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NEW DEVELOPMENTS IN GASEOUS DETECTORS

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1. PRELUDE

The multiwire proportional chamber (MWPC) has been introduced more than a decade ago as a powerful, fast detector suited for high-energy physics experimentation (Charpak et al., 1968). Since then, an impressive amount of work has been realized both on the improvement and the better understanding of the original detector, and on the development of various derived structures. For a review of detectors' performances and a general discussion of their use in experimental physics, see, for example, Charpak (1970), Rice-Evans (1974), Sauli (1977), Fabjan and Fisher (1980).

It is clear that a detailed knowledge of all aspects of charge drift and multiplication is necessary for the understanding of the behaviour of a given detector configuration. In what follows, I will describe in some detail only the processes directly connected with the main subject of interest; the reader is referred to the quoted papers and to the references there given to more detailed studies.

2. POSITION DETECTORS: PROPERTIES, LIMITATIONS AND POSSIBLE DEVELOPMENTS

Localization accuracy in the original MWPC was restricted to the anode wire spacing, typically 2 mm, although it was soon realized that a complementary measurement of electron collection time could largely improve localization (Charpak, Rahm and Steiner, 1970; Walenta, Heintze and Schürlein 1971). Many geometries have been developed to better profit from this property, leading to

various kinds of thin layer multiwire drift chambers with localization accuracies around 100 μm or better. A considerable advance in the multiple track recognition capability has been realized by the development of large volume drift chambers such as ISIS (Allison et al., 1974), Time Projection Chamber (Clark et al., 1976; Nygren and Marx, 1978), JADE (Drumm et al., 1980), UA1 Imaging Chambers (Barranco Luque et al., 1980) and similar devices. In this kind of detector, ionized trails produced in a large gas volume are drifted to a plane of proportional wires where recording of position, drift time, pulse height can provide a very detailed description of the event pattern (see Figs. 1 and 2).

In this section I will analyse some of the factors that contribute to the localization accuracy obtainable in a gaseous device, and that can indeed spoil the performance of the detector if not properly taken into account. They are, in order of relevance: correct knowledge of the drift velocity, including the distorting effects of magnetic fields; lateral and transverse diffusion of the electrons in the ionization trail while drifting; positioning error in the induced cathode readout due to angular and track density effects; primary energy deposition statistics; positive ions interference.

Fig. 1

Fig. 2

The drift velocity has been measured and computed in a large number of gases and gas mixtures; for general reviews see, for example, Palladino and Sadoulet (1975), Shultz and Gresser (1978), Jean-Marie et al. (1979). As an example, Fig. 3 shows the comparison between computed and measured drift velocity in various mixtures of argon and isobutane, from Shultz and Gresser. The effect of the magnetic field can also be taken into account (Ramanantsizehena, 1979). A large software effort is however required to extract from the measured drift time the actual coordinate, especially when the electric field is not uniform (as always the case around the anode wires) and in presence of magnetic fields; Figure 4 shows the computed electron trajectories and equal time distances from a wire in the JADE jet-chamber (Drumm et al., 1980). The space-time correlation is obviously asymmetric and all but linear. Moreover, it is not always obvious that somebody else's measurements can be used, due to the different calibration methods used for the gas mixture; temperature and pressure can also influence the calibration. In general, the programmer is reduced to adjusting painfully many parameters to obtain a satisfactory fit to the data.

As compared to the systematic shift of coordinates due to a poor knowledge of drift velocity and trajectories, electron diffusion represents an intrinsic limit to localization accuracy. Figure 5 from Palladino and Sadoulet (1975) shows the dependence

Fig. 3

Fig. 4

Fig. 5

of the space diffusion on the electric field for several gases and mixtures and 1 cm of drift; it equals about 100 μm for common mixtures. Since the curves refer to a single electron, while segments of tracks contain several of them, the accuracy obtained in practice can be slightly better, around 60 μm for 1 cm of drift in ordinary conditions, see Fig. 6 (Filatova et al., 1977).

An increase in the operating gas pressure, for equal field conditions, directly reduces the diffusion in proportion to the square root of the pressure; Figure 7 shows the effect of going from one to four atmospheres (Farr et al., 1978). Both TPC and JADE operate at pressures higher than atmospheric, 10 and 4 atm, respectively, to increase the energy resolution, and this is beneficial to the resulting accuracy. It should be noted also that generally the drift time dispersion is determined by the longitudinal and not the transverse diffusion, whose value is given by the classic theory of drift (as in Fig. 5). In some gases, and at high values of the field, the longitudinal diffusion coefficient is considerably

Fig. 6

Fig. 7

Fig. 8

smaller than the transverse; Figure 8 shows that the measured values for D_L in the JADE chamber are six times smaller than D_T at the operational fields. Since the space accuracy is proportional to $\sqrt{D_L}$, a considerable gain can be expected: a more systematic investigation on the matter is desirable.

Presence of a strong magnetic field also reduces the diffusion in some gases, but only in the transverse direction: this is exploited in the TPC to keep a small lateral track size but does not influence the space accuracy determined by the drift time measurement.

A localization method used often in conjunction with the drift time measurement is the determination of the centre of gravity of the induced signal on cathode strips or pads, a method which is known to allow intrinsic accuracies of 30-40 μm for soft X-rays (Charpak et al., 1978).

It consists of recording the charge profile of the pulses induced by an avalanche on suitably stripped cathode planes, and computing the centre of the distributions (Fig. 9). In imaging chambers, the cathode wire strips are replaced by individual pads facing some wires which allows the determination of the coordinate along the wires themselves. Preserving a good accuracy in running conditions and for charged particles is, however, all but easy, for technical as well as physical reasons. On the one hand, obtaining an accuracy corresponding to a fraction of the pad width from ratios of pulse heights requires calibrations and overall stabilities

Fig. 9

of a few percent or so. Moreover, the discrete structure of the pads and the cross-talks due to capacitive couplings introduce various kinds of modulations and interactions. The scatter plot of Fig. 10, representing the difference between real and measured coordinates in a cathode readout chamber, shows the modulation effect due to a 1.4% cross-talk between adjacent strips, before and after correction (Piuz, Roosen and Timmermans, 1982). After correction, the space resolution has about $60\text{ }\mu\text{m}$ r.m.s. (this measurement refers to tracks perpendicular to the wire planes). For inclined tracks, a dispersive effect of physical nature appears however. It has to do with the large fluctuations in the rate of energy deposition by fast particles in thin layers of gases (the Landau distribution). Consider indeed the case of a slanted ionizing track traversing a chamber and intersecting the same anode wire. The induced pulse distribution on cathodes at any given instant reflects the asymmetry in the ionization density; let one side contain two times as many charges than the other (a likely happening with typical energy loss resolutions of 100%!); the actual charge centre of gravity will be displaced by almost $\frac{1}{4}$ of the gap width for 45° tracks. The effect on localization accuracy is visible in Fig. 11 for increasing incidence angles ($\theta = 0^\circ$ meaning tracks perpendicular to the wire planes). At 30° the average accuracy has moved to almost $300\text{ }\mu\text{m}$, and is obviously the worse for events in the tail of the energy loss distribution (Charpak et al., 1979).

Let me analyse now in some detail the process which is at the origin of the detection process, i.e. the energy loss by ionization of charged particles in matter. The average rate of energy loss reaches a minimum at high energies (around 1 GeV) and has then a small increase, the relativistic rise, at even higher energies; for more details on this region, see the next section, devoted to particle identification.

Fig. 10

Fig. 11

The electromagnetic field of the charged particles interacts with the one of the molecules in a discrete number of collisions, whose probability is a fast decreasing function of the energy transfer implied; at increasing energy transfers, ionization is the most likely outcome and the excess energy is provided to the ejected electrons. These can further ionize the medium, if they have sufficient energy; the outcome of the process is therefore a succession of clusters of ion-electron pairs, whose average number (that can be estimated from the nature and density of the medium) follows a Poisson-like distribution. Within each cluster, one or more electrons are produced depending on the energy transfer in the primary collision: the average is between two and three for most gases. In some cases the ejected electron has enough energy to travel considerably in the medium (the so-called δ -electrons);

for such events, the energy loss on a given layer of gas can exceed several times the average leading to the typical Landau distribution of energy in thin samples of gas (Fig. 11). For a modern formulation of the theory of energy loss for fast particles, see, for example, Talman (1979), Allison and Cobb (1980), Lapique and Piuze (1980).

Presence around the primary trail of secondary ionization clusters due to long-range electrons spoils the localization accuracy of most gaseous detectors, since the two components cannot in general be separated. It is relatively straightforward to obtain an approximate expression for the number of δ electrons having an energy equal or larger than E_0 in a layer of material of thickness x and density ρ (see, for example, Ritson, 1961):

$$N(E \geq E_0) \approx \frac{K}{\beta^2} \frac{Z}{A} \frac{1}{E_0} \rho x ,$$

where Z and A are the medium atomic number and mass, and $k = 0.15 \text{ MeV g}^{-1} \text{ cm}^2$. Figure 12 shows the computed value of N for 1 cm of argon at normal conditions, where the average number of primary ionizing collisions is $n_p \approx 29$. One can see, for example, that about 5% of the tracks contain one electron with an energy exceeding 2 keV, and whose range in the gas (Fig. 13) is about 150 μm .

Consider now a typical drift chamber structure, as in Fig. 4. The coordinate of the track is deduced from a measurement of drift time, i.e. of the lap between the ionizing encounter and detection of the electron trail at the wire. A long-range δ -ray on one side of the trail will obviously result in a shorter measured time. An asymmetric localization accuracy distribution is indeed observed in high accuracy drift chambers, see Fig. 14 (Charpak et al., 1973), with a tail extending as far as 600 μm from the centre! About 5% of the events are contained in the non-Gaussian tail. The question may arise as to whether an increase of pressure in the detector would help: it does so by reducing the range of electrons, but unfortunately the number of δ electrons produced in a given thickness of gas increases as well. Obviously in a large volume drift chamber where a given track is measured many times in small segments, a fit procedure eliminates such tail events, at the expense of a reduced number of coordinates effectively used.

The last source of troubles I would like to discuss has to do with the presence in the detector of positive ions, produced copiously in the avalanches; they interfere with the localization process at two levels. To begin with, ions are responsible for the detected signal in the chamber, as a result of their motion away from the anode wire. For typical values of the time constant of the amplifiers mounted on cathode strips, the signal induced by a given avalanche lasts for about 100 ns. During this time,

Fig. 12

Fig. 13

Fig. 14

electrons from a section of the same track around 5 mm away keep reaching the anode and producing avalanches. For an inclined track drifting into the proportional chamber detector, this means a systematic displacement, at any given time, of the recorded charge profile as compared to the actual position of the track segment (identified by the drift time measurement). This effect has received so far little attention. Ions drifting into the large volume of detection of imaging chambers take a long time to clear the region (several ms). At large enough counting rates, this can create a permanent charge density, localized around the hot spots of the detector, and resulting in substantial modifications of the electric field strength and direction. Electrons drifting close or into these hot spots follow distorted trajectories. Figure 15 is a measurement of the lateral displacement on the recorded position for a cluster of electrons drifting 1 cm aside a column of positive ions with the indicated density in a 10 cm thick drift volume. The average particle rate producing, at gains around 10^5 , the indicated density is also shown (Friedrich et al., 1979).

Fig. 15

Various electrode structures have been proposed to gate on and off the charges entering the multiplying element, so as to reduce the build up of positive ions (Allison et al., 1973; Breskin et al., 1980).

The fact that charge detection in proportional counters relies on the copious production of positive ions has another important consequence, apart from the ones mentioned. The charge signal detected on the anodes is mainly due to the motion of ions away from the wires, towards regions of lower and lower fields; on infinite impedance, the signal would have the shape shown in Fig. 16a, lasting for many μ s. With a short differentiating RC constant on the amplifier, at best a signal decay time of 20-30 ns can be obtained (Fig. 16b), and this limits the two-track resolution, with the usual values of drift velocity, to 1-2 mm. With the increasingly complex topology of events at high energies, this may seriously limit the detector performances. Moreover, the localized high density positive ion cloud produced in the first avalanche can decrease, if not suppress, any further amplification in a given spot of the wire. A possible solution to the second problem was found several years ago in the so-called scintillating drift chambers (Fig. 17) (Charpak, Majewski and Sauli, 1975). Tracks were detected through the light flash produced, in suitable conditions, on a photomultiplier, in a condition of moderate charge gain; no

a)

b)

Fig. 16

Fig. 17

space charge effects were noticed up to very high fluxes (above 10^6 counts $s^{-1} \cdot mm^{-2}$). In the geometry and for the gas filling used, however, the average width of the detected light flash was around 50-100 ns, thus offering no improvement on the two-track resolution. The limit seemed intrinsic at the time, since light emission goes through many long-lived molecular de-excitation modes (for a review on secondary gas scintillation, see, for example, Salet-Leite, 1980 and Policarpo, 1981). A recent work has completely changed the picture (Siegmund et al., 1982). By a proper choice of the gas mixture, these authors could obtain light flashes as short as 2-3 ns at the base in the detection of single electrons. Developed to allow single electron counting in low energy X-ray spectroscopy, the device may allow considerable progress in the two-track separation. One can indeed imagine a TPC-like drift chamber, operated at very high pressures so as to reduce electron diffusion, and where detection of tracks through the light flash produced in a parallel plate chamber at the end would allow space resolutions of perhaps 200-300 μm (Anderson and Charpak, 1982).

3. PARTICLE IDENTIFICATION THROUGH ENERGY LOSS

Fast charged particles traversing a medium lose energy through ionizing collisions at a rate which is a function of their velocity. After a fast decrease, the differential energy loss reaches a minimum around $\beta \approx 0.9$ and then slightly increases until saturation is reached; the increase is relevant (40-50%) in gases, see Fig. 18

Fig. 18

(in argon at normal conditions). A good measurement of dE/dx in the relativistic rise region allows, in principle, the determination of the particle's velocity and the identification of its mass if the momentum is known (through magnetic analysis). The practical problem resides in the large fluctuations of the energy loss in thin samples of gas caused by the ejection of energetic δ electrons in the primary interactions; with an average loss of 2 keV cm^{-1} , as in argon at NTP, a fast particle may eject a 2 keV electron per cm with 10% probability, thus doubling the loss in that sample (see Fig. 12). In Fig. 19 the two energy loss distributions measured in 1.5 cm of argon correspond to 25 GeV/c protons and π , whose averages differ by about 20%, see Fig. 18 (Allison et al., 1976). The distributions largely overlap and obviously only a multiple sampling followed by adequate fitting procedures may allow identification; a truncated mean is generally used, i.e. the average on a given fraction of the smallest energy losses (40 to 60% of the total).

The analysis of the expected detector performance begins with a good knowledge of the energy loss process for fast particles. This has been discussed recently both analytically (Talman, 1979) and computed for some noble gases using phenomenological model calculations (Allison and Cobb, 1980; Lapique and Piuz, 1980). In Fig. 20 the experimental histogram of energy loss measured for

Fig. 19

Fig. 20

3 GeV/c π^- in 1.5 cm of argon is compared with the Landau (dotted curve), Blunk and Leisegang (dashed) and phenomenological photo-absorption model (full curve, from Cobb, Allison and Bunch, 1976). Clearly the last model provides a distribution rather closely matching the experimental one, and has been used for the optimization of the ISIS detector; we will see some outcomes of the model later.

From the knowledge of the single layer resolution for a given gas, one can compute the expected separation power for a multilayer device. For argon, the experimental resolution (the FWHM divided by the average) is shown in Fig. 21 (Lazeyras, Lehraus, Mattewson and Tejessy, 1979); using these values, the curves of Fig. 22 have been computed, giving the expected dE/dx resolution as a function of sample size and number and of total detector thickness (Walenta,

Fig. 21

1981). Letters in the graph refer to existing detectors, in project or already in operation: point (b) corresponds to the Time Projection Chamber, (c) to ISIS, (f) to JADE; for a complete list of references, see the quoted work. As an example, the Time Projection Chamber (TPC), where 180 ionization samples are measured in a little less than 1 m long detector operated at 8 atm, has a computed resolution of 5.5% FWHM, sufficient to identify π and k within 3 standard deviations between 1.5 and 20 GeV/c (compare with Fig. 18). The first data from the TPC group show indeed that the goal is reached, at least for a restricted class of events.

Note that resolution is very quickly lost if the number and thickness of samples is far from optimum, or if the detector suffers from systematic dispersions. In the case of JADE the expected 10% resolution, computed for 48 ionization samples 1.5 cm thick each, turned out in practice to be around 14% FWHM at the beginning of the operation; the result is shown in the scatter plot of Fig. 23, where obviously particles of different masses largely overlap in dE/dx in the relativistic rise region.

In what follows, I would like to discuss the various components that add up to define the dE/dx resolution obtainable in an ionization sampling device, and to describe some proposed improvements on the technique.

Fig. 22

Fig. 23

First, let us consider the influence of the choice of the gas filling and pressure on the expected resolution. From Fig. 22 it is obvious that, given the detector length and sample size, an increase in gas pressure improves the resolution. The amount of relativistic rise before saturation, however, decreases due to the increased density of the medium, as shown in Fig. 24 (from Lehraus, Matthewson and Tejessy, 1981). The choice therefore depends on the range of momenta where a given level of separation is demanded.

Another aspect of the choice concerns the intrinsic energy resolution in thin samples, that was given for argon in Fig. 21. It has been realized by several authors that in hydrocarbons and in CO_2 the single layer resolution is better, for a given thickness, than for the noble gases (Walenta, Fisher, Okuno and Wang, 1979; Lehraus, Matthewson and Tejessy, 1982). As shown in Fig. 25, the relative resolution measured for identical sample thickness can be a factor of two better in some hydrocarbons as compared to argon. It has been found (Walenta, 1981) that the relative resolution in all measured gases is a simple function of the reduced absorber length $\alpha t/I$, where I is the mean ionization potential of the medium (Fig. 26). Is it then obvious that in all existing devices one should replace noble gas filling with hydrocarbons? This is not so for two reasons. The first is purely technical: the operating voltage for a proportional chamber would have to be almost doubled, and generally this is impossible if not foreseen in the original design (both because of localized breakdowns and of electrostatic instabilities). The second reason is however more fundamental: what happens to the relativistic rise in hydrocarbons? The

Fig. 24

Fig. 25

unfortunate answer is that the rise is smaller and that saturation is reached faster, see Fig. 27 (Allison, Bunch and Cobb, 1978). Again there seems to be a simple dependence of the amount of relativistic rise on the molecular properties of the absorbing medium which does not leave much space for "new" gases, as shown in Fig. 28 (Walenta, 1981; for the definition of the gas constant k that depends on the average energy loss and ionization potential, see the quoted reference). Figure 29 shows examples of measured πp and $e\pi$ identification power, given as a ratio between the difference in average energy loss and resolution, for different gases and mixtures at 15 GeV/c (Lehraus, Matthewson and Tejessy, 1982). The detector used for the measurement is the External Particle Identifier (EPI) where 64 samples, 4 cm thick each are measured for each track.

There appears then to be no best general choice and the operating conditions depend on the technological constraints (size and pressure of the detector) and on the momentum range in which the particle separation has to be optimized. For an extended discussion on the subject, see Allison (1982). Special mention deserves the region of decreasing energy loss, before the minimum; it seems obvious that the use of pure hydrocarbons as detecting media in this case is bound to provide better particle identification in existing detectors, or else allow the design of detectors with a smaller number of samples for a given resolution.

Having described some limits in resolution intrinsic to the energy loss process, I would like now to mention several non-trivial sources of dispersion connected with the detecting instrument, a multiwire gas proportional counter. Because of the fluctuations in the avalanche process, the gas multiplication adds dispersion to the energy loss sample. In a simple formulation, one can write for the variance of the recorded pulse height:

$$\left(\frac{\sigma_P}{P}\right)^2 = \left(\frac{\sigma_N}{N}\right)^2 + \frac{1}{N} \left(\frac{\sigma_A}{A}\right)^2,$$

where σ_N/N is the relative dispersion of the original charges, and σ_A/A the variance of the avalanche produced by a single electron. The second term is gain-dependent, and has been computed and measured for several gases; Figure 30 shows a typical behaviour in argon with $f = (\sigma_A/A)^2$; $\bar{K}$ is the average amplification and $p r_a$ the product of pressure times wire diameter (Alkhazov, 1970). For minimum ionizing particles, where $N \approx 100$ cm⁻¹ in typical samples and $\sigma_N/N \sim 50\%$, the dispersion due to gas gain is negligible unless the sample size is very small (this is not so in X-ray detection). When one looks to experimental data, however, the outcome is very

Fig. 26

Fig. 27

Fig. 28

Fig. 29

different (see Fig. 31), from Benjamin, Kemshall and Redfearn, 1968). Above a certain value of total charge, about 10^6 electrons detected, the resolution quickly deteriorates: this is understood as being due to space charge gain modification when the total charge exceeds a critical value. In ionization sampling detectors one tends therefore to work at the lowest possible proportional gain, depending on sample size and electronics noise: typically between 10^3 and 10^4 . What happens is that when electrons from a track

Fig. 30

Fig. 31

segment reach the anode in a localized spot but dispersed in time, the positive ions produced in the early avalanches decrease the electric field, and therefore the gain, for the following electrons. As the time structure of the detected electrons varies, a large fluctuation in the final detected size results. The effect is particularly relevant when particles traverse the detector at different angles: Figure 32 (Frehse, Lapique, Panter and Piuz, 1978) shows the variation in normalized detected charge as a function of gain for various angles of incidence (0° means a track perpendicular to the anode wire). At gains around 10^4 the variation is already 30%

Fig. 32

between tracks at 0° and 45° . Taking into account such geometric effects in the real data is very tedious and may be impossible if the data do not contain clean enough samples of events (such as cosmic muons).

Non-trivial electronics effects can also contribute to the loss of energy resolution. Since most of the amplitude measuring channels are a.c. coupled, a baseline shift can occur even at

moderate rates. Moreover, the physical process of signal creation produces itself a tail extending to very long times (corresponding to the slow motion of ions); this has to be removed by suitable choice of the amplifiers' time constant. The resolution can be spoiled also by cross-talk, either internal (i.e. due to the charge induced mutually by positive ions in neighbouring channels) or external, in the chamber or in the electronics due to capacitive couplings. For an extended discussion on these points, see Allison, 1982.

Many of the above mentioned problems may be solved by replacing the global energy loss measurement by a measurement of the number of primary ionizing encounters (cluster counting). As indicated before, the origin of the large fluctuations of energy loss is the ejection of energetic electrons with their peculiar statistics. The number n of primary interactions, on the other hand, follows a Poisson distribution with a dispersion simply proportional to $\sqrt{n}$. In 1 cm of argon, while the dE/dx resolution exceeds 100% (see Fig. 21), one expects $n \approx 30$ with a FWHM of $2.34 \times \sqrt{n}$ or about 40%.

Counting the number of clusters in a gas detector is, however, not straightforward. Indeed, the average distance between primary interactions, ($\sim 300 \mu\text{m}$ in argon at NTP) is close to the typical values of dispersion due to electron diffusion (see Fig. 5) and clusters quickly mix during the drift. Moreover, the minimum width of a proportional pulse (20-30 ns) results in substantial dead time losses. In the so-called Time Expansion Chamber (Walenta, 1979) good cluster separation is achieved by operating the detector at very low drift fields so as to spread out the time distance between clusters, and using thin anode wires and fast electronics to reduce dead times. A typical result is shown in Fig. 33, (Rehak and Walenta, 1980), measured in a 10 mm thick chamber filled with P-10 (10% CH_4 in argon). The distribution is indeed Poisson-like, but the average number of clusters disagrees with the expected value (around 25 cm^{-1} , see, for example, Korff, 1955) indicating that clusters largely overlap at the detection. Properties and limitations of cluster counting have been statistically analysed by Lapique and Piuz (1980) introducing realistic values for the diffusion coefficient and double-cluster resolution. The general outcome of this study is that with existing detectors the losses are too important and overcome the gain due to the favourable primary statistics.

While one can hope to improve the cluster counting technique for better resolution (see below), there is a more fundamental limitation in what concerns particle identification. It appears indeed that a good part of the relativistic rise in energy loss is due not to an increase in the number of clusters, but in the amount of energy imparted to inner shell δ electrons. Figure 34, from Lapique and Piuz (1980) shows indeed the result of the photoabsorption

Fig. 33

model calculation, described previously, for argon at NTP; the relative relativistic rise is computed as a function of γ using a truncated mean on the energy loss (curves c), total electron counting (b), and cluster counting (a); the dots are experimental points. The number of primary clusters saturates at lower momenta, a fact which is experimentally verified, see Fig. 35 (Rehak and Walenta, 1980).

A considerable advance in the obtainable resolution can be foreseen using the single electron counting technique developed to improve the energy resolution for soft X-rays (Siegmund et al., 1982). Coupling a low field drift space to a region of charge multiplication, and looking with a photomultiplier at the flashes of light emitted in the avalanches, these authors have optimized the gas mixture to obtain very short (2-3 ns) pulses for single

Fig. 34

Fig. 35

Fig. 36

electrons; Figure 36 shows the photomultiplier output in the detection of 300 eV X-rays (producing a cluster of about 10 electrons). Individual electrons can be counted, with a time resolving power which is an order of magnitude better than in analogous proportional counters. It seems very interesting to apply this technique to cluster counting in the relativistic rise region.

4. PARTICLE IDENTIFICATION THROUGH CHERENKOV RING IMAGING

Cherenkov ring imaging is a recent very promising technique for charged particle identification in the range between several and a few hundred GeV/c. Various gaseous detectors have been developed for this purpose, that can operate using in the gas mixture a photoionizing vapour with high quantum efficiency for detection and localization of individual ultraviolet photons.

Charged particles of velocity β traversing a transparent medium with index of refraction n radiate by Cherenkov effect photons at an angle θ given by:

$$\theta = \cos^{-1} (n\beta)^{-1}, \quad \beta \geq n^{-1}$$

using a spherical mirror with radius r at the far end of the radiator, photons can be focused on a circular pattern of radius R on a spherical image plane (see Fig. 37). For $r \gg R$, and a plane detector:

$$R = \frac{r}{2} \tan \theta$$

a measurement of R provides the particle's velocity and therefore its mass if the momentum is known. The number of detected photons is given by $N = N_0 L \sin^2 \theta$, where L is the radiator length, and

Figure 38 summarizes the quantum efficiency of some vapours and the cut-off of windows as a function of wavelength.

Not only a vapour with lower ionization potential allows the use of a simpler window material, but also the chromatic dispersions are reduced at the longer wavelengths; Figure 39 shows how the index of refraction depends on wavelength for argon and helium. In the region of sensitivity of TEA, with a CaF_2 window (1300 to 1600 Å) the expected aberration is about three times larger than in the region of sensitivity of TMAE with a fused silica window (1600 to 2200 Å). However, a substantial difference appears because of the vapour pressure of the two products at room temperature: 55 Torr for TEA, 0.35 Torr for TMAE. This means that with TEA full photon absorption can be obtained in 1-2 mm of gas while using TMAE even at high temperatures (35-40 °C), the mean path of absorption is 20-30 mm. This has implications both on the time resolution of detectors (at least an order of magnitude worse for TMAE than using TEA) and on the general background due to direct ionization in the gas by charged particles.

A detailed discussion of the particle identification properties of Cherenkov ring imaging devices, taking into account the various sources of dispersion, has been given by Ypsilantis (1981).

Let me here first consider the process of amplification of single electrons in proportional counters, extensively studied because of its relevance in determining the avalanche dispersion as indicated in the previous section.

Under simple assumptions, it can be shown that the avalanche size distribution when multiplying a single electron is an exponential of the kind:

$$P(n) = \frac{1}{\bar{n}} e^{-n/\bar{n}}$$

where $\bar{n}$ is the average avalanche size. Such pulse height distribution is indeed observed at small field values. At increasing fields, however, the distribution develops a peak with a reduction of the variance, as shown in Fig. 40 (Schlumbohm, 1958). Several theoretical models have been proposed to explain the observed avalanche size distribution (for a summary, see Alkhazov, 1970). They suggest a functional form of the Polya kind:

$$P(n) = \frac{b^b}{\Gamma(b)} \left(\frac{n}{\bar{n}} \right)^{b-1} e^{-b(n/\bar{n})}$$

with $b \approx 2$. The practical implications of a peaked distribution are obvious: in the case of simple signal discrimination and

Fig. 38

Fig. 39

Fig. 40

counting, the appearance of a peak implies that for low enough threshold setting a constant efficiency plateau can be obtained above a given gain. Moreover, when using a centre-of-gravity localization method (see below) a peaked distribution largely decreases the dynamic range of pulses to be measured and reduces electronics dispersions.

The practical problem is to get in a proportional chamber large enough gains, and this in a gas mixture that is by definition photosensitive. Photons produced in the avalanches themselves tend indeed to spread in the gas and reconvert on cathodes, inducing secondary discharges and limiting the stable gain. In a normal counter operating with argon-TEA the limiting gain is around 10^5 , and even lower using TMAE. Apart from the shape of the distribution, 10^{-2} pC is a small charge to detect.

Larger gains, in excess of 10^6 , have been obtained in two kinds of detectors developed for Cherenkov ring imaging: the multi-needle counter and the multistep proportional chamber.

The first device consists in a matrix of closely peaked needles, each acting as an individual Geiger counter, see Fig. 41 (Comby et al., 1980). The typical cell size is around 3 mm, which constitutes a natural limit in the localization accuracy. This kind of device has the advantage of being able to detect a large number of simultaneous photons; on the other hand, the complexity of construction and the number of electronics channels involved restricts its use in small size detectors. Moreover, the very long dead time per element typical of a Geiger discharge (several ms) limits the accepted rate, especially when charged particles traverse the detector. The device has been extensively tested in a beam using as

Fig. 41

radiator a CaF_2 crystal, producing a large number of photons. Figure 42 shows an example of Cherenkov ring recorded for 1.2 GeV/c protons, and having a radius of around 30 mm.

A second approach to the detection problem is based on the multistep proportional chamber, a device originally developed to allow a gated operation of proportional chambers (Charpak and Sauli, 1978). By separating the overall gain in two amplification elements, each below the critical value for secondary effects to appear, this detector allows gains close to 10^7 to be obtained in a photosensitive gas mixture. The operation is as follows (Fig. 43). A photoelectron produced in the upper region, the conversion space, drifts into a region of very high field, the pre-amplification region. Here avalanche multiplication occurs, and in some gas mixtures (a noble gas and a photosensitive vapour) the transverse avalanche growth is very large, 1 mm or so. Electrons in the avalanche produced within the field tubes connecting to the lower transfer region are injected there, in proportion to the total that equals the fields ratio: the process is uniform (independent on the original centre of the avalanche) because the spread exceeds the grid wire spacing. With a typical preamplification of 10^4 and a transfer efficiency of 10%, 10^3 electrons per primary charge are injected in the transfer region. A two-step proportional chamber is shown in Fig. 44: the second element of amplification, that brings the overall gain to 10^6 - 10^7 is a thin-gap proportional chamber, where bi-dimensional localization can be achieved for example using the centre-of-gravity readout method on cathodes. The efficiency, time resolution and localization properties of such a device in detecting photons with TEA as photosensitive vapour have been extensively studied (Bouclier et al., 1982). Figure 45 (Cattai, 1981) shows pulse-height spectra measured for single photoelectrons at increasing overall gains: the peaked structure is apparent. Figure 46 shows instead relative efficiency plateaus measured in helium-TEA as a function of anodic potential, for several values of the preamplification voltage and a detection threshold of 0.1 pC. Using 2 mm wide cathode strips readout, the centre-of-gravity method (see Section 2) allow the reconstruction of the photon position with an accuracy of about 400 μm r.m.s., suited for most Cherenkov ring imaging applications (the typical chromatic aberration being of the same order). Notice that localization accuracy in the direction perpendicular to the anode wires, bound to be equal to the wire spacing in a conventional chamber, is better in the multistep detector because the large avalanche spread in the preamplification region results in charge sharing and interpolation at the anodes.

To resolve the geometrical ambiguities in case of several simultaneous points, the anode wires can be mounted at 45° with the orthogonal cathodes thus providing three independent projections

Fig. 42

Fig. 43

Fig. 44

Fig. 45

Fig. 46

Fig. 47

of the event. Figure 47 shows an example of ring reconstruction (Coutrakon et al., 1982). A detector of this kind is almost completed at Fermilab, and will be used for hadron identification up to 400 GeV/c. It consists of a 16 m long radiator, $3 \times 3 \text{ m}^2$ in section, with two multistep photon detectors on the two sides where images are focused by the rows of mirrors (Fig. 48). Figure 49 shows one composite CaF_2 window, $40 \times 80 \text{ cm}^2$, separating the detector from the radiator gas (helium at atmospheric pressure).

With a smaller size prototype detector of similar design, the results shown in Figs. 50 and 51 have been obtained in a test run at 200 GeV/c. The picture shows an overlap of ~ 100 events, with the typical ring pattern, about 70 mm in radius, while Fig. 51 gives the reconstructed radius distribution, in logarithmic scale, showing the good πK separation obtained, around six standard deviations (Coutrakon et al., 1982). From the known detectors parameters and extrapolating the experimental results, one can compute the expected particle identification properties of the full device given in Fig. 52 (Peisert, 1982).

The multistep proportional chamber photon detector has the advantage of a good time resolution, 40-50 ns using TEA, but is

Fig. 48

Fig. 49

Fig. 50

Fig. 51

Fig. 52

limited in the number of photons per event that can be unambiguously reconstructed, typically 3 or 4, because of the modest double point resolution of the cathode readout method (induced signals distributions overlap for points closer than 10 mm in projection). It is therefore suited for very high energies and high flux experiments. For momenta up to 60-70 GeV, where radiators with lower threshold (larger index of refraction) have to be used, one can easily produce dozens of photons per event and another kind of detector had to be developed. It consists of a drift chamber of special design,

Fig. 53

originally proposed by Séguinot and Ypsilantis (1977), see Fig. 53. Photons convert in the drift space, and the ring pattern is reconstructed measuring the drift time on a set of proportional wires as shown in the figure. The time resolution of the device corresponds obviously to the maximum drift length, around 1 μ s or so, depending on the size.

Drifting electrons close to an insulator (the window) is, however, not straightforward, because of distortions in the electric field. The problem has been solved by doubling the drift field shaping electrodes on the outside of the window (Barrelet et al., 1982). Moreover, the diffusion of electrons during drift is an intrinsic limitation to the localization accuracy. Operating in pure methane with TEA and TMAE, the quoted authors have measured typical diffusion rates of about $250 \mu\text{m}/\text{cm}^{1/2}$; for a 10 cm long drift, this implies a localization accuracy for one photon of around 800 μm .

Fig. 54

For the particular needs of DELPHI, a detector proposed for the LEP e^+e^- storage rings, a large amount of work is being done on the use of TMAE as photoionizing vapour. Apart from the already mentioned advantages of reduced chromatic aberrations and of using quartz windows, photon detection at longer wavelengths opens up the possibility of using radiating media other than pure noble gases. Isobutane, for example, has a transmission cut-off almost coinciding with the one of fused silica (Fig. 54, from Barrelet et al., 1982). Liquid freon can also be used as radiator for the lower momenta. Figure 55 shows the expected πK and Kp separations computed by the authors of the proposed detector in a combined liquid and gas Ring Imaging Cherenkov device (RICH). Figure 56 shows a simulated event with about 20 charged particles as seen by the detector.

I should mention in conclusion that operating with TMAE is very attractive but rather difficult because of its low vapour pressure. Photons emitted in the avalanches tend to spread far from the wires and reconvert in the gas producing spurious hits; a mechanical construction that prevents each wire from seeing the next one partly solves the problem, but is rather difficult to implement. Finding a low ionization potential vapour with decent vapour pressure would certainly constitute a considerable advance in the field.

Fig. 55

Fig. 56

REFERENCES

- Alkhazov, G. D., 1970, Nucl. Instrum. Methods 89:155.
- Allison, W. W. M., Brooks, C. B., Bunch, J. N., Cobb, J. H., Lloyd, J. L., and Fleming, R. W., 1974, Nucl. Instrum. Methods 119:499.
- Allison, W. W. M., Brooks, C. B., Bunch, J. N., Fleming, R. W., and Yamamoto, R. K., 1976, Nucl. Instrum. Methods 133:325.
- Allison, W. W. M., Brooks, C. B., Lyons, L. Romaya, A. M., Shield, P. D., and McPherson, A., 1979, Nucl. Instrum. Methods 163:331.
- Allison, W. W. M., and Cobb, J. H., 1980, Ann. Rev. Nucl. Sci. 30:253.
- Allison, W. W. M., (Stanford, 1982), Proc. Int. Conf. on Instrumentation for Colliding Beam Physics.
- Anderson, D., 1981, IEEE Trans. Nucl. Sci. NS-28:842.
- Anderson, D., and Charpak, G., 1982, CERN-EP/82-52, submitted to Nuclear Instruments and Methods.
- Barranco Luque, M., Calvetti, M., Dumps, L., Girard, C., Hoffmann, H., Maurin, G., Naumann, L., Perez, J., Piano Mortari, G., Placci, A., Queru, P., Rijssenbeek, M., Rubbia, C., Sadoulet, B., and Tao, C., 1980, Nucl. Instrum. Methods 176:175.
- Barrelet, E., Ekelöf, T., Lund-Jensen, B., Séguinot, J., Tocqueville, J., Urban, M., and Ypsilantis, T., 1982, CERN-EP/82-09 (submitted to Nuclear Instruments and Methods).
- Benjamin, P. W., Kemshall, C. D., and Redfearn, J., 1968, Nucl. Instrum. Methods 59:77.
- Bouclier, R., Cattai, A., Charpak, G., Million, J., Peisert, A., Santiard, J.C., Sauli, F., Coutrakon, G., Hubbard, J. R., Mangeot, Ph., Mullié, J., Tichit, J., Glass, H., Kirz, J., and McCarty, R., 1982, CERN-EP/82-83 (submitted to Nuclear Instruments and Methods).
- Breskin, A., Charpak, G., Majewski, S., Melchart, G., Peisert, A., Sauli, F., Mathy, F., and Petersen, G., 1980, Nucl. Instrum. Methods 178:11.
- Cattai, A., 1981, Thesis at the University of Trieste.
- Charpak, G., Bouclier, R., Bressani, T., Favier, J., and Zupančič, Č., 1968, Nucl. Instrum. Methods 62:235.
- Charpak, G., 1970, Ann. Rev. Nucl. Sci. 20:195.
- Charpak, G., Rahm, D., and Steiner, H., 1970, Nucl. Instrum. Methods 80:13.
- Charpak, G., Sauli, F., and Duinker, W., 1977, Nucl. Instrum. Methods 108:413.
- Charpak, G., Majewski, S., and Sauli, F., 1975, Nucl. Instrum. Methods 126:381.
- Charpak, G., and Sauli, F., 1978, Phys. Lett. 78B:523.
- Charpak, G., Petersen, G., Policarpo, A., and Sauli, F., 1978, Nucl. Instrum. Methods 148:471.
- Charpak, G., Majewski, S., Melchart, G., Sauli, F., and Ypsilantis, T., 1979, Nucl. Instrum. Methods 164:419.

- Charpak, G., Melchart, G., Petersen, G., and Sauli, F., 1979, Nucl. Instrum. Methods 167:455.
- Charpak, G., Peisert, A., Sauli, F., Cavestro, A., Vascon, M., and Zanella, G., 1981, Nucl. Instrum. Methods 180:387.
- Clark, A. R., et al., (PEP-4, 1976), Proposal for a PEP facility based on the Time Projection Chamber.
- Cobb, J. H., Allison, W. W. M., and Bunch, J. N., 1976, Nucl. Instrum. Methods 133:315.
- Comby, G., Mangeot, Ph., Auguères, J.-L., Chaudet, Y., Chalot, J. F., Tichit, J., de Lignères, H., and Zadra, A., 1980, Nucl. Instrum. Methods 174:93.
- Coutrakon, G., Cribier, M., Hubbard, J. R., Mangeot, Ph., Mullié, J., Tichit, J., Bouclier, R., Breskin, A., Charpak, G., Million, J., Peisert, A., Santiard, J. C., Sauli, F., Brown, C. N., Finley, D., Glass, H., Kirz, J., and McCarty, R., 1982, IEEE Trans. Nucl. Sci. NS-29:323.
- Drumm, H., Granz, B., Heintze, J., Heinzelmann, G., Heuer, R. D., van Krogh, J., Lennert, P., Nozaki, T., Rieselberg, H., Wagner, A., Eichler, R., Olsson, J., Steffen, P., Goddard, M. C., Pearce, G. F., and Warming, P., 1980, DESY 80/38.
- Fabjan, C. W., and Fischer, H. G., 1980, Rep. Prog. Phys. 43:1003.
- Farr, W., Heintze, J., Hellenbrand, K. H., and Walenta, M., 1978, Nucl. Instrum. Methods 156:283.
- Filatova, N. A., Nigmanov, T. S., Pugachevich, V. P., Riabtsov, V. D., Shafranov, M. D., Tsyganov, E. N., Uralsky, D. V., Vodopianov, A. S., Sauli, F., and Atac, M., 1977, Nucl. Instrum. Methods 143:17.
- Frehse, H., Lapique, F., Panter, M., and Piuze, F., 1978, Nucl. Instrum. Methods 156:87.
- Friedrich, D., Melchart, G., Sadoulet, B., and Sauli, F., 1979, Nucl. Instrum. Methods 158:81.
- Jean-Marie, B., Lepeltier, V., and L'Hôte, D., 1979, Nucl. Instrum. Methods 159:213.
- Korff, K. S. A., 1955, Electrons and nuclear counters (Van Nostrand, New York, 1955).
- Lapique, F., and Piuze, F., 1980, Nucl. Instrum. Methods 175:247.
- Lazeyras, P., Lehraus, I., Matthewson, R., and Tejessy, W., 1979, IEEE Trans. Nucl. Sci. NS-26:89.
- Lehraus, I., Matthewson, R., and Tejessy, W., 1981, CERN-EF/81-14 (submitted to Nuclear Instruments and Methods).
- Lehraus, I., Matthewson, R., and Tejessy, W., 1982, CERN-EF/82-1 (submitted to Nuclear Instruments and Methods).
- Nygren, D., and Marx, J., 1978, Physics Today, Vol. 31, No. 10.
- Palladino, V., and Sadoulet, B., 1975, Nucl. Instrum. Methods 128:323.
- Peisert, A., 1982, Thesis at the University of Geneva.

- Piuz, F., Roosen, R., and Timmermans, J., 1982, Nucl. Instrum. Methods 196:451.
- Policarpo, A., 1981, Phys. Scripta 23:539.
- Ramanantsohena, P., 1979, CRN/HE 79-13.
- Rehak, P., and Walenta, A. M., 1980, IEEE Trans. Nucl. Sci. NS-27:53.
- Rice-Evans, P., 1974, Spark, streamer, proportional and drift chambers (Richelieu, London, 1974).
- Ritson, D. M., 1961, Techniques of High Energy Physics (Interscience, New York, 1961).
- Roberts, A., 1960, Nucl. Instrum. Methods 9:55.
- Robinson, B., 1981, Phys. Scripta 23:716.
- Salete Leite, M., 1980, Portugal Phys. 11:53.
- Sauli, F., 1977, CERN 77-09.
- Schlumbohm, H., 1958, Z. Phys. 151:563.
- Séguinot, J., and Ypsilantis, T., 1977, Nucl. Instrum. Methods 142:377.
- Séguinot, J., Tocqueville, J., and Ypsilantis, T., 1980, Nucl. Instrum. Methods 173:283.
- Shultz, G., and Gresser, J., 1978, Nucl. Instrum. Methods 151:413.
- Siegmund, D. H., Culhane, J. L., Mason, I. M., and Sanford, P. W., 1982, Nature 295:678.
- Talman, R., 1979, Nucl. Instrum. Methods 159:189.
- Walenta, A. H., Heintze, J., and Schürlein, B., 1971, Nucl. Instrum. Methods 92:373.
- Walenta, A. H., 1979, IEEE Trans. Nucl. Sci. NS-26:73.
- Walenta, A. H., Fisher, J., Okuno, H., and Wang, C. L., 1979, Nucl. Instrum. Methods 161:45.
- Walenta, A. H., 1981, Phys. Scripta 23:353.
- Williams, S. H., Leith, D. W., Poppe, M., and Ypsilantis, T., 1980, IEEE Trans. Nucl. Sci. NS-27:91.
- Ypsilantis, T., 1981, Phys. Scripta 23:371.