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TARANTULA - A 100 kV PINCH DISCHARGE APPARATUS FOR STUDYING SHOCK WAVES

W. R. BELL
A.E. BISHOP
H. J. CRAWLEY
G. D. EDMONDS
J. W. M. PAUL
J. SHEFFIELD

Culham Laboratory,

Culham, Abingdon, Berkshire

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by

W.R. Bell, A.E. Bishop, H.J. Crawley,
G.D. Edmonds, J.W.M. Paul, J. Sheffield

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ABSTRACT

An experimental apparatus for research on powerful shock waves in a plasma is described. The shock waves are produced by the cylindrical compression of a plasma by the pinch effect.

The experiment is performed in a fused silica discharge tube 1 m long by 0.5 m bore. An initial axial magnetic field of up to 0.5 Wb/m^2 is provided. A low pressure gas in the tube is pre-ionized by using various capacitor discharge circuits.

A high voltage is then applied inductively between the end electrodes of the tube from a low inductance circuit. This circuit which stores up to 100 kJ at 100 kV is switched by 40 spark gaps and can deliver up to 1 MA with a peak dI/dt of 2.5×10^{12} A/s. These high currents generate large impulsive forces which, without care, could damage the fragile silica tube. This tube is held in place by silicone rubber which also provides the main insulation.

The design and operation of the apparatus are described with particular emphasis on the two major problems encountered; (a) switching the 100 kV circuit and (b) providing insulation and support for the silica tube.

U.K.A.E.A. Research Group,
Culham Laboratory,
Nr. Abingdon,
Berks.

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1. INTRODUCTION

This paper describes the technological design, construction and commissioning of an experimental apparatus for research on shock waves in a gas discharge plasma. This subject is of particular interest for controlled thermonuclear research because a shock wave can rapidly heat a plasma, through which it passes, to thermonuclear temperatures. For these conditions an unusual type of M.H.D. shock wave, the collisionless shock, was predicted theoretically. Such shocks have been observed and studied using the Tarantula apparatus.

A shock wave is produced when a gas or plasma is compressed sufficiently rapidly. Such a rapid compression of a plasma can be obtained when a high current gas discharge contracts under the pressure of its own azimuthal magnetic field ('pinch effect')(1). The presence of an initial axial magnetic field helps to stabilise the final plasma column and allows studies to be made of the shock under varying conditions. On the basis of low power experiments at Harwell(2,3), which demonstrated the basic dynamics of the shock pinch without producing appreciable shock heating, a more powerful shock heated linear pinch, Tarantula, has been constructed at Culham.

The physics performance of Tarantula has been predicted by digital computation using measured circuit parameters and the results indicate that an appreciable proportion of the plasma would be heated to over 10^6 deg.K.

The starting conditions for the rapid compression are an almost fully ionized plasma with electron number density about $10^{21}/m^3$, electron temperature about 2×10^4 deg.K and impurity less than 1%. During the compression the plasma resistance can be neglected compared with inductive effects. The inductance of the plasma column depends on its radius and therefore increases as the plasma is compressed inwards. Consequently the driving voltage is given by

$$V = \frac{d}{dt}(Li) = L\frac{di}{dt} + i\frac{dL}{dt}$$

where L and i are the instantaneous plasma inductance and current respectively.

To obtain the maximum amount of shock heating it is necessary to accelerate the plasma rapidly to a high velocity and to maintain this velocity over the time of the pinch. The acceleration phase depends on the rate of change of current, and as initially the current is zero it can be seen that this requirement of rapid acceleration is met by having a low starting inductance and a high voltage. The acceleration phase finishes when the current becomes constant. Then the first term in the equation above goes to zero and the applied voltage is driving the changing inductance. This corresponds to the contracting plasma column and a high voltage is required to maintain a high steady collapse velocity.

This paper is concerned with the technological problems encountered in building an apparatus to achieve these conditions.

2. GENERAL DESCRIPTION OF THE EXPERIMENT

The discharge takes place between metal electrodes in a fused silica tube which is evacuated and then filled with specific gases (e.g. hydrogen or deuterium). The silica tube is surrounded by a close fitting metal conductor to which it is bounded with cold setting silicone rubber. The assembly is shown in Fig.1.

The discharge sequence (Fig.2) is started by producing a uniform axial magnetic field, at the peak of which the gas in the tube is ionized and preheated by the passage of an axial current between the electrodes, the current being too low to produce a pinch. Before this gas current can flow it is necessary to produce electrical breakdown of the gas. This breakdown is initiated either by a ring of 'ignitors' (sparking plugs) in the cathode or by a high voltage preionizer connected between the electrodes.

The main pinch is then established by discharging a fast voltage capacitor bank into the initial plasma created by the preheat. A thin skin current forms near the wall and pinches towards the axis compressing the initial plasma. The main capacitor bank is inductively coupled to the discharge so that the electrostatic potential does not appear on the plasma. The capacitor bank discharge current flows up the close fitting metal cylinder 'A' (Fig.3) and returns in parallel down both the 'earthy' outer metal cylinder 'B' producing the primary magnetising flux Φm, and the 'earthy' plasma column with flux Φ_s forming the secondary. The proportion of the total current in the two circuits is determined by their relative inductances. As the plasma pinches the inductance of the plasma circuit increases and an increasing proportion of the total current flows in the outer cylinder. The system is designed so that after the acceleration phase the currents will distribute so as to maintain an approximately constant current in the plasma.

The final design figures, (Table I) were chosen by considering both the physics requirements and the technological problems.

TABLE I

Discharge tube;	length 1m, diameter 0.5m
Initial gas;	hydrogen or deuterium at 1-100 m torr pressure
Initial axial magnetic field;	0-0.5 wb/m^2
Pre-heating current;	100 kA
Pinch current;	200-500 kA
Initial di/dt at 100 kV;	2.5×10^{12} A/s
Initial circuit inductance;	40 nH

The apparatus can be operated either manually or automatically on a three minute cycle. Special control and monitoring features have been incorporated as well as special facilities for measurements on both the apparatus and the plasma itself.

At the time of writing the whole assembly has been operating successfully at 50kV for many thousands of discharges. The results of physics experiments, which show good agreement with theory, have been reported(4). All the components have been tested successfully up to 100kV and it is expected to operate at this voltage soon.

3. DISCHARGE TUBE ASSEMBLY

The main components are the fused silica discharge tube with close fitting metal cylinder and outer metal can, the collector plates for the input coaxial cables, the vacuum system, the coils producing the axial magnetic field, the ignitor units and the diagnostic ports and probes. (Fig.1)

3.1 Discharge Tube

The most important design consideration was to produce a tube which would operate at 100kV but with as low an inductance as possible. The diameter was made large, 50cms, to give a reasonable radial distance for the investigation of shock propagation and shock front structure, and the choice of length, 100 cm, was a compromise between keeping the axial electric stress high and preventing the electrodes from interfering with the properties of the discharge. The wall thickness of 1-1.5cm was chosen to give adequate mechanical strength coupled with a sufficiently small inductance. The system as a vacuum vessel is designed to attain a base pressure of 10^{-7}torr.

The first tube was made of fused silica because this had been shown in an investigation at Culham Laboratory to be the best insulating material to withstand the peak thermal shock loading, 3 joules/cm^2, which occurs when the plasma touches the tube walls. The external surface had to be ground to give an accurate fit. It was decided to leave the bore of the tube unground partly because of the difficulty of the grinding operation and partly because of the possibility that the vacuum properties of the material might be affected. In the manufacture of these tubes the inner surface acquires a dense glazed character and porosity is likely to occur to an increasing extent towards their outer surface. Although electrical grade porcelain is thermally inferior it has proved to be easier to grind the inner surface to the precise dimensions required. A second assembly is now available with a porcelain tube which is ground on both inner and outer surfaces to provide a 1 cm thick wall.

The choice of the main 100kV insulation was governed not only by the dielectric strength of the insulating material, but by the difficulty of holding the various parts of the system in the correct position relative to one another. Also, the method of assembly had to be such that it can sustain fairly large forces due to the impulsive electromagnetic fields. Three methods of insulation were considered, gas, oil and solid insulation.

With gas or oil insulation there remains the problem of fastening the high voltage parts of the machine together. The self healing properties offer no advantage as the energy released at failure would irrevocably damage the machine. Further, even a gas such as SF_6 would have to be contained under two or three atmospheres of pressure and oil, although at atmospheric pressure, would transmit the rapidly rising stresses as if it were a solid. Gas and oil were therefore rejected.

The main difficulty with the use of solid insulation is the elimination of small voids in regions of high electric stress. This applies to insulation both pre-formed and cast in situ. The former of these was rejected because the problem of fitting pre-formed solid insulation sufficiently well to exclude all air from regions of high stress was considered to be too difficult. It was therefore decided to investigate the possibility of using some form of cold setting insulation which could be cast in situ.

Two such solid insulation materials were studied - epoxy resin and silicone rubber. Both of these by bonding to the surface would provide mechanical fixing of the assembly. They both have a high electric strength and would allow a sufficiently small insulation thickness to satisfy the low inductance requirements of the apparatus.

Preliminary tests on epoxy resin indicated that it would be difficult to guarantee a crack-free cast, and even if this were achieved, there was always the possibility that cracks might develop in the insulation due to mechanical stressing during the operation of the machine. The problem of cracking is associated with the high exothermic reaction during polymerisation. Attention was therefore turned to silicone rubber.

Small scale insulation tests confirmed that adequate electric strength was obtainable from silicone rubber samples 6 mm thick and a half scale simulation of the electrical geometry of the assembly showed that this material would provide the solution to the insulation problem. The tests are listed in Appendix A.

The trade literature and development tests showed that ths basic silicone gum will dissolve a large proportion of its own volume of air (approximately 20%). Consequently if the uncured gum with silica flour filler is sufficiently well outgassed, and admitted into the insulation region under vacuum, permanent voids are unlikely. However the vacuum filling procedure put a number of additional design requirements on the assembly.

Measurements in the plasma required two radial probe ports. These were provided by bonding two short tubes with epoxy resin into tapered holes lapped in the wall of the discharge tube. Electrical tests were carried out on the strength of such a joint and it was found to be satisfactory.

Current is fed to the assembly by 50 cables which are terminated on the collector plate (40 for the shock bank and 10 for the preheat bank). The cable terminations are resistively graded with potassium dichromate solution to produce a constant electric gradient along the cable surface. A grading length of ten centimetres was found to be adequate for a ringing voltage of ± 100 kV.

The large forces experienced by various components of the assembly are discussed in Appendix B. The most dangerous stress is the concentration of the hoop stress at the probe ports. This should not exceed 150 p.s.i. which allows a safety factor of over three on the tensile strength of fused silica.

Vacuum pumping was by a nine inch oil diffusion pump with a liquid nitrogen cooled trap offset from the bottom of the tube so that optical diagnostics could 'look' axially through the discharge. The tube is pumped down after each discharge and then isolated. During the pump down a predetermined quantity of gas is introduced into a transfer vessel by means of a time controlled leak. This gas is then transferred to the discharge tube. The repeatability of the discharge tube pressure over the range 1-100 m torr is 2%.

3.2 Axial Magnetic Field System

The experiment requires an axial magnetic field variable from

0-0.5 wb/m^2, uniform in magnitude within 2% over the whole of the discharge tube including the electrodes, and constant in time over the period under investigation (500 μsec if the preheating system is included).

The field is produced by coils outside the close fitting metal cylinder and partly inside and partly outside the earthy outer cylinder. The field, therefore, has to penetrate these components and the criterion used in the design was to make the time constant of the axial field much greater than the penetration time constant of these components. The components were manufactured from non-magnetic 18/8/1 stainless steel (electrical resistivity 50×10^{-4} ohm-m) as thin as possible but strong enough to prevent mechanical collapse. The time constants of the various components finally used were about 1 msec. It was therefore necessary to keep the rise time of the magnetic field considerably longer than this. A steady state would have been ideal, but the extra difficulty in water cooling the coils was not justified. Furthermore, 8 kV capacitors were readily available. Analysis showed that it was simpler to use the 8 kV capacitors directly on to the axial field coils and insulate for 8 kV, rather than use a step down transformer and insulate for some lower voltage. The current waveform finally chosen rose sinusoidally in 20 msec and decayed exponentially with a time constant of 20 msec.

The axial field was produced by an array of lumped coils. To make the field uniform over the length of the discharge it was necessary to extend these coils axially beyond the electrodes. The coil sizes and position were determined using a digital computer and the measured results showed a field uniformity within 2%. Each coil was totally enclosed in a thin stainless steel casing which was extended radially inwards at one point to enable the inter coil connecting leads to be carried close to, but insulated from the inner cylindrical can. This screening was designed to protect the inter turn insulation of the coils from flashover which might be caused by the linkage with the magnetising flux.

4. AUXILIARY CAPACITOR BANKS

Five separate power supplies are used on the experiment. Each consists of a bank of high voltage capacitors which is charged slowly and discharged rapidly by means of ignitrons or triggered spark gaps.

1. The axial field bank: to provide a uniform field in the discharge tube.
2. The pre-ionization bank: to fire thirty sparking plugs, inserted in the lower electrode and so provide initial ionization of the gas.
3. The alternative pre-ionization bank: to apply a high voltage discharge between the two electrodes.
4. The pre-heat bank: for pre-heating the gas to a suitable temperature for applying shock heating.
5. The 100 kV shock producing bank: this will be described separately.

The capacitor banks are charged from the mains through high voltage transformer/rectifier sets. To protect these sets from voltage oscillations RC filters are inserted in the high voltage line. During operation the capacitor banks are connected to earth at the discharge tube only, and the charging current for the banks flows through this point. Earths are applied to the capacitors directly when it is required to make them safe. (Two completely separate systems are used to ensure adequate safety). The resistors used in charging or dumping of capacitor energy must be able to absorb the full energy stored in the capacitor bank. Liquid filled resistors which are used for this purpose were developed because of their ability to withstand high voltages across a short length, their capacity to absorb large amounts of energy and because it is comparatively easy to change their value by altering the concentration of the solution. The electrodes are copper and the electrolyte aqueous copper sulphate solution$^{(5)}$.

The pre-ionizing bank current is allowed to oscillate, but the axial field bank and the pre-heat banks are provided with means of maintaining the directions of the currents by ignitrons which close directly across the load when the capacitor bank voltage is zero ('clamp' or 'crowbar'). The current then decays with the time constant of the load circuit (Fig.3). The voltage across the axial field bank is monitored by a potential divider and the firing point is sensed electronically. On the pre-heat bank the 'clamp' ignitrons are fired after a preset time interval.

4.1 Axial Field Capacitor Bank

This bank, consisting of sixty 78 μF capacitors rated at 8 kV (allowed voltage reversal 10%), has a total energy storage of 150 kJ. The capacitors are grouped in units of ten and connected together to the charge and discharge busbars, through protective resistors, which are liquid filled. These also serve as charging and discharging wave shaping resistors, and are capable of absorbing the energy of the whole bank in the event of one capacitor going faulty and the rest of the bank feeding the fault.

The bank is discharged and 'clamped' by ignitrons. This circuit is dominated by the load inductance and resistance (60 mH and 1.55 ohms) and the current rises in about 20 msec to a peak value of 1200 amps at 8 kV. A resistor of 390 ohms in parallel with the load insures that the starting ignitron remains conducting until the current through the load has built up to a sufficient value to maintain the arc in the ignitron. Variation of the axial field is obtained by altering the voltage to which the bank is charged. The circuit is shown in Fig.4.

4.2 Pre-ionize Capacitor Banks

A single 0.01 μF capacitor is charged to 15 kV from a constant voltage source through a charging resistor of 2 MΩ. Thus the bank may be fired when required without any detailed control of the charging sequence.

The bank is fired by a simple trigatron atmospheric spark gap as shown in Fig.5. Thirty co-axial output cables go to the discharge tube where the outers are bonded together to earth and the inners are connected each to one of the ring of ignitors (sparking plugs). Reliable operation of the capacitor banks from 7 to 15 kV is obtained with one setting of the spark gap. The discharge current from this bank is allowed to ring and the majoirty of the thirty spark plugs fire simultaneously.

The high voltage pre-ionizer is identical to one unit of the shock bank. It consists of one 0.5 μF 100 kV capacitor, usually operated at about 70 kV, and fired by a triggered spark gap. It is directly connected to the discharge tube circuit as shown in Fig.11.

4.3 Pre-heat Capacitor Bank

This is a bank of 25 μF capacitors rated at either:-

(a) 14 kV voltage, reversal 2 kV, stored energy 50 kJ:

(b) 10 kV voltage, reversal 6 kV, stored energy 25 kJ.

The ratings allow the bank to be discharged in an oscillating manner if charged to 10 kV but if charged to 14 kV the bank must be clamped to reduce the reversal.

The pre-heat bank is connected to the discharge tube via an isolating inductance to avoid damage to the pre-heat bank when the shock bank is discharged. Under the most severe operating conditions a current of 500 kA will flow in the pre-heat circuit.

Due to the limited current capacity of the ignitrons the pre-heat circuit is divided into five sections each consisting of a start and clamp ignitron and four 25 μF capacitors. Current sharing of the ignitrons is ensured by matching the inductances and resistances of each section. The ignitrons have molybdenum anodes which enables large oscillating currents to be carried, which is an unusual duty for ignitrons.

The main circuit of the pre-heat bank is shown in Fig.6. The isolating inductance can be adjusted to give pre-heat current rise times variable from a minimum of 15 μsec.

5. 100 kV SHOCK CAPACITOR BANK

The requirement of high voltage and low inductance described in the introduction made the technology of this bank the most difficult and all the components had to be specially developed. The bank is made up of forty 0.5 μF, 100 kV low inductance capacitors each fitted with a start switch and each connected to the discharge tube by 1.8 metres of low inductance cable, the system being coaxial throughout. (Fig.1) The inductance of each element is as follows:-

Capacitor/start switch	340 nH
Cable (1.8 metres)	240 nH

Thus the total inductance of forty units in parallel is 14 nH. The equivalent circuit for the shock bank discharge is shown in Fig.7.

The capacitors are built of twelve tubular elements in series, each consisting of wound paper dielectric impregnated with castor oil. The whole is enclosed in a metal cylinder which acts as a return conductor and is provided with a rear-end charging termination. The front end is then free to take the start switch. From acceptance tests the expected life of these capacitors is over 10,000 discharges at 100 kV with 89% voltage reversal.

It is required that the shock bank should operate in the range 30 to 100 kV and that the spread in closing times from switch to switch should be less than 30 nsec to prevent damage. The most suitable switches for this duty are swinging cascade spark gaps. These are operated with fixed gap spacings and the voltage range is achieved by changing the operating pressure. (While it is possible to work at atmospheric pressure and alter the gap settings as the capacitor voltage (V_c) is changed, this is very inconvenient when a number of switches are used). Compressed air is employed to pressurise the switches, and is dried to a dew point of - 30°C (0.3 g/m^3) to reduce the risk of surface flashover of the switch insulation.

The design of the start switch is shown in Figs.1 and 8. There are three main electrodes, one is connected to the capacitor, another is attached to the output cable (initially at earth potential) and the third electrode, situated between these two electrodes, is held at an intermediate potential. For convenience it was decided to make this voltage half that to which the capacitor is charged (i.e. $V_c/2$) The initial inter-electrode spacings were set to values established in preliminary tests. The discharge circuit and triggering circuit are shown in Fig.9.

The operating pressure was chosen high enough to give a large margin above static breakdown but at the same time low enough to give low breakdown times with small spread. The major insulation of the switch was designed to be out of the main blast of the arc when the switch was conducting and away from the regions of high stress. Electrical grade porcelain was chosen and shaped so as to give low surface stress. The electrodes were made of brass, without any special surface preparation except sand blasting which was intended to stop the erosion by the arc altering the characteristics of the switch after a number of firings.

The output termination was required to have a low inductance and so was made as short as practical. To achieve this the insulation of the output cable was graded by means of a resistive sheath of liquid acting as a continuous potential divider. The liquid was aqueous potassium dichromate solution.

The discharge of the shock bank is oscillatory with a maximum charge flow of half a coulomb per switch on each discharge. The maximum peak current through each switch is 30 kA, giving a total shock bank current of 1.2 A. The proto-type tests for these start switches have been previously reported(6). Since then a satisfactory life test of more than 10,000 discharges by a single switch with a peak current of 80 kA at 100 kV has been completed.

The intermediate, or trigger electrodes of all forty switches are connected through a bypass resistor and blocking capacitor in parallel, and a trigger cable to one master triggering switch. (Fig.9) This master switch is charged to half the shock bank voltage, and the bypass resistor (1 MΩ) allows this voltage, $V_c/2$, to appear on the intermediate electrode. The blocking capacitor passes the fast triggering pulse from the master switch to fire the start switches, but prevents current being drawn from the main circuit into the triggering circuit.

To trigger the start switches the master switch is closed and this shorts the ends of the forty charged trigger cables. A negative pulse of half the capacitor voltage, $V_c/2$ (rise time 20 nsec) passes down the trigger cables. At the start switch it sees a high impedence and therefore doubles in value. The double voltage, - V_c, is impressed on the intermediate electrode driving it negatively towards - $V_c/2$, as shown in Fig.2. This raises the voltage across the first stage to about three times its standing voltage, exceeding the breakdown voltage of the gap by a large margin and causing the first stage to breakdown rapidly. When this has occurred the intermediate electrode is charged to the same voltage as the capacitor, V_c, and the voltage across the second stage, which is double its standing voltage, is sufficient to cause its rapid breakdown.

The total breakdown time, which varies with pressure, is in the range 10 to 100 nsec. This time is made up of the formative time lags of breakdown of the two stages. The statistical time lag is eliminated by ultra violet illumination which is produced at the same time as the trigger pulse is applied. The intermediate electrode is connected to the trigger circuit by a small resistor, 20 kΩ. Inserted in the electrode is a tungsten pin which is directly connected to the trigger circuit. On the leading edge of the pulse a voltage develops between the tungsten pin and the intermediate electrode because of their differing response times, and the subsidiary gap between pin and trigger electrode breaks down, illuminating both the first and second stages with ultra violet light. Small modifications which were made at the time of commissioning the bank are described in Appendix C.

The master switch used for triggering the bank was a specially designed two electrode spark gap with a subsidiary trigger electrode. Fig.10 shows the construction of this switch . The subsidiary trigger electrode is designed to give illumination of the gap with simultaneous overvolting to produce rapid breakdown with small spread in breakdown times. With this design breakdown times of 50 ± 6 nsec have been achieved.

The wave forms of current and voltage in the various component circuits (e.g. shock bank, pre-heat bank, pre-ionization bank) when connected as a complete assembly have been calculated by analogue computer for both normal and fault conditions. The complete circuit is shown in Fig.11.

6. SAFETY

Because of the lethal nature of the electrical equipment and the danger from components which can fail with explosive violence, great care was taken to provide adequate safety, while allowing convenient access for experimental work.

All of the equipment apart from the control and screened rooms is enclosed by a high metal partitioning which is bonded to earth. Access is by keys which are interlocked with the isolator of the power supplies to the high voltage equipment. Opening the isolator causes fail-safe dumping of the energy in every capacitor bank and also shorts and earths the capacitors. If the main earthing switches fail a back-up system allows electrically operated solenoid bolts (gravity controlled fail-safe) to fall locking every door and preventing access.

7. OVERALL CONTROL AND INSTRUMENTATION

Control of the machine is based on a cycle time which can be varied between 1 and 5 minutes, but which is normally 3 minutes. The cycle time is determined mainly by the time taken to perform the following tasks:-

(a) Pump down the tube to a pressure of 10^{-6} torr
(b) Purge and re-pressurise the spark gaps

(c) Re-charge the capacitor banks

This overall timing sequence is controlled by a rotating drum timer which allows the timing and duration of each operation to be altered independently. After the charging period a 'fire' signal initiates the electronic triggering system situated in the screened room.

This system provides a sequence of 200 V trigger pulses which can be delayed, one signal relative to another by any time from 1 μsec up to 100 msec with repeatability of about 1%. These 200 V pulses pass through isolating transformers and trigger the 15 kV hydrogen thyratrons which in turn trigger the atmospheric trigatron spark gaps and the pressurised master spark gap directly. The ignitron cathodes are at bank voltage and therefore have to be triggered through high voltage isolating pulse transformers.

In addition interlocks are provided which enable the firing sequence to be interrupted if the previous banks in the sequence have not fired correctly. Any part of this interlocking may be used or over-ridden at will.

7.1 Facilities for Experimental Measurements

The experiment involves measurements of a wide range of transient signals with amplitudes as low as a millivolt. These are subject to electrical interference from the machine. The whole machine was made coaxial or screened in order to reduce the level of electrical interference. All signals are taken from their source by 100 ohm coaxial cables housed in copper tubes which form an integral part of the outer of a doubly screened room. This contains the electronic sequencing system and the measuring equipment, mainly oscilloscopes. There are 8 oscilloscopes (maximum sweep speed 20 nsec/cm) each provided with an automatic camera controlled from the drum timer.

Earth loops have been eliminated by using a single earth point for the machine, which is also the earth point for the screened room, and triggering through isolating pulse transformers.

7.2 Monitoring

The firing sequence is monitored to ensure that no capacitor bank is fired until the previous one has correctly performed its task. Pick up coils are inserted in the silicone rubber insulation between the metal discharge tube and the fused silica liner at the top of the tube. Signals from these gate the electronic boxes which give out signals for the next operation. If the appropriate signal does not arrive the whole sequence is stopped. If required these interlocks can be bypassed.

The spread in the firing times of the start switches on the shock bank must be less than 30 nsec to avoid damage from transients. These and other transients were calculated using an analoge computer. It is therefore necessary to identify any start switch which is malfunctioning. A monitor has been constructed to do this which receives 40 incoming signals from loops placed inside each pressurised gap, and generates a gating pulse from the first signal received. The width of this gate may be adjusted between the limits of 10-100 nsec. Signals which arrive within the gate width are indicated to have fired correctly; any signals later than this are rejected. If just one signal is received and the remainder of the signals are late, then that gap is deemed to have fired untriggered, i.e. spuriously. Using this instrument the spread in the breakdown time can also be measured.

The 100 kV capacitors are monitored after each discharge to detect a faulty unit prior to charging. The monitor injects a signal at 1 kc/sec into a group of ten capacitors while they are short circuited.

The impedance of each group of ten capacitors is measured by comparison with a standard circuit of known capacitance, the resistive components being balanced out. Changes in capacitance of 10% (one capacitor in a group) can be detected.

In order to study the fast transient voltages, capacitive voltage dividers are provided on a number of the cables.

8. COMMISSIONING

As is usual on machines of this type a considerable time was spent making every control perform satisfactorily. One by one the various discharge circuits were tested, initially on simulated loads and later on the complete discharge tube assembly.

Serious problems were encountered with the insulation of both the discharge tube and the 100 kV spark gaps. However, these were eventually overcome by minor modifications to these components. In particular the spark gaps had to be operated at a higher pressure with a smaller electrode spacing. See Appendix B.

With a new discharge tube assembly and the equipment running satisfactorily, the physics programme was commenced, and results have been given elsewhere(4). A thorough investigation of the plasma behaviour is under way with the shock bank operated at 50 kV. So far 5000 discharges have been carried out. A space-time streak diagram of the plasma collapse is given in Fig.12, which shows good agreement with theory. When this phase of the investigation is complete and when the more uniform porcelain discharge tube is available the shock bank voltage will be raised to 100 kV.

9. CONCLUSIONS

The present machine was designed to investigate a certain field of plasma physics of interest to the thermonuclear power programme. It has been built to have a life of 10,000 discharges at full shock bank voltage and the insulation has been stressed with this in mind.

This experiment incorporates a number of features which make the assembly unique.

1. The 100 kV capacitor bank with multiple spark gap switching;
2. Vacuum poured silicone rubber for the discharge tube insulation and support.
3. The application of liquid resistors to cable grading and energy dumping.
4. The particular use of inductive coupling

Further technological developments along the lines reported in this paper have been achieved. For example, a 100 kV capacitor/start switch combination with a reduction in inductance from 340 nH to 150 nH and a 100 kV discharge cable with a reduction of inductance from 130 to 72 nH/m have been produced.

10. ACKNOWLEDGEMENTS

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The capacitors and 100 kV cables were developed and manufactured by B.I.C.C. Ltd., at Helsby and Belvedere.

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APPENDIX A

Sample Tests on Silicone Rubber Insulation

The thickness of cold curing silicone rubber on test was about 6 mm, approximately the same as that intended to be used on the experiment. Two test assemblies were used, one with the electrode area of 7 cm^2 and the other 120 cm^2. The results were as follows:-

Smaller assembly

Sample No.	Test Voltage	Time to Breakdown
1 and 2	50 kV rms	30 mins. no breakdown
	80 kV rms	3 mins.
3 and 4	50 kV rms	30 mins. no breakdown
	80 kV rms	60 mins. no breakdown
5	50 kV rms	30 mins. no breakdown
	80 kV rms	60 mins.
6,7, and 8	50 kV rms	30 mins. no breakdown
	80 kV rms	90 mins. no breakdown

Larger assembly

4 samples each	50 kV rms	30 mins. no breakdown
	80 kV rms	60 mins. no breakdown
	Impulse 125 kV peak	10,000 shots no breakdown
	Impulse 140 kV peak	2 failed after 500 shots 2 withstood 10,000 shots

(The impulse was a 250 kc/sec damped wave train with a Q of about 8. The 125 kV impulse produced a stress of 190 kV/cm.)

Half Scale Model

A half size model of the machine's high voltage flange assembly was tested in the following manner:-

1. 100 kV dc. for 45 minutes

2. Impulse test. Wave form as impulse above.

Peak Volts. kV.	75	90	110	115	130	140	150	180	204
Number of shots.	900	1800	1800	2200	1000	1000	1000	1500	20

Failure occurred outside the test area at 204 kV.

Final Machine

A few impulses at 110 kV peak were applied to the final machine without insulation failure.

APPENDIX B

Electro-magnetic Forces on the Discharge Assembly

The component parts of the discharge assembly are subjected to a sequence of forces arising from the various large and changing magnetic fields in their vicinity. The maximum axial force due to the main discharge current was estimated to be about ten tons, with an additional four tons arising from the axial field coils. These presented no design difficulties and are easily sustained by the tie bar construction adopted. (Fig.1)

The most fragile component of the discharge assembly is the quartz vacuum discharge tubeand it was essential to establish what mechanical stresses it would be called upon to withstand during the operating cycle. Calculating the stresses arising from the vacuum is a straight forward matter but those induced by the electromagnetic forces strictly require the analysis of stress waves reflected many times between the quartz and the surrounding current carrying cylinder via the layer of rubber insulation. This problem is complex and would only be essential if the results of more approximate methods suggested an unsatisfactory margin of safety.

The maximum value of both the radial and hoop stresses need to be estimated. The former is associated with the radial propagation and reflection of dilational stress waves through the wall of the quartz while the latter is determined from the maximum amplitude of the radial vibration of the quartz tube.

A dilational stress wave will take some seven or eight microseconds to travel from the metal conductor through the rubber and quartz to the inner face of the quartz tube, whereas the magnetic pressure on the conducting cylinder reaches its maximum in less than one microsecond. If it is assumed that a perfect mechanical impedence match exists at the quartz interface, then it follows that the radial stress could be equal to the maximum applied magnetic pressure. However this stress was found to be very small (about 10 psi).

Although the radial stress is small it is possible for a considerable amount of momentum to be acquired by the quartz liner during the period of the discharge field pressure. This must give rise to radial vibration in which the momentum is absorbed as strain energy with the possibility of large hoop stresses.

Considering the quartz tube as a simple free cylinder in radial vibration the maximum hoop stress is given by:-

$$\sigma_\theta = \rho c v$$

where

ρ is density of quartz

c is velocity of longitudinal stress waves in quartz

v is maximum radial velocity

The velocity v is calculated from the total impulse of the radial magnetic pressure assuming that the momentum is absorbed only by the quartz. The problem is simplified and the requirements made more stringent by ignoring the magnetising current and assuming that peak inductive energy is dissipated by a constant resistance

$$\frac{1}{2} LI^2 = R \int i^2 \, dt$$

where L and R are inductance and resistance; I and i are peak and instantaneous gas current respectively. The radial magnetic pressure can be represented by $p = ki^2$ where k is a constant. This impulsive pressure produces the change of momentum of the quartz tube

$$\rho v d = \int p dt = k \int i^2 \, dt$$

where d is the thickness of the quartz cylinder. Substituting from the above energy relation

$$\rho vd = \frac{L}{2R} kI^2 = \frac{L}{2R} P_{max}$$

where P_{max} is the maximum magnetic pressure and (L/2R) is the effective time for an impulse of this value.

Substituting this velocity, v, into the equation for the maximum hoop stress

$$\sigma_\theta = \rho cv = \frac{L}{2R} \cdot \frac{c}{d} P_{max}$$

However the static hoop stress produced by a static pressure P_{max} would be

$$\sigma_s = \frac{a}{d} P_{max}$$

where a is the radius of the quartz cylinder. Consequently the impulsive hoop stress

$$\sigma_\theta = \sigma_s \frac{L/2R}{a/c} = \sigma_s \frac{\text{(Effective impulse time)}}{\text{(Stress transit time across a radius)}}$$

For Tarantula $L/2R \simeq 10\ \mu S$ and $a/c \simeq 50\ \mu S$ so that

$$\sigma_\theta = \frac{1}{5} \sigma_s$$

For the calculated value $P_{max} = 10$ psi and a ratio $a/d \simeq 25$

$$\sigma_s \simeq 250 \text{ psi} \quad \text{and} \quad \sigma_\theta \simeq 50 \text{ psi}.$$

The tensile strength of fused quartz is about 600 psi so that a factor of safety of about ten exists. However the presence of the port holes drilled in the quartz produces a stress concentration at their edges; ignoring any stiffening effect from the tubes bonded into these holes, the concentration factor should not exceed 3.

Thus the peak stress will be approximately 150 psi with an overall safety factor of about three. Although not generous for a brittle material this was considered to be acceptable for an experimental assembly. Further, the magnetising field, which for simplicity was ignored in this calculation, will have the effect of reducing the radial impulse on the system.

APPENDIX C

Modifications to the Start Switches on Commissioning

The prototype tests on the start switches were all carried out with a single switch firing into a dummy load and these tests are fully reported in reference 6. However during commissioning of the machine, when forty of the start switches were fired in parallel for the first time, three problems arose.

Flashover of the Intermediate Electrode Insulation

On commissioning the forty start switches with the load assembly, the gas discharge was simulated by a tube of stainless steel bolted between the two end electrodes. This gave a fixed instead of a varying gas inductance but greatly simplified the circuit.

However the main discharge voltage appearing, by inductive division, on the intermediate electrode of the spark gap was 95% of the capacitor voltage. The prototype tests were performed with lower effective load inductance resulting in only 78% of the capacitor voltage appearing on the intermediate electrode. Unfortunately this 22% increase of voltage caused sporadic flashover of the insulation of the intermediate electrodes during commissioning.

The voltage on the intermediate electrode during normal operation with a gas discharge was obtained from the calculation of the physics performance using a digital computer. The maximum voltage on the intermediate electrode was found to be 90% of the capacitor voltage and consequently the insulation had to be improved. This was achieved by increasing the operating pressure and reducing the gap spacings to maintain the same breakdown times.

Shattering of the Bypass Resistors

In the course of commissioning, the bypass resistor (a resistive glaze on the porcelain insulator) failed occasionally and this caused the porcelain to shatter destroying the major insulation of the intermediate electrode.

If the switch is fired at the too low a voltage for a given pressure it is possible for the first gap to breakdown without the second gap following afterwards. This means that all the energy stored in the capacitor is discharged into the bypass resistor, shattering it. This condition could occur with the gap spacings as first set in the following manner. (The relevant part of the circuit is shown in Fig.13.)

The breakdown stress of both the first and the second gaps is about 160 kV/cm, at a pressure of 75 psig. (this corresponds with an operating voltage of 100 kV). When triggered the first stage will be stressed to $\frac{3 \times 50}{0.7} = 215$ kV/cm for a 7 mm gap, which is adequate to break it down but the second stage will be stressed to only $\frac{2 \times 50}{0.6} = 167$ kV/cm for a 6 mm gap. This is only just enough to cause breakdown of the second gap. If instead of 100 kV the capacitor is only charged to 90 kV it can be appreciated that the first stage will still be overstressed and will breakdown, but the second stage will not be overstressed and will not breakdown. Of course, if the capacitor were only charged to 50 kV then neither gap would break down and the switch would just not operate; however there would be no damage. There is thus a critical voltage region for any operating pressure where it is dangerous to fire the start switches. This is shown graphically in Fig.14. It was possible during the running of the experiment to attempt to fire the start switches in this region either if the pressure was incorrectly set or if the charge on the capacitor bank was allowed to leak away, taking the bank into the dangerous region, before the start switches are fired.

By reducing the second gap spacing with respect to the first gap, it is possible to ensure that the second gap will be more highly stressed than the first gap, and so the dangerous region is removed.

Variation in the Setting Gaps

When the forty switches were fired in parallel for the first time it was noticed that individual switches were firing correctly but that some were consistently earlier or later than the rest due to their spacings being inaccurately set. In order to make the setting more precise the new centre electrodes were made with flat sides. This did not appreciably alter the performance of the switch.

Conclusion

The voltage flashover of the intermediate electrode insulation made a higher operating pressure necessary, the failure of the bypass resistor made it necessary to have a smaller second gap in relation to the first gap; and the setting of the spacings needed slightly modified intermediate electrodes.

When these changes had been made a new operating curve was obtained for the spacings of 6 mm first stage, 4 mm second stage and the switches have operated with these settings ever since. The two operating curves are shown in Fig.15.

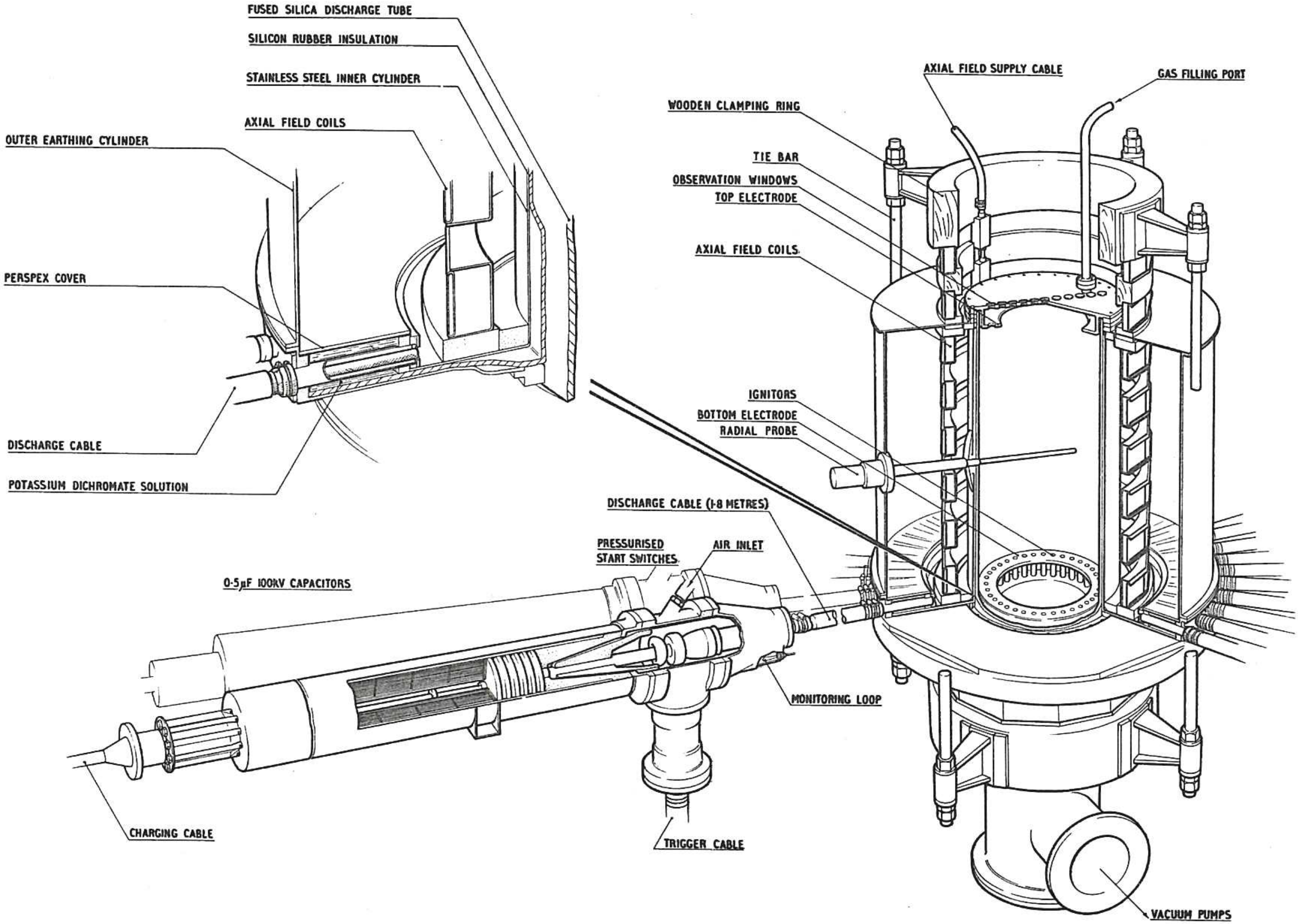

Fig. 1 Main features of the assembly (CLM-P78)

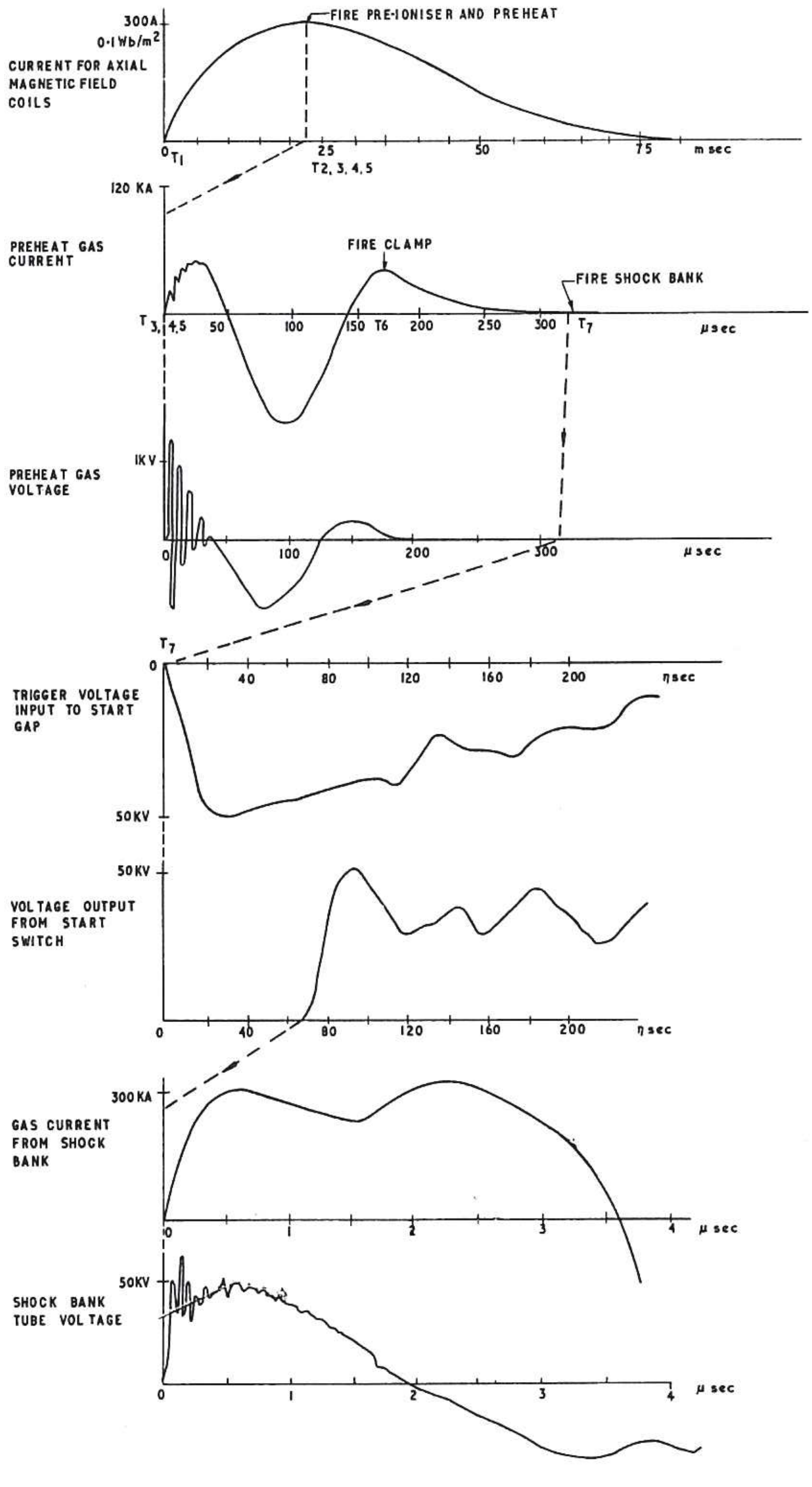

Fig. 2 Main waveforms and discharge sequence (CLM-P78)

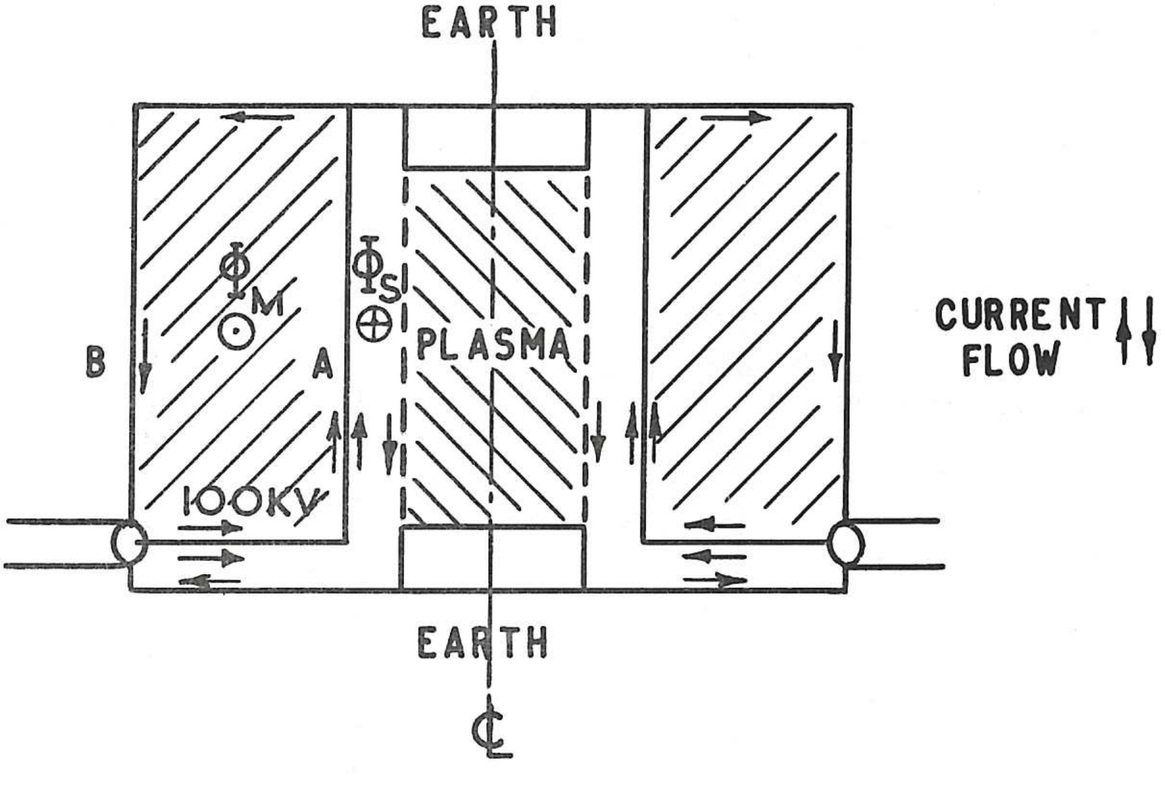

Fig. 3 Inductive coupling (CLM-P78)

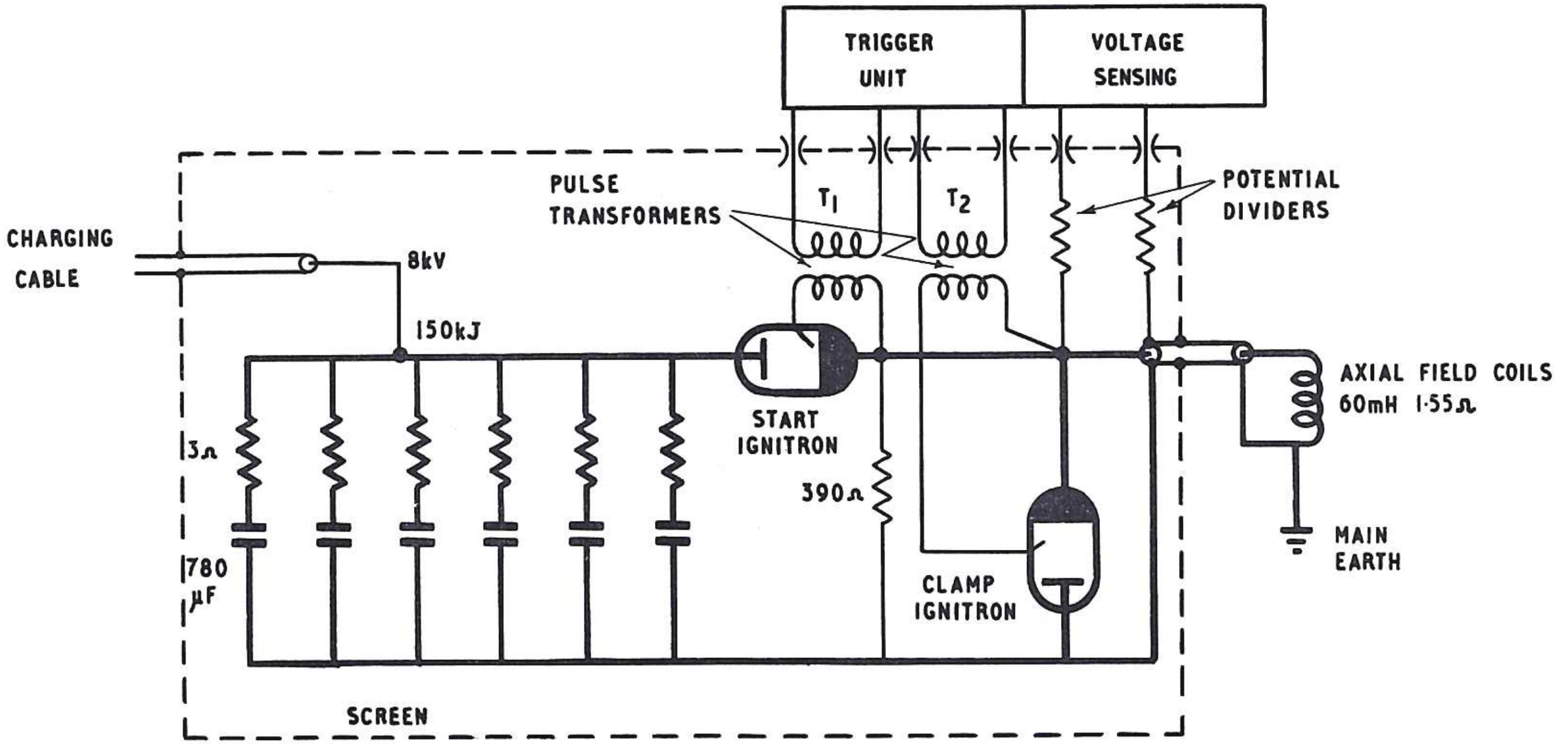

Fig. 4 Axial magnetic field discharge circuit (CLM-P 78)

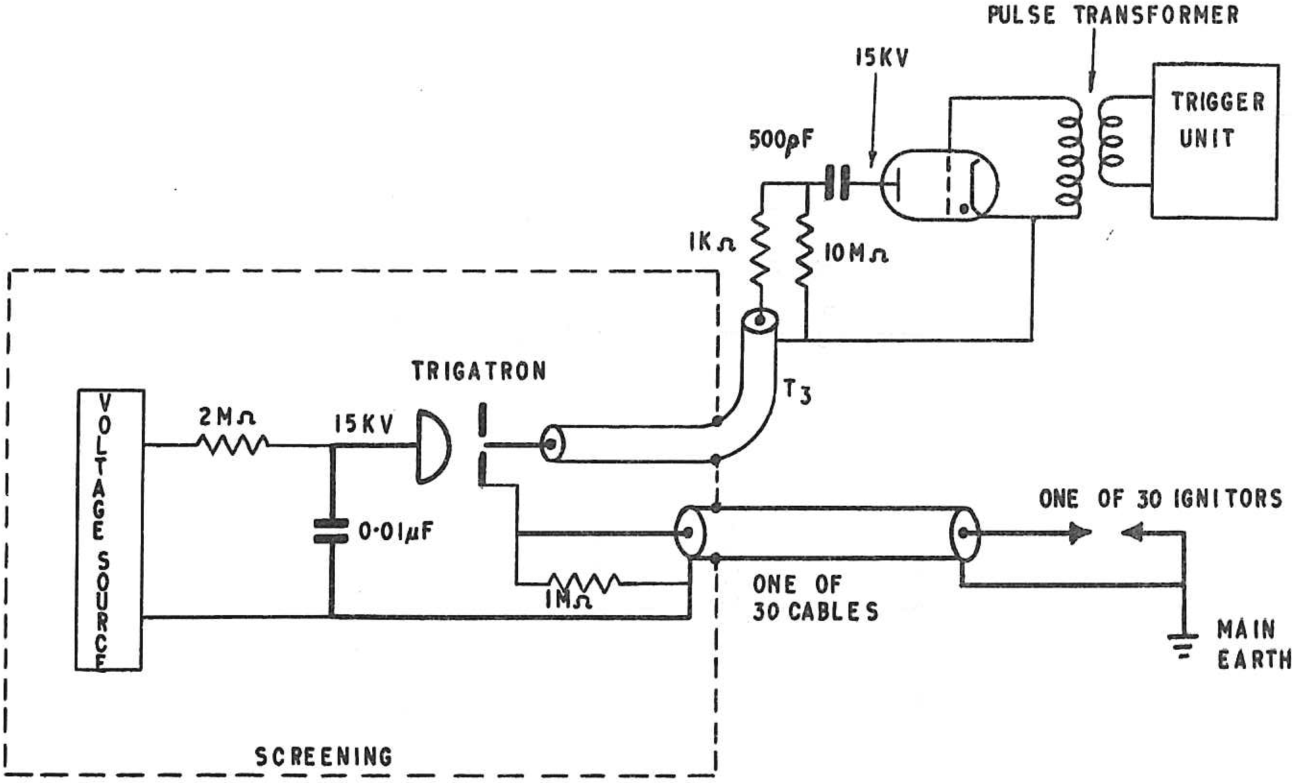

Fig. 5 Ignitor pre-ionization discharge circuit (CLM-P78)

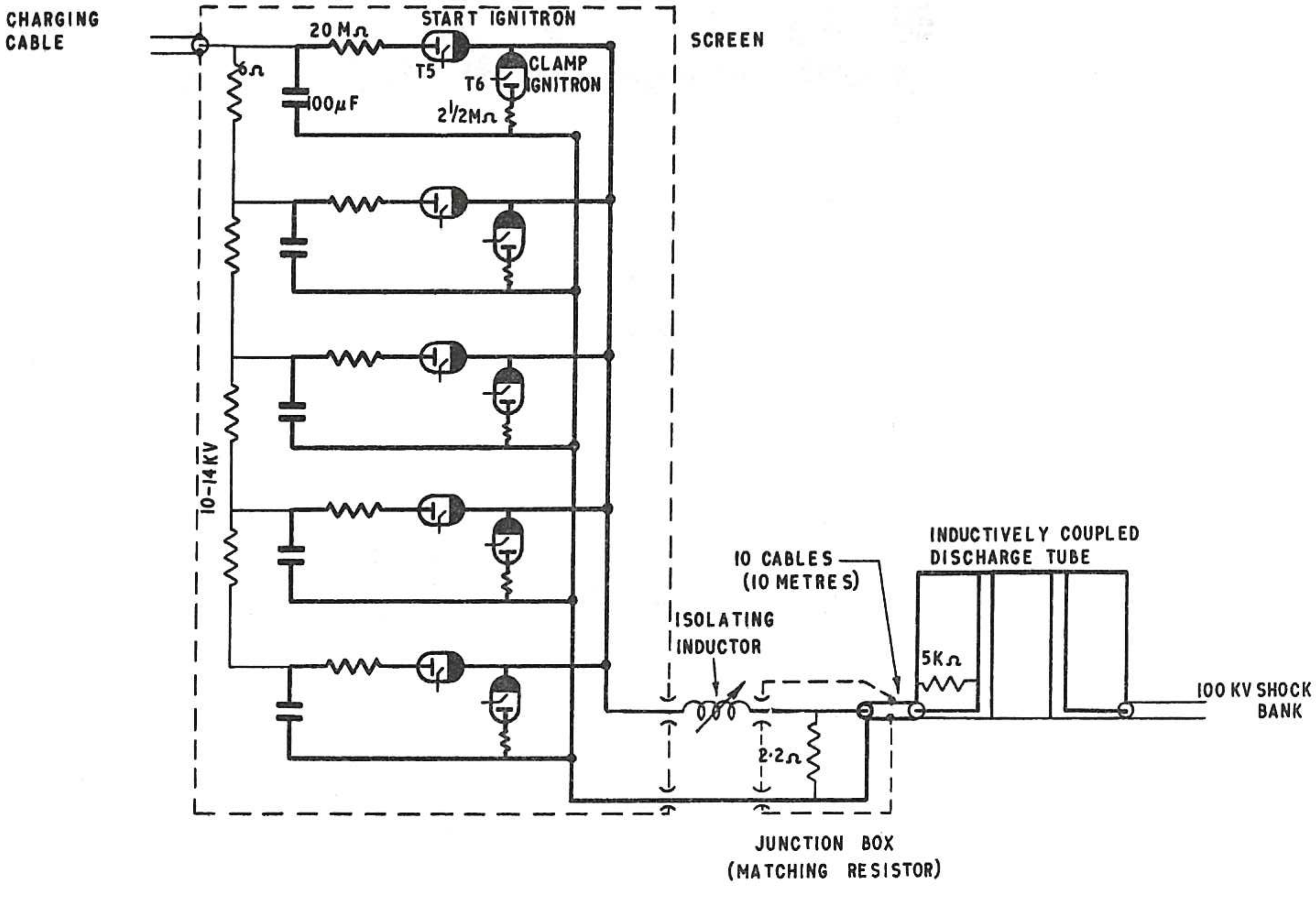

Fig. 6 Pre-heat discharge circuit (CLM-P78)

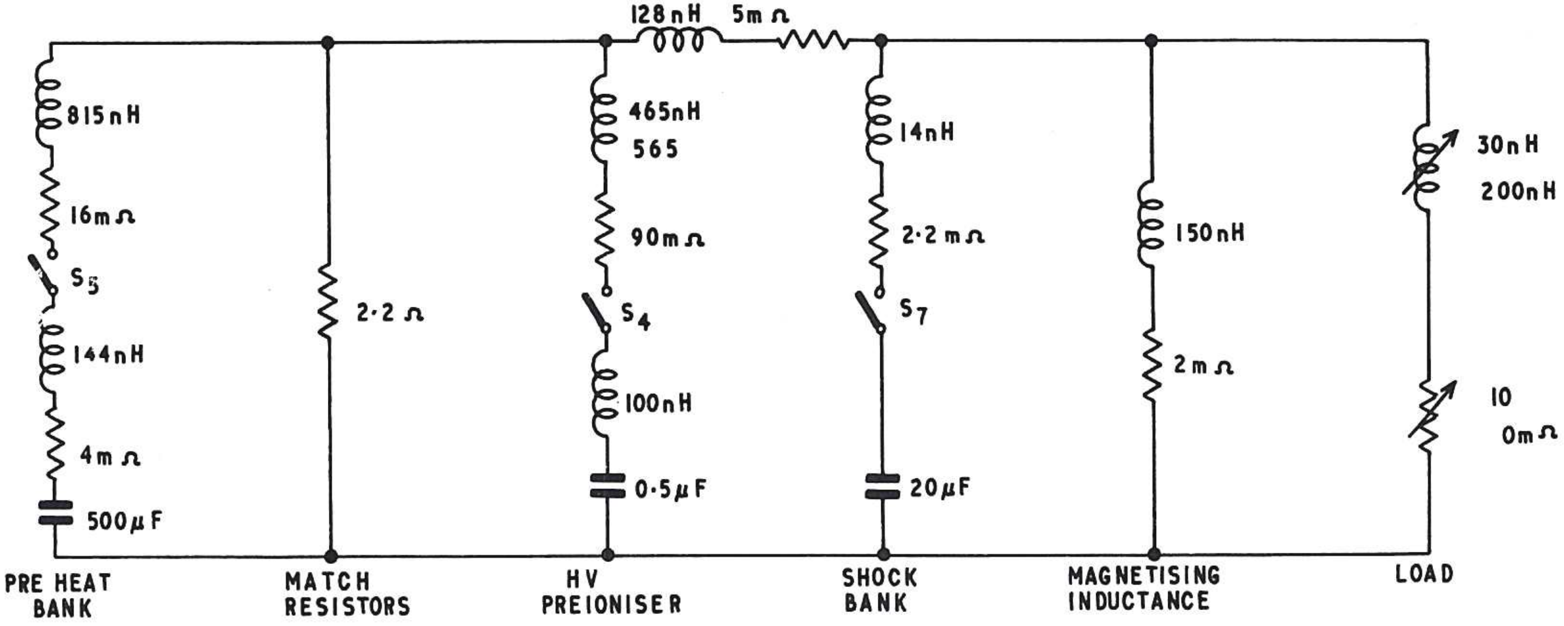

Fig. 7 Equivalent circuit for gas discharges (CLM-P78)

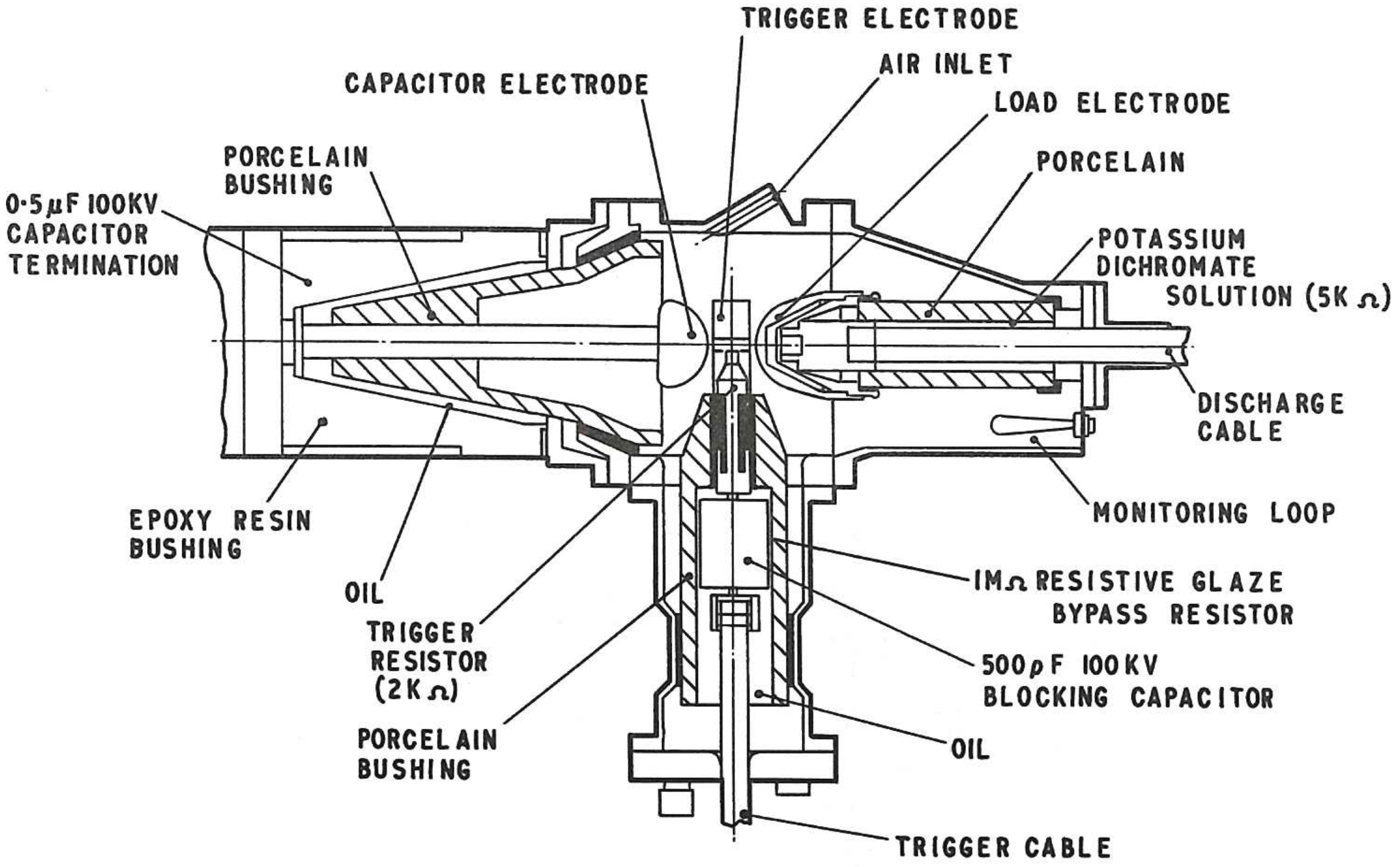

Fig. 8 100 kV start switch (CLM-P78)

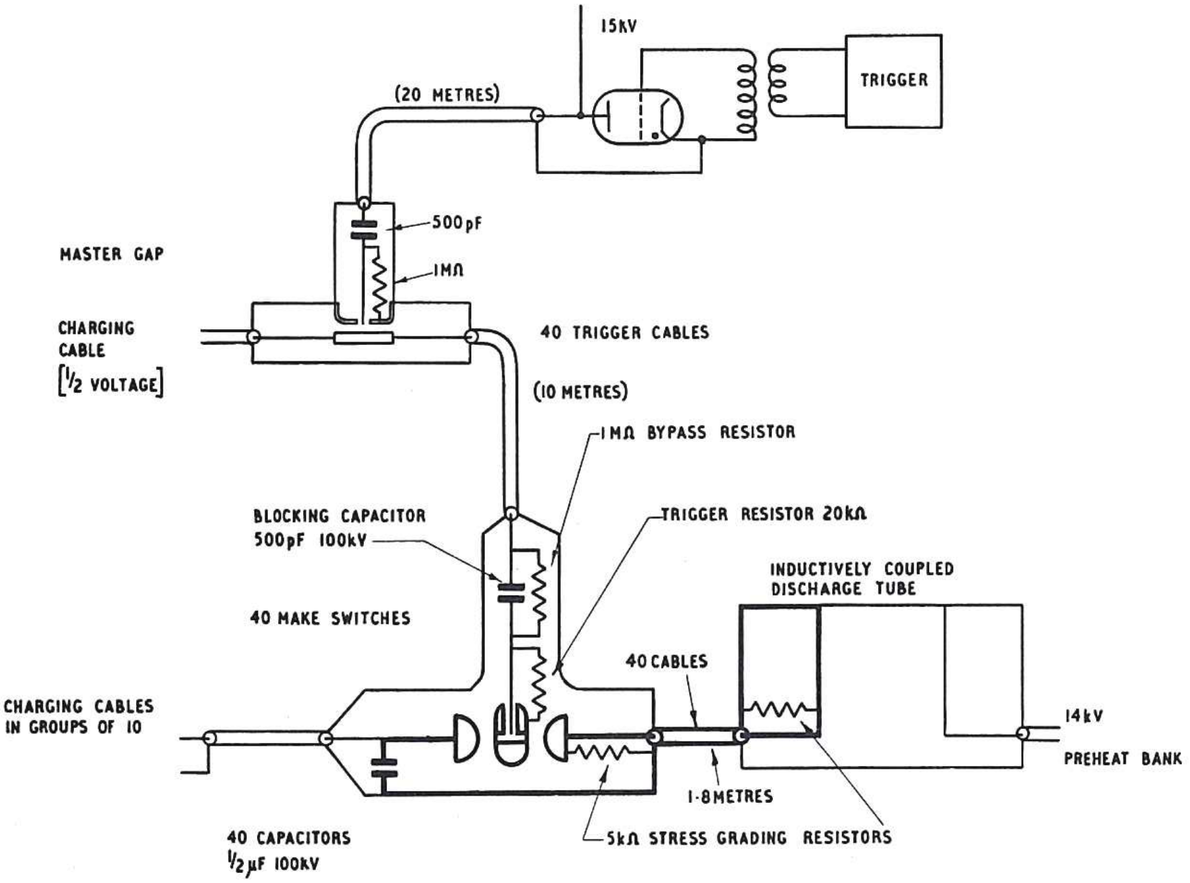

Fig. 9 Triggering circuit for shock-bank (CLM-P78)

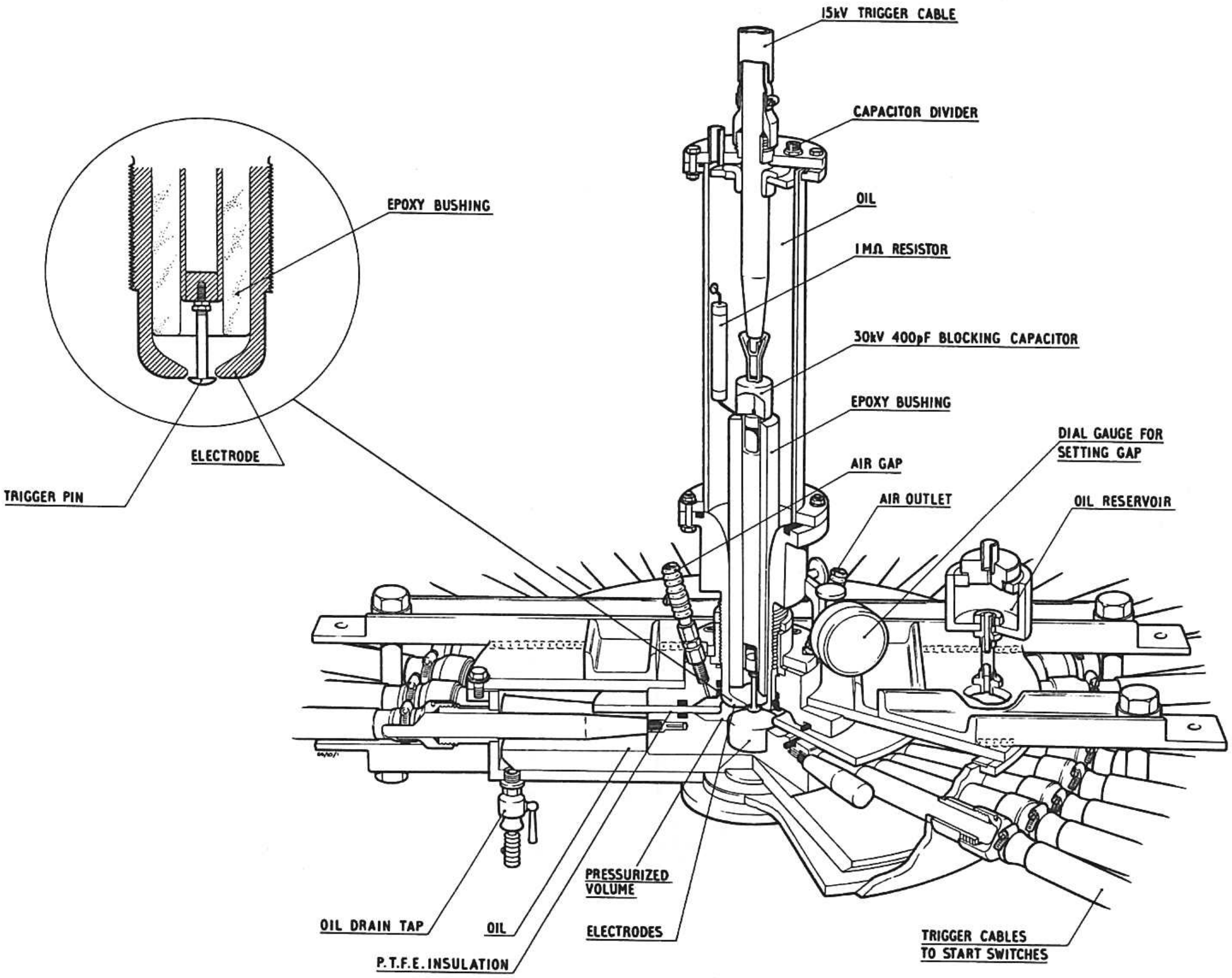

Fig. 10 Master switch (CLM-P78)

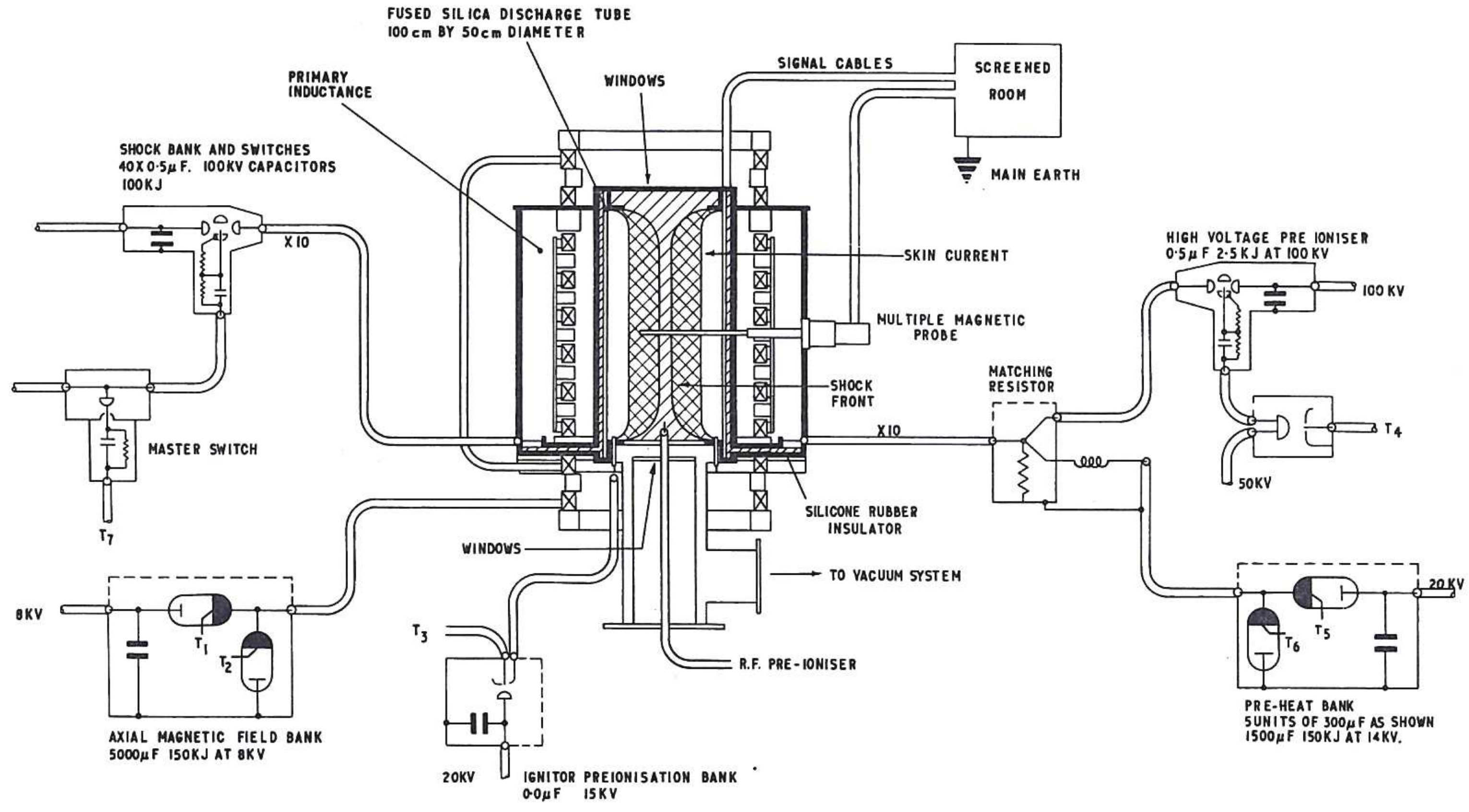

Fig. 11 Schematic circuit of assembly (CLM-P78)

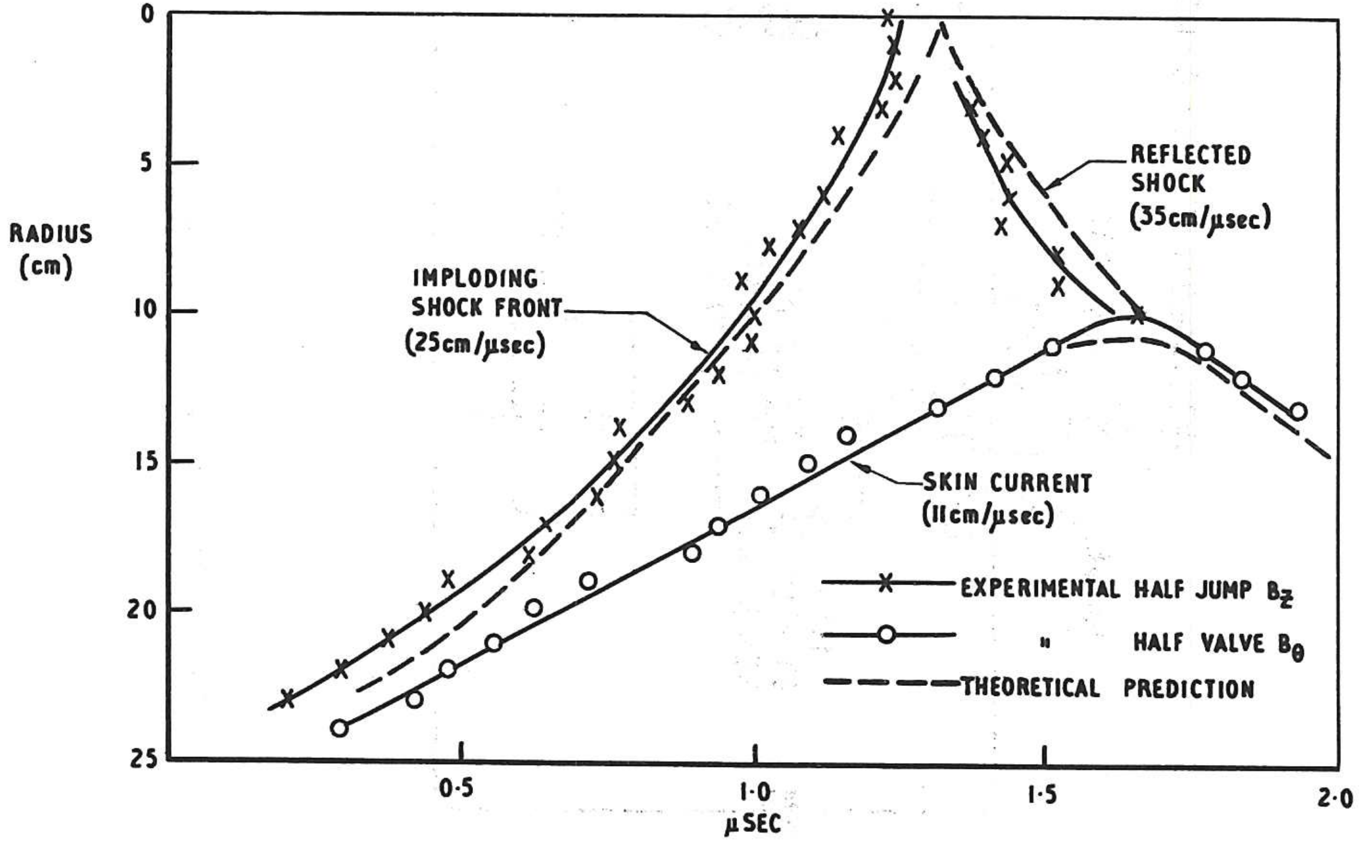

Fig. 12 Space time diagram of plasma collapse (CLM-P78)
(50 kV; 0.12 Wb/m^2; 20 mT Hydrogen)

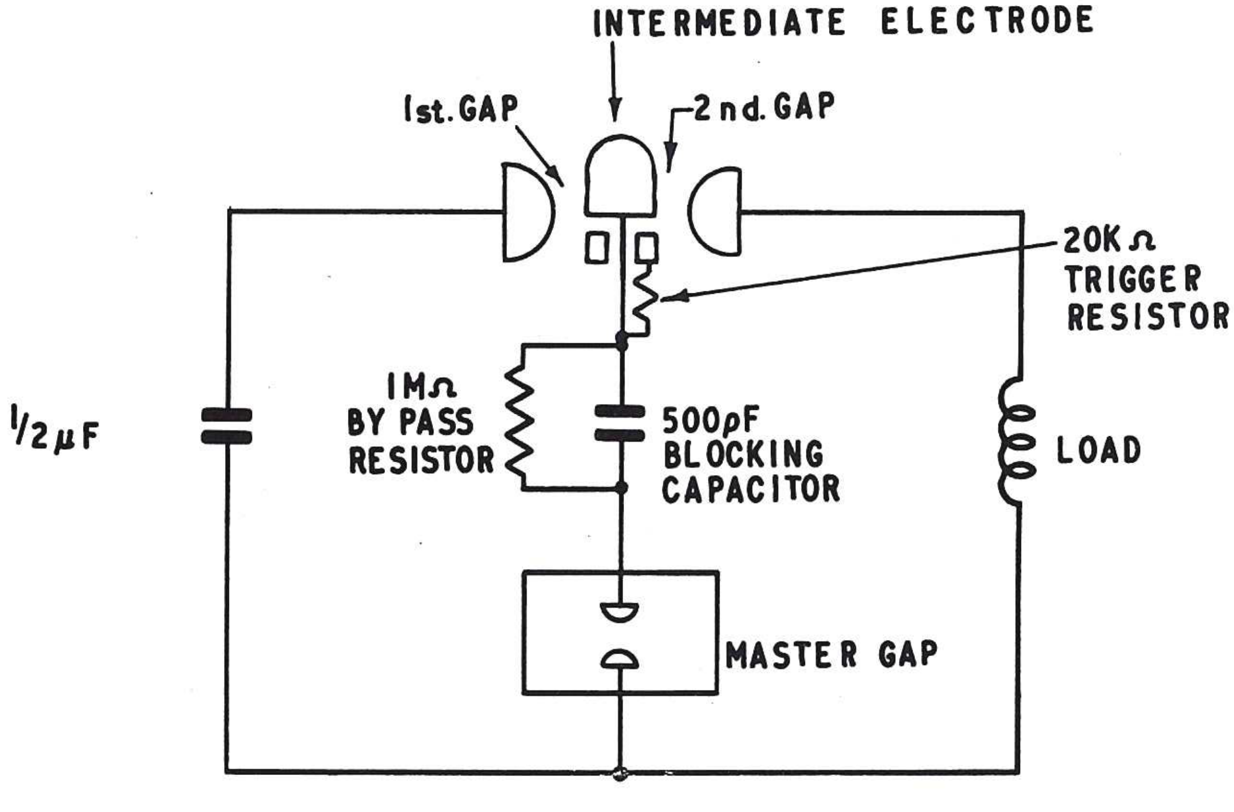

Fig. 13 Circuit for by-pass resistor fault (CLM-P 78)

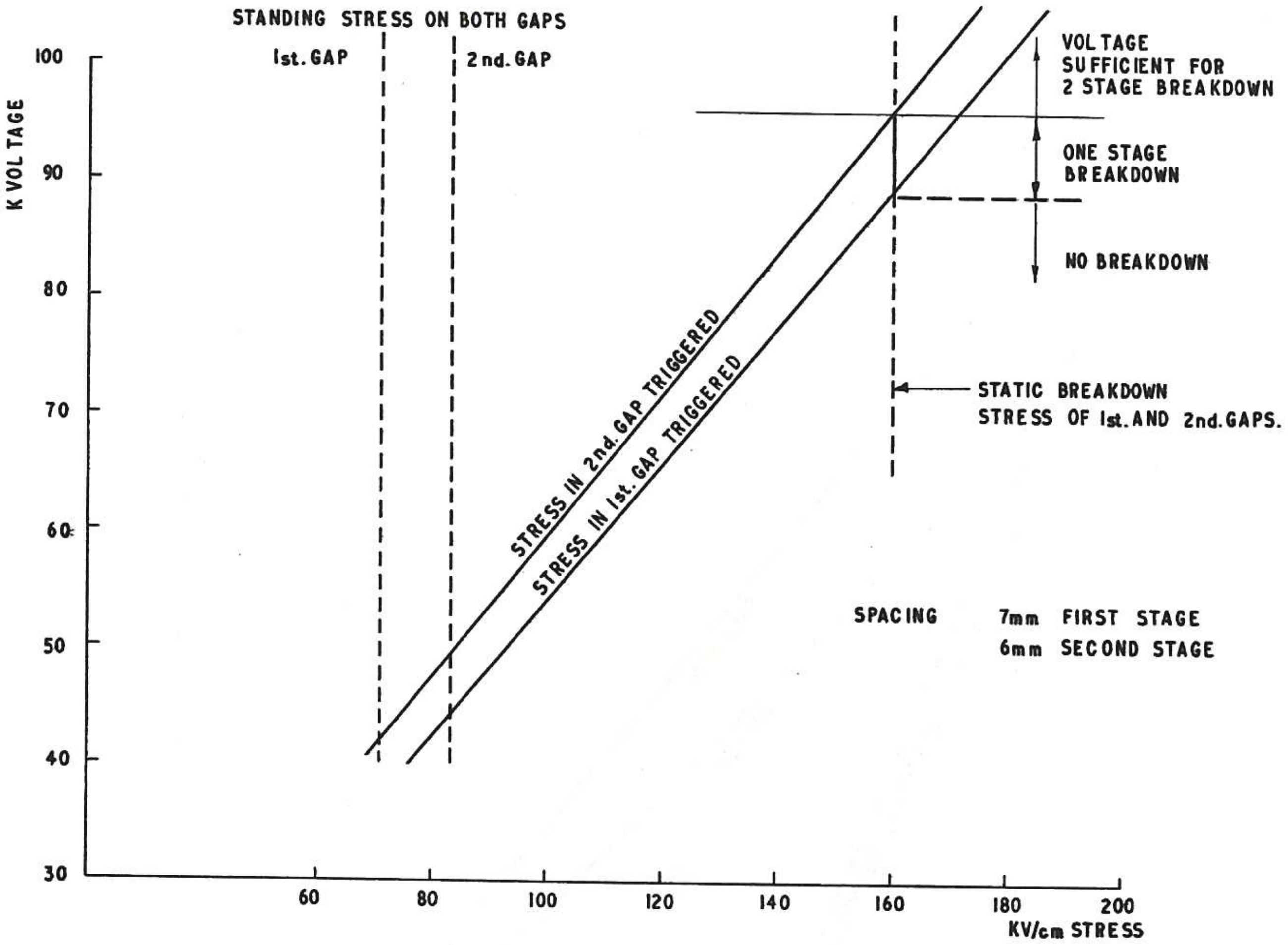

Fig. 14 Operating region for single stage breakdown (CLM-P78)

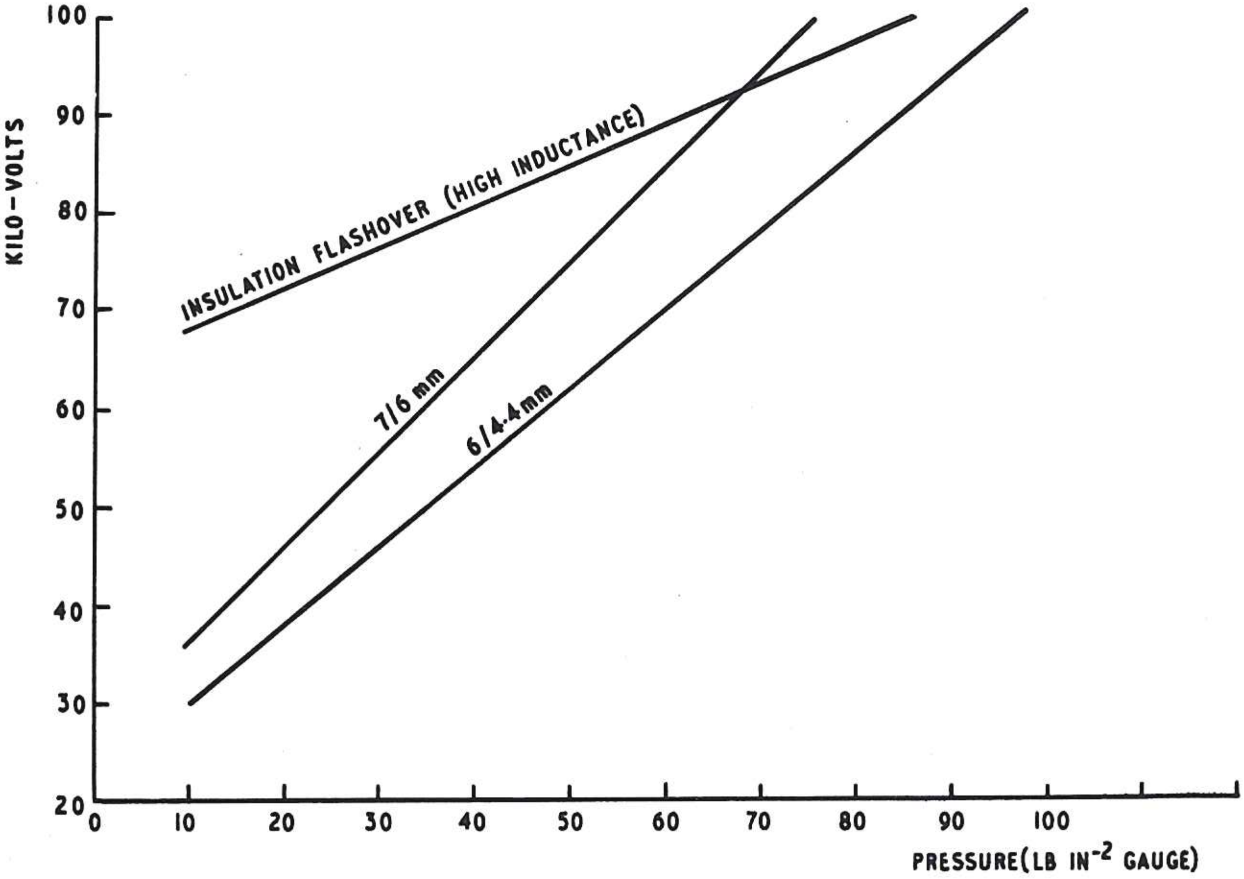

Fig. 15 100 kV start switch pressure voltage characteristics (CLM-P78)