One-dimensional gas position sensitive X-ray detector

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The construction of Gas X-Ray Detectors used to count and localize X-Ray photons in one dimension is reported. The principles of operation of the detector are described, as well as the electronic signal processing comprised in the data acquisition system. Results obtained with the detectors are shown, illustrating good performance as compared to other detecting systems: spatial resolution $\approx 300\ \mu$m, linearity $< 0,1\%$ and homogeneity $< 4\%$.

Relatamos a construção de Detetores de Raios-X a Gás usados para contar e localizar fotons em uma dimensão. Os princípios de operação do detetor são descritos, bem como o tratamento de sinais compreendido no sistema de aquisição de dados. Resultados obtidos com os detetores são mostrados, ilustrando bom desempenho em comparação com outros sistemas de detecção: resolução espacial $\approx 300\ \mu$m, linearidade $< 0,1\%$ e homogeneidade $< 4\%$.

I. Introduction

Gas Position Sensitive X-Ray Detectors are presently built at the Brazilian Center for Physics Research (CBPF). 'Position Sensitive' stands for the fact that, besides counting single photons interacting with the gas atoms, these detectors are able to measure their position of incidence with some accuracy, in one or two dimensions.

The one-dimensional position sensitive detector (PSD) is currently built, and is used for scanning X-Ray scattering patterns in applications such as Small Angle X-Ray Scattering, Wide Angle X-Ray Scattering, Computerized Tomography, etc. Usuallly, in these applications, one detector is used to measure the intensity of X-Ray scattering on discrete points along a line. In these cases, the time taken to scan a scattering pattern tends to be long, specially if high position resolution and high counting statistics are required. The use of PSD's strongly reduces the experiment time, since all the the scattering points of a pattern are scanned almost simultaneously.

A two-dimensional PSD is under developement. It will allow on-line storage of data corresponding to X-Ray images on the detector window. Among the different possible applications of this kind of detectors, the fast scanning of two-dimensional scattering patterns from samples should be pointed, in particular in cases where structural transformation occur in a short time range.

In this report we describe the operation, construction and characterisation of the one-dimensional PSD's, as well as the electronic parts involved in their data acquisition systems.

II. One dimensional position sensitive detector

II.1 - Principle of operation

In the X-Ray range of energy (≈ 1 KeV to 100 KeV), the photo-electric effect is one of the most likely interactions to take place between photons and matter. The photo-electron resulting from this interaction is at the origin of the 'signal' to be observed after the passing of a photon through a detecting medium. It loses its energy by ionisation of atoms of the medium, generating other electrons of lower energy. Thus, the absorption of an X-Ray photon produces an amount of electric charge that could be collected at an electrode.

The detector consists essentially in a gas chamber where electrodes are provided in order to establish an electric field that drives electrons to a charge collecting circuit. The geometry of the electrodes is optimised in some features, so that the measurement of the position of incoming photons is made possible. One of these features is the anode wire, which is set to a high electric potential ($\approx$ 2 Kilo-Volts). Since the electric field at a point around a cylindrical wire is inversely proportional to the radial distance, very high values of electric field are attained close to the wire surface. This field accelerates the electrons towards the wire. The accelerated electrons generate other electrons in shocks with gas molecules along their path. This phenomenon is known as 'avalanche'. It produces a high density of electric charge in a small region close to the wire surface, thus providing the spatially localized information needed in the position measurement. When the magnitude of the electric field is such that the avalanche charge is linearly proportional do the energy of the incident photon, the detector is said to operate in the 'proportional' mode.

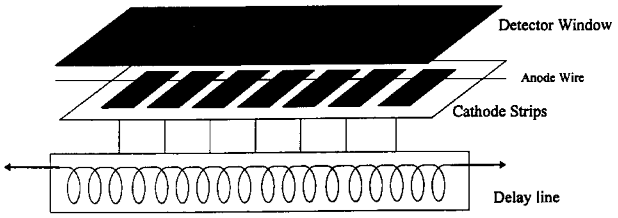


Figure 1. Scheme of the detecting cell

The avalanche charge induces a charge distribution on the cathode surface, which is a flat electrode subdivided in conducting strips (See Fig. 1). The detector window plays the role of a cathode which, together with the other cathode plane, confines the anode wire approximately as in a co-axial cylinders geometry.

The cathode strips are connected to a delay line, just as sketched in Fig. 01. The signal induced in the strips by an avalanche is thus driven to travel along the delay line, and so the position of the incoming photon may be estimated from the time taken by the signal to reach the ends of the line[1].

Presently built detectors feature an active window of 80 mm x 6 mm. The distance from anode to cathode is 3 mm. The operating voltage is about 2 Kilo-Volt for 2 Atm gas pressure (Ar + 10% CH_4). At this pressure, the absorption efficiency for X-Ray photons in the energy range of 5 KeV to 10 KeV is > 60%. Less than 10% of the photons in this range of energy are absorbed by the 300 μm beryllium window.

II.2 The Delay Line

In order to measure the position of a photon producing an avalanche on the anode wire with best accuracy, we would expect the delay line not to introduce any distortion to the shape of the signal. This implies: no loss in amplitude and no distortion in its time development. Ideally, the delay line should reproduce the input signal at the output, after a time interval.

We can briefly show that these requirements can only approximately be satisfied. If we consider the amplitude of the signal as a function of time and look at it in the frequency domain, we may write for one of its spectral components:

$$A_{in}(\omega) = A_0 \sin(\omega \cdot t)$$

The ideal delay line would respond to this input with the same wave form, introducing only a phase shift, φ, to account for the delay:

$$A_{out}(\omega) = A_0 \sin(\omega \cdot t - \varphi) = A_0 \sin[\omega \cdot (t - \varphi/\omega)]$$

We see that the output spectral component is delayed of φ/ω with respect to the input. If the signal is not to be distorted, each spectral component should have a phase shift linearly proportional to its frequency, so that the delay turns out to be a constant.

The delay time is comparable (or greater than) the time duration of the input signal. Consequently, reflections of the input signal may not be neglected and the delay line must be terminated with some circuit of impedance as close as possible to the characteristic impedance of the line.

If we consider the delay line as being a perfect co-axial cable - that is, a cable featuring zero resistance - and consider only its capacitance (C) and auto-inductance (L) per unit length, we can demonstrate that the following expression is valid for any spectral component of the signal:

$$A_{out}(\omega) = A_{in}(\omega) \cdot Exp(-i \cdot \varphi)$$

where

$$\varphi = ArcCos(1 - \mathcal{O}^2) \quad [\mathcal{O} < 1]$$

$$\mathcal{O} = \omega/\omega_c$$

$$\omega_c^2 = 1/LC$$

ω_c is a critical frequency above which the cable attenuates the spectral components. Its is assumed that the cable is perfectly terminated.

Although the output has the same the amplitude as the input spectral component, it is clear that the phase shift φ is not a linear function of the frequency. However, if we neglect higher orders terms in the series expansion of φ in terms of $\mathcal{O}$, we find that:

$$\varphi(\omega) \approx 2 \cdot \mathcal{O} = 2 \cdot \omega/\omega_c$$

We can conclude that the delay line is likely to transfer almost ideally the spectral components of a signal, provided that the frequencies of spectral components are much lower than ω_c. In this frequency range the delay time is a constant, τ, given by

$$\tau = \varphi(\omega)/\omega = 2/\omega_c \ .$$

In the construction of the delay line, we use discrete L and C components in cascade (See Fig. 2). Each L-C cell is connected to one cathode strip. The limitations discussed above are taken into account by choosing L and C so that ω_c is high enough not to disturb critically the signal propagation. The delay lines used in the detectors here described have a total delay time of $\approx$ 300 ns, $\approx$ 200 Ω characteristic impedance. Details on the theory and design of delay lines for use in PSD's are the object of a separate study.

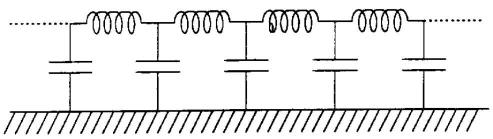


Figure 2. Delay line circuit.

II.3 Associated Electronics

Since the ionization potential for the atoms of the gas (usually Argon) is about 30 eV, photo-eletrons in the energy range of 10^3 eV are likely to generate an average of $10^3/30$ other electrons by ionizing the gas molecules[2]. This number is further amplified, by a factor as high as $10^3 - 10^5$, due to the avalanche phenomenon previously mentioned. The total charge per absorbed photon is therefore $\delta q \approx 10^{-15}$ Coulomb. This charge entails a potential variation in the electrodes of the detector:

$$\delta V = \delta q/C \approx 10^{-3} \text{ Volt} \ ,$$

where C ($\approx$ some pico-farads) is the capacitance defined by the electrodes.

The signal to be observed when X-Ray photons are absorbed in the detector is thus in the amplitude range of 10^{-3} Volt. Any circuit provided for observing the signal has a finite input impedance which, combined with the detector capacity, defines a differentiating circuit (See Fig. 3) that shapes the observed signal. The RC product is the shaping time constant.

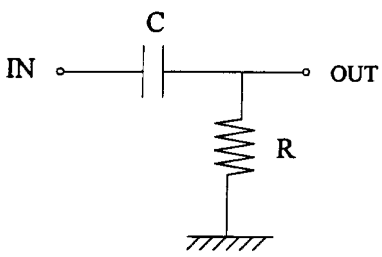


Figure 3. Equivalent circuit for detector + delay line.

After travelling through the delay line, the signal is treated by some electronic circuitry necessary to translate the detector internal phenomena to the expected information about the photon's incidence position. As shown in Fig. 4, the circuitry first includes pre-amplifiers, which amplify signals up to a range of amplitudes compabitle with standard electronic modules, besides matching the delay line impedance. The Amplifier & Discriminator triggers a fast logic pulse whenever the input signal has an amplitude higher than the electronic noise. The time difference for each pair of pulses corresponding to a detected photon is converted to amplitude by a Time-to-Amplitude Converter. The External Delay is added to avoid the measurement of negative time intervals. The output of the Time-to-Amplitude converter is directly associated to the position of the detected photons. It is digitized by an Analog-to-Digital Converter. A software package stores and displays data in the screen of a microcomputer's monitor.

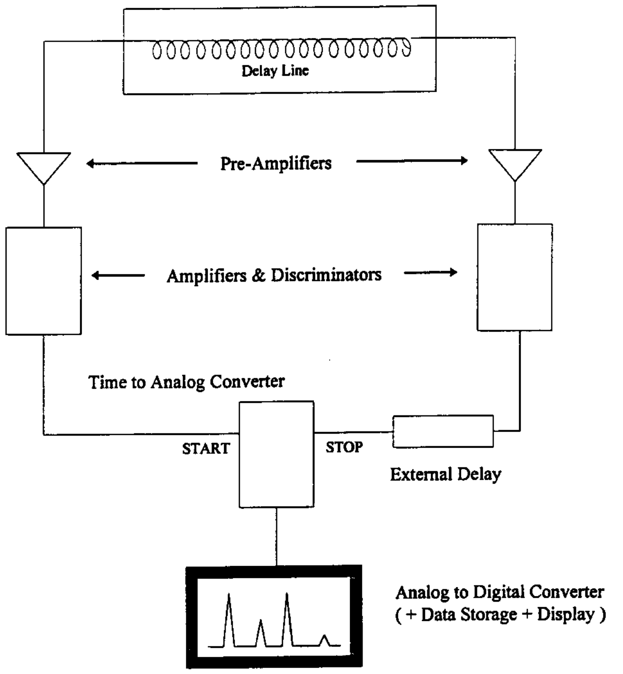


Figure 4. Electronic parts composing the Data Acquisition System.

III. Characterisation measurements

The performance of a PSD may be characterised by specific measurements which show the important parameters to be taken into account when the detector is used in a defined application[3]. We describe below some of these measurements and the associated characterisation parameters. It must be noted that the results of these measurements refer not only to the detector but to the whole detection system, including the electronic parts mentioned in Section II.3. As far as these electronic parts are well adjusted to the role they play in the the detection system, so far the characterisation measurements show the detector individual performance.

- **Spatial Resolution** (RES): If the detector were exposed to an infinitely narrow beam of photons, the PSD response would present a finite width. The response is visualized as a plot of *Number of Counts x Position,* which may be interpreted as the experimental points of a mathematical function called "point- spread function". The full width af half maximum (FWHM) of this function is the parameter characterising the detector spatial resolution. In fact, since a beam of photons is never 'infinitely narrow', the point-spread function (f) may not be perfectly measured. The experimental data (e) represent the convolution of the true beam (g) by (f):

$$e = f^* g$$

The shape of the beam profile and the point-spread function are usually fitted by gaussian functions. In this case, the experimental data are also fitted by a gaussian of FWHM given by:

$$[FWHM]_{\text{measured}} = \sqrt{RES^2 + \Delta^2}$$

Where RES ($\approx$ spatial resolution of the detector) and Δ ($\approx$ width of the photon beam) are respectively the FWHM for the point-spread function and for the beam profile. This is a practical relation from which one may estimate the spatial resolution.

In Fig. 5 is shown the spectrum obtained for the illumination (by an Fe^{55} X-Ray source) of a 50 μm slit placed close to the window of a one-dimensional PSD. The FWHM of the measured spectrum is 0.312 mm. From the considerations above we estimate the spatial resolution of the detector: RES $\approx$ 300 μm.

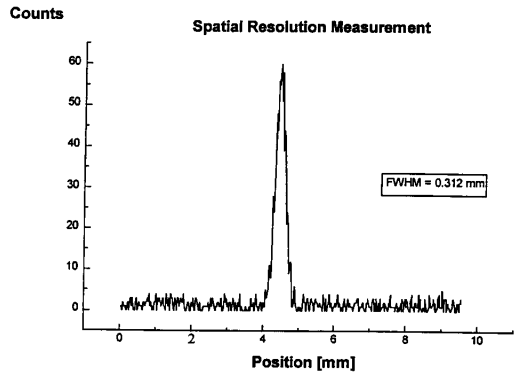


Figure 5. Detector response for a 50 μm wide slit.

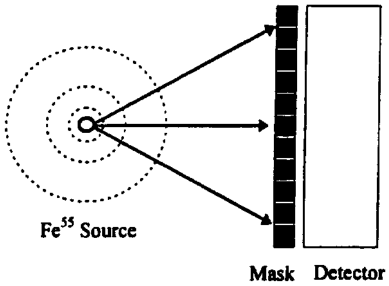


Figure 6. Overview of the linearity measurement setup.

- **Linearity** (LIN): A linear relation is expected to exist between the actual position of incidence of photons and the position measurement provided by the detection system. In the case of the detectors here described, the linearity measurement mainly evaluates the quality of the delay line. The time taken for the avalanche signal to travel from the incidence position until the extremities of the delay line is the essential measurement done by the detection sytem. Irregularities in the delay line construction may introduce linearity losses.

In order to evaluate the detector linearity, a simple technique consists in providing a mask containing regularly spaced slits. The mask is placed upon the detector window as it is illuminated by an isotropic X-Ray emitting source (See Fig. 6). Photons passing through the slits are counted by the detector and a set of peaks should be measured by the detection system, corresponding to the positions of the slits in the mask. Fig. 7 shows a spectrum obtained with one such mask. The slits are 300 μm wide, 8 mm long, spaced at a pitch of 2 mm.

We note that, due to the finite distance from detector to source and to the length of the mask, the amplitude of the peaks decreases from the center to the edges of the illuminated region. In the lower graph of Fig. 7, a line has been fitted to the plot of channel number x incidence position. The maximum deviation of the measured channel number with respect to the line fit is fairly below 0.1% of the active length of the detector. This is the usual parameter evaluating the detector linearity. In the case illustrated by Fig. 7: LIN $<$ 0.1%.

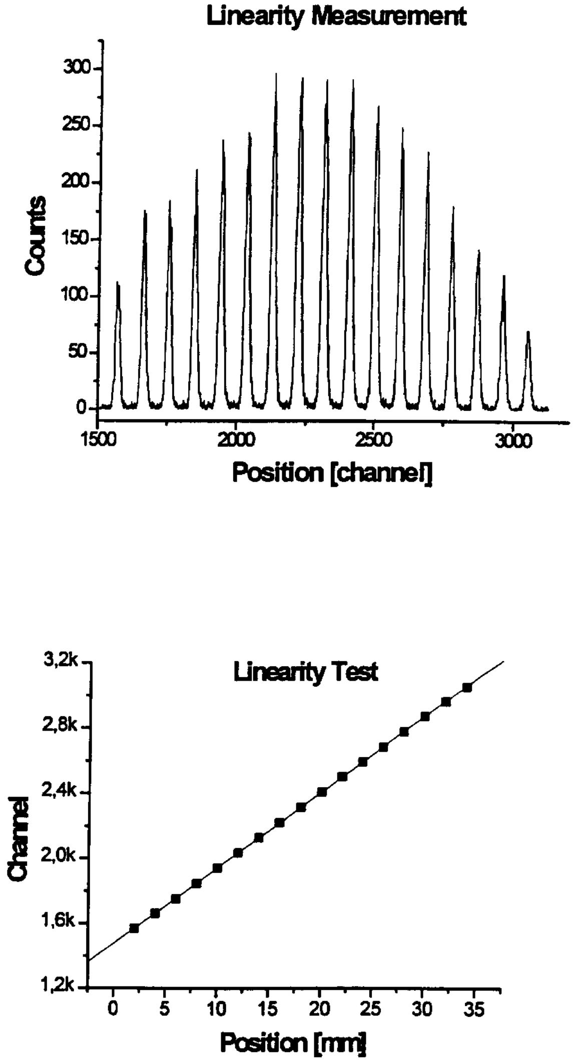


Figure 7. Upper graph: linearity spectrum obtained with mask. Lower graph: plot of *true x measured* position, with line fit to data.

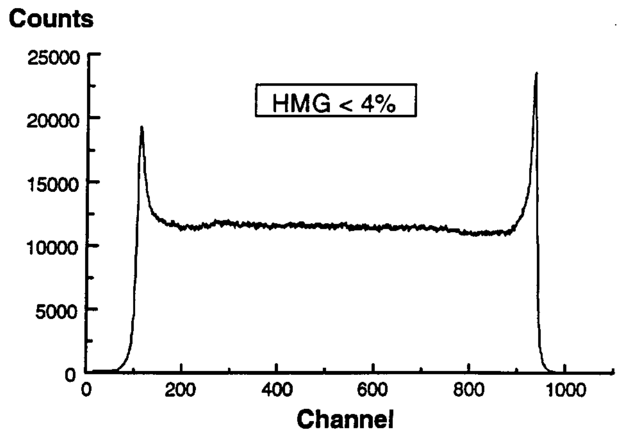
- **Homogeneity** (HMG): When the active window of a PSD is illuminated with a homogeneous and isotropic X-Ray emitting source, a corresponding homogeneous response of the detector is expected. The homogeneity measurement evaluates the overall detecting efficiency of the detector. The quantum nature of a photon source implies that an average emission rate of N photons/second exhibits a statistic fluctuation,

$$\Delta N = \sqrt{N}$$

This relation is obtained when one considers the photon emission as a Poisson process[4]. Therefore, if every pixel of a PSD is hit by an average number of N photons per second, a minimum deviation of $\pm\Delta N$

may be present in the counting response of each pixel. Deviations exceeding ΔN are in principle due to the detecting system. In the case of uniform illumination of the active window of a PSD, the parameter (HMG) describing homogeneity is defined as the maximum deviation of the measured number of counts per pixel relatively to the average number, N_{avg}, of counts over all detecting pixels (= channels).

Clearly, if N_{avg} is a high number, the relative statistic fluctuation, $\Delta N/N$, is negligible and non-homogeneities are more easily observed.



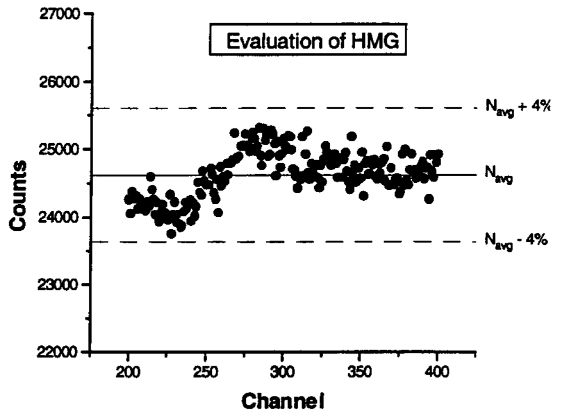


Figure 8. Upper plot: homogeneity spectrum with high counting statistics Lower plot: evaluation of the HMG parameter.

The experimental setup for measuring homogeneity is similar to the one shown in Fig. 6, except that the X-Ray source is placed as far as possible from the detecting window - in order to assure uniform illumination - and the mask is removed.

In Fig. 8 is shown a homogeneity spectrum with high counting statistics ($\Delta N/N$ less than 1%). Excluding the regions close to the extremities of the spectrum, where edge effects are present, and computing the average number of counts per channel, we note that the region between channels 200 and 400 exhibit the maximum deviation with respect to the average. The lower plot in Fig. 8 shows a close view of this region, taken from a spectrum where the statistical fluctuation is less than 0.7%. From this the homogeneity parameter for the detector is evaluated: HMG $< 4\%$.

V. Conclusion

The use of a delay line in the measurement of the position of X-Ray photons from the propagation time of electric pulses in a gas detector is quite effective. Only two channels ("start" and "stop") of electronic signal proccessing are required, independently of the active region of the detector. The ammount of electronic modules necessary in the data acquisition is relatively small, constituting a low cost detection system for real-time operation under high counting rates ($\approx 10^5$ photons per second).

The Linear Position Sensitive Detectors + Pre-Amplifiers built at CBPF exhibit position resolution of $\approx 300\ \mu$m, linearity better than 0.1% and homogeneity $< 4\%$. These features are fairly comparable to commercially available detectors using delay lines to encode the position of the absorbed photons. A two-dimensional detector is under development and should be comissioned in the near future.

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