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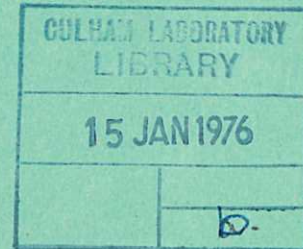
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RESEARCH GROUP

Report



HIGH CURRENT SWITCHING USING  
LOW INDUCTANCE FIELD DISTORTION  
SPARK GAPS CLOSELY CONNECTED  
IN PARALLEL

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1967

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HIGH CURRENT SWITCHING USING LOW INDUCTANCE FIELD DISTORTION  
SPARK GAPS CLOSELY CONNECTED IN PARALLEL

by

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A B S T R A C T

The development of 60 kV low inductance (15 nH) pressurised field distortion spark gaps is described, and the influence of electrode arrangement and trigger circuit parameters on breakdown time and jitter has been investigated. The necessary conditions for the satisfactory parallel operation of spark gaps with no transit time isolation between them, has been deduced theoretically. Such a 60 kV capacitor bank with closely connected parallel spark gaps has been operated successfully. The same principles are being used in the design of multiple arc spark gaps.

\*On attachment from Plasma Physics Institute, Garching.

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## 1. INTRODUCTION

The study of shock heated plasmas in theta-pinch guns has necessitated the development of high performance capacitor banks of compact design. Low inductance capacitor banks have generally been designed with a large number of relatively high inductance spark gaps in parallel. The gaps have been triggered using the principle that each gap should be separated from others by individual connections having an electrical transit time at least equal to the spread in breakdown time between the gaps.

To enable simpler and more compact banks to be built, low inductance field distortion gaps have been developed for 60 kV applications at approaching 500 kA peak current and 10 coulombs per gap. These gaps can be successfully triggered with virtually no transit time isolation between them, because of their short breakdown times and low jitter. This means that during the rapid decay of voltage produced by the firing of early gaps, those with a longer than average breakdown time can still be triggered at the reduced voltage.

A 60 kV, 30 kJ, 8nH bank giving a peak current of 1.4MA rising in 1.0  $\mu$ sec has been built. After one half-period, the load coil is short circuited by a low inductance (1.25nH) 'diversion' switch system to reduce the coil current to 10% of its peak value, which increases the bank current to 1.9MA. Successful triggering of the closely connected parallel gaps has been demonstrated.

## 2. FIELD DISTORTION GAPS

Field distortion gaps have three electrodes, the centre trigger electrode having a relatively sharp edge. This is positioned between the main electrodes (Figs.1,2 & 3) either symmetrically (50/50 spacing) or asymmetrically (e.g. 60/40 or 70/30 spacing in which the gap to the H.V. main electrode is 60 or 70% of the total air gap). The trigger electrode is normally held at the proportion of the gap voltage corresponding to its physical spacing, so that the sharp edge does not disturb the equipotential surfaces appreciably from that given by a uniform field distribution. For triggering, a fast-rising negative pulse is applied to the electrode and a very large increase in stress occurs at the sharp edge due to over voltage and field distortion. This 'overstress' can in some circumstances be about 3 times the 'over-voltage' of the gap<sup>(1)</sup>, and being accompanied by field emission will cause breakdown to a main electrode in a short time with low jitter, and without the need for irradiation. The trigger electrode will then approach the potential of this main electrode, so that the second half of the gap is irradiated and over-stressed due to over voltage and field distortion.

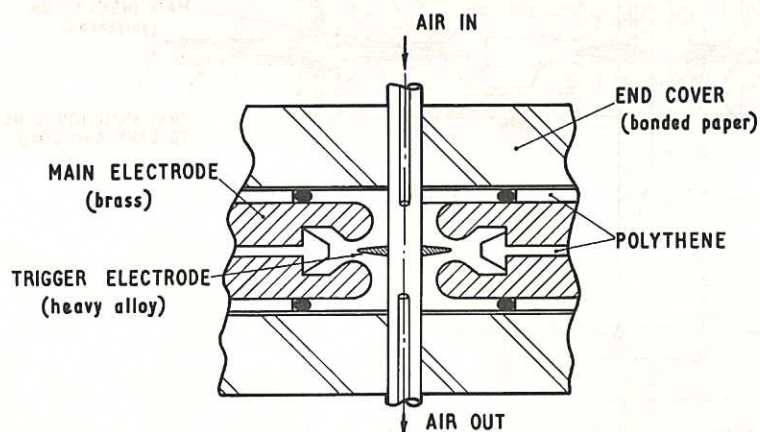


Fig.1 Mark I gap (CLM-R71)

A full discussion of triggering tests and requirements is given in sections 3 and 4, for

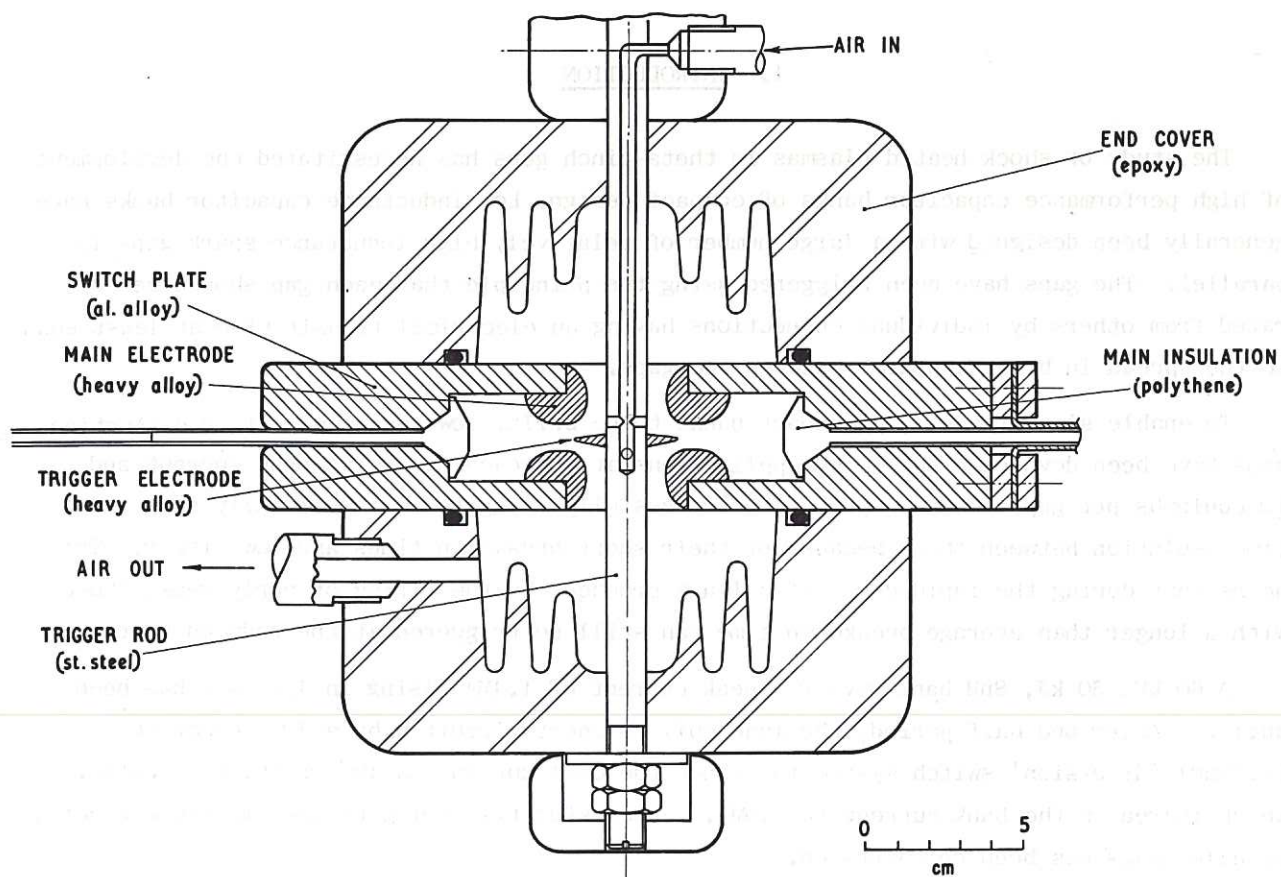


Fig.2 Mark II gap (CLM-R71)

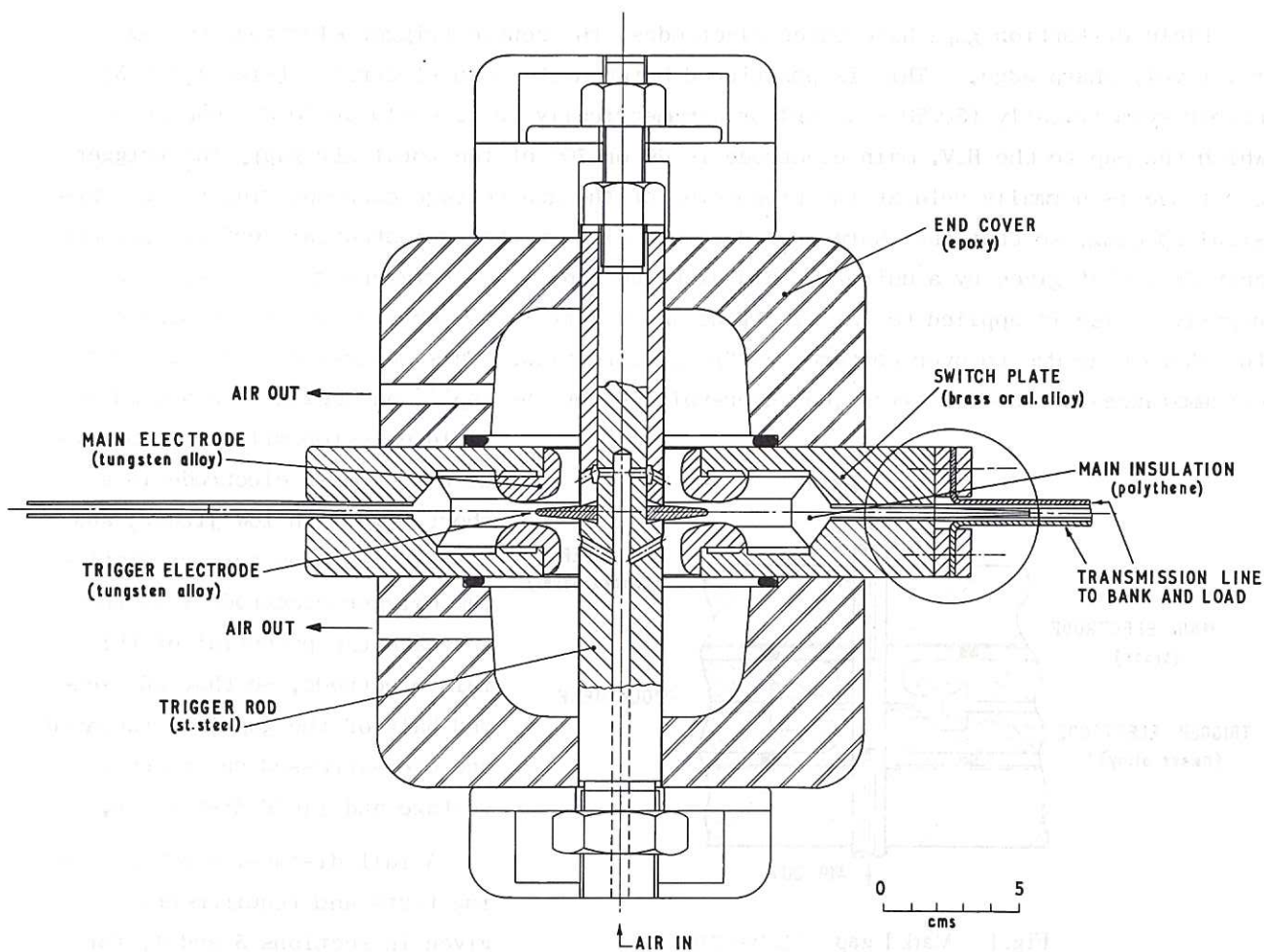


Fig.3 Mark III gap (CLM-R71)



start, diversion and clamp gap duty. Start gaps connect the capacitor bank to the load inductance, whereas diversion and clamp gaps short circuit the load after a half-period and quarter period of current respectively.

#### PREVIOUS WORK

Field distortion spark gaps have been used in parallel plate<sup>(2,3)</sup> and coaxial geometry<sup>(1)</sup>, though previously it has proved very difficult to prevent premature voltage breakdowns in 60 kV high energy pressurised gaps having an inductance of about 15nH, due to contamination of the internal insulation surfaces by erosion products<sup>(4)</sup>. The starting point for the present work was the Mark I gap (Fig.1) of 12nH inductance, which operated satisfactorily at 60 kV, with low bank energy, but gave an excessive number of premature breakdowns when carrying 210 kA peak, 1.5 coulombs<sup>(2)</sup>. As a result of tests on this gap and modifications of it, the following principles were adopted in developing the final design of the Mk II and Mk III gaps.

- (a) To avoid insulation contamination, dry compressed air ( $-50^{\circ}\text{C}$  Dew point) should be used. This is especially true where epoxy resin insulation surfaces are present.
- (b) An adequate through-put of dry 'flushing' air, which should enter the gap near the electrodes, is required between discharges to prevent the accumulation of erosion products on insulation surfaces.
- (c) For high energy applications, adequate gap internal volume is necessary. Increasing the end cover size achieves this without increasing the inductance.
- (d) The trigger-to-main electrode insulation surface should be moved away from the arc region. The main insulation surface should be coincident with the electric field lines.
- (e) The electrode shapes should be such that the magnetic forces move the arc away from the main insulation surfaces.
- (f) The premature breakdown rate increases with the repetition rate.
- (g) The sharpness of the trigger disc edge is not critical in maintaining a low jitter.

#### CONSTRUCTION OF MK II AND MK III GAPS. (FIGS.2 AND 3)

The main electrode system consists of two replaceable heavy alloy toroidally shaped electrodes mounted on aluminium alloy switch plates which are in turn connected directly to a polythene insulated transmission line.

The trigger electrode is a heavy alloy disc which is smaller in diameter than the position of minimum main electrode separation. This arrangement prevents magnetic pressure blowing the arc towards the main insulation surface. The edge radius is 0.5 mm because experience shows that this is the radius typically achieved by the erosion processes in operation. The trigger disc is supported on a stainless steel rod which holds the assembly together and resists the continuous and transient gas pressure and magnetic forces.

The switch plates are insulated from each other by polythene, shaped as shown, so that the surface electric field is as uniform as possible, and the insulation inner surface (adjacent to the arc) is coincident with the electric field lines between the electrode



plates. Thus the electric stress in the air gap is relatively unaffected by leakage across the insulation surface. The polythene insulation is 0.3 cm thick over most of the switch plate area, increasing to 2.5 cm thickness at its inside diameter, and forms an adequate seal against internal air pressure. The inside diameter is 10 cm for D.C. applications, (start gap Mk II C) but can be reduced to 7 cm for pulsed voltages, (clamp or diversion gap Mk II D) giving a decrease in inductance from 18nH to 15nH.

The endcovers are moulded in epoxy resin to give adequate strength, and are designed to give a large internal volume (to keep down the transient gas pressure and temperature rise); a long tracking surface to the trigger electrode is provided by internal sheds.

The gap is pressurised at up to 90 p.s.i.g. (6.0 atm)\* with dry air, which enters through the trigger bolt and is expelled from the end covers. Clean air from a 90 p.s.i.g. supply is passed through the gap for 10 sec between shots (1 shot/minute), this process being described as 'flushing'.

The Mk III gap was designed for 40 kV higher energy applications, because the erosion of the trigger and main electrodes of a Mk II gap was excessive at 7 coulombs per shot. Also cracks in the epoxy cover and fracture of the internal sheds showed that a mechanically stronger design was necessary to withstand the higher gas pressure at these ratings. The trigger rod diameter and also the area of the support discs, which press on the top end of the epoxy covers, was increased. Removal of the internal sheds was proved to be an adequate measure for a 40 kV application but it may lead to an increased premature rate when the Mk III gap is operated at 60 kV. The larger diameters of the main and trigger electrodes enable satisfactory operation of the gap for several thousand shots to be achieved, before replacements of the electrodes is necessary.

#### LIFE TESTS AT 60 kV D.C. ON MK II GAP

Tests were made at 210 kA peak, 1.5 coulombs, 1 shot/minute on a Mk II gap with a preliminary design of end cover (epoxy/perspex) and a moderate flushing air through-put compared with the final design. The gap was connected as a start switch to a 60 kV 2  $\mu$ F capacitor. The pressure was alternately 70 p.s.i.g. (4.7 atm.) (pw/pb = 2.0) or 40 p.s.i.g. (2.7 atm.) (pw/pb = 1.3), the change from one pressure to the other being made every 150 shots throughout the test which lasted for 4000 shots. The D.C. voltage was noted by means of a pen recorder so that an accurate assessment of the number and frequency of premature breakdowns could be made.

It was found that the premature breakdown rate at any time, for say 500 consecutive shots, does not differ appreciably from the overall mean premature rate. There was therefore no deterioration in performance during this test. At 70 p.s.i.g. the mean premature rate of 0.28% is satisfactory. However, it is very pressure dependent and the mean value of 2.3% at 40 p.s.i.g. would be unsatisfactory with a number of gaps in parallel.

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\*All figures for pressure are given as the increase above normal atmospheric pressure, whether in "Atmospheres" or p.s.i.g. (pounds per square inch, gauge). pw and pb, the working and breakdown pressures respectively, are however absolute pressures.



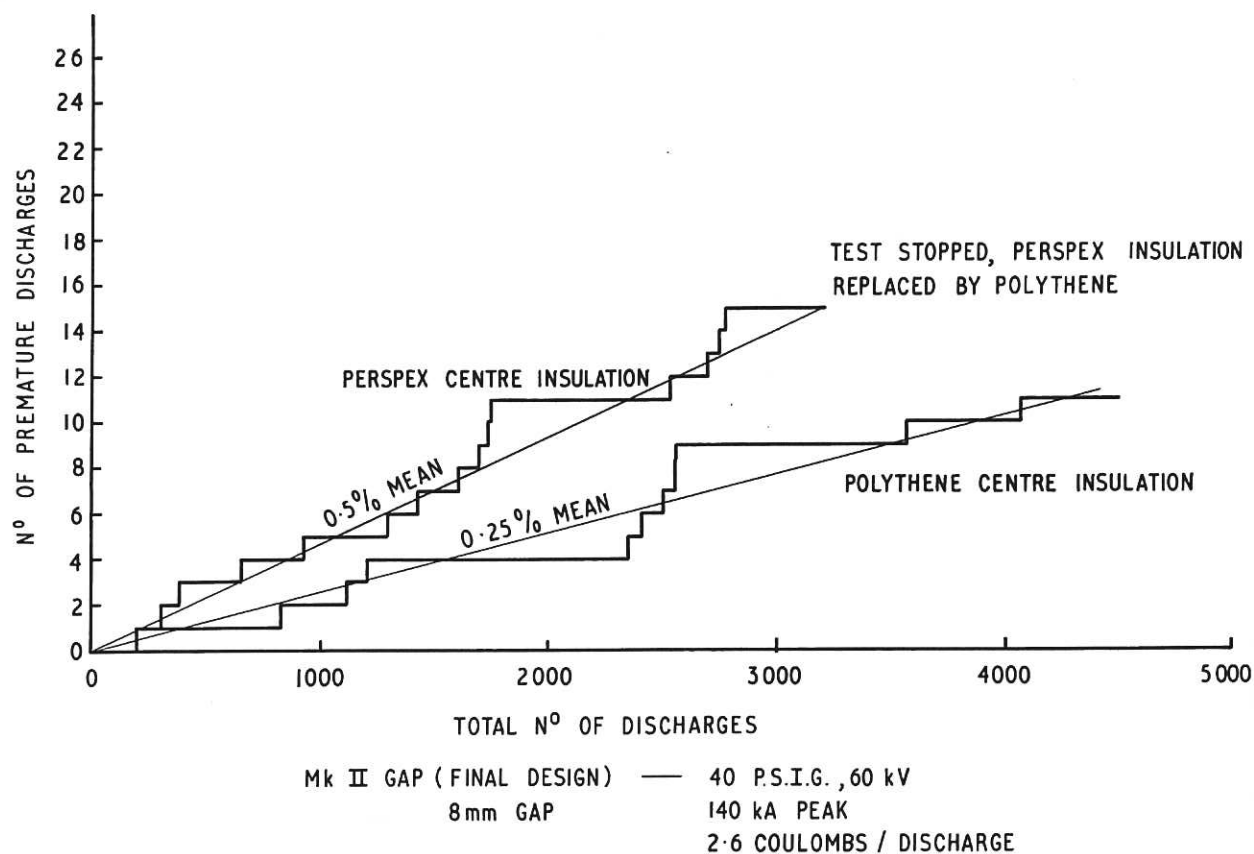


Fig.4 Premature breakdown rate 60 kV, d.c. Mk.II (CLM-R71)

A further life test at 40 p.s.i.g. was carried out for 8000 shots at 140 kA, 2.6 coulombs with a final Mk II design (epoxy end covers as Fig.2) and an increased 'flushing through-put' of air between shots. The test was started with perspex (polymethylmethacrylate) centre insulation for 3500 shots, which was then replaced by polythene insulation for a further 4500 shots. The number and frequency of premature shots are given in Fig.4. It will again be noted that there is no deterioration in performance during the test, and that with the final design the mean premature breakdown rate has been reduced to an acceptable value of between 0.25% and 0.5%. Though the current and coulombs are slightly different from the earlier tests, it is thought that this improvement is due to the longer tracking path in the epoxy end cover and the improved flushing conditions.

There is no evidence of flashover along the insulation surface, and the latter has maintained a clean shiny appearance. However, from previous experience it is still considered probable that the condition of the insulation surface is the determining factor in promoting premature breakdowns although these seem to occur between the main electrodes.

The condition of the main electrodes, centre insulation and trigger electrodes is shown in Figs.5 and 6. The erosion of main and trigger electrode is uniform round the major diameter so that in principle, a very much higher coulomb rating could be obtained by increasing the major diameter of the electrodes (as in the Mk III gap). The position of the erosion confirms that blow-out of the arc towards the main insulation does not occur.

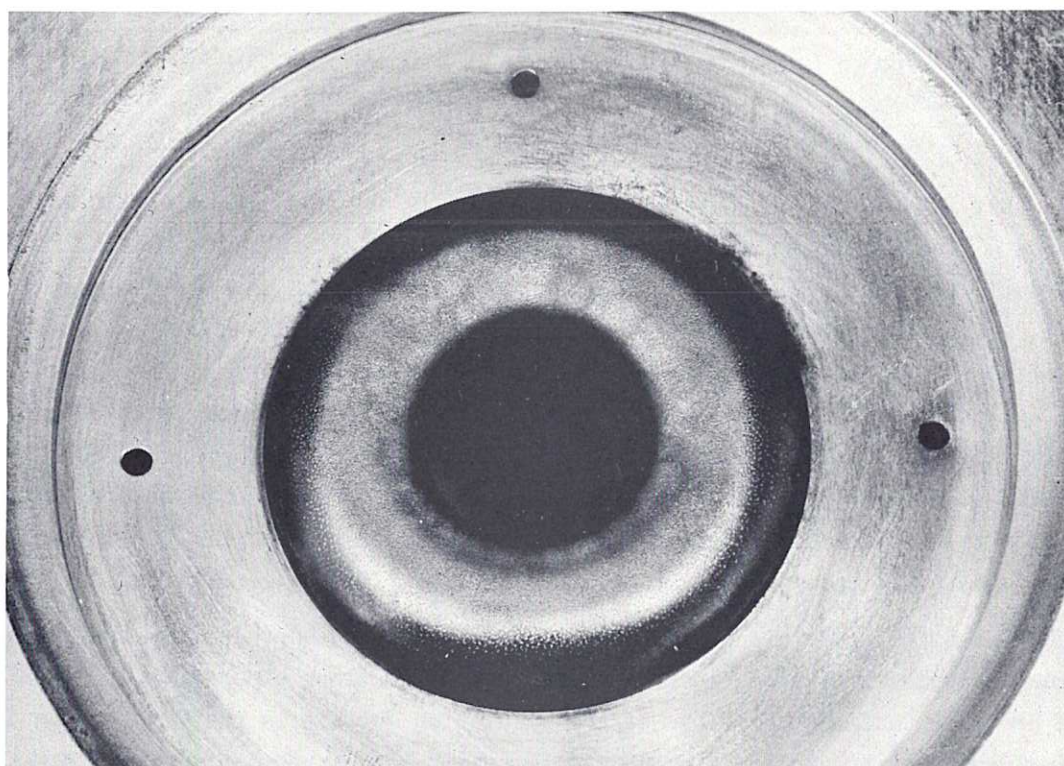
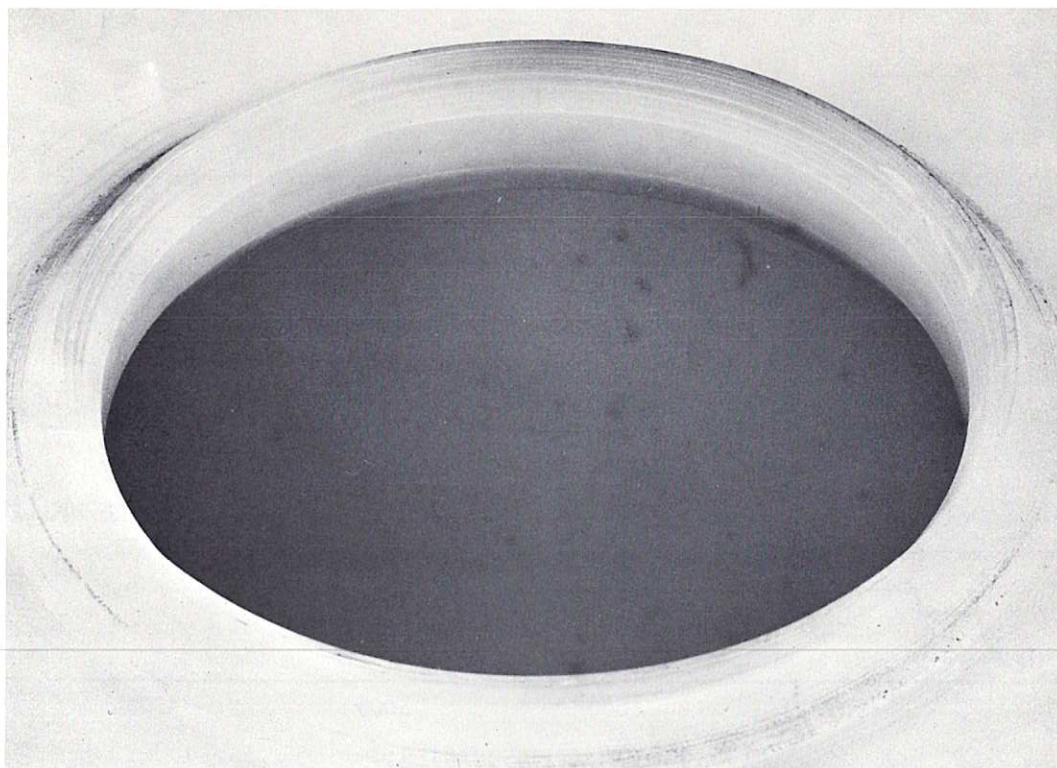


Fig.5 Centre insulation and eroded main electrodes (CLM-R71)



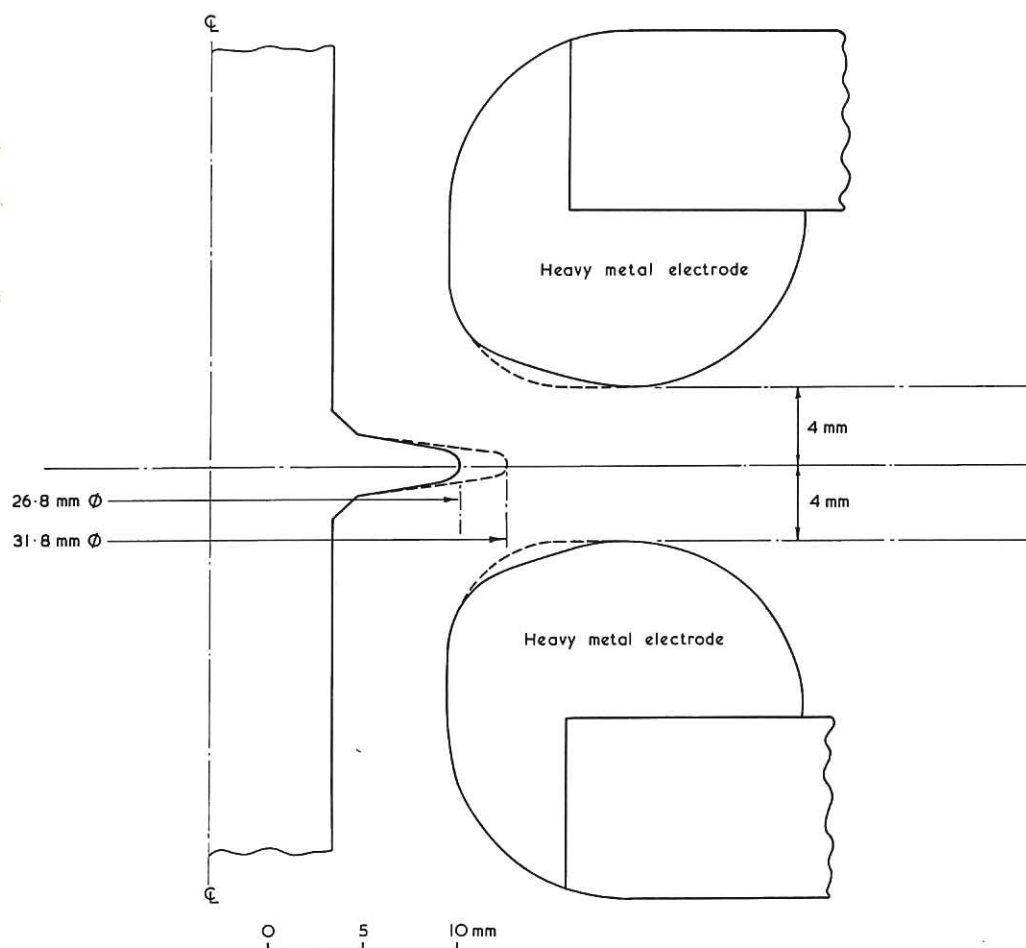
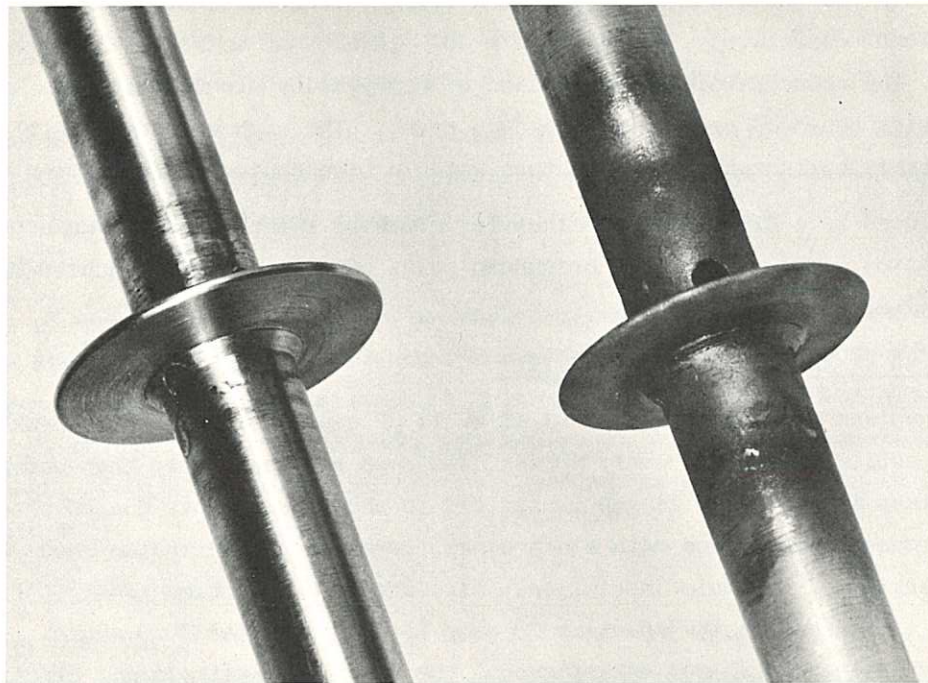


Fig. 6 (CLM-R71)  
Erosion on main electrodes and trigger disc. 8000 shots, 140 kA, 2.6 coulombs/  
discharge - - - Original shape — Eroded shape

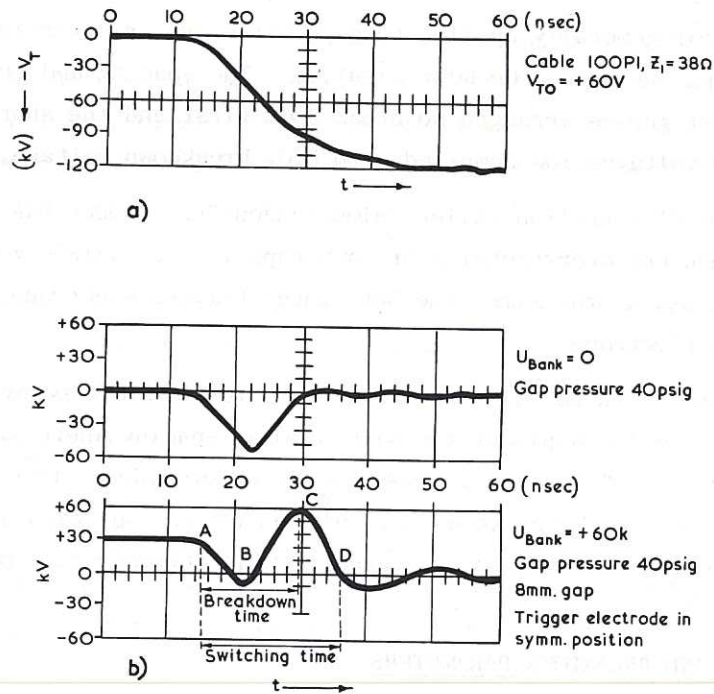


Fig.9 (CLM-R71)  
 (a) Trigger pulse at open cable-end (b) Trigger pulse at trigger electrode

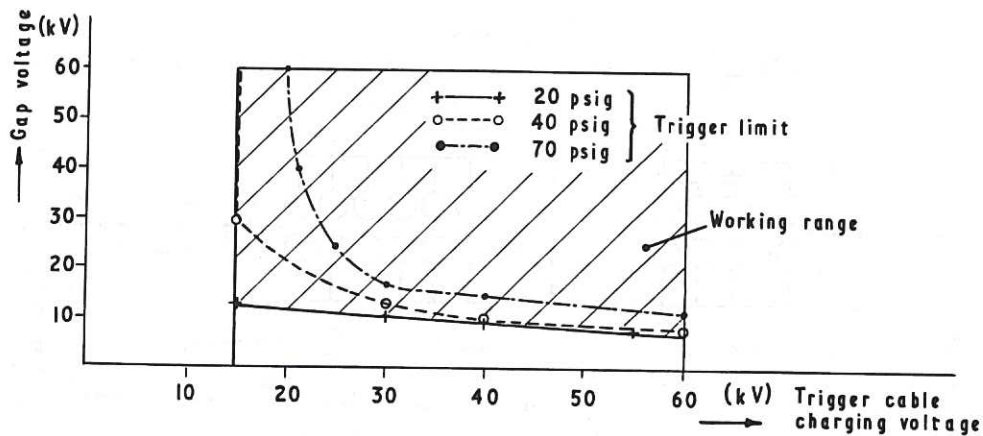


Fig.10 Minimum required trigger voltage (CLM-R71)

Fig.9(a) shows the trigger pulse with trigger cable open-circuit, and Fig.9(b) the voltage if the cable is connected to the gap. The minimum trigger voltage at which the gap will break down completely is given in Fig.10 for a 50/50 spacing, though the single gap tests described below have all been carried out with a D.C. trigger voltage ( $V_T$ ) of 60 kV.

In the case of diversion and clamp gaps an auxiliary series gap is needed which has two functions. First, it ensures that the resistive divider ( $R_3$  and  $R_4$ ) is able to maintain the trigger electrode at the correct potential when subjected to transient voltages, following the breakdown of the start gaps. Secondly, it sharpens the trigger pulse, which favours the formation of "simultaneous" arc channels in clamp gaps. In diversion gaps the mode of operation is normally "cascade" breakdown, and the use of a simple air auxiliary gap is



adequate. For triggering clamp gaps a pressurised auxiliary gap is used to give a rate of rise of the voltage pulse at the trigger electrode of 20 kV/nsec. This enables the triggering of clamp gaps with a symmetrical spacing to be achieved very near the current maximum (and zero gap voltage).

The static breakdown voltage curves for Mk II and Mk III gaps are given in Fig.11. The spread in breakdown voltage is due to mechanical tolerances which occur between different gaps, and the effect of the asymmetrical position of the trigger electrode, i.e. the lower values of breakdown voltage apply to the 70/30 spacing and the higher values to the 50/50 spacing.

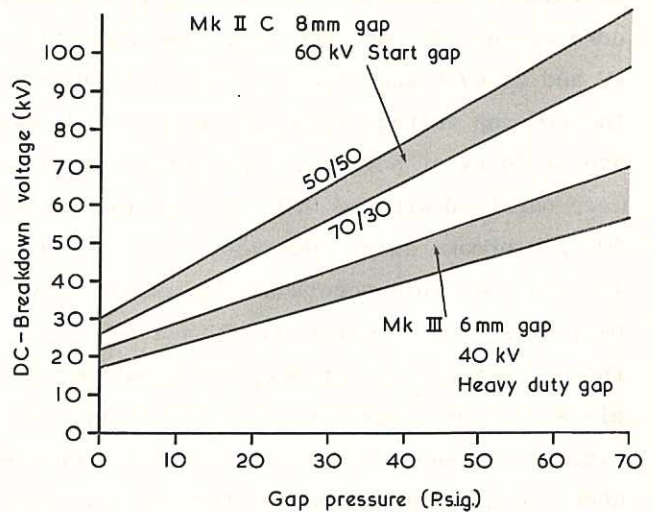


Fig.11 Gap breakdown voltage (d.c.) (CLM-R71)

Pulse breakdown voltage and breakdown time curves have also been measured as in Fig.12, for both the long and short gaps with a 60/40 gap spacing at 40 p.s.i.g. and a total air gap of 8 mm. A linearly rising trigger pulse was applied to the trigger electrode at rates

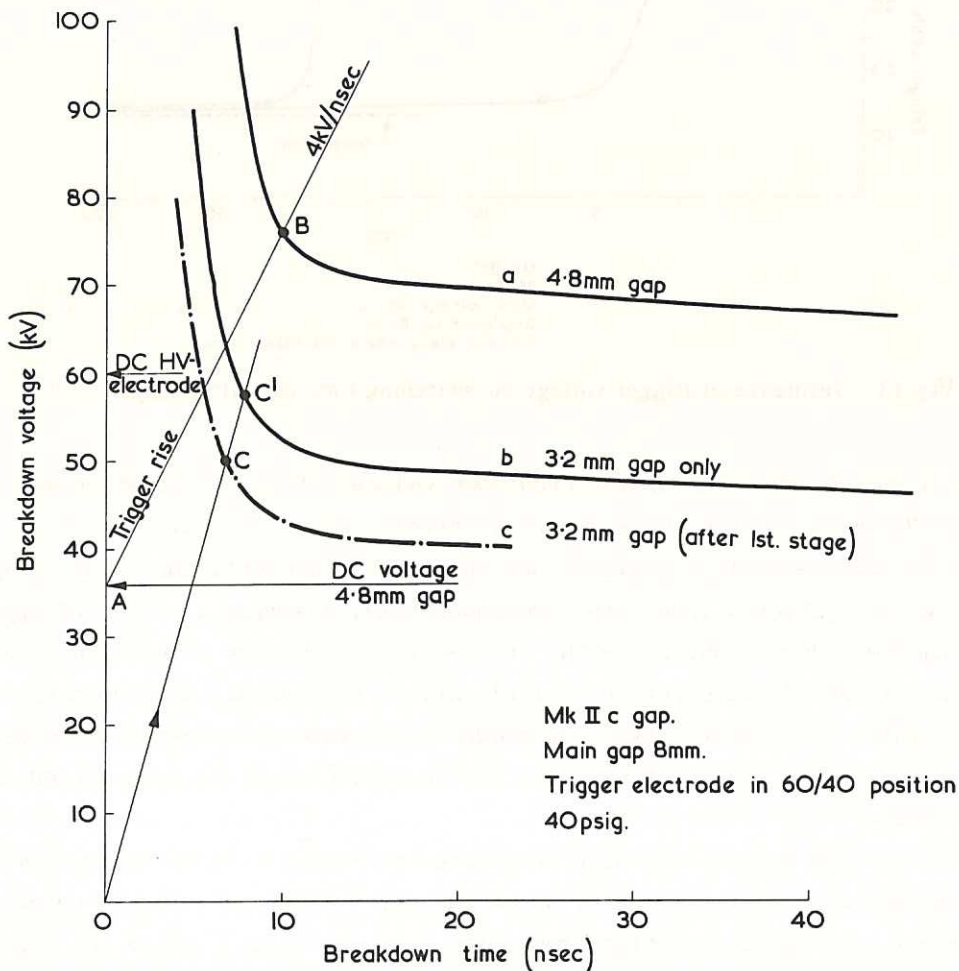


Fig.12 (CLM-R71)  
Pulse breakdown voltage for linear rising voltage pulse at trigger electrode (a) 60% gap (4.8mm), 36 kV, d.c. plus linear rising pulse. 60 kV on main gap; (b) 40% gap (3.2mm), linear rising pulse, no voltage on main gap; (c) 40% gap (3.2mm), linear rising pulse (overswing), breakdown in the second stage after the first stage breakdown at 60 kV.

of voltage rise from 1 kV/nsec to 10 kV/nsec. Curve (a) refers to the first stage breakdown of the 60% gap, the H.T. electrode and trigger electrode being at D.C. voltages of 60 kV and 24 kV respectively. Thus a trigger pulse rising at 4 kV/nsec, for example, increases the 60% gap voltage from the initial D.C. value of 36 kV at point A, to the breakdown voltage of 76 kV at point B. The pulse breakdown parameters of the shorter 40% gap (curve (b)) were obtained with no D.C. voltage initially applied to the electrodes because then only the 40% gap breaks down. However, curve (b) does not accurately represent the breakdown of the 40% gap when this occurs as the second stage of a cascade breakdown as, in this case, some overstress and irradiation of this gap occurs during the breakdown of the first stage. Under these 'cascade' conditions, the breakdown of the 40% gap is represented by curve (c), which gives shorter breakdown times than curve (b) as would be expected (compare points C and C', Fig.12). It should be noted that the breakdown time plotted in curve (c) is measured from when the gap voltage passes through zero and the trigger electrode potential becomes positive, whereas a negative pulse was applied in the case of curves (a) and (b).

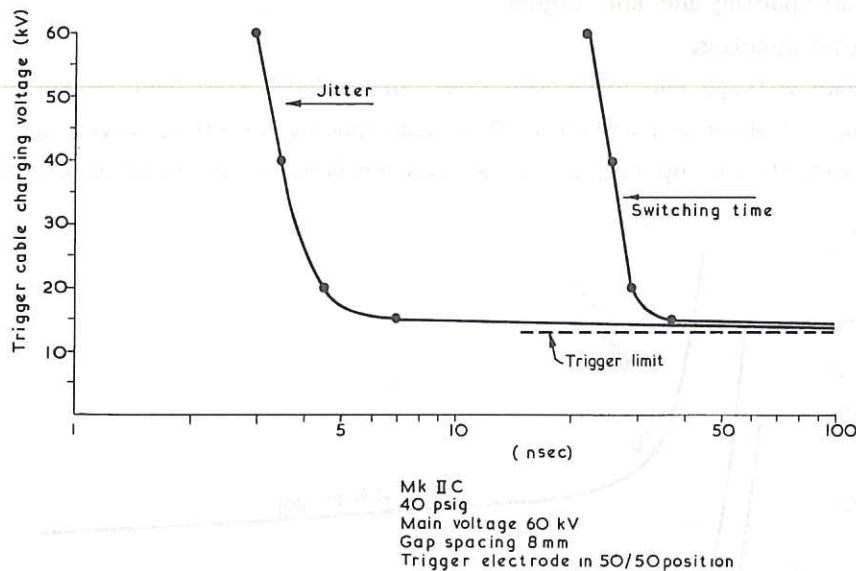
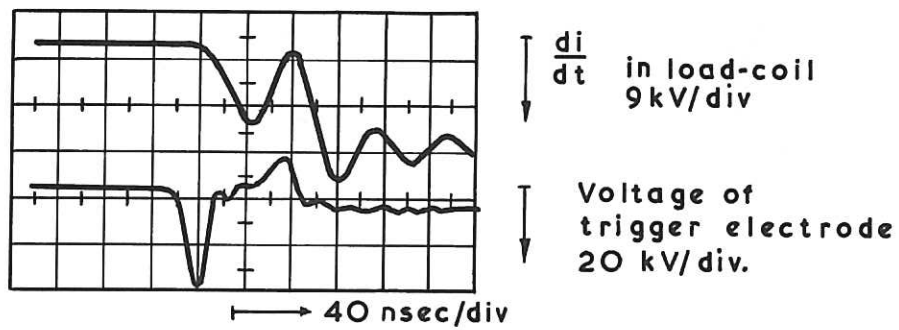


Fig.13 Influence of trigger voltage on switching time and jitter (CLM-R71)

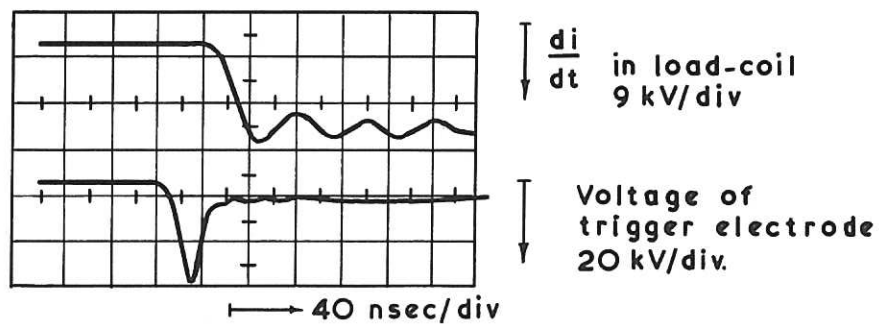
The mean standard deviation of the breakdown voltage of the first stage was found to be 1 or 2 kV for 40 or 70 p.s.i.g. pressure respectively, which is equivalent to a time deviation of 0.15 or 0.30 nsec. This implies that the first stage will contribute only about one nsec to the overall jitter of the total breakdown time, assuming a jitter of approximately three times the mean deviation. Since the trigger voltage mainly affects the breakdown of the first stage it should also not appreciably affect the overall breakdown time and jitter, provided the minimum trigger voltage is exceeded by a reasonable margin. This is confirmed by the test results in Fig.13, where the jitter and switching time are plotted as a function of trigger voltage.

The switching time is defined, with reference to Fig.9(b), as the time from the start of the trigger pulse A, to the point D, where the gap voltage has dropped to zero. The breakdown time is defined as the time from point A to the point C where the centre electrode voltage begins to collapse. In the case of 'simultaneous' breakdown at low gap voltages it is necessary to observe also the coil voltage to be certain that complete breakdown has occurred. It should however be noted that in the case of "cascade" breakdown the switching time includes the time (between C and D) taken by the arc inductance and resistive voltage components to fall to near zero. Fig.14(a) shows a typical trace of a "cascade" breakdown,



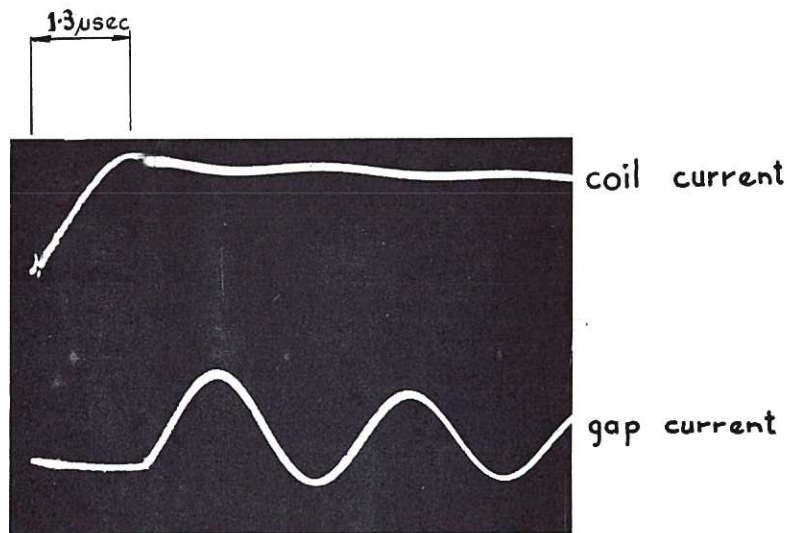


Mk II C  
 40 psig  
 $V_{TO} = 60 \text{ kV}$   
 Bank voltage 20 kV  
 Trigger electrode,  
 symm. position



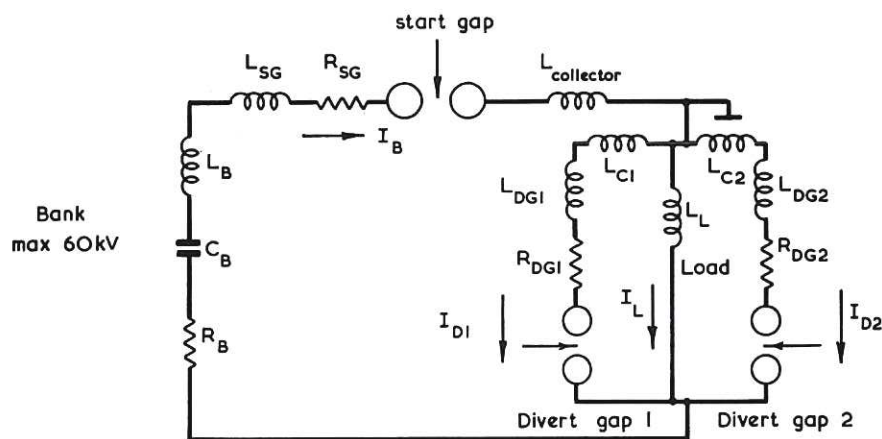
Mk II C  
 40 psig  
 $V_{TO} = 60 \text{ kV}$   
 Bank voltage 17 kV  
 Trigger electrode  
 symm. position

Fig. 14(a) "Cascade" breakdown; (b) "Simultaneous breakdown" (CLM-R71)



bank voltage 60kV  
 pressure 40psig  
 spacing 50/50  $R_1 = 0$   
 20 superimposed shots

Fig.15 Single clamp switch test (CLM-R71)



Bank :  $C_B = 2.0 \mu H$       Gap :  $L_{SG} \doteq L_{DG1} = L_{DG2} \doteq 15 \text{ nano H}$       Load :  $L_L = 240 \text{ nano H}$   
 $L_B = 90 \text{ nano H}$        $R_{SG} \doteq R_{DG1} = R_{DG2} \doteq 5 \text{ m}\Omega$        $L_{coll} = 3 \text{ nano H}$   
 $R_B = 22 \text{ m}\Omega$        $L_{C1} = L_{C2} \doteq 3 \text{ nano H}$

$I_{LI} \doteq 140 \text{ kA} - 190 \text{ kC rise}$

Diverted :  $I_{D1} = I_{D2} = 87 \text{ kA} - I_L = 6 \text{ kA}, I_B = 180 \text{ kA}$

Fig.16 Test circuit, equivalent diagram (CLM-R71)



where the first peak of the coil  $di/dt$  trace is due to trigger current through the load coil after the breakdown of the first stage, (between electrodes C and A in Fig.8). The waveforms obtained in the case of "simultaneous" breakdown at a slightly lower gap voltage, are shown in Fig.14(b), and the absence of the former peak in the coil  $di/dt$  trace, indicates that breakdown of both stages has been accomplished "simultaneously". It should be noted that the "simultaneous" mode gives a much shorter breakdown time than the "cascade" mode at approximately the same bank voltage.

The transition from "cascade" to "simultaneous" breakdown at low voltages suggests that a gap with 50/50 spacing can be triggered down to zero gap voltage, i.e. it would have a 100% voltage range, though this has not yet been achieved experimentally. A gap with 50/50 spacing has however, been triggered successfully as a single clamp switch at less than 5% of the bank voltage as shown in Fig.15.

#### START GAP BREAKDOWN TIME

Investigations into breakdown time were made with a fast rise oscilloscope (Tektronix 519) and a resistive voltage divider giving an overall response time of 2.5 nsec. The tests were carried out in a test circuit as shown in Fig.16.

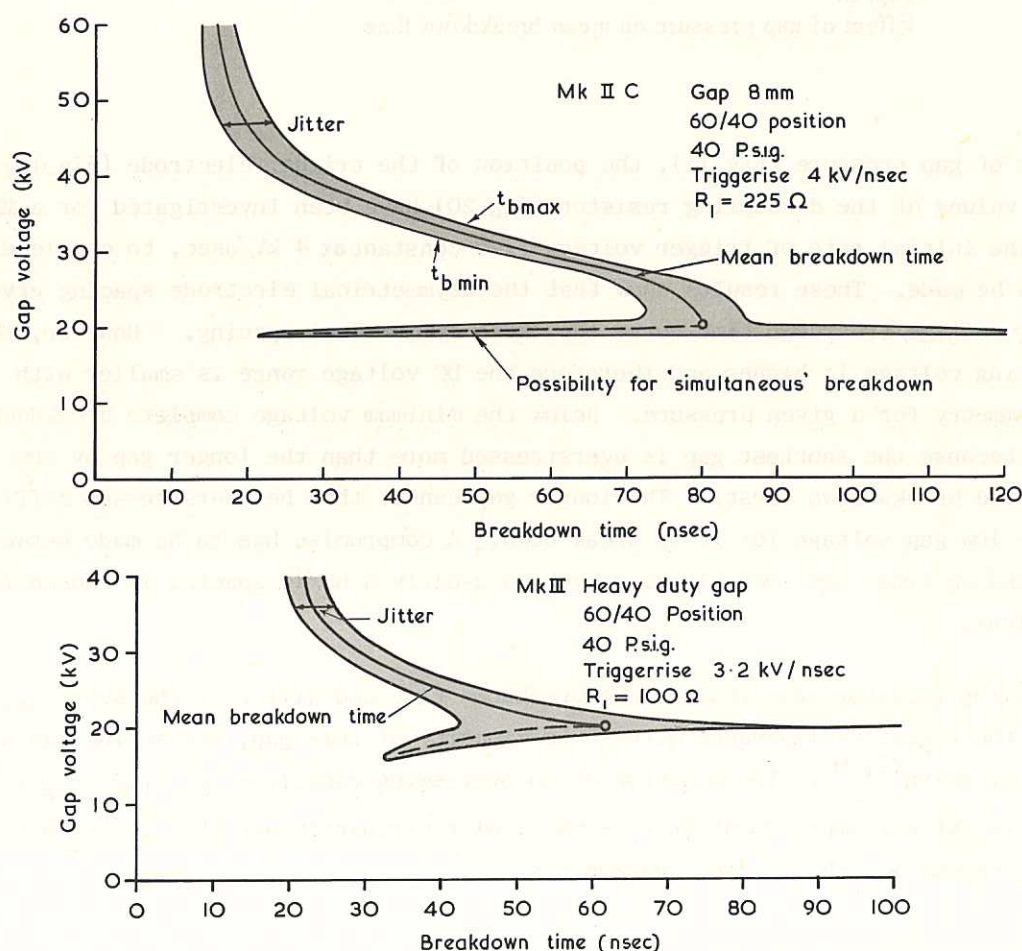


Fig.17 (CLM-R71)  
 (a) Typical distribution of breakdown time (Mk.II)  
 (b) Typical distribution of breakdown time (Mk.III)

Values of the breakdown times of a Mk II and a Mk III gap as a function of the applied gap voltage are given in Fig.17. The important features are the short breakdown times down to about half the working voltage, and the low jitter of  $\pm 3$  nsec at 60 kV, increasing to

$\pm 6$  nsec at 25 kV. A changeover in the breakdown mechanism at about 20 kV takes place and both types of breakdown modes have been noted even at the same gap voltage. This is accompanied by a large increase in jitter and therefore this region should be avoided in applications where many start gaps have to be triggered in parallel.

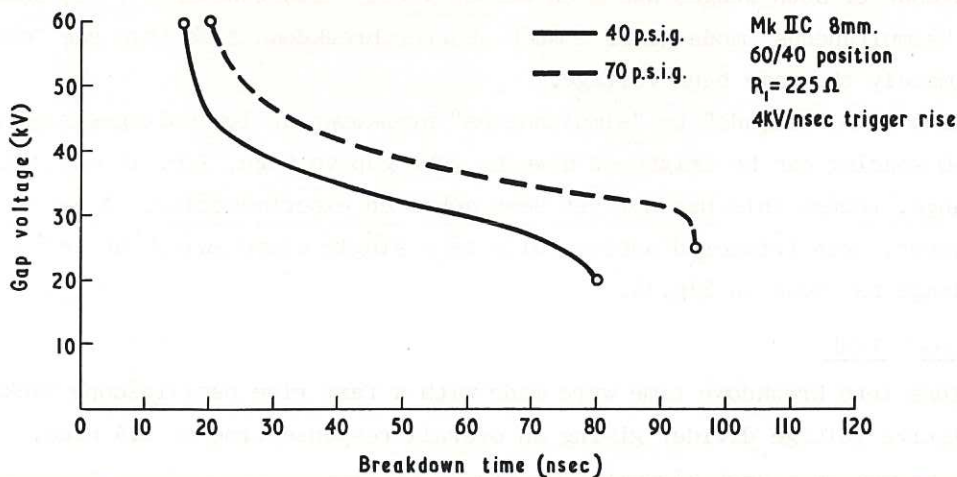


Fig.18 (CLM-R71)  
Effect of gap pressure on mean breakdown time

The effect of gap pressure (Fig.18), the position of the trigger electrode (Fig.19) and different values of the decoupling resistor (Fig.20) have been investigated for a Mk II gap, keeping the initial rate of trigger voltage rise constant at 4 kV/nsec, to enable direct comparisons to be made. These results show that the asymmetrical electrode spacing gives a much steeper voltage/breakdown time curve than with symmetrical spacing. However, the minimum operating voltage is higher and therefore the DC voltage range is smaller with increasing asymmetry for a given pressure. Below the minimum voltage complete breakdown cannot occur, because the shortest gap is overstressed more than the longer gap by the trigger pulse and breaks down first. The longer gap cannot then be overstressed sufficiently by the low gap voltage for it to break down. A compromise has to be made between the short breakdown times and low voltage range and usually a 60/40 spacing is chosen for most applications.

The decoupling resistor  $R_1$  reduces the breakdown time and jitter of the second gap by increasing the resistive impedance across the capacity of this gap, and so increasing its voltage over swing<sup>(5,10)</sup>. The addition of an over-swing capacitor  $C_2$  (see Fig.8) however, gave no further improvement in this particular circuit though this is not necessarily true of circuits with different parameters.



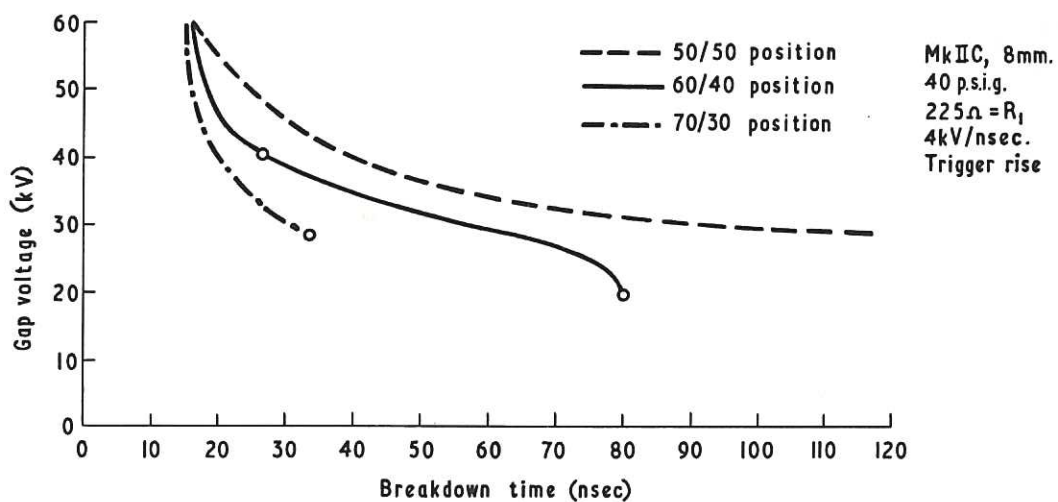


Fig. 19 (CLM-R71)  
Effect of trigger electrode position on mean breakdown time

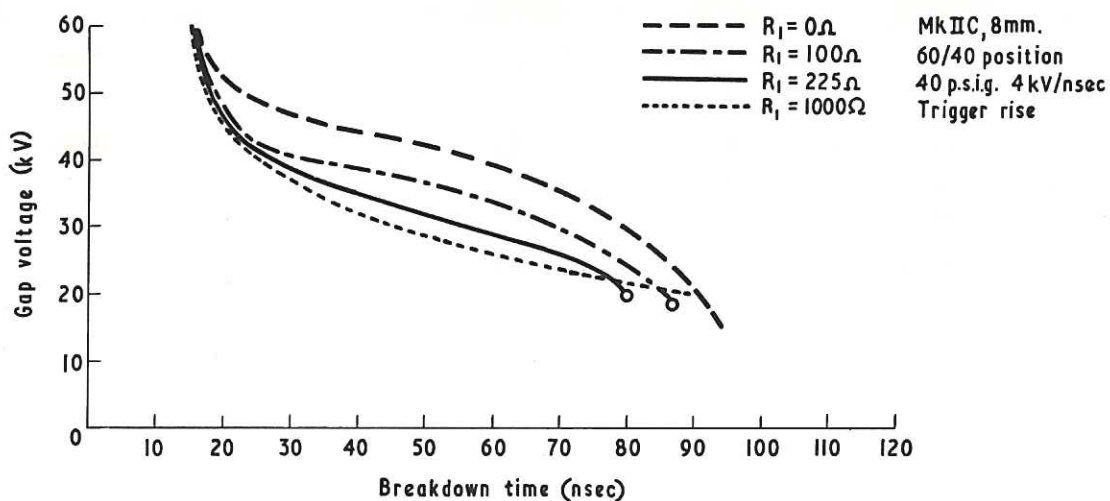














Fig. 20 (CLM-R71)  
Effect of decoupling resistor on mean breakdown time

GAP VOLTAGE	50/50 SPACING	60/40 SPACING	70/30 SPACING
60 kV	 $R_f = 0$	 $R_f = 0$	 $R_f = 0$
	 $R_f = 225 \Omega$	 $R_f = 225 \Omega$	 $R_f = 225 \Omega$
40 kV	 $R_f = 0$	 $R_f = 0$	 $R_f = 0$
	 $R_f = 225 \Omega$	 $R_f = 225 \Omega$	 $R_f = 225 \Omega$

Mk IC, Pressure 40 psig (2.8 atm), Trigger voltage 60 kV, 10  $\mu$ sec/div (unless otherwise stated)

Fig.21  
(CLM-R71)  
Variation of breakdown time (jitter). 20 shots superimposed



It can be seen from Fig.21 that with  $R_1$  in the circuit the jitter is only  $\pm 3$  nsec, even when the gap is operated at 40 kV. When the decoupling resistor is removed, the jitter increases to about  $\pm 10$  nsec at 40 kV, with a corresponding increase in breakdown time. Again a compromise in the value of resistance has to be made because too high a value of  $R_1$  results in a lower rate of trigger voltage rise and would thus increase the jitter of the first stage. A value of 100-200 Ohms for  $R_1$  has given good results and is therefore used.

#### DIVERSION SWITCH TESTS

These tests were also carried out on the test circuit shown in Fig.16. Setting of the auxiliary gap was not found to be critical between 7 and 15 mm and a spacing of 10 mm was therefore chosen. The impulse voltage breakdown characteristics of the diversion gaps were checked by firing the start gap only. No breakdown occurred at 5 p.s.i.g. (0.33 atm.), and a 50% probability of breakdown resulted at zero p.s.i.g. An operating pressure of 20 p.s.i.g. (1.3 atm.) at 60 kV was therefore chosen (i.e.  $pw/pb = 0.8$ ). Thus for a half-period (2  $\mu$ sec) the gap can withstand voltages greater than the static breakdown value.

The diversion switch triggering conditions are similar to those of the start gap and need not be considered further. The triggering of the two diversion gaps is however of interest since they are connected directly to the same transmission line, so that the transit time between their breakdown points is only 2 nsec, and therefore negligible. The inductive voltage across one gap is also very low, being 14% of the bank voltage.

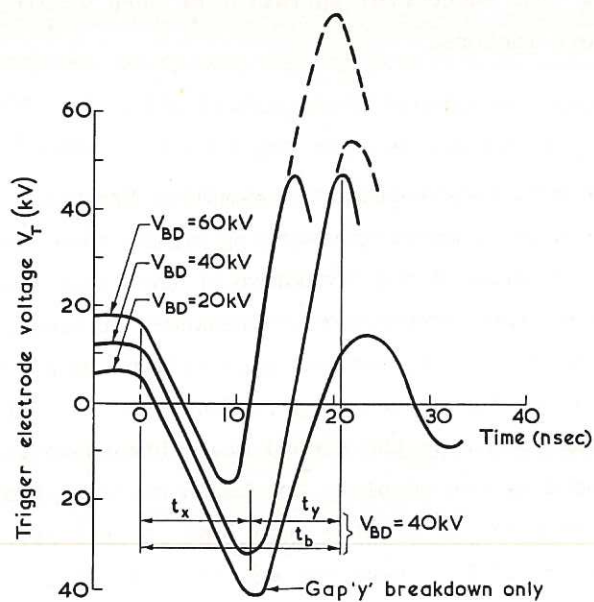
The two gaps were triggered without difficulty with current sharing within  $\pm 15\%$ , showing that the two parallel gaps can be operated consistently, with virtually no transit time isolation between them.

#### 4. THEORETICAL ASPECTS OF TRIGGERING PARALLEL GAPS

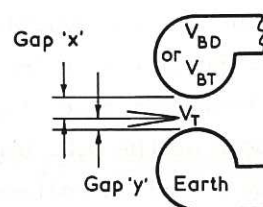
##### PARALLEL GAPS WITH TRANSIT TIME ISOLATION

It has been general practice<sup>(4,5,7,8,9)</sup> to arrange that parallel spark gaps have individual connections with an electrical transit time greater than the spread in breakdown time of the gaps. This is based on the fact that a gap with a longer than average breakdown time will otherwise have its voltage considerably reduced by the earlier breakdown of other gaps, and may not then fire if its voltage range is limited. Though this principle is a useful basis for the design of large capacitor banks, a more accurate consideration of the problem shows it to be pessimistic, especially if variable pressure swinging cascade gaps are used, for the following reasons:

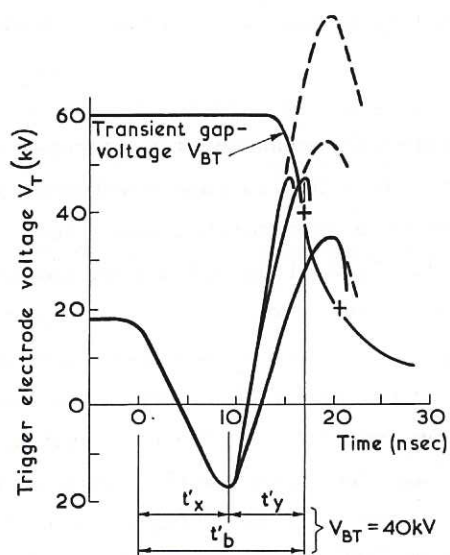
- (a) The gap voltage decays only at a rate fixed by the circuit inductance and transmission line characteristic impedance.
- (b) The spread in breakdown time of a group of parallel gaps will inevitably reduce the initial rate of voltage decay.
- (c) Most three electrode gaps with an asymmetrical electrode spacing, can be triggered down to a D.C. bank voltage at least 50% of the maximum working value. This voltage range is even greater under the transient voltages which are applicable to parallel triggering of gaps, for the reasons discussed below.



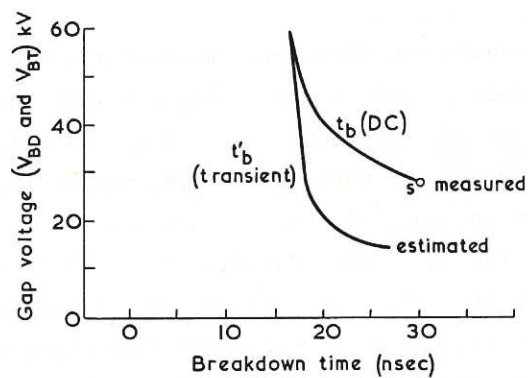
a) DC-Conditions



Electrode spacing



b) Transient conditions



c) Breakdown time

Fig.23

(CLM-R71)

Trigger electrode voltage and breakdown time (d.c. and transient) Mk.IIc, 40 p.s.i.g., 70/30 spacing



It will be seen that the transient characteristic is much steeper and has a wider voltage range than the D.C. characteristic, and therefore breakdown will occur with less jitter and down to a lower transient gap voltage. This characteristic has been used in plotting Fig.22(b), which shows that such a switching system should result in satisfactory operation of parallel gaps without transit time isolation. It is possible that the transient characteristic may be made even steeper by using a more asymmetrical spacing (say 80/20). However, this could result in too much jitter in the first breakdown and therefore failure of some gaps to fire, or alternatively would reduce the margin of over pressure that can be maintained to prevent premature breakdowns.

## 5. 60 kV 30 kJ CAPACITOR BANK

### GENERAL DESCRIPTION

The bank is designed to give a peak current of 1.5 MA rising in 1.0  $\mu$ sec in a theta-pinch coil. The latter has two feed points, to give a nominal coil voltage of 120 kV and an effective inductance of 15 nH, the bank inductance being 8 nH. After one half-period (2.0  $\mu$ secs) the coil current is reduced to less than 10% of its peak value by being short circuited or "diverted" by twelve diversion gaps. After diversion the total capacitor current rises to 1.9 MA or 240 kA/unit.

The general arrangement of the bank is shown in Fig.24. The equivalent circuit and performance curves, derived from experimental data are shown in Fig.25. The bank circuit

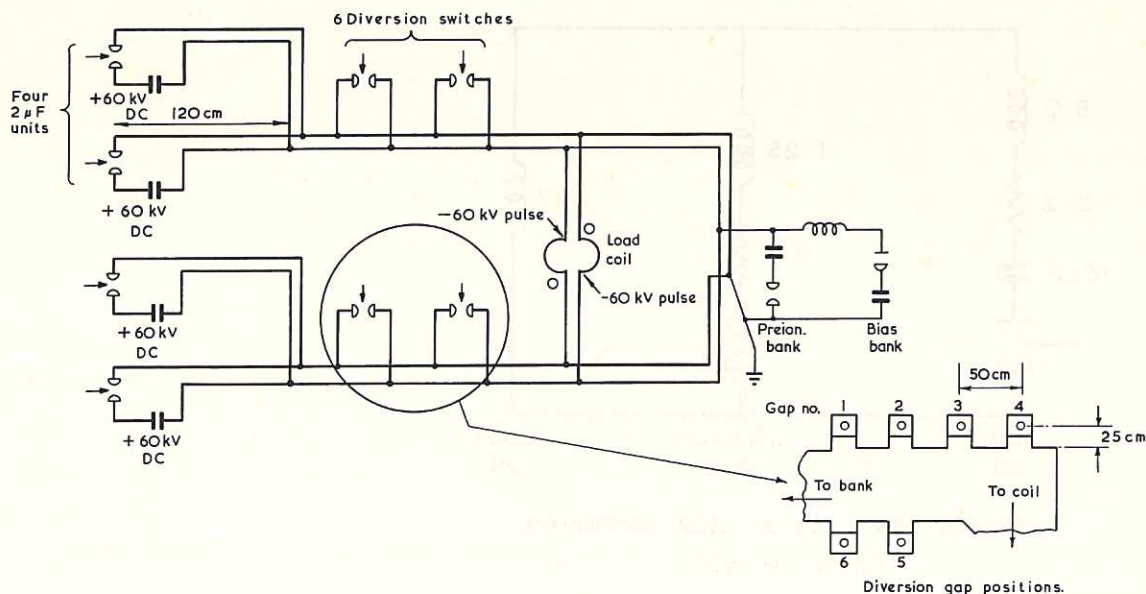
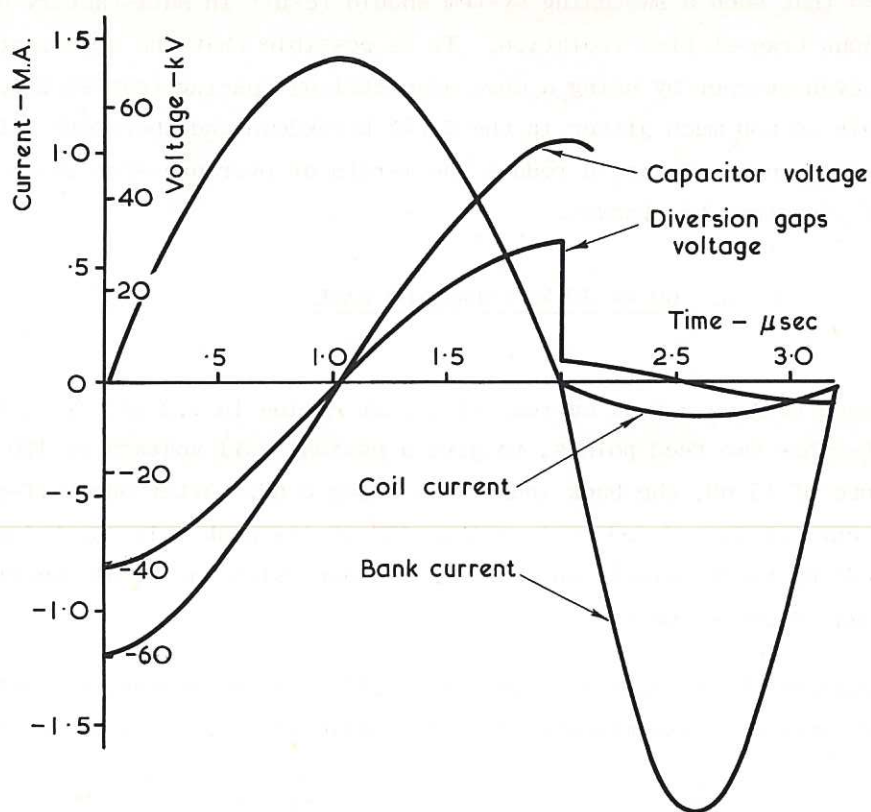
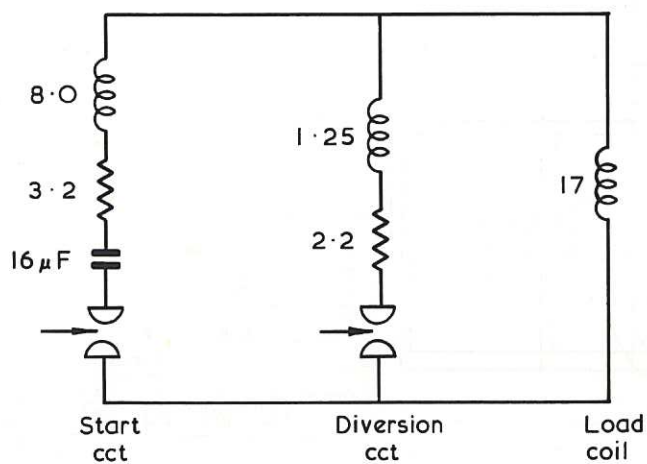


Fig.24 60 kV, 30 kJ bank arrangement (CLM-R71)



(a) Bank performance at 60 kV



(b) Equivalent circuit (test parameters)  
(units nH, m $\Omega$ )

Fig. 25 60 kV, 30 kJ bank performance (CLM-R71)



parameters have been measured or calculated from the tests described below, as follows:-

<u>START CIRCUIT</u>	<u>INDUCTANCE</u>	<u>RESISTANCE</u>
8 start gaps (18 nH)	2.3 nH	
8 capacitors (10 nH)	1.3	
Transmission lines	<u>4.4</u>	
	<u>8.0</u>	3.2 m $\Omega$

#### DIVERSION CIRCUIT

12 Diversion gaps (15 nH)	1.25 nH	2.2 m $\Omega$
---------------------------	---------	----------------

When the diversion gaps are used as clamp gaps the gap resistance is reduced and is equivalent to a constant arc voltage of 600 volts.

#### TRIGGER CIRCUIT

Master Gap	28 nH including terminations
------------	------------------------------

#### PARALLEL START GAP TESTS

These tests were carried out on half the complete bank i.e. 4 capacitor/start gap units at 40 kV, and with a dummy load inductance of 65 nH, giving 160 kA/unit. The gap trigger electrodes were placed in the 60/40 position, with an operating pressure of 40 p.s.i.g. (2.7 atm).

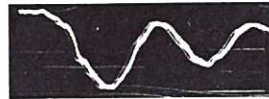
Simultaneous measurement of the individual gap currents were made using magnetic probes placed in the transmission line connections. Ten superimposed shots were photographed in Fig.26, with the oscilloscope being triggered from the output of the start master gap. It will be noted that the jitter of individual gaps is less than  $\pm 3$  ns, and that there is no measureable difference in peak current from shot to shot. This is in spite of having no decoupling resistor  $R_1$  (Fig.8)

#### PARALLEL OPERATION OF SIX DIVERSION GAPS

The triggering tests carried out on the closely parallel diversion spark gaps are of interest since they are a means of experimentally checking the theoretical proposals made in section 4 above. These tests are particularly significant, because (a) the six gaps (2.5 nH inductance) and their common transmission line  $Z_0$  combine to give a rapid decay of voltage across late gaps (about 20 nsec time constant), and (b) the parallel gap inductance is only 14% of the total circuit inductance after diversion.

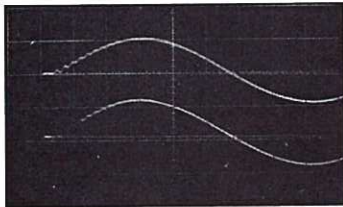
The trigger electrodes were initially placed in the 60/40 position, the voltage and pressure being 40 kV and 20 p.s.i.g. (1.3 atm) respectively; a decoupling resistor  $R_1$  of 125  $\Omega$  was used. The start circuit, diversion circuits (suitably delayed), and oscilloscopes are triggered from the same time reference. It follows that the combined jitter of the start and diversion switch systems (thyratrons, master gaps and parallel spark gaps) can be computed from the variation in coil current after diversion, and is  $\pm 30$  nsec. This jitter and the ratio of diversion circuit to load inductance are the significant factors in maintaining the coil current below 5% of its peak value in the present circuit.

Simultaneous current measurements in the six gaps and the load coil were made, which showed that all gaps could be triggered consistently. Ten superimposed traces are shown in Fig.27(a).



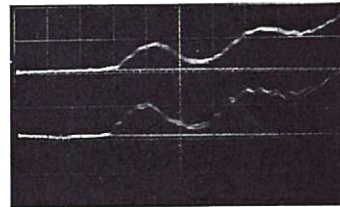
50 nsec/div  
(a) load coil voltage  
(ten superimposed shots)

gap  
No  
3



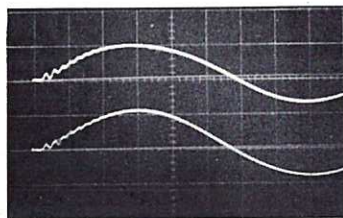
2

gap  
No  
2



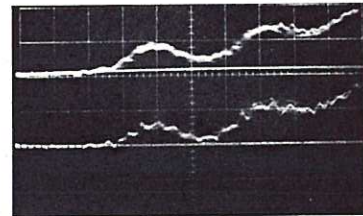
1

1



4

0.5  $\mu$  sec/div



4

3

40 n sec/div

(b) gap currents  
(ten superimposed shots)

bank voltage 40 kV  
pressure 40 psig  
60/40 gap spacing  
 $R_i = 0$

Fig.26 Parallel operation of start gaps (CLM-R71)



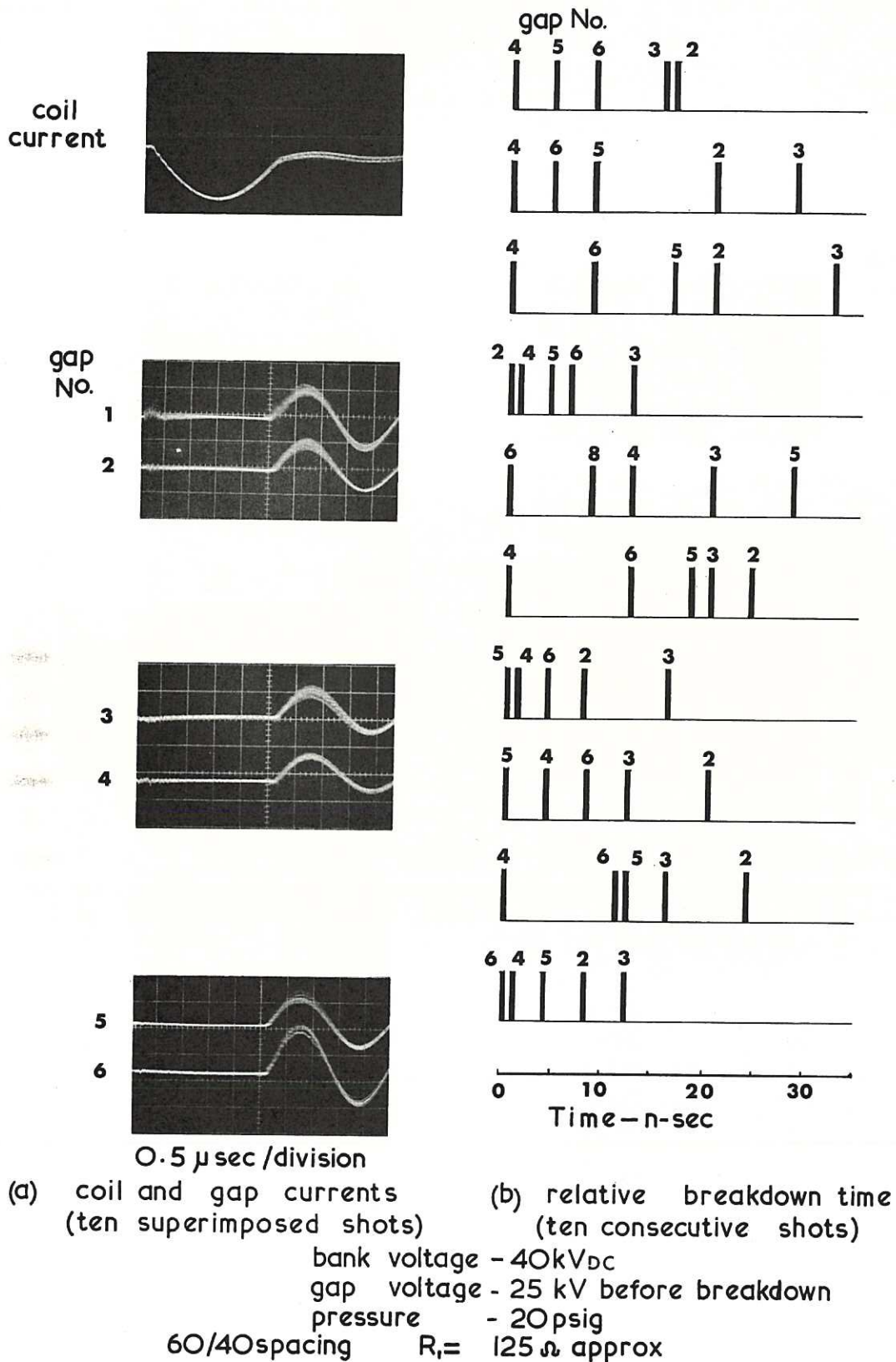
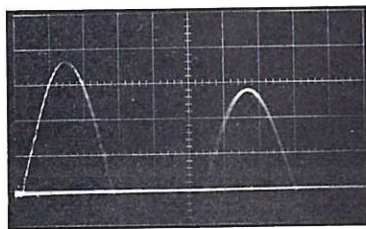


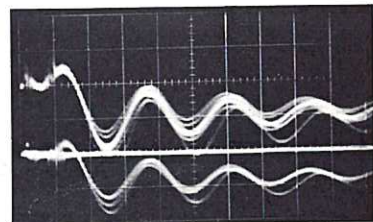
Fig.27 Parallel operation of diversion gaps (CLM-R71)

Simultaneous measurements of the breakdown time were also made for five gaps (No.1 gap became faulty during this test). The time difference between the 'late' gaps and the first gap is given in Fig.27(b) for 10 consecutive shots, which gives a maximum spread in breakdown time of  $\pm 15$  nsec between gaps. This represents about 7 times the transit time between gaps and therefore these results demonstrate conclusively that gaps can be operated consistently when closely connected in parallel.

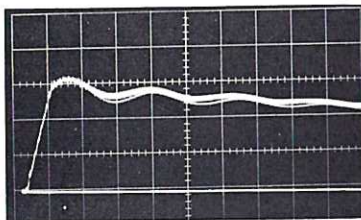
The variation in peak current in individual gaps from shot to shot of about  $\pm 20\%$  is noticeably greater than in the case of the start switches, probably because the inductance of a diversion gap and its connections is much less than that of the separate start gap/capacitor circuits. Thus its current sharing could be affected by variations in arc resistance. A difference in peak current between gaps of about  $\pm 30\%$  will be noted, which is associated with the geometrical position of the gaps in relation to the start circuit connections. For example, gap 6 and gap 4 are nearest and furthest from the start circuit connections respectively. Similar simultaneity tests were repeated with a 50/50 spacing of the trigger electrode. In this case, reliable parallel operation was not achieved.



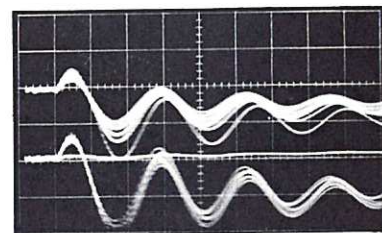
(a) coil current (unclamped)



gap  
No  
2  
3



(b) coil current (clamped)



4  
5

(c) gap currents

ten superimposed shots  
1.0  $\mu$ sec/division  
bank voltage 40kV  
pressure 20psig  
50/50 gap spacing  
 $R_i = 125 \Omega$

Fig. 28 Parallel operation of clamp gaps (CLM-R71)



Reference to Fig.19 shows that symmetrical spacing of the trigger electrode results in a much less steep voltage/breakdown time curve (though the D.C. voltage triggering range is increased), compared with the 60/40 and 70/30 electrode position. Unsatisfactory parallel operation is therefore consistent with the theoretical considerations given above.

A 60 kV multiple arc gap of 5 nH inductance, with six breakdown points, has also been designed to give the same performance as six separate diversion gaps. Preliminary experiments show that multiple arc breakdowns are being achieved consistently.

#### PARALLEL CLAMP GAP OPERATION

Some very preliminary experiments have been carried out to show whether the diversion gaps can be used as clamp gaps, by triggering them near peak current.

These tests were made with a 50/50 trigger electrode position and a decoupling trigger circuit resistance of 125  $\Omega$ . This should be the best condition for clamp operation, where simultaneous breakdown of both halves is the ideal.

In the tests it was found that not all the gaps fired consistently, but a satisfactory clamped waveform was obtained if the gaps were triggered slightly before peak current, resulting in a reduction of current to 90% of the un-clamped value. The ten superimposed current traces are shown in Fig.28. These results indicate that the gaps are still working in the cascade mode. No further experiments were carried out to obtain more consistent "simultaneous" breakdown at peak current and zero voltage because this was not required for this capacitor bank. However, it appears that the very low gap inductance combined with the short connection directly into a low impedance transmission line makes it extremely difficult to complete the breakdown of the slower of the two halves of the gap. Thus, when the first half of the gap breaks down the trigger electrode voltage decreases very rapidly because the source impedance of the trigger circuit cannot be made sufficiently small compared with the very 'low' impedance of the first breakdown.

#### 6. CONCLUSIONS

- (a) 60 kV field distortion pressurised spark gaps having an inductance of 15 to 18 nH, have been developed for use at 450 kA, 7.0 coulombs per gap.
- (b) Life tests on these gaps show that it is essential (a) to use the correct shape of insulation surface close to the arc, (b) that the electrode geometry should be such that the arc is not blown towards this insulation surface (c) that adequate internal volume is provided (d) that the repetition rate is not too high (e) that clean dry air be used and (f) that adequate 'flushing' of the gap between shots be carried out.
- (c) Single gap tests give a breakdown time of 18 nsec at 60 kV with a jitter of about  $\pm 2$  nsec. This low breakdown time and jitter are essential for satisfactory parallel operation, without transit time isolation between gaps.
- (d) A theoretical analysis based on the above triggering data, shows that to obtain satisfactory parallel operation of spark gaps without transit time isolation, the voltage/breakdown time characteristic under these transient conditions must be steeper than the decay of gap voltage.

(c) Tests on a 60 kV 15 kJ capacitor bank module have demonstrated that closely connected parallel gaps with virtually no transit time isolation can be triggered successfully. Reasonable agreement between theory and experiment has been achieved.

(f) The above conclusions show that in principle a 'multiple arc' spark gap can be operated successfully. Experiments on such a spark gap of 5 nH inductance, are now being carried out.

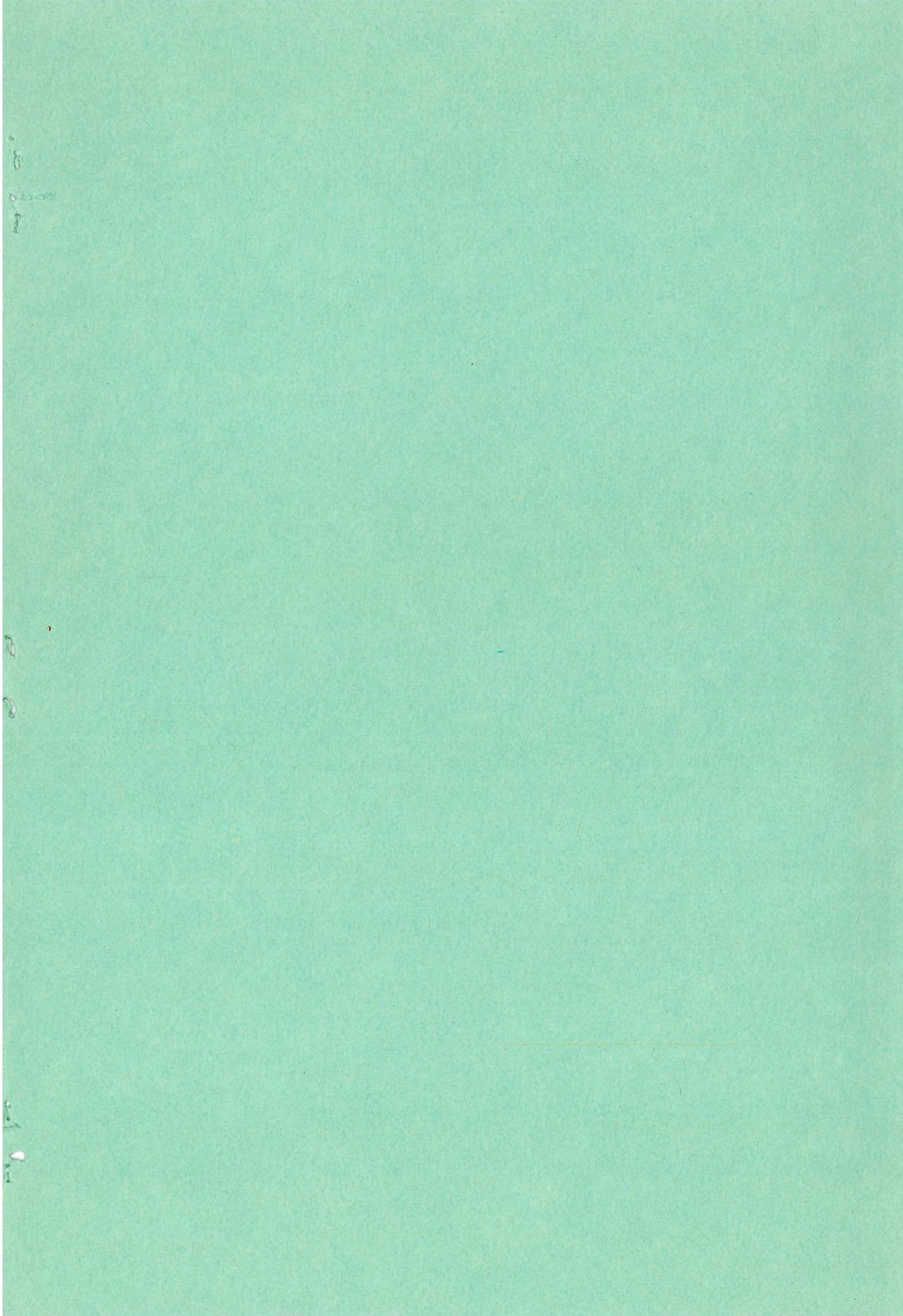
#### 7. ACKNOWLEDGEMENTS

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