A TWO-DIMENSIONAL PARALLEL-PLATE CHAMBER
FOR HIGH-RATE SOFT X-RAY DETECTION

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ABSTRACT

We describe a soft X-ray detector having a 20 × 20 cm² active area and constituted by a
conversion and drift space followed by a parallel-plate avalanche chamber. Bidimensional
localization of the detected charge is performed on the last electrode recording the pulse-height
profiles of the fast electron-induced signals on a two-sided thin printed circuit with orthogonal
sets of conducting strips at 500 µm pitch. Localization accuracies of around 120 µm r.m.s. are
obtained in both directions for 8 keV X-rays. It has been observed that, whilst the induced charge
on the side of the board internal to the chamber (the anode) is negative (as one would expect), the
charge seen by the pick-up electrode on the back face of the readout board is positive, much as it
would appear on the cathode of a multiwire proportional chamber.

Because of its very good two-track resolution, one can envisage the use of this device in
transition radiation detectors.

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1. INTRODUCTION

The parallel-plate avalanche chamber has been, and still is, extensively used in low-energy nuclear physics for the detection of heavily ionizing particles because of its good intrinsic energy and time resolution, to which can be added its simplicity of construction compared with that of multiwire proportional chambers (MWPCs). Its use as a position-sensitive detector for low specific ionization radiation, such as soft X-rays and minimum-ionizing particles, has however been rather restricted by the difficulty of obtaining large enough proportional gains in stable conditions and without spark breakdown. Our experience with multiplication in uniform fields acquired in the course of development of the multistep proportional chamber [1-3] has naturally led to reconsideration of this simple detection structure. A parallel-plate device as end-cap detector for the time projection chamber (TPC) was indeed proposed by one of the present authors [4], and has been further developed in collaboration with others [5]. Compared with the more ambitious aim of detecting minimum-ionizing particles, which necessitated a multistep configuration, the present work describes the performance of a simple parallel-plate chamber used for localizing soft X-rays, between 6 and 8 keV. The construction and geometry of the multiplying gap and readout electrode is indeed much the same as described in ref. [5].

2. THE PARALLEL-PLATE X-RAY DETECTOR

The structure of the detector, which has an active area of $20 \times 20$ cm$^2$, is schematized in fig. 1. Two stainless-steel crossed-wire meshes, with 50 $\mu$m thickness and 500 $\mu$m pitch, are stretched and soldered to an insulating frame with copper-clad inserts; they define the conversion and drift region, where X-rays entering through a thin mylar window convert by photoelectric effect. The thickness of this region depends on the efficiency one wants to obtain at a given energy. We have operated the chamber with a 10 cm thick layer, having about 65% conversion efficiency for 8 keV X-rays when filled with argon (90%) + methane (10%) at atmospheric pressure; this efficiency can be increased by replacing argon with xenon. The electric field is kept uniform in the drift region and near the edges by a set of closely spaced copper strips, at linearly increasing potentials, printed on the walls of the chamber. For part of the measurements, related to the localization accuracy, we have reduced the conversion region thickness to 6 mm in order to decrease the contributions of the electron diffusion and of the parallax error at the conversion of the collimated source (which has a finite divergency). The last electrode (see fig. 1 and also fig. 2 of ref. [5]) is realized with a thin, 1 mm thick, printed-circuit board having parallel conducting strips 250 $\mu$m wide at 500 $\mu$m pitch; contact with each strip is individually available on an external connector. On the back of the board the same strip pattern is repeated, rotated by 90°; in the following, this is referred to as the pick-up electrode. Both sides of the circuit are kept at ground potential. To ensure its flatness, the board is glued on a 1 cm thick insulating plate*. The avalanche amplification of conversion electrons occurs in the high field between the lower mesh and the printed-circuit plate; to avoid edge breakdown, we have used the expedient, described in ref. [6], of increasing the distance between the electrodes near the frame's edges. This is realized by the use of a special profile, in the frame supporting the drift region, which pushes the mesh downwards when assembling the chamber. A reduction from 5 to 4 mm of the gap thickness over the surface of the detector is sufficient to avoid edge breakdown. The pusher is precisely

*) All frames and supporting plates are realized in high quality fibreglass (manufactured by Stesalit AG, CH-4249 Zvilwil, Switzerland).
machined, since it represents the most critical element in determining the gain non-uniformities; with an estimated mechanical tolerance of about \( \pm 30 \mu m \) we could achieve, as will be shown later, a \( \pm 15\% \) maximum gain variation across the whole sensitive area.

Forty channels have been instrumented with a fast charge amplifier\(^*\) and a gated analog-to-digital converter (ADC)\(^**\), and distributed between the two readout electrodes according to the experimental needs. Since we have analysed both direct negative signals and smaller induced positive signals (see later) two kinds of amplifiers have been used, referred to as anodic (type A) and cathodic (type C); their main characteristics are summarized in table 1. A single-channel cathodic amplifier is connected to the multiplying mesh in order to provide, after discrimination and shaping, the gating signal to the ADC converters.

For the operating gas, we have tested various mixtures of argon with ethanol, methylal, methane, ethane, or isobutane; as a general rule, we preferred to use small quantities of quencher so as to avoid the need for very high operating voltages in the parallel-plate region. Indeed, very good results were obtained with the classic P-10 mixture of 10\% methane in argon; all measurements described below were realized with this gas. In the near future it is planned to replace argon with xenon in order to increase the conversion efficiency and reduce dispersive effects of electron diffusion.

As ionization source we have used 5.9 keV X-rays from a \(^{55}\)Fe source, or a collimated beam from an X-ray generator with a copper anticathode having its main emission line at 8 keV. Data were recorded and analysed with the help of a small on-line computer.

3. GAIN UNIFORMITY AND ENERGY RESOLUTION

The gain characteristics and energy resolution of the detector have been studied, connecting the described electronic amplifiers and converters to the anode and pick-up strips, as well as to the facing cathode, and irradiating the chamber with monoenergetic X-rays from a \(^{55}\)Fe source. The charge \( Q \) measured on the anode as a function of the potential difference across the amplifying gap (4 mm thick) is given in fig. 2; above the last measured point, occasional sparking in the region of irradiation begins to appear. Note that the detected charge does not provide the proportional gain directly. It is a well-known feature of parallel-plate counters that, when detecting only the electron component of the avalanche with fast charge amplifiers, the detected charge is given by (see, for example, ref. [4]):

\[
Q = q_0 \exp (\alpha d)/\alpha d,
\]

where \( q_0 \) is the initial charge (around 220 electrons for 5.9 keV conversions), \( \alpha \) is the first Townsend coefficient, and \( d \) is the gap thickness; the true multiplication factor \( M = \exp (\alpha d) \) can be deduced from the expression using the measurement of \( Q \) (see fig. 2).

Figure 3 shows the pulse-height spectrum recorded on the anode at an intermediate gain value, detecting a well-collimated \(^{55}\)Fe source; the good linearity of the proportional gain is apparent from comparison of the main line and the argon escape peak. The corresponding energy resolution is 20\% FWHM at 5.9 keV.

The gain uniformity across the \( 20 \times 20 \) cm\(^2 \) active area depends strongly on the deviations from the nominal gap thickness; in fig. 4 we show the relative pulse heights measured with the

\(^*\) Developed at CERN by J.C. Santiard.
\(^**\) LeCroy 2249 A 12-channel ADC.
same collimated source, as a function of position along three scan lines centred at a 5, 10, and 15 cm distance from one side of the chamber. The maximum deviation from the average is about ± 15%. According to ref. [4], the relative gain variation in a parallel-plate chamber for a change δ in the gap can be expressed in first approximation as

$$\Delta M = 1 - e^{b\delta},$$

where the parameter b is provided by a straight-line approximation of the first Townsend coefficient for the gas mixture employed:

$$\alpha = aE + b,$$

E being the field strength. For a gas mixture close to ours, ref. [4] gives a value $b = -5.5 \text{ mm}^{-1}$; the measured ±15% gain variation is then consistent with the estimated ±30 μm overall mechanical tolerance. From the shape of the curves in fig. 4 one can also infer that electrostatic deflections due to mutual attraction of the electrodes (which should be maximum in the centre of the chamber) do not yet play an important role, but that there is instead a systematic twisting in the gap.

When amplifiers are connected to individual readout strips on the anode plane and on the pick-up circuit, a rather surprising observation is made: whilst the overall signal on the anode is negative, as expected from collecting the electrons in the avalanche, the charge induced on the facing circuit through the insulating board is positive and broader in spatial extension, much as one would expect to see on a cathode of a MWPC. These signals are therefore not simply an image of the electron avalanche as seen through the clearing between the anode strips by capacitive coupling, but correspond to a more subtle physical mechanism. Our phenomenological interpretation is as follows: because of the exponential multiplication process, most of the charge is produced very close to the anode strips. The collection of these electrons on the anode, which produces a negative signal, appears to the electrode on the back of the board as a disappearance of negative charge and therefore induces a positive signal.

A closer look at the anodic charge profile, obtained using bipolar amplifiers, reveals that the main negative cluster on the strips facing the source is accompanied by small positive tails at the two sides of the distribution. This was already mentioned in ref. 4. These signals on the anode are indeed generated by the same mechanism that produces a positive induced charge on the pick-up electrode. It is necessary that most of the charge is produced very close to the electrodes; a simple drift of electrons across the gap would induce a negative charge in both electrodes for all of the trip. This was indeed observed to take place in the multistep detector described in ref. [5], which could be operated in the preamplification and transfer mode where the last gap is traversed by a constant cloud of electrons. The induced charge profile, in this case, is broad and negative on both sides of the printed circuit (but too small on the pick-up electrode to be used in practice for localization).

The charge profile recorded on the two perpendicular readout electrodes for a single event (a 5.9 keV X-ray conversion) is shown in fig. 5. The distribution on the left, measured on the anode strips at 500 μm pitch, has been inverted in sign for convenience of display; an offset to the ADCs, indicated by the horizontal line, allows one to see the two positive induced signal tails on the side of the main negative peak (although not with a full dynamic range, because of amplifier saturation). On the right-hand side of the picture can be seen the positive charge profile recorded
on the back of the printed circuit, grouping the strips in pairs, i.e. at 1 mm pitch. Note that for most of the measurement we have restored the baseline of the converters, thus recording only the negative charge on the anodes.

Figure 6 shows the distribution of the cluster sizes (FWHM) for the anode and pick-up electrode respectively, measured when irradiating the detector that has the thin (6 mm) conversion space; the averages are 0.8 mm and 2 mm. When the chamber is equipped with the full 10 cm thick conversion volume, the average FWHM increases to 2.1 mm and 3.2 mm, respectively, because of the contribution of electron diffusion (most of the conversions take place at the farther end of the drift space, facing the input window). Adding up the signals in each cluster, one gets the pulse-height distributions shown in figs. 7a and 7b for the anode and the pick-up electrodes, respectively; the spectrum measured on the cathode mesh is shown in fig. 7c for comparison. The positive integral charge on the pick-up electrode has an average peak value which is 25% of the (negative) amplitude on the anode, and is about equal to the charge measured directly on the cathode. The two positive induced charges do not add up to equal, in absolute value, the negative signal seen on the anode, because the positive signals at the two edges of the anodic profile are not recorded; owing to the very narrow width of the anodic distribution (one strip in 20% of the cases, see fig. 6), the fraction of lost charge is probably position-dependent, which explains the worse energy resolution on the anode despite the larger pulse height.

4. LOCALIZATION ACCURACY

We have measured the bidimensional localization accuracy of the detector using a collimated beam from an X-ray generator with a copper anticathode, with the main emission at 8 keV; a cut on the recorded pulse height was applied to reject the continuous background. The range in the gas of the photoelectron emitted in argon contributes, of course, to the spread and has not been subtracted from the data.

All channels have been calibrated by injecting a known amount of charge at the input of the amplifiers and recording the relative pulse heights; a linear response has been assumed. Data from the strips are corrected, subtracting the known ADCs' pedestal and multiplying by a gain constant proper to each channel and deduced from the electronic calibration. The space coordinates are then computed with the simple centre-of-gravity expression:

\[ x = \frac{\Sigma X_i y_i}{\Sigma X_i} \quad \text{and} \quad y = \frac{\Sigma X_i y_i}{\Sigma X_i}, \]

where \( x_i, y_i \) and \( X_i, Y_i \) are the strip positions and pulse heights for the anode and pick-up electrode, respectively.

In fig. 8a we show the bidimensional display obtained by exposing the chamber to a narrow collimated beam in several adjacent positions, 1 mm from each other, along two scan lines also 1 mm apart; the uniformity and linearity of the response are apparent. A projection on the horizontal axis (fig. 8b) provides information on the localization accuracy; each peak has a FWHM of about 400 \( \mu \)m. Note that the spots at 1 mm distance are fully resolved. Taking into account the contributions of the beam width (200 \( \mu \)m FWHM) and of the parallax error (about the same over the 6 mm conversion space), one can infer from the measurement an intrinsic localization accuracy of 280 \( \mu \)m FWHM (120 \( \mu \)m r.m.s.). This includes, of course, the dispersions due to the range of the photoelectrons in the gas and the electron diffusion.

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In order to make a better analysis of the response of the detector over extended areas, we have exposed the chamber to an X-ray beam from the generator through a masking collimator with bar patterns of various widths; a large distance between the source and the detector (about 1 m) reduced the parallax error. An example of bidimensional distribution obtained in such a way in a particular position is shown in fig. 9. The overall image is contained in a $8 \times 8 \text{ mm}^2$ square; the largest bars are 1 mm wide at 1 mm distance, and these values decrease in 250 $\mu$m steps for the other patterns. One can see that the 500 $\mu$m wide strips are still well resolved, as one would expect from the quoted localization accuracy.

5. CONCLUSIONS AND SUMMARY

We have operated a parallel-plate chamber capable of accurate bidimensional localization of soft X-rays over large areas; simpler in construction than a MWPC, this kind of detector is intrinsically capable of withstanding larger fluxes of radiation without deterioration of the local energy resolution. Although for the measurement described we have operated with moderate resolution times, mostly limited by the integration and decay constants of the charge amplifiers (about 100 ns), it has been shown in previous works [4] that resolutions below 10 nsec can be obtained with the use of fast current amplifiers. The small width of the induced charge profile (between 1 and 3 mm FWHM in the worst case, including electron diffusion) should allow its use in all cases where multiple events within the time resolution can be expected owing to the rate or to the reconversion of fluorescence X-rays close to the primary conversion. One can also envisage replacing the expensive charge-recording electronics, used for the measurements described in this paper, by a much simpler threshold system, with an amplifier–discriminator circuit on each strip and an encoding of the centre of the cluster to represent the coordinate. Because of the small number of strips affected by each avalanche, one would expect a submillimetre localization accuracy even with such a simplified readout scheme, which would have the additional advantage of a very fast readout. Similar systems have already been developed for the fast readout of the coordinates in conventional multiwire chambers (see, for example, ref. 7).

The very good two-cluster resolution in the x–y plane, at least an order of magnitude better than in MWPCs with cathode readout, and the good time-separation that can be achieved, suggest the possibility of using this kind of device in transition radiation detectors where X-rays (which contain information on the velocity of the particle) are emitted at very small angles to the trajectory of the radiating particle.

On the negative side, one should mention the rather poor gain uniformity over the detection area of the parallel-plate detector, mostly due to mechanical tolerances, although the local resolution is rather good; long-term stability measurements and radiation damage studies are certainly required before this kind of detector can be used for practical applications.
Table 1
Main characteristics of the amplifiers

<table>
<thead>
<tr>
<th>Amplifier type</th>
<th>Sensitivity (mV/pC)</th>
<th>Rise-time (ns)</th>
<th>Decay-time (ns)</th>
<th>Input noise</th>
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<tbody>
<tr>
<td>A (anodic) non-inverting</td>
<td>250</td>
<td>10</td>
<td>100</td>
<td>2000 electrons</td>
</tr>
<tr>
<td>B (cathodic) inverting</td>
<td>1000</td>
<td>10</td>
<td>100</td>
<td>2000 electrons</td>
</tr>
</tbody>
</table>
REFERENCES

Figure captions

Fig. 1 Schematics of the parallel-plate detector. Two electrodes, 10 cm apart, define a region of moderate field for the collection and drift of the electrons (produced by X-ray conversions) into the multiplying gap. This is a 4 mm thick region with high field, where proportional multiplication occurs. To avoid edge sparking, the upper mesh of this gap is pushed inwards by a suitable insulating profile on the edges of the frame. The last electrode is a two-sided printed circuit, with two sets of parallel-signal readout strips at 500 μm pitch, perpendicular to each other.

Fig. 2 Detected charge Q on the anode as a function of operating voltage on the parallel-plate chamber. Since the amplifiers detect only the fast electron component of the signal, this is not directly the true gain M which can be computed and is shown also in the figure.

Fig. 3 Pulse-height spectrum recorded for collimated 55Fe X-rays on the anode plane. The energy resolution is 20% FWHM at 5.9 keV.

Fig. 4 Relative gain variations across the sensitive area of the chamber, measured along three scan lines, 5 cm apart from each other (1/4, 1/2, 3/4 of the chamber’s width). The maximum deviation from the average is about ±15%.

Fig. 5 Charge profiles recorded for one avalanche on the anode (left) and pick-up electrode (right). The anode distribution is inverted in sign for convenience of display, and an offset to the ADCs allows one to see the inversion of sign on the two sides of the main negative peak. The bin widths are 500 μm and 1 mm for the anode and pick-up electrode distributions, respectively.

Fig. 6 Distribution of the cluster width (FWHM) recorded on the anode and pick-up electrode, with a short (6 mm) conversion gap to reduce diffusion and parallax dispersions.

Fig. 7 Integral pulse-height spectrum obtained adding up the recorded charge on each cluster for the anode (fig. 7a) and pick-up electrode (fig. 7b). In fig. 7c the pulse height recorded on the cathode mesh is shown for comparison.

Fig. 8 a) Two-dimensional display obtained by exposing the detector to a collimated X-ray beam in several adjacent positions; the distance between positions, as well as the spacing between the two scan lines, is 1 mm. b) Projection of the previous image on the horizontal axis, showing the complete resolution of the spots at 1 mm distance. The FWHM of each distribution is 400 μm.

Fig. 9 Bar pattern obtained by exposing the detector to a parallel X-ray beam through a collimating mask. The width of the bars is 1 mm, and the distances between them are 1 mm, 750 μm, 500 μm, and 250 μm (the last bars are not resolved).