventional thyratron, t_{ad} represents the time taken for the cathode–grid discharge to develop and for electrons in the grid plasma to find their way to the high–voltage region through the grid slots. The time taken for the plasma to reach the grid slots is 40 nsec as calculated on the assumption of ambipolar diffusion. This value is consistent with the measured t_{ad} of 100 nsec in a typical thyratron. Temperature variations at the cathode and electrode structures in the period shortly after the start of operation can cause a drift in the switching delay and this drift is designated Δt_{ad}. Variation in t_{ad}, which results from the statistical behaviour of the emission and gaseous conduction processes and their interaction with varying electric and magnetic fields, is called time jitter and is designated t_j.

The emission and conduction processes in a hydrogen thyratron are critically dependent on the maintenance of precise operating temperatures at the cathode surface and in the titanium hydride capsule which acts as a gas reservoir. Specifications for the heater voltages, heater currents and envelope cooling arrangements are included in the EEV Product Data (EEV, 1989). In all cases, optimum switch performance is obtained when a tetrode thyratron is supplied with separate trigger pulses to grids 1 and 2, with the pulse to grid 2 delayed by several hundred nanoseconds. A data sheet describing the capability of the CX1625 thyratron is included in Appendix A. The CX1625 has been tested under demanding conditions by McDuff and Rust (McDuff & Rust, 1985). They used a modulator similar to that illustrated in Figure 1.9(c), designed to drive a XeCl laser. Such a modulator design has two features which extend the thyratron towards the limit of its operating range. Firstly, the rate of rise of current at 10^{11} A/sec, is about 10 times higher than that normally encountered in a radar or linac modulator (Figure 1.9(a)). This means that significantly large currents are passing through the switch while the anode voltage is falling. During this commutation phase, conduction is in the form of a high energy electron beam originating at some point in the grid aperture annulus and terminating at the anode disc. There is thus a high yield of heat, X–rays and evaporated material from the point of impact of the beam. In the case of prolonged operation at low gas pressure, the beam has been known to machine a hole or slot in an anode consisting of a molybdenum disc of thickness 2 mm. McDuff and Rust have demonstrated that the use of an optimum trigger system can allow the CX1625 to operate at high rates of rise of current for $2 \cdot 10^9$ pulses or more. The second feature of the XeCl modulator is that the laser load has a time–varying impedance which falls to a value below 1 Ω in the period of the pulse. This invariably means that the discharge circuit is under–damped and a large reverse voltage appears on the thyratron anode immediately after the forward current pulse. Unfortunately, the thyratron has a poor reverse hold–off capability in the presence of the post–conduction plasma. Reverse conduction is thus an inevitable consequence of operation in an under–damped circuit and it causes extensive and, eventually, fatal damage to the anode region of a normal thyratron. EEV developed a method to overcome this limitation as reported by Menown and Neale (Menown & Neale, 1978). The method depends on a cavity in the anode, which becomes filled with plasma during forward current conduction. When the anode voltage reverses, ionisation is already established in the cavity and the reverse current is conducted using the anode cavity as a hollow, cold cathode. As demonstrated by McDuff and Rust (McDuff & Rust, 1985), the CX1625 anode structure conducted $2{\cdot}10^9$ reverse current pulses, each with a peak value of 4 kA. This performance would seem to indicate that the structure used for the hollow anode could be used to form the cathode of a low pressure gas switch. Further evidence of its capability is presented in the following section.

1.5 The cold hollow cathode.

We are now ready to consider the design of a cold cathode for a low pressure gas switch. As indicated in the previous section, the hollow anode structure developed at EEV has been shown to function as a cold cathode at low pressure. A number of results of hollow anode thyratron operation have been published and these results show the ability of the hollow anode to conduct large pulse currents and to sustain operation for a large number of shots. McDuff and Rust (McDuff & Rust, 1990) update the CX1625 operating endurance to 10^{10} shots, with 4 kA reverse current at 500 Hz. Weatherup (Weatherup, 1984) reports a 4 kA, 15 μsec reverse current pulse in a narrow (< 3 mm) cavity. Fiander *et al.* (Fiander *et al.*, 1985) report a kicker magnet modulator in which the hollow anode of a CX1671 multi–gap thyratron conducted a 2500 A, 2 μsec reverse current pulse for $30 \cdot 10^6$ shots. Menown *et al.* (Menown *et al.*, 1986) record tests with a CX1625 thyratron in which the peak reverse current was about 16 kA. On the basis of this reported performance, we can conclude that a hollow metal cavity of appropriate internal dimensions can provide pulse currents of tens of microseconds, up to tens of kiloamps at repetition rates in excess of 500 Hz for 10^{10} shots, and that such a cavity could provide a useful cathode for a low pressure gas switch.

1.6 New low pressure gas switches.

In order to use the cold hollow cathode in a low pressure gas switch, it is necessary to find a reliable means of triggering it into conduction. In a thyratron with a hollow anode, reverse conduction is initiated by the post–conduction plasma which is still present in the anode cavity when voltage reversal occurs. For a triggered switch, some other method is required. Fiander *et al.* (Fiander *et al.*, 1985) observed that the CX1671 thyratron could conduct a reverse current pulse in the absence of a preceding forward current pulse if a trigger pulse was applied to the thyratron shortly beforehand. This unusual phenomenon was confirmed in a CX1154 thyratron whose design is shown in

Figure 1.10. It was operated in a test modulator with a circuit similar to that of Figure 1.9(a). It was connected 'upside down', with the hollow anode structure at earth potential and the cathode and grids at 25 kV positive and the electrode labelling in Figure 1.10 indicates the polarity of the electrodes during these tests. Isolating transformers were used to provide heater power and trigger pulses to the cathode–grid region. The cold hollow cathode was observed to conduct forward current pulses reliably in response to trigger pulses as shown in Photograph 1.2. It is apparent that conduction from the hollow cathode is initiated by trigger plasma ions which diffuse into the grid slots by ambipolar diffusion. The process is identical to that occuring in a normal thyratron except that ions (not electrons) are accelerated across the high voltage gap to initiate conduction.

The switch designs to be investigated in this thesis use a cold, hollow cathode for main current conduction. The processes occuring during main current conduction are described by cold cathode glow discharge theory. In addition, certain properties of the glow discharge are utilised as triggering methods for the switches. The following chapters therefore discuss glow discharge theory and describe glow discharge phenomena that can be applied to switch triggering. The construction and testing of several new switches is described.

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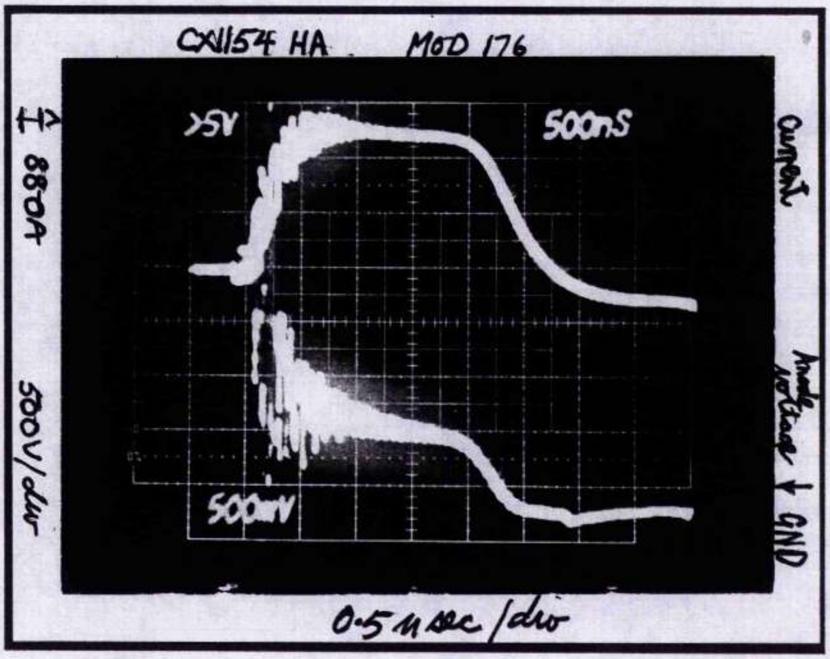
Table 1.1

Work functions of different atomic layers on tungsten.
(after Kohl, 1967, p 498)

Atomic layer	ϕ_0 (eV)
Zirconium	3.1
Thorium	2.7
Cerium	2.7
Barium	1.6
Cesium	1.5
Oxygen–Cesium	1.4
Oxygen–Barium	1.3

Photograph 1.1

A selection of the 300 thyratron types produced by EEV Ltd.



Photograph 1.2

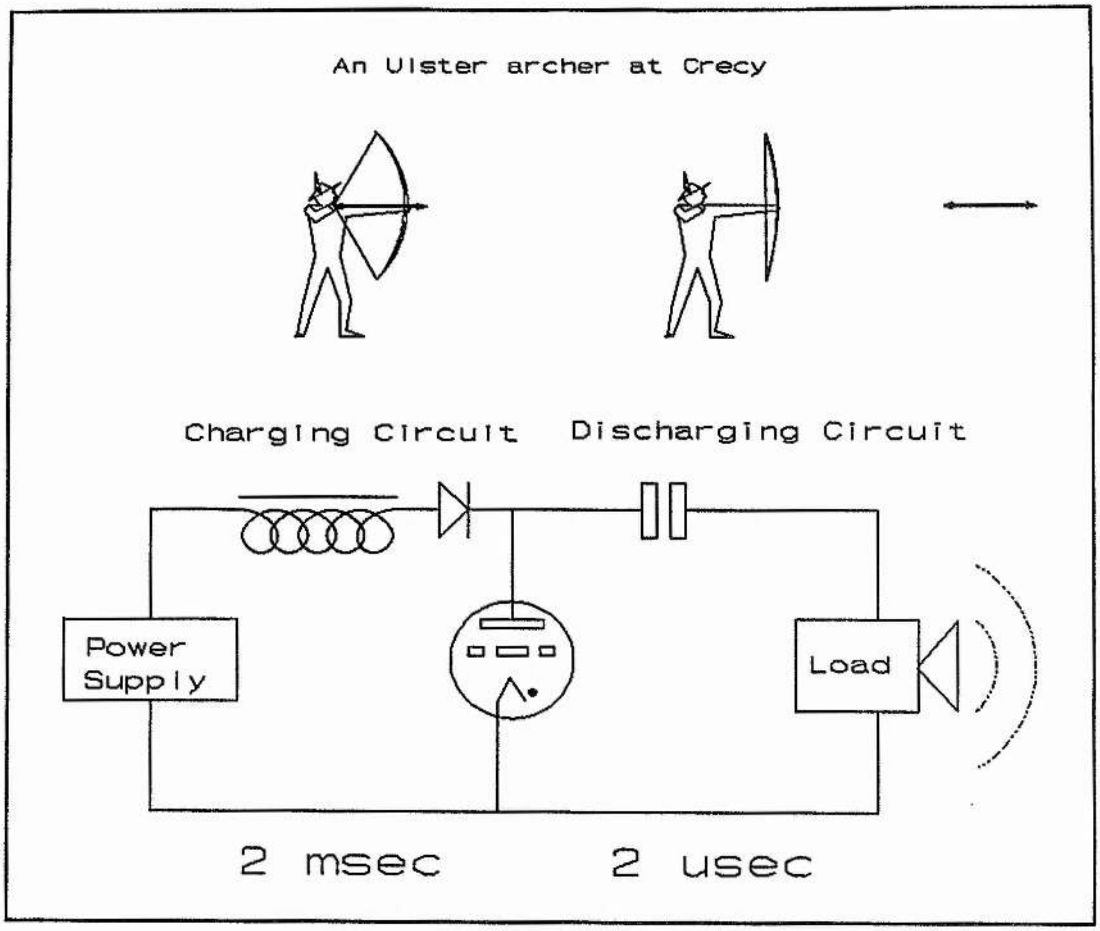


Figure 1.1
The pulse modulator principle. The peak power delivered by the power supply is multiplied by a factor of 1000 at the load.

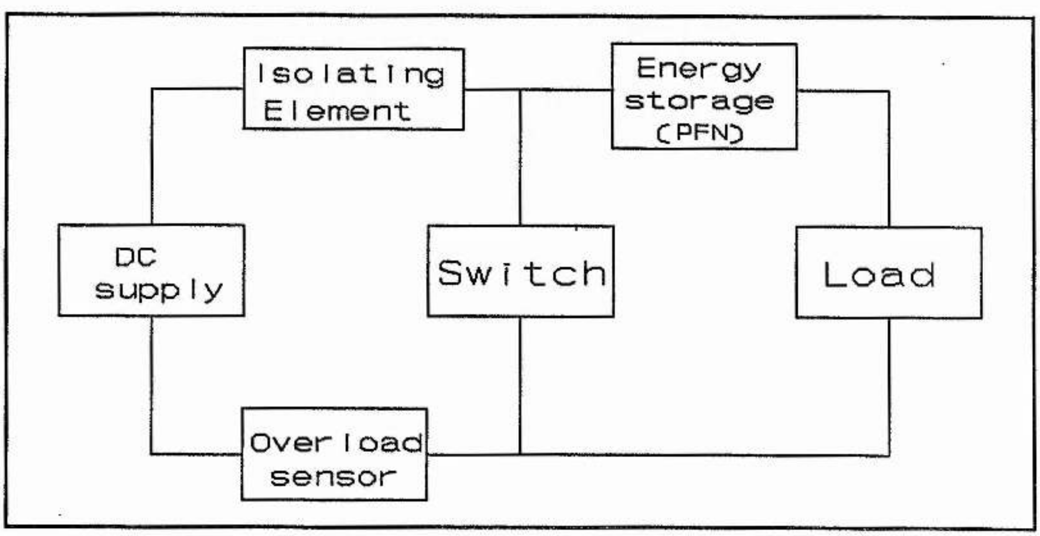


Figure 1.2
Block diagram of the line-type modulator.

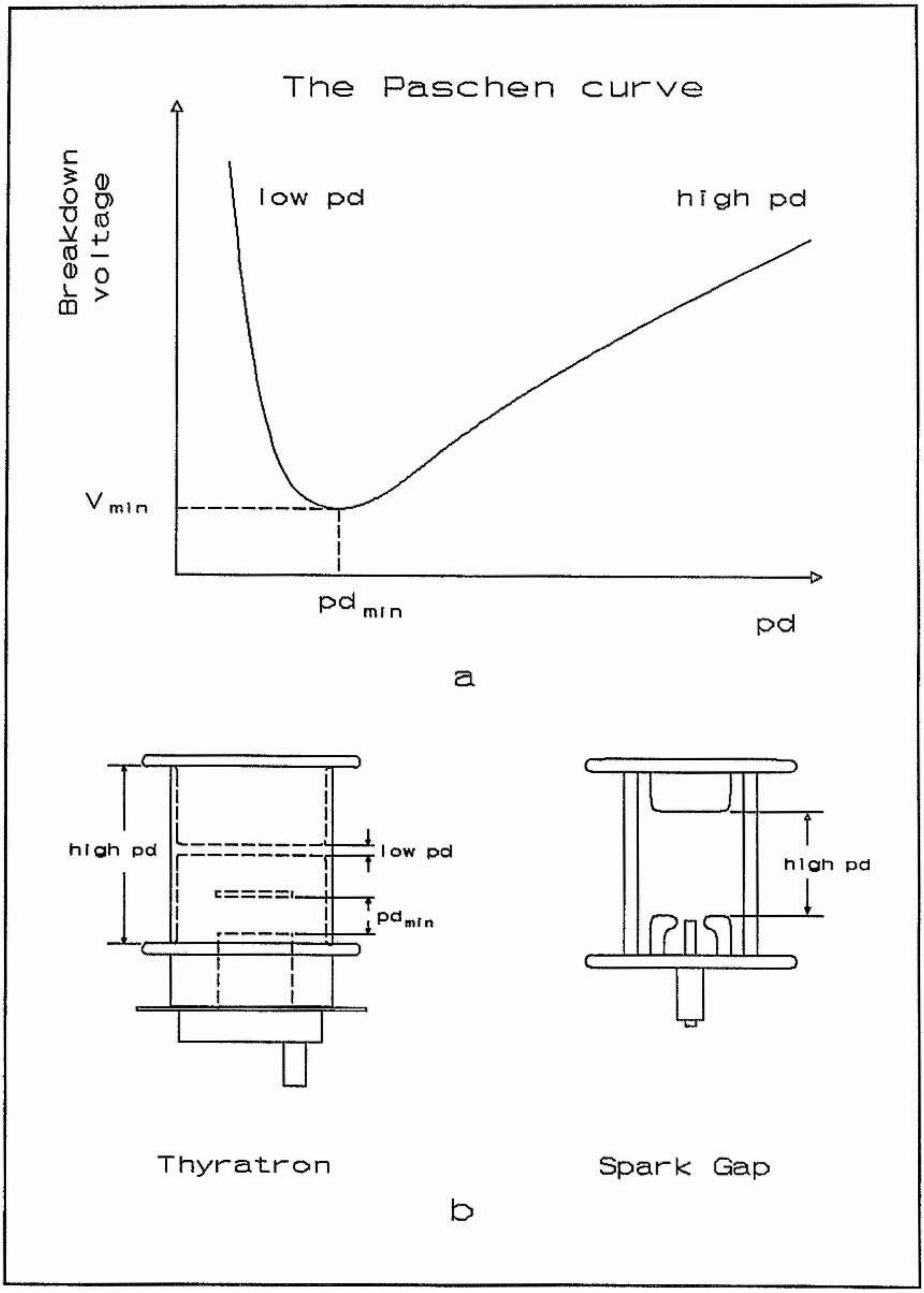


Figure 1.3
The Paschen curve and its application to gas switch design.

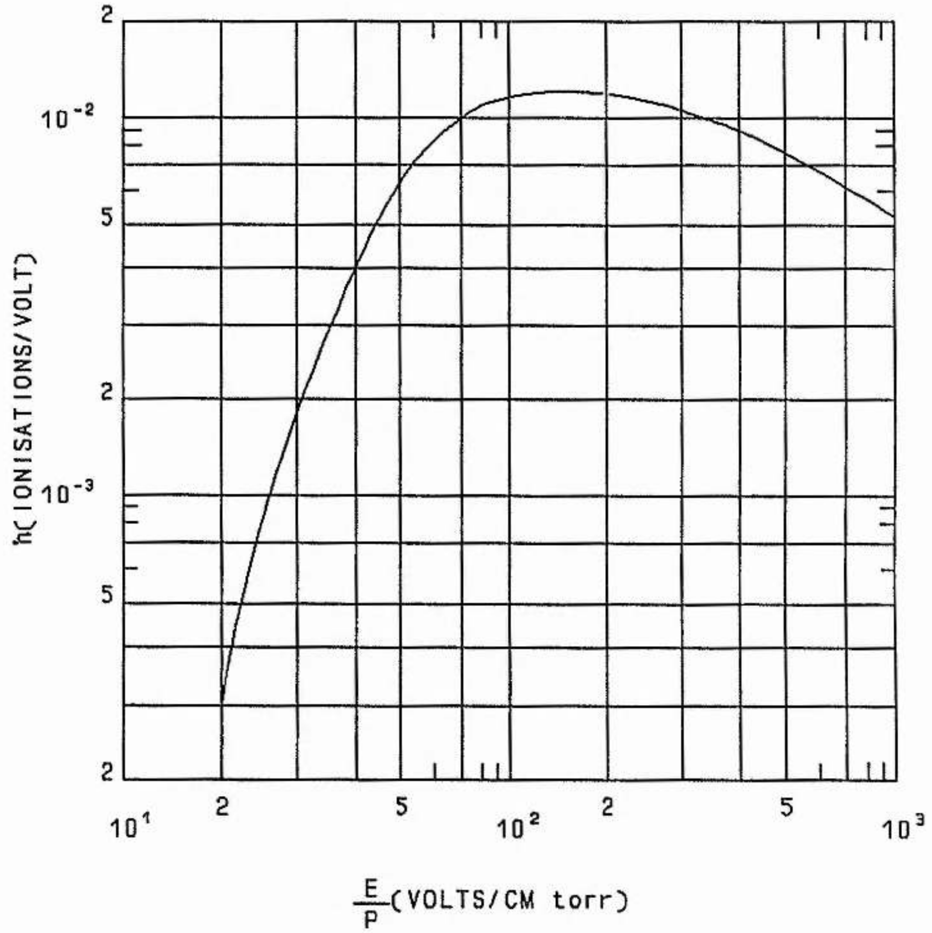


Figure 1.4 (after Rose, 1956)

Number of ionisations/volt as a function of E/p for hydrogen.

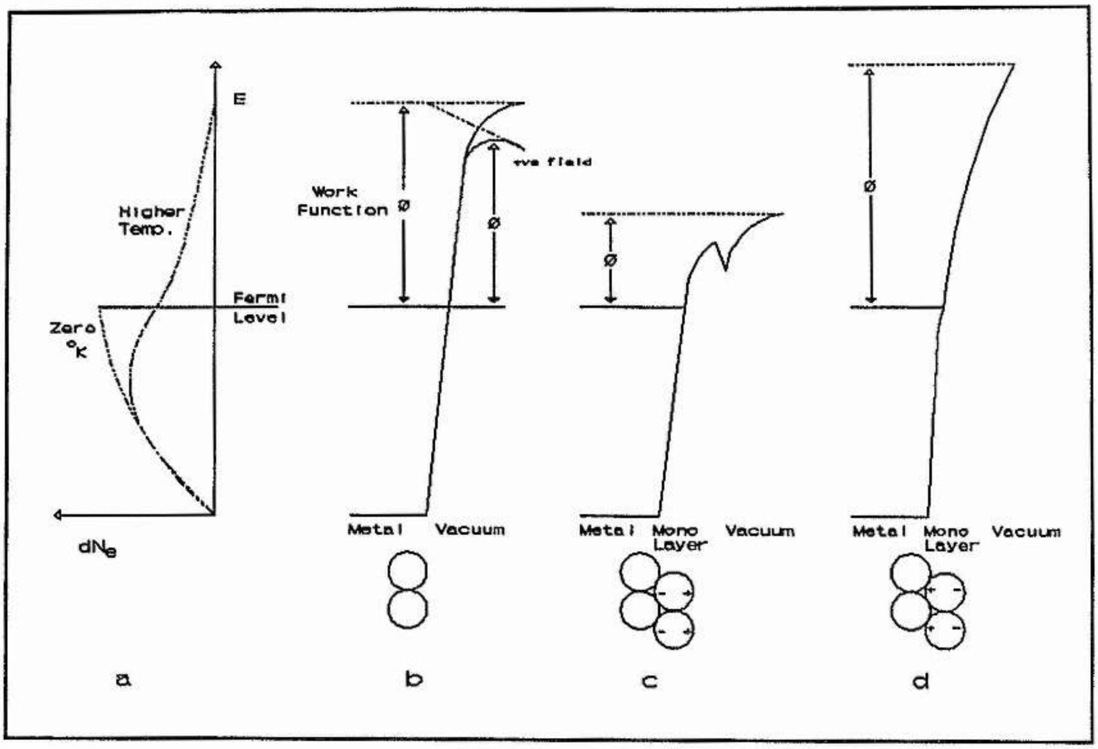


Figure 1.5 (after Jenkins, 1969)
Factors influencing electron emission from a metal: a) the electron energy distribution, b) an external field c) an electropositive monolayer and d) an electronegative layer.

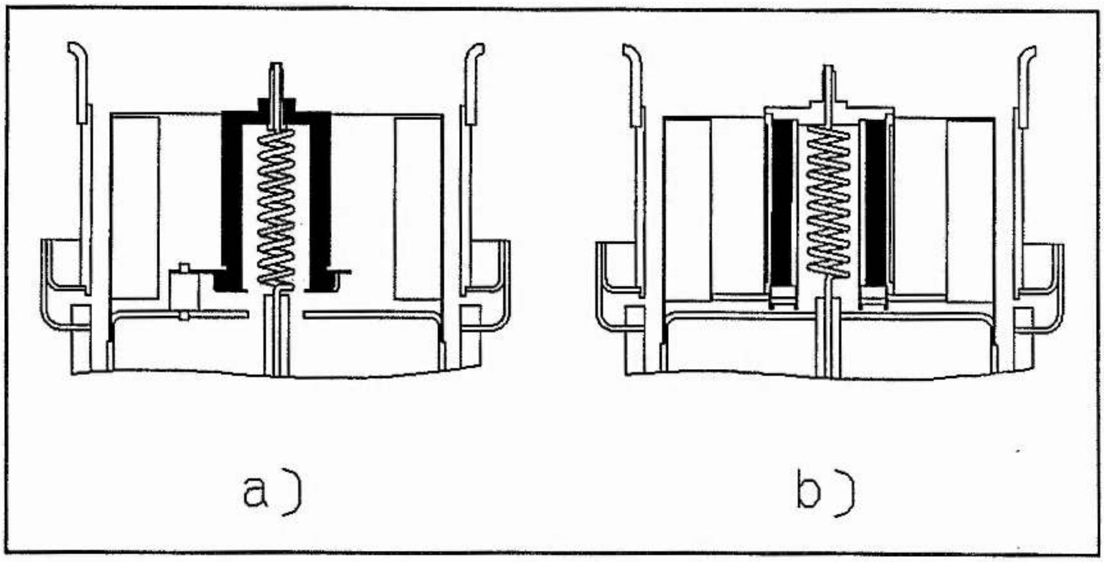


Figure 1.6
The dispenser cathode, showing a) the impregnated cathode and b) the L cathode with the associated heat shield structures.

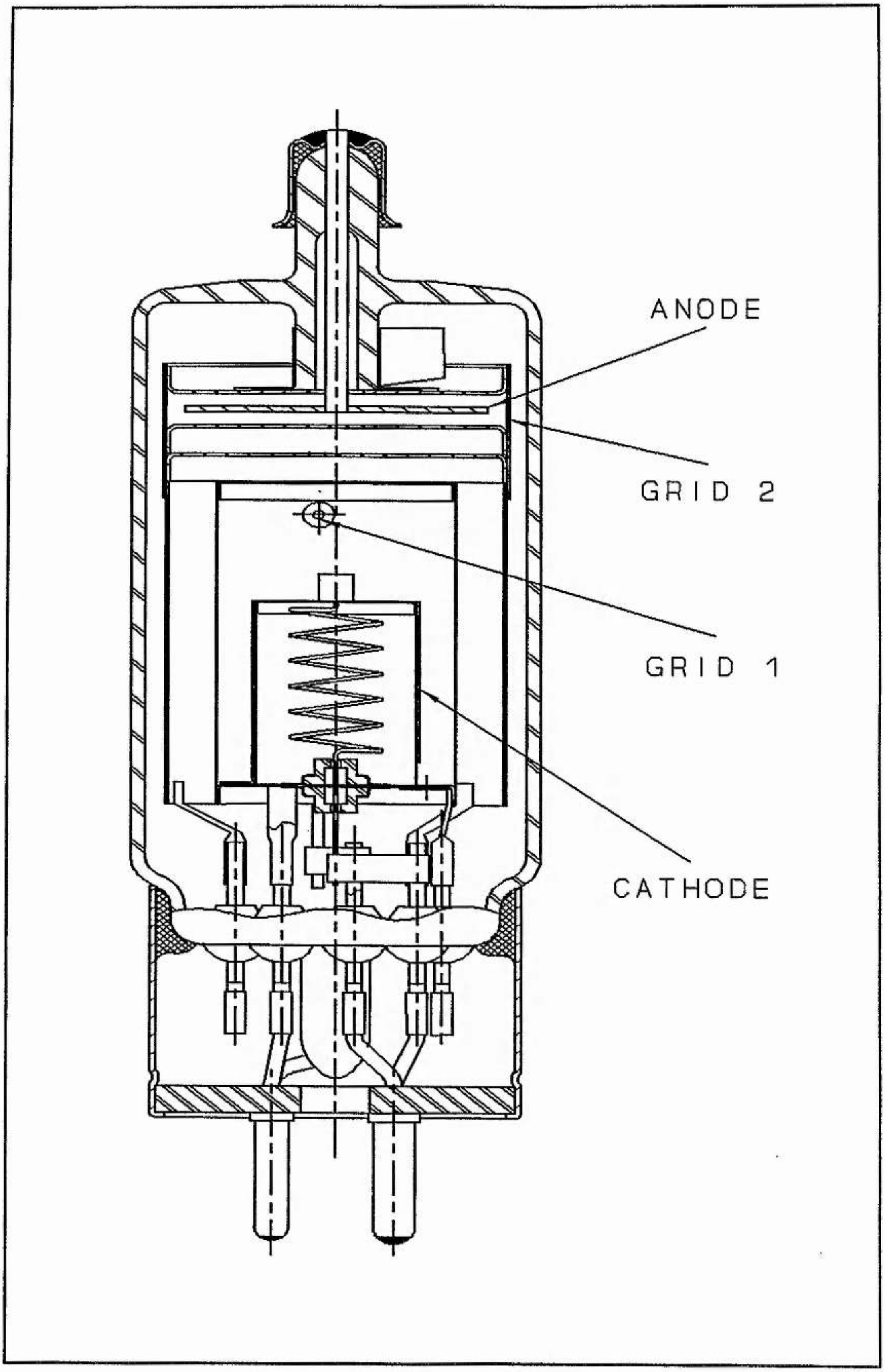


Figure 1.7
The hydrogen thyratron in a glass envelope.

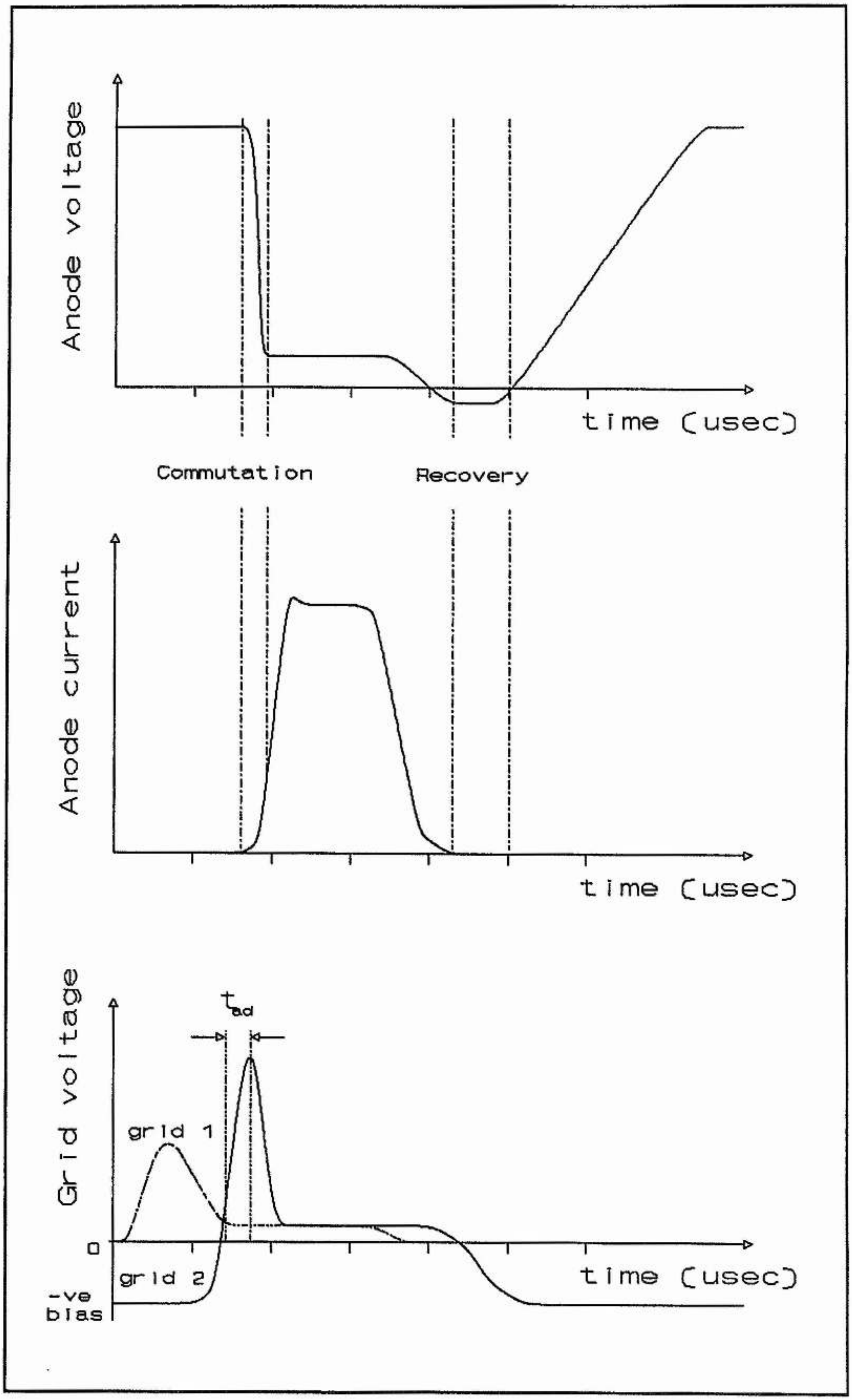


Figure 1.8

Typical anode and grid waveforms for a hydrogen thyratron operating in a pulse modulator.

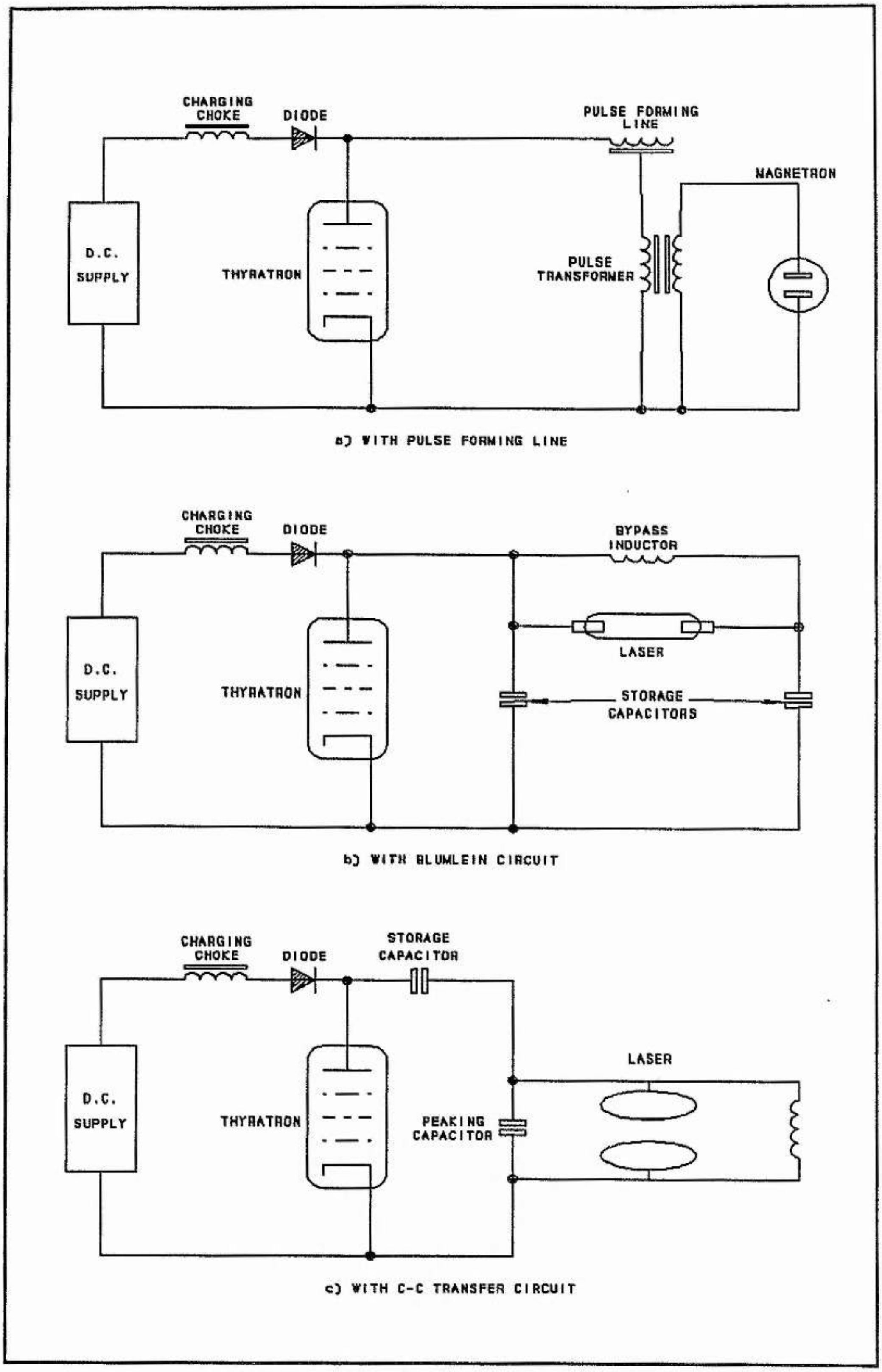


Figure 1.9
Pulse modulators with discharge circuits for a) Radars and Kicker magnets b) Nitrogen lasers c) Copper vapour and Excimer lasers.

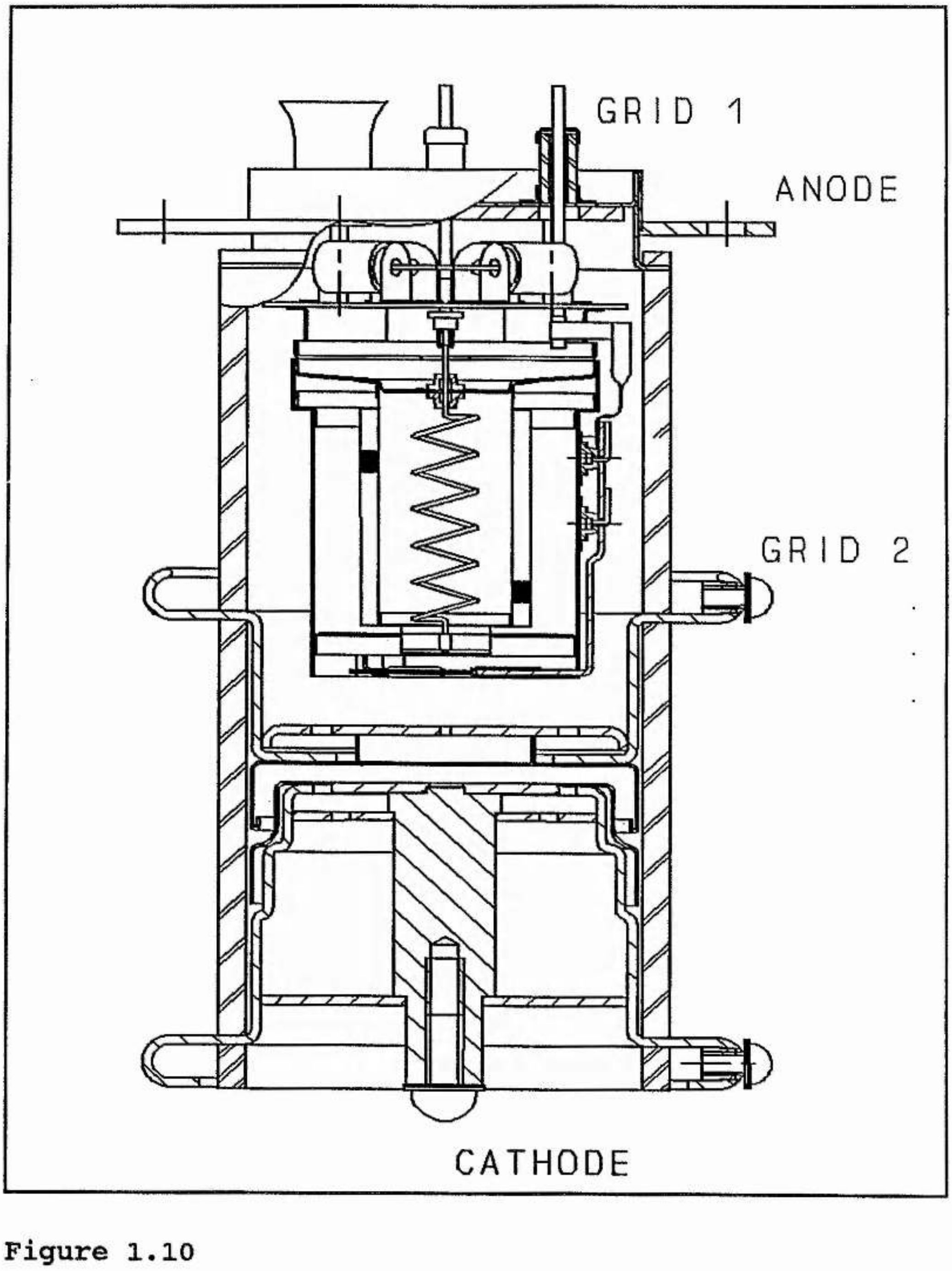


Figure 1.10
CX1154 thyratron used in hollow cathode triggering tests.

CHAPTER TWO

Electron beams in the glow discharge.

2.1 Introduction.

Jan Baptista van Helmont was a Flemish physician and alchemist whose experiments involved the collection of vapours. Helmont was the first person to realise that these vapours were different substances, each with its own distinct properties. He observed that a vapour does not have a definite form, but expands to fill a closed volume. Helmont considered therefore, that vapours were examples of matter in disorder. In 1620, he called them 'chaos', a Greek word representing the formless void supposed to exist before the ordered universe. As a result, such a vapour is now known as a 'gas'.

About 200 years later another level of chaos was explored when Faraday, amongst others, began to study the passage of electric currents through low pressure gases and the glow discharge was discovered. The first observation of electron beams, or cathode rays as they were then called, in low pressure gas discharges is attributed to Plücker (Plücker, 1858). In his discharge tubes he observed the ionised track of rays generated at the cathode, and the fluorescence they excited on striking the glass walls. Cathode rays in gas discharges were further studied by Goldstein (Goldstein, 1899). New phenomena were revealed in these early gas discharge tubes, leading to the development of ideas about the structure of matter, and the eventual discovery of the electron by J.J. Thomson. The principal concern of this thesis is the application of such glow discharge electron beams to high voltage, high current switching. However, it should be noted that the ability to produce directed electron beams in low pressure gases in a controlled way, opens up possibilities in a number of different fields. This chapter therefore introduces some glow discharge physics and relates it to the production of electron beams in low pressure gases.

2.2 The glow discharge.

2.2.1 Introduction.

When an electric field of sufficient strength and duration is applied between two electrodes in a low pressure gas a glow discharge results (Photograph 2.1).

Conduction is initiated by free electrons which accelerate in the field until they begin to make inelastic collisions with gas molecules. The major products resulting from these collisions are electrons, ions and photons. The ions and electrons move under the influence of the field but in opposite directions. The electrons travel to the anode and make further inelastic collisions with gas molecules on the way. The ions are drawn to the cathode and collect electrons from its surface to become neutral particles again. Ions bombarding the cathode also cause extra electrons to be emitted, and thus a cycle is established which allows the current flow to be sustained. The discharge current grows until it is limited by the external circuit, usually in tens of nanoseconds. The electric field between the electrodes is now distorted by the presence of charges and the distinctive dark and bright regions of the discharge are developed. Photons are emitted from the bright regions, where excitation occurs, giving the discharge its characteristic appearance. The photons play an important role in the maintenance of the discharge, as some produce electrons from the electrodes, while others produce electrons in the gas. In the steady state, every electron leaving the cathode creates enough ionisation and excitation in the gas to cause, ultimately, one further electron to be emitted from the cathode. This is known as the maintenance condition. The operating conditions in the steady state are determined by the parameters of the circuit in which the glow discharge is connected.

As can be seen in the current/voltage characteristic of a typical glow discharge in neon (Figure 2.1) there are a number of well–defined modes. As the potential between the electrodes is increased, small bursts of current of the order of 10^{-18} A are recorded. The electrons which initiate these bursts are released by the action of cosmic rays, natural radioactivity, and ultra–violet light. Illuminating the cathode with an intense ultra–violet source provides continuous emission from the cathode and gives rise to the Townsend or dark discharge whose position on the characteristic is indicated by the dotted line in Figure 2.1. As the current increases, it becomes independent of any external ionisation (at B), and the discharge is self–sustaining. The voltage at which this occurs is called the breakdown voltage. The voltage falls rapidly to a low level (after C), where it remains steady as the current is increased. The region between E and F is called the normal glow discharge and it is characterised by a constant discharge voltage and a constant current density at the cathode, so that as the current is increased, the area of the discharge covering the cathode is increased. At point F, the entire surface of the cathode is covered. Now, in order to increase the current, it is necessary to increase the electron emission per unit area at the cathode. The voltage across the discharge therefore rises. This is the region of the abnormal glow discharge (F to G). Beyond G a transition from glow to arc occurs, and the current is drawn from localised spots on the cathode surface, accompanied by evaporation of the cathode material. In the transition to the arc mode, the voltage drops from hundreds to tens of volts and huge currents may be drawn from the cathode. It is customary, therefore, to limit the current that can be drawn from the power supply to prevent prolonged operation in this damaging mode.

2.2.2 The glow discharge regions.

A glow discharge is a highly complex system in which there are many atomic and molecular species undergoing a variety of dynamic processes. Nevertheless, the main mechanisms of the glow discharge are reasonably well understood (Chapman, 1980; Druyvesteyn & Penning, 1940; von Engel, 1955; Francis, 1956). The most obvious visual feature is the variation in light intensity which identifies the different regions and indicates a variation in their other discharge parameters as detailed in Figure 2.2. The cathode dark space, negative glow and Faraday dark space comprise the cathode regions, and they arise from the need to generate electrons from the cathode. The positive column, when present, serves principally to complete the connection to the anode. As will be shown, the electrons emitted from the cathode have a high velocity component perpendicular to the cathode surface, and under certain conditions of voltage, gas pressure and electrode geometry, form the distinct beams of the e–beam discharge.

2.2.3 The cathode dark space.

The processes essential to the maintenance of the glow discharge are driven by the cathode dark space (CDS). There is a strong electric field in the CDS which arises from the large positive space charge in this region. The exact form of the variation of field strength with distance from the cathode is still a matter of debate (Ingold, 1978), but it is usually assumed to have a high value at the cathode surface decreasing linearly to zero at the boundary of the negative glow, and this implies a uniform positive space charge density throughout the CDS.

Electrons are ejected from the cathode by the impact of ions, neutrals, and photons, and are accelerated by the electric field until they begin to excite and ionise the gas. There is a thin, completely dark area just in front of the cathode called the Aston dark space where the electron collisions are elastic only. At the point where the electron energy reaches the peak of the excitation probability, about 15 eV in atomic hydrogen, a very thin cathode glow is formed. The electron energy continues to increase rapidly beyond this point but excitation becomes much less probable, as may be seen in graphs of excitation cross–section against electron energy (Figures 2.3 and 2.4). Similar graphs for the total ionisation cross–section are shown in Figures 2.5 and 2.6. The situation for hydrogen is summarised in Figure 2.7. The cross–sections have broad peaks and fall off at values over 100 eV. Since the CDS will have at least a few hundred volts across it, many of the electrons cross the CDS without making any collisions and enter the negative glow with an energy equal to the full voltage across the CDS. This stream of high energy electrons creates ionisation and excitation in the negative glow. The photons arising from these processes are energetic enough to cause photoemission from the cathode and they make a significant contribution to the total electron emission.

The ions created in the CDS, and those which enter it from the negative glow, are accelerated towards the cathode, where they recombine and release secondary electrons. There are many possible collision processes in the gas, and the energetic particles that impinge on the cathode in an argon discharge have been studied by Davis and Vanderslice (Davis and Vanderslice, 1963) using a cathode with a small hole leading to an analyser. They found that about half the ions become neutrals without losing their directed energy, which makes charge transfer a fairly important process in the CDS. As a result of their larger charge exchange cross–sections, there are more fast atomic ions than molecular ions reaching the cathode.

2.2.3.1 Theory of the cathode dark space.

Early cathode dark space theories are based on Townsend's dark discharge theory (Townsend, 1915), where he assumed that the growth in electron current could be described by an exponential increase with distance x from the cathode giving

$$N_e(x) = N_e(0)\ e^{\alpha x} \quad , \qquad 2.1$$

where N_e is the electron number density and α is the first ionisation coefficient. He then assumed that electrons are released by ions accelerated back to the cathode and that this gave an electron current density $N_e(0)$ related to the incoming ion current density by

$$N_e(0) = -\gamma N_p(0) + N_0 \ , \tag{2.2}$$

where N_0 is the emission caused by an external source and γ is the second ionisation coefficient. Further manipulation of these equations leads to the equation for current growth in an externally maintained Townsend discharge

$$N_e(d) = \frac{N_0 e^{\alpha d}}{1 - \gamma(e^{\alpha d} - 1)} \ , \tag{2.3}$$

where d is the distance between the electrodes. For a self-sustained discharge there is no external source of ionisation and we have $N_0 = 0$. This equation shows that, for there to be a current to the anode, the denominator must also be zero. The maintenance condition for a self-sustained discharge is then

$$1 + \frac{1}{\gamma} = e^{\alpha d} \ . \tag{2.4}$$

Since α depends on the electric field, the maintenance condition defines the field required to maintain a self-sustained discharge. In the CDS of normal and abnormal glow discharges the field is a strong function of x and α is replaced by α' , which is defined by

$$\alpha' = \frac{1}{d}\int_0^d \alpha \ dx \ . \tag{2.5}$$

Since α' depends strongly on the gas type and pressure and γ depends on gas type, cathode material and the cathode surface condition, it is clear that the properties of the CDS will depend markedly on these factors. In spite of the simplifications, which cause some inaccuracy in detailed predictions for the normal and abnormal glow discharge, insight can be gained into various practical situations on the basis of this simple outline. In fact, this model and the maintenance equation forms the basis of most presently accepted theories of the cathode fall.

An introduction to theories of the cathode dark space and a review of particular examples is given by Druyvesteyn & Penning (1940) and Francis (1956). A modern account of the glow discharge and theory of the cathode fall is given by Ingold (1978). The general approach is to relate the total current density j to the secondary processes at the cathode to obtain

$$j = j_p + j_e = j_p(1 + \gamma)$$

or 2.6

$$j = e N_p v_p (1 + \gamma) \quad ,$$

where N_p is the ion number density and v_p is the ion velocity. Note that the maintenance condition is included in this equation. In order to develop the equation further, it is necessary to know the electric field, X, in the dark space and the ionisation function of the gas. Three equations are required.

These are:

1. Poisson's equation:

$$\frac{dX}{dx} = \frac{-e(N_p - N_e)}{\varepsilon_0} \quad . \tag{2.7}$$

2. The continuity equations:

For ions

$$z = \frac{d}{dx}(N_p v_p) \quad , \tag{2.8}$$

and electrons

$$z = \frac{d}{dx}\left[N_e v_e + D\frac{dN_e}{dx}\right] \quad , \tag{2.9}$$

where D is the diffusion coefficient and z is the number of ionisations/cm^3.

3. The mobility equations:

$$v_p = F(X) \quad ie. \;\; b_p X \;\; or \;\; \sqrt{X} \quad , \tag{2.10}$$

$$v_e = F(X) \quad ie. \;\; b_e X \;\; or \;\; \sqrt{X} \quad . \tag{2.11}$$

From these equations, X, N_p and N_e can be determined as functions of x. With $X = 0$ at $x = d$ as a boundary condition, where d is the width of the dark space, we have

$$V_c = \int_0^d X \, dx \quad , \tag{2.12}$$

thus allowing the voltage across the dark space V_c, j and d to be determined. A particular example is an early theory due to von Engel & Steenbeck (von Engel & Steenbeck, 1934), who omitted the equations of continuity and introduced the experimentally determined linear field distribution

$$\frac{X}{X_c} = 1 - \frac{x}{d} \ . \qquad 2.13$$

They used $v_p = b_p X$ and α as given by Townsend's relation

$$\frac{\alpha}{p} = Ae^{-\frac{B}{\left(\frac{X}{p}\right)}} \ , \qquad 2.14$$

where A and B are constants, and derived

$$j = \frac{b_p}{\pi} (1 + \gamma) \frac{V^2}{d^3} \ . \qquad 2.15$$

The theory compares reasonably well with experiment as shown in the curves of Figure 2.8.

2.2.4 The negative glow.

The negative glow (NG) is a region of almost zero field and high luminosity. It has a sharp boundary with the CDS and a diffuse boundary with the Faraday dark space. The light emitted from the NG is a by–product of the excitation of gas molecules by energetic electrons. In fact, the negative glow is driven by the stream of electrons arriving from the cathode. They lose their energy by making inelastic collisions with the gas and, as there is essentially no field to accelerate them, they rapidly thermalise. The electron energy distribution in the NG has been measured using a retarding field analyser technique (Gill & Webb, 1977). It shows a significant peak of electrons which have suffered no collisions and have an energy equal to the cathode fall, and a tail of electrons going down to lower energies. Below 20 eV there is a large group of slow electrons, arising from ionising collisions in the CDS, having energies which allow them to excite the intense glow at the cathode end of the NG. The faster electrons lose energy in inelastic collisions in the NG until they begin to participate in excitation. There is, therefore, a gradually decreasing intensity away from the cathode. The length of the NG is essentially determined by the distance over which collisions reduce the electron energy below the level required for excitation. The statistical nature of the collision processes gives an indefinite boundary between the negative glow and the Faraday dark space.

2.2.5 The hollow cathode effect.

Before proceeding with the description of the glow discharge, it is appropriate to consider the influence of cathode geometry on the efficiency of the discharge sustaining processes. Figure 2.9 shows a discharge tube in which the separation of parallel cathode plates can be adjusted. When the plates are at their greatest separation, each has its own cathode regions and these regions connect to the anode via a common positive column. As the cathode plates are brought together, the positive column shortens, but no change occurs in the cathode regions until the negative glows begin to overlap. When this point is reached, the negative glow brightens and the cathode current density at a given voltage increases markedly. Further reduction in the cathode separation causes an increase in cathode current density as shown in the graph of Figure 4.3. The maximum cathode current density for a given voltage is obtained from a cathode in the form of a hollow cavity which encloses the cathode regions. The increased cathode current density observed with hollow cathodes is the result of an increased capture of photons from the negative glow by the cathode surface (Little & von Engel, 1954) and the effect emphasises the importance of photons from the negative glow in sustaining cathode emission. A second feature of a hollow cathode geometry is that electrons can oscillate between opposing cathode dark spaces and the ionisation density of the negative glow is increased. In summary, the use of a hollow cathode in a glow discharge increases the cathode current density and thus the available current, at a given voltage.

2.2.6 The Faraday dark space.

The Faraday dark space (FDS) is a region of near zero field, where all the electrons have low energies (<1 eV) due to collisions in the NG. In contrast to the cathode dark space, which is dark because the electrons are too fast to cause excitation, the FDS is dark because its electrons are too slow. As a result, the current in the FDS is carried by diffusion of electrons from the NG, where there is a high concentration of electrons and ions. However, at sufficiently low pressures, high energy electrons accelerated in the CDS travel through the FDS causing local ionisation in the path of the beam (Goldstein, 1899; Smith, Tait & Whiddington, 1949). At the anode end of the FDS, the field increases and electrons gain enough energy to excite and ionise the gas. This marks the start of the positive column.

2.2.7 The positive column.

The positive column (PC) is a uniform, luminous plasma whose principal function is to connect the FDS to the anode region. Its common use is in neon signs, where it will extend through twisted shapes of various lengths. In a system with a movable anode, it is the PC which accommodates the change in inter–electrode gap as shown in Figure 2.2(vi). Ionisation in this region is maintained against recombination and losses to the walls by the energy supplied to the electrons by the electric field. In contrast with the CDS, the field is low and constant in the PC, and Poisson's equation thus indicates overall charge neutrality. The electron energy is in equilibrium with the field and can be assumed to have a Boltzmann distribution. The greater mobility of electrons means that they carry most of the discharge current in the PC (Figure 2.2(v)). In order to maintain the continuity of current and the overall neutrality of the

PC, electrons enter from the FDS, and ions are replaced by those moving in from the anode region.

2.2.8 The anode fall.

The principal role of the anode in a glow discharge is to transfer electrons to the external circuit. The field in the PC draws ions away from the anode region and a negative space charge sheath forms in front of the anode thereby giving rise to a potential difference called the anode fall. The anode fall must be of sufficiently high value to ensure that enough ions are available to balance those moving out of the cathode end of the PC. The energy of the electrons must therefore increase in the anode fall to create this ionisation. In fact the magnitude of the anode fall is usually found to be close to the ionisation potential of the gas, although the ionisation of already excited atoms may cause the value to be smaller (Druyvesteyn, 1937). The increased electron energy also gives rise to sufficient excitation to cause a reasonably bright anode glow. In discharges where the anode is moved into the FDS, a region where there is no field to draw ions away, ions and electrons diffuse together to the anode and charge neutrality is maintained. The anode fall may become very small or perhaps negative as evidenced by an abrupt change in the voltage drop across the discharge and the disappearance of the anode glow.

2.3 Charged particles in the cathode regions.

The discussion above gives an introduction to the general behaviour of a glow discharge. As we have seen, the cathode regions of the glow discharge are essential for its maintenance. In fact, a discharge can be maintained with only a cathode dark space and a negative glow as is common in sputter deposition systems. We shall now examine the behaviour of electrons and ions in the cathode regions and describe the conditions that give rise to a well defined e–beam in a glow discharge. An initial appreciation of the strongly directed nature of the current flow in these regions can be gained from the results of two simple experiments. In a discharge tube whose cathode is mounted perpendicular to the anode, it is observed that the boundaries of the cathode regions remain parallel to the cathode surface and that it is the PC that deforms to make the necessary connection to the anode. Again, with small obstacles placed in the CDS, a distinct shadow is cast both on the cathode and in the NG (Wehnelt, 1899). These experiments lead to two important conclusions: the electrons have a large velocity component directed away from the cathode at right angles to its surface, and secondly, the ion flux is essential to the emission of electrons and is also directed at right angles to the cathode surface.

2.3.1 The origin of the ions.

This raises the question 'where do the ions originate'? Going back to the model of the CDS presented in §2.2.3.1, it was assumed that the ionisation required to sustain the discharge is produced in the CDS. Using equation 2.1 and substituting nq for α, where n is the number density and q is the ionisation collision cross-section, the number of electrons at the CDS/NG boundary is given by

$$N_e(x) = N_e(0)\ e^{nqx} \quad , \qquad 2.16$$

where x is distance from the cathode. Each electron that leaves the target is multiplied by e^{nqL} in crossing a CDS of length L. This result can be applied to the data of Davis & Vanderslice who found a CDS thickness of 1.3 cm for a discharge voltage of 600 V in argon at 60 mtorr ($n = 2.1{\cdot}10^{15}$). Taking the maximum ionisation cross-section for electrons in argon at 100 eV as $2.9{\cdot}10^{-16}$, this gives an upper limit on electron multiplication of 2.2. Each of these electron impacts forms a new ion as well as a new electron, so that for each electron that leaves the cathode, $e^{(nqL\ -\ 1)}$ ions will be formed. As each of these ions hits the cathode, γ secondary electrons are emitted and $\gamma e^{(nqL\ -\ 1)}$ ions are generated in the dark space. Typical values for γ for most metals are usually less than 0.2 and this gives an ion production rate of 0.24 ions per ion. Photo–ionisation and ion–impact ionisation may also be occurring. Unfortunately, accurate data for photo–ionisation in a discharge are not readily available but it is possible to estimate the contribution from ion–impact ionisation. Under the Davis and Vanderslice discharge conditions and taking an ion impact ionisation cross–section of $5 \cdot 10^{-17}$ cm^2 for ions of 100 eV or so (von Engel, 1955 p.57), an ion multiplication factor of 1.15 is obtained. This brings the ion production rate up to 0.28 ions per ion. In order to maintain a steady discharge, a production rate of 1 ion per ion is necessary (see the maintenance condition in §2.2.3.1). Examination of the equation shows that this would only happen if L was between 3 and 4 cm and errors of this size in L are improbable. The alternative is to have $\gamma = 0.8$, which is unlikely, although the contribution of neutral and photon bombardment have not been included in this analysis. It must be noted, however, that the q values used are the maximum possible and are unlikely to be realised in practice.

Druyvesteyn and Penning (1940) estimate the number of ions produced in the CDS and the NG for a 200 V and a 1000 V cathode fall. When an electron leaving the cathode creates J_{CDS} ions in the CDS and J_{NG} ions in the NG with a fraction s of the electrons in the NG returning to the cathode, we have

$$\gamma (J_{CDS} + sJ_{NG}) = 1 \quad . \qquad 2.17$$

In order to derive values for J_{CDS} and J_{NG}, they divide the CDS into four parts and use data for ionising efficiencies at each of the four electron energies to calculate the numbers of ions produced. They also give values for the length of the CDS, d_c; the electron mean free path λ at half the CDS voltage; and the length l in which an electron of energy eV_c causes one ionisation. Their results indicate a significant amount of ionisation in the CDS of the normal glow discharge at 200 V (Table 2.1), but a trivial amount of ionisation in the CDS of the abnormal discharge at 1000 V (Table 2.2). Our conclusion must be that there is not enough ionisation in the CDS alone to support the discharge, especially in the abnormal glow, and that many of the electrons cross the CDS without making a collision. We thus expect that many of the ions which bombard the cathode will originate in the NG and that the electron energy distribution in the NG will have a high energy component which will increase in magnitude as the gas pressure is reduced and as the discharge voltage is increased.

2.3.2 Supporting evidence.

Experiments reported by Brewer and Westhaver (Brewer and Westhaver, 1937) give results which support the conclusion in §2.3.1 above. They examined the energy distribution of electrons at the CDS/NG boundary and concluded that less than 1.25 ions per electron were formed in the CDS, which is in agreement with the analysis above. It is interesting to note from their results that the rate of electron formation falls markedly as the pressure is reduced from 1 to 0.2 torr. They also measured the length of the NG and related it to the theory of Lehmann (Lehmann, 1927) for the range of fast electrons. They obtained good agreement and concluded that the electrons from the CDS produce the NG and that most of the electrons cross the CDS with no collisions.

Gill & Webb (1977) used a differentially pumped, retarding field analyser to investigate the electron energy distribution in the NG of a discharge in helium. They applied relatively low voltages (<300 V) to create the discharge and produced an electron energy distribution as shown in Figure 2.10. The distinct peak at a retarding voltage equivalent to the full voltage across the CDS represents about 3% of the electron current.

Chaudri and Chaudri (Chaudri and Chaudri, 1965) used an electrostatic energy analyser to investigate the energy of electrons in the NG in air, oxygen and CO_2. Their results at constant pressure in air are reproduced in Figure 2.11. They conclude that, at low pressures, the electrons are accelerated to the full CDS voltage and that there are an insignificant number of collisions in the CDS. They show the electron energy distribution at three different discharge voltages and in each case it consists of a narrow peak of electrons at an energy equivalent to the discharge voltage. The numbers of electrons with lower energies increases as the pressure is increased. This is consistent with an increase in the number of collisions in the CDS.

The weight of experimental evidence supports the conclusion from the theoretical considerations in §2.3.1 that, in the abnormal glow at low pressures (< 1 torr), electrons cross the CDS without making collisions and travel through the NG until their energy is dissipated in collisions.

2.3.3 Electron beams in the glow discharge.

The conditions under which extensive, well–defined electron beams can exist in a glow discharge will now be outlined. When the anode is moved towards the cathode in a typical glow discharge with planar electrodes, the PC reduces in length until it disappears, leaving the other regions unaffected (Figure 2.2(vi)). Alternatively, it is possible to eliminate the PC by progressively reducing the gas pressure. When this is done, the cathode regions expand at the expense of the PC and eventually the NG extends to the anode Photograph 2.1(f). The NG may reach lengths of tens of centimetres depending on the voltage that is applied. As the voltage across the discharge is increased, the NG becomes more beam–like and high energy electrons bombard the anode to produce heating and X–rays. The electron beam is emitted in a direction normal to the cathode surface. If the anode is placed off the cathode axis, the beam is quite distinct and travels through the gas until its energy is dissipated in ionisation and excitation, or until it impinges on the wall of the vessel at the end of its trajectory.

The conditions required for the production of an electron beam in a glow discharge are then as follows.

(a) An unobstructed electron path: it is necessary to move the anode off–axis or to place suitable apertures in the anode to allow the beam to reach its maximum extension.

(b) The appropriate cathode geometry: since the electrons move at right angles to the cathode surface, convex cathodes will produce divergent beams and concave cathodes will produce convergent beams; cathodes with holes in line with an anode aperture are particularly effective in producing well–defined beams.

(c) Operation in the abnormal glow regime: this will require cathode current densities well in excess of 100 $\mu A/cm^2$ in the case where hydrogen is used.

(d) Operation at low pressure: this ensures that few collisions take place in the CDS and increases the range of electrons in the NG; in practice, distinct beams can be found at pressures below 1 torr in most gases.

2.4 The electron beam discharge.

A particular example of an electron beam discharge in deuterium is shown in Photograph 2.2. The electron beam extends from a hole in the anode, which is placed close to the cathode. We can confirm that the excitation of the gas molecules which mark the beam is due to energetic electrons by the direction of their deflection in a magnetic field (Photograph 2.3). The cathode of this device has a hole which is 3 mm in diameter by 15 mm deep, and the e–beam discharge only appears when the pressure is below 1 torr. A typical operating point for this arrangement is 0.3 torr, 3 kV, 3 mA. Increasing the gas pressure beyond ~1 torr causes a change to the hollow cathode mode, and a well–defined beam is no longer apparent. Typical operating parameters are now 1 torr, 0.5 kV, 20 mA. The key difference between these two modes is a sudden change in impedance. The e–beam discharge is characterised by a high voltage drop and a positive resistance. This is in contrast to common discharges which have a low voltage drop and a negative resistance and require a series resistance in the circuit to prevent the full short circuit current being drawn from the power supply. The nature of the e–beam discharge will be investigated in Chapter Three.

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Table 2.1

Ionisation parameters in the normal glow.

	pd_c	$p\lambda(100V)$	$pl(200V)$	J_{CDS}	J_{NG}
He	1.37	0.25	0.87	2.6	6.1
A	0.30	0.05	0.095	13.0	3.4
H_2	0.80	0.17	0.40	7.1	2.7

(after Druyvesteyn & Penning, 1940)

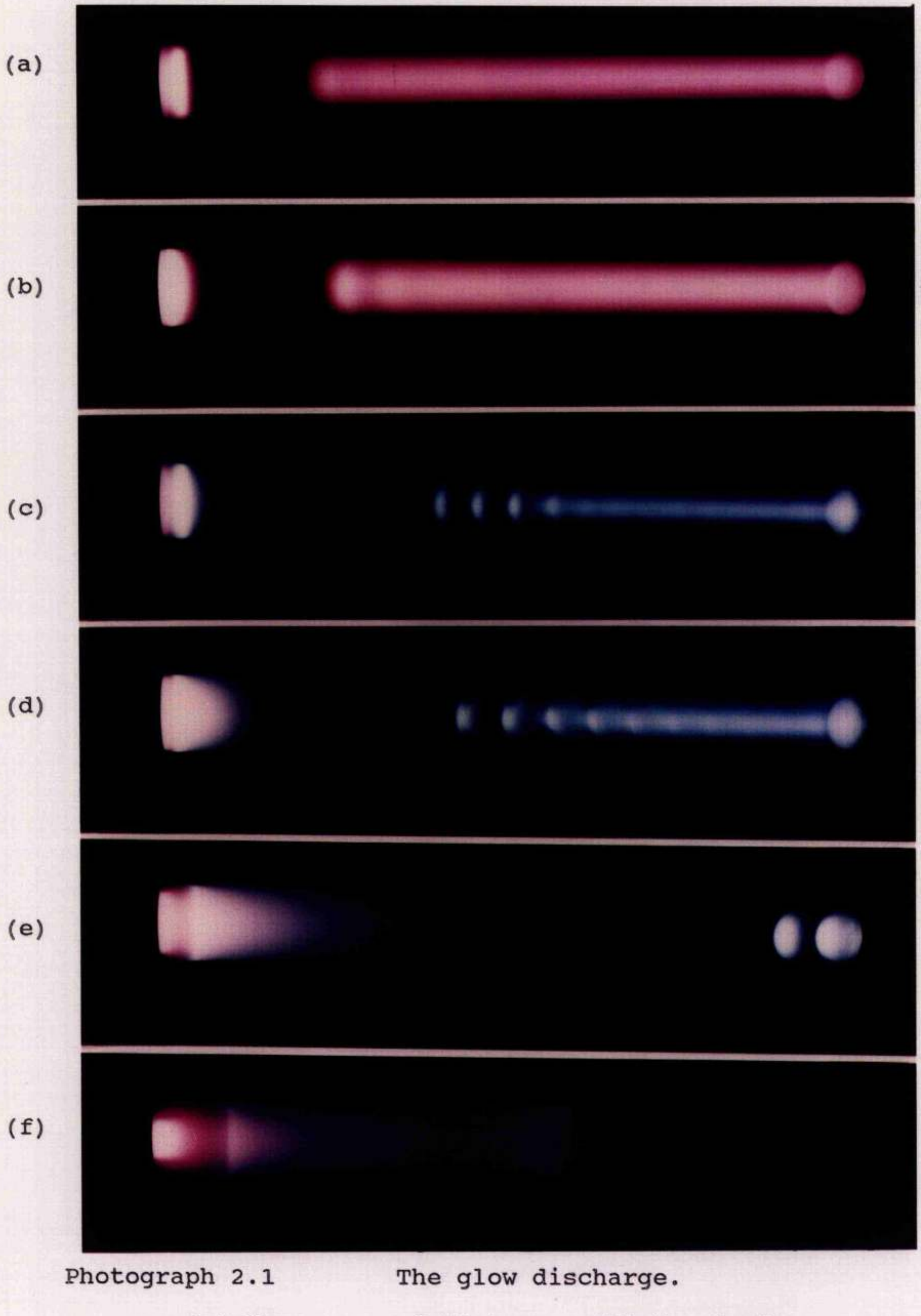
Table 2.2

Ionisation parameters in the abnormal glow.

	pd_c	$p\lambda(500V)$	$pl(1000V)$	J_{CDS}	J_{NG}
He	0.50	0.80	2.23	0.25	32.0
A	0.05	0.15	0.27	0.22	30.0
H_2	0.30	0.56	1.30	0.26	27.0

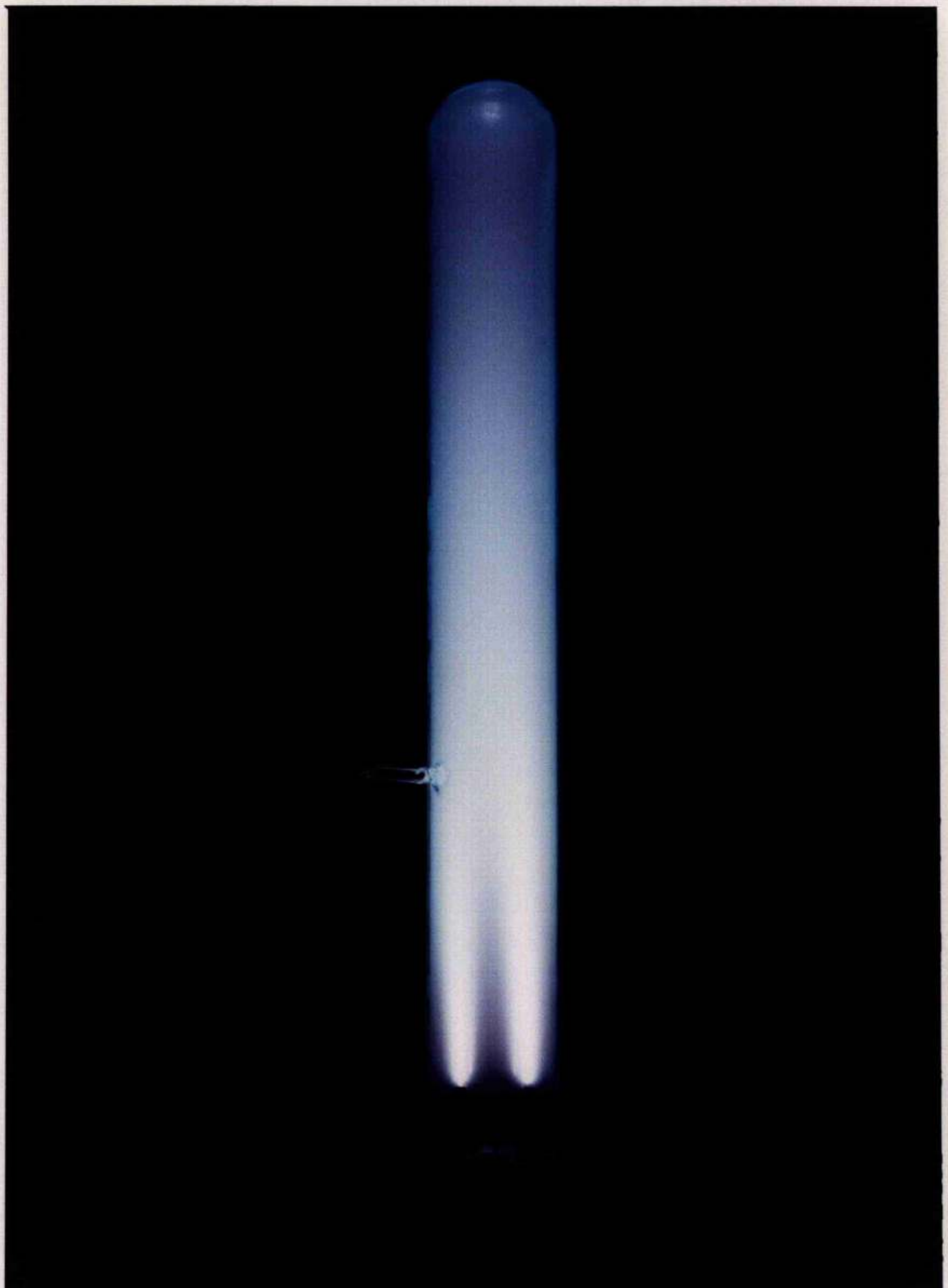
(after Druyvesteyn & Penning, 1940)

The values given in the Tables above are: the length of the CDS, d_c; the electron mean free path λ at half the CDS voltage; the length l in which an electron of energy eV_c causes one ionisation; the number of ions/emitted electron created in the CDS, J_{CDS}; and the number of ions/emitted electron created in the NG, J_{NG}.



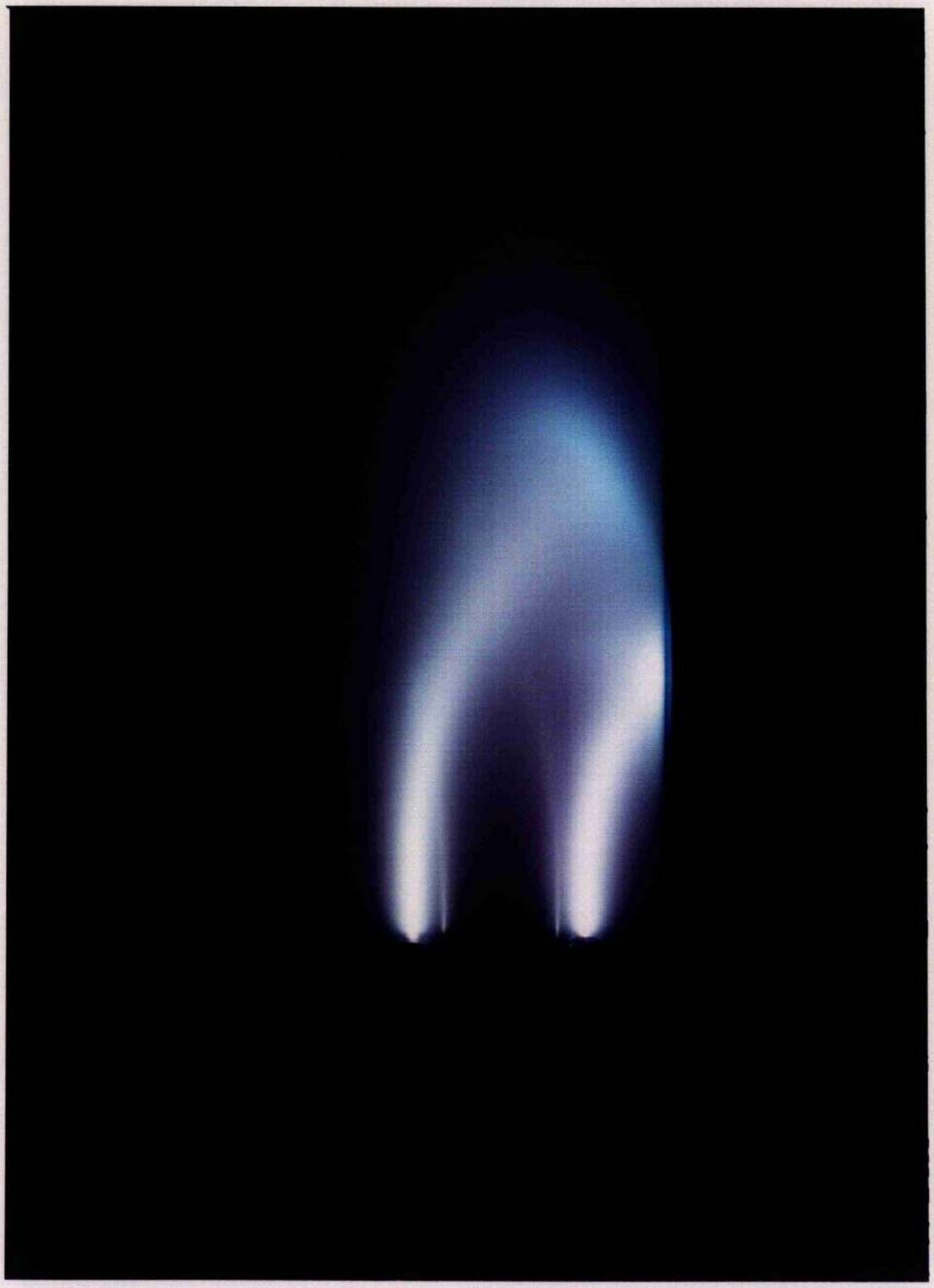
Photograph 2.1 The glow discharge.

(a)	Neon:	0.75 torr,	750 V,	2 mA.
(b)	Neon:	0.75 torr,	800 V,	10 mA.
(c)	Hydrogen:	0.75 torr,	840 V,	2 mA.
(d)	Hydrogen:	0.75 torr,	920 V,	10 mA.
(e)	Hydrogen:	0.25 torr,	1000 V,	5 mA.
(f)	Hydrogen:	0.1 torr,	3500 V,	5 mA.



Photograph 2.2

Glow discharge electron beam (GDEB) guns operating in deuterium at 0.1 torr.



Photograph 2.3

Glow discharge electron beams bending in a magnetic field directed into the plane of the paper.

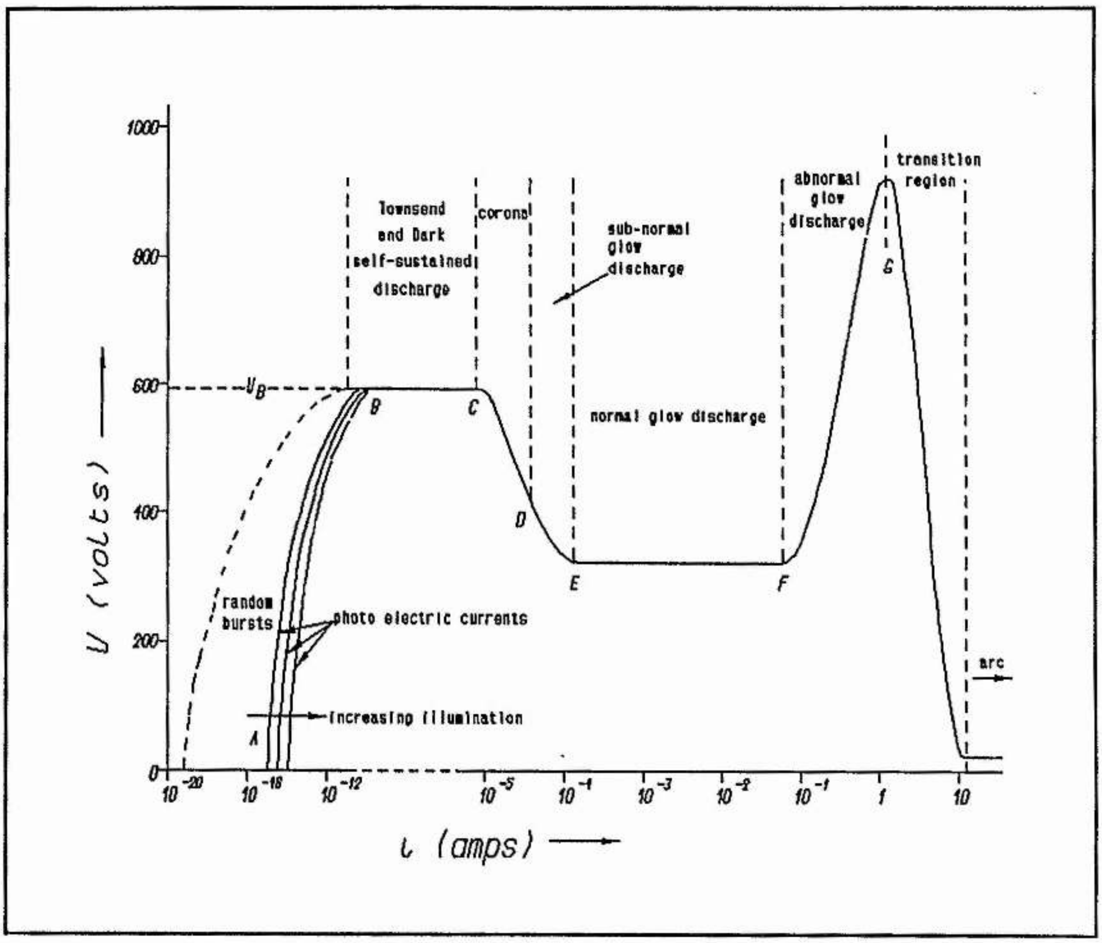


Figure 2.1 (after Francis, 1956, p54)

The dependence of voltage on current for a discharge between copper electrodes of area 10 cm^2, 50 cm apart in Neon at 1 torr.

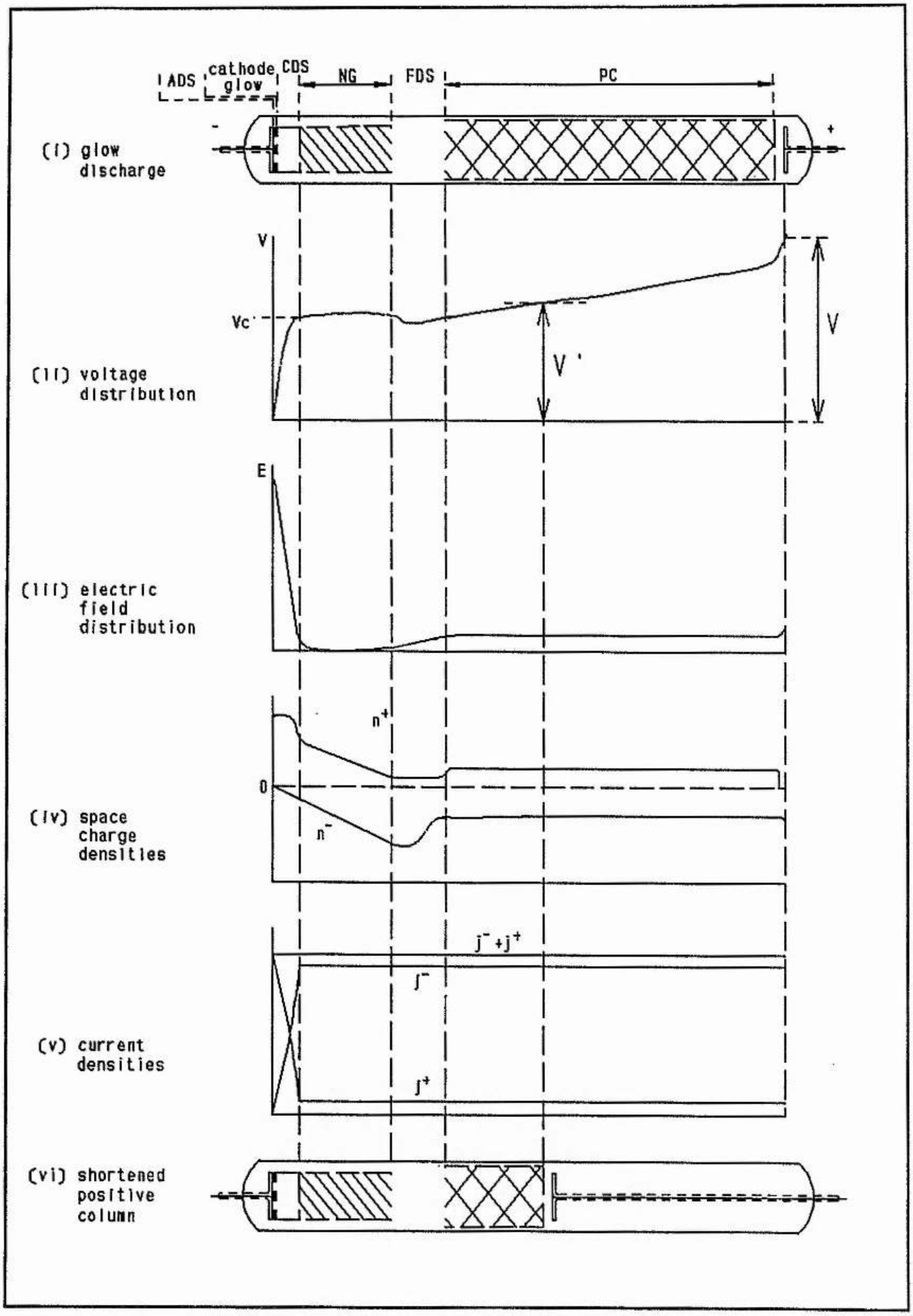


Figure 2.2 (after Chapman, 1980, p79)
The normal glow discharge in Neon. The luminous regions are drawn shaded. (see Photograph 2.1 & Figure 2.1)

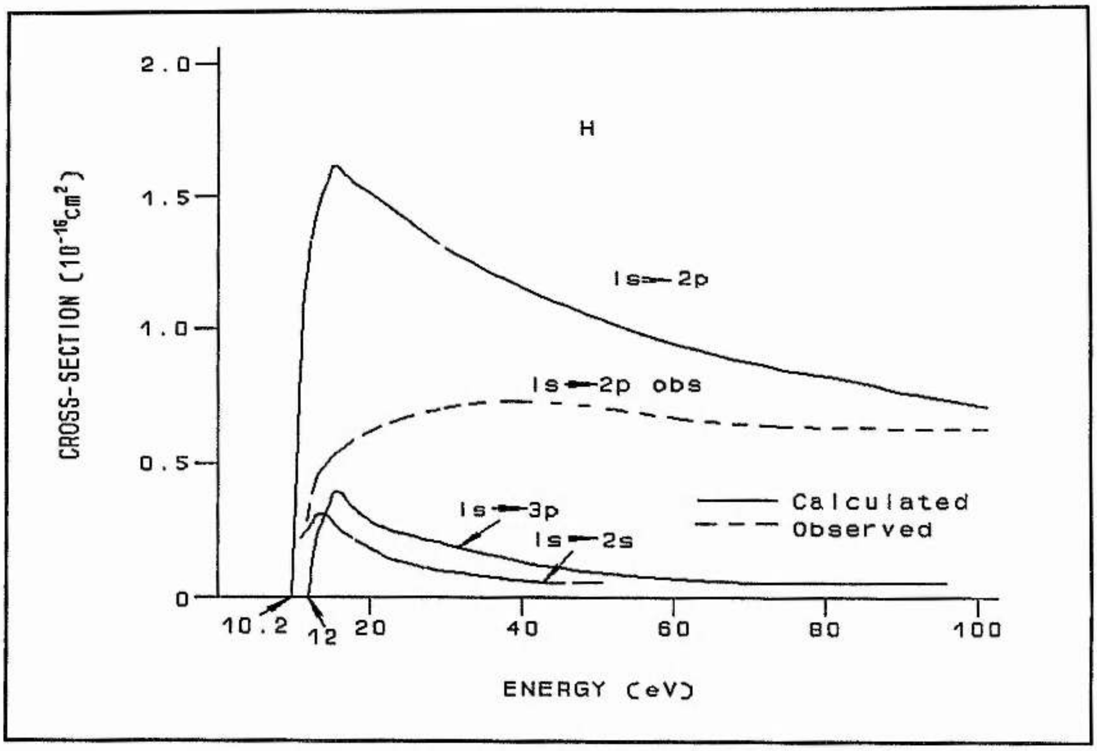


Figure 2.3 (after Chapman, 1980, p33)
Excitation cross-section for electrons in atomic hydrogen.

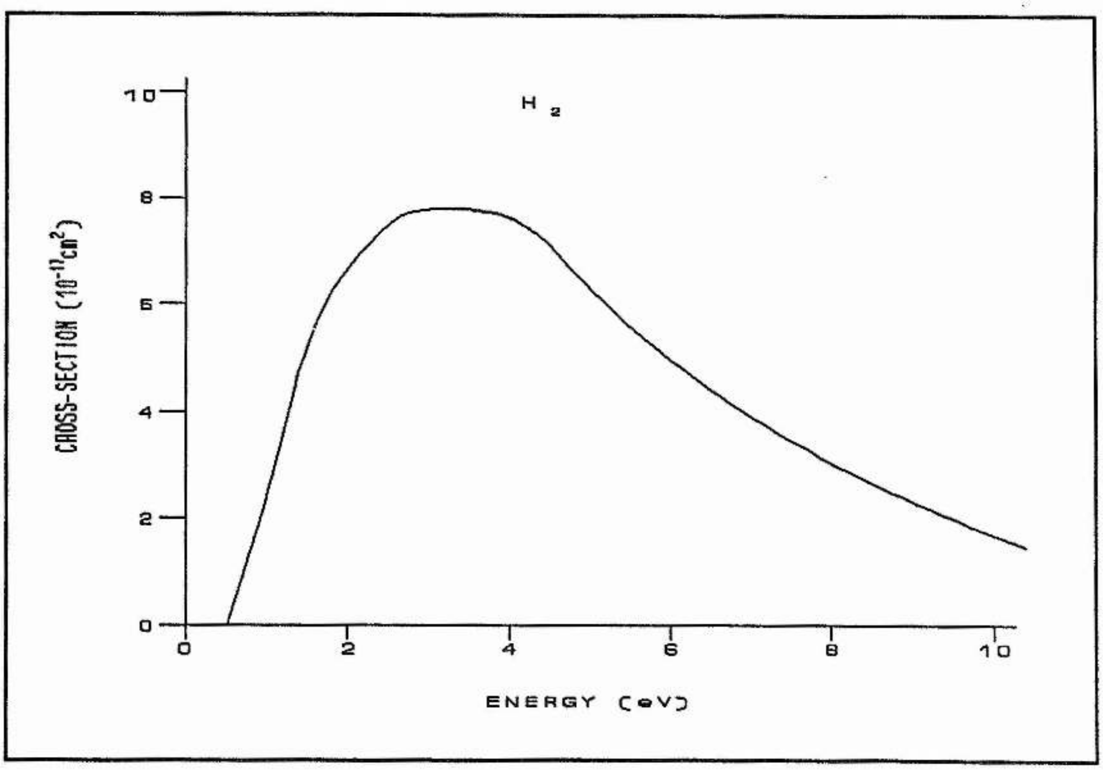


Figure 2.4 (after Frost & Phelps, 1962)
Excitation cross-section for electrons in molecular hydrogen.

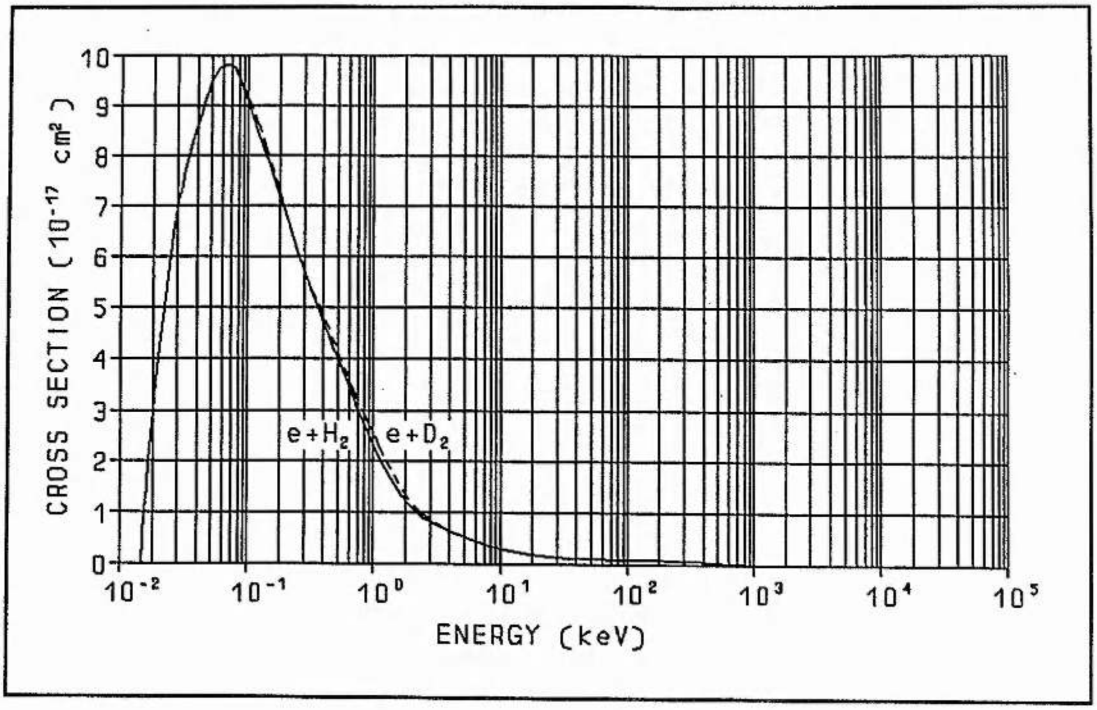


Figure 2.5 (McDaniel <u>et al.</u>, 1977, p533)
Total ionisation cross-sections for electrons in molecular hydrogen and deuterium.

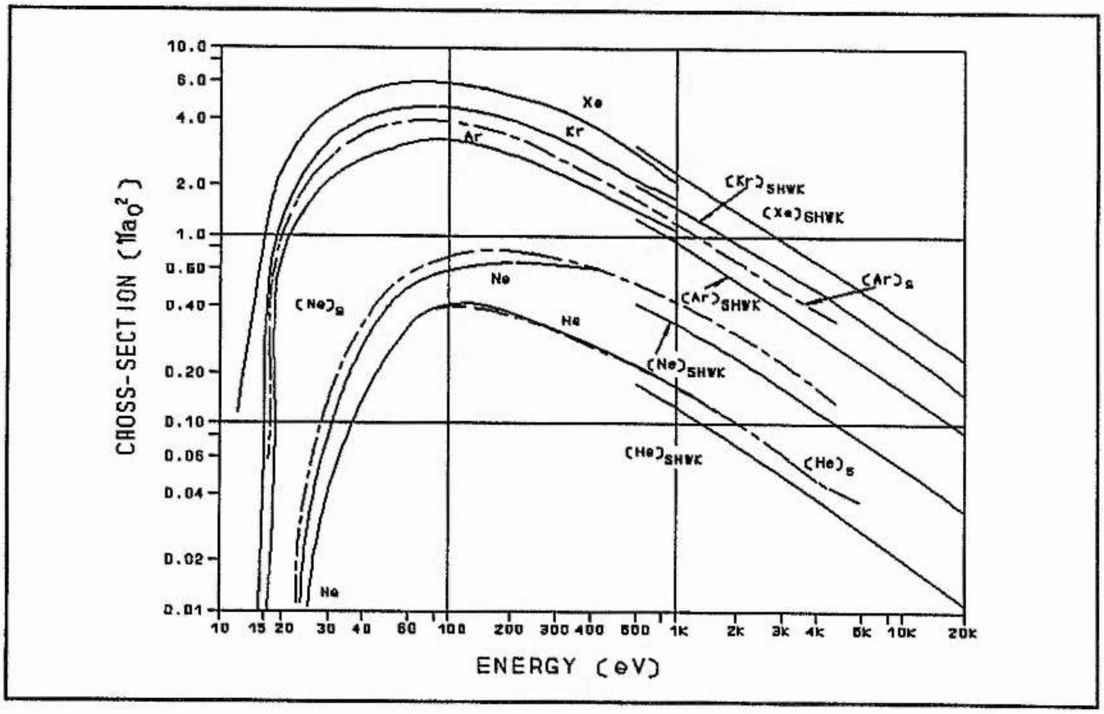


Figure 2.6 (after Chapman, 1980, p29)
Ionisation cross-sections for electrons in the noble gases.
($\pi a_0^2 = 8.82 \cdot 10^{-17}$ cm^2)

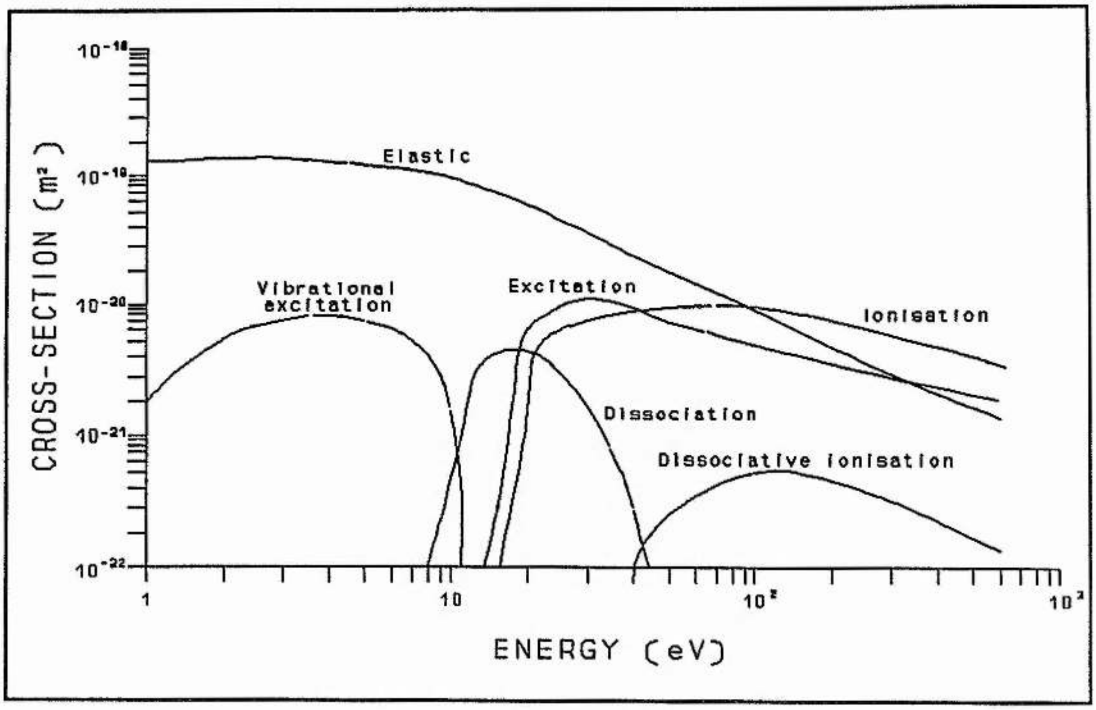


Figure 2.7 (after Dexter, Farrell & Lees, 1980)
Total collision cross-sections for electrons in molecular hydrogen.

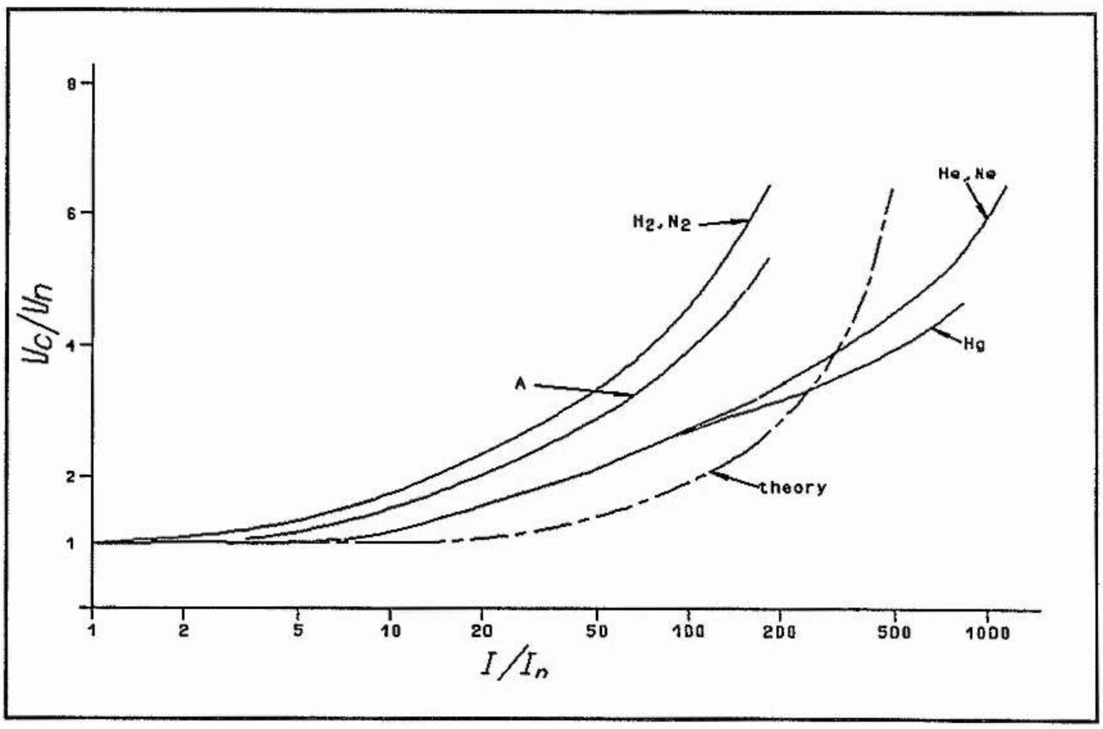


Figure 2.8 (after Francis, 1956)
Cathode fall as a function of current density. Experiment compared with theory.

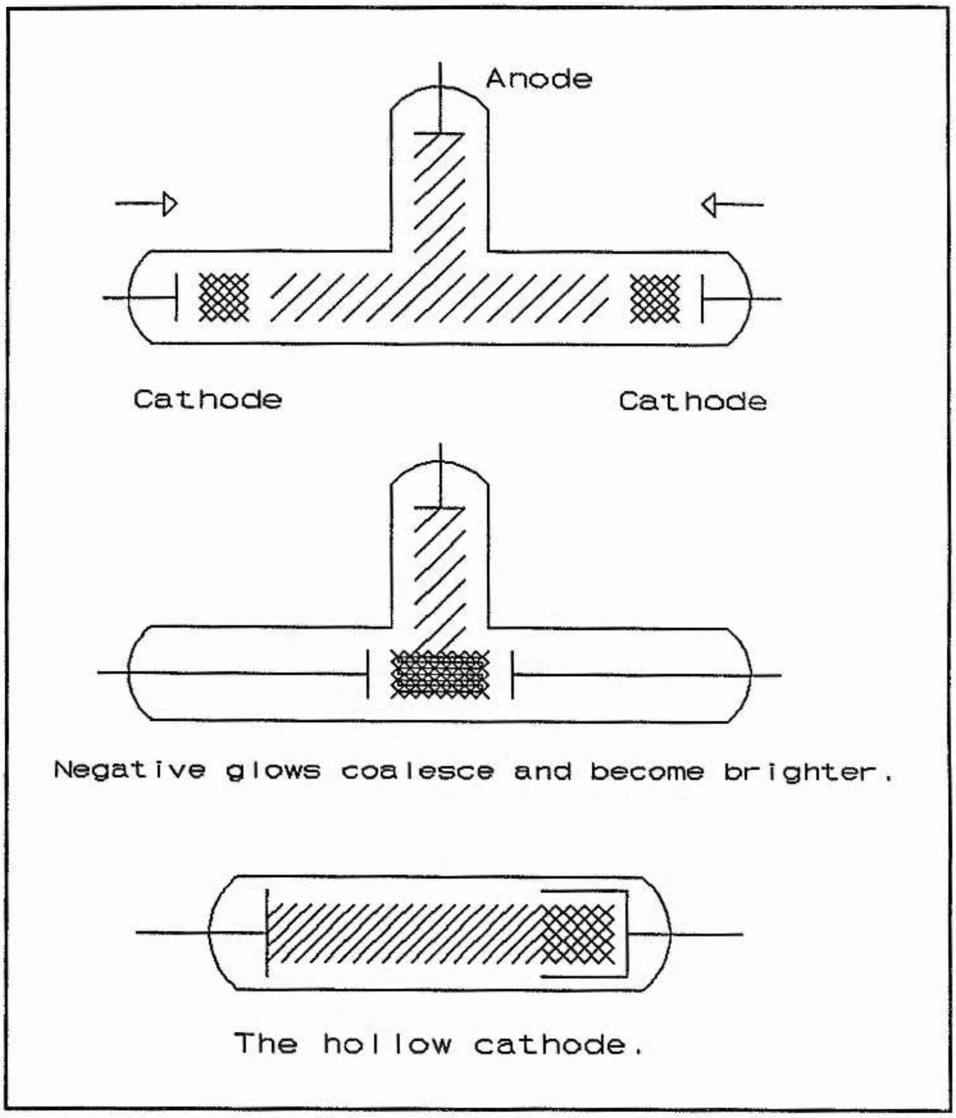


Figure 2.9
The development of the hollow cathode effect as a result of changes in cathode geometry.

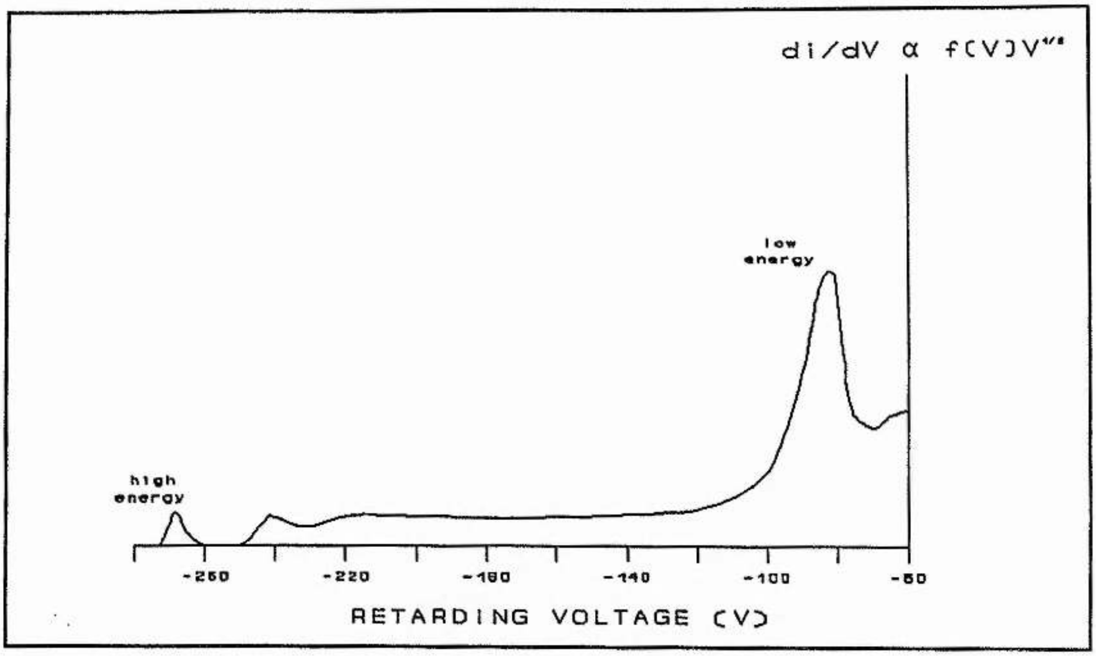


Figure 2.10 (after Gill & Webb, 1977)
Electron energy distribution function close to the CDS/NG boundary. (Discharge of 270 V, 8 mA in helium at 15 torr with an electrode separation of 1 mm).

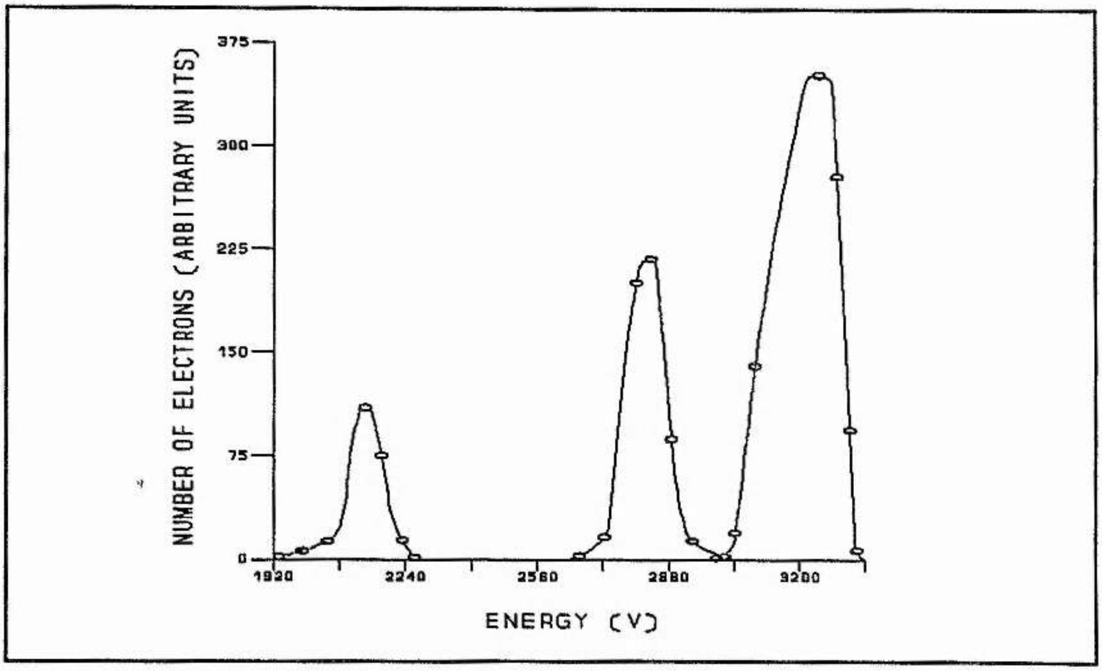


Figure 2.11 (after Chaudri & Chaudri, 1965)
Energy of electrons in an abnormal glow discharge in air at low pressure for three different voltages. In each case the peak energy corresponds to the discharge voltage.

CHAPTER THREE

Glow discharge electron beam guns.

3.1 Introduction.

It is usually possible to obtain electron beams in a glow discharge by progressively reducing the gas pressure and increasing the applied voltage to maintain the discharge. During this process, the discharge moves into the abnormal glow mode (see Figure 2.1) and emission occurs over the entire exposed cathode surface. In the abnormal glow discharge, the increased voltage ensures that the electron collision cross–section in the cathode dark space is much smaller than in the normal glow and the electrons make very few collisions. In addition, the reduced pressure means that there are less molecules to hit, and so, under these conditions, the electrons travel appreciable distances in the gas to form extensive electron beams. If the CDS is in view, it will be seen as a dark sheath of several mm thickness in front of the cathode. The electron trajectories in the CDS are directed normal to the cathode surface and follow the electric field lines in the CDS. The electrode geometry thus determines the shape and focus of the electron beam. Photograph 2.1(d), (e) and (f) shows the formation of an electron beam between planar electrodes as the gas pressure is reduced and the discharge voltage is increased. The discharge covers the front surface of the cathode completely and is only prevented from running off the rear surfaces by the insulating wall of the tube, which almost touches the edge of the cathode. The CDS/NG boundary is curved convex away from the cathode and so the electron beam diverges as it leaves the cathode. In Photograph 2.1(f), the divergent electron beam causes fluorescence on the walls of the tube all the way up to the anode. Conversely, the ions converge as they cross the CDS and produce a reddish pink cathode glow concentrated towards the centre of the cathode. In this planar electrode system, there does not seem to be a distinct transition that leads to the production of electron beams, but this is not the case when the cathode contains a hole of a few mm diameter as in Figure 3.1. Here, when the pressure is above a few torr, the discharge begins in the hollow cathode mode with a voltage of a few hundred volts. As the pressure is reduced, there is a sudden and dramatic change to a high voltage (about 1 kV) and a low current. This corresponds with the formation of a distinct electron beam, which emerges from the hole and leaves a trail of excited molecules as it passes through the gas.

In order to use these effects in a glow discharge electron beam (GDEB) gun, it is necessary to define the beam by limiting the extent of the discharge on the cathode surface; to control the focus of the beam by shaping the field in the CDS; and to locate the anode off the beam axis to allow the beam to reach its full extent. This chapter describes a number of techniques for fabricating GDEB guns. Current/voltage characteristics are presented for GDEB diodes producing electron beams in deuterium. These characteristics show that electron beams are produced in glow discharges which operate in a high impedance mode rather than in the more familiar low impedance mode. The high impedance discharge which produces an electron beam will be called the e–beam discharge. The dependence of I upon V is obtained from the characteristic and the current flow in the e–beam discharge is found to be space–charge limited with a dependence on V^2 at high pressure and on $V^{3/2}$ at low pressure. Mechanisms which could account for this behaviour are proposed. The factors which influence glow discharge electron gun design are discussed.

3.2 Electron beam cathode designs.

Early attempts to produce electron beam discharges for this study, revealed the need for good insulation over the area of the cathode that was not required for e–beam generation. Failure to meet the required level of insulation resulted in intermittent low impedance discharges at the weak points in the insulation and these discharges interrupt the e–beam and overload the power supply. In general terms, the e–beam cathode could be shielded by solid, liquid or gaseous insulators. Of these, liquids can be neglected immediately because of their (usually) high vapour pressures and the limitations they would impose on the orientation of the system. Gaseous insulators are restricted to the operating gas of the discharge at its working pressure. A solid insulator is likely to be necessary in the design and is required to form at least part of the vacuum envelope of any e–beam device.

3.2.1 Solid insulators.

These investigations covered ceramic and glass insulation. Plastics were excluded since they are unsuitable for use in vacuum or low pressure systems for two reasons. First, they contain materials with high vapour pressures, which act as strong sources of contamination. Second, they deform or disintegrate at temperatures much above 100°C.

3.2.1.1 Flame–sprayed insulator.

Flame spraying is a technique which can be used to cover surfaces with a thin layer of ceramic. The system used here has the trade name 'Rokide'. The spray head is a modified oxy–acetylene torch which allows a rod of the ceramic material to be fed into the flame. The nozzle is designed to entrain the molten material in the flame. The ceramic emerges from the nozzle as a molten spray and lays down a layer of the material on the target object. The target is usually rotated to ensure even coverage on all sides. The insulating coating grows thicker as globules of molten alumina hit the surface and solidify. Since the ceramic on the surface is solid before fresh droplets hit it, the structure tends to be porous. Cathodes insulated in this way are shown in Photograph 3.1(b) and (c). Electron beams can be produced from 'Rokide' coated cathodes but the cathode performance is unsatisfactory in two respects. First, the expansion coefficient of the alumina and the molybdenum do not match and the heating of the cathode causes disruption of the coating. The maximum voltage that can be applied before this happens is quite low, in the region of 1.5 kV. Above this level the Rokide coating begins to develop cracks and the discharge concentrates at the breaks, intensifying the local heating to the point at which the coating flakes off. Second, the porosity of the structure can lead to the development of a spray discharge (von Engel 1955, p 207) through the alumina coating. For the devices shown, at voltages above 1.5 kV, emission from the pores in the insulator surface was observed. In essence, the coatings tested were judged to be unsuitable for durable, reliable devices.

3.2.1.2 Pre–formed alumina ceramic.

High purity, alumina ceramic can be cast and fired in a variety of shapes and sizes, and is a common material for the production of vacuum envelopes in the electronic valve industry. It is a durable and robust insulator and it is relatively straightforward to metallise selected areas of the surface, and thus to join ceramics and metals using conventional brazing techniques. Ceramic cylinders were used as simple sleeves to insulate an e–beam cathode in a glass envelope as shown in Photograph 3.1(a). In a typical glow discharge regime, such as is found in hollow cathode light sources, this design restricts the discharge to the cathode hole. In the e–beam mode, where voltages in the region of 5 kV are applied, it is possible to initiate discharges from even the smallest breaks in the insulators. When voltages greater than 3 kV were applied to the devices in Photograph 3.1(a), discharges were observed to occur at the junction of the ceramic sleeve and the glass envelope. As in the 'Rokide' case, e–beams were produced, but only over a limited range of voltage. Ceramic insulators can be more usefully employed in designs like that of Figure 3.2, where the ceramic forms part of the vacuum envelope.

3.2.1.3 Glass.

Glass and metal can be made to form a robust, vacuum tight seal by selecting the particular glass and metal so that the molten glass wets the metal and their respective coefficients of thermal expansion are matched over the temperature range from the melting point of glass to the lowest temperature at which the seal will be used. The glass–metal sealing process was extended in this investigation to provide a glass insulating layer over the complete surface of the cathode. The metal used was a nickel/cobalt/iron alloy (29%/17%/54%), known as Kovar, and the glass was an expansion–matched sealing glass. The cathode was formed from a Kovar rod with an axial hole drilled into one end. After coating the rod with glass it was sealed into a glass bulb which had a tungsten lead–through as anode (see Figure 3.1). Hollow tubes made from Kovar were used in the arrangement of Figure 3.3, in which the shaped glass flare on the cathode was seated on an opening in a powder glass base. The different expansion coefficients of the two glasses precluded joining them together directly. This e–beam cathode design is used as a trigger in one of the switches described in Chapter 5.

3.2.2 Gaseous insulator.

For obvious reasons, the only gas that can be used as an insulator in a glow discharge device is the working gas. The Paschen law, described in Chapter 1, shows that it is possible to use a gas as a high voltage insulator between two electrodes by arranging them in an appropriate geometry. The e–beam discharge appears in the low pressure region on the left hand side of the Paschen curve (§1.3.1). A high breakdown voltage is thus achieved by moving the anode close to the cathode surface to reduce the pd product. The breakdown voltage, as seen from Figure 1.3, can easily be made larger than the applied voltage, up to the point where the electric field at the cathode surface is strong enough ($\sim10^5$–10^7 V/cm) to cause field emission. An aperture in the anode acts to increase the pd product locally and thus a discharge occurs from a selected area of the cathode. Such an arrangement is shown in Figure 3.4 with the anode closely surrounding the cathode at a distance which allows an e–beam discharge to be sustained.

The main advantage of the gaseous insulator is that it is self–repairing if any spurious discharge should occur. The solid insulator necessary to support the electrodes can be placed well away from the discharge region and is therefore protected from sputtered cathode material. In systems where the solid insulator is close to the discharge region, precautions against the development of continuous conducting films between anode and cathode, along the insulator surface, can be taken. However, it is more difficult to prevent deposited metal films from changing the shape of the electric field at the cathode and thereby altering the shape of the e–beam. The gas–insulated cathode represents a major improvement on the glass–insulated cathode since it can be designed to operate at much higher voltages and will withstand much higher temperatures without damage. A secondary advantage arises from the convenience of creating new electrode designs. Modifications are easily made to the metallic cathode and anode structures while retaining the same glass or ceramic insulator design. A range of possibilities is illustrated in Figure 3.5.

3.3 Electrical characteristics.

This section explores the electrical characteristics of the e–beam discharge over a range of pressures in deuterium using gas–insulated GDEB guns of the designs shown in Figure 3.4 and 3.5. Three approaches to the measurement of the *IV* characteristic are followed in the present investigation. The first two, involving manual adjustment of the voltage level, are found to be of limited accuracy because of the rapid increase in impedance following an increase in power input to the cathode. The results show a drop in current with increasing power input. The most obvious cause of this change in impedance is a reduction in gas density in the cathode region as it heats. A simple analysis of the thermal situation at the cathode confirms that the reduction in gas density corresponds to the increase in cathode temperature due to the power input. In the third method an AC supply is used to drive the discharge, and voltage and current are monitored simultaneously for display on an oscilloscope. The shape of the AC characteristic is recorded photographically. This third method provides a good approach to measuring the *IV* characteristic at a constant gas density.

3.3.1 Manual methods of *IV* measurement (1).

The manual methods to be described are all of a pseudo–DC variety. The experimental arrangement (1) is shown in Figure 3.6. The power is delivered by a switched mode supply with an adjustable output up to 20 kV at 80 mA. It maintains the selected voltage at a constant level and allows the current to vary according to the impedance of the load. The device to be tested is connected in the circuit while still attached to the pumping system described in Appendix B. As part of the process of outgassing and cleaning the cathode, a discharge is established in the device, and voltage and current are recorded. When the impedance of the discharge is constant over three trials the device is considered to be conditioned. The voltage across the discharge is recorded using a Fluke 8021B DVM with a 1000:1 high voltage probe. The current through the tube is measured using an AVO 8 multimeter or a second Fluke 8021B DVM.

3.3.2 Results obtained by manual method (1).

Immediately after the e–beam discharge is established, its current falls rapidly, indicating a corresponding increase in the impedance of the discharge. Graphs of *I* against *V* for the cylindrical hollow cathode CHK1 of Figure 3.4 are shown in Figure 3.7. Results at 0.6 torr for the lower graph were obtained by selecting a current level and increasing the voltage to maintain the current at that level until it became stable. As the current level in the device was increased it took longer for the discharge to stabilise. At the highest point of 5 mA it required about 5 minutes. This time–scale is consistent with an increase in temperature of the cathode due to discharge heating. A simple thermal analysis of the effect is given in §3.3.5. The graph at 0.6 torr shows a decrease in slope as the power input is increased. The reducing impedance of the discharge is caused by the decreasing gas density in the cathode region as the temperature increases.

In order to obtain *IV* characteristics free from time–dependant thermal effects, cathode heating must be reduced. The ideal measurement method would be to apply a known voltage to the device and to measure the current through it when the discharge is established, but before substantial thermal effects have set in. To achieve something close to this, the following procedure was adopted. The discharge was established at a given voltage level, and the supply was then switched off. After a period of at least 1 minute, to allow the cathode to cool, the supply was switched on again. The voltage rose to the predetermined level and the current meter reading was recorded as quickly as possible. A new voltage level was selected and the process repeated. Results taken in this way at 0.5 torr gave the upper graph in Figure 3.7. It does not show a decrease in slope as the voltage is increased. This version of the manual *IV* measurement method, although it is a move in the right direction, gives results which are limited by the response times of the current meter and the observer. An AVO 8 multimeter and a Fluke 8021B DVM are both unsatisfactory above the level of

5 mA in the graph (Figure 3.7) at 0.5 torr. An instrument with fast response and the ability to store the peak value of the measurement is required.

3.3.3 Manual methods of *IV* measurement (2)

The experimental arrangement (2) is also as shown in Figure 3.6. The device to be tested is connected in circuit while attached to the pump system (Appendix B). In arrangement (2), the voltage and current signals are sent to a chart recorder, JJ Instruments PL2000, in order to record the *IV* characteristic as the power supply voltage is increased manually. Unfortunately, the shape of the trace depends on the response time of the chart recorder in relation to the rate of rise of voltage applied. The maximum speed of the chart recorder (JJ Instruments, 1985) on the voltage axis is 0.5 ms^{-1}. For a typical sensitivity of 500 V/cm, the corresponding maximum rate of rise of voltage is 500 V per 20 msec. A circuit to produce a ramp voltage with this rate of rise could have been constructed, but this and other forms of DC method were discontinued in favour of the AC method described in §3.3.7. The chart recorder was used to produce a sample plot (Figure 3.8) and to provide data to estimate the change in gas density which causes the drift in discharge operating conditions.

3.3.4 Results obtained by manual method (2).

The sample trace shown in Figure 3.8 was obtained by increasing the voltage in steps every 30 sec. In each interval, the voltage was manually increased to its new level at a steady rate in about 20 sec. The current then fell during the next 10 sec to give the 'sawtooth' effect shown in the trace. As can be seen in Figure 3.8, the magnitude of the fall increased with increasing power input until the current reached a plateau level. The net effect is that the plateau current is lower than is appropriate for the selected (cold) gas pressure, especially at the higher voltage levels. This is consistent with gas density reduction in the cathode region due to discharge heating. It is shown in the following section that the decrease in gas density at the cathode results from the power input to the cathode.

3.3.5 Thermal effects on the e–beam cathode.

An estimate of the heating effect in the cathode can be obtained from a simple model of the heat flow in the cathode. A drawing of the cathode is shown in Figure 3.4. The cathode rod forming the e–beam emitter is made of molybdenum. The rate of increase of temperature of the rod is given by

$$\frac{dT}{dt} = \frac{P_I}{MS} \ , \qquad 3.1$$

where P_I is power input, M is the mass of the rod and S is the specific heat capacity of its material. This rate of increase assumes that power losses are negligible. In the case considered here, the cathode is surrounded by an alumina sheath and the power lost by convection to the gas is likely to be small. The power lost by radiation to free space is given by

$$P_R = A \varepsilon \sigma T^4 \quad , \qquad 3.2$$

where P_R is radiated power, A is surface area, ε is emissivitty (estimated to be 0.3 for the molybdenum cathode), σ is Stefan's constant and T is the temperature of the cathode. At a temperature of 500 K, equation 3.2 gives a radiated power of 1 W. Once again the presence of the alumina sheath will reduce this figure markedly. The indications are that most of the power supplied to the cathode will be removed by conduction through the support pin. We can calculate the temperature gradient needed to drive the heat through the support pin. This is given by

$$\delta T = \frac{P_I \, l}{\kappa A} \quad , \qquad 3.3$$

where P_I is power input, l is length, A is the cross-sectional area and κ is the conductivity of the material. For molybdenum, κ is 1.35 W cm^{-1} K^{-1} at about 373 K. The final equilibrium temperature of the cathode will be δT above the ambient temperature. Integration of equation 3.1 gives the time t taken to reach the equilibrium temperature. In practice, the time to equilibrium is found to be greater than t by about a factor of five because of the ongoing reduction in power input to the cathode as the gas density at the cathode decreases. The reducing gas density at the cathode and the corresponding drop in current at a given voltage, can be compensated for by increasing the pressure in the envelope. At constant power input, the ratio of the starting pressure to final pressure is equal to the ratio of the starting temperature to final temperature of the cathode, since for equal volumes

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} = Nk \qquad 3.4$$

where P is pressure, T is temperature, N is the number of molecules, and k is Boltzmann's constant. The change in gas pressure can thus be used as a crude thermometer. A particular example is provided by the cathode of Figure 3.4, operating with a voltage of 3 kV, and a current of 3 mA at a starting pressure of 0.4 torr. The power input is about 10 W and the radiated power is thus less than 10% of the conducted power. The equilibrium temperature given by equation 3.3 is 560 K. The final pressure required to stabilise the current at 3 mA is 0.72 torr. The operating temperature calculated from this change in gas density is 520 K. This is in good agreement with the equilibrium temperature calculated from the heat flow.

3.3.6 Summary of manual methods (1) & (2).

The main difficulty with the measurement of *IV* characteristics using the methods in §3.3.1 and §3.3.3 is that the power input to the cathode from the discharge causes its temperature to rise during the measurement. This causes a decrease in the gas density. As the results show, the operating point drifts markedly with time after ignition of the discharge. This drift tends to defeat the aim of observing the characteristic at a fixed gas density. Historically, this problem has arisen in all measurements of glow discharge properties and is acute in the abnormal glow at high voltages. The common method of dealing with it is to design a cathode with a water cooling system which can remove the heat generated by the discharge and keep the cathode at a constant temperature during the measurements.

The meters or chart recorder described in §3.3.1 and §3.3.3 cannot respond in a time short enough to eliminate the gas density drift. An alternative approach which overcomes this difficulty is to use an AC method to drive the discharge and to use voltage and current signals from it to drive the XY input of an oscilloscope (CRO). The instantaneous record of *IV* which the trace gives, can be photographed for subsequent analysis.

3.3.7 AC method of *IV* measurement.

The third experimental arrangement (see Figure 3.9) uses the AC mains supply to provide a controlled, repeatable voltage to the device under investigation. The circuit consists of a Variac for voltage control, a transformer, a high voltage diode and a current limiting resistor. The device sees a half–rectified sine wave at 50 Hz, whose magnitude is controlled by the Variac. The voltage across the discharge is measured by a Tektronix P6015 high voltage probe with a 1000:1 ratio, and the current is measured as the voltage across a 994 ohm Welwyn wirewound resistor. These signals are fed to the *X* and *Y* inputs of a cathode ray oscilloscope (CRO) and they produce a trace typically like the one of Photograph 3.2.

The procedure for obtaining such a trace is as follows. Gas is admitted to the device until it has reached the required pressure. The voltage applied to the device is adjusted and the sensitivity of the CRO is optimised. The power supply is switched off to allow the device to cool to room temperature (~18°C). After an off period of at least three minutes, the power is applied and a photograph of the trace is taken immediately. The time interval between switch–on and shutter release is less than 0.5 sec. The shutter speed is set at 1/8 sec and the photograph records 6 excursions to full voltage. A complete record of the characteristic is thus obtained in less than 30 cycles. This is much better than the DC case, since the voltage is not applied for 50% of the time. During the on–time, the instantaneous power P at phase angle θ is given by the product of the instantaneous voltage V and instantaneous current I. Assuming a resistive load,

$$V = V_p \sin\theta \qquad 3.5$$

$$I = I_p \sin\theta \quad , \qquad 3.6$$

where V_P and I_P are the peak AC values applied. Integrating between 0 and π to obtain the power delivered during one on–period gives

$$P = \frac{1}{2} V_P \, I_P \, \pi \quad . \tag{3.7}$$

This is half the power delivered during the same time (half period) for the case in which the DC level is V_P. The heating effect of the discharge in the AC method is therefore only 25% of the heating effect of the methods used in §3.3.1 and §3.3.3. In fact, since the discharge current depends on V^n where $n>1$, the current waveform will enclose an area smaller than in the resistive case assumed above and the power delivered to the cathode will be somewhat less than 25% of the DC case. The AC method was therefore used for measuring the *IV* characteristic of glow discharge electron beam diodes for the rest of this investigation.

A further, large reduction in cathode heating could be achieved by the use of a zero voltage switch on the input of the transformer of Figure 3.9, arranged to allow one cycle of the mains waveform to be applied on command. This would allow one *IV* characteristic to be recorded on the oscilloscope, with a reduction in heating by up to 20 times. Limiting the heating in this way would enable studies of temperature effects to be made with greater precision.

3.3.8 Results obtained by AC method.

Typical *IV* characteristics are shown in Photographs 3.2 and 3.3. The curve begins at the origin with *I* and *V* equal to zero. As the voltage increases, no current flows until the breakdown voltage is exceeded, at which point the current jumps above zero. Once the current is established, it climbs smoothly as the voltage increases until the maximum voltage set by the Variac is reached. The current then falls back close to its original track and drops evenly to zero. Close inspection of the photographs shows that there is a definite hysteresis in the trace, which becomes more pronounced as the pressure is reduced. The $V_{increasing}$ limb of the trace is identified by the discontinuity at striking and is, therefore, the lower part of the curve. The $V_{decreasing}$ limb has higher values of current for a given voltage. It may be that ion pumping towards the cathode is significant during the $V_{increasing}$ trace and that the $V_{decreasing}$ trace corresponds to a higher gas density at the cathode, in line with the general trend of the characteristic to have higher currents at higher pressures. It might also be that surface effects cause a change in emission from the cathode during the cycle but, if this is the case, the surface recovers during the off-cycle as evidenced by the lack of drift in the 6 superimposed cycles on the photograph. For the purposes of this study, data was taken from the $V_{increasing}$ trace as being representative of the gas density indicated by the pressure meter.

Data is extracted from a photograph by carefully scribing the $x = 0$ line vertically followed by a set of lines parallel to the $y = 0$ line at convenient points on the graticule. The coordinates of points on the curve are measured with Vernier callipers. The coordinates are converted to V (volts) and I (amps) using the measured graticule spacing and the sensitivity of the CRO for each axis. The data derived from the photographs of the *IV* characteristic of cathode CHK1 (Figure 3.4) are presented in Figure 3.10 with pressure as a parameter. The curves are shifted to higher voltages as the pressure is reduced and, at pressures below 0.3 torr, each curve has two sections with a transition region between them.

3.4 Analysis of the *IV* characteristics.

The *IV* characteristic of a glow discharge provides an important insight into the physical mechanisms of the discharge. In the normal glow, as discussed in Chapter 2, the voltage dropped across the discharge is small and remains nearly constant over many orders of magnitude of current. In fact, the discharge behaves as if it has a negative resistance and the current grows without limit if a ballast resistor is not included in series with the power supply. In contrast, the e–beam discharge has a high voltage drop and a positive resistance, allowing it to be run without a ballast resistor. The e–beam discharge is thus a high impedance discharge and high voltages, generally in the range from 1 kV to 10 kV and above, produce currents in the milliampere range. Its *IV* characteristic has a distinct concave–upwards shape which is maintained until the device undergoes a transition to a low impedance mode, or until the limit of the power supply or electrode design is reached. The general shape of the *IV* characteristic with its concavity upwards, suggests that the curve can be described by a power law of the form

$$I \propto V^{n} \quad , \tag{3.8}$$

where $n > 1$. In previous work (Holliday & Isaacs, 1971; McClure, 1961) with glow discharges conducting in the 'e–beam mode' (§3.1), experimental results yield empirical relationships between I and V of the following form,

$$I \propto V^{2.5} \quad , \tag{3.9}$$

and

$$I \propto V^{2.9} \quad . \tag{3.10}$$

It is well known that the Child–Langmuir theory of space charge limited electron current in a vacuum diode gives an *IV* characteristic of the form

$$I \propto V^{\frac{3}{2}} \quad , \tag{3.11}$$

which is confirmed by experimental results obtained with vacuum diodes. Thus, we see that the empirical values of n in the *IV* characteristic of a diode can lie between 1.5 and 2.9 depending on whether the diode is a vacuum diode or a gas diode. Whilst theory of the *IV* characteristic of vacuum diodes is established as definitive, theoretical developments for gas diodes generally are in a more primitive state and, for gas diodes operating in the e–beam mode, theory appears not to have progressed beyond statements of the empirical forms given in equations 3.9 and 3.10. In order to explain the mechanisms of the e–beam discharge, we will apply the theory of Child–Langmuir and show that a law of $V^{3/2}$ is applicable when the pressure is below a certain range. The theory requires modification to allow for mobility limited charge motion (Chapman, 1980) and a law of V^2 becomes appropriate. Before embarking on a discussion of the law relating I and V for the data presented in this thesis, it is worth recalling the theoretical situation as regards the space charge limitation of current.

3.4.1 Space charge limited current in vacuum.

The simplest case of space charge limited current flow occurs between parallel plate electrodes of separation d and applied potential V, arranged so that the field is uniform between the electrodes and the trajectories of the charge carriers are straight lines. It is customary to consider one plate to be an emitter of electrons and for a vacuum to exist between the plates so that the model represents the situation in a vacuum diode with a thermionic cathode. It is not necessary for the charge carriers to be electrons however, and von Engel (von Engel, 1955, p 75) describes a Kunsman electrode which can emit ions. Naturally, the mass of the particle has a direct influence on the flow of charge in the diode, and mass is introduced in the development of the equation relating current density and potential when the energy term is considered. The variation of potential V with distance x from the cathode in this system is governed by Poisson's equation,

$$\frac{d^2V}{dx^2} = -\frac{\rho}{\varepsilon_0} \quad , \qquad 3.12$$

where ρ is the space charge density and ε_0 is the permittivity of free space. The current density vector j is related to ρ by

$$j = \rho v \quad , \qquad 3.13$$

where v is the particle velocity.

Two other relations apply, the equation of continuity,

$$\nabla \cdot j = 0 \qquad 3.14$$

and the energy equation,

$$\frac{1}{2} m v^2 = e V \quad , \qquad 3.15$$

where e and m are the charge and mass of the particle. It is assumed that v is small compared with the velocity of light. For charge carriers of one sign only, these relations combine to give the differential equation,

$$\frac{d^2V}{dx^2} = -\frac{j}{\varepsilon_0}\left(\frac{m}{2e}\right)^{\frac{1}{2}} V^{-\frac{1}{2}} \quad . \qquad 3.16$$

In the simple case of rectilinear flow considered here, this equation can be solved on the assumption that the charge emitter has a uniform potential, the emission velocities are zero and that there is no limitation on the flow except that due to space charge. Solving the equation and adding the boundary conditions for a parallel plate electrode system gives

$$j = \frac{4}{9}\, \varepsilon_0 \left(\frac{2e}{m}\right)^{\frac{1}{2}} \frac{V^{\frac{3}{2}}}{d^2} \;, \qquad 3.17$$

or

$$j \propto V^{\frac{3}{2}} \;. \qquad 3.18$$

This equation is known as the Child–Langmuir equation or the 'three–halves power law'. The solution of the equations for non–planar electrode geometries is difficult, but it is interesting to note that current density still depends on $V^{3/2}$. Ivey (Ivey, 1954, p 152) points to a number of studies (e.g. Langmuir & Compton, 1931) confirming that the three–halves power law is valid in any electrode system. Ivey also discusses a number of factors which have an influence on the validity of the Child–Langmuir equation in thermionic cathode systems. Of these, the relevant factors for a glow discharge electron beam arrangement are:

(i) Positive ions.

In a glow discharge, positive ions are a necessary part of the discharge sustaining process. Since they tend to have lower velocities than the electrons and a correspondingly higher space charge density ($j = \rho v$), one positive ion can neutralise the space charge effect of many electrons. They would therefore tend to increase the observed current to a value greater than that predicted by the Child–Langmuir equation.

(ii) Initial velocities.

In practice, very few of the electrons emitted have initial velocities of zero. Electrons emitted with non–zero initial velocities will tend to increase the observed current.

(iii) Relativistic effects.

At an anode voltage of 30 kV, electrons are accelerated to a velocity one third that of light and relativistic effects become increasingly significant. The relativistic electron velocity, v, (Cobine, 1941, p 553) is given by

$$v = c\left(1 - \frac{1}{\left(1 + \frac{eV}{mc^2}\right)^2}\right)^{\frac{1}{2}} \qquad 3.19$$

The increase in mass acts to reduce the current below the level expected.

(iv) Electron reflection and secondary emission.

Electron reflection and secondary emission at the anode or target increases the space charge density near the anode and causes the observed currents to be less than predicted.

It should be noted that the Child–Langmuir law applies to charges of either sign. However, it is not immediately clear how the presence of gas will effect the law through collisions or how the presence of positive and negative charges together with the factors (i)–(iv), above, might change the law. An empirical expression based on data collected in the present studies is developed in the next section.

3.4.2 The empirical *IV* laws.

The purpose of this section is to determine the law relating I and V for the data obtained in §3.3.8. The Child–Langmuir equation described above, indicates that the relationship between I and V for the e–beam discharge is likely to be of the form

$$y = a\,x^n \quad . \qquad 3.20$$

This equation can be reduced to the form $y = mx + c$ by taking logarithms to a base 10 of both sides to give

$$\log y = n \log x + \log a \quad . \qquad 3.21$$

If the data conforms to $y = ax^n$ then plotting *log y* against *log x* produces a straight line graph. A direct application of this approach to the data obtained from the *IV* curve photographs leads to values of n which are different for each pressure. The reason for this can be seen from an inspection of the curves in Figure 3.10. The fact that the curve is offset along the V axis by a voltage V_0, which is different for each pressure, means that the law of the curve is actually

$$I = a\,(V')n \quad , \tag{3.22}$$

where V' is $(V_{MEAS} - V_0)$. Obtaining the value V' is equivalent to shifting the curve to the origin and allows n to be determined independently of pressure. The intercept voltage is equivalent to the minimum voltage required to keep a current flowing and it can be obtained directly from the *IV* characteristic photograph at each pressure. Once the curve is shifted to the origin, the law relating I and V' can be determined from the $\log I$ versus $\log V'$ graph. A set of $\log I$ versus $\log V'$ graphs are shown in Figures 3.11 & 3.12. Inspection of these graphs indicates that the upper portions of the curves, *ie.* high current densities, have the same slopes. Figure 3.11 covers the pressure region above 0.25 torr and Figure 3.12 covers the region below 0.25 torr. In practice, rather than measuring the slopes of the graphs, it is more convenient to feed the logarithms of I and V' to a computer programme which can calculate a and n directly from the data, based on the approach outlined in Appendix C.

As it turns out, the experimental results indicate that there are two laws. At pressures below a critical pressure region, I is proportional to $V^{3/2}$. At pressures above this critical region, I is proportional to V^2. The three–halves dependence on voltage at lower pressures indicates that the current in this region is space charge limited in accordance with the Child–Langmuir equation. It remains now to consider the phenomena occurring in the higher pressure region where I is proportional to V^2.

3.4.3 Space charge limited current (mobility).

We shall now consider the pressure region where the IV characteristic is of the form $I \propto V^2$. As has been seen in the derivation of the Child–Langmuir equation (§3.4.1), the current in the diode is determined by the movement of charges in the electric field E. In the derivation of the Child–Langmuir equation, the charges are assumed to be falling freely (without collision) in the field and their velocity is given by

$$v = \sqrt{\frac{2e}{m}V} . \qquad 3.23$$

At higher pressures the charges make collisions as they move in the field and thus acquire a drift velocity in the direction of the electric field E given by

$$v = \mu E \ , \qquad 3.24$$

where μ is the charge mobility. The current density j is then given by the continuity equation

$$j = ne v = ne \mu E \quad . \tag{3.25}$$

Combining 3.24 with Poisson's equation gives

$$E\,dE = \frac{j}{\mu \varepsilon_0}\,dx \quad . \tag{3.26}$$

Integrating 3.25 with respect to x gives

$$E = \left(\frac{2jx}{\mu \varepsilon_0}\right)^{\frac{1}{2}} = \frac{dV}{dx} \quad . \tag{3.27}$$

Integrating again gives the potential difference, V, between the electrodes

$$V = \frac{2}{3}\left(\frac{2j}{\mu \varepsilon_0}\right)^{\frac{1}{2}} x^{\frac{3}{2}} \quad . \tag{3.28}$$

The current density is, therefore,

$$j = \frac{9}{8}\mu \varepsilon_0 \frac{V^2}{d^3} \quad , \tag{3.29}$$

which agrees with the empirically determined form, $I \propto V^2$.

We now appear to have explanations for both the $V^{3/2}$ and the V^2 laws for the IV characteristics of the e–beam discharge. In each case, the experimental results are consistent with the proposal that the e–beam discharge current is determined by the flow of charges under the influence of their own space charge in response to an applied potential. In the following section, this proposal will form the basis of a description of the e–beam discharge.

3.4.4 The glow discharge in the e–beam mode.

Observations of the glass–insulated GDEB guns of Figure 3.1 reveal that a distinct sheath is formed in front of the cathode surface. This sheath is the cathode dark space (CDS) discussed in §2.2.3, where it was described as a region with a large positive space charge. This is illustrated in Figure 2.2(iv), which shows the space charge density as a function of axial position between the electrodes. In the GDEB gun designs of Figures 3.4 & 3.5, the anode is spaced from the cathode by a distance of several mm and the discharge is restricted to the region of the aperture in the anode. For the pressures and voltages at which the e–beam discharge appears and at which the *IV* characteristics were obtained, it is reasonable to assume that the CDS occupied the space between cathode and anode. We can now propose that the experimental laws relating I and V for the e–beam discharge arise from the space–charge limited flow of ions in the cathode dark space of the discharge. In the low pressure case, below 0.25 torr, the ions fall freely as they cross the CDS and a $V^{3/2}$ law is applicable. In the high pressure case, above 0.25 torr, the ions are colliding with molecules in the CDS and a V^2 law results.

Positive space–charge limited flow also occurs in the CDS of the normal glow discharge (M.I.T., 1943, p 211). However, the current flow through the normal glow discharge is not observed to be space–charge limited, and the reason for this is that the CDS width can change in response to discharge conditions. As can be seen from equations 3.17 and 3.29, if d can change, then the discharge current is constrained only by the external circuit. In the GDEB gun of Figure 3.4 however, the CDS width is restricted by the position of the anode and current flow is thus observed to be space–charge limited. Positioning the anode in the CDS would usually cause the discharge maintaining voltage to rise to such a high value that current flow would cease (Figure 3.13), but, in the e–beam discharge, the aperture in the anode permits the flow of ions from the NG to maintain the discharge.

A schematic of the e–beam discharge is shown in Figure 3.14. As in a normal glow discharge, it is assumed that all the electrons emitted from the cathode are generated by the action of positive ions or fast neutral atoms on the cathode surface and that photoemission is negligible because of the geometry. The emitted electrons travel through the CDS without creating ions and form the electron beam or negative glow (NG) extending away from the anode aperture. As a result of the low electron collision cross–section in the CDS, all the ions which reach the cathode originate in the electron beam (NG) and diffuse into the cathode region from there. The ions move through the CDS under mobility or free–fall space–charge limitation to complete the discharge cycle.

3.5 Vacuum electron guns.

In general, electron guns are used to produce, accelerate and focus free electrons to form a beam (or beams) which can then be used for microscopy, heat treatment, welding, machining, excitation of phosphors, microwave generation, etc. Each of these applications has its own requirements for beam properties and these requirements strongly influence the design of the electron gun to meet the limitations imposed by the transport of free charges.

Conduction in a metal is carried by electrons moving through a lattice of positive charges so that charge neutrality is maintained. In an electron beam, however, each electron experiences the force produced by the presence of the surrounding space charge. The current density j in the space between parallel plates of area A and separation d in a vacuum is related to the voltage between the plates by the Child–Langmuir equation (developed in §3.4.1). The current I is thus given by

$$I = \frac{4}{9}\,\varepsilon_0 \left(\frac{2e}{m}\right)^{\frac{1}{2}} \frac{A}{d^2}\, V^{\frac{3}{2}} \quad . \qquad 3.30$$

For a given voltage V, the current I depends on the value of a constant consisting of a geometrical factor and fundamental constants. This constant provides a 'design' term in the equation since electrode area and gap spacing are at the discretion of the designer. It is given the name perveance (K). As

Langmuir and Compton demonstrated (Langmuir & Compton, 1931), the 3/2 law holds for electrodes of any geometry. Thus, in any diode system, the perveance is defined as

$$K = \frac{I}{V^{\frac{3}{2}}} \quad . \qquad 3.31$$

The equation shows that, in order to maximise the current available at a given voltage, the perveance of the electrode system must be maximised. The perveance of a vacuum diode is analogous to the conductance G of a metal, given by

$$G = \frac{I}{V} \quad . \qquad 3.32$$

From equation 3.30, increasing the area or decreasing the length of the vacuum gap increases the perveance, just as increasing the area or reducing the length of a piece of metal increases its conductance.

One of the major and more demanding applications for vacuum electron guns is in the generation of microwaves. The demands that this application puts on the properties of an electron beam will now be outlined. The energy of the electron beam is determined by its voltage. The current in the beam is then set by the perveance of the gun. It is generally desirable to have a large current at low voltage, so the perveance must be maximised. A further constraint on the beam is imposed in travelling wave tube design, where the beam radius is determined by the desired frequency of operation. This introduces the beam current density as an important parameter since the gun must be designed to produce a beam of the required radius. As will be seen later in this section, the challenge in electron gun design is to produce an electron beam with a high perveance and a high current density, simultaneously.

An overview of electron guns and beams is shown graphically by Figure 3.15. The perveance of the gun is plotted against maximum beam current density. The diagonal line L/r represents the axial distance of travel in units of beam radii for the beam to expand to twice its radius plotted as a function of perveance. Applications above this line have beam expansions which are not consistent with the required perveance and a method of limiting the expansion of the beam is needed.

A range of electron guns is shown in Figure 3.16. Guns for electron microscopes (Figure 3.16(b)) in which only very small currents are required, can utilise the electrons from a hot tungsten filament and focus them with electric and magnetic lenses. Guns for cathode ray tubes (Figure 3.16(c)) produce currents up to tens of mA (Moss, 1968). They use flat circular cathodes and employ beam limiting stops, so that only a small fraction of the current, perhaps less than 5%, is finally focused onto the screen. In contrast to this, guns for klystrons and other high power microwave tubes (Figure 3.16(a)) deliver more than 99.9% of the emitted electrons to the output beam. In order to produce the desired microwave output, these devices require beams with current densities of 1–500 A/cm^2 at energies of 1–50 kV which travel through the appropriate structures for distances of 100 – 1000 beam diameters. The electrons in beams with these current densities experience space charge repulsion which is strong enough to cause them to expand by a factor of two in travelling a path length of 1 – 10 beam diameters. This beam spread makes some kind of focusing essential to maintain current density and thereby introduces particular requirements which the optical quality of the gun must satisfy.

In order to provide a theoretical basis for electron gun design, Pierce (Pierce, 1949) considered only those situations for which exact solutions of the space charge equations for electrons leaving a space charge limited cathode are known, that is, infinite parallel planes, concentric cylinders and concentric spheres. The case of most interest for klystron and TWT design is that of flow from a spherical cathode to form a converging cone of electrons. The electrons emerge from the gun as a solid beam with cylindrical symmetry. Pierce treats this as a segment of flow between concentric spheres as shown in Figure 3.17. It is only possible to treat mathematically an electron gun design in which the flow is rectilinear, laminar or homocentric; in other words, in guns where the electrons are emitted in directions which are normal to the cathode surface and thereafter travel in straight lines. When the electrodes are segments of concentric spheres, the beam is brought to a focus at the centre and enters a magnetic focusing system. Unfortunately, the anode segment must have an exit hole for the beam and this introduces a major constraint to the performance of the gun. Attempts to increase the perveance of the electrode design by decreasing the electrode spacing are penalised by a concomitant increase in anode hole size. The influence of the hole on the field in the inter–electrode space creates an electrostatic lens (Davisson & Calbick, 1931) which increases the divergence of the beam. Electron gun design is therefore an attempt to find the best compromise between these competing factors.

In order to reduce spread of the beam in the gun, the charge–free regions outside the beam must contain certain fields which mimic the effect of the missing space charge and thus oppose the radial expansion of the beam. Pierce (Pierce, 1949, p 171) has shown that this can be accomplished by introducing a surface at cathode potential inclined at 67.5° to the edge of the beam. Such a gun is shown in Figure 3.18(a). The curves of perveance shown in Figure 3.18(b) relate to this design. The perveance is shown as a function of the half angle of the cone of flow, and the ratio of cathode–anode spacing to cathode radius. From these curves it can be seen that, in order to obtain a high value of perveance, it is necessary to have a large cone angle and/or a small cathode–anode spacing. In decreasing the cathode–anode spacing, we note that the anode moves into the cone of electron flow and the hole must necessarily become larger to avoid intercepting the beam (Figure 3.19). Unfortunately, this requires removal of the very metal that provides the field to accelerate the beam. The option of decreasing the cathode–anode spacing is therefore limited in what it can achieve in terms of high perveance. Attempts to increase the perveance by increasing the cone angle are only partially successful because beam aberrations are introduced. These aberrations increase the diameter of the beam at the focal plane and thus reduce the current density. Also, the high divergence increases the difficulty of injecting the beam into the focusing structure of a klystron or TWT. These factors combine to limit the maximum perveance that can be achieved in practice. High power klystrons have a maximum perveance of about $2 \cdot 10^{-6}$. Other high power microwave tubes achieve a maximum perveance of about $10 \cdot 10^{-6}$. In general terms, the higher the perveance the more difficult gun design becomes (Pierce, 1949, p 168).

3.5.1 Electron beam focusing methods.

Once an electron beam has been created and converged to a desired radius, it is necessary to apply some force to keep it in shape while it travels through the succeeding structure. Electrostatic or magnetic means can be used to do this. It is the intention here to introduce only the use of an axial magnetic field in the mode proposed by Brillouin (Brillouin, 1945), since it is simple and widely used. The beam of electrons injected into the magnetic field, move in helical paths in the cylindrical beam. In the ideal case, the centrifugal force F_c and the electrostatic force F_e, are in balance with the magnetic force F_m and

$$F_c + F_e = F_m \quad . \qquad 3.33$$

Substituting the expressions for the forces,

$$\frac{I_0}{2\pi\varepsilon_0 v_0}\frac{1}{r} + m r \dot{\theta}^2 = -q r \dot{\theta} B_0 \quad , \tag{3.34}$$

where $\dot{\theta}$ is angular velocity. Equation 3.34 can be rewritten in terms of the cyclotron frequency $\omega_c = \eta B$ and the plasma frequency $\omega_p = (\eta\rho/\varepsilon_0)^{1/2}$ to give

$$\dot{\theta}^2 + \omega_c \dot{\theta} + \frac{1}{2}\omega_p^2 = 0 \quad , \tag{3.35}$$

so

$$\dot{\theta} = \frac{-\omega_c \pm \sqrt{\omega_c^2 - 2\omega_p^2}}{2} \quad . \tag{3.36}$$

This has real solutions when

$$\omega_c = \sqrt{2}\,\omega_p \quad . \tag{3.37}$$

Thus, the applied magnetic field B must be greater than or equal to the 'Brillouin field' B_B, given by

$$B \geq B_B = \frac{\sqrt{2}\,\omega_p}{\eta} \quad , \tag{3.38}$$

in order for smooth flow to result.

3.5.2 Space charge forces in electron beams.

Assume that the beam is substantially cylindrical with an energy corresponding to an axial voltage V_a, and that conditions of laminar flow exist so that the space charge produces an electric field only in the radial direction. The field acting at the circumference is

$$E_{r_0} = \frac{q}{2 \pi \varepsilon_0 r_0} = \frac{I_a}{2 \pi \varepsilon_0 v_a r_0} , \qquad 3.39$$

where q is the charge per unit length, I_a is the total beam current and r_0 is the beam radius.

Within the beam, the charge per unit length, q, is

$$q = \frac{J_0 \pi r^2}{v_a} \qquad 3.40$$

and the current density, J_0, is

$$J_0 = \frac{I_a}{\pi r_0^2} . \qquad 3.41$$

The space charge field at radius r is given by

$$E_r = \frac{q}{2 \pi \varepsilon_0 r} = \frac{I_a r}{2 \pi \varepsilon_0 v_a r_0^2} . \qquad 3.42$$

The field inside and outside the beam is shown in Figure 3.20. The potential difference V_r between the beam axis and the beam edge can be obtained by integrating equation 3.42 from $r = 0$ to $r = r_0$ to give

$$V_r = \frac{I_a}{4 \pi \varepsilon_0 v_a} = \frac{1}{4 \pi \varepsilon_0 \sqrt{2 \eta}} \frac{I_a}{\sqrt{V_a}} , \qquad 3.43$$

where $\eta = e/m$. In a beam of 1 A at 10 kV the value of V_r is 150 volts. An electron that has traversed from the centre to the beam edge therefore, will have a radial velocity v_r given by

$$v_r = \sqrt{2 \eta} \sqrt{V_r} . \qquad 3.44$$

If an arbitrary limit for the onset of space charge effects is chosen as an expansion of 1 beam diameter in travelling 1000 beam diameters, then the ratio of V_r to V_a is 1/1000. Dividing equation 3.43 by V_a gives

$$\frac{V_r}{V_a} = \frac{1}{4 \pi \varepsilon_0 \sqrt{2 \eta}} \frac{I_a}{V_a^{\frac{3}{2}}} . \qquad 3.45$$

Space charge effects can thus be expected to occur at values of perveance above 10^{-7}. The analysis given above applies when the electron beam is travelling through a vacuum, so we can expect that the presence of a gas will modify the results considerably. Collisions with gas molecules will create ions in the path of the beam and these ions will tend to reduce the space charge forces acting to expand the beam diameter. In fact, the field in the electron beam

(Figure 3.20) will tend to retain ions near the beam axis and thus reduce the electron space charge repulsion. The beams shown in Photograph 2.2 are thus benefitting from this gas focusing.

3.6 GDEB guns.

This chapter has shown that the electron beam discharge has an *IV* characteristic which indicates that the current flow in the discharge is space–charge limited. It has been proposed (§3.4.4) that the space–charge limitation occurs in the CDS where there is a large positive space charge due to ions. The description of vacuum electron guns has identified some of the factors that are important in designing high perveance guns and these factors are also relevant in GDEB guns where it is desirable to achieve higher ion currents at lower voltages in the interest of maximising the electron beam current. In this study, GDEB guns are of particular interest because they offer the possibility of directing high energy electrons to a remote location in a low pressure gas switch where they can cause ionisation in the gas and thus initiate a discharge through the switch. We have already observed in the previous section that the presence of the gas reduces the electron beam expansion. We might also expect that the gas will reduce the range of the beam. The average range of energetic electrons in a gas is described by their mean free path.

The mean free path λ is related to the microscopic cross-section q by

$$\lambda = \frac{1}{Nq} \quad . \tag{3.46}$$

where N is the number density of the gas. According to Lehmann (Lehmann, 1927), an electron beam with an energy corresponding to 650 V in hydrogen at 1 torr has a range of about 12 cm. Since the beams created by the GDEB guns described in this chapter have energies of several kV, it is apparent that they will travel several meters through the gas. In any case, for application to triggering in a low pressure gas switch, the beams will not be required to travel more than about 5 cm. As will be seen in Chapter 5 (§5.3 and §5.6), the GDEB gun does successfully trigger a low pressure gas switch.

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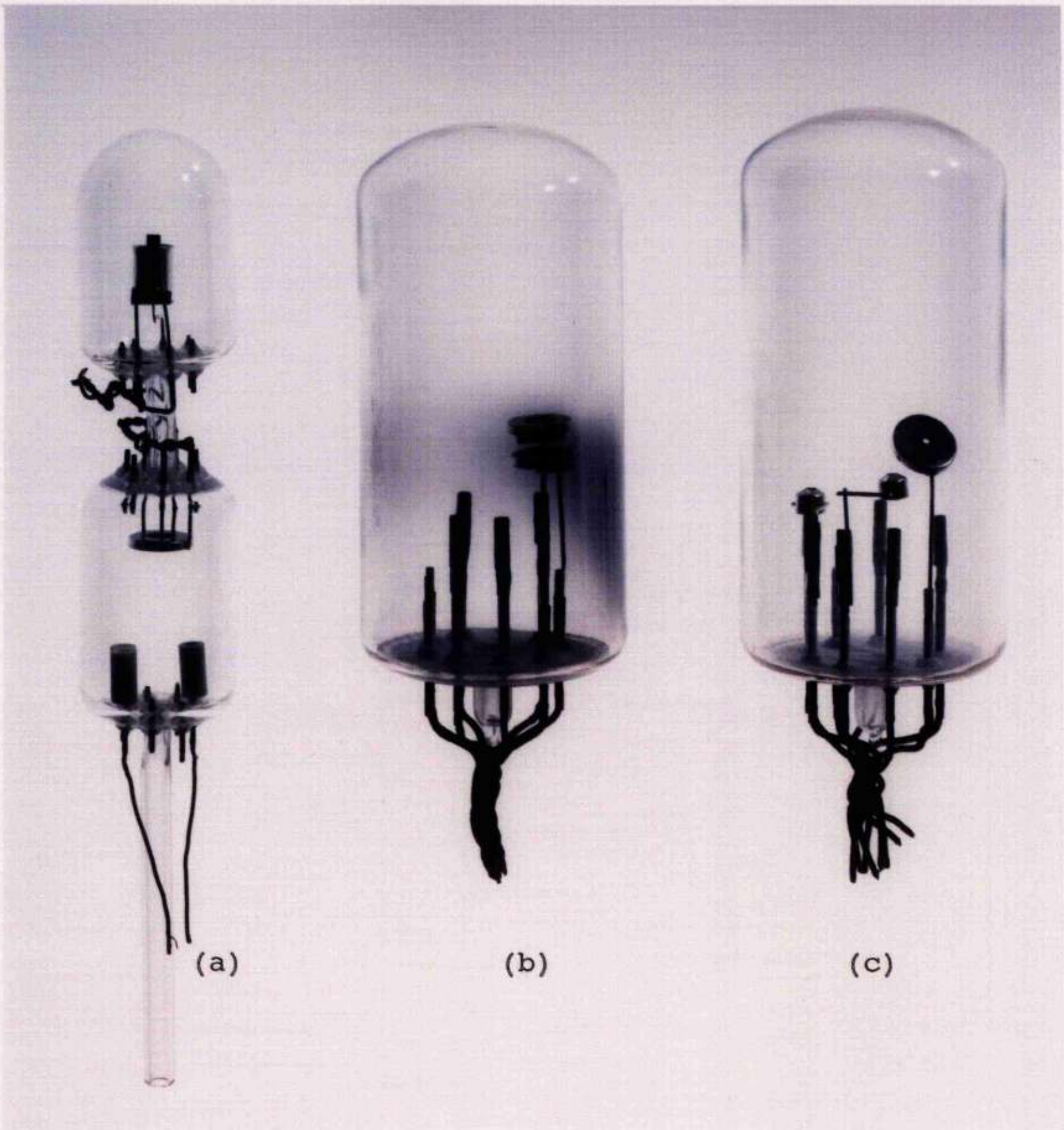
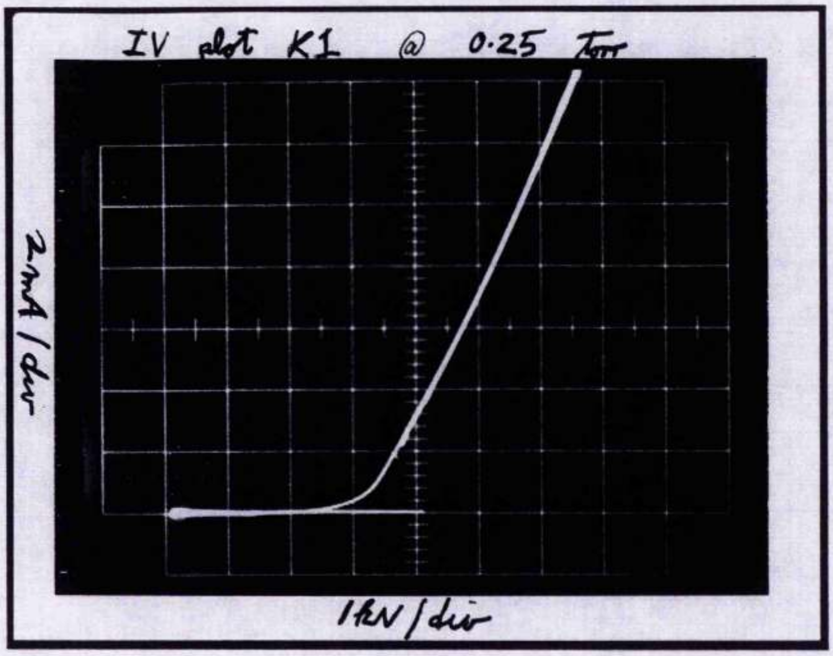
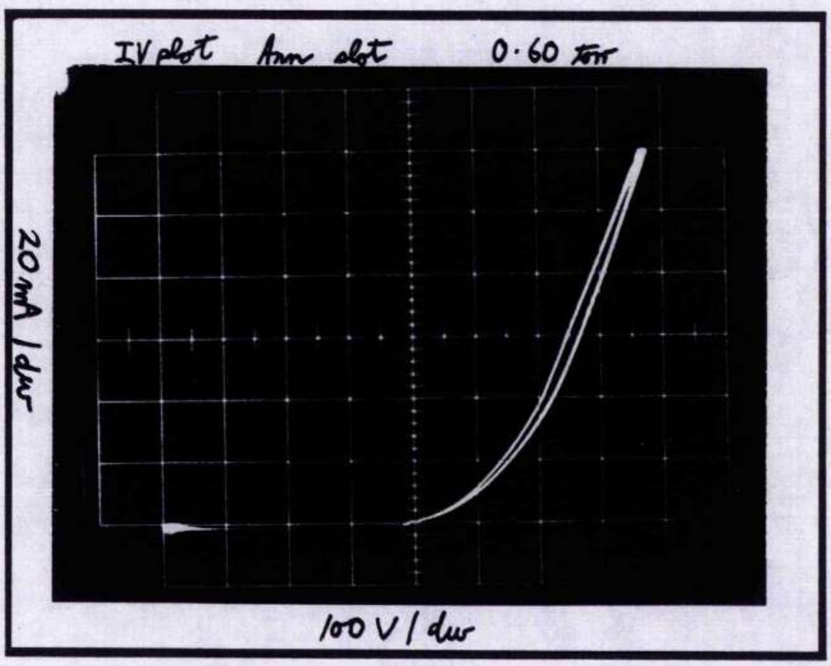


Photograph 3.1

Glow discharge electron beam (GDEB) guns with (a) alumina and (b & c) 'Rokide' insulated cathodes.



Photograph 3.2



Photograph 3.3

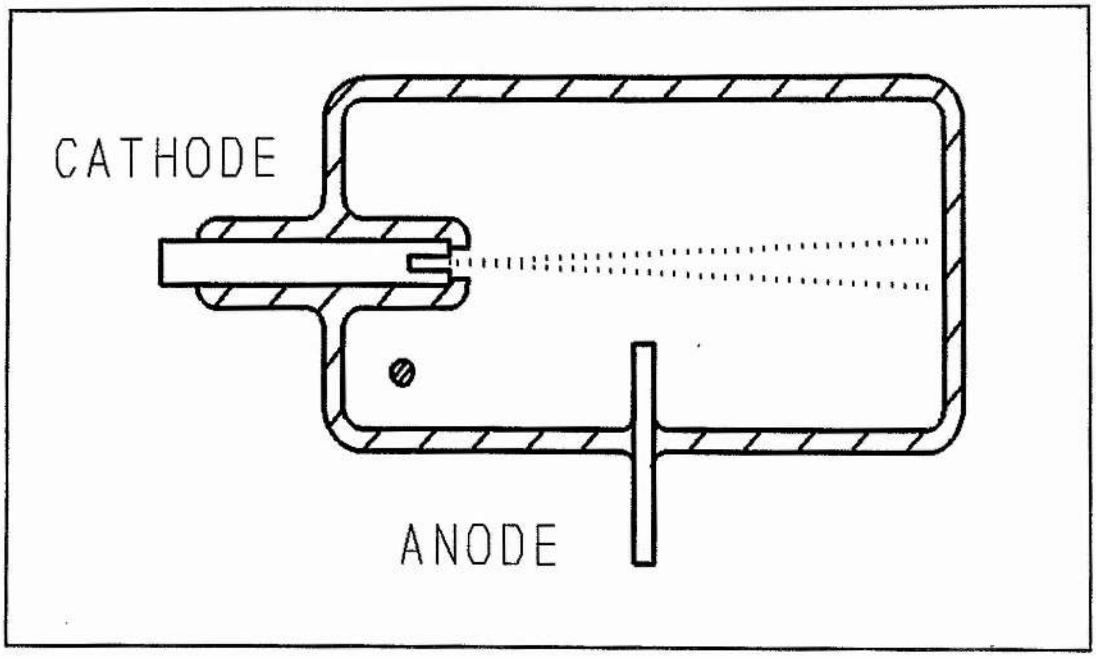


Figure 3.1

A glass-insulated e-beam diode. (Kovar cathode with 1 mm diameter hole, 10 mm deep, filled with deuterium to 0.5 torr.

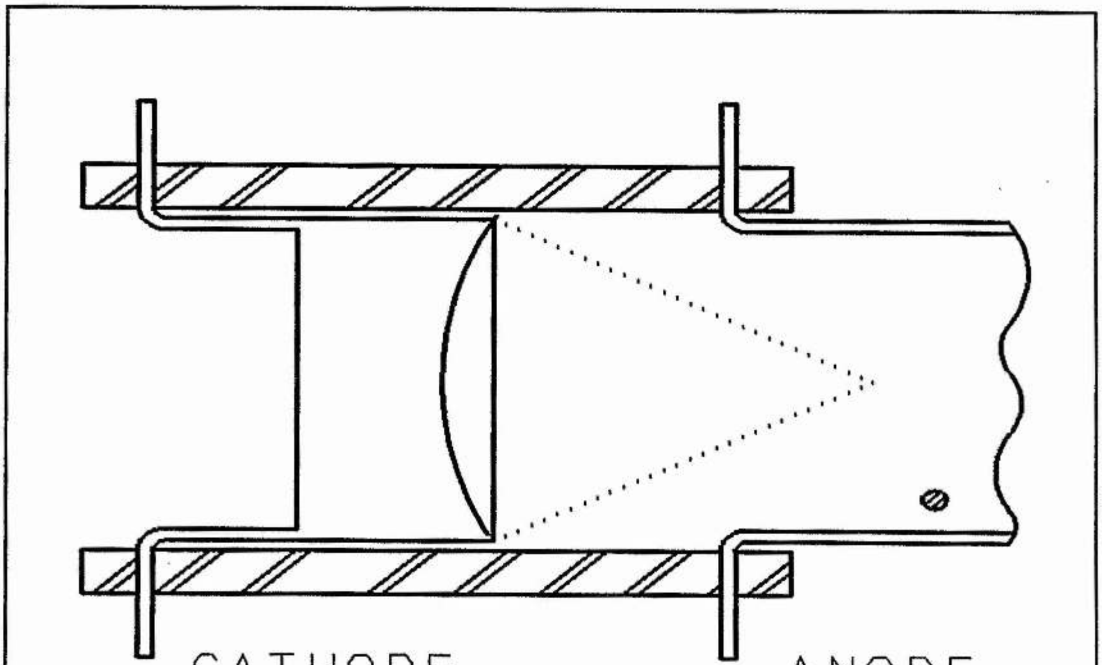


Figure 3.2

A ceramic-insulated e-beam diode.

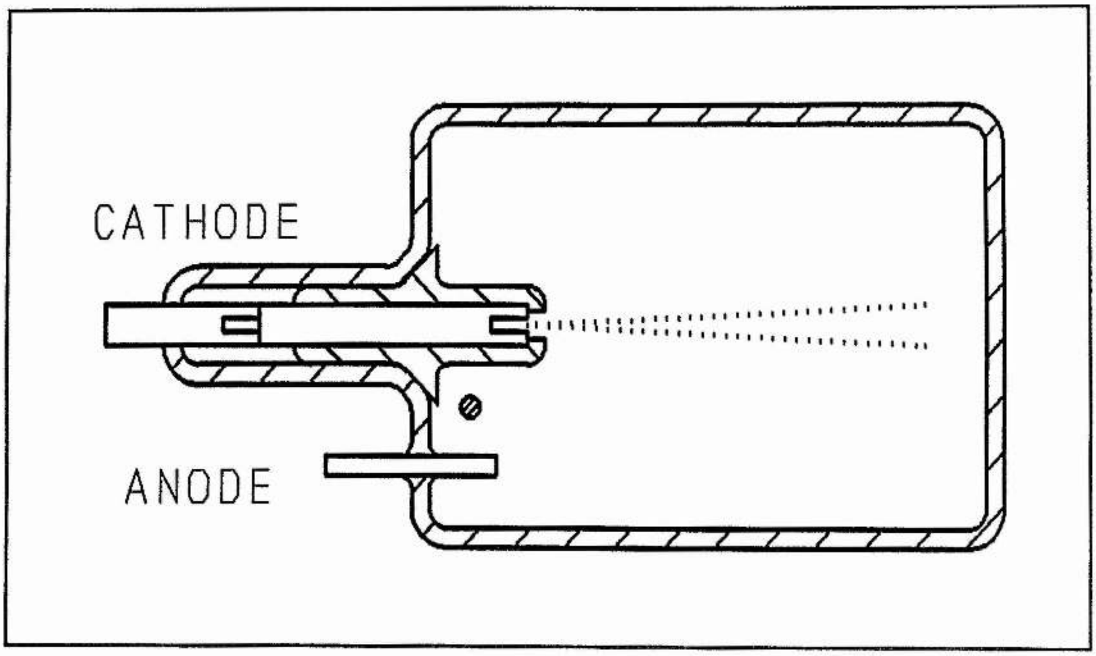


Figure 3.3
A glass-insulated Kovar cathode mounted in a Pyrex powder glass base.

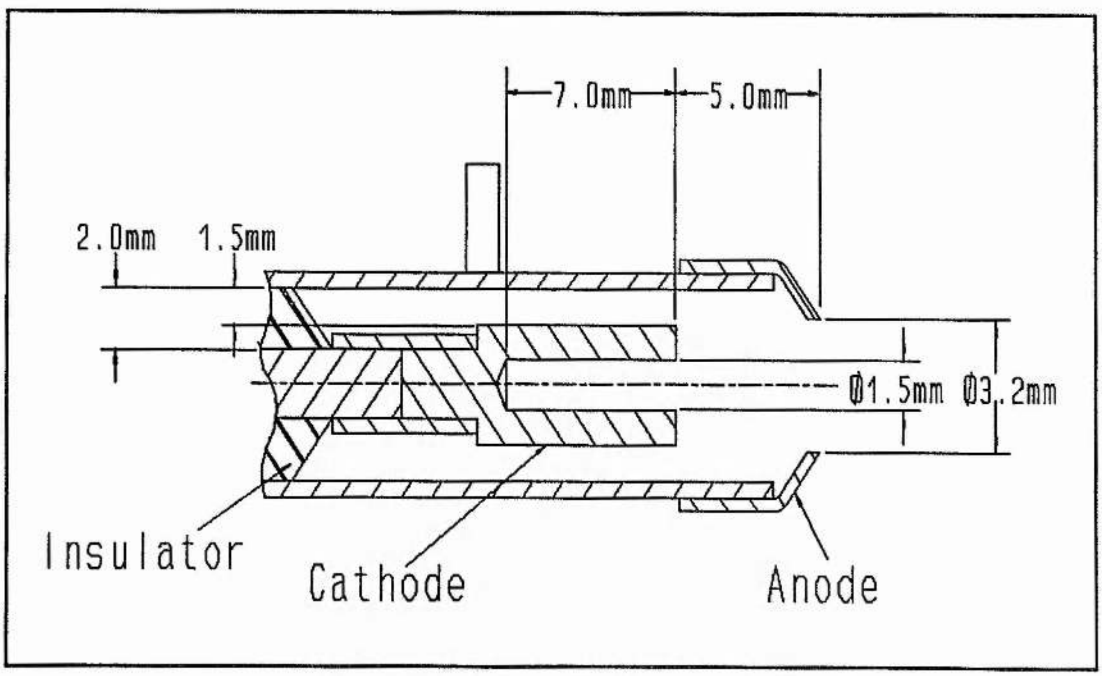


Figure 3.4
A gas-insulated molybdenum cathode of the design used for CHK1 and CHK2.

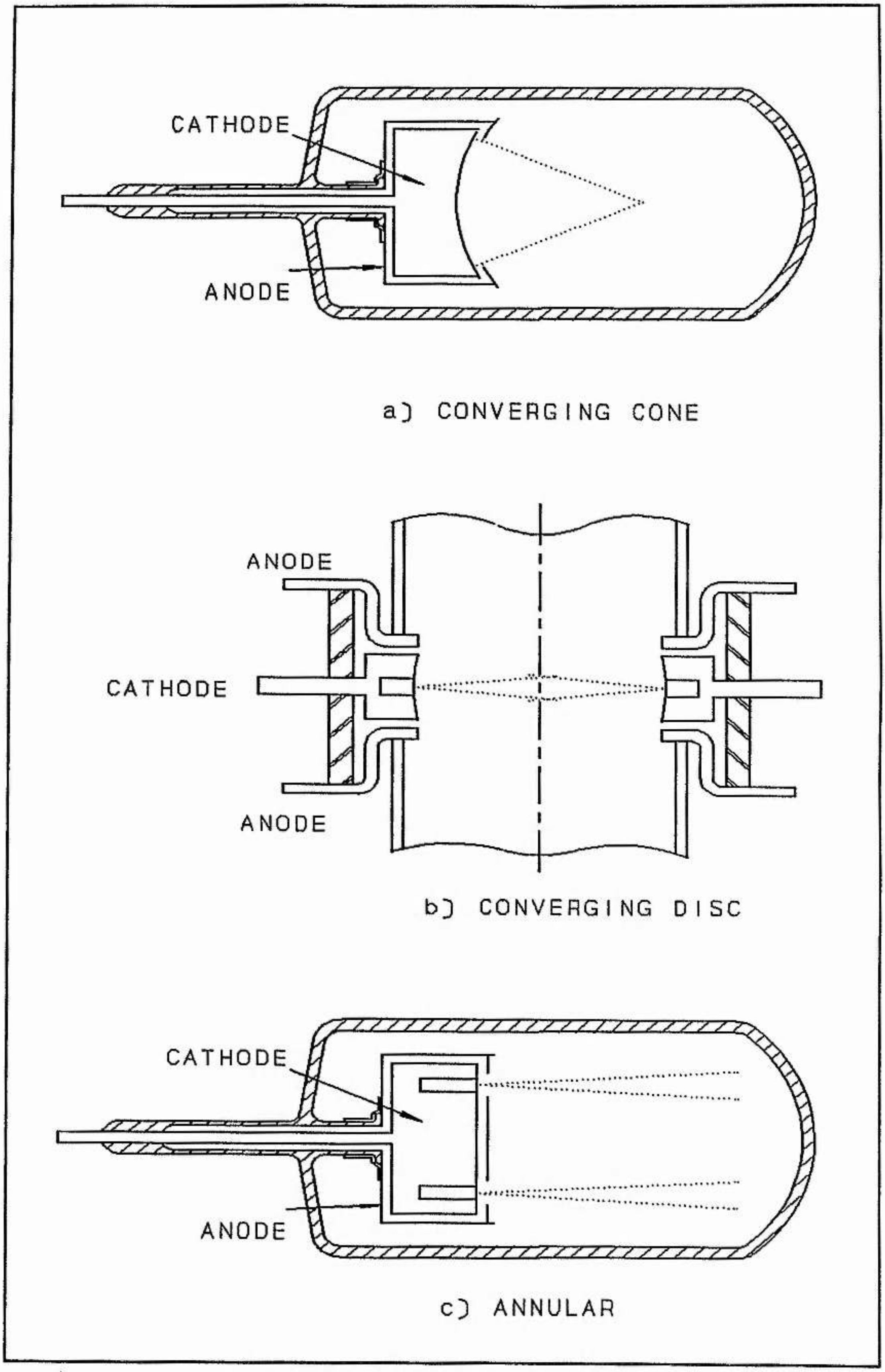


Figure 3.5

Gas-insulated e-beam cathode designs.

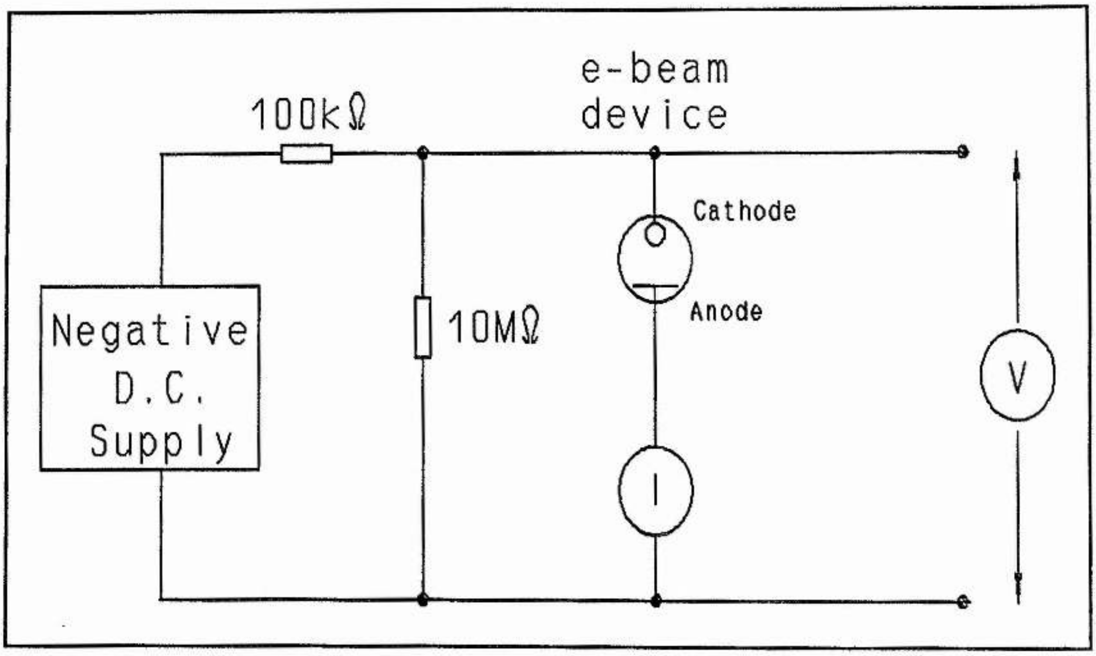


Figure 3.6

The circuit arrangement for the measurement of the IV characteristic by methods (1) and (2).

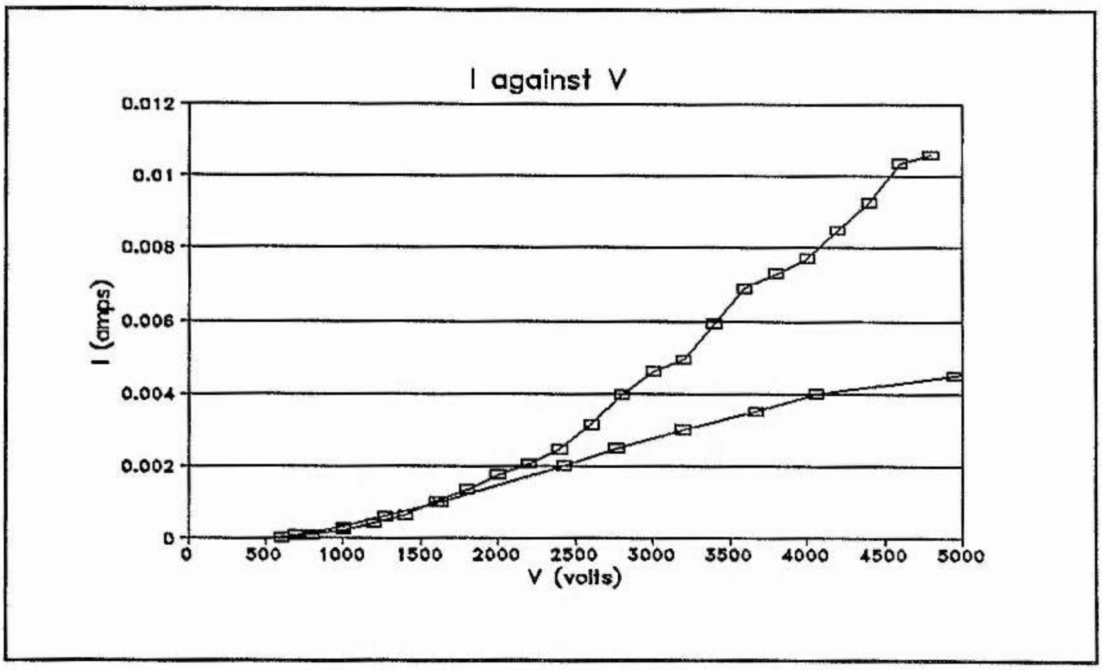


Figure 3.7

Graphs of the IV characteristic of cathode CHK1 at 0.5 torr (upper trace, measurement at switch on) and 0.6 torr (lower trace, measurement after current stabilisation).

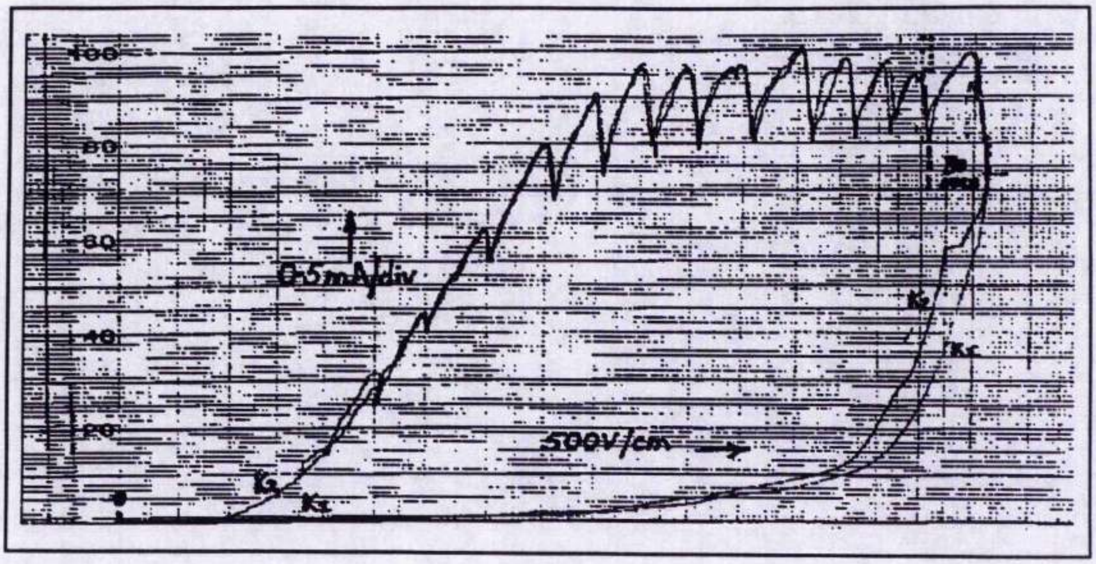


Figure 3.8
A chart recorder plot of the IV characteristic of cathodes CHK1 and CHK2 at 0.4 torr (overlaid on the same axes). The voltage was increased at 30 second intervals. The falling side of each hump lasted 10 seconds.

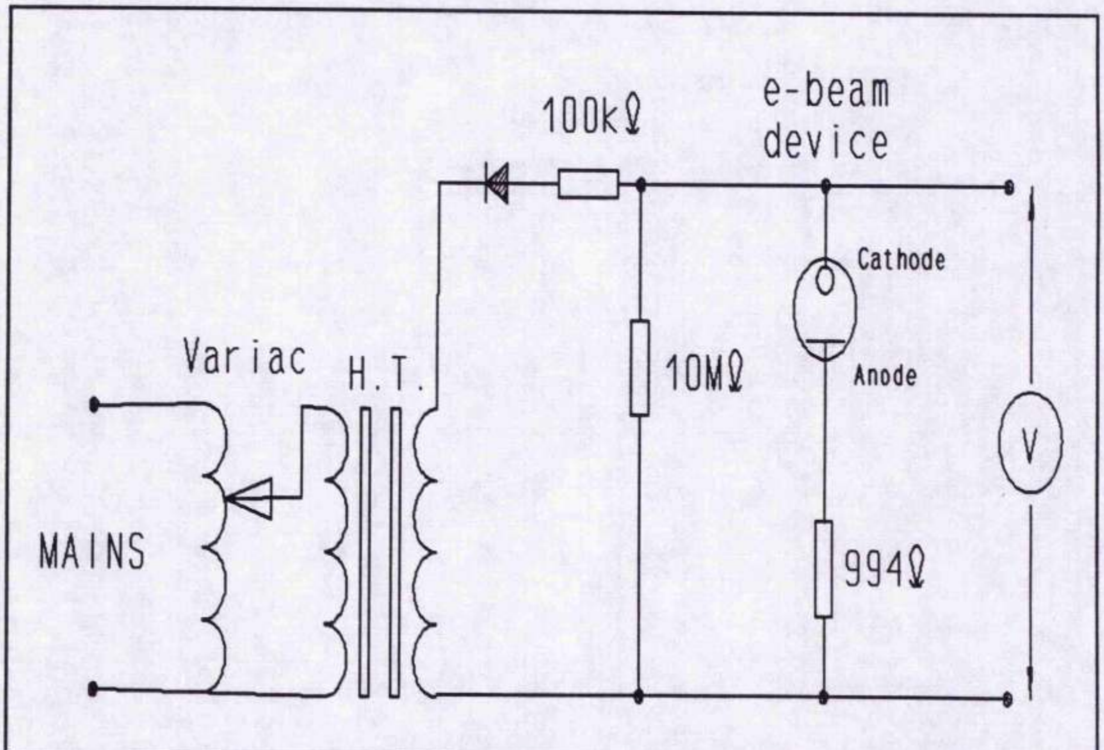


Figure 3.9
The circuit arrangement for the measurement of the IV characteristic by method (3).

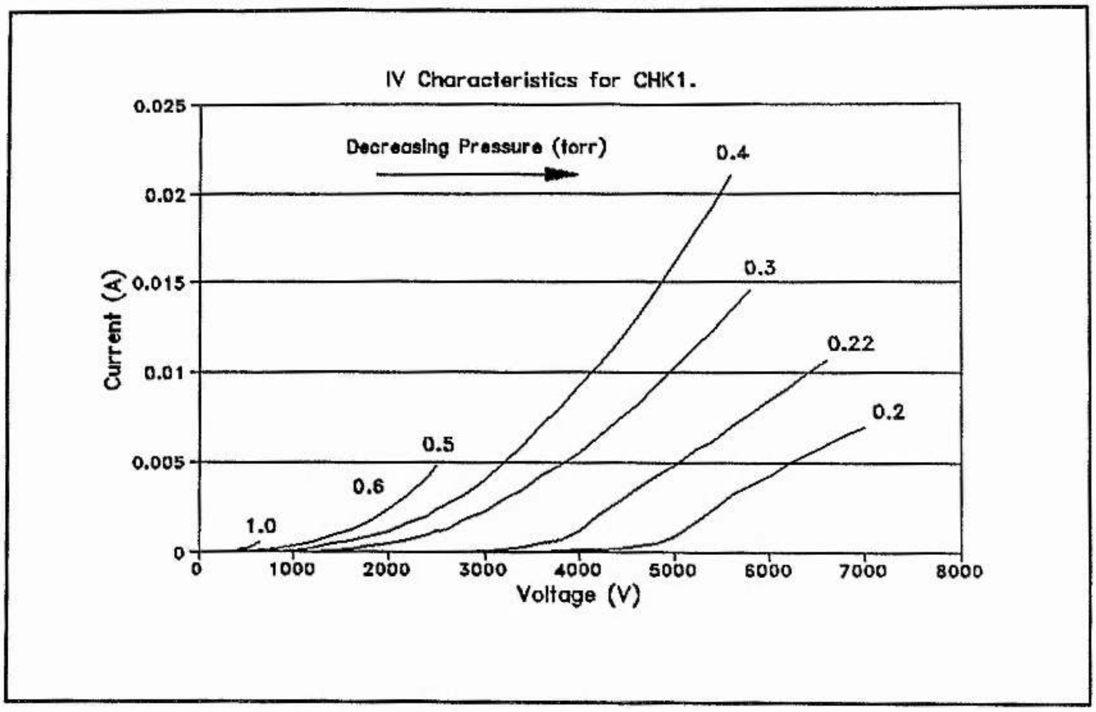


Figure 3.10
IV characteristics for CHK1 in deuterium plotted on a linear scale.

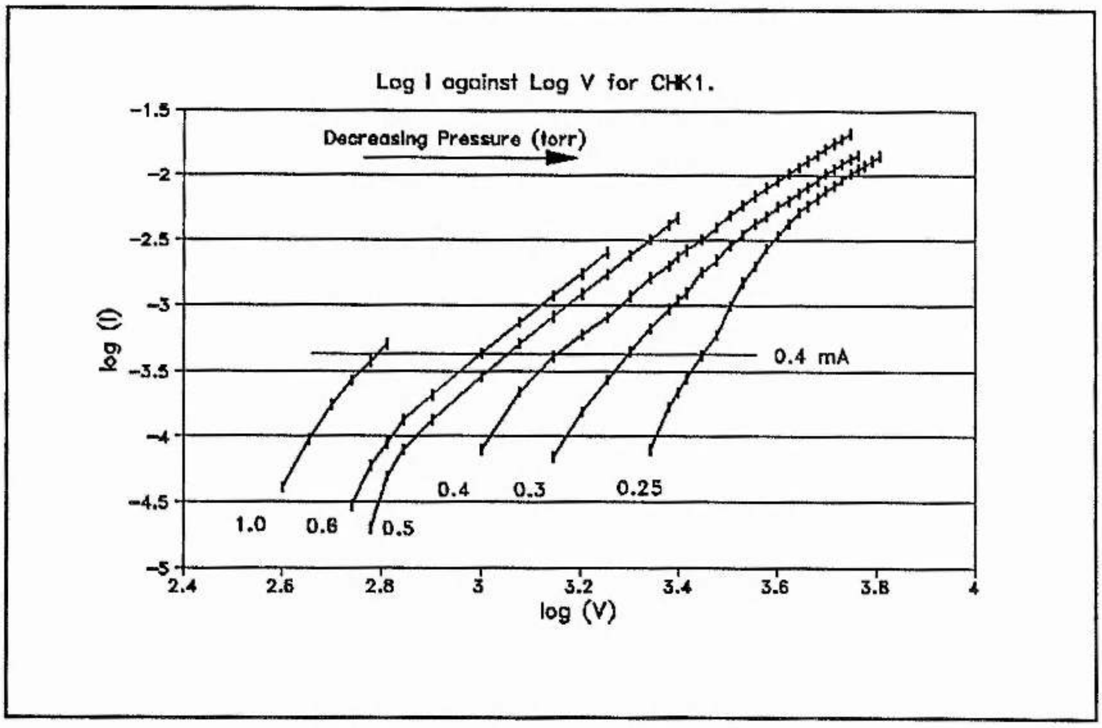


Figure 3.11
IV characteristics for CHK1 at pressures above 0.25 torr plotted on a log scale.

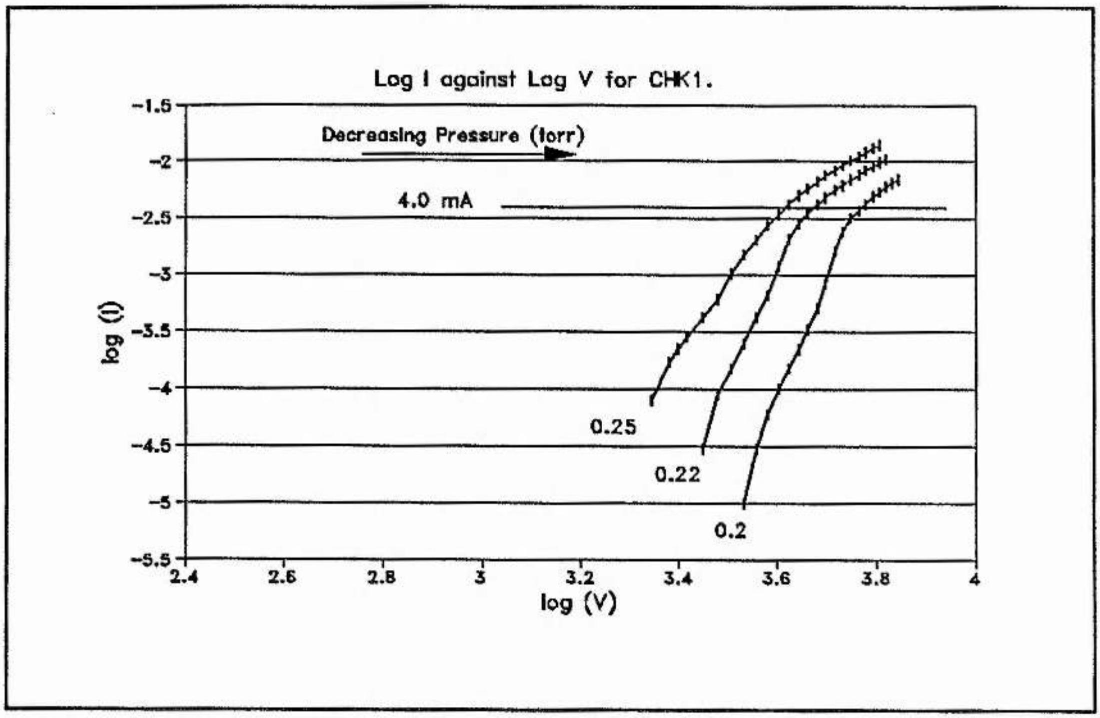


Figure 3.12

IV characteristics for CHK1 in deuterium at pressures below 0.25 torr plotted on a log scale.

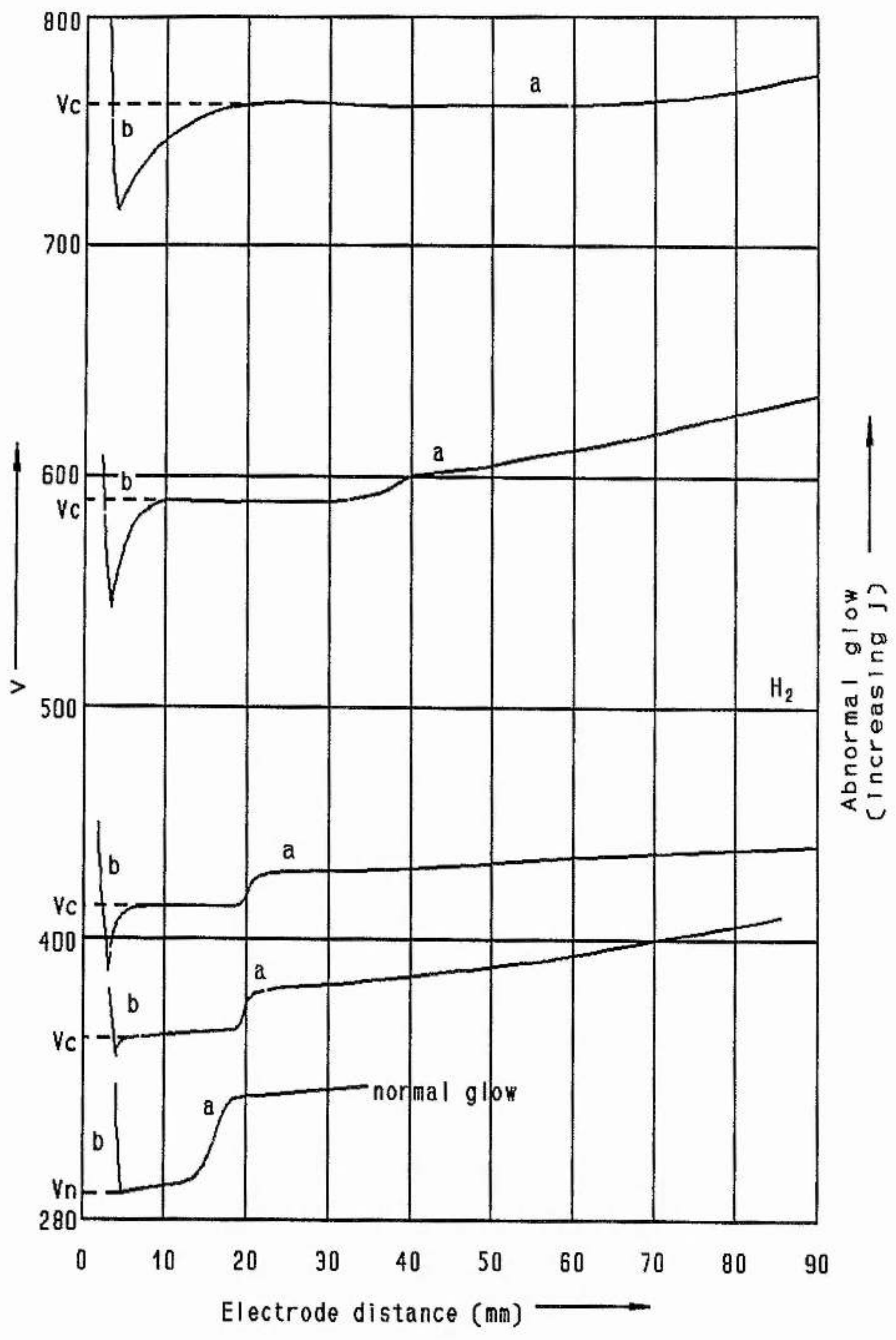


Figure 3.13 (after Francis, 1956, p83)
Discharge maintaining voltage as a function of electrode seperation showing the steep increase in maintaining voltage when the anode is close to the CDS/NG boundary.

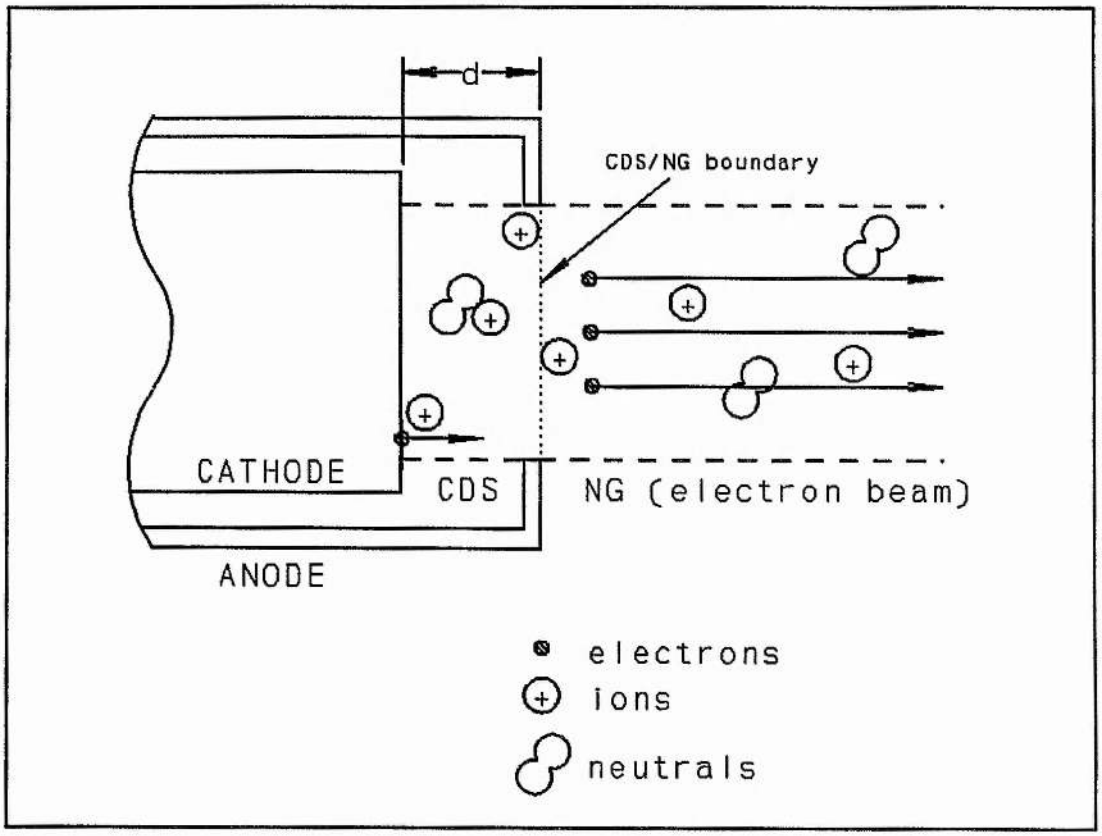


Figure 3.14
A schematic of the e-beam discharge. The CDS is a region of positive space charge where the electrons make very few collisions. Ions in the CDS enter from the NG.

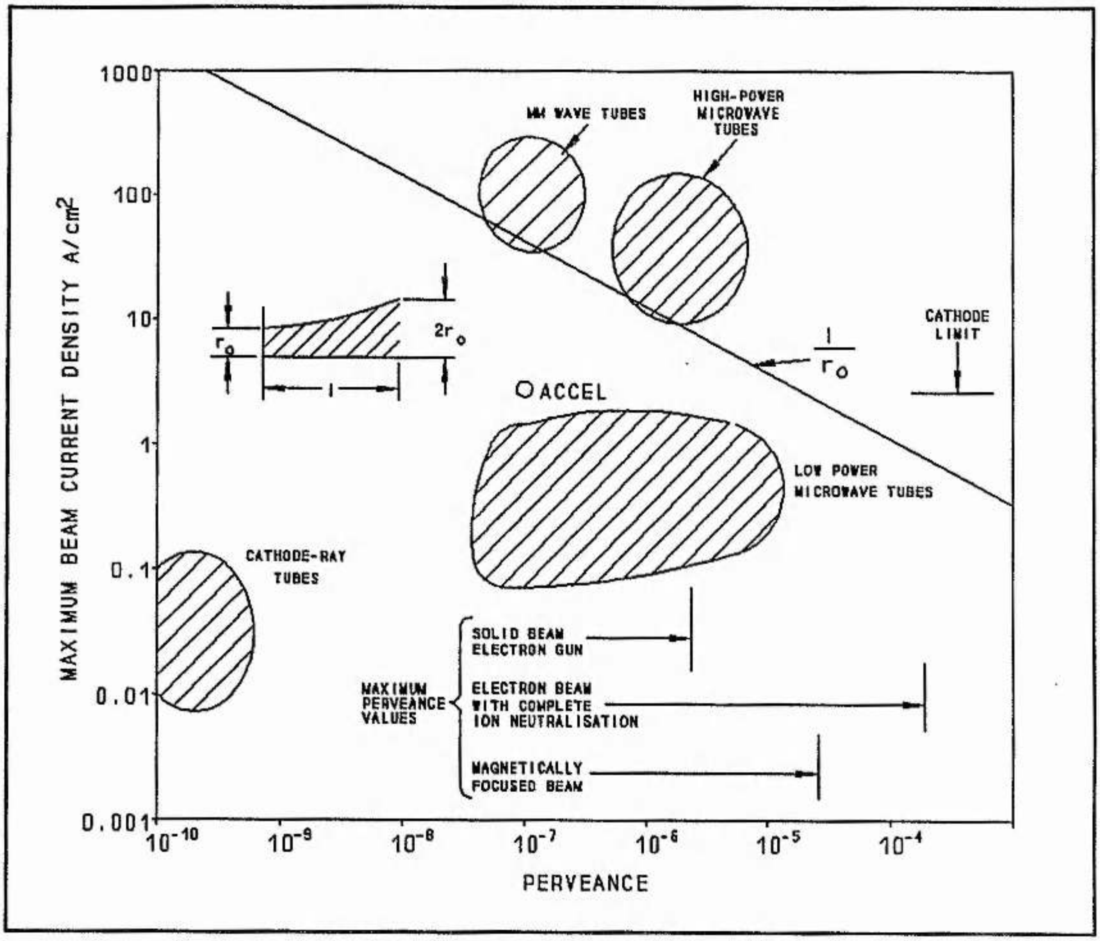


Figure 3.15 (after Brewer, 1967, p25)

An overview of electron guns and beams.

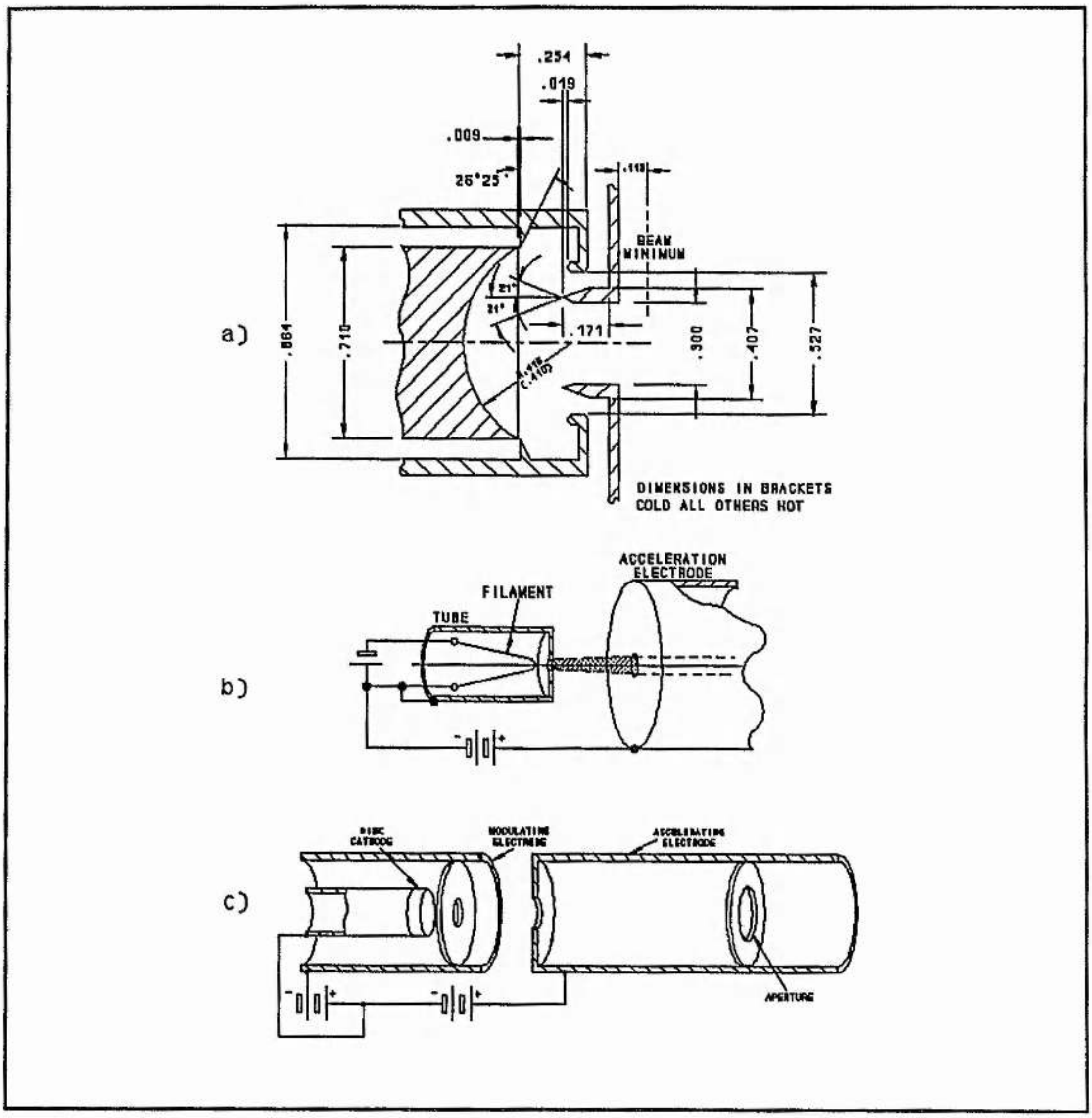


Figure 3.16 (after Pierce, 1949, pp167 & 186)
Electron guns for a) klystrons b) electron microscopes c) cathode ray tubes.

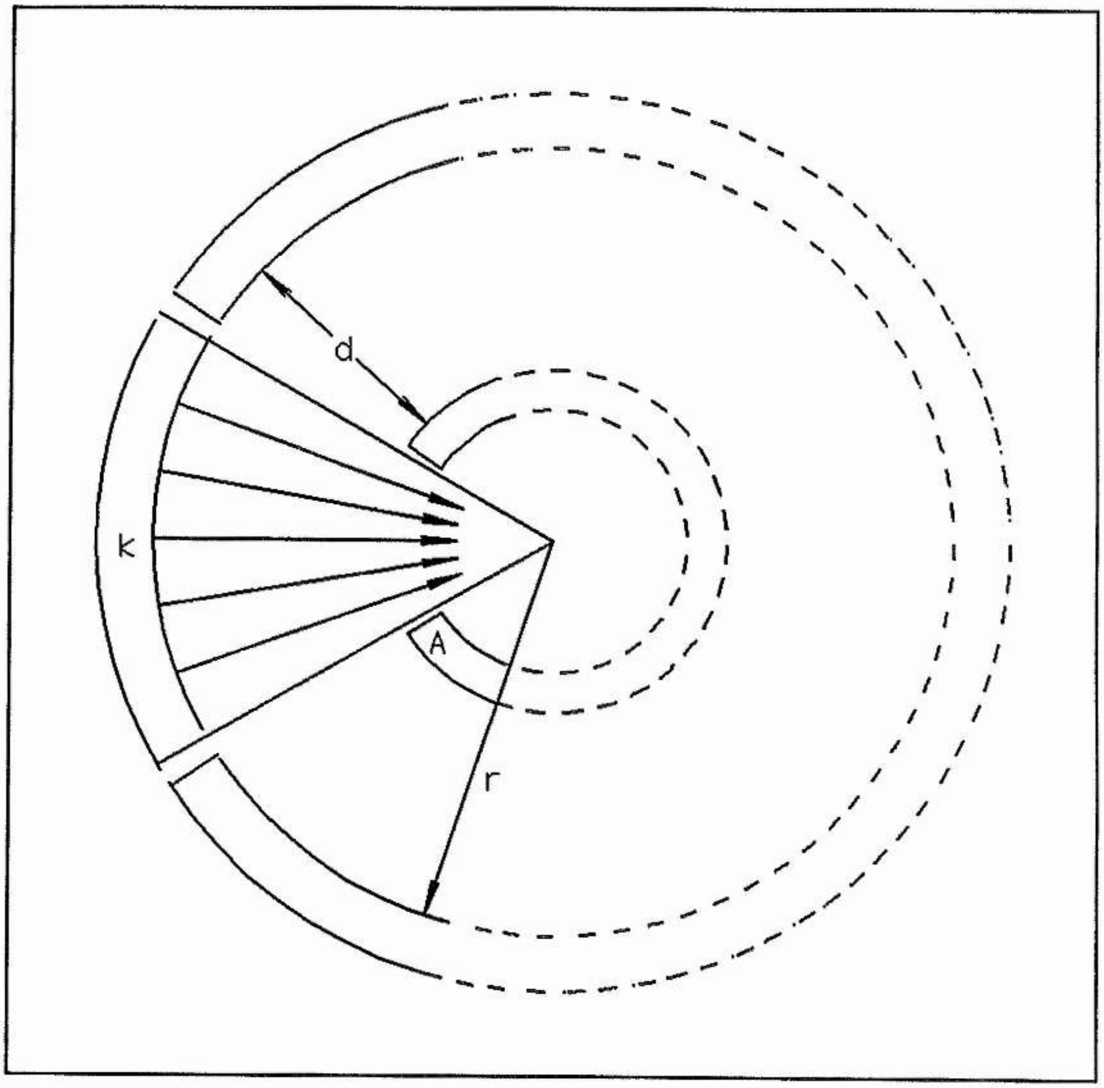


Figure 3.17

A segment of electron flow between concentric spheres.

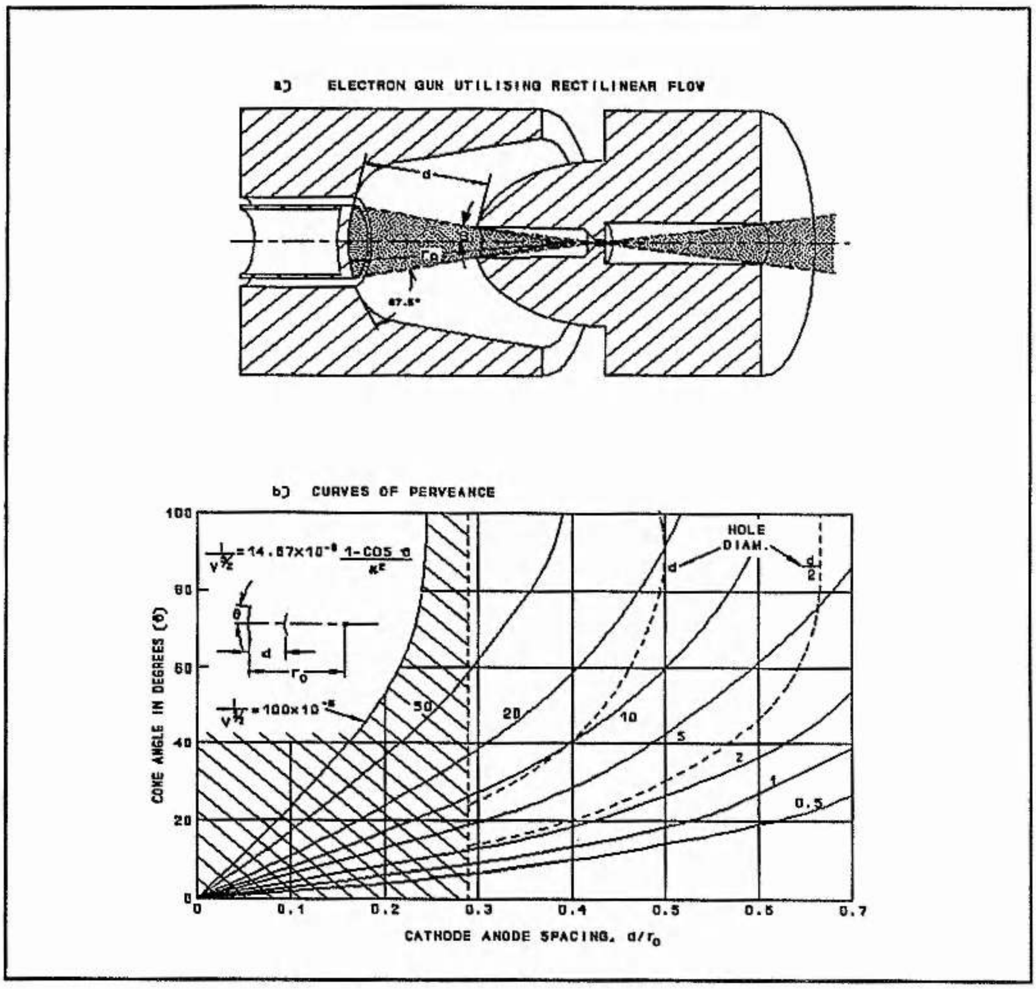


Figure 3.18 (after Pierce, 1945, p314)
Perveance curves used in design of vacuum electron guns.

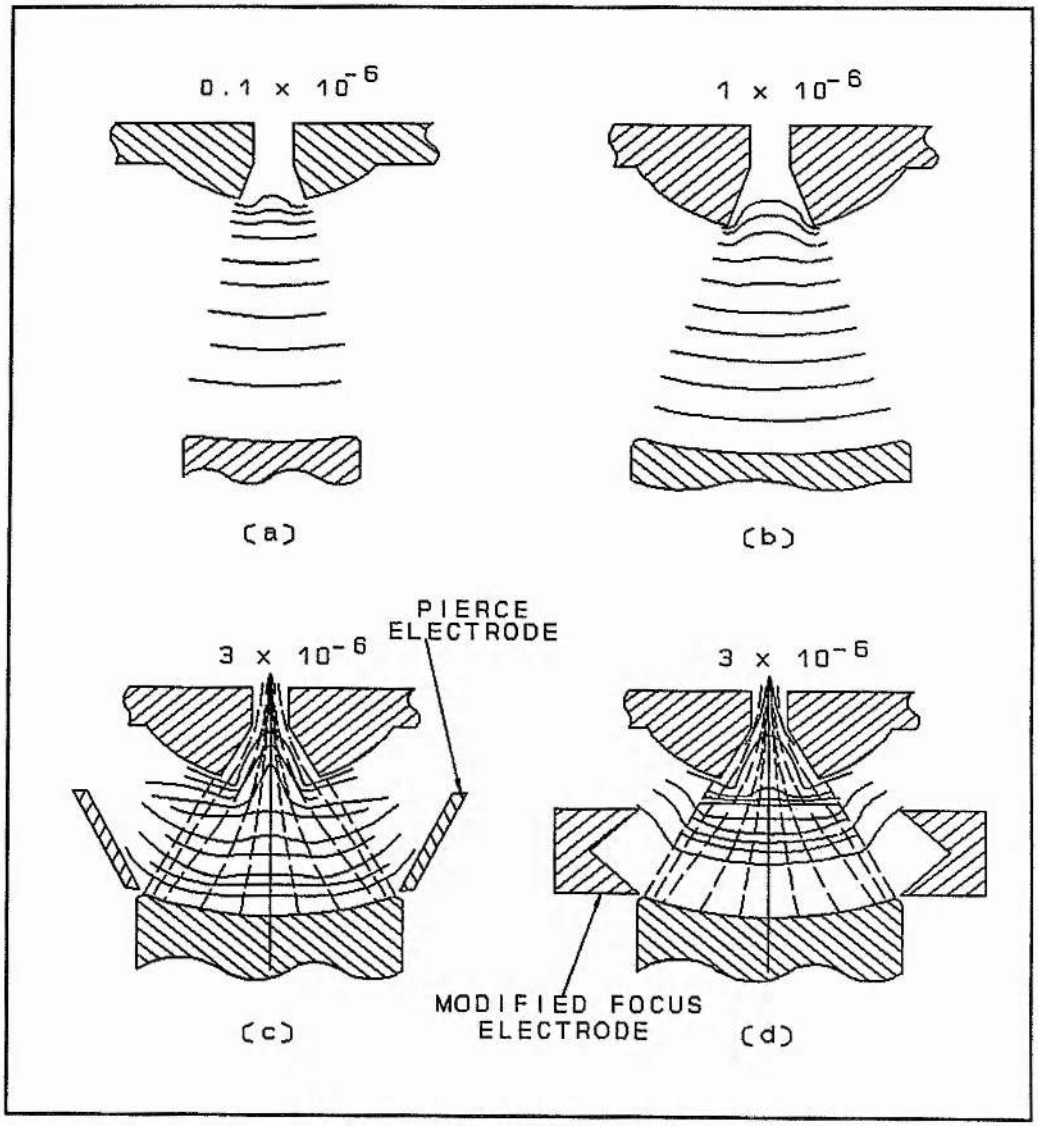


Figure 3.19
Equipotential lines in guns of different perveances. Field shaping electrodes are used to optimise the focus of the beam, but they cannot prevent the diverging effect of the anode aperture.

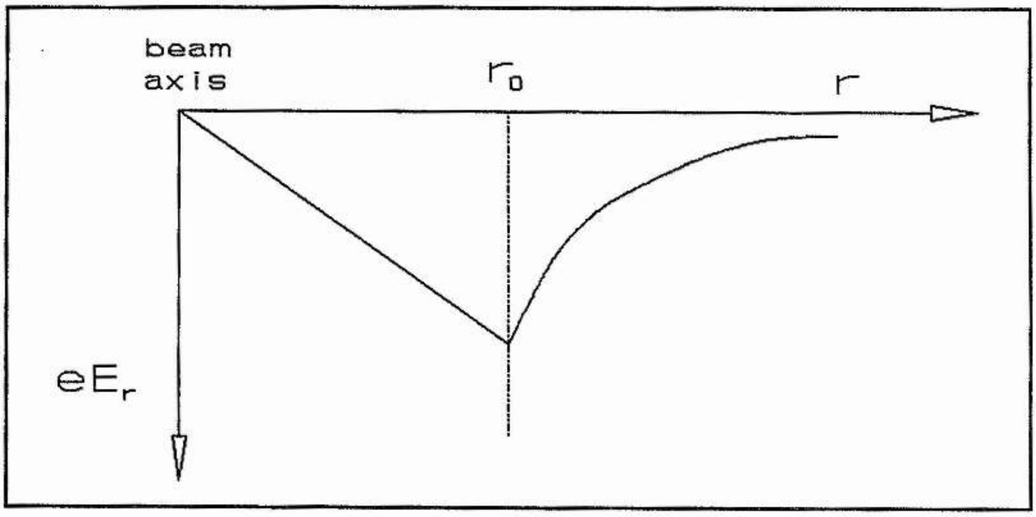


Figure 3.20
The force experienced by an electron in a beam as a function of distance $\underline{r}$ from the beam axis. The edge of the beam is at $\underline{r_0}$.

CHAPTER FOUR

The triggered hollow cathode switch.

4.1 Introduction.

In a conventional thyratron operating in a line–type modulator, conduction is initiated by creating a dense plasma between a trigger grid and the hot cathode, as described in Chapter 1. On triggering, the plasma diffuses into slots in the grid, where it comes under the influence of the anode field and causes the switch to conduct a large current pulse which may have a peak value of thousands of amps. Hot cathodes are considered to be essential in the thyratron to produce precise, reliable switching with low dissipation. As has been outlined in Chapter 1, a cold cathode switch would offer the significant advantages of instant readiness and low standby power consumption if a performance similar to a thyratron could be achieved.

In this chapter, we describe the design and operating characteristics of a cold cathode switch with the potential to sustain large pulse currents. The design of the switch is as follows: a conventional thyratron structure is used to achieve voltage hold–off; a hollow box serves as the cathode for the main discharge current; and the normal glow discharge is exploited as a triggering method.

The triggering method is based on the constant current density which is a characteristic of the normal glow discharge. As more current is drawn from the cathode, the area covered by the glow increases. In principle, this effect allows the area of emission of the cathode to be controlled by adjustments to the current drawn from it. The first step towards designing a switch to be triggered by this principle was to study the behaviour of glows on the inside of a long tubular cathode.

Experience gained from life–testing of glow modulators shows that hollow cathodes having diameters of 1 mm and depths of 15 mm, running a discharge of 15 mA in 25 torr of neon, exhibit sputtering erosion at some point down the hole, in a way that might indicate a preferred running depth. Consideration of the current flow in a long hollow cathode also suggests the hypothesis that it may be beneficial to the discharge to increase its current density at some given depth, rather than to penetrate further into the cathode. The chapter therefore commences with an investigation of a gas diode with a hollow cylindrical cathode. The penetration of the emission area into the cathode cylinder as a function of current is investigated, to determine if the relationship is linear or if there are limits to the penetration that can be achieved. The results of the investigation are applied to triggering a hollow cathode switch. The influence of the triggering arrangement on the switching properties is also reported.

4.2 A discharge with a cylindrical cathode.

4.2.1 Introduction.

In a low pressure discharge, the normal glow occurs at a current density for which the ionisation processes are at their most efficient. In consequence, the area of cathode participating in conduction grows in proportion to the current being drawn from it. The voltage across the normal glow discharge with planar electrodes has a value of a few hundred volts and this voltage is maintained at a nearly constant level as the current varies over several orders of magnitude as shown in the VI characteristic of Figure 2.1. At the smallest currents, when the discharge diameter on the cathode approaches the width of the cathode dark space, the loss of ions by lateral diffusion requires the voltage to increase to maintain conduction. At the largest currents, the entire cathode is utilised and a further increase in current entails an increase in current density which again requires an increase in voltage. Between these limits the discharge area simply expands or contracts to maintain a constant current density on the cathode.

4.2.2 The cylindrical cathode.

The shape of the cathode surface does not influence the principle of the optimum ionisation efficiency giving rise to the constant current density in the normal glow, but, for a different cathode shape, the constant current density may take a different value than in the case of the planar cathode. The growth of the discharge over the cathode surface can be studied in the hollow cylindrical cathode of the test diode shown in Figure 4.1. The cathode is a tube of nickel gauze which has the anode entering it through one end. The anode is insulated over most of its length by a high voltage 'pant leg' structure which is used in glass thyratrons to prevent long path breakdown from the anode to the outside of the cathode.

Notwithstanding the attempt to restrict the discharge to the inside of the cylinder, a glow does appear on the outside of the cathode cylinder when the pressure is in the range from 1 torr to 10 torr. Under these conditions, the discharge originates on the outside surface of the cathode cylinder and passes through a small break at the junction between the cylinder and the end face to complete the connection to the anode inside the cathode cylinder. Investigations in the pressure range above 1.0 torr were conducted by initiating the discharge at 0.5 torr and admitting gas until the desired pressure was reached. The discharge remained inside the cathode cylinder during the pressure increase. At pressures under 0.1 torr, a discharge was not observed for an applied voltage up to 2 kV. The pressure range below about 0.1 torr, used in conjunction with thyratron high voltage structures, presents conditions which are too far to the left of the Paschen minimum to be of interest for high current switching in a glow discharge mode and was not investigated further. In the pressure range 0.1 to 1 torr, which is the area of interest for thyratron switching, the discharge was active only inside the cathode cylinder. As a general description of its behaviour, when the discharge is established in the diode at a pressure of 0.5 torr, the discharge glow remains near the anode. As the current is increased, the discharge glow moves up the cylinder away from the anode and more of the cathode cylinder wall participates in conduction. The cathode region of the discharge can thus be made to move up or down the inner surface of the cylinder by adjusting the current drawn from it.

A rather curious effect was observed when the current was raised to the point where the cathode regions spread outside the open end of the cylinder. As can be seen in Photograph 4.1, a sequence of coaxial plasma toroids, reminiscent of 'smoke rings', encircle the cathode cylinder. Their number can be increased by simply increasing the current. It is not clear how these rings arise or what influences their dimensions, but as they are not important for the application of the normal glow to triggered switching, they will be left for the consideration of the reader.

4.2.3 The cathode structure.

Nickel gauze was chosen for the cathode to allow easy observation of the discharge. However, this choice could also influence the detail of the processes occurring at the cathode. For example, a substantial fraction of the photons created in the glow will escape through the nickel gauze. One consequence of this loss is that the cathode current density will not be enhanced by photoemission to the same extent as it would for a solid cathode. The direct ion flux will be similarly modified, with some ions going directly through the cathode. The reddish glow outside the cylinder observed in Photograph 4.1 may thus be due to ion impact excitation. Ions that do escape through the holes in the gauze are not ultimately lost, since they are retarded both by the space charge of other ions outside the cathode and by the electrostatic image force so that they eventually return to the cathode. With this modified ion bombardment, there is a strong possibility that the secondary emission coefficient will be different for a gauze cathode as compared with a solid cathode. In practice, these effects, if present, did not appear to cause a large deviation from normal glow discharge behaviour.

When the discharge emerges from the open end of the cylinder and generates the plasma toroids, the cathode dark space folds over the end and begins to extend back down the outside of the cathode. This leads to the interesting situation of two cathode dark spaces back to back and able to communicate through the holes in the gauze. The possibility then arises that ions oscillate back and forth through the holes in the gauze in a way somewhat similar to the behaviour of electrons oscillating between the cathode dark spaces of a hollow cathode discharge.

4.2.4 The discharge properties.

The discharge property that primarily determines the penetration of the discharge into the cylindrical cathode is the current density at the cathode surface. Glow discharge theory can be used to give an estimate of this and other properties and the formulae and data required are included in Appendix D. For the diode of Figure 4.1, the cathode material is high purity nickel and the gas is hydrogen. All the values reported below are for a pressure of 0.5 torr. Using Appendix D, the running voltage of the discharge is calculated to be about 300 V, the striking voltage to be slightly larger and the normal current density to be about 18 $\mu A/cm^2$. For various reasons, the accuracy claimed for the last value is low and it may be out by a factor of 3 either way. An experimentally determined value is likely to be of more use. The experimental data tabulated by von Engel (von Engel, 1955, p 197) gives a normal current density of about 18 $\mu A/cm^2$ and a running voltage of about 210 V, which is lower than the theoretical value of about 300 V. His data for the CDS width, *d*, in hydrogen do not include nickel as a cathode material but the result for iron should be adequate for a qualitative approach. For a pressure of 0.5 torr, d is 18 mm in the normal glow. The negative glow width, x_{NG}, is usually assumed to be equal to the maximum range of electrons having the energy of the cathode fall. An estimate of the NG width can be obtained from the graph of Figure 4.2. For the conditions in the cylindrical cathode, a value of 2 cm is indicated. With these values for the CDS and NG widths, it is obvious that the hollow cathode effect discussed in Chapter 2 should be considered. Figure 4.3 shows the increased current density available from a parallel plate cathode as a function of the plate separation. For the cathode of Figure 4.1, an estimate of the hollow cathode effect can be made by substituting the cathode internal diameter for the plate separation. When this substitution is made, the graph of Figure 4.3 indicates that the hollow cathode effect will increase the cathode current density in the test diode at pressures below about 1.2 torr. At a pressure of 0.5 torr, for example, the test diode's cathode current density is multiplied by a factor of about 7. Therefore, the hollow cathode effect must be taken into account when making a prediction of the cathode current density for the test diode.

4.2.5 Cathode penetration results.

Penetration of the discharge into the cathode of the test diode (Figure 4.1) was measured as a function of current. The diode was processed as described in Appendix B and filled with hydrogen. It was left on the pump system to allow different pressures to be selected. The diode was connected in a circuit similar to that of Figure 3.6. The penetration of the discharge into the cathode cylinder was estimated by visual observation in low ambient light conditions and measured against a scale fixed to the discharge tube. The scale zero was set to the tip of the anode rod. Although it was convenient to fix zero at this point, it left an area of the cathode which was not included in the measurement of the discharge penetration. There is thus an offset error in the penetration data, but the error will not effect the form of the variation of penetration with current drawn from the cathode. The offset is equivalent to about 1.5 cm, with an accuracy depending on how much of the end disc is used by the discharge. The value of 1.5 cm offset will be used in calculations of cathode current density.

Penetration results for a discharge in hydrogen are shown in Figure 4.4. At the higher pressures of 1.57 and 2.98 torr, the data lie on reasonably straight lines, while at 0.58 torr, the data lie on a curve concave downwards. The curves for 0.58 and 1.57 torr are almost coincident.

The trend of the penetration depth curves should follow the current density variation with pressure predicted from the theory of the normal glow discharge. This theory (Acton & Swift, 1963, p 214), indicates that the relationship is

$$j = Jp^2, \qquad 4.1$$

where J is a constant for a given gas and p is its pressure. The value of J for hydrogen is $7 \cdot 10^7$ (Acton & Swift, 1963, p 238). In the arrangement of

Figure 4.1 therefore, equation 4.1 can be used to obtain the cathode penetration depth D_P, so that

$$D_P = \frac{I}{2\pi r_c} \frac{1}{Jp^2} \quad , \qquad 4.2$$

where I is cathode current and r_c is the cathode radius. The depth thus increases as the inverse square of pressure. Equation 4.2 shows that, compared to the 2.98 torr discharge, the 1.57 torr discharge would be expected to penetrate about 4 times as far and the 0.58 torr discharge about 25 times as far. This expectation is confirmed in the results for 1.57 torr, where the penetration factor measured from Figure 4.4, lies between 3 and 5 at currents above 24 mA. Below 24 mA the results lose accuracy because of the offset error mentioned earlier.

The fact that the penetration depths for 0.58 torr are not as large as expected indicates that some other factor is increasing the cathode current density at this pressure. The likely cause is the hollow cathode effect, as described in §2.2.5. For the test diode at 0.58 torr, Figure 4.3 indicates that the discharge was well into the hollow cathode regime and predicts a cathode current density increased by a factor of about 5. Thus, the penetration depth for a pressure of 0.5 torr is predicted to be 5 times (rather than 25 times) larger than for a pressure of 2.98 torr. The measured factor for the 0.58 data lies between 2.8 and 5 for currents above 24 mA and is consistent with the predicted increase in current density from the hollow cathode effect.

A graph of current density against current is plotted in Figure 4.5 for 2.98 and 0.58 torr. The 0.58 torr curve shows a linear growth in current density as current is increased, so that increasing the current by a factor of 3 causes a 1.5 times increase in cathode current density. From the data in §4.2.4, and including the hollow cathode effect, the calculated value of current density is about 120 $\mu A/cm^2$, which is indeed within a factor of three of the measured values of 170 – 300 $\mu A/cm_2$. The graph of voltage against current (Figure 4.6) also shows a linear increase. The estimated value of 300 V is in reasonable agreement with the measured values. It is apparent that the current density and voltage both increase as the current is increased (*ie.* as the discharge penetrates further into the cathode) in contrast to the planar cathode situation. The explanation for this is likely to lie in the fact that in the cylindrical cathode, the current from all parts of the cathode must converge into the same path to the anode, giving a central column with a non–uniform axial current density.

The conclusion of this study with the cylindrical hollow cathode is that the discharge broadly follows simple glow discharge theory. The discharge does spread over the cathode surface as the current is increased and the discharge can be made to extend to the limit of the cathode cylinder (10 inches in this case) and beyond. There does not therefore, seem to be a preferred running depth for the discharge in a DC discharge. The current density and voltage of the discharge both increase faster for a cylindrical cathode than for a planar cathode (Figure 2.1) but this does not present difficulties in controlling the discharge. The cylindrical cathode arrangement of Figure 4.1 therefore lends itself to control of the penetration of the discharge into the cathode. The next section will describe how this effect can be used to trigger the main discharge in a cold cathode switch.

4.3 The normal glow triggered switch (NGTS).

The triggered hollow cathode switch combines the cathode arrangement investigated above and the high voltage hold–off structure typical of glass thyratrons. The switch is shown in Photograph 4.2 and the design is shown in Figure 4.7. It has a conventional glass thyratron design with an anode closely surrounded by a metal structure at cathode potential. The high voltage hold–off arises from the design of the baffle structure, placed so that the anode is completely surrounded, at a distance of a few millimetres, by surfaces at the cathode potential so as to operate on the left of the Paschen minimum where the pd product permits a high voltage (> 25 kV) to be applied between anode and cathode without breakdown. The baffle incorporates holes or slots in a staggered double–layer, which does not compromise the voltage hold–off capability of the switch, but allows a discharge in the cathode cylinder to connect to the anode for initiation and conduction of the main current pulse. The cathode of the device is formed from two hollow cylindrical structures connected to the baffle and closed at the end remote from the anode. The main triggering electrode is a tungsten rod which penetrates the cathode cylinder at the closed end. The rod is isolated from the cathode box by a long glass tube similar to the glass insulator at the anode. This electrode will be referred to as the trigger rod. The switch also includes another trigger electrode placed below the baffle and isolated from it by small ceramic insulators. This will be referred to as the trigger grid.

Switching function is related to the structural elements described above in the following way. The anode with its surrounding box and baffle forms the high voltage hold-off region. The box below the baffle forms the main discharge cathode. The trigger rod has the same function as the anode in the device of Figure 4.1 and initiates a discharge which is then driven up the cathode cylinder by increasing the current until it reaches the baffle slots and fires the switch. A more detailed examination of the trigger process and the trigger options available is given in the next section.

4.3.1 Triggering the switch.

In principle, the switch is triggered by a method which introduces electrons into the high voltage region. The design in Figure 4.7 provides two electrodes to do this. In the simplest case, a discharge is initiated in the cathode cylinder by a positive voltage pulse applied to the trigger rod. The expected sequence of events in the switch would then be as follows: a discharge is initiated between the cathode cylinder and the rod electrode, with a delay which depends on the number density of free electrons in the cathode box; the trigger discharge penetrates further into the cathode in the direction of the grid slots as the trigger current increases; the anode field captures electrons released by the trigger discharge near the baffle slots and the processes leading to switch conduction are initiated. The inclusion of a second triggering electrode, and the use of a DC bias, was intended to offer flexibility in testing the performance of the switch. In fact, the voltages required to drive the trigger electrodes in this device were found to be higher than those normally encountered in hot cathode thyratrons and the design of the trigger grid connection was such that breakdown to the outside of the cathode box occurred when a pulse was applied to it alone. The use of a bias discharge to the trigger rod allowed the grid to be pulsed without spurious breakdown. The triggering options were therefore as listed below.

(i) trigger rod with pulse and trigger grid earthed

(ii) trigger rod with pulse and DC bias and trigger grid earthed

(iii) trigger rod with pulse and trigger grid with DC bias.

In the investigation which follows, the voltages applied to the trigger electrodes were positive and current was therefore drawn from the cathode box both for the trigger discharge and for the main discharge.

4.3.2 Trigger discharge conditions.

The values for the discharge properties obtained in §4.2.4 require only minor modification for the NGTS. The cathode is again nickel gauze with dimensions as shown in Figure 4.7. The gas is deuterium at a pressure of 0.5 torr when the reservoir heater voltage is at 6.3 V. Adjusting the reservoir voltage from 5.0 – 7.0 V adjusts the pressure from about 0.2 – 0.7 torr. The calculated value for the cathode current density is about 70 $\mu A/cm^2$. The measured values from the test diode indicate that this should be increased by a factor of 3 to give a value of about 200 $\mu A/cm^2$. Since the total cathode area is about 100 cm^2, this gives an estimate of at least 20 mA required to drive the cathode emission area close to the baffle slots to cause triggering.

4.3.3 Switch operation.

The discussion in §4.3.2 and §4.3.3 has shown that the discharge properties in the NGTS are different to those found in conventional thyratrons and consequent differences in switch operation are to be expected. In the NGTS, the cathode regions of the glow discharge are essential to the maintenance of electron emission from the cathode and the operation of the switch is likely to be strongly influenced by factors which alter the parameters of the cathode dark space and negative glow. The principal factor to be considered is the gas density variation in the cathode box which results from discharge heating. As discussed in Appendix F, the gas density in the cathode box when the switch is operating may drop to half its room temperature value and the pressure measured external to the switch envelope can be expected to give a poor indication of the effective pressure in the discharge region. A further factor to be considered is the pulse repetition frequency. At the end of switch conduction, the ionisation left in the switch is dissipated by diffusion and recombination processes. Since the ionising processes have ceased, there is a gradual decay of ionisation with time. If this decay is not complete at the end of the inter-pulse period, the development of the subsequent trigger discharge is influenced by the degree of ionisation which remains in the cathode box. Thus, as the pulse repetition frequency gets higher and the inter-pulse period gets shorter we might expect switch parameters such as jitter and t_{ad} to be reduced. The anode time delay, t_{ad}, as defined in Appendix A, is the interval between the application of the trigger pulse and the start of switch conduction. In order to measure t_{ad} properly, the 26% point on the unloaded trigger pulse must be aligned with a defined position on the oscilloscope screen. This is easily done in the course of a regular test procedure, but was not convenient for the investigation carried out here. Because of the variability of the rising edge of the trigger pulse as the conditions in the switch change, it is not possible to define a fixed point on the rising edge of the loaded trigger pulse. In the measurements that follow therefore, t_{ad} will be taken to start when the trigger pulse comes above zero. This is not as accurate as the BS 9014 method, nor does it allow direct comparison with typical thyratron results. For comparison purposes, it should be noted that the values of t_{ad} measured here are 30–60 nsec longer than those measured by the BS 9014 method. In a conventional thyratron, t_{ad} represents the time taken for the cathode to grid discharge to develop and for electrons in the grid plasma to find their way to the high voltage region through the grid baffles. The electrons move from the cathode–grid plasma by ambipolar diffusion at a speed such that t_{ad} is about 100 nsec in a typical thyratron. The processes defining the t_{ad} of a normal glow triggered switch are different from those in the hot cathode thyratron. Figure 4.8 shows a cross–section of the trigger discharge in the NGTS. As already described, the CDS and NG regions propagate into the hollow cathode by spreading laterally over the surface. The t_{ad} of the NGTS will therefore depend on the statistical and formative times for the discharge to fill the cathode.

4.4 Characterisation of the NGTS.

4.4.1 Introduction.

This section introduces the methodology and equipment used in the NGTS characterisation. The performance of the switch under the different triggering conditions is described below. The device was processed as described in Appendix B and filled with deuterium to a pressure of 0.5 torr. To test its performance, the device was used as the switching element in a conventional line–type modulator, with a circuit similar to that illustrated in Figure 4.9. The particular conditions of operation of the switch are described later for each of the triggering options tested. The trigger pulse was supplied by a trigger unit designed to have an output of a maximum of 2 kV with a source impedance of 100 Ω, at a repetition rate adjustable in the range 20 – 1000 Hz, with a pulse width of 1 μsec. The circuit of this unit is shown in Figure 4.10. When required, the trigger pulse was fed to a 3:1 pulse transformer giving a 6 kV pulse. The pulse transformer design is described in Appendix E. A DC supply with an output of 2 kV (+ve) and 100 mA was also used to provide a 'keep–alive' or bias supply for the trigger electrodes.

In order to characterise the performance of the switch in the modulator, the fast–rising, short–duration voltage and current pulses on the various electrodes entering the device need to be recorded. In addition, measurements of the pulses yield information on the magnitude and time relationship of some of the discharge phenomena. The pulse waveforms were displayed using a high bandwidth oscilloscope (Tektronix 2465, 300 MHz) and were recorded photographically. Voltages were measured with 1000:1 probes (Tektronix P6015) and the currents were measured with current transformers (Ion Physics) with sensitivities of 1 A/V and 10 A/V.

4.4.2 Initial Behaviour

In the first experiments with the normal glow triggered switch, it was connected into the modulator circuit of Figure 4.9 with the trigger rod pulsed and the trigger grid earthed. Photograph 4.3 shows the switch successfully operating at Epy, 10 kV; I, 150 A; p.r.f., 400 Hz and the results described in the following paragraphs were obtained.

The trigger rod voltage and current waveforms in the absence of anode voltage, are shown in Photograph 4.4. A variety of electrode waveforms when anode voltage was applied, are shown in Photographs 4.5, 4.6 and 4.7. The lower waveform in Photograph 4.5 is the trigger voltage pulse. The onset of anode conduction is clearly marked by the 'grid spike' described in §1.4. The t_{ad} measured from this photograph is about 600 nsec. The anode voltage and current are shown in Photograph 4.6. The anode voltage (lower trace) collapses within 20 nsec and the current (upper trace) rises in about 100 nsec as determined by the discharge circuit. The traces shown in Photograph 4.6 are similar to those expected from a thyratron. The anode voltage trace shows the effect of the inductance of the switch L_s during the current rise−time. During this time, the measured anode voltage is elevated by

$$V_{L_s} = L_s \frac{dI}{dt} \quad . \qquad 4.3$$

A similar but opposite voltage appears during the current fall–time and this is also apparent on the anode voltage trace. During the flat portion of the current pulse, the measured anode voltage corresponds to the voltage across the switch and we shall call it the running voltage. The importance of the running voltage lies in the fact that it determines the energy dissipated in the switch at a given current. Unfortunately, it is difficult to measure reliably, the main problem being that the running voltage is very small in relation to the hold–off voltage. One way of dealing with this difficulty is to measure energy dissipation in the switch by a calorimetric method in addition to more convenient probe methods so as to obtain an independent check. In any case, switch running voltages measured with high voltage probes (Tektronix P6015) alone should be treated with some caution. In order to achieve the best fidelity from the probes in this study, their compensating boxes were set up in the manner recommended in the P6015 handbook (Tektronix, P6015 handbook, 1987) using a pulse generator with a high rate of rise. The running voltages reported here were taken from the oscilloscope screen or the recorded photographs. The width of the trace means that an accuracy of about ±50 V can be associated with the measurements. The running voltage measured from Photograph 4.6 is about 900 V.

The anode current pulse is shown in Photograph 4.7. The jitter over 400 pulses, estimated from the trace width, is greater than 40 nsec. More precise measurements of all these parameters are reported later. The tube was operated in the modulator for a period of 30 minutes.

On a second attempt to run the tube, it demonstrated erratic triggering (missed pulses) and the jitter had increased to 100 nsec. Reliable operation was restored by running a DC discharge of a few mA to the rod and applying the trigger pulse to the grid, as in the circuit of Figure 4.11(a). A further 8 hours operation was achieved. The jitter was measured at 40 nsec as shown in Photograph 4.8, but reducing the resistance in series with the grid from 100 Ω to 25 Ω brought the jitter down to 10 nsec.

At the end of 8 hours the triggering was again found to be erratic. The switch was removed from the modulator and the electrode insulation was checked using a high voltage insulation tester (Megger). The insulation was good to the maximum level of 500 V and the test confirmed that no substantial conducting films had been deposited on the insulators during the previous runs. The measurements of IV characteristic, striking voltage and maintaining voltage were repeated. The DC measurements before and after are laid out in Table 4.1. They have all increased by a few tens of volts. The IV characteristics before ageing are shown in Photographs 4.9 and 4.10 and after ageing in Photographs 4.11 and 4.12. In contrast to the DC measurements, they show that the voltage required to obtain a given current has decreased by about 100 V for both trigger electrodes after ageing. These measurements indicate that the cathode surface changed during the first eight hours of operation, presumably due to the sputtering which gave the metallic film on the glass envelope adjacent to the cathode. The magnitudes of the shifts in the DC measurements and the IV characteristics do not indicate that triggering should necessarily be more difficult, and the change in triggering behaviour remains unexplained.

In response to the difficulty experienced at the end of the 8 hour run, the triggering arrangement was changed to apply DC bias to the grid and a trigger pulse to the rod (Figure 4.11(b)) and reliable triggering was restored. The jitter was measured from the anode voltage fall in Photograph 4.13 as 6 nsec, which is encouragingly close to thyratron capabilities.

These initial runs established the switch concept and revealed some useful information about its operation. Firstly and not unexpectedly, the switch cathode ages (Acton & Swift, 1963, p 268) over a period of eight hours operation under the conditions given above. This ageing leads to a requirement for a higher voltage trigger drive and/or the inclusion of a source of ionisation. Secondly, and in line with thyratron experience, the triggering circuit arrangement has a marked impact on the performance of the switch. The triggering options and their effect on the switch performance will be investigated in the following sections.

4.4.3 Pulse on the rod.

The simplest trigger arrangement for the switch is to supply a voltage pulse to the trigger rod only, with the trigger grid earthed. In view of the difficulties encountered earlier with the trigger discharge to the rod, it was decided to increase the trigger voltage by feeding it through a 3:1 step–up pulse transformer of the design described in Appendix E. The output pulse from this transformer is shown in Photograph 4.14. As a consequence of using a higher voltage trigger drive, the switch operated reliably in the single trigger pulse mode. The voltage and current waveforms of the trigger rod discharge, driven by the 3:1 transformer and measured in the absence of anode voltage, are shown in Photograph 4.15. The current pulse trace had a small initial peak, which coincided with the rising edge of the voltage pulse. This peak was due to displacement current as the voltage pulse charged the 20 pF trigger rod capacitance. The displacement current peak stands out more clearly in some of the later photographs (*eg.* 4.18 – 4.21). As soon as the voltage on the trigger rod had grown sufficiently, the initiation of the trigger discharge began and, after a delay of less than 50 nsec in Photograph 4.15, the trigger current grew rapidly. We would expect the NGTS to trigger as soon as the trigger discharge has filled the cathode box, so the trigger current rise–time will have a direct influence on the anode time delay t_{ad}. In practice, the trigger current rise–time seen in the photograph is a convolution of the rise–time of the applied current pulse and the formation and propagation times for the discharge, so it is somewhat difficult to separate the various contributions. However, the trigger current is observed to rise in about 100 nanoseconds to a peak level of 12 A. Based on the cathode current densities of §4.3.2, this pulse should be more than large enough to fill the cathode and trigger the switch.

When the anode voltage is applied and cathode–anode conduction occurs, the trigger rod waveforms change to those shown in Photograph 4.16. The discharge breakdown voltage is higher, the t_{ad} is longer and the trigger current pulse smaller. The transition to a higher breakdown voltage is thought to arise from the decrease in gas density due to discharge heating of the cathode. This hypothesis was tested by running the trigger discharge without anode voltage at a reduced gas pressure. The trigger rod waveforms at reduced gas pressure, shown in Photograph 4.17, were found to be similar to those observed with anode voltage at the higher initial gas pressure. Thus the change in the trigger discharge seems to be due to the gas density change (see Chapter 1). The reduced trigger current pulse observed under conditions of lower gas density, is a result of a feature of the trigger unit design (Figure 4.10). The trigger unit includes an internal resistance of 300 Ω on the output of the pulse transformer to allow a voltage pulse amplitude to be set while the output is otherwise unloaded. Thus, if trigger breakdown occurs late in the voltage pulse, much of the stored energy is dissipated in this internal load, and the trigger current pulse is smaller.

The same reduced current pulse was observed when the repetition rate was varied. The ionisation created by the cathode–anode current recombines in the cathode box during the interpulse interval; its presence assists the initiation of subsequent trigger pulses. Operation at high frequency favours early breakdown of the trigger voltage pulse and this was indeed observed over the range of pulse repetition frequencies in Photographs 4.18 – 4.21, where the measured t_{ad} values are 1200 nsec at 400 Hz and 640 nsec at 1000 Hz.

Photograph 4.22 shows the anode voltage and current pulse. At a voltage of 10 kV applied to the anode, the peak current in the switch is 100 A and compares favourably with a thyratron under the same conditions. During the flat portion of the current pulse, when the voltage probe does not record an inductive voltage, the running voltage is about 600 V. This is higher than the typical running voltage of less than 200 V for a hot cathode thyratron under similar conditions. However, the reservations expressed in §4.4.2 about the reliability of the probe measurement should be borne in mind.

The minimum t_{ad} for this trigger mode was found under the conditions of Photograph 4.15, and was measured as 650 nsec. The jitter was measured from Photograph 4.23 as 10 nsec. This was a minimum value and small variations in trigger voltage or gas density caused the jitter to increase to a maximum of about 60 nsec. The minimum current pulse which will initiate conduction at an anode voltage of 5 kV was found to be 800 mA. The NGTS switching performance data available from the photographs for all the trigger options is summarised in Table 4.4.

4.4.4 Pulse and bias on the rod.

One of the features of a cold cathode discharge is the large statistical time–lag between the application of voltage and the initiation of current conduction. The statistical time–lag is a result of the very low numbers of suitably placed free electrons created in the discharge volume by the action of cosmic rays, natural radioactivity and ultra–violet photons (Llewellyn–Jones, 1966, pp 105, 129). For the NGTS, statistical time–lag would be expected to show up as jitter. When repetitive switching has been established, residual ionisation from the main discharge current remains in the cathode box at the end of each inter–pulse period. The trigger pulse is initiated in the presence of ionisation of a density which depends on the pulse repetition frequency (p.r.f.) and its statistical time–lag will be reduced. Thus, we might expect to see a reduced jitter at high p.r.f. The presence of ionisation in the cathode box also has an influence on the formation of the trigger discharge and, as we have seen in §4.4.3, the anode delay time, t_{ad}, has a resulting sensitivity to changes in the pulse repetition frequency. To avoid this sensitivity, a steady source of electrons can be provided by running a low level DC bias discharge ('keep alive') from the cathode to the trigger rod. The trigger pulse can then be imposed on top of the DC bias in order to initiate conduction in the switch.

The circuit needed to implement the bias–trigger system is shown in Figure 4.11(c). The trigger rod waveforms that result from this arrangement were as shown in Photograph 4.24. The trigger voltage (upper trace) starts at a voltage above zero equal to the bias discharge running voltage. The time delay from trigger voltage breakdown to trigger current initiation is so short as to seem simultaneous, so the bias discharge appears to be pre–ionising the cathode box as planned. When anode voltage is applied, the trigger rod waveforms were as shown in Photograph 4.25. The t_{ad} measured from the photograph was about 600 nsec and was observed to be largely independent of pulse repetition frequency which confirms that the ionisation from the bias supply stabilises the formation time of the trigger discharge. After a few minutes running, it was found that the trigger pulse extinguished the DC discharge and thereby prevented the triggering of the main discharge. The 'blow–out' phenomenon was observed after the device had been switching anode current pulses for some time, and the loss of the DC discharge prevented the development of the trigger pulse and so caused anode conduction to cease. Occasionally the DC discharge re–struck and the cycle repeated. The reason for the 'blow–out' can be found in Photograph 4.25, which shows that the voltage on the trigger rod goes to zero after anode conduction. The voltage was observed to remain at zero for up to 60 microseconds as shown in Photograph 4.26. The period of zero voltage is likely to be a consequence of the large random electron current available from the post–conduction plasma. In contrast, in the absence of the main current pulse (Photograph 4.24), the bias voltage on the trigger rod began to rise immediately after the end of the trigger pulse. The post–conduction plasma acts as an effective short circuit for the trigger supply until recombination reduces the random electron current below the supply's current capability. The effect is also found on the positive and negative grid supplies of thyratrons. As a result of main discharge current conduction and the existence of post–conduction plasma, the nominally DC voltages from the bias supplies are found to have waveforms similar to those of Photograph 4.26. In the thyratron case, it is unknown for the discharge to be extinguished. In the NGTS, the failure of the discharge to re–establish at the end of the zero voltage period is due to the striking and running voltage of the discharge becoming higher than the voltage level available from the bias supply. Reasons for this could include a reduced gas density due to heating or transient gas density fluctuations as a result of ion pumping. In any event, the bias discharge was not able to re–strike and switching ceased. In order to obviate the effects of 'blow–out', the DC bias supply was modified to provide an output voltage of 4 kV maximum, to ensure that the bias discharge could be re–struck and run under all circumstances. With this modification, the bias discharge remained stable and the switch triggered reliably.

The anode voltage and current are shown in Photograph 4.27. The running voltage of the switch in this trigger mode appears to be about 800 V, which is unexpectedly higher than in the absence of bias (§4.4.3). The jitter was measured on 400 current pulses at an anode voltage of 10 kV and was found to have a minimum value of 4 nsec, which is a big improvement on the 10 nsec jitter achieved with trigger pulse alone (§4.4.3). A jitter of 4 nsec for the NGTS puts it on a par with glass thyratron jitter performance and seems to confirm that a DC bias discharge can reduce the statistical time–lag of the trigger discharge. As in §4.4.3, the minimum current pulse which will initiate conduction at an anode voltage of 5 kV was found to be 800 mA.

As discussed in Chapter 1, the trigger discharge parameters have a large effect on the performance of a hydrogen thyratron. Amongst other benefits, the t_{ad} and jitter are minimised when the trigger pulse current prior to switch conduction is maximised. It seems reasonable that the t_{ad} in the NGTS could see a similar reduction as the trigger current is increased. In a simple scenario, the NGTS fires when the trigger current is large enough, as determined by the cathode current density, to cause the emission area to enter the baffle slots. Accordingly, an increased trigger current would reduce t_{ad} by causing the firing current to be reached more quickly. In order to establish if the trigger discharge current has such an effect on t_{ad} in the NGTS, various trigger currents were selected by adjustment of the trigger unit voltage. The p.r.f. was fixed at 400 Hz and the series impedance was 220 Ω. The trigger voltage and current traces are shown in Photographs 4.28 – 4.32. It should be noted that t_{ad} is increased by about 50 nsec at the lowest selected trigger voltage because of a shift in trigger voltage breakdown point. However, the trigger current has a much greater influence on t_{ad}. As measured from the photographs, t_{ad} increases from its minimum value of 250 nsec, achieved at a trigger current of 8 A, to a value of 600 nsec at a trigger current of 1.2 A. The trigger current traces shown in the photographs are oscillatory. The first trigger current peak is due to capacitative current as described in §4.4.3. The second peak is due to the trigger discharge and it appears that firing occurs at some point after the trigger discharge current peak and that the firing point moves closer to the trigger discharge current peak as the trigger current is increased. The presence of the delay between the trigger current pulse peak and anode conduction suggests that the simple scenario for NGTS triggering , proposed earlier in this section, does not give the full picture and it may be necessary to consider factors other than cathode current density (*eg.* the propagation speed of the discharge or the penetration of the cathode dark space into the baffle slot) in order to explain the processes underlying the triggering behaviour. In any case, it can be stated that the t_{ad} in the NGTS is decreased as the trigger current is increased.

The Photographs 4.33 – 4.37 show an increase in t_{ad} of about 50 nsec as the trigger series impedance is increased from 47 Ω to 1000 Ω. The increase in impedance gives a trigger current reduction of about 25% as estimated from the photographs and corresponds with a t_{ad} increase of about 25%, which seems to confirm the conclusion of the previous paragraph.

A small decrease in t_{ad} of about 30 nsec was also observed as a result of increasing the bias current from 13 mA to 30 mA as seen in Photographs 4.38

and 4.39 and the improvement may be related to a reduced discharge formation time as a result of the higher pre–ionisation density when the bias current was 30 mA.

The conclusion that can be drawn from the investigation above is that the provision of a DC pre–ionisation current in the cathode box has a stabilising effect on the t_{ad} under various conditions of gas density and pulse repetition frequency and reduces the jitter from 10 nsec to 4 nsec. The DC bias current does not seem to have a marked effect on t_{ad} in the range 15–30 mA. The t_{ad} is mainly determined by the trigger current and a limiting value of about 250 nsec can be reached with the equipment and methods used here.

4.4.5 Pulse on the rod, bias on the grid.

A variation of the above method of obtaining pre–ionisation in the cathode box is to use the second trigger electrode provided in the switch. This section will examine the effect of having the DC bias discharge running to the trigger grid of the switch using the circuit shown in Figure 4.11(b). With this arrangement, electrons are drawn from the cathode box surface to the trigger grid. When the voltage pulse is applied to the trigger rod, electrons created in the bias discharge begin to flow to the rod. As the pulse current grows to be much larger than the DC bias current, the discharge can be said to have transferred to the pulsed electrode. The effect of the bias current on the trigger rod waveforms is shown in Photographs 4.40 – 4.42. An increased bias current reduced the breakdown voltage and advanced the initiation of the trigger current. When anode voltage was applied, the trigger waveforms were as shown in Photograph 4.43. The upper trace shows the DC bias and how its voltage changes in response to the changing discharge conditions. The initial positive humps mirror the trigger rod voltage (middle trace) before anode conduction causes the large positive kick followed by a collapse to zero. Photograph 4.44 is noteworthy because it illustrates the shorting of the bias supply by the post–conduction plasma as discussed in §4.4.4. The grid remains at zero for about 60 μsec after switch conduction.

While recording the photographs described above, a change was noted in the bias discharge and it was suspected that this was due to a reduced gas density. In order to study the effect of a lowered gas density, the anode voltage was switched off to allow the cathode to cool and a reduced gas pressure was selected by setting the reservoir heater voltage to 5.5 V. When the bias current was increased to 15 mA, it was apparent that the discharge ran in one of two modes. The first mode had a domed pink glow on the grid disc and a blue glow extending into the lower cathode cylinder. The second mode ran at a higher voltage, with a domed blue glow on the grid disc and a pink glow which did not penetrate the lower cathode cylinder. A comparison of the running voltages of the two modes is given in Table 4.2. At a reservoir heater voltage of 6.0 V, mode 2 was observed only at currents below about 4 mA and a transition to mode 1 occurred if this current was exceeded. At 6.5 V on the reservoir heater, mode 2 did not appear. It is known that the cathode dark space width increases as gas density reduces and, for the conditions under which mode 2 appears, the cathode dark space width could become as large as the lower cathode cylinder radius (Figure 4.7). The development of a negative glow in the lower cylinder would thus be prevented. The absence of the NG, with its essential contribution to discharge maintenance, could explain why the discharge does not penetrate the lower cylinder when the gas density is reduced. In §4.2.4, the cathode dark space width at 0.5 torr was estimated to be about 18 mm, which would fill the lower cathode cylinder and prevent the discharge forming there. Under some operating conditions and especially when switching higher powers, the switch failed to trigger on all trigger pulses. The failure to trigger may have been due to a temporary reduction of gas density to the point where the running voltage of the bias discharge was higher than the voltage output of the DC bias supply. The significance of these observations for switch design improvements will be discussed in §4.5.

To return to the triggering of the switch, once the discharge has transferred from the grid to the rod, it would be expected to grow over the surface of the cathode box and trigger the switch in the manner already described in §4.4.3 and §4.4.4. In fact, a new type of triggering appears when anode voltage is applied to the switch. It is observed that anode conduction does not start until the trigger pulse is over (see Photograph 4.45). This is in spite of a well established discharge in the cathode box with a peak current of 10 amps. We shall call this phenomenon 'post–trigger firing'.

A closer examination of the trigger waveforms in Photograph 4.45 indicates that the switch fires during the period of voltage and current reversal at the end of the current pulse. It is possible that the switch was being triggered by the negative–going portion of the trigger waveform. This possibility was rejected when a test with an inverted trigger pulse, shown in Photograph 4.46, failed to trigger the switch. Another hypothesis is that t_{ad} for this trigger arrangement happens to be of about the same duration as that of the trigger pulse. This was checked by adjusting the trigger pulse length. A simple modification to the trigger unit circuit (Figure 4.10) allowed the pulse length to be extended from 1.1 μsec to 1.75 μsec. Once again, as can be seen in Photograph 4.47, anode conduction did not occur until after the end of the trigger pulse. Extending the trigger pulse duration simply extends the t_{ad}. It seems that firing of the switch occurs in the first 100 nsec after trigger current zero (Photograph 4.45). It is likely that the switch is actually triggered by the decaying ionisation which diffuses into the baffle slots at the end of the trigger pulse. Reducing the density of ionisation at the end of the trigger pulse by reducing its peak current does delay the onset of anode conduction, as shown in Photographs 4.48 – 4.51. Reducing the trigger pulse current below 1 A delays firing by about 700 nsec. This extra delay gradually reduced to about 300 nsec as the current was increased to 1.7 A. The importance of the trigger current is confirmed by

Photographs 4.52 and 4.53 which show the appearance of an extra delay when the grid series impedance is increased from 1 kΩ to 4.7 kΩ thus reducing the current to about 1 A.

The effect of grid bias current on jitter was particularly strong in this trigger arrangement as laid out in Table 4.3. At 15 mA bias current, the switch achieved 3 nsec jitter, its lowest figure for any trigger mode.

The anode voltage and current waveforms are shown in Photographs 4.54 and 4.55. The anode voltage trace in Photograph 4.54, indicates that the running voltage is almost 2 kV for the duration of the pulse. In fact, the impedance of the discharge is large enough to reduce the peak current by about 40 A. The higher impedance of the discharge also causes a positive mismatch between the pulse forming network and the load (Figure 4.9) and a second small current pulse is observed. The running voltage during the second pulse is back to a normal level. In Photograph 4.55, the reservoir heater voltage has been raised to increase the gas density. Now, although an initial high impedance transient is observed, the running voltage remains low ($\sim$ 350 V) and a normal current pulse is passed. The circumstance which gives rise to the high impedance discharge seems to be the presence of a reduced gas density in the switch. We can speculate that the main pulse current at reduced gas density is drawn in a discharge mode similar to mode 2 for the bias discharge. This will be discussed further in §4.5.

4.4.6 Bias on the rod, pulse on the grid.

The final trigger option is to apply DC bias to the trigger rod and pulse to the trigger grid as shown in Figure 4.11(a). As mentioned in §4.3.1, the grid connection suffered surface flashover on its insulation ceramic when the 5 kV trigger pulse from the 3:1 pulse transformer was applied and the trigger unit was run at 40% – 65% of full voltage during the investigation reported in this section. Samples of the trigger waveforms at two voltage levels are shown in Photograph 4.56 and 4.57. The traces appear similar to previous trigger pulse traces such as Photograph 4.41, albeit with a reduced trigger voltage peak. The upper and middle traces of Photograph 4.58 record the trigger waveforms with the switch operating and the lower trace shows the anode current, again starting after the trigger current goes to zero. It appears that the use of the trigger grid is correlated with the phenomenon of post–trigger firing. A possible explanation for post–trigger firing will be presented in §4.5.

The operation of the bias discharge in the absence of anode voltage was checked at reduced gas pressure to compare it with the findings of §4.4.5. No evidence of two modes of operation was found in this case. The 'two modes' phenomenon (Table 4.2) for the trigger discharge, is thus almost certainly a feature of the geometry of the cathode in relation to that of the trigger grid disc.

The anode voltage and current are shown in Photograph 4.59. The running voltage of the switch in this trigger mode appears to be about 200 V, which is the lowest value recorded for all of the trigger arrangements. This may indicate that the presence of the bias on the trigger rod forces the trigger discharge to pre–ionise the lower cathode cylinder and that this pre–ionisation assists the development of the main discharge pulse over the entire cathode surface. The constraints imposed on the trigger voltage for this electrode prevented a comparative set of measurements of t_{ad} from being taken. However, the indications are that the behaviour of t_{ad} is broadly similar to that in §4.4.5, with no anode conduction until after trigger pulse current zero as illustrated in Photograph 4.50. The firing point is largely identical to that in Photograph 4.47 and we can conclude that the trigger grid is instrumental in preventing the initiation of the main current pulse until the trigger current pulse has terminated.

4.5 The behaviour of the switch.

The normal glow triggered switch (NGTS) depends for its operation on the properties of the cold cathode glow discharge. Thus there are distinct differences between the NGTS and the hydrogen thyratron. In both switches, triggering depends on the development of a discharge between the cathode and a trigger grid. The thermionic cathode of the thyratron, with a cathode current density capability of 10 A/cm^2 (Jenkins, 1969), can easily support the emission required for the trigger discharge. The ready availability of electrons from the thermionic cathode makes the CDS and NG regions of the glow discharge either small or absent (Cayless, 1957). The discharge current from the thyratron cathode therefore connects to the grid via a positive column and triggering of the thyratron takes place as a result of the diffusion of charges from this column into the high voltage region of the switch. The NGTS, on the other hand, creates a discharge from a cold cathode and the 'constant' cathode current density of about $2 \cdot 10^{-4}$ A/cm^2 (§4.3.2) causes the emission area to expand into the high voltage region of the switch, where electrons are emitted directly into the anode field to trigger the main current pulse. An extraordinary feature of the operation of the NGTS when positive bias is applied to either of the two trigger electrodes is the phenomena of post trigger pulse firing described in §4.4.5 and §4.4.6. In both cases, anode conduction occurs a few tens of nanoseconds after the current zero of the trigger pulse. The mechanism of this behaviour is not immediately obvious, since the effect occurs under two different conditions. However, the use of the trigger grid is a significant common factor.

It can be assumed that when the cathode emission area can penetrate the baffle slots and inject electrons directly into the anode region, the main discharge will develop rapidly thereafter. The fact that the main discharge does not occur implies that the emission area has not reached the grid slot or that it has reached the slots but at such a low charge density that the main discharge channel cannot develop. In the case of a plasma filling the cathode box, sheaths can be expected to form at all surfaces in contact with the plasma, including the baffle slot walls and the trigger grid. The trigger grid is within about 3 mm of the baffle slot, so a thick sheath on the grid or on the baffle slot itself could act to prevent the movement of charge through the baffle slots. The characteristic thickness of a sheath in a plasma is determined by the Debye length λ_D, the distance for which a voltage perturbation in a plasma is reduced to 1/e of its initial value, given by

$$\lambda_D = \sqrt{\frac{\varepsilon_0 \kappa T_e}{n_e e^2}} \quad , \qquad 4.4$$

where the universal constants are permittivity, Boltzmann's and electron charge and n_e and T_e are electron density and temperature. Unfortunately for this argument, using values of electron temperature T_e = 12000 K and electron number density $n_e = 10^{20}/m^3$ as found in the thyratron plasma (Kunc & Gunderson, 1983), the Debye length takes a value of 0.75 μm. This value for λ_D is about 1000 times too small to explain why the grid slots might be 'choked off'.

The assumption of plasma–like conditions is not generally valid for all the regions of a cold cathode glow discharge, since electron emission from the cold cathode depends on the formation of a cathode dark space and a negative glow (see Chapter 2). These two regions, rather than a plasma, are likely to be occupying the space in the NGTS cathode box and thus, the trigger discharge in the NGTS is fundamentally different from the trigger discharge in a conventional thyratron. The sizes of the cathode regions have been estimated in §4.2.4, where a CDS width of 18 mm and a NG width of 20 mm were obtained. Two competing effects could modify these estimates. Glow discharge theory indicates that the cathode dark space width will tend to increase as the gas density is reduced (*ie.* when the switch is operating). Against this, when the trigger discharge expansion is restricted, as it must be if it cannot move into the baffle slots, the cathode current density is forced to increase. As the cathode current density is increased, the width of the cathode dark space tends to decrease. The graph of Figure 4.12 indicates that the CDS width is reduced from a value of about 18 mm at a voltage of about 400 V before the trigger voltage is applied, to a value of about 6 mm at a voltage of about 900 V during the trigger pulse (Photograph 4.44). It seems reasonable therefore, to estimate that the cathode dark space, for the conditions in the NGTS during the tests reported in §4.4.5 and §4.4.6, was likely to have a width of about 6–10 mm. In support, the discharge of Photograph 2.1(d) in hydrogen at 0.75 torr has a CDS width which appears to be about 10 mm.

With these considerations and estimates now in mind, it can be seen that the position of the grid electrode in the NGTS (Figure 4.7) can influence the behaviour of the trigger discharge. The cathode dark space has a width which is about equal to the gap between the edge of the grid disc and the cathode cylinder wall. In the NGTS, the growth of the trigger discharge in the cathode box eventually brings the cathode dark space close to the trigger grid. As shown in Figure 3.13, the voltage required to maintain a given current density in a discharge increases very steeply when the anode is moved into the cathode dark space. Figure 3.13 indicates that a high voltage would be required to obtain current emission from the area of the NGTS cathode surface close to the trigger grid. In the trigger discharge, this voltage is not available and so the cathode emission area is effectively prevented from reaching the baffle slots when the trigger grid is acting as an anode for the trigger discharge, as it does in the trigger arrangements of §4.4.5 and §4.4.6. This argument seems to offer an explanation of post–trigger firing and it is reasonable to conclude that, when the trigger grid is in use, the switch is triggered by the diffusion of electrons from the trigger pulse afterglow.

It is now possible to suggest a number of design changes to the cathode box and trigger electrodes of the NGTS to improve its switching performance. To deal with the trigger electrodes first, the study shows that the best overall switching performance arises from the use of two trigger electrodes. The location of a trigger electrode close to the baffle slots causes switch conduction to be delayed until the end of the trigger pulse. It is not yet clear if some advantage can be gained from the delayed switch conduction, but, if a short t_{ad} is required, it is necessary to place the trigger electrodes at least 20 mm away from the baffle slots. As regards the cathode box, the results show that the switch occasionally operated in a high impedance mode as a result of a reduced gas density in the switch. In order for the main discharge to utilise the entire cathode, the cathode cavity dimensions should be selected to ensure that the pd product in the cavity is such that $pd \geq 10$ torr·cm for deuterium. The final desideratum is to gain control of the temperature of the switch and especially the cathode so that a reasonably constant gas density can be maintained. Designs to implement this are under consideration. If the temperature of the cathode box can be controlled, benefits would accrue in the stability of the cathode running voltage, t_{ad} and jitter. Moving into speculation, it is likely that advantages could be gained from the use of other metals or structures for the cathode and perhaps, from the use of other gases.

In conclusion, the normal glow triggered switch is a cold cathode switch with a switching performance that is comparable with a glass thyratron of a similar size. It has the potential for development to the status of a commercial product and could find ready use in applications where a combination of low standby power, instant readiness and thyratron–like switching precision is required.

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Table 4.1

Striking and running voltages for the trigger electrodes after 8 hours operation. The values at the start of operation are given in brackets. All values taken at V_R = 6.3 V

	Striking Voltage (V)	Running Voltage (V)
Trigger rod	900 (820)	420 (408)
Trigger grid	345 (330)	418 (386)

Table 4.2

Grid bias voltage measurements showing two modes.

	Running Voltage (V) @ V_R=5.5 V		
	@ 5 mA	@ 10 mA	@ 15 mA
Mode 1	930	456	453
Mode 2	1034	1100	1030

Table 4.3

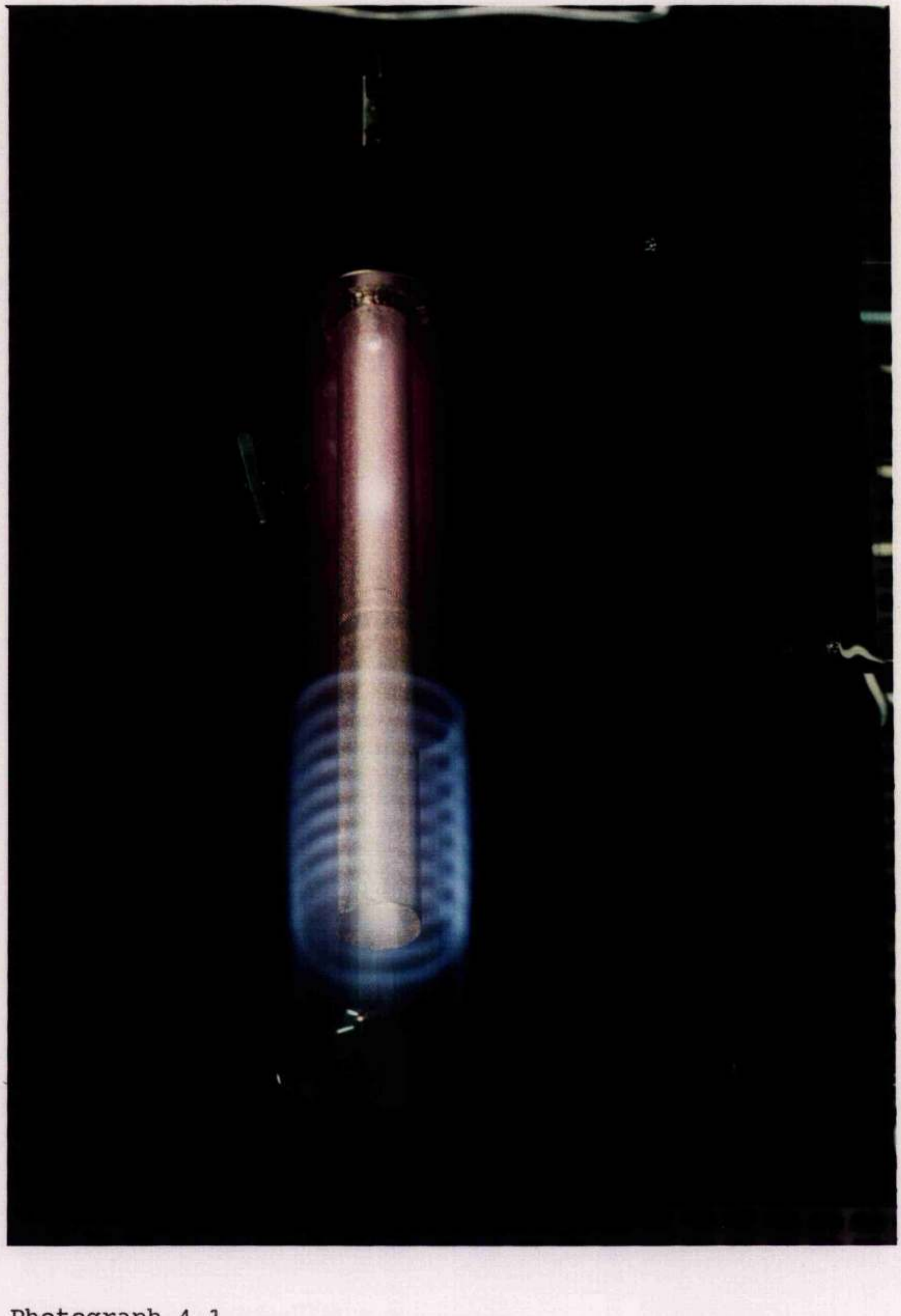
NGTS jitter as a function of grid bias current.
All values taken at V_R = 6.3 V.

Grid current (mA)	8	9	10	12.5	15
Jitter (nsec)	24	15	10	5	3

Table 4.4

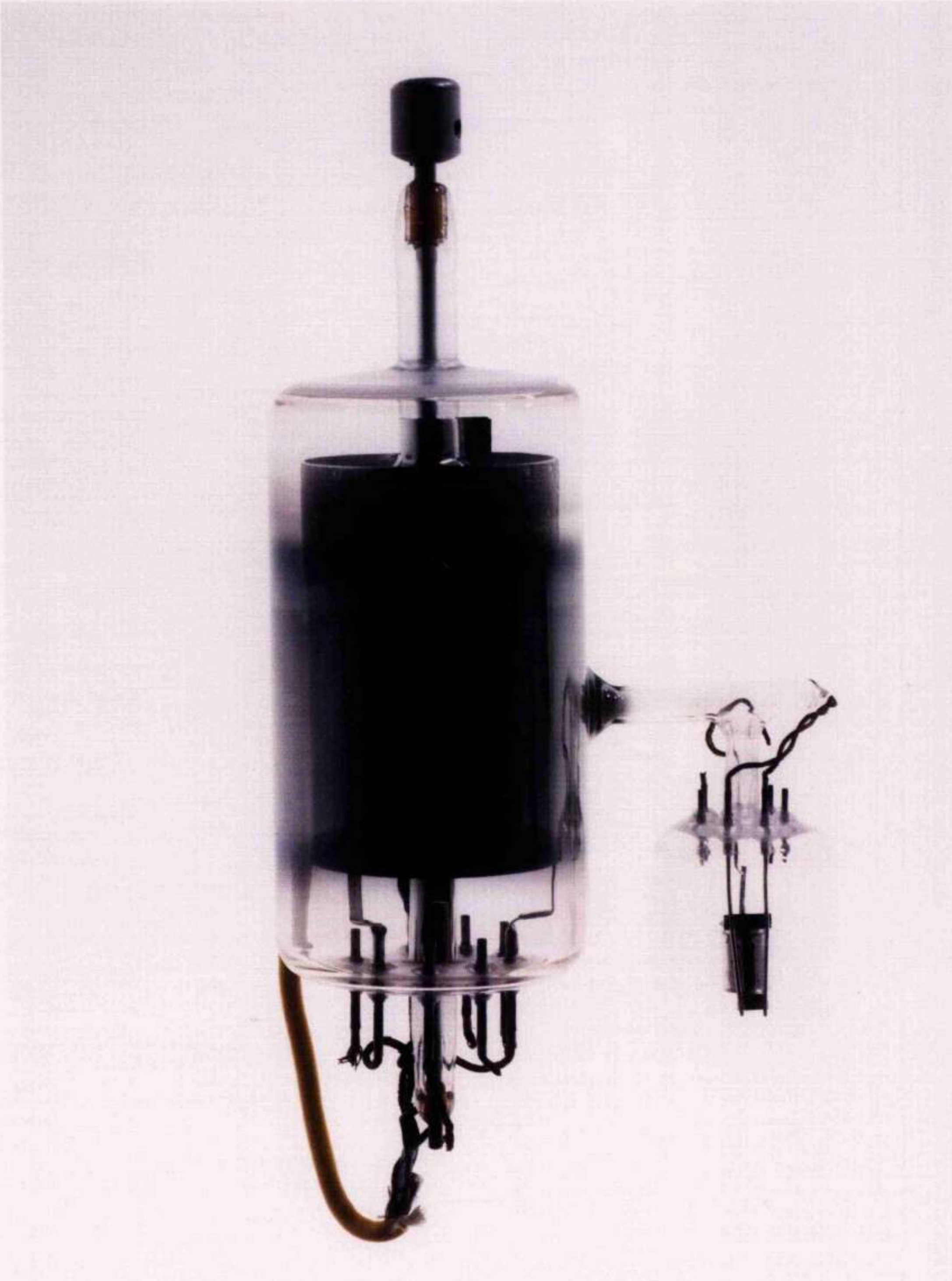
Achieved normal glow triggered switch (NGTS) performance with different trigger arrangements.

NGTS Trigger Conditions Rod	Grid	t_{ad} (nsec)	Jitter (nsec)	Arc drop @100 A (volts)	Comments
Pulse	Earth	650	10	600	The t_{ad} was sensitive to gas density and p.r.f.
Pulse & +ve bias	Earth	250	4	800	The t_{ad} was not sensitive to gas density and p.r.f. The arc drop was high.
Pulse	+ve bias	1200	3	260	The t_{ad} was determined by trigger pulse length. The arc drop was low.
+ve bias	Pulse	1200		200	The t_{ad} was determined by trigger pulse length. The arc drop was low.
Typical Thyratron		200	<5	100	



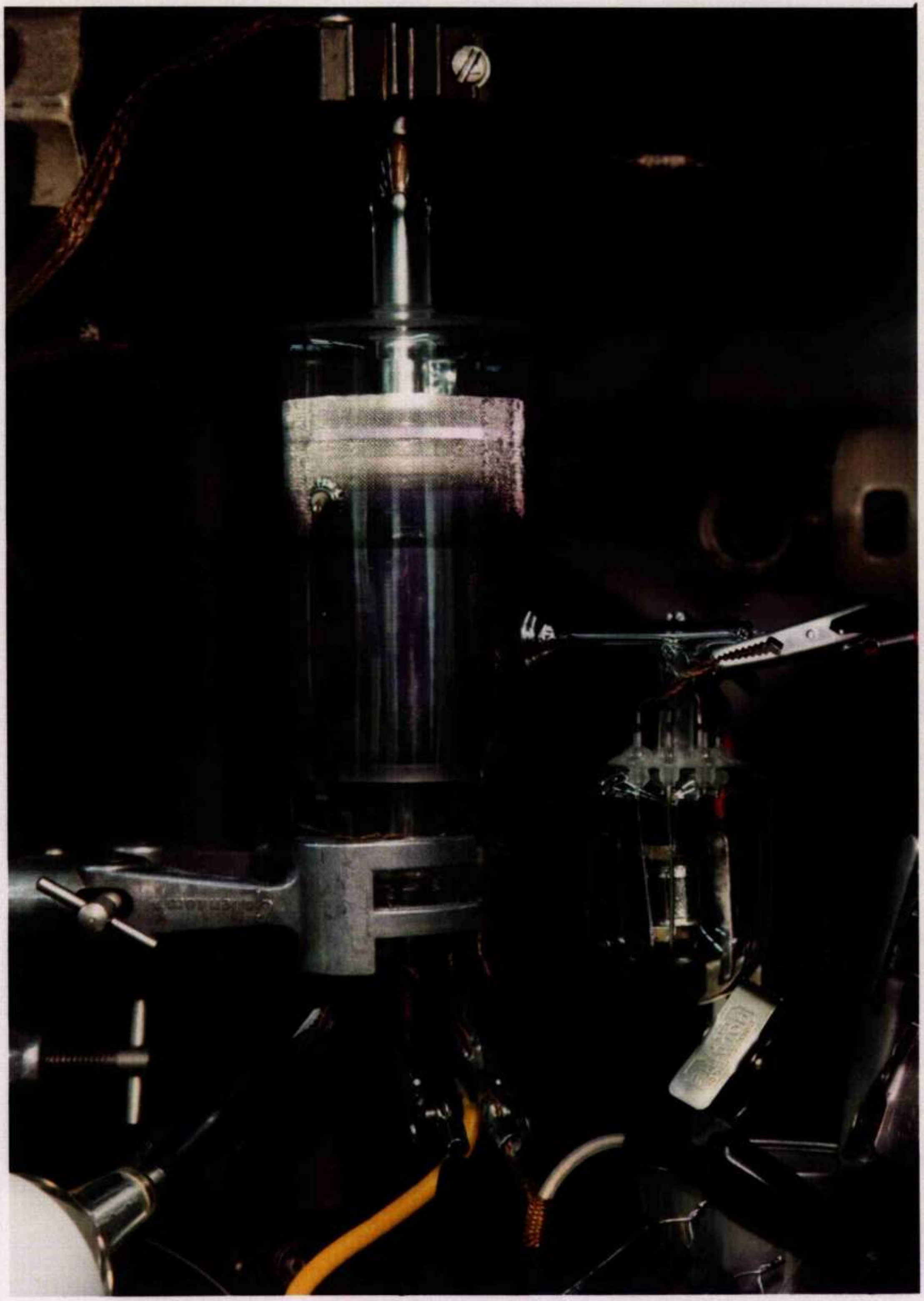
Photograph 4.1

A hydrogen discharge at 0.75 torr in the test diode of Figure 4.1, drawing sufficient current to cause the glow to emerge from the open end of the cathode.



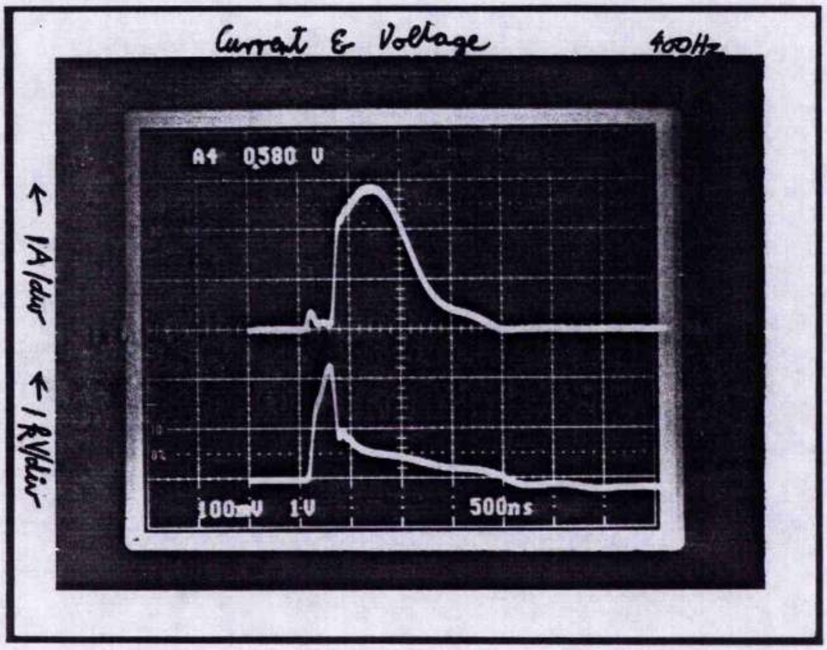
Photograph 4.2

The normal glow triggered switch (NGTS).

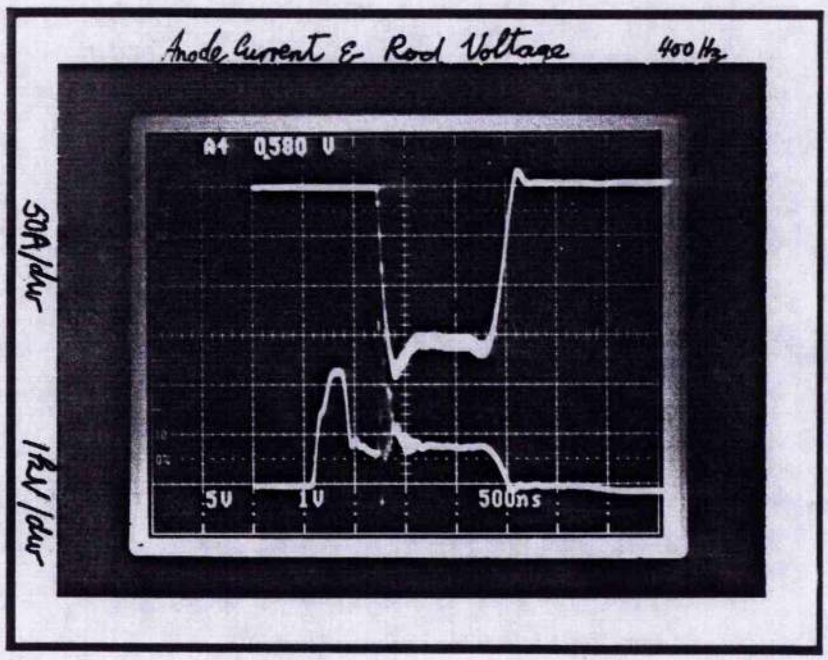


Photograph 4.3

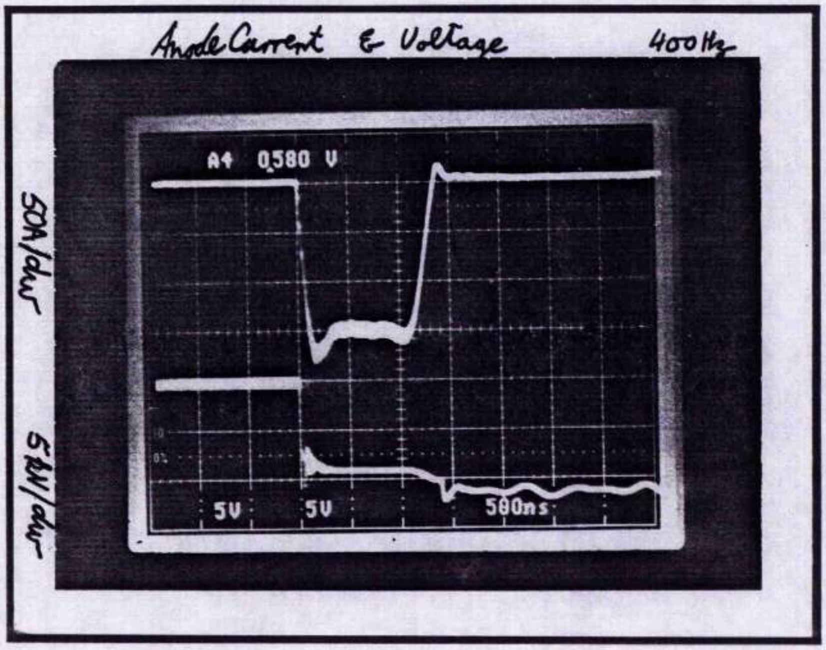
The normal glow triggered switch operating in the test modulator.



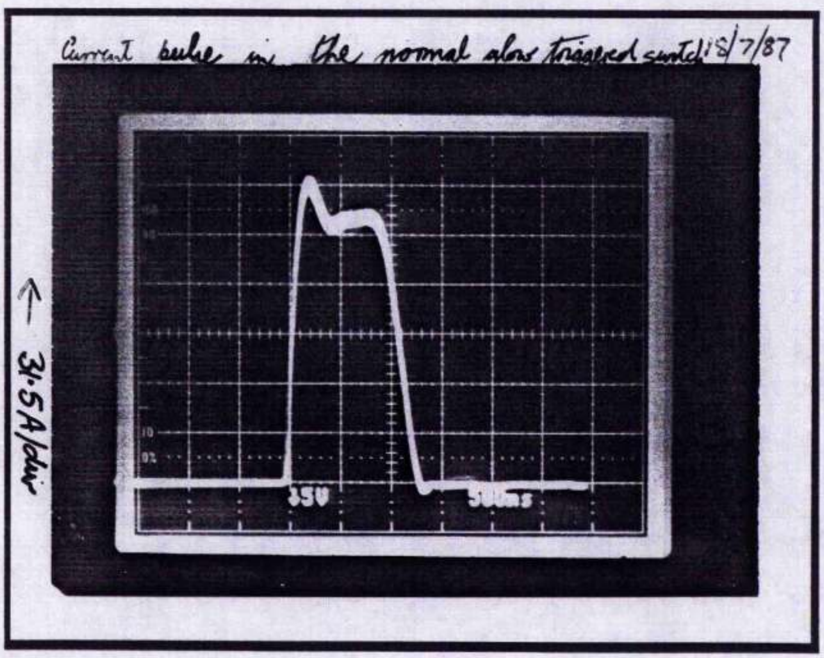
Photograph 4.4



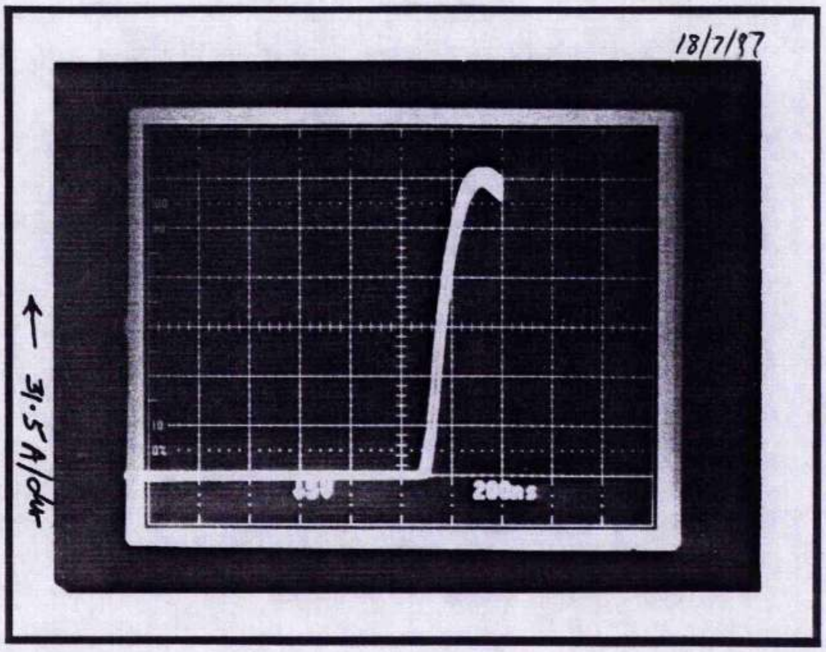
Photograph 4.5



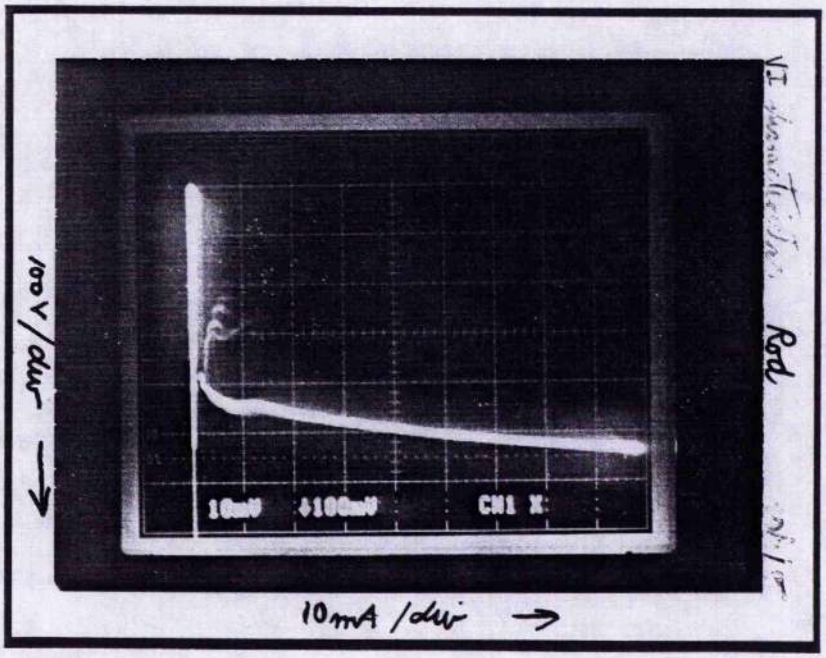
Photograph 4.6



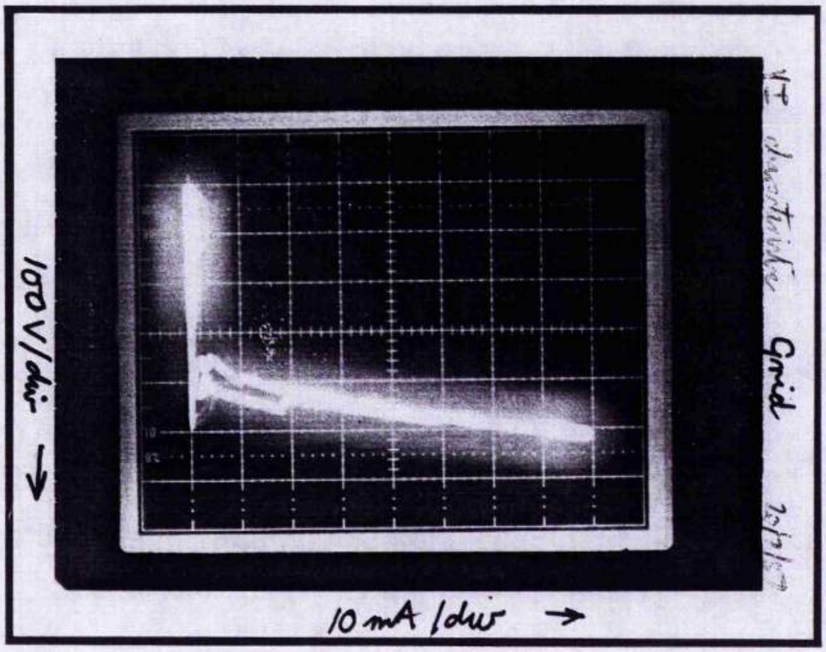
Photograph 4.7



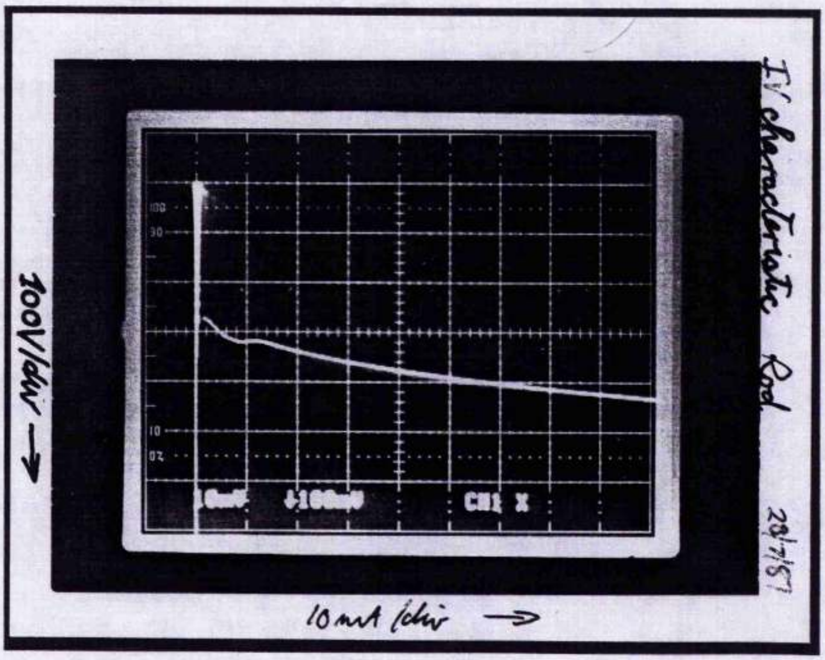
Photograph 4.8



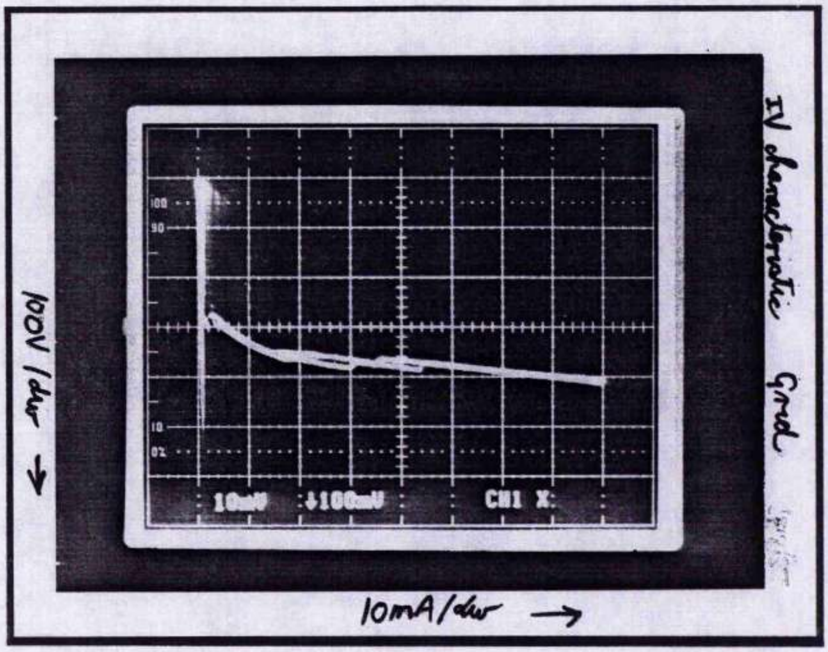
Photograph 4.9



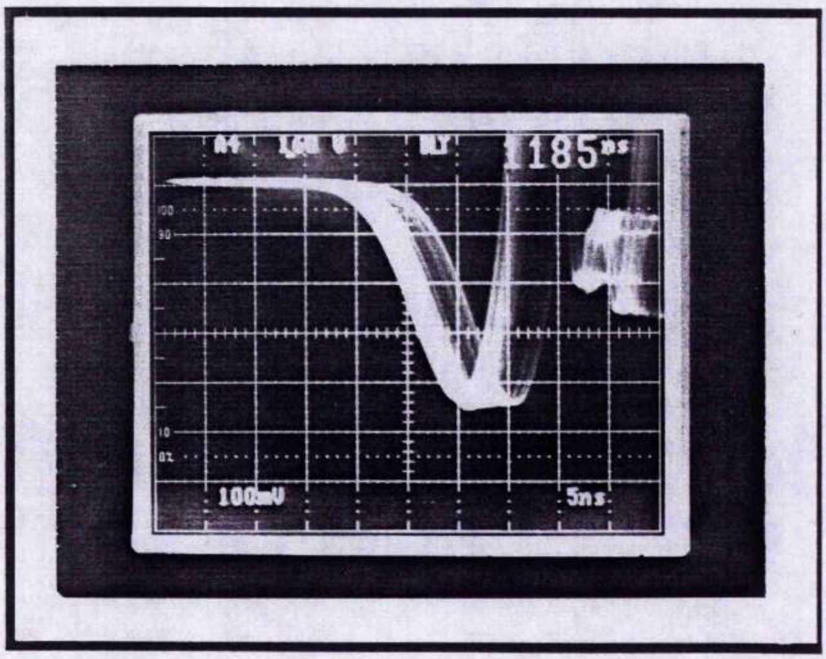
Photograph 4.10



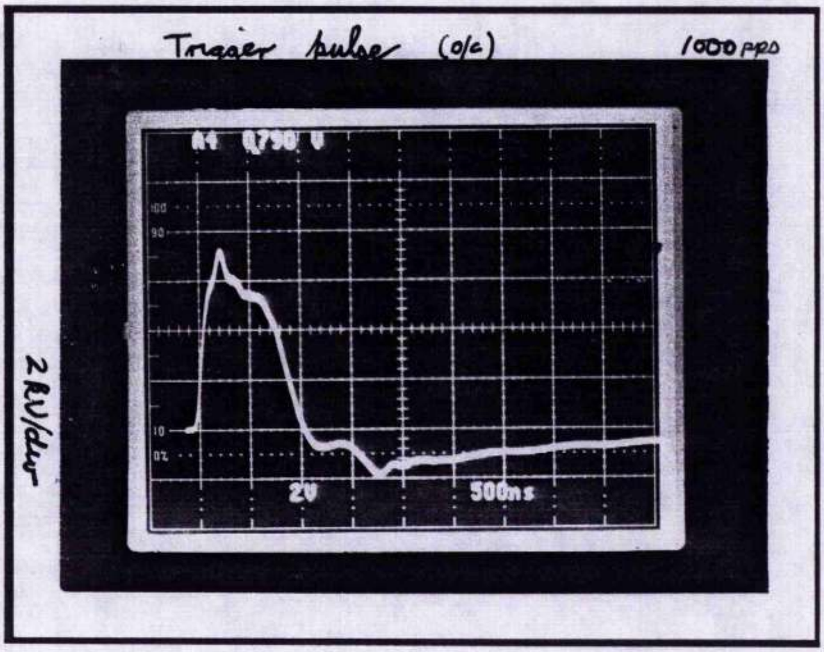
Photograph 4.11



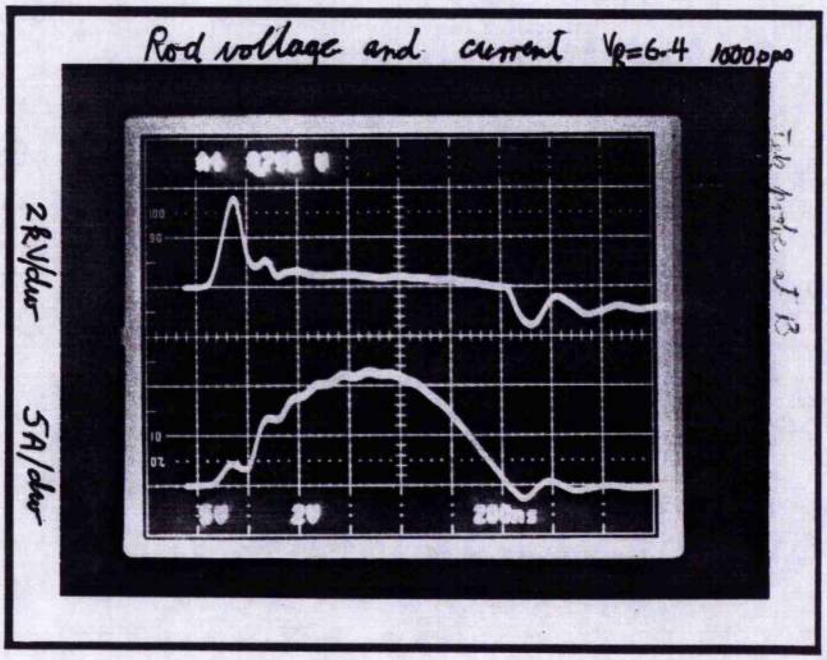
Photograph 4.12



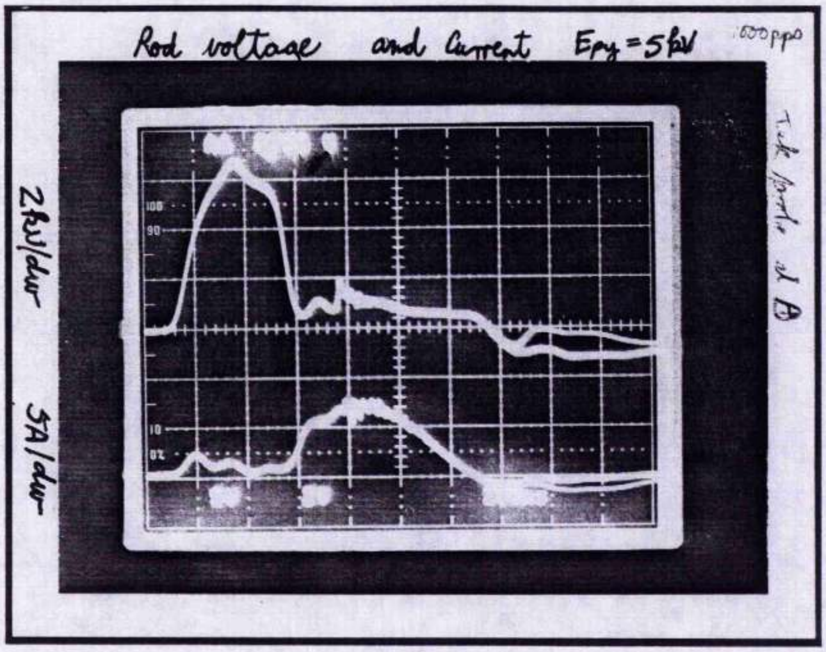
Photograph 4.13



Photograph 4.14



Photograph 4.15



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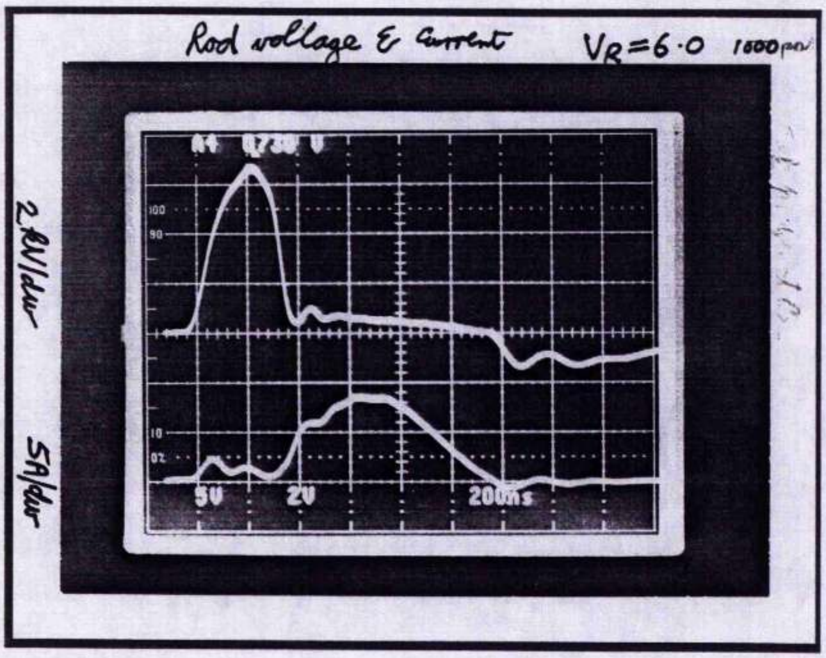

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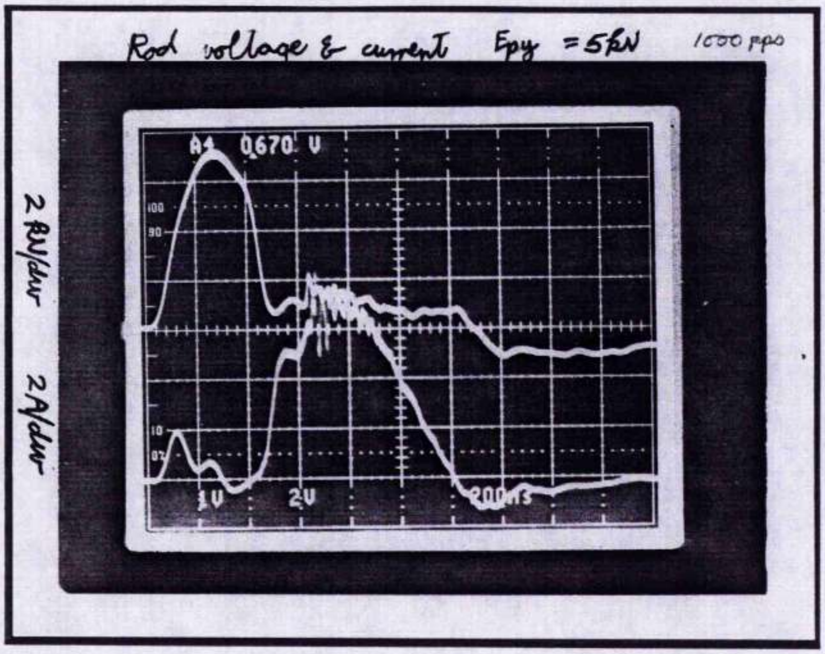

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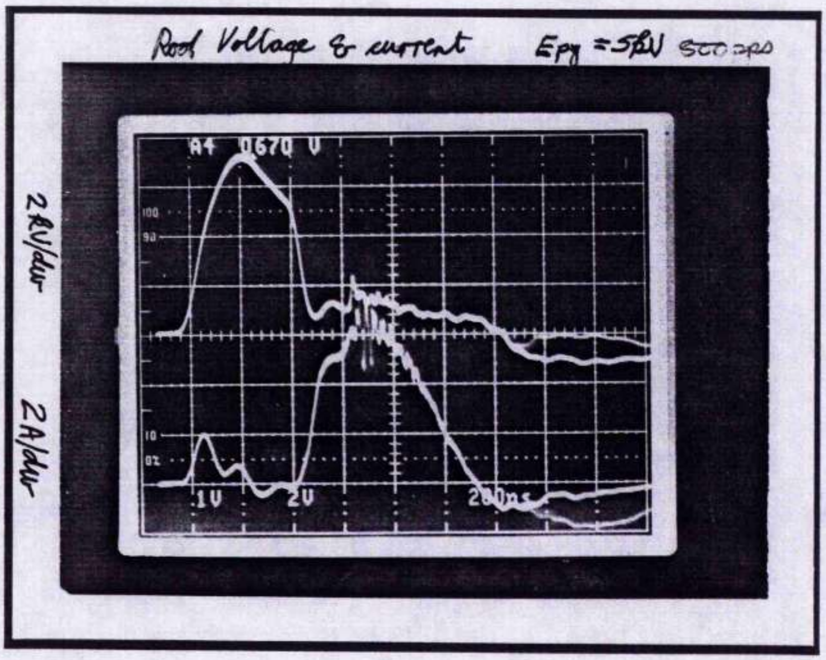

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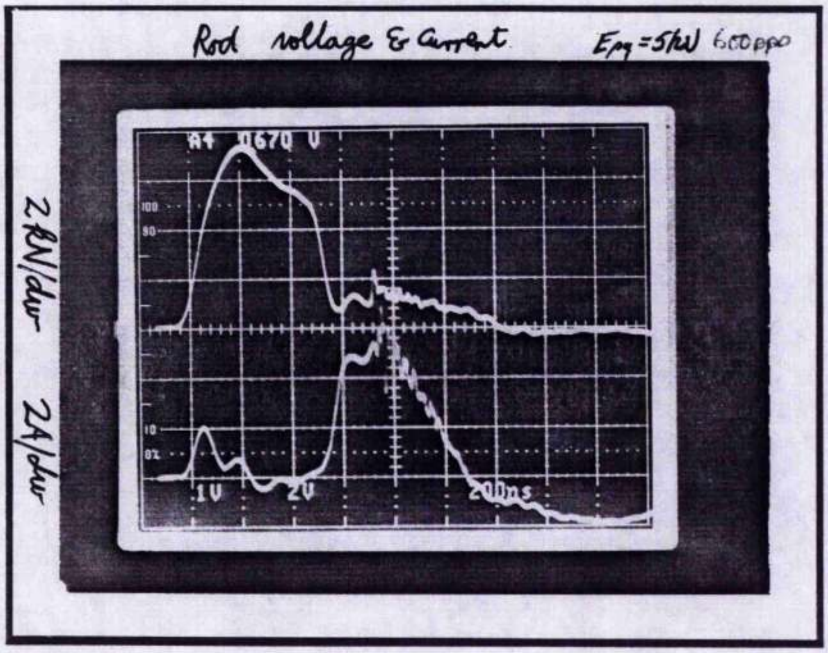

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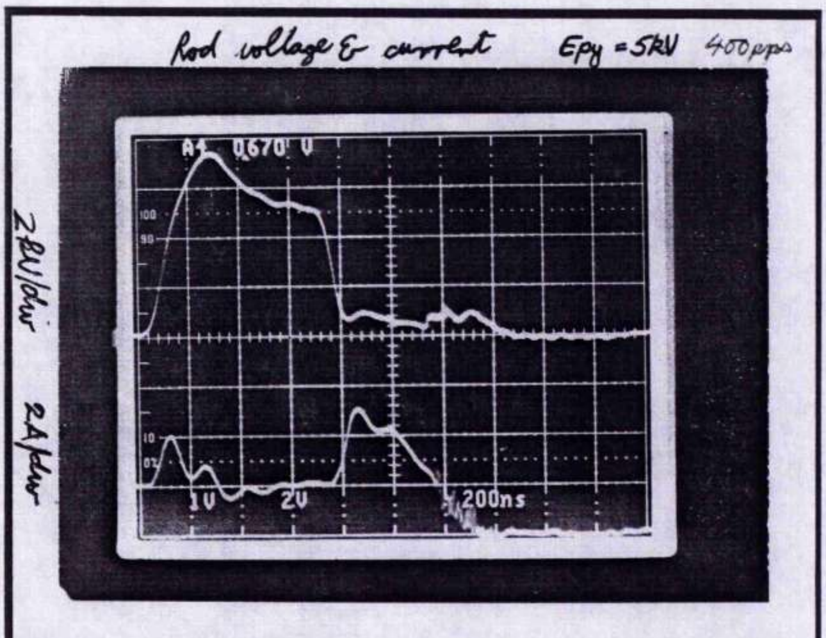

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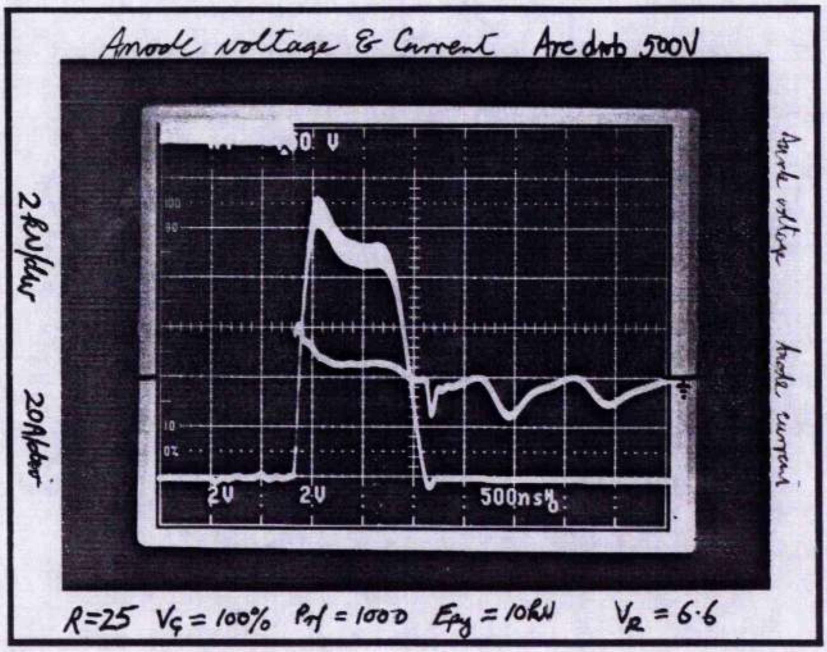

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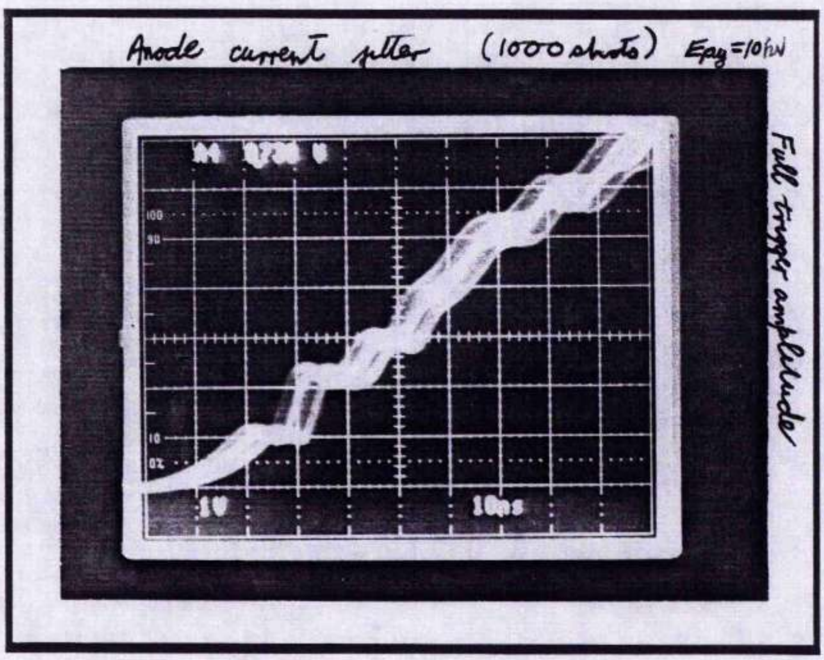

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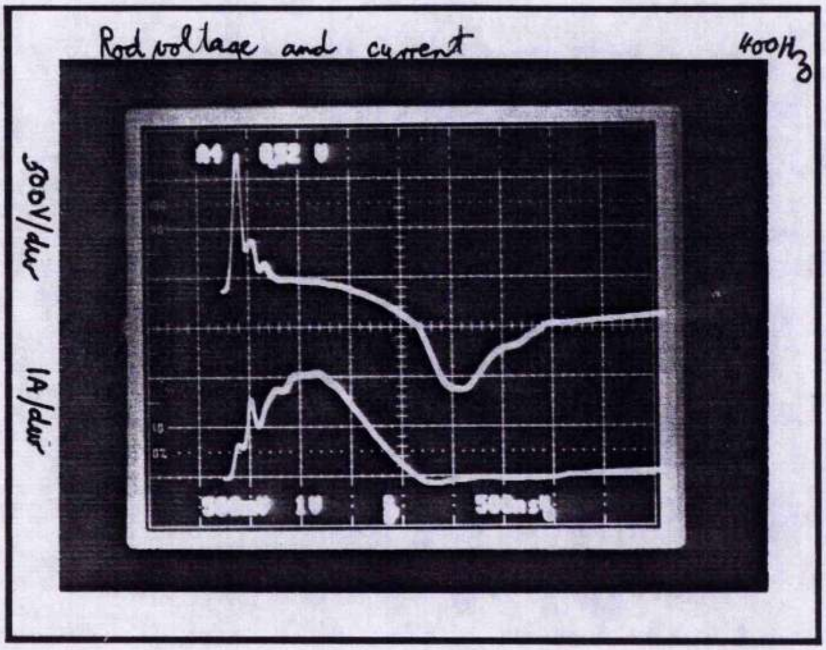

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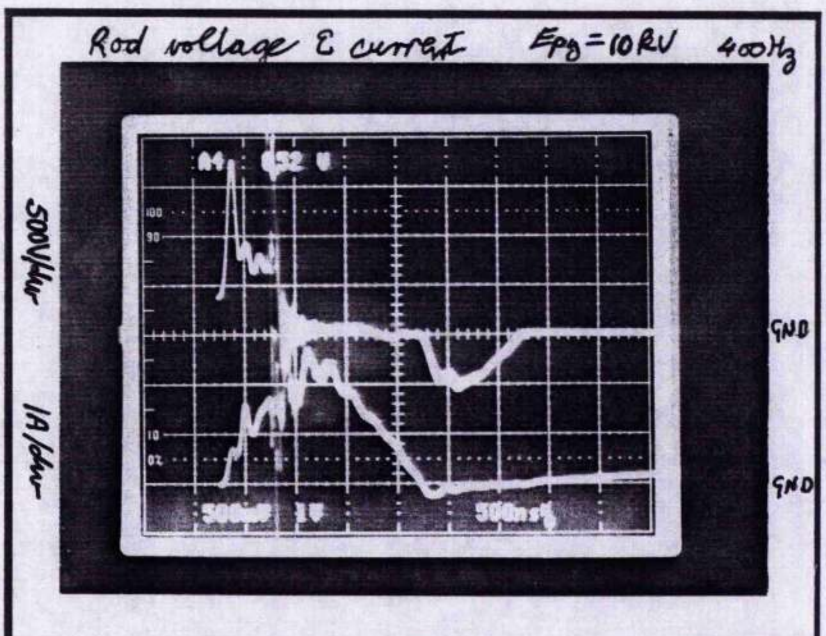

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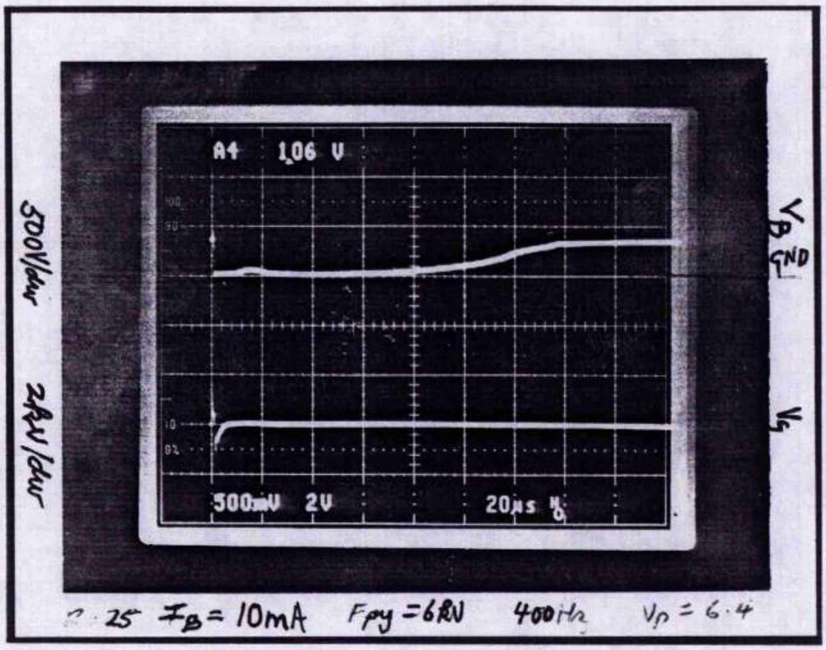

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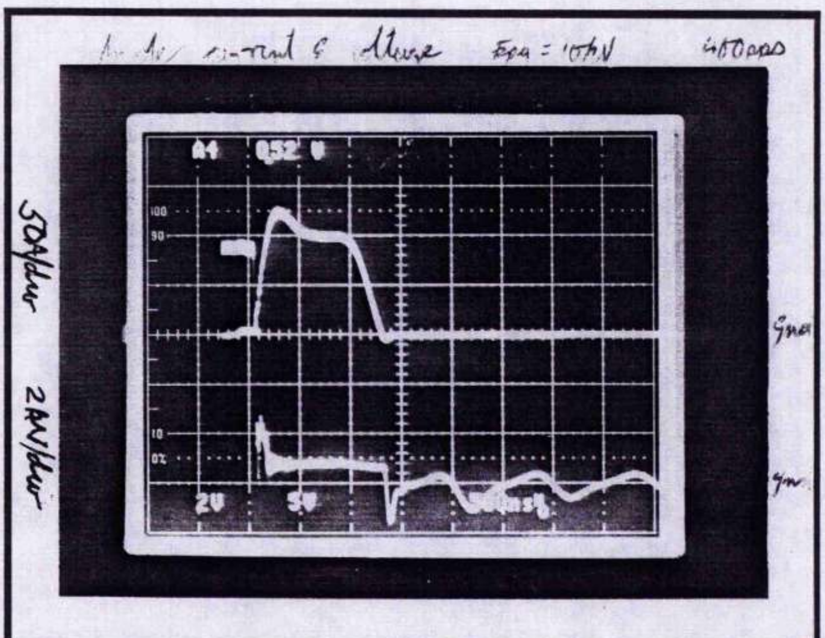

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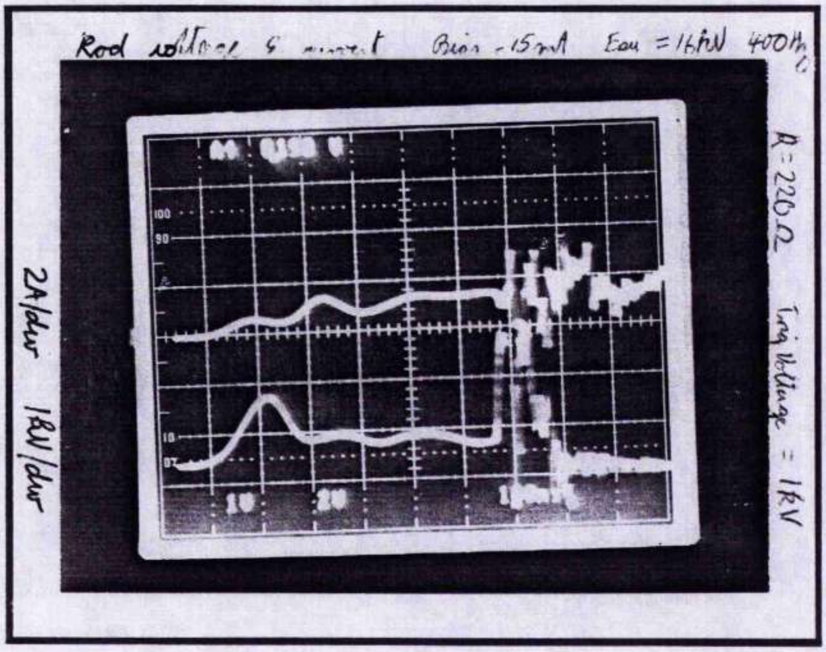

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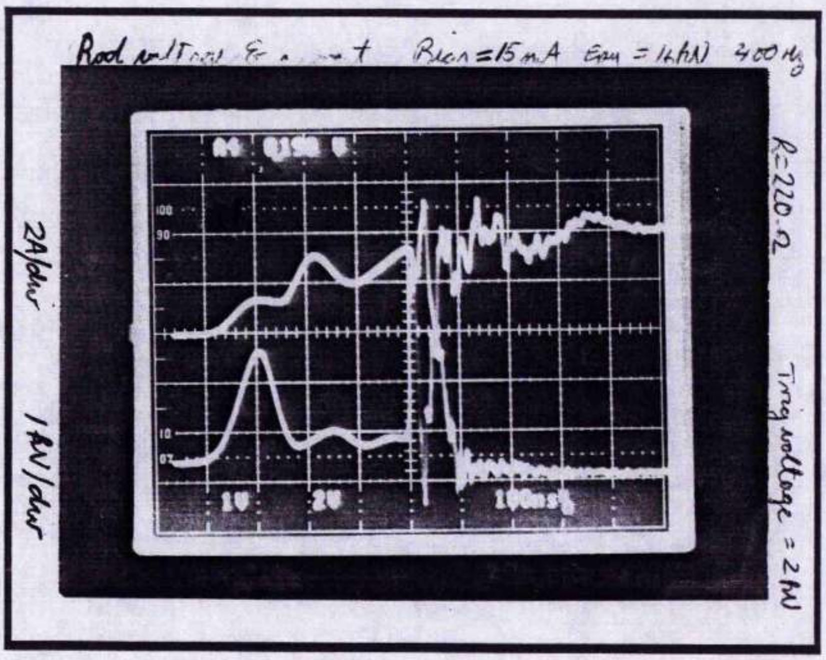

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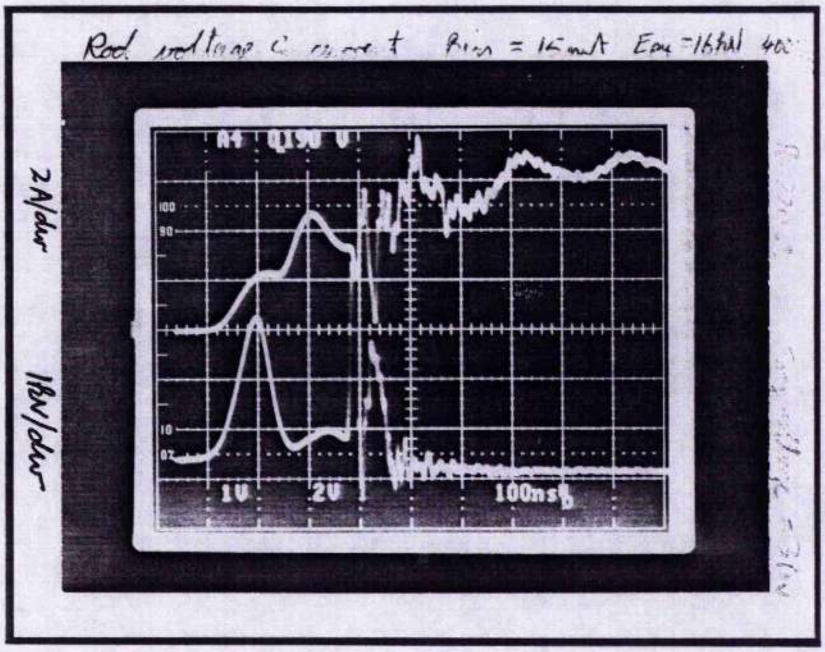

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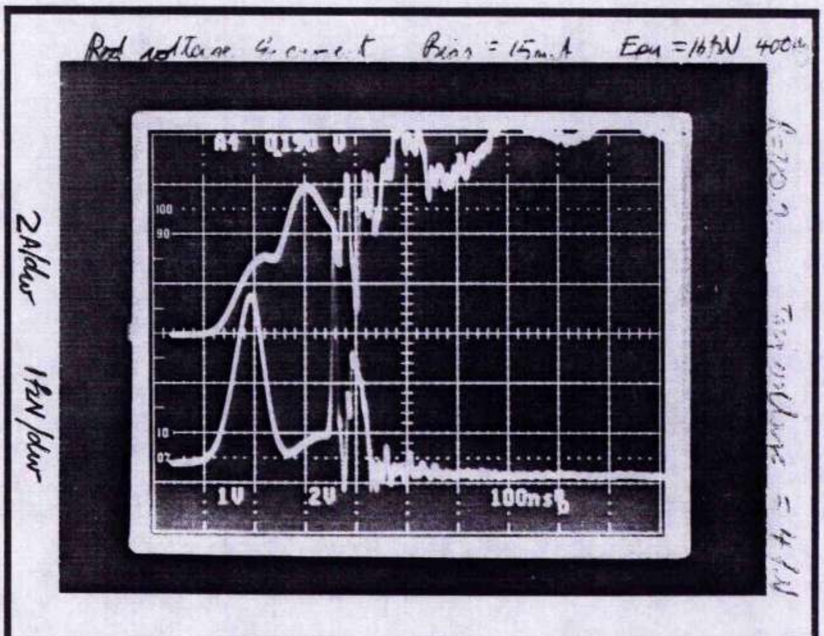

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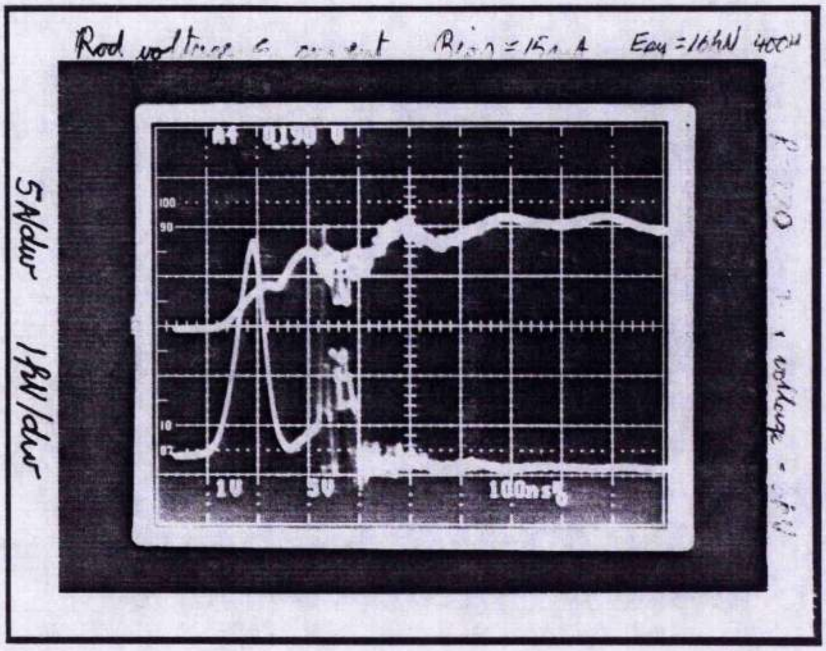

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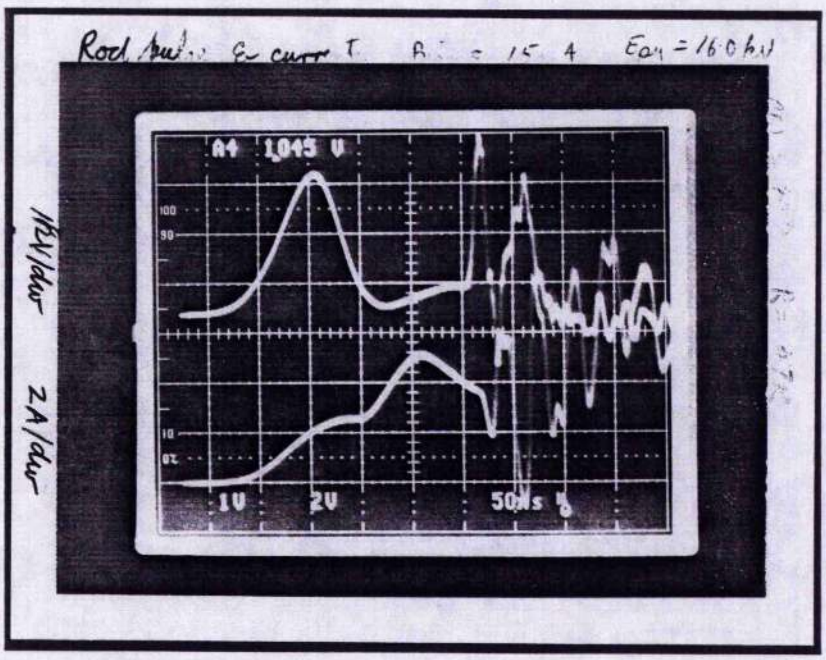

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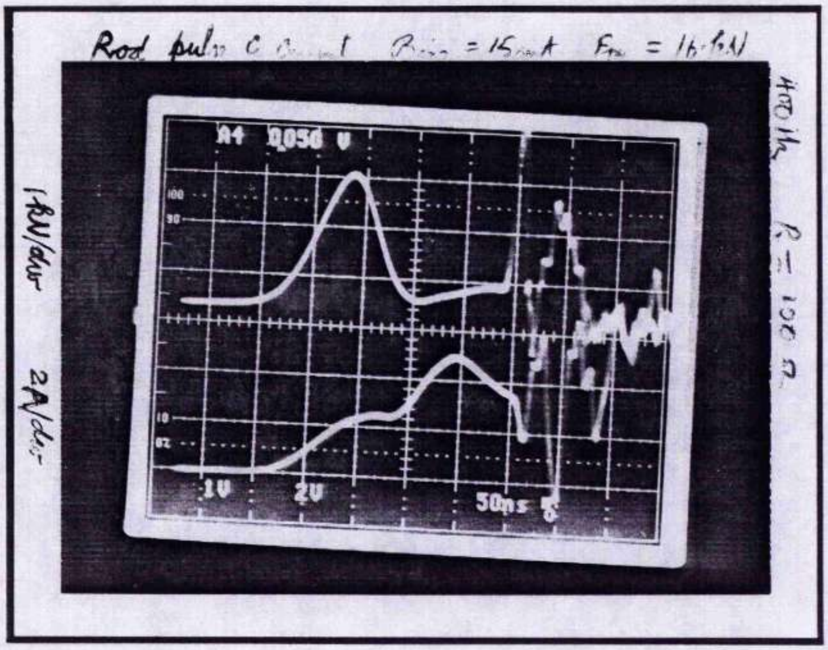

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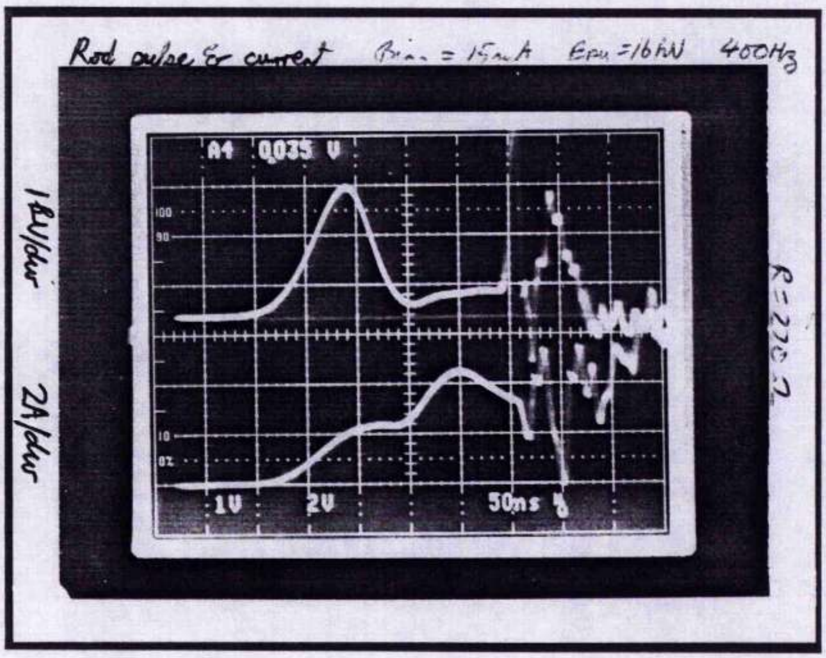

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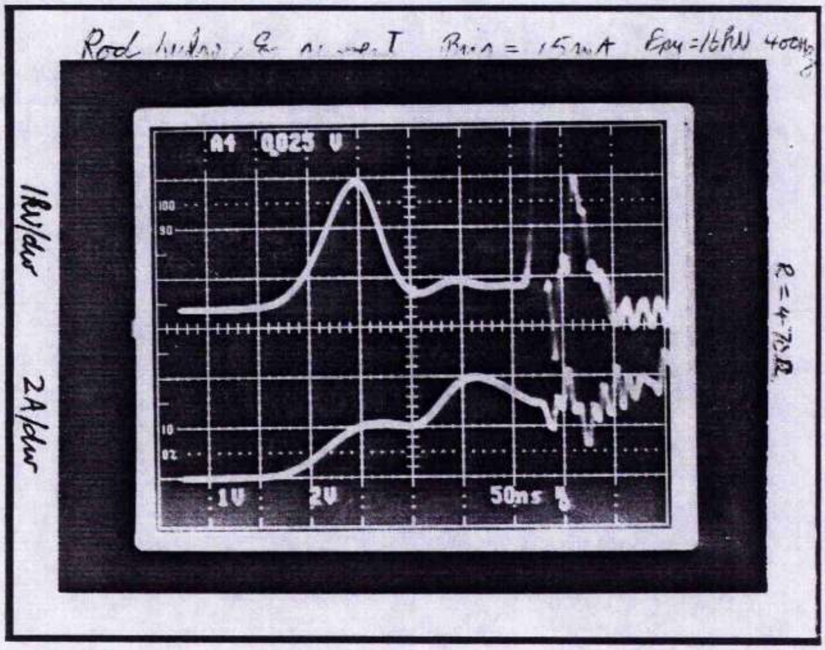

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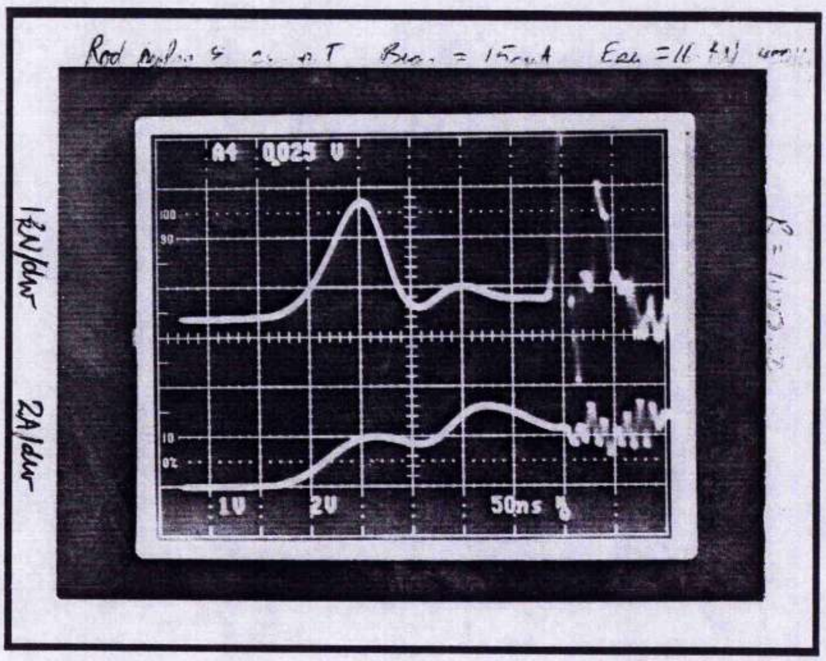

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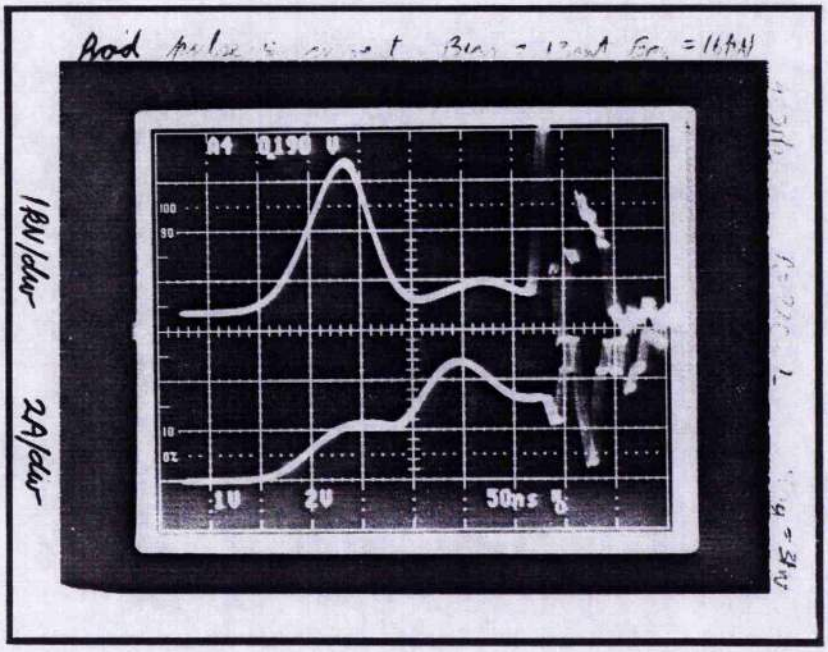

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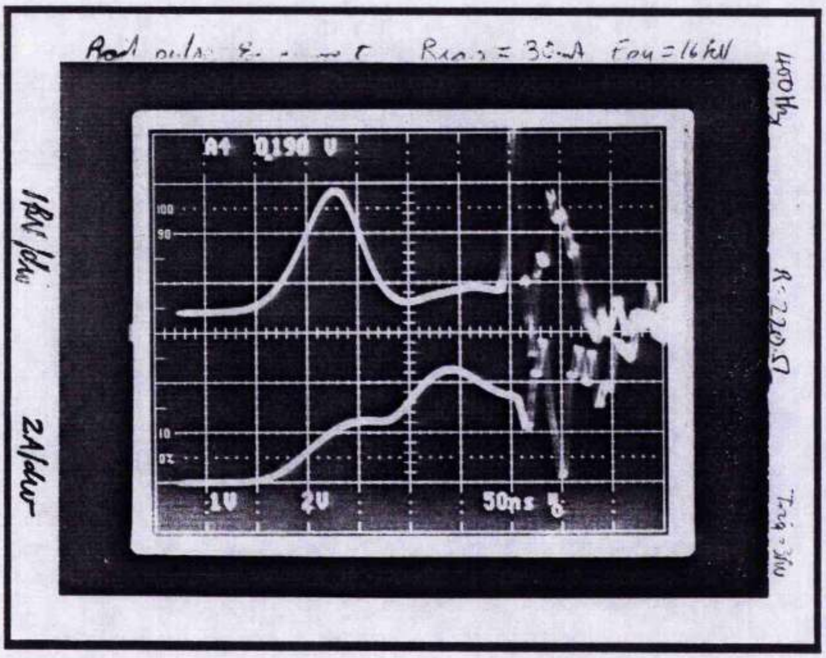

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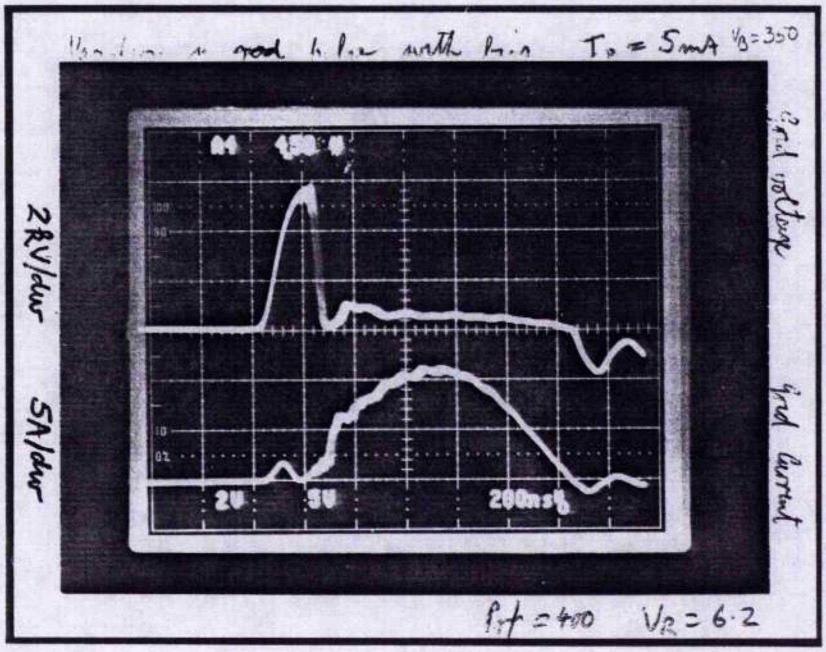

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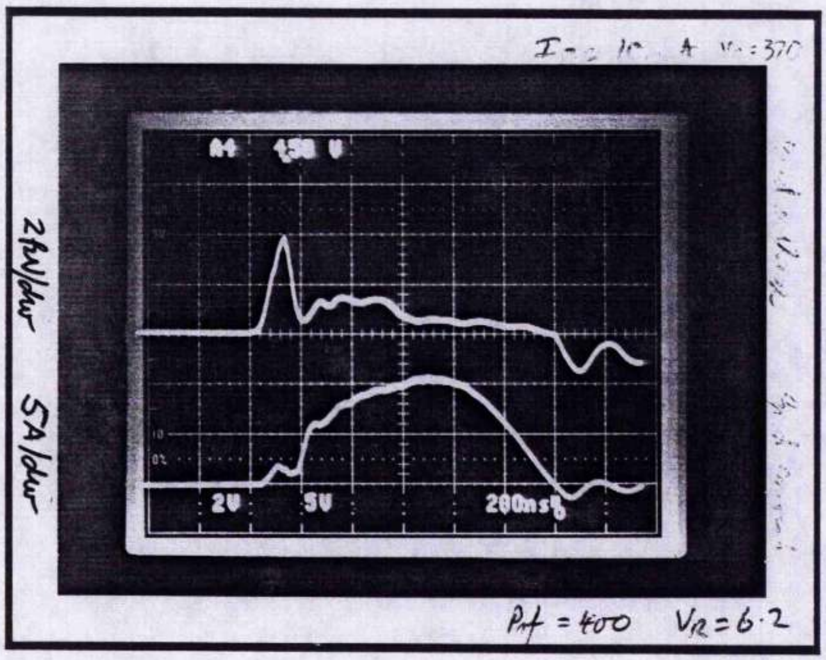

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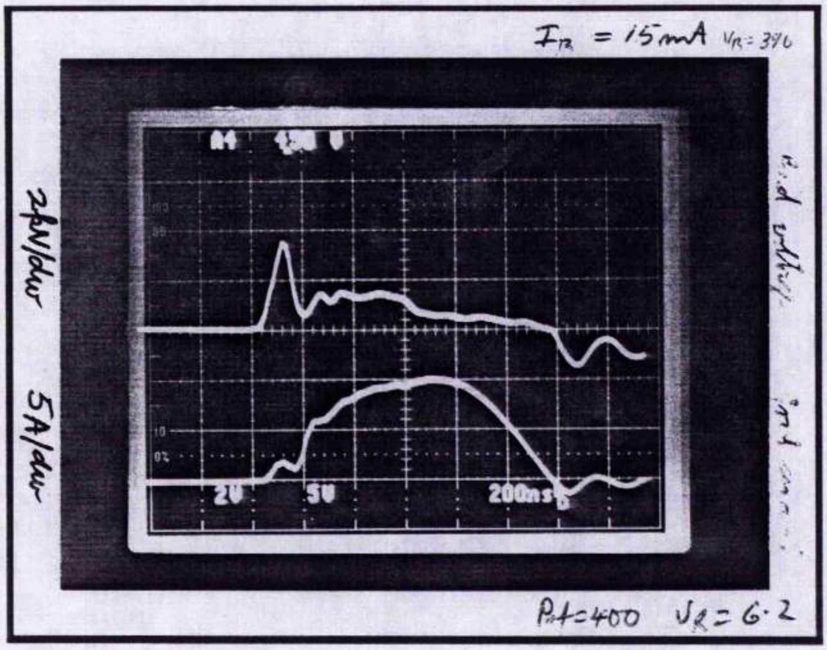

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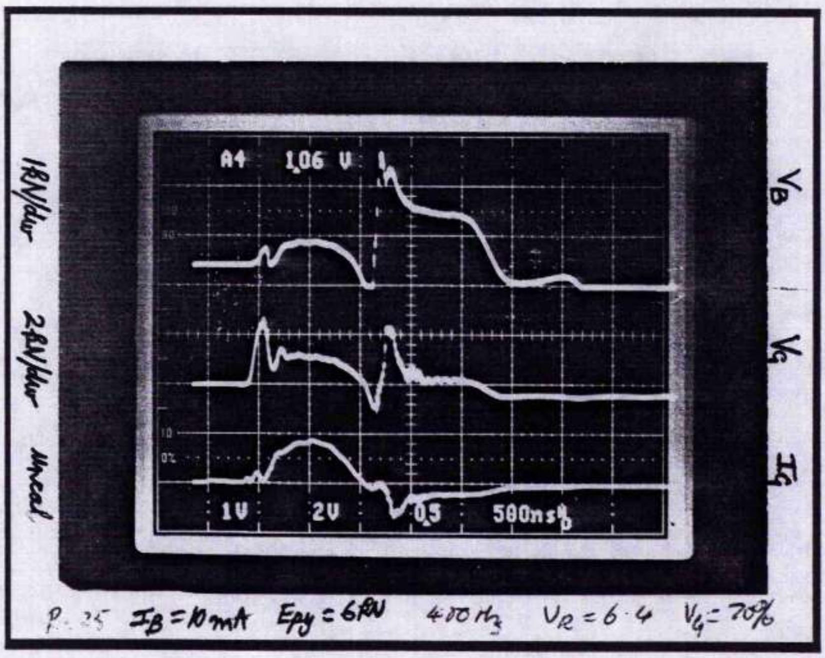

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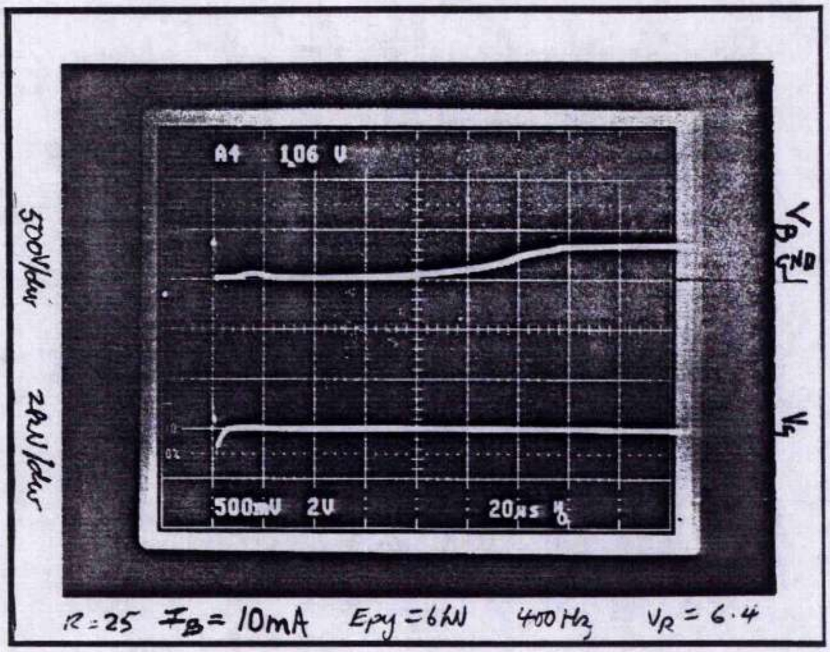

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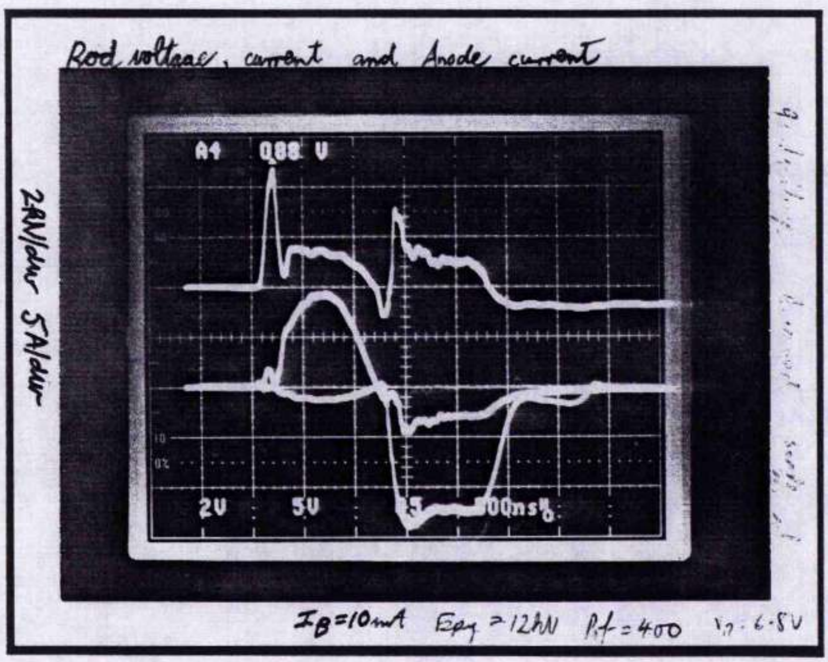

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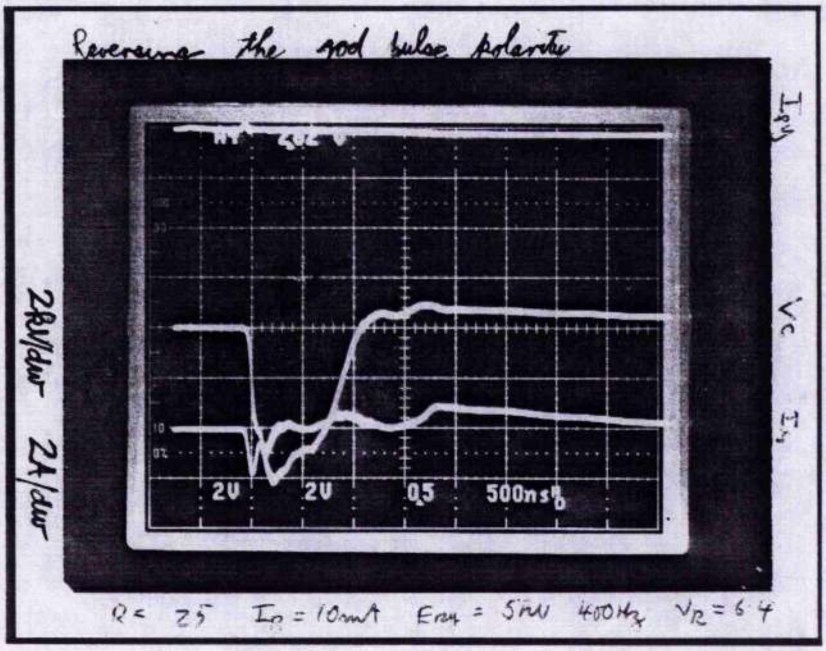

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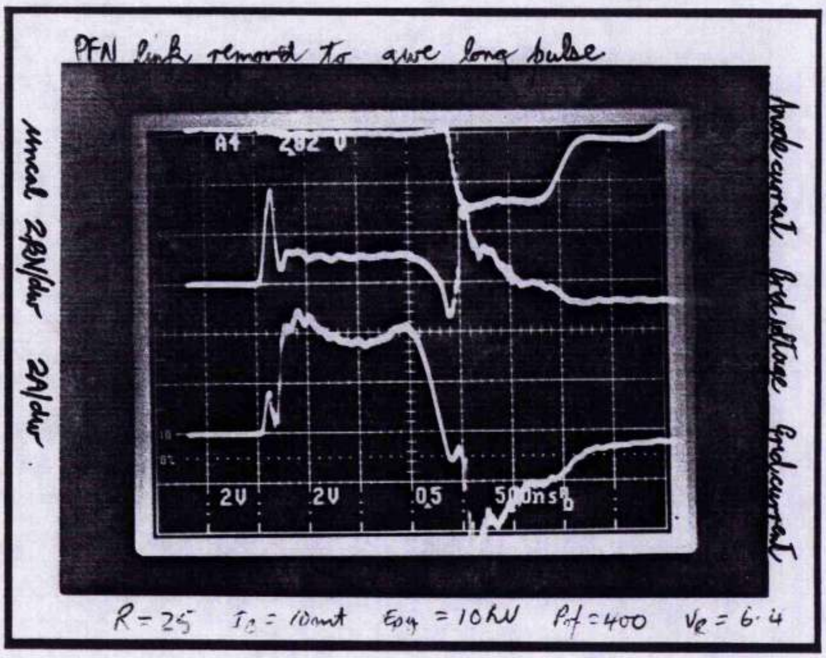

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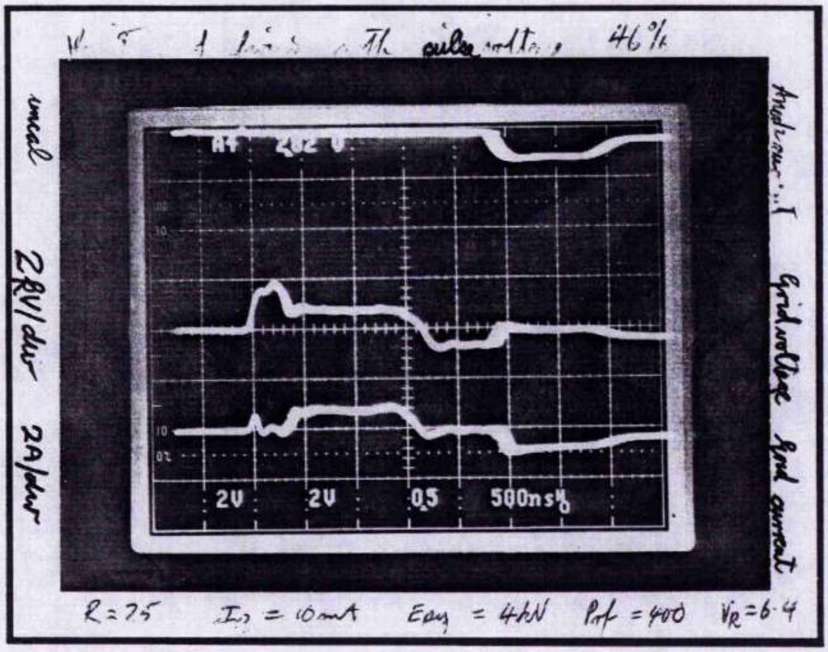

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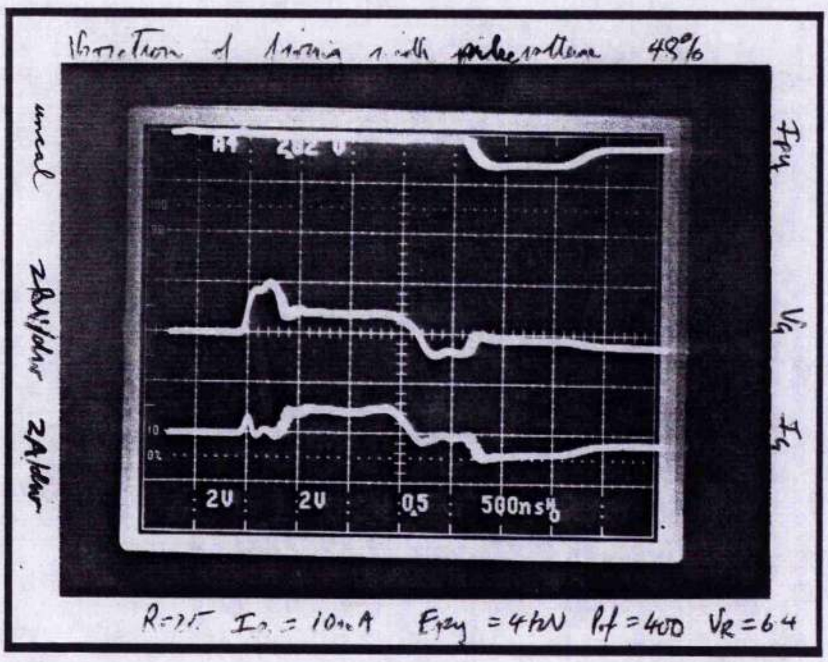

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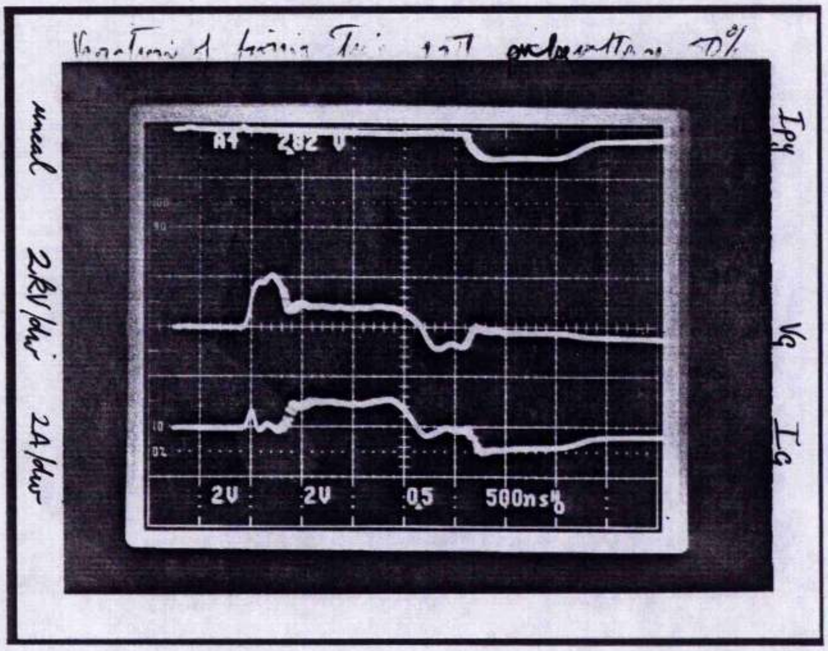

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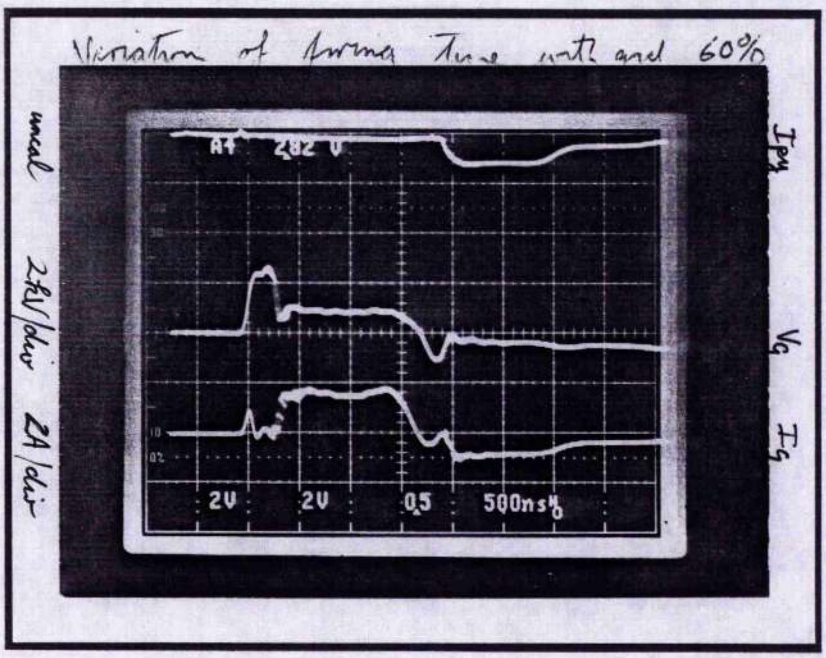

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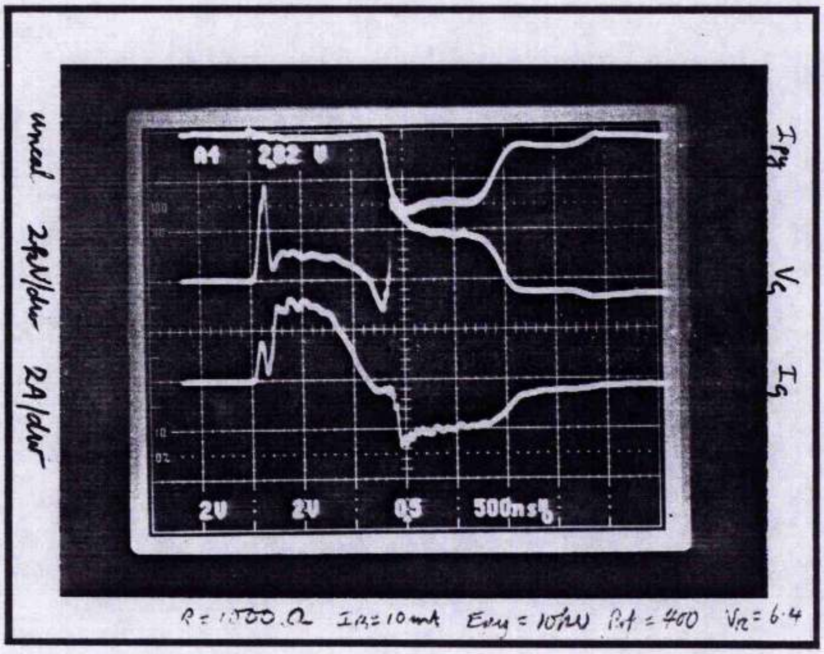

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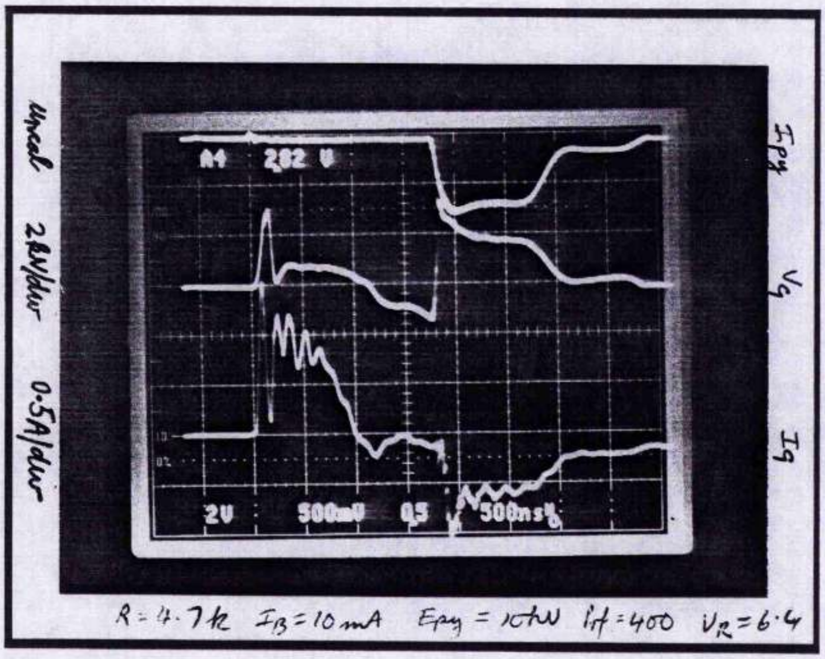

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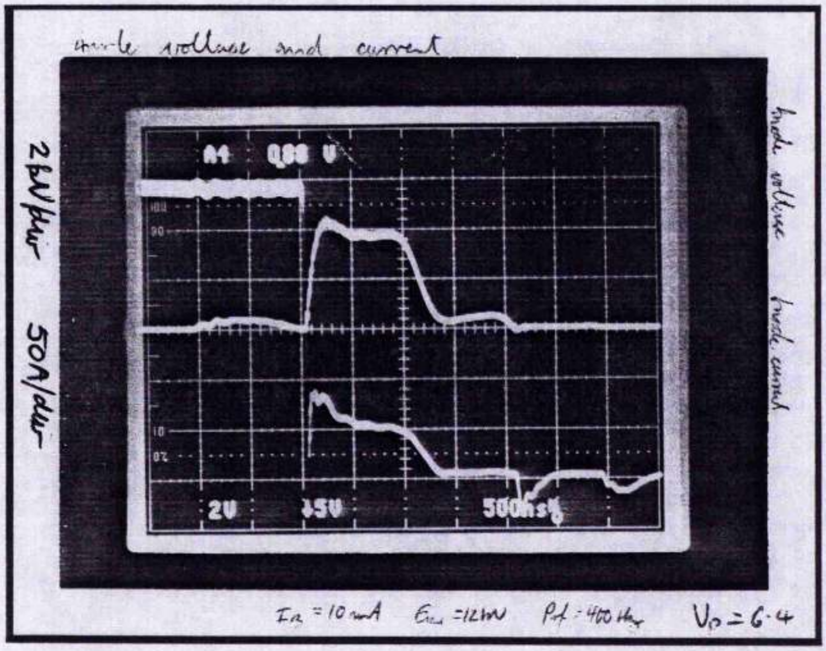

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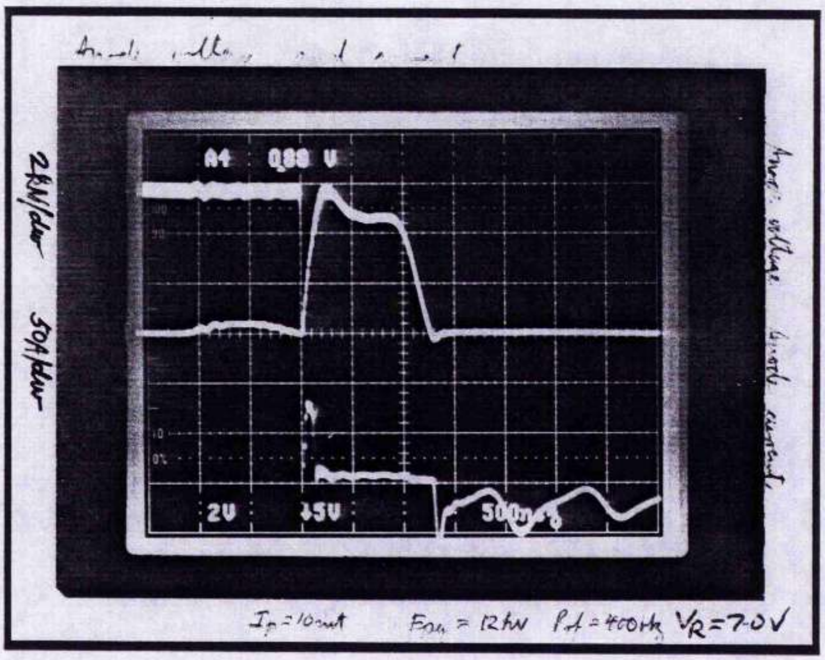

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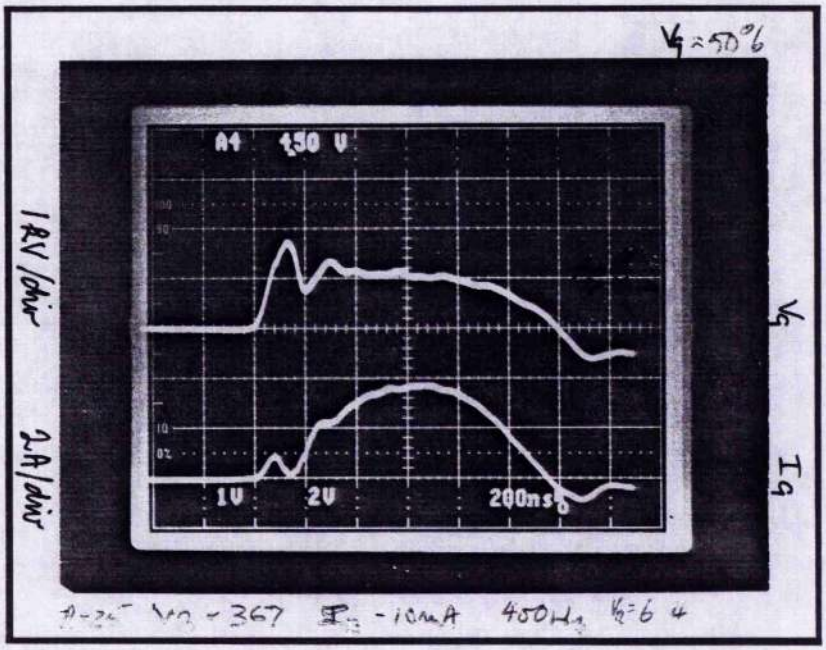

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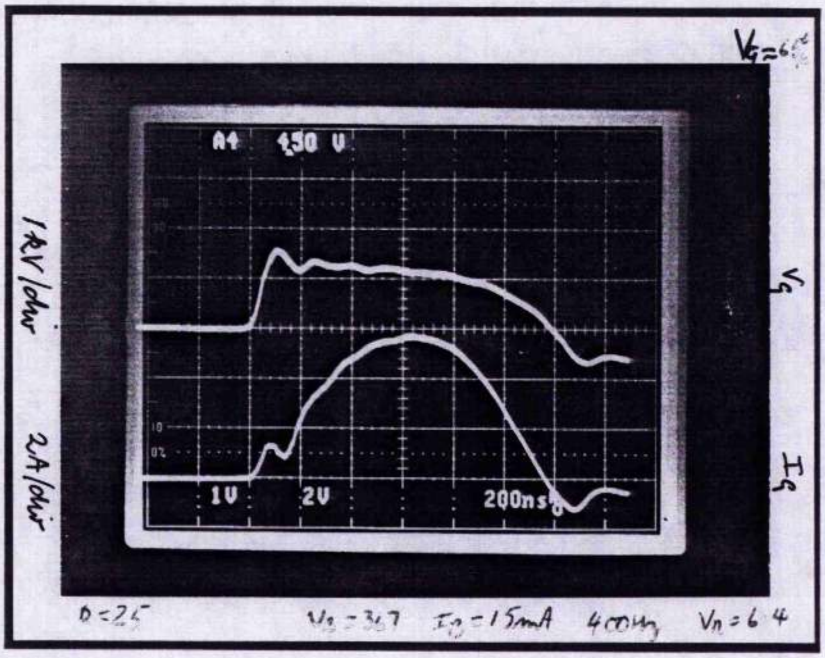

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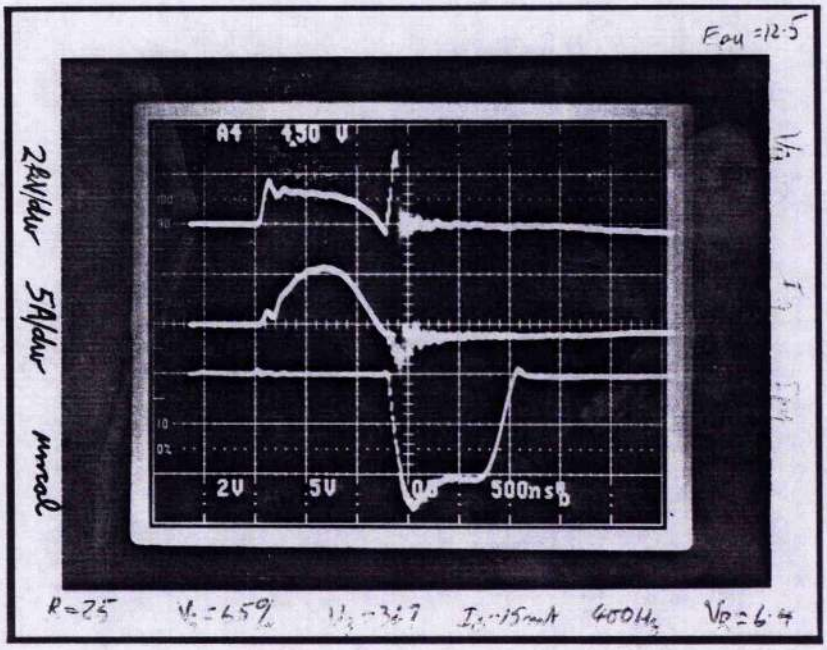

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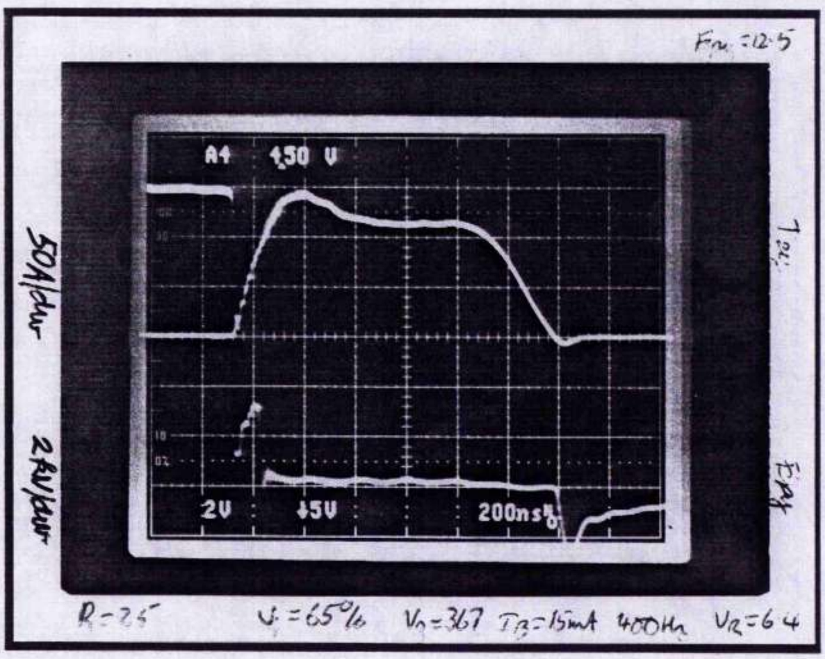

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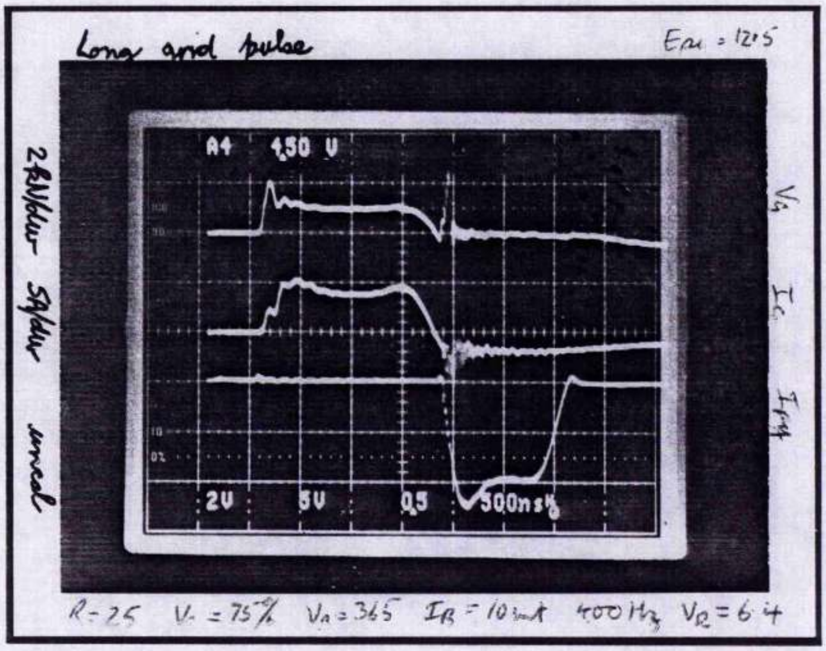

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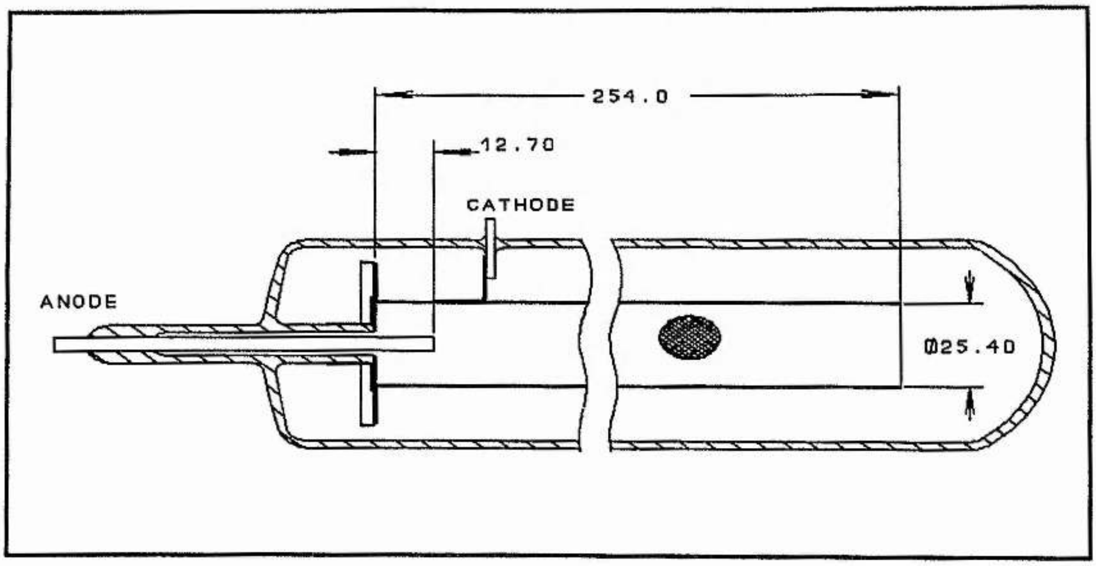

Figure 4.1
Cross-section of the test diode showing the hollow cylindrical gauze cathode.

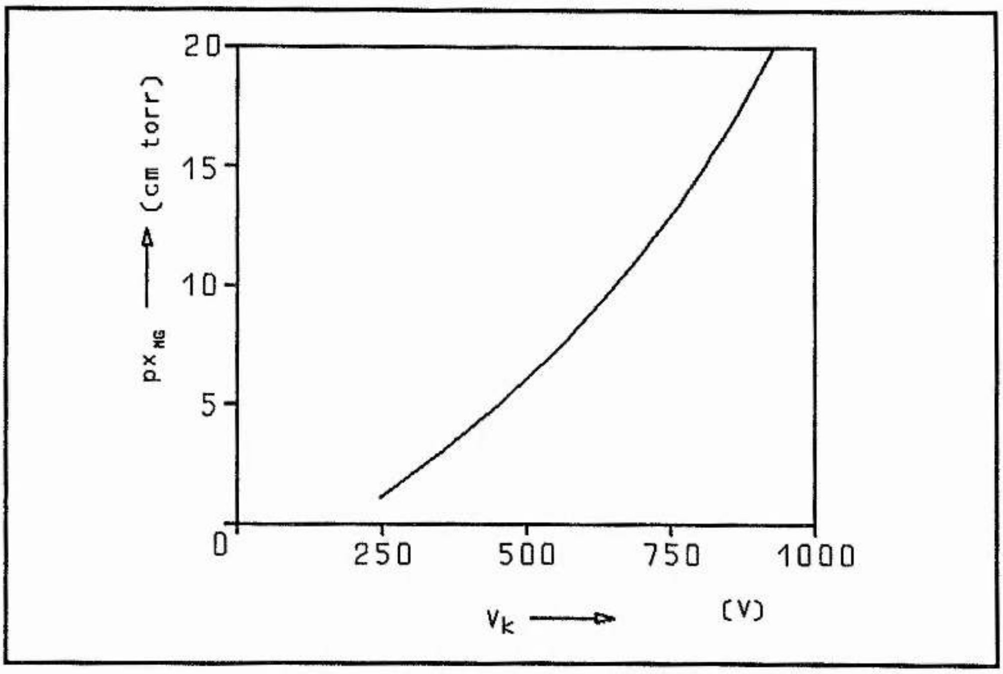

Figure 4.2 (after Brewer & Westhaver, 1937)
Negative glow width as a function of cathode fall voltage for a discharge in hydrogen with an aluminium cathode.

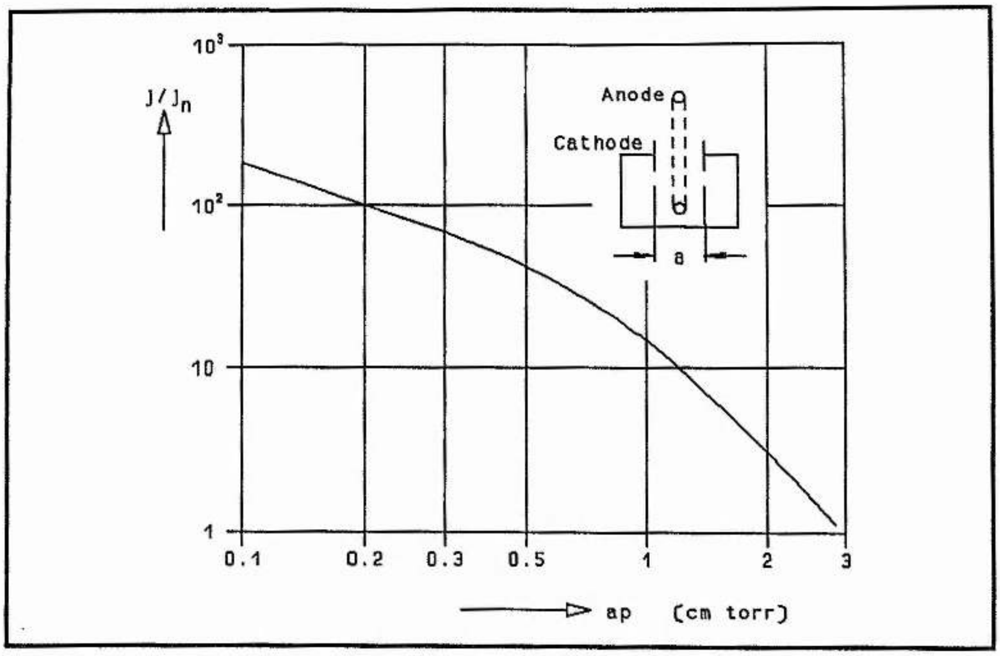

Figure 4.3 (after von Engel, 1955)
Current density as a function of inter-cathode separation for a glow discharge at 400 V in hydrogen with an iron cathode.

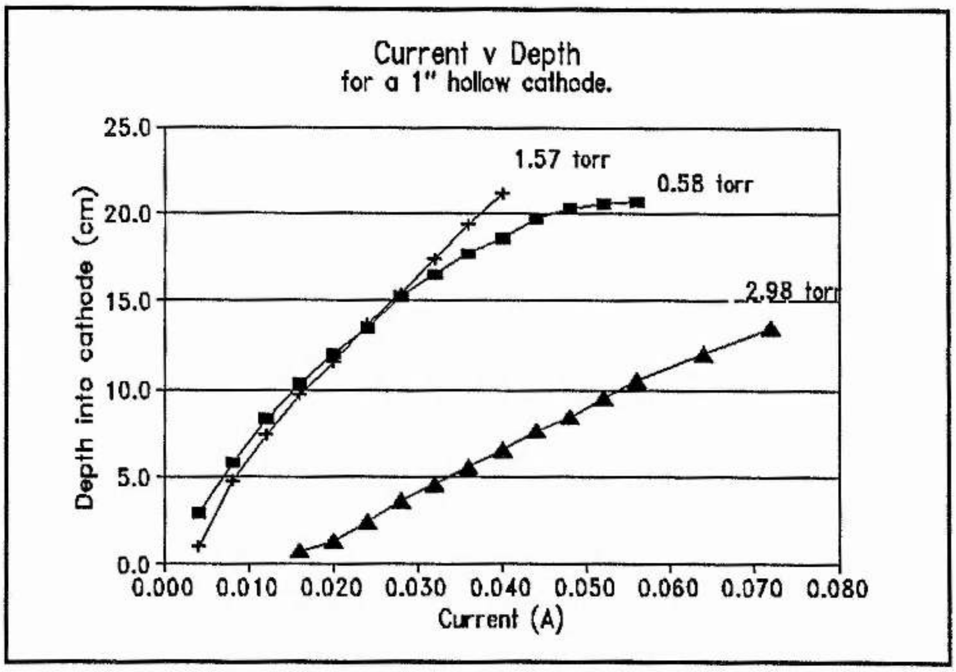

Figure 4.4
Penetration depth as a function of current for a hydrogen discharge in the test diode of Figure 4.1.

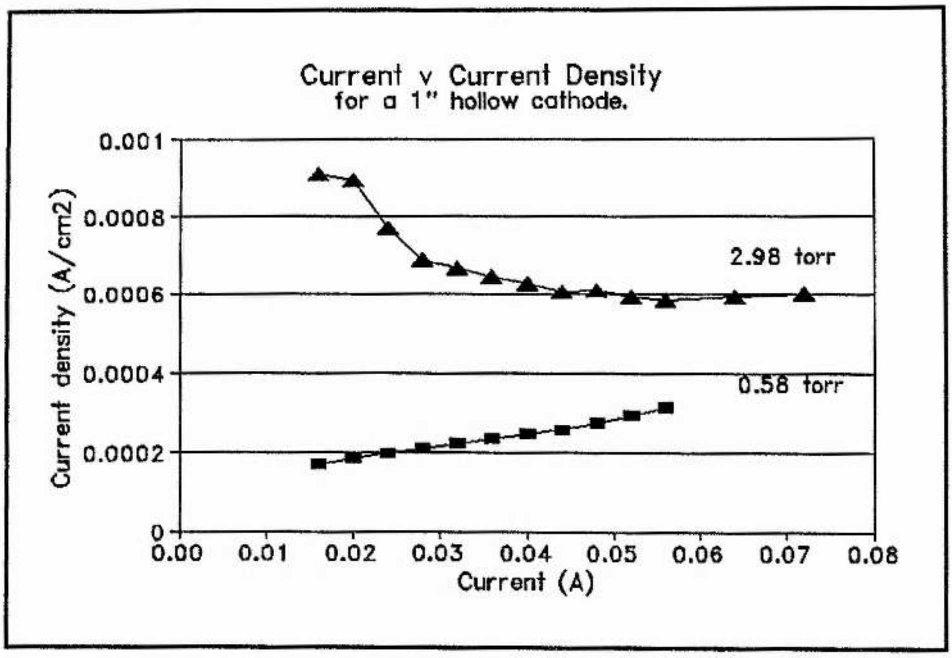

Figure 4.5
Current density as a function of current for a hydrogen discharge in the test diode of Figure 4.1.

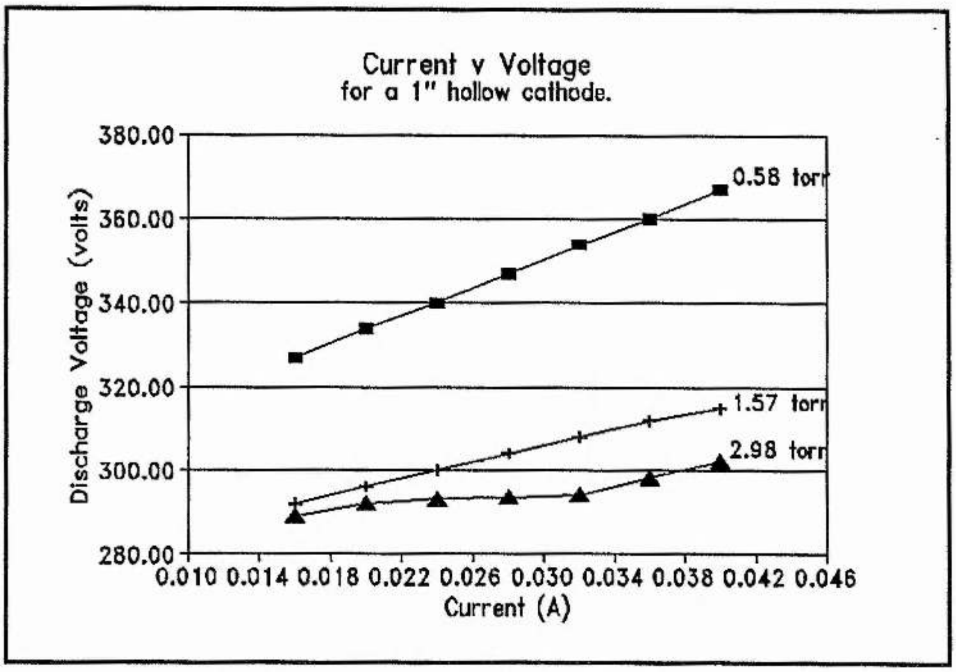

Figure 4.6
Discharge voltage as a function of current for a hydrogen discharge in the test diode of Figure 4.1.

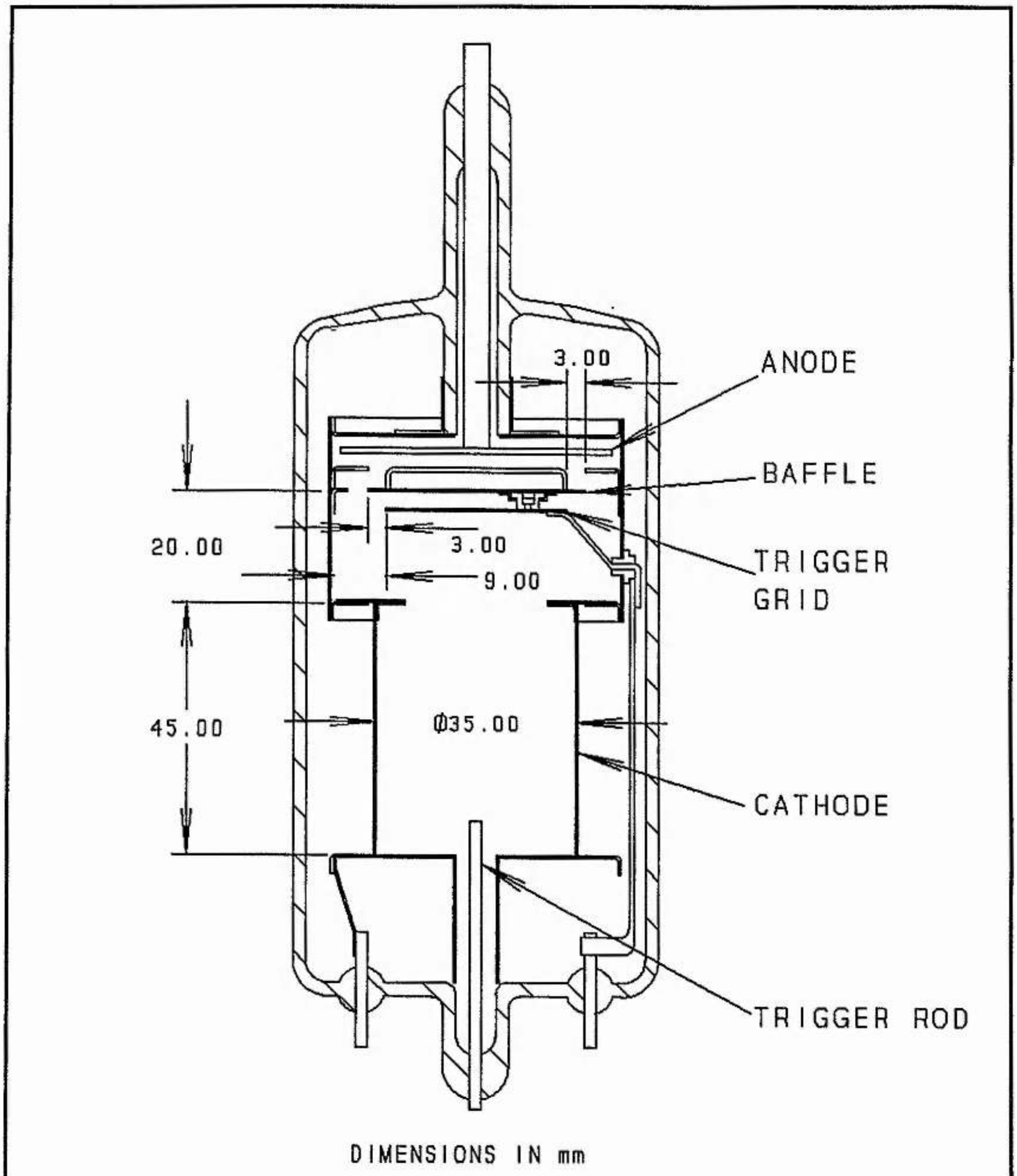

Figure 4.7
Cross-section of the normal glow triggered switch (NGTS).

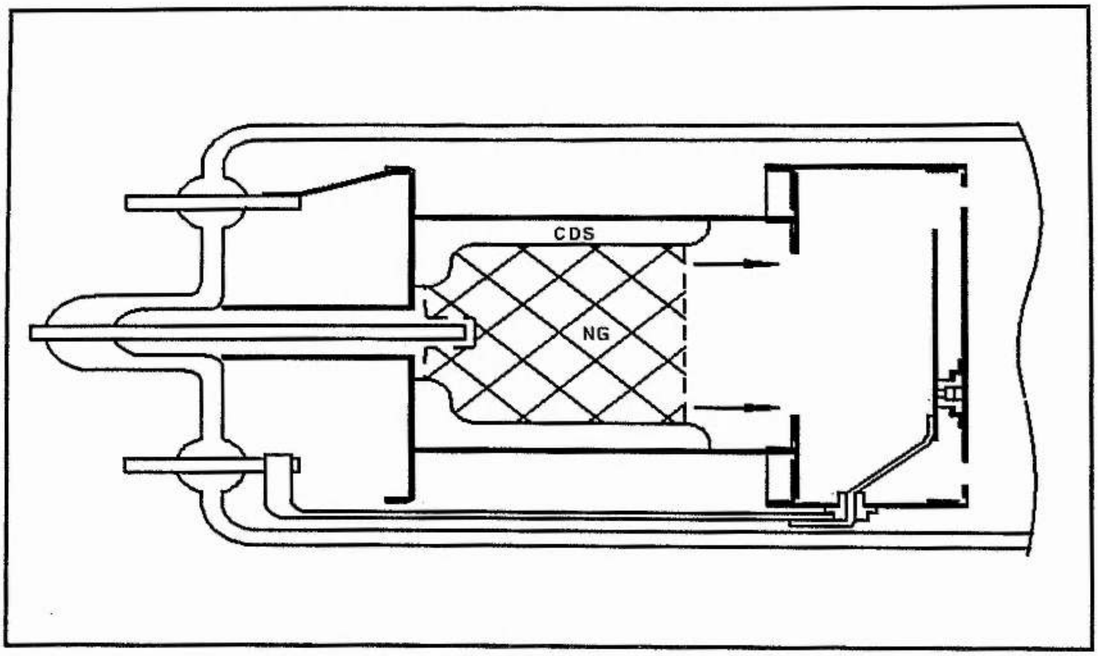

Figure 4.8
Cross-section of the trigger discharge in the NGTS showing the movement of the discharge towards the baffle slots.

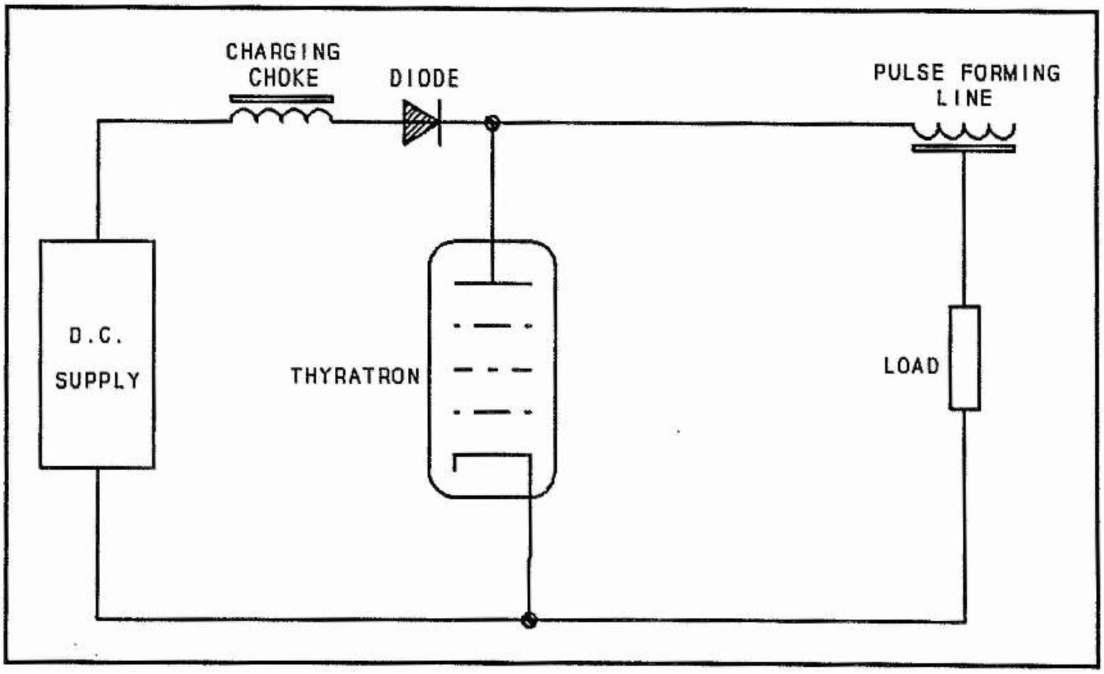

Figure 4.9
Schematic of the NGTS test modulator circuit.

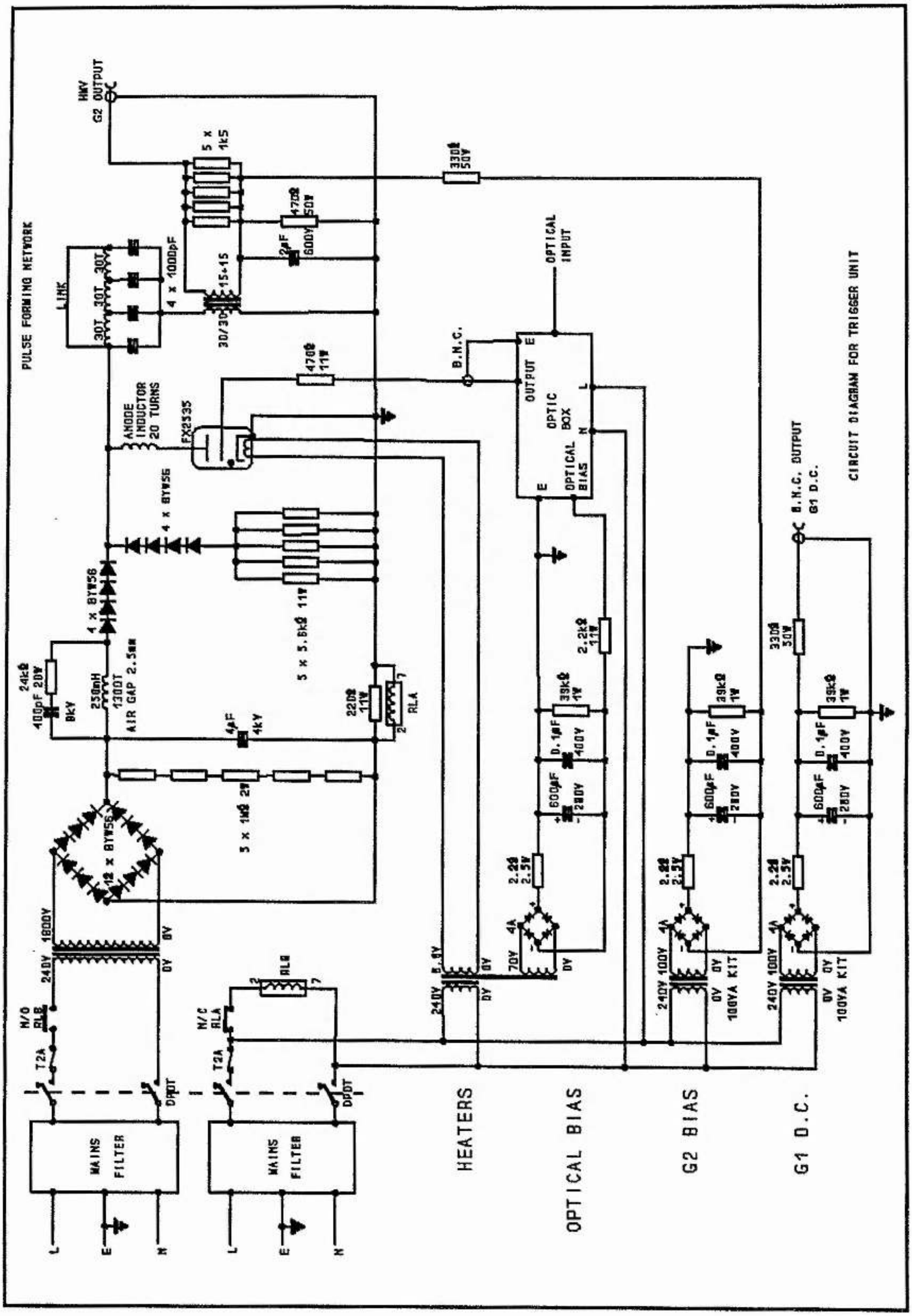

Figure 4.10

Circuit diagram for 2 kV trigger unit.

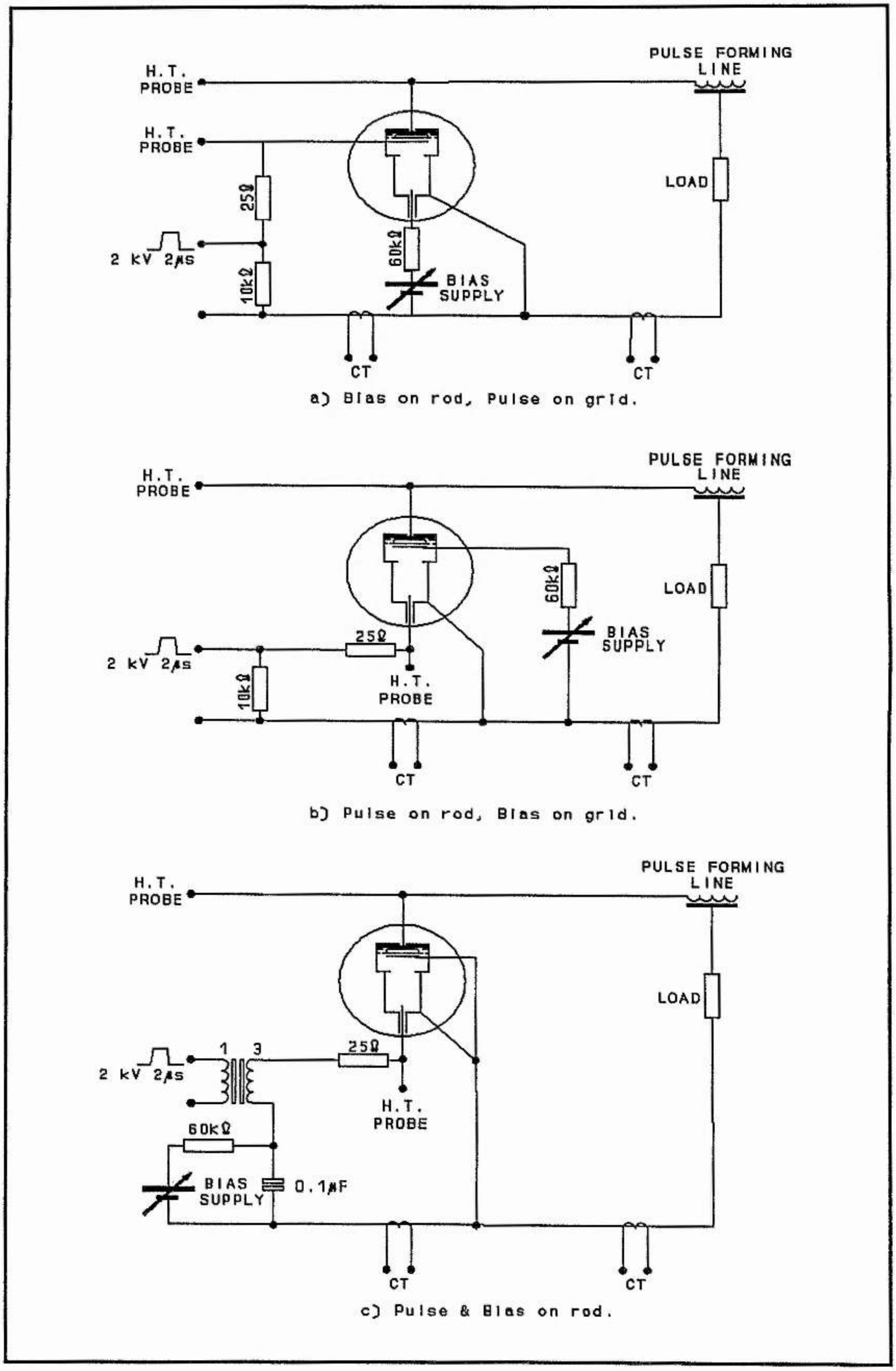

Figure 4.11

Trigger circuits used in the NGTS characterisation.

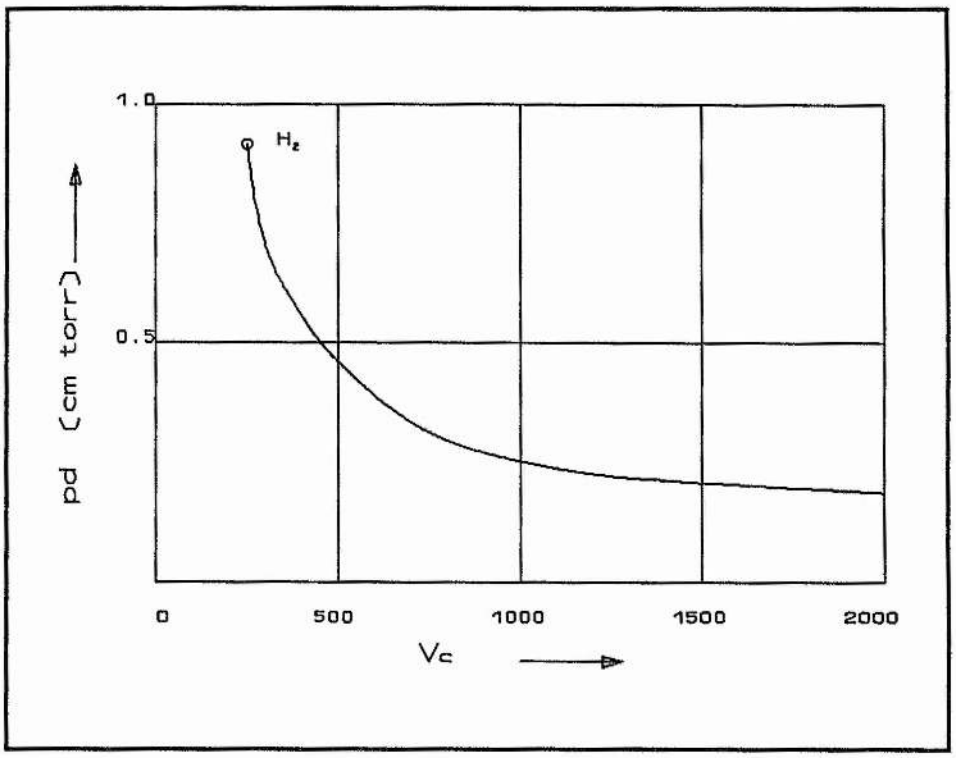

Figure 4.12 (after von Engel, 1955, p 201)
Cathode dark space width as a function of cathode fall V_c for an iron cathode in hydrogen.

CHAPTER FIVE

The e–beam triggered switch.

5.1 Introduction.

In this final chapter we will consider possible future directions for the development of the low pressure gas switching principles described in this thesis. The ideas to be presented here have been the subject of several successful patent applications and the granted patent documents form the main substance of the chapter. A number of switches based on the concepts described in the patents have been constructed and the initial results of tests conducted on these switches are included with the appropriate patent. The switches use the hollow, metallic cathode already established in Chapters 1 & 4. Their unusual feature is that they utilise the glow discharge electron beam gun of Chapter 3 to assist or initiate the cathode action. In addition to the benefits of cold–cathode, instant–start operation, it is possible that the projection of electrons directly into the high voltage region of the switch as described in UK patent GB 2194674 could offer improvements in t_{ad} and jitter compared to conventional thyratron performance. Each of the following sections consists of a short introduction, applicable results and the patent document.

5.2 UK Patent GB 2153140B UK, Japan, USA, Europe.

Apparatus for forming electron beams.

This patent describes novel methods by which a single electron beam or a multiplicity of beams may be produced in a low pressure gas. A variety of applications of the beams are described and include: flat addressable arrays for display devices; bombardment–heated, rapid–start thermionic–cathode switches; and electron beam pre–ionised, cold–cathode switches.

(12) UK Patent (19) GB (11) 2 153 140 (13) B

(54) Title of Invention

Apparatus for forming electron beams

(51) INT CL^4; **H01J 3/02, 1/30 // 1/20**

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(22) Date of filing
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8333879
8413791

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30 May 1984

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(Edition J)
H1D 12B47Y 12B4 12B6 12C 17A3 17AY 17D 1D12 1D1 1D4 1E1 1EY 1J2 1JY 1L 31 34 4A12 4A4 4A7 4A8B 4A8Y 4E3A 4E3Y 4K3B 4K8
U1S 1719 1724 2284 AC1 AC2 CJ H1D

(56) Documents cited
GB A 2117173
GB A 2023922
GB 1557094
GB 1490463
GB 1370656
GB 1136144
GB 0763670
GB 0603088

(58) Field of search
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H1D 12B47Y 12B4 12B6 12C 17A3 17AY 17D 1D12 1D1 1D4 1E1 1EY 1J2 1JY 1L 31 34 4A12 4A4 4A7 4A8B 4A8Y 4E3A 4E3Y 4K3B 4K8
U1S 1719 1724 2284 H1D

(56) Documents cited
GB A 2117173 GB 1490463 GB 0763670
GB A 2023922 GB 1370656 GB 0603088
GB 1557094 GB 1136144

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(54) Apparatus for forming electron beams

(57) An envelope containing a gas filling includes a cathode 3 having, except for one or more portions or (as shown) notes 5 formed in a front surface thereof, all surfaces which would otherwise be exposed to the gas filling covered with an electrically insulating material, such as glass, and an anode 9 such that upon application of a suitably high voltage between the cathode and anode an electron beam is formed directed away from the front surface of the cathode. A grid 11, alternatively located in hole 5, modulates the beam; the anode may be located behind the front surface of the cathode, and still form a beam in front of the front surface. Fig. 18 shows such an arrangement in which the anodes and cathodes form an addressable crossed matrix. The front cathode surface may be oblique with respect to the hole or holes therein (Fig. 20) or may be curved (Fig. 21) to form a plurality of beams focussed to a point. The apparatus may comprise a CRT display when provided with a phosphor layer 2 or may be used for electron beam welding. The described beam arrangement can form the cathode of the thyratron (Figs. 22–24) or can be used to heat a separate thermionic cathode or can be used to ionise the gas filling locally in front of a conventionally heated thyratron cathode. Materials of electrodes and gas filling are given.

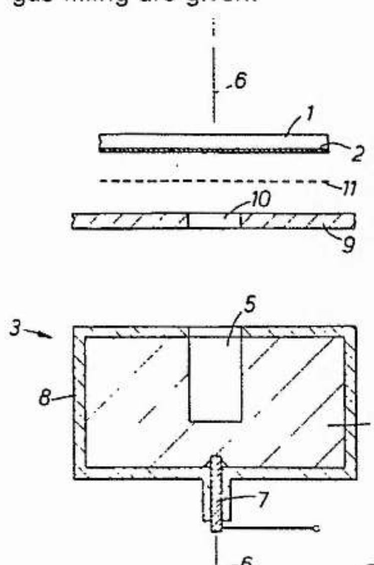

FIG. 1.

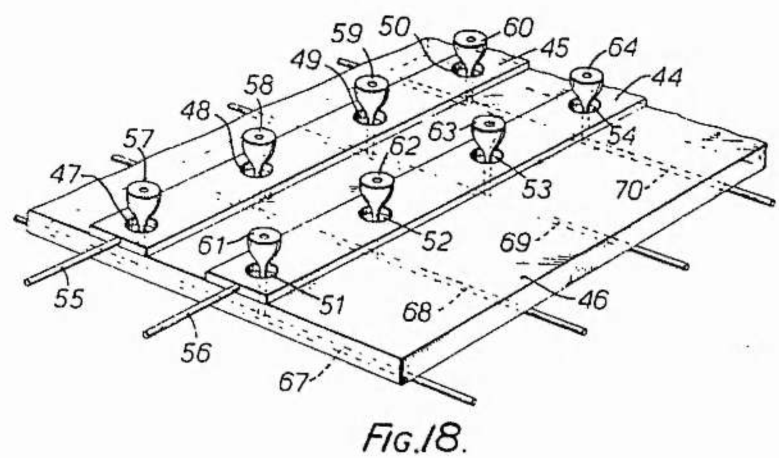

FIG. 18.

The drawing(s) originally filed was/were informal and the print here reproduced is taken from a later filed formal copy.

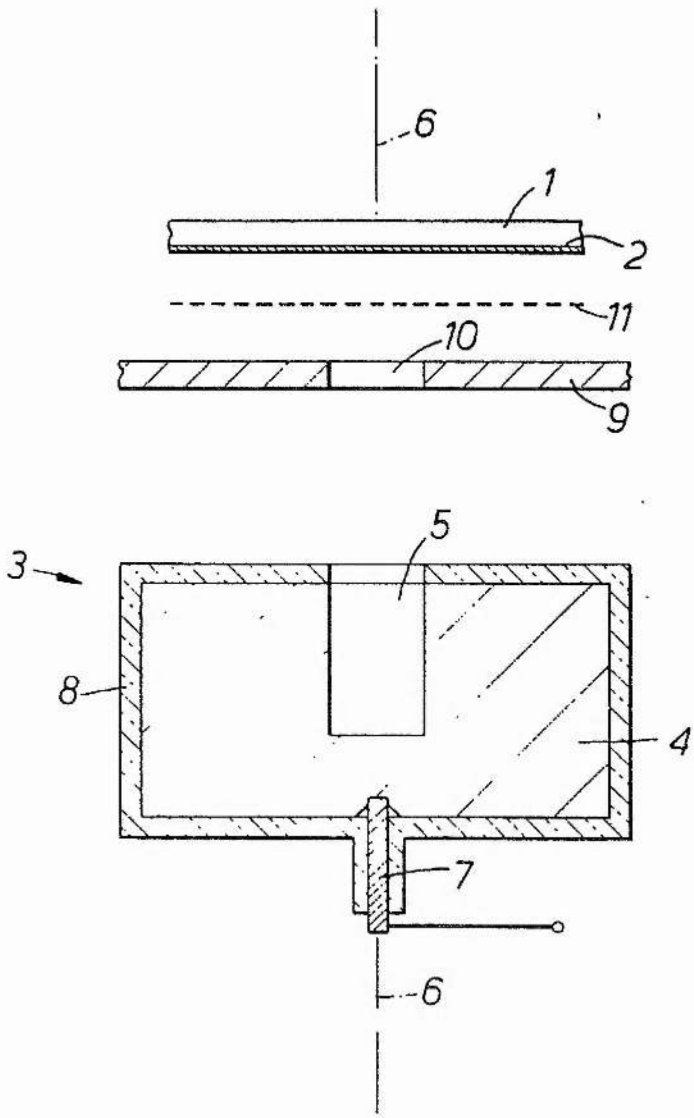

FIG. 1.

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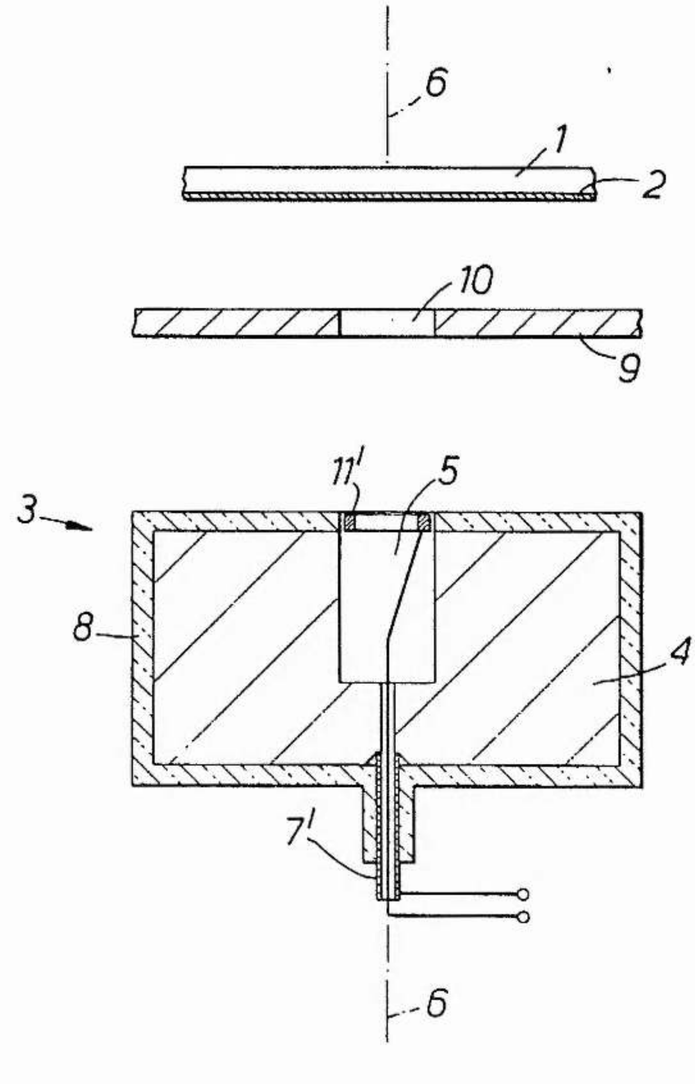


FIG. 2.

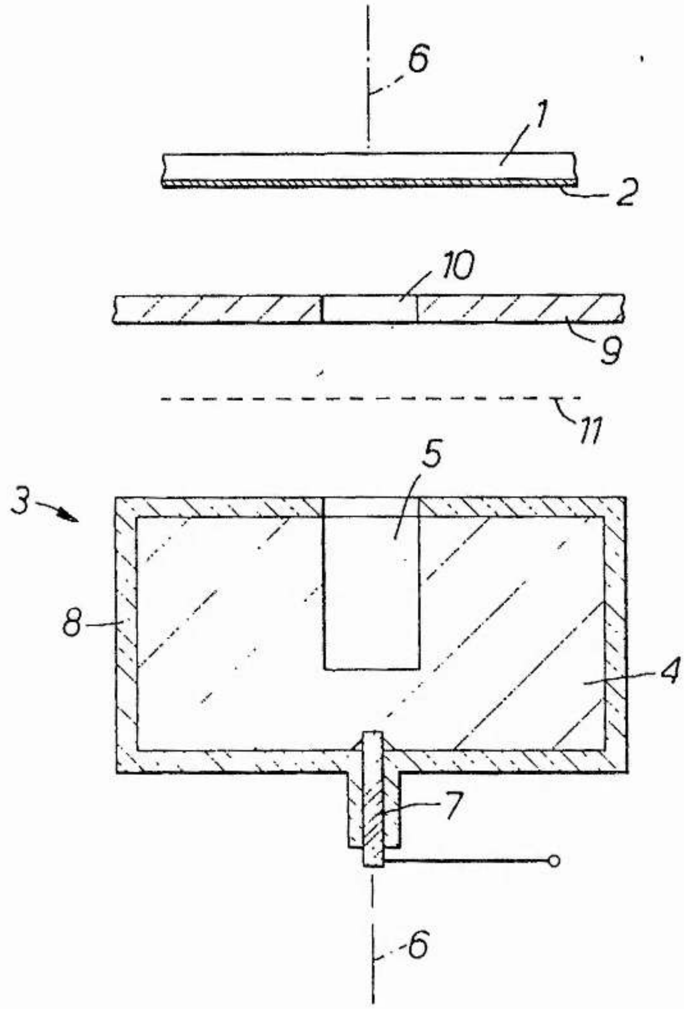
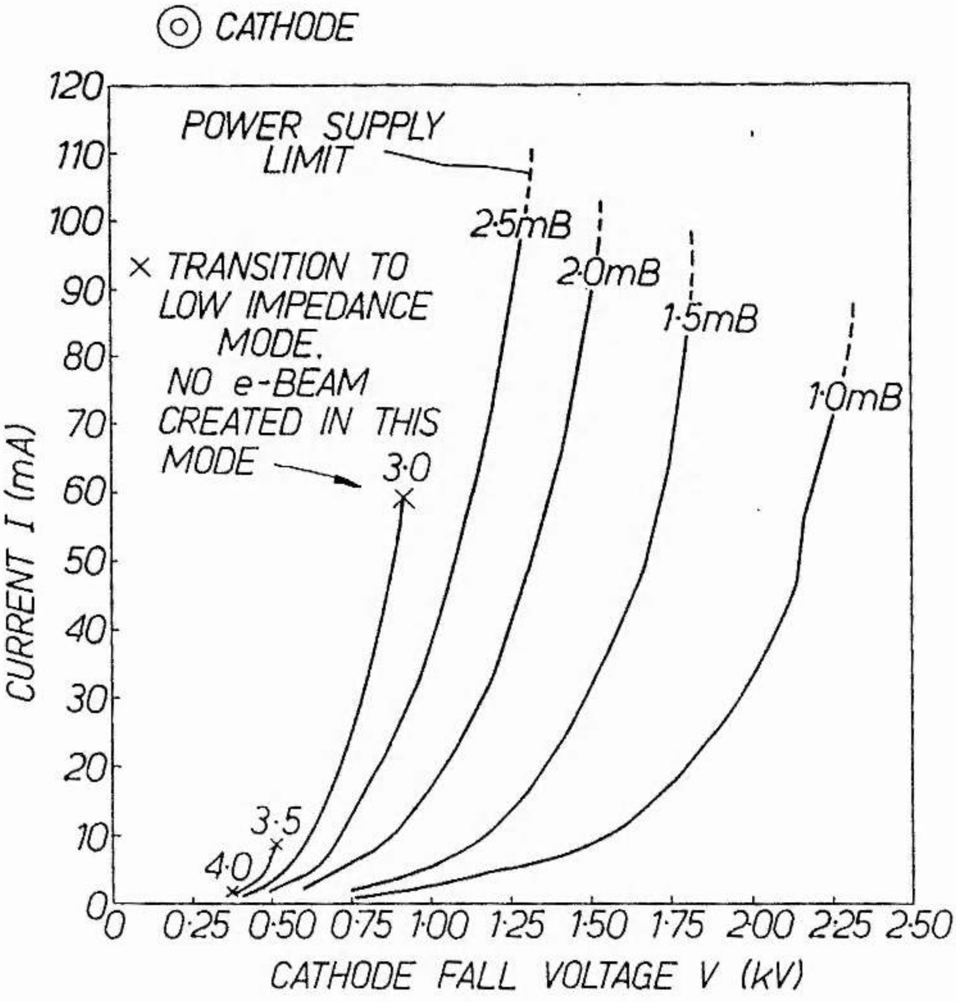


FIG. 3.



CATHODE
POWER SUPPLY LIMIT
2·5mB
2·0mB
1·5mB
1·0mB
× TRANSITION TO LOW IMPEDANCE MODE.
NO e-BEAM CREATED IN THIS MODE
3·0
3·5
4·0
CURRENT I (mA)
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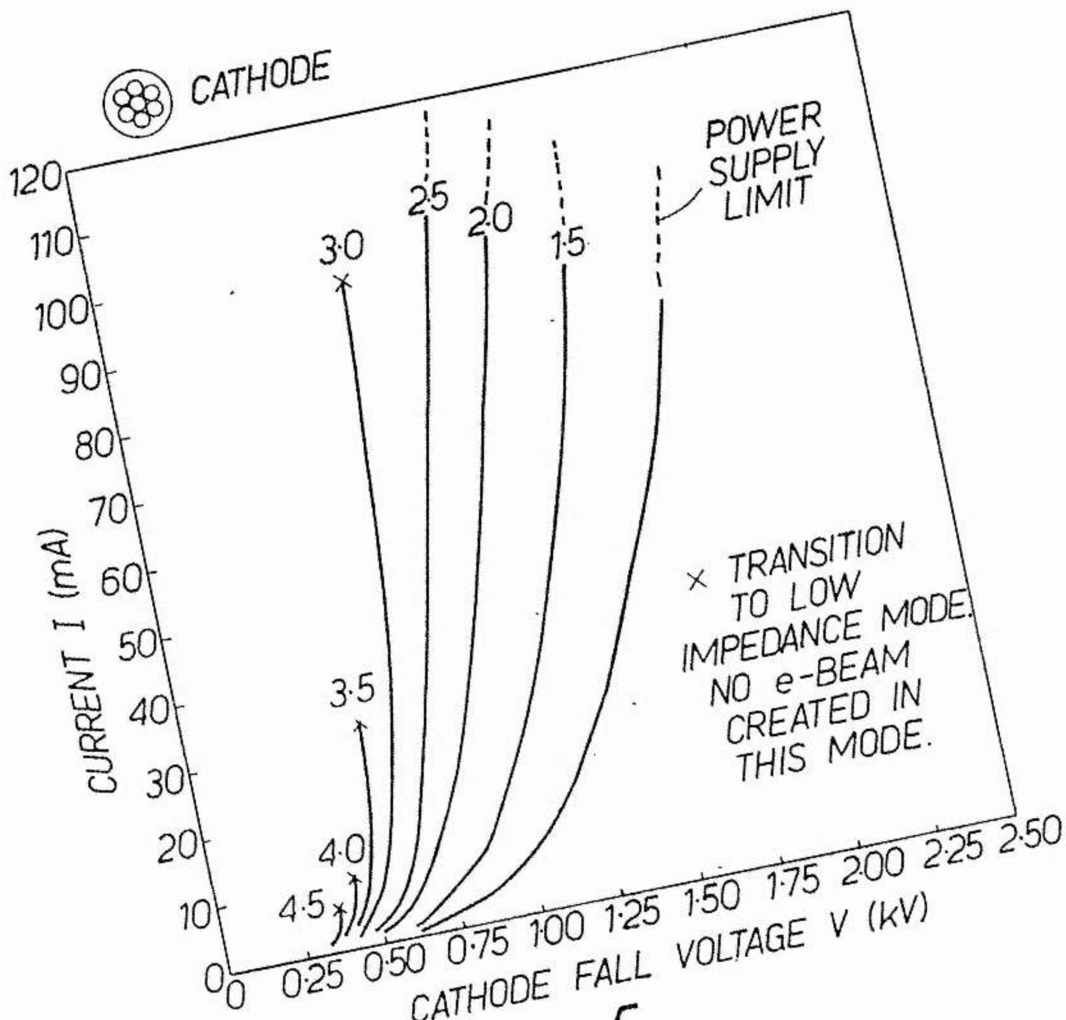
CATHODE FALL VOLTAGE V (kV)

FIG. 4.



CATHODE
POWER SUPPLY LIMIT
3·0
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× TRANSITION TO LOW IMPEDANCE MODE. NO e-BEAM CREATED IN THIS MODE.
CURRENT I (mA)
CATHODE FALL VOLTAGE V (kV)
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FIG. 5.

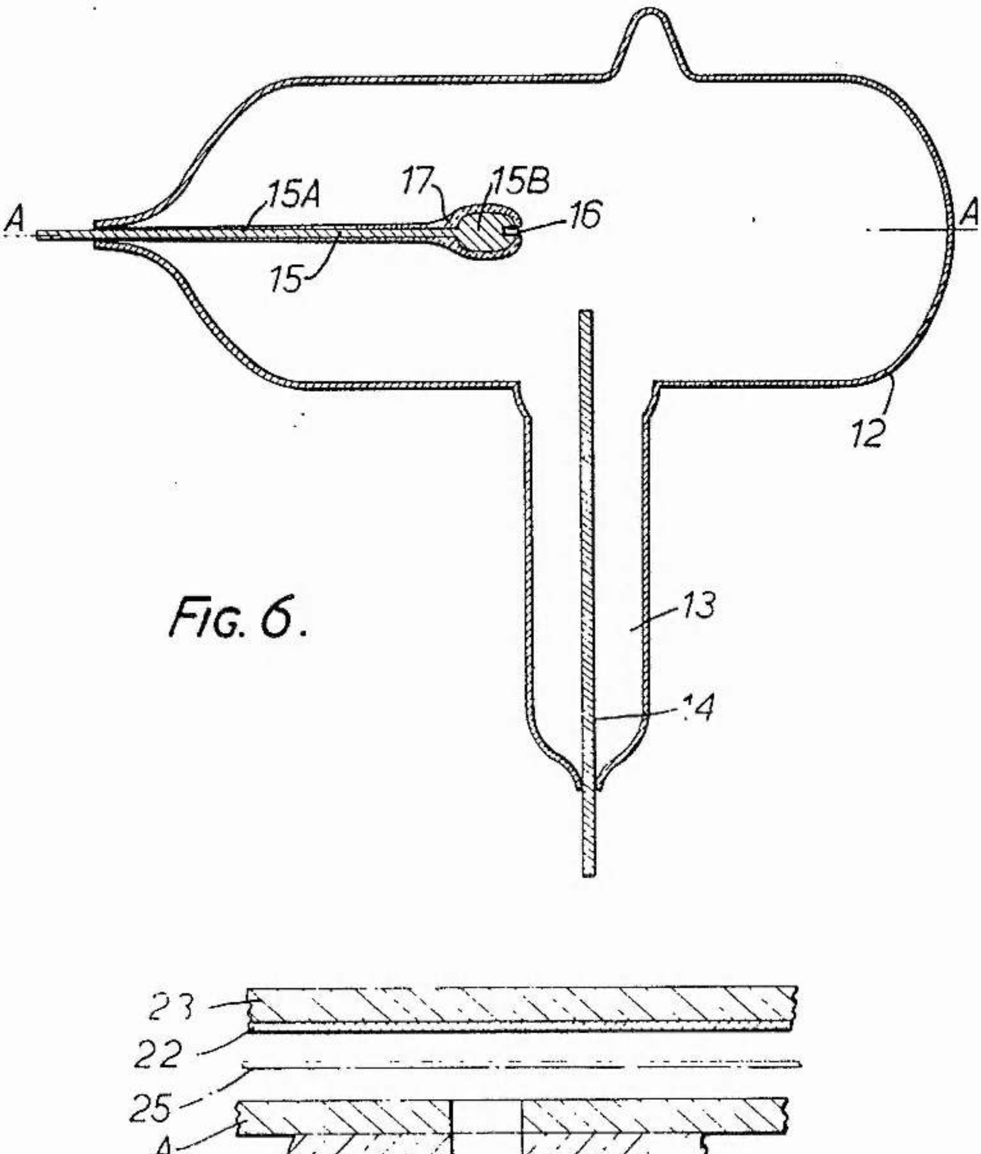


FIG. 6.

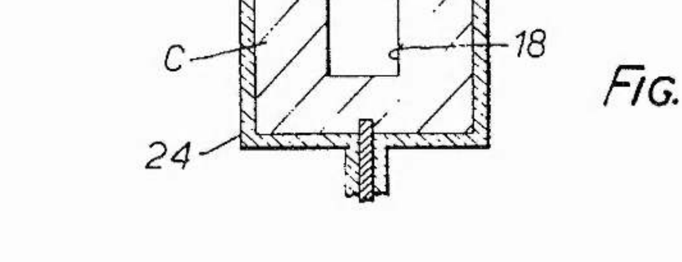


FIG. 7.

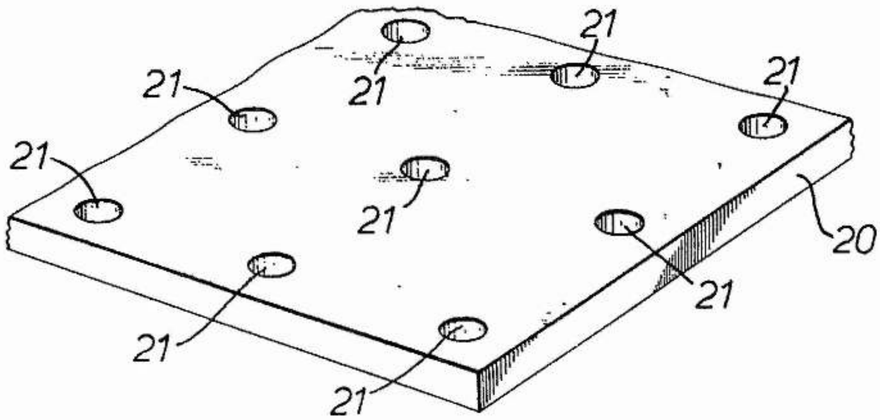


FIG. 8.

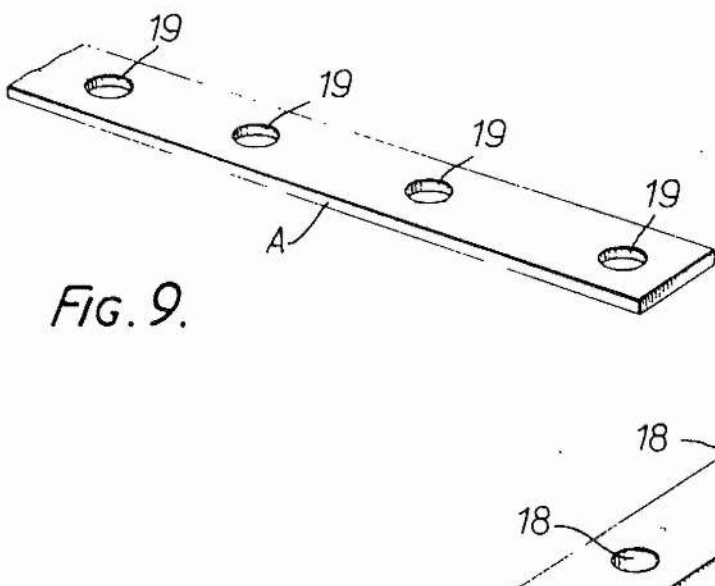


FIG. 9.

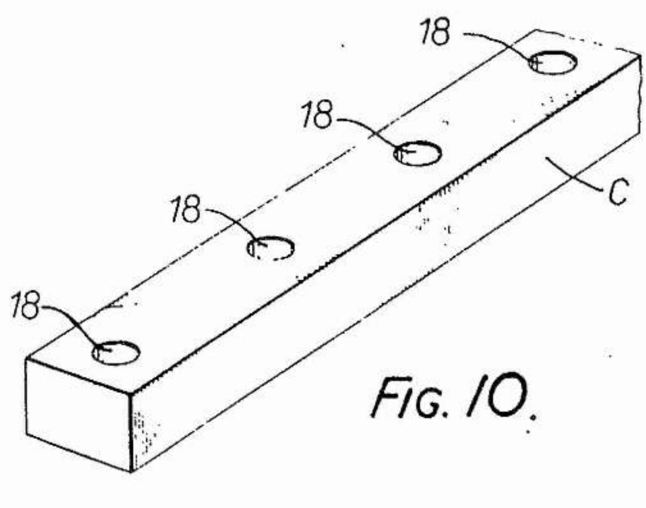


FIG. 10.

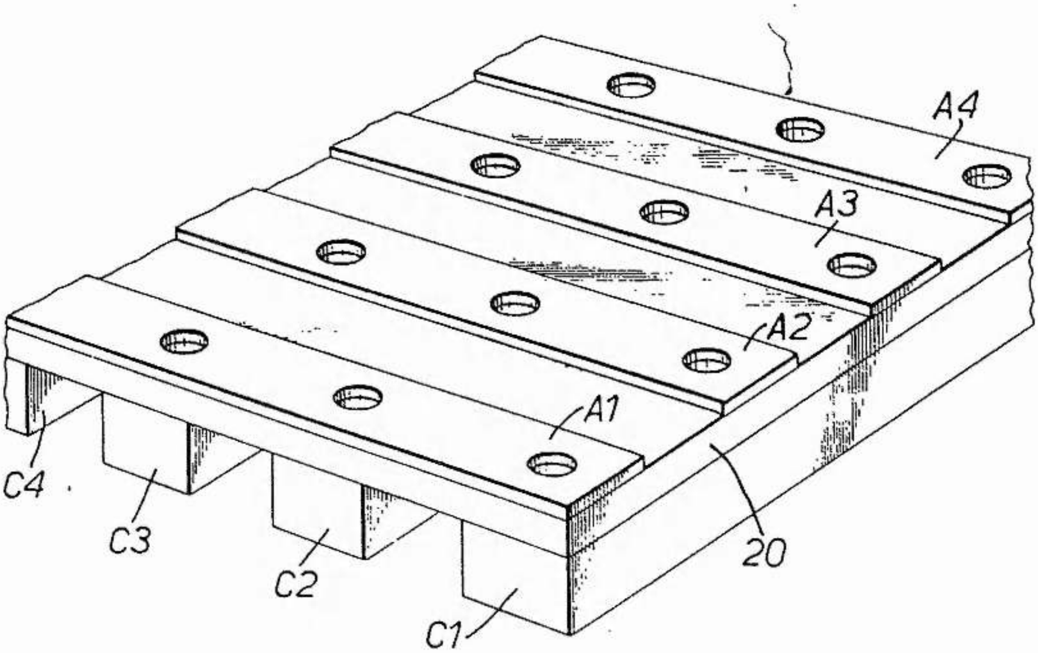


FIG. 11.

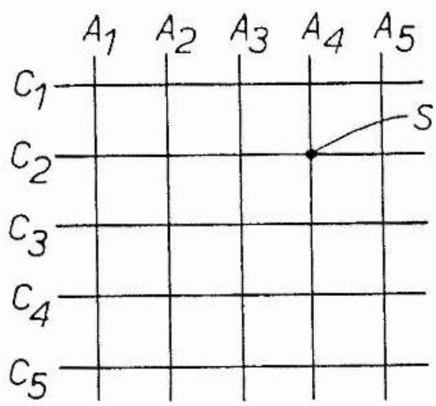


FIG. 12.

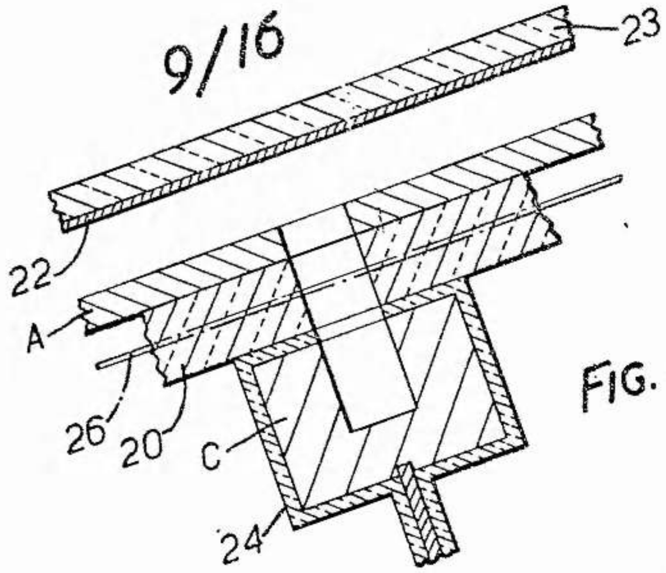
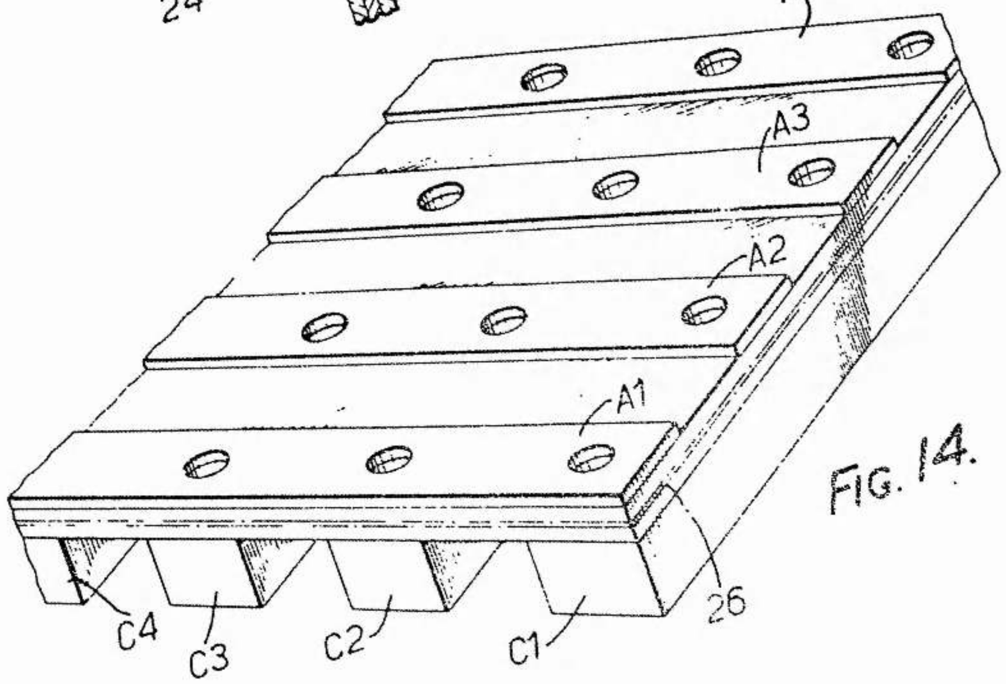


FIG. 13.



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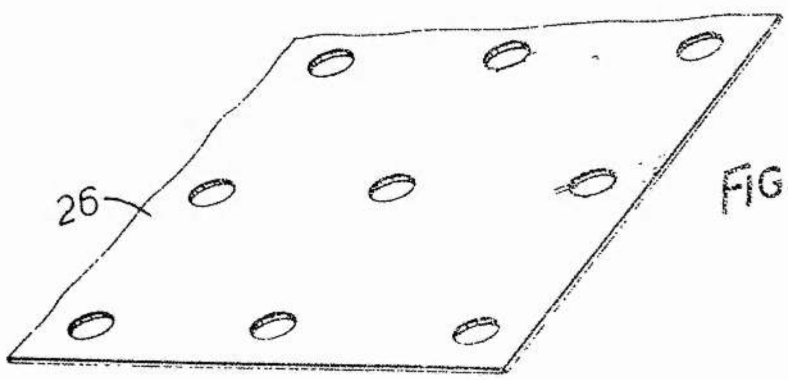


FIG. 15.

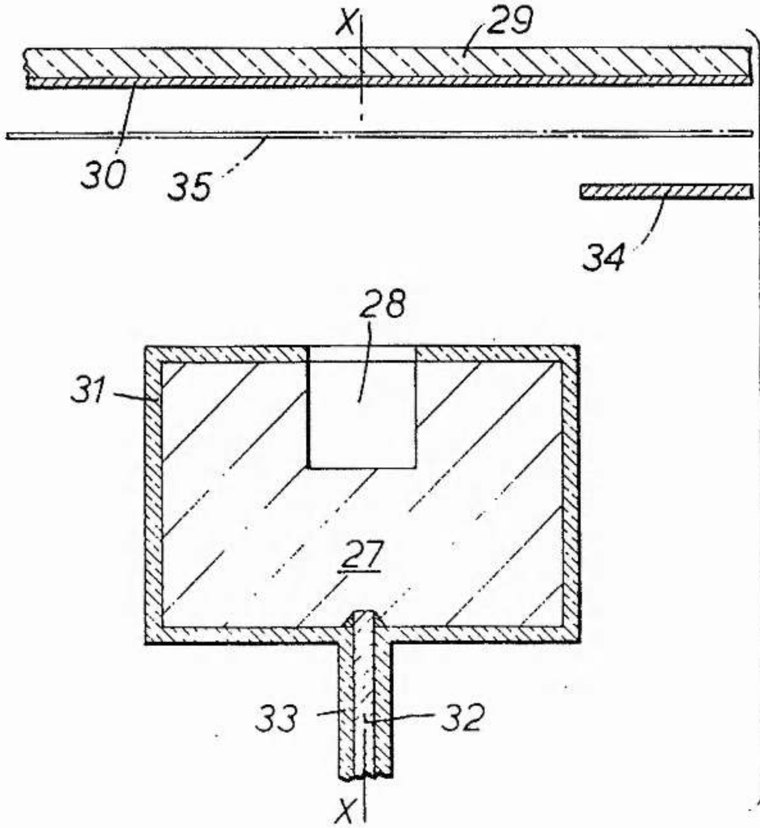
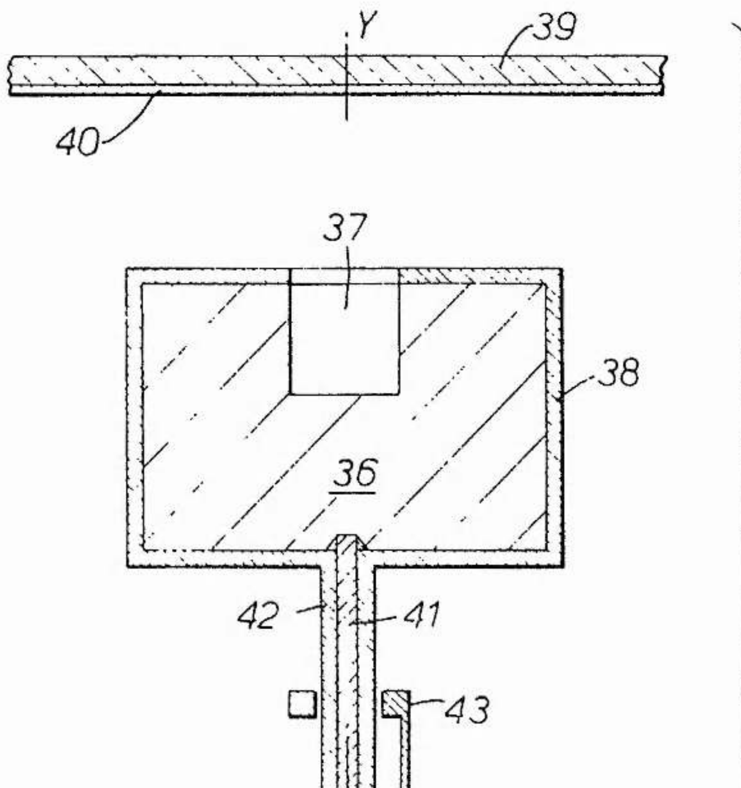


FIG. 16.



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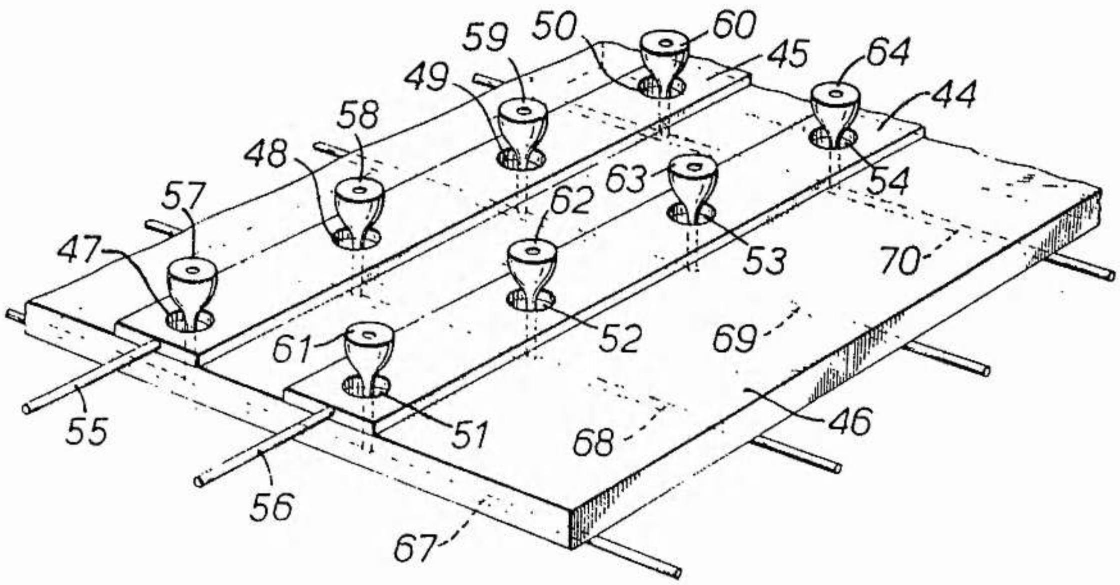
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FIG.18.

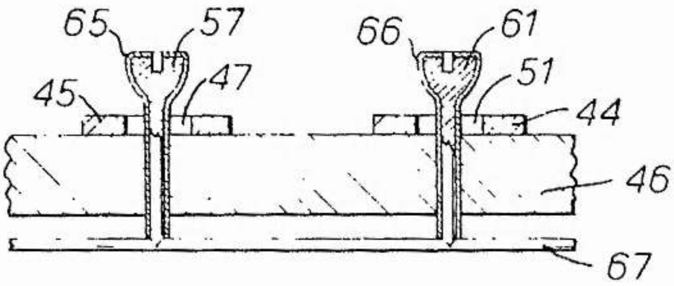
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FIG.19.

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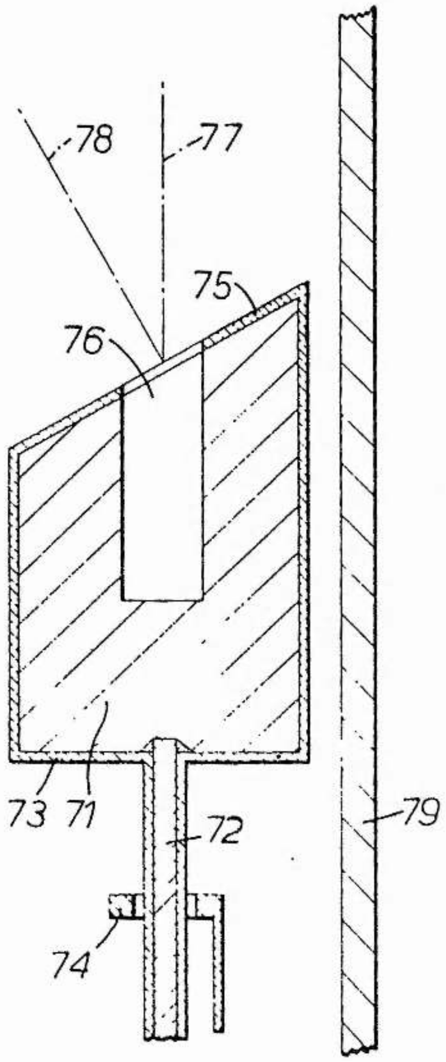


FIG. 20.

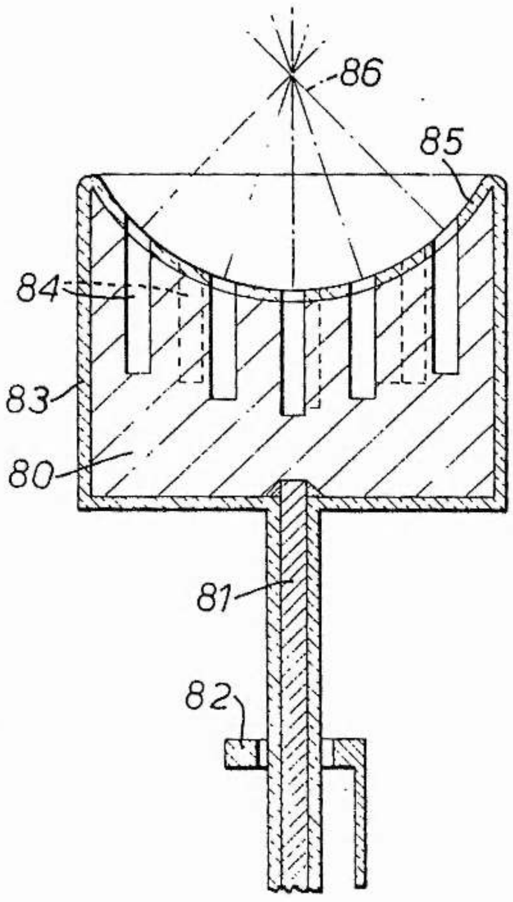
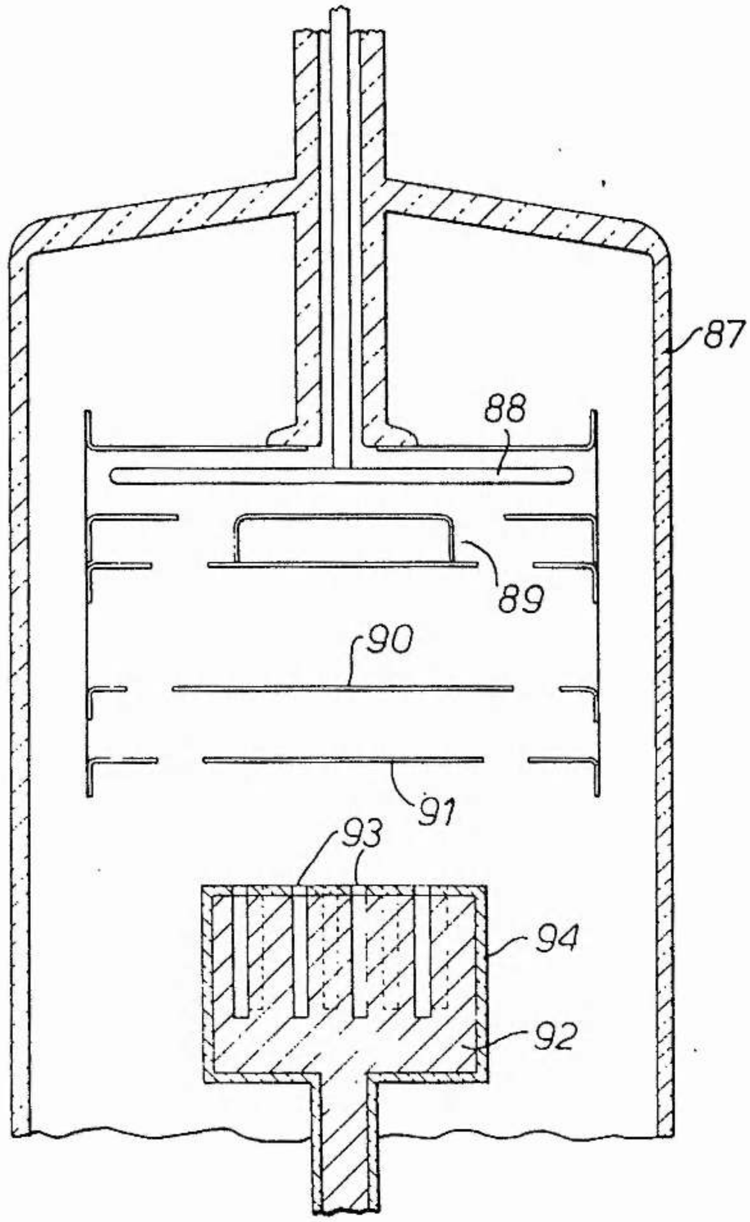


FIG. 21.



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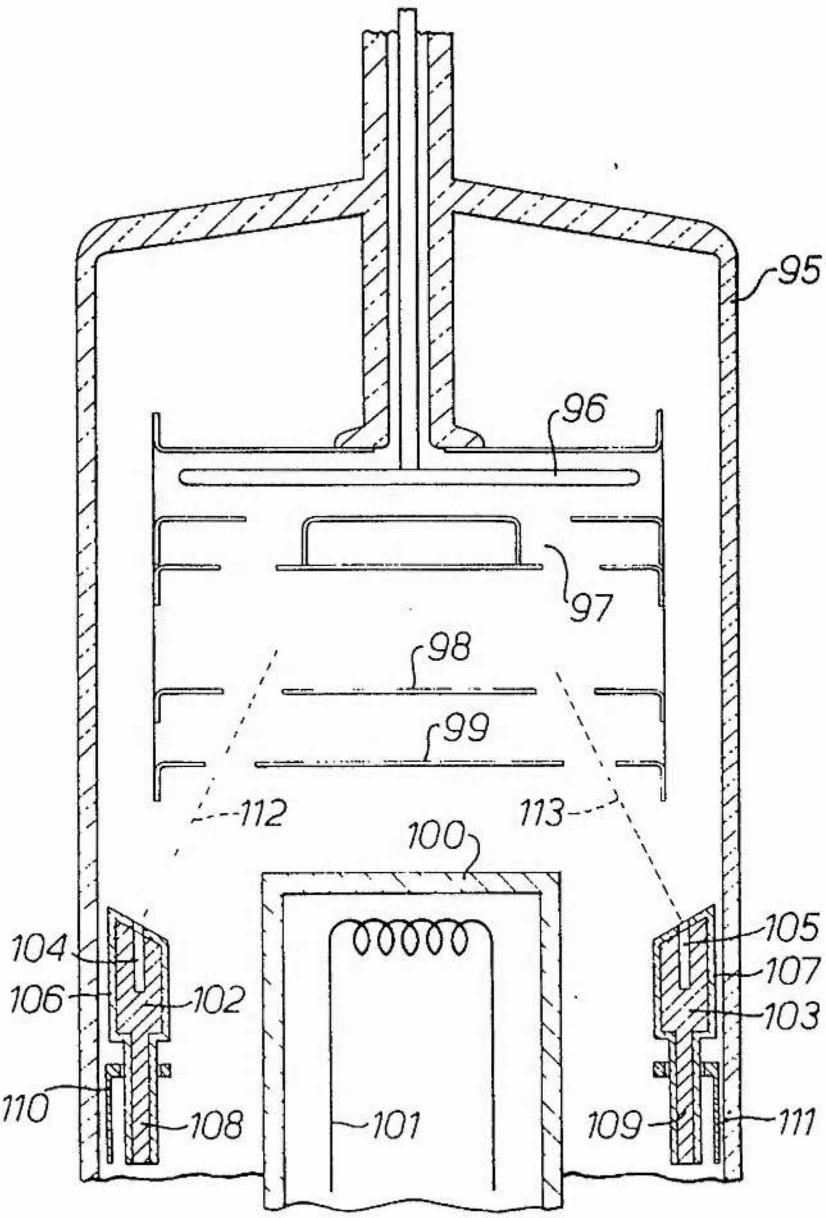
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FIG. 23.

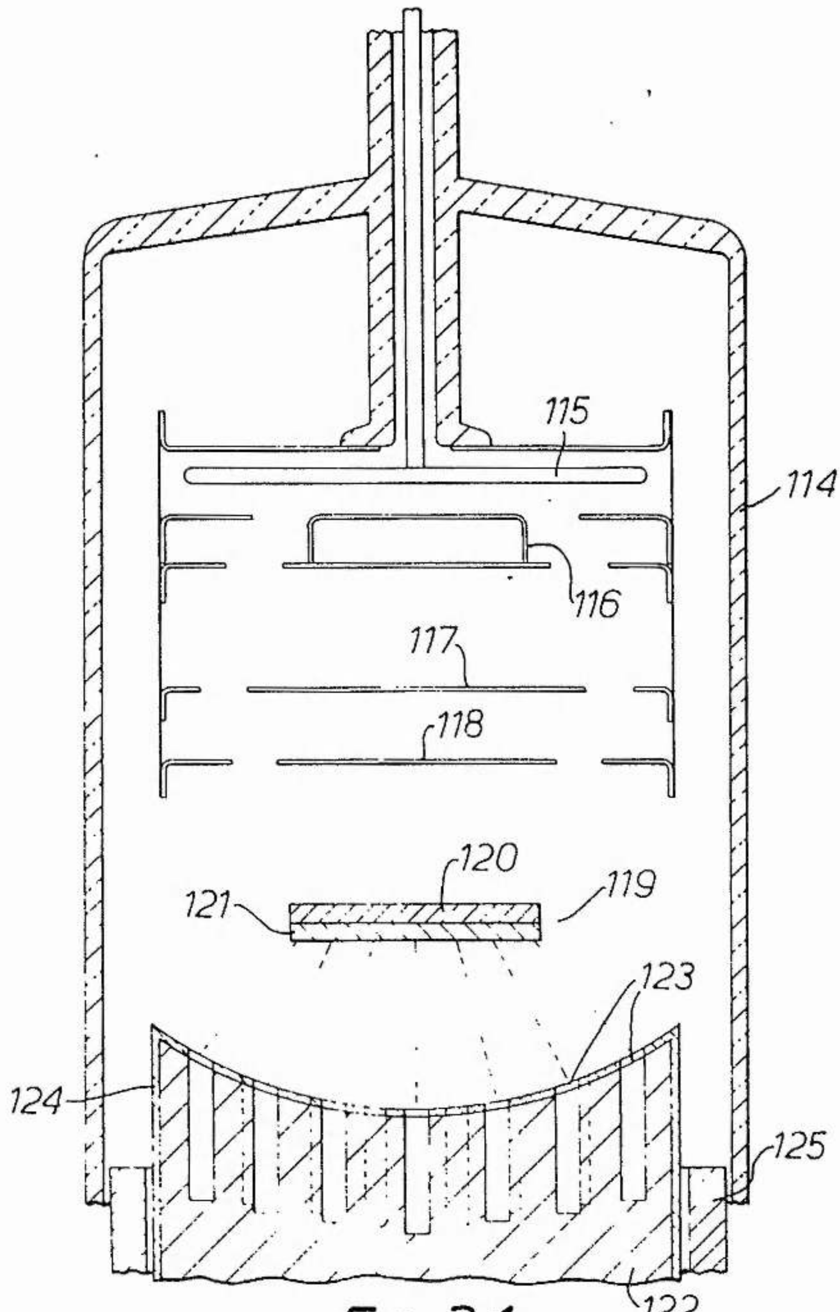
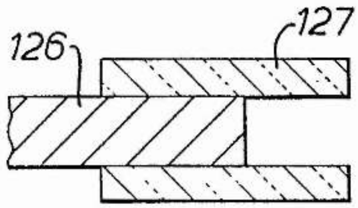


FIG. 24.



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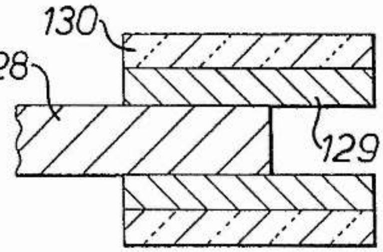

FIG. 26.

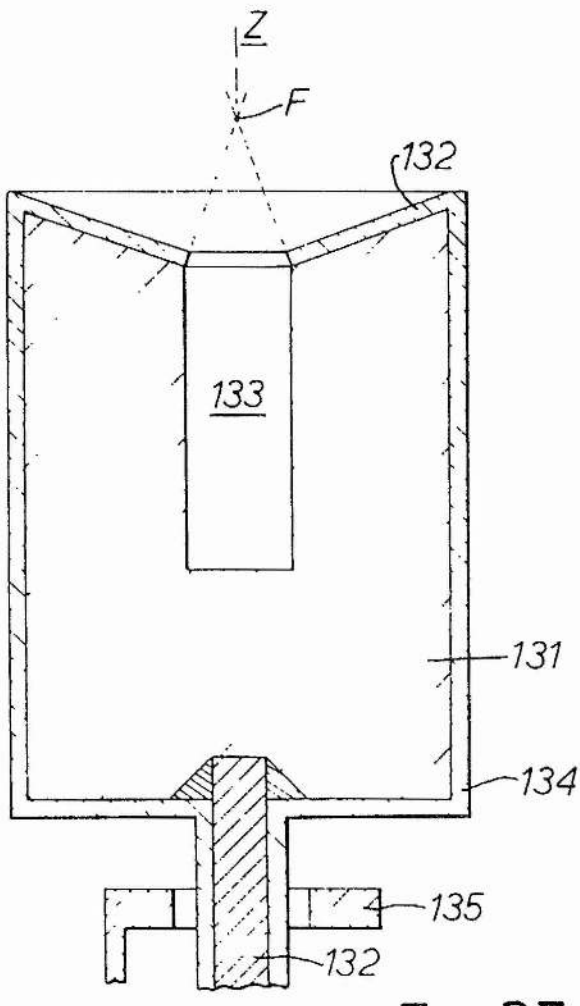

FIG. 27.

SPECIFICATION

Apparatus for forming electron beams

This invention relates to apparatus for forming electron beams, and to apparatus requiring the formation of electron beams, such as, for example, display devices and thyratrons.

The present invention seeks to provide improved apparatus for forming electron beams.

According to a first aspect of the invention there is provided apparatus for forming an electron beam comprising, within an envelope, an anode member; a cathode member of electrically conductive material; and a gas filling, and wherein, except for part of a front surface of said cathode member, at least substantially the whole of the surface of said cathode member which would otherwise be exposed to the gas filling within said envelope is covered with an electrically insulating material; the whole arrangement being such that upon the application of a suitably high voltage between said anode member and said cathode member an electron beam is formed extensive in a direction away from said part of said front surface.

According to a second aspect of the invention there is provided apparatus for forming an electron beam comprising, within an envelope, an anode member; a cathode member of electrically conductive material and having a hole in a front surface thereof; and a gas filling, and wherein, except within said hole, at least substantially the whole of the surface of said cathode member which would otherwise be exposed to the gas filling within said envelope is covered with an electrically insulating material, the whole arrangement being such that upon the application of a suitably high voltage between said anode member and said cathode member an electron beam is formed extensive in a direction away from said hole.

According to a third aspect of the invention, the anode member is located in front of the front surface of the cathode member.

Preferably a control grid electrode is included through which operation the electron beam passes, enabling the intensity or energy of the electron beam, to be modulated.

Preferably the apparatus includes a plurality of elongate cathode members arranged in a grid formation, and a plurality of elongate anode members arranged in a grid formation with said grid of anode members superimposed over said grid of cathode members, but spaced therefrom, with said anode members in crossing relationship with said cathode members to form a matrix, each of said cathode members having a series of holes entering into its surface facing said grid of anode members and each of said anode members having a series of holes passing therethrough, with each hole in an anode member aligned with a hole in a different one of the cathode members, and all surfaces of said cathode members, except for surfaces within said holes in said cathode members, which would otherwise be exposed to said gas filling are isolated therefrom by electrically insulting material, and the whole arrangement being such that by applying a high potential between one of said anode members and one of said cathode members an electron beam is formed at the crossing point of said last-mentioned two members, said electron beam being extensive in the space between the mouth of the hole in the cathode member at said crossing point and said anode member, said beam being arranged to penetrate through the corresponding hole in said addressed anode member.

It will be appreciated that by suitably addressing selected ones of said anode and cathode members an electron beam may be created which, by varying the selection of anode and cathode members addressed may be caused to be animated.

Preferably, insulating material is interposed between said grid of cathode members and said grid of anode members, which insulating material has passages therethrough aligned with said holes in said cathode and anode members whereby to permit communication between one cathode hole and the appropriate anode hole but impede communication between that cathode hole and any other anode hole.

Preferably, said last-mentioned interposed insulating material is provided in the form of a slab having holes extending between its major surfaces and forming the said passages.

A control grid electrode may be located on the side of the grid of anode members other than that on which the grid of cathode members is located, or alternatively it may be located between the grid of cathode members and the grid of anode members, and where insulating material is interposed between the cathode and anode grids the control grid electrode may be embedded in the interposed insulating material.

The anode member may be to one side of the axis of the electron beam formed in operation, such that said beam passes by said anode. It has been found by the inventors that the electron beam may be formed along the axis of the hole even though the anode member is displaced to the side of its path.

According to a forth aspect of the invention the anode member is located behind said front surface of the cathode member, and again in this configuration the electron beam may be formed along the axis of the hole, rather than along the shortest path between the anode and cathode members.

Preferably the anode member is co-axial with the cathode member. Preferably a grid is included through which in operation the electron beam passes, enabling it to be modulated in intensity or energy, although of course, this may be achieved by varying the high voltage between the anode and cathode members.

Preferably there are included a plurality of elongate anode members, each having apertures therein; and a plurality of stemmed cathode members, each having a hole in the front surface thereof and arranged such that its stem extends through one of said apertures, such that each anode member is located behind the front surfaces of cathode members whose stems pass through apertures in said anode member, whereby by applying a high potential between an anode member and one of the cathode members extending through an aperture therein an electron beam is formed extensive in a direction away from the hole in said one of the cathode members.

As previously described where the grid of anode members are located in front of the grid of cathode members, by addressing selected cathode and anode members an electron beam may be formed in a desired location, or number of such beams formed simultaneously if cathode members may be individually addressed.

Preferably a cathode member extending through an aperture in one anode member is electrically connected to another cathode member extending through an aperture in another anode member and also preferably a connector connecting two cathode members is spaced from the anode members by electrically insulating material.

Preferably where the apparatus in accordance with this invention is included in a display device a phosphor layer is included and is arranged so that when an electron beam is formed it impinges upon a spot upon said layer whereby to excite the same and preferably said envelope has a portion formed as a faceplate on the interior of which said phosphor layer is provided.

According to a feature of this invention a video signal reproducing apparatus includes apparatus as described above.

According to a feature of the invention in its third aspect a cathode ray tube apparatus comprises a plurality of elongate cathode members arranged in a grid formation, a plurality of elongate anode members arranged in a grid formation with said grid of anode members superimposed over said grid of cathode members, but space therefrom, with said anode members in crossing relationship with said cathode members to form a matrix, each of said cathode members having a plurality of holes entering into its surface facing said grid of anode members and each of said anode members having a plurality of holes passing therethrough, with each hole in an anode member aligned with a hole in a different one of the cathode members and, superimposed over said grid of anode members on the side thereof remote from said grid of cathode members, a phosphor screen, the two grids being enclosed within an envelope having a gas filling from which all surfaces of said cathode members, except for surfaces within said holes in said cathode members, which would otherwise be exposed to said gas filling are isolated therefrom by electrically insulating material, and the whole arrangement being such that by applying a high potential between one of said anode members and one of said cathode members an electron beam is formed at the crossing point of said last-mentioned two members, said electron beam being extensive in the space between the mouth of the hole in the cathode member at said crossing point and said anode member, said beam penetrating through the corresponding hole in said addressed anode member to impinge upon a spot upon said phosphor whereby to excite the same.

According to a fifth aspect of the invention the longitudinal axis of said hole is oblique to the normal of said front surface, and the electron beam is formed normal to said front surface of said hole. The inventors discovered that, when the hole is arranged with its longitudinal axis inclined to the normal of the front surface, an electron beam is not formed parallel to the aforesaid axis as might be expected but is in fact, surprisingly, formed in a direction normal to the front surface. Where in this specification the term "normal" is used, it should be taken to include "substantially normal". Apparatus utilising this principle may be useful where, for example, space is restricted and it would not be possible to employ a device in which the hole is arranged normal to the surface of the cathode. Also manufacture of the device is facilitated since only the direction of the front surface need be accurately machined.

Such apparatus may include a plurality of holes in said front surface, at least one of said holes having its longitudinal axis oblique to the normal of said front surface at that hole, such that upon the application of said suitably high voltage electron beams are formed extensive normal to said front surface at and in a direction away from respective holes. Since the configuration of the front surface was found by the inventors to determine the direction of electron beams produced, a desired pattern of electron beams or concentration of electron beams may be achieved without costly machining. For example, if a plurality of beams which are mutually parallel are required the holes need not be drilled in precise relationship to each other, as might have been thought, as only the front surface need be made flat. Of course the front surface can be curved if more complex patterns are required, and because of leniency in the disposition of the holes the cathode member may be more conveniently shaped for a desired application.

According to a sixth aspect of the invention there is provided apparatus for forming electron beams comprising, within an envelope, an anode member; a cathode member of electrically conductive material having a front surface which is curved; and a gas filling, and wherein, except for a plurality of discrete parts of the said front surface, at least substantially the whole of the surface of said cathode member which would otherwise be exposed to the gas filling within said envelope is covered with an electrically insulating material, the whole arrangement being such that upon the application of a suitably high voltage between said anode member and said cathode member electron beams are formed extensive normal to said front surface at and in a direction away from respective parts.

It is preferred that, where there are a plurality of electron beams formed, the front surface is curved such that they are focussed or concentrated at a point or small region. This is a particularly useful configuration providing apparatus suitable for inclusion in an electron beam welder, or as a point source of soft X-rays or incandescent black body radiation.

According to a seventh aspect of this invention there is included a layer of phosphor material on a viewable screen arranged such that upon the application of said suitably high voltage the electron beam impinges upon said phosphor layer and so excites the same.

According to a feature of the seventh aspect of this invention a display apparatus comprises, within an envelope, a layer of phosphor material on a viewable screen; remote from said phosphor layer, a metallic cathode member having a hole formed in a front surface thereof; between said cathode member and said phosphor layer, an apertured anode electrode; and a gas filling, and wherein, except within said hole, at least substantially the whole of the surface of said cathode member which would otherwise be exposed to the gas filling within said envelope is covered with an electrically insulating material, the whole arrangement being such that upon the application of a suitably high voltage between said anode member and said cathode member an electron beam is formed extensive in the space between the mouth of the hole in said cathode member and said anode member, and is arranged to penetrate through an aperture in said anode member to impinge upon said phosphor layer and so excite the same.

Preferably said envelope has a portion formed as a faceplate upon the inner surface of which said phosphor layer is provided.

The apparatus may include a modulating grid provided to affect the strength or intensity of the electron beam impinging upon said phosphor layer.

Said modulating grid may be a perforated grid or gauze provided either between said anode member and said phosphor layer or between said anode member and said cathode member. In other embodiments of the invention said modulating grid comprises a ring grid provided within the mouth of said hole in said cathode member. In this last mentioned case preferably an electrical connection for said grid is taken out, in insulated fashion through said cathode member in a direction away from said anode member, i.e. through the base of said cathode member.

Where, as is preferable, electrical connection to said cathode member is provided for by means of an electrical connector connected to the base of said cathode member, said last mentioned connector is preferably in the form of a hollow cylinder with an electrical connector for said grid passing, in insulated fashion, therethrough.

There may be provided a single hole in said cathode member with a corresponding single aperture in said anode member but alternatively a plurality of holes may be provided in said cathode member with a corresponding plurality of holes in said anode member. Where a plurality of holes and apertures are provided these may be in ring formation, with or without a central disposed hole and aperture.

According to a feature of the second aspect of the invention thyratron apparatus comprises, within an envelope, an anode member; a cathode member of electrically conductive material and having a hole in a front surface thereof; and a gas filling, and wherein, except within said hole, at least substantially the whole of the surface of said cathode member which would otherwise be exposed to the gas filling within said envelope is covered with an electrically insulating material, the whole arrangement being such that upon the application of a suitably high voltage between said anode member and said cathode member an electron beam is formed extensive in a direction away from said hole.

Preferably said cathode member has a plurality of holes in the front surface thereof, such that upon application of a suitably high voltage electron beams are formd extensive in a direction away from respective holes, and it is preferred that said front surface is curved, such that some focussing of the electron beams to a point may be obtained. Also it is preferred, where the front surface is curved, that at least one of said holes has its longitudinal axis oblique to the normal of said front surface at that hole. The cathode member may form the cathode of a thyratron, or advantageously thermionic material may be included and arranged such that when an electron beam or beams are formed they heat the same. This heating may be direct or indirect. For example, a substrate carrying the thermionic material may be exposed to the electron beam or beams and heat transmitted to the thermionic material by conduction.

Alternatively, when the electron beam is formed, it may be arranged to ionize the gas filling in a localised region, and so improve operating characteristics of a thyratron, and advantageously the longitudinal axis of the hole is oblique to the normal of said front surface at the hole, enabling the cathode member to be accommodated in a restricted space. Of course, more than one such cathode member may be employed.

According to an eighth aspect of the invention said front surface is shaped to focus said electron beam. Thus even where only one hole is employed the electron beam may be focussed. Each point of the surface around the mouth of the hole and at its edge may be thought of as directing components of the electron beam normal to the surface at respective points. Thus by providing the surface with a certain configuration, for example a convex shape or advantageously a frusto-conical configuration, with the hole being centrally located, a desired degree of focussing may be obtained. For example, the electron beam may be focussed to a point ot ir could be focussed merely enough to aid in further collimation of the electron beam.

Generally the, or each hole in a cathode member is blind, and preferably of circular cross-section.

Preferably said insulating material insulating surfaces of said cathode member, or plurality of cathode members, from said gas filling is glass, but where said cathode member, or members, is of an anodisable metal, such as aluminium or titanium, the insulating material may be anodisation.

Preferably said cathode and anode members are of Kovar (R.T.M.) but other metals or alloys may be used, such as aluminiumm copper or tungsten, or of molybdenum, tantalum or other refractory metals for high current use.

Generally said envelope is of glass or quartz.

Preferably the side wall and base surfaces of each hole is entirely free of a covering of electrically insulating material.

A number of gases, or mixture of gases, may be used for said gas filling including helium and/or argon and/or deuterium and/or neon. The hole size and voltages applied are related to the type of gas employed. Typically, hole sizes for argon are 0.2 to 0.1 of the size of those for helium, giving the possibility of more compact devices.

Preferably said gas filling is at a pressure of between 0.5 and 2.5 mB.

Normally the higher voltage utilised to address the anode and cathode members is from 1 to 5 kV and preferably between 1 and 2.5 kV.

The invention is further described by way of example with reference to the accompanying drawings in which:

Figure 1 is a schematic cross-section of one simple electronic display device in accordance with the present invention;

Figure 2 and 3 illustrate modifications of the device illustrated in Fig. 1, like references being used for like parts in Figs. 1 to 3;

Figure 4 and 5 are explanatory graphs;

Figure 6 shows, in longitudinal cross-section, another example of an electron beam device in accordance with the present invention;

Figure 7 is a schematic cross-section through a flat screen cathode ray display device in accordance with the present invention;

Figure 8 illustrates in perspective part of the insulating slab 20 of Fig. 7;

Figure 9 illustrates, part broken away, one elongate anode member A used in the device of Fig. 7;

Figure 10 illustrates, part broken away, one elongate cathode member C utilised in Fig. 7;

Figure 11 is a perspective view, part broken away, of an assembly of cathode and anode members with the slab of insulating material shown in Fig. 8 sandwiched therebetween;

Figure 12 is a schematic diagram illustrating the operation of the device illustrated in Figs. 7 to 11;

Figure 13 is a schematic cross-section through another flat screen cathode ray device in accordance with the present invention;

Figure 14 illustrates in perspective part of the device of Fig. 13;

Figure 15 illustrates in perspective part of the device of Fig. 13; with like references being used for like parts;

Figure 16 is a schematic cross-section of a display device in accordance with the invention;

Figure 17 is a schematic cross-section of another display device in accordance with the invention;

Figure 18 is a perspective view, part broken away, and

Figure 19 a cross-sectional view, of yet another device in accordance with the invention;

Figure 20 shows a longitudinal section of a further apparatus in accordance with the invention;

Figure 21 is a longitudinal section of another apparatus in accordance with the invention;

Figure 22 illustrates a thyratron in accordance with the invention;

Figure 23 illustrates another thyratron in accordance with the invention;

Figure 24 shows yet another thyratron in accordance with the invention;

Figure 25 illustrates a cathode member in accordance with the invention;

Figure 26 shows another cathode member; and

Figure 27 illustrates another device in accordance with the invention.

Referring to Fig. 1, a device comprises a quartz envelope of which only one portion 1 is shown. The envelope portion 1 is provided as a faceplate having on its interior a layer 2 of phosphor material similar to that used in conventional cathode ray display tubes. Associated with the phosphor layer 2 is a transparent metal layer (not shown but somewhat akin to the transparent metal layer forming part of the screen of a conventional cathode ray tube) between the layer 2 and the faceplate. The faceplate formed by the portion 1 of the envelope of the device is transparent.

Within the envelope and at the end thereof opposite to the faceplate portion 1, is a cathode member 3 which comprises a block 4 of Kovar having a blind hole 5 formed therein, in this case by drilling coaxially with the axis of cylindrical symmetry 6 of the device. The open mouth of the hole 5 faces the phosphor layer 2. In the base of the block 4, adjacent the blind end of the hole 5, a connecting pin 7 is inserted so as to enable electrical connection to be made to the Kovar block 4.

All of the external surfaces of the Kovar cathode block 4, with the exception of the wall and base surfaces of the blind hole 5, which would otherwise be exposed to a gas filling within the envelope of the device are covered by electrically isolating material represented at 8. In this example, the insulating material 8 is glass.

Between the cathode 3 and the phosphor layer 2 is an anode electrode 9 which has a circular hole 10 passing therethrough. Circular hole 10 is coaxially aligned with the blind hole 5 within the Kovar block 4.

It will be noted that the cathode 3 is devoid of a heater as such, or any electron emissive cathode material, such as barium.

The envelope of the tube is filled with helium at a pressure of between 0.2 and 10 mB.

As so far described the device is in its simplest form. For the moment it will be assumed that grid 11, shown between the anode electrode 9 and the phosphor layer 2, is absent.

Provided that the dimensions of the cathode and anode holes 5 and 10 and the spacing of the anode 9 to the cathode 3 is suitably chosen, a type of electrical discharge will be established between the anode 9 and the cathode 3 which results in the formation of an electron beam along the axis 6 of the coaxially aligned anode and cathode holes when a potential difference in the range of from several hundred volts to several thousand volts is established between the anode 9 and the block 4 of cathode 3. Within limits, the electron beam acquires energy approximately equal to the anode to cathode potential difference and so extends into the region beyond the anode hole 10 to impinge, finally, upon the phosphor layer 2 thus exciting it.

Thus, in operation, whenever a potential as aforesaid is established between anode 9 and block 4 of cathode 3, the resulting electron beam causes a spot to appear on the screen 1 due to excitation of the phosphor layer 2. Whilst the aforementioned dimensions and spacing may be arrived at empirically, in the particular example illustrated in Fig. 1, the cathode and anode holes were of 5 mm diameter. With a gas filling of helium at a pressure of 2 mB and a potential difference between anode 9 and cathode 3 of approximately 1.5 kV, the device was found to operate with a spacing between the plane of the anode 9 and the surface of the phosphor layer 2 of up to a few centimetres, and a spacing between the anode 9 and the cathode 3 of at least 3 mm. With the above-mentioned potential difference of 1.5 kV the current drawn from the cathode, was of the order of 15 mA.

Reverting to the aforementioned grid 11—by introducing a control grid, modulation of the intensity or energy of the electron beam arriving at the surface of the phosphor layer 2 may be achieved by varying a potential applied to the grid 11. Alternatively or additionally varying the potential between the anode 9 and the cathode 3 will produce or enhance a modulation effect but, of course, it is much less convenient to apply modulation at high potential.

Referring to Fig. 2, the essential difference between the device shown in Fig. 2 and the device shown in Fig. 1 resides in the fact that a mesh grid such as 11 in Fig. 1 is not provided between the anode 9 and the phosphor layer 2. Instead, a ring grid 11′ is provided within the mouth of the blind hole 5 in the Kovar block 4. Electrical connection is made to the ring grid 11′ by means of a connector passing out through the base of the Kovar block 4. In fact, instead of a pin 7 making contact with the block 4 the contact, here referenced 7′, is cylindrical with the connecting lead for the grid 11′ passing coaxially therethrough in insulated fashion. Although not shown in Fig. 2, insulting material would be provided to support the connecting lead for the grid 11 within the cylindrical connector 7′.

Referring to Fig. 3, in this case, compared to Fig. 1, the position of the grid 11 is changed. Instead of providing this between anode 9 and the phosphor layer 2 it is provided between the anode 9 and the cathode 3. In some cases this may be preferred since a relatively lower voltage is required compared to that required with the grid in the position shown in Fig. 1.

The graph of Fig. 4 shows the relationship between beam current I and cathode fall voltage V (i.e. the voltage applied between anode and cathode) for different gas filling pressures, for a device as described above having cathode and anode holes of 5 mm in diameter.

In any of the embodiments described above with reference to Figs. 1, 2 and 3, instead of a single cathode hole and a single anode hole a plurality of blind holes may be provided in the Kovar block 4 with each cathode hole being coaxially aligned with a corresponding hole passing through the anode member 9. Typically in such a case, the holes will be arranged in a ring formation, with or without cathode and anode holes on-centre. The effect achieved using a plurality of cathode and anode holes in a simple device as illustrated in Figs. 1 to 3, is that the areas of excitation thus created in the phosphor layer 2 tend to merge to produce a larger illuminated spot (or other prescribed pattern as determined by the pattern of holes on the faceplate 1) than would otherwise be the case.

The graph of Fig. 5 shows parameters for this last-mentioned case corresponding to those shown in the graph of Fig. 4 for this embodiment shown in Fig. 1.

One application for a device as described above is in large area displays such as those sometimes found in public places in order to impart information, e.g. in airport terminals or sports areas. By arranging devices such as those described above in rows and columns and addressing individual devices appropriately, letters and words—and even graphics—may be produced.

Referring to Fig. 6, another device in accordance with the invention includes a glass envelope 12 which is of generally circular cross-section and has a transversely extending side-arm 13 about mid-way along its length. An anode member 14 extends through the end wall of the side-arm 13 and into the main part of the volume enclosed by the envelope 12.

A cathode member 15 passes through an end wall of the envelope 12. It has a stem portion 15A and an enlarged end 15B with a blind hole 16 of circular cross-section in its front surface. All of the surfaces of the cathode member 15 contained within the envelope 12, except for the side wall and base surfaces of the hole 16, are coated with a layer of glass 17. The envelope 12 contains helium at a pressure of 2 mB.

In operation, a potential difference of about 1 kV is applied across the anode and cathode members 14 and 15 and an electron beam is formed along the axis A–A of the hole 16.

The envelope 12 has a length of about 7 cm and a diameter of about 3.5 cm.

The anode and cathode members 14 and 15 are separated by approximately 1 cm in the axial direction and 0.5 cm in the transverse direction. The diameter of the hole 16 is 5 mm, with a depth (i.e. axial length) of 3 mm.

Referring to Figs. 7 to 11 a display device comprises a plurality of elongate cathode members C1 to C4 arranged parallel to one another to form a grid. Each cathode member, as shown in Fig. 10, comprises a bar of Kovar having at regular intervals along its length blind holes 18. The holes 18 extend into the same planar surface of the cathode member. Each cathode member is provided with an electrical connector (not shown) by means of which it may be individually addressed.

Superimposed above the grid of cathode members is a grid of parallel elongate anode members A1 to A5 each of which consists of a bar of Kovar having a series of holes 19 passing therethrough from one planar face to its opposite planar face as illustrated in Fig. 9. The pitch of the holes 19 in an anode member corresponds to the spacing between the cathode members in the cathode grid and the spacing of the anode members in the anode grid corresponds to the pitch of the cathode holes 18 in a cathode member so that each cathode hole 18 is aligned with an anode hole 19 at the crossing point of the anode and cathode conductors in which those particular holes appear.

Sandwiched between the grid of cathode members and the grid of anode members is a slab 20 of glass which has rows and columns of holes 21 therein extending from one major planar face to its opposite major planar face, as illustrated in Fig. 8. The rows and columns of holes are spaced such that when the slab is sandwiched between the grid of cathode members and the grid of anode members, as shown in Fig. 11, each aligned cathode and anode hole at the crossing point of an anode and cathode member is also aligned with a hole in the slab of insulating material 20. Thus, the holes 21 in the insulating slab 20 permit communication between appropriate ones of the cathode and anode holes 18 and 19 but impede communication between each cathode hole and other than the anode holes with which it is directly aligned. Thus the tendency for so-called "long path" discharges to take place is reduced.

Superimposed over the grid of anode members is a phosphor screen comprising of a layer of phosphor material 22 on the inside of part of an enclosing envelope which is formed as a faceplate 23. Associated with the layer 22 of phosphor material is a transparent layer of conductive material (somewhat akin to the transparent metal layer of the phosphor screen of a conventional cathode ray tube device) between the phosphor layer 22 and the faceplate 23. The envelope in this case is of glass and encloses the anode and cathode members together, of course, with the interposed slab of insulating material 20.

The envelope has a gas filling of helium and, as illustrated only in Fig. 7, each cathode member C is entirely covered with an electrically isolating layer 24 of glass, except within the holes 18. Thus, save for the wall and base surfaces of the holes 18 all surfaces of the cathode members which would otherwise be exposed to the helium gas filling are isolated therefrom. In fact, save for the interior surfaces of the holes 18 as aforesaid, all surfaces at cathode potential are so isolated from the gas filling. In this particular case the wall and base surfaces of the holes 18 are entirely free from glass. In this particular example the cathode and anode holes 18 and 21 are of circular cross-section with a diameter of 5 mm. The helium gas filling is at a pressure of 2 mB. The distance separating the grid of cathode members from the grid of anode members (i.e. the thickness of the slab 20) is a few millimetres whilst the distance separating the grid of anode members from the phosphor layer 22 is in the region of 0.5 to 2 cm.

If now, and referring particularly to Fig. 12, a 1.5 kV potential difference is established between cathode member C2 and anode member A4 than en electron beam will be formed in the region of the crossing point of members C2 and A4 which beam extends from out of the mouth of the cathode hole 18 at the crossing point through the corresponding hole in the insulating slab 20 to penetrate through the corresponding anode hole 19 in anode members A4 and impinge upon the phosphor screen to form a spot as represented at S in Fig. 12. By addressing different combinations of anode members and cathode members corresponding spots may be caused to appear on the screen at any of the crossing points and by suitably changing the combination of crossing points selected an animated display may be achieved.

No mention has so far been made of grid 25 shown in Fig. 7 as located between the grid of anode members A and the phosphor layer 22. The purpose of this grid, if provided, is to modulate the intensity or energy of the electron beams arriving at the phosphor.

Alternatively, with or without the grid 25, the overall intensity or energy of the electrons beams may be modulated or adjusted by appropriate alterations to the anode to cathode discharge current as determined by the voltage applied between the cathode and anode members.

In another embodiment a grid 26 is embedded in the slab 20, as shown in Figs. 13 and 14, and may comprise a gauze or as metal plate having holes which correspond to the anode and cathode holes, as illustrated in Figs. 15.

It will be noted particularly the absence of any form of conventional electron gun. No cathode heaters are employed in the device illustrated, the cathodes being cold cathodes, and no cathode material such as barium is employed.

With reference to Fig. 16, another embodiment of the invention includes a cathode member 27 of Kovar having a hole 28 of about 5 mm diameter in its front surface and being enclosed in a glass envelope 29 which also contains helium gas at a pressure of about 2 mB and has a layer of phosphor on its inner surface to form a screen 30. The surfaces of the cathode member 27, except the side wall and base of the hole 28, are covered in a glass layer 31, which electrically insulates the cathode member 27 from the helium gas filling. Electrical connection to the cathode member 27 is made via a pin 32 which is sheathed with a layer 33 of glass.

An anode member 34 is located between the front surface of the cathode member 27 and the phosphor screen 30, being about 2 cm from the cathode member 27, and 2 cm from the screen 30. The anode member 34 is also offset from the axis X–X of the hole 28, being about 2 cm to the right as shown.

When a 1.5 kV potential difference is established between the cathode member 27 and the anode member 34, an electron beam is formed along the axis X–X of the hole, even though the anode member 34 is offset from that axis. The electron beam impinges on the phosphor screen 30 to form a spot.

The intensity of the spot may be varied by modulating the voltage applied to a grid electrode 35, shown in this embodiment to be positioned between the screen 30 and the anode member 34, although it could be located between the anode and cathode members 34 and 27.

A further embodiment of the invention is illustrated schematically in Fig. 17. A cathode member 36 of Kovar has a hole 37 in its front surface and is coated with an electrically insulating layer of glass 38. The cathode member 36 is contained within a glass envelope 39 having on its inner surface a layer of phosphor which acts as a screen 40, and enclosing helium gas at 2 mB pressure. The cathode member 36 is electrically connected via a pin 41, which is also coated in glass 42, forming a stem. In this embodiment a Kovar anode member 43 is located behind the front surface of the cathode member 36 and is positioned co-axially with it about the pin 41.

When in operation a potential difference of 1.5 kV is applied between the cathode and anode members 36 and 43, an electron beam forms along the axis Y–Y of the hole 37 and impinges on the screen 40.

As in the previously described embodiments, a modulating grid may also be included, and/or modulation may be carried out by varying the potential difference applied.

The hole 37 has a diameter of about 5 mm and the front surface of the cathode member 36 may be between a few millimetres and a few centimetres from the screen 40.

Yet another embodiment of the invention is now described with reference to Figs. 18 and

19. A plurality of Kovar strips, only two of which 44 and 45 are shown, are arranged parallel to each other on a glass slab 46. Each of the strips has a plurality of apertures through it, only four of which, 47, 48, 49 and 50; 51, 52, 53 and 54 are shown for each strip. Each strips forms an anode member, electrical signals being applied to them via rods 55 and 56.

Cathode members 57 to 64 are of Kovar and have stems extending through the apertures in the strips 44 and 45, there being one cathode member to each aperture, and passing through the glass slab 46. The surfaces of each cathode member, including the connecting pin comprising its stem, are coated in glass layers 65 and 66 except for the side wall and base of the single hole in each ones front surface.

The ends of the cathode members 57 to 64 on the side of the glass slab 46 other than the anode strips 44 and 45 are connected via rods 67, 68, 69 and 70, such that one cathode member associated with one strip is electrically connected to a cathode member associated with each of the other strips, giving a crossing relationship between the cathode and anode members. Thus, by applying a potential difference between a suitable cathode member and anode strip, an electron beam may be formed in front of that cathode member.

By placing the structure within an envelope filled with helium at 2 mB pressure, and having a phosphor screen on its inner surface, a display may be produced.

The front surfaces of the cathode members 57 to 64 may be as little as 5 mm from the surface of the screen, and a potential difference between the anode and cathode members of 1.5 kV would be required.

With reference to Fig. 20, a thorated tungsten cathode member 71 has a stem 72 via which electrical connection is made, and is covered with a layer 73 of electrically insulating glass which also extends to the stem 72. An anode member 74 surrounds and is coaxial with the stem 72.

The cathode member 71 has a front surface 75 in which is formed a blind hole 76 of circular cross-section, being 5 mm deep and having a diameter of about 1.5 mm, and having surfaces which are free of the layer 73 of glass. The front surface 73 is inclined with respect to the hole 76 such that the longitudinal axis of the hole 76, shown as broken line 77, is oblique to the normal 78 of the front surface 75 at that point, the angle between them being about 30°.

The cathode and anode arrangement is enclosed within a glass envelope which also contains a gas filling of deuterium at about 2 mB pressure.

In operation, when a suitably high voltage, say 2 kV, is established between the anode and the cathode members 74 and 71, an electron beam is formed extensive in a direction away from the hole 76 and normal to the front surface 75. If, as illustrated a wall 79, which might be for example the wall of the envelope or some other obstruction, is present, this could restrict the space available to the arrangement. By giving a suitable incline to the front surface 75 the hole 76 can have a depth which might not be possible if its longitudinal axis 77 were arranged to be parallel to the normal 78 to the front surface 75.

With reference to Fig. 21, a thorated tungsten cathode member 80 is connected to stem 81 and is contained within an envelope (not shown) together with a deuterium gas filling at about 2 mB pressure and an anode member 82, which is coaxial with and surrounds the stem 81.

The cathode member 80 and stem 81 are coated with a layer 83 of glass which electrically insulates them from the deuterium gas filling.

A plurality of holes 84 ar formed in a front surface 85 of the cathode member 80, each of them being of circular cross-section with a diameter of about 1.5 mm and a depth of 5 mm and having surfaces which are free of the layer 83 of glass. The front surface 85 is curved, for example, it may be parabolically or spherically shaped, rather than the flat surface 75 shown in Fig. 20.

In operation, when a voltage of about 2 kV is applied between the cathode and anode members 80 and 82 a plurality of electron beams are formed extensive normal to the front surface 85 at and in directions away from respective holes, and come to a focus at a point 86 which is located according to the configuration of the front surface 85.

Although the holes 84 are illustrated as being disposed mutually parallel, they could be arranged in some other way, since their attitude does not affect the directions of the electrons beams which are formed during operation.

Apparatus according to the invention in which the surface is curved to produce such focussing might find application in an electron beam welder, for example, in which case the piece being welded may also be for example contained within the envelope. It might also find application in the production of a point source of soft X-rays, having a wavelength of about 6.10^{-10}m, for use in spectroscopy for example, or to generate a point source of incandescent black body radiation.

With reference to Fig. 22, a thyratron in accordance with the invention includes a glass envelope 87, containing a gas filling, an anode 88, a screen grid 89 and control grids 90 and 91, such as might be found in a conventional thyratron. However, instead of the conventionally provided heated cathode, the cathode comprises a cathode member 92 of tungsten having a plurality of holes 93 in its front surface, facing the anode 88. The surface of the cathode member 92 is entirely covered with a glass layer 94 except for the walls and bases of the holes 93. When the thyratron is required to become conducting a suitably high voltage is applied between the anode 88 and the cathode member 92 such that an electron beam is formed extensive in a direction away from each hole. The gas filling becomes ionized and a conduction path is established between the anode 88 and cathode member 92.

Referring to Fig. 23, another thyratron in accordance with the invention includes a glass envelope 95 containing a gas filling, an anode 96, a screen grid 97 and controls grids 98 and 99. It also includes a conventional heated cathode, comprising a hollow cylinder 100 of thermionic material and a heater filament 101.

Two cathode members 102 and 103 are located within the glass envelope 95. Each has a hole 104 and 105 in its front surface and is coated with a glass layer 106 and 107. The longitudinal axes of the holes 104 and 105 are oblique to the front surfaces of the cathode members 102 and 103. The cathode members 102 and 103 also have stem portions 108 and 109 which are surrounded by coaxial anode members 110 and 111 respectively.

During operation of the thyratron, the thermionic material 100 is heated by the heater filament 101 causing electrons to be emitted from its surface. The emitted electrons ionize that part of the gas filling between the controls grids 98 and 99 and the cathode to establish a primary discharge. Then conventionally, to trigger the thyratron, a positive voltage pulse is applied to the control grids 98 and 99, allowing the discharge to penetrate through them to initiate the main discharge, and thus to render the thyratron conducting. However, in addition to this, a voltage may be applied between the cathode members 102 and 103 and the cathode members 110 and 111 respectively, such that electrons beams are formed extensive of the holes 104 and 105 and normal to the front surfaces of the cathode members 102 and 103, their path being shown by broken lines 112 and 113. These beams may be formed simultaneously with, or shortly before or after, the application of the voltage pulse to the control grids 98 and 99. The beams are arranged to pass through apertures in the control grids 98 and 99 and penetrate into the volume beyond them, to ionize the gas filling.

The cathode members could be located elsewhere within the envelope 95 if it is desired to promote ionization in other regions of the thyratron, and of course only one, or more than two cathode members could be used.

With reference to Fig. 24, another thyratron includes a glass envelope 114, gas filling, an anode 115, a screen grid 116 and control grids 117 and 118. The thyratron includes a thermionic cathode 119 having thermionic material 120 carried by a substrate 121 of high thermal conductivity which may be nickel, for example. A cathode member 122 of tungsten is positioned on the substrate side of the cathode 120. The cathode member 122 has a plurality of holes 123 in its front surface which is concave. The surface of the cathode member 122, except for the walls and bases of holes 123, are covered with a layer 124 of glass. An anode member 125 surrounds the cathode member 122.

In operation, a voltage is applied between the anode member 125 and the cathode member 122 such that a beam of electrons is formed extensive of each hole. The curved surface of the block 122 gives a focussing effect, and the electrons are directed to impinge on the substrate 121, their kinetic energy being converted into heat. Heat is conducted to the thermionic material 120 causing electrons to be emitted to produce ionization of the gas filling.

With reference to Fig. 25, a cathode member is formed by inserting a tungsten cylindrical rod 126 into a hollow tube 127 of an electrically insulating material, such as a ceramic or glass.

Fig. 26 illustrates another cathode member in which a tungsten rod 128 is inserted into a hollow metal tube 129, which may also be of tungsten, and a ceramic tube 130 is fitted over the metal tube 129. Any metal surfaces which would be exposed in use to a gas filling may then be covered with an insulating layer. By employing cathode members of this type no drilling is required, as it is with those previously described.

With reference to Fig. 27, a device in accordance with the invention comprises within an envelope (not shown) which also contains a gas filling, a cylindrical cathode member 131 having a stem portion 132 via which electrical connection is made to the cathode member 131. The cathode member 131 has a front surface 132 of circular transverse cross-section which is of a 'dished' or frusto-conical configuration, the front surface being inclined such that the length of the cathode member 131 along its axis Z–Z increases from its centre to its circumference. Other surface configuration may of course be employed if desired. A hole 133 is located in the centre of the front surface 132 and is coaxial with axis Z–Z of the cathode member 131. The surfaces of the cathode member 131 and the stem portion 132 are covered with a layer 134 of electrically insulating glass, and an anode member 135 surrounds and is coaxial with the stem portion 132.

When a voltage is applied between the cathode member 131 and the anode member 135 an electron beam is formed extensive of the hole 133. The beam is formed in a direction normal to the front surface 132. Since at the edge of the hole 133 the front surface 132 is inclined, components of the beam at points around the edge of the hole 133 are directed towards the axis Z–Z, such that the beam is brought to a focus F. The position of the focus F depends on the amount of inclination of the front surface. Such a device may thus produce a lens-like action, without the need for electron lens.

If the front surface is flat then a beam is produced which, although it is highly collimated, tends to diverge to some extent because of, for example, scattering processes. By using a front surface having a small degree of dishing, this tendency may be counteracted.

CLAIMS

1. Apparatus for forming an electron beam comprises, within an envelope, an anode member; a cathode member of electrically conductive material; and a gas filling, and wherein, except for part of a front surface of said cathode member, at least substantially the whole of the surface of said cathode member which would otherwise be exposed to the gas filling within said envelope is covered with an electrically insulating material, the whole arrangement being such that upon the application of a suitably high voltage between said anode member and said cathode member an electron beam is formed extensive in a direction away from said part of said front surface.

2. Apparatus for forming an electron beam comprising, within an envelope, an anode member; a cathode member of electrically conductive material and having a hole in a front surface thereof; and a gas filling, and wherein, except within said hole, at least substantially the whole of the surface of said cathode member which would otherwise be exposed to the gas filling within said envelope is covered with an electrically insulating material, the whole arrangement being such that upon the application of a suitably high voltage between said anode member and said cathode member an electron beam is formed extensive in a direction away from said hole.

3. Apparatus as claimed in claim 2 and wherein the anode member is located in front of the front surface of the cathode member.

4. Apparatus as claimed in claim 3 and including a control grid electrode through which in operation the electron beam passes.

5. Apparatus as claimed in claim 3 or 4 and including a plurality of elongate cathode members arranged in a grid formation, and a plurality of elongate anode members arranged in a grid formation with said grid of anode members superimposed over said grid of cathode members, but spaced therefrom, with said anode members in crossing relationship with said cathode members to form a matrix, each of said cathode members having a series of holes entering into its surface facing said grid of anode members and each of said anode members having a series of holes passing therethrough, with each hole in an anode member aligned with a hole in a different one of the cathode members, and all surfaces of said cathode members, except for the surfaces within said holes in said cathode members, which would otherwise be exposed to said gas filling are isolated therefrom by electrically insulating material, and the whole arrangement being such that by applying a high potential between one of said anode members and one of said cathode members an electron beam is formed at the crossing point of said last-mentioned two members, said electron beam being extensive in the space between the mouth of the hole in the cathode member at said crossing point and said anode member, said beam being arranged to penetrate through the corresponding hole in said addressed anode member.

6. Apparatus as claimed in claim 5 and wherein insulating material is interposed between said grid of cathode members and said grid of anode members, which insulating material has passages therethrough aligned with said holes in said cathode and anode members whereby to permit communication between one cathode hole and appropriate anode hole but impede communication between that cathode hole and any other anode hole.

7. Apparatus as claimed in claim 6 and wherein said interposed insulating material is provided in the form of a slab having holes extending between its major surfaces and forming the said passages.

8. Apparatus as claimed in claim 5, 6 or 7 and including a control grid electrode located on the inside of the grid of anode members other than that on which the grid of cathode members is located.

9. Apparatus as claimed in claim 5, 6 or 7 and wherein a control grid electrode is located between the grid of cathode members and the grid of anode members.

10. Apparatus as claimed in claim 9 when dependent on claim 6 or 7 and wherein the grid electrode is embedded in the interposed insulating material.

11. Apparatus as claimed in claim 2 and wherein the anode member is located to one side of the axis of the electron beam formed in operation.

12. Apparatus as claimed in claim 2 and wherein the anode member is located behind said front surface of the cathode member.

13. Apparatus as claimed in claim 12 and wherein the anode member is co-axial with

the cathode member.

14. Apparatus as claimed in claim 12 or 13 and including a grid electrode through which in operation the electron beam passes.

15. Apparatus as claimed in claim 12, 13, or 14 and wherein there are included a plurality of elongated anode members, each having apertures therein; and a plurality of stemmed cathode members, each having a hole in the front surface thereof and arranged such that its stem extends through one of said apertures, such that each anode member is located behind the front surfaces of cathode members whose stems pass through apertures in said anode member, whereby by applying a high potential between an anode member and one of the cathode members extending through an aperture therein an electron beam is formed extensive in a direction away from the hole in said one of the cathode members.

16. Apparatus as claimed in claim 15 and wherein a cathode member extending through an aperture in one anode member is electrically connected to another cathode member extending through an aperture in another anode member.

17. Apparatus as claimed in claim 16 and wherein a connector connecting two cathode members is spaced from the anode members by electrically insulating material.

18. Apparatus as claimed in any preceding claim and including a phosphor layer arranged so that when an electron beam is formed it impinges upon a spot upon said layer whereby to excite the same.

19. Apparatus as claimed in claim 18 and wherein said envelope has a portion formed as a faceplate on the interior of which said phosphor layer is provided.

20. A video signal reproducing apparatus including apparatus as claimed in any preceding claim.

21. Cathode ray tube apparatus comprising a plurality of elongate cathode members arranged in a grid information, a plurality of elongate anode members arranged in a grid formation with said grid of anode members superimposed over said grid of cathode members, but spaced therefrom, with said anode members in crossing relationship with said cathode members to form a matrix, each of said cathode members having a plurality of holes entering into its surface facing said grid of anode members and each of said anode members having a plurality of holes passing therethrough, with each hole in an anode member aligned with a hole in a different one of the cathode members and, superimposed over said grid of anode members on the side thereof remote from said grid of cathode members, a phosphor screen, the two grids being enclosed within an envelope having a gas filling from which all surfaces of said cathode members except for surfaces within said holes in said cathode members, which would otherwise be exposed to said gas filling are isolated therefrom by electrically insulating material and the whole arrangement being such that by applying a high potential between one of said anode members and one of said cathode members, an electron beam is formed at the crossing point of said last-mentioned two members, said electron beam being extensive in the space between the mouth of the hole in the cathode member at said crossing point and said anode member, said beam penetrating through the corresponding hole in said addressed anode member to impinge upon a spot upon said phosphor screen whereby to excite the same.

22. Apparatus as claimed in claim 2 and wherein the longitudinal axis of said hole is oblique to the normal of said front surface, and the electron beam is formed normal to said front surface at said hole.

23. Apparatus as claimed in claim 22 and including a plurality of holes in said front surface, at least one of said holes having its longitudinal axis oblique to the normal of said surface at the hole, such that upon the application of said suitability high voltage electron beams are formed extensive normal to said front surface at and in a direction away from respective holes.

24. Apparatus as claimed in claim 23 and wherein said front surface is curved.

25. Apparatus for forming electron beams comprising, within an envelope, an anode member; a cathode member of electrically conductive material having a front surface which is curved; and a gas filling, and wherein, except for a plurality of discrete parts of the said front surface, at least substantially the whole of the surface of said cathode member which would otherwise be exposed to the gas filling within said envelope is covered with an electrically insulating material, the whole arrangement being such that upon the application of a suitably high voltage between said anode member and said cathode member electron beams are formed extensive normal to said front surface at and in a direction away from respective parts.

26. Apparatus as claimed in claim 24 or 25 and wherein said front surface is curved such that the electron beams formed are focussed at a point.

27. Apparatus as claimed in claim 22, 23, 24, 25 or 26 and wherein said anode member co-axially surrounds and is behind said front surface of said cathode member.

28. Apparatus as claimed in claim 2 and including a layer of phosphor material on a viewable screen arranged such that upon the application of said suitably high voltage the electron beam impinges upon said phosphor layer and so excites the same.

29. Apparatus as claimed in claim 28 and wherein said anode member has an aperture therein and is located between said cathode

member and said phosphor layer, said electron beam being arranged to penetrate through said aperture.

30. Apparatus as claimed in claim 29 and wherein the hole in said cathode member and said aperture in said anode member are coaxially aligned.

31. Apparatus as claimed in claim 28, 29 or 30 and wherein said envelope has a portion formed as a faceplate upon the inner surface of which said phosphor layer is provided.

32. Apparatus as claimed in any of claims 28 to 31 including a modulating grid provided to affect the strength or intensity of the electron beam impinging upon said phosphor layer.

33. Apparatus as claimed in claim 32 and wherein said modulating grid is a perforated grid or gauze provided between said anode member and said phosphor layer.

34. Apparatus as claimed in claim 32 and wherein said modulating grid or gauze is provided between said anode member and said cathode member.

35. Apparatus as claimed in claim 32 and wherein said modulating grid comprises a ring grid provided within the mouth of said hole in said cathode member.

36. Apparatus as claimed in claim 35 and wherein an electrical connection for said grid is taken out, in insulated fashion, through said cathode member in a direction away from said anode member.

37. Apparatus as claimed in any of claims 28 to 36 wherein electrical connection to said cathode member is provided for by means of a first electrical connector connected to the base of said cathode member.

38. Apparatus as claimed in claim 37 and wherein said first electrical connector is preferably in the form of a hollow cylinder.

39. Apparatus as claimed in claim 38 and wherein, where said modulating grid comprises a ring grid provided within the mouth of said hole in said cathode member and an electrical connection for said grid is taken out, in insulated fashion, through said cathode member in a direction away from said anode member, a second electrical connector for said grid passes through said hollow cylinder.

40. Apparatus as claimed in any of claims 28 to 39 wherein a plurality of holes are provided in said cathode member and a corresponding plurality of holes are provided in said anode member.

41. Display apparatus comprising, within an envelope, a layer of phosphor material on a viewable screen; remote from said phosphor layer, a metallic cathode member having a hole formed in a front surface thereof; between said cathode member and said phosphor layer, an apertured anode electrode; and a gas filling, and wherein, except within said hole at least substantially the whole of the surface of said cathode member which would otherwise be exposed to the gas filling within said envelope is covered with an electrically insulating material, the whole arrangement being such that upon the application of a suitably high voltage between said anode member and said cathode member an electron beam is formed extensive in the space between the mouth of the hole in said cathode member and said anode member, and is arranged to penetrate through an aperture in said anode member to impinge upon said phosphor layer and so excite the same.

42. Thyratron apparatus comprising, within an envelope, an anode member; a cathode member of electrically conductive material and having a hole in a front surface thereof; and a gas filling, and wherein, except within said hole, at least substantially the whole of the surface of said cathode member which would otherwise be exposed to the gas filling within said envelope is covered with an electrically insulating material, the whole arrangement being such that upon the application of a suitably high voltage between said anode member and said cathode member an electron beam is formed extensive in a direction away from said hole.

43. Apparatus as claimed in claim 42 and wherein said cathode member has a plurality of holes in the front surface thereof, such that upon application of a suitably high voltage electron beams are formed extensive in a direction away from respective holes.

44. Apparatus as claimed in claim 43 and wherein said front surface is curved.

45. Apparatus as claimed in claim 44 and wherein at least one of said holes has its longitudinal axis oblique to the normal of said front surface at that hole.

46. Apparatus as claimed in any of claims 42 to 45 and including thermionic material arranged such that when an electron beam, or beams are formed they heat the same.

46. Apparatus as claimed in claim 42 and wherein, when said electron beam is formed it is arranged to ionize the gas filling in a localised region.

48. Apparatus as claimed in claim 47 and wherein the longitudinal axis of said hole is oblique to the normal of said front surface at the hole.

49. Apparatus as claimed in claim 2 and wherein said front surface is shaped to focus said electron beam.

50. Apparatus as claimed in claim 2 or 49 and wherein said front surface is substantially frusto-conical, the hole being centrally located.

51. Apparatus as claimed in any of claims 2 to 50 and wherein the or each hole in a cathode member is blind.

52. Apparatus as claimed in any of claims 2 to 51 and wherein the or each hole in a cathode member is of circular cross-section.

53. Apparatus as claimed in any of claims 2 to 52 and wherein the side wall and base surfaces of the or each hole in a cathode member is entirely free of a covering of electrically insulating material.

54. Apparatus as claimed in any preceding claim and wherein said insulating material insulating surfaces of said cathode member or plurality of cathode members from said gas filling is glass.

55. Apparatus as claimed in any preceding claim and wherein said cathode member, or plurality of cathode members,, is of Kovar.

56. Apparatus as claimed in any preceding claim and where said anode member, or plurality of anode members, is of Kovar.

57. Apparatus as claimed in any preceding claim, and wherein said envelope is of glass.

58. Apparatus as claimed in any preceding claim and wherein the said gas filling is helium.

59. Apparatus as claimed in any preceding claim and wherein said gas filling is at a pressure of between 0.5 and 2.5 mB.

60. Apparatus as claimed in any preceding claim and wherein the high voltage applied between the anode member and the cathode member is between 1 and 2.5 kV.

61. Apparatus as claimed in any preceding claim and wherein said cathode member is of thorated tungsten.

62. Apparatus substantially as illustrated in and described with reference to Fig. 1 of the accompanying drawings.

63. Apparatus substantially as illustrated in and described with reference to Fig. 2 of the accompanying drawings.

64. Apparatus substantially as illustrated in and described with reference to Fig. 3 of the accompanying drawings.

65. Apparatus substantially as illustrated in and described with reference to Fig. 6 of the accompanying drawings.

66. Apparatus substantially as illustrated in and described with reference to Figs. 7 to 12 of the accompanying drawings.

67. Apparatus substantially as illustrated in and described with reference to Figs. 13 to 15 of the accompanying drawings.

68. Apparatus substantially as illustrated in and described with reference to Fig. 16 of the accompanying drawings.

69. Apparatus substantially as illustrated in and described with reference to Fig. 17 of the accompanying drawings.

70. Apparatus substantially as illustrated in and described with reference to Figs. 18 and 19 of the accompanying drawings.

71. Apparatus substantially as illustrated in and described with reference to Fig. 20 of the accompanying drawings.

72. Apparatus substantially as illustrated in and described with reference to Fig. 21 of the accompanying drawings.

73. Apparatus substantially as illustrated in and described with reference to Fig. 22 of the accompanying drawings.

74. Apparatus substantially as illustrated in and described with reference to Fig. 23 of the accompanying drawings.

75. Apparatus substantially as illustrated in and described with reference to Figs. 24 of the accompanying drawings.

76. Apparatus substantially as illustrated in and described with reference to Fig. 25 of the accompanying drawings.

77. Apparatus substantially as illustrated in and described with reference to Fig. 26 of the accompanying drawings.

78. Apparatus substantially as illustrated in and described with reference to Fig. 27 of the accompanying drawings.

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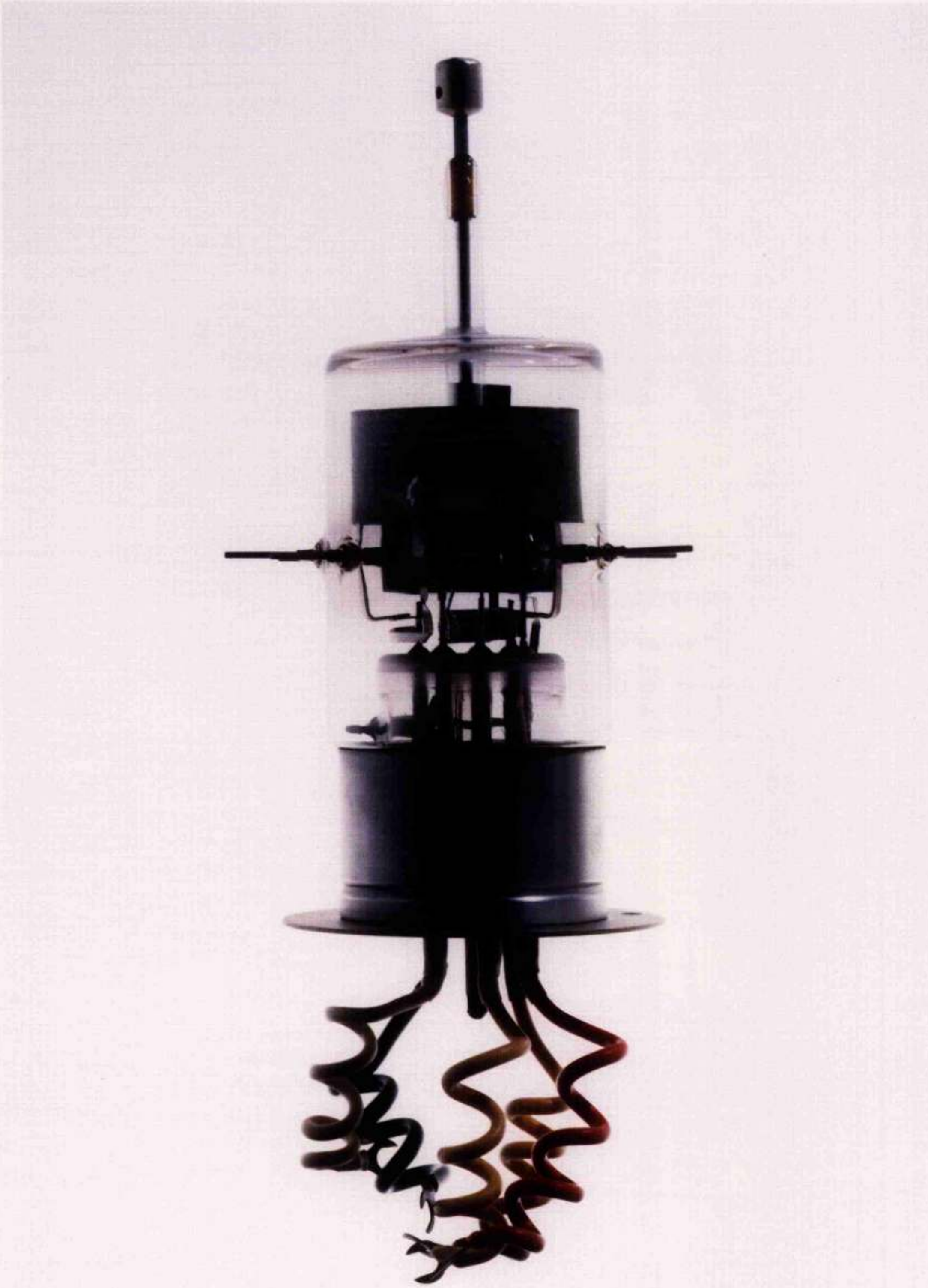
5.3 UK Patent GB 2169131B UK, Japan, USA

Gas discharge devices.

Conventional thyratrons make use of thermionic cathodes and thus require a minimum heating time of 5 minutes before operation can commence. Failure to observe this requirement results in a rapid and fatal degradation of the cathode's emissive properties. UK Patent GB 2169131B describes a means of providing a cold cathode in the form of a hollow metallic box pre–ionised by a multiplicity of electron beams. This box cathode has the ability to sustain electron emission for the main switch current from an instant start without suffering damage.

An embodiment of this concept is shown in Photograph 5.1 where the internal structures of the switch are contained in a glass envelope which is penetrated by nine glow discharge electron beam (GDEB) guns similar to that illustrated in Figure 3.1. The switch was processed as described in Appendix B, filled with deuterium to 0.5 torr and connected into a line–type modulator similar to that of Figure 4.9. The switch was able to hold–off 23 kV at the selected gas pressure. Referring to GB 2169131B Figure 1, a negative DC voltage of about 3 kV with respect to the cathode box 7 was applied to the GDEB guns 13. The cathode box 7 was observed to be filled with ionisation. It is worth noting that the GDEB guns were connected in parallel without the benefit of individual series ballast resistors on each gun. Current sharing between multiple, parallel

GDEBs is a feature of their operation. The switch was then triggered by the application of pulses from a trigger unit of the design in Figure 4.10 to the control grids 4 & 5 and the switch passed a 1 kA main current pulse at a pulse repetition frequency of 200 Hz.



Photograph 5.1

A switch employing glow discharge electron beam (GDEB) guns to pre-ionise a hollow cold-cathode.

(12) UK Patent (19) GB (11) 2 169 131 (13) B

(54) Title of Invention

Gas discharge devices

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GB 1583493
GB 1518360
GB 1334527
GB 1140374
GB 1094738
GB 1084908
GB 1060309
GB 0987371
GB 0913956

(58) Field of search
H1D
Selected US specifications from IPC sub-class H01J

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(51) INT CL⁴
H01J 17/46

(52) Domestic classification (Edition H):
H1D 12B47Y 12B6 12C 17D 1D12 1D15 1D1 1D4 1E3 1EY 1J2 1JY 31 C

(56) Documents cited

GB 1583493	GB 1140374	GB 1060309
GB 1518360	GB 1094738	GB 0987371
GB 1334527	GB 1084908	GB 0913956

(58) Field of search
H1D
Selected US specifications from IPC sub-class H01J

(54) Gas discharge devices

(57) A thyratron includes a glass envelope 1 containing a filling of hydrogen gas, an anode 2, screen grid 3, and control grids 4 and 5. An enclosure member is also contained within the envelope 1 comprises a side wall 7 and end walls 8 and 9 and encloses part of the gas filling. Nine rod members 13 are spaced equidistant around a circumference of the enclosure member and exterior to it. During operation of the thyratron an electron beam is emitted from a hole 14 in the surface facing the enclosure member of each rod 13. The electrons pass through apertures 12 in the side wall 7 and cause ionization of the gas filling contained within the enclosure member. The enclosure member and ionization combine to form a cathode, and a conduction path is established between the cathode and the anode 2.

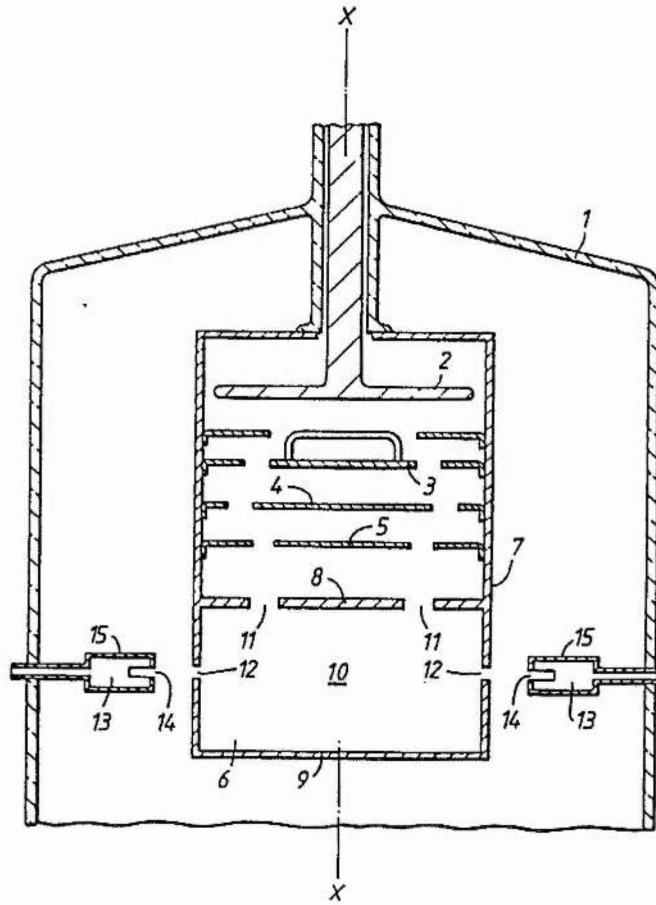

FIG. 1.

The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.

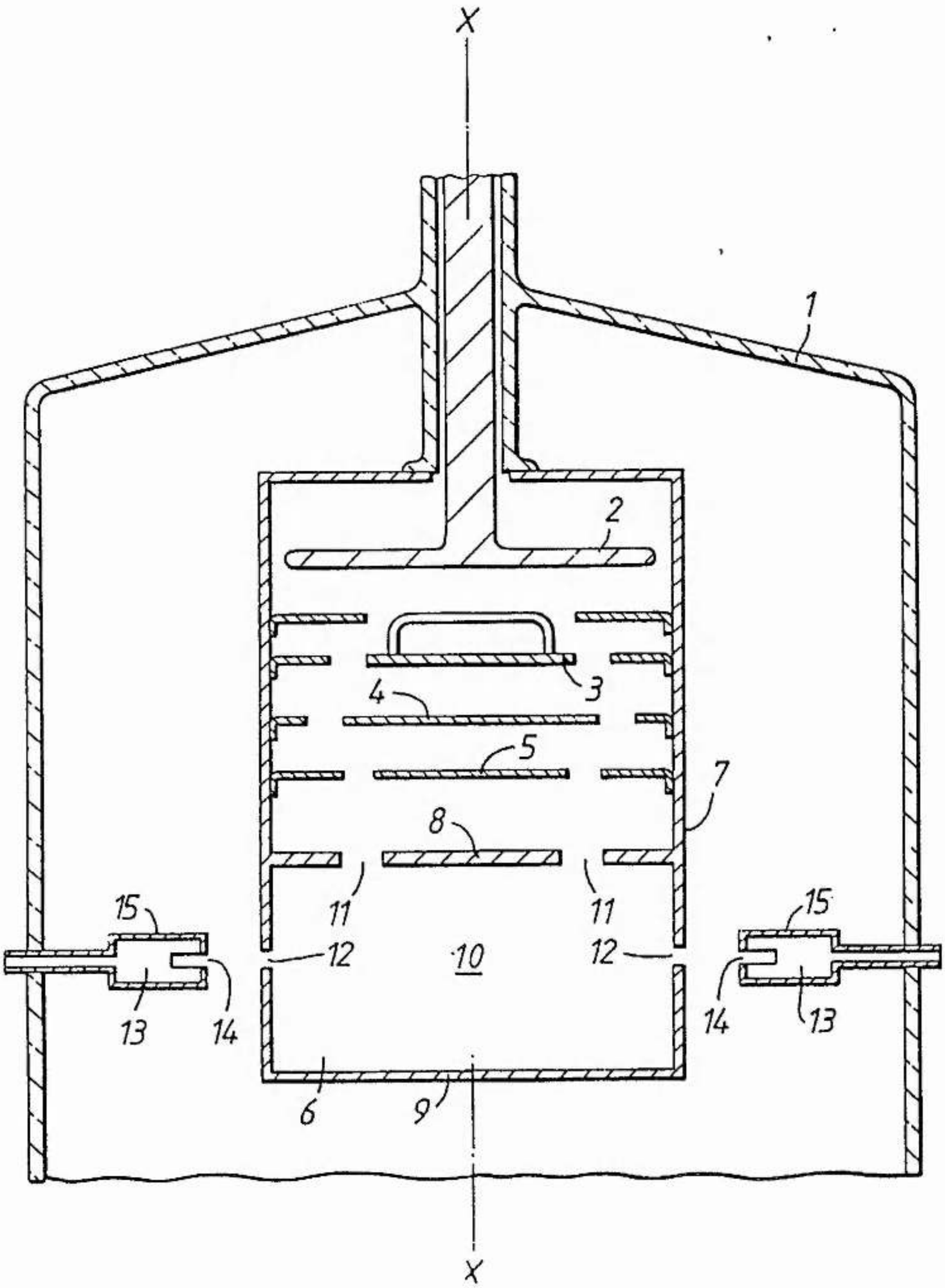

FIG. 1.

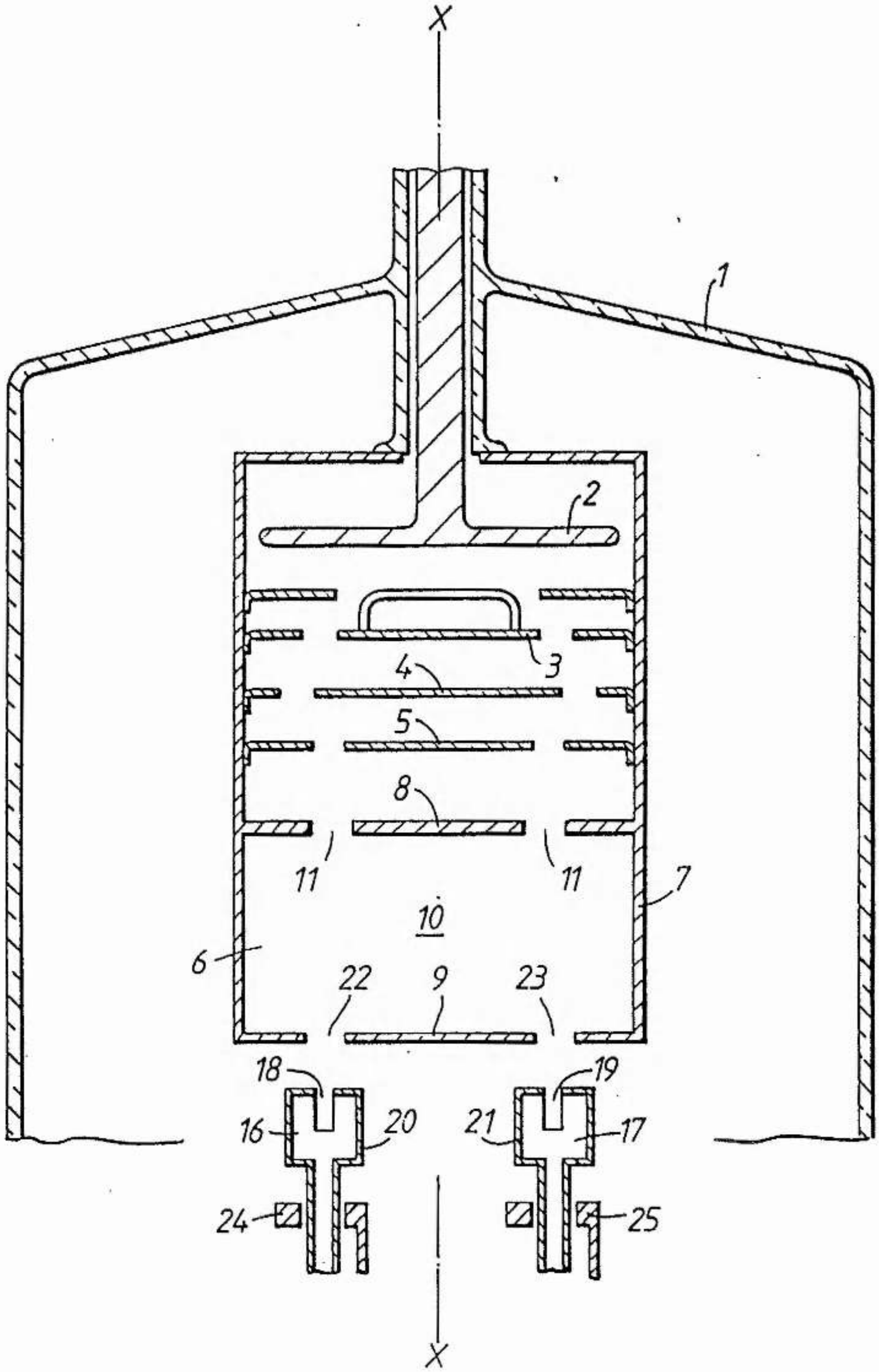

FIG. 2.

SPECIFICATION

Gas discharge devices

This invention relates to gas discharge devices and more particularly, but not exclusively to thyratrons.

A thyratron includes an anode and a cathode. The cathode may be what is termed a 'cold cathode', that is, one which emits electrons when it is subjected to a large enough electric field. Such cold cathodes have advantages over heated cathodes in that they become emitting as soon as a discharge voltage is established between the anode and the cathode. Also a cold cathode does not require a heater filament.

However, conventional cold cathodes suffer from a significant disadvantage when used in thyratrons or lasers in that the lifetime of a cold cathode is generally short, being of the order of 50 to 100 hours.

According to a first aspect of the invention there is provided a gas discharge device, including: an anode, an enclosure member having an aperture therein and substantially enclosing a volume of a gas filling, and means for producing ionization of the gas filling within the volume, such that during operation of the device the enclosure member and the ionization comprise a cathode, and a conduction path is established between the interior of the cathode and the anode through the aperture.

According to a second aspect of the invention there is provided a gas discharge device, including: an anode, an enclosure member having an aperture therein and substantially enclosing a volume of a gas filling, and means for introducing electrons into the volume to produce ionization of the gas filling within the volume such that during operation of the device the enclosure member and the ionization comprise a cathode, and a conduction path is established between the interior of the cathode and the anode through the aperture.

The invention may be advantageously used in any device requiring the production of a plasma to establish a discharge in a gas filled device, for example, it may be used in a laser or thyratron.

By employing the invention cathode lifetimes of the order of thousands of hours may be achieved.

Where electrons are introduced into the volume to produce ionization of the gas filling, they must have an energy sufficient to give a plasma of positive ions and electrons. The plasma causes electrons to be emitted by the inner surface of the enclosure member, and thus the ionization and enclosure member combine to act as an effective cathode.

Preferably electrons introduced into the volume are arranged to pass through said aperture. The ionization produced by the electrons after they have passed through the aperture may then be used to trigger the main discharge of the thyratron.

It is preferred that the means for introducing electrons comprises one or more electron emitting members outside of the enclosure member and each communicating with the said volume via a respective hole in an outside wall of the enclosure member.

Preferably the electrons introduced into the volume are produced by an electron emitting member having a hole in a surface thereof and wherein, except within the hole, at least substantially the whole of the surface of the electron emitting member is covered with an electrically insulating material, an electron beam being produced extensive of the hole when a suitably high voltage is applied between the electron emitting member and an associated anode. Such an electron emitting member is described in our co-pending UK patent applications Nos. 8333879, 8333880 and 8413791. The electron emitting member produces a beam of electrons which tends to be well collimated. This is an advantage in that the electron emitting member may be placed some distance from the enclosure member and the electron beam directed through a hole in the enclosure member to the volume. Thus the electron emitting member may be spaced from the volume in which ionization takes place and which may cause deterioration of the electron emitting member.

Preferably the enclosure member acts as an anode for the electron emitting member although a separate anode may be provided, for example, it might surround the electron emitting member and be placed behind the surface in which the hole is formed. Also it is preferred that a plurality of electron emitting members are included.

Preferably the gas filling is of hydrogen although deuterium or some other gas, or mixture of gases, may be employed. It is also preferred that the member is of molybdenum, although for example it could be of high purity nickel or of tungsten.

Preferably the member is integral with a support structure for another element, such as for example a control grid in a thyratron, giving added strength and robustness to the apparatus, although it may of course, be separate.

The device is advantageously a thyratron.

The invention is now further described by way of example with reference to the accompanying drawing in which:

Figure 1 is part of a longitudinal section of a thyratron in accordance with the invention; and

Figure 2 is part of a longitudinal section of another thyratron in accordance with the invention with like references being used for like parts.

Referring to Figure 1 a thyratron includes a glass envelope 1 (only part of which is shown) which contains a filling of hydrogen gas at a pressure of about 0.5 Torr. An anode 2, screen grid 3 and control grids 4 and 5 are also contained within the envelope 1 and are similar to those employed in a conventional thyratron.

A hollow cylindrical enclosure member having a height and diameter of about 50 mm and enclosing a volume 6, is also contained within the envelope 1, and consists of a side wall 7 and end walls 8 and 9 of molybdenum. The cylindrical enclosure member is co-axial with the longitudinal axis X-X of the thyratron, the screen grid 3, and control grids 4 and 5 lying between it and the anode 2. An annular aperture 11 is included in the end wall 8 which is nearest the control grid 5. The side wall 7 includes nine apertures 12 having a diameter of a few millimetres, only two of which are shown. The apertures 12 are spaced equidistant around a circumference of the side wall 7.

Nine electron emitting members in the form of cylindrical rods 13 of tungsten, again only two of which are shown, are arranged around the outside of the enclosure member and are also spaced equidistant around the circumference, each being associated with a respective aperture 12. Each rod 13 has a hole 14 in its front surface extending along its longitudinal axis which is perpendicular to the axis X-X of the thyratron. Each hole 14 is aligned with the aperture 12 associated with that rod 13. The whole surface of each rod 13 contained within the envelope 1 is coated with a glass layer 15, except for that part of the surface forming the base or wall of the hole 14.

In operation, the walls 7, 8 and 9 of the enclosure member are earthed and a positive potential is applied to the anode 2. When a thyratron is to become conducting a negative potential is applied to the rods 13, the enclosure member thus being at positive potential with respect to them. An electron beam then forms extensive of each hole 14 and in a direction away from it. The electron beams pass through the apertures 12 and enter the volume 6. These electrons cause ionization of the gas filling contained by the enclosure member to produce a plasma of positive ions and electrons. Thus the enclosure member and the ionization within the volume 6 combine to form a cathode 10. The main discharge then occurs when the thyratron is triggered into its conducting state.

The thyratron could be arranged such that the rods 13 are always maintained at negative potential to produce beams of electrons, and the main discharge is initiated by voltages of up to 5kV applied to the control grids 4 and 5.

An alternative form of operation is to pulse the rods 13 with a current of up to 500 A for up to 1.0 microsecond before a pulse is applied to the grids 4 and 5.

The cathode 10 formed by the enclosure member and the ionization is capable of sustaining curent pulses of 10-15 kA lasting from 10—15 microseconds.

With reference to Figure 2 a thyratron is shown which is similar to that of Figure 1. However, instead of having nine rods spaced around the circumference of the side wall 7, two cylindrical tungsten rods 16 and 17 are located adjacent the end wall 9. Each of the rods 16 and 17 has a hole 18 and 19 respectively in its front surface, and the surface of each rod, save for within the hole, is coated with a layer 20 and 21 respectively of glass. Each of the holes 18 and 19 is aligned with a respective aperture 22 and 23 in the end wall 9. Anode members 24 and 25 coaxially surround the rods 16 and 17 respectively and are located behind their front surfaces.

When a suitably high voltage is applied between the rods 16 and 17 and their respective anodes 24 and 25 electron beams are formed extensive of the holes 18 and 19 and penetrate via the apertures 22 and 23 into the volume 6 where the gas filling becomes ionized. The rods 16 and 17 are also aranged to be aligned with aperture 11 in the end wall 8 such that the electron beams penetrate therethrough. Thus ionization may also be produced within the region between the end wall 8 and control grid 5, and may be used to trigger the main thyratron discharge.

CLAIMS

1. A gas discharge device, including: an anode, an enclosure member having an aperture therein and substantially enclosing a volume of a gas filling, and means for producing ionization of the gas filling within the volume, such that during operation of the device the enclosure member and the ionization comprise a cathode, and a conduction path is established between the interior and the cathode and the anode through the aperture.

2. A gas discharge device, including: an anode, an enclosure member having an aperture therein and substantially enclosing a volume of a gas filling, and means for introducing electrons into the volume to produce ionization of the gas filling within the volume such that during operation of the device the enclosure member and the ionization comprise a cathode, and a conduction path is established between the interior of the cathode and the anode through the aperture.

3. A device as claimed in claim 2 and wherein electrons introduced into the volume are arranged to pass through said aperture.

4. A device as claimed in claim 2 or 3 and wherein the means for introducing electrons comprises one or more electron emitting members outside of the enclosure member and each communicating with the said volume via a respective hole in an outside wall of the

enclosure member.

5. A device as claimed in claim 2, 3 or 4 and wherein the electrons introduced into the volume are produced by an electron emitting member having a hole in a surface thereof and wherein, except within the hole, at least substantially the whole of the surface of the electron emitting member is covered with an electrically insulating material, electrons being produced extensive of the hole when a suitably high voltage is applied between the electron emitting member and an anode.

6. A device as claimed in claim 4 or 5 and wherein the enclosure member acts as an anode for the electron emitting member.

7. A device as claimed in claim 4, 5 or 6 and including a plurality of electron emitting members spaced equidistant around the enclosure member.

8. A device as claimed in any preceding claim and wherein the gas filling is hydrogen.

9. A device as claimed in any preceding claim and wherein the enclosure member is of molybdenum.

10. A device as claimed in any poreceding claim and wherein the enclosure member is integral with a support structure for another element.

11. A device as claimed in any preceding claim and wherein the gas filling is at a pressure of approximately 0.5 Torr.

12. A device as claimed in any preceding claim, and wherein the device is a thyratron.

13. A thyratron substantially as illustrated in and described with reference to Figure 1 of the accompanying drawings.

14. A thyratron substantially as illustrated in and described with reference to Figure 2 of the accompanying drawings.

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5.4 UK Patent GB 2191628B UK, Japan, USA

Electron beam apparatus.

The essence of this patent is a glow discharge electron beam (GDEB) whose power is increased by an electrode arrangement which forms the electron beams in a cascaded sequence. By arranging a coaxial series of electrodes so that they are alternately cathode and anode with respect to each other, the electron beam from the cathode maintains its coaxial path into the anode which is itself acting as a cathode for the next cylindrical electrode. Thus, the electron beams join sequentially and remain confined to the axis of the series of electrodes. Such beams have been found to excite Ar II states associated with the Ar II laser in prototype systems (Carman, 1986).

Reference.

Carman R.J., *DC glow discharge electron guns for the excitation of rare gases.*, Ph.D. Thesis, p 115, University of St. Andrews, (1986)

(12) UK Patent (19) GB (11) 2 191 628 (13) B

(54) Title of Invention

Electron beam apparatus

(51) INT CL^4; H01S 3/09

(21) Application No
8710444.4

(22) Date of filing
1 May 1987

(30) Priority data

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(32) 14 Jun 1986

(33) GB

(43) Application published
16 Dec 1987

(45) Patent published
17 Jan 1990

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(Edition J)
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(56) Documents cited
GB 2189074 A
GB 1390309 A
EP 0015297 A1
US 3543182 A

(58) Field of search

As for published application
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UK CL H1C H1D
INT CL^4 H01J H01S
updated as appropriate

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(12) UK Patent Application (19) GB (11) 2 191 628 (13) A

(43) Application published 16 Dec 1987

(21) Application No 8710444

(22) Date of filing 1 May 1987

(30) Priority data

(31) 8614541 (32) 14 Jun 1986 (33) GB

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(51) INT CL[4]
H01S 3/09

(52) Domestic classification (Edition I)
H1C 218 34Y 470 BX

(56) Documents cited
GB 1390309 US 3543182
EP A1 0015297

(58) Field of search
H1C
H1D
Selected US specifications from IPC sub-classes H01J
H01S

(54) Electron beam apparatus

(57) A laser arrangement includes electron beam apparatus comprising a plurality of electrodes 4, 5, 6 and 7 each of which has an aperture 8, 9, 10 and 11 therethrough. The apertures are aligned along the longitudinal axis X-X of an envelope 1 which surrounds them. The electrodes are electrically connected such that each is at a lower potential than an adjacent one. An electron beam is produced between the first electrode 4 and an adjacent electrode 5, and is accelerated along the axis, the electron current also increasing in magnitude. The electron beam produced is used to provide pumping power to a gas contained within the envelope 1 such that it acts as a laser active medium.

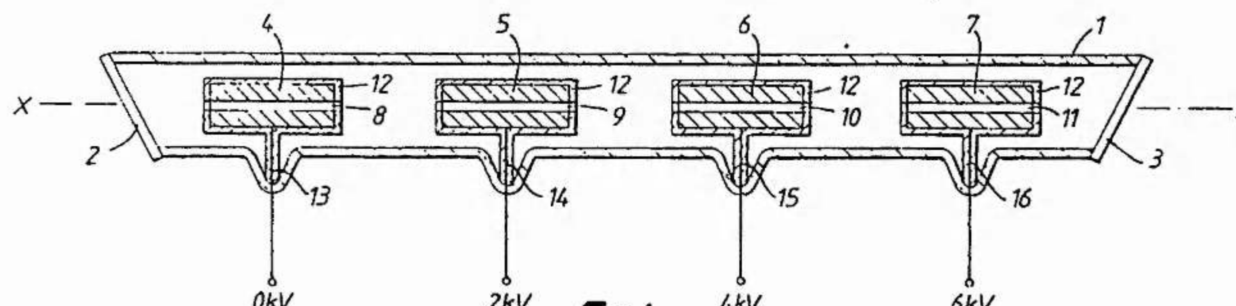

FIG.1.

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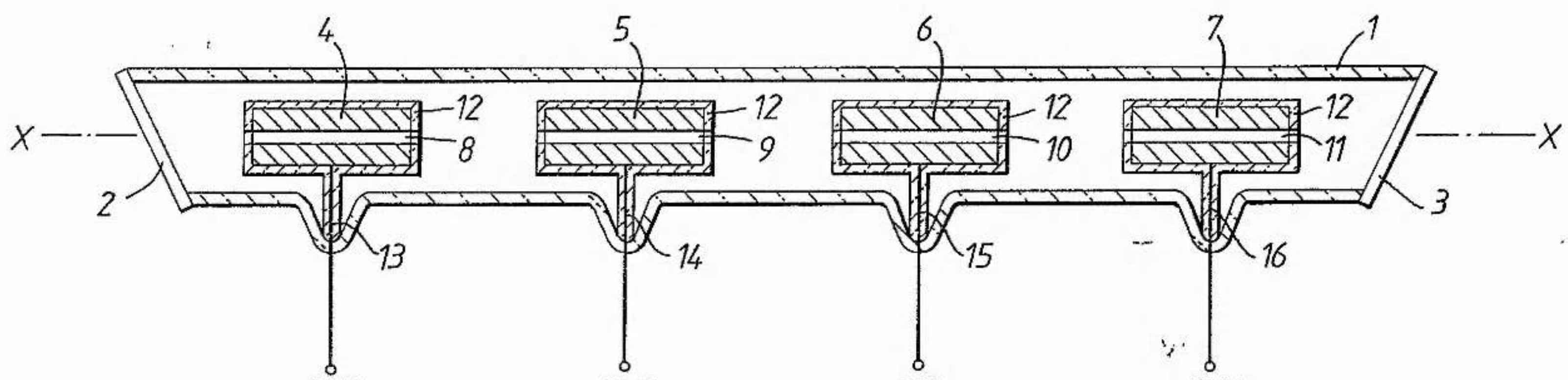

FIG.1.

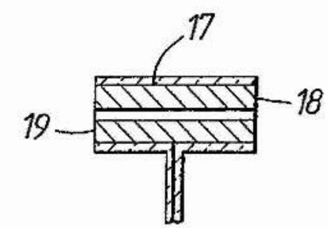

FIG.2.

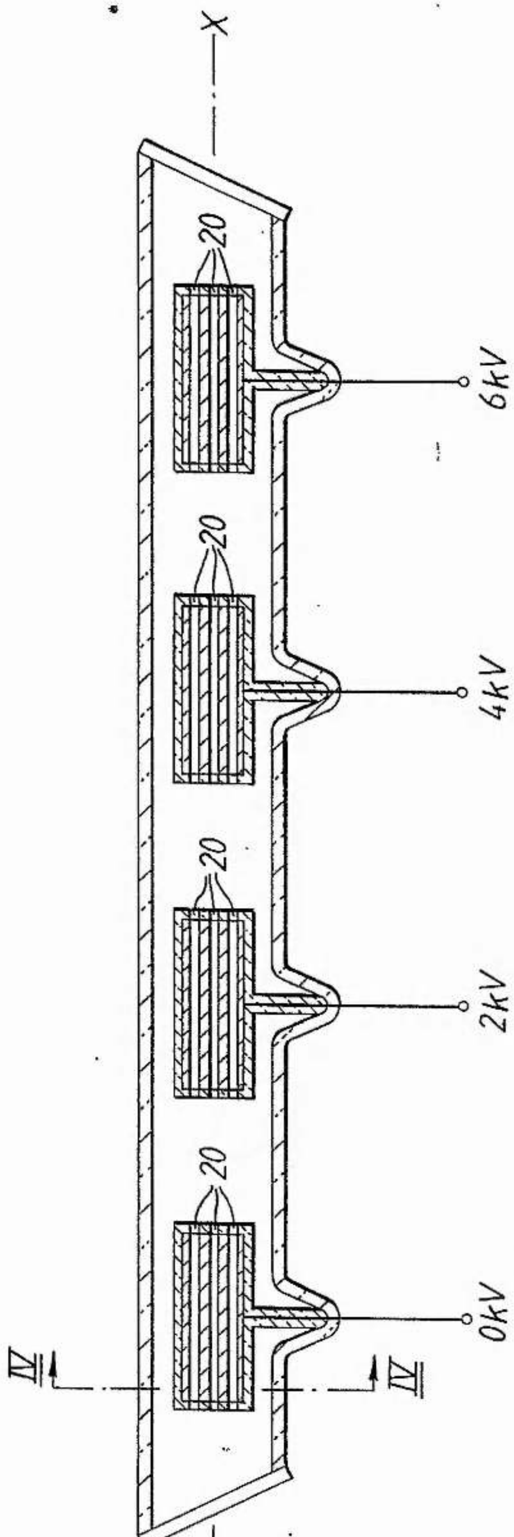

FIG. 3.

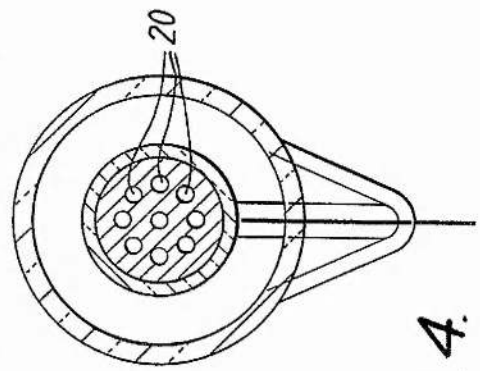

FIG. 4.

SPECIFICATION

Electron beam apparatus

This invention relates to electron beam apparatus and more particularly, but not exclusively, to laser apparatus which includes the use of an electron beam.

It is known, for example as described in our UK Patent Application, publication serial no. 2153140A, that an electron beam may be formed in a device comprising an anode and cathode arranged within a gas filled envelope, the cathode having a hole in a surface and, except for the area within the hole, being substantially covered by a layer of insulating material. An electron beam is obtained on application of a suitably high voltage between the anode and the cathode when a gas discharge is formed. The electron beam originates from within the hole and emerges from the hole in a direction which is normal to the metal surface of the cathode in which the hole is located.

According to this invention, there is provided electron beam apparatus comprising means for forming an electron beam; an electrode contained within a gas-filled envelope, said electrode having an aperture therethrough and, except within the aperture, being coated over substantially all its surface with electrically insulating material; and means for accelarating electrons of the beam through the aperture. Apparatus in accordance with the invention enables the energy of the electron beam and the magnitude of the beam current to be increased. Such apparatus is particularly useful therefore in devices such as for example lasers, x-ray sources, and in electron beam welding apparatus. The electrode tends to keep the electron beam well collimated, reducing dispersion and enabling a relatively long path length to be achieved.

Preferably, the means for forming an electron beam comprises, within the envelope, a cathode having a hole therein and, except within the hole, being coated over substantially all its surface with electrically insulating material; and an anode, the arrangement being such that when a suitably high voltage is applied between the cathode and the anode an electron beam is formed extensive in a direction away from said hole. Some means for forming an electron beam may be arranged to produce a well collimated, highly directional electron beam. It may be advantageous that the hole is an aperture which extends through the cathode from one face to another, but it could of course be closed or blind. Where the means for forming an electron beam includes a cathode and anode as mentioned above, the electrode may conveniently and advantageously be arranged to be the anode.

Alternatively, an arrangement for forming an electron beam may be used which is similar to that described above but in which the cathode is not coated with electrically insulating material. The anode is then spaced from the bare cathode surface by such a distance that there is substantially no discharge between them, except in the region of the hole, when the potential difference is applied between them. The spacing between the cathode and anode is appropriately chosen in accordance with Paschen's law, and depends on the gas pressure and voltage employed.

It is preferred that a plurality of electrodes are included, each having an aperture therethrough and being arranged such that the electron beam passes through each of the apertures in turn. In such an arrangement, some amplification occurs at each electrode, giving a larger resultant beam current than would be obtained from a single electrode. It is preferred that the electrodes are arranged such that the apertures are aligned, this being a particularly convenient arrangement. Preferably, for an adjacent pair of electrodes, the one which the electron beam is arranged to pass through first is at a lower potential than the other. Thus, where several electrodes are spaced apart along an axis, with their apertures being coaxially aligned, each is maintained at a higher potential than a preceding one, and thus acts as the means for accelarating electrons of the beam through the aperture of the preceding electrode. An increase in electron energy and electron current is obtained at each electrode. Since the electron beam is collimated as it emerges from each aperture, the total path length of the electron beam from the first electrode to the last may be made as long as desired, for example, a metre or more which is desirable in some applications of the apparatus. To obtain an electron beam over a substantial length in a gas would normally require that the beam be confined by a magnetic field of a long solenoid. Apparatus in accordance with the invention does not require a solenoid to obtain a long, well collimated electron beam.

The or each electrode may have more than one aperture therethrough, with respective electron beams being arranged to pass through respective apertures. This may prove particularly suitable in apparatus in which it is desired, for example, to direct a relatively large amount of energy from the electron beams within a given volume, since each beam may deliver substantially the same amount of energy as a single one would, or where it is required to irradiate a body or region over a relatively large area.

According to a feature of this invention, a laser arrangement includes apparatus in accordance with the invention, wherein the or an electron beam is arranged to provide pumping power to material which is arranged to form at least part of a laser active medium, and preferably, the envelope contains the electrodes and the material. Apparatus in accordance with the invention is particularly useful in a laser arrangement, since the apertures of the electrodes may be arranged along the optical axis of the laser, the electron beam then being created and directed through the region where it desired to produce the laser radiation. Where the or an electron beam is obtained by employing a cathode having a hole in a surface thereof, the hole advantageously passes through the cathode to present an unobstructed path through the apparatus to laser radiation.

The invention is now further described by way of example with reference to the accompanying drawings, in which:

Figure 1 is a schematic longitudinal section of a laser arrangement in accordance with the invention;

Figure 2 illustrates an alternative component of the apparatus of Figure 1; and

Figures 3 and *4* illustrate schematically in longitudinal and transverse section respectively another laser arrangement in accordance with the invention.

With reference to Figure 1, a laser arrangement includes a cylindrical ceramic envelope 1 having windows 2 and 3 at each end. Electrodes, only four of which 4, 5, 6 and 7 are shown, are spaced apart from one another along, and co-axially about, the longitudinal axis X-X, which is the optical axis of the laser. Each of the electrodes 4, 5, 6 and 7 is a metal cylinder having a cylindrical aperture 8, 9, 10 and 11 respectively therethrough, the apertures being aligned along the longitudinal axis X-X. Substantially the whole of the surface of each of the electrodes 4, 5, 6 and 7 is coated with a layer 12 of electrically insulating material, which may conveniently be for example, glass or ceramic. The walls of the apertures 8, 9, 10 and 11 are not coated with the electrically insulating material but are left bare. Each of the electrodes is connected to an electrical conductor 13, 14, 15 and 16 which passes out of the envelope via one of a plurality of side arms, and is also coated with electrically insulating material. The electrodes 8, 9, 10 and 11 are connected such that one end electrode 4 is maintained at a low potential and the other end electrode 7 is maintained at a higher potential, with intermediate electrodes being maintained at potentials lying between these two extremes, being arranged such that the electrode potentials progressively increase along the axis X-X. The envelope 1 also contains a gas which is to be pumped by the electron beam to form a laser active medium. A suitable gas may be argon, for example, at a pressure of several hundred millitor (tens of Pa). Typically, an electrode has a length of 3cm and a diameter of 1cm, with an aperture diameter of about 2mm. Adjacent electrodes may be spaced apart by 3cm. Thus for an electron beam length of about 1m fifteen of such electrodes would be required.

During operation of the arrangement shown in Figure 1, one end electrode 4 is maintained at earth potential, the adjacent electrode 5 at a potential of 2kV, the next at 2kV higher and so on. The difference in potential between the end electrode 4 and the adjacent electrode 5 is large enough to cause an electron beam to be formed extensive in a direction away from the aperture 8 from the electrode 4, the adjacent electrode 5 acting as an anode. The electron beam is accelarated through the aperture 9 of the electrode 5 because of the potential difference wich exists between the electrode and the adjacent electrode 6. As the electron beam is accelerated through the aperture 9, additional electrons from the surface of the aperture 9 add to the beam and the electron beam current is thereby increased. The increase in electron beam current also occurs at subsequent electrodes to give a larger beam current at the final electrode 7 than that which is produced at the first electrode 4.

The amplified electron beam current provides pumping power to the gas contained within the envelope 1 and may be made great enough to cause laser action to be initiated along the axis X-X.

With reference to Figure 2, although each of the electrodes 8, 9, 10 and 11 of the arrangement shown in Figure 1 is coated over all its surfaces with electrically insulated material, except for the surface of the hole, only the surface 16 parallel to the axis may be coated to provide the insulating material over substantially all its surfaces, leaving the ends 18 and 19 free of electrically insulating material.

With reference to Figures 3 and 4, a laser arrangement is similar to that described with reference to Figure 1, except that in this case each electrode includes a plurality of apertures 20 passing from one of its surfaces to the other. This enables increased power to be delivered to the gas contained within the envelope and thus aids in creating laser action.

CLAIMS

1. Electron beam apparatus comprising means for forming an electron beam; an electrode within a gas-filled envelope, said electrode having an aperture therethrough and, except within the aperture, being coated over substantially all its surface with electrically insulating material; and means for accelerating electrons of the beam through the aperture.

2. Apparatus as claimed in claim 1, and wherein the means for forming an electron beams comprises, within the envelope, a cathode having a hole therein and, except within the hole, being coated over substantially all its surface with electrically insulating material, and an anode, the arrangement being such that when a suitably high voltage is applied between the cathode and the anode, an electron beam is formed extensive in a direction away from said hole.

3. Apparatus as claimed in claim 2, and wherein said hole is an aperture extending through the cathode from one face to another.

4. Apparatus as claimed in claim 2 or 3 and wherein the said electrode is arranged to act as the anode.

5. Apparatus as claimed in any preceding claim and including a plurality of electrodes, each having an aperture therethrough and, except within the aperture, being coated over substantially all its surface with electrically insulating material, the electrodes being arranged such that the electron beam passes through each of them in turn.

6. Apparatus as claimed in claim 5, and wherein the electrodes are arranged such that the apertures are aligned along the longitudinal axis of the envelope.

7. Apparatus as claimed in claim 5 or 6 and wherein an adjacent pair of electrodes are arranged such that that which the electron beam passes through first is at a lower potential than the other.

8. Apparatus as claimed in any preceding claim

and wherein the, or each, electrode includes a plurality of apertures therethrough and respective electron beams being arranged to pass through respective apertures.

9. A laser arrangement including apparatus as claimed in any preceding claim and wherein the or an electron beam is arranged to provide pumping power for a material which is arranged to form at least part of a laser active medium.

10. An arrangement is claimed in claim 9, and wherein the envelope contains the electrodes and the laser active medium.

11. Apparatus substantially as illustrated in and described with reference to Figure 1 of the accompanying drawings.

12. Apparatus substantially as illustrated in and described with reference to Figures 3 and 4 of the accompanying drawings.

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5.5 UK Patent GB 2194673B

UK, Japan, USA,
Europe, Australia

Apparatus for forming an electron beam sheet.

This patent describes how an electron beam in the form of a sheet can be produced by a cathode slot of suitable dimensions in a gas discharge at low pressure. The advantage of the sheet form is that the pre–ionisation density is higher than that provided by a single cylindrical beam. A further benefit is that the sheet generating electrodes can be conveniently stacked as shown in GB 2194673B Figure 3 to provide pre–ionisation of an extensive volume. The generation of the electron beam sheet has been demonstrated in a test device and sheet generating electrodes have been incorporated in a cold–cathode gas switch.

(12) UK Patent (19) GB (11) 2 194 673 (13) B

(54) Title of Invention

Apparatus for forming an electron beam sheet

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D1S3 D1S4 D12B47Y D12B6
D12C D17AY D17A3 D17B D17D
D31 D9CY D9C1A D9C1Y
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H1C C34Y C471

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GB 0456776 A

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H01J 1/02 17/06 H01S 3/03

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H1C 34Y 471 BB

(56) Documents cited
GB A 2170949 GB A 2150742 GB 1121115
GB A 2169131 GB 1520935 GB 0456776
GB A 2153140 GB 1292016

(58) Field of search
H1D
H1C
Selected US specifications from IPC sub-classes H01J H01S

(54) Apparatus for forming an electron beam sheet

(57) Discharge apparatus, eg a thyratron or a gas laser, includes, in a gas-filled envelope, a metal cathode member having an elongate slot in a surface thereof and an anode member such that applying a large potential difference therebetween causes electron emission in the form of a beam sheet from the length of the slot. In the thyratron of Fig. 1, cathode member 5 is annular with an annular slot 6 and is mounted in the envelope wall adjacent a grid 4 between main cathode 2 and anode 1. By applying a few kilovolts between the cathode 5 and grid 4 an electron beam sheet is produced across the width of the thyratron causing ionisation which establishes the main discharge current. A further anode member (12, Fig. 2, not shown) forming part of the envelope wall may be located between the slotted cathode member and the main cathode. In the thyratron of Fig. 3 (not shown) a plurality of slotted cathodes together with a further cathode having a plurality of slots are provided.

In the gas laser of Fig. 4 ceramic envelope tube 25 contains cylindrical cathode member 24 being a plurality of longitudinal slots 26, a millimetre or so wide, which are aligned with the rod anode member 27 along the longitudinal axis.

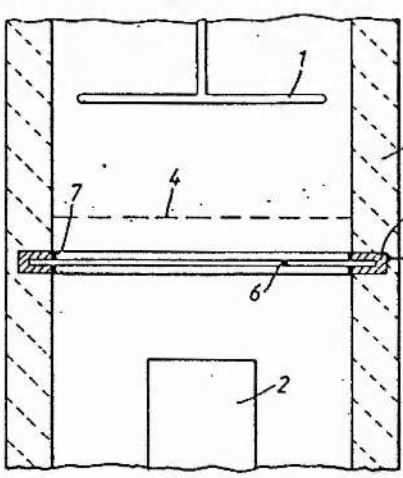

FIG. 1.

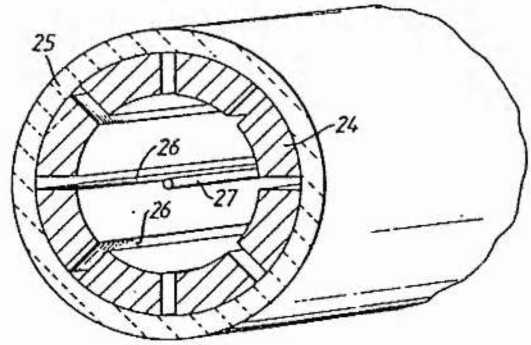

FIG. 4.

The drawings originally filed were informal and the print here reproduced is taken from a later filed formal copy.

1/2

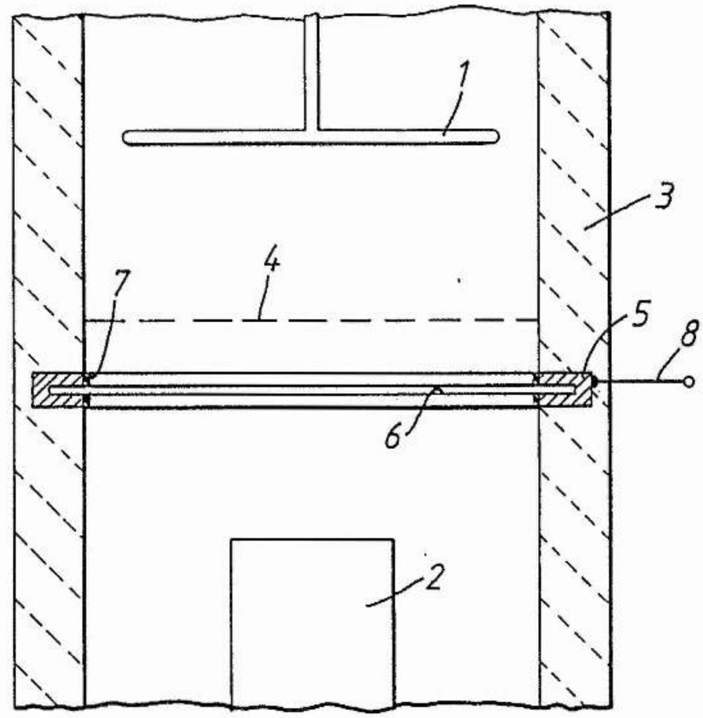

FIG. 1.

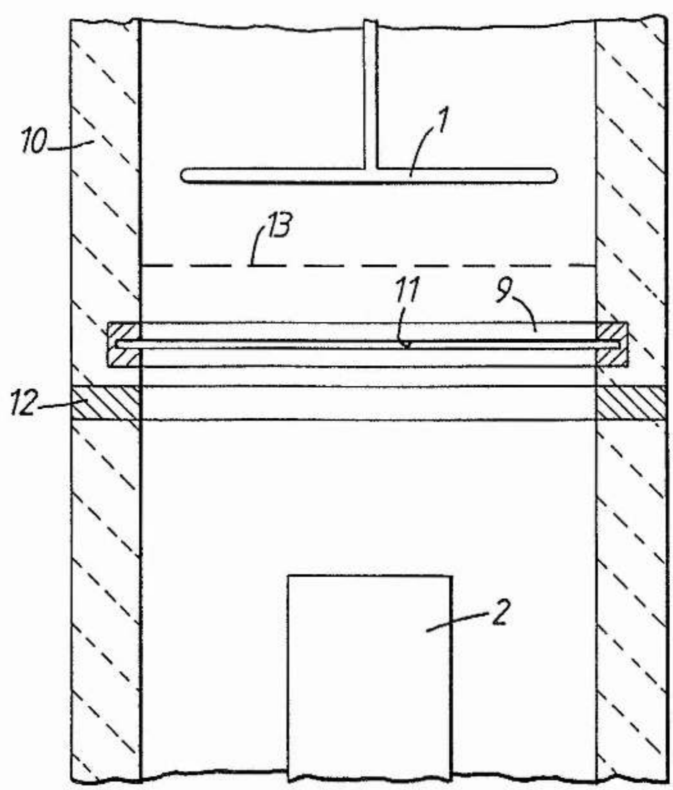

FIG. 2.

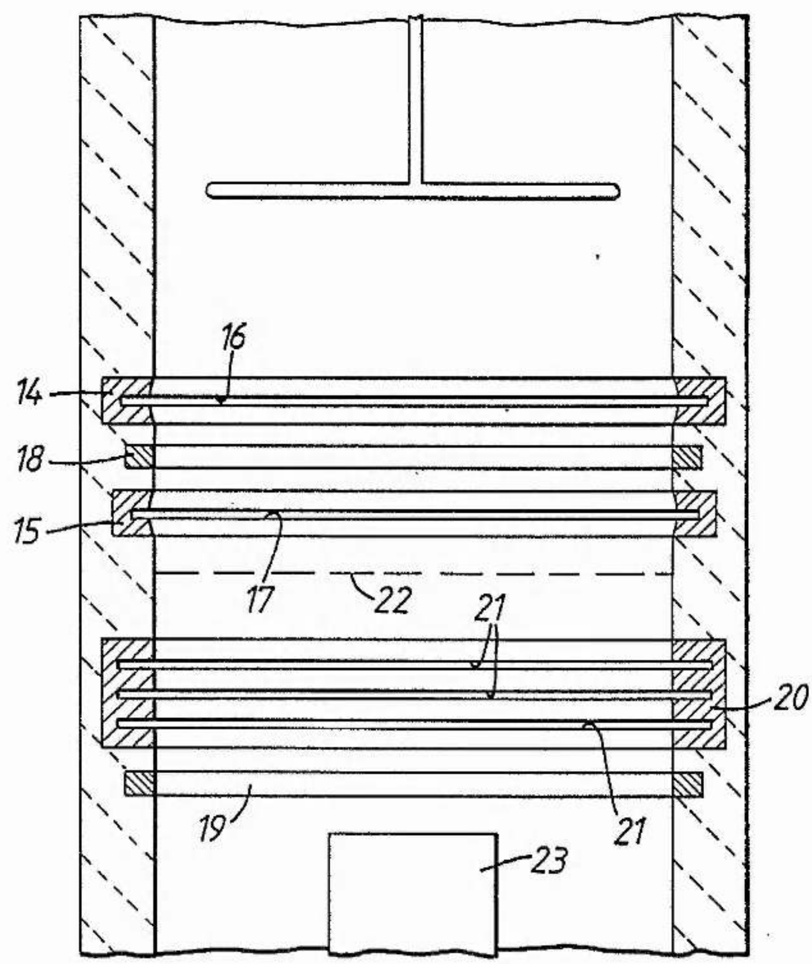

FIG. 3.

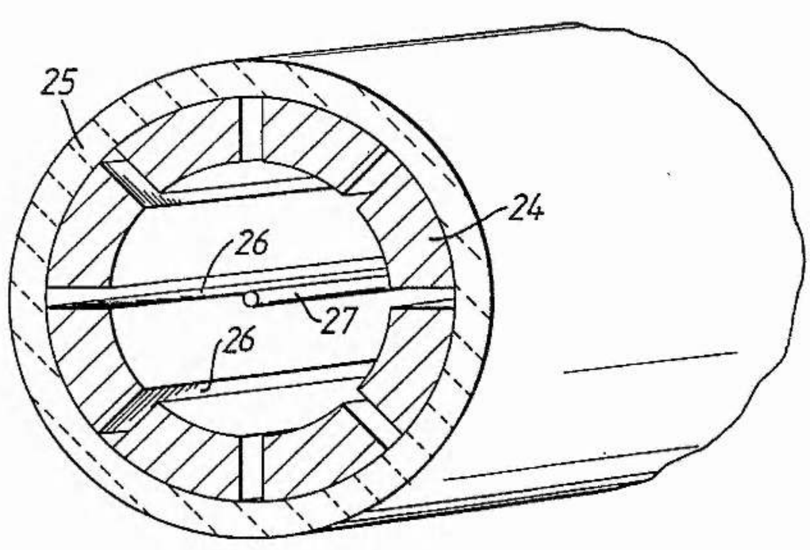

FIG. 4.

SPECIFICATION

Apparatus for forming an electron beam sheet

This invention relates to apparatus for forming an electron beam, and more particularly for forming an electron beam sheet which extends over a relatively large region.

According to this invention, there is provided apparatus for forming an electron beam sheet comprising a metal cathode member having an elongate slot in a surface thereof and an anode member the cathode and anode members being arranged within a gas-filled envelope, and the arrangement being such that on application of a suitably large potential difference between the anode and cathode members an electron beam sheet is formed extensive in a direction away from the slot. By "electron beam sheet" it is meant that the electron beam is produced along substantially the whole of the length of the slot and extends outwards from it. The potential difference required to obtain the electron beam sheet depends on the particular arrangement employed and is typically a few kilovolts. The electron beam sheet is produced as a result of gas discharge processes, in which the walls of the slot are bombarded by ions produced on application of the large potential difference, causing secondary emission of electrons from the slot surfaces which add to the beam sheet. The electron beam sheet obtained is highly collimated, and, above a certain threshold current, its width and length are determined by the width and length of the slot. The direction in which the electron beam sheet is formed is determined by the configuration of the cathode member surface in which the slot is located, the sheet being produced normal to the surface of the cathode member at the slot. Some degree of focusing may be obtained by curving the surface in which the slot is located. Substantially all surfaces of the cathode member may be coated with a layer of electrically insulating material, except within the slot, since this tends to enable a larger electron beam sheet current density to be obtained for a given current than when such an insulating layer is not employed.

In a thyratron in accordance with the invention, the anode member may be arranged to be the main cathode itself, or one of the thyratron grids, or another electrode included specifically for that purpose.

The slot may be any convenient configuration for example it may be helical, but it is preferred for many applications that the slot be arcuate. It may be advantageous that the slot is continuous, that is, that it has no ends, for example it may be circular. The surface configuration of the cathode member around the slot may be chosen such that the electron beam sheet is formed in a substantially single plane, or it could be made conical, for example. Where the electron beam sheet is arranged to extend in a single plane it may be arranged to extend substantially continuously over an area defined by the slot, such that where the slot is circular, the electron beam sheet is produced over substantially all the area surrounded by the slot.

Advantageously, for some applications a plurality of slots are included in the apparatus. An electron beam sheet is then produced extensive of each of the slots, and each electron beam sheet has an energy and magnitude which is substantially unaffected by the presence of the others. Thus the total energy available may be increased over that available when only one slot is included in the apparatus.

According to a first feature of the invention, a thyratron arrangement includes apparatus in accordance with the invention, wherein the electron beam sheet is arranged to produce ionisation within the thyratron. The electron beam sheet may then be used to trigger the thyratron into the conducting state. Preferably a control grid electrode is included in the thyratron, being arranged between the main anode and main cathode, and the electron beam sheet is arranged to be directed into the region of the grid apertures.

Advantageously, the electron beam sheet may be directed so as to produce uniform ionisation over substantially all of a cross-sectional area between the thyratron main anode and cathode, thus reducing jitter and rise time of the main discharge current between the main cathode and anode.

The electron beam sheet may advantageously be arranged to produce a primary discharge between a cathode and a grid within the thyratron, prior to the thyratron conducting its main current. More than one cathode member may be included, for example one may be used to produce a primary discharge and another arranged to trigger the thyratron.

Advantageously, the anode member may form part of the wall of the thyratron, and one anode member may be associated with more than one slot.

According to a second feature of the invention, a laser arrangement includes apparatus in accordance with the invention, wherein the electron beam is arranged to provide pumping power to a material which is arranged to form part at least of a laser active medium.

Some ways in which the invention may be performed are now further described by way of example with reference to the accompanying drawings in which:

Figures 1, 2 and 3 are schematic sectional views of respective thyratron arrangements in accordance with the invention; and

Figure 4 schematically illustrates a laser arrangement in accordance with the invention.

With reference to Figure 1, a thyratron arrangement includes a thyratron anode 1 and a main cathode 2 located within a ceramic envelope or wall 3, being spaced apart from one another and having a control grid electrode 4 located between them. The envelope 3 also contains a hydrogen gas filling at a typical thyratron pressure, say a fraction of a torr or so. A metallic cathode member 5 is located between the grid 4 and the cathode 2 and comprises a metallic ring set into the thyratron wall 3. A slot 6 is included in the front surface of the cathode member 5 and extends continuously and circumferentially around the inside of the cathode member 5. Most of the cathode member 5 is surrounded by the envelope 3 and a layer 7 of electrically insulating material is laid down on its front surface to insulate the metallic cathode member 5 from the gas filling, except for within the slot 6, the surfaces of which are bare of insulating material. An electrical lead 8 enables the cathode 5 to be attached to a source of suitable potential.

The grid 4 is maintained at a negative potential to prevent breakdown and conduction between the anode 1 and main cathode 2 of the thyratron during the hold-off period. When it is desired to trigger the thyratron into conduction, a relatively large positive potential of a few kilovolts is applied to the grid 4, resulting in a electron beam sheet being produced along the length of the slot 6 of the cathode member 5 and across the width of the thyratron. Thus ionisation is produced and a main discharge current is established between the anode 1 and main cathode 2.

With reference to Figure 2, in another thyratron arrangement a cathode member 9 is located in the envelope wall 10 and has a slot 11 in the surface thereof which faces the interior of the thyratron. In this embodiment, no electrically insulating material covers its front surface. An anode member 12 is located between the cathode member 9, and the main cathode 2. A control grid 13 is positioned between the main anode 1 and the cathode member 9. During operation, a potential difference is established between the anode member 12 and the cathode member 9 such that an electron beam sheet is produced extensive of the slot 11. The resulting ionization acts as a primary discharge, so that when a trigger potential is applied to the control grid 13, the main discharge current is established quickly and with low jitter.

Figure 3 illustrates another thyratron arrangement, in which two cathode members 14 and 15 are included having slots 16 and 17 respectively, and which are included to provide triggering of the thyratron when desired. In this embodiment the anode member 18 is located between the two cathode members 14 and 15. A further anode member 19 is also included in the arrangement adjacent a cathode member 20, which has a plurality of parallel slots 21 around its circumference. Prior to triggering the main thyratron discharge current, a potential difference is applied between the cathode member 20 and anode member 19 to produce an electron beam sheet extensive of each of the slots 21 in the region between the grid 22 and the thyratron main cathode 23. Thus a primary discharge is obtained, which reduces jitter and decreases the main current rise time when current conduction through the thyratron is required. The surfaces of the triggering cathode members 14 and 15 are curved to provide some focusing of the electron beam sheets.

With reference to Figure 4, a laser arrangement includes a cylindrical cathode member 24 which is surrounded by a ceramic envelope tube 25 and includes a plurality of slots 26 which each have a width of a millimetre or so and which are aligned with the longitudinal axis of the tube 25. A rod anode member 27 is located along the longitudinal axis of the tube 25. Windows (not shown) are included at each end of the tube 25. The tube 25 and cathode member 24 contain a gas or vapour at a pressure of a fraction of a torr or so, such that when a suitably high potential difference of a few kilovolts is applied between the anode member 27 and cathode member 24 a plurality of electron beam sheets are produced extensive of the slots 26. The electron beam sheets cause excitation of the gas filling, enabling laser action to be achieved.

CLAIMS

1. Apparatus for forming an electron beam sheet comprising a metal cathode member having an elongate slot in a surface thereof and an anode member, the cathode and anode members being arranged within a gas-filled envelope, and the arrangement being such that on application of a suitably large potential difference between the anode and cathode members, an electron beam sheet is formed extensive in a direction away from the slot.

2. Apparatus as claimed in claim 1 and wherein the slot is arcuate.

3. Apparatus as claimed in claim 2 and wherein the slot is continuous.

4. Apparatus as claimed in claim 1, 2 or 3 and wherein the electron beam sheet is arranged to extend substantially continuously over an area defined by the slot.

5. Apparatus as claimed in claim 1, 2, 3 or 4 and wherein the surface of the cathode member in which the slot is located is curved so as to focus the electron beam sheet.

6. Apparatus as claimed in any preceding claim and wherein the anode member is arranged to be substantially parallel to, and of the same length as, the slot.

7. Apparatus as claimed in any preceding claim and wherein a plurality of elongate slots are included in the surface of the cathode member, such that on application of a suitably

large potential difference between the anode and cathode members, respective electron beam sheets are formed extensive of each slot.

8. A thyratron arrangement including apparatus as claimed in any preceding claim and wherein the or an electron beam sheet is arranged to produce ionisation within the thyratron.

9. An arrangement as claimed in claim 8 and wherein production of the or an electron beam sheet is arranged to trigger the thyratron into conduction.

10. An arrangement as claimed in claim 9 and including a control grid electrode, the or an electron beam sheet being arranged to be produced in the region of an aperture of the said grid.

11. An arrangement as claimed in claim 8 and wherein the or an electron beam sheet is arranged to provide a primary discharge within the thyratron prior to conduction of a main discharge current.

12. An arrangement as claimed in any of claims 8 to 11 and wherein the or a slot is located circumferentially around the inside of the thyratron envelope.

13. An arrangement as claimed in any of claims 8 to 12 and wherein the anode member forms part of the wall of the thyratron.

14. A laser arrangement including apparatus as claimed in any of claims 1 to 7 and wherein the electron beam sheet is arranged to provide pumping power to a material which is to form part at least of the active laser medium.

15. A thyratron arrangement substantially as illustrated in and described with reference to Figure 1, 2 or 3 of the accompanying drawings.

16. A laser arrangement substantially as described and illustrated in Figure 4 of the accompanying drawings.

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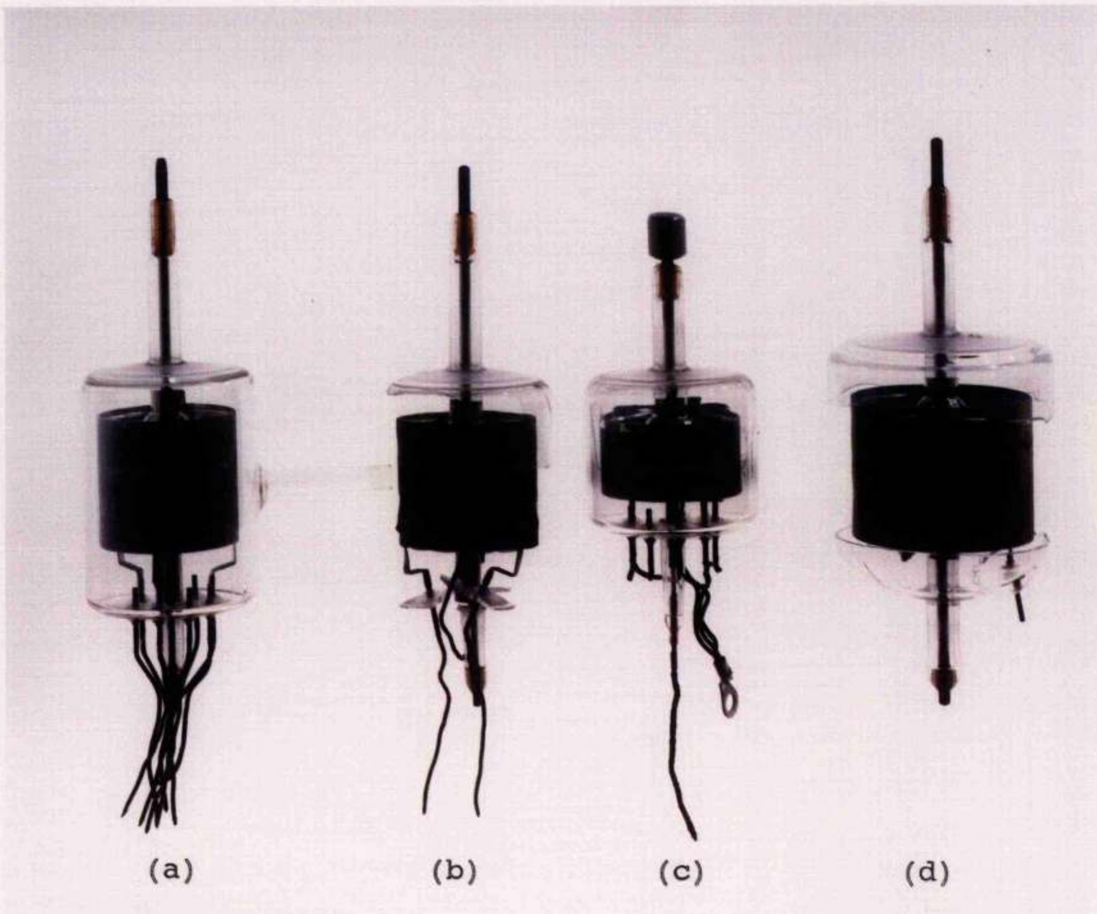
5.6 UK Patent GB 2194674B UK, Japan, USA, Europe

Gas discharge devices.

The switches described in this patent use the GDEB gun of Chapter 3 to project electrons directly into the high voltage region of the switch and these electrons initiate main current conduction without the use of subsidiary trigger grids. The absence of trigger grids represents a simplification in the construction of the switch. A proposed advantage of the switch is that the GDEB guns can be placed behind baffles in the cathode box where they would be substantially protected from any transient voltage that might arise during the initiation of main current conduction. In thyratrons, such a voltage appearing on a trigger grid is known as a grid spike and it can be severe enough to cause arcing at the grid insulator or destruction of the trigger circuit components.

In arrangements where the electron beam passes through the cathode box, the functions of cathode box pre–ionisation and triggering are combined. In particular, the switch shown in GB 2194674B Figure 3 allows a staggered–slot baffle to be used with an annular or cylindrical electron beam parallel to the switch axis by placing a metallic surface in the baffle slots so that primary and secondary electrons from the metal surface are directed into the high voltage region.

Photograph 5.2 shows a number of test devices which were constructed to establish the principle of direct triggering of the switch by the electron beam. In order to simplify their construction, the devices employed GDEB guns producing electron beams parallel to the switch axis and double layer baffles with holes or slots to allow passage of the electron beam into the high voltage region as shown in Figure 5.1. Tests established that the e–beam provides an effective trigger for low pressure gas switches.



Photograph 5.2

Switches employing a cylindrical or annular glow discharge electron beam (GDEB) gun to trigger anode conduction directly.

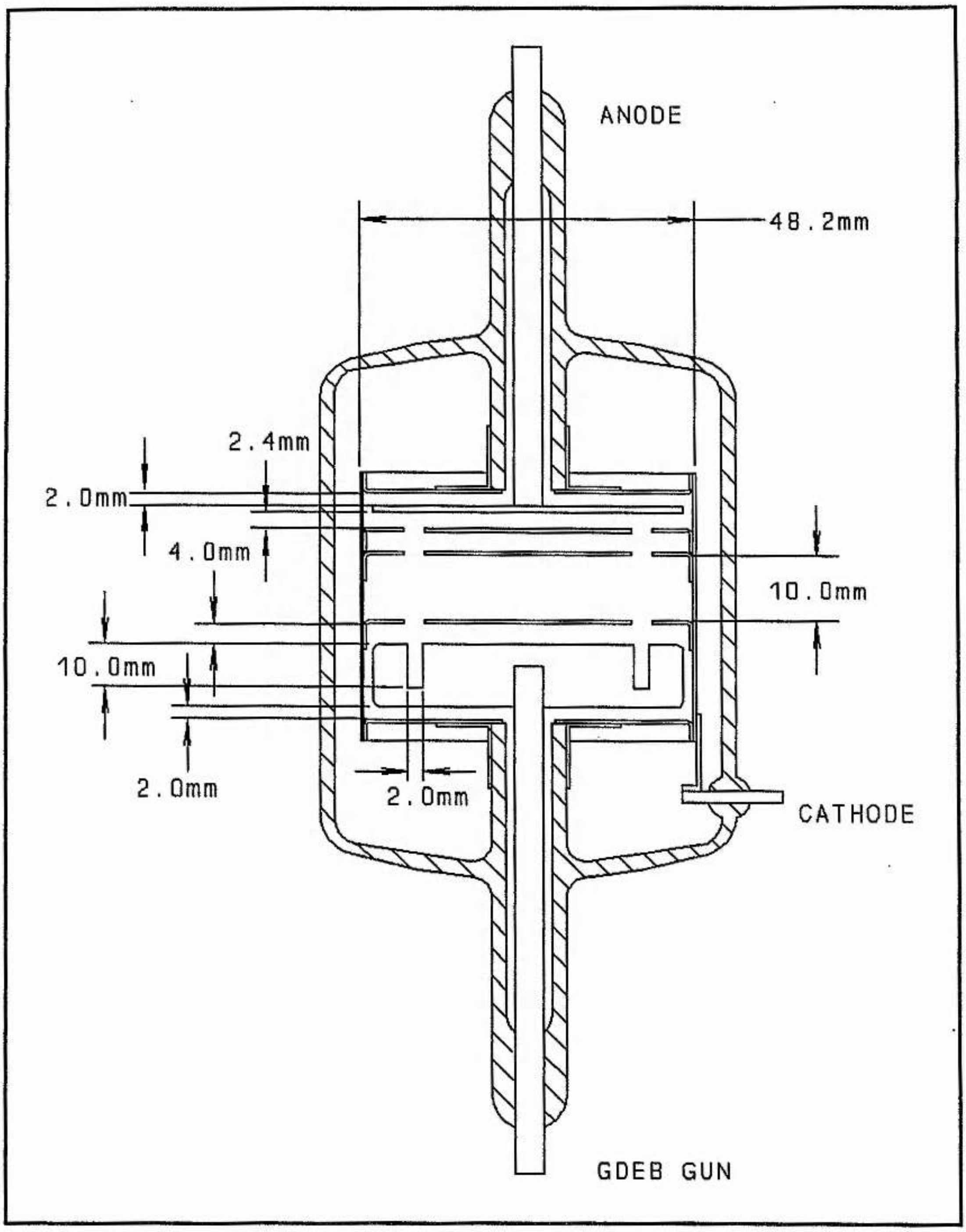


Figure 5.1
The electron beam triggered switch (BTS) with an annular GDEB gun.

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(54) Title of Invention

Gas discharge devices

(51) INT CL^5; **H01J 17/30, 17/06, 17/38, 17/58**

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D12B6 D12C D17B D17D D31
D9CY D9C2 D9Y

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GB 2125613 A
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GB 1583493 A
GB 0824762 A

(58) Field of search

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UK CL **H1D**
INT CL^4 **H01J**
updated as appropriate

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(56) Documents cited
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GB A 2169131 GB A 2065962
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H1D
Selected US specifications from IPC sub-classes H01J

(54) **Gas discharge devices**

(57) A gas discharge device includes means for injecting electrons into a high field region 8 between an anode 1 and a cathode structure 2. This causes ionisation within the region and triggers the device into conduction.

In the thyratron shown, the injected electrons are produced by generating a number of collimated electron beams 7 from holes 6 formed in a cathode member 5 and directing the beams obliquely into the region 8 through the ionizable volume 4 of the hollow cathode structure 2. Alternatively, Fig. 2 (not shown) the electron beam generators may be radially spaced from the region 8 and the electrons injected directly into the region. In a further arrangement, Fig. 3 (not shown), the beams are incident on a surface (20) prior to entering the region 8.

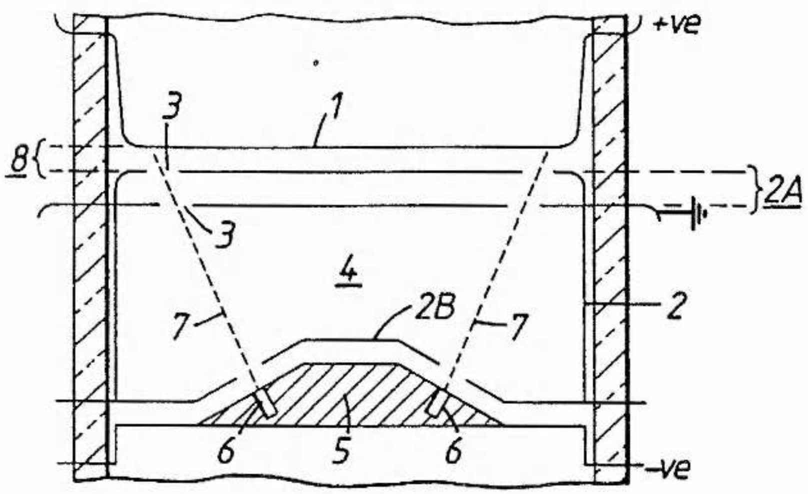

FIG. 1.

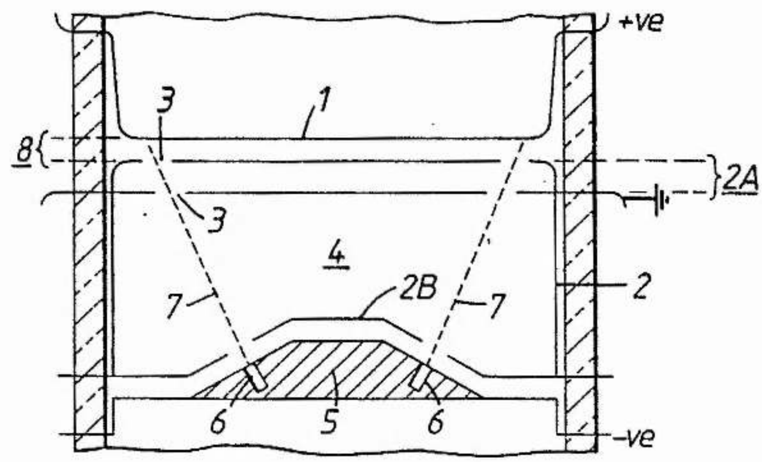

FIG. 1.

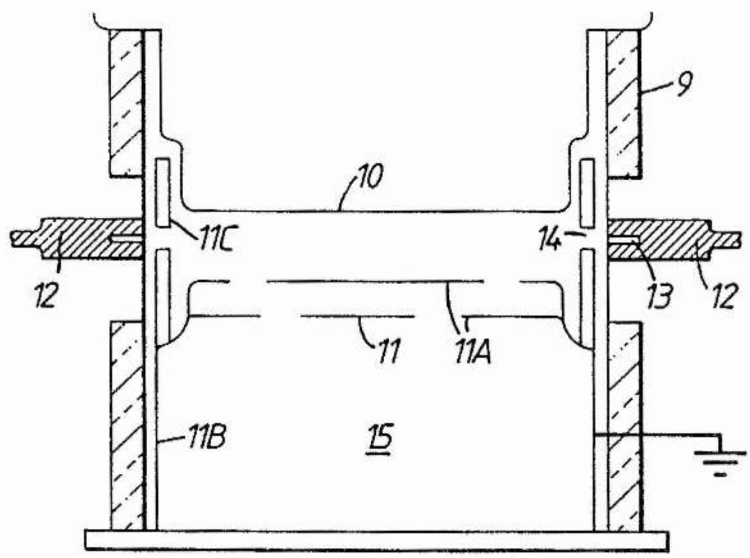

FIG. 2.

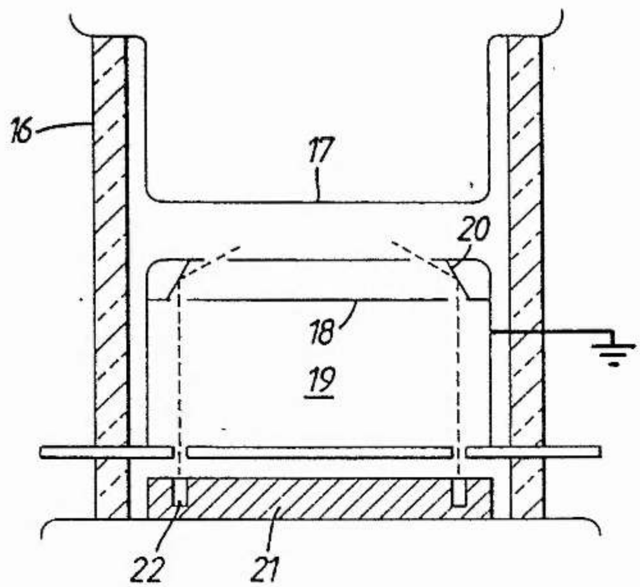

FIG. 3.

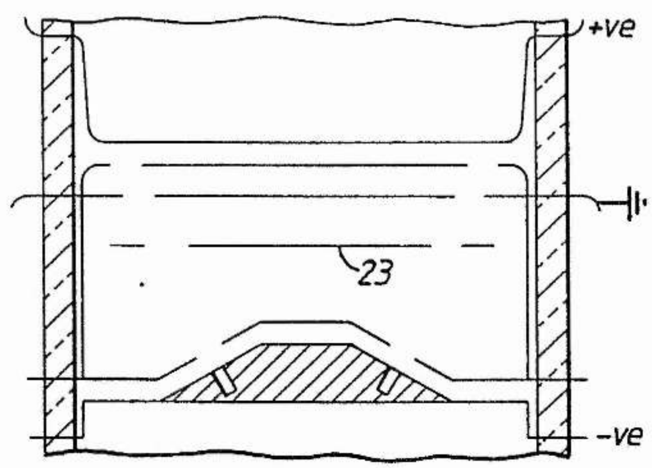

FIG. 4.

SPECIFICATION

Gas discharge devices

This invention relates to gas discharge devices.

Gas discharge devices are typically used as closing switches in pulse power systems and generally comprise an anode and a cathode in a gas filled envelope. The device must be constructed so as to withstand a high potential different until triggered into conduction.

The present invention seeks to provide a gas discharge closing switch triggered by an electron beam.

According to the invention there is provided a gas discharge device comprising, within a gas filled envelope, an anode and a cathode and means for injecting electrons into a high field region between them whereby a discharge is initiated within the device. As the electrons are injected into the high field region, they are accelerated and a relatively high degree of ionisation is achieved through collision processes. This enables rapid turn-on of the device to be achieved and tends to produce a uniform discharge across the device. The cathode may comprise a volume of ionised gas substantially contained within a metallic enclosure, the required ionisation being produced during operation of the device. Where such a "hollow cathode box" is employed preferably the electrons injected into the high field region are arranged to pass through the volume which is substantially contained within the enclosure. In another embodiment of the invention, the electrons are injected directly into the high field region, that is, they are not required to pass through intervening apertures in a cathode structure.

Advantageously, injected electrons are arranged to be incident on a surface such that they are reflected into the high field region.

Preferably the electrons are produced by an electron beam-forming device comprising a beam cathode member having a hole in the surface thereof and an anode member being arranged such that, when a sufficiently high potential difference is applied between them, a collimated beam of electrons is formed extensive of the hole. Such an arrangement enables high energy electrons to be produced and, since they are well collimated, the path travelled by the injected electrons may be accurately controlled. The cathode of the device may be arranged to act as the anode member, and the hole may be circular or be a slot, such as for example an annular channel.

Some ways in which the invention may be performed are now described by way of example with reference to the accompanying drawings in which:

Figures 1, 2, 3 and 4 schematically illustrate respective gas discharge switches in accordance with the invention.

With reference to Figure 1 a gas discharge switch includes an anode 1 and a cathode structure 2, the electrode assembly being contained within a ceramic envelope which also contains hydrogen at 1 torr pressure. The cathode structure 2 is generally cylindrical in configuration having an upper part 2A, which is a double layer portion having apertures 3 therein, and a lower part 2B. The cathode structure 2 substantially encloses a volume 4 which comprises the cathode of the switch when it contains ionised gas during operation of the device. The apertures 3 in one layer of part 2A are offset from those in the other. The switch also includes a beam cathode member 5 within which are located a plurality of holes 6. The holes 6 are located in faces of the cathode member 5 which are inclined with respect to the surfaces of the upper part 2A of the cathode and the anode 1. The holes 5 are drilled normal to the surfaces of the beam cathode member 5 in which they are located and are aligned with the aperture 3 in the cathode structure 2 to point in a direction towards the anode 1. The lower part 2B of the cathode structure 2 is located close to, but spaced apart from, the beam cathode member 5, conforming to its surface configuration.

During operation of the gas discharge switch, a positive voltage is applied to the anode 1 and the cathode structure 2 is maintained at earth potential. When it is wished to initiate conduction, a voltage of -10 kV is applied to the beam cathode member 5. This causes collimated electron beams to be formed extensive of each of the holes 6 in directions indicated by the broken lines 7. The electron beams are arranged to pass through apertures in the part 2B, through the apertures 3 in the part 2A and into the high field region 8 between the anode 1 and the cathode structure 2, causing ionisation to be produced. Positive ions are attracted towards the cathode structure 2 causing secondary emission of electrons from its surfaces and the volume 4 becomes filled with plasma and the walls defining the volume together.

With reference to Figure 2, in another gas discharge switch in accordance with the invention, a helium filled envelope 9 contains an anode 10 and a cathode structure 11, the cathode structure comprising a double layer part 11A and a cylindrical part 11B and an upper cylindrical portion 11C which is an extension of part 11B. A plurality of beam cathode members 12 are located around the circumference of the switch and have holes 13 in their front surfaces, which are located in the volume between the anode 10 and cathode structure 11. The upper cylindrical portion 11C is located coaxially within the envelope 9 in front of the beam cathode members 12 and has apertures 14 therein which are in register with the holes 13. During operation of the switch, a high field region exists between the anode 10 and cathode structure 11, the latter being at earth potential. When it is wished to establish a discharge within the switch a negative potential is applied to the beam cathode members 12 such that a potential difference of approximately 10 kV exists between them and the cathode structure 11. A collimated electron beam is produced extensive of each hole 13 and is injected into the high field region. This causes ionisation within that region and a plasma is produced within a volume 15 defined by the cathode structure 11. The ionisation so produced and the enclosure together act as a cathode, and conduction occurs between it and the anode 10.

With reference to Figure 3, a gas discharge switch has an envelope 16 within which is contained hydrogen at about 1 torr pressure. An anode 17 is contained within the envelope 16 together with a cathode structure 18 which is cylindrical and substantially encloses a volume 19. The cathode structure 18 includes a double layer part having offset apertures and an angled portion 20 connecting the two layers. A beam cathode member 21 is also included within the envelope 16 and has an annular slot 22 in its front surface, that is in the surface directed towards the anode 17. When it is wished to trigger a discharge within the switch, the beam cathode member 21 is made negative with respect to the cathode structure 18 causing an annular collimated electron beam to be produced from the slot. The electrons are directed towards the anode 17 through the apertures in the cathode structure 18 where they are incident on the inclined part 20, their path being shown by broken lines. They are reflected from the surface 20 into the high field region between the anode 17 and the cathode structure 18. Collision of the electrons with the surface 21 may also cause secondary electrons to be emitted, producing additional ionisation and enabling ionisation to be achieved rapidly within the volume 19. The inclined portions 20 may be made of material which has good secondary emission characteristics to enable a large number of relatively high energy electrons to be produced.

With reference to Figure 4, another gas discharge device is similar to that illustrated in Figure 1, but also includes a grid 23 located in the enclosed volume. This enables modification of the triggering characteristics and/or recovery characteristics of the switch if desired.

CLAIMS

1. A gas discharge device comprising, within a gas-filled envelope, an anode and a cathode and means for injecting electrons into a high field region between them whereby a discharge is initiated within the device.

2. A device as claimed in claim 1 wherein electrons are arranged to be injected into the high field region directly.

3. A device as claimed in claim 1 or 2 wherein the cathode comprises a volume of ionised gas filling substantially contained within a metallic enclosure, the required ionisation being produced during operation of the device.

4. A device as claimed in claim 3 wherein the electrons injected into the high field region are arranged to pass through the said volume.

5. A device as claimed in any preceding claim wherein injected electrons are arranged to be incident on a surface prior to entering the high field region.

6. A device as claimed in any preceding claim wherein the electrons to be injected into the high field region are produced by an electron beam forming device comprising a beam cathode member having a hole in a surface thereof and an anode member, being arranged such that, when a sufficiently high potential difference is applied between them, a collimated beam of electrons is formed extensive of the hole.

7. A device as claimed in claim 6 wherein the anode member is part of the cathode.

8. A device as claimed in any preceding claim and including a control grid.

9. A device as claimed in claim 8 and, when the cathode comprises a volume of ionised gas contained within a metallic enclosure, the grid is located in the enclosure.

10. Gas discharge device substantially as illustrated in and described with reference to Figures 1, 2, 3 or 4 of the accompanying drawings.

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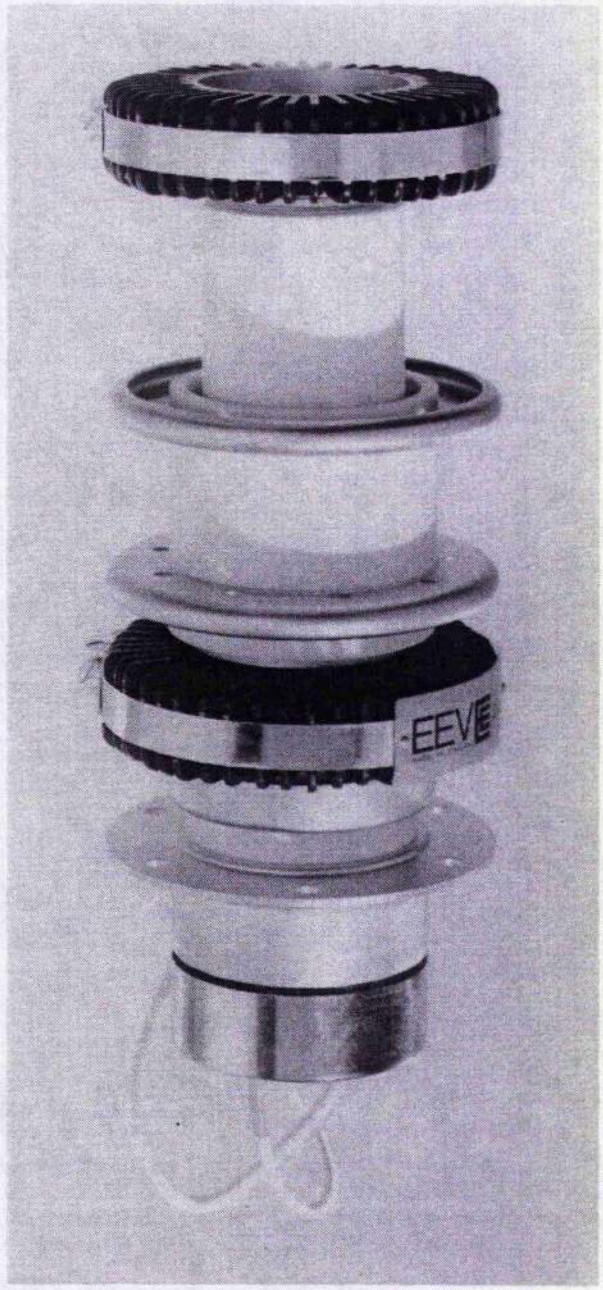
APPENDIX A

A CX1625 data sheet and extracts from BS9014.

Liquid Cooled, Deuterium Filled, Metal/Ceramic Pentode Thyratron

CX1625

The data to be read in conjunction with the Hydrogen Thyratron Preamble.



ABRIDGED DATA

Hollow anode, deuterium-filled pentode thyratron with metal/ ceramic envelope, featuring high peak current, high rate of rise of current, low jitter and 50% voltage current reversal. It has been developed specifically for use in low inductance circuits associated with excimer lasers.

The patented hollow anode structure enables the tube to cope with inverse voltage and current without consequent reduction in its high voltage hold off capability due to electrode damage.

A reservoir normally operated from a separate heater supply is incorporated. The reservoir heater voltage can be adjusted to a value consistent with anode voltage hold-off in order to acheive the fastest rate of rise of current possible from the tube in the circuit.

Peak forward anode voltage	35	kV max
Peak forward anode current	15	kA max
Peak reverse anode current	7.5	kA max
Average anode current	5.0	A max
Rate of rise of current	>100	kA/μs
Jitter	1.0	ns
Pulse repetition rate	2000	p.p.s. max

GENERAL DATA

Electrical

Cathode	barium aluminate impregnated tungsten	
Cathode heater voltage (see note 1)	6.6 ± 0.2	V
Cathode heater current	37.5	A
Reservoir heater voltage (see notes 1 and 2)	$6.3 \begin{smallmatrix} +0.7 \\ -0.3 \end{smallmatrix}$	V
Reservoir heater current	7.0	A
Tube heating time (minimum)	10.0	min

Mechanical

Seated height	240 mm (9.449 inches) max
Clearance required below mounting flange	80 mm (3.150 inches) min
Overall diameter (excluding connections)	122 mm (4.803 inches) max
Net weight	3.6 kg (8 pounds) approx
Mounting position	see note 3
Tube connections	see outline

Cooling

The tube must be cooled by total liquid immersion, for example in force-circulated transformer oil (see EEV Technical Reprint No. 108 'The cooling of oil-filled electrical equipment, with special reference to high power line-type pulse generators' by G. Scoles). Care must be taken to ensure that air is not trapped inside the tube end cover.

In addition to 275 W of heater power, the tube dissipates from 100 watts per ampere average anode current, rising to 300 W/A or greater at the highest rate of rise and fall of anode current.

PULSE LASER SERVICE

MAXIMUM AND MINIMUM RATINGS (Absolute values)

These ratings cannot necessarily be used simultaneously.

	Min	Typical	Max	
Anode				
Peak forward anode voltage (see note 4)	–	–	35	kV
Peak inverse anode voltage	–	–	25	kV
Peak forward anode current	–	–	15	kA
Peak reverse anode current	–	–	7.5	kA
Average anode current	–	–	5.0	A
Pulse duration	–	–	0.5	μs
Rate of rise of anode current (see note 5)	–	>100	–	kA/μs
Pulse repetition rate	–	–	2000	p.p.s.
Grid 2 (Voltage driven)				
Unloaded grid 2 drive pulse voltage (see note 6)	600	–	2000	V
Grid 2 pulse duration	–	0.5	–	μs
Rate of rise of grid 2 pulse (see notes 5 and 7)	10	–	–	kV/μs
Grid 2 pulse delay (see note 8)	0.2	–	3.0	μs
Peak inverse grid 2 voltage	–	–	450	V
Loaded grid 2 bias voltage (see note 9)	−100	–	−300	V
Impedance of grid 2 drive circuit (see note 10)	25	–	200	Ω
Grid 0 and 1 – Pulsed (Current driven) (see note 11)				
Unloaded grid 1 drive pulse voltage	300	–	2000	V
Grid 1 pulse duration	2.0	–	–	μs
Rate of rise of grid 1 pulse	1.0	–	–	kV/μs
Peak inverse grid 1 voltage	–	–	450	V
Loaded grid 1 bias voltage				see note 12
Peak grid 1 drive current (see note 9)	15	20	35	A
Cathode				
Heater voltage	6.4	6.6	6.8	V
Heating time	10.0	–	–	min
Reservoir				
Heater voltage	6.0	6.3	7.0	V
Heating time	10.0	–	–	min

CHARACTERISTICS

	Min	Typical	Max	
Critical d.c. anode voltage for conduction	–	0.5	1.0	kV
Anode delay time	–	200	250	ns
Anode delay time drift (see note 13)	–	15	25	ns
Time jitter (see note 14)	–	1.0	5.0	ns
Recovery time (see note 15)	–	20	–	μs
Cathode heater current (at 6.6 V)	30	37.5	45	A
Reservoir heater current (at 6.3 V)	6.0	7.0	8.0	A

NOTES

1. The reservoir heater can be supplied from a transformer common to the cathode heater supply or a separate transformer. If a common transformer is used, the reservoir lead (red sleeve) must be connected to the mounting flange, (see Fig. 1 below). Each tube is labelled for the single transformer case.

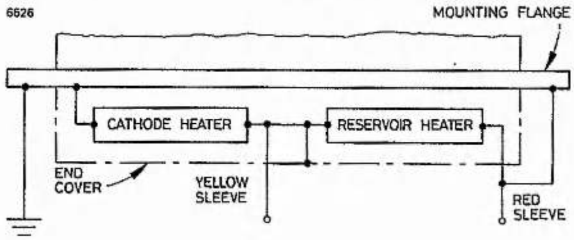


Fig. 1. Connections when using Single Transformer

When a separate transformer is used it must be connected between the reservoir lead (red sleeve) and cathode heater lead (yellow sleeve). Care should be taken to ensure that excessive voltages are not applied to the reservoir heater circuit from the cathode heater supply because of high impedance cathode heater connections. For example, in the worst case, an open circuit heater lead will impress almost double voltage on the reservoir heater, especially on switch-on, when the cathode heater impedance is minimal. This situation can be avoided by ensuring that the two supplies are in anti-phase. **The reservoir heater circuit must be decoupled with suitable capacitors, for example, a 1 μF capacitor in parallel with a low inductance 1000 pF capacitor.**

The heater supply systems should be connected directly between the cathode flange and the heater leads. This avoids the possibility of injecting voltages into the cathode and reservoir heaters. At high rates of rise of anode current, the cathode potential may rise significantly at the beginning of the pulse, depending on the cathode lead inductance, which must be minimized at all times.

2. The reservoir system of the CX1625 contains a barretter but variations of the reservoir supply voltage within the limits given will alter the gas pressure. Highest gas pressure is obtained at the highest reservoir heater supply voltage, provided the tube base is adequately cooled.
3. The tube must be fitted using its mounting flange.
4. The maximum permissible peak forward voltage for instantaneous starting is 30 kV and there must be no overshoot.
5. This rate of rise refers to that part of the leading edge of the pulse between 25% and 75% of the pulse amplitude.
6. Measured with respect to cathode.
7. A lower rate of rise may be used, but this may result in the anode delay time, delay time drift and jitter exceeding the limits quoted.
8. The last 0.25 μs of the top of the grid 1 pulse must overlap the corresponding first 0.25 μs of the top of the delayed grid 2 pulse.
9. The high grid 1 peak currents specified are essential for fast rise time. The required level of grid 2 negative bias depends upon the peak grid 1 current used.

   If the peak grid 1 current used is too high for the applied grid 2 negative bias, detrimental switching may occur with the grid 1 pulse, instead of the grid 2 pulse as intended.
10. During both the drive pulse period and during recovery when the current flow is reversed.
11. The current pulse must be shared between grid 0 and grid 1, preferably in the ratio $i_{g0} : i_{g1} = 1 : 10$.
12. D.C. negative bias voltages must not be applied to grid 1. When grid 1 is pulse driven, the potential of grid 1 may vary between −10 V and +5 V with respect to cathode potential during the period between the completion of recovery and the commencement of the succeeding grid pulse.
13. Measured between the second minute after the application of h.t. and 30 minutes later.
14. A time jitter of less than 1 ns can be obtained if the cathode heater voltage is supplied from a d.c. source and the rate of rise of the grid 2 pulse is in excess of 20 kV/μs.
15. Measured after a current pulse of 1000 A, with a grid 2 bias voltage of −100 V, a recovery impedance of 500 Ω and a 1.0 kV anode probe.

HEALTH AND SAFETY HAZARDS

EEV hydrogen thyratrons are safe to handle and operate, provided that the relevant precautions stated herein are observed. EEV does not accept responsibility for damage or injury resulting from the use of electronic devices it produces. Equipment manufacturers and users must ensure that adequate precautions are taken. Appropriate warning labels and notices must be provided on equipments incorporating EEV devices and in operating manuals.

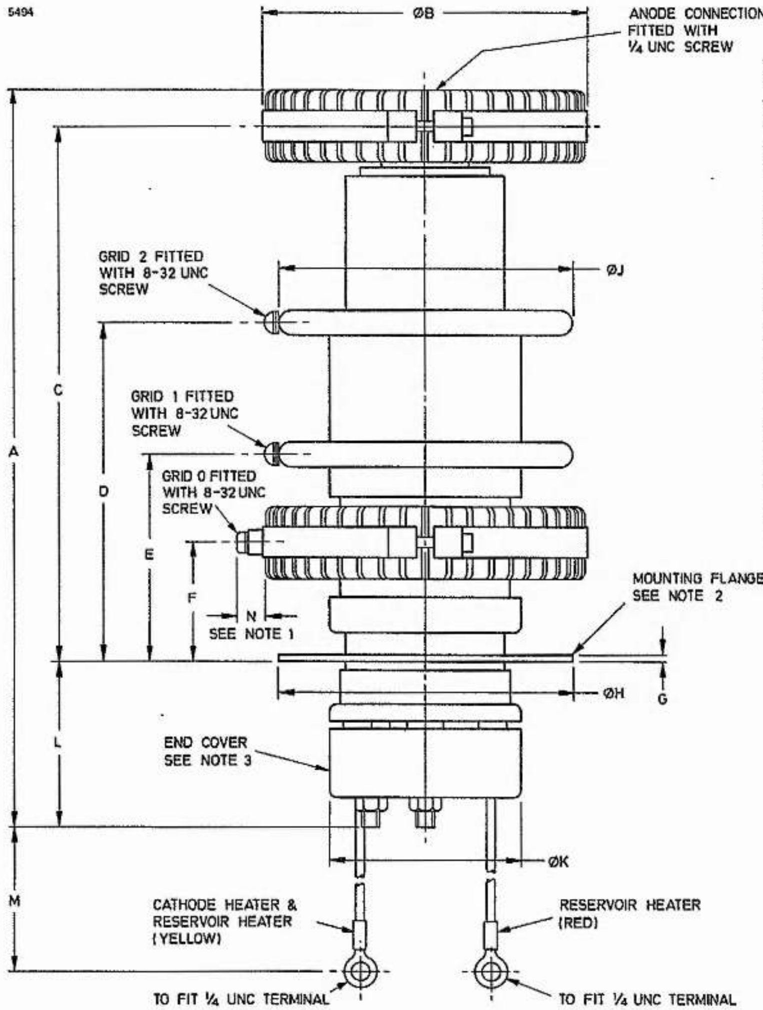
High Voltage

Equipment must be designed so that personnel cannot come into contact with high voltage circuits. All high voltage circuits and terminals must be enclosed and fail-safe interlock switches must be fitted to disconnect the primary power supply and discharge all high voltage capacitors and other stored charges before allowing access. Interlock switches must not be bypassed to allow operation with access doors open.

X-Ray Radiation

X-rays may be emitted by the CX1625 but the radiation is usually reduced to a safe level by the steel panels of the equipment in which the tube operates.

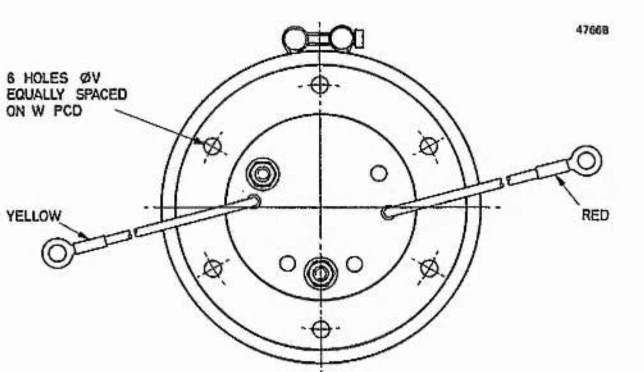
OUTLINE (All dimensions without limits are nominal)



Ref	Millimetres	Inches
A	285.0 max	11.220 max
B	122.0 max	4.803 max
C	208.0	8.189
D	131.0	5.157
E	80.0	3.150
F	46.0	1.811
G	2.50	0.100
H	111.0	4.375
J	111.0	4.375
K	75.00 max	2.953 max
L	70.0 max	2.756 max
M	305.0	12.008
N	15.00 max	0.591 max
V	6.50	0.256
W	95.25	3.750

Inch dimensions have been derived from millimetres.

Detail of Mounting Flange



Outline Notes

1. This dimension also applies to the clamping screws and lugs.
2. The mounting flange is the connection for the cathode and cathode heater return.
3. The end cover is at heater potential and must not be grounded.

BRITISH STANDARD SPECIFICATION FOR PULSE MODULATOR HYDROGEN THYRATRON TUBES OF ASSESSED QUALITY : GENERIC DATA AND METHODS OF TEST

1. GENERAL MATTERS

1.1 SCOPE

This standard forms part of the system of common standard specifications for electronic components of assessed quality and should be read in conjunction with the standards in the series BS 9000 to BS 9009. It applies to pulse modulator hydrogen thyratron tubes as defined in 1.3 and gives the terms, definitions, symbols, test methods and other material required for implementing the detail specifications for these tubes.

The material herein shall be applicable only when called up by the detail specification, except for 1.6 to 1.18 which are mandatory requirements.

1.2 RELATED DOCUMENTS

BS 448	Dimensions of electronic tubes and valves.
BS 1991	Letter symbols, signs and abbreviations.
BS 2011*	Basic environmental testing procedures.
BS 3939	Graphical symbols for electrical power, telecommunication and electronics diagrams (IEC Publication 117).
BS 4727	Glossary of electrotechnical, power, telecommunications, electronics, lighting and colour terms.
BS 6001	Sampling procedures and tables for inspection by attributes.
BS 9000	General requirements for electronic components of assessed quality. Part 1. General description and basic rules.
IEC 134	Rating system for electronic tubes and valves and analogous semiconductor devices.
IEC 151-20	Methods of measurement of thyratron pulse modulators

1.3 TERMINOLOGY

For the purpose of this British Standard, the following terms and definitions apply, in addition to those from BS 4727: Part 1: Group 06.

NOTE. A number of the following definitions are identical with those given in IEC publications; these are indicated by the inclusion of the relevant IEC reference in parentheses at the end of the definition.

1.3.1 *Pulse modulator hydrogen thyratron tube*. A thyratron, as defined in 3401 of BS 4727: Part 1: Group 06, but which switches energy from a storing circuit to another tube, usually a magnetron, in pulses of short duration.

1.3.2 *Pulse and other relevant characteristics* are defined below and in Fig. 1.

(1) *Pulse amplitude*. The maximum value of a smooth curve through the average of the variations on the top of the pulse, exclusive of spike.

* The tests referred to in this document are to BS 2011: 1967. These will be reviewed where necessary in the next amendment.

(2) *Pulse duration*. The time interval between the instants at which the value of the parameter equals 70 % of the pulse amplitude unless otherwise stated (151-20 2.3)

(3) *Pulse rise time*. The time required for the pulse to rise from 26 % to 70 % of the pulse amplitude. (151-20 2.4)

(4) *Pulse fall time*. The time required for the pulse to fall from 70 % to 26 % of the pulse amplitude. (151-20 2.5)

(5) *Spike*. A surge above the pulse amplitude of duration less than 10 % of the pulse duration.

(6) *Spike duration*. The time interval between the instants when the spike departs from and returns to the pulse amplitude level. (151-20 2.7)

(7) *Spike amplitude*. The maximum excursion of the spike above the pulse amplitude. (151-20 2.8)

(8) *Pulse repetition rate*. The average quantity of pulses in unit time. (Unless otherwise stated, unit time is one second.) (151-20 2.10)

(9) *Average rate of rise of anode pulse current*. The quotient of the change of current during the pulse rise time to the period of the rise time. (See Fig. 2.) (151-20 2.17)

(10) *Critical d.c. anode-voltage for conduction*. The minimum d.c. voltage at the anode which causes conduction under specified conditions. (151-20 2.21)

(11) *Unloaded grid pulse voltage*. The pulse amplitude at the grid terminal with respect to cathode with the tube removed from the socket and the grid drive supply set to the operating conditions.

(12) *Anode delay time*. The time interval between the instant at which the unloaded grid pulse reaches 26 % of the pulse amplitude and the instant when anode conduction takes place. In multi-grid tubes the reference grid pulse should be stated. (151-20 2.37)

(13) *Anode delay time drift*. The change in anode delay time after a specified duration of operation.

(14) *Jitter (pulse jitter time)*. Pulse to pulse variation of the anode delay time.

(15) *Peak forward anode voltage*. The maximum positive voltage applied to the anode with respect to the cathode.

(16) *Peak inverse anode voltage*. The maximum negative voltage applied to the anode with respect to the cathode.

(17) *Anode heating factor*. The product of peak forward anode voltage, anode pulse current and pulse repetition rate.

(18) *Unloaded grid bias voltage*. The negative d.c. voltage at the grid terminal with respect to cathode with the tube removed from the socket and the grid bias supply set to the operating conditions.

(19) *Loaded grid bias voltage*. The inter-pulse negative d.c. voltage at the grid with respect to the cathode, when the tube is operating.

(20) *Average rate of rise of unloaded grid pulse voltage*. The quotient of the change of voltage during the pulse rise time to the period of the pulse rise time. (151-20 2.30)

(21) *Priming*. The initiation of a local discharge between cathode and grid 1 of the tetrode thyratron tube.

NOTE. Priming may be achieved either by the application of a d.c. voltage to grid 1 so maintaining a continuous discharge current or by the application to grid 1 of a pre-pulse. The purpose of priming is to reduce pulse jitter and anode delay time.

(22) *Unloaded grid 1 d.c. priming voltage*. The d.c. voltage measured at the grid 1 socket terminal with the tube removed from its socket and the grid 1 d.c. priming voltage supply set to the operating conditions.

(23) *Grid 2 pulse delay*. In a pulse primed tube, the time interval between the voltage pulses on grid 1 and grid 2 terminals with the tube removed from its socket, measured at 26 % of the pulse amplitude, on the leading edge of each pulse.

(24) *Grid firing time*. The time interval between the instant of simultaneous application of cathode heater, reservoir heater and specified grid voltages, and the instant when the grid-cathode gap breaks down.

(25) *Forward grid circuit impedance*. The output impedance of the grid drive and bias circuit. (51-20 2.33)

(26) *Recovery*. The re-establishment of grid control following interruption of forward anode current.

(27) *Recovery impedance,* Z_R. The impedance through which the decaying ion-recombination grid current flows during the recovery period. Recovery impedance can be calculated from the following formula:

$$Z_R = \frac{\text{(Instantaneous grid voltage) - (Loaded bias voltage)}}{\text{(Instantaneous ion-recombination grid current)}}$$

(28) *Recovery time*. The time required after cessation of forward anode current for the grid to regain control, under specified operating conditions.

(29) *Reservoir*. A device inside the tube for controlling the gas pressure.

(30) *D.C. resistance between grid and cathode*. The resistance measured between the grid and cathode terminals with the tube removed from its circuit.

(31) *Tube heating time*. The time required for all essential parts of the tube to attain temperatures such that the tube will operate satisfactorily.

(32) *Resonant charging*. The condition achieved when the pulse repetition frequency is equal to twice the natural resonance frequency of the charging inductance with the capacitance of the pulse-forming-network, so that the firing pulse occurs when the voltage on the capacitance is maximum; the network is discharged and recharges to attain the maximum voltage of the moment of incidence of the next successive firing pulse.

(33) *Charging diode*. A diode inserted between the supply and the pulse forming network to prevent any current from the network flowing back into the supply.

(34) *Inverse diode*. A diode in series with a resistance placed in parallel with the modulator tube to dissipate the negative charge of the pulse-forming-network and in addition to limit the peak inverse voltage after it has discharged through the tube.

(35) *Surface temperature (envelope temperature)*. The temperature measured at specified point(s) on the surface of the tube. (BS 2011: Part 1·: 4.5)

(36) *Trip*. Interruption of the power supply by an operation of an overload relay.

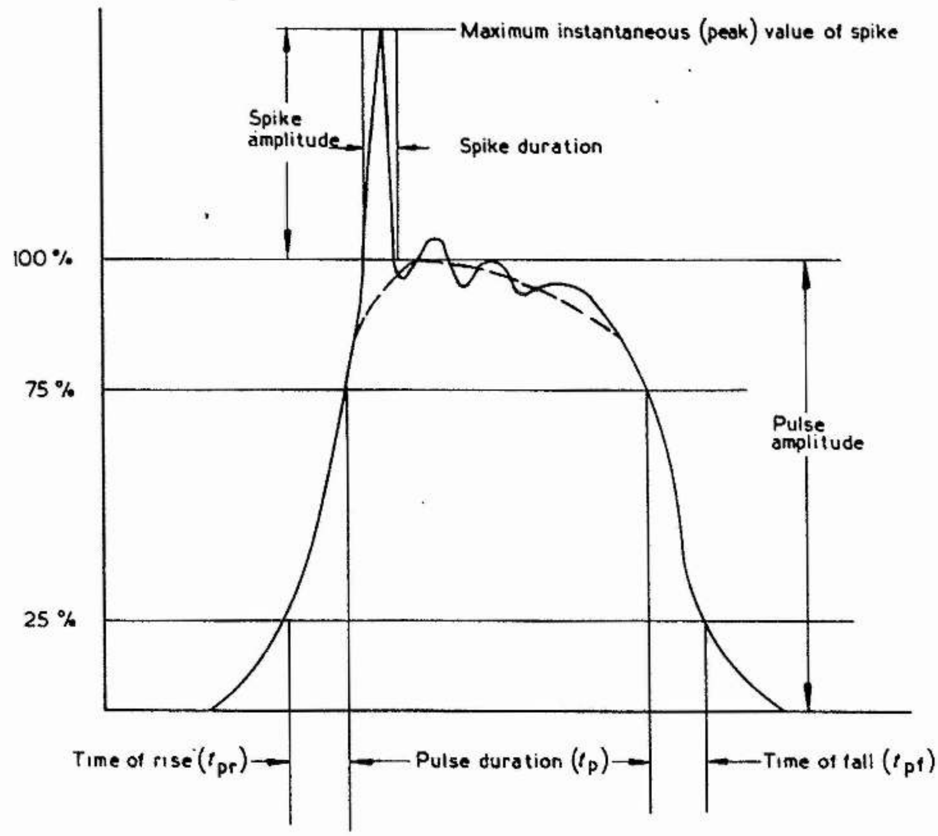


Fig. 1. General pulse characteristics

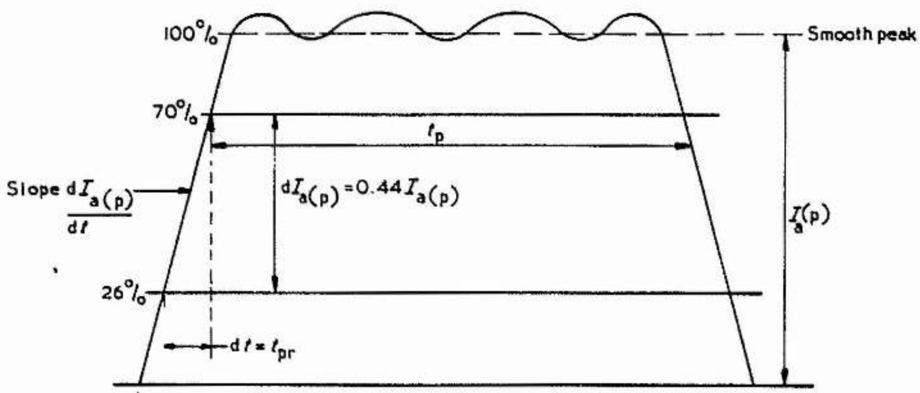


Fig. 2. Anode current pulse

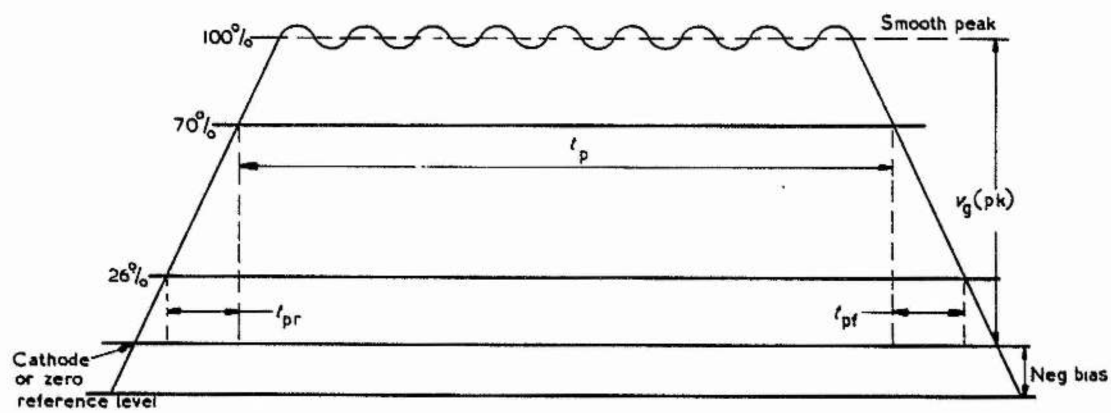


Fig. 3. Unloaded grid voltage pulse

1.4 LETTER SYMBOLS, SIGNS AND ABBREVIATIONS

For the purpose of this British Standard, the following letter symbols apply:

$\frac{dI_{a(p)}}{dt}$	average rate of rise of anode pulse current
$V_{a(crit)}$	critical d.c. anode voltage for conduction
$v_{g(pk)}$	peak forward grid voltage
$v_{a(pk)inv}$	peak inverse anode voltage
$v_{a(pk)}$	peak forward anode voltage
$I_{a(p)}$	anode pulse current
I_a	average anode current
$i_{a(pk)}$	peak anode current
F_{ah}	anode heating factor

Text deleted

p.r.r.	pulse repetition rate
t_{ad}	anode delay time
Δt_{ad}	anode delay time drift
t_{pf}	pulse fall time
t_{pj}	pulse jitter time
t_p	pulse duration
t_R	recovery time
t_{pr}	pulse rise time
Z_R	recovery impedance
TUT	tube under test
$V_{a(p)}$	anode pulse voltage
V_a	anode d.c. voltage
$-V_{g1}$	grid 1 negative d.c. voltage
$-V_{g2}$	grid 2 negative d.c. voltage

METHOD 1001. INSTANTANEOUS (SNAP-ON) START

PURPOSE

To ensure that following the specified tube heating time, the tube operates within a specified number of attempts to start.

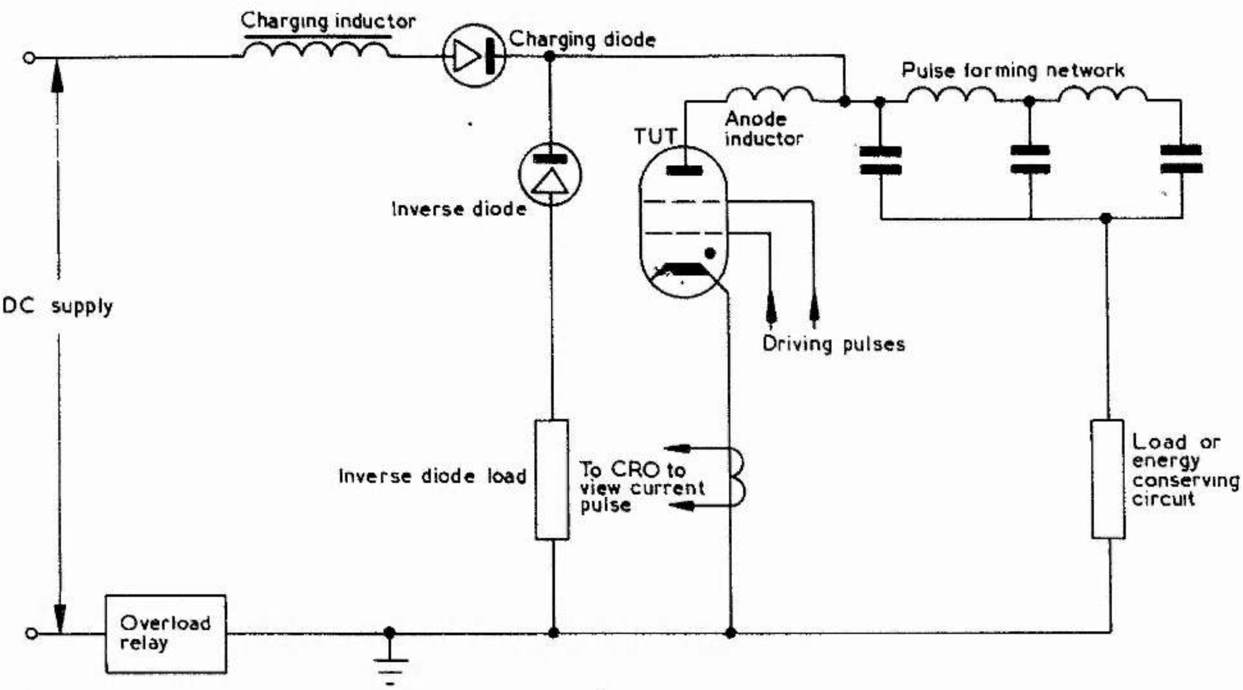


Fig. 1001

PROCEDURE

(1) Apply heater and grid voltages and allow the rated tube-heating time.

(2) Apply anode voltage directly at specified value whilst observing current pulses on the oscilloscope; examine for immediate starting and for continued normal operation over at least the following 10 s.

(3) In the event of a trip, repeat procedure (2).

Intervals between successive attempts shall be not less than 10 s nor more than 30 s.

METHOD 1006. ANODE DELAY TIME, t_{ad}

PURPOSE

To measure anode delay time and anode delay time drift.

TEST CIRCUIT

Use the circuit shown in Fig. 1001, *but with an oscilloscope connected between control grid and cathode* for monitoring the grid pulse voltage.

PROCEDURE

Anode delay time. Observe the wave form of the grid pulse voltage displayed on the oscilloscope, firstly with the tube removed then with the pre-heated tube connected*. The anode delay time is the time interval between the instant at which the unloaded grid pulse reaches 26 % of the pulse amplitude and the instant when anode conduction takes place. The occurrence of anode conduction is indicated on the loaded grid pulse by a sudden change of slope. An example of a possible waveform is given in Fig. 1006.

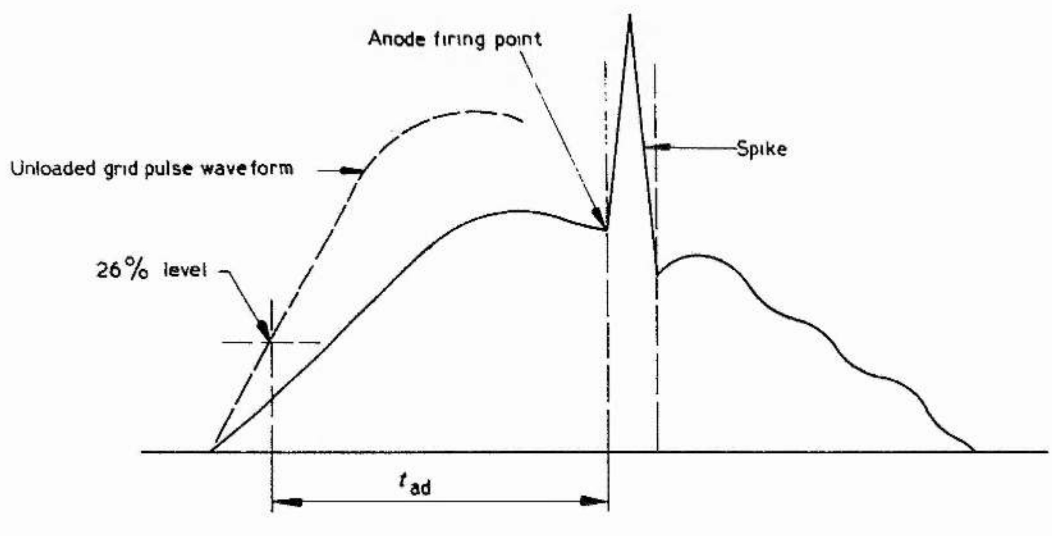


Fig. 1006

Anode delay time drift. The anode delay time shall be measured as above at specified intervals during operation of the tube. The maximum difference between any two measurements is the anode delay time drift.

* For measurements on multi-grid tubes the reference point is read on the drive pulse applied to that grid which is the last to be triggered.

METHOD 1011. PULSE JITTER TIME, t_{pj}

PURPOSE

To measure the variation in anode firing time.

TEST CIRCUIT

See Fig. 1001.

PROCEDURE

Display the current pulse and/or the grid drive pulse (preferably both simultaneously on two traces).

Measure over a large number of pulses the spread in time of the instant of anode firing, i.e. the arithmetic difference between the longest and shortest anode delay times (Method 1006).

The reference point for multigrid tubes is read on the drive pulse applied to that grid which is the last to be triggered.

CONDITIONS PRESCRIBED IN THE DETAIL SPECIFICATION

As in 2.4.5.

APPENDIX B

B Device Processing.

The fabrication of consistent and reliable gas discharge devices requires that particular attention is paid to the cleanliness and purity of the materials used in their construction. For example, in order to avoid the loss of hydrogen by chemical combination, the nickel used for thyratron cathode and grid structures is required to have an impurity content of lower than 0.005% for aluminium, sulphur and magnesium. It is also vitally important to remove surface contamination prior to device assembly. Surface contaminants may include machining oils, particulates and oxide layers, introduced during the manufacture and storage of parts. Suitable treatments to remove these contaminants include degreasing, ultrasonic cleaning and electropolishing. Clean room conditions are necessary for subsequent storage and assembly. Once the device is assembled in its vacuum envelope, the atmosphere must be removed. The constituents of the normal atmosphere are mainly nitrogen and oxygen in the ratio of 80% to 20% together with small traces of inert gases, carbon dioxide, hydrogen and a variable quantity of water vapour depending on ambient temperature and humidity. The partial pressures of these constituents are shown in Table B.1. At room temperature and normal atmospheric pressure, one cubic centimetre of air contains approximately $2.5 \cdot 10^{19}$ molecules. When the device is evacuated, the number of molecules/cm^3 and the molecular impingement flux are reduced as shown in Table B.2. Notice that, even at a pressure of 10^{-9} torr, there are still $3.5 \cdot 10^7$ molecules/cm^3 present. Gases such as N_2, O_2, CO and CO_2 are also present in the bulk of many metals. In order to reduce the amount of desorption of these gases during the life of the device, pretreatment of the device sub–assemblies includes a furnacing stage in which the component is heated in an atmosphere of H_2 at 1000°C for several hours. N_2, O_2, CO and CO_2 are released and some of the hydrogen is absorbed into the metal. The presence of hydrogen as a bulk sorbed gas does not generally present any problems in a thyratron. The atmosphere in the device at the end of assembly and processing is removed by evacuating the device on a pumping system of the design shown in Figure B.1. The pumping process is designed to remove adsorbed atmospheric contamination both from the pump system and from the device before pure gas of the required type is admitted. The pump system is heated to 120°C under vacuum to release air and water vapour from the internal surfaces of the system and the device itself is heated to about 500°C. This ensures that most adsorbed gas is removed by the end of four hours of processing. In the devices made for this study, final pressures of $< 2 \cdot 10^{-6}$ torr were recorded at the end of pumping. Cleaning of the cathode surface was accomplished by running a discharge in the required gas, followed by pumping and refilling.

Table B.1
The constituents of the normal atmosphere.

Partial Pressures of Atmospheric Constituents	
Gas	Partial Pressure (torr)
Nitrogen	596
Oxygen	159
Argon	7.1
Water vapour	~7.0
Carbon Dioxide	0.23
Neon	$1.4 \cdot 10^{-2}$
Helium	$3.8 \cdot 10^{-3}$
Krypton	$7.6 \cdot 10^{-4}$
Hydrogen	$3.8 \cdot 10^{-4}$
Xenon	$6.8 \cdot 10^{-5}$

Table B.2
Gas density and impingement flux at various pressures.

Pressure (torr)	Molecules/cm^3	Impacts/cm^2/sec
760	$2.5 \cdot 10^{19}$	$3 \cdot 10^{23}$
1	$3.5 \cdot 10^{16}$	$4 \cdot 10^{20}$
10^{-3}	$3.5 \cdot 10^{13}$	$4 \cdot 10^{17}$
10^{-4}	$3.5 \cdot 10^{12}$	$4 \cdot 10^{16}$
10^{-6}	$3.5 \cdot 10^{10}$	$4 \cdot 10^{14}$
10^{-9}	$3.5 \cdot 10^{7}$	$4 \cdot 10^{11}$

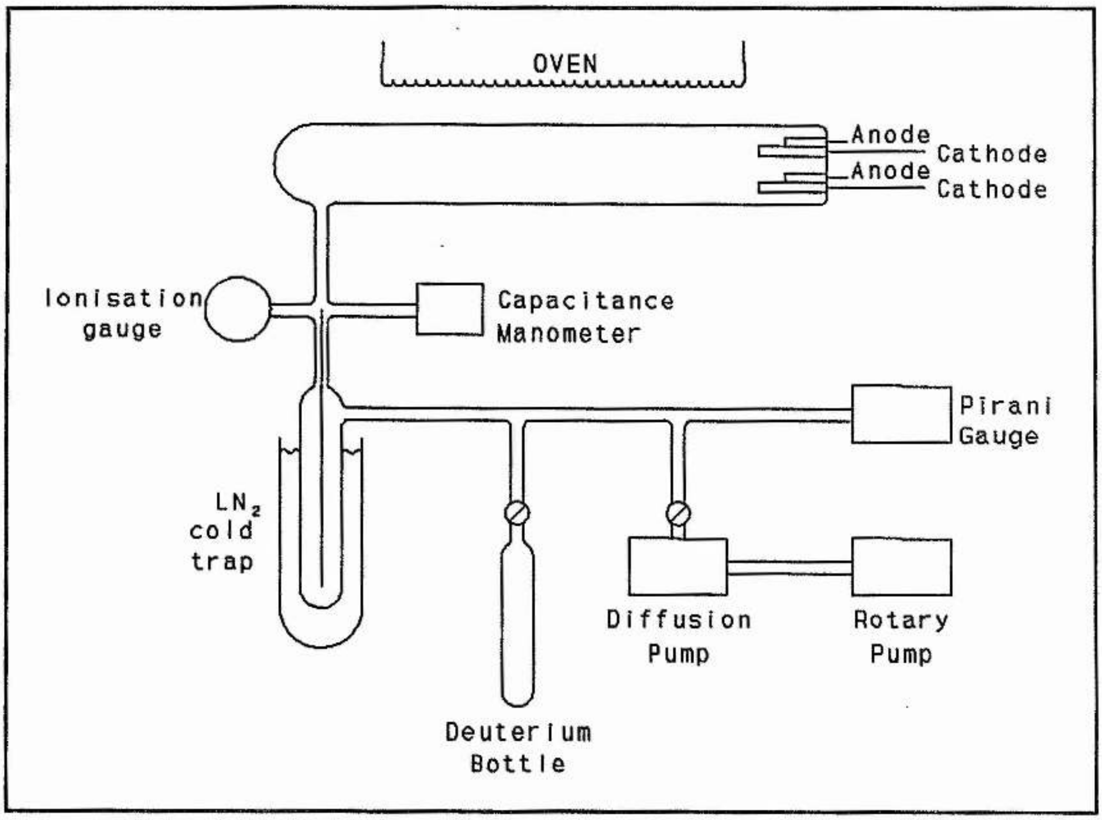


Figure B.1

A schematic of the pump system used to process the devices constructed for this thesis.

APPENDIX C

C Linear Regression.

Regression is used to draw the 'best–fit' straight line through points on a graph. The analysis is aimed at finding values for m and c in the equation

$$y = mx + c \quad . \tag{C.1}$$

The values m and c are deduced from a set of co–ordinate values in such a way that the sum of the deviations of the values from the straight line $y = mx + c$ is a minimum.

The values of m and c which conform to the above requirement can be obtained from the two equations:

$$\sum y = cN + m\sum x \quad ,$$

$$\sum xy = c\sum x + m\sum x^2 \quad . \tag{C.2}$$

Eliminating to give m and c

$$m = \frac{N\sum xy - \sum x \sum y}{N\sum x^2 - (\sum x)^2} \ ,$$

$$c = \frac{\sum y - m\sum x}{N} \ . \qquad \text{C.3}$$

For the purpose of analysing the data of Chapter 3, these formula were included in a computer programme, enabling values of *m* and *c* to be easily generated for a set of *IV* characteristic data.

APPENDIX D

D Glow discharge formulae and data.

The formulae presented here arise from the theory of the glow discharge (Acton & Swift, 1963, pp 239–241) and they allow some of the normal glow discharge parameters to be estimated for cases of practical interest. The data required for the formulae are included in tables at the end of this Appendix.

D.1 The maintaining voltage.

The maintaining voltage of the discharge, V_m, depends on gas filling and cathode material. The cathode surface condition may cause the actual value of $ln(1/\gamma)$ to be different to the value quoted in Table D.2. As the gas pressure is increased, the maintaining voltage falls asymptotically to a value given by

$$V_m = V_g + \frac{1}{\eta_g}\log\frac{1}{\gamma} \quad . \qquad \text{D.1}$$

where V_g and η_g are constants of the gas and $ln(1/\gamma)$ depends on the type of the bombarding ion and the nature of the cathode surface. The values of these constants are given in Tables D.1 and D.2.

D.2 The striking voltage.

The striking voltage V_s of a cold cathode depends on the gas filling, the cathode surface and the product of pressure and cathode–anode spacing, pd. At a certain value of pd, V_s takes a minimum value, designated V_{sm}, given by

$$V_{sm} = V_i + \frac{1}{\eta_m} \log \frac{1}{\gamma} \quad . \qquad \text{D.2}$$

where V_i and η_m are constants of the gas. The data required for this equation are given in Tables D.1 and D.2. The value pd_{min} for which V_s is a minimum is given by

$$(p\,d)_{\min} = \frac{V_{sm}}{Z_m} \quad , \qquad \text{D.3}$$

where Z_m depends only on the gas type and takes values as given in Table D.3. For values of V_s greater than $2V_{sm}$, V_s can be found from

$$V_s = V_{sm} + B\,(p\,d) \quad , \qquad \text{D.4}$$

where B depends on the gas type, with values as given in Table D.3.

D.3 The normal current density.

An indicative value of the cathode current density in the normal glow is given by

$$j = Jp^2 \quad , \tag{D.5}$$

where J is a constant depending on gas type, with values as given in Table D.3. Estimates of j obtained from this equation differ from the value obtained in practice by as much as a factor of 3.

Reference.

Acton J.R. & Swift J.D., *Cold Cathode Discharge Tubes*, Heywood & Company Ltd, London (1963)

Table D.1

Gas	V_i	V_g	η_m	η_g
He	24.5	20.0	0.012	0.020
Ne	21.5	17.0	0.015	0.022
A	15.6	12.5	0.022	0.029
H_2	15.4	15.0	0.015	0.015

Table D.2

Gas	$ln(1/\gamma)$				
	Mo (s)	Ni (s)	Ni	Mg	Ba (ev)
He	1.8	2.30	2.60	1.80	1.22
Ne	2.0	2.65	3.05	2.25	–
A	2.6	3.60	4.50	2.45	1.70
H_2	4.2	4.35	–	–	2.20

In the table above, (s) denotes a sputter–eroded surface and (ev) denotes that the surface is an evaporated film.

Table D.3

Gas	$J \cdot 10^6$	Z_m	B
He	2	50	7
Ne	2	100	5
A	10	200	20
H_2	70	120	35

APPENDIX E

E The pulse transformer.

The pulse transformer used to increase the trigger pulse voltage for the NGTS testing described in Chapter 4 is shown in Figure E.1. The equivalent circuit of the pulse transformer is shown in Figure E.2. The design of a pulse transformer is an iterative process, described as follows. For the sake of simplicity, we will consider a 1:1 transformer. For a given core, the magnetising inductance L_M is given by

$$L_M = \frac{V\tau}{I_{MAG}} \quad , \qquad \text{E.1}$$

where V is the input voltage, τ is pulse duration and I_{MAG} is magnetising current. I_{MAG} is usually required to be about $5\%-10\%$ of the output current and thus sets the minimum value of L_M. The number of turns N needed to achieve the required magnetising inductance is given by

$$N = \sqrt{\frac{L_M l_a}{\mu_0 A}} \quad , \qquad \text{E.2}$$

where, μ_0 is permittivity, l_a is air gap length and A is magnetic core area. It is necessary to establish that N is large enough to prevent the flux density in the core rising above the saturated flux density B_{SAT}. The minimum value of N which prevents saturation is given by

$$N = \frac{V\ \tau}{B_{SAT}\ A} \quad . \qquad \text{E.3}$$

The larger of the two values of N from equations E.2 and E.3 gives the minimum number of turns required in the winding. If the value is too large to be accommodated in the winding design, then the values of l_a and A must be changed and a new minimum turns value must be calculated. The pulse transformer in Figure E.1 is designed to produce a 6 kV output from a 2 kV input with a risetime of about 100 nsec. The risetime is determined by the time constant

$$\frac{L_1 + L_2}{R_L} \quad . \qquad \text{E.4}$$

L_1 and L_2 are the leakage inductances of the windings and R_L is the load resistance. L_1 and L_2 were minimised in the design of Figure E.1 by dividing the windings between two limbs of the core and by reducing the spacing between the primary and secondary windings to the minimum consistent with the dielectric strength of the insulating bobbins.

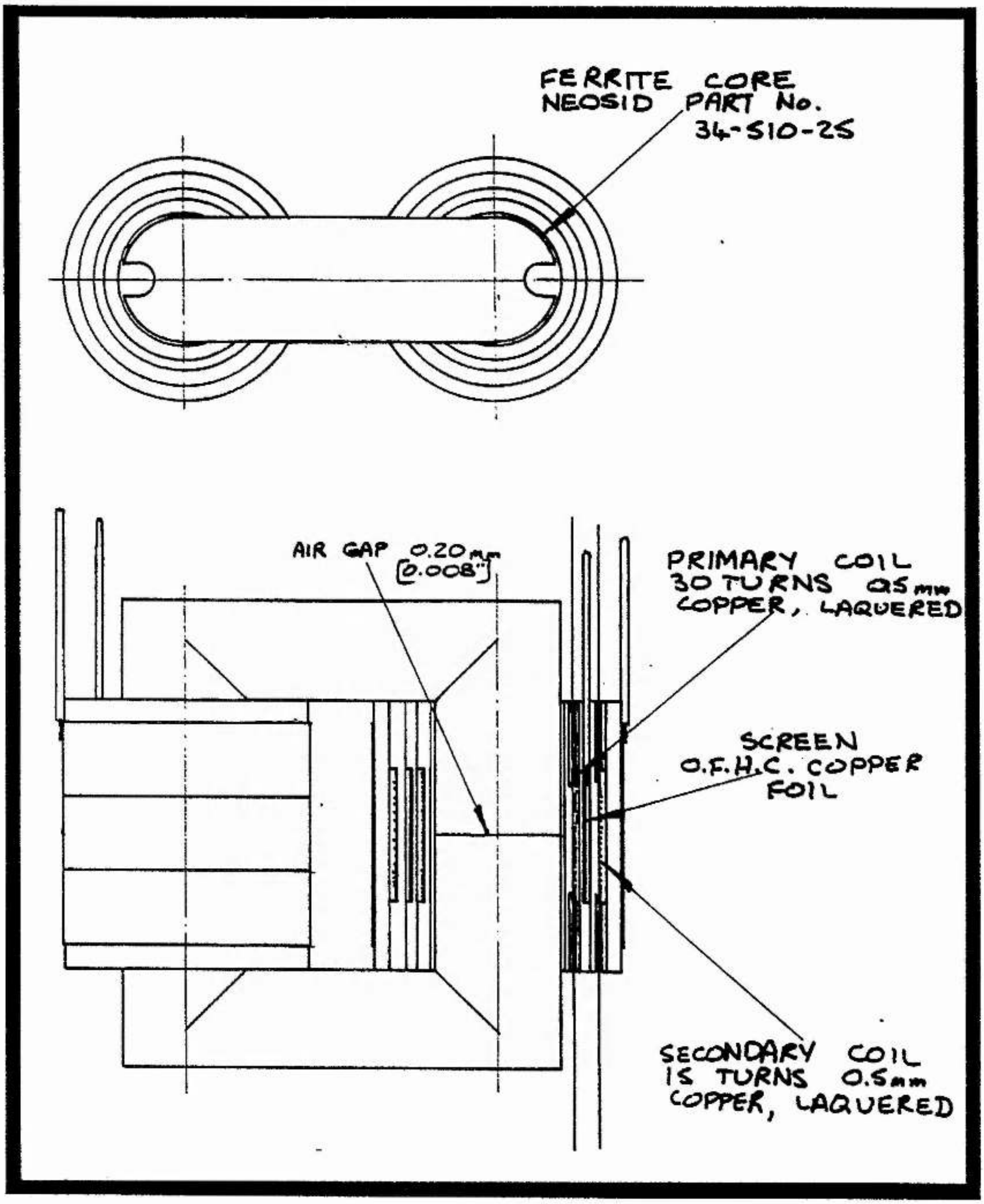


Figure E.1

The 1:3 step-up pulse transformer used in Chapter 4.

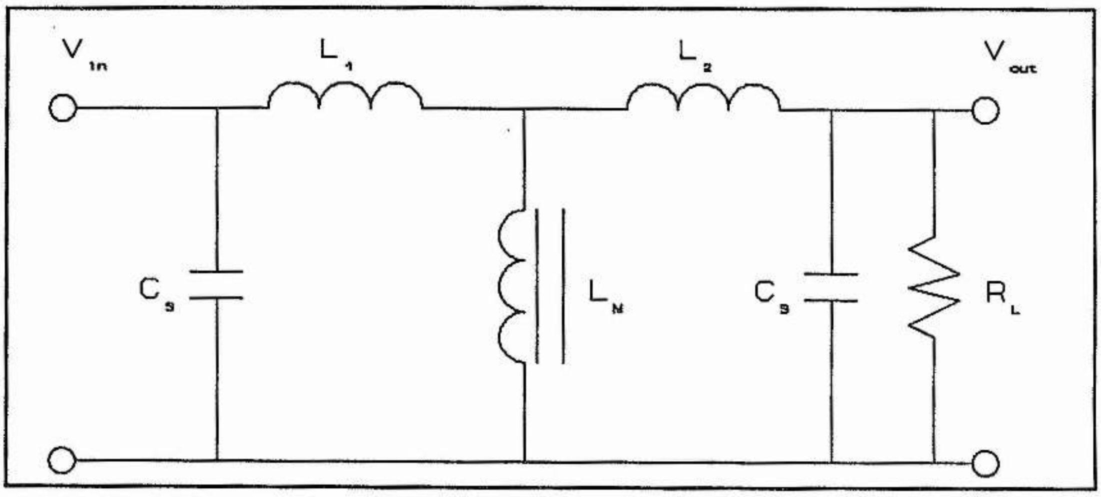


Figure E.2

The equivalent circuit of the pulse transformer where L_1 and L_2 are leakage inductance, L_M is magnetising inductance and R_L is load resistance.

APPENDIX F

F Gas density in low pressure gas switches.

It is worth considering how the gas density in the low pressure gas switch is changed as a result of passing the current pulse. The electric field across the switch during conduction draws ions to the cathode where they are neutralised and returned to the gas thus creating transient gas density gradients. The gas density transient is likely to propagate adiabatically as a sound wave in the gas (Tabor, 1979, p 74) with a velocity given by

$$v = \sqrt{\frac{\gamma P}{\rho}} \,, \qquad \text{F.1}$$

where γ is the ratio of specific heats, P is pressure and ρ is density. For a mole of gas having mass M in a volume V, we have

$$v = \sqrt{\frac{\gamma P V}{M}} = \sqrt{\frac{\gamma R T}{M}} \,, \qquad \text{F.2}$$

where R is the molar gas constant and T is absolute temperature. As γ, R and M are constants for a given gas, it follows that the velocity of sound in a gas is independent of pressure if T remains constant. The velocity of sound in deuterium is 890 m/sec (Weast, 1981, p E–45) and a pressure transient will propagate at this speed. Expressing it roughly, the wave will travel at about 1 mm/μsec and at this speed, the gas density build-up at the cathode will not dissipate in the time scale of the pulse. We might expect it to take many tens of μsec to come back to normal. In addition to the transient effect described above, the input of energy to the cathode during the current pulse tends to reduce the average gas density in the cathode box as a result of the rise in cathode temperature. Under the conditions of operation experienced by the NGTS in Chapter 3, the cathode may have reached temperatures of several hundred degrees centigrade, especially as it was isolated thermally in the glass envelope. Thus, at the operating temperature, the gas density may have been reduced to as little as half its room temperature value.

Reference.

Tabor D., *Gases, Liquids and Solids*, 2nd Ed., CUP, Cambridge (1979)

Weast R.C., *CRC Handbook of Chemistry & Physics*, 62nd Ed., CRC Press, Inc. Boca Raton, Florida (1981)