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THE SPARK-GAP SWITCHES OF THE NEW FAST BEAM EXTRACTION
SYSTEM AT THE CERN PROTON SYNCHROTRON

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1. INTRODUCTION

The continual demand for increased versatility from the fast beam extraction system at the CERN Proton Synchrotron led in 1967 to a proposal by van Breugel et al.,\(^1\) for supplementary ejection facilities. This proposal, named "Operation Straight Flush", envisaged the possibility of multibunching, of multiple shot, and of sequencing. Basically, these are facilities that enable a choice to be made of the number of ejected proton bunches; that permit several ejections to the same or different experimental areas during the same machine cycle; and that allow the beam extraction programme to be varied from cycle to cycle. The apparatus for this project was installed at the proton synchrotron in September 1968, and by this time the successful operation of the facilities foreseen in the proposal has been demonstrated\(^2\).

Whilst the basic principle of operation of the new fast extraction system remains the same as that of its earlier counterpart\(^3\), a considerable number of modifications and refinements have been made in order to arrive at the extra dimension of versatility now available. In the case of the high-voltage pulse generator which feeds a current pulse to the kicker magnet, a facility has been incorporated that enables the length of the pulse to be varied continuously -- it may be recalled that the high-voltage pulse generator used in this work is a line-type pulser in which a lumped delay line is discharged through a kicker magnet built as a delay line of matched impedance and terminated by the appropriate end resistor. With the new design of pulse generator (see Fig. 1), provision is made for discharging the delay line at both ends, so that by changing the relative instants of firing of the spark gap switches A and B, the pulse length at the kicker magnet may continuously be varied. This provides a means by which the number of proton bunches to be ejected from the synchrotron may rapidly be changed.

The feasibility of this method of controlling a pulse length was first demonstrated in our laboratory early in 1967, using a cable as a charge-storing network\(^4\). But in employing a lumped delay line as the charge store, the rise- and fall-times of the output pulse would be too long for beam extraction purposes; for this reason two additional devices, which also served in the older design, are incorporated. The one that affects the rise-time of the output pulse is the adaptor formed by \(R_A\) and \(C_A\). This is essentially a pulse-peak ing device that creates an exponentially decaying pulse in front of the pulse of the delay line. The rise-time is thus mainly given by the loop inductance of the adaptor. The second device, the spark gap D, improves the fall-time of the output pulse by short-circuiting the pulse to ground. It may be noted that the spark gaps A and D alone would provide a means of varying the length of the output pulse. However, using the third spark gap B provides the advantages that, firstly, the charge handled by the spark gap D is always small, and this simplifies its construction considerably; secondly, on short-circuiting with the spark gap D, a negative voltage front is propagated back into the delay line (with the delay line initially charged to a positive potential). In the absence of spark gap B, this front would be reflected back and forth in the delay line, the polarity being reversed at each re-arrival at the spark gap D. With the spark gap B in position, the initial negative voltage front is absorbed after only one traversal of
the delay line at the termination resistor connected to the spark gap B. In this way the problem of rapid voltage reversals, which can seriously impair the life of condensors, is minimized.

The present report is concerned primarily with studies we have made of the performance of the spark gaps employed in the new pulse-forming system. The spark gaps A and B, known respectively as the front and tail gaps, operate under more or less identical conditions and are mechanically and electrically similar. The spark gap D, known as the short-circuit spark gap, receives potential only after the front spark gap has fired, and so the design considerations are quite distinct from those of the other spark gaps. The present designs are due to B. Kuiper and S. Milner, who chose to depart as little as possible from the principles employed in the spark gaps of the earlier fast beam extraction system$^{5}$. The major innovations concern the reliability of the operation of the spark gaps over long periods, and the ease with which they may be demounted and remounted. This has resulted in a system that is of larger dimension and is less coaxial than that of the earlier design, and as a consequence the waveforms (see Figs. 11 and 21) exhibit deviations from an ideal square wave impulse. This compromise is permitted in the present application since i) the rise-time of the magnetic field in the kicker magnet can, if necessary, be boosted by decreasing the resistor $R_a$ of the adaptor, and ii) any ripple present in the waveform is, to a first approximation, not important because the total deflection of the proton beam is proportional to the integral of the magnetic field along the magnet.

The present measurements were commenced in June, 1968, when the first items of the new pulse generator became available from the production line. The assembly chosen for the measurements was one that resembled as closely as possible the layout of the actual pulse generator, but i) using a reduced length of delay line, ii) with only one front and one short-circuit spark gap, i.e. resembling only the side of the pulse generator that would incorporate the kicker magnet, and iii) with the output pulse fed directly to a termination resistor. A description of the spark gaps will be given in the following section, and the features of the assembly used for measurements will be further described. Before proceeding, however, it may be of interest to readers who are not closely acquainted with the ejection system to note some quantitative features of its design and operation. The impedance level of the delay line and kicker magnet is 10 $\Omega$, and for ejection at the maximum proton energy of 24 GeV the line-charging voltage is around 60 kV. This provides a current of 3,000 A in the kicker magnet, which delivers a magnetic field of about 1,500 gauss. The elements of the delay line are $L = 10^{-4}$ H and $C = 10^{-8}$ F, and with the eleven-stage line used for ejection, the charge transmitted by the front and tail spark gaps can range up to a maximum of $6.6 \times 10^{-3}$ C, corresponding to a pulse length of 2.2 $\mu$s. In the ejection scheme, the line-charging voltage is always of positive polarity; if the kicker magnet is required to deflect the proton beam in the opposite sense, the direction of the current is changed. The duty cycle is such that the system should be able to deliver at least one million impulses over a period of some ten days, without any need of servicing during this period. The present system was designed with the aim of clearly exceeding this minimum requirement.
2. DESCRIPTION OF THE SPARK GAPS
AND OF THE ASSEMBLY EMPLOYED FOR THEIR STUDY

2.1 The front spark gap

The front spark gap is essentially a three-electrode device based on the swinging cascade principle\(^5,6\)). Figure 2 shows a longitudinal section of the spark gap, Fig. 3 gives a simplified version of the electrode configuration, and Fig. 4 gives the equivalent electrical circuit. From Fig. 2 it may be noted that the spark gap is clearly of open construction. The high-voltage electrode, the central electrode surround, and the output electrode are all of annular form, and are insulated and spaced by means of araldite cylinders. The central electrode, also of annular form, is supported at the surround by means of three araldite arms. The position of these arms at the surround may be adjusted independently of the setting of the other electrodes, and in this way the level of the central electrode may be changed.

The HV, central, and output electrodes are provided with tungsten inserts at the discharge regions. The photons necessary to initiate the switching action are provided by means of discharges initiated by the trigger pulse around the ends of a pin located at the centre of the central electrode. This pin (see Fig. 3) is made of tungsten and is surrounded at each end by collars, also provided with tungsten inserts. The collar (1) opposite the HV electrode is connected directly to the trigger lead, whilst the collar (2) opposite the output electrode is connected to the central electrode. Under d.c. conditions, the pin, collars, central electrode, and central electrode surround are all maintained at the same potential by means of the bias resistors, each of 1 MO\(\Omega\) impedance. A (negative) trigger pulse brings about breakdown first between the collar (1) and pin, and then between pin and collar (2); thereafter the trigger pulse is fed directly to the central electrode, and the switching action of the spark gap proceeds according to the swinging cascade principle. The conditions for successful triggering of the spark gap are the following:

i) In order to obtain a favourable distribution of the trigger potential across the trigger gaps [collar (1)-pin, pin-collar (2)], the total capacity between collar (1) and collar (2) should be small in comparison with the capacity \(C_T\) from central electrode to ground. Moreover, capacity \(C_1\) should be smaller than \(C_2\), and \(C_2\), in turn, should be small with respect to \(C_T\). In the present design the total capacity between collar (1) and collar (2) is 5.5 pF, and the capacity \(C_T\) is around 20 pF. The capacities \(C_1\) and \(C_2\) are 2.5 pF and 4 pF, respectively.

ii) During the delay in the firing of the trigger gaps, the potential difference imposed across each gap should be maintained. That is, the time constant for the flow of charge, firstly from collar (1) to pin, and secondly from pin to collar (2), should be much greater than the breakdown delay, typically around 10 nsec \(^1\). With bias resistors of 1 MO\(\Omega\), these time constants are at least a few \(\mu\)sec.
iii) In order not to slow down the rise-time of the trigger pulse at the spark gap, the time constant given by the trigger cable impedance (50 n), and the capacity to ground of any point to which the trigger potential is connected directly, should be small in comparison with the rise-time of the trigger pulse. With the present construction this requirement is easily met.

It may be noted that with the pin and collars away from the region of the main discharge between the central and the HV, and between the central and the output electrodes, no erosion of the trigger gaps is brought about by the main current pulse. Furthermore, with the main electrodes being of annular form, use is made of the so-called revolving discharge principle to extend the working life of the spark gap. In order to obtain an enhancement in the action of the trigger pulse, a ceramic tube of high dielectric constant is incorporated between each collar and pin. Experiments in our laboratory have shown that in comparison with a trigger discharge between electrodes in air, this kind of surface discharge has a lower initiation voltage and is more stable in operation. The trigger pulse is coupled to the spark gap by means of a condenser. In comparison with resistive coupling, this arrangement provides a faster rate of rise of the trigger voltage at the spark gap, but must, to a certain extent, reduce the rate of build-up of potential at the central electrode once the gap between the central and the HV electrodes has fired.

The spark gap is kept rigidly in position by means of the external clamp arrangement shown in Fig. 2. The system was designed to operate at pressures up to 4.5 atm, and provision is made for flushing gas through the spark gap by means of connections located at the base.

2.2 The short-circuit spark gap

It may be recalled that the function of the short-circuit spark gap is to shorten the fall-time of the pulse delivered by the front gap. The voltage pulse only appears at the short-circuit spark gap after the front gap has fired, and, as discussed by van Breugel et al.\textsuperscript{3}), the obvious approach is to employ a trigatron. However, consideration of the duty cycle in the present application led to a design incorporating a trigatron together with a three-electrode spark gap operating in the swinging cascade mode.

Figure 5 shows a section of the short-circuit spark gap, and Fig. 6 shows its mounting close to the output electrode of the front gap. In Fig. 7 the essential electrode configuration of the short-circuit spark gap is represented schematically, whilst Fig. 8 presents the equivalent electrical circuit of the system. The pin and the surround electrodes constitute a trigatron with a high resistive coupling to ground. A pulse applied to the pin brings about breakdown between pin and surround, and subsequently breakdown occurs between the surround and a bolt located at the centre of the central electrode. At this point the trigger potential is fed directly to the central electrode, and the switching proceeds as in the front spark gap. In this scheme the photoelectrons that are necessary to initiate discharges between the main electrodes are obtained from the initial discharges between pin and surround and between surround and central electrodes. The potential at the central electrode is derived inductively when the switching action of the front gap provides a voltage step at the HV electrode of the short-circuit spark gap.
As in the front gap, the pin is surrounded by a ceramic tube of high dielectric constant, and all electrodes are provided with tungsten inserts at the discharge regions. Furthermore, the trigatron is away from the main discharge regions, and the HV, central, and earth electrodes are of annular construction. The conditions for the successful operation of a spark gap operating in this way have previously been given by van Breugel et al.⁵, but for completeness these conditions will be reiterated and examined below.

i) The ratio of the total capacity between the HV and the central electrodes, and between the central and the earth electrodes, should be equal to \( d_1/d_2 \) \([d_1 \text{ the distance between central and earth electrodes}; d_2 \text{ the distance between HV and central electrodes} (\text{see Fig. 7})]\). This permits both gaps to be set with an equal margin of safety against spontaneous firing between the electrodes.

ii) For the voltage at the central electrode to remain constant up to the moment of triggering, the time constant for the leakage of charge from the central electrode should be large in comparison with the maximum pulse length (T) provided by the pulse generator. A sufficient condition for this is that \((C_1 + C_2) \cdot (R_1 + R_2) > T\). In the present design \((C_1 + C_2) \cdot (R_1 + R_2) \approx 30 \mu\text{sec},\) which compares with the maximum pulse length of 2.2 \(\mu\text{sec}\) used for ejection.

iii) In order to avoid premature breakdown at the trigatron when the voltage pulse appears at the HV electrode, \(C_3\) should be much less than the total capacity from surround to ground. With the present construction \(C_3 = 3\ \text{pF}\), and the total capacity from surround to ground is 9 \(\text{pF}\).

iv) For efficient triggering, the trigger voltage should first appear between pin and surround, so that the capacity between pin and surround should be small in comparison with the capacity from surround to earth. In the present case these capacities are approximately equal (7 \(\text{pF}\)).

v) For the trigger voltage to appear between surround and centre after the trigatron has fired, \(C_3\) should be less than \(C_1 + C_2\). In the present case \(C_3 = 3\ \text{pF}\) and \(C_1 + C_2 = 14\ \text{pF}\).

vi) During the delay in the firing of the trigatron and in the firing of the gap between trigatron and central electrode, the potential difference imposed by the trigger pulse should be maintained. That is, the time constant for the flow of charge, firstly from trigger pin to surround, and secondly from surround to central electrode, should be much greater than the breakdown delay, typically around 10\(\ \text{nsec}\). The time constants, approximately \(R_2 \cdot (C_4 + C_6)\) and \(R_1 \cdot (C_1 + C_2 + C_3)\), are of the order of 10 \(\mu\text{sec}\).

vii) The time constant given by the coupling resistor of 800 \(\Omega\) in the trigger lead, and the capacity to ground of any point to which the trigger potential is directly applied, should be small in comparison with the rise-time of the trigger pulse. In the worst case this time constant is around 16 \(\text{nsec}\), which compares with the rise-time of around 20\(\ \text{nsec}\) for the trigger signals used in this work (see Sections 3 and 4).
The weakest aspect of the present design is with regard to point (iv), and this could be most conveniently improved by increasing the capacity $C_5$ from surround to ground to around 10 pF. However, this modification would slow down slightly the rate of rise of trigger potential [see point (vii)], but would improve all the other considerations which involve $C_4$.

From the user's point of view, the regulation of the distance settings $d_1$ and $d_2$ is facilitated by mechanical movements that are accessible from the exterior of the spark gap. One movement controls the distance setting $d_1$ directly, whilst a second controls the total distance setting $d$ ($d = d_1 + d_2$). The short-circuit spark gap was designed to operate at pressures up to 4.5 atm, and gas is admitted via an internal connection with the gas input lead of the front spark gap. Similarly, there is an internal connection with the gas exhaust lead of the front gap, so that gas fed to the assembly of front and short-circuit spark gaps is effectively vented through a parallel arrangement of two spark gaps.

2.3 The assembly employed for measurements

Figure 9 shows a representation of the arrangement employed for the study of the performance of the spark gaps. The system was built using some equipment already available in the laboratory, but in the immediate vicinity of the spark gaps the connections and layout were made identical with those of the pulse generator used for beam extraction. The high-voltage $V$ from a Früngel power supply is fed to a distribution box incorporating a resistive divider ($R_7, R_8$), which provides output voltages of $V$ and $V/2$. These outputs are connected by cables to a box containing a two-stage lumped delay line. The resistors $R_5$ and $R_6$ serve to decouple the input cables, and the voltage $V/2$ is led to the central electrode surround of the front spark gap. The voltage $V$ is applied to the delay line, which in turn is connected to the HV electrode of the front spark gap. From the HV electrode, connection is made with the adaptor formed by $R_1$ and $C_3$. The output HV signal from the spark gap is fed along two cables, each of 20 Ω impedance, which are connected with termination resistors. Observation of the output HV signals is made by means of capacitive probes located at the termination resistors.

The trigger signals for the spark gaps are brought along 50 Ω cables. While the trigger lead to the front spark gap is terminated and capacitatively coupled to the trigger system, the trigger lead of the short-circuit spark gap is coupled by the resistor $R_3$ of a few hundred ohm impedance.

The high voltage applied to the system is measured with an accuracy ~ 0.5% by means of a wire-wound resistive divider ($R_{15}, R_{11}$) placed in parallel with the divider $R_7R_8$.

The measurements of time jitter to be referred to in the text were obtained from photographs of about 80 superimposed waveforms.

3. EXPERIMENTAL STUDIES WITH THE FRONT SPARK GAP

3.1 Considerations of operation

If $V_H$ is the voltage at the HV electrode of the front spark gap, then $V_C$, the voltage at the central electrode, may be expressed as $V_C = rV_H$, where $r$ is the division provided by the resistive divider $R_7, R_8$ (see Fig. 9). The potential difference between the HV and central
electrodes is then $V_H(1 - r)$, and between the central and the output electrodes $rV_H$. In operation, these potential differences have to be less than the breakdown voltages in these regions.

For the present work, as with the pulse generator used for beam extraction, the gas used in the spark gaps was air; the air was dried and vented at the rate of 200 cm³ min⁻¹. The results of measurements of the breakdown potential $V_S$ between the electrodes of the front spark gap are shown in Fig. 10, plotted as $V_S$, $p \times d$ ($p$ is the gas pressure and $d$ is the inter-electrode spacing). The data shown were measured for the gap between the central and the HV electrodes, but within the precision of measurement the results also apply for the gap between the central and the output electrodes. The results cover a range $2 < d < 4.05$ mm and $1 < p < 4$ atm, and show that the breakdown voltage may be expressed as

$$V_S = A_fpd + B_f,$$

where $A_f = 26.45$ kV atm⁻¹ cm⁻¹ and $B_f = 2.5$ kV. This behaviour is in agreement with Paschen's law, and furthermore the measurements are in quite close agreement with the results of measurements of breakdown strength in air under uniform field conditions.

If $D_1$ and $D_2$ are the spacings between the central and the output electrodes, and between the central and the HV electrodes, respectively, then one may write

$$rV_H = k_{f1}(A_fpd_1 + B_f)$$
$$V_H(1-r) = k_{f2}(A_fpd_2 + B_f),$$

where, as indicated earlier, $V_H$ is the voltage at the HV electrode and $r$ is the value of the potential division provided by the resistive divider; $k_{f1}$ and $k_{f2}$ define the ratio of the applied to static breakdown voltage, such that $k_f = 1$ at breakdown. With the present system the value of $r$ was designed to be $1/2$, so that to obtain $k_{f1} = k_{f2}$, $D_1$ should be equal to $D_2$. The procedure of making $k_{f1} = k_{f2}$ is not to be regarded as a criterion for obtaining the most favourable response from the spark gap. Any detailed calculation of the ratio $k_{f1}/k_{f2}$ to be employed for optimum performance must consider i) the relative strengths and impedance levels of the trigger voltage and the voltage at the HV electrode, ii) the precise electrical circuit, and iii) the characteristics of breakdown under impulse conditions. However, inasmuch as both sides of the spark gap were found to have identical static characteristics, and since making each $k_f$ as high as possible enables the highest voltage to be switched (for a given gas pressure), the procedure in the present work was to set $k_{f1} = k_{f2}$ at a value as high as could be permitted. With $k_{f1} = k_{f2} = k_f$, the voltage to be switched by the spark gap is related to pressure according to

$$V_H = k_f (A_fpd + 2B_f)$$

with

$$D/2 = D_1 = D_2.$$
The equivalence of the roles of pressure and distance in determining the breakdown voltage provides some freedom of choice of the inter-electrode distance to be employed in the spark gap. The considerations to be applied have been demonstrated earlier\(^1\), and are concerned with, firstly, the influence of pressure on the breakdown at trigger pins. It has been shown that the breakdown times at trigger pins increase with increasing pressure, so that to obtain the most favourable time jitter characteristics the pressure should be low. Secondly, the influence of gas pressure on the rate of build-up of ionization between the main electrodes of the spark gap must be considered. The current will grow, at least in its initial stages, as \(\exp(\alpha \nu t)\), where the primary ionization coefficient \(\alpha = p \cdot f(E/p)\) and the electron drift velocity \(\nu = f(E/p)\); \(E\) is the electric field strength and \(t\) is the time. Once a value of \(k_f\) is chosen, the ratio of the parameter \(E/p\) before triggering is essentially constant, independent of the inter-electrode distance [see Eq. (3) with \(B_f << A_f P_f\)]. Similarly, during the different stages of the switching action, the instantaneous values of the ratio \(E/p\) will be independent of the inter-electrode spacing. Since \(\alpha = p \cdot f(E/p)\), the fastest rate of current growth, and hence least time jitter, can be obtained by operating at high pressure. There are therefore two conflicting trends, and it is clear that conditions have to be chosen so that neither trend is too critical.

### 3.2 Observations of the switching action

Examples of the leading edge of the output pulse from the spark gap for charging voltages in the range 30 kV to 65 kV are given in Fig. 11. It may be seen that the forms contain some appreciable ripple, which maintains the same broad character throughout the voltage range. Similar oscillations were also observed in low-voltage tests made with the assembly, and the indications are that these oscillations are a consequence of the open feature of the present design. At the higher range of voltage the 5% to 95% rise-time of the pulse is around 20 nsec, but with decreasing voltage the rise-time deteriorates, and at 33.3 kV it is around 40 nsec. These oscillograms were obtained with inter-electrode spacings of 3 mm in the spark gap. With spacings of 4 mm, the deterioration in rise-time with decreasing pressure was considerably more marked, and the value of 3 mm was chosen as a compromise between i) the quality of the rise-time at low voltage and pressure, ii) the maximum voltage required from the system together with the maximum pressure permissible in the spark gap, and iii) the performance of the trigger action at high pressure.

Results of measurements of the time jitter and time delay in the switching action of the spark gap are given in Figs. 12 and 13. Figure 12 shows the time jitter and delay over the range 50-63 kV with the spark gap maintained 10% below the static firing limit, i.e. a value of \(k_f\) of 0.9. Data are presented for two settings of the peak amplitude of the negative trigger pulse, of 5% to 95% rise-time around 20 nsec, applied to the spark gap. The time jitter and the delay both exhibit the same general trends, and, in accordance with the views expressed in Section 3.1, the height of the trigger pulse is of most influence at high pressure and voltage. At a trigger level of 22 kV, the graphs indicate that the time jitter can be maintained at a value of around \(\pm 2.5\) nsec throughout the range. The variation of time jitter with charging voltage at constant values of gas pressure is shown in Fig. 13. Again,
the trigger pulse is of strong influence at the higher pressure, but at a trigger level of some 22 kV the characteristics at both high and low pressure indicate that the setting of $k_f$ may be reduced to around 0.7 before any appreciable loss of performance.

3.3 Preliminary observations of the stability of operation

The measurements described above were made with a more or less brand-new spark gap. Under the conditions of measurement, the spark gap behaved in a reproducible manner with no evidence of any irregular or premature firing. However, in the course of further study, difficulties were encountered with the refiring of the spark gap during the recharging process following the application of a trigger. This phenomenon was most pronounced at high voltage and high pressure, and could only be suppressed by operating some 20% to 30% below the static limit as inferred from the measurements presented in Fig. 10. At the same time it was noted that the static characteristics themselves were somewhat undefined at high pressure, and tended to be consistently lower than the earlier measured values. A quantitative measure of this influence may be seen from Fig. 14 in which the breakdown voltage -- with both central and HV electrodes connected to their appropriate potential source -- is shown plotted as a function of pressure.

The line ABC gives the relation between breakdown voltage and pressure found with the system when new, whilst the form ABD shows the modified result found with the onset of premature firing. Despite cleaning the spark gap and polishing the electrodes, it was not possible to fully restore the linear form ABC; the experience was that the breakdown voltage after cleaning tended to be somewhere between BC and BD, but that after some further use the characteristic again followed the form ABD. The time scale for the change was not very predictable, but once the form ABD was attained, observations over some million operations showed this form to be stable.

A possible explanation for these effects may be a fluctuation in the potential of the electrodes of the spark gap brought about by a current drain across the inside surface of the araldite cylinders used as the principal insulators of the spark gap (see Fig. 2). It was observed that products of erosion deposited on araldite surfaces form a conductive film, and in one case, when the normal precautions were not taken to dry the air introduced into the spark gap, the conduction built up to such a level that there was a continuous drain of a few milliamperes of current across the surface of the araldite cylinders. The araldite surface in no way exhibited evidence of any tracking, but the only means of removing the conduction was found to be by abrading the araldite surface. It is interesting to note that similar difficulties and phenomena have been reported by Barnes et al.\(^7\), and that the conclusion drawn by these authors is that the condition of the insulating surface is the determining factor in promoting premature breakdowns, although these seem to occur between the main electrodes. In the present work it was not possible to demonstrate conclusively that there is a relation between the surface condition of the araldite cylinders and the rate of occurrence of premature firings.

The difficulty was circumvented by working with an increased margin between charging voltages and the corresponding static limit, so that the rate of premature firing was in the
worst case around 0.5%. The relation between charging voltage and pressure was chosen as that given by the line XY of Fig. 14, and following this line the values of $k_e$ range from 0.85 at the highest pressure of 4.5 atm to 0.9 at the lowest pressure of 2 atm (with the static limit now defined by ABD). With the spark gap reassembled and fitted with a new tungsten pin and ceramic tube at the central electrode, an inspection showed the time jitter to be ±2.5 nsec over the range of voltage and pressure represented by the line XY. This result is the same as that presented in Fig. 12, for which the charging voltage was 10% below the line ABC of Fig. 14, and it is consistent with the data given in Fig. 13 with the voltage 55 kV at 4 atm and 37 kV at 2.2 atm.

3.4 Evolution of the dynamic characteristics of the spark gap

At the proton synchrotron each spark gap is triggered by a generator of the Marx design which, at an impedance level of 50 Ω, delivers a negative pulse of peak amplitude 28 kV with 5% to 95% rise-time around 20 nsec. In view of this, the study of the ageing of the spark gap was made, using mostly a similar Marx trigger that became available at the start of this part of the investigation.

With the 28 kV trigger, the operation of the spark gap was followed over 1 million shots at a charging voltage of 55 kV and gas pressure of 4 atm. Moreover, at a point around 600,000 shots and at the end of the test, a more detailed examination was made i) of the time jitter over the high-voltage operation range for trigger levels of 28 kV and 22 kV, and ii) of the dependence of time jitter on charging voltage at two fixed values of gas pressure and for a trigger of 28 kV. For (i) the voltage and pressure were set according to the line XY of Fig. 14, whilst for (ii) the gas pressures were chosen as 2 atm and 4.5 atm, corresponding to extreme limits of operation. Figure 15 shows the evolution of the time jitter at the charging voltage of 55 kV; the starting point was with the spark gap newly cleaned, and with a new pin and ceramic tube at the central electrode. It may be seen that during the first 200,000 shots the time jitter grows from the original level of ±2.5 nsec to around ±6.7 nsec thereafter the jitter remains sensibly constant. Measurements of jitter over the HV range at two stages in the test are compared in Fig. 16. At 600,000 operations the form of the results, with greatest jitter at high values of charging voltage and correspondingly high pressure, is consistent with an explanation in terms of a reduction in the efficiency of the trigger action; it may be recalled that at the starting point of these measurements the time jitter at a trigger level of 22 kV was constant at around ±2.5 nsec over the complete range of charging voltage. At 1 million operations the most noticeable aspect of the data is the increase in jitter at low values of charging voltage. A possible explanation for this behaviour may be associated with a reduction in the photoelectric efficiency of cathode surfaces during the switching action between the main electrodes of the spark gap. After 1 million shots the spark gap was found to contain a considerable amount of erosion products, and the electrode surfaces were heavily pitted and contaminated with oxide layers. If in these conditions the photoelectric efficiency is reduced, the number of electron avalanches will be correspondingly less; consequently, the probability at a given time of finding an avalanche of some critical amplification will also be less. Such an effect would increase the time delay and time jitter in the switching action, and would be most pronounced at low
pressure when the frequency of ionizing collision is lowest. In this way the time delay and jitter in the switching action could become a critical factor at low values of charging voltage.

The dependence of time jitter on charging voltage at constant values of gas pressure is shown in Figs. 17 and 18 for \( p = 4.5 \text{ atm} \) and 2.0 atm, respectively. From Fig. 17 it may be noted that at the higher pressure the jitter retains some independence of charging voltage even after 1 million operations. In contrast, at 2.0 atm, the form of the data is less satisfactory, particularly after 1 million operations.

These results may be regarded as being characteristic of the front spark gap, in that from a total of three ageing tests made with the system, one resulted in the data given above, another gave more or less the same pattern of behaviour, whilst in the third test the spark gap failed to fire after 200,000 operations. The cause of failure was a fracture of the ceramic tube around the trigger pin, which resulted in no illumination of cathode surfaces during the switching action between the main electrodes.

4. EXPERIMENTAL STUDIES WITH THE SHORT-CIRCUIT SPARK GAP

4.1 Considerations of operation

It may be recalled that the charging voltage \( V_H \) at the front spark gap can be related to the value of \( k_f \) and the total inter-electrode distance \( D \) by a relation of the form

\[
V_H = k_f (A_f D^2 + B_f^2),
\]

where in the present case, with a resistive divider giving a ratio of 1/2, \( D/2 = D_1 = D_2 \).

Following the conditions chosen to operate the front spark gap, \( k_f \) ranges from 0.85 at \( p = 4.5 \text{ atm} \) to \( k_f = 0.9 \) at \( p = 2 \text{ atm} \).

With the switching action of the front spark gap, a voltage of height \( V_H/2 \) appears at the output electrode and simultaneously at the HV electrode of the short-circuit spark gap. The voltage induced at the central electrode of the short-circuit spark gap will be a function of the distance settings \( d_1 \) and \( d_2 \) (see Fig. 7), and as the pressure is the same as that of the front spark gap these distances represent the only free parameters in choosing the operating conditions for the short-circuit spark gap.

If \( q = f(d_1, d_2) \), where \( d = d_1 + d_2 \) is the ratio of the voltages at the central and HV electrodes of the short-circuit spark gap, then analogous to Eq. (2) one may write:

\[
\frac{qV_H}{2} = k_{S_1} (A_S pd_1 + B_S^2),
\]

\[
\frac{V_H}{2} (1-q) = k_{S_2} (A_S pd_2 + B_S^2),
\]

where \( A_S \) and \( B_S \) are the constants of the static breakdown law between the electrodes of the short-circuit spark gap. The static behaviour was investigated for \( 1 < d < 4 \text{ mm} \) and
1 < p < 4.5 atm, and showed the constants \( A_S \) and \( B_S \) to be 27.8 kV atm\(^{-1} \text{ cm}^{-1} \) and 2.2 kV, respectively, in reasonable agreement with the values measured for the front spark gap (see Section 4.1). However, in describing the behaviour of the short-circuit spark gap, measurements of breakdown strength under impulse conditions are clearly more appropriate. A few measurements made in this way showed the dynamic breakdown strengths to be within about 10% of the corresponding values derived from the static measurements.

Using Eqs. (3) and (4), we have

\[
V_H = k_f (A_S p d + 2B_S) = 2k_S (A_S p d + 2B_S) \tag{5}
\]

for the case \( k_{S_1} = k_{S_2} = k_S \). As a first approximation, therefore, the total distance setting \( d \) in the short-circuit spark gap should be half that in the front spark gap, i.e. \( d = 3 \text{ mm} \).

4.2 Preliminary investigations of the role of distance settings

The results of measurements of the probability of spontaneous breakdown between the main electrodes of the short-circuit spark gap are shown in Fig. 19. For these measurements the total inter-electrode spacing was set at 3 mm, and the probability of breakdown is shown plotted as a function of \( d_1 \) for two settings of charging voltage and pressure: 61 kV with \( p = 4.5 \text{ atm} \), and 33 kV with \( p = 2.0 \text{ atm} \). (It may be noted that for these measurements the gap between the trigatron and the screw at the centre of the central electrode was increased so that no spontaneous firing could originate from a discharge at this region). At \( p = 4.5 \text{ atm} \) the results show that the safe operating region lies between \( d_1 = 1.1 \text{ mm} \) and 1.9 mm. With a decrease in pressure and voltage, the width of the safe operating region increases to between \( d_1 = 0.6 \text{ mm} \) and 1.9 mm. Further measurements with \( d = 2.6 \text{ mm} \) showed that at the highest pressure and voltage the safe operating region lay between \( d_1 = 1.1 \text{ mm} \) and 1.5 mm. In general, however, the setting \( d = 3.0 \text{ mm} \), with \( d_1 = 1.5 \text{ mm} \), was to be preferred since this provided a more convenient margin of \( \pm 0.4 \text{ mm} \) in setting the position of the central electrode.

The induced voltage at the central electrode is a function of \( d_1 \) and of \( d \), in that these distances determine the ratio of the capacities between the central and the HV electrodes and between the central and the earth electrodes. At \( d = 3.0 \text{ mm} \), measurements were made of this capacity ratio as a function of \( d_1 \), and used to calculate the voltage induced at the central electrode corresponding to a charging voltage of 61 kV at the front spark gap. The results, presented in Fig. 20, show how the induced voltage varies between the limits 0 at \( d_1 = 0 \) to 30.5 kV (i.e. half the charging voltage) at \( d_1 = 5.0 \text{ mm} \). At \( d_1 = 1.5 \text{ mm} \), the induced voltage is within 8% of the value of 15.25 kV to be expected if the total capacity from the central to the HV and earth electrodes was symmetrical around \( d_1 = d/2 \). The line ABC in Fig. 20 shows the calculated static breakdown voltage at \( p = 4.5 \text{ atm} \) for the lower gap, whilst the line DEF shows the static breakdown voltage for the upper gap at the same pressure -- taking in turn the top right-hand corner as origin of coordinates. Under operational conditions the induced voltage should be less than the breakdown voltage, and on this basis the operating region is with the central electrode situated between points B and E, i.e. \( 0.8 < d_1 < 2 \text{ mm} \).
This result may be compared with the corresponding result \(1.1 < d_1 < 1.9 \text{ mm}\) derived from direct measurements of the probability of spontaneous firing (see Fig. 19). For charging voltage of 33 kV and \(p = 2.0 \text{ atm}\), a calculation along the same lines as the above gives \(0.6 < d_1 < 2 \text{ mm}\), which compares with the experimental result \(0.6 < d_1 < 1.9 \text{ mm}\) given in Fig. 19. The general level of agreement between the calculated and experimental results lends support to the view that the breakdown voltage under the impulse conditions of the present experiment was not very different from that measured under static conditions.

The distance between the trigatron and the bolt at the centre of the central electrode was set to the minimum value, which at the highest voltage and pressure gave no reduction in the width of the region of safe operation from that shown in Fig. 19. On this basis the value chosen was 1.8 mm.

To summarize, this work indicated that with the charging voltage and pressure related according to the line XY of Fig. 14, convenient settings for the inter-electrode distances were \(d_1 = d_2 = 1.5 \text{ mm}\), with the distance between the trigatron and the central electrode as 1.8 mm. Of course, these settings should also be judged in terms of the dynamic response of the spark gap; this work is described in the next section.

4.3 Observations of the switching action

Examples of the cutting action of the short-circuit spark gap are given in Fig. 21. The oscillograms cover the pressure range 2 atm to 4.5 atm with charging voltages from 33.3 kV to 61 kV (following the line XY of Fig. 14), and were obtained with \(d = 3.0 \text{ mm}\), \(d_1 = 1.5 \text{ mm}\). The 5% to 95% fall-time of the pulse is around 25 nsec over the range of pressure and voltages shown. It is interesting to note that some earlier tests of the switching action of the spark gap were made without the stop resistor \(R_1\) in the trigger input lead (see Fig. 9), and that under these conditions a distinct step of between 5 nsec and 10 nsec was observed in the fall of the pulse. Presumably, this result can be attributed to a too strong feedthrough of the trigger pulse, resulting in a slow rise of positive potential at the central electrode once the gap between the central and the HV electrodes has fired.

Results of measurements of the time jitter in the switching action, with the spark gap in a newly assembled condition, are shown in Figs. 22 and 23. Figure 22 shows that with \(d = 3.0 \text{ mm}\) and with a trigger level of 28 kV, the time jitter over the normal range of operation is around \(\pm 3 \text{ nsec}\). It was found that this result was not changed by decreasing the total inter-electrode spacing to 2.6 mm, or by decreasing the trigger level to 15 kV.

Figure 23 gives the results of measurements of time jitter as a function of charging voltage at constant values of gas pressure of 4.5 atm and 2.0 atm. Data are included for \(d = 2.6 \text{ mm}\) and 3.0 mm, and for trigger levels of 15 kV and 28 kV. At the higher pressure both the trigger voltage and the distance setting determine the extent to which the charging voltage may be reduced before the time jitter begins to grow, whereas at the lower pressure only the distance setting is of real influence. This behaviour can be qualitatively understood on the basis that the trigger action is most critical at high pressure (see Section 3.1).
With the distance setting of \( d = 3.0 \text{ mm} \), as favoured in the work described in Section 4.2, the above results showed that at a trigger level of 28 kV the performance of the spark gap was quite satisfactory. This distance setting was adopted in a long-term test made with the spark gap, and this work is described in the next section.

4.4 Evolution of the dynamic characteristics of the spark gap

The spark gap was operated over 1 million shots at a pressure of 4 atm and a charging voltage 55 kV, with a trigger voltage of 28 kV. At these settings the time jitter in the switching action was measured throughout the test, and the results are given in Fig. 24. During the first 400,000 operations, the time jitter gradually increases from the initial level of around \( \pm 3 \) nsec to around \( \pm 5 \) nsec, and thereafter remains effectively constant. With the completion of 1 million operations, the opportunity was taken to make a more exhaustive test of i) the time jitter over the normal range of voltage and pressure, and ii) the dependence of time jitter on charging voltage at constant pressures of 4.5 atm and 2.0 atm. Measurements were attempted using triggers of 15 kV and 28 kV, but with the lower value of trigger voltage the spark gap refused to fire. Moreover, with a trigger voltage of some 20 kV, the system again refused to fire. Data with the 28 kV trigger for the normal range of operation of the spark gap are given in Fig. 25, from which it may be seen that the time jitter is constant at around \( \pm 6 \) nsec over the whole range. The dependence of time jitter on charging voltage at constant gas pressure is shown in Fig. 26. From a comparison with the corresponding data for a new assembly (see Fig. 23) it may be noted that the voltage range for which the jitter is independent of charging voltage is reduced, but even after 1 million operations the characteristics are still quite favourable.

5. CONCLUSION

A systematic study has been made of the performance of the spark gaps in the course of 1 million operations. The pulse forms obtained with the front spark gap were found to contain some appreciable ripple, which is attributed to the rather open feature of the present design. The rise-time of the output pulse at 60 kV is around 20 nsec, but with decreasing voltage the rise-time deteriorates and at 35 kV it is around 40 nsec. In a clean condition the time jitter in the switching action is around \( \pm 2.5 \) nsec over the voltage range from 30 kV to 65 kV, with a corresponding delay in the switching action of about 43 nsec. With continued use the time jitter in the firing action becomes greater, and at the higher range of voltage it was found to remain stable at around \( \pm 6 \) nsec from 200,000 operations up to the maximum 1 million consecutive operations investigated in the present study. Towards the lower voltage range, the time jitter in the switching action after 1 million operations was found to be nearly 50\% greater than the values found at high voltages, and a possible explanation for this behaviour could be associated with a reduction in the photoelectric efficiency of cathode surfaces. The most troublesome aspect of the operation of the front spark gap was the tendency to premature firings, apparently concurring with the onset of an unstable behaviour of the static breakdown characteristics towards the higher voltage range. There is evidence, both from the present work and from work conducted at other laboratories, that suggests that these difficulties originate from a phenomenon occurring at the surface of insulators.
The performance of the short-circuit spark gap was found to be quite satisfactory. The fall-time of the pulse is around 25 nsec over the voltage range from 30 kV to 65 kV. In a clean condition the time jitter in the switching action is ±3 nsec, and it increases to a level of about ±6 nsec after 1 million operations. These results were found to be applicable over the whole range of voltages investigated.

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Fig. 1 Schematic representation of the new pulse-forming system.
A - front spark gap; B - tail spark gap; D - short-circuit spark gap; E - kicker magnet; C and L - elements of delay lines; R₀ and C₀ - elements of adapter; R - termination resistor.
Fig. 2  Longitudinal section of the front spark gap.
Fig. 3  Schematic representation of the front spark gap.

Fig. 4  Equivalent electrical circuit of the front spark gap as seen from the trigger input.
Fig. 5 Longitudinal section of the short-circuit spark gap.
Fig. 6  The mounting of the front spark gap with the short-circuit spark gap.
Fig. 7 Schematic representation of the short-circuit spark gap.

Fig. 8 Equivalent electrical circuit of the short-circuit spark gap. The measured values of capacity correspond to the settings \( d_1 = d_2 = 1.5 \text{ mm} \).
Fig. 9  Schematic representation of the experimental system.

$C_1, C_2, C_3 = 10^{-8}$ F; $C_4 = 3.3 \times 10^{-10}$ F; $C_5 = 2 \times 10^{-8}$ F;

$C_6 = 1.5 \times 10^{-10}$ F; $R_1 = 10$ Ω; $R_2 = 50$ Ω; $R_3 = 800$ Ω; $R_4 = 20$ Ω;

$R_5, R_6 = 10^6$ Ω; $R_7, R_8 = 5 \times 10^7$ Ω; $R_9 = 5 \times 10^6$ Ω; $R_{10} = 10^8$ Ω;

$R_{11} = 2 \times 10^6$ Ω; $L_1 = 10^{-6}$ H; $L_2 = 1.8 \times 10^{-6}$ H; $L_3, L_4 = 4 \times 10^{-5}$ H.
Fig. 10 Measurements of static breakdown potential between the main electrodes of the front spark gap.
Fig. 11 Examples of the output pulses from the front spark gap.
Fig. 12 The time jitter and delay in the switching action of the front spark gap in a new condition. Data are given for trigger amplitudes of 18 kV and 22 kV, with charging voltages 10% below the static breakdown limit.
Fig. 13 The time jitter in the firing action of the front spark gap as a function of charging voltage at gas pressures of 2.2 atm and 4.0 atm with the spark gap in a new condition. Data are given for trigger amplitudes of 18 kV and 22 kV. $V_s$ - breakdown voltage; $V_L$ - lower firing limit.
The breakdown voltage of the front spark gap with both the central and the HV electrodes connected to their appropriate potential source. The line ABC was obtained with the system as new; the form ABD was observed with the onset of premature firing. The line XY gives the relation adopted between charging voltage and pressure in order to operate the spark gap.
Fig. 15  The evolution of the time jitter in the switching action of the front spark gap at charging voltage 55 kV and gas pressure 4 atm. Trigger amplitude 28 kV.
Fig. 16 The time jitter in the switching action of the front spark gap over the range of HV at a) $0.6 \times 10^6$ operations, and b) $1 \times 10^6$ operations. Data are given for trigger amplitudes of 22 kV and 28 kV.
Fig. 17 The time jitter in the switching action of the front spark gap as a function of charging voltage at constant pressure of 4.5 atm
a) at $0.6 \times 10^6$ operations, and b) at $1 \times 10^6$ operations. Trigger amplitude 28 kV. $V_S$ - breakdown voltage; $V_L$ - lower firing limit.
Fig. 18 The time jitter in the switching action of the front spark gap as a function of charging voltage at constant pressure of 2.0 atm. a) at $0.6 \times 10^8$ operations, and b) at $1 \times 10^8$ operations. Trigger amplitude 28 kV. $V_S$ - breakdown voltage; $V_L$ - lower firing limit.
Fig. 19 Measurements of spontaneous breakdown in the short-circuit spark gap as a function of the distance setting $d_1$ for $d = 3.0$ mm.

Fig. 20 Calculated values of the induced voltage at the central electrode of the short-circuit spark gap with charging voltage 61 kV at the front spark gap. The lines ABC and DEF give the static breakdown voltages at $p = 4.5$ atm.
Fig. 21 Examples of the cutting action of the short-circuit spark gap. The voltages indicated are the charging voltages of the delay line, so that the actual heights of the signals are half the indicated values.
Fig. 22 The time jitter in the switching action of the short-circuit spark gap over the range of normal operation. Trigger voltage 28 kV; d = 3.0 mm; d₁ = 1.5 mm.
Fig. 23 The time jitter in the switching action of the short-circuit spark gap as a function of charging voltage at constant gas pressure of a) 4.5 atm and b) 2.0 atm. The value of the trigger voltage and the value of d, the total inter-electrode spacing, are indicated with the data. In all cases d₁ = d/2.
Fig. 24 The evolution of the time jitter in the switching action of the short-circuit spark gap at charging voltage 55 kV and gas pressure 4 atm. Trigger voltage 28 kV; d = 3.0 mm; d₂ = 1.5 mm.
Fig. 25 The time jitter in the switching action of the short-circuit spark gap over the range of normal operation -- after completion of 1 million shots. Trigger voltage 28 kV; d = 3.0 mm; d₁ = 1.5 mm.
Fig. 26 The time jitter in the switching action of the short-circuit spark gap as a function of charging voltage at constant pressure of a) 4.5 atm, and b) 2.0 atm -- after completion of 1 million operations. Trigger voltage 28 kV; d = 3.0 mm; d₁ = 1.5 mm.