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THE PRODUCTION OF A 320 kA HALF SINE WAVE OF CURRENT AT 220 kc/s, 60 kV FOR A THETATRON GUN

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ABSTRACT

The design and performance of a capacitor storage and switching system to produce a half sine wave of current (320 kA) in a 100 nH coil is described. The main points of interest are the combined start and divert switches which fit closely to the storage capacitors, and the overall performance of the switching system (overall accuracy ± 30 ns) incorporating trigatron master gaps.

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1. INTRODUCTION

Part of the work of the Cusp Group at Culham Laboratory has been concentrated on the injection of plasma blobs from thetatron guns along a solenoidal guide field into a cusp shaped containing field. By means of a fast opening and closing magnetic valve, a small amount of gas ($\sim$ 1 cm^3) in a plenum chamber is released into an evacuated vessel where it is first lightly ionised, then more fully ionised (pre-ionisation) and finally compressed and ejected from the original volume, travelling one to two metres along the solenoid field into the cusp region.

The compressing and ejecting of the plasma from the gun is effected by the axial field produced by a half sine wave of azimuthal current in a slightly conical sheet of copper 10 cm long, 10 cm diameter as shown in Fig.1. As the plasma blob is required to be as free from trapped magnetic field as possible the guide field is biased out in the gun region by passing current azimuthally through the coil just before pre-ionisation - this also assists the pre-ionisation process. The idealised coltage and current waveform in the thetatron coil are shown in Fig.2.

Previous work had already clarified the main parameters of the thetatron gun and had shown that a 60 kV accelerating voltage producing $\sim$ 300 kA rising in $\sim$ 1 μsec would generate a sufficiently hot plasma blob. Also a reduction in current oscillation after the first half sine wave to 10% of the maximum would reduce the secondary blobs of plasma to negligible proportions.

Similar current pulses have been produced by these methods.

(1) using a critically damped discharge

(2) using a second capacitor bank to oppose the first discharge at first current zero,

(3) short circuiting the source capacitor at first current zero.

The first two of these methods are extravagant in their use of high voltage storage capacitors and so the third method was adopted.

This paper describes the novel 60 kV switches and associated triggering used to provide the main gun power.

2. SWITCHING OF THE MAIN GUN CURRENT

The idealised 320 kA current pulse has been shown in Fig.2. but with the practical circuit of Fig.3 the resulting current and voltage wave forms in the thetatron coil and in the start and divert switches are as shown in Fig.4. The oscillations in the tail of the thetatron coil current are due to the inductances of the divert switch, and in addition there will be a slow decaying exponential current (10 μsec time constant) after diversion if there is any mistiming of the firing of the divert switch. The effect on the current waveforms of early and late firing of the divert switch is shown in Fig.5.

The main requirements for the storage capacitor/switching system can be summarised as follows:-

1. Maximum voltage — 60 kV
2. Thetatron load coil — ~ 100 nH
3. Peak current — ~ 300 kA
4. Rise time of current — ~ 1 μsec
5. Storage capacitance — 4 μF
6. Inductance of Start switch(es) — << 100 nH
   (to keep the voltage on the thetatron coil as near to 60 kV as possible.)
7. Inductance of Divert switch(es) — << start circuit
   (to keep the overswing after diversion < 5% of peak current)
8. Jitter of divert switch(es) firing — < ± 10 nsec
   (to keep exponentially decaying d.c. component after diversion to < 5% of peak current.)

The circuit values used in Fig.3 were obtained from a bank of eight 0.5 μF capacitors in parallel each with its own start/divert switch controlled by two master switches and connected by melinex insulated open transmission line to the thetatron coil.

3. START AND DIVERT SWITCH DESIGN

Although in previous experiments the start and divert function had been performed by separate switches it was decided that a combined start and divert switch would be more economical and have a low divert inductance. A difficulty to be overcome with this arrangement is that both switches must have compatible operating characteristics.

The form of start switch chosen was the swinging cascade type with field distortion triggering which had previously been developed. In these switches, the flat centre-electrode has a small radius of curvature at its edge, and emits electrons freely without requiring irradiation, when the trigger pulse is applied to it. The use of a similar switch for the divert duty would have necessitated a device for holding the central trigger electrode at its correct relative potential during the first half cycle. A modified form of trigatron was therefore used, so that the trigger electrode is normally at earth potential.

The combined start/divert switch is shown in Fig.6 integral with a 0.5 μF storage capacitor capable of operating at 100 kV but only used in this circuit at 60 kV. Conversion of the co-axial capacitor/switch combinations to open transmission line which is required for the thetatron coil is by a double "top hat" of metal insulated by silicone rubber, vacuum cast in situ. The inside of the switch is pressurised with dry clean compressed air (dew point less than - 30°C, dust particle size less than one micron). Charging of the storage capacitors is by a coaxial bushing at the rear end of the capacitor to avoid making a charging connection at the switch.

With eight 0.5 μF capacitors being used to make a 4 μF bank the performance of each of eight start switches and eight divert switches could be tabulated:-

1.	Voltage Hold off	30-60 kV d.c. with oscillations up to 50 kV (1 Mc/sec) on the output electrode due to the pre-ionising circuit. The effect of the bias discharge is small and can be neglected.	30-60 kV at 220 kc/sec for one half period and up to 50 kV (1 Mc/sec) on the output electrode due to the pre-ionising circuit. The effect of the bias discharge is small and can be neglected.
2.	Current carrying capacity per discharge.	40 kA at 220 kc/sec for a half period ($Q \sim 14$) followed by 90 kA at ~ 600 kc/s ($Q \sim 6$)	90 kA ~ 600 kc/s ($Q \sim 6$)
3.	Accuracy of firing	Due to transmit time of signals from one switch to the next the spread of firing times to be 10-15 ns.	Similar to start switches but must fire down to 90% of the start voltage and within ± 30 ns of current zero.
4.	Operating pressure	The maximum permissible pressure (due to the capacitor termination) 7 atmos. Varied to suit the operating voltage.	This switch must be operated at the same pressure as the start switch.
5.	Life	10,000 discharges at full power.	10,000 discharges at full power

3.1. Start Switches

To avoid spurious firing of the start switches with large voltage fluctuations on the output electrode a high operating pressure at a particular operating voltage must be used, but not so high as to lengthen the firing time of the switches and increase the jitter between switches. Previous work[1] on the 100 kV field distortion switch had shown that this type of switch would perform the start duty satisfactorily when operated on the voltage/pressure line shown in Fig.7. The breakdown time of the switches under these conditions is about 70 ns ± 5 ns.

3.2. Divert Switches

The divert switch duty is performed by eight modified trigatrons integral with the start switches as shown in Fig.6. The divert trigatron is not of the conventional design. Normally the spacing between the high voltage and earthy electrodes is adjusted so that it is near to breakdown and the trigger pin made flush with the earthy electrode. A voltage pulse applied to the trigger pin causes distortion of the field near it and the high stressing, and subsequent spark between the pin and the earthy electrode provide ionisation in the main gap. Breakdown of the main gap ensues if the stressing is sufficiently severe. Higher trigger pin voltages do not help very much to reduce breakdown times as breakdown will occur to the earthy electrode at the same value. In this design the trigger pin is shaped as shown in Fig.8, and by adjustment of the spacings trigger pin/earthy electrode and trigger pin/high voltage electrode it is possible to have, on triggering, the main gap fully stressed and breaking down before the trigger pin breaks down to the earthy electrode, although corona from the sharp edge of the trigger pin illuminates the main gap. Breakdown between the trigger pin and the earthy electrode follows shortly after, leading to total breakdown.

In order to obtain rapid overstressing of the main gap it is important to have the polarity of the voltage pulse applied to the trigger pin opposite that of the high voltage electrode. In the case of the divert switch the high voltage electrode would be negative at the time of firing having reversed after one half cycle from a positive charging voltage (see Fig.4), so the trigger voltage applied was positive. In addition maximum reliability was found to occur if the trigger pin/earthy electrode gap had a sharp edge at its cathode to enhance field emission effects. For the divert switch this meant putting a sharp edge on the earthy electrode. Fig.8 shows the details of the electrode shapes, with the gap spacings together with a table of the divert switch operating conditions. This trigatron is triggered by a 90 kV pulse rising in approximately 60 nsec.

4. TRIGGERING

The capacitor/switch circuit with the triggering is shown in Fig.9. The eight start switches are controlled from a master switch charged to the same positive potential as the storage capacitors and the eight (integral) divert switches are controlled from a separate master switch charged to -45kV. Both master switches are pressurised and are triggered by + 15 kV thyratrons, in the case of the divert master gap through a reversing pulse transformer. It should be noted that due to the circuits used a trigger voltage of 30 kV (twice that of the thyratron unit) is applied to the trigger pins of the master switches. In addition the output of the master switches is effectively twice the voltage to which they were originally charged. The tyratrons are triggered by + 200 volt pulses from variable delay units. After allowing for jitter in the firing times of the delay units and thyratrons the allowable jitter in the master switch and divert switches could not be greater than ± 10 nsec each, the jitter in the start switches being ± 5 nsec.

4.1. Start Master Switch

The start master switch is a trigatron similar to the divert trigatron but designed for a positive voltage on the high voltage electrode and a negative trigger pulse. The electrode shapes and gap spacings are shown in Fig.10 together with a table which shows the operating conditions of the switch. The earthy electrode is rounded in this design and the trigger pin edge facing the earthy electrode sharpened to produce the maximum field emission. A sectional view of the start master and divert master switches is shown in Fig.11.

4.2. Divert Master Switch

The divert master switch is similar to the divert switch except that the electrode spacings are adjusted for working at a lower pressure. Fig.12 shows details of the profiles and gap spacings. This switch is fired with the high voltage electrode negative and it is necessary to use a sharp edged earthy electrode and to drive the trigger pin positive on triggering. For this reason the input pulse to the switch from a positive 15 kV thyratron unit was reversed by means of a transformer.

5. PERFORMANCE

With the circuit values shown in Fig.3, about 75% of the capacitor voltage appears on the thetatron coil, the capacitor/start switch combination being only about 12% of the total start circuit inductance. The total divert switch inductance is 11% of the capacitor/start switch inductance and the resulting thetatron coil main current pulse with the storage capacitors charged to 60 kV achieved the design requirements of section 3. Fig.13 is an oscilloscope record of the current pulse achieved the oscillation on the waveform being due to the transmission line capacitance.

The apparatus (CUSIE) was commissioned at the end of 1964 and more than 10,000 discharges have been fired under different conditions up to 60 kV and the erosion of the electrodes of the start switches and the two master switches has been negligible. However there has been blunting of the sharp edge of the brass earthy electrodes of the divert switches due to erosion and the triggering of the divert switch under these conditions becomes erratic. The edges of these electrodes in this switch have been replaced with ones made of a sintered silver/tungsten/copper alloy. Erosion of the trigger pins in the divert switch has also been severe but this does not effect the performance of the switches. (During development tests the diameter of the pin was actually reduced to about 85% of its original diameter after 1000 discharges at 60 kV without changing the performance of the switches).

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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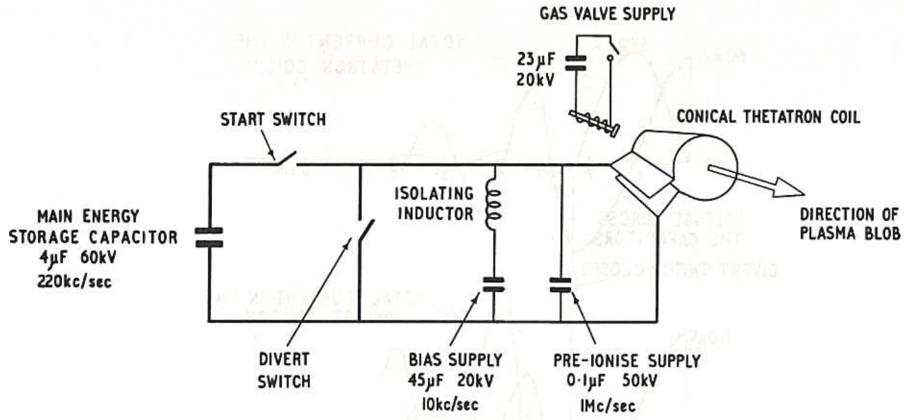

Fig. 1 Equivalent circuit of thetatron gun (CLM-P 123)

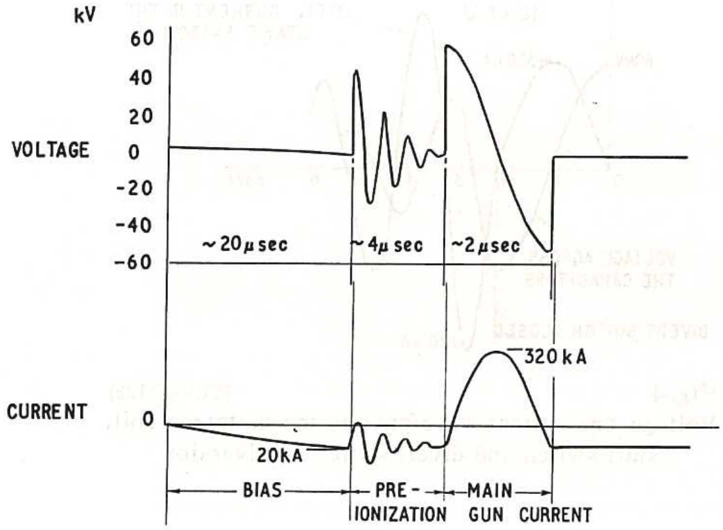

Fig. 2 (CLM-P 123)
Idealised voltage and current waveforms in the thetatron coil

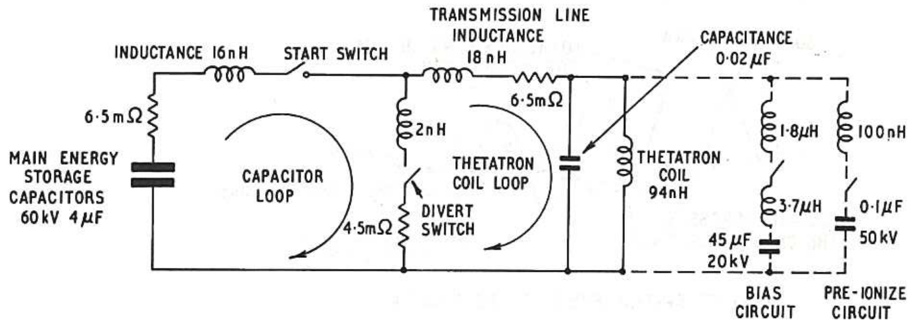

Fig. 3 (CLM-P 123)
Equivalent circuit of thetatron coil discharge circuits

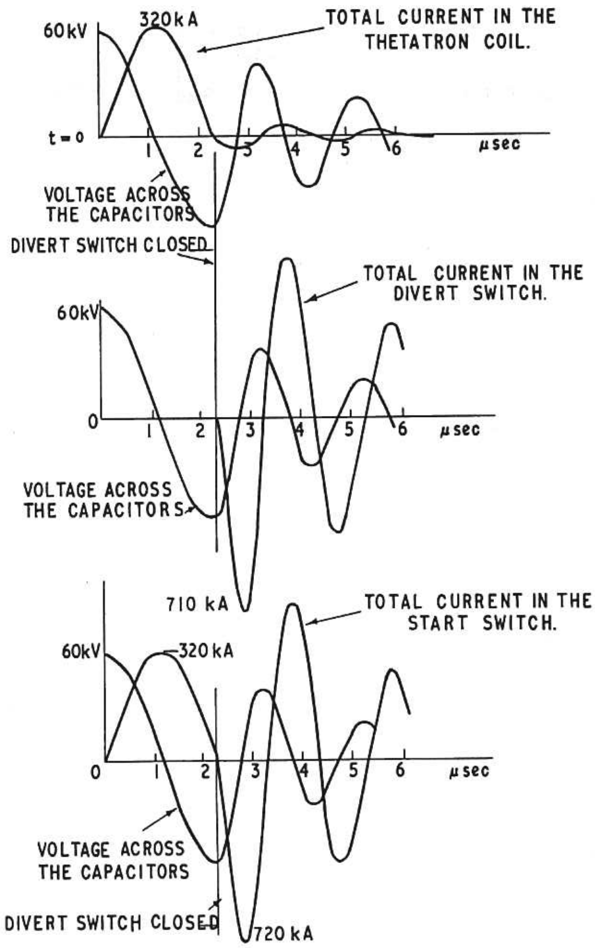

Fig. 4 (CLM-P 123)
Voltage and current waveforms in the thetatron coil, start switch and divert switch on diversion

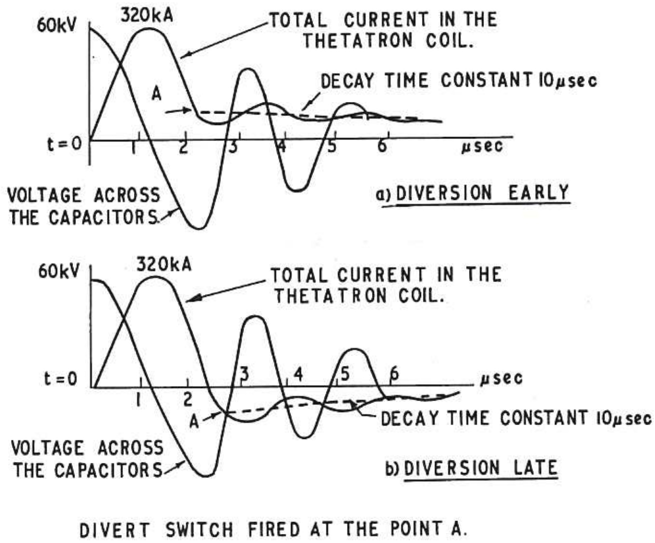

Fig. 5 (CLM-P 123)
Current waveforms in the thetatron coil on early and late diversion

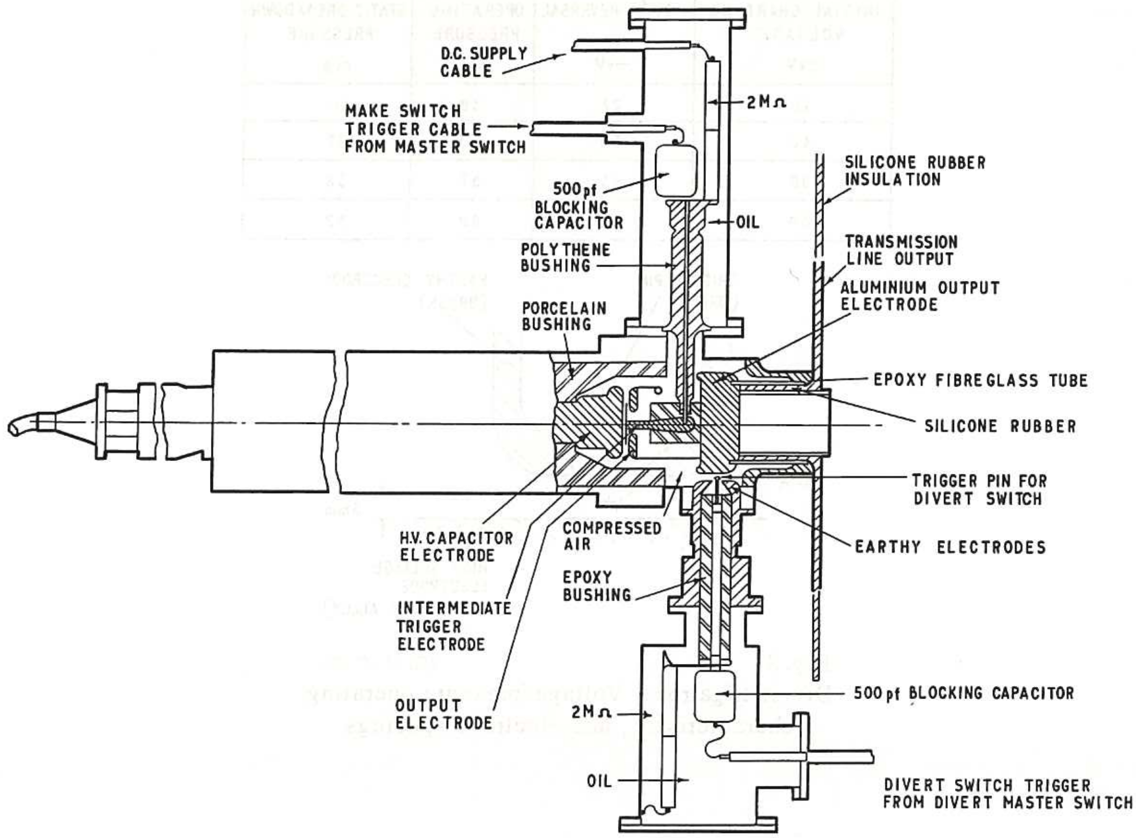

Fig. 6 Start switch with integral divert trigatron (CLM-P123)

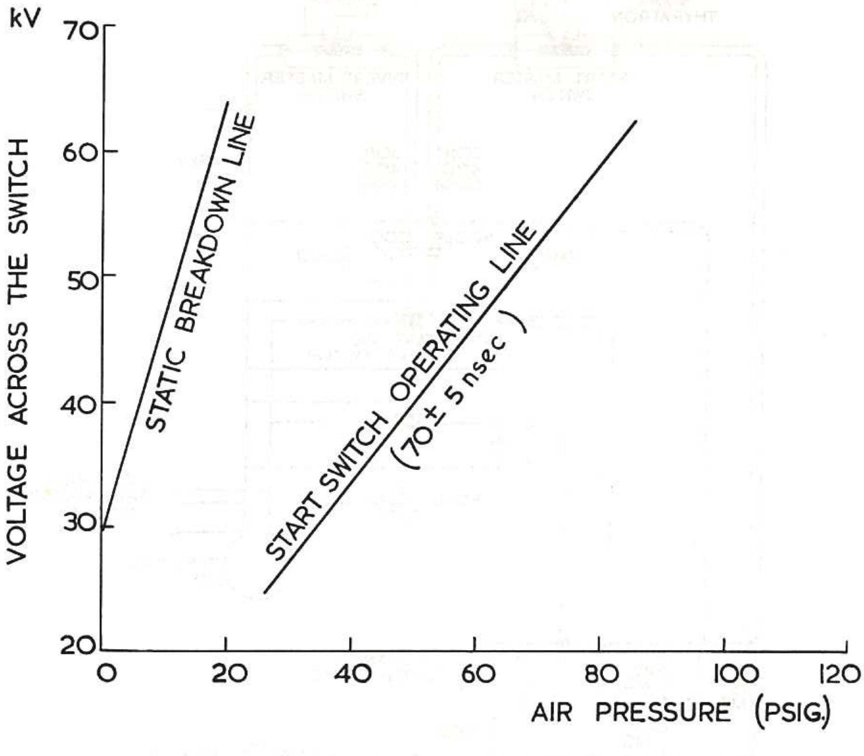

Fig. 7 (CLM-P123)
Voltage/pressure operating line for CUSIE field distortion start switch

INITIAL CHARGING VOLTAGE +kV	90 % REVERSAL −kV	OPERATING PRESSURE psig	STATIC BREAKDOWN PRESSURE psig
30	27	38	16
40	36	50	27
50	45	67	38
60	54	80	52

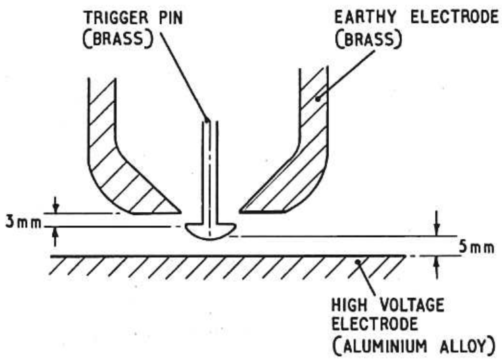

Fig. 8 (CLM-P 123)
Divert trigatron. Voltage/pressure operating characteristic, and electrode spacings

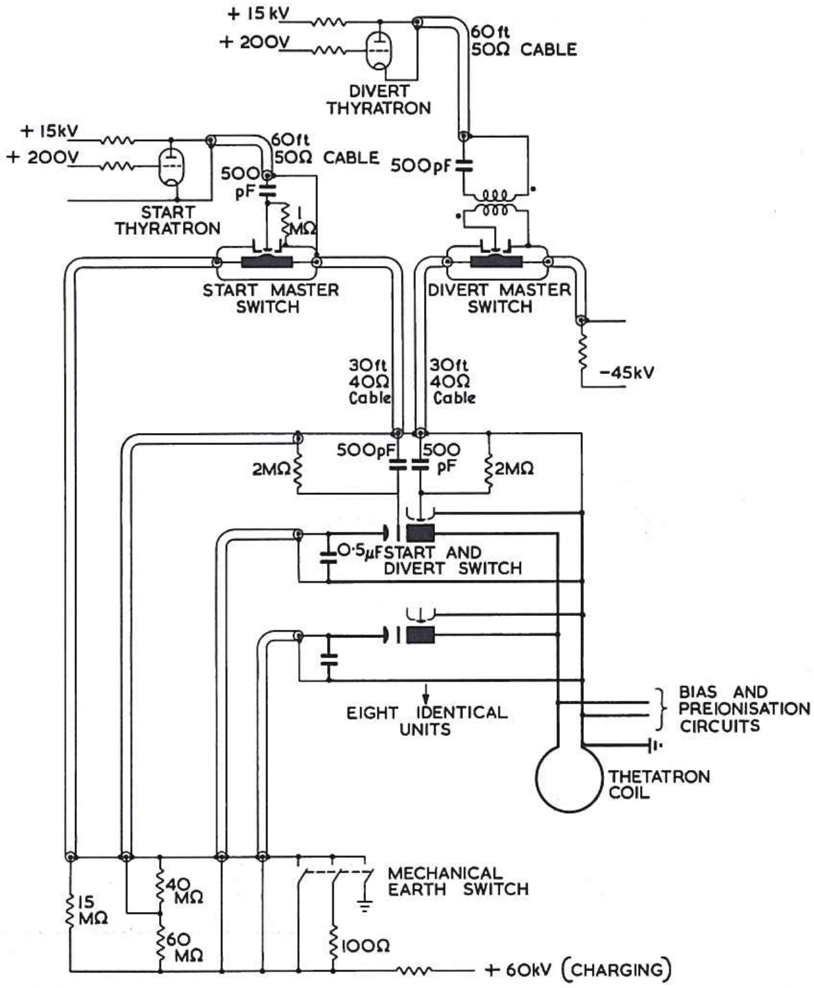

Fig. 9 Storage capacitor, start and divert switches with triggering

OPERATING VOLTAGE kV	OPERATING PRESSURE psig	STATIC BREAKDOWN PRESSURE psig
30	35	28
40	53	43
50	67	55
60	73	64

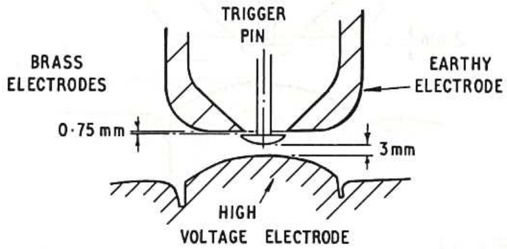

Fig. 10 (CLM-P 123)
Start master switch, operating pressure, and electrode spacings

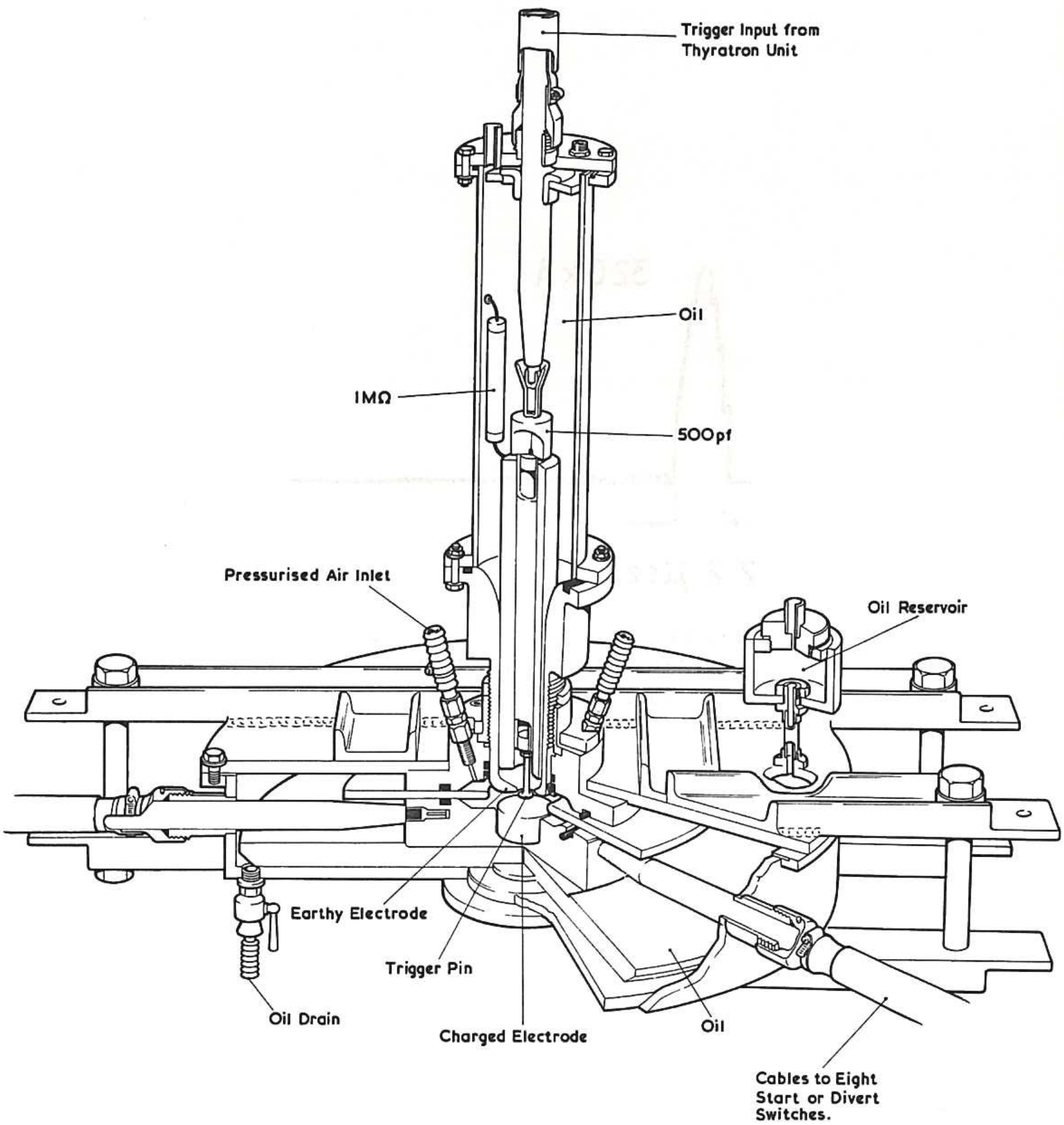

Fig. 11 Sectional view of start master and divert master switches (CLM-P 123)

THE DIVERT MASTER SWITCH IS OPERATED AT A FIXED VOLTAGE OF -45kV, AND A PRESSURE OF 45psig.

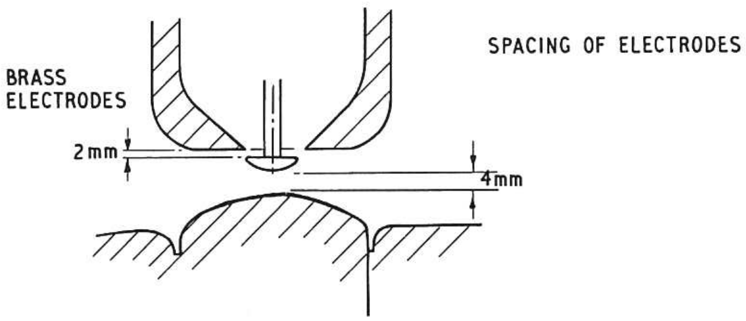

Fig. 12 (CLM-P 123)
Divert master switch operating voltage/pressure, and electrode spacings

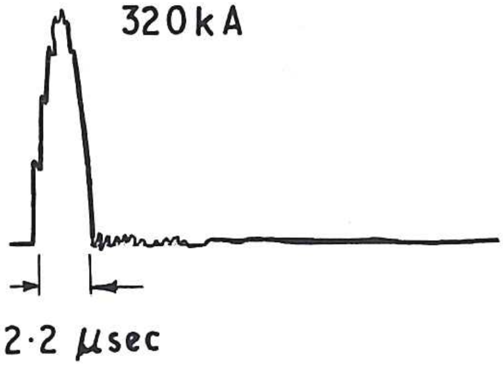

Fig. 13 (CLM-P 123)
Oscilloscope record of 320 kA half sine wave of current at 220 kc/s