Wire Chambers: A Review and Forecast

Introduction

In a 1969 issue of these Comments, L. Lederman[1] appraised the development at CERN[2-4] of multiwire proportional chambers (MWPCs) and drift chambers, as a "new revolution in particle techniques". He underlined the importance of some of the properties of the chambers: accuracy of localisation of about 1 mm, time resolution of about 30 ns, counting rate capabilities at least three orders of magnitude larger than in spark chambers. He was particularly impressed by the potential resolution power of drift chambers and gave, as a reasonable prediction, 60 μm for their accuracy, which is exactly what is now obtained in operation with very high-energy particles. The eight years which have elapsed have indeed confirmed the expectations of 1969.

Most experiments in particle physics use multiwire chambers. These tend to replace or complement scintillator hodoscopes or spark chambers, and they are becoming a precious auxiliary for bubble chambers. Large systems of chambers are placed in front of or behind the bubble chambers in order to provide supplementary information on the nature of the particles or on their momentum.

The field of application of the wire chambers is extending rapidly to x-rays and neutron imaging with the hope of serious improvements in classical methods of structure analysis by means of diffraction techniques.

A considerable amount of original effort and experimental talent has been invested by many groups in trying to find the best ways of exploiting the properties of the chambers, at the lowest cost or to the best of their characteristics. It may be a good time to try to appreciate the trends in these research efforts. First, let us summarise the present characteristics of the MWPCs and drift chambers.

Characteristics of Multiwire Proportional Chambers

A MWPC is a structure made of a surface of thin anode wires, stretched between two parallel cathode surfaces (plane or cylindrical) and embedded in a gas.

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When an electron is liberated in the gas, it drifts towards the anode wire and, close to it, experiences inelastic ionizing collisions giving rise to an avalanche. The collision mean-free path, at atmospheric pressure, is a few microns. Most of the collected electrons have thus crossed a modest potential difference and give rise to a usually undetectable very rapid small pulse. It is the motion of the positive ions, left behind the avalanche, that is the source of the most interesting properties of the MWPC.

i) In the intense field around the anode wires, the motion is fast enough to give rise to rapidly rising pulses, typically negative pulses with 20 ns rise-time.

ii) The motion induces positive pulses on the neighboring anode wires. This was, for many, the surprise of our work in 1968. It is the reason why the anode wires all work as independent detectors, despite their strong capacitive coupling.

iii) The positive ion motion induces also similar positive pulses on the cathode. If the cathodes are made of strips or wires at angles with the anode wires, the centroid of the induced charges is correlated to the position of the avalanche along the anode wire.[3,5,6] This is the essential property that opened the way to the detection of low-energy neutral radiation: x-rays, or slow neutrons. Such radiations require self-triggering and two-dimensional read-out from a single gap, since the secondary radiation electrons from x-rays or nuclei following a neutron capture are usually not penetrating enough to cross several consecutive gaps.

The pulses of a MWPC are suitable for the treatment by fast analog methods, such as delay line or current division localization, which are widely used for the read-out of the avalanche position along the anode wires.

The characteristics of the chambers in their most common uses in particle physics are the following.

i) *Space resolution*

The wire spacing governs, in general, the space resolution in the direction orthogonal to the anode wire. The use of the coordinates of the avalanche along the wire is still very rare in high-energy physics, although it can lead to accuracies of the order of 100 μm. However, in some cases where the geometry imposes the read-out of the coordinates from a single gap, as in cylindrical chambers, or where redundancy in the number of coordinate measurements is strongly required, the coordinates are read out from the signal induced on cathode wires or cathode bands, at various angles to the anode sense wires.

Small chambers, of about 100 mm x 100 mm with 1 mm wire spacing, are commonly used in intense beams.

Smaller wire spacings are much more difficult to handle and exceptionally, at high pressures, 3 wires/mm have been used.

Wire spacing of 2 mm is well suited for large chambers of several square metres.

ii) *Time resolution*

The time resolution is a function of the wire spacing. The maximum time jitter is in principle close to the time necessary for the electrons to drift along a distance of half the wire spacing. It is equal to about 20 ns for 1 mm wire spacing, 25 ns for 2 mm wire spacing, and 35 ns for 3 mm wire spacing.

In practice, most of the experiments operate the chambers with resolutions of 40 to 100 ns since the read-out methods introduce additional jitter.

iii) *Maximum counting rates*

Two factors limit the counting rates. The time necessary to sweep away all the electrons from a single track is a function of the chamber thickness. It is usually of the order of 100 ns for a 10 mm thick chamber, and the rate of accidentals is often governed by this clearing time.

Losses are also introduced by the space charge produced by the positive ions left behind by an avalanche. The dead region along a wire of 20 μm diameter extends over a length of about 0.3 mm and lasts for tens of microseconds. At 10^4 counts per second per mm of wire, the losses amount to about 1%. At 5×10^4 counts per second per mm they reach 30%. It is sometimes an illusion to believe that by increasing the number of wires per unit length one can gain in the same proportion with the limiting counting rate. The space charge produced by an avalanche around a wire may well paralyse the neighbouring wire if it is too close to it.

Applications of MWPCs in Particle Physics

The chambers are used to localize the position of particles but also sometimes as proportional counters in methods permitting the identification of the nature of particles.

Localization detector: An alternative to bubble chamber?

In their most simple use the chambers are used in the focal plane of magnetic spectrometers. In the most sophisticated one, they are used in large systems to reconstruct nuclear events of extreme complexity. Typical in this respect is the detector equipping one intersection of the CERN storage rings. In a magnet gap of 10 m length, 3 m width, and 1 m height, 70 000 wires of 20 μm diameter, of lengths of 2 m and 1 m, measure the coordinates of the charged reaction products from two protons of 28 GeV experiencing a head-on collision. Out of

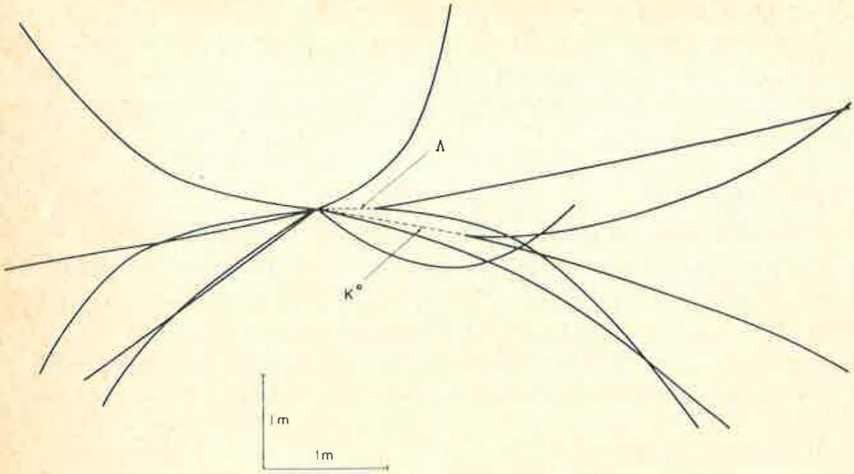

FIGURE 1. Computer display of a high-energy interaction viewed by a multiwire proportional chamber. At an intersection of the CERN Proton Storage Ring, a system made of 70 000 wires of proportional chambers in a magnetic field detects the coordinates of the charged particles produced in the interaction. A CDC 7600 reconstructs the trajectories. An associated production of strange particles can be detected by the fast trigger before being memorized. Typical interaction rate: 150 000/sec. Typical background: 10^6/s per chamber. Resolution time: ~/or ns.

10^5/s collisions, in a background 10 times higher, the electronics selects events of the type represented in Fig. 1, which is the display of an interaction reconstructed in 1 s by a large computer. It is clear, from the experience accumulated in the construction of this type of detector, that, with a sufficient amount of redundance, events of an extreme complexity occurring in any type of target can be reconstructed with MWPCs. Hydrogen targets surrounded by MWPCs may well be a serious competition for visual detectors such as the bubble chamber. For the time being, the MWPCs are becoming a vital auxiliary for these chambers. As the energy of the accelerator increases, the number of particles concentrated in the forward cone is so high that even the largest bubble chambers do not provide enough separating power to offer quantitative information on the momentum or the nature of the particles. Multiwire proportional chambers placed behind the bubble chambers, with or without additional magnets, absorbers and counters, increase considerably the amount of information and the accuracy of momentum measurement.

Rapid cycling bubbling chambers, with up to 50 expansions per second, are under construction, with auxiliary systems of MWPCs which are used in decision-making modes and thus limit the expensive photographs to a class of selected events.

Use as a proportional counter

The signal collected from an anode wire is proportional to the energy locally deposited in the gas by the particles, if the chamber is operated at moderate amplification.

Despite the wide-energy spectrum, reflected by the width of the Landau distribution, the chambers offer a possibility of a good resolution with a sampling of the energy losses along a trajectory.

The chambers are well adapted to such application, and systems with 128 successive chambers of large surfaces, placed behind the CERN 3.5 m hydrogen bubble chamber, permit the identification of secondary particles by the measuring of differences in the relativistic rise of their energy losses.[7] Pions and kaons of up to 70 GeV/c will be distinguished.

For the exploitation of the transition radiation which offers such promising features at the highest energies, MWPCs are well adapted to the measurement of the energy and localization of the x-rays produced by the particles crossing a succession of radiators.[8]

In the measurement of the shower developments of high-energy γ rays or electrons, the chambers also offer possibilities that should be actively investigated, since they permit the measurement of both the energy and the direction of the γ rays.

Drift Chambers

In a drift chamber,[3,9] the electrons liberated in a medium by ionizing collisions can be moved away from their initial position by appropriate electrical fields, and transported to well-determined positions where they are detected. The displacement of the electrons may serve many purposes:

i) The measurement of the time interval between the production and detection yields the position of the initial electrons, if the drift velocity is known. The importance of the drift chambers stems from the fact that the drift velocities in gases can be brought to a very convenient range where it is possible to achieve spatial accuracies of 50 μm, corresponding to 1 ns. Large chambers of tens of square metres can be easily built, and these are now in the process of becoming the most accurate and inexpensive detectors.

ii) The transport of electrons along well-defined lines of force may be used to match many geometrical situations. For instance, we shall see an application of this flexibility in the spherical drift chamber, where all the electrons produced by soft x-rays along straight lines originating from a focal point give rise to a point image.

iii) Drift spaces may be filled with divided dense matter used as converter for charged or neutral particles. The ionization electrons produced in the gas surrounding the converters are transferred to MWPCs when they are measured. Detectors for γ rays and neutrons of any energy can be foreseen and are actively investigated.

iv) Large drift volumes offer interesting possibilities. The three-dimensional position of electrons liberated in a large gaseous volume, and the energy loss along a track, can be measured after the transfer of the initial electrons to a MWPC.

Drift chambers for particle localization: The accurate and cheap detector of the future!

The simplest drift chambers[10] were made like MWPCs but with a larger wire spacing. The measurement of the detection time permitted the interpolation of the trajectory position between two wires.

In such a chamber the electric fields collecting the electrons and giving rise to the amplification around the sense wires are coupled together by the operating potential. This limits the choice of the gases and the chamber thickness which has to be of the same order as the wire spacing in order to avoid too great inhomogeneity of the electric fields. For very large surfaces (of tens of square metres), in order to limit the excessive number of wires, a rather thick structure has thus to be envisaged.[11] The advantage of such chambers is their ease of construction.

Of a very opposite conception, chambers with electrons drifting along long paths in uniform electric field, up to 1 m, are now being operated. Here also simplicity of construction can be claimed.[12] The disadvantage lies in the huge potentials that have to be used and in the degradation of the accuracy which, however, still stays in the millimetre range since it degrades only like the square root of the drifting distance.

A multiwire structure with thin gaps of 6 mm, a wire spacing of 50 mm, an electric drifting field controlled by cathode wires or strips at a rising potential, has been extensively studied at CERN[13] (Fig. 2). It has shown perfect linearity along the chamber, within the accuracy of the measurements which ranges from 60 μm to 100 μm.[13,14] Although it is of a slightly more difficult construction than a structure with a cathode at a uniform potential, it is so much better adapted to the drift method that it is likely that it will be generalized. Chambers of several square meters with the same accuracy have been constructed.

By making use of the correlation in the time measurements in two staggered chambers, timing accuracies of 5 ns can be reached. In other words, a drift chamber has a better time resolution than any MWPC. It has a longer memory time, 0.5 μs for 50 mm wire spacing. Except when very large counting rates incompatible with this memory time are encountered, the drift chamber is preferable to a MWPC. The limitation arising from the local dead-time

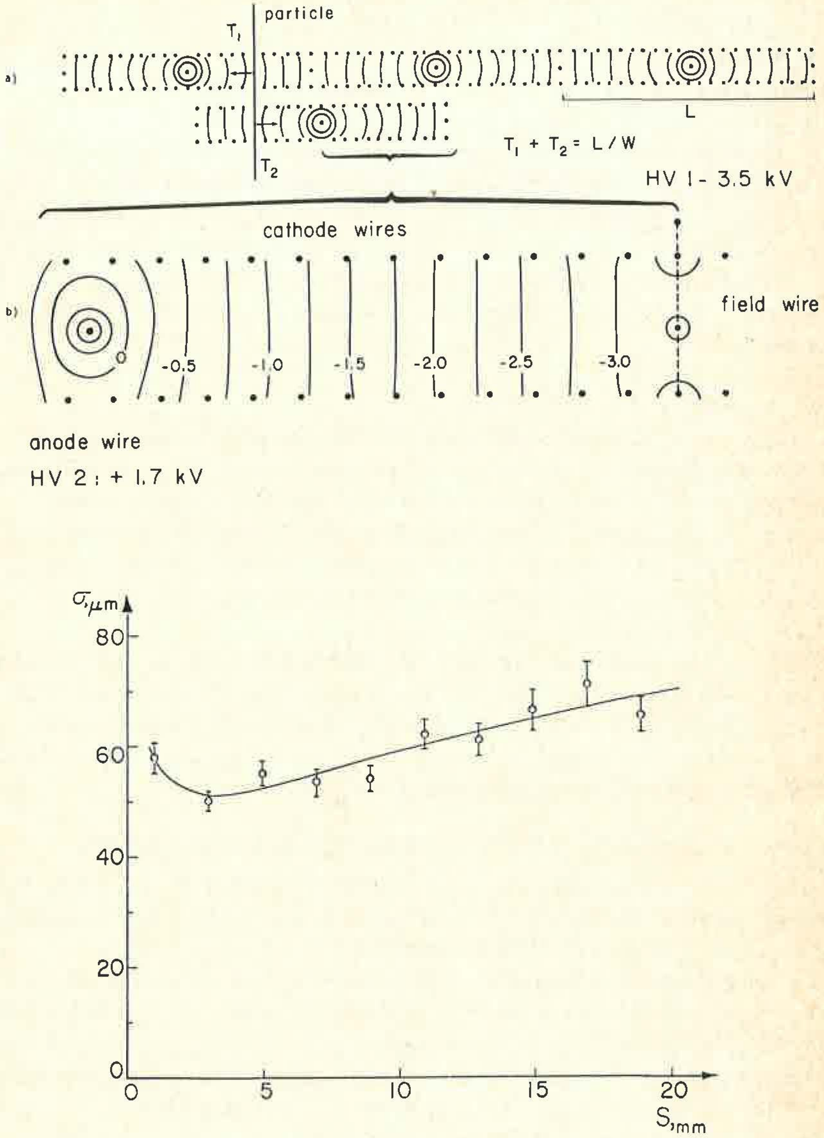

FIGURE 2. Multiwire drift chambers with cathodes at a graded potential: (a) The planes are divided into cells of width L. With two staggered planes, the right-left ambiguity is lifted and the resolution time is ~5 ns. (b) Equipotentials in half a cell of the adjustable electric field drift chamber. (c) The accuracy is $\sigma = 60\ \mu m$ (from Ref. 14) and the space-time relation is linear over all the drift length.

produced by an avalanche is also greater than in a MWPC, in inverse proportion to the wire spacing.

However, the considerable reduction of cost due to the large wire spacing and the greater ease of construction will in future certainly promote the drift chambers to the state of the most used localization detector.

The twisting ot the lines of force of the guiding electric field permits the use of drift chambers in strong magnetic fields without degrading their properties.[13] Two-dimensional drift chambers have been constructed. The coordinate along the wire can be obtained either by current division or by narrow delay-lines with the cathode plane, parallel to the sense wires. Such structures are very suitable for cylindrical chambers, which are of special interest for storage ring physics.

The three-dimensional drift chamber

In a large volume, we may imagine methods of localizing any electron cluster produced in the gas by particles, if the time origin is known. The electrons have to be transferred to a place where they are detected and where the time of arrival gives the coordinate along the guiding electric field. The localization in the two dimensions orthogonal to the drift path must also be done. This localization is slightly more difficult than in cases of isolated clusters, because of the continuous character of the trajectories.

Nygren[15] has made a detailed analysis of the possible construction of such a detector, which offers the attractive character of a three-dimensional streamer chamber. We shall see, with the spherical drift chamber and the high-density drift chambers mentioned later, how flexible structures are permitted by drifting the electrons outside their production volume.

Application of MWPCs and Drift Chambers in Biophysics and Medicine

In parallel with the expansion of MWPCs and drift chambers in particle physics, many applications are under active investigation. They usually require chambers with a special design adapted to the radiation.

Imaging of soft x-rays, between 5 KeV and 40 KeV, can transform the traditional techniques of molecular structure studies by means of Bragg diffraction scattering. Imaging of γ rays between 30 KeV and 150 KeV has wide applications in nuclear medicine. So far the considerable advantages of scintillation cameras limit the applications to cases where large sizes, greater than 500 mm, or high accuracies, of the order of 1 mm, are required.

Imaging of 0.511 γ rays from positron annihilation opens the way for large-acceptance positron cameras used to localize β^+– emitters injected in human bodies.[16,17] Large-acceptance imaging of slow neutrons may well represent an essential step in the use of monochromatic slow neutrons in protein crystal structure.

An extensive review of all these applications has recently been made by Perez-Mendez,[18] who pioneered these fields. Only two examples will be given in this Comment. They are probably among the most important applications.

The spherical drift chamber for soft x-ray imaging: Three orders of magnitude improvement!

Structural determination of large protein and nucleic acid molecules relies on high resolution x-ray diffraction measurements of the crystallized material. These intensity measurements supply information which is essential for the accurate electron density maps of the molecules. With the increase of the complexity and molecular weight of the materials there are more Bragg reflections, and hence less intensity, at a given pattern location. The use of films or of scanning techniques with small counters may lead to unacceptable response times, of the order of months.

The MWPC offers the possibility of a large acceptance with a high accuracy. Its limitations lie in the poor efficiency of gaseous absorption. This requires either pressurized or thick chambers. Since reasonable thicknesses are of the order of 10 mm, a strong error is introduced in the position measurement of x-rays emitted at large angles to the chambers: the image of a direction is a straight line.

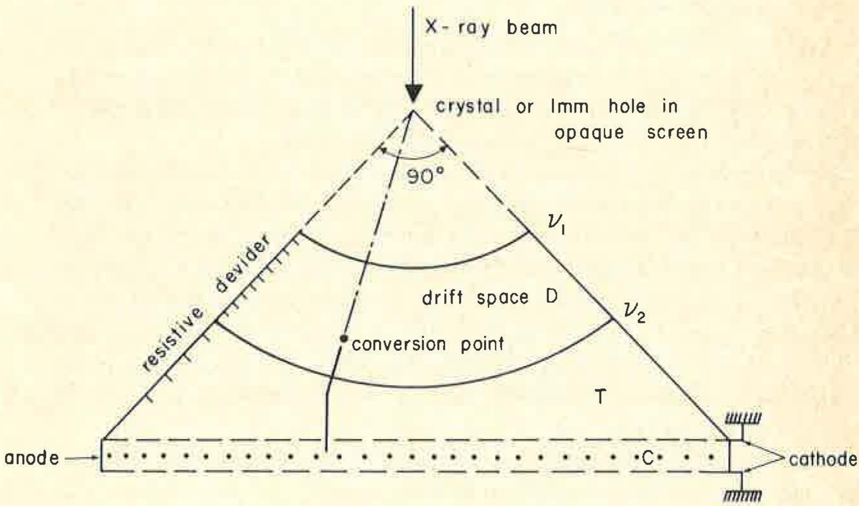

FIGURE 3. Spherical drift chamber: 10 cm drift space, 90° aperture. Accuracy: 0.7 mm (FWHM) in all directions of the 500 X 500 mm² MWPC.

The spherical drift chambers[19] now built at CERN (Fig. 3) offer a simple solution to this. The x-rays are absorbed in a 100 mm drift space of spherical shape. The entrance window is a thin spherical window, gas tight, with its focus at the crystal location. The exit window is a spherical grid with the same focus, transparent to electrons. The conversion electrons are transferred to a MWPC where their two-dimensional position is read out. The present CERN chamber has an angular aperture of 90° and an angular resolution of about 7 mrad (FWHM) in all directions, and a counting-rate capability close to 1 MHz. The accuracy for x-rays of 1.5 Å, of the localization of the photoelectron in the $500 \times 500\ mm^2$ chamber is about 0.7 mm (FWHM) in two coordinates.

This represents a gain of several orders of magnitude over the conventional scanning methods. The interest of the instrument is increased by the availability of high luminosity x-ray sources from the synchrotron radiation produced around electron storage rings. These sources can produce about 10^6 diffracted photons per second in a typical protein crystal. This opens the way to study systems under fast evolution. For instance, live muscles undergoing contraction show changing patterns of the diffracted images. The limits of the time variations that can be studied are directly connected to the efficiency and rapidity of the x-ray detector.

With an opaque window and a hole at the focus location, the spherical drift chamber is an ideal pinhole camera for soft x-rays with a large-aperture angle.

The imaging of slow neutrons

Slow monochromatic neutrons offer considerable interest for protein structure studies. The practical wavelength limit for x-rays is set by their increasing absorption cross section to about 2 to 3 Å, while in most cases living matter is transparent to neutrons of even much larger wavelength.

With the availability of intense beams of slow neutrons up to wavelengths of 20 Å a considerable interest arises in large-acceptance detectors. Here also the MWPC is adapted as a solution. The detection relies on the absorption of the neutrons in a gas with a high cross section: BF_3 or ^3He. Let us give, as an example, the solution adopted in Grenoble,[20] with the slow neutron sources from the fast neutron reactor: the filling gas is BF_3 at 1.2 atm; the size of the chamber is $640 \times 640\ mm^2$; the accuracy of localization is 10 mm in all directions. The efficiency of detection is 50% at 6 Å; the rate of data processing is 1 MHz. The processing time is 0.5 μs.

Figure 4 shows the diffraction pattern from the tobacco-mosaic virus as determined from the data obtained with this chamber.

The Read-Out Methods of MWPCs and Drift Chambers

The last eight years have seen a proliferation of circuits adapted to MWPCs. Half-a-dozen patents, some of dubious validity, have been taken out on the

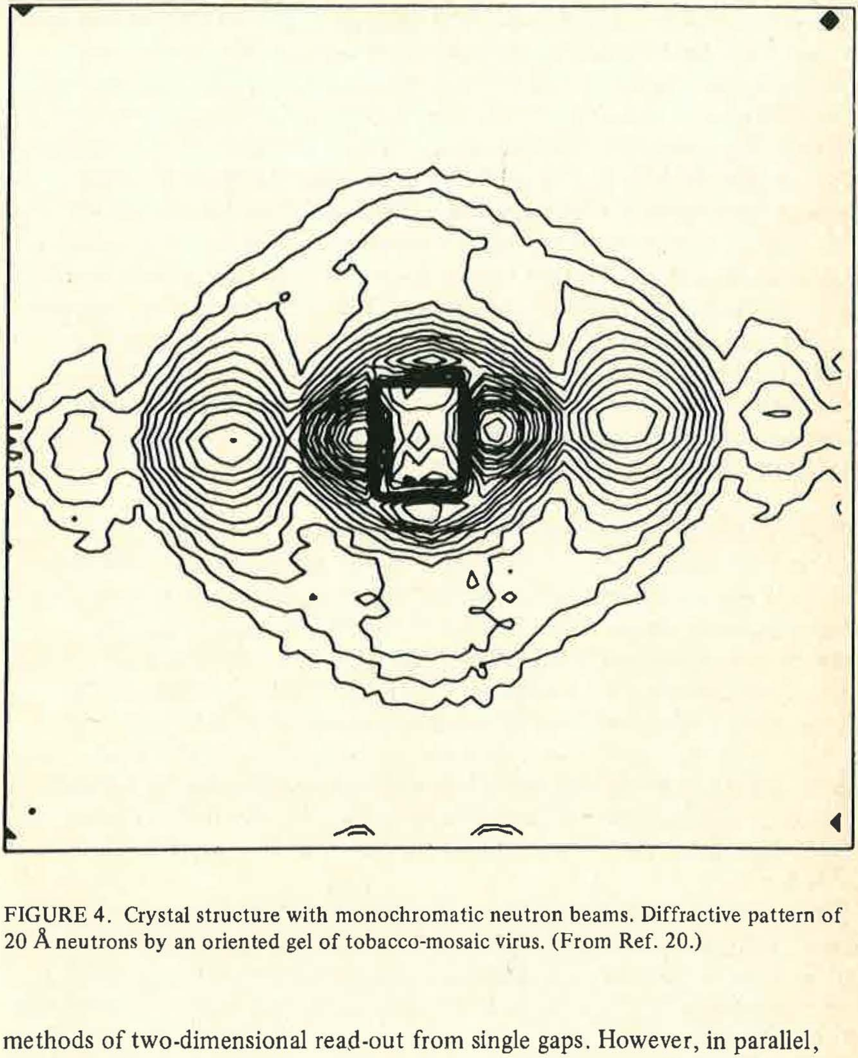

FIGURE 4. Crystal structure with monochromatic neutron beams. Diffractive pattern of 20 Å neutrons by an oriented gel of tobacco-mosaic virus. (From Ref. 20.)

methods of two-dimensional read-out from single gaps. However, in parallel, the fast evolution in the electronics and more so in the cost of large-scale integration of complex systems brings with it some clear indications as to what may be the relevant solution in the future.

The read-out of individual wires of MWPCs

In most laboratories a similar scheme is adopted: an amplifier brings the pulses of the chambers from the level of a millivolt to values suitable to logic treatment. The pulses are then delayed by a few hundred nanoseconds before being accepted in a memory through a gate controlled by fast decision-making circuits. The first attempts at large-scale standardization of these circuits have met with considerable resistance, since the integrated circuits were not perfectly tailored to the real (or imaginary) needs of all the users and because they were not optimized in some characteristics. However, the cut in cost and time represented by this approach is so great that this solution will certainly prevail over the individualism of the groups. One can predict that at a total cost of $\leqslant$ \$ 10 per wire, specialized electronics with good characteristics will be available in the near future. The electronics will be made of miniature circuits, all on the chambers, with only a few cables carrying out the address of events selected by sophisticated fast-decision-making circuitry controlling the strobing into memory. It is there that individual groups will invest their ingenuity. The dead-time of the circuits will be around 50 ns per wire; the strobe width of 100 ns will be sufficient for most experiments. For some cases, as in small intense beam regions, faster, more expensive circuits will be used, where a factor of 2 or 3 in speed will be gained if the space charge effects in the chambers permit it.

The analog read-out methods of MWPCs

The future of the various analog methods is also to some extent controlled by the price of circuits used in digital methods. All analog techniques have to give up some essential qualities of the MWPCs: time resolution, multi-track separation power, counting rate. This is why they are rarely adopted in high-energy physics. In some cases, however, they offer serious advantages. If the read-out of the avalanches along the anode wires is essential, as in x-ray detection, they reach the ultimate accuracy set by the physical absorption process itself, such as the range of the conversion photoelectrons, for instance.

The delay-line methods are the easiest to employ, as compared to current division. The reader will find a precise critical survey of all these methods elsewhere.[21]

However, all these methods may also become obsolete because of the evolution of electronics. If circuits digitizing the height of the pulses induced on cathode strips become available at as low a cost as can be foreseen, then the direct computation of the centroid of the induced charge will make most analog methods obsolete, since it gives the ultimate accuracy, without size limitation of the chambers.

There are cases, however, where conditions dictate a solution. For instance, on a satellite the choice of the method will be determined by power consumption. In this respect a delay-line method is probably by far the best.

The read-out of drift chambers

Relatively expensive circuits were first available for drift chambers. They were perfectly matched to the characteristics of the chamber: a time accuracy of

1 ns ($\sim$50 μm), a capability of multitracks up to a dozen per wire, etc. It rapidly appeared – essentially for larger systems – that slightly more modest characteristics are acceptable and, as a result, circuits with a revolutionary small cost are in sight, such as $ 30 per wire. With the wire every 50 mm or 100 mm, this will bring the drift chamber to a level of cost and performance where no other localization detector or read-out method can compete in price or performance. Some efforts being made to bring the construction to a level of simplicity permitting both a low cost and the advantages of a controllable uniform drift field will complete this evolution.

The Near-Future Evolution

In trying to appreciate the present states of the art and forecasting its future developments, we are necessarily guided by taste and intuition.

The near future will see the appearance on the market of cheap, specialized circuits for the individual wire read-out.

High-energy physicists are far behind groups working in low-energy x-ray detection as far as cathode read-out is concerned. They will have to learn how to use in a clever way, all the information contained in a single gap: the coordinates in three directions if the cathodes are made of strips or wires set at various angles to the sense wires. They can thus reduce, by a factor of three, the number of chambers necessary in the reconstruction of high multiplicity events. Such a set-up is constructed in the system of chambers behind the FNAL hydrogen bubble chamber, using delay-line read-out for three directions, but a great variety of methods is available, adapted to the physics or the taste of the various groups.

The drift chambers may well eliminate the use of MWPCs in most cases, since they are the best large-size, low-cost detectors. Only for complex patterns, or high counting rates, or high multiplicity, or aberrant duty cycles as in systems associated with bubble chambers, will the MWPC be used.

The efforts to build chambers with wire spacings smaller than 1 mm will be given up, since the high-energy physicist will have learned to measure the position of an avalanche along a wire of a chamber of any size, with the highest time resolution compatible with the chamber wire spacing, i.e., to an accuracy of 100 μm.

Drift chambers of a higher complexity will appear: many wires in a single gap to obtain not only position but also directions from a single gap in order to facilitate the pattern reconstruction by large computers;[22] three-dimensional reconstruction of the electron coordinates in large gaps.

The biological applications will grow to a stage where they may acquire considerable importance; where they will offer the high-energy laboratories an opportunity for ambitious interdisciplinary ventures; where in fact these laboratories can contribute their experience in the construction of chambers.

In turn, the physicist will learn how to get much more information from these small avalanches around a wire.

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