EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/86-25
20 February 1986

**SELECTED TOPICS ON THE SPATIAL INFORMATION
FROM PROPORTIONAL COUNTERS USED FOR
TWO-DIMENSIONAL IMAGING OF X-RAYS AND VUV PHOTONS**

Georges Charpak
CERN, Geneva, Switzerland

Invited paper presented at the
2nd International Technical Symposium
on Optical and Electro-optical Science
and Engineering and Instrument Display
25 November–6 December 1985, Cannes, France

Selected topics on the spatial information from proportional counters used for two-dimensional imaging of X-rays and VUV photons

Georges Charpak
CERN, 1211 Geneva 23, Switzerland

Abstract

Some recent methods are discussed which permit a two-dimensional imaging of the spatial distribution of X-rays and VUV photons with gaseous detectors; multiwire chambers, multistep chambers, chambers with parallel electrodes, and scintillation chambers.

1. Introduction

A variety of counters exist which deliver an electric pulse proportional to the energy released in the detecting medium and also give the spatial coordinates of the interaction point where the absorption process of the photon occurred—solid-state, gaseous, or liquid absorbing media, with or without electronic amplification—exploiting the liberated electric charges or excitation photons in various spectral domains. I will limit my contribution to some gaseous detectors where the amplification, produced by electrons accelerated in electric fields, produce electric pulses or flashes of photons, and where the primary radiation consists of low-energy X-rays down to the vacuum ultraviolet (VUV) region.

The sources of error, in the localization of electromagnetic radiation, are of a great variety: parallax error due to the finite thickness of the absorbing medium, range of the photoelectron, diffusion of the ionization electrons drifting to the region of gaseous amplification, diffusion in the process of amplification itself, and noise of the electronics. The great variety of proportional gaseous detectors precludes a general discussion of all these factors. Solid-state detectors present considerable advantages over gaseous detectors by avoiding many of the above-mentioned sources of error. However, gaseous detectors still remain the only alternative where surfaces of the order of 1 m^2 are required, or where low-energy quanta liberating only a few electrons have to be localized.

2. Proportional gaseous detectors

Various electrode configurations are used to amplify the primary ionization produced by X-rays being absorbed by a gas. Figure 1 illustrates some of the available architectures. Some of the localization methods being used were invented for the readout of the position of sparks in spark chambers, such as the current division or the delay line method, or have been developed for charged-particle detection for nuclear-physics applications where the wide use of this technology has given rise to an intense development of localization techniques. However, the detection of X-rays presents specific features which do not exist in the detection of penetrating charged particles and has given rise to original methods of localization which may, in turn, influence the high-energy physics localization techniques as we will see with the example of the wedge and strips cathodes.

Since the multiwire chamber readout has given rise to many of the methods of localization used in other structures, let me begin with a discussion of the localization of avalanches in wire chambers, limiting myself to the methods where the two coordinates can be obtained with similar accuracies on the surface of a chamber.

2.1 Two-dimensional, continuous, readout of avalanche coordinates from multiwire chambers

In a wire chamber the basic process of detection is an avalanche produced in the vicinity of an anode wire. This is not true for counters filled with gases at pressures lower than about 20 Torr, which are of interest, for us, in the detection of VUV photons. Figure 2, from an earlier paper¹, which gives most of the references relevant to this article, shows the succession of events around a wire, following the liberation of one electron. At atmospheric pressure the ionization mean free path of one electron in the intense field near a wire is of the order of $1 \mu\text{m}$ and the times involved in the first stages, which lead to the absorption of all the avalanche electrons by the anode wire and the release of a sheath of positive ions close to the wire, are of the order of less than 1 ns. This first stage is usually undetectable. It is only the motion of the positive ions which gives rise to the exploitable induced pulses, which are schematically shown in a particular structure in Figure 3, made of a plane of anode wires sandwiched between two cathode wire planes parallel and orthogonal to the anode wires. This motion of the positive ions is responsible for the difference in sign of the pulses induced on the anode wire collecting the avalanche, and that of its neighbours. This is the basic property which gives to the multiwire chamber the independence of each anode wire despite the capacitive coupling. In addition, a proper exploitation of the pulses induced on neighbouring electrodes to the avalanche permit the coordinate along the wire and, in many cases, the azimuthal angle of the avalanches to be obtained.

2.1.1 Measuring the longitudinal and the azimuthal position of avalanches along wires. The development of the avalanche can be confined to a quite limited azimuthal angle around the anode wire or surrounding the wire more or less completely, depending on the level of amplification or on the implication of VUV photons in the spread of the avalanche. However, even in the case of very high amplification factors, one may observe a strong azimuthal asymmetry in the distribution of charges around the anode wire.

In the structure illustrated by Figure 3 the cathodes are made of wires grouped into strips of width $2a$ with an anode-cathode gap D . The theory of Gatti et al.² gives a rigorous electrostatic analysis of the influence of the geometric

parameters on the integral and differential dispersion. If one measures the pulse height of the induced pulses, and calculates the electric centre of gravity, one obtains the greatest accuracy. An optimum in the accuracy is obtained for a ratio $2a/D = 1$, i.e. a strip width equal to the anode-cathode gap.

Figure 4 shows our results, when we first started to develop this method, with X-rays of 1.5 keV. The accuracy of $35 \mu\text{m}$ (r.m.s.) is equal to the range of the photoelectrons in the gas. More recent measurements, by Fisher et al.³, at high pressures, where the range of the electrons is much smaller, have resulted in much higher accuracies, i.e. $15 \mu\text{m}$ (FWHM), along the wires. With the present gains attainable with the wire chambers, and the present quality of the amplifiers, the real limit to accuracy comes from geometric asymmetries. This is illustrated by the fact that the azimuth of the avalanches can be computed from the pulse-height distribution on strips parallel to the anode wire. Figure 5 shows the two-dimensional picture of an X-ray distribution of 1.5 keV X-rays, absorbed in a 1 cm drift space, with the ionization electrons following parallel field lines arriving at a specific azimuthal angle correlated to the distance of the line of flight of the photons to the anode wires.

The multiwire chamber thus appears, in an unexpected way, as a two-dimensional X-ray detector, with a continuous response even in the direction orthogonal to the anode wires.

2.1.2 Exploiting the spatial extension of avalanches. This is, however, not the only method which permits one to get rid of the discontinuities introduced by the finite distance between anode wires. These discontinuities disappear whenever the size of the electron swarm that reaches the anode plane is wider than the anode-wire separation and any analog or digital method of centroid readout is being used. We will see that this is the case in the multistep structure, where diffusion and photon propagation give rise to an extended avalanche. This is also the case with X-rays wherever the primary swarm of ionization electrons has to drift over a sufficient distance before reaching the anode plane. The properties of the spherical drift chamber are in this respect significative. In the first large-scale spherical drift chamber, which we built at CERN for crystallographic application with a drift length of 10 cm, we observed a complete obliteration of the anode wire structure⁴.

This is illustrated by Figure 6, which shows the wire structure when a ^{55}Fe source is placed directly against the wire chamber or when it is placed at the focal point, and by Figure 7, which shows a continuous image of a radioactive ^{55}Fe source when the detector is used as a pinhole camera. We also observed an improvement of the energy resolution owing to the drift. This is due to a reduction of space-charge effects limiting the energy resolution with high gains of the chamber. It may explain some of the improvements in energy resolution observed by some groups using multistep imaging chambers. The spreading of the ionization electrons along the wire due to any process, such as diffusion or the Penning effect, is favourable to the energy resolution.

2.1.3 Exploiting directly the collection of the positive ions. Besides giving rise to induced pulses during the motion towards the cathode one may wonder if the positive ions could not be used directly for localization. I have tried with J.-C. Santiard, at CERN, to detect the positive ions by transferring them to a drift space placed after the cathode, accelerate them on a thin wire of $50 \mu\text{m}$ diameter, and detect a signal during the short time of acceleration near the wire. By having the collecting wires placed at various distances we could localize the position of the ions since they were arriving at different times. Figure 8 illustrates the localization power of this method. The pulses arrive after a considerable delay, of the order of $100 \mu\text{s}$. I mention this method since it could be of interest for chambers working at very low pressures. Most of the above considerations were valid for chambers working at pressures well above a critical value close to 20 Torr. It has been demonstrated by Breskin⁵ that below this pressure the mechanism of amplification is very different. There is first a multiplication in the region of uniform field followed by an amplification around the wires, and such chambers have remarkable properties of time resolutions which are better than 1 ns. This can be of interest for the detection of VUV photons when the chamber is filled with appropriate photo-ionizable vapours, for energies between 5.3 eV—which is the lowest ionization potential so far known for a vapour—and 10 eV—which is the limit imposed by the most transparent windows. In these chambers the positive ions travel fast; they cross the chamber in only $1 \mu\text{s}$, and the measurement of the position, by directly using the collection of the positive ions, may be of interest. The fixed delay of the detection may be of interest for some exotic applications. The separation of very nearby avalanches would be easier with the positive ions. It has been the dream of some physicists to find a photosensitive surface compatible with these low-pressure counters. It is still an open challenge!

2.1.4 The position readout from the light emitted in the avalanches. Avalanches in gas produce not only electrons but also atomic excited states emitting photons. This is an active area of research. With some vapours the gains are sufficient for the detection of single electrons liberated in the gas by VUV radiation. Figure 9, from an earlier paper⁶, illustrates the quality of the images. The key factor was the use of triethylamine (TEA) vapour in the gas filling since it emits abundantly an UV line centred on a wavelength of about 300 nm ^{6,7}. This permitted substantial progress in the light intensity as compared to the usual gas components of proportional counters used in the pioneering attempts to image the light from avalanches^{8,9}.

2.1.5 The electronic readout of the avalanche positions. The digital computation of the electric centre of gravity is the most accurate and most complete way to extract the information from a wire chamber. With the progress of the complex miniature electronic chips, it may well be that, in the future, it will supersede the many cheap analog methods which have been invented and which I will not discuss here since they are described in many text books, or review articles: e.g. delay lines, current division.

Great progress has been introduced by using the pulses induced on electrodes of shapes very different from the simple strips parallel or orthogonal to the anode wires. The first step introduced by a group from Grenoble¹⁰, which demonstrated the power of the method, was to use on the cathode a backgammon-shaped electrode, where the charges induced on the two adjacent parts of the electrode are dependent on the position along the anode wire. This gives the position along the

wire and imposes no limitation of the impedance of the electrodes. It permits also, by a simple extension of the same principle, to have the two-dimensional readout of the coordinate on a single electrode¹¹, which is very practical for many applications. Finally, we found out that it permits, by the simple application of a Vernier method, to obtain the same type of accuracy in the fraction of a millimetre range, on any length of chamber¹². At present a muon detector of one acre surface is being built on this principle, with chambers of 6 m length, at Fermilab⁶.

The choice of the readout method is governed not only by cost but also by the size of the chamber, the required accuracy, and the counting rate. Any method which requires only a measurement localized to a small fraction of a chamber is more accurate than one requiring the measurement from a large surface electrode, and, in this respect, the readout of the pulses induced on strips or wedges or any combination of these is the best. It is also compatible with a splitting of the cathodes when high rates or high multiplicities are required. For high rates let me mention the method we are using with the X-ray imaging spherical drift chamber at Orsay. We determine, in a digital way, the centre of the cluster of cathode wires detecting the pulses above a given threshold. This permits a speed in the megacycle range for a large chamber, with an accuracy of one half the wire distance. Figure 10 shows, for instance, the images obtained with a new spherical drift chamber of $50 \times 50 \text{ cm}^2$ and 15 cm of drift length, used at Orsay (LURE) for the imaging of X-rays of 8 keV diffracted by a protein crystal. This chamber, filled with xenon, argon and ethane, also illustrates how the diffusion increases the accuracy of a proportional chamber by removing the structure introduced by the separation of the anode wires. The primary electron cloud of about $250 \mu\text{m}$ is spread over several anode wires, at a distance of 1 mm from each other, and the centroid of the distribution does not reflect the wire structure. This is a considerable advantage which could not, in principle, be exploited for single electrons but which reappears, as we will see, even for single electrons, when a preliminary amplification between parallel grids replaces the single electron by a swarm of finite extension.

Let me now consider some of the specific problems encountered when structures different from the simple wire chamber are being used.

2.2 Multistep chambers

In a multistep chamber the electrons are first amplified between parallel grids, and a fraction of the electrons is then transferred to a drift space and a further amplifying structure. The multistep chambers were first invented for high-energy physics applications¹, in order to solve a problem of high rate, since it is possible to gate the swarm of electrons drifting between two amplifying structures. It then appeared that it is an ideal structure for the detection of single electrons, since many of the feedback problems which limit the maximum amplification of a wire chamber are strongly reduced by intermediate drift space. By introducing a photo-ionizable vapour it is an ideal detector for VUV photons, and it is now applied for Cherenkov Ring Imaging. We have used such a multistep chamber for an experiment at Fermilab¹³ and Figure 11 shows the imaging of VUV photons emitted by a helium Cherenkov converter. The coordinates of the avalanches are measured by computing the centroid of the pulses induced on cathode wire strips. σ is $500 \mu\text{m}$ (r.m.s.) for a chamber of $80 \times 40 \text{ cm}^2$. The anode wire structure is not visible, just as with the spherical drift chamber. Here it is the spread of the electron swarm extracted from the preamplifying stage which is responsible for this improvement of the quality of the information. This spread is due either to the role of the photons in the spread of the avalanche, as is the case if a Penning mixture is used, or simply to the spread due to diffusion for other mixtures. The accuracy of $500 \mu\text{m}$ included, in our case, other sources of error due to the geometry of our detector.

It is gratifying that this type of detector can be tuned up to an energy resolution better than that of a normal wire chamber, as shown by two detectors presented at this meeting. It leads to an imaging chamber of large surface, good two-dimensional accuracy, and good energy resolution. The localization problems in the proportional ionization photo-ionization scintillation counter (PIPS) are very similar to those of the multistep chamber. The spread of the avalanches in the wire chamber is introduced by the large range of the VUV photons crossing the separation window.

2.3 Parallel-plate counter

When we developed the multistep chamber we were surprised to see how easy it is to obtain with X-rays a good energy resolution in the first stage of preamplification. Other groups have simultaneously or afterwards concentrated their efforts on this single-step operation of the parallel-plate proportional chamber for X-ray imaging. It is at first sight surprising that such counters were not used much earlier since they present the advantage of not requiring any wire, which eliminates a source of fragility in proportional counters, but they present their own difficulties whenever large surfaces with uniform gain are desired.

The imaging of the avalanches in such counters has been done by using the photons emitted in the avalanches, localized by image intensifier cameras⁹. It can also be obtained by all the classical methods developed for the wire chamber with, however, some peculiarities coming from the fact that the source of the induced pulses most easily exploitable is due to the electrons and not to the motion of the positive ions.

Let me illustrate this point with a recent development of Sauli and Peisert, at CERN¹⁴. They studied X-rays of 6 keV absorbed in a drift space and then transferred the ionization electrons to an amplifying gap of 4 mm thickness. The original part of the localization is made by a cathode which consists of $250 \mu\text{m}$ strips, placed every $500 \mu\text{m}$, perpendicularly to each other, on the front and back of this cathode. The pulses induced in these strips are negative on the front face and positive on the rear face, which is at first sight surprising and permits a two-dimensional high-accuracy on the centroid of the pulses. The explanation seems simple: the avalanche spreads laterally over distances larger than the strip distance, and, every time a swarm of electrons is swallowed by a strip on the front side of the cathode, a positive pulse is produced on the strip behind the cathode board, which sees the disappearance of the lines of force projected by the electron swarm. We then have, in principle, the simplest X-ray imaging detector: a drift space, a single parallel-electrode gap, and a single cathode-plane two-dimensional read-out. Figure 12 illustrates the imaging qualities of the chamber.

3. Conclusions

Gaseous detectors can be used for the imaging of X-rays or VUV light. The great variety of the electrode configurations or gas fillings available at present open up wide fields of application. Their large gain permits the detection of single electrons liberated by UV light from photo-ionizable vapours. The present localization techniques give the two coordinates on an imaging surface with a continuous response and an accuracy which is often limited only by the physical asymmetries of the charge distributions in the gas or around the electrodes.

References

1. Charpak, G., and Sauli, F., *Annu. Rev. Nucl. Part. Sci.*, Vol. 34, p. 285, 1984.
2. Kanter, H., *Phys. Rev.* Vol. 121, p. 461, 1961.
3. Fisher, J., Radeka, V., and Smith, G.C., Position detection of 17-25 keV X-rays in krypton and xenon with a resolution of 18-50 μm (FWHM), BNL 37 295, presented at Nuclear Science Symposium, San Francisco, 1985.
4. Charpak, G., Demierre, C., Kahn, R., Santiard, J.C., and Sauli, F., *Nucl. Instrum. Methods*, Vol. 141, p. 141, 1977.
5. Breskin, A., *Nucl. Instrum. Methods*, Vol. 196, p. 11, 1982.
6. Charpak, G., 'Trends in Particle Detectors', preprint CERN-EP/85-127, 12 August 1985, to be published in Proc. Int. Symposium on Lepton and Photon Interactions at High Energies, Kyoto, 1985.
7. Gooch, T.K., et al., 'A Multi-step Avalanche Chamber with Optical Read-out for use as a 2-Dimensional VUV Photon or Particle-Track Detector', University of Bristol, Submitted to *Nucl. Instrum. Methods*.
8. Gilmore, R.S., et al., *Nucl. Instrum. Methods*, Vol. 206, p. 206, 1983.
9. Siegmund, O.H.W., Culhane, J.C., Mason, I.M., and Sanford, P.W., *Nature*, Vol. 295, p. 678, 1982.
10. Allemand, R., and Thomas, G., *Nucl. Instrum. Methods*, Vol. 137, p. 141, 1978.
11. Siegmund, O.H.W., Clothier, S., Thornton, J., Lemen, J., Harper, R., Mason, I.M., and Culhane, J.C., *IEEE Trans. Nucl. Sci.* Vol. NS 30, p. 503, 1983.
12. Anderson, D.F., Arvela, H.K., Breskin, A., and Charpak, G., preprint CERN-EP/84-01, 6 January 1984.
13. McCarthy, R., et al., *IEEE Trans. Nucl. Sci.*, Vol. NS-32, p. 692, 1985.
14. Peisert, A., and Sauli, F., 'Bi-dimensional Localization of Soft X-rays with a Parallel-Plate Chamber', to be submitted to *Nucl. Instrum. Methods*.

Figure 1. Examples of imaging gaseous detectors for X-rays and VUV photons.

- a) The multiwire proportional chamber.** Avalanches produced near the anode wire are responsible for most of the localization processes. The gas fillings are very diversified and may contain heavy noble gases for X-ray detection and photo-ionizable vapours for VUV detection.
- b) The gas scintillation proportional chamber.** Electrons drifting in an electric field produce VUV photons by exciting dimers in a noble gas. The photons can be detected by photomultipliers or, in the example of this figure, by a wire chamber containing photo-ionizable vapours.
- c) Parallel-grid avalanche chamber.** Electrons produced in a region of uniform field are amplified by the Townsend mechanism. Gains of 5×10^4 are obtained. The position readout is obtained from the collected electrons or the photons emitted in the avalanche.
- d) Multistep avalanche chambers.** Electrons, extracted from a conversion space, are first multiplied between parallel grids, then transferred to successive drift spaces or amplifying gaps made of parallel grids or wire chambers. The localization can be obtained from the electron pulses or the photons emitted in the avalanches.

Figure 2.
Schematic picture of the time development of the avalanche around the anode wire of a proportional counter (from Ref. 1.)

Figure 3.
Principle of the centre-of-gravity localization method by readout of the induced charges on cathode planes.

Figure 4.
Position resolution, measured with the centre-of-gravity method, in the direction parallel to the anode wires for three positions, 200 μm apart, of a collimated source.

Figure 5.
Bidimensional image obtained with a high-accuracy MWPC with cathode readout using a collimator with letters cut out; the size of the mask is $4 \times 2 \text{ mm}^2$.

Figure 6. Localization in the spherical chamber. Source of ^{55}Fe ; a) against C, b) at the focus S of the spherical chamber.

Figure 7. Image of an X-ray source in a spherical drift chamber. A solution of ^{55}Fe is deposited on letters grooved in a plastic foil. Vertical letter size: 8 mm. Source at 5 cm from a pinhole of 1 mm diameter in a gold foil. Magnification factor: 6. a) Image from the spherical chamber. b) Autoradiography of the source.

Figure 8. Direct detection of the positive ions. The positive ions are collected in an auxiliary space following the cathode. They are then accelerated to a collecting wire where they give a detectable signal. a) Structure of the special wire chamber. b) Pulses from the wire. c) Delay of the detected pulse as a function of the position of a 5.9 keV source along the anode wire. Source displaced by steps of 5 mm. Fillings of Ar (90%) + CO_2 (10%). (G. Charpak and J.-C. Santiard, CERN, 1985, unpublished.)

Figure 9. Images from cosmic-rays and local radioactivity in a light-emitting chamber. A drift volume of $10 \times 10 \times 10 \text{ cm}^3$ is filled with Ar + isobutane + TEA. The electrons drift to an end-cap wire chamber, with wires of $\varnothing = 35 \mu\text{m}$ and 4 mm spacing. (M. Suzuki et al., CERN, unpublished). Images obtained with an UV-to-visible light converter (Proxitronic, BV 25329615) of 25 mm diameter, of gain 10, followed by a VARO electrostatic double stage of gain 5000, viewed by a Thomson video camera of sensitivity equivalent to 10^5 ASA.

Figure 10. Image obtained with a spherical drift chamber. One quarter of a chamber of $50 \times 50 \text{ cm}^2$. Photons of 8 keV are diffracted by a protein crystal. The diffracted peaks are collected over a rotation angle of 1° of the crystal. The image does not reflect at all the anode wire structure. The readout, based on the digital computation of the centre of the cluster of cathode wires detecting the pulses induced by the avalanche, permits a 1 MHz rate with an accuracy of about one half wire spacing.

Figure 11. Images of Cherenkov light in a multistep avalanche chamber (from Ref. 13). First step: parallel gap; Second step: MWPC. Gas mixture: Ar + CH₄ + TEA. Total gain: 5×10^7 . a) Single event; b) 200 events. Cherenkov ring radius = 6.8 cm. Beam of 200 GeV pions.

Figure 12. Imaging of X-rays with a single-step parallel-plate counter. The X-rays are collected in a drift space of 8 mm and the electrons are transferred to a multiplying gap of 4 mm filled with Ar (96%) + isobutane (2%) + methylal (2%). The originality of the imaging comes from the back cathode which is made of a thin board with strips of 250 μ m orthogonal to each other, on each side of the board (see text). a) Energy resolution. b) Image of a pattern with 5.9 keV X-rays.