PARALLAX-FREE, HIGH-ACCURACY GASEOUS DETECTORS
FOR X-RAY AND VUV LOCALIZATION

G. Charpak
CERN, Geneva, Switzerland

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1. INTRODUCTION

Recent years have seen a growing interest in the imaging capabilities of gaseous detectors.

Many qualities make them attractive: large surfaces can be built, the intrinsic localization accuracy can be as low as a few tens of microns, high counting rates and good energy resolution can be obtained. Their use and maintenance, however, require more constant attention from skilled staff than solid-state or scintillation detectors and this has repelled many interested users or industrial firms from making full use of the potentialities of gaseous detectors. One of their major defects, for many applications, is the low efficiency of the gases for absorption of X-rays, leading to a thickness of detector which makes it unsuitable for the precise localization of photons emitted in a broad angular range.

A variety of solutions has been imagined and tested to overcome the parallax error connected with the finite width of the detector. I will shortly survey various attempts and discuss proposals for new schemes which rely to a large extent on the observations we have made in operating the multistep avalanche chamber^{1,2)}, a new type of fast detector for high-energy physics particles. It so happens that this work has also contributed to progress in the imaging of the VUV photons with essentially the same technique and this will lead me to expand the subject of this article to the detection of VUV photons, where a single electron is liberated in the gas and is localized.

2. VARIOUS TYPES OF PARALLAX-FREE GASEOUS DETECTORS FOR X-RAY LOCALIZATION

One obvious way to have a high efficiency and reduce the gap of a gaseous detector is to go to high pressures. I wish first to mention that, apart from technological difficulties connected with the mechanics of high-pressure vessels, there is no difficulty in operating proportional chambers or drift chambers at such high pressures as several hundred atmospheres³⁾. It is precisely to avoid these mechanical difficulties that some effort has been invested in finding other solutions.

2.1 Measurement of the diffusion width

When a quasi-punctual cluster of electrons is produced by absorbing a photon in a dense gas, the cluster size grows as it drifts, under the influence of the atomic collisions.

Measuring the cluster size one can, in principle, deduce the drift length and, hence, the depth of absorption of the photon. Unfortunately, the size grows like the square root of the diffusion length and the method is not very sensitive. An attempt, along these lines⁴⁾, at CERN, has shown that in a drift space of 8 cm it is possible to reach an accuracy of only 40% (FWHM) for the depth at which the photon has been absorbed. This was done by using the rise-time change of the detected pulse as the ionization cluster from 5.9 keV X-rays drifted in a proportional counter. This is certainly not the most sensitive method, since the rise-time is governed by the diffusion along the electrical lines of force, which is known to be appreciably shorter than the lateral diffusion and this is probably one reason why the accuracy was deceptively small.

2.2 Spherical or cylindrical drift spaces

A drift space with the lines of force centred at the source is a natural solution for the problem of the parallax. All ionization electrons drift radially and are transferred, through an exit spherical grid, to a localization wire chamber.

Some authors have used such geometries as a solution to the parallax problem⁵⁾ in imaging ionization chambers with a thick high-pressure xenon converter for X-rays. The realization, which succeeded in coupling such a structure with multi-wire proportional chambers (MWPCs) and brought to light their properties, has been done at CERN^{6,7)} and recently in England⁸⁾. The interest of the first measurements at CERN lies in the properties which were displayed by such a structure, besides the disappearance of the parallax error. Such a chamber appeared to be free from the inherent differential non-linearity and inaccuracy connected with the existence of wires. The response is continuous even in the coordinate orthogonal to the wire direction; with a wire spacing of 2.5 mm no structure in the coordinate

measurement is observed and an accuracy of better than 1 mm can be achieved over a wide angle, even close to the maximum acceptance angle of $\pm 45^\circ$.

An efficiency close to 100% at 8 keV is reached with a gas mixture where the main absorbing components are argon and 20% xenon. A system continuously purifying the gas is one essential ingredient of such a device, because of the small leaks which have so far been inherent in most large wire chambers of the type used in high-energy physics, and which lead to intolerable electron attachment in the long drift path which can be close to 20 cm.

Three such chambers built at CERN are now in operation: one at Max-Planck Institute, one at MIT, and one at Orsay. They are very similar and we will hear at this conference some information concerning their results.

A chamber built according to a similar concept but with a cylindrical drift space, for one-dimensional localization, has also been built at CERN for the Laboratoire pour l'utilisation du rayonnement électromagnétique (LURE), Orsay. The wire chamber is equipped with wires 1 mm apart and with independent scalers. A rate of about 5×10^5 per s, per wire, is possible with the chamber.

An original way to correct for the parallax error in a one-dimensional wire chamber has been introduced by Perez-Mendez⁹⁾. He bends the wire to the appropriate radius by passing a current in the wire in a permanent magnetic field.

2.3 Flat chambers with radial electric field lines: the "zoom chambers"

Although feasible, it appeared that spherical drift chambers are difficult to make and have one main unattractive feature: their radius is fixed. This has led us to examine the possibility of having the same lines of force as in a spherical drift chamber, but with flat boundaries (Fig. 1b). This can be obtained by having the electrodes made of thin strips or wires set at graded potentials. As a simpler step we constructed a cylindrical chamber, on the same principle, also intended to be used at LURE. It is presently being tested.

It is essential to have a drift and absorbing space of sufficient depth in order to minimize the number of photons absorbed near the entrance surface, where the field will be perturbed, thus introducing unpleasant modulation of the spatial response. Our chamber has a depth of 10 cm.

I have deliberately ignored in this review the chambers associated with pulsed X-ray sources where, obviously, the time information permits one to obtain easily the depth of absorption, provided the time difference between successive pulses is larger than the total drift-time in the absorbing drift space, which is about 200 ns for 1 cm at atmospheric pressure with fields of the order of 1000 V/cm in gas mixtures with a high proportion of noble gases.

3. NEW APPROACHES TO PHOTON DETECTION WITH
PARALLEL-GRID AMPLIFICATION AND UNIFORM TRANSFER GAPS

3.1 Single-stage and multistep avalanche chambers (Fig. 2)

It is well known that parallel-grid structures permit an amplification. They suffer, however, from several defects when compared with wire chambers.

The gain is a function of the distance of the initial ionization electrons to the anode, which is not the case in a wire chamber where all of the amplification is concentrated close to the wire, at distances of the order of the wire radius. Typically, in a wire chamber at atmospheric pressure the mean free path for ionizing collisions is close to 1 μm . In a parallel-grid chamber it is often close to 1 mm and is the same all over the volume of the chamber. The gain is $e^{\alpha x}$, where x is the distance to the anode grid or plate and α the number of ionizing collisions per centimetre. Gains of the order of 1000 are easy to reach, while higher gains are more difficult to reach and are usually highly unstable, leading to local sparking if the field is not perfectly homogeneous.

With an absorption drift space in front of an amplification gap a good energy resolution can be obtained. We observed 16% (FWHM) with ^{55}Fe 5.9 keV X-rays, Fig. 3a. Figure 4a shows the variation of gain as a function of voltage. Such structures can compete successfully with wire chambers owing to the progress in low-cost, low-noise, high-gain amplifiers, which permit us to live with the smaller amplification provided by the parallel-gap structure. We have got rid of the fragile thin wires, but we have nevertheless to deal with a structure which has intrinsically much higher requirements concerning the mechanical accuracy and the electronic sensitivity.

An important fact which we have observed^{1,2,10)} is that with a proper choice of gases the electrons amplified in such a gap can be transferred to a drift space *with a constant loss* of the amplified charge, independent of the position of the initial ionization electrons. Such an observation of a transferred fraction distributed uniformly excluded the possible intervention of charge amplification around the wires of the exit grids. The consequence of this is that the cloud of electrons extracted from the amplifying gap keeps the information concerning the total charge for further use: it can be amplified in a second parallel-grid structure, or a wire chamber, with only a mild degradation of the energy resolution. Figure 3b shows the pulse height obtained after extraction of the electrons from the amplifying gap, with a loss of about 80%. Such a structure, illustrated in Fig. 2, opens the way to a considerable variety of unusual handling of the pulses produced by X-rays. We will illustrate this by showing how it permits one to get rid of the parallax defect in thick gaps and how it can lead to new types of localization techniques.

3.2 Parallax-free avalanche chambers for monoenergetic X-rays

One obvious way to build a parallax-free chamber would be to build a spherical drift space terminated by a preamplification gap made of two spherical concentric grids, Fig. 1c. The transfer of charges in a drift space and in a final amplifying stage would offer no special difficulty. The major problem could be to have a sufficient parallelism of the two grids to ensure a constant amplification. The advantage of such a structure compared with the normal spherical drift chamber is that photons traversing the absorption gap would not lead to a detectable background. However, owing to the unattractive mechanical difficulty of such a scheme we have imagined a method which exploits the properties of the multistep chamber and permits reaching the same result with flat electrodes. The method applies to monoenergetic X-rays. It relies on a simple observation: if the X-rays are absorbed in the gas of a gap limited by two parallel-plate electrodes, the gain which can be reached by applying a sufficient voltage is equal to e^{0x} , where x is the distance to the anode, as stated before. If this pulse

height can be measured we have the information concerning the depth at which the photon has been absorbed and can thus correct for the parallax error.

To achieve this we transfer the cloud of amplified electrons from the first gap to a second stage of amplification which will be used to reach enough gain to obtain the information concerning the pulse height and for the lateral localization of the electron cloud, Fig. 1d. It is our experience that an intermediate drift space between these two amplifying gaps permits an easier operation, higher total gains, more flexibility; but it is not compulsory. The nice feature of such a scheme is that it is not necessary to have all the photons absorbed in the first gap. Those photons reaching the second amplifying structure are not detected at all because of insufficient amplification and do not give rise to smeared out background. Figure 5 shows typical results obtained in such a double-step structure when an absorption drift space is placed in front of the first amplifying gap. These pictures illustrate the excellent energy resolution of such a device and its intrinsic features. If the absorption gap is not used and the photons are absorbed directly in the first amplification gap, we do not have any longer a quasi-monoenergetic line and by simply measuring the pulse height we have the depth at which it has been absorbed. Figure 4b shows the pulse height observed when the photons are detected in an amplification gap. The average observed peak height fits exactly the predicted variation with voltage and is equal to the maximum value $e^{\alpha x}$, divided by αx , as shown by a simple calculation. We have tested gaps of various thicknesses, up to 2 cm, filled with argon + 2% acetone, flushing the chamber continuously. A gain of 1000 can easily be attained in all gaps. What accuracy can we expect? We observe a resolution better than 25% FWHM for the 5.9 keV X-rays all over this range of amplifications.

We assume that the gain can vary over a maximum range of $G_{\max}$. A straightforward calculation shows that

$$\Delta x = \frac{\Delta G}{G} \frac{L}{\ln G_{\max}},$$

where L is the gap length. With a gap of 5 cm and a maximum gain of 1000, we have $\Delta x \approx 1.8$ mm (FWHM).

3.3 Parallax-free avalanche chambers for high-energy gamma-rays

A second method exploiting the properties of such a structure would be to use a thin metallic foil as a converter for the X-rays or γ -rays, Fig. 6a. The electrons extracted from the converter by Compton or photoelectric effect have an energy which usually is large enough to give them a large range in the gas which is incompatible with an accurate measurement of their starting coordinates. By having an avalanche gap in contact with the converter used as a cathode, those ionization electrons produced near the cathode are more amplified than the others. By measuring the centroid of the pulses in a second-stage MWPC, we have shown that an accuracy of 0.8 mm (FWHM) can be reached. This was applied successfully to the localization of β -emitters in radiochromatography¹¹⁾ and to the localization of thermal neutrons¹²⁾. In the case of γ -rays the efficiency would be only of the order of 10^{-3} , but for some applications a parallax-free high-accuracy device can be useful if sources of sufficient intensity are available. The second stage of amplification is quite insensitive to background because of its low gain. A method to increase the efficiency would be to use stacks of perforated converters or lead-glass tubes with an extracting field¹³⁻¹⁵⁾. However, since at least thicknesses of about 1 cm have so far appeared necessary for reaching 10% efficiency, a parallax error also afflicts the ultimate accuracy that can be reached by this method. We will see in the next section that the new developments should permit one, in principle, to overcome this defect.

3.4 New localization methods connected with the parallel-grid chambers

In contrast to the pulse-forming mechanism in wire chambers, where usually the detectable pulses are induced by the heavy ions moving rapidly in intense fields, the pulses induced in successive multistep structures are due to the motion of electrons.

Figure 7a shows the pulse induced in the collecting anode by an avalanche, while Fig. 7b shows the pulse induced when the electrons are sucked through the

anode grid by an appropriate field in the following transfer space. By transferring these electrons from grid to grid in successive spaces many new localization possibilities are opened up. I wish to draw attention to a simple one. If such a transfer gap is provided with a grid of wires placed at different depths and set at the potentials corresponding to a uniform field (Fig. 8), a fraction of the electrons will be collected by the field wire and a fraction will traverse this grid.

The pulses induced on the grid will have a shape depending on the position at which they have crossed it. The rise-time and decay-time of the pulse contain the information concerning the position. By simply measuring the time at which the maximum of the pulse occurs, one can obtain the position.

With a 10 cm wide chamber and a gap of 1 cm, an accuracy of 1 mm could be achieved by measuring time to a 2 ns accuracy. It is a drift chamber where the lateral coordinate is obtained from the longitudinal delay. Many other structures permit exploitation of this approach to the localization problems. We have given this example in order to illustrate the new possibilities available with these charge-transfer techniques.

4. NEW APPROACHES TO PHOTON DETECTION BY ASSOCIATION OF SCINTILLATION DETECTORS AND AVALANCHE CHAMBERS

4.1 The multistep avalanche chamber as a detector for single VUV photons

A multistep avalanche chamber has some advantages over a single-step parallel-plate structure for single-photon detection: the secondary emission of electrons by the cathode, induced by the UV photons or the positive ions produced at the head of the avalanche, is strongly reduced. This permits larger gains before reaching breakdown. This feature is an advantage for the detection of low-energy photons liberating a single electron in the gas.

With an adequate gas filling containing a component with a low ionization potential I_G and with an appropriate window with a cut-off energy of $I_W > I_G$, the photons in the energy interval I_G to I_W can be easily detected, amplified, and localized.

In high-energy physics this approach has been launched^{16,17)} in order to localize the VUV photons from Čerenkov radiation emitted by relativistic particles. The multistep chamber appeared to be an adequate tool for this purpose¹⁸⁾.

It has given rise now to active research by many groups. Figure 9 shows the quantum efficiencies of the different gas components used or envisaged in these detectors, together with the transparency of the most commonly used windows.

Very promising is a rather uncommon gas¹⁹⁾ tetrakis(dimethylamine)ethylene (TMAE) with an ionization threshold of 5.4 eV, which makes it compatible with the use of quartz windows. Its quantum efficiency, measured by our group and other authors, is higher than any photocathode used so far, since it is higher than 60% in some wavelength ranges. However, the vapour pressure is rather low, 0.3 Torr at 20 °C, leading to a mean free path close to 2 cm and thus giving rise to parallax errors if divergent VUV sources are used. With triethylamine (TEA) as a filling vapour the mean free path of VUV photons is only 2 mm per 1% of vapour pressure and it is easy and convenient to work with 2 or 3% of TEA in argon. For this reason, our own efforts for the localization of VUV photons from Čerenkov light have concentrated on this mixture, and promising results have been obtained. Total gains of 10^7 are achieved in multistep structures with this gas²⁰⁾ and a localization of about 0.5 mm is easily reached. With TEA the peak quantum efficiency is close to 40%. Figure 10 shows the total charge obtained in a multistep chamber with single electrons.

A detector with about 1 m² sensitive surface is under study, for the imaging of a large Čerenkov counter, as a joint effort of our group and a Saclay group.

4.2 The association of gaseous scintillation detectors and avalanche chambers

Scintillation detectors rely on the excitation of VUV light by electrons drifting in noble gases under the influence of strong electric fields²¹⁾.

They have raised interest because of the very good energy resolution obtained when this light is converted into visible light by fluorescence on an appropriate thin screen and detected with a photomultiplier. The typical energy resolution is 8.5% FWHM at 6 keV ²¹⁾ and 80 eV (FWHM) at 150 eV ²²⁾.

Recent work at Orsay with high-pressure xenon scintillation chambers has shown that excellent efficiency can be reached for high-energy X-rays, with an energy resolution matched only by solid-state detectors²³⁾. Figure 11 illustrates this excellence of energy resolution.

The advent of the gaseous detectors sensitive to VUV radiations has led naturally to a successful combination of the two detectors²⁴⁾, Fig. 12.

We have obtained at CERN²⁵⁾, with a krypton scintillation chamber viewed by a proportional chamber through a CAF_2 window, with Ar + TEA, an energy resolution of 10% FWHM, with all the attractive properties of localization characterizing this chamber.

Anderson^{19,26)}, who launched the use of TMAE, has built a similar chamber with a xenon scintillation chamber, a quartz window, and Ar + TMAE in a multiwire chamber. Our own best result with such a filling is now 8.3% FWHM at 5.9 keV. Figure 13 shows the results obtained with the K_α and K_β lines of silver.

With the same gases a group of astrophysicists at Columbia University²⁷⁾ has obtained a good energy resolution and a localization of 0.8 mm (FWHM). We can thus say that we have in our hands a new tool for X-ray detection, with an energy resolution seriously improved compared to that of the normal wire chamber.

Can we envisage a solution to the parallax problem connected with the imaging of punctual sources? Spherical electrode structures can indeed be envisaged. The problem of parallelism for the amplifying gaps, be it for light amplification or electron amplification, seems more delicate than for parallel-plate structures, but may be manageable. The problem of the window is more delicate. Who wants to grind a spherical quartz window! Some simpler methods specific to the mechanism of light production in these chambers can be envisaged.

The emission of light by the atoms excited by the drifting electrodes is a linear function of the electric field up to the point where electron multiplication starts to occur. Typically the threshold in xenon at 1 atm is at 700 V/cm, the breakdown at 6300 V/cm, and at this point the number of VUV photons is equal to the energy taken from the field by the drifting electron divided by 8.4 eV,

which is very close to the mean energy value of the VUV photons²⁸). We then see that with the electrons liberated by 6 keV photons we can produce more than 10^5 VUV photons with electrons drifting 1 cm at maximum permissible field.

We can then imagine a scheme where the electrons drift in a moderate field, where they emit say 10^3 photons per cm and then produce 10^4 photons in the last 5 mm against the exit window.

The length of the pulse will then be a measure of the drift length of the electron cloud and, hence, of the depth of absorption, thus permitting correction for the parallax, while the intense flash of light at the end of the drift, for a fixed time window, would give the energy resolution and could be used for the localization of the centroid of the light source.

This requires that the VUV photons be absorbed in a short path after entering the localization photo-ionization chamber in order to avoid a convolution of the light-pulse shape with a slow response function due to the variable drift length of the electron liberated by the VUV photon. In this respect TEA is perfect, while TMAE would require higher temperatures for a sufficiently high partial pressure. These speculations are given just to illustrate the new features belonging to this type of detector.

The emission of VUV light in a high-density conversion gap could also be used to detect γ 's in the MeV range with a high accuracy, without the low efficiency connected with a thin-foil converter and with a possible correction of the parallax error.

Instead of using lead-glass channels or successive layers of heavy metal and insulation in the drift mode, we could produce VUV light by drifting the electrons in the channels in an appropriate field in a pure argon or, better, a krypton or xenon filling and transfer this light, through an appropriate window, to the localization chamber, Fig. 6b. This would have the advantage of eliminating the jitter connected with the slow drift of electrons in the channels, since the photons would be detected at times independent of the depth at which the ionization electrons have been liberated in the channel. The pulse length would give information on the initial point of production, since it should be proportional to the drift length.

Surprisingly, a similar gain of time resolution is quoted²⁹⁾, without going through the complication of using the VUV photons, by simple electron multiplication in the drift channels and extraction of the electron cloud, whose timing should be dependent on the initial creation point. A timing of 13 ns (FWHM) is quoted with a 4 mm deep converter.

The main advantage of using the VUV light instead of the charges could be a slightly improved efficiency, since a single ionization electron should be detectable. Glass channels of the type used by Perez-Mendez are most favourable for the use of pure noble gases. If the parallax problem is ignored, this approach also permits the use of electric fields in alternate directions, by splitting the converter into several layers, hence requiring smaller voltages.

It should be stressed that this is a heavy approach to the problem of γ detection and localization. Since the efficiency is still 10 times smaller than that of appropriate scintillators, it requires, for the acquisition of a given number of good events, a chamber surface that is 10 times larger for single counting and 100 times larger for coincidence counting in positron cameras than with scintillators, even if the resolution time can be brought to a value where the accidental rate is not a problem. This approach is, however, of decisive value, for problems where the position resolution is of prime importance, as is demonstrated by the beautiful application of converters in solid-state physics¹⁴⁾. In medical applications the scintillators are so far the only practical solution acceptable in the technical environment of hospitals.

A recent step in the combination of scintillators with photo-ionization chambers may well lead to a radical change. Anderson²⁶⁾ has shown that a BaF_2 crystal scintillates in the VUV region and can be coupled to a MWPC where TMAE absorbs the photons. Table 1 summarizes his results at various energies. This preliminary result is very exciting. If a crystallographer could find how to dope BaF_2 in order to enhance the number of VUV photons, we would have full efficiency and energy resolution as with NaI, and in addition, millimetre accuracy. This could have considerable technical, scientific and commercial consequences.

5. CONCLUSION

The parallax-free detection and localization of photon quanta of energies ranging from 6 eV to 1 MeV, has found a surprisingly broad variety of possible solutions by using the properties of gaseous detectors.

One major defect connected with the low efficiency of gases for a large range of X-ray energies and the correlated request for thick sensitive gas layers leading to parallax errors has found a complete cure with the use of radial electrical fields.

The development of the multistep avalanche chamber is leading to different alternative solutions, with planar detectors. New localization methods are also possible with these new structures.

Finally, the combination of the scintillation proportional chambers with photo-ionization detectors developed for imaging of VUV light in Čerenkov counters has resulted in the development of new tools with a much improved energy resolution compared with that of wire chambers and still remarkably good sub-millimetre localization accuracies, with possible ways of reducing the parallax errors.

Table 1

The radioactive source, primary energies, the half-maximum number of ultraviolet photons detected per event, and efficiency of a BaF₂ crystal coupled to a photo-ionization detector (from Ref. 26).

Source	Primary energies (keV)	Half-maximum number of UV photons	Detection efficiency (%)
⁵⁷ Co	122	3.3	0.5
¹³³ Ba	356	4.8	2.0
¹³⁷ Cs	662	5.4	2.5
⁵⁴ Mn	835	5.0	2.6
⁶⁰ Co	1173, 1332	10.7	3.0
⁸⁸ Y	1836, 898	10.5	5.0

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Figure captions

Fig. 1 : Parallax-free gaseous detectors.

- a) Spherical or cylindrical structure centred on the point or line source.
- b) Flat structure limited by printed circuits and wires set at potentials creating a radial field: S_1 are Al strips on mylar, S_2 are wires or circular rings supported by insulating net.
- c) Spherical drift space with an amplifying parallel-grid gap.
- d) Parallax-free planar detector. The photons absorbed at different depths give rise to avalanches of different sizes. By measuring the pulse height in the localization detector one obtains the depth. The transfer from the first space to the last space is uniform with proper gases and is roughly equal to the ratio of the fields in gaps 1 and 2.

Fig. 2 : Multistep structures.

- a) A preamplifying (PA) and transfer (T) element followed by a conventional MWPC; addition of a conversion and drift space allows injection into the amplifying sections of a constant amount of charges (X-ray photoconversion).
- b) Two parallel-plate elements, with a transfer of charge from PA1 to PA2. The best time resolutions have been obtained using this configuration.
- c) A gated multistep chamber (MSC), where wires of grid G are at alternate potentials of ± 70 V, blocking the transmission of electrons from the PAT element to the MWPC, or transferring them when brought to the same potential, either d.c. or by short pulses of 30 ns, selecting rare events in a high-rate environment.

- Fig. 3 : Energy resolution in parallel-plate structure. Ar + 2% acetone.
- a) 5.9 keV photons converted in space C (Fig. 2). Avalanche in PA. No transfer of the electrons to T. Pulses measured from anode of PA.
 - b) The same with a field of 1200 V/cm in T. Pulses viewed at the anode of the last-stage MWPC.
- Fig. 4 : Variation of gain with voltage in a parallel-grid gap. Ar + 2% acetone.
- a) 5.9 keV X-rays converted in space C (Fig. 2). Pulses from anode of PA, fitting curve $e^{\alpha x}$.
 - b) 5.9 keV X-rays converted directly in PA, fitting curve $e^{\alpha x}/\alpha x$. Gains higher than 10^4 can be reached, with occasional sparking.
- Fig. 5 : Pulses in a multistep structure. 5.9 keV X-rays converted in C. Ar + 2% acetone. Amplifier: 300 mV/pC. Horizontal scale: 200 ns/div.
- a) Pulses in the PA1 gap of Fig. 2b: 5 mm, 10 mV/div.
 - b) Pulses in the PA2 gap of Fig. 2b: 200 mV/div.
- Fig. 6 : Detection of high-energy γ -rays.
- a) The photons are converted in a thin metallic foil limiting an amplifying gap. The electrons have a large range in the gas. The centroid of the electron avalanche transferred to the final gap is strongly displaced towards the starting point of the track. An accuracy of 1 mm is reached. Efficiency $\sim 10^{-3}$.
 - b) With tubes or stacks of converters of about 1 cm thickness the efficiency can reach 10%, but the parallax limits the resolution. If the ionization electrons produce VUV converted in a multistep photo-ionization chamber, the length of the pulse is dependent on the depth, and the time jitter due to the finite drift-time of the electrons in the tube is reduced. In principle, a time resolution of 10 to 20 nsec can be reached.

- Fig. 7 : Pulses in parallel-grid chambers.
- a) Pulse at the anode in an amplifying gap.
 - b) Pulse at the anode of an amplifying gap with a transfer of electrons to a following drift space.
- Fig. 8 : Lateral localization by longitudinal drift-time. The wires of a grid in the localization space are set at variable potentials. The pulses induced on the grid have a shape depending on the position of the electron cloud. The pulses on the electrodes limiting the localization gap have also shapes reflecting the drift length and hence the longitudinal and lateral positions.
- Fig. 9 : a) Quantum efficiency of various vapours, and transparency of various windows. TMAE and TEA: see text.
- b) Absorption of some vapours.
- Fig. 10 : Charge distribution from single photoelectrons in a multistep chamber. Total charge distribution collected at the anodes of a MWPC. Gas filling Ar + TEA (98%, 2%). Anode wires spacing 1.27 mm. Photoelectrons are released by light at the cathode of space (1). ($V = 2$ kV) = potential applied to the preamplification gap.
- Fig. 11 : Energy spectrum from a scintillation proportional counter.
- 5×10^5 Pa Xe; 10 cm absorption depth; 0.7 cm light-generating gap at $3.3 \text{ kV cm}^{-1} (10^5 \text{ Pa})^{-1}$; VUV converted by p-terphenyl to visible light viewed by photomultipliers.
- Fig. 12 : Photo-ionization proportional scintillation counter (PIPS). The X-rays are absorbed in a pure noble gas. The drifting ionization electrons produce VUV light in a scintillation gap. The VUV photons traverse a window and are detected and localized in a wire chamber with a photo-ionizable vapour (TEA, TMAE, acetone, etc.).
- Fig. 13 : Energy resolution of a PIPS. X-rays from ^{109}Cd . The K_α line (22 keV) and K_β line (25 keV) are separated. Energy resolution $\sim 4.4\%$ FWHM.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

Fig. 9

Fig. 10

Fig. 11

Fig. 12

Fig. 13