Multiwire and drift proportional chambers

These detectors, able to determine trajectory positions to better than 50 microns, now equip nearly every high-energy physics experiment in which charged particles have to be localized.

Georges Charpak

In some kinds of experiments, the accurate localization of ionizing particles is essential. Multiwire proportional chambers and drift chambers, first developed in the late 1960's,[1,2] are now routine tools in such applications. Although the structure of these detectors is very simple, our understanding of them has evolved rapidly in recent years, as has the variety of modes in which they have been operated. Here we shall consider briefly the operation of these detectors. Then we can proceed to a discussion of the latest developments, which aim to obtain information on the reaction products of the most complex high-energy collisions, with the utmost accuracy and efficiency. (Detailed descriptions of the detectors and their properties can now be found abundantly in the literature, which is extensively reviewed in references 3 and 4.)

Some early work, in 1968 and 1969,[1,2] revealed a few important properties of multiwire structures that boosted the study and use of this modern variety of proportional counters:

▶ Arrays of anode wires, whatever their distance, sandwiched between two cathode planes, constitute independent detectors. They localize ionizing radiation with an error equal to the wire spacing. Distances of 2 mm are now used for large detectors (several square meters), and 1 mm is usual for small detectors (20 cm × 20 cm).

▶ The signals induced on cathode strips or wires perpendicular to the anode wires permit the localization of the avalanches along the wires. This is an essential property for the localization of low-energy neutral radiation such as x-rays or neutrons.[2]

▶ The time lag between the production of ionization electrons in the filling gas and the appearance of a pulse could be used to determine the position of the initial trajectory. Our early work showed that accuracies of at least 100 microns were possible for a drift distance of several centimeters.[5] This observation led to a class of gaseous detectors called drift chambers, with a great variety of structures, where the localization relies on the measurement of time.

The simplest proportional counter consists of an anode wire, usually thinner than 50 microns, set at the axis of a cylindrical cathode, in a gas filling made typically of a noble gas with the addition of some molecular gas. The electric field, which varies as the inverse of the distance to the axis, collects the electrons liberated in the gas by some ionization radiation, and brings them close to the wire where they undergo inelastic ionizing collisions leading to a well localized avalanche. The maximum size of this avalanche is set by discharge propagation, mediated by the ultraviolet photons from the excited atoms that are left behind by the avalanche. Avalanche size varies with the gas composition and can reach a maximum close to 10^7 ions.

The motion and collection of the electrons and ions liberated in this avalanche cause the pulses on the anode, which are used for the detection of the ionizing event. Such counters were essential tools on the eve of nuclear physics in the 1930's and 1940's. They lost their importance after the introduction of the scintillation counters, which have better resolution times, higher rate capabilities and higher efficiencies for gamma rays. The tide has now turned again in favor of the proportional counter for many applications (see figure 1), due to a combination of progress in their conception and the recent revolution in electronics.

Multiwire chambers

A multiwire proportional chamber is usually made of planes of anode wires, sandwiched between two cathode planes (figure 2a). The distribution of equipotentials in a typical structure shows that there are three distinct regions of electrical fields: in most of the volume A, far from the anode wires, the field is uniform; just between the anode wires there is a small region B of weak field, and in region C close to the wires the equipotentials are concentric to the wires, as in an ordinary cylindrical counter. Since the avalanches develop only within a radial distance of the order of the wire diameter, we expect the same amplification properties on each wire as in a single proportional counter. If an ionizing particle liberates electrons in the filling gas those electrons will drift in the nearly uniform field and produce an avalanche only when they reach the closest wire.

It is rather surprising, at first glance, that when an avalanche occurs at an anode wire, inducing a *negative* pulse

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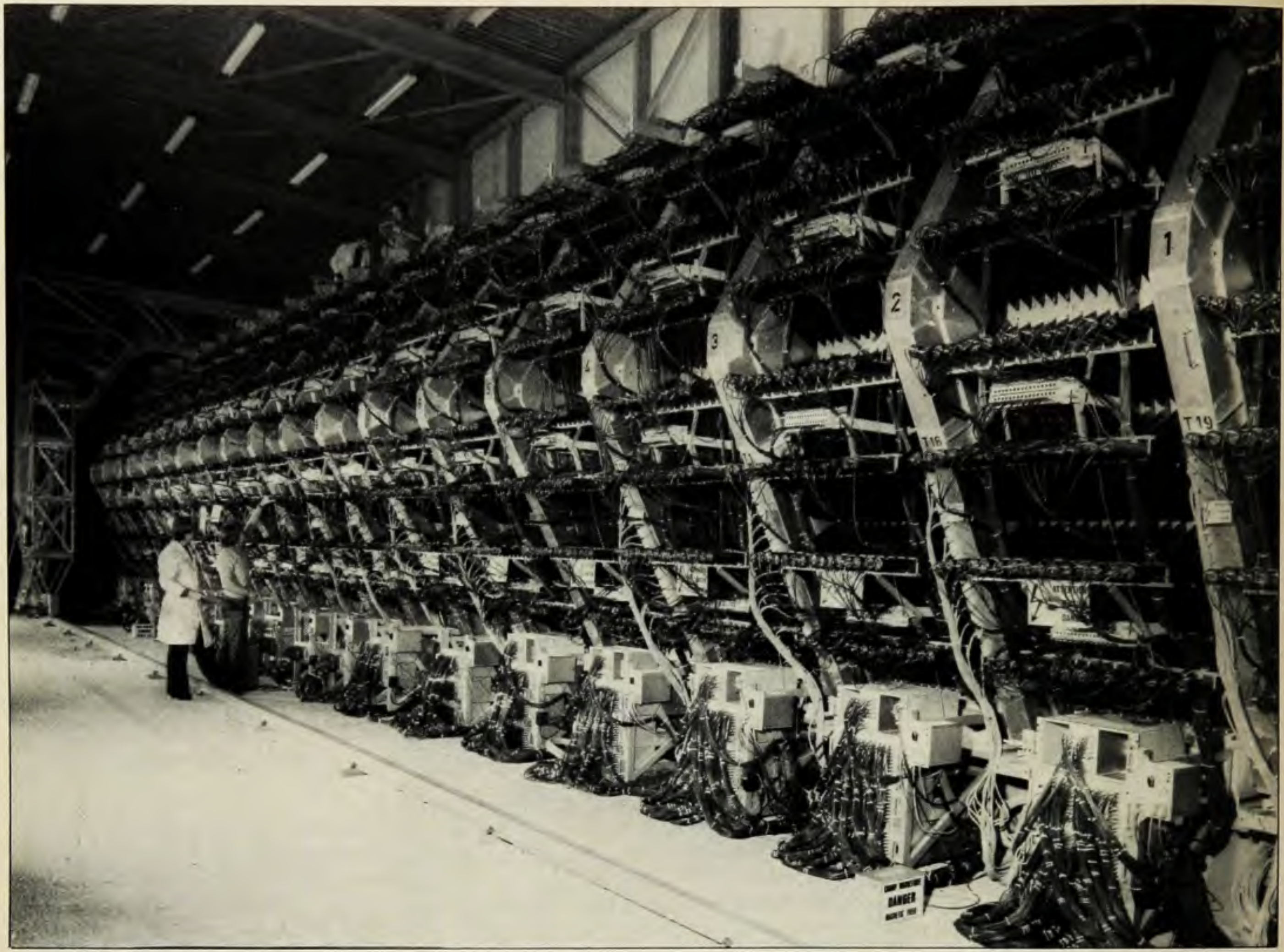


Neutrino detector with drift chambers at CERN. In this detector 1500 tons of magnetized iron interleaved with scintillation counters and large drift chambers sample the position of muon trajectories with an accuracy better than 1 mm. From reference 16. Figure 1

there, one does not observe a negative pulse on the neighboring wires as would be expected from simple capacitative coupling. What is observed is a *positive* pulse, thus making it very easy to localize the wire that is collecting the avalanche. As a consequence all anode wires are independent detectors, irrespective of their spacing, which can be as small as 0.5 mm, although 2 mm is the most practical minimum distance for the large counters (sometimes 5 m × 5 m) that are used in high-energy physics. Equipping every wire with a complicated circuit is easy now, and detectors with nearly 10^5 wires are in operation.

The factor that ensured the success of this structure is that the time resolution of the counters is very good: With 2 mm wire spacing, the maximum time taken by the ionization electron closest to a wire for any trajectory of a charged particle crossing the chamber is about 25 nsec. This is one order of magnitude better than the time resolution achievable with the simple cylindrical counters, where the low fields far from the wire lead to a slow collection of the ionization electrons; in a multiwire structure the collecting fields in region A (figure 2) are much stronger, the electrons drift faster and the nearest wire can be as close as 0.5 mm. However, the positive pulses induced on the neighboring wires not only provide the independence of detecting anodes: They are the results of a mechanism that permits localization of the position of the avalanches along the wire,[2] and this property turned the proportional chamber into the most promising device for the two-dimensional imaging of soft x-ray distributions and many other applications in which they can be as important and decisive as in nuclear physics.

Most of the positive ions are liberated close to the nearest anode wire A_i since the mean free path of ionizing collisions at atmospheric pressure is close to 1 micron. The lines of force from the charges go mainly to the wire A_i. As the ions move away from A_i fewer lines will go to it and more will go to the neighboring wires A_{i-1} and A_{i+1} and to the cathodes. In other words the charges induced on all electrodes except A_i are of the same sign, mainly positive, irrespective of the azimuthal position of the charges and irrespective of the direction of motion, provided they move away from A_i. This will not be true anymore if the charges reach the vicinity of a cathode which will then draw in most of the lines of force. But this occurs at a much later step, after nearly one hundred microseconds for 1 cm of gap. In most applications the electronics picks up only the fast pulses induced in the first tens of nanoseconds following the avalanches and within that time the positive ions, although moving in the very intense fields, higher than 10^5 volts per cm in the immediate vicinity of the wire, have not moved by more than 100 microns. The consequence of this pulse-formation mechanism is that if the cathodes are built in a segmented way, it is possible to obtain accurately from the relative size of the different induced positive pulses, the position of an avalanche along the wire and the azimuth angle of an avalanche with respect to an anode wire. Accuracy in the localization of the avalanches is limited practically only by the intrinsic physical fluctuations in the centroid of these avalanches, down to distances close to 10 microns.

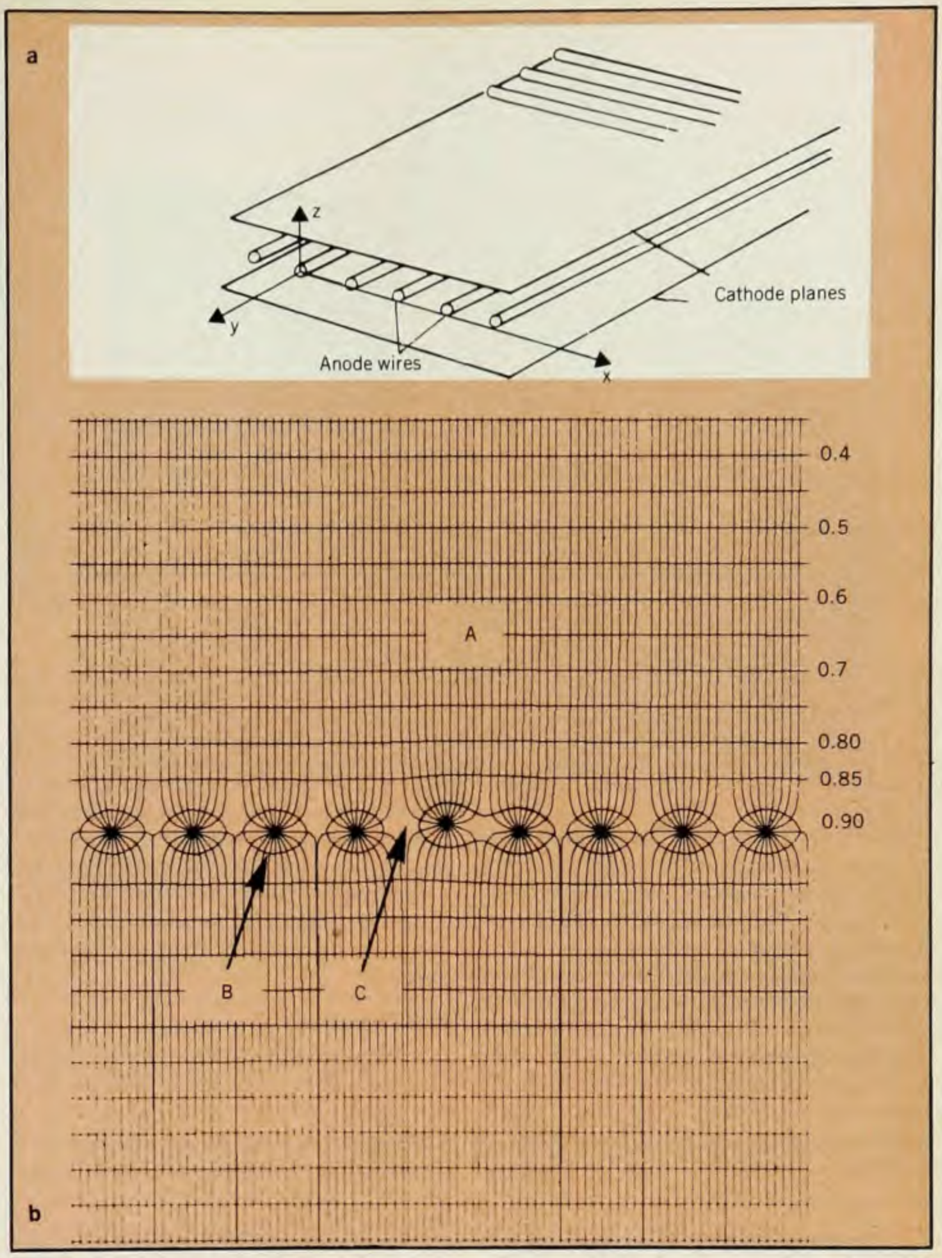
Information from the pulses

The cathodes of a multiwire chamber are usually uniform conductive planes when only the anode wires are used for the information about the position of the trajectories of particles. This is the case for chambers measuring only the dispersion in focal planes of particle spectrometers and also quite often in high-energy physics. The highly penetrating particles permit the stacking of many successive chambers, with the wires oriented in different directions. To obtain a multidimensional coordinate read-out of the trajectories when two-dimensional information must be obtained from a single chamber the structure is different. At least one cathode plane is made of strips or wires orthogonal to the anode wire (figure 3).

The pulses induced on those strips vary in magnitude as a function of their distance from the avalanche. Their centroid clearly must coincide closely with the position of the avalanche. Several analog methods have been invented to find this centroid. They rely either on delay lines or on resistive lines coupled in various ways to the cathodes. They were most widely used in the pioneering work with two-dimensional multiwire chambers.[6,7] It is interesting to consider another possibility—direct computation of the centroid of the induced pulses. By measuring directly the pulse height induced on the various strips or wires one gains much more information than just the position of the center of gravity, and what would have appeared a few years ago as only an investigative tool is now being considered as a good read-out method because of the fantastic decrease in the cost of electronic components performing fast complex computations.

A glance at the information obtained from the analysis of the pulse heights X_i on strips of coordinate x_i will be very useful for an understanding of the latest developments. With three collimated beams of 1.4-keV x rays, separated by 200 microns along the wires, we see in the distribution of the centroids, that is, in $\bar{x} = \sum x_i X_i / \sum X_i$, three peaks with an rms error of 35 microns (figure 4). Analysis of the sources of error shows that the electronics contributes only 10 microns, and the range of the photoelectrons contributes most of it. These are probably the most accurate measurements ever made in gaseous detectors at atmospheric pressure, with these energies.

If the second cathode plane is made of strips parallel to the wire, the centroids of the induced pulse also give the localization of the avalanche. Surprisingly enough, they do not simply show points corresponding to the position of the anode wires: Their distributions show that the avalanches usually do not surround the wires uniformly, as was believed in the early days of the multiwire chambers,[2] but are concentrated in a well defined angular range around the anode wire when they orginate from a point in the region of uniform field of the chamber.[8] This is best illustrated by the diagrams of figure

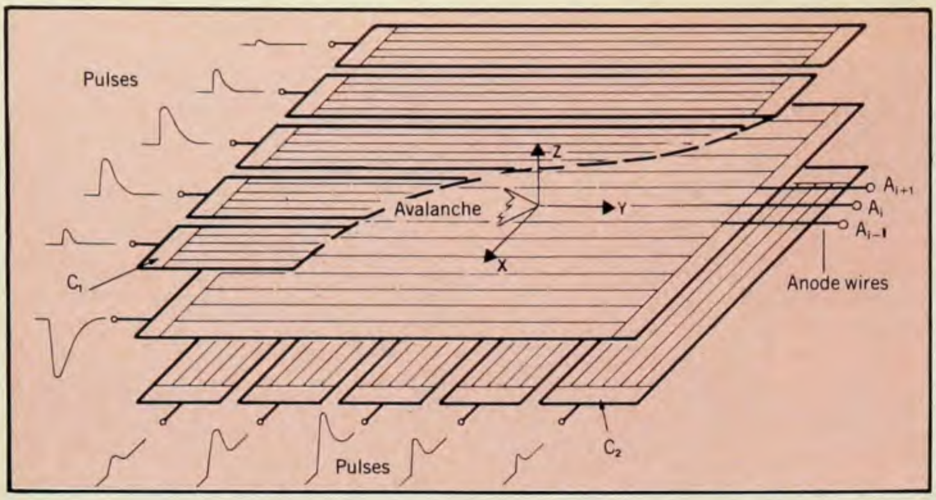


Multiwire proportional chamber is a grid of uniformly spaced thin anode wires, sandwiched between two cathode planes. Cathodes may consist of either uniform conducting foils or of wire grids (**a**). In this typical structure the distance between the wires is 1 mm, the cathode–anode distance is 8 mm and the wire diameter is 20 microns. When a symmetric potential difference is applied between anodes and cathodes, an electric field develops (**b**) in a plane perpendicular to the anodes. The two main field regions are a region (A) of roughly constant field, extending across most of the gap, and a region (C) of rapidly increasing field around the wires where avalanche multiplication occurs. Moreover, low-field regions (B) exist between the wires, with some consequences for the collection properties of the chamber. Figure 2

5, where the abscissa is the centroid of charges in the direction of the anode plane perpendicular to the wires, and the ordinate is the ratio of the total induced charges on the two opposite cathodes.

We see rings (a) at the position of anode wires, for a uniform irradiation of the chamber by 5.9-keV x rays producing short-range photoelectrons in the volume of the chamber. The meaning of the ring is clarified by observing the distribution, around one wire (b), from three narrow collimated beams of x rays orthogonal to the chamber, centered on the wire and at 500 microns on each side. The centroid distributions are clearly separated. Their position is strictly correlated to the position of the beam with respect to the wire, and to the site of absorption with respect to the anode plane. In other words it is now possible to tell where a photoelectron has been liberated between the wires of a multiwire chamber, whereas it had been accepted that the accuracy of multiwire chambers could not be better than the wire distance.

An illustration of this increased accuracy can be seen in figure 6, where the radiography of a simple object with 5.9-keV x rays is represented without interpolation (a) and with interpolation (b) between wires. Such progress may have



Localization by center of gravity of the induced pulses. The motion of ions leaving the vicinity of the anode wires in a multiwire proportional counter induces positive pulses on all surrounding electrodes. The centroid of the pulses is centered on the avalanche. For a coordinate x, the centroid $\bar{x} = \sum x_i X_i / \sum X_i$, where X_i is the charge induced on the strip centered at x_i. Figure 3

quite interesting implications in some astrophysics problems, where one wants to image 0.2-keV–5-keV x rays from grazing mirrors. Not many methods are available for a two-dimensional accuracy of this quality.

We have illustrated the properties of the chambers with soft x rays, which give rise to phenomena simpler than do particles, since the initial ionization is very localized. However, the read-out of the induced pulses, quickly and cheaply as made possible now by the development of electronics, also permits new uses of the chambers in particle physics.[8] Accuracies of 50 microns along the wire are obtained, with time resolution of 50 nsec. Interpolation of trajectories between wires is possible. The distinction of the "side" of a trajectory with respect to a wire is itself a gain by a factor of two in the spatial accuracy with respect to a read-out of the active anode wires. Despite the higher cost of this approach several powerful detectors are being built along this line. However, its main competition in large-size detectors is still the drift chamber, which has led to the construction of the cheapest large-size accurate electronic detectors currently being used in particle physics.

Drift chambers

An observation to which we attributed the greatest importance in 1968 was that the delay between the passage of a charged particle crossing a chamber and the detection of a pulse is correlated to the distance between the trajectory and the nearest wire.[1]

This delay is of the order of 20 nanosec per mm, and it was immediately foreseen[9] that with the available electronics, and with fast scintillation counters used to define the initial passage time of the particles, timing accuracies of the order of 1 nsec could be reached, leading to spatial accuracies of 50 microns.

At CERN we started a development program of detectors based exclusively on the time measurement and called them "drift chambers."[2] In its basic form, a single-cell drift chamber is a region of moderate electric field, where the electrons liberated in the gas drift to the wire of a proportional counter. In our initial work in 1968 the structure was similar[5] to this basic form. The electric field was uniform in most of the volume. We found that for drift lengths of the order of one cm, accuracies of 100 microns could readily be obtained, and with three successive chambers a timing accuracy of 5 nanosec could be obtained.[2,5]

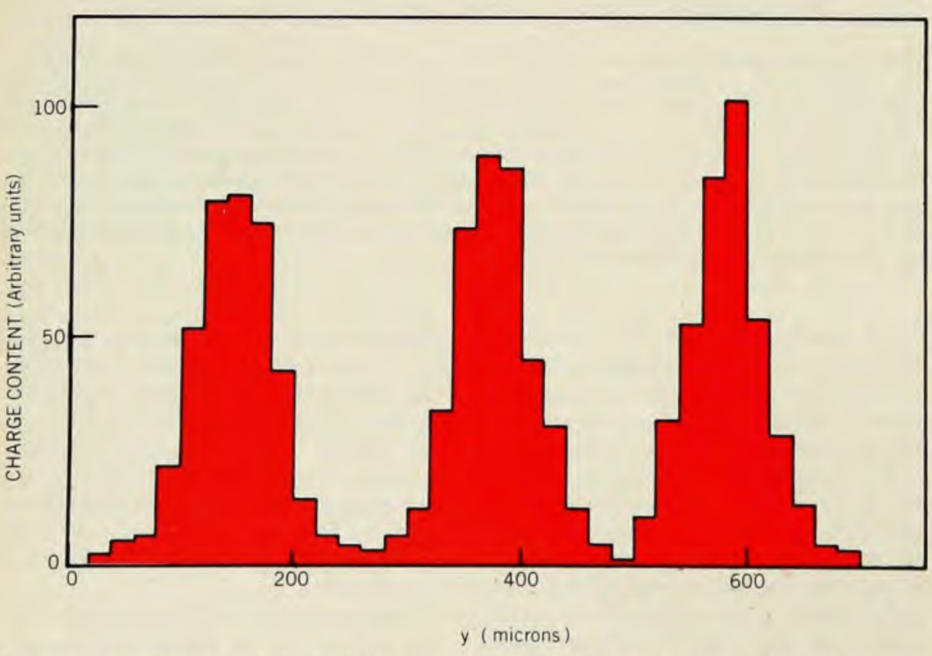
In 1969 a group at Saclay developed this type of structure for the localization of protons in a magnetic spectrometer with one important new feature: The drift length was 25 cm. It is certainly among the most original initial contributions to present-day drift chambers.[10,11] The accuracy they obtained illustrates the considerable advantage of drift chambers: a small number of detecting wires, and hence a much lower cost, permits localization of particles with extreme accuracy. Figure 7, taken from this work in 1969, shows no loss of accuracy within their measuring accuracy (which was 1 mm) over a drift distance of 25 cm.

In high-energy physics two requirements, sometimes conflicting, contributed to the fast development of drift chambers:

- Very high-energy particles have a small bending angle in magnetic fields and the higher the spatial accuracy the better the momentum determination. Accuracies of 100 microns are then extremely useful.
- Very large surfaces, of the order of hundreds of square meters, with an accuracy of 1 mm, are often necessary, and the cost of multiwire chambers with 2-mm wire spacing can be prohibitive. Long drift spaces permit a drastic reduction in the number of sense wires.

We developed drift chambers at CERN with a structure (figure 8) that is a simple repetition of the basic cell and in which the sense wire distance can be varied at will in a very wide range.

The detecting wire spacing varies from 5 to 15 cm in most very large detectors, some of which reach 6 meters. The desired accuracy is rarely better than a millimeter in these large detectors. For chambers of sizes below 50 cm, accuracies of 50 microns are now obtained. The accuracy decreases as $x^{1/2}$, where x is the

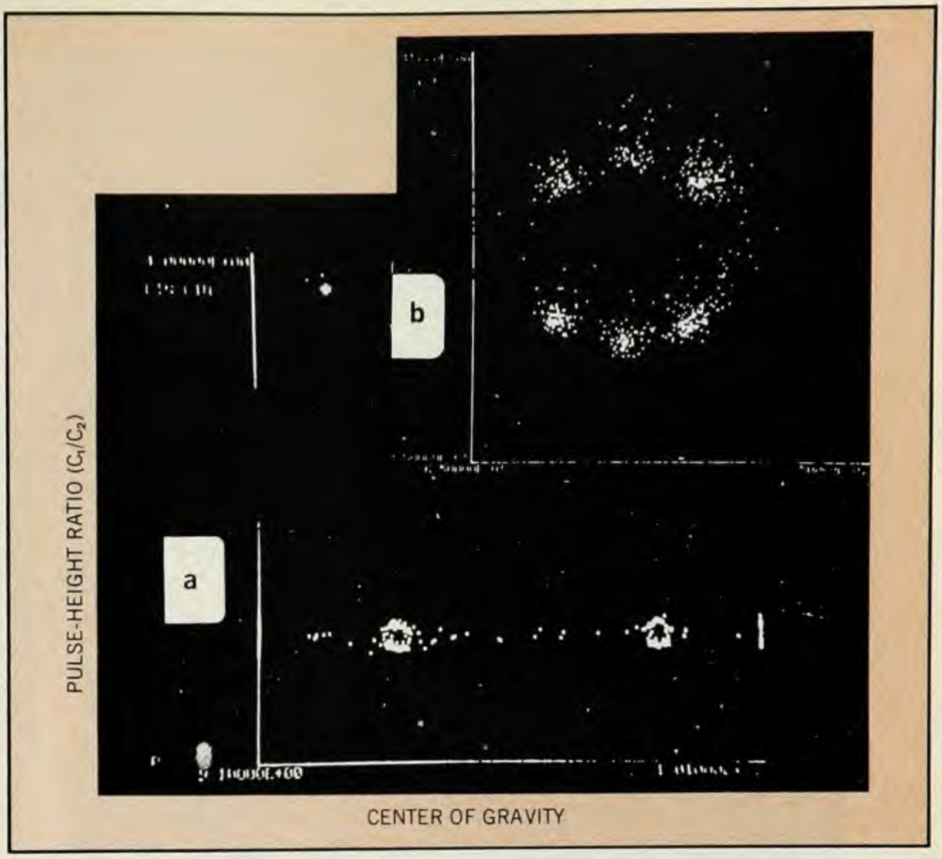


Precise localization of a soft (1.4 keV) x-ray beam along the y direction (parallel to the anode wires), with the center-of-gravity method. The computed coordinates for three positions of the collimated beam, 200 microns apart, are seen, with a localization accuracy of 35 microns. This value is rather close to the limit imposed by the range of the photoelectron. From reference 8. Figure 4 drift length, because of electron diffusion.

A somewhat different and simpler drift-chamber structure was investigated and developed at Heidelberg.[13] By keeping the structure of a simple wire chamber, with a wire spacing of about 1 cm, they were able to interpolate the position of the trajectories between the wires with accuracies of the order of 200 microns. In order to correct the weak field existing between the wires, an additional field wire repelling the electrons was added between the anode wires.

The mechanical construction is simpler since the cathode planes are at a uniform potential. The response is not linear, and such a structure does not permit a wire spacing larger than the chamber thickness. However, its simplicity makes this chamber attractive in many applications and the choice of a structure is not governed only by accuracy or cost considerations. A leading factor in the choice of a type of structure is often the maximum permissible rate. The limitation comes from the accumulation of slow ions around a wire. The maximum rate on a wire is about 10^4 counts per mm per sec. In this respect multiwire chambers are the best for high rates, followed by drift chambers of the latest type, which are better than very widely spaced wires. For applications in which accuracies of 100 microns are required in two-dimensional chambers, with very high rates as well as very high particle multiplicities to be detected simultaneously in a chamber, simple wire chambers of the Heidelberg type with measurement of the drift time for one coordinate and measurement of the charge centroid along the wire for the other coordinate may be a solution. The ambiguity resulting from the ignorance of which side of the wire the electrons arrive was initially forbidding. But we now know how to detect the side of arrival by using induced pulses on cathode wires or on adjacent wires.[8,14]

The structures we have described, and which played the greatest role in the introduction of drift chambers in particle physics, have not exhausted all the possibilities of drift chambers. Some ingenious ways have been found to obtain not only the positions but also the trajectory angles by measuring the detection times in a succession of adjacent wires.[15] Several such detectors were described in detail at a recent conference.[16] One of the most sophisticated drift chambers is described in this issue by Jay Marx and David Nygren (page 46).



Increased localization in the x–z plane, perpendicular to the anodes, is possible when the information provided by the induced pulses on the cathodes is fully exploited. In both pictures the horizontal scale is the measured center of gravity in the x direction, and the vertical scale is the ratio of total pulse heights induced on the two cathodes (or z coordinate). When the chamber is uniformly irradiated with a soft x-ray source, the majority of reconstructed points in this representation cluster in circles centered around the anode wires, with a few events in between, corresponding to energy-sharing between wires (**a**). Expanding the scales around one wire and exposing the chamber to three collimated beams produces the image shown in (**b**): the three beam positions differ by 500 microns, with the middle one centered on the wire. From reference 8. Figure 5

Uses for the new chambers

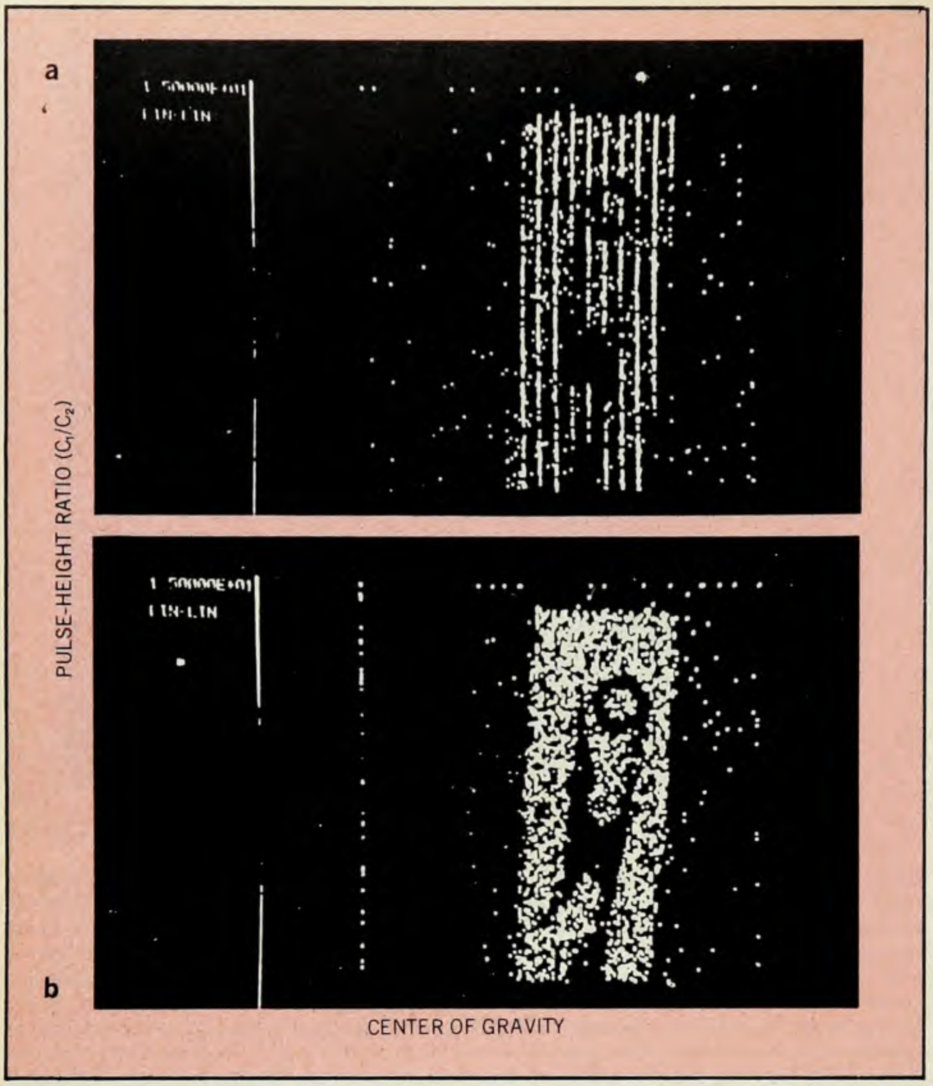
The multiwire and drift chambers are used not only in high-energy physics and nuclear physics but also in astrophysics, crystallography, nuclear medicine and other fields. The applications in high-energy physics range from simple wire planes used as counters to mammoth detectors with chambers that are meters in length and with the number of wires approaching 100 000. The cost of the circuitry for each wire can be as low as $10. This circuitry usually consists of an amplifier, adjustable delays, memory, inscription and readout gates. It permits counting rates of the order of 10^5 to 10^6 per wire and resolution times down to about 40 nsec.

Figure 9 shows the reconstruction, by a computer, of a complex event produced in the high-energy collision of two 30-GeV protons at the CERN storage rings. We see that the complexity of the configurations that can be disentangled approaches that to which we were so far accustomed only in visual detectors like bubble chambers or streamer chambers. For high accuracy, better than a millimeter, drift chambers are preferred to wire chambers. However, the need for large detecting surfaces with moderate accuracy for some experiments where the rates are reasonably low also leads to an increasing role for drift chambers. An illustration of this is a neutrino experiment at CERN, in which 1500 tons of magnetized iron, interleaved with drift chambers, permits the reconstruction of the trajectories of the high-energy muons produced by neutrinos of several hundred GeV (figure 1).

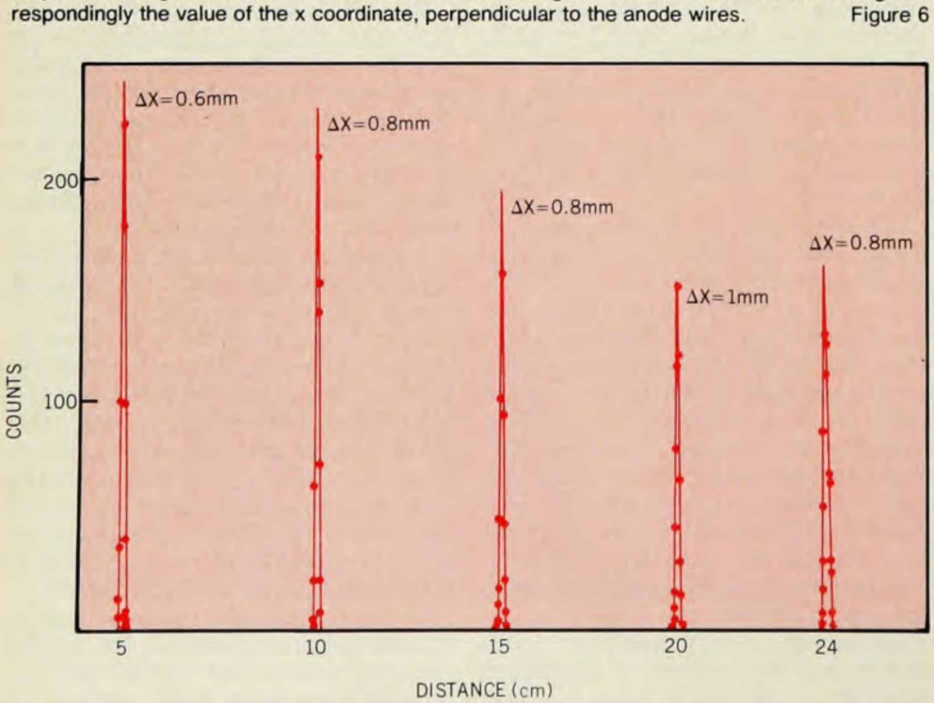
In nuclear-physics experiments the multiwire chambers are used for the localization in the focal plane of magnetic spectrometers. Chambers with pressures as low as 1 torr appear to be well suited to heavy-ion localization and exhibit surprisingly good resolution times (better than 1 nsec) and permit time-of-flight measurements of slow particles.[17]

Multiwire chambers and drift chambers are presently flown on the satellites that are the modern cosmic-ray laboratories. A special effort is invested in trying to adapt the chambers to the detection of low-energy x rays (0.2 keV to 5 keV) and high-energy gamma rays. The use of thin converters and drift chambers to measure accurately the position of the electron–positron pairs opens the way for determining the direction of gamma rays above a few tens of MeV. Resolutions of 0.3 deg are foreseen around 1 GeV.[18]

In crystallography and molecular structure, a growing use can be foreseen for multiwire chambers when they essentially replace films as two-dimensional screens for the read-out of diffraction patterns. The diffraction of x rays by crystals is a basic tool for the unfolding of



Absorption radiography of a simple object (a metal clip holding a ring) by means of a bidimensional chamber such as the one in figure 3. In (**a**) we see the centroids as computed directly from the induced charge distribution; the anode wire structure appears clearly. In (**b**) we see a continuous response, taking into account the measured azimuthal angle of the avalanche and correcting correspondingly the value of the x coordinate, perpendicular to the anode wires. Figure 6



Drifting electrons over large distances in a uniform field. Beam width is 0.6 mm. Almost no broadening is observed over the entire 25-cm drift length, showing that the intrinsic accuracy is much better than the beam width. From references 10 and 11. Figure 7

the molecular structure of the constituents of the crystals. With complicated molecules, such as proteins of molecular weights above 10 000, the intensities of hundreds of thousands of diffraction spots with considerable variations in their values must be measured. Several months of irradiation are sometimes needed to collect the information with films or by scanning the space with single small counters.

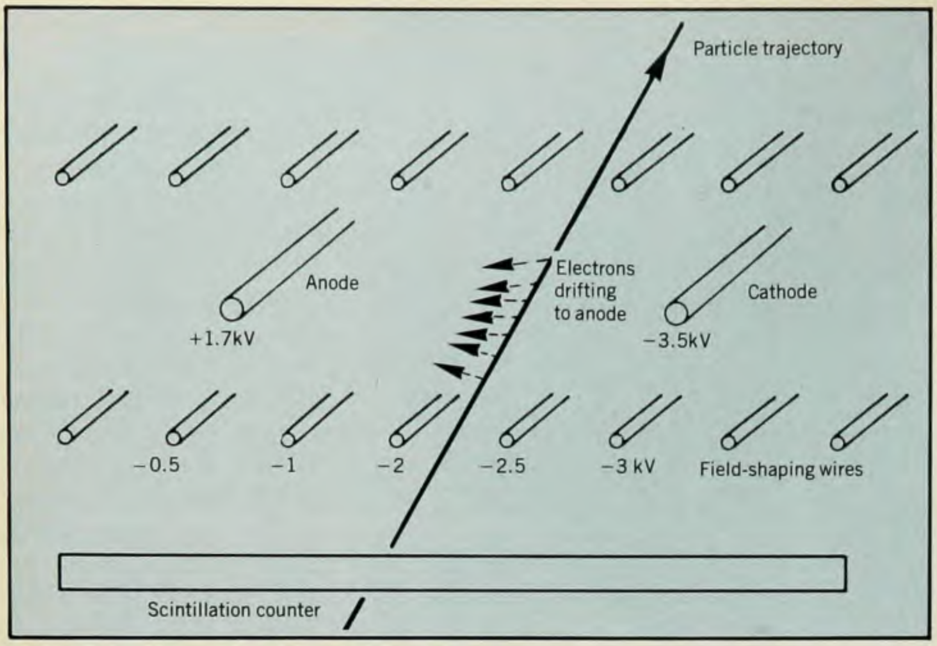
The two-dimensional multiwire chambers are adequate for this work. The introduction of new sources of x rays, the so-called synchrotron radiation from electron storage rings, has revolutionized this field by providing sources 1000 times more luminous than conventional x-ray tubes. The multiwire chambers can be a tool for the exploitation of these intense sources, and we can foresee gains by a factor of 1000 in the time taken to analyze the structure of a molecule.

The results of the pioneering work of Nguyen huu Xuong and his colleagues at San Diego[19] are extremely encouraging in this field, and a recent workshop at Stanford on the instrumentation needed to exploit synchrotron radiation is very illustrative of the growing importance of the chambers.[20]

The use of slow neutrons is another important tool in molecular-structure investigation. Intense sources of monochromatic neutrons are becoming available near intense specialized reactors. They permit the investigation of larger structures than do x rays, since matter can be transparent to neutrons of long wavelengths at which x rays are completely absorbed. Two-dimensional neutron detectors with multiwire chambers are being actively developed in these applications.[21,22]

The imaging of gamma rays is an important tool in medical diagnosis. Two-dimensional scintillation "Gamma-Cameras" are routinely used in thousands of hospitals. The multiwire chamber cannot compete with the Na I scintillators usually used in these instruments because of its lack of efficiency for gamma rays in the energy range most commonly used, well above 100 keV. However there are a few applications where the interest lies in the detection of low-energy gamma-rays, between 30 and 80 keV. In this case high-pressure xenon-filled chambers compete with scintillators, and use can be made of their much better spatial accuracy. Several groups in the US and in Europe are actively developing this field.[23,24]

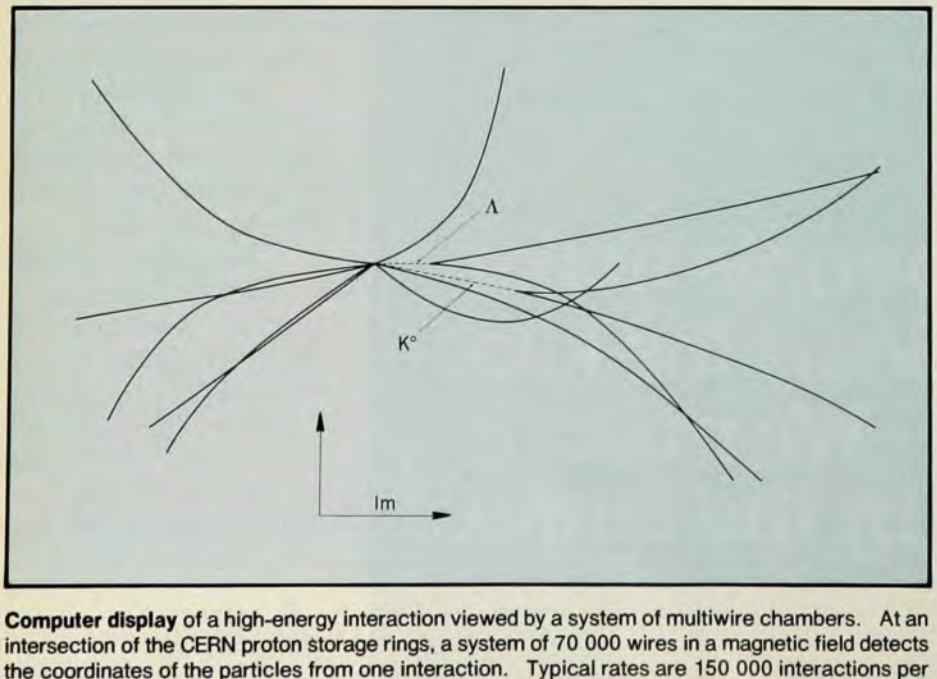
The development of multiwire and drift chambers has reached a stage in high-energy physics where they equip nearly every experiment in which charged particles have to be localized, and in the last ten years spark chambers have been gradually eliminated. Many bubble chambers now have huge external auxiliary equipment based on proportional



Construction principle of a multiwire drift chamber is seen in this schematic view. Cathode wires are connected to uniformly decreasing potentials, starting from ground in front of the anode. Field wires reinforce the field in the transition region to the next cell. The time between detection by a scintillation counter and the pulse on the anode wire gives the trajectory position. Figure 8

chambers. The bubble chamber is then used as a vertex detector in cases where the details of the particle configurations close to the interaction points are too complicated to be handled by a purely electronic detector, but where the limit of spatial extension of the bubble chambers does not allow efficient analysis of the great multiplicity of narrowly bunched jets emitted in the forward direction in ultrarelativistic reactions. However, even in this field the ambitions of the gaseous detectors are increasing, as will be clear from the Marx–Nygren article elsewhere in this issue.

The massive use of these detectors has also led to a much better understanding of the mechanisms underlying their operation. Accuracies better than 50 microns in the localization of fast particles have been reached by several methods. The arsenal of technology that has been developed is just beginning to be exploited in other domains. It may well be that its importance in fields such as structure studies by crystallographic methods could be as decisive as it was in particle physics. We have here an interesting example of technology developed from pure research problems in high-energy physics having a possible delayed spinoff in quite different fields.



Computer display of a high-energy interaction viewed by a system of multiwire chambers. At an intersection of the CERN proton storage rings, a system of 70 000 wires in a magnetic field detects the coordinates of the particles from one interaction. Typical rates are 150 000 interactions per sec; background, 10^6 per sec per chamber; resolution time about 100 nanosec. Figure 9

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