CHARACTERISTICS OF ELECTRICAL BREAKDOWN ALONG PARTICLE TRAJECTORIES
IN A WIDE GAP SPARK CHAMBER

by

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Abstract

An experimental investigation is described of the phenomena of electrical breakdown along particle trajectories in a wide gap spark chamber. Data are presented for the spark formation time, and the development of the spark is discussed in terms of measurements of the growth of luminescence as observed with a photomultiplier.

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1. Introduction

The phenomena of the track following spark in a spark chamber with plate separation greater than a few centimetres ^{1,2,3)} has aroused considerable interest. Whilst numerous authors have published photographs of these discharges ⁴⁾, a discussion of their formation, and its dependence on experimental parameters, has in most cases remained rather vague.

The present paper is concerned with the operation of a wide gap spark chamber in a plate-to-plate spark mode. In an attempt to obtain an understanding of the mechanism of the inclined spark, measurements have been made of the spark formation time, and the development of the spark has been studied using a photomultiplier to measure the light output. This work forms part of a systematic investigation of the basic characteristics of a wide gap spark chamber operated in the spark mode which is in progress at the N.P.A. Division, CERN. The object of the work is to fully evaluate the potentialities and limitations of a wide gap spark chamber as an instrument in nuclear physics.

2. Experimental System

A schematic representation of the experimental system employed in the investigation is given in Fig. 1. The spark chamber consisted of a series of four parallel metal plates, with inter-plate spacing of 45 mm. In order to simplify the interpretation of experimental data, the chamber was excited by a rectangular high voltage pulse. This was arranged by incorporating the chamber as a matched element into a transmission line terminated by its characteristic impedance of 50 Ohm. The rectangular voltage pulse was generated by the switching action of a pressurized spark gap which discharged a length of charged cable. With this arrangement, the pulse length is given by twice the electrical length of the charged cable, while the height of the voltage pulse is equal to half the charging voltage of the cable. The latter was in the range 40 - 100 KV with a stability ≥ 0.1 %, and was measured by means of a resistor divider.

Experiments were conducted with the spark chamber placed in a beam of π^- particles of energy around 1 GeV, arriving in bursts of length ~ 100 ns from the CERN Proton Synchrotron. The beam line was defined by a pair of scintillation counters placed on either side of the chamber. The chamber could be rotated with respect to the particle beam with an absolute angular variation $\Delta\phi$ of about 0.5° at each fixed angular setting ϕ . A coincidence signal derived from the scintillation counters triggered the high voltage pulse, and a gate incorporated into the circuit ensured only one trigger per machine cycle. The total delay between the traversal of the particle and the appearance of the high voltage pulse at the spark chamber was constant and around 400 ns. The 5 - 95 % rise time of the high voltage pulse at the spark chamber was 15 ns.

The gas used in the experiments was the, so-called, henogal - a mixture by volume of 70 % neon and 30 % helium. The gas was continually flushed through the chamber and vented to the atmosphere. Precautions were taken to stabilize the gas pressure and also the rate of flow of gas, since these factors were found to be of appreciable influence. For example, the photomultiplier studies showed that at a light level ~ 5 orders of magnitude below that corresponding to a spark discharge, a change in flow rate by 10 % produced a change of up to 35 % in the light output. The data presented in this paper were all obtained with a rate of flow of gas of 250 cc min^{-1} which was stabilized to around 1 %. The gas pressure p_0 (corresponding to 0° C) was 680 or 689 torr as indicated in the text, and was stabilized to around 0.5 %.

The high voltage generator, as already described, provided a rectangular pulse of fixed length as determined by the length of the charged cable. This arrangement was suitable for measurements of spark formation time and for measurements of the growth of luminosity as a function of electric field strength. To enable studies of the temporal growth of light intensity to be made, and so provide a direct measure of the growth of electrons (see § 4), an additional voltage generator which provided an output pulse of continually variable length was constructed. This generator embodied the same basic principles as that shown in Fig. 1, however, in this case a spark gap was located at each

end of the charged cable. One spark gap was connected to the spark chamber while the other was connected directly to a termination resistor. By changing the relative delay in the firing of the two spark gaps, the length of the high voltage pulse applied to the spark chamber could be continually varied. Data on the temporal growth of ionization in a wide gap spark chamber obtained in this way are described in § 4.2.

3. Measurements of Spark Formation Time

Data on the spark formation time were obtained from photographs of the voltage pulse arriving at the termination resistor (see Fig. 1). The total length of the voltage pulse applied to the spark chamber was ~ 80 ns. However, at the moment of spark formation the voltage collapses and the pulse observed at the termination resistor is shortened. The spark formation time t_s is taken as the width of the shortened pulse at half intensity. Data were collected for the spark formation time as a function of electric field strength E with particles making angles ϕ of 0, 20 and 37.5° with the electric field, and these are shown in Fig. 2. The values of t_s decrease steadily with increasing field strength, and for a fixed field strength the values of t_s increase with increasing angle.

These results indicate a possible contributory cause for the dependence of spark luminosity on angle found in photographs of track following sparks ⁷⁾. The intensity of a spark will depend on the excess pulse length i.e. the amount by which the length of the applied pulse exceeds the spark formation time. The latter is found to increase with increasing angle, so that the intensity of track following sparks should systematically decrease with increasing angle. This conclusion is in keeping with observations.

4. Photomultiplier Studies of the Development of the Spark Discharge

A photomultiplier provided a means of studying the evolution of the spark discharge in the spark chamber. The total number of light quanta produced in a time t by a swarm of electrons drifting in a gas under the influence of an uniform electric field E may be

expressed as

$$L = \frac{\varepsilon}{\alpha} n_0 \exp. (\alpha v_- t) . \quad (1)$$

ε is the number of excitation collisions per cm and α is the number of ionizing collisions per cm. v_- is the electron drift velocity and n_0 is the number of electrons at $t = 0$. As already intimated, the growth of light was first studied as a function of electric field strength. Although such measurements are important for the practical utilization of a wide gap spark chamber, they do not, in principle, convey accurate information about the growth of electron number ($n = n_0 \exp. (\alpha v_- t)$), since ε may change with E ⁸).

The photomultiplier employed in the investigation was of the type RCA 931 A, and a lens was used to image the discharge on to a diffuser screen situated in front of the cathode of the photomultiplier. The linearity range of the photomultiplier could be extended over several orders of magnitude by using neutral density filters to attenuate the light output. The current pulse from the photomultiplier was integrated, and a sample of the height of the integrated pulse was fed to a 100 channel, pulse height analyser. In this manner, a large number of discharges, under fixed experimental conditions, could be observed in a relatively short time. The resulting histogram was then displayed on an oscilloscope and also printed out.

4.1 Measurements of light output as a function of electric field strength

The influence of field strength on light intensity (defined as the light emitted per unit length of track) is shown in Fig. 3. The data were obtained with the particle beam parallel to the direction of the electric field ($\phi = 0$) and for three values 30, 50 and 80 ns of pulse length. Each point shown on the graph represents an average value of intensity calculated from the histogram obtained with some 100 shots, while the vertical lines show the r.m.s. deviation about the average value. The three curves have the same general form, but are displaced towards higher values of E with decreasing pulse length.

The light intensity first increases exponentially with E , and towards the end of this region of exponential growth faint tracks are seen between the electrodes. For further increase in E there is a rapid increase in light intensity and ultimately the rate of increase of the intensity of bright tracks tends to a constant exponential form. The operating region of a wide gap spark chamber is clearly in this latter region, and the onset of the region corresponds with a complete collapse of the applied voltage pulse as defined for the measurements of spark formation time discussed in § 3.

The influence of the direction of the particle with respect to the electric field on the growth of light intensity is given in Fig. 4. A series of graphs are shown of light intensity versus field strength for a fixed pulse length of 50 ns, and with particles making angles up to $\phi = 40^\circ$ with the direction of the electric field. In changing the angle, two effects are observed. Firstly, for all values of E the intensity decreases with increasing angle ϕ ; the effect is most pronounced towards the higher values of light intensity but is also systematically present at low values of E . Secondly, the enhanced rate of growth of intensity in the region following the initial region of exponential growth becomes reduced; until at $\phi = 40^\circ$ the deviation from the constant exponential form obtained at low values of E is small.

4.2 Measurements of light output as a function of time

Data on the temporal growth of light intensity in a wide gap spark chamber are presented in Fig. 5. Results were obtained for three values of field strength and with $\phi = 0^\circ$ and 30° as indicated with the data. As with the measurements described in § 4.1, each point shown on the graph represents an average value of light intensity calculated from the histogram obtained with some 100 shots, while the vertical lines show the r.m.s. deviation about the mean value. The r.m.s. deviations are in this case greater than for the data shown in Fig. 3, and this result is attributed to a jitter, of absolute value $\lesssim 2$ ns, in the length of the voltage pulse at each fixed setting. For each curve, or family of curves, obtained at fixed value of E , the light intensity is proportional to the electron number n , provided of course that the motion of electrons is not significantly perturbed as a result of local space charge fields which may be induced in the spark chamber.

The general form of the data is similar to that of the earlier measurements of light output as a function of E . Initially the light intensity increases exponentially with time, at a rate dependent on the electric field strength and independent of angle. This result is in accordance with electron multiplication according to $n = n_0 \exp(\alpha v_- t)$, with the product αv_- regarded as a function of E . Values of αv_- have been derived from the measurements and are given in Fig. 6, where they are compared with values of the product αv_- calculated using values of α measured for neon gas by Kruithopf and Penning⁹⁾, and values of v_- measured by Bailey¹⁰⁾ in neon gas containing one per cent helium. The latter data is available for $E/p_0 \leq 7 \text{ volt cm}^{-1} \text{ torr}^{-1}$, and the values of αv_- derived from the present measurements (for $8 < E/p_0 < 14 \text{ volt cm}^{-1} \text{ torr}^{-1}$) merge smoothly with values of αv_- calculated in the above manner.

After the initial region of exponential growth, the light intensity grows at a higher rate which is dependent on the field strength E and on the angle θ of the particle with respect to the electric field. Finally the rate of growth is reduced, and in this region the characteristic bright track following spark is observed. The higher rate of light growth is accounted for in terms of a space charge field (see 5). On this basis, the light intensity above the region of exponential growth is not strictly proportional to the electron number. The general form of each graph is, however, not expected to deviate by any large extent from the form of the growth of electron number, since ϵ/α is a decreasing function of E .

It is interesting to note that the data show no evidence of a retardation in growth in the late avalanche stage as has been predicted by Lyubimov et al.¹¹⁾ on the basis of space charge influence.

5. Discussion

The initial exponential form of the growth of ionization in the spark chamber is consistent with the growth of electron avalanches under the influence of an uniform electric field. This exponential behaviour is, paradoxically, also characteristic of the data on light intensity as a function of electric field strength E . A possible explanation for the similarity lies with the facts that over the rather
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restricted range of E investigated in each graph shown in Figs. 3 and 4, the quotient ϵ/α remains practically constant and the product αv_- depends linearly on E (see equ. 1).

Although the rate of avalanche growth is independent of angle, the absolute magnitude of the electron number at a fixed time decreases with increasing angle ϕ . Since the average number of ion pairs formed by the particle per cm along the track is in each case constant, it follows that the dependence of electron number on angle is established at a stage in the development of the discharge earlier than that investigated in the present work. The presence of metastable atoms produced by the particle along the track could possibly account for the dependence of electron number on angle, since the metastable atoms would bring about an initial enhanced rate of growth and the contribution from the effect would depend on the angle ϕ . The effect would be greatest when the electrons of the early generations of avalanches have the largest path-length through the region, surrounding the track, in which these metastable atoms were located. This would clearly be the case when the direction of the track coincided with the direction of the applied field ($\phi = 0$). With the destruction of the majority of the metastable atoms, or with the growth of avalanches away from the region of the track, electron multiplication would proceed as $\exp(\alpha v_- t)$ irrespective of angle but with an absolute level dependent on angle.

The faster growth rate following the avalanche development is akin to the "upcurving" found in gas discharge studies of the growth of ionization¹²⁾. In the present case, the faster rate of growth can only be realistically accounted for in terms of a space charge phenomena. During the avalanche stage in the development of the track following spark, growth takes place in the direction of the applied electric field. However, for a spark discharge to occur at an angle to the applied electric field, then an additional field must be induced which causes the preferential drift of electrons along the track and not in the direction of the applied field, i.e. the resultant of the applied and induced fields should have a significant component along the direction of the particle track. This additional field can only

be of a space charge origin, and is most probably identified with the space charge field which brings about the higher rate of growth of electron number observed experimentally. On this basis the direction of the space charge field is such as to reinforce the applied field.

The development of a track following spark may be considered along two extreme schemes which satisfy the above consideration.

In the first scheme, the discharge develops from a series of distinct avalanches between the electrodes of the spark gap. If the amplification of these avalanches is high, the electrons at the head of one avalanche will experience the space charge field due to the ion cloud of the foregoing neighbouring avalanche¹³⁾. The situation would be equivalent to a series of dipoles along the track, with the axis of each dipole aligned, initially at least, in the direction of the applied field. This space charge field would direct the growth of electrons along the track, and the magnitude of the field would depend on the number of electrons and ions in each avalanche, and upon the separation between the electrons and ions of adjacent avalanches.

According to the second scheme, the inter-diffusion of avalanches at an early stage gives rise to an uniform charge front between the electrodes. The charge density in this front would increase with time, and at the region of the anode there would accumulate a net positive ion space charge due to the collection of electrons at the anode. The field due to this positive ion space charge would direct the growth of electrons to a specific point at the anode, and so in effect would represent a space charge field directed along the particle track. The process would start at the region of the anode, but the motion along the track of electrons near to the anode would cause the build up of net positive charge in regions further away from the anode, so that the influence of the space charge at the anode would quickly be propagated along the track.

With both these proposals, the onset of the influence of the space charge field is concerned primarily with the attainment of some specific high multiplication factor of electrons, and so would be

largely independent of angle. On the other hand, the effect brought about for a fixed value E_s of the space charge field would depend on the angle of the track with respect to the applied field E , since the net force acting on the electrons would be the resultant of the two fields E and E_s . If the higher rate of growth observed experimentally is identified with the influence of these space charge phenomena, the above considerations are consistent with the findings (a) that a 10 % deviation from the initial exponential form of the growth of light intensity occurs at the same light level for $\phi = 0$ and 30° , and (b) that the rate of growth of the faster process is dependent on angle.

The question as to whether the discharge develops as an uniform front or as separate avalanches depends on the relative values of the initial number density of avalanches along the track, and the diffusion radius of the heads of electron avalanches as they grow under the action of an applied electric field. Whilst the latter quantity may be derived from published data relating to the motion of electron swarms ^{9,10)}, the number density of avalanches which develop along the track is uncertain. Calculations using the Bethe-Bloch theory in conjunction with the data of Jesse and Sadauskis ¹⁴⁾ yield a value of 40 for the number of ion pairs produced per cm along the track of a π^- particle of energy 1 GeV in neon at atmospheric pressure. If these initial electrons are assumed to be uniformly spaced along the track and each gives rise to an electron avalanche, then calculations for the case of $E = 6.73 \text{ KV cm}^{-1}$ (as for the temporal growth measurements obtained at $\phi = 0$ and 30°) show that fusion between adjacent avalanches occurs at times $\leq 2 \text{ ns}$ even for $\phi = 30^\circ$. This time is clearly much shorter than the time $\sim 60 \text{ ns}$ observed experimentally for the onset of the higher rate of growth. On this basis, therefore, the development of the discharge as an uniform front would seem to be plausible. But on the other hand, experiments with streamer chamber ^{15,16)} have shown that the number of streamers per cm along the track is in general very much less than the number of ion pairs produced by the particle per cm along the track. Quoted values for the average number of streamers range from 1.4 to 10 per cm, but depend on the delay in applying the high voltage pulse. For a delay $\sim 400 \text{ ns}$ as in the

present work, the average number of streamers per cm has been quoted by Odian ¹⁶⁾ as 2.5. If this figure is considered as the average avalanche density, calculations for $E = 6.73 \text{ KV cm}^{-1}$ show that fusion between adjacent avalanches occurs at times $\sim 100 \text{ ns}$ for $\phi = 30^\circ$. This time is greater than the time $\sim 60 \text{ ns}$ observed experimentally, and the result lends support to the view that inter-avalanche space charge fields play the dominant role in the development of the discharge. It is relevant to consider, however, that streamer chambers are operated at much higher field strengths than in the present spark chamber. It is, therefore, possible that a transition between the two proposed schemes may occur as the field is increased.

6. Conclusions

The data on the temporal growth of electron number in a wide gap spark chamber is consistent with the view that the mechanism of spark formation involves the establishment of a space charge field which directs the motion of electrons along the direction of the track. This space charge field could arise from the interaction between avalanches, and/or from the build up of positive ion density at the region of the anode. The speed of the final process leading to spark formation decreases as the angle of the particle with respect to the electric field increases, and this result is in accordance with independent measurements of spark formation time which showed that the spark formation time increases with increasing angle.

A dependence of spark intensity on angle is a feature of a wide gap spark chamber with bare metal electrodes (see, for example, Fig. 4, $E = 8.0 \text{ kV cm}^{-1}$). The measured increase of spark formation time with increasing angle provides a possible cause of this variation in spark intensity.

The experiments are currently being extended so as to correlate measurements of electron number with photographic evidence as to the physical condition of the discharge in a wide gap spark chamber.

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Fig. 1 Schematic representation of the experimental arrangement.

Fig. 2 Spark formation time t_s versus electric field strength E for various values of angle θ between the direction of the particle beam and the electric field. $p_0 = 680$ torr.

Fig. 3 Intensity of light emitted from spark chamber as a function of electric field strength E for various values of pulse length. A) minimum light detectable with unaided eye; B) characteristic position of voltage collapse. $\phi = 0^\circ$; $p_0 = 680$ torr.

Fig. 4 Intensity of light emitted from spark chamber as a function of electric field strength E for various values of the angle ϕ between the direction of the particle beam and the electric field. $p_0 = 680$ torr; pulse length = 50 ns.

Fig. 5 Temporal growth of the intensity of light emitted from a spark chamber for various values of electric field strength E and angle ϕ between the direction of the particle beam and the electric field. $p_0 = 689$ torr.

Fig. 6 Values of $\alpha \nu_-$ as a function of E/p_0 . $p_0 = 689$ torr.