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HIGH RATE, HIGH RESOLUTION, TWO-DIMENSIONAL GAS PROPORTIONAL DETECTORS FOR X-RAY SYNCHROTRON RADIATION EXPERIMENTS*

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HIGH RATE, HIGH RESOLUTION, TWO-DIMENSIONAL GAS PROPORTIONAL DETECTORS FOR X-RAY SYNCHROTRON RADIATION EXPERIMENTS*

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Abstract

Two-dimensional, gas proportional detectors are being developed for use with X-ray synchrotron radiation. Two new types of interpolating cathode structures have been investigated, both of which can operate with a significantly smaller number of readout nodes along each sensing axis than previous cathodes. Lumped parameter delay lines are used as the position encoders. Timing signals from fast, low noise shaping electronics are fed to a new, dual TDC system developed for this purpose. Operating with a clock frequency of 500 MHz, the TDCs have an intrinsic differential non-linearity of 0.1%. The complete system can handle X-ray fluxes in excess of 10^6 per sec without distortion of the position information. A resolution of approximately 100 μm FWHM and differential non-linearity of $\pm 4\%$ have been achieved. Application of a detector with active area 10 cm $\times$ 10 cm using synchrotron radiation is described.

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1. Introduction.

Position-sensitive X-ray detectors based on the multi-wire gas, proportional chamber have been in use for small angle scattering investigations and protein crystallography for over a decade now, for example see refs [1,2]. In the last few years, several different detectors have become established for these same types of experiments, for example the Image Plate [3], TV detectors [4], and CCD based detectors [5], while X-ray film is still used in many instances. Each of these devices has certain characteristics and limitations which make it more suitable for one experiment than another. The multi-wire detector, a single photon counting device, remains a very important member of this collection of imaging devices available for X-ray scattering measurements. Our group at Brookhaven has already produced one-dimensional, delay line detectors and readout electronics [6,7] which have yielded the best position resolution, and one of the highest counting rate capabilities, of any proportional chamber device in operation to date. We have also carefully studied some of the fundamental limits to position resolution for X-rays in gases [8]. Building on this experience and knowledge, we have recently constructed our first two-dimensional X-ray detector. In this paper, we give short descriptions of the detector design philosophy, the choice and linearity performance of newly developed cathodes, position resolution, counting rate, and finally an example of the detector's operation at a synchrotron source.

2. Detector Structure.

a) Design Considerations.

The detector design results basically from a modification and extension of our existing one-dimensional detector [6] with delay line position encoding into a device with two-dimensional readout. The main parameters of the existing device are: anode wire spacing, 3.18 mm; anode, cathode spacing, 3.3 mm; cathode strip spacing, 2.54 mm; area of entrance window, 10 cm $\times$ 2 cm. The delay line [9] used to encode the cathode signals was specifically designed for the purpose. It is a lumped parameter line with forty nodes; the inductance between taps is

matched to better than 2%, and therefore the delay line has a very linear position response.

The new, two-dimensional detector design has a larger entrance window, 10 cm $\times$ 10 cm, and has position readout based upon the same delay line, one on each of the two cathodes. It was important, however, that certain changes be made to the existing detector geometric parameters. A much smaller anode wire spacing is required to obtain a good position resolution in the axis across the anode wires. In order to ensure a stable operating condition, and, further, to prevent significant reduction of induced cathode charge, the anode, cathode spacing should be of the same order as, or less than, the anode wire spacing. The cathode induced charge distribution has a quasi-Lorentzian profile, with FWHM approximately 1.6 times the anode, cathode spacing, and therefore the width of the cathode charge distribution becomes smaller as the anode, cathode spacing is reduced. Finer spatial sampling of the cathode charge is therefore required to achieve good position linearity. Although in this case the delay line provides a limit to the number of readout lines, new designs of interpolating cathodes have, nevertheless, produced a very linear response within this constraint. The parameters of the present two-dimensional detector are as shown in Table 1.

b) Fabrication.

Figure 1 shows a cut-away view of the detector, whose active depth is 6.35 mm. This comprises a 3.85 mm absorption and drift region between the window and upper cathode, followed by a 2.5 mm region between the upper and lower cathodes. The detector window is made from 250 μ m thick beryllium sheet, which gives very good X-ray transmission and remains flat to within about 50 μ m over its entire area. The electron cloud created by the stopping of an X-ray in the absorption region, drifts in a field of a several hundred volts per cm, then enters the multiplication region through the upper wire cathode, whose wires run parallel to those of the anode. The lower cathode is fabricated from printed circuit board, and contains strips running at right angles to the anode direction. The primary electron cloud avalanches on the nearest anode wire and charge is induced on both cathodes. For notation purposes, we define the X-axis

as that along the anode wires (lower cathode readout) and the Y-axis as that across the anode wires (upper cathode readout). With an operating gas mixture of Xe/10%CO₂, the window transmission and gas absorption result in a detection efficiency of about 80% at 6 keV, falling approximately monotonically to 20% at 15 keV.

Each cathode contains forty readout lines, or nodes, which are directly connected to the corresponding forty taps of the delay line, via flexible, kapton connectors. The detector, kapton connectors, delay lines and dual preamplifier cards are shown in figure 2.

The detector is made from four main pieces. The beryllium window is held on the underside of the top fibreglass frame. This sits on top of a 6.35 mm thick fibreglass frame which holds both the upper cathode and anode wires. Then comes the lower, printed circuit cathode, made from 1.6 mm thick fibreglass. All of these are bolted to a one inch thick aluminum support plate which provides structural rigidity, and also contains input and output gas ports. Because the upper cathode and anode wires run parallel to each another, and also because their respective planes are very close together (only 1.25 mm apart), special care is required in the design of the inside edge of their frame in order to avoid either surface currents or direct edge breakdown between anode and cathode during normal operation.

3. Linearity of Position Readout

A detailed description was given in ref. [6] of the optimum characteristics for position encoding by delay line. The induced signal from a cathode, for one detected event, is collected by the delay line, where it divides; one half travels to a preamplifier and shaping amplifier at one end of the line, and the other half does likewise at the other end of the line. The time difference of these signals determines the event's position in the detector; if τ is the transit time of the delay line, t_1 and t_2 are the signal arrival times at the left and right end of the delay line, and L is the detector's physical length, then the X-ray position as measured from the left end of the detector

is determined by $x = [1 - (t_2 - t_1)/\tau](L/2)$. In our present setup, the timing signals, obtained by double-delay line clipping and zero-cross detection following the preamplifiers at each end of the line, are analysed by a high-bandwidth time-to-digital converter (TDC) [7], which has a significantly smaller dead-time associated with it compared to a pulse height converter. A dual TDC is used for the two dimensional detector: timing signals from the lower cathode provide the X co-ordinate TDC signal, while those from the upper cathode provide the Y co-ordinate TDC signal.

The major change in the detector, compared with the original one-dimensional detector, which directly affects position encoding is a significant reduction in the anode, cathode spacing. With the number of readout nodes fixed by the delay line, significant differential non-linearity will occur with a standard cathode containing one strip per node, and we have therefore investigated two further types of interpolating cathode structure which result in a much improved differential non-linearity without the need to reduce the node spacing. We will describe the detector performance in the X co-ordinate in relation to all three types of cathode.

a) Conventional, Single Strip (SS), Cathode.

In the design of conventional, single strip (SS) cathodes, the condition for negligible differential non-linearity of the position readout is given by the inequality $w/d \leq 0.8$, where w is the strip pitch, and d is the anode, cathode spacing. The cathode and anode lengths in each axis of the new detector are approximately 11.4 cm, in order to ensure there is no gain reduction or non-linearity, due to edge effects, at the boundaries of the window. Thus, for the printed circuit SS cathode, $w = 2.85$ mm (also in this case, $w = w_r$, where w_r is the node spacing), and the value of w/d is almost 2.3, for which differential non-linearity is substantial (10). A part of this cathode pattern is shown in figure 3(a). The most accurate method of determining differential non-linearity is by measuring the detector position response with a beam of X-rays whose intensity is uniform along the axis under test - this is referred to as the uniform irradiation

response (UIR). The experimental UIR from the detector with a lower cathode constructed as a single strip version, is shown in fig. 4(a). The differential non-linearity is determined as: $DFNL = (I_{max} - I_{min}) / ((I_{max} + I_{min}) / 2)$, where I_{max} and I_{min} are the magnitudes of peak and valley in the UIR spectrum. For the SS cathode, DFNL is approximately 68%. This corresponds to a maximum position error in the recorded position of just over $150\mu m$. It is useful to compare the measured DFNL with that from simulation; the calculation should, strictly, take account of delay line and preamp rise-time, but earlier work [11] has shown that a calculation of the geometric center of gravity of charge on the cathode strips is very close to the real situation. The calculated DFNL for this cathode is 76%.

b) Two Intermediate Strip (TIS) Cathode.

The modulation in the UIR of the conventional cathode is due to a systematic error in the encoded position, which results directly from the strip pitch being too large compared to the anode, cathode spacing. This error would be reduced with a smaller strip pitch, but because the readout pitch, w_r , is fixed by the delay line, charge from some strips would then be coupled to their neighboring readout strips. A "noiseless" method of accomplishing this is to employ capacitively coupled strips. Recently we have been investigating the performance of cathodes with a single intermediate strip between nodes, the SIS cathode (10), and with two intermediate strips between nodes, the TIS cathode (11). For this detector, the TIS cathode is the most suitable: figure 3(b) shows a part of the cathode pattern of this type. Now w/d is just less than 0.8, while w_r is still 2.85 mm. Fig. 5 shows the stray capacitance due to the printed circuit board, that exists between cathode strips. If C_2 , the capacitance of each strip to ground, were zero, perfect charge division would occur and the encoded position would be exactly as if all strips were readout nodes of the encoding system. However, obviously C_2 can never be zero, but its value should be kept as small as possible compared to C_1 , the inter-strip capacitance. By ensuring all ground planes are as far away from the intermediate strips as possible, C_2 can be minimised. For example, that part of the aluminum support plate which would lie directly below the cathode

strips is completely machined away, and care is exercised in the design of the edges of the detector. Ref. [11] gives a more complete account of the optimization of this type of cathode, which requires a particular increase in the capacitance between the two intermediate strips, depending on the ratio C_1/C_2 . Intermediate strips also require a high resistance ($1\text{ M}\Omega$) to adjacent readout strips to stabilize their potential. The UIR from the near optimized TIS cathode is shown in fig 4(b), where the DFNL is of the order 8%. This represents negligible error in encoded position. A major advantage of this cathode is the relatively low inter-strip capacitance, due to there being three capacitances in series; this is particularly important to delay line operation since dispersion increases along with inter-node capacitance.

c) Zigzag Strip (ZZS) Cathode.

Another method of improving the differential non-linearity is to employ cathode strips with zigzag shaped boundaries, as was used by Miki et al. [12] in a time projection chamber. This type of cathode has been further studied [11] to determine the relationship between the depth of zigzag and non-linearity. Based on these results, a near optimum ZZS cathode for the present detector is one in which the depth of the zigzag is approximately equal to the node spacing, and a part of the cathode pattern is shown in fig. 3(c); the readout spacing, w_r , is still 2.85 mm. The UIR from a cathode with this array of strips is shown in fig 4(c), where the DFNL is approximately 10%. Thus, the difference between a near-optimized TIS and near-optimized ZZS cathode is almost negligible in terms of their non-linearity. However, a negative aspect of the ZZS cathode, for delay line use, is its large inter-strip capacitance. In this example, considerable signal dispersion occurs along the delay line, amplitude is decreased and signal to noise is reduced.

4. Position Resolution.

One of the most informative methods of presenting position resolution for a gas proportional chamber is by the relationship of resolution to anode charge. If good resolution can

be obtained only at high charge levels, this may lead to undesirable chamber behavior in terms of space charge, instability and ageing effects at high counting rates. The detailed description in ref.[6] illustrated the steps that have been taken with this delay line and preamplifier design to minimise electronic noise, thereby ensuring a particular resolution can be achieved with the minimum charge. A measurement of position resolution vs anode charge was made using a 5.4 keV X-ray source, collimated to about 15 μm , with the detector filled with Ar/20%CO₂ and the TIS electrode in place as the rear cathode. Fig 6 shows the resulting resolution as a function of anode charge, measured in 1 μs . This behavior is very similar to that for the original one-dimensional detector [6]. The figure illustrates the importance of operating the detector at the lowest possible charge for the desired resolution; minimum resolution of about 120 μm is obtained with an anode charge just less than 1pC, but above this charge, position resolution begins to deteriorate because of avalanche spread along the anode wire. This resolution represents about the lower limit for 5.4 keV X-rays absorbed in one atmosphere of argon [8], and a similar curve is obtained for 8 keV X-rays in Xe/10%CO₂. The detector is usually operated with an anode charge less than 1 pC, and not higher than that value which yields the required resolution for a particular experiment; this helps to minimise any effects of chamber ageing and space charge saturation. It should be noted that the equivalent resolution curve for the ZZS cathode is displaced by about a factor two to higher anode charges, because of the signal attenuation in the delay line.

5. Time-to-Digital Converter and Data Acquisition.

In normal operation, the detector provides two coordinates of information simultaneously, the lower cathode furnishing the 'X' signal, and the upper cathode furnishing the 'Y' signal. The dual TDCs are NIM modules which have been fully described in ref. [7]. The block diagram in fig. 7 shows timing signals from the two-dimensional detector feeding the dual TDC, whose outputs are analysed by a fast histogramming memory under computer control. The output of

the histogramming memory is displayed on a video monitor, in either one or two dimensional format.

The TDCs operate from a 500 MHz clock, converting the time difference between a prompt anode signal and the stop signal from the left hand (t_1) and right hand (t_2) end of the delay line into a digital number. The timing resolution of 2ns corresponds to 1000 resolution elements for a 1 μ s delay line. It can be seen from fig. 6 that this is well matched to the analog resolution from the detector, approximately 100 μ m in 10 cm, or 1 part in 1000. The intrinsic differential non-linearity of the TDCs is 0.1% [7], so they are not a limiting factor in detector linearity measurements. The average dead-time of the detector and TDCs is approximately $(0.75 \tau + 100)$ ns. Furthermore, internal discriminators are able to detect pulse pile-up and eliminate ambiguous events. When the actual flux incident on the detector is about 10^6 s^{-1} , the system throughput reaches a maximum of approximately $2 \times 10^5 \text{ s}^{-1}$. If the flux on the detector exceeds 10^6 s^{-1} , recorded events are still analysed correctly but system throughput begins to fall because a larger fraction of events are rejected. All our measurements to date, including linearity and resolution, have been performed with a 1 μ s delay line. We will shortly be testing the system with delay lines of 500ns transit time, which should increase the maximum throughput, but may limit the best resolution achievable.

Fig. 8 illustrates an X-ray image taken with the detector at beamline X12B of the National Synchrotron Light Source at Brookhaven. The diffraction rings are from a crystalline powder sample of cholesterol myristate, using 9.8 keV X-rays in Xe/10%CO₂. This figure illustrates the excellent global linearity of the detector in both axes (the slightly smaller position scale in the Y-axis is due to the video display). In this image, the position modulation due to the anode wire locations, in the (vertical) Y axis, has been eliminated by applying a matrix correction to the raw data, evaluated from uniform irradiation of the detector with X-rays of the same energy as the original image.

6. Discussion.

The design of the two dimensional detector described in this work has focussed on the provision of good signal to noise from the position encoder at moderate avalanche size, a high count rate capability, good position linearity, and operational stability. During routine use on a synchrotron beam line, it has been subjected to counting rates of 10^6 s^{-1} or greater for prolonged periods, generating nearly $1 \mu\text{A}$ in the high voltage line, without any instability in the high voltage or position response. Careful choice of electrode spacings, materials, edge designs and a high purity gas mixture have all contributed to this reliable operation. The anode voltage is normally in the range 1400-1500 volts, with a few hundred volts (negative) applied to the window. The two cathodes are at ground potential.

The development of interpolating cathode structures for position encoding with a limited number of readout nodes has resulted in a cathode design not only with much better linearity than a conventional cathode, but also with a smaller inter-node capacitance. For example, the conventional, or SS, cathode (fig 3(a)) has an internode (and therefore interstrip) capacitance of about 6pF on its full-size version for the present detector, which is greater than 10% of the node capacitance to ground required for the delay line. Negligible dispersion occurs only when this fraction is below about 5%. The near optimized TIS cathode has an inter-node capacitance of less than 2.5pF (there are three capacitances in series between each node). Thus, the TIS cathode, in addition to yielding a much superior non-linearity to the SS cathode, also allows the delay line to operate with much less dispersion and hence yields well shaped signals at the end of the delay line. The ZZS cathode (fig3(c)) has an inter-node (and therefore inter-strip) capacitance of just over 25pF. This high value is mainly due to the boundary length between strips being nearly six times as long as that for the SS cathode. It is quite surprising that the ZZS cathode performs as well as it does, because dispersion along the delay line is very significant. Nevertheless, the ZZS cathode is not a good choice for delay line operation in this case, though this design could well prove useful in one-dimensional detectors where the cathode

strip lengths are, in general, much shorter. Investigations are currently in progress on newer, interpolating cathode geometries.

The upper wire cathode of the detector, like the lower cathode, is constructed in the form of a TIS cathode, except that pairs of cathode wires are grouped together to form the equivalent of a cathode strip. In fact, since the upper cathode must be made of wires in order to allow electrons to drift through, the TIS design is most appropriate for this electrode; a wire cathode could not be fabricated as a ZZS electrode. The position response from the upper cathode is, however, strongly modulated by the 1.1 mm spacing of the anode wires. In general, the Y-axis position resolution is always worse than that in the X-axis; the Y-axis position modulation, and its correction as applied to fig. 8, is dependent upon X-ray energy, and will be described in more detail in a future report.

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Table 1

Anode Wire Spacing	1.1 mm
Anode Wire Diameter (Au plated W)	12 μm
Anode, Cathode Spacing	1.25 mm
Cathode Type	TIS (see section 3)
(Upper) Cathode Wire Spacing	0.475 mm
(Upper) Cathode Wire Diameter (Au plated W)	50 μm
(Lower) Cathode Strip Spacing	0.95 mm
Absorption/Drift Region Depth	3.85 mm
Area of Beryllium Entrance Window	10 cm $\times$ 10 cm

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Figure Captions.

- Figure 1 Cut-away view of two-dimensional detector. For reference, the beryllium window is 10 cm × 10 cm. The lower cathode is shown as a conventional, single strip type (for clarity), see section 3 for details.
- Figure 2 Photograph of two-dimensional detector (upper right), with kapton connector and delay line/dual preamplifier card for both the X-axis and the Y-axis.
- Figure 3 Schematic diagrams illustrating electrode geometries for
a) Conventional, or Single Strip (SS), cathode,
b) Two Intermediate Strip (TIS) cathode,
c) Zigzag Strip (ZZS) cathode (the periodicity of the zigzag is equal to the anode wire pitch)
- Figure 4 Uniform Irradiation Response (UIR) of complete 10 cm length of X axis from:
a) Single Strip (SS) cathode.
b) Two Intermediate Strip (TIS) cathode
c) Zigzag Strip (ZZS) cathode
- Figure 5 Inter-electrode capacitance associated with the Two Intermediate Strip cathode.
- Figure 6 Position Resolution vs Anode Charge, for 5.4 keV X-rays absorbed in Ar/20%CO₂, in X-axis using TIS cathode. The anode charge is measured in 1 μs.
- Figure 7 Block diagram illustrating two-dimensional detector operation with two synchronized TDCs.
- Figure 8 Diffraction rings from crystalline powder sample of cholesterol myristate, illustrating excellent global linearity of both X and Y co-ordinates.

FIGURE 1

a)

b)

c)

a)

b)

c)

FIGURE 5

FIGURE 6

FIGURE 7

FIGURE 8

END

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