Combined Start and Crowbar Sparkgap
with Wide Operating Range

H. Häglsperger, G. Klement, R.C. Kunze,
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IPP 4/28 April, 1966

**INSTITUT FÜR PLASMAPHYSIK**

**GARCHING BEI MÜNCHEN**

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The contents of this report will be presented at the 4th Symposium on Engineering Problems in Thermonuclear Research, Frascati - Rome 23 - 27 May, 1966

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# Combined Start and Crowbar Sparkgap with Wide Operating Range

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Abstract:

A sparkgap and its triggering mode are described having an operating range of 1 : 5 with a jitter of mainly less than 20 ns within the range. The gap ratio and the electrode geometry relative to earth are unsymmetrical. Using these principles the development and characteristics of an open, normalpressure coaxial and a pressurised, parallel plate transmission line start and crowbar switch unit of small dimensions are reported. In both cases the crowbar gap is of the ferrite decoupled type, which is reported by another author at this conference (ref. 1). Also the start and crowbar gaps are moulded together in a chamber formed by an epoxy resin insulation. Experience in operation, life test data and development will be given.

Contents:

This report presented to the Symposium indicates our experience and thought in the development of switch units for use in crowbarred, fast capacity energy storage systems. Because of the shortage of given time, and the progress of continuing development, it is only possible to give a brief summary of our results and experiences. While supressing our theoretical calculations, we report mainly technical design, which we feel is more important to the progress in thermonuclear research. Also we hope that we will be able to deliver an appendix to this report later this year, which we offer to the members of the assembly on demand.

## 1. Introduction

The planning and design of crowbarred condenser banks for short current rise time and long current decay, being often declared to be sucessfull for controlling and heating plasmas, and the use of voltages up to 40 kV and soon probably higher, stimulated the development of a new type of spark gap. Higher energy density of newer banks has to be considered, accompanied of course by lower self-inductance and shorter length of energy transmission lines.

All this development in building large condenser banks with the mentioned characteristics and the possibility to control the demandedenergy by choice of the operating voltage, encouraged the design of spark gaps as a cheap and simple switch in the demanded voltage range, which must have exact time chracteristics, quite low inductance and an operating range of about 1 : 5.

Most condenser banks of modern design involve some hundreds of switches. Therefore the engineer has to consider economic problems, which are not only the costs of manufacture, but also questions of mounting, maintenance and trouble-free operation.

Tu fulfill these requirements we are developing a switching unit formed by a start and crowbar gap, which can be handled easily and connected near to the condenser unit of the bank, so that the exchange of both causes low bank outage time, which is in the deepest interest of the user.

## 2. Development and construction of a 40 kV start switch

### 2.1 Main Physical design aspects

The switching of a sparkgap is a problem of ionisation, which has to be solved mainly by fast liberation of electrons or better, electron avalanches. Space ionisation, caused by irradiation with ultra short wavelengths, originates electrons in the space between the electrodes. Further electrons are liberated at metallic surfaces by thermal emission, field emission and irradiation, which means particulary photo emission and particle bombardement. A combination of these methods of ionisation usually gives rise to dc-breakdown of a gap.

To trigger a gap, one has to select those electron sources, which could be controlled easily. Considering the possibilities of originating electrons, we can make the following assumptions.

To produce space ionisation requires a pulsed electromagnetic irratiation of $\lambda < 10^{-5}$ cm (Röntgen range) or electrons of more than 15 eV, both are inconvenient and expensive. Thermal emission is slow and therefore of no use, so field emission and irradiating emission remain for controlled ionisations.

We cannot be sure that the necessary field strength for field emission of about $10^{6} - 10^{8}$ V/cm is reached, considering a macroscopic view and usual even surfaces. On the other hand, because of statistical distributions there are different mechanisms working together. Field emission is independant of pressure up to at least 110 kg/cm$^2$, proved by Gänger (ref. 2). Therefore its influence rises considerably with increasing pressure due to smaller separations.

To liberate electrons by irradiation from usual electrode materials we need wavelengths of about 300 - 500 nm, which is uV.

Considering these aspects, we feel that it is favourable to take a most jitterless source of irradiation and to support the photo emission so caused by strong electric fields.

Three electrode sparkgaps, especially of the trigatron type are normally used. They work with small delay and jitter also within wide operating range, if "Längsstriggerung" is used. (Breakdown to opposite electrode, see Kauffmann, ref. 3). To reach this triggering mode at higher voltages the breakdown voltage between trigger pin and adjacent electrode must come to such a value, that the main field becomes nonuniform. This causes wider gaps or reduced hold off. The first breakdown, considering "Längsstriggerung", is governed by a Townsend mechanism, which is rather slow e.g. an overvoltage factor of 2 give a statistical time lag of 8 - 15 ns and a formative time lag of 10 - 15 ns (ref. 2), during second breakdown is of the same type assisted by ionisation.

The independant work of Fletcher, Skurophat and Petersen et. al. (ref.4,5,6) shows the increasing jitter of trigatrons at higher voltages, but also the important influence of electrode irradiation (Fletcher). The further development of trigatrons should be first a three electrode spark gap with potential controlled auxiliary electrode and second a cascade trigatron, which is triggered by an auxiliary arc, being on the same potential as the controlled electrode.

This is the known 4-electrode sparkgap switch, which is triggered by a toroidal or disc electrode, having a tungsten pin to ignite the triggered breakdown. If gap ratio and trigger polarity is cho-sen successfully, an operating range of 1 : 3 could be reached.

The construction of the new sparkgap is outlined by the following conditions, which differ from the formally used principles and depends upon the concept already stated, taking advantage of photo and field emission.

The auxiliary electrodes should

1) not distort the static field between the main electrodes (uniform static field, therefore smaller gaps)
2) distort strongly the dynamic triggered field (nonuniform dynamic field, therefore may give rise to field emission)

and

3) ionization should occur on a small area of the surface of at least 2 electrodes, where a sufficiently large positive voltage gradient exists, to accelerate the electrons

and also

4) the influence of the erosion of those parts of the auxiliary electrodes, which give the initial arc, must be unimportant.

2.2 Performance of a start spark gap

Fig. H 035 shows a schematic of spark gap I being a test type, to prove the validity of the stated main design aspects. First constructed as switch unit containing a crowbar gap, as shown in fig. H 036, (two photographs of the start electrode system).

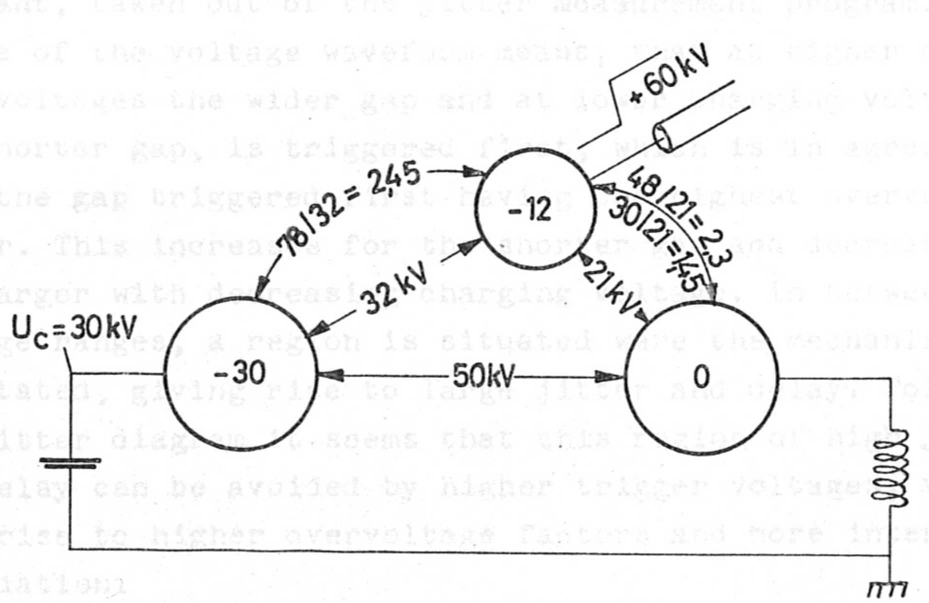
The initial electrode is taken out of the area of erosion by mounting it inside the hollow trigger electrode, and receives the trigger pulse, which causes breakdown between the pin and the trigger electrode with no greater jitter and delay, than the formative and statistical time lag of a very high overvolted gap. (dc-breakdown in the range of 4 - 10 kV, applied pulse 40 - 70 kV) The irradiation coming from this initial arc is lead to both gaps by holes in the trigger rod, assisting their breakdown. The potential of the trigger rod now becomes that of the trigger pulse by mean of the auxiliary arc, producing a strongly heterogeneous field between the main electrodes. The breakdown is no longer a pure overvolted Townsend mechanism, but being assisted by irradiation and high field strength acceleration just on those spots, where electrons are liberated. High field strength exists in the surrounding of the trigger rod holes and adjacent to the opposite surface of the main electrodes. At both spots irradiation is most intense. By choice of a trigger pulse polarity with opposite sign to bank charging voltage, electrons are in areas of large positive voltage gradient at both bank charging polarities. Because of the applied trigger pulse circuit, pulse polarity is opposite to the trigger charging voltage. Selection of the geometrical position and the static potential of the trigger rod, the amplitude of the pulse, and even the intensity of radiation influences the overvoltage of the working gaps.

Although all variations of parameters have not been tested yet e.g. rod and hole diameter, we have results with the initial gap formed by aluminium pins which work a little better than for tungsten pins, because of the different arc sp-ectra. We made some research in controlling the energy of the initial arc by using different capacitors to lead the trigger pulse to earth, which is finally chosen to 250 pF as we show on the circuit diagram fig. H 037, which also illustrates the whole arrangement of testing and measurement. The chosen value of C is a compromise between the height of overvoltage produced on the rod and the energy of irradiation, being proportional to the square of the pulse current.

The static voltage of the rod is controlled by an ohmic voltage divider, whose ratio we choose to 2 : 3 (earth-rod-charging electrode), but there may be better ratios as the reward of further research. The summarised breakdown voltages of the auxiliary gaps might be a little higher than the breakdown voltage of the working gap, to avoid unwanted breakdown and to reduce the rod erosion caused by the main arc.

As we think, most successful triggering occurs, if the overvoltage factor, considering also the decreased dc-breakdown by the initial processes, of both gaps is similar but a little higher for the large gap, so that trigger processes start at both gaps immediately, which is valid before arcing. After switching the wider gap, the overvoltage of the shorter gap is that of the charging voltage.

Taking for instance a 50 kV dc-breakdown, a 21 kV/32 kV auxiliary gap ratio, a charging voltage of -30 kV and a trigger



pulse amplitude of +60 kV give overvoltage factors of 78/32 = 2.45 for the large gap and 48/21 = 2.3 (after arcing 30/21 = 1.45) for the other, calculated without irradiation, which has a greater influence on the shorter gap. Explanation of low jitter of the second auxiliary breakdown with a comparatively low voltage factor might be, that the trigger overvoltage partly preionises the gap and assists the final breakdown.

Fig. H 038 shows the operational characteristic of the switch "jitter and delay versus charging voltage" at both polarities, with constant trigger supply voltage as parameter. (Trigger pulse voltage is about 190 % and of opposite sign). The diagram is taken by oscillographing 10 discharges at various charging voltages with Tektronix 507 being external triggered by the trigger pulse itself. In spite of the 4 ns jitter of the oscilloscope, proved with internal triggering, we got oscillograms where the trace is smaller using the latter arrangement.

Discussion of the jitter diagram is possible with regard to fig. H 039 which shows di/dt in the load, being the voltage there at various working voltages, trigger voltage constant, taken out of the jitter measurement program. The change of the voltage waveform means, that at higher charging voltages the wider gap and at lower charging voltages the shorter gap, is triggered first, which is in agreement with the gap triggered first having the highest overvoltage factor. This increases for the shorter gap and decreases for the larger with decreasing charging voltage. In between these voltage ranges, a region is situated were the mechanism is not stated, giving rise to large jitter and delay. Following the jitter diagram it seems that this region of high jitter and delay can be avoided by higher trigger voltages, which give rise to higher overvoltage factors and more intense irradiation.

## 3. Statement on the measurement of jitter

During our measurements to obtain the characteristics of this switch by using 10 discharges of each value, we made some experimental research on jitter variations with increasing number of discharges. The results are given with fig. H 041 and H 040. The first shows oscillograms of the mentioned di/dt measurement, having the same conditions but differing only by the number of discharges. This is tested for two charging voltages taken out of a range of the gap characteristic, where low jitter is established. The influence of increasing number of discharges is to increase the jitter by a factor of two or three.

With regard to H 040, where we chose a charging voltage having large jitter to consider the distribution, we plotted the oscillogram on Gaussian paper, having the characteristic of "nano-seconds jitter" on the horizontal and the sum of relative frequency of events on the vertical axis. A straight line on this paper is given by a Gaussian or normal distribution. The Gaussian plot of the oscillogram is not a straight line, that means the population of all jitter events is not distributed normally. As seen, the curve is approximated by three straight lines. This approximation we feel to be justified, because jitter is influenced by the variation of charging and trigger voltage and by the mechanism it-self, which seemed to be normally distributed. Otherwise it has to be observed, that charging and trigger voltage are not uncorrelated. Further experimental and theoretical research is needed.

## 4. Switch unit design

To install a start and crowbar gap as one unit, needs some consideration. Regarding capacity energy storage systems approaching an energy density of 0,2 Joules/cm$^3$, which then is concentrated in the coil to a much higher value of magnetic energy density, it seemed to be success-ful to situate the spark gap adjacent to the condenser unit, whose capacitance is restrained by the inductance ratio of the system.

Considering only a ferrite decoupled crowbar switch (Ref. 1 and 7), characterized by the cylindrical ferrite element which is best mounted parallel to the transmission line. This gives us the possibility to reduce the geometrical dimen-sions of the spark gap, together with the whole circuit, to a size comparable to the cross section of the condenser unit. The application of this thought is now given in two examples, concerning a parallel plate transmission line design as well as a coaxial system.

## 5. Applications

### 5.1 Pressurised start and crowbar switch unit

This spark gap was developed for a 40 kV, 10 kJ bank, which will have a working frequency of about 500 kc/sec (Reported here by A. Knobloch Ref. 8). Such a high working frequency depends on the construction of the bank with many individual parallel circuits. Also because of the li-mited room, the start and ferrite decoupled crowbar switch must be constructed within a cross section of about 150 x 220 mm. The switch had to be accomodated in the limited space available and was arranged to fit into a parallel plate transmission line. The spark gap, a schematic is seen in fig. H. 042, which is built in an epoxy resin chamber, has cylindrical electrodes and a parallel rod trigger electrode, whose gaps are at right angles to the crowbar gap. Coaxial ferrite cores, which decouple the crowbar electrode, lie outside the pressure chamber, parallel to the plate line. The pressure chamber contains also the necessary pulse sharpening gap to trigger the crowbar spark gap. Changing the switch range is achieved by changing the pressure, when the breakdown voltage of all gaps will be changed proportionately. Fig. H 043 shows a photograph of this arrangement mounted on the condenser unit together with the trigger and controlling equipment. The circuit diagram for testing and measurement is given in fig. H 037, already presented. The necessary bushing are made of aluminium because of the better bonding to epoxy resin. Also the electrodes are of the same material, due to its lower emission work funktion. We think this is very important to increase the influence of irradiation, which is assisted also by the smaller separations at higher pressure. The current of the switch is not very high (25 kA) and the behavior of aluminium at higher currents remains untested. In fig. H 043, we plotted out the start electrodes, to show the difference between new electrodes and those, which have endured 5000 discharges. Inspite of the erosion,which is visible, it seems not very serious. Looking also at fig. H. 044 where dc breakdown voltage versus pressure is plotted, indicating also the minimum operating voltage of the gap. This characteristic is taken before and after a great number of discharges. Fig. H 045 shows the influence of discharge number on jitter, which we feel is quite satisfactory.

The inductance of the start gap is in the range of 35 nH, meanwhile the whole unit is of about 65 nH, where we reduced the inductance of the condenser by installing a special connection. We have had some difficulties in achieving a sufficient insulation with the characteristic of epoxy resin, but with the help of foils (Hostaphan and Polye/thylene) a satisfactory outer and inner hold off is reached.

The spark gap chamber is pressured with normal compressed air, which we used also for life testing. We want to prove other gases, if we install the spark gap in a circuit with higher current, to investigate the influence on erosion.

5.2 Normal pressure coaxial start and crowbar switch unit

For installation in a 40 kV, 500 kJ bank, we developed a normal pressure coaxial switch unit, carrying a current of 60 kA, 100 kc/sec. The bank consists of 240 capacitors of 2,6 $\mu$F, having 44 nH selfinductance. Fig. H 046, giving a schematic of the gap arrangement, shows the condenser electrode, the unsymmetrical trigger electrode, now being a sphere with irradiation holes and the combined second and crowbar electrode, decoupled by ferrite cores extended parallel to four load cables. The spark chamber is formed by the outer cylindrical conductor and epoxy resin insulation, as we show also in the photograph, fig. H 047.

The inductance of the whole unit, including condenser and switch is 120 nH. Life test is proceeding and has reached 25 000 discharges, without exchange of any part.

This work was performed unter the terms of the agreement on association between the Institut für Plasmaphysik and Euratom

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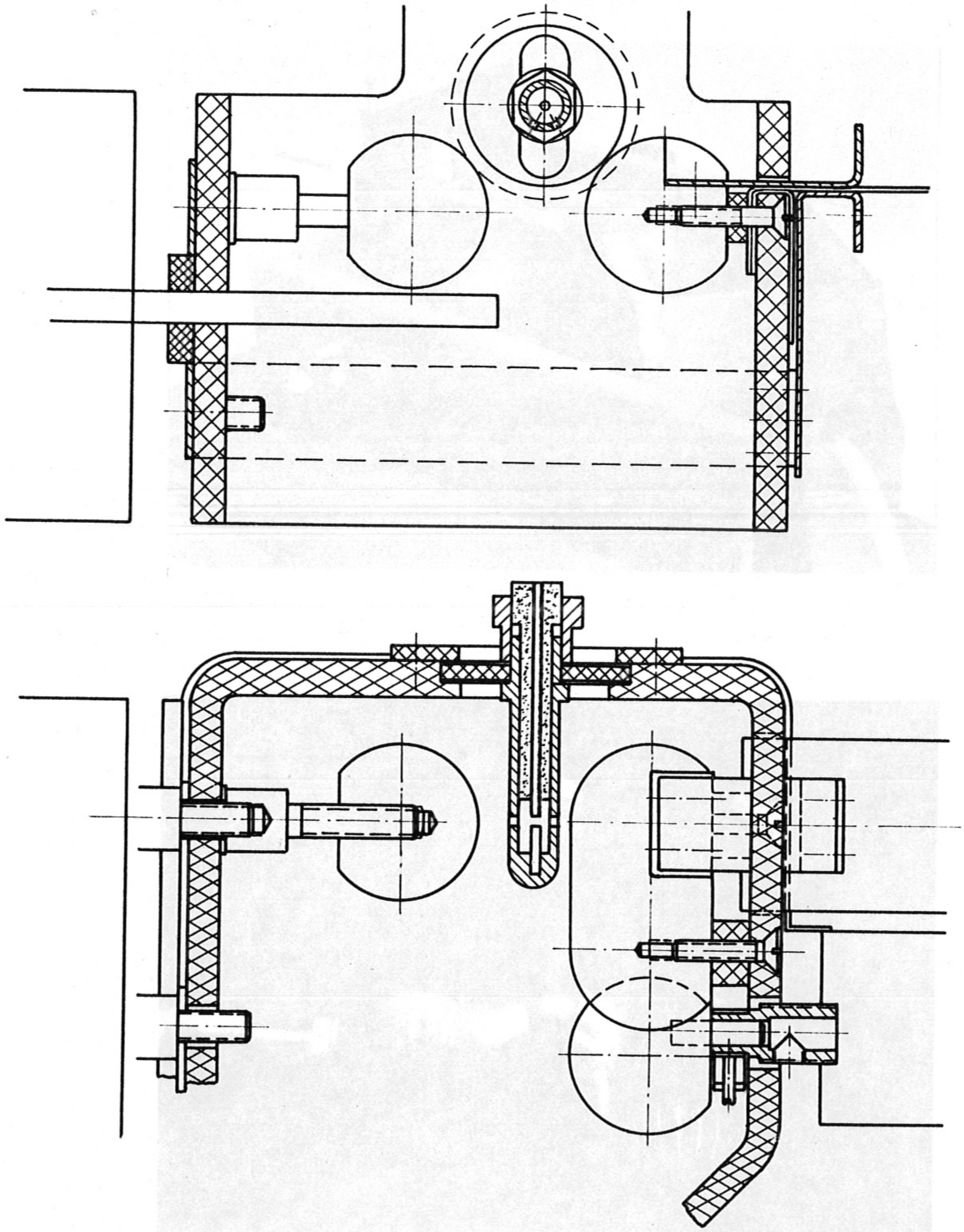
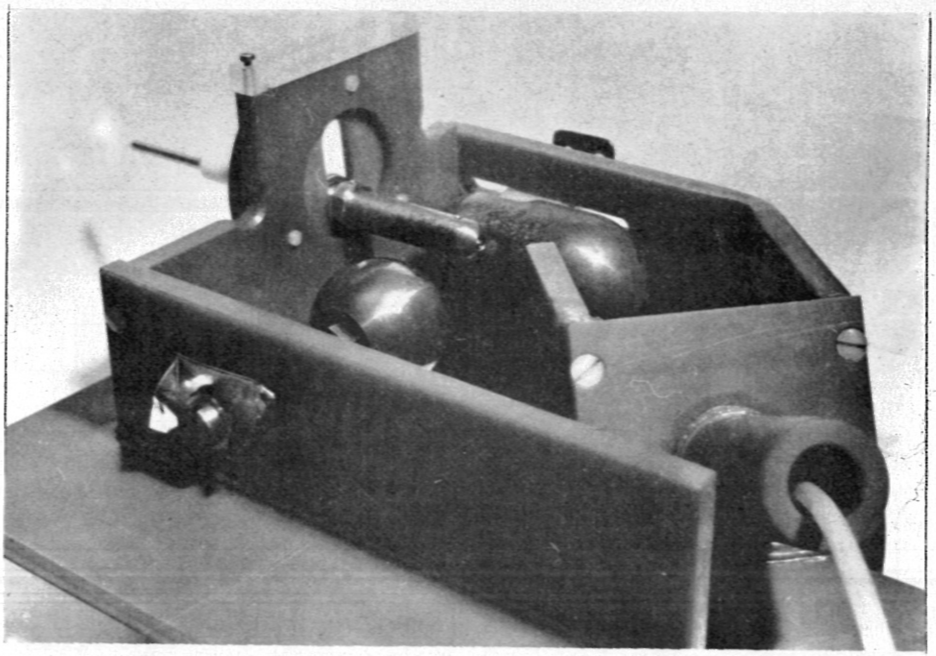
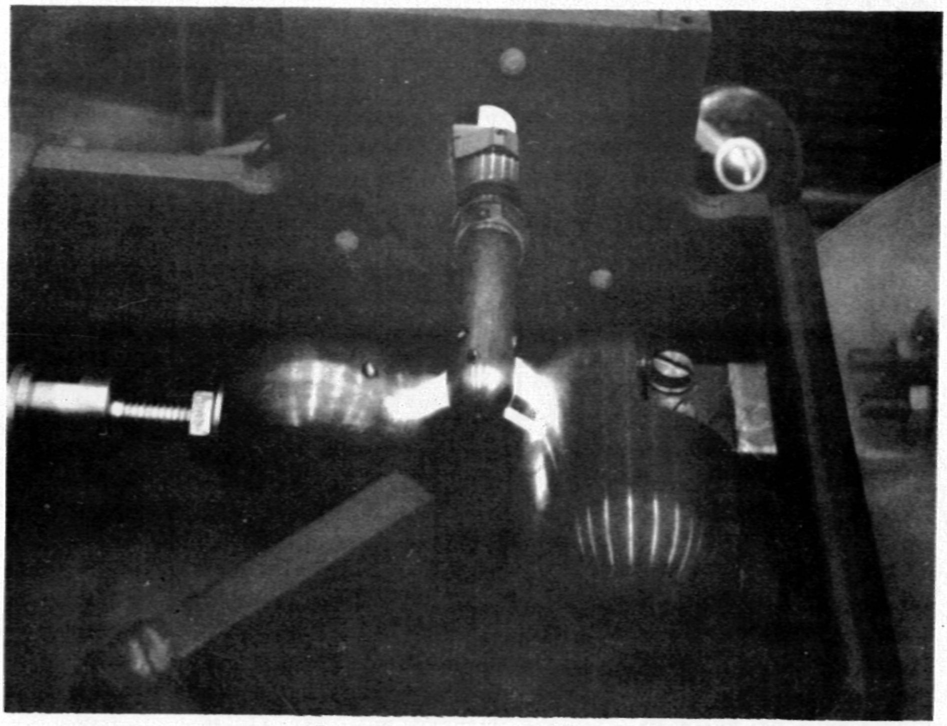


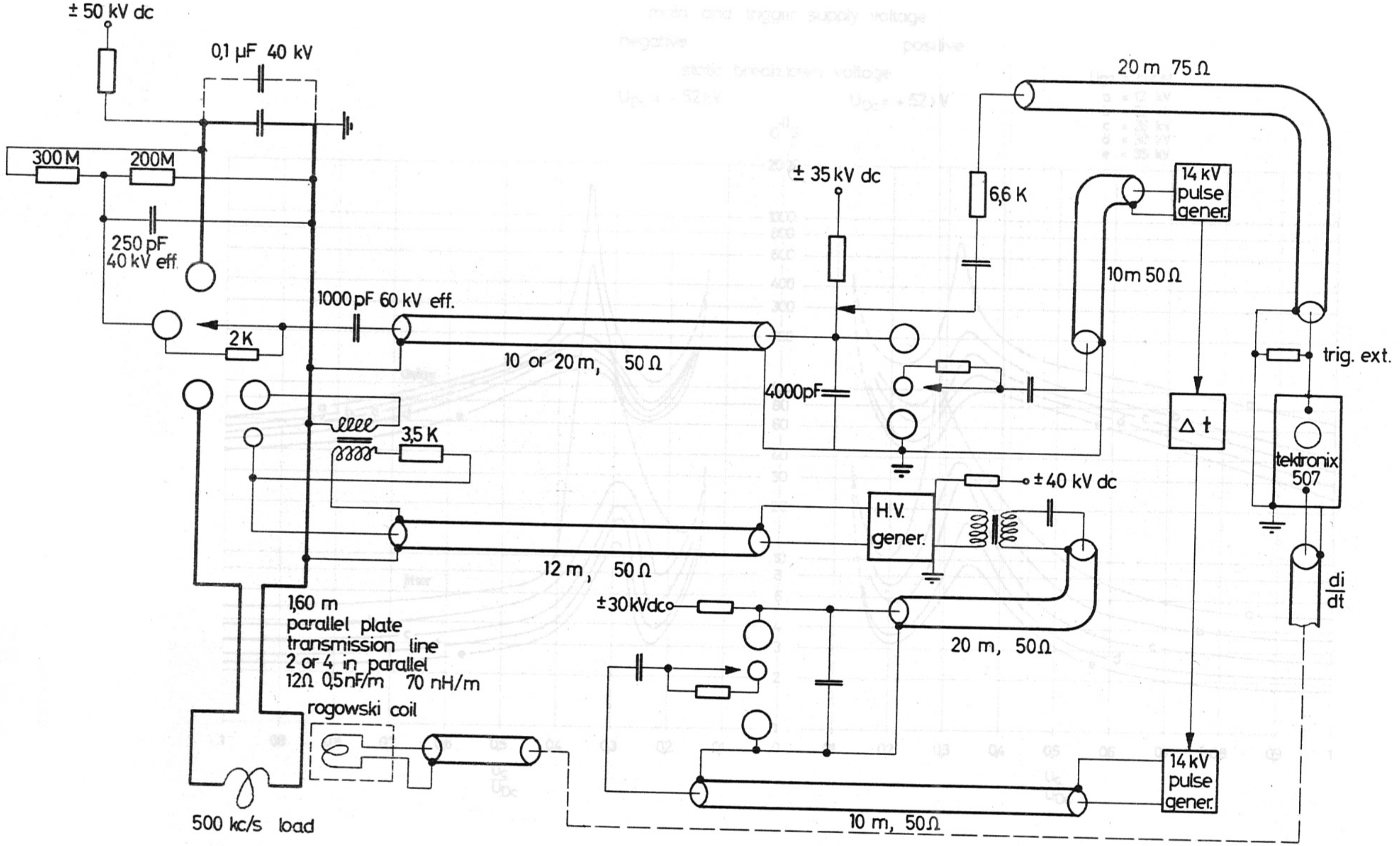
**Schematic Drawing of Spark Gap I**



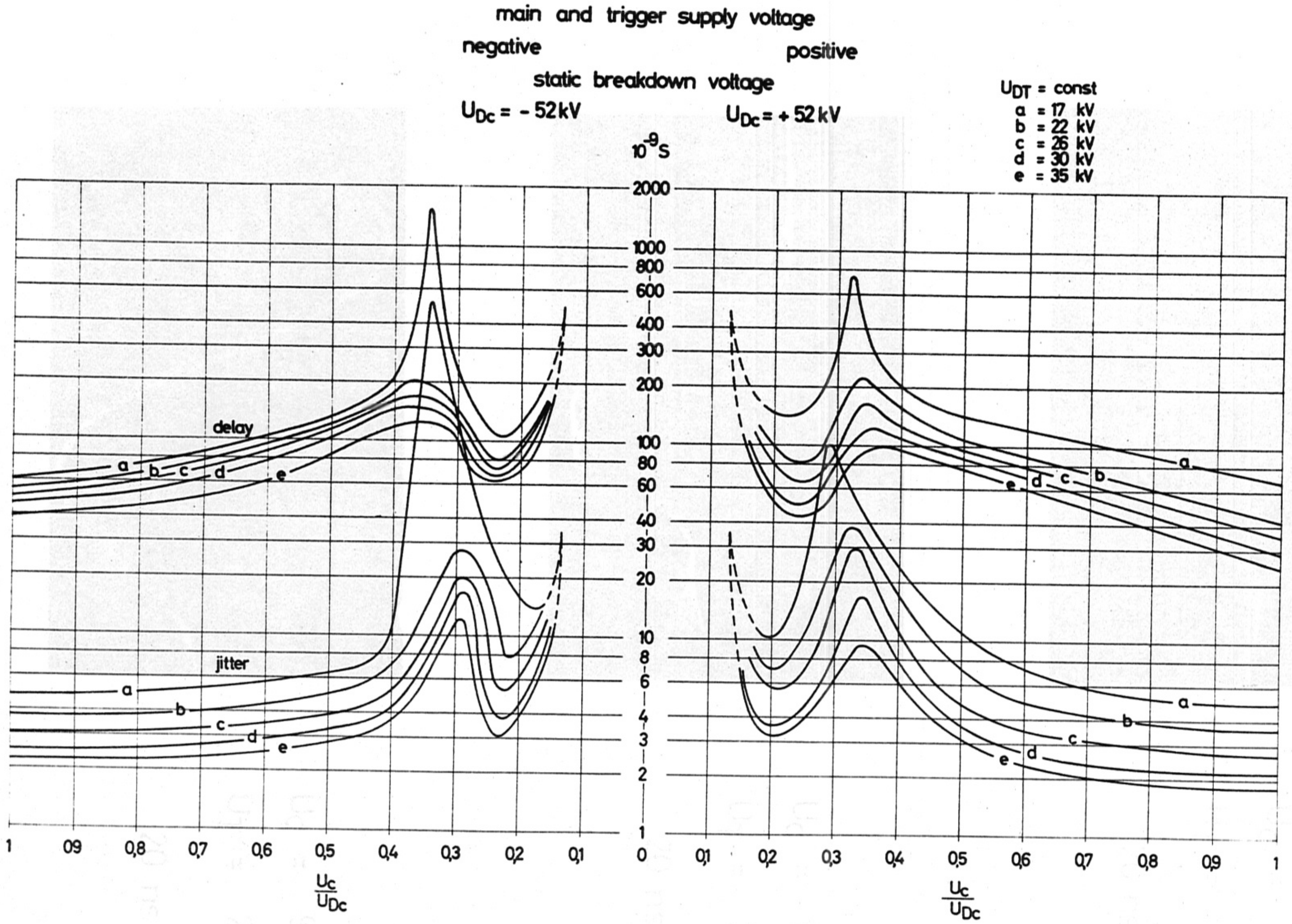


Spark Gap I and

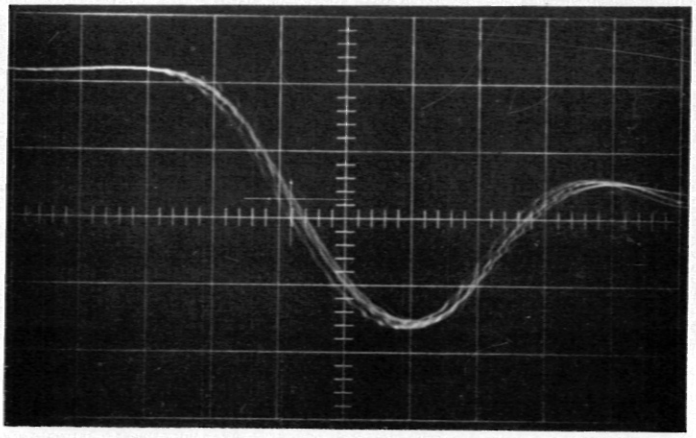
Spark Gap I in Operation




Circuit Diagram



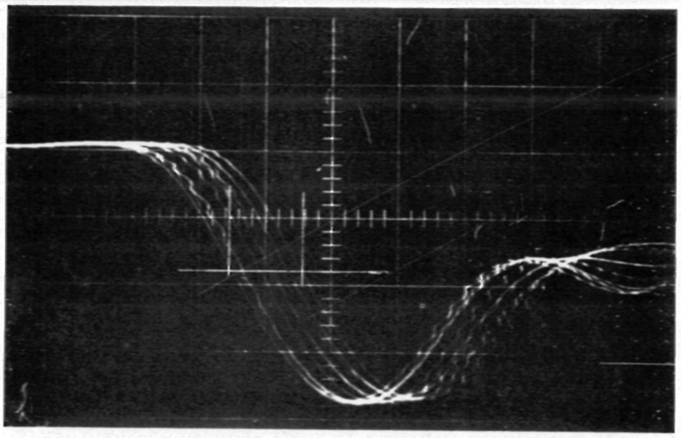

# Jitter and Delay versus Charging Voltage



$U_C$ = 22 kv

$U_T$ = 27 kv

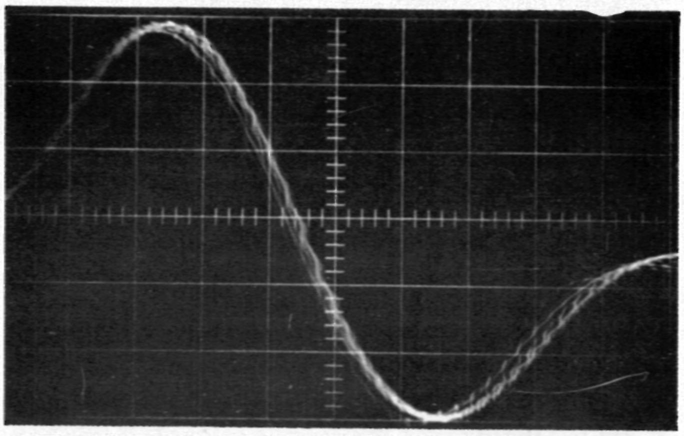
20 ns/cm



$U_C$ = 18 kv

$U_T$ = 27 kv

20 ns/cm

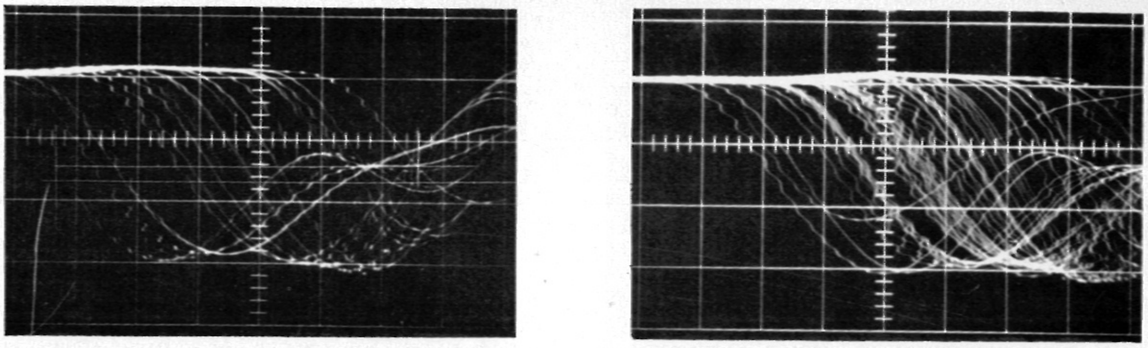


$U_C$ = 9 kv

$U_T$ = 27 kv

20 ns/cm

$\frac{di}{dt}$ **in the Load at Varions Charging Voltages**

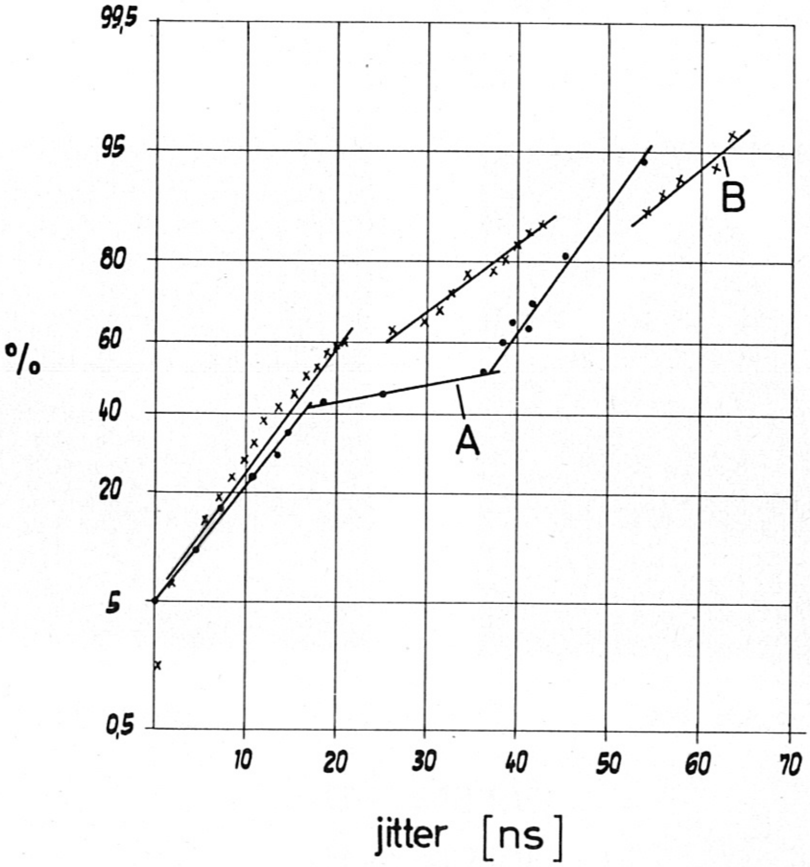


A. 10 discharges　　　B. 50 discharges

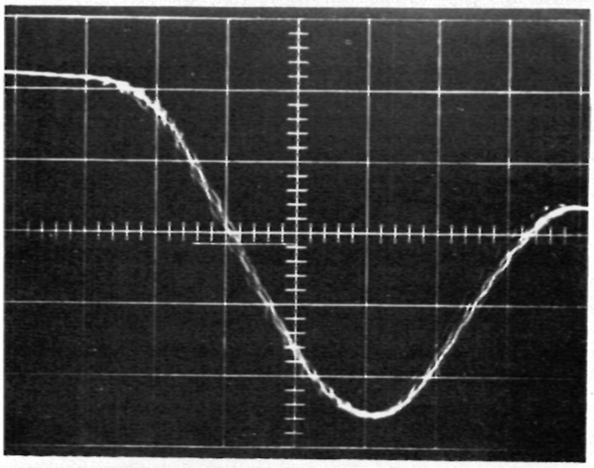
$U_C$ = 14 kv

$U_T$ = 17 kv

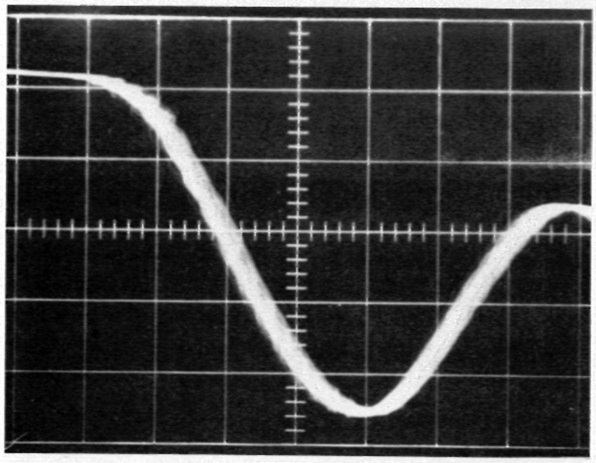
20ns/cm




## Measurements of Jitter



10 discharges

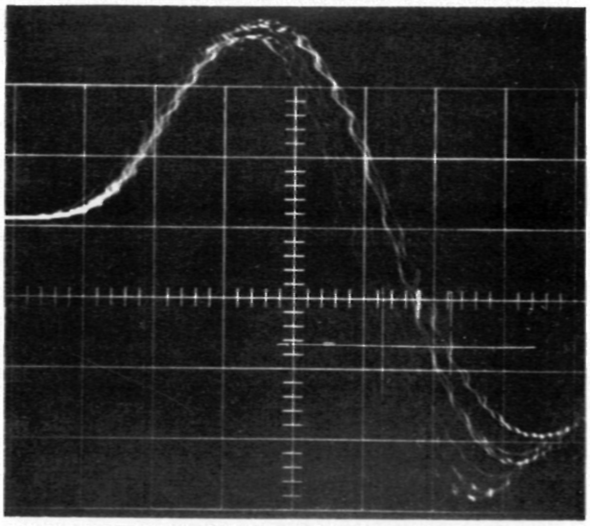


100 discharges

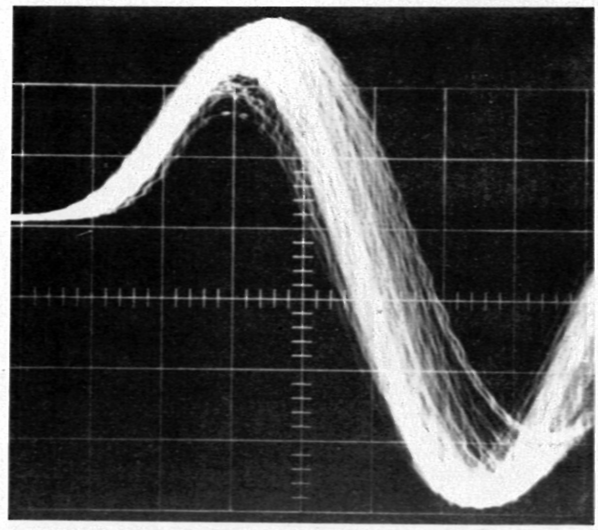
$U_C$ = 30 kV

$U_T$ = 27 kV

20 ns/cm



10 discharges



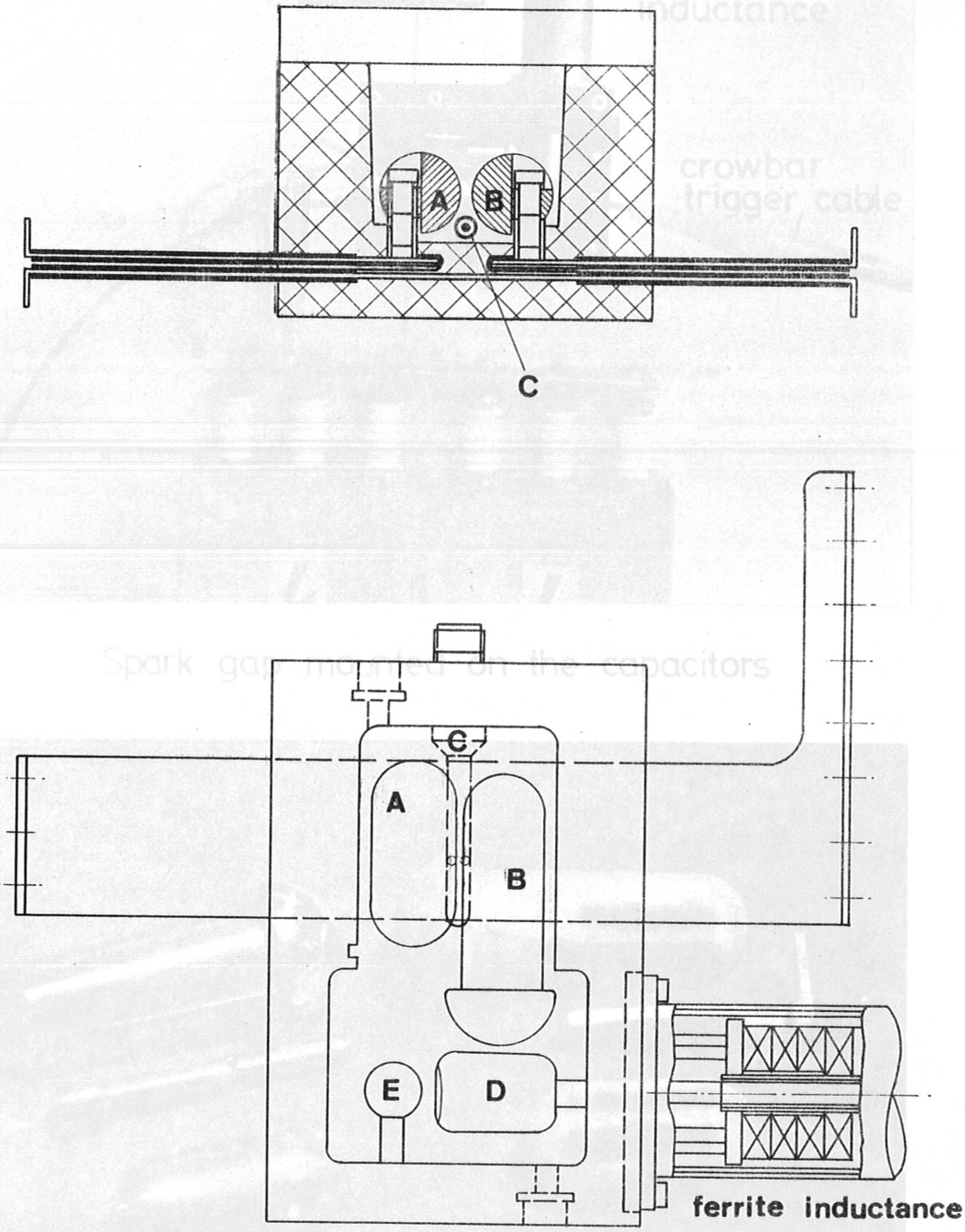
350 discharges

$U_C$ = 10 kV

$U_T$ = 27 kV

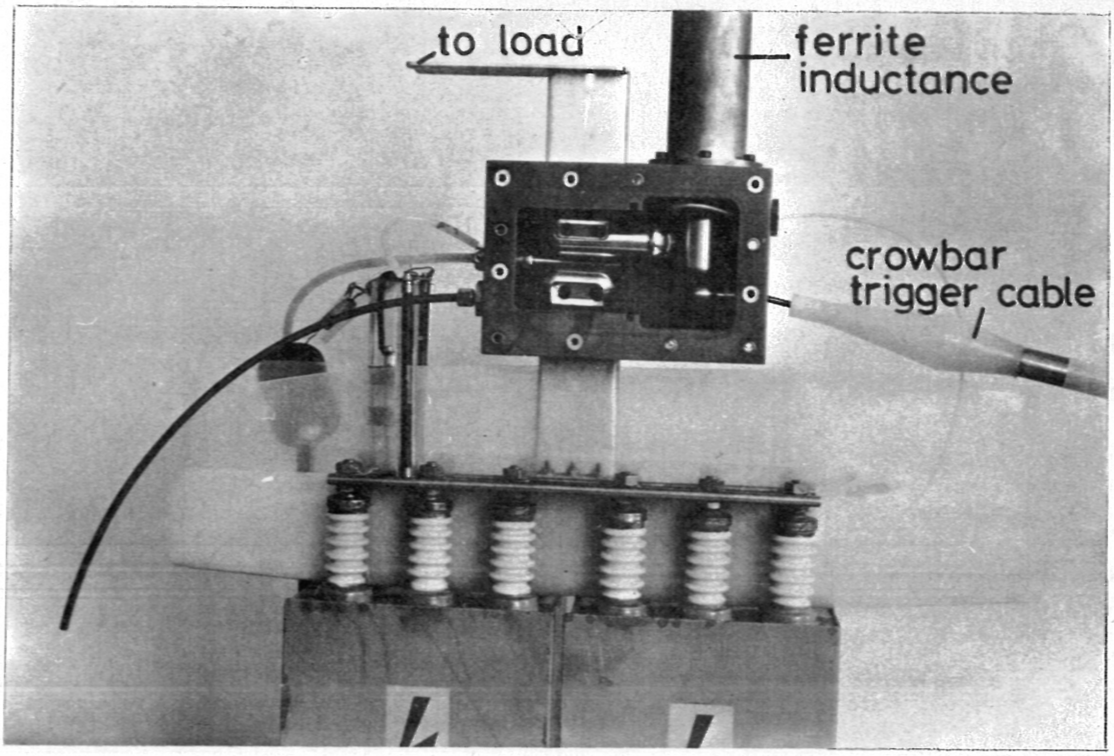
20 ns/cm

Measurements of Jitter

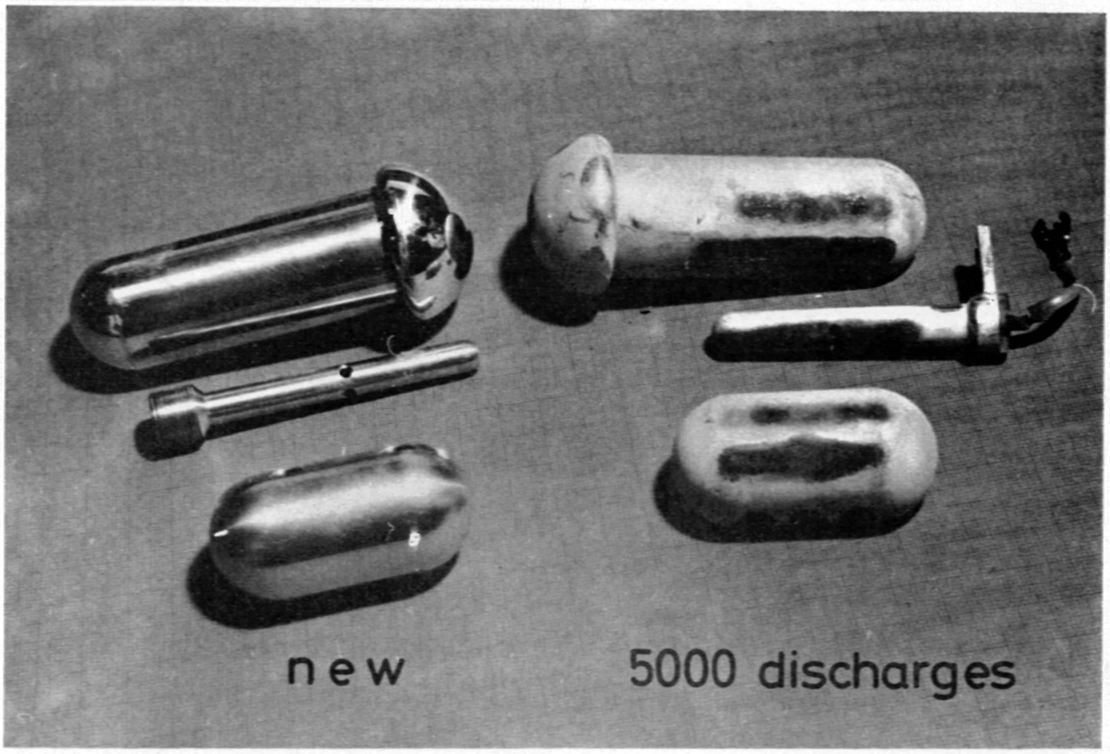



**A,B** main start electrodes
**C** start trigger electrode
**B,D** main crowbar electrodes
**E** crowbar trigger electrode

# Schematic Drawing of Pressurised Spark Gap (II)

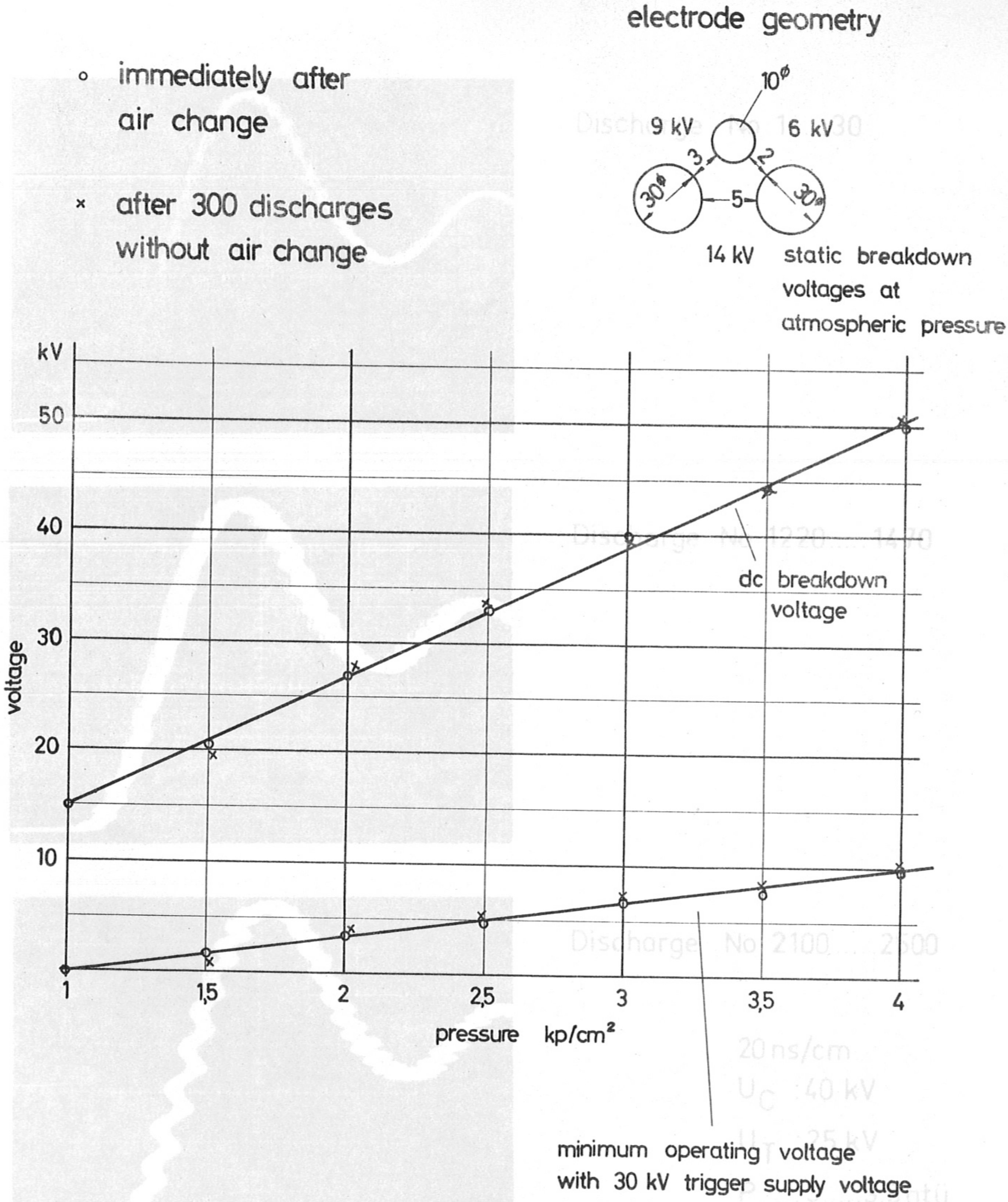



Spark gap mounted on the capacitors

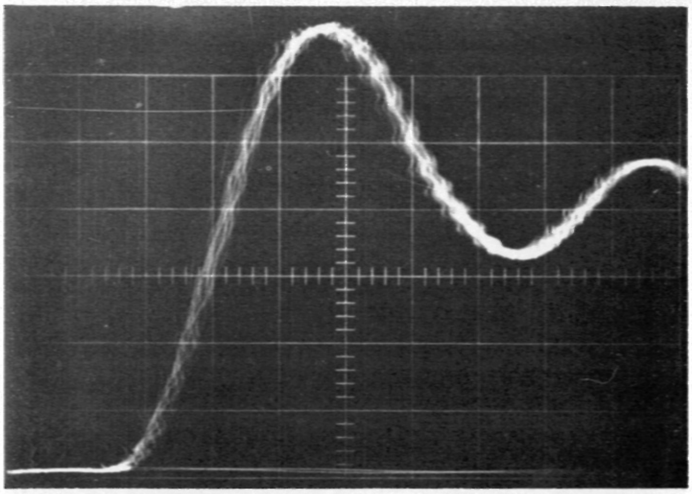



Electrodes new and after 5000 discharges

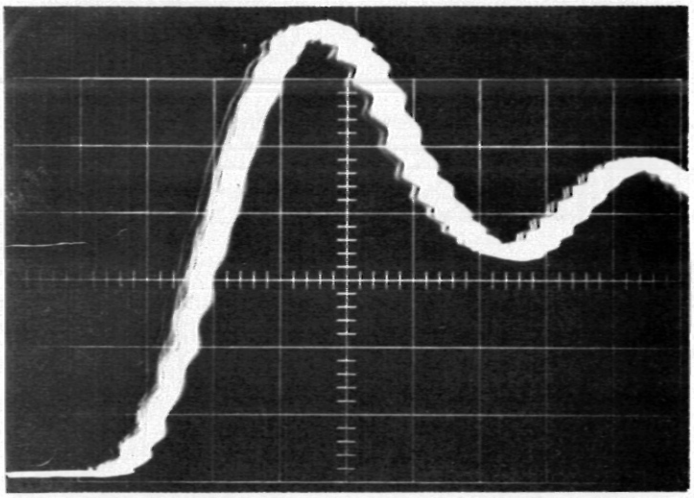
# Pressurised Spark Gap II



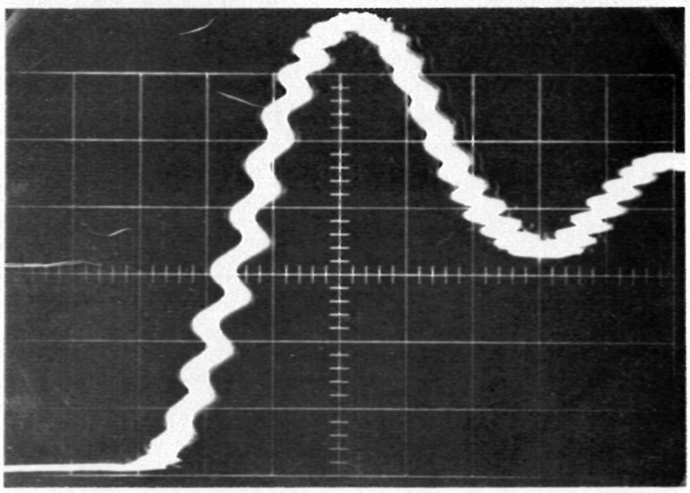

**DC Breakdown Voltage and Minimum Operating Voltage Versus Air Pressure**



Discharge No 1.....30



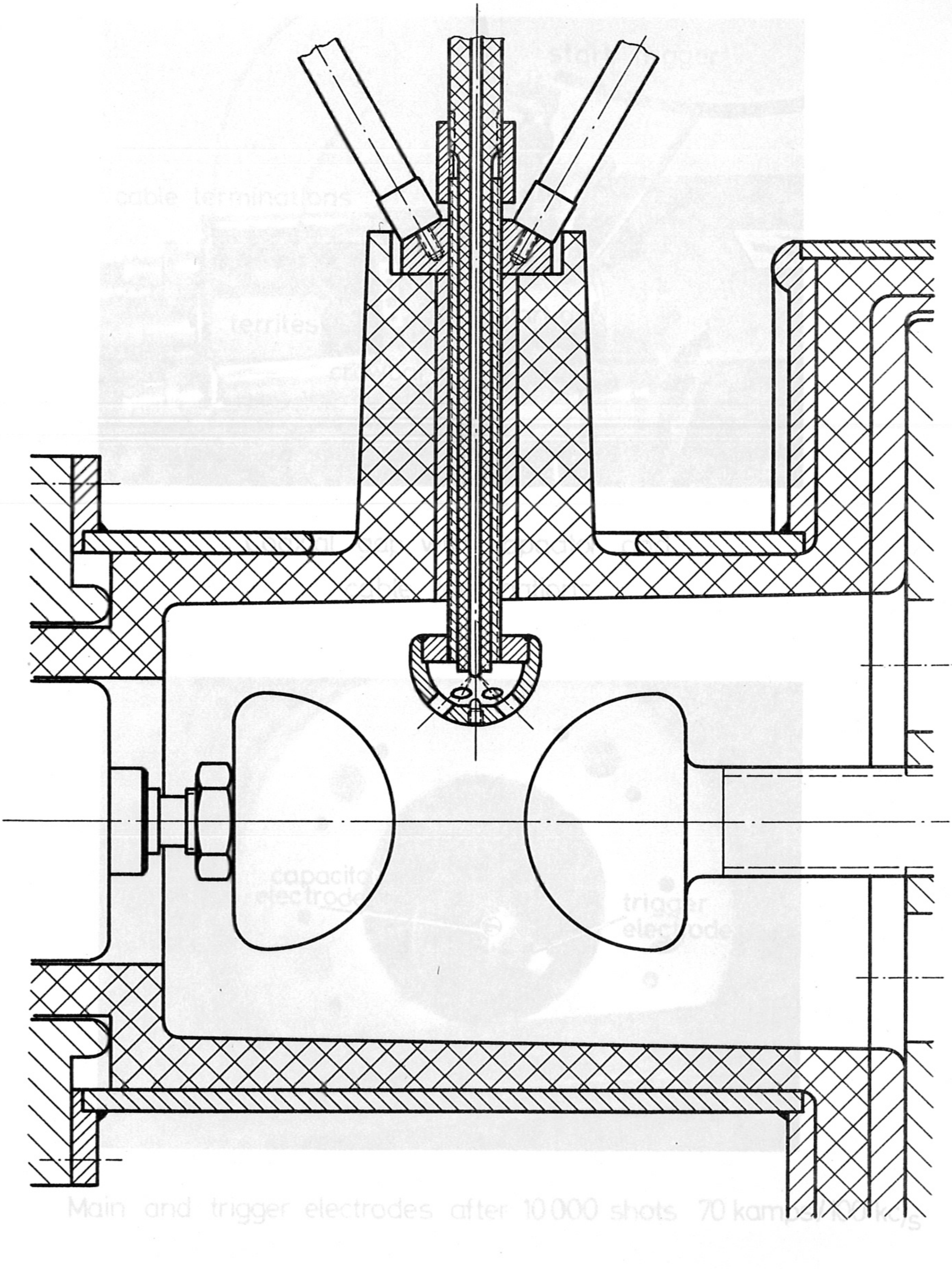
Discharge No 1220.....1470



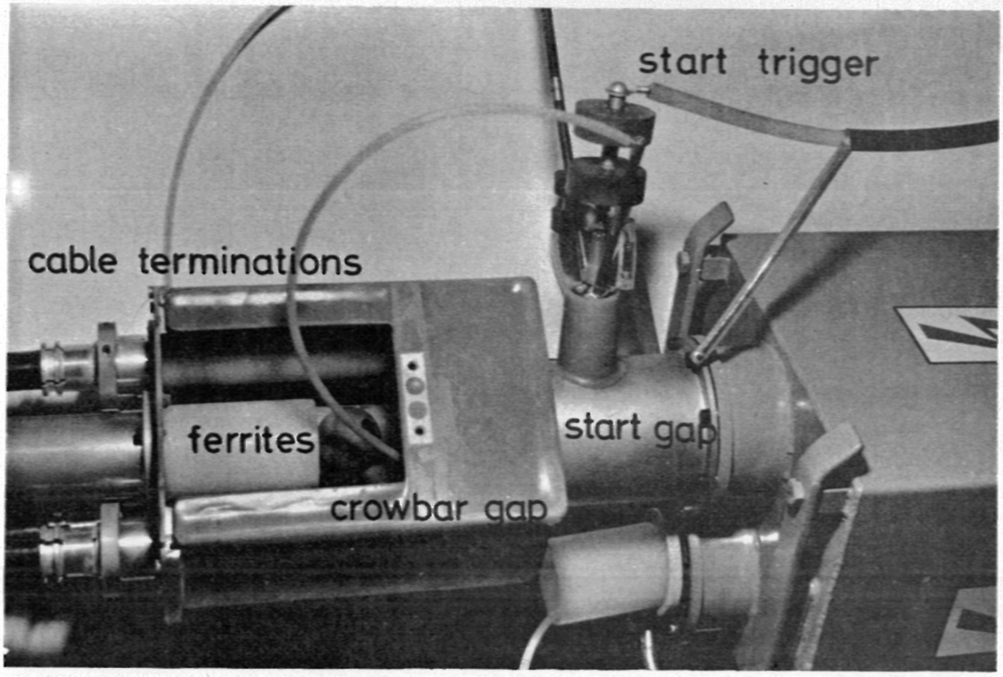
Discharge No 2100.....2500

20 ns/cm
$U_C$ : 40 kV
$U_T$ : 25 kV
P : 3.....3,5 atü

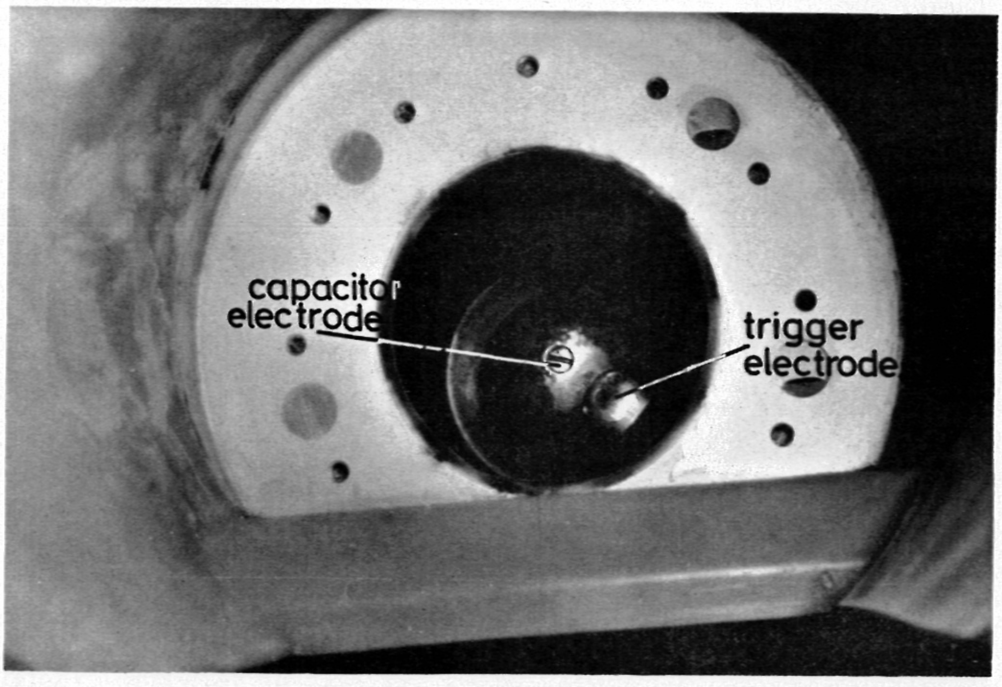
Jitter of the Pressurised Gap
During Life Test



**Schematic of the Coaxial Gap (III)**




Coaxial gap with capacitor and
cable terminations




Main and trigger electrodes after 10 000 shots 70 kamps/100 kc/s

## Coaxial Gap III Mounted on Capacitor
## Electrodes after 10 000 Discharges