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POSITIVE ION EFFECTS
IN LARGE-VOLUME DRIFT CHAMBERS

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ABSTRACT

Large gaseous drift volumes followed by a bidimensional multiwire chamber and a sophisticated electronic storage of track topology and energy loss make a very promising detector for complex geometry events. However, the positive ions produced in the avalanche process at the anodes induce non-negligible electric field distortions that may result in a substantial loss of information. The different levels at which this may happen are briefly analysed here.

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1. INTRODUCTION

The use of thin-gap multiwire proportional and drift chambers is nowadays a widespread technique for detection and localization of fast charged particles in high-energy physics; large detectors are built by suitably stacking the required number of independent wire planes or modules. The increasing size of the experiments, however, together with the large particle multiplicities appearing at the highest energies, often results in a considerable mechanical complexity for such systems. Recently, a new approach to the detection problem has appeared, with the introduction of large-volume drift chambers such as the ISIS detector¹⁾, the Time Projection Chamber²⁾ and similar devices³⁻⁵⁾.

Essentially, these detectors consist of a large gas container, constituting the sensitive volume, in which the electrons produced by the ionizing tracks drift along a suitable electric field to an end-cap multiwire proportional chamber; through avalanche multiplication the charges are amplified there to allow electronic detection. As can be seen from Fig. 1, the cathode plane C1 is built with a wire mesh or a grid having good electrical transparency for the drifting electrons, while cathode C2 can be a conducting foil or a printed circuit suitably stripped to provide a coordinate measurement. The anode plane A can either be constituted by a single mesh of thin wires, or by an alternation of thin (anode) and thick (field) wires. Suitable guard rings (not represented in the figure) on the periphery of the drift volume, maintain the uniformity of the applied drift field E_D over all the sensitive volume.

In the Time Projection Chamber project, the event topology sliced in narrow time intervals (hence the name of the detector) is rapidly stored in a large system of analogue shift registers^{*)} that are then multiplexed and read out at a conveniently lower speed. The order number of the considered time slice, as referred to the event time, gives the elevation of each projection, while the anodic wire number and the induced pulse-height distribution on cathode strips or pads gives the two-dimensional coordinates of each segment in the projection; the anode pulse height is considered to represent the energy deposit of the corresponding track segment.

*) Fairchild CCD 321

In principle, therefore, both the geometry and the energy deposit of even complex events is measured with a point density hardly obtainable by any other electronic method. It is the purpose of this paper to analyse several mechanisms, all connected with the creation of a positive ion cloud in the avalanche process, that can substantially distort the reconstructed event topology if not properly taken into account.

We will consider separately the space-charge effects on the anodic potential (and therefore on the proportional gain), and on the electric field in the drift region.

2. SPACE-CHARGE MODIFICATION OF THE PROPORTIONAL GAIN

Space-charge build-up during the avalanche growth in the multiplication process is a well-known phenomenon degrading the proportionality between the actual energy deposit and the detected charge in a gas proportional counter. For heavily ionizing charged particles, a critical avalanche size between 2×10^5 and 10^6 is often quoted as the limit of proportionality⁶⁻⁸⁾; however, even at very low multiplication factors, a distinct dependence of the detected charge on the spatial distribution of the primary ionization has been observed in proportional drift chambers. For 5 MeV α particles emitted parallel or perpendicular to the anode wires plane, a 10% pulse-height variation has been measured at a multiplication factor of 10, corresponding to about 1.7×10^6 detected charges⁹⁾.

For minimum ionizing particles and gains around 10^5 , Breskin et al.¹⁰⁾ have found a very strong dependence of the detected pulse height on the spatial extension of the avalanches along the anode wires. Figure 2, which is taken from their paper, shows the measured pulse-height per unit length of the tracks as a function of the angle θ_H between the track and the normal to the chamber, in a plane containing the anode wire and perpendicular to the chamber itself. A clear saturation effect appears at small incidence angles, while it is only for angles above 45° or so that the avalanches appear to be sufficiently separated along the wire to provide a true proportionality between track length and pulse height.

Recently, Frehse et al. have measured the angular dependence of the detected charge for minimum ionizing particles, in a wide range of track geometries and multiplication factors¹¹⁾. Their results show that the measured pulse height for a given energy loss depends both on the time structure of the electrons reaching the anodes, and on the geometrical extension of the detected charge along the wires. As an example, at a multiplication factor around 10^4 , a 25% pulse-height difference is measured between tracks perpendicular to an anode wire and inclined, with respect to the anode, by 45° so as to spread the avalanches along the wire (see Fig. 9 in Ref. 11). At higher values of the multiplication factor the effect is largely increased.

The dependence for charged particles of the measured pulse height on the space distribution of the detected charges casts serious doubts on the correctness of the conventional energy calibration procedure using X-ray emitters of various energies. This doubt has already been expressed by several authors in view of the discrepancy with theory of the measured energy losses in thin proportional counters¹²⁾.

Obviously, operation at moderate multiplication factors reduces the relevance of all these effects; however, more experimental work on the matter seems to be required. The effect of high gas pressures, increasing the charge densities but possibly reducing the spatial extension of the avalanches, should also be investigated¹³⁾.

In the relativistic rise region, ionization measurements better than 2% are required in order to achieve good particle identification; substantial corrections to the measured pulse height may therefore be necessary, depending on the track geometry and on the multiplication factor used. Electron diffusion, modifying the spatial extension of avalanches, may even introduce a drift distance dependence; it has been found, indeed, that whenever the lateral diffusion of drifting electrons is large enough to spread the charges along a wire or several wires, substantially larger pulse heights are measured for soft X-rays. Charpak et al.¹⁴⁾ found a 10% pulse-height increase when electrons produced by 5.9 keV X-rays drifted 15 cm instead of a few mm.

Positive ions produced in the avalanches only slowly drift towards the cathodes; for a typical narrow-gap multiwire proportional chamber the total collection time is around 200-300 μsec , while for a large drift volume chamber it can reach few tenths of a second^{*)}. The positive space charge thus generated, depending on the counter gain and the incident particle rate, modifies the electric field distribution in the counter, and can therefore influence both the multiplication factor and the electron-drift properties. Figure 3 (taken from Ref. 10) shows, for example, the pulse-height reduction on minimum ionizing tracks as a function of the beam flux, per unit length of anode wires, and for several multiplication factors. The effects of space-charge pulse-height reduction on the efficiency of multiwire proportional chambers were first measured by Sadoulet and Makowski¹⁶⁾. Hendricks¹⁷⁾ has given an approximate mathematical expression for the gain reduction versus rate (see also Ref. 10). As seen from Fig. 3, at the lowest avalanche size ($M \approx 2 \times 10^6$), a 10% gain reduction is observed for an incident rate of about $2 \times 10^3 \text{ mm}^{-1} \text{ sec}^{-1}$. In a $1 \times 1 \times 1 \text{ m}^3$ drift volume chamber, operated at the same avalanche size and for tracks uniformly traversing the sensitive volume, an equal charge density is obtained at a particle flux of about $2 \times 10^2 \text{ cm}^{-2} \text{ sec}^{-1}$, and one would therefore expect the same gain reduction, under the assumption of complete screening by the cathode plane C1 (see Fig. 1), of the effects, on the anodic field, of the charges in the drift volume (as we will see, this is a rather optimistic assumption).

We may mention here that more exotic reasons for gain reduction have been considered, such as ion columnar recombination¹⁸⁾ and influence of the cathode nature and geometry¹⁹⁾, which in certain cases could have an even stronger rate dependence than the ion space charge.

3. SPACE-CHARGE EFFECTS IN THE DRIFT REGION

The low velocity of the positive ions results in a substantial charge integration in large drift volumes; indeed, at electric field values that are practical for a large-volume detector, the total collection time of ions is of several hundred

*) Tables of mobilities for ions of gases commonly used in proportional counters can be found in Schultz et al.¹⁵⁾.

milliseconds per metre of drift. The ensuing rate-dependent space charge modifies the electric field strength and direction in the drift volume. For a uniform charge distribution of density ρ in an infinite layer of thickness Δx , the electric field modification in the direction perpendicular to the layer can be written as

$$\Delta E = \frac{\rho}{\epsilon_0} \Delta x . \quad (1)$$

The charge density ρ in the volume V is given by

$$\rho = \frac{N T e}{V} , \quad (2)$$

where T is the total drift time of the ions and N their production rate per unit time. Let n be the number of primary electrons generated per unit time, and M the proportional gain of the chamber, then

$$N = n M \epsilon , \quad (3)$$

where the efficiency factor ϵ takes into account that not all ions produced at the anode leak into the drift space, part of them being collected by the two cathodes. The field modification, of course, implies a change in the electron drift velocity and therefore a rate-dependent space-to-time relationship. If, as is very likely to be the case in practice, the ionization distribution in the detection volume is not uniform, field modifications along the other components also appear, causing distortions in the drift path of the electrons (this effect being particularly relevant in the presence of strong magnetic fields). As for the magnitude of the effect, let us consider the case of a 1 m long chamber, working with argon-methane (80%-20%) at 10 atm, at a reduced field of $1.5 \times 10^4 \text{ V} \cdot \text{m}^{-1} \cdot \text{atm}^{-1}$ ²⁾. Taking into account the mobility of the methane ions in the mixture, $\mu^+ \approx 1.9 \times 10^{-4} \text{ m}^2 \text{ V}^{-1} \text{ sec}^{-1}$ [see, for example, Schultz et al. ¹⁵⁾], one finds $T \approx 0.35 \text{ sec}$. If the device is operated, as suggested, at $M = 1.6 \times 10^3$ in a minimum ionizing particle flux of 10^5 sec^{-1} , the positive charge density can be computed to be $\rho \approx 4 \times 10^{-8} \text{ C} \cdot \text{m}^{-3}$ assuming [see expression (3)] an average ionization density of $60 \text{ ion pairs} \cdot \text{cm}^{-1} \cdot \text{atm}^{-1}$, 1 m long tracks, and $\epsilon = 8 \times 10^{-2}$, as suggested by the authors of Ref. 2. The maximum axial field modification, in this case, would be around $5 \text{ kV} \cdot \text{m}^{-1}$, or about 3%.

Even such a small field modification has to be taken into account to meet the expected performances; in fact, owing to the large size of the detector and the high gas pressure, the operational point has been chosen at a value of the reduced field where the drift velocity is almost a linear function of the ratio between the electric field and the pressure E/P . Operation above velocity saturation would, of course, reduce or cancel the field dependence¹⁰⁾.

Of primary importance for the above-mentioned estimate of the field modification is the correct knowledge of the cathode feedthrough efficiency ϵ . For a uniformly generated charge, calculation of grid transparency is a pure electrostatics problem that has been analysed long ago to describe the behaviour of vacuum tubes²⁰⁾ and grid ionization chambers²¹⁾; in good approximation the computed transparency equals the ratio of the fields above and below the grid, for ratios smaller than ~ 0.5 . In our case, however, the distribution of the ions in the avalanches at the production is far from being uniform. Indeed it has recently been found that, especially at low proportional gains, the avalanches are very localized around the original direction of drift of the multiplied electrons^{22,23)}, and this of course strongly favours the leakthrough of the positive ions in the drift region.

We have therefore directly measured the feedback of the ions in a prototype chamber of the kind illustrated in Fig. 1, having a drift volume of $20 \times 20 \times 20 \text{ cm}^3$. The proportional chamber section had $10 \text{ }\mu\text{m}$ diameter anode wires, 2.54 mm apart, a $2 \times 5 \text{ mm}$ gap, and $100 \text{ }\mu\text{m}$ diameter cathode wires, 1.27 mm apart; wires in the cathode plane facing the drift volume were parallel to the anodes. The electric field in the drift volume could be varied independently from the anodic potential (and therefore from the gain of the proportional chamber). The chamber was operated in an argon-ethane (60%-40%) mixture, at atmospheric pressure. For a uniform flux of ionizing radiation traversing the system, as provided by an X-ray tube, the displacement currents were measured on the anode and on the three cathodes (see Fig. 1). Care was taken at each anodic voltage not to approach the rate-dependent space-charge gain modification region in order to avoid distortions in the distribution of the avalanches. The results of the measurements are summarized in Figs. 4 to 6.

Let I_A , I_{C1} , I_{C2} , I_{C3} be the measured currents on the corresponding electrodes (as from Fig. 1); Fig. 4 shows, as a function of the electric field in the drift region E_D and for several values of the anodic potential V_A , the cathode feedthrough efficiency I_{C3}/I_A (full curves) and the avalanche asymmetry $I_{C2}/(I_{C1} + I_{C3})$ (dashed curves). The same quantities are plotted in Fig. 5 for a fixed drift field, $1.5 \text{ kV}\cdot\text{cm}^{-1}\cdot\text{atm}^{-1}$, as a function of the anodic potential. In Fig. 6 instead, all measured values of $I_{C3}/(I_{C1} + I_{C3})$, which can be defined as the electrical transparency of the grid C1, are represented as a function of E_D/E_A , the ratio of the electric fields in the drift and proportional chamber regions. For the calculation of E_A from V_A we have used the approximate expression that can be found, for example, in a review paper by one of the present authors²⁴):

$$E_A \simeq \frac{CV_A}{2\epsilon_0 s}, \quad (4)$$

where C is the capacitance per unit length of the anode wires ($\sim 6 \text{ pF}\cdot\text{m}^{-1}$ in our case) and s the wire spacing. It can be seen that the experimental electrical transparency is always lower than the one expected from the above-mentioned pure electrostatics considerations (broken line). A possible explanation for the discrepancy lies in the non-uniform distribution of the avalanches at generation, with cathode wires systematically facing the anode wires because of chamber construction.

In Fig. 7 we have represented the measured proportional multiplication factor as a function of the anodic potential, to help in locating the operational conditions of the multiwire proportional chamber (for a drift field $E_D = 1.5 \text{ kV}\cdot\text{cm}^{-1}$). As one would expect from the previous considerations, at small multiplication factors the electrical transparency of the cathode C1 increases (since so does the number of lines of force connecting the anode with the drift cathode C3), and also the avalanches preferentially grow on the side of the anode wire facing the drift space. Both effects have the tendency to reduce the advantage, in terms of the number of produced ions, of operating at low gains. A reduction by one order of magnitude of the multiplication factor (from 3 kV to 2.5 kV for the anodic voltage) only reduces the feedthrough of the ions by a factor of six.

For practical reasons (amplifiers noise, etc.) we could not extend our measurements to proportional gains below 10^4 ; therefore direct reading of the data for the operational conditions of the proposed Time Projection Chamber is not possible. However, a sensible extrapolation of our measurements to gains around 2×10^3 ($V_A \approx 2$ kV) suggests an electrical transparency around 40% (see Figs. 5 and 7); taking into account that at low gains the avalanches are strongly asymmetric [Fig. 5 would suggest that 90% of the avalanches grow on the upper side of the anode (see also Ref. 23)], our results seem to be in contradiction with the previously quoted 8% feedthrough efficiency measured by the authors of Ref. 2. The relevance of the chamber construction and geometry should, however, be further studied, and, in particular, the effect of field wires alternated with anode wires.

As mentioned, for non-uniform particle fluxes detected in the drift volume not only the strength but also the direction of the electric field is modified; calculation of the effect involves a precise knowledge of the charge distributions. To understand the relevance of the problem, we have performed the following experiment: in the model chamber, as shown in Fig. 1, a collimated, 10 mm diameter, 8 keV X-ray beam traversed the drift volume in a direction parallel to the anode wires, thus producing a continuous sheath of positive ions in the drift volume. A well-collimated 5.9 keV X-ray source produced photoelectrons about 10 mm from the centre of the ion sheath, at an elevation (drift distance) of 100 mm. Discrimination and scaling on the anode wires allowed the determination of the average position of the detected photoelectron cloud as a function of the X-ray tube intensity. The measurement was performed at a drift field of $1 \text{ kV} \cdot \text{cm}^{-1}$ and a proportional chamber voltage of 3 kV. The results are given in Fig. 8, which shows the apparent lateral shift of the average source position, as a function both of the X-ray tube intensity in counts per second, as directly monitored by the proportional chamber, and of the average charge density in the sheath as computed from expressions (2) and (3), taking into account the ion feedthrough efficiency measured previously in the same conditions. The measured displacement corresponds rather well with the result of a simple calculation, giving the electric field outside the charge layer as $\sigma/2\epsilon_0$, where σ is the

surface density of charges. When detecting minimum ionizing particles, in the same gain conditions, comparable charge densities would be obtained in the 20 cm drift-space model chamber at a flux of around $50 \text{ tracks} \cdot \text{cm}^{-2} \cdot \text{sec}^{-1}$, uniformly distributed. Obviously, operation at lower proportional multiplication factors will correspondingly reduce the density of the positive ions, although not linearly as a consequence of the increased cathode feedthrough efficiency discussed above.

4. CONCLUSIONS AND SUMMARY

In the previous sections we have analysed several factors which, if not properly taken into account, can degrade the expected performances of large-volume drift chambers. They are due to the electric field modification induced by the positive space-charge build-up in the avalanche process. Both the proportional gain and the coordinate information may be modified, to an extent that depends on the detected track density and rate; particularly strong trajectory deformations are expected in the case of non-uniform particle distributions in the sensitive volume.

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Figure captions

- Fig. 1 : Principle of construction of a large-volume drift chamber. Ionizing tracks are detected in the drift volume, and a suitable electric field transfers the electrons to an end-cap multiwire proportional chamber, where detection is accomplished through avalanche multiplication.
- Fig. 2 : Normalized pulse height (per unit length of track) measured in a drift chamber, at gains around 10^5 as a function of the extension of the detected charge along the anode wires (from Ref. 10). θ_H represents the angle between the detected track and the normal to the chamber, in a plane perpendicular to the chamber itself and containing the anode wire.
- Fig. 3 : Dependence of the pulse height for minimum ionizing tracks on the rate per unit length of the anode wire, as measured in a thin-gap drift chamber at different anodic potentials¹⁰). The corresponding avalanche size is indicated on the right scale; as an example, at a rate of $2 \times 10^3 \text{ mm}^{-1} \cdot \text{sec}^{-1}$ a gain reduction of about 10% is observed (dashed lines in the figure).
- Fig. 4 : Positive ion feedthrough efficiency (I_{C3}/I_A , full lines) and avalanche asymmetry [$I_{C3}/(I_{C1} + I_{C3})$, dashed lines] as a function of the electric field in the drift region and for several anodic potentials, as measured in a chamber like the one illustrated in Fig. 1.
- Fig. 5 : Positive ion feedthrough efficiency (full line) and avalanche asymmetry (dashed line) as a function of the anodic potential for a fixed drift field ($1.5 \text{ kV} \cdot \text{cm}^{-1} \cdot \text{atm}^{-1}$).
- Fig. 6 : Electrostatic transparency, defined as the ratio of the ions reaching the cathode C3 (as from Fig. 1) to the total number of ions leaving the anodes in the direction of the cathode C1. The full line is an eye fit to the experimental points, while the dashed curve represents the computed value from purely electrostatics considerations.

Fig. 7 : Measured multiplication factor as a function of the anodic potential, in the test chamber used for the measurements shown in Figs. 3 to 5.

Fig. 8 : Measured lateral displacement of a stream of electrons drifting for about 10 cm on the side of a sheath of positive ions whose density is indicated in the bottom scale.

Fig. 1

$(\cos \theta_H)^{-1}$

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8