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HIGH ACCURACY GASEOUS X-RAY DETECTORS*

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HIGH ACCURACY GASEOUS X-RAY DETECTORS^{*}

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Abstract

An outline is given of the design and operation of high accuracy position-sensitive x-ray detectors suitable for experiments using synchrotron radiation. They are based on the gas proportional detector, with position readout using a delay line; a detailed examination is made of factors which limit spatial resolution. Individual wire readout may be used for extremely high counting rates.

1. Introduction

The wide range of photon energies available from synchrotron radiation sources requires the use of several different types of photon detector. In the UV to soft x-ray region, for instance, microchannel plates provide useful coverage and for soft to hard x-rays, various types of solid state detector are utilized. The intense flux from synchrotron sources places demanding requirements on the particular detector; we are concerned here only with the single photon counting mode, but the high flux of photons in some synchrotron experiments can sometimes only be effectively utilized by operating detectors in the current mode.¹

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In the soft to medium x-ray range of a few hundred eV to ~ 20 keV, the gas proportional detector possesses, for single photon counting, five important attributes which are not readily achievable simultaneously by any other detector: i) high efficiency, ii) excellent position resolution, iii) moderately high counting rate capability, iv) integral non-linearity of a fraction of a percent and differential non-linearity of a percent or so, and v) a large variety of collecting areas. There are several x-ray scattering phenomena which make use of these properties, e.g., time resolved studies in biological structures² and x-ray crystal diffraction.³

The design of such high performance detectors is easiest for the energy range of about 3-10 keV. We will describe here, with particular reference to development work carried out at Brookhaven National Laboratory, the design and operational features of such x-ray gas detectors; critical examination of the limiting spatial resolution is made from both geometrical and physical factors. A very comprehensive description of some of this work can be found in Ref. 4.

2. General Detector Concept

The detectors are based on conventional multiwire proportional chambers, with position information being determined from a delay line which is connected to the lower cathode. Figure 1 shows a schematic, exploded view of the detector and delay line readout scheme.

The anode is a plane of wires, with pitch s , whose direction (left to right) defines the position sensing axis. The lower cathode is constructed in the form of strips, pitch w , which run perpendicularly to the anode

wire direction; the strips are connected directly to the taps of a lumped delay line. A thin beryllium window forms the upper cathode, though no signal is read from it as it is electrically connected to the ground of the detector housing. Anode-cathode spacing is denoted by d .

An avalanche on one of the anode wires creates induced charge on a few of the cathode strips, which is fed into the delay line. This charge divides and travels to each end of the delay line where it is collected by low noise charge-sensitive preamplifiers, which correctly terminate the delay line. Timing information is obtained from optimized, delay line clipping amplifiers and zero-cross detectors; constant fraction discriminators can be used in place of zero-cross detectors, though they are not intrinsically capable of greater accuracy. The difference in arrival time of the charge signal at each end of the delay line is directly proportional to the centroid of induced charge on the cathode, i.e., to the centroid of the anode avalanche. Most of the results to be described here are obtained by analyzing this time difference with a time-to-amplitude converter (TAC), as shown in Fig. 1; the full counting rate capability of this system can only be effectively utilized by analyzing the two delay line timing signals with separate time-to-digital converters, which have been started by a prompt anode signal.

One important goal of this development work was to achieve a design in which detector dimensions could be linearly scaled, with certain limitations, while the position readout remained the same. This is illustrated by the division (Fig. 1) of the whole system into three main components: detector, connecting board, and delay line/electronics. (The

delay line is a discrete unit, with a fixed size and fixed number of sections, or inductors.) As the detector size is increased or decreased, the connecting board, which directly couples the cathode strips to the delay line, has an appropriate fan-in or fan-out shape.

For reasons primarily of cost and simplicity, the initial detector design is based on one dimension position readout, along the anode wire direction. It is possible to obtain position information in the second dimension, across the anode wires (but with reduced spatial accuracy) using, for example, a similar delay line technique or by reading out each anode wire with its own preamplifier.

3. Operating Characteristics

The operation and performance of the gas proportional detectors will now be described with reference to the five important attributes cited in Section 1.

i) Efficiency

In the application of detectors to diffraction experiments, it is important to minimize the degradation in spatial resolution, resulting from parallax error, which occurs when photons enter a detector at a finite angle to the normal of the window. An effective method of achieving this is to restrict the depth of the detector without significantly diminishing x-ray detection efficiency. A depth of 6.6 mm (i.e., $d = 3.3$ mm) was used for the mid-size detector of this work: at 2° angle of incidence, this results in an average 100 μ m broadening of the position distribution.

Figure 2 shows $1/e$ absorption depth (that depth in which 63% of incoming radiation is absorbed) vs photon energy for three typical counter

gases. In a depth of 6.6 mm, xenon provides $\geq 50\%$ efficiency up to ~ 10 keV; 4 atm of xenon would extend this efficiency up to nearly 20 keV.

Photon detection below 2 or 3 keV is more effective with argon or methane, for example, since the very small absorption depth in xenon can result in loss to the window of some of the primary ionization. Argon may also be used up to 10 keV, but the detection efficiency begins to degrade fairly rapidly above ~ 5 keV for the depth of gas referred to above.

The data in Fig. 2 are for pure argon and pure xenon: in practice, these gases are used with $\sim 10\%$ by volume of a suitable quenching agent such as methane or carbon dioxide (the latter generally results in longer detector lifetime than methane).

The most common window material is beryllium; for operation at atmospheric pressure, 250 μm , or even 100 μm , thick beryllium sheet provides a flat window over several tens of square centimeters. To safely sustain a pressure of 4 atm, it is usually necessary to use ~ 1 mm thick beryllium. Figure 3 shows transmission vs x-ray energy curves for these thicknesses and, very approximately, they define low energy cut-offs of 3 to 5 keV for the 1 atm detector and ~ 10 keV for the 4 atm detector.

A frequently used window material for x-ray detection below 2 or 3 keV is stretched polypropylene and its transmission characteristics are also shown in Fig. 3. Generally, this material (and all other stretched plastics) require some form of support, such as fine wire mesh, even when there is no pressure differential across it. For convenience, therefore, the group of detectors constructed here was designed for ~ 3 keV to 10 keV x-rays with

1 atm operation and ~ 10 to 20 keV x-rays for 4 atm operation.

The curves in Fig. 2 and Fig. 3 have been plotted from calculations based upon absorption coefficients in Refs. 5 and 6.

ii) Position Resolution

Intrinsic position resolution is dependent upon at least three phenomena which can be described with reference to Fig. 4a and b. Figure 4a shows a side view of the detector geometry. A photon enters through the window and is absorbed by a gas atom via the photoelectric effect: the bulk of the x-ray energy is transferred into either a photoelectron or photoelectron and Auger electron. The primary electron(s) thermalizes by creating secondary ionization of surrounding gas atoms and then the cloud of secondary electrons drifts to and avalanches on an anode wire. It is the centroid of the anode avalanche which the position readout electronics determines, but there are dispersive effects in the gas which limit the accuracy of this recorded position with respect to the true x-ray absorption position along the sensing axis: the finite range of the primary electron(s) and subsequent diffusion on the secondary electron cloud during its drift to the anode wire. These gas phenomena will be analyzed in Section 4. A further, limiting phenomena is that of electronic noise, which will now be assessed.

The anode avalanche gives rise to a quasi-Gaussian shaped induced charge distribution on the lower cathode, as indicated by the dashed line in Fig. 4b; the total charge, Q_c , on the cathode is determined by the area under this curve and, on average, is half the anode charge. The exact shape

of the cathode charge distribution is actually narrower than a Gaussian, with higher and longer wings; an analytical calculation of the shape has been made by Gatti et al.⁷

The charge induced on each strip is shown by the histogram in Fig. 4b. It is the centroid of this composite signal, propagating down the delay line, which is determined by the timing signals from the cross-over detector electronics: this interpolating property results in a spatial accuracy which is unlimited by the strip width. The interpolating property holds true not only for the delay line, but for any readout principle using strips, e.g., capacitive charge division;⁸ delay line position sensing was used here because of its relative simplicity and generally higher counting rate capability. From linearity considerations (see section 3(iv)), the histogram centroid is close enough to that of the true analog charge distribution provided $w/d \leq 0.75$. The centroid finding characteristic of the delay line and electronics is true provided the delay per section of the line, and intrinsic delay line rise time, are below certain critical values (see Ref. 4).

The intrinsic accuracy in determining the anode avalanche centroid is mainly limited by the accuracy of zero-cross timing: this accuracy is inversely proportional to preamplifier electronic noise at each end of the delay line and directly proportional to signal, i.e., to the area under the curve, Fig. 4b. Position resolution is determined experimentally by directing a finely collimated beam of x-rays ($\sim 32 \mu\text{m}$ wide) onto the detector, normal to the window, and measuring the width of the position distribution as a function of anode charge, Q_a . A typical result of such a test is shown in Fig. 5 for 8.04 keV x-rays and a gas mixture Xe/10% CO₂; the detector

dimensions were 6 cm (along the sensing axis) by 2 cm. As pointed out above, the resolution, initially, improves in direct proportion to the anode charge, but then gradually reaches a plateau level of $\sim 70 \mu\text{m}$ FWHM. The electronic resolution, i.e., the contribution of preamplifier electronic noise to position resolution, continues to improve linearly with anode charge. The gradual levelling off of x-ray spatial accuracy is due mainly to the photoelectron range and electron diffusion causing fluctuation in the avalanche centroid with respect to the true x-ray absorption position. At $Q_a \sim 5.10^6$ electrons, the position readout locates without any electronic error the correct anode avalanche centroid.

The design and optimization of the position encoding electronics (shown in rather simplified form in Fig. 1), from which the type of resolution performance shown in Fig. 5 is obtainable, is not a simple matter and is treated in detail in Refs. 4 and 9. Minimization of noise in the preamplifiers at each end of the delay line is most important: the greater their noise, the more the electronic resolution line, in Fig. 5, is shifted to the right, with the resultant need to operate the detector at proportionally higher avalanche charge (i.e., higher operating voltage).

It should be emphasized that presentation of resolution performance as in Fig. 5 is very important for any position-sensitive system. It provides the experimenter with a means of determining the maximum anode charge (or gain) at which the detector need be operated: space charge limitations and detector lifetime are both more troublesome at higher avalanche charges. It also allows the calculation of a useful parameter, that of equivalent position noise charge, ENC_{pos} . If l = length of the position sensing axis, and δl = electronic position resolution, then

$$\frac{\delta l}{l} = \frac{ENC_{pos}}{Q_a} .$$

Thus we find $ENC_{pos} \sim 2000$ e's FWHM for the present system. This figure of merit provides a convenient method, within certain limitations, of comparing the performance of different position-sensitive detecting systems.

iii) Counting Rate Capability

In general, it is not easy to determine at what point counting rate effects become significant; much depends upon the intensity distribution of the position spectrum being measured.

Counting rate effects on the position distribution from the detector can occur from at least two causes: i) a high local flux can cause space charge saturation which reduces the local electric field, thus reducing detector gain and possibly degrading position resolution (e.g., broadening of a diffraction peak); ii) a similar flux more evenly distributed over the whole area of the detector can result in a gradual distortion of the image when a delay line stop signal from one event is associated with the start signal of a preceding event from a different part of the detector.

Type (i) effects are minimized in the following way: the lower the avalanche size on an anode wire, the higher can be the counting rate in one spot before space charge saturation reduces the local electric field. This point emphasizes the need to operate a particular detector at as low an anode high voltage as possible. A further way in which space charge saturation is minimized is by using a multiwire anode so that the avalanches from all events at one particular position along the sensing axis do not occur only on one wire. It is important that $s \gg d$, otherwise the induced cathode signal is significantly reduced.⁷

Effects of type (ii) can be reduced by employing a large total delay, T_D , of the delay line. Unfortunately, ENC_{pos} is inversely proportional to

T_D (see Ref. 4) and the value $T_D = 1 \mu\text{sec}$ used in this work is, in part, a compromise between capability of reasonably high counting rates and retaining a fairly low noise readout system. At a counting rate of $2 \cdot 10^5 \text{ Hz}$, $\sim 20\%$ of events result in an error of position measurement with this delay time.

The resolution performance described earlier in Fig. 5 can, in general, be maintained at $2 \cdot 10^5 \text{ Hz}$ if $Q_a \leq 3 \cdot 10^6$ electrons. This represents an approximate upper limit to counting rate for the system described here.

iv) Non-linearity

Integral non-linearity (defined as the absolute position error normalized to detector length) better than $\pm 0.1\%$ is achievable. A more demanding parameter is that of differential non-linearity, which is most easily measured by illuminating the detector uniformly along its sensing axis with x-ray radiation and recording the position output spectrum. The result of such a test is shown in Fig. 6, performed on a detector with sensing length 10 cm, and width 2 cm. Fluctuations in the spectrum are no greater than $\pm 2\%$, except for end effects; the slight curvature is due to the finite distance between source and detector.

Besides assessing the position readout linearity, a positive result, such as that shown in Fig. 6, indicates the uniformity of detection efficiency. The linearity of position readout is most sensitive to the following parameters:

a) Cross-talk between the two amplifier channels. If cross-talk occurs, cross-over timing can be affected and most frequently exhibits itself as peaks or troughs around the center of the position output spectrum. Extreme care is therefore required in ensuring the electrical isolation of one amplifier channel from the other.

b) The inductor values, L_s , and capacitance values C_s . These should exhibit less than $\sim 4\%$ tolerance on their correct value. (The delay line used for this work has $L_s \sim 12.5 \mu\text{H}$, $C_s \sim 50 \text{ pF}$, and contains 40 such sections. Its characteristic impedance $Z_0 \sim 500 \Omega$.)

c) The inequality $w/d \leq 0.75$. If this is not satisfied, the centroid of charge induced on the strips deviates sufficiently from the true avalanche centroid, with a periodicity of w , that a modulation of the same period is formed on the uniform irradiation position spectrum.

v) Detector Size

The different sizes of detector which have been constructed as a part of the general system described in Sections 2 and 3 are indicated in Table I.

TABLE I

Detector Collecting Area	Operating Pressure	Energy Range
6x2 cm ²	1 atm.	3-10 keV
10x2 cm ²	1 atm.	3-10 keV
18x10 cm ²	1 atm.	3-10 keV
10x1 cm ²	4 atm.	10-20 keV

TABLE II

Spatial Resolution	: $\sim 100 \mu\text{m}$ (FWHM) or 1 part in 10^3
Integral Non-linearity	: Less than $\pm 0.1\%$
Differential Non-linearity	: Less than $\pm 2\%$
Detection Efficiency	: $\geq 50\%$ for all appropriate energy ranges

For completeness, Table II summarizes their basic capabilities.

4. Limit Imposed by Photoelectron Range

Section 3(ii) assessed the limitation to spatial resolution of electronic noise. As was shown in Fig. 5, when the anode charge reaches a particular level, the true centroid of the anode avalanche is determined without error by the position readout system, but a plateau of x-ray position resolution is attained due to dispersive effects occurring in the gas. Unlike electronic noise, these effects cannot be overcome just by "raising the high voltage" and they represent the minimum resolution achievable for a particular detector geometry, gas and gas pressure. These effects are determined primarily by electron range; electron diffusion and avalanche spread also occur, but their dispersive effects are smaller than those of electron range when these relatively thin detectors are operated at anode charge levels below 1 pC.

We have made a series of measurements in which photoelectron range was the main factor limiting spatial resolution, for the gases considered in Fig. 2, and for x-ray energies from a few eV to 18 keV. The results of this work¹⁰ will be outlined here. Interaction of an x-ray with a gas atom first results in the emission of a photoelectron with kinetic energy $E_X - E_B$, where E_X is the x-ray energy and E_B the binding energy of the shell in which the x-ray interacts. The photoelectron has a certain range in the gas, in which it ionizes surrounding atoms (~ 25 eV per ion pair is required for most counter gases) until it thermalizes; in some x-ray interactions an Auger electron with significant energy is also emitted. For a gas such as methane, the main absorbing atom is carbon whose K shell binding energy is 0.28 keV. For the x-ray energy range we are considering here, therefore, the photoelectron takes nearly all the x-ray energy; the measured

value of the exact x-ray absorption point is determined by the centroid of the secondary ionization, which in turn is found to show a fluctuation which varies as a power law of x-ray energy: Fig. 7 shows the methane resolution results. This behavior is similar to that of electron range with electron energy in metal foils.¹¹

In argon and xenon gas mixtures, however, a significant proportion of the x-ray energy can be taken by the Auger electron, emitted during a radiationless transition as the atom de-excites. The Auger electron energies for argon and xenon are ~ 2.7 keV and ~ 3.6 keV, respectively (this discussion neglects those events in which fluorescent emission occurs since their probability is less than 15%). The experimental data for argon and xenon mixtures, shown in Fig. 7, indicate that minimum resolution probably occurs when the photoelectron and Auger electron have roughly equal energies, which occurs around 6 keV and 8.5 keV for argon and xenon, respectively. Since the emission directions of the photoelectron and Auger electron are independent of each other, the centroid of their secondary ionization will clearly exhibit less fluctuation, over many events, than that from one electron with energy equal to the sum of the two. At higher x-ray energies, the initial photoelectron progressively takes a larger proportion of the x-ray energy and limiting resolution appears to approach a similar power law dependence with x-ray energy that is exhibited in methane.

The best spatial resolution measurement is $65 \mu\text{m}$ FWHM in Xe/10% CO₂ at 8.04 keV x-ray energy. The progressively deteriorating spatial resolution for 10-20 keV x-rays in this gas mixture provides a further reason, in addition to the need to maintain high efficiency, for using a detector at 4 atm in this energy range, since electron range will reduce with increasing gas pressure.

5. Extremely High Counting Rate Detectors

With the high photon flux available from synchrotron radiation sources, there are experiments which yield detectable fluxes potentially greater than can be handled by the two channel position readout described in Sections 2 and 3. Time resolved studies on biological specimens such as muscle² can generate thousands of photon counts in ~ 1 msec time slices, for example. For this and other applications, we are developing a one-dimensional detector which is shown, schematically only, in Fig. 8. The window and lower cathode are flat, plane electrodes and the anode plane consists of wires running across the width of the detector; each wire is connected to its own, low noise preamplifier. There can, in addition, be a fine wire cathode plane, with wire direction at right angles to the anode wires, between the anode plane and window in order to create a separate absorption and drift region below the window.

The position sensing axis of this detector is from left to right (Fig. 8) across the anode wires. Each anode wire is essentially its own counter and therefore spatial resolution is determined primarily by anode wire pitch, which is presently limited to ~ 1 mm for two reasons: i) construction and operation difficulties are greater for significantly smaller pitch, ii) installation of low noise preamplifiers presents space problems since each amplifier needs to be very close to its own anode wire to minimize capacitance. With a detector length ~ 10 cm, the number of pixels is ~ 100 ; this number is determined by the number of wires and is unrelated to electronic noise and electron range considerations. Spatial resolution is therefore about 1 part in 10^2 .

Each anode channel comprises a wire and preamplifier (as indicated in Fig. 8), followed by a fast signal processing filter which cancels the long tail of the anode signal by pole/zero circuits in ~ 50 nsec or less.¹² Provided the detector is operated at low charge levels (a few times 10^5 electrons per event), in order to minimize space charge problems, each channel is capable of counting rates ~ 1 MHz. The detector is therefore capable of an integrated counting rate of ~ 100 MHz. Acquisition and storage of data at such very high rates takes place further along each anode channel and is a separate, non-trivial problem.

The work outlined in this paper results from a general, ongoing development of x-ray position sensitive detectors by numerous personnel in the Instrumentation Division at Brookhaven. In particular, the author wishes to acknowledge Veljko Radeka, Joachim Fischer, Fred Merritt, Lee Rogers, Dmitri Stephani, Robert Boie (Bell Labs), and Yosuke Inagaki (Kyoto University, Japan).

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Figure Captions

- Fig. 1. Schematic view of position sensitive x-ray detection system showing division into three principal sections: i) detector (sensing axis is from left to right along the anode wires), ii) connecting board, iii) delay line and position encoding electronics.
- Fig. 2. $1/e$ absorption depth (in which 63% of all radiation is absorbed) vs photon energy for three proportional counter gases: methane, argon, and xenon.
- Fig. 3. Transmission efficiency vs photon energy for two counter window materials: beryllium and polypropylene.
- Fig. 4a Side view of detector illustrating absorption of x-ray photon in the gas.
- 4b Charge distribution (dashed line) induced on cathode and actual charge (full line histogram) formed on cathode strips.
- Fig. 5. Position resolution (FWHM) vs anode charge (measured in $1 \mu\text{sec}$) in $6 \times 2 \text{ cm}^2$ detector containing Xe/10% CO_2 , with 8.04 keV x-rays. This figure is taken from Ref. 4.
- Fig. 6. Position output spectrum from $10 \times 2 \text{ cm}^2$ detector when uniformly illuminated by 5.41 keV photons. Differential non-linearity is $\pm 2\%$, except for end effects. This figure is taken from Ref. 4.
- Fig. 7. Photoelectron (and Auger electron) limited spatial resolution vs photon energy for CH_4 , A/10% CH_4 , and Xe/10% CO_2 .
- Fig. 8. Schematic, exploded view of position sensitive x-ray detector for extremely high counting rates; sensing axis is from left to right across the anode wires.

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4

Fig. 5.

Fig. 6.

Fig. 7.

Fig. 8