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LIMITING ACCURACIES IN MULTIWIRE PROPORTIONAL AND DRIFT CHAMBERS

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ABSTRACT

The different sources of errors in the position determination of fast charged tracks and soft X-rays using multiwire gas detectors are analysed, and the results of the calculations are compared with the most recent available data.

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1. INTRODUCTION

Multiwire proportional chambers, first introduced about ten years ago¹⁾, are nowadays widely used in high-energy physics experimental set-ups²⁻⁴⁾ and in many other applied research fields^{5,6)}. With the most commonly used read-out scheme, the space accuracy of multiwire proportional chambers corresponds to the anode wire spacing, and this cannot be reduced safely below 1 mm or so (most large size detectors have indeed 2 or 3 mm wire spacing). Multiwire drift chambers^{2,7)}, where the space coordinate is obtained by the measurement of the ionization trail drift time, make it possible to obtain space accuracies that are better by one order of magnitude, at least for moderate detector sizes⁸⁻¹⁰⁾. Recently, new work on the so-called centre-of-gravity read-out method¹¹⁾ has shown that space accuracies of a few tens of microns can be reached for soft X-rays, and possibly also for charged particles¹²⁾. The interest in obtaining high accuracies in elementary particle physics derives from the fact that new accelerators are available at higher and higher energies, while the magnetic bending powers that can be used in the analysing spectrometers are limited. Obtaining better accuracies is not, however, only a question of improving the read-out electronics and the general mechanical tolerances. Many processes are involved in the generation of the physical position message in a gas detector, in particular the number and distribution of the ionization clusters, their diffusion properties in the gas, the avalanche multiplication, and so on. It is the purpose of the present note to analyse in some detail the different sources of intrinsic limitations to the localization properties of a thin gas counter^{*)}.

2. ACCURACY LIMITS INTRINSIC IN THE IONIZATION PROCESS

2.1 General

Detection of charged and neutral radiation in proportional counters is mediated by the ionization processes in the gas. As a result of the electromagnetic interaction between the incoming radiation and the gas molecules, one or more electrons are liberated in the gas. If ejected with enough energy, the primary electrons will travel in the medium, eventually producing secondary ionization and therefore increasing the intrinsic track width. In the energy domain with which we will be mostly concerned, up to a few kiloelectronvolts or so, the ejected electrons suffer also a considerable amount of multiple scattering that somehow randomizes the secondary ionization trail. Old cloud chamber observations by Williams¹³⁾ suggest that a good way of parametrizing the effective penetration depth of a slow electron is the so-called practical range, i.e. the extrapolation

*) A preliminary version of this paper has been presented by the author at the "Journées d'Etudes sur les Détecteurs et les Ensembles de Détection utilisés en Physique Nucléaire", CESI, Gif-sur-Yvette (14-18 March 1977).

to zero of an absorption curve. The rate of energy loss, or ionization per unit path length, is relatively uniform at electron energies in the keV region, and therefore the problem of charge distribution can be reduced to a geometrical one.

Figure 1 (from Ref. 13) shows both the measured penetration depth [maximum distance from the emission point (curve a)] and the integrated path length (curve b) for 20 keV electrons in oxygen. The definition of the practical range R is also shown; the FWHM of the penetration depth distribution is about one half of the practical range. The difference between curves (a) and (b) gives an idea of the randomizing effect of multiple scattering; it is sufficiently large to justify the assumption that photoelectrons or δ -electrons in the keV region produce ionization trails around the emission centre with equal angular probability. In this case, the charge distribution around a given emission point has a FWHM of $\sqrt{3} R/2$, or $\sim 0.87 R$. This will be assumed in all the following considerations.

A simple practical range-energy relationship will be used (as given in Fig. 2) for several gases, that represents an exponential fit to existing transmission data obtained with thin foils¹⁴⁾.

2.2 Detection of soft X-rays

The detection and localization of soft X-rays, up to 10 keV or so, by non-photographic methods has several possibilities of application in biomedicine, astronomy, and elsewhere^{5,6)}. Furthermore, X-ray sources in this energy range are very often used for laboratory testing of multiwire chambers, since photoelectric conversion causes them to lose an amount of energy comparable to the minimum ionizing tracks in thin gas detectors. It is therefore interesting to analyse the intrinsic limits of position accuracy one can hope to measure in this case. Let E_x be the energy of the incoming photon; then absorption in a shell of energy E_i results in the emission of a photoelectron of energy $E_1 = E_x - E_i$. The two main processes by which the excited molecule can dissipate the excess energy are: emission of a fluorescence X-ray of energy $E_i - E_j$ (j being a lower energy level); or, emission of an Auger electron of energy E_2 (smaller than but close to E_i). The two processes lead to rather different localization properties: the fluorescence X-ray may have a long range before reconverting in the gas, and therefore induce a big error; while emission of an Auger electron only increases the width of the ionization trail locally.

Figure 3 shows, as a function of the X-ray energy, the practical range of the primary photoelectron E_1 and of the Auger electron E_2 emitted with the probability indicated in argon at normal conditions. For the commonly used 5.9 keV ^{55}Fe source, 88% of the conversions in argon lead to two electrons with roughly the same practical range, close to 200 μm . From the considerations of the previous

section, and assuming there are no correlations between the directions of the two emitted electrons, this sets a limit to the width of the physical message of about 250 μm FWHM (or $\sigma \approx 100 \mu\text{m}$ in a Gaussian approximation), and it is clearly useless to make a better collimation of the source when measuring space accuracies. For the remaining 12% of the events, the result depends on the capability of the detector to recognize two spatially separated conversion points; if the separation is not possible, a halo of reconstructed points will appear around the real source position.

A detailed analysis of these processes, with a view to improving the imaging quality of a xenon-operated chamber at energies around 40 keV, has recently been published¹⁵⁾.

2.3 Detection of fast charged particles

Charged particles traversing a medium have ionizing encounters with the molecules at a discrete number of points, generating electron-ion pairs. The electrons may be ejected with high enough energy to produce additional ionization trails (δ -rays). Detailed analysis of the ionization processes exist and can be found in many textbooks and review articles¹⁶⁾; for the needs of this work, however, a simple picture of the process will be considered, corresponding essentially to a first-order approximation of the Bethe-Bloch energy loss formula [see, for example, Ritson¹⁷⁾]. The number of δ -electrons ejected with a kinetic energy equal to or larger than E_0 is then given by

$$N(E \geq E_0) = \frac{K}{\beta^2} \frac{Z}{A} \rho x \left(\frac{1}{E_0} - \frac{1}{E_M} \right), \quad (1)$$

where E_M is the maximum allowed energy transfer in one collision; Z , A , ρ , and x are the respectively detecting medium's atomic number, mass, density, and thickness, and β is the incoming particle velocity. Expression (1) has been plotted in Fig. 4 for 1 cm of argon at normal conditions (from Ref. 4), and for 1 GeV/c protons. It can be seen, for example, that about 5% of the tracks detected in 1 cm of argon contain at least one electron with an energy exceeding 2 keV, and whose range in the gas (see Fig. 2) is about 150 μm . This implies a corresponding asymmetry in the distribution of the detected charges, and is therefore an intrinsic source of error in the localization.

When the gas pressure is increased in the detector, although the range of the produced electrons decreases, the number of them produced at a given energy increases. In Fig. 5 the probability of ejection by fast particles of a δ -electron of range equal to or larger than R is shown, as a function of the range, and for several geometries of detectors. Increasing the pressure at a given thickness clearly results in a larger amount of long-range electrons; on the other hand,

decreasing the detector thickness reduces the δ -ray track smearing. This explains the choice, for high-accuracy drift chambers, of rather thin detection gaps^{8,9)}.

The asymmetry in the produced physical message results in a decreased localization accuracy, depending on the detection method adopted. In drift chambers, where normally the first detected electrons define the time of drift, and therefore the space coordinate, one expects to find a tail of events at times shorter than the average because of the long-range δ -electrons. This is apparent, for example, in Fig. 6, where a typical drift-time plot for a well-collimated beam is shown (from unpublished results of the authors of Ref. 8), as obtained in a 6 mm gap drift chamber operating in 70% argon + 30% isobutane at normal conditions. A Gaussian distribution, expected from other dispersion sources in the measurement (electron diffusion, electronics noise, etc.), shows a substantial tail on the short drift-time side; although the standard deviation of the distribution is 85 μm (and this is normally quoted as the space accuracy of the detector), about 2.5% of the tracks exceed the average value by more than 250 μm . This value matches the computed one rather well (from Fig. 5, curve b). If, on the other hand, zero-crossing read-out electronics are used for the time pick-up in a drift chamber, one expects to obtain symmetric tails on each side of the quasi-Gaussian distribution; this is strictly true only if the detector is operated in the proportional multiplication region (space charge effects due to the large avalanche sizes may markedly modify the time structure of the detected charges). Figure 7 [from Baskakov et al.¹⁸⁾] shows such a measurement obtained in an electroluminescent drift chamber operated at high xenon pressure; the symmetric tails are clearly visible, and are attributed by the authors to δ -rays (they correspond to about 6% of the total events). It should be noted here that in the majority of papers written on high-accuracy proportional and drift chambers, the presence of such tails is ignored and only the Gaussian approximated standard deviation is given for the distributions. The dangers of such a procedure for the effective use of these detectors are apparent.

A much more detailed analysis of the track width caused by the energy deposition of δ -rays, has been done by Kobetich and Katz, but unfortunately only for condensed materials¹⁹⁾; a calculation along similar lines for gases would be highly desirable.

3. ACCURACY LIMITS IN POSITIONING BY DRIFT TIME

We have seen in the previous section that the physics of the ionization process sets a natural limit to the localization accuracy that can be obtained in a gas detector. Depending on the detection method, other factors contribute to the limiting accuracy that can be reached in practice. In drift chambers, the space

coordinates of charged particles are reconstructed from a measurement of the drift time of electrons liberated in the gas and migrating to the anode wire under the influence of a suitable electric field (see Fig. 8); the space-time correlation, or drift velocity, must obviously be known to the desired degree of accuracy. We will define as systematic all sources of positioning errors originating from the inaccurate knowledge of the correlation. The drift velocity w in gases is a function of many parameters: the electric field strength and the gas pressure (through the ratio E/P), the gas composition and temperature, the magnetic field if any. It has been found^{8, 20-22)} that the dependence of w on these factors is reduced at high electric fields for some particular gas mixtures, where drift velocity saturation appears.

For a mixture of argon, isobutane, and methylal^{*)}, the following relative variations of the drift velocity $\Delta w/w$ have been measured in saturation for a field around 1.4 kV/cm atm:

- field dependence $< 10^{-3}$ per kV cm⁻¹ atm⁻¹
- temperature dependence 3×10^{-4} per °C
- gas composition 1.2×10^{-3} per % variation in gas mixture
- magnetic field 3×10^{-3} per kG.

As an example, a 10°C variation in the gas temperature produces a 0.3% change in the drift velocity; if not properly taken into account, the change implies a maximum error of around 100 μ m in a 3 cm drift-space chamber. As shown for example by Schultz²²⁾, operation below full saturation or in other gas mixtures may largely increase the dependence of w on the above-mentioned parameters, requiring a high level of monitoring or data corrections in order to maintain a given level of accuracy.

Apart from the systematic effects, other sources of spread are intrinsic in the drift chambers' localization properties: the physical track width, the electron diffusion during drift, the statistical fluctuations in the primary ionization clusters, the jitters in the discrimination and in the time-measuring electronics. The first effect has been discussed in the previous section and, as stated, it is not apparent in a Gaussian analysis of the data. In Fig. 9 the relative importance of the three other factors is shown and compared with recent experimental data obtained in a set of drift chambers, such as the one illustrated in Fig. 8, and in the saturated mode of operation⁹⁾. An eye-fit to the measured points has been decomposed (in the Gaussian sense) in three independent contributions: a constant electronics spread; a diffusion term depending on the square

*) In the quoted references, the standard gas mixture has been given as 67.2% argon, 30.3% isobutane and 2.5% methylal. Some incompatibilities with the calculations by Schultz²²⁾ have suggested a new calibration of the gas system used for the measurements, resulting in the corrected set of values, 66.4%, 30.2% and 3.4%, respectively.

root of the drift distance; and a contribution due to the primary pairs statistics. The last contribution is clearly dominant for tracks crossing the chamber in the vicinity of the anode wire. Simple statistical considerations provide the distribution of the distance between the closest ionization cluster and the anode⁴⁾. For the gas mixture used in the measurement, where an average of three ionizing collisions occur per millimetre, the calculation gives a standard deviation in accuracy, due to primary statistics, of about 60 μm close to the anode wire, in good agreement with the measurement.

The diffusion-dependent term deserves a more detailed analysis. An initially point-like charge migrating along a direction x in the gas under the effect of an electric field, diffuses following a Gaussian distribution with standard deviation given by

$$\sigma_x = \sqrt{2Dt} \quad (2)$$

where t is the time of drift and D the diffusion coefficient. Using the definition of characteristic energy $\epsilon_k = eDE/w$, where w is the drift velocity of electrons migrating in the field E , we get

$$\sigma_x = \sqrt{\frac{2\epsilon_k x}{eE}} = \sqrt{\frac{2\epsilon_k x}{e}} \frac{P}{E} \frac{1}{\sqrt{P}} \quad (3)$$

where x is the drift length. One can therefore see that the diffusion in a given gas depends not only on E/P (since ϵ_k does) but also on $1/\sqrt{P}$. At a given gas pressure, diffusion is smaller for "cool" gases, i.e. gases in which the characteristic energy is small even at high E/P values. Figure 10 shows the computed standard deviation due to diffusion, after 1 cm of drift in several gases²³⁾. For the argon-isobutane mixture, at $E \approx 1.4$ keV/cm atm one gets $\sigma_x \approx 200$ μm . Of course, this value represents the width of the charge distribution, and not the error on its localization; Schultz²²⁾ has computed the dispersion in the position of the electron i in a cluster of n to be

$$\sigma_i = \frac{\sigma_x}{\sqrt{2 \ln n}} \sqrt{\sum_{j=1}^n \frac{1}{j^2}} \quad (4)$$

For the first electron reaching the anode, expression (4) reduces to

$$\sigma_1 = 0.91 \frac{\sigma}{\sqrt{\ln n}}, \quad (5)$$

which should correspond to the measured dispersion if high-sensitivity threshold discrimination electronics are used (as in most applications). Under the conditions of the measurement shown in Fig. 9, $n = 70$; and expression (5) gives $\sigma_1 \approx 90$ μm for 1 cm of drift, while the experimental value for the pure diffusion

contribution is about 45 μm , a factor of two better than expected. A possible explanation of the discrepancy, based on the assumption that the detection electronics operate some sort of average over the timing of successive avalanches, has been put forward but does not seem very convincing. The true explanation is probably to be found in the following effect.

All characteristic energy measurements that are at the basis of the calculation of σ_x , are at the origin measurements of transverse diffusion, i.e. of the increase in the size of a migrating charge in a direction perpendicular to the electric field (Townsend's method); the assumption that the diffusion is symmetric in space is implicit. Recently, however, it has been found²⁴⁾ that the longitudinal diffusion, i.e. in the direction of the field, can in some gases be much smaller than the transverse diffusion. This is shown in Fig. 11 for argon²⁵⁾. At the fields we are concerned with, around $1 \text{ V cm}^{-1} \text{ Torr}^{-1}$, the longitudinal diffusion is about a factor of six smaller than the transverse one. We should therefore reconsider the theory of gaseous diffusion that allowed us to obtain the curves of Fig. 10, putting in the correct value for the longitudinal diffusion.

Unfortunately, measurements of this parameter have been realized only for a restricted number of gases. If we assume that, in the argon-isobutane mixture, there is a factor of four between the two diffusion coefficients, this would explain the quoted factor of two discrepancy between the computed and the measured accuracies.

If the centre of gravity of the detected charge is measured, the expected dispersion due to diffusion is simply given by

$$\sigma_G = \frac{\sigma_x}{\sqrt{n}} \quad (6)$$

which in the condition described would provide an intrinsic accuracy, due to diffusion, of about 25 μm . Until now, however, and to the best of our knowledge, none of the measurements of position by centre of gravity of drifting charges in proportional chambers have shown any substantial improvement in accuracy over the conventional threshold detection methods. It is suspected that, with the rather high amplification factors used, a quick development of a positive space charge on the first amplified electrons prevents a uniform detection of all charges.

An increase in the gas pressure reduces both the primary ionization cluster's fluctuation and the diffusion, as apparent from expression (3), at a given value of E/P . This is clearly shown in Fig. 12 [taken from Farr et al.¹⁰⁾] where the standard deviation of the measured accuracy in a set of drift chambers is given for increasingly high gas pressures. Working with a scintillating drift chamber,

where space-charge effects are absent, and measuring the centre of gravity of the detected light pulse, the authors of Ref. 9 have found the results shown in Fig. 13 for a 5 mm thick drift gap operating in pure xenon at 20 atm, and for $E/P = 0.2 \text{ V cm}^{-1} \text{ Torr}^{-1}$. In these conditions, the drift velocity of electrons is about $0.13 \text{ cm}/\mu\text{sec}$ and, for longitudinal diffusion, $D \approx 75 \text{ cm}^2 \text{ sec}^{-1}$ ²⁵⁾. From expressions (6) and (2) we can therefore compute, for 3 cm of drift, a diffusion standard deviation, when measuring the centre of gravity on $n \approx 1500$ electrons, of around $15 \mu\text{m}$; this is consistent with the experimental result (which contains a non-subtracted electronics contribution). An example of accuracy distribution obtained in these conditions was given in Fig. 7.

4. LIMITING ACCURACY IN THE LOCALIZATION BY CENTRE OF GRAVITY OF INDUCED SIGNALS

The method of localization by centre of gravity of the signals induced on the cathodes of a multiwire proportional chamber (MWPC) was originally developed to measure the coordinates of conversion points of neutral radiation, since this method is intrinsically two-dimensional ¹¹⁾. Recent measurements have shown, however, that it can compete in positioning accuracy with the drift chamber method for the detection of charged particles, with the advantage of a much improved time resolution ^{12, 26)}.

The principle of the method is shown in Fig. 14; in a conventional MWPC, the motion of positive ions (produced in the avalanches around the anode wires) induces positive signals on the cathode planes, with a distribution centred around the position of the avalanches. A measurement of the centre of gravity of the induced pulses on the two planes provides the two-dimensional coordinates of the ionizing event.

Localization has been obtained using several analog methods, e.g. by delay lines or by direct measurement of the pulse heights on suitably stripped cathode planes. It is this last method which, despite its obvious practical complications, allows one to obtain the best results in terms of accuracy. Each cathode strip is equipped with an electronic circuit including a charge amplifier and a gated analog-to-digital converter. During a fixed time gate, the induced signal amplitude on all cathode strips is recorded. The gating signal may be provided either by the anodic pulse or by an external selective time reference. Let X_i be the measured amplitude on the cathode strips x_i ; the centre of gravity is defined as

$$x = \frac{\sum x_i X_i}{\sum X_i} \quad (7)$$

and similarly for the y direction. Owing to the chamber construction, one would expect to find in one direction (the x coordinate, as from Fig. 14, corresponding to cathode strips parallel to the anodes) a positioning accuracy limited to the anode wire spacing. It has been proved^{12,27)}, however, that under moderate gain conditions the avalanches produced by a localized distribution of charges (such as the one generated by a photoelectron) are highly localized in the direction of approach to the anode wire of the charges, and do not surround the anode symmetrically, as is generally believed. Therefore the centre of gravity of the induced charge distribution, even along the x direction, contains information about the position of the original ionization cluster. This is clearly shown in Fig. 15 (Ref. 12), which represents the measured centres of gravity around one anode wire in the x, z plane for a uniform irradiation of a chamber with 5.9 keV X-rays.

In the picture, each point represents a measured event having a horizontal coordinate x, as defined by expression (7), and a vertical coordinate z computed as

$$z = \frac{\sum Y_i}{\sum X_i}, \quad (8)$$

representing the degree of asymmetry in the induced charge distribution with respect to the anode plane. For a collimated source measurement, the correlation between the real and the computed source position along the x direction is almost linear, with a positioning accuracy of around 150 μm , which is more than 10 times better than the anode wire spacing (2 mm). The limits in accuracy expected from the centre-of-gravity method have been investigated by the authors of Ref. 12 using 1.5 keV X-rays, and a xenon-isobutane filling that reduces the practical range of the photoelectron to about 50 μm . Figure 16 shows the reconstructed position along the anode wire (y direction) for three positions of the collimated source, 200 μm apart; the r.m.s. of the distributions is around 35 μm , consistent with the expected value (see the discussion in Section 2.1), and proving that other sources of dispersion are well below the quoted value. The good localization accuracy for soft X-rays in two directions has allowed us to obtain the image shown in Fig. 17, collimating a 1.5 keV X-ray beam with a letter cut-out mask. The over-all size of the word is $1.5 \times 4 \text{ mm}^2$, with one anode wire centred along the length.

As in drift chambers, we can separate the systematic sources of positioning errors from the intrinsic ones. The main systematic errors in the centre-of-gravity read-out method are connected with non-linearities and instabilities of the analog-to-digital conversion. However, as can be seen from expression (7), the effect of a variation in one of the measured pulses is somehow reduced by the normalization to the total pulse height. Assuming an approximated Gaussian shape for the pulse-height distribution on the cathodes, and with a standard deviation

equivalent to one strip width²⁶⁾, it can be seen that a 10% variation in the pulse height of one strip results in a change of the reconstructed coordinate of about 2% of the strip width, or a 100 μm shift for a 5 mm strip width. A correct calibration procedure is obviously essential for minimizing the described systematic effects.

The major sources of intrinsic dispersions -- e.g. physical track width due to δ -rays, primary cluster's statistics, and electronics noise -- are essentially as discussed in the previous section.

We will present here some recent unpublished results obtained by our CERN group²⁸⁾ with a set of high-accuracy MWPCs in a minimum ionizing beam. The active size of the chambers is about $10 \times 10 \text{ cm}^2$; the anode wire spacing is 1.27 mm, and the cathode strips are obtained by connecting together four wires with the same spacing. The chambers are operated with magic gas filling²⁹⁾, which makes it possible to obtain very large pulse heights and decrease electronics noise problems; on the other hand, as shown in Ref. 27, in these conditions the avalanches often surround the anode wire symmetrically, thus preventing us from getting an accuracy along the x direction (see Fig. 14) that is better than the wire spacing. An x, y plot of measured coordinates in one chamber, for a uniform beam exposure, is shown in Fig. 18; the anode wire structure clearly appears, and the regularity of the pattern demonstrates the correctness of the calibration procedure. Figure 19 instead shows the measured accuracy along the y direction, perpendicular to the anodes, as a function of the y coordinate itself, as reconstructed in a set of three equal chambers and for all the useful surface. The equivalent scale in space is indicated in the figure, and gives an idea of the over-all systematic stability. A projection on the horizontal axis of the measured points is shown in the histogram of Fig. 20, having a standard deviation of about 65 μm . This represents the integrated accuracy, in the y direction, over the whole active area of the chamber; non-Gaussian tails due to the long-range δ -electrons are also apparent. Work is in progress to allow the operation of the system in the quasi-proportional region, using a non-electronegative gas; it is hoped that the asymmetry of the avalanches at moderate gains, combined with the charge interpolation obtained with a slightly inclined beam, will improve the accuracy in the x direction above the simple wire spacing, as is the case for soft X-rays.

REFERENCES

- 1) G. Charpak, R. Bouclier, T. Bressani, J. Favier and Č. Zupančič, Nuclear Instrum. Methods 62, 235 (1968).
- 2) G. Charpak, Annu. Rev. Nuclear Sci. 20, 195 (1970).
- 3) P. Rice-Evans, Spark, streamer, proportional, and drift chambers (Richelieu, London, 1974).
- 4) F. Sauli, CERN 77-09 (1977).
- 5) G. Charpak and F. Sauli, Proc. Conf. on Computer-Assisted Scanning, Padova, 1976 (Istituto di Fisica, Univ. di Padova, 1976), p. 592.
- 6) V. Perez-Mendez, IEEE Trans. Nuclear Sci. NS-23, 1334 (1976).
- 7) A.H. Walenta, J. Heintze and B. Schürlein, Nuclear Instrum. Methods 92, 373 (1971).
- 8) G. Charpak, F. Sauli and W. Duinker, Nuclear Instrum. Methods 108, 413 (1973).
- 9) T.S. Nigmanov, V.P. Pugachevic, V.D. Riabtsov, M.D. Shafranov, E.N. Tsyganov, D.V. Uralsky, A.S. Vodopianov, F. Sauli, M. Atac and J. Tompkins, Nuclear Instrum. Methods 143, 17 (1977).
- 10) W. Farr, J. Heintze, K.H. Hellenbrand and A.H. Walenta, Space resolution of drift chambers operated at high gas pressure (submitted to Nuclear Instrum. Methods, January 1978).
- 11) G. Charpak and F. Sauli, Nuclear Instrum. Methods 113, 381 (1973).
- 12) G. Charpak, G. Petersen, A. Policarpo and F. Sauli, Nuclear Instrum. Methods, 148, 471 (1978).
- 13) E.J. Williams, Proc. Roy. Soc. A 130, 310 (1931).
- 14) K. Kanter, Phys. Rev. 121, 461 (1961).
- 15) J.E. Bateman, M.W. Waters and R.E. Jones, Spatial resolution in a xenon-filled MWPC X-ray imaging detector, Rutherford Lab. Report RL-75-140 (1975).
- 16) See, for example, V. Fano, Annu. Rev. Nuclear Sci. 13, 1 (1963).
- 17) D.M. Ritson, Techniques of high-energy physics (Interscience Publ., New York, 1961).
- 18) V.I. Baskakov, V.K. Chernjatin, B.A. Dolgoshein, V.M. Fedorov, I.L. Gavrilenko, S.P. Konovalov, V.N. Lebedenko, S.N. Majburov, S.V. Muravjev, V.P. Pastovetov, A.S. Romanjuk, A.P. Shmeleva and P.S. Vasiljev, The electroluminescent drift chamber with spatial resolution 16 μm (submitted to Nuclear Instrum. Methods, October 1977).
- 19) E.J. Kobetich and R. Katz, Phys. Rev. 170, 391 (1968).
- 20) A. Breskin, G. Charpak, B. Gabioud, F. Sauli, N. Trautner, W. Duinker and G. Schultz, Nuclear Instrum. Methods 119, 9 (1974).

- 21) A. Breskin, G. Charpak, F. Sauli, M. Atkinson and G. Schultz, Nuclear Instrum. Methods 124, 189 (1975).
- 22) G. Schultz, Etude d'un détecteur de particules à très haute précision spatiale (chambre à drift). Thèse, Université L. Pasteur de Strasbourg (1976); also CERN EP Internal Report 76-19 (1976).
- 23) V. Palladino and B. Sadoulet, Nuclear Instrum. Methods 128, 323 (1975).
- 24) E.B. Wagner, F.J. Davis and G.S. Hurst, J. Chem. Phys. 47, 3138 (1967).
- 25) J.J. Lowke and J.H. Parker, Phys. Rev. 181, 302 (1969).
- 26) A. Breskin, G. Charpak, C. Demierre, S. Majewski, A. Policarpo, F. Sauli and J.C. Santiard, Nuclear Instrum. Methods 143, 29 (1977).
- 27) J. Fischer, H. Okuno and A.H. Walenta, Spatial distribution of the avalanches in proportional counters, BNL 23163 (August 1977); submitted to Nuclear Instrum. Methods.
- 28) G. Melchart and G. Petersen, private communication at CERN.
- 29) R. Bouclier, G. Charpak, Z. Dimčovski, G. Fischer, F. Sauli, G. Coignet and G. Flügge, Nuclear Instrum. Methods 88, 149 (1970).

Figure captions

- Fig. 1 : Penetration depth (curve a) and integrated path length (curve b) in oxygen, for 20 keV electrons (Ref. 13). The definition of the practical range R is also shown.
- Fig. 2 : Practical range for electrons versus kinetic energy for several gases under normal conditions; an approximated relationship, as given by Kanter (Ref. 14) for thin foils, has been used.
- Fig. 3 : Practical range in argon under normal conditions of photoelectrons (E_1) and Auger electrons (E_2) as a function of X-ray energy.
- Fig. 4 : Computed number of δ -electrons with energy equal to or larger than E_0 , produced in 1 cm of argon under normal conditions by 1 GeV/c protons. The approximated expression (1) has been used.
- Fig. 5 : Probability of obtaining a δ -electron with a range equal to or larger than R_0 , in the detection of minimum ionizing tracks in the indicated gas mixture and conditions.
- Fig. 6 : Measured accuracy distribution in a drift chamber (from unpublished data of the authors of Ref. 8). The effect of long-range δ -rays is clearly visible at the left of the distribution, obtained measuring the drift time of ionization trails produced by a well-collimated beam.
- Fig. 7 : Measured accuracy distribution in a scintillating drift chamber (Ref. 18) operated at 20 atm of pure xenon. Since a centre-of-gravity determination of the drift time has been used, the effect of long-range δ -electrons appears as two symmetric tails. About 6% of the events fall outside the Gaussian fit.
- Fig. 8 : Schematic diagram of a high-accuracy drift chamber, showing the electric field equipotentials (Ref. 8). When a charged particle traverses the structure, a measurement of the drift time of the ionization trail to the anode wire allows the space coordinates of the tracks to be deduced.
- Fig. 9 : Measured standard deviations in a Gaussian fit to the data, obtained in a set of drift chambers such as the one shown in Fig. 8, as a function of the distance from an anode wire (Ref. 9). An eye-fit to the data has been decomposed in three contributions, due to electron diffusion, electronics noise and resolution, and fluctuations in the primary ionization cluster statistics.

- Fig. 10 : Computed standard deviation of an initially point-like electron distribution, after 1 cm of drift in several gases as a function of the electric field (Ref. 23).
- Fig. 11 : Measured values of the ratio between the electron diffusion coefficient and the mobility in argon, as a function of the electric field (Ref. 25). Quite different values are obtained for the transverse and the longitudinal diffusion.
- Fig. 12 : Measured dependence of the positioning accuracy on the gas pressure, as measured by the authors of Ref. 10 in a set of drift chambers. The gas filling is a mixture of propane and ethylene in the indicated proportions.
- Fig. 13 : Measured accuracy in a scintillating drift chamber operated in 20 atm xenon, as a function of drift space (Ref. 18).
- Fig. 14 : Principle of operation of a MWPC with cathode-induced pulse read-out (Ref. 11). The centre of gravity of the measured induced pulses represents the two-dimensional coordinates of the initial avalanche.
- Fig. 15 : Localization properties around one anode wire for soft X-rays (Ref. 12). In a uniformly irradiated chamber, for each event the centre of gravity of the induced pulses in the x direction (see Fig. 14b) is shown as a function of the ratio between the over-all pulse heights on the X and Y cathode strips. A ring-shaped image results, indicating the high degree of asymmetry of the avalanches produced on the anode.
- Fig. 16 : Localization accuracy obtained along the anode wires with 1.5 keV X-rays (Ref. 12). The width of the distributions, about 35 μm standard deviation, corresponds well to the expected physical width due to the range in the gas of the photoelectrons.
- Fig. 17 : Two-dimensional image obtained by the centre-of-gravity method; letters were cut out in a copper mask irradiated by a soft X-ray beam (Ref. 12). The real size of the image is $1.5 \times 4 \text{ mm}^2$.
- Fig. 18 : Measured distribution of the centre of gravity for minimum ionizing particles, in a 1.27 mm spacing wire chamber (Ref. 28). The x and y coordinates, defined in Fig. 14b, are represented in the abscissa and ordinate, respectively. Magic gas filling.
- Fig. 19 : Measured space accuracy along the y coordinate, as a function of y (on the vertical axis) (Ref. 28). A reference scale is shown; the slight oscillations around the average value at low y are due to a defective pulse-height calibration.

Fig. 20 : Integrated accuracy over the active area of the chambers
($10 \times 10 \text{ cm}^2$) in the y direction, corresponding to a projection on
the horizontal axis of the data shown in Fig. 19 (Ref. 28).

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13

Fig. 14

Fig. 15

Fig. 16

Fig. 17

Fig. 18

200 μm

Fig. 19

Fig. 20