EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/87-233

23 December 1987

**THE TIME PROJECTION CHAMBER FOR HEAVY-ION COLLISIONS:
TRENDS AND PERSPECTIVES**

Fabio Sauli
CERN, Geneva, Switzerland

ABSTRACT

The very large charged-particle multiplicities expected in a high-energy nucleon-nucleon collision, together with the wide range of energy loss by ionization, makes the conception of a tracking detector extremely challenging. One device, the time projection chamber, widely used in particle-physics experimentation, seems very promising in this context. In the present paper, after a brief summary of the operating principles and of the performances achieved in the existing detectors, I will discuss in more detail the expected performances in a high-multiplicity environment, as well as the recognized problems arising from the large charge densities detected. Some alternative devices that might overcome the recognized limitations of the standard design will also be described.

Invited talk given
at the International Conference on Ultrarelativistic Nucleus-Nucleus Collisions,
Nordkirchen, 24-28 August 1987,
to be published by Zeitschrift für Physik

1. INTRODUCTION

The multiwire proportional chamber (MWPC) was developed in the late sixties by Charpak and collaborators to perform fast electronic detection of ionization produced by charged particles or photons in a thin layer of gas contained between grids or meshes of parallel wires [1–3]. Exploitation, in various ways, of the electron collection or drift-time and of the charge induced on cathode planes by the anodic avalanche allowed the achievement of accurate, two-dimensional localization of radiation (for a review, see for example Refs. [4] and [5]). Continuous tracks could then be reconstructed stacking several layers of MWPCs, each performing independent two-dimensional localization.

The idea of coupling the drift-time measurement to the readout of signals induced on cathode wires or pads, to obtain a three-dimensional localization, appeared already in the early works on the subject [2]. It was further developed and extended by Nygren and collaborators, who named the new device the time projection chamber (TPC) [6]. In this detector, a large gaseous volume embedded in a uniform electric (and often also magnetic) field, the drift space, is followed by a MWPC with a padded cathode that serves as an amplifying and two-dimensional localizing element, the third coordinate being derived from the measurement of the drift-time of ionization electrons released by charged tracks in the sensitive volume. Recording simultaneously the charge on the anode wires and on rows of rectangular pads on the facing cathode plane in regular short time intervals, one can achieve true three-dimensional and ambiguity-free localization of tracks. The somewhat misleading name of time ‘projection’ derives from the fact that information is recorded in thin time slices. The recorded charge provides also a measurement of the ionization in short segments of the tracks, and repeated sampling of the charge deposition allows estimation of the differential energy loss in the detector (which in turn contains information on the particles’ velocity).

The first large TPC, built at LBL Berkeley for an experiment at the Stanford collider PEP, demonstrated the powerful tracking and particle identification properties of the device, and was soon followed by the construction of other similar detectors (for a review, see for example the Proceedings of the TPC Workshop in Vancouver [7]). Two large TPCs are now in construction at CERN and will be used at the large electron-positron collider (LEP) [8, 9].

In the following I will briefly summarize the operating principles of the TPC, pointing out the latest achievements and the general trends of the research in this field, with a special concern for the problem of detecting large charged-particle multiplicities such as those expected at a heavy-ion collider.

2. THE TIME PROJECTION CHAMBER

A TPC consists of a large, gas-tight container filled with a high-purity gas, sometimes at high pressure, and constituting the sensitive volume, with at one end a MWPC where charge multiplication and detection is performed. A uniform electric field (several hundred volts per centimetre or so) is applied across the gas volume, in order to smoothly drift the ionization trails left by charged particles into the MWPC; for this purpose, a potential difference is applied between the upper electrode of the drift volume and the first cathode of the MWPC (usually grounded); multiple guard electrodes on the sides of the drift volume are kept at appropriate potentials to obtain a uniform and undistorted field. Detectors of this kind designed for experiments at colliders tend to be cylindrical in shape, with the MWPC at one end, in order to allow their installation inside a solenoid for momentum analysis. Also, vacuum pipes for the circulating beams have to run across the central axis of the detector, which has then an inner cylindrical field-shaping structure as well as an outer one.

Figure 1a shows a schematic view of the ALEPH TPC, under construction for LEP [10] (the DELPHI TPC, also under construction at CERN, is similar in design). The detector consists in fact

of two independent sections, each more than 2 m long and mounted back to back, with the end-cap MWPCs arranged in sectors at each outer end. The modular construction chosen for the end-cap chambers is better seen in Fig. 1b, which also shows the orientation of the rows of circular pads facing the anode wires (mounted tangentially to the rows of pads in each segment).

The operation of a TPC will be described in more detail in the following sections; here I would like to give an overview of its performances (for a review, see for example Ref. [11]). With a typical localization accuracy of a few hundred microns for each segment of track detected in a time slice, and several hundred slices of measurement, the TPC is an extremely good, ambiguity-free tracking detector for moderate multiplicities. An example of a three-dimensional reconstruction for a complex event in the ALEPH TPC (generated, for the time being, with a Monte Carlo program) is shown in Fig. 2 [12]. The event contains an energetic electron spiraling back and forth in the sensitive volume, under the action of the solenoidal magnetic field. Although simulated, the tracks have been generated with the appropriate dispersions and resolution limits, experimentally known, adding the background expected in the real operation.

As indicated, the repeated sampling of the tracks can be exploited to deduce the differential energy loss. When properly averaged over the samples and corrected for various non-linearities, this quantity can be compared with the particle momentum, known from the tracks' deflection in a magnetic field. Figure 3 shows an example of this correlation, measured in operating conditions with the Berkeley TPC [13]; particles of different mass are clearly identified up to a few GeV/c (electrons up to much higher momenta), and a more refined analysis allows limited identification in the relativistic rise region.

The powerful tracking and particle identification properties of the TPC, obtained in the detection of events of moderate complexity, have stimulated the interest of various groups facing the very challenging experimental problem of detecting the outcome of a high-energy ion-ion collision, which typically results in the production of several hundred charged particles, some of which are heavily ionizing. Figure 4 gives an example of a simulated Au-Au collision at 1 GeV per nucleon as it would appear in a TPC, optimized for operation at such extreme track densities, and proposed by a group in Berkeley [14]. Tracks overlap so badly that they are almost completely confused in the drawing (but, hopefully, not quite so in the real reconstruction!); it will be one of the aims of this article to discuss the known intrinsic limits in resolution of the gaseous detectors in general and of the TPC in particular.

3. CHARGE INDUCTION ON CATHODES AND PAD RESPONSE FUNCTION

The process leading to localization can be better understood by referring to Fig. 5a [15], which shows schematically a typical geometry of the anode wires and of the facing cathode pad rows, parallel to the anodes (the upper cathode mesh and the field wires, mounted between anodes, have been omitted for clarity). Electrons produced by ionizing tracks in the drift volume approach the anode wires and are there multiplied by the avalanche process. Negative signals are detected on the anodes, and a positive charge distribution is induced on the cathode pads facing the avalanche; a typical charge profile as seen on the pads shortly after the avalanche has occurred is shown in Fig. 5b. On a given electrode, the signal develops in time with a shape determined by the physical process and by the characteristics of the amplifiers; Fig. 5c shows a typical signal detected on an electrode and registered, as a function of time, by a fast waveform digitizer, e.g. a flash analogue-to-digital converter (flash ADC). With a suitable analysis of the signals, one can then deduce the average location of each segment along the y coordinate (parallel to the anodes) at position x, the vertical z coordinate being provided by the drift-time. Note that the pulse heights detected on cathode pads are always smaller than the corresponding signals on the anode wires; indeed, for a typical MWPC, the positive overall charge induction (equal in magnitude to the anode signal) is more or less equally

shared between the two cathode planes and the two field wires; moreover, on the readout cathode, the charge is shared between several adjacent pads.

The shape of the induced charge distribution on cathodes has been analysed by many authors using various algorithms [16–19]. For a point-like avalanche, the distribution depends essentially on the anode-to-cathode distance (the gap G), and has an approximately Gaussian shape with a standard deviation about equal to G ; Fig. 6a gives an example computed in three dimensions for a 4 mm gap [19]. The convolution of the intrinsic distribution with the pad width Δ , projected along the direction of the pad row, determines what is usually called the two-dimensional pad response function (PRF); the width of the distribution depends on the ratio between gap and pad width. Figure 6b shows the PRF for a point-like avalanche and several values of Δ (computed with the expression given in Ref. [16] for $G = 4$ mm); as one could expect, for $\Delta/G \gg 1$ the induced charge tends to be insensitive to the position of the avalanche; on the other hand, the fraction of detected charge on a pad (the signal pulse height) decreases for small values of Δ/G thus deteriorating the signal-to-noise ratio. It has been shown, both experimentally and theoretically, that the best localization accuracy is obtained using a pad width about equal to the r.m.s. of the induced charge distribution ($\Delta/G \approx 2$) [5, 16]. The charge profile of a localized avalanche is then sampled on an average on three or four adjacent pads.

The PRF for extended tracks is similar to the one computed for point-like avalanches only in the case of tracks perpendicular to the pad row; it broadens rapidly for inclined tracks as shown for example in Fig. 6, that provides the squared standard deviation of the PRF and the corresponding FWHM for tracks as a function of their angle with the anode wire, in the plane of the MWPC ($\alpha = 0$ corresponds to tracks perpendicular to the pad row), computed for the geometry of the original TPC (4 mm gap, 7.5×7.5 mm² pads) [19]. Because of the dispersions intrinsic to the energy loss and charge induction process, the localization accuracy is proportional to the PRF width; the same is true for the two-track resolution. Both the physical track length and the diffusion of electrons during drift contribute to broadening the PRF and consequently to worsening the spatial resolution for extended tracks.

The presence of a strong magnetic field modifies the drift properties of electrons. For the particular case of $\vec{B}$ strictly parallel to $\vec{E}$ (a design goal for TPCs), the drift velocity remains unchanged, but in some gases (such as in the case of argon–methane mixtures) the transverse diffusion coefficient, perpendicular to the drift direction, is strongly reduced. As a consequence, the PRF for tracks drifting from the far end of a TPC is much narrower than it would be in the absence of magnetic field. Figure 7 shows the measured standard deviation of the PRF, normalized to the pad width Δ (8 mm in this case) for various distances of drift and at increasing values of magnetic field [20]. Both the localization accuracy and the two-track resolution are greatly improved for long drift distances at high magnetic fields.

Various disturbing effects appear when $\vec{E}$ and $\vec{B}$ are not parallel to each other; both the drift velocity and the trajectory are modified, and the data have to be correspondingly corrected. Owing to the intense work in the last few years, the drift properties of electrons in crossed electric and magnetic fields are so well understood today that, interestingly enough, one can use the measured distortions of known tracks (e.g. generated by an ionizing laser) to reconstruct the value of non-parallel components of the fields, or in other words to map the fields inside the TPC [21, 22].

Upon approaching the anode wires, electrons drift in a region where the electric field (that tends to become radial) is no longer parallel to $\vec{B}$; they receive a transverse twist and, depending on the angle of the track segment with the wires, the detected charge interests a shorter or longer segment of the anode (the so-called $\vec{E} \times \vec{B}$ effect). This strongly affects again the width of the PRF, which is minimum at an angle of the track with the anodes close to the average magnetic deflection angle of electrons approaching the wires (around 30° for the typical TPC geometries), and increases on the

two sides (Fig. 8a [23]); the localization accuracy follows the same dependence, and largely deteriorates on both sides of the average magnetic angle, see Fig. 8b [15] (see also Ref. [24]).

Fluctuations in the ionization energy loss add further dispersions to the resolution, particularly in the case where each pad in the cathode plane detects the charge induced by several anode wires. Such behaviour is illustrated in Fig. 9a [25]; in the example, a long pad collects the signals from five adjacent anodes; a larger signal on the first wire offsets the centre of gravity of the induced charge by an amount that depends on the angle α . In principle, by measuring the pulse height on each anode wire, one can compute a weighted centre of gravity, thus reducing the dispersive effects of the energy-loss statistics as shown in Fig. 9b [15]. As we will see later, because of the pileup of anodic signals, such a correction is in general not possible at high multiplicities. The particular design of the end-cap MWPC for the TRIUMF TPC [23], with each anode wire individually encased in U-shaped rectangular profiles with facing pad rows, does not suffer from this inconvenience, and should be kept in mind when designing a detector aimed at handling very high multiplicities.

To the above-mentioned sources of distortion one has to add those due to mechanical imperfections, temperature gradients, gas purity, etc.; use of the TPC at the nominal accuracy levels would be impossible without a continuous calibration system. Indeed this is an integral part of the recent TPC designs, and consists in one or several pulsed ultraviolet laser beams traversing the drift volume under various known angles [26]. Being undeflected by the magnetic field, ionized tracks generated by a laser must of course be measured as straight lines and, if such is not the case, one can pinpoint the possible sources of distortion. An example of laser calibration realized with the OPAL jet-chamber prototype is shown in Fig. 10 [27] (although not a TPC, this multiwire gaseous device has a very similar behaviour in many respects). Using an optical splitter, two ionizing parallel beams about 1 cm apart were sent through the drift volume; in the figure, the drift-time measured by adjacent anode wires is shown as a function of wire position. The time distance between the two tracks provides a direct measurement of the local electron drift velocity. A deviation from a straight line is apparent at one end, and was identified as being due to a defective potential distribution in the outer field cage (corrected afterwards).

In conclusion, the very detailed knowledge of the drift properties of electrons in electric and magnetic fields and of the charge-induction mechanism, coupled to effective calibration procedures, makes one confident that localization accuracies close to the theoretical limits can indeed be obtained in running conditions at low rates and moderate multiplicities and charge densities. In the following section I will discuss what happens when these conditions are not met.

4. PROBLEMS ARISING AT HIGH RATES AND LARGE MULTIPLICITIES

Limits in multitrack resolution at high multiplicities and rates appear at several levels, from trivial to fundamental ones; I will discuss them here in an increasing order of annoyance.

4.1 Electronic two-track resolution

The charge induced in a MWPC by the avalanches has a characteristic steep rise-time blending into a slower slope, a consequence of the decrease in velocity of the positive ions leaving the immediate neighbourhood of the anode wires (see, for example, Ref. [4]). For fast applications, signals are usually differentiated, and charge signals detected on the anode wires and on the pads have a time duration that, for point-like avalanches, depends mainly on the shaping or time constant of the amplifier, τ . Two tracks can be well resolved if they differ in space by at least $w\tau$, w being the electron drift velocity in the gas ($w \approx 5 \text{ cm}/\mu\text{s}$). Of course, a short time constant implies that only a fraction of the available induced charge is really exploited for detection (at $\tau = 100 \text{ ns}$, this corresponds to about 20% of the total). While it is possible at high multiplication factors to use time constants as short as 30–40 ns, the usual choice in TPCs to reduce space-charge problems (see later),

is to operate at moderate proportional gains, 10^4 or so, increasing the shaping constants of the amplifiers to several hundred nanoseconds in order to obtain a better signal-to-noise ratio. Figure 11, computed for a typical MWPC with a space of 2 mm between anode wires and operated at atmospheric pressure, illustrates the gain-shaping constant trade off. As a function of the amplifiers' differentiating time constant, the full curves show the detected charge on anodes for minimum ionizing particles at various proportional gains M (on cathodes, signals are much smaller, as discussed in the previous section); the dashed curves represent, again as a function of τ , the typical r.m.s. input noise of amplifiers realized with the indicated technologies for gaseous detectors. As an example, using a metal oxide semiconductor field-effect transistor (MOSFET) suitable for large-scale integration, with a shaping of 50 ns, the signal-to-noise ratio on anodes is ten (quite marginal for a good charge measurement) at $M = 10^4$. With a typical drift velocity of 5 cm/ μ s, this leads to an intrinsic two-track resolution along the drift direction of around 3 mm. I should mention that long shaping constants (200 to 500 ns) with sampling intervals in the waveform encoders around 50 ns have been chosen for TPCs existing or under construction, mostly for economical reasons; this results in a moderate resolution in the drift direction. When recording the complete signal shape, sampled at short time intervals with a waveform analyser, one can partly recover the multitrack resolution with a proper algorithm, even if signals overlap; a 2 mm resolution has been demonstrated using a simple difference-of-samples method on data recorded with a 100 MHz flash ADC [28]; for high multiplicities, however, one would quickly run into pileup and dynamic range problems, and a fast shaping at the input of the amplifier may remain the only possible solution.

Charge profiles induced on the cathode pad rows have a characteristic shape defined by the PRF (see the previous section); two tracks tend to be confused if they are close in drift-time and if their distance is smaller than the width of the PRF. For example, it has been shown that in the ALEPH TPC prototype, with 8 mm wide pads and 4 mm gaps, two tracks (generated by a pulsed laser and perpendicular to the pad rows) are well resolved above about 15 mm spacing; for closer distances, down to 9 mm or so, one can identify a double track analysing the charge distribution, which is larger than expected [29]. Obviously, in the general case of inclined tracks the resolution will be degraded, to an extent that seems not to have been measured or estimated so far.

The local charge induction will extend into contiguous time slices, their number depending on the amplifier shaping constant and on the angle of the tracks; tracks locally overlapping in projection but sufficiently separated in time are of course unambiguously resolved. It is convenient to express the resolution element as a three-dimensional volume, or pixel, having a width along the three axes determined by the corresponding resolutions. For example, with the choice of parameters of the ALEPH TPC, one expects a pixel size for the pads of about $10 \times 40 \times 15 \text{ mm}^3$ (FWHM).

The anode wires, piling up the detected signals over all their length during a time slice, have of course a much worse multitrack resolution; one can assume in this case the resolution element to have a size given by the product of length and pitch of the anodes times the resolution in the drift direction. In a typical TPC geometry, this would correspond to a pixel of $4 \times 1000 \times 15 \text{ mm}^3$. Even at moderate multiplicities, tracks have a fairly large chance of overlapping in time as seen by the anodes, and the usefulness of the wire information becomes questionable.

At the simplest level, when analysing the multitrack capability of a TPC, one can assume the total sensitive volume to be divided into independent pixels of a size corresponding to the quoted resolution; this is of course rather optimistic, since it does not take into account the widening of the PRF and the correlations between adjacent resolution elements due in particular to the angle of the tracks and to the ionization statistics. In a recent study for a high-multiplicity TPC suitable for detecting nucleus-nucleus collisions, the authors have computed the expected probability of multiple, non-resolved, hits on pads and wires [14]. Figure 12 shows their results for collisions at 1 GeV per nucleon, as a function of angle off the beam axis in the proposed TPC (see Fig. 4). Curves in each

figure refer to different choices of geometrical parameters in the end-cap MWPC; in the cathode plane (left figure) the pads have a size of $5 \times 5 \text{ mm}^2$ (curve a), $10 \times 10 \text{ mm}^2$ (curve b) and a variable size, between these two values, adjusted to the local rate (curve c). For the wires (right figure) the multiple-hit probability has been computed again for various assumptions on the wire spacing and length. While the loss seems to be tolerable for the pads, especially for the smaller size, the wire information is made almost useless by the pileup of signals.

It seems obvious that one way to cope with the high multiplicities of nucleon collisions is to realize a TPC with, as the only readout electrode, a cathode plane with a very fine subdivision into pads over its whole surface. The considerations of the previous section on the intrinsic width of the PRF limit the minimum useful pad size to about $5 \times 5 \text{ mm}^2$; this implies the use of around 40,000 readout channels per square metre of detection in the end-cap MWPC. On the other hand, in a fixed-target experiment the charged-track density decreases with the production angle; in Ref. [14] various solutions have been described that allow adjustment of the pad size to the local multiplicity, thus reducing the required number of electronic channels. This approach, however, is probably not applicable around a collider, and moreover might seriously spoil the pattern recognition capability of the detector for events, such as jets, having high multiplicities at large angles. Notice also that the previously discussed dispersive effect, appearing when one pad detects the induced signal from several adjacent wires, could be corrected for by exploiting the measurement of pulse heights on each anode; this no longer appears to be feasible at high multiplicities. It seems a priori that an end-cap MWPC designed with individual channels containing the anode wires and the facing pad row, such as the TRIUMF TPC [23], should be preferred in this case, since it completely avoids the problem. The somewhat more involved mechanical construction of the MWPC should be compensated by an increased reliability, since one can easily imagine a way to disconnect a defective or broken wire without affecting all the others (such is not the case for the standard construction). A variable pad and wire pitch, adjusted to the local rate, is also easy to conceive in this design.

It should be recalled at this time that all previous considerations apply to a sample of tracks producing comparable energy losses; a multiply charged ion, providing much larger ionization densities, adds a serious problem of dynamic range to the detector electronics. If the induced charge is large enough to saturate one or more amplification channels, a severe loss of two-track resolution will result. For an ion collider, this might be a very severe technical problem to solve.

4.2 Space charge in the drift volume

Positive ions, produced in the avalanches, drift along the field lines towards the various electrodes, and are neutralized there. Because of the low mobility of ions (thousands of times slower than electrons at equal fields) a positive space charge is created, with as a consequence a local distortion of the electric field. This is particularly disturbing in the drift space, an extended region of moderate electric field; in a typical TPC geometry, ions will take around a third of a second to cross a 1 m long drift space. At any given time, the charge density in the volume V is given by $\rho = NTe/V$, where T is the total drift-time of the ions and N their production rate per unit time. This rate, in turn, is given by $N = nM\epsilon$, n being the number of primary ionization charges released per unit time, M the multiplication factor of the chamber, and ϵ the ion feedback efficiency.

Only a fraction of the ions generated at the anodes migrate into the drift space; for a uniform avalanche distribution around the wires, one would expect that half of the ions are collected by the padded cathode, and of the remaining half only a fraction, equal to the ratio of fields in the drift region and in the MWPC, usually about 20%, really contribute to the creation of the space charge in the drift space. It has however been shown [30] that, at least at moderate gains in the MWPC, the ion feedback into the drift region can be higher than a purely electrostatic calculation would indicate, because of the preferential development of the avalanches around the original direction of approach

of the electrons. At a gain around 10^4 , the authors measured an ion feedback efficiency close to 40% as compared to 8% expected from a calculation assuming uniform charge distributions.

The electric field modification in a layer of thickness L can then be estimated approximately from the expression $\Delta E = \rho L / \epsilon_0$. For example, in a 1 m long TPC operated in argon-methane at a drift field of 150 V/cm, the collection time for ions is $T \approx 0.3$ s; at a gain of 10^4 , and assuming a feedback efficiency $\epsilon = 0.4$, a minimum ionizing particle flux of 10^4 s^{-1} produces a positive charge density of about 10^{-8} C/m^3 . The consequent field modification is then, from the previous expression, about 1 kV/m, or 8%.

The positive space charge in the drift region modifies the field strength and therefore the drift velocity; for spatially non-uniform ion production rates (such is always the case in a practical detector), transverse components of field are generated and result in distortions in the trajectories of drifting electrons, even more so in the presence of a magnetic field. In a small TPC having a drift region 200 mm thick, a lateral deflection of about 1 mm has been measured for tracks drifting close to a local charge density equivalent to that produced by a minimum ionizing particle flux of about $10^3 \text{ cm}^{-2} \text{ s}^{-1}$ at a proportional gain of around 10^4 [30].

A solution to the problem of positive space charge in the drift volume has been found by introducing a gating electrode before the MWPC, made transparent to electrons only on selected events. Originally developed for high-rate multistep chambers [31], gating was included in the Berkeley TPC [32]. The gating electrode consists of a mesh of close parallel wires alternatively polarized to opposite potentials so as to block all drifting charges. In coincidence with events recognized of interest by an external trigger, the gating wires are pulsed at a potential restoring transparency for a time as long as the maximum drift of electrons from the sensitive volume, a few tens of microseconds. Figure 13 shows the electric field lines in a TPC with the gating electrode in the open and closed configuration [21]. Gating has been tested and introduced in the design of most TPCs [32–37]. The positive ion feedback is then reduced by the trigger rate. One should, however, note that the noise pick-up of the gating pulse usually prevents the electronic detection of tracks for 1 or 2 μs , thus reducing the effective sensitive volume. It has also been found that the different magnetic behaviour of ions and electrons allows the realization of an electrode structure transparent for electrons but strongly suppressing ion feedthrough [38, 35]. All these solutions however, while effectively increasing the rate capability of a TPC, introduce further distortions in the trajectory of electrons roaming around the additional electrodes in the presence of magnetic fields (see the previous discussion on the $\vec{E} \times \vec{B}$ effects).

4.3 Space charge in the MWPC

The positive space-charge buildup in the gap of the MWPC results in a reduction of the electric field close to the anode wire surface, and therefore of the effective gain of the chamber. Because of the MWPC geometry, this effect depends on the charge flow per unit length of wire more than on the surface rate (closer wire spacings reduce the charge rate on each wire at a given flux). An example of such a measurement is given in Fig. 14 [39], showing the relative gain reduction plotted as a function of the charge rate and current per unit length of wire; points measured at different avalanche sizes (different gains) all follow the same trend; the critical space-charge density for gain reduction is observed at $10^9 \text{ electrons s}^{-1} \text{ mm}^{-1}$. At a gain around 10^4 and in the detection of minimum ionizing particles, this would correspond to a rate of $5 \times 10^5 \text{ s}^{-1} \text{ cm}^{-2}$ for a 2 mm pitch MWPC. There is no simple remedy for this effect, apart from operating the chamber at the lowest possible gain; gating, as described in the previous section, reduces of course the ion production rate (except for that fraction of ionization produced directly in the MWPC by traversing particles).

The described gain reduction as a function of rate is an average effect caused by uniformly distributed charges. It appears that on the tiny segment of the anode wire interested by a single

avalanche, the field modification can be already so large as to reduce the gain for a second electron cloud approaching a close spot, and this for extended lengths of time (tens of microseconds). Such an effect has been observed using a double laser beam simulating the ionization of fast charged particles, in a geometry such that both tracks are detected on very close regions of the wire [40] (see Fig. 15). The abscissa gives the ratio of pulse heights of the second to the first track, as a function of proportional gain. At gains above 10^5 the second track is no longer detected; similar effects are quoted in Ref. [27]. In the case of charged nucleons, producing orders of magnitude larger ionization densities, this blinding effect might appear at much lower gain. This point certainly requires further investigation in order to properly estimate the two-track resolution around a heavy-ion collider.

4.4 Self space-charge effects

When electrons reach the anode with a time spread, always the case for extended tracks, ions generated at early times can modify the field in such a way as to reduce dynamically the gain for later fractions of the same track. Usually this time-dependent gain reduction is not observed in the integral of the detected charge, because of the fast collection time, but as a practical consequence the gain appears to depend on the angle of the tracks with respect to the anodes. An example is given in Fig. 16 [41], which shows the pulse height (normalized to the effective track length) as a function of voltage, measured in a thin-gap MWPC for various angles of incidence of a minimum ionizing particle beam ($\alpha = 0$ corresponds to tracks perpendicular to the anode). At high voltages, the detected charge, and therefore the apparent gain, is much larger for inclined tracks; this is obviously a consequence of the spread of the avalanches along the wire, mitigating self space-charge effects. The effect persists even at low gains, 10^4 or so, and its relevance for TPCs exploiting the measurement of energy loss for particle identification should be taken into account; in principle, a correction to the data making use of the measured angle is of course possible. The dependence of gain on the time structure of the ionization explains the loss of energy resolution in proportional counters above a critical detected avalanche size of about 10^6 electrons, verified in a wide range of primary ionization densities (see for example Refs. [42] and [43]).

Being charge-density dependent, the effect is bound to be more severe for heavily ionizing particles; while angular effects seem not to have been reported so far, measurements exist for the proportionality (or, better, the lack of proportionality) between energy loss and detected charge, in fixed geometry, as a function of the ion charge. An example is given in Fig. 17 [44] showing the detected pulse height as a function of operating voltage for various ions (strict proportionality would imply, of course, parallel lines in the logarithmic scale). While disturbing for measurements of energy loss and ion identification, the saturation of detected signals at high charge densities might in fact be handy since it reduces the dynamic range required for the amplifiers.

5. ALTERNATIVES TO THE STANDARD TPC DESIGN

I have discussed, in the previous sections, various problems arising in the TPCs at high rates and multiplicities. It appears that one way of improving the tracking and multihit capabilities of the device is to realize the end-cap MWPC with the smallest possible gap and pad size; a realistic limit, with the present technologies, could be around 3 mm for the gap, with perhaps 1 mm spacing between anodes and field wires; a pad size of $3 \times 3 \text{ mm}^2$ would then be the optimum choice based on the previous considerations on the PRF. At high rates, one would ignore the anode wire information, and only read out the induced-charge profiles on pads. With full covering of the cathode surface, this implies a readout of around 10^5 channels per square metre, a rather frightening number that will become feasible only following the availability of dedicated large scale integrated circuits (the TPCs of the present generation have typically 20 to 40 thousand instrumented readout channels).

Several groups have realized or proposed alternatives to the standard design, in an attempt to improve the performances of the device at high rates. One was already mentioned, the individually encased anode wires in the TRIUMF TPC; at the price of an increased mechanical complexity, it avoids interactions between adjacent wires in the signal-induction process and improves the reliability of operation. On the other hand, the problems associated with high rates and multiplicities are substantially the same.

The TPC built for the NA36 experiment at CERN [45], actually the first designed and operated specifically for studying collisions between heavy ions and nuclei, represents an attempt to increase the rate capability by splitting the anode wires into very short segments not connected together and individually read out. A similar device is under construction at Brookhaven [46, 47]. The basic design of the end-cap MWPC is shown in Fig. 18; it consists of 40 rows of 1 cm long anode wires, having a 2.54 mm pitch and alternated with field wires, facing the cathodes with a very small gap (2 and 3 mm, respectively, from the lower printed circuit cathode and from the upper wire mesh). Only the anodes are read out: this has the noticeable advantage, as compared to a pad readout, of providing larger signals for the same gain. Moreover, the multitrack resolution in the direction of the rows corresponds to the wire pitch and not to the width of induced signals on the pads as in the standard design; the pixel size is in this case $2.5 \times 10 \times 10 \text{ mm}^3$. On the negative side, the device is very likely not suitable for measurements of energy loss (not required by the experiment, which indeed makes use of a purely digital recording of the wire information), since the gain profile along the segments of wire is certainly far from uniform (owing to the influence of the insulators at the edges, see for example Ref. [10]); its construction is also much more intricate than the standard one. Figure 19 shows a three-dimensional display of an event, recorded with the NA36 TPC for an ion-nucleon collision. The experiment itself is designed in such a way as to limit the average multiplicity in the detector to about 20 charged tracks, mostly minimum ionizing, and is therefore not very demanding in terms of multitrack capability.

The alternative designs discussed above are aimed at improving the tracking capabilities of the TPC, but are substantially equivalent to the standard device concerning the problems generated by the positive space charge at high fluxes and multiplicities. Gating can be used to reduce the rate effects, but on the one hand that implies the availability of a very selective fast trigger, and on the other hand the self space-charge effects described in Section 4.4 remain unsolved. It was proposed some time ago [48, 49] to replace the MWPC end cap with a parallel-plate avalanche chamber (PPAC), a device intrinsically capable of withstanding very high charge densities without a decrease in gain. This kind of gaseous detector, where multiplication is obtained between two parallel foils or meshes in a uniform electric field, is widely used for the detection of heavily ionizing particles; it is indeed in many respects, such as time and energy resolution, superior to MWPCs (see, for example, Refs. [50–52]). The major limitation to a wider use of the device comes from the fact that the maximum gain attainable is usually restricted by spark breakdown to 10^3 – 10^4 , depending on gas and geometry, when operated at atmospheric pressure (indeed, for most applications in the detection of heavily ionizing particles, PPACs are filled by a gas at low pressure, where operation is much more reliable). A TPC designed for the tracking of minimum ionizing particles cannot of course be operated at low pressures, because of both the low ionization yield and the mechanical constraints due to the large sensitive volume required.

The reason for a better gain uniformity of the PPAC at high fluxes can easily be understood. The electric field in a MWPC is high around the anode wire and decreases very quickly away from its surface; avalanche charge multiplication begins above a critical value of the field, rather close to the wire surface. The effect of a positive-ion cloud in the gap is to decrease the field on the anode side, thus reducing the gain; the small increase within the gap is irrelevant. In the PPAC, on the other hand, the field is uniform over the whole gap, and multiplication occurs all the way through; a

positive space charge, while decreasing the field (and the gain) on the anode side, increases its strength on the cathode side, and in first approximation the overall gain is unaffected. Figure 20 shows indeed the gain as a function of rate, measured detecting 8 keV X-rays in a small TPC having a parallel-plate end cap (full curve) [48], compared with a similar measurement in a typical MWPC (dashed curve); there is no detectable change in pulse height up to the highest flux. Taking into account the gain, 3.2×10^4 , and the number of ionization electrons released in each event, a rate of 10^5 in the figure corresponds to 10^{12} electrons $\text{s}^{-1} \text{mm}^{-2}$ (compare also with Fig. 14).

Because of the geometry of the multiplying element, charges are directly collected on the last electrode, stripped or padded, and therefore the signal width is small and corresponds to the avalanche size; about 1 mm FWHM has been measured for a localized avalanche, an order of magnitude better than for signals induced in an equivalent MWPC. Figure 21 shows an example of charge profile detected on the last electrode of a PPAC, having readout strips 500 μm wide, for tracks perpendicular to the plane and 2.5 mm apart: they are fully resolved [31].

A small size TPC with a PPAC end cap has been successfully operated in the detection of soft X-rays and minimum ionizing particles [53, 54]. Because of the particularities of the charge multiplication in uniform fields, most of the detected signal is due to the electron collection and is therefore very fast (the contribution of ions, a constant current, can easily be differentiated away); the vertical, or drift, resolution around 1 mm is correspondingly better than in a standard TPC. Problems have appeared however for operation in high magnetic fields; the PPAC tends to spark at lower voltages when exposed to the beam than in the absence of a magnetic field, thus preventing operation at full efficiency [54]. The reasons for this behaviour are obscure; it may be due to the strong reduction in the transverse electron diffusion coefficient, with a consequent increase of the charge density in the avalanches. More experimental work is certainly required on the subject, particularly to optimize the choice of gas and geometry, before attempting to use the PPAC as a reliable end-cap multiplier for TPCs. Use of a multistep PPAC, with its proven better stability of operation at high gains and rates [31], may also help to solve the breakdown problem. The simplicity of construction (no thin wires) and the superior performances make this design of detector worth very serious consideration for high multiplicities.

As a final remark, I would like to mention that, even in the most optimistic assumptions on the performances of the TPC and on the improvements made perhaps possible by the alternative designs of the end cap, it might turn out that events overlap so badly at the highest multiplicities as to make tracking almost hopeless with the device. Since the major limiting factor in the TPC is generated by the pileup, in time and space, of the detected ionization in the multiplying element due to the long active drift space, one might have to abandon altogether the idea of the time slicing with a single detector—which is so attractive since it limits the instrumented region to a surface—and have recourse to a stack of wire chambers with short drift regions filling the desired volume (for a general review on multiwire three-dimensional detectors see, for example, Ref. [55]). An example of a detector of this kind is the multidrift tube, under development in our group at CERN [56, 57]. Conceived as a fast, high-multiplicity and high-resolution vertex detector, the device consists of an array of modules each containing close to a hundred independent drift cells. In each cell, constituted by an anode and six cathode wires in a hexagonal geometry (in the present design, 3 mm in diameter), the measurement of the drift-time and of the current ratio on both ends of the anode provides three-dimensional coordinates; tracks are sampled around ten times in each module. Figure 22 shows an example of tracks, recorded with the multidrift module: the outer diameter of the module is 30 mm. Because of the small cell size, close tracks are well resolved, and the maximum drift-time is around 30 ns. A full detector is then realized, stacking together as many modules as required. Again, the use of a multiwire detector, such as the one described for instrumenting large sensitive volumes,

will depend on the availability of cheap large-scale integrated circuits capable of measuring time and pulse height with the required accuracies.

REFERENCES

- [1] G. Charpak et al., Nucl. Instrum. Methods **62**, 235 (1968).
- [2] G. Charpak, D. Rahm and H. Steiner, Nucl. Instrum. Methods **80**, 13 (1970).
- [3] G. Charpak, Annu. Rev. Nucl. Sci. **20**, 195 (1970).
- [4] F. Sauli, CERN 77-09 (1977).
- [5] G. Charpak and F. Sauli, Annu. Rev. Nucl. Part. Sci. **34**, 285 (1984).
- [6] A.R. Clark et al., Proposal for a PEP facility based on the TPC, PEP-4 (1976).
- [7] The Time Projection Chamber, ed. J.A. Macdonald, AIP Conf. Proc. **108** (1984).
- [8] ALEPH Technical report, CERN/LEPC/83-2 (1983).
- [9] DELPHI Technical proposal, CERN/LEPC/83-3 (1983).
- [10] S.R. Amendolia et al., Nucl. Instrum. Methods **A252**, 399 (1986).
- [11] F. Sauli, Basic processes in the time projection like detectors, in Ref. [7], p. 171.
- [12] Event generated by the Wisconsin University group in ALEPH.
- [13] H. Aihara et al., IEEE Trans. Nucl. Sci. **NS-30**, 63 (1983).
- [14] H.G. Pugh et al., EOS: A TPC for the study of nucleus-nucleus collisions at the Bevalac, Berkeley report LBL-22314 (1986).
- [15] L. Rolandi, Space resolution of the TPC, Trieste report INFN/AE-86/5 (1986).
- [16] E. Gatti et al., Nucl. Instrum. Methods **163**, 83 (1979).
- [17] E. Mathieson and T.J. Harris, Nucl. Instrum. Methods **159**, 483 (1979).
- [18] H. Van der Graaf and J.P. Wagenaar, Nucl. Instrum. Methods **A252**, 311 (1986).
- [19] R. Bellazzini et al., IEEE Trans. Nucl. Sci. **NS-32**, 389 (1985).
- [20] S. Amendolia et al., Nucl. Instrum. Methods **A252**, 392 (1986).
- [21] S.R. Amendolia et al., Nucl. Instrum. Methods **A235**, 296 (1985).
- [22] M. Benetta et al., IEEE Trans. Nucl. Sci. **NS-32**, 605 (1985).
- [23] D. Bryman et al., in Ref. [7], p. 12.
- [24] W. Blum et al., Nucl. Instrum. Methods **A252**, 407 (1986).
- [25] S.R. Amendolia et al., Nucl. Instrum. Methods **217**, 317 (1983).
- [26] H. Hilke, Nucl. Instrum. Methods **252**, 169 (1986).
- [27] A. Wagner, paper presented at Int.Conf. on Advances in Experimental Methods for Colliding Beam Physics, Stanford, 1987 (to be published by Nucl. Instrum. Methods).
- [28] D. Schaile, O. Schaile and J. Schwarz, Nucl. Instrum. Methods **A242**, 247 (1986).
- [29] A. Peisert, Preliminary results of the two-track resolution in TPC90, ALEPH TPC note 85-16 (1985).
- [30] D. Friedrich et al., Nucl. Instrum. Methods **158**, 81 (1979).
- [31] A. Breskin et al., Nucl. Instrum. Methods **178**, 11 (1980).
- [32] P. Nemethy et al., Nucl. Instrum. Methods **212**, 273 (1983).
- [33] S.R. Amendolia et al., Nucl. Instrum. Methods **A234**, 47 (1985).
- [34] D.A. Bryman et al., Nucl. Instrum. Methods **A234**, 42 (1985).
- [35] S.R. Amendolia et al., Nucl. Instrum. Methods **A239**, 192 (1985).
- [36] S.S. Amendolia et al., Nucl. Instrum. Methods **A252**, 403 (1986).
- [37] C. Brand et al., Nucl. Instrum. Methods **A252**, 413 (1986).
- [38] J. Kent, Positive ion suppression with untriggered TPC, Collège de France report LPC 84-17 (1984).
- [39] A.H. Walenta, Phys. Scripta **23**, 354 (1981).
- [40] I. Va'vra, IEEE Trans. Nucl. Sci. **NS-30**, 82 (1983).
- [41] H. Frehse et al., Nucl. Instrum. Methods **156**, 87 (1978).
- [42] P.W. Benjamin, C.D. Kernshell and J. Redfearn, Nucl. Instrum. Methods **59**, 77 (1968).

- [43] S. Behrends and A.C. Melissinos, Nucl. Instrum. Methods **188**, 521 (1981).
- [44] T. Kobayashi et al., Berkeley report LBL-22164 (1986).
- [45] C. Gruhn, Nucl. Phys. **A461**, 391 (1987).
- [46] S. J.Lindenbaum et al., Nucl. Phys. **A461**, 431 (1987).
- [47] W.A. Love, TPC spectrometers for AGS and RICH, presented at this conference.
- [48] A. Peisert, Nucl. Instrum. Methods **217**, 229 (1983).
- [49] H.J. Hilke, Nucl. Instrum. Methods **217**, 189 (1983).
- [50] G. Hempel, F. Hopkins and G. Schatz, Nucl. Instrum. Methods **131**, 445 (1975).
- [51] H. Stelzer, Nucl. Instrum. Methods **133**, 409 (1976).
- [52] J. Sernicki, Nucl. Instrum. Methods **212**, 195 (1983).
- [53] A. Peisert and F. Sauli, Nucl. Instrum. Methods **A247**, 453 (1986).
- [54] C. Gruhn et al., Nucl. Instrum. Methods **A247**, 460 (1986).
- [55] F. Sauli, Three-dimensional gaseous detectors, preprint CERN-EP/87-193 (1987), Invited talk at the London Conf. on Position-Sensitive Detectors, London, 1987 (to be published in Nucl. Instrum. Methods).
- [56] R. Bouclier et al., Nucl. Instrum. Methods **A252**, 373 (1986).
- [57] R. Bouclier et al., preprint CERN-EP/87-89, paper presented at Int. Conf. on Advances in Experimental Methods for Colliding Beam Physics, Stanford, 1987 (to be published by Nucl. Instrum. Methods).

Figure captions

- Fig. 1: Schematics of the ALEPH TPC (a) and of the end-cap geometry (b) [10].
- Fig. 2: Three-dimensional display of a simulated event in the ALEPH TPC [12].
- Fig. 3: Differential energy loss as a function of momentum, measured in the Berkeley TPC [13].
- Fig. 4: A simulated event in a Au–Au collision at 1 GeV per nucleon, as seen in a proposed TPC [14].
- Fig. 5: Schematics of the detection process on the end-cap MWPC in a TPC (a) [15], and the corresponding induced signals as a function of pad number (b) and of time (c).
- Fig. 6: Three-dimensional induced charge profile on cathodes for a point-like avalanche (a) [19], and the corresponding PRF computed for various pad widths (b). For extended tracks, the dependence of the width of the PRF as a function of angle is shown in (c) [19].
- Fig. 7: The width of the PRF (normalized to the pad width) measured as a function of magnetic field, for various drift distances [20].
- Fig. 8: The $\vec{E} \times \vec{B}$ effect: width of the PRF for real tracks in a magnetic field, as a function of angle, measured in the TRIUMF TPC (a) [23], and the corresponding localization accuracy, measured with the ALEPH prototype (c) [15].
- Fig. 9: Degradation of the resolution due to the statistics of energy loss, in the case where several adjacent wires contribute to the signal induced on one pad (a) [25]; a suitable correction taking into account the anodic pulse height restores the resolution (b) [15].
- Fig. 10: Two close tracks, 1 cm apart, generated by laser beams and reconstructed in a jet chamber [27].
- Fig. 11: Charge detected in a typical MWPC for minimum ionizing particles at several gains, as a function of the time constant of the amplifier (full curves), and corresponding typical electronics noise for various input transistors.
- Fig. 12: Multihit probability in a Au–Au collision, computed for pads (left) and wires (right) in the TPC proposed for nucleus–nucleus collisions [14].
- Fig. 13: Electric field configuration in a gated TPC, with open and closed gate respectively [21].
- Fig. 14: Measured rate dependence of the detected charge in a MWPC [39].
- Fig. 15: Modification of the gain for the second of two tracks hitting close spots on the wire, as a function of gain [40].
- Fig. 16: Angular dependence of the gain for charged tracks as a function of multiplication factor; the ordinate gives the detected charge, normalized to the track length [41].
- Fig. 17: Pulse height as a function of operating voltage measured in a drift chamber for several ionizing nuclei [44].
- Fig. 18: Schematics of the NA36 TPC, showing the end-cap geometry with rows of short anode wires [45].
- Fig. 19: Three-dimensional view of an event recorded for nucleon–nucleon collisions at CERN with the NA36 TPC [45].
- Fig. 20: Rate dependence of the detected charge in a PPAC (full curve) [48], compared with the same measured in a MWPC (dashed curve).
- Fig. 21: Charge profile detected on the last electrode in a PPAC for two avalanches 2.5 mm apart; the pitch of the readout strips is 500 μm [31].
- Fig. 22: A track recorded with the multidrift tube [57]. The diameter of the module is 30 mm.

Fig. 1

Fig. 2

Fig. 3

TPC SIDE-VIEW

05/08/88

Fig. 4

Pad number

Time Slice

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

NA36 TPC

CENTRAL

RUN
TAPE
DATE 12
TIME 0
EVENT
568
37227
00105
22970

Fig. 19

Fig. 20

Fig. 21

Fig. 22