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NEW METHOD OF GAMMA DOSE-RATE MEASUREMENT USING ENERGY-SENSITIVE COUNTERS*

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Abstract

A new concept of charge quantization and pulse-rate measurement was developed to monitor low-level gamma dose rates using energy-sensitive, air-equivalent counters. Applying this concept, the charge from each detected photon is quantized by level-sensitive comparators so that the resulting total output pulse rate is proportional to dose rate.

The concept was tested with a proportional counter and a solid-state detector for wide-range dose-rate monitoring applications. The prototypic monitors cover a dose-rate range from background radiation levels (10 μR/h) to 10 R/h.

Introduction

A method of charge quantization and pulse-rate measurement was developed and tested for possible applications of energy-sensitive detectors (gas-proportional counters and PIN diodes) as radiation dose-rate monitors in the range 10 μR/h to 10 R/h.

This research was aimed at showing the potential of the charge quantization method as an improved radiation monitoring scheme and to demonstrate its suitability as a replacement for the two most commonly used monitoring methods, Geiger-Mueller (G-M) tube and ionization-chamber based instruments. These existing instruments have several problems: air-equivalent ionization chambers do not generate enough current ($>10^{-12}$ A) at background levels (10 μR/h) to make dose-rate measurements quickly enough, and G-M tubes ignore the gamma energy deposited and therefore do not directly measure dose rate.[1]

For test and evaluation of this method we developed and built a proportional counter of near air-equivalent characteristics, used it and a silicon PIN diode as detectors in benchtop instruments, and acquired preliminary data for evaluation of the merits of this method in civil defense applications.

Method of Dose-Rate Monitoring

Gamma dose-rate in Roentgens per hour (R/h) is defined as the ionization produced per unit of time by photons in a detector volume of air.[1] Therefore, dose rate may be measured by counting the number of detected photons per unit of time multiplied by the energy each dissipates in the detector volume. Conventionally, this product is obtained by monitoring the ionization current from an air-filled chamber of known volume. The energy required to dissociate one electron-ion pair in air is ~30 eV, so that in a reasonably sized chamber at background radiation levels (10 μR/h), the ionization current is <<1 pA. This makes the measurement difficult and limits the response time of the instrument. On the other hand, pulses from G-M tubes are independent of the energy of the detected photons, so that air-equivalent response must be achieved by careful compensation.

The method proposed here makes use of several desirable properties of energy-sensitive detectors (gas-proportional counters and silicon PIN diodes) combined with a multilevel discriminator and counting instrument. Proportional counters with air-equivalent fill gas have characteristics similar to those of air-filled ionization chambers. Operating at gas-multiplication factors of 100, they generate ~3 electron-ion pairs per electron volt of transferred photon energy. In comparison, silicon PIN diodes generate ~0.3 electron-ion pairs per electron volt. But even at these relatively high charge levels, the average currents are not large enough (>1 pA) for fast response (<10 s) dose-rate monitoring at background levels.

Consequently, we developed a pulse-counting method (Fig. 1) consisting of an energy-sensitive detector, a low-noise preamplifier and filter, a multilevel discriminator for charge quantization, and a count-rate meter. As an example (Fig. 2), the conversion of detector charge quanta to pulse rate is illustrated for three detector output pulse heights. The amplitude of each filter-amplifier output pulse is

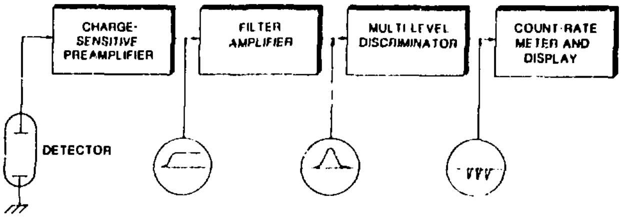

Fig. 1. A current pulse from an energy-sensitive detector is amplified, filtered, and converted into a train of pulses suitable for processing by a count-rate meter.

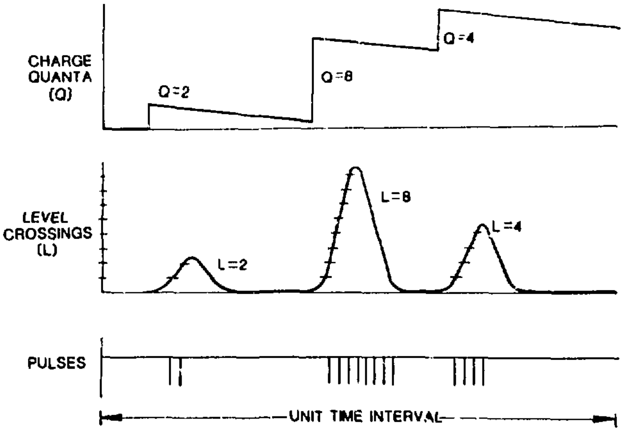

Fig. 2. The charges of three pulses occurring within a given time interval at the output of a charge-sensitive preamplifier are quantized by charge-to-pulse height conversion in a filter amplifier and subsequent counting of the number of level crossings during the same interval. (In this example, a total of 14 charge quanta per unit of time results in 14 level crossings and, consequently, 14 countable pulses per unit of time).

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proportional to the detector charge (Q). The multilevel discriminator in this example uses eight stacked discriminators to quantize the amplifier pulses. Each positive level crossing represents one quantum of detector charge; therefore, the sum of all level crossings (i.e., the sum of all charge quanta) per unit of time is proportional to the true dose rate for an air-equivalent detector.

Description and Characteristics of Prototypic Monitors

Two benchtop dose-rate monitors were built and tested to evaluate the concept of charge quantization.

Radiation Detectors

Of the two gamma radiation detectors used in evaluating the dose-rate monitors, one was a silicon PIN photo-diode 1 cm × 1 cm square and 200 µm thick. This detector operated at a 25-V bias. Direct energy conversion in the intrinsic region was used to produce charge quanta in response to detected photons. The detector was compensated[2] with aluminum and copper sheets to achieve a near air-equivalent response in the photon energy range 80 to 3000 keV.

The second detector was a cylindrical proportional counter. Its cathode was an aluminum cylinder of 3 mm wall thickness, 2.3 cm diam and 5 cm length. The wall thickness was calculated for near air-equivalent response to photons in the energy range 60 to 3000 keV.[2] The coaxial anode was made of 13-µm-diam stainless steel wire. The detector was filled with a gas mixture of 90% Ne and 10% CF_4 at 150 kPa pressure. Because no data were available for this gas mixture in proportional counters, we measured the gas multiplication factor (M) as a function of bias voltage for this counter to calculate the coefficients ΔV and K from Diethorn's formula,[3]

$$M = \exp \frac{V \ln 2}{V \ln(b/a)} \ln \frac{V}{K\, p\, a \ln(b/a)}$$

where V is the anode bias voltage (V), p is the counter gas pressure (atm), and a and b are the anode and cathode radii (cm) respectively. The values of the constants calculated for the 90% Ne + 10% CF_4 mixture were $\Delta V = 30$ V and $K = 2.2 \times 10^4$ V (atm cm^{-1}). The proportional counter was operated at $M = 200$ and $V = 1000$ V.

Electronic System

The electronic modules (Fig. 1) used for the benchtop monitors include a standard low-noise, wideband preamplifier having a charge gain of 1 V/pC followed by a NIM filter amplifier operating at a gain of 400 and a filter time constant of 0.25 µs. The filter amplifier output pulses are unipolar and have a dwell time of 2 µs. The amplitude of these output pulses (proportional to the detector charge) are quantized in the multilevel discriminator. Two different circuits were developed and tested for this function, and both performed equally well. Both circuits used the same input stage, which consisted of eight stacked comparators.

One of these circuits (Fig. 3a) uses eight one-shots (based on 7400 Series Schottky logic chips) to convert the comparator outputs into pulses of short duration (10 ns). Parallel-to-serial conversion is performed by summing and additive delay circuits that generate a train of pulses. The number of pulses is proportional to the input pulse amplitude V_m. The delay circuits assure that these pulses are adequately spaced (>10 ns) even for an input pulse of short risetime (overload pulse).

The other circuit (Fig. 3b) performs the parallel-to-serial conversion using a counter (e.g., 74XX161) to generate addresses for a data selector (e.g., 74XX151) that sequentially scans the outputs of the D flip-flops and generates one output pulse for each flip-flop set. This circuit generates its own clock and reset pulses, so its speed is essentially determined by the characteristic operating frequency of whatever logic family is used for implementation (e.g., XX = LS, HC, S, etc.).

Finally, the count rate meter and display function was performed by using a fast pulse counter capable of counting at 10^8 counts/s.

Measurement Results

The response of both benchtop monitors was tested in radiation fields of 0.4, 4, 40, and 400 R/h with 662-keV photons from a ^{137}Cs calibration source. The

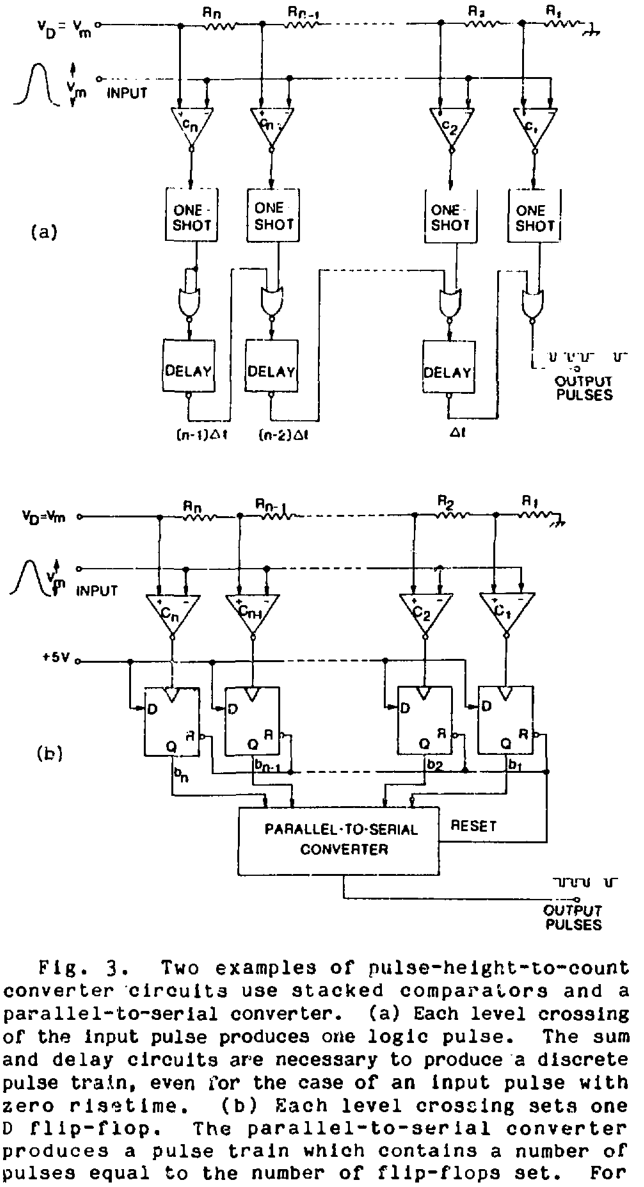

Fig. 3. Two examples of pulse-height-to-count converter circuits use stacked comparators and a parallel-to-serial converter. (a) Each level crossing of the input pulse produces one logic pulse. The sum and delay circuits are necessary to produce a discrete pulse train, even for the case of an input pulse with zero risetime. (b) Each level crossing sets one D flip-flop. The parallel-to-serial converter produces a pulse train which contains a number of pulses equal to the number of flip-flops set. For input pulses with zero risetime, an internal clock sets the minimum spacing between successive output pulses.

proportional counter-based monitor had a linear response from 10 μR/h to 10 R/h, corresponding to a count rate of 0.4 to 4 × 10^5 counts/s (Fig. 4). The response of this monitor to 59-keV photons from a ^{241}Am source in a field of 2 ± 0.5 R/h fell close to the 662-keV response curve. The PIN diode-based monitor had a linear response over the same range (10 μR/h to 10 R/h) with a corresponding count-rate range from 0.25 to 2.5 × 10^5 counts/s.

The saturation in the response is caused by the finite bandwidth of the filter amplifier, which in the limit (at high dose rates) produces an output that crosses each of the eight discriminator levels at a maximum rate of ~5 × 10^5 s^{-1}, thus limiting the count rate to ~4 × 10^6 counts/s. The onset of saturation of the proportional counter response at lower count-rate levels is probably caused by space charge effects in the counter. Both response curves show a positive slope up to the maximum test field intensity of 400 R/h.

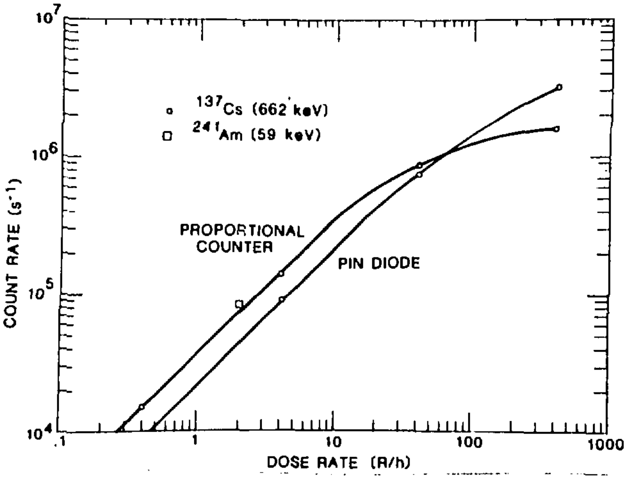

Fig. 4. The output count rate of both monitors is a linear function of dose rate up to 10 R/h.

From these preliminary test results, the following conclusions can be drawn:

1. Energy-sensitive counters can be used as dose-rate monitors, provided that a method of charge quantization is used.
2. The full range from background radiation levels (10 μR/h) to at least 10 R/h can be covered with either a proportional counter or a PIN diode of reasonable size.
3. By altering the spacing between adjacent discriminator levels, the response curve may be shaped to suit a variety of design requirements (e.g., energy compensation, nonlinear response).
4. Even though other schemes of charge quantization are available (e.g., flash ADCs), we chose the methods presented here because (a) the quantization is done in real time, directly on an optimum pulse shape, resulting in faster conversion and (b) the output in serial form permits simple frequency measurement without the need for microprocessor-based readout, which is an advantage for low-power, portable monitors.

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