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LARGE-AREA PROPORTIONAL COUNTER CAMERA FOR THE U.S. NATIONAL SMALL-ANGLE NEUTRON SCATTERING FACILITY*

R. K. Abele, G. W. Allin, W. T. Clay, C. E. Fowler, and M. K. Kopp**

Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830, USA

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LARGE-AREA PROPORTIONAL COUNTER CAMERA FOR THE U.S. NATIONAL SMALL-ANGLE NEUTRON SCATTERING FACILITY*

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Abstract

An engineering model of a multiwire position-sensitive proportional-counter (PSPC) was developed, tested, and installed at the U.S. National Small-Angle Neutron Scattering Facility at ORNL. The PSPC is based on the RC-encoding and time-difference decoding method to measure the spatial coordinates of the interaction loci of individual scattered neutrons. The active area of the PSPC is 65 cm × 65 cm, and the active depth is 3.6 cm. The spatial uncertainty in both coordinates is ~1.0 cm (fwhm) for thermal neutrons; thus, a matrix of 64 × 64 picture elements is resolved. The count rate capability for randomly detected neutrons is 10^4 counts per second, with <3% coincidence loss. The PSPC gas composition is 63% ^3He, 32% Xe, and 5% CO_2 at an absolute pressure of ~3×10^5 Pa (3 atm). The detection efficiency is ~90% for the 0.475-nm (4.75-Å) neutrons used in the scattering experiments. These results confirm that the parameters of the RC encoding method can be scaled to successfully design large-area PSPCs.

Introduction

In support of the U.S. National Small-Angle Neutron Scattering (SANS) Facility,[1] we developed a large-area (65 cm × 65 cm), position-sensitive proportional counter (PSPC) camera with RC encoding[2] which measures the spatial coordinates of individual thermal neutrons scattered from a sample. An engineering model of the camera was installed and tested at the SANS Facility. A second PSPC is being constructed. The large active area of these PSPCs was necessary to match the requirements for good angular resolution of the SANS Facility, and the RC encoding method was chosen for simplicity of construction and good spatial resolution capabilities.

Previous experience with RC encoded PSPCs had been limited to smaller PSPCs of less than 25 cm × 25 cm active area; therefore, the main objective of this development was to determine whether the RC encoding parameters and construction methods would scale well for large area PSPCs. Also, a generalized method was developed to calculate the gas multiplication and bias voltages for multiwire proportional counters based on Diethorn's formula.[3,4]

Description and Specifications of the Neutron Camera

SANS Facility

The camera is one of the functional components of the 30-m, SANS Facility (Fig. 1) operating at the ORNL High-Flux Isotope Reactor. Related functional components are monochromators A and B that extract a beam of 0.475-nm (4.75 Å) neutrons from the reactor and deflect these neutrons through collimator E into sample chamber F. The neutrons strike the sample, causing neutron scattering into vacuum flight path H. Most of the scattered neutrons are detected by PSPC K, and their energy losses and spatial coordinates are measured by the encoding, decoding, and display systems of the camera. The PSPC is mounted on motorized carriage J that is movable along a rail inside the flight path to adjust the angular resolution of the camera by varying the distance between the PSPC and the sample from 1.5 to ~20 m.

Camera Requirements

The camera is composed of three main parts: the PSPC, the analog signal processing system, and the digital data acquisition system, which has been published separately.[5] The design requirements to make the camera compatible with the other components of the facility were as follows: spatial resolution element (pixel) dimensions of 1 cm × 1 cm to match a typical beam diameter and sample area, parallax error[2] of <1 pixel with the PSPC at the 1.5-m distance from the sample (maximum scattering angle of ~12° with distortion ≤0.8 cm), detection efficiency of >90% for 0.475-nm (4.75-Å) neutrons, resolution of spatial matrix of 64 × 64 pixels, coincidence loss of <3% at an average detection rate of 10^4 neutrons/s, and PSPC entrance window of <2 cm thick soft aluminum to reduce spurious scattering.

PSPC Specifications

The following specifications for the PSPC are based on the camera requirements.

Active area. 65 cm × 65 cm, given by the product of the pixel area and number of pixels required.

Thickness of active volume. $t \leq 0.8 \cot 12° = 3.8$ cm, to meet the parallax requirements.

Counter gas. 63% ^3He, 32% Xe, and 5% CO_2 at 3×10^5 Pa abs. ^3He was chosen over $^{10}BF_3$ because it is safer to handle and is noncorrosive. The detection efficiency of ^3He is[6] $\eta = 1 - \exp(-c \lambda p_1 t)$, where $c = 7.25 \times 10^{-6}$, λ is the neutron wave length, nm; p_1 the ^3He pressure, Pa; and t the thickness of the active volume, cm. For $\eta = 0.9$, $\lambda = 0.475$ nm, and $t = 3.6$ cm, the required partial pressure of ^3He in the PSPC is ~2×10^5 Pa. The radius of the charge centroid sphere[2] for the proton-triton tracks resulting from the detection of a neutron in ^3He must be <0.5 cm to meet the spatial resolution requirement. This requirement is met by the addition of Xe-CO_2 mixture at ~10^5 Pa to the ^3He gas to reduce the proton track length (the main contributor to the centroid radius) to ~0.35 cm. (The CO_2 is added for ultraviolet radiation quenching.) Consequently, the partial pressures of the gas mixture are $^3He = 1.9 \times 10^5$ Pa, $Xe = 0.9 \times 10^5$ Pa, and $CO_2 = 0.2 \times 10^5$ Pa.

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Fig. 1. Functional components of the U.S. National Small-Angle Neutron Scattering Facility. Shown are the monochromator housings A,B, graphite monochromator crystals C, cold beryllium filter D, collimator and beam guide E, sample chamber F, gate valve G, vacuum flight path H, wood shielding I, PSPC carriage J, PSPC K, and data acquisition system L.

PSPC Mechanical Design

Basically, the PSPC is a scaled up version of the proportional counter photon camera of ref. 7. The mutually parallel anode and cathode wire planes are strung on three individual frames stacked inside the counter gas volume (Fig. 2) so that the wires of the front cathode (closest to the entrance window) are parallel to the anode wires and the wires of the back cathode are orthogonal to the anode wires. This set of frames is mounted inside the aluminum counter body, which is closed and sealed by an aluminum entrance window. One of the main problems of this design, containing the PSPC gas at $\sim 3 \times 10^5$ Pa using a flat, <2-cm-thick aluminum disk, is solved by using an 0.8-cm-thick flat window but adding a buffer volume filled with ^4He at the same pressure as the PSPC gas. This buffer gas, which is, for all practical purposes, transparent to the 0.475-nm neutrons, is contained by a pressure-vessel flanged disk of $\sim$1 cm thickness. The curved surface structure is of no consequence to the PSPC operation because this surface is not -- as is the entrance window -- an electrode of the proportional counter.

The preamplifiers and bias circuits are housed in three separate, sealed boxes, each aerated at atmospheric pressure to avoid operation in vacuum and to cool the preamplifiers. The connecting cables to the electronics and drive motor and the air supply hoses are attached to and guided by an articulated cable carrier (Fig. 1, J) to provide a flexible, yet reliable connection between the movable PSPC and the signal processing and control units outside the vacuum flight path. To assure long-term (several years) purity of the counter gas, a purifier containing a molecular sieve is connected permanently to the PSPC. The connecting tubes of this unit can be heated when needed to accelerate the convective flow of counter gas through the purifier.

Position Encoding and Bias Circuits

The method of RC position encoding described in detail in ref. 2 was applied in this PSPC. Electronically, the two cathode wire grids perform as two independent, orthogonal RC lines terminated by the preamplifier input impedance, which is essentially a 2 pF capacitor. Since this small reactance value is negligible compared to the distributed parameters of the RC line, the position encoder is an open-circuit RC line. The impulse response of such a line[2,8] is

$$V_{01}(Z_L \to \infty) = I_g Z_0 \frac{\cosh p(L - x)}{\sinh pL} , \qquad (1)$$

and

$$V_{02}(Z_L \to \infty) = I_g Z_0 \frac{\cosh px}{\sinh pL} , \qquad (2)$$

Fig. 2. Method used to contain the counter gas and wire frames with a flat entrance window by adding a buffer container filled with ^4He (transparent to thermal neutrons) at the same pressure as the counter gas.

where V_{01} and V_{02} are the Laplace transforms of the RC line output voltages in response to the current impulse I_g occurring at any position $0 \geqslant x \geqslant L$ (L is the length of the RC line). Further, $p = (R_0C_0s)^{1/2}$, $Z_0 = R_0/p$, R_0 and C_0 are the distributed resistance and capacitance of the RC line, respectively, and s is the Laplace transform variable.

The cathode grids were fabricated by applying a continuous wire construction method,[2] using 125-μm-diam stainless steel wire of ~0.6 Ω/cm resistivity. Each wire turn is ~70 cm long, the spacing between adjacent wire turns is ~0.5 cm, and the separation between anode and cathode planes is ~0.5 cm. The resulting RC line parameters are: $R_{0x} \approx 87$ Ω/cm, $C_{0x} \approx 11$ pF/cm, and $L_x = 65$ cm for the front cathode; and $R_{0y} \approx 87$ Ω/cm, $C_{0y} = 13$ pF/cm and $L_y = 65$ cm for the rear cathode.

From these measured parameters, the estimated spatial sensitivity[2] is $S_x = R_{0x}C_{0x}L_x = 62.2$ ns/cm for the front cathode and $S_y = R_{0y}C_{0y}L_y = 73.5$ ns/cm for the rear cathode. The estimated spatial uncertainty is $x_n = (2.35\ L/Q)(kTC_0L)^{1/2} \approx 1$ cm (fwhm) for a charge input to each cathode $Q \approx 2.7 \times 10^{-13}$ C. (k is the Boltzman constant and T the absolute temperature of the RC line.) The gas amplification factor required for this charge input is $M = (2QW)/(qE) = 113$, where $W \approx 25$ eV is the energy converted to create one electron-ion pair in the counter gas, $q = 1.6 \times 10^{-19}$ C is the charge of an electron, and $E \approx 760$ keV is the total energy converted to ionization for each thermal neutron detected in ^3He.

The anode-to-cathode bias voltage V_2 required for the value $M = 113$ is calculated using the procedure outlined in the Appendix. For the virtual, cylindrical counter (Eq. A3), the bias voltage is $V_1 \approx 663$ V with $M = 113$, $\Delta V = 32$ V, $K = 3.6 \times 10^4$ V/(atm cm), $p_t = 3$ atm (3×10^5 Pa), and $a = 1.25 \times 10^{-3}$ cm. Then, from Eqs. A4 and A5, the estimated anode-to-cathode bias for $d = b = 0.5$ cm is $V_2 \approx 2100$ V. The estimated field strength at the cathode planes is $E_y(0,d) = 1810$ V/cm (Eq. A2). Since the separation between the entrance window and the front cathode is ~2.1 cm (Fig. 2), a cathode bias voltage $V_c \approx 3800$ V (Eq. A6) is required to meet the conditions assumed in the Appendix. However since the electron drift velocity reaches a saturation value at a field strength of ~300 V/cm and since the cathode wire quantization does not affect the resolution, the PSPC is operated at lower bias voltages, i.e., cathode bias $V_c = 600$ V and anode bias $V_a = 2700$ V (Eq. A7).

Analog Decoding System

The analog decoding circuit (Fig. 3) is composed of two position decoders, one for each coordinate, and an energy-loss and pulse-shape discriminator. Each decoder (Fig. 4) comprises two preamplifiers and filter amplifiers, two crossover detectors, and a time-to-amplitude converter. The discriminator comprises a summing amplifier, two constant-fraction discriminators, a time-to-amplitude converter, a single-channel analyzer, and a gate generator.

Decoding of position coordinates from the detector outputs (Eqs. 1 and 2) in response to each detected neutron follows the principle outlined in ref. 2. The selected time constant of the filter amplifiers is $T_0 \approx 0.3\ R_0C_0L^2 \approx 3$ μs so that the spatial sensitivity is essentially independent of position.[8] The zero crossing time of the bipolar output from each filter amplifier is sensed by a crossover detector. For each decoder, the time interval Δt between the outputs of the two crossover detectors is measured in the time-to-amplitude converter (TAC). The output of this converter is digitized by the data acquisition system. The total

Fig. 3. The x, y position coordinates of each detected neutron are decoded independently from the four cathode outputs. The energy-loss and pulse-shape discriminator detects background signals which inhibit the decoders.

Fig. 4. Each analog decoder uses two preamplifiers and filter amplifiers connecting the RC-line outputs to generate two bipolar pulses for each detected neutron. The time of zero level crossing of these pulses is measured by the crossover detectors. The time-to-amplitude converter measures the time interval between the zero level crossings and generates an output pulse whose amplitude is proportional to this time interval. (The delays are adjusted so that the time interval is positive for all positions.)

gain of the position decoder is set at $G_A = \Delta V_T \; \Delta t \approx 1$ V/μs, where ΔV_T is the variation in the TAC output voltage in response to a variation in Δt. The gain of the data acquisition system is set at $G_D = 14$ channels/V so that the total gain of the decoding system is $G = G_A G_P = 14$ channels/μs.

The purpose of the energy-loss and pulse-shape discriminator[9] is to reject all detected events that have amplitude and/or risetime signals different from those of the thermal neutrons. For all acceptable events, this discriminator generates a gate output, which is a coincidence requirement for the position decoders to process a signal.

Experimental Results

Because the camera was installed only recently at the SANS Facility, only preliminary test results are available. These results are concerned mainly with the calibration and specifications of the camera; future reports will include more-detailed experimental results.

The following set of test data was measured with an applied bias voltage of 2.7 kV, which resulted in an anode-to-cathode bias of $V_2 = 2.1$ kV and a drift region field of $E_d = 300$ V/cm. (The filter amplifier time constant was set at $T_o = 3$ μs.)

1. The spatial sensitivity is $S_x = 63$ ns/cm for the front cathode and $S_y = 73$ ns/cm for the rear cathode. These measured values are in good agreement with those estimated. With the total decoder gain set at $G_x = 15.9$ channels/μs for the front cathode and $G_y = 13.7$ channels/μs for the rear cathode, a uniform sensitivity $S_T = 1$ channel/cm is obtained in both coordinates.

2. The spatial uncertainty is <1 cm (fwhm) for thermal neutrons.

3. The signal processing time is <10 μs per detected neutron; thus, the count-rate capability of the camera is $>10^4$ neutrons per second, with <3% coincidence loss.

4. The amplitude resolution is ∿30% (fwhm) for the pulses resulting from the detection of thermal neutrons.

5. The integral nonlinearity is <2% of the cathode length (∿1.2 cm).

6. The differential nonlinearity, i.e., the maximum change in sensitivity, is <12% of the average sensitivity.

7. The background count rate not rejected by the energy-loss and pulse-shape discriminator is <13 counts per second uniformly distributed over the total active area (equivalent to ∿0.2 count per minute per picture element).

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Appendix

Relationship of the Gas Amplification Factor and Bias Voltages for Multiwire Proportional Counters

The gas amplification factor for position-sensitive proportional counters is generally determined from the spatial resolution requirements, energy loss of the detected particles or photons, and specific ionization of the counter gas.[2] This gas amplification factor is related to the anode-cathode bias potential difference by Diethorn's formula,[3] which, however, is applicable only to cylindrical cathode counters. This appendix presents a practical method, based on Diethorn's formula, to extend its application to multiwire proportional counters (MWPCs).

A typical MWPC (Fig. 5) is bounded by two ground planes enclosing three multiwire structures: the anode grid plane sandwiched between two cathode grid planes. All these planes are parallel and symmetric about the anode plane. Generally, the distance between the anode and cathode planes is $d > b$, where b is the spacing between adjacent anode wires. The distance between the ground and cathode planes (h) is selected on the basis of detection efficiency and parallax distortion specifications. The bias potentials are V_a for the anode wires, V_c for the cathode wires, and V_o for the ground planes. The MWPC is referred to a Cartesian coordinate system; the anode grid is in the $y = 0$ plane, and one, arbitrary anode wire is on the z axis. We make the following assumptions:

1. Each anode wire operates as an independent, cylindrical proportional counter in the region $a < r < 10a$ because in this region the radial field is $E_r \propto 1/r$ [a is the anode wire radius, and $r = (x^2 + y^2)^{1/2}$ is the radial variable].

2. The components of the electric field throughout the drift regions are $E_y = E_d = (V_o - V_c)/h$ and $E_x = E_z = 0$; i.e., all equipotential surfaces in the drift regions are planes parallel to the cathode grids. The potentials V_c and V_a are selected so that $E_y(d) > E_d$ to assure ~100% transmission of the drift electrons through the cathode grids.

3. The electric potential and field distributions between the anode and cathodes in the $x = 0$ plane for $y > 0$ are:[10]

$$V(0,y) = \mu \ln \sinh (\pi y/b) \qquad \text{(A1)}$$

and

$$E_y(0,y) = -\Delta V/\Delta y = -\mu\pi/b \coth (\pi y/b) , \qquad \text{(A2)}$$

where μ is a reference voltage to be determined (Eq. A4) from the required gas amplification factor. (Owing to the assumed symmetry about the anode plane, we do not consider values for $y < 0$.)

With these three assumptions, the procedure is as follows:

1. Determine the gas amplification M required to meet the design specifications for spatial resolution.

Fig. 5. Section of the upper half of a typical multiwire proportional counter (MWPC), with reference to a Cartesian coordinate system defining bias and dimension parameters. The section is through the $z = 0$ plane, the anode wire grid is in the $y = 0$ plane, and the lower half of the MWPC is considered symmetrical about the $y = 0$ plane.

2. Calculate $V_1 = V_p - V_a$, the bias required for the virtual, cylindrical proportional counter with anode and cathode radii of a and 10a, respectively, from Diethorn's formula:[3]

$$M = \exp \{[V_1 \ln 2/(\ln 10\ \Delta V)] \ln [V_1/(Kp_t a \ln 10)]\} , \qquad \text{(A3)}$$

where ΔV (in V) and K (in V/atm cm) are constants related to the counter gas mixture,[4] p_t is the counter gas pressure (in atm), and a is the anode wire radius (in cm).

3. Using Eq. A1 and the value of V_1, calculate the reference voltage:

$$\mu = V_1[\ln \sinh (\pi a/b) - \ln \sinh (10\pi a/b)]^{-1} , \qquad \text{(A4)}$$

and the anode-to-cathode potential difference,

$$V_2 = \mu[\ln \sinh (\pi a/b) - \ln \sinh (\pi d/b)] . \qquad \text{(A5)}$$

4. To comply with assumption 2, select the cathode bias voltage as

$$V_c \,\Delta\, h E_y(0,d) + V_o , \qquad \text{(A6)}$$

where $E_y(0,d) = -\mu\pi/b \coth (\pi d/b)$ from Eq. A2. Then, the anode bias voltage is

$$V_a = V_2 + V_c . \qquad \text{(A7)}$$

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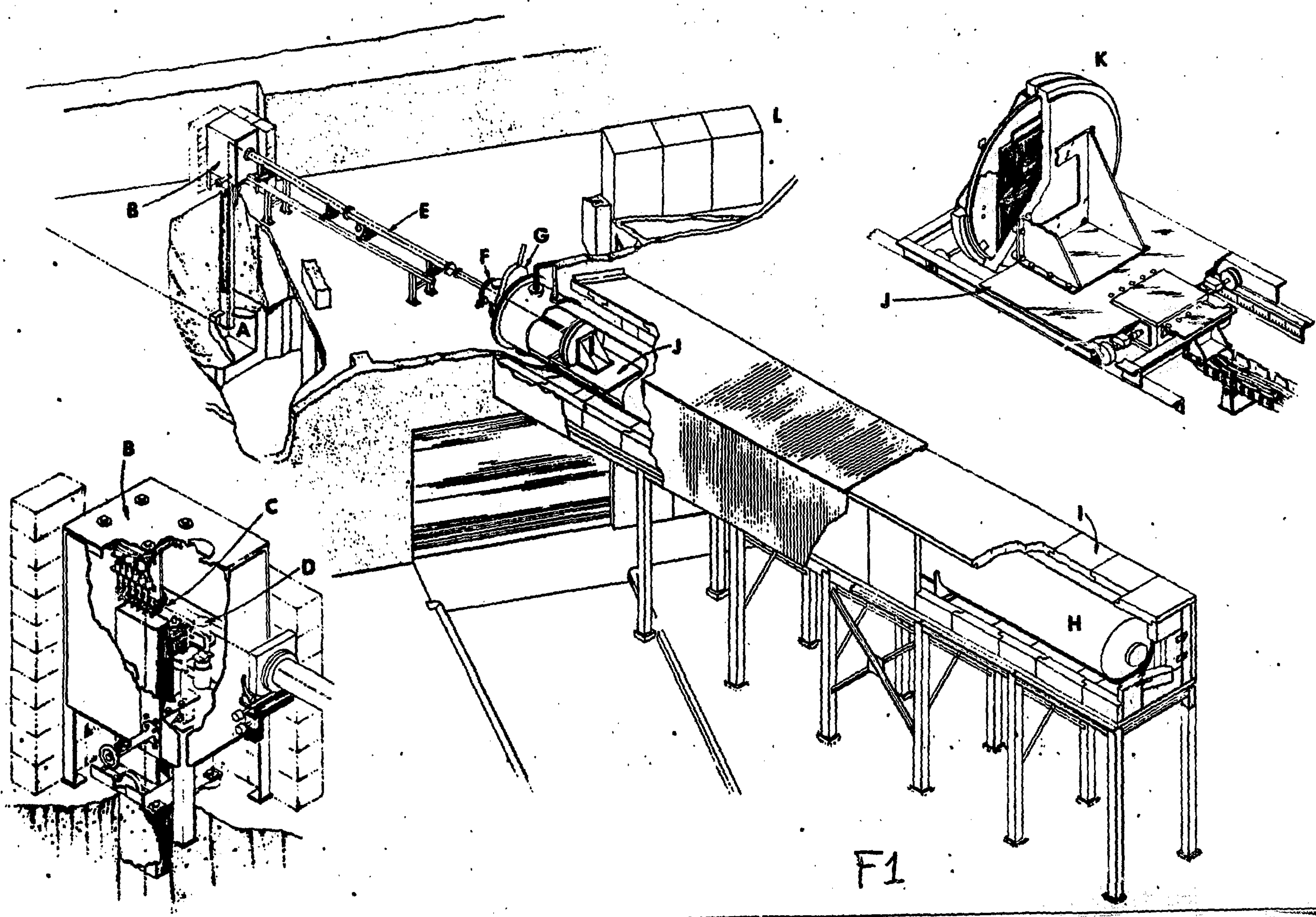

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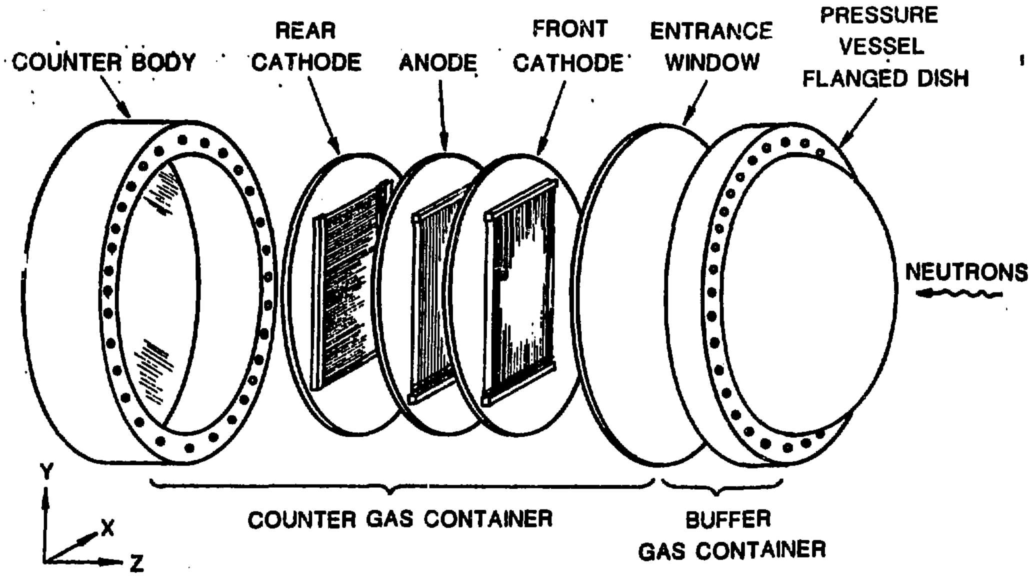
COUNTER BODY
REAR CATHODE
ANODE
FRONT CATHODE
ENTRANCE WINDOW
PRESSURE VESSEL FLANGED DISH
NEUTRONS
Y
X
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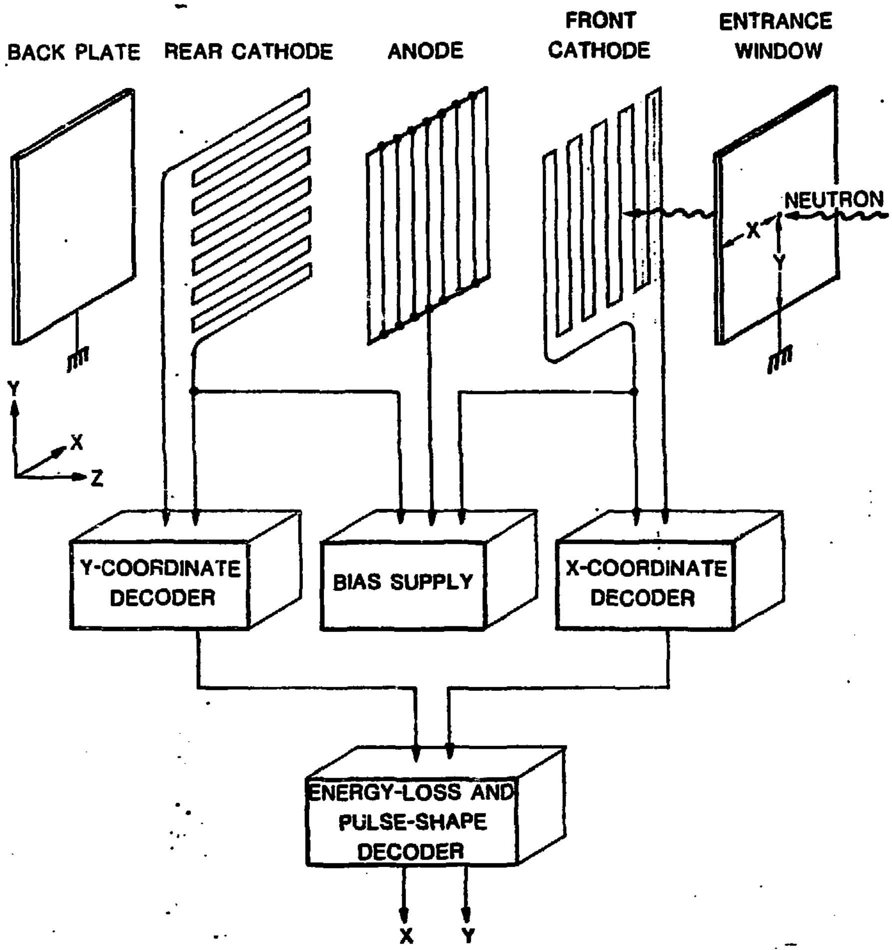
COUNTER GAS CONTAINER
BUFFER GAS CONTAINER

F2


BACK PLATE
REAR CATHODE
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ENTRANCE WINDOW
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X
Y
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Z
Y-COORDINATE DECODER
BIAS SUPPLY
X-COORDINATE DECODER
ENERGY-LOSS AND PULSE-SHAPE DECODER
X
Y

F3

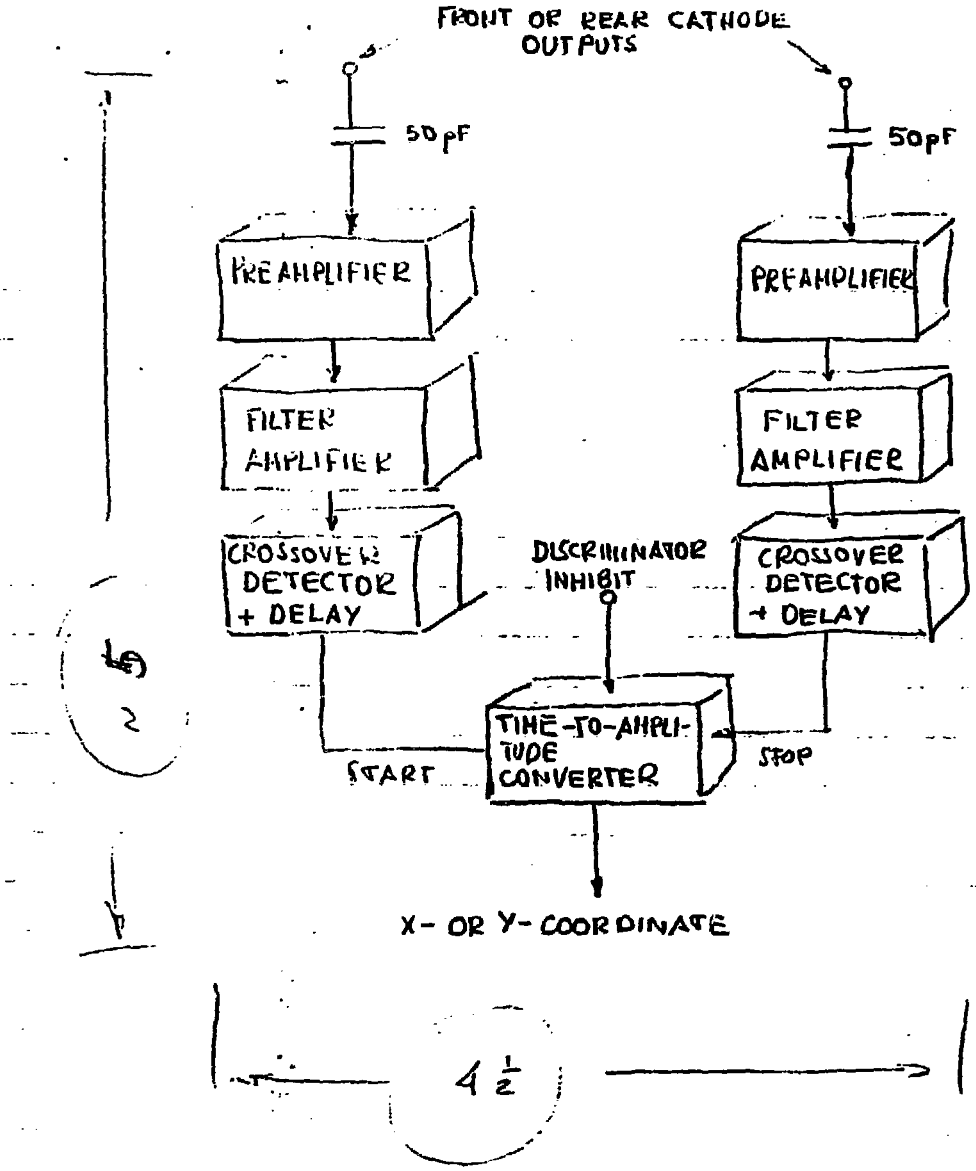
FRONT OR REAR CATHODE OUTPUTS
50pF
50pF
PREAMPLIFIER
PREAMPLIFIER
FILTER AMPLIFIER
FILTER AMPLIFIER
CROSSOVER DETECTOR + DELAY
DISCRIMINATOR INHIBIT
CROSSOVER DETECTOR + DELAY
TIME-TO-AMPLITUDE CONVERTER
START
STOP
X- OR Y- COORDINATE

FIG. 4

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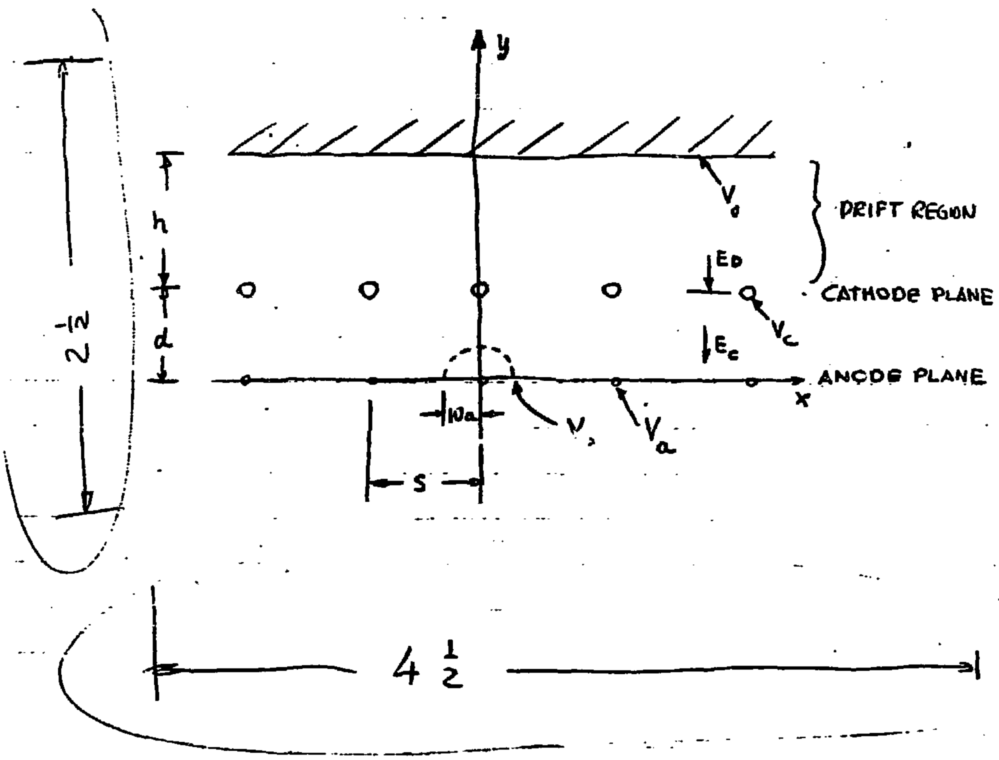

y
V0
DRIFT REGION
h
E0
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Vc
d
Ec
ANODE PLANE
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10a
V1
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s
4 1/2

Fig. 5