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PARALLEL-PLATE TIME PROJECTION CHAMBER OPERATION IN A MAGNETIC FIELD

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ABSTRACT

A small time projection chamber with a parallel-plate avalanche chamber as an end-cap detector was tested in a magnetic field of up to 10 kG. An increase of sparking rate at a given gain with increasing magnetic field was observed.

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1. INTRODUCTION

The parallel-plate avalanche chamber shows very interesting features if used as an end-cap detector for a time projection chamber (TPC) [1–3]. It accepts very high particle fluxes with no loss of amplitude; it reduces by a factor of up to one hundred the density of positive ions in the drift volume; the loss of space resolution in the region around wires where the electric and magnetic fields are not parallel is expected to be much smaller than in a conventional TPC because of smaller wire spacing and higher electric field; finally, a very good two-track resolution of less than 2 mm can be obtained with appropriate geometry of anode pads.

The device suffers, however, from breakdowns at high electric fields. Ions feeding back from the avalanche appear to initiate sparking. In this case there are three possible mechanisms which can lead to a spark:

- i) The space-charge electric field is such that αd , where α is the first Townsend coefficient and d is the gap, exceeds a critical value (~ 20) for the gas.
- ii) The space-charge electric field of the ions as they approach the screen wires induces field emission.
- iii) The ions collect on a thin insulating layer (defect or impurity) on the metal screen creating a space-charge field which lowers the work function of the metal thus leading to field emission.

The second mechanism is unlikely because extremely high fields are required ($10^7 - 10^8$ V/cm) and the dimensions of the charge distribution and wires are such that fields of 100 times less than required are achieved.

The third mechanism is unlikely because it would lead to sustained discharges at the site of the defect or impurity. The major portion of the sparking does not have a strong correlation with a specific pattern. A very small fraction of the sparks could, in fact, be identified with this mechanism because of pattern correlations. This mechanism can be avoided with a clean construction.

The first mechanism is the one most likely to lead to the sparks. A simple calculation shows that values of αd exceeding the critical value of 20 are achievable in the space-charge field of the ions from an ionization cluster superimposed upon the electric field near the wire screen. Experimentally, this situation had been realized in the operation of hybrid spark chambers.

The purpose of the present work was to check this hypothesis experimentally and to try to describe this phenomenon quantitatively. In Section 2 we describe the experimental set-up and in Section 3 we present measurements of the gas amplification factor, charge distribution, and pulse-height spectra. Section 4 is devoted to sparking studies, including measurements of breakdown voltage and sparking rate as a function of ionization density with and without the magnetic field, and to calculations of the electric-field distortion due to the density of positive ions. Finally, in the last section, we summarize the results.

2. EXPERIMENTAL SET-UP

The layout of the chamber used for most of the measurements is shown in fig. 1. It has a surface of 20×20 cm² and a drift space 10 cm long. The field cage is made of fibre glass with 25 field-shaping copper strips and is closed by a mylar window. The electrodes C1, C2, and C3, in fig. 1, are screens of 50 μ m diameter and 500 μ m pitch. The last electrode, C4, is a printed circuit segmented in 10 strips, 2×20 cm², and 5 rows of pads of 1.27×15 mm² (see the inset in fig. 1). The two amplification gaps formed by C2 – C3 and C3 – C4 electrodes are 4 mm and 2 mm thick,

respectively. The power supply HV1 provides the high voltage to the upper electrode through the resistor R_1 , to the copper strips and the second electrode through the resistor chain of $26 \times R_2$, and is finally grounded through R_3 . We have tried different values of resistors in order to change the field ratio E_2/E_1 and to reduce the energy dumped into sparks. One set of resistors used is R_1 , $R_2 = 10 \text{ M}\Omega$ and $R_3 = 800 \text{ M}\Omega$. Such high values produced however a non-negligible voltage drop at very high particles fluxes, resulting in a lower gas gain.

The value of the protection resistor R_4 was $10 \text{ M}\Omega$.

3. GENERAL MEASUREMENTS

The chamber with the described configuration can be operated in single- or double-step multiplication mode. The gas gain in a single step of thickness d is equal to

$$M = e^{\alpha d}.$$

The fast charge signal due to electrons on the anode (electrode C3 in this case in fig. 1) is

$$M_1 = M/\alpha d,$$

because electrons produced at a depth x from the cathode contribute with a weight $(d-x)/d$ to the observed signal. If, however, by applying a drift field E_2 one allows a fraction f of them to enter the second gap the signal measured on C4 will be

$$M_2 = M f.$$

The fraction f is roughly equal to the field ratio E_2/E_1 and can be adjusted to be larger than $1/\alpha d$. In this case the signal observed on C4 is bigger than the one measured directly on C3 although not as fast (its rise-time is equal to the drift-time across C3 – C4). By applying a very high field in the second gap one can multiply again the transferred charge, but the maximum signal one can obtain below the sparking point is often smaller than in the single-step operation.

Figure 2 shows examples of gain curves measured in a mixture of argon and methane (91% – 9%) as a function of field in the first gap, E_1 , for different values of E_2 in the range of 6 kV/cm – 15 kV/cm . The amplification factor is estimated from the amplitude of the signal obtained with a charge integrating amplifier of known sensitivity. The limit at high gains is due to breakdown. One sees that the multiplication in the second gap starts only at fields of about 15 kV/cm . The reason for this is that the second gap is thin and requires a much higher value of α for the same factor αd . It turns out that the operation in a multiplication and transfer mode is the best in terms of signal amplitude and narrow spatial charge distribution.

Figure 3 presents the efficiency plateau measured by exposing the chamber to a minimum ionizing muon beam at the CERN North Area. We counted pulses on a $2 \times 20 \text{ cm}^2$ strip (see fig. 1) connected to a hybrid preamplifier–discriminator circuit set at a threshold of 0.1 mV [4]. The plateau obtained without the magnetic field is about 400 V long. In the presence of a 10 kG magnetic field parallel to the electric one the chamber counts as before for low gains, but the plateau is reduced to about 100 V because of sparking. The problem of discharges in the presence of the magnetic field will be discussed in detail in the next section.

We have measured the charge distribution on anode pads, operating the chamber in the multiplication and transfer mode and using a LeCroy 2261 image chamber analyser system for storing and digitizing of pulses. Figure 4a shows signals produced by a gamma-ray from the ^{55}Fe source recorded on subsequent anode pads. Each track in the figure represents pulses recorded on one pad in 20 ns time bins. The distribution is rather wide, extending over six 1.27 mm pads.

Another event taken in the same conditions, but in the presence of a magnetic field of 10 kG, is shown in fig. 4b. The diffusion, reduced by a factor of about 6 [5], spreads the cluster over only two pads.

Figure 5 shows the pad response function measured with the ^{55}Fe source. For every event we have counted the number of pads having signals above 10%, 20%, and so on up to 90% of the maximum. The resulting distribution has 2.8 mm full width half maximum (FWHM). This width is a convolution of the detector response itself and of the diffusion. Gamma-rays having a mean free path of about 1.5 cm convert very close to the mylar window and drift over almost 10 cm to the end plate. This results in a spread of the electron cloud with a standard deviation of about 2 mm [6]. The FWHM of the pad response function is about 1 mm in the presence of the magnetic field.

During the measurements without the magnetic field we have observed modulations of amplitudes on pads with a step of 1 – 3 mm. Figure 6 shows an example of such an event. Each horizontal bin represents the integrated signal of one pad. For these measurements we have used an end plate with very narrow — 500 μm — pads. One sees two peaks, which are at a distance of about 2 mm from each other, belonging to the same avalanche.

The observed modulation is a superposition of two effects: diffusion of electrons deposited in the conversion space and interference created by the non-parallelism of the two electrodes C3 and C4, creating Moiré patterns in the electrical transparency. Figure 7 shows a simulated event obtained by taking 200 electrons created in one point in the conversion space and drifting them over 10 cm to the end plate. We have assumed a diffusion of 400 μm for 1 cm drift, a value corresponding to our gas and field conditions. Each bin represents the number of electrons detected on one pad of 500 μm width. No other assumptions were put into the simulation. One sees that with such a fine pad spacing one is able to detect single-electron clusters. The non-parallelism of screens enhances this effect as shown in fig. 6.

Further evidence that we were not seeing a trivial electronic effect lay in the pulse-height spectrum obtained by adding up all signals in a cluster (see fig. 8) that has clearly the expected resolution for the main 5.9 keV and the argon escape peaks.

4. SPARKING STUDIES

Searching for the best operating conditions we have tested several gases using a low intensity ^{55}Fe source for gain calibration. Figure 9 shows sparking rates measured in argon-methane, argon-methane-ethyl alcohol, and argon-ethane-ethyl alcohol mixtures as a function of gas gain. Of all tested gases the standard TPC mixture of argon and methane turns out to be the best for our counter.

The measurement was repeated with the detector mounted in a magnet such that the electric and magnetic fields were parallel. Figures 10a and b show sparking rates as a function of gain for two operating conditions ($\text{HV}_2 = 1.25 \text{ kV}$ and 1.75 kV , respectively) and different values of the

magnetic field between 0 and 10 kG. Because of the reduction of avalanche size in the presence of the magnetic field, we think that the increase in sparking rate is correlated with charge density.

In a previous work, the rate dependence of breakdown voltage (in the absence of magnetic field) was measured in a very similar parallel-plate detector [7] filled with an argon and acetone mixture of 98% – 2%. The detector was irradiated with 8 keV X-rays from a generator with variable flux and collimator width. The curves a, b, and c in fig. 11 [7] correspond to collimator diameters of 4 mm, 2 mm, and 0.5 mm, respectively. The breakdown point decreases with increasing ionization density and total charge.

One can calculate the electric field created by positive ions produced between electrodes and drifting towards the cathode [7]. Assuming a very simple model of a uniform charge density ϱ , contained in a cylinder of radius b between two conductive plates at a distance of d from each other, one can calculate the field component perpendicular to the plates from:

$$E_i(z) = (\varrho d / 4\epsilon_0) \left(2z + \sqrt{[\epsilon^2 + (\zeta - 1)^2]} - \sqrt{[\epsilon^2 + (\zeta + 1)^2]} + \sum_{k=1}^{\infty} (-1)^k [\sqrt{(\epsilon^2 + (2k + 1 - \zeta)^2)} \right. \\ \left. + \sqrt{[\epsilon^2 + (2k - 1 + \zeta)^2]} - \sqrt{[\epsilon^2 + (2k - 1 - \zeta)^2]} - \sqrt{[\epsilon^2 + (2k + 1 + \zeta)^2]} \right).$$

The origin of the reference system is in the centre of the gap. We have used the following parametrization: $\epsilon = 2b/d$ and $\zeta = 2z/d$; ϵ_0 is the dielectric constant. Figure 12a shows the shape of the field between the anode and the cathode calculated for $\epsilon = 0.1$. One sees that it is highest at the electrodes but has opposite sign. This field superposed onto the existing, uniform, field E_0 results in lowering the field at the anode and increasing it at the cathode (see fig. 12b). The positive charge density can be calculated from $\varrho = RnMeT/V$, where R is the rate of gamma-rays producing $n = 300$ electrons each, M is the gain of the chamber, T is the drift-time, and $V = \pi b^2 d$ is the volume occupied by the charge. The radius b can be estimated from the collimator geometry, taking into account the divergence of the beam and the diffusion. Assuming the drift-time T of about $40 \mu s$ and an appropriate gain M , the authors of ref. [7] have calculated the field E_i and plotted the measured points as a function of $E_0 + E_i$. The value of E_i was however too small and introduced no significant change in the picture. When assuming the E_i field to be 5 times bigger than calculated for conductive plates, all points fall on one curve (d in fig. 11), giving the value of the critical field. It seemed that the approximation of a wire plane by a plate was too simple and the effective modification of the field on the wire surface is much larger. In fact the b parameter is reduced as ions approach wires. Since ϱ is proportional to $1/b^2$, a compression of a factor of $\sqrt{5}$ in b is enough to explain this discrepancy.

5. SUMMARY AND CONCLUSIONS

We have identified the sparking in the multistep avalanche chamber to be ionization density dependent. The sparking probability increases with gain in the chamber, with magnetic field, with ionization flux (X-rays, cosmic rays, ionizing tracks). The sparking probability depends upon the gas mixture; for a fixed gain, the gas with the greatest diffusion has the lowest probability of sparking.

Such an ionization density dependent sparking leads to a bias in detectable physics. There is a probability of sparking per detected metre of track which is not small, such that the probability of sparking per event depends upon multiplicity and track correlations. One obvious track

correlation which will cause a higher probability of sparking is the decay of either Λ^0 or K_S^0 . Delta-rays in a magnetic field will also have a higher probability of sparking. A particular charge density and the charge of ions feeding back from the avalanche is believed to cause the spark. This implies an ionization density $\times$ gain product ambiguity associated with the sparking probability, which in turn fixes a dynamic range $\times$ gain product (high gain yields low dynamic range).

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Figure captions

- Fig. 1** Schematics of the parallel-plate time projection chamber used for sparking studies. The electrodes C1, C2, and C3 are screens; the C4 electrode is a printed circuit segmented in strips and pad rows as shown in the inset.
- Fig. 2** Dependence of the gas amplification factor on the electric field in the first gap, E_1 , for different values of the field in the second gap, E_2 .
- Fig. 3** Efficiency plateau measured on a $2 \times 20 \text{ cm}^2$ strip with a wide energy spectrum muon beam with and without the magnetic field.
- Fig. 4** Signals obtained from a 5.9 keV gamma-ray on a sequence of anode pads, digitized with 50 MHz frequency. The horizontal scale is given in 20 ns bins.
a) $B = 0$, b) $B = 10 \text{ kG}$.
- Fig. 5** Pad response function obtained with a ^{55}Fe source by counting pads with signals above 10%, 20%, and up to 90% of the maximum.
- Fig. 6** Amplitudes measured on anode pads ($500 \mu\text{m}$ wide) produced by a single gamma-ray. The two peaks are due to the diffusion and to the channelling of electron clusters due to the Moiré effect.
- Fig. 7** Simulated event: 200 electrons deposited in one point in the conversion space and drifting to the end plate. Each bin corresponds to the number of electrons detected on one pad. The fluctuation is due only to the diffusion.
- Fig. 8** Pulse-height spectrum of the ^{55}Fe source measured as the sum of pulses in a cluster.
- Fig. 9** Sparking rate as a function of applied voltage for different gas mixtures.
- Fig. 10** Sparking rate measured as a function of gain at different values of the magnetic field.
a) $\text{HV2} = 1.25 \text{ kV}$, b) $\text{HV2} = 1.75 \text{ kV}$.
- Fig. 11** Dependence of the breakdown field on X-ray density for three collimator widths (points corresponding to curves a, b, and c). Points falling around the curve d represent the same measurements plotted as a function of the modified electric field.
- Fig. 12** a) Electric field created by a charge density ρ contained in a cylinder of radius b in between two conductive plates at a distance of d from each other. b) Superposition of the uniform field in a parallel-plate counter E_0 on the field created by positive charge E_i .

Fig. 1

Fig. 2

Fig. 3

a)

b)

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12