RECENT IMPROVEMENTS TO RC-LINE ENCODED POSITION-SENSITIVE PROPORTIONAL COUNTERS*

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ABSTRACT

Continuing research on the principles of position encoding with RC lines has advanced the design of position-sensitive proportional counters (PSPCs) to meet the requirements for high count rates (>10^5 counts/sec) and good spatial resolution (>10^4 spatial elements) in small-angle scattering experiments with x rays and neutrons. We developed low-noise preamplifiers with pole-zero cancellation in the feedback circuit and modular linear amplifiers with passive RCL shaping which, compared to previous designs, reduce output saturation at high count rates ~20 times and shorten the position signal processing time to <1 μsec. Using resistive self-heating and propylene decomposition, we increased the conductance and film thickness of pyrolytic-carbon anodes to match the RC time-constants of line PSPCs with the linear amplifiers, to reduce the effects of electron erosion of the anodes at high count rates, and to improve the PSPC linearity. We developed a large-area PSPC (480 × 780 mm^2) for low-energy (<60 keV) photon imaging. The electronic uncertainty in the position measurement of 20-keV photons is

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<0.5 mm (fwhm) in both dimensions. The technology developed for this PSPC is applicable to the design of large-area detectors (>800 × 800 mm^2) for the measurement of small-angle scattering with neutrons. We applied the method of electronic thickness discrimination to change the effective thickness of an area PSPC from 12 to 2 cm whenever the molybdenum target of an x-ray generator was changed to a copper target. This thickness adjustment increased the signal-to-background ratio by a factor of ∿6 for the 8-keV photons from the copper target, while maintaining a >90% detection efficiency.

INTRODUCTION

We continued research on the RC-line encoding method (Borkowski and Kopp, 1975) to improve position-sensitive proportional counters (PSPCs); i.e., to enable them to operate at higher count rates (>10^5 counts/sec) and to achieve better spatial resolution than attainable with present RC-line PSPCs in small-angle scattering experiments with x rays and neutrons.

Proportional counters are excellent detectors for low-energy x rays (<25 keV) and thermal neutrons because they feature ∿100% detection efficiency, high count rate capability (>5 × 10^5 counts/sec), and good energy resolution [∿6% (fwhm) for 22-keV x rays]. Compared to other x-ray and neutron detectors, proportional counters are relatively easy to build, operate, and maintain, and their size and shape can be adapted to most small-angle scattering cameras. Large-area proportional counters (1 × 1 m^2) are feasible because the virtually noiseless gas gain compensates for the signal-to-noise ratio degradation caused by the large capacitance of the counter.

RC-line position encoding with proportional counters has been widely applied in small-angle scattering experiments (Hendricks, 1976) because it offers advantages over other encoding methods. First, line PSPCs with RC-line encoding and all the electronic modules required for signal processing are commercially available. Second, position information is decoded entirely by time-difference measurement, which is faster and more accurate than amplitude-ratio measurement. Area PSPCs do not require special encoding circuits or taps on the anode and cathode, which would add unnecessary capacitance, degrade the spatial resolution, and complicate the design. Finally, a conventional, well-designed proportional counter generally requires only minor modification to adapt it for RC-line-position encoding.

This article reviews recent improvements in the design and operation of RC-line-encoded PSPCs aimed at increasing their count-rate capability and spatial resolution. These improved characteristics are necessary to make full use of modern, high-flux, x-ray and neutron generators for crystallography and small-angle scattering.

REVIEW OF RC-LINE POSITION ENCODING AND SIGNAL PROCESSING

We developed the method of RC-line position encoding (Borkowski and Kopp, 1975) for line and area PSPCs because it utilizes two characteristic properties of a standard proportional counter in the simplest form—the resistance of the anode wire or the cathode, and the capacitance between the anode and cathode—to determine the position of every detected ionizing event (charged particle, photon, or neutron) with great accuracy (0.1% of the anode wire length). In addition to position, we measure the energy loss and detection time, as with a standard proportional counter.

PSPC Construction

The construction and operation of a typical *line* (one-dimensional) PSPC with RC-line encoding are similar to a conventional proportional counter (Borkowski and Kopp, 1975). The only requirement for position measurement is that both ends of the anode must be accessible as signal outputs. Otherwise, we recommend that the precautions and practices for the design and construction of conventional proportional counters be applied to the line PSPCs; i.e., avoid outgasing materials and dielectrics, install guard rings around all anode outputs, and make the preamplifier input leads as short as possible to reduce stray capacitance.

The most convenient configuration for an *area* (two-dimensional) PSPC in crystallography and small-angle scattering is a multiwire anode grid and two cathode grids for position encoding (Borkowski and Kopp, 1972). These grids are planar and parallel to each other. The grids are enclosed by a container filled with the counter gas. Each anode wire operates as an independent proportional counter, but, in this configuration, the signals are not taken from the anode, because all anode wires are connected to signal ground potential. Instead, a current pulse is induced in both cathodes by the electron avalanche in response to every detected event. The cathode-to-anode spacing is small (2-5 mm) for good capacitive coupling to preserve the coordinates of the avalanche at the anode. The cathode grids are continuously strung metal wires. The wires of one cathode are orthogonal to the wires of the other; thus, the electronic equivalent of the two cathodes comprises two independent, orthogonal RC lines. The anode shields one cathode from the other to prevent interaction between the cathode signals.

We used this configuration because it simplifies the PSPC construction, reduces the amount of outgasing materials, and does not require capacitive taps to the electrodes for position encoding. The small spacing between the cathodes does limit the stopping power and the detection efficiency of the gas for photons or neutrons in some cases, but, in these cases, we increase the detection efficiency by increasing the counter gas pressure or by applying linear or spherical drift-field regions (Borkowski and Kopp, 1974).

Basically, these drift-field regions are extensions of the counter gas volume above and/or below the cathode grids in the direction of the trajectories of the ionizing events (x rays and neutrons). These regions increase the thickness of the PSPC and, therefore, the probability of detection, i.e., interaction of the ionizing events with the counter gas to produce primary ionization. Generally, the drift regions are bounded by a system of electrodes. These electrodes are biased to create an electrostatic field configuration that forces the electrons, generated in the detection process, to drift toward the anode and to follow a prescribed path that preserves their spatial coordinates. This method of increasing the detection efficiency is especially useful when the counter gas pressure cannot be increased due to structural limitation of the gas container.

Position Encoding and Signal Processing

The cathodes of the area PSPC are two independent RC lines. Even though both spatial coordinates are measured simultaneously, the measurement of the x coordinate is independent of the measurement of the y coordinate. Therefore, for the purpose of describing position encoding and signal processing, an area PSPC is equivalent to two independent, orthogonal, line PSPCs.

We define the position of any detected event as the position of the point source from which this event originated, and relate this position to the PSPC by a Cartesian coordinate system. This system is defined such that the x axis is coincident with the anode of a line PSPC, or the z = 0 plane is coincident with the anode of an area PSPC. Then, for a *line* PSPC, the position coordinate x_o is assigned to all point sources on the plane $x = x_o$; for an *area* PSPC, the position coordinates x_o and y_o are assigned to all sources on the intersection of the planes $x = x_o$ and $y = y_o$.

The position coordinate x_o (or y_o) of every detected event is estimated by measuring and comparing the pulse shapes of the two simultaneous currents [$I_1(t)$ and $I_2(t)$] that flow through the load impedances (C_L) connected between the cathode and anode (Fig. 1). This estimate is $x_e = \Delta t_c/S$, where Δt_c is a measured time interval obtained by crossover timing (Borkowski and Kopp, 1975) and S is a proportionality constant. Of the several methods that make S independent of x, we recommend (1) the use of high-input-impedance preamplifiers with a low input capacitance, such that the total load impedance can be approximated by C_L; and (2) the selection of the center of the frequency pass-band of the filter as

$\omega_o = 4C_o/R_oC_{GT}^2$ to linearize the PSPC, where C_o and R_o are the distributed capacitance and resistance per unit length of the RC line, and $C_{GT} = C_oL + 2C_L$ is the total capacitance (L is the total length of the RC line). Note that for most commercial pulse amplifiers $\omega_o \cong \tau^{-1}$, where τ is the filter time constant. With this selection, the sensitivity constant is

$$S = R_oC_{GT} . \tag{1}$$

The measured value $\Delta t_c = Sx_e$ can be digitized and stored in many different ways with the simultaneously measured values of the estimates of the y coordinate, energy loss, and detection time of the same event. Since the most convenient forms of data storage and analysis depend on the particular requirements of each experiment, a general treatment is impossible within the limits of this paper.

Sources of Measurement Error

The best estimates from a measurement do not exactly determine the position, energy loss, or detection time of any detected event, because these measured signals are corrupted by noise. We will analyze some sources of spatial uncertainty, and suggest methods to reduce their effect on the position measurement.

The estimate of the position of x rays and neutrons is modulated by thermal noise, drift field distortion, and the detection process (Borkowski and Kopp, 1975). These noise sources are not correlated.

Thermal noise. Thermal noise is generated mainly in the resistance of the RC line. For a linearized PSPC [Eq. (1)] and a typical filter noise bandwidth of $2\omega_o$, the rms value of x_e caused by thermal noise alone is

$$x_n \cong L(C_{GT}/Q)(kT/C_oL)^{1/2} , \quad (2)$$

where Q is the total charge generated by avalanche multiplication, k is the Boltzmann constant, and T is the absolute temperature of the anode or cathode RC line. Note, that even though the noise is generated by the RC-line resistance, its value does not enter in Eq. (2); thus, any value of R_o can be selected without affecting spatial resolution in a linearized PSPC.

Drift field distortion. The drift field of a PSPC is responsible for the transport of the electrons from the point of detection to the anode. (These electrons originate from the ionization of the counter gas when a photon or neutron is detected.) The path of these drifting electrons is perpendicular to the equipotential surfaces of the drift field. If these surfaces are parallel to the anode everywhere in the PSPC, the coordinates of the interaction point and the charge centroid of the avalanche on the anode are the same. However, where the drift field is distorted, i.e., where the equipotential surfaces are not parallel to the anode, the electrons drift along a path that is not perpendicular to the anode. As a result of this distortion, the position estimated from the measurement of the charge centroid and the position of the interaction point have different coordinates.

The main causes of drift field distortion are inaccuracies in the construction of the drift region, structures in the electrostatic field of multianode PSPCs, and space charge surrounding the anode at high count rates. The first two causes are controlled by accurate machining, precision biasing, and optimization of depth and drift velocity in the drift region (Borkowski and Kopp, 1975). However, at high count rates, the drift field distortion caused by the space charge of the ion cloud surrounding the anode after each avalanche is probably the most important source of error in the position estimate of individual events (photons or neutrons). This distortion--an inherent property of proportional counters (Hendricks, 1969), which is independent of the position-encoding method--has its origin in the avalanche multiplication process. As an electron drifts to within a distance of a few anode diameters of an anode wire, it acquires enough kinetic energy between collisions to produce an avalanche. The electrons of this avalanche are collected by the anode, and the positive ions drift away from the anode. (The movement of these ions induces most of the signal current in the external circuit that connects the anode to the cathode of a proportional counter.) The number of ions from the avalanche is much greater than the number of original drift electrons. The velocity of the ions decreases rapidly with increasing distance from the anode. Consequently, a large ion cloud surrounds the anode for several milliseconds after each avalanche. The space charge of these ion clouds distorts the original drift field; and drift electrons from subsequent events are deflected from a path perpendicular to the anode, thus, changing their position coordinates.

The position error increases with the average rate of event detection and the amount of charge (Q) generated in each avalanche. Therefore, at high detection rates, the anode bias should be lowered to decrease the gas multiplication and the value of Q, and, consequently, the position error.

On the other hand, the value of Q should be as large as necessary to reduce the thermal noise error [Eq. (2)], which is proportional to 1/Q. Therefore, to minimize the position error, a compromise between these conflicting requirements should be determined experimentally for each application.

Detection process. The spatial error in the detection process of thermal neutrons and low-energy photons is, as with the drift field distortion, an inherent property of proportional counters which is independent of the position-encoding method.

We distinguish between two main sources of error: parallax, and distribution of the primary ionization. Parallactic errors occur where the trajectories of the incident photons or neutrons are not perpendicular to the equipotential surfaces of the drift field (Borkowski and Kopp, 1975). The following techniques are used to minimize this error: reduction of the effective thickness of the detector to the smallest possible magnitude; shaping of the drift field (e.g., spherical drift fields for focal point geometry, Borkowski and Kopp, 1974, and Charpak et al., 1975); and measurement of the position-dependent point-spread-function and application of deconvolution techniques to reduce the distortion due to parallax.

The distribution of the primary ionization from the detection of a photon or thermal neutron causes errors in the position estimate of the interaction point when the charge centroid of this primary ionization is not coincident with the interaction point. Several methods of reducing this spatial error are described in detail by Borkowski and Kopp (1975).

RECENT IMPROVEMENTS TO RC-LINE ENCODING

In our work with prototypic PSPCs, we determined that reducing the saturation of the electronic signal processing system, shortening the time constants of the RC lines, and eliminating the erosion of the anode wire would improve the utilization of RC-line encoding at high count rates ($>2 \times 10^4$ random counts/sec). Also, increasing the size of area PSPCs to 1×1 m^2 would be useful for small-angle scattering with neutrons and for nuclear medicine. Consequently, we developed the following methods to enlarge the size and increase the count rate capabilities of these PSPCs.

Pole-Zero Cancellation in the Feedback Circuit of a Low-Noise Preamplifier

We developed pole-zero cancellation in the feedback circuit (Kopp and Williams, 1977) to stabilize the output voltage of low-noise, voltage-sensitive preamplifiers against fluctuations in ambient temperature and to reduce preamplifier saturation at high count-rates. Pole-zero cancellation does not affect the input noise of the preamplifier, and, in most cases, requires only an adjustment of a capacitor in the feedback circuit. Therefore, it is a simple method to reduce the preamplifier saturation when the PSPC transmits large signal amplitudes (>100 mV) at high count rates ($>10^4$ counts/sec) and when the preamplifiers generate bipolar output pulses in response to detected events. At random count rates, these bipolar pulses cause fluctuations in the output voltage of the preamplifier (which are proportional to fluctuations of the mean count rate and amplitude) and drive the preamplifier into saturation. Pole-zero cancellation restores the unipolar pulse response, makes the output voltage independent of count rate, and reduces the preamplifier saturation. For example, with 10^4 random counts/sec of 120 mV amplitude transmitted by a preamplifier without pole-zero cancellation, half of all signals were distorted or lost due to saturation. The distortion and loss of signals was reduced to <1% when we applied pole-zero cancellation in the feedback circuit of the same preamplifier.

Passive RCL Filtering in a Modular, Linear Amplifier

A near-optimum filter for position and energy decoding was evolved from the passive filter concept developed by Blankenship and Nowlin (1966) and Nowlin (1970, 1971). This filter is better than commercially available, active filter amplifiers for crossover timing at high count rates ($>10^5$ counts/sec) because the filter output pulse response to a detected event is bipolar, with nearly equal peak amplitudes and similar shape of the positive and negative lobes to increase the crossover timing accuracy. We built and tested filters with a pass-band center frequency of $\sim 10^7$ radians/sec (pulse duration ~ 0.5 μsec); we used off-the-shelf, standard metal-film resistors, ferrite-core inductors, and silver-mica capacitors--allowing 5% tolerance for each component (Nowlin et al., 1977).

The filter transfer function is realized in three partial sections. Each section is isolated from the other sections by a wide-band amplifier stage (Kopp, 1978); no interaction between these sections takes place. This filter amplifier has excellent gain stability and linearity because $A\beta$ (the product of open-loop gain and feedback factor), the indicator of improvement in gain stability and linearity, is large ($\sim 5 \times 10^3$) and independent of frequency for frequencies <30 MHz. Several filter amplifier prototypes were built and tested to decode position information of PSPCs. The position decoding time was <1 μsec. These filter amplifiers did not degrade the spatial resolution of the PSPC when the count rate was increased to 10^5 random counts/sec.

Anode Resistance-to-Filter Matching

To measure position signals occurring randomly at a rate of 10^5 counts/sec with <3% coincidence loss, the total processing time should be <1 μsec/signal. This short processing time requires the center frequency (ω_o) of the filter amplifier to be $<10^7$ radians/sec (τ < 100 nsec). The anode resistivity R_o should be $4C_o/[\omega_o(2C_L + C_oL)^2]$ to match the filter and the PSPC for linear position sensing [Eq. (1)]. For a typical RC-line capacitance (C_o) of $\sim 10^{-14}$ F/mm, a load capacitance (C_L) at the RC-line output of ∿2 pF, and a center frequency (ω_o) of 10^7 radians/sec, the matching anode resistivity for a 10-cm-long PSPC should be 160 Ω/mm. This value should decrease to ∿110, 50, and 20 Ω/mm if the PSPC length L increases to 20, 50, and 100 cm, respectively. The anode diameter should be between 7.5 and 75 μm for operation as a proportional counter. The resistivities available in this range are <30 Ω/mm (Molecu-Wire Corp.) for Moleculoy wire of >7.5-μm diameter and >400 Ω/mm (Carl M. Zvanut Co.) for pyrolytic-carbon-coated quartz fiber of <75-μm diameter.

Borkowski and Kopp (1975) reported a method to reduce the resistivity of pyrolytic-carbon-coated quartz fibers by resistive self heating. Resistive self-heating of pyrolytic-carbon-coated quartz fibers is a convenient method to adjust the anode resistivity of line PSPCs and to match R_o and ω_o for high count rates ($>10^5$ counts/sec) and PSPC lengths from 10 to 100 cm. The fiber is strung under tension inside a glass tube between two electrodes. The tube is filled with propylene at ∿4 cm Hg pressure. Power is supplied to the electrodes to heat the fiber to ∿1000°C (red glow). At this temperature the propylene decomposes and coats the fiber with additional pyrolytic carbon, resulting in a decrease of the fiber resistivity. As the resistance decreases, the voltage is adjusted to maintain constant power dissipation and a constant temperature of the fiber. The power requirement is ∿1 W/cm for fiber diameters in the range from 25 to 75 μm.

A constant-power supply was developed (Rush, 1976) to automate the voltage adjustment for constant power dissipation. Using this constant power supply, Zedler (1976) decreased the resistivity of 25-μm-diameter fibers to ∿300 Ω/mm, which is the ideal resistivity for 20-cm-long line PSPCs, capable of measuring 10^5 counts/sec.

We observed that the resistivity of the coated fibers is more uniform than that of original fibers. At the beginning of the coating process, the color of the heated fiber is not uniform if the resistivity is not uniform, because power dissipation is proportional to resistivity at any point on the fiber. However, the rate of carbon deposition is also proportional to the temperature (color) at any point. Therefore, initially, most carbon is deposited where the temperature (i.e., the resistivity) is highest. Then, after the coating time is increased, the resistivity of the fiber tends to become uniform over its entire length.

Faruqi (1975) reported a deterioration of the linearity and spatial resolution of a PSPC, the probable cause of which was electron erosion of the carbon film after 2×10^7 ionizing events had been detected over a 100-μm length of the 10-cm-long PSPC. We believe that a thicker carbon film would virtually eliminate electron erosion of the anode at high count rates, thus prolonging the useful life of PSPCs. However, anode erosion at high count rates is also avoided by lowering the bias voltage to reduce Q (as described above in the section on drift field distortion) to the smallest value that is necessary to fulfill the spatial resolution requirements of each application of the PSPC. Hendricks and Schelten (1976) operated a 10-cm-long PSPC for more than 2 years without observing erosion of the 12-μm-diameter anode fiber of 8-kΩ/mm resistivity. In their experiments, the bias was adjusted for a spatial uncertainty of <0.5 mm (fwhm).

Large-Area PSPC Development

From the geometrical considerations presented by Hendricks (1978), it is apparent that large-area PSPCs (>60 × 60 cm^2) are required to meet the physical constraints on the angular resolution and on the size of the focal spot and specimen for efficient use of neutrons for small-angle scattering. To develop the technology for large-area PSPCs, we built a PSPC prototype with an active area of 44 × 79 cm^2 for human torso imaging with low-energy (<60 keV) photons (Borkowski et al., 1976). The anode wires are spaced ∿4 mm; the cathode wires are spaced ∿2 mm. The spacing between the two cathode planes is 1 cm; the anode plane is centered between the cathodes. The anode and cathode wires are stainless steel wires, 12 and 125-μm diameter, respectively. The spatial uncertainty caused by thermal noise is <0.5 mm (fwhm) in both dimensions for 20-keV x rays. Thus, the spatial resolution is excellent; >10^6 spatial elements are resolved with this PSPC when thermal noise is the only source of error. A PSPC of similar design will be used in the U. S. national small-angle neutron scattering facility (Koehler and Hendricks, 1977) now under construction at the Oak Ridge National Laboratory.

Electronic Thickness Discrimination

Electronic discrimination of the effective thickness of proportional counters was developed (Borkowski and Kopp, 1977) to adjust the effective aperture of PSPCs, i.e., the combination of detection efficiency and spatial resolution for imaging in nuclear medicine. We applied a variation of this method of thickness discrimination to small-angle x-ray scattering to control the signal-to-background ratio for different photon energies measured with the same counter. For example, to detect 17-keV photons (MoK_α) with >90% efficiency in xenon at atmospheric pressure, a PSPC with a 12-cm-thick drift region was required; but, in the same PSPC, a 2-cm thickness was sufficient to detect 8-keV photons (CuK_α) with >90% efficiency, whereas the rest of the drift region mostly contributed background counts.

We applied electronic thickness discrimination to change the effective thickness of the drift region of this PSPC from 12 to 2 cm whenever the target of the x-ray generator was changed from molybdenum to copper. This thickness adjustment increased the signal-to-background ratio by a factor ∿6 for the 8-keV photons from the copper target as follows: We placed the anode wire plane of the 12-cm-thick PSPC ∿2 cm from the window through which the x rays entered the PSPC. The spacing between the anode and cathode planes was ∿0.3 cm. Two drift regions result from this configuration, one, ∿1.7 cm deep between the anode and the entrance window, and the other, ∿9.7 cm deep, between the anode and a back electrode inside the PSPC.

When measuring molybdenum x rays, we biased the entrance window and the back electrode at a negative potential with respect to the cathode potential. The voltage gradient of both drift regions was set to ∿600 V/cm for maximum electron drift velocity (∿2.3 cm/μsec for the 96% Xe, 4% CO_2 counter gas mixture at atmospheric pressure). Using this bias configuration, we collected drift electrons from the whole 12-cm-thick volume of the PSPC. Thus, the detection efficiency for the 17-keV x rays was >90%.

We reduced the effective thickness of this PSPC to ∿2 cm when measuring copper x rays, by changing the bias of the back electrode to a positive potential with respect to the cathode while maintaining the negative potential of the entrance window with respect to the cathode. Using this bias configuration, we collected drift electrons from the 2-cm-thick volume between the anode and entrance window, but all drift electrons from the volume between the anode and the back electrode were rejected. Thus, the detection efficiency for the 8-keV x ray remained >90%, but all background counts from the volume between the anode and back electrode were rejected.

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