Presented at the IEEE Nuclear Science
Symposium, San Francisco, CA, October 19-21,
1977; also published in IEEE TRANSACTIONS
ON NUCLEAR SCIENCE, Vol. NS-25, No. 2
(April 1978)

LBL-7281

conf. 771023--51

SOME ELECTRONIC ASPECTS OF ENERGY MEASUREMENTS WITH SOLID-STATE DETECTORS

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April 1977

Prepared for the U. S. Department of Energy
under Contract W-7405-ENG-48

Preamplifiers

Figure 2 shows a block diagram of the charge-sensitive preamplifier and two methods of connecting the detector. In the upper circuit the detector is ac coupled to the preamplifier and while it is dc coupled in the lower circuit. The ac coupling requires two extra components, the detector load resistor (RL) and the coupling capacitor (Cc). These components contribute noise and increase the stray capacitance to ground, thereby degrading the energy resolution seriously in a high resolution spectrometer system. Furthermore, an additional differentiation is produced in this input circuit. For these reasons, most high-resolution spectrometers are dc coupled. One disadvantage with dc coupling is that the detector leakage flows through the feedback resistor causing an offset in the output voltage of the preamplifier. This is normally not a problem in cooled detector systems. The important components of the preamplifiers are the FET, feedback capacitor, and feedback resistor. The feedback capacitor determines the charge sensitivity of the preamplifier. The feedback resistor contributes step noise as do leakage currents of the detector and the FET gate circuit. The resistor value should be large to minimize its contribution to the noise. However, the feedback resistor also determines the value of the product of input rate and average energy per pulse at which the preamplifier will saturate.

Figure 3 shows the electronic resolution of a high-resolution silicon system as a function of shaping time (peaking time) of the main amplifier. The one dotted line (N_S^2) represents the step noise, and is proportional to the total leakage current (I) at the input of the preamplifier, and to the shaping time (T). The noise from any parallel resistive components in the input circuit (+feedback) has the same characteristic as leakage current noise and can be included with the total leakage according to the relationship $I_R = \frac{2\,KT}{qR}$. The dotted line marked N_Δ^2 represents the high frequency or delta noise is mainly due to FET channel noise. The mean square resolution is proportional to the absolute temperature (T), and to the total input capacitance squared (C^2). It is inversely proportional to the transconductance of the FET (gm) and to the shaping time (T).

The FET is probably the most important electronic component in determining the electronic resolution of the spectrometer. In the ideal case, a FET with an input capacitance equal to the detector capacitance should be used. In practice this is just a guide as other factors may determine the correct choice of FET. The resolution shown in Fig. 3 is of a 2N4416 FET remounted in a low loss header and used in a low capacity, high resolution silicon-detector x-ray spectrometer. The particular FET was selected from a large number. The FET's are first tested in the standard header in a test jig that can be cooled quickly nearly to 77°K, and the promising candidates are remounted in special headers and tested in a high-resolution pulsed-light feedback[3] system. Larger FET's than the 2N4416 are used with large planar and coaxial germanium detector systems.

Very high resolution spectrometers as used in x-ray spectrometers do not use the resistor-feedback charge-sensitive preamplifiers discussed earlier. Instead the pulsed-light feedback method of discharging the feedback capacitor is employed. The advantages of the pulsed-light feedback system are that the stray capacitance and noise of the feedback resistor are eliminated, and also the decay time constant of the preamplifier feedback components is

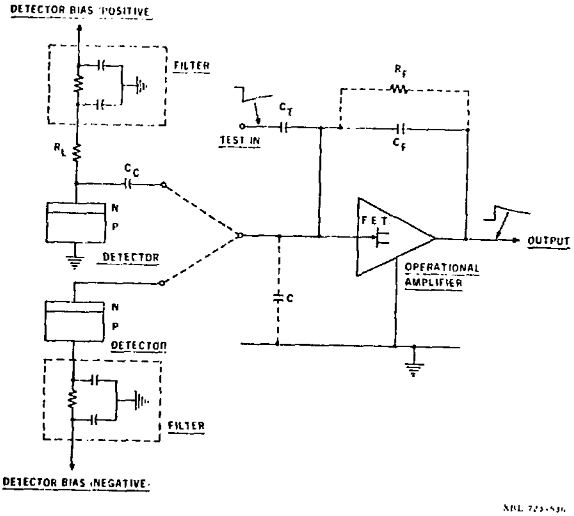

Fig. 2 Charge-sensitive preamplifier configuration

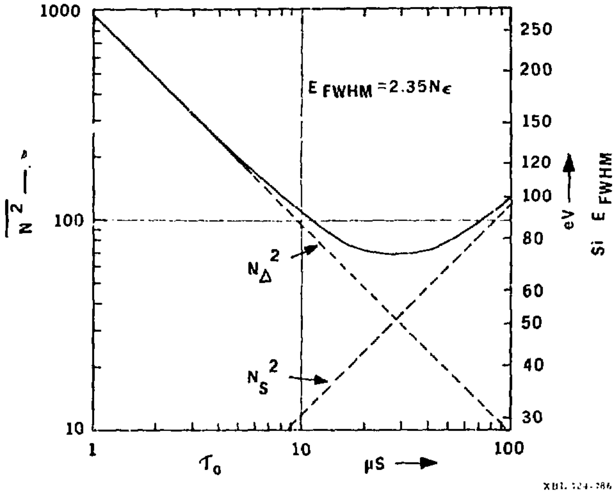

Fig. 3 Resolution as a function of time constant of a high-resolution silicon detector system. (Silicon detector at 77°K, FET 5 mA/V at 100°K, 5 pF total capacitance; 10^{-13} A total leakage.)

eliminated so that no pole-zero correction is needed in the amplifier. A block diagram of the pulsed light-feedback preamplifier is shown in Fig. 4. Both leakage current and signals from the detector cause the preamplifier output to move in a positive direction; when the output reaches an upper level, a light directed onto the FET chip is turned on. This causes the FET gate current to increase, causing the feedback capacitor to discharge until the output reaches a lower discriminator level. At this point, the light is turned off. The light intensity is adjusted to give a reset time in the range of 5 to 10 μs. Since the pulsed-light feedback preamplifier has a fixed output voltage range (in our case about 2 V), it does not saturate even when high rates and high energies are encountered.

High-Rate Performance

The main amplifier used with the pulsed-light feedback preamplifier must be able to handle the large overload produced by differentiation of the fast reset waveform from the preamplifier and recover rapidly from it. The amplifier used by us produces a nearly Gaussian shape and has a recover time to within about 0.1% of the baseline of less than four times the peaking time. The peaking time can be changed to optimize the output rate and resolution when used at high rates. Figure 5 compares the input rate with the output rate and resolution of a silicon pulsed-light feedback system of an Fe^{55} 6 keV x-ray source. A pile-up rejector removes interfering pulses. The output rate for this particular system can be doubled by reducing the 17 μs peaking time to 9 μs with only about 35 eV degradation in resolution in the 6 keV x-ray peaks.

Some FET's, when reset with the light, have a low level after-effect that can last for several milliseconds. With care this can be compensated electronically to reduce the effect to a time less than 100 μs. Much care must be taken to reduce after-effects in the whole system to obtain good energy resolution for high energy signals at high rates. For example, if there are many slow pulses from the uncompensated or dead regions in the detector, the resolution is degraded at high rates. Planar high-purity germanium detectors produce practically no slow pulses compared with Li-drifted germanium detectors and therefore produce better spectra at high rates.

While very low noise and good electronic resolution is most important in low energy spectroscopy other factors become important at high energy and high counting rates. Figure 6 shows the variation in energy resolution of a cooled silicon detector as a function of energy due to statistical effects of charge production in the detector and for various values of electronic resolution. The curves assume a Fano factor of 0.12 for silicon. The energy range is from 100 eV to 100 keV. Note that at 100 keV, if the electronic resolution is under 50 eV, the spectrometer resolution is 500 eV, and if the electronic resolution is 250 eV, the total resolution is about 550 eV. This 50 eV change is only 0.05% of the total energy. At high rates, the resolution can easily degrade much more than this if care is not taken to minimize all after-effects in the system.

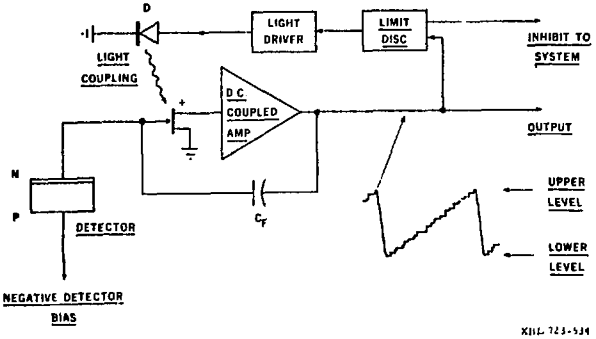

Fig. 4 Pulse light method of discharging the feedback capacitor.

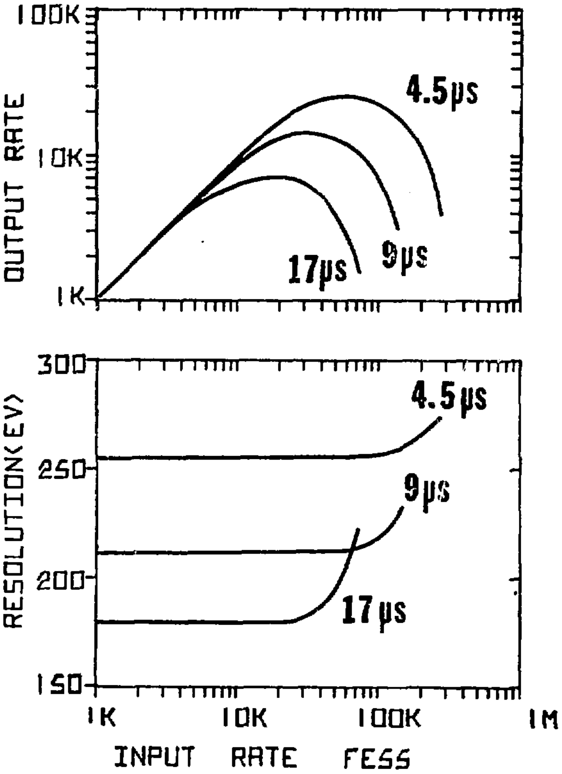

Fig. 5 Shows the effect of counting rate on resolution on Mn x-rays for different Gaussian peaking times. The output counting rate is also shown.

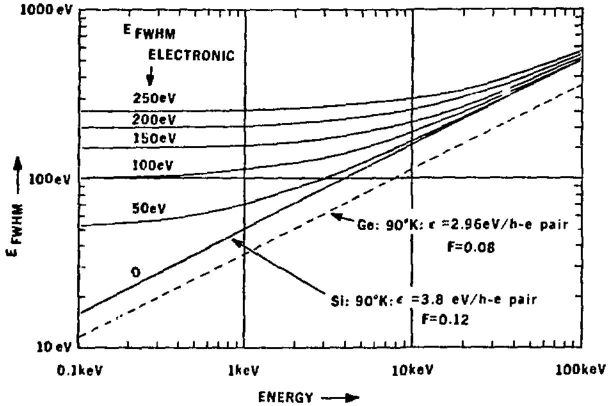

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Fig. 6 Energy resolution of a silicon detector system as a function of energy and electronic resolution in the range of 0.1 to 100 keV. The best achievable germanium detector resolution is also shown.

These include slow pulses from the detector, light after-effects in the FET and detector in a pulsed-light feedback system, non-perfect feedback resistors in resistor systems, linearity and temperature effects in the transistors and integrated circuits of the preamplifier and main amplifier and effects in base-line recovery and linear gate circuits. With care spectrometers can be made that give very good resolution at high rates and high energies. As an example, an 8 cc planar high-purity germanium detector system with a cooled FET in a pulsed light-feedback system which exhibits an electronic resolution of about 900 eV at 6 μs peaking time gives 1.64 keV at energy of 1.33 MeV at low rates and the resolution degrades to only 1.65 keV at 100,000 counts per second. This particular system uses a gated, wrap-a-round baseline restorer that exhibits negligible peak shift from low to high rates.

Pile-up rejectors must be included in all systems to be used at high rates. Figure 7 shows a block diagram of one type of pile-up rejector. Signals from the preamplifier are differentiated or clipped by a delay line to short pulses that feed the input of the circuit. These pulses trigger an updating one-shot whose width is equal to the total width of the pulses in the shaping amplifier. The short pulses and the updating one-shot output are fed to an AND gate. Any output from the AND gate indicates that two pulses came within one inspection time. The short delay prevents an output from the AND gate from the initial pulse. (If the one-shot is triggered on the back edge of the clipped pulse, no delay is needed.) The AND gate output sets a flip-flop which when set, inhibits the linear gate and prevents the piled-up signals from being measured. Figure 8 illustrates the effect of such a pile-up circuit. A cooled silicon x-ray pulsed-light feedback system with a Gaussian-shaped pulse that peaks at 4.5 μs and has a total width of about 12 μs was operated at an output rate of 260,000 counts/sec from an Fe^{55} x-ray source. The two spectra were run for the same counting time. The particular pile-up rejector had a resolving time of about 300 ns. This means that if two or more pulses occur within 300 ns of each other the rejector cannot recognize the interference and the pulses would be measured as a single sum pulse. The spectrum with the pile-up rejector shows these sum pulses with double, triple, and quadruple pile-ups. When the rejector is not used, the background at energies higher than the x-ray peaks, was almost two orders of magnitude larger. Consequently, weak peaks at energies higher than strong peak tend to be lost in the pile-up background if no pile-up rejector is used. Note that the counting rate in the main x-ray peaks is roughly the same with or without the pile-up rejector.

References

1. Goulding, F. S., Nucl. Instrum. Methods, 100, 493, (1972).

2. Fairstein, E. and Hahn, J., Nucleonics, 23, No. 11, 50 (1965).

3. Landis, D. A., Goulding, F. S., Pehl, R. H., and Walton, J. T., IEEE Trans. Nucl. Sci., NS-18, No. 1, 115 (1971).

4. Nowlin, C. H. and Blankenship, J. L., Rev. Sci. Instrum., 36, 1830 (1965).

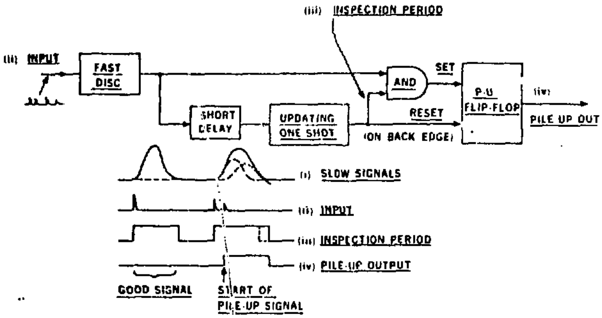

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Fig. 7 Shows the operation of a pile-up rejector

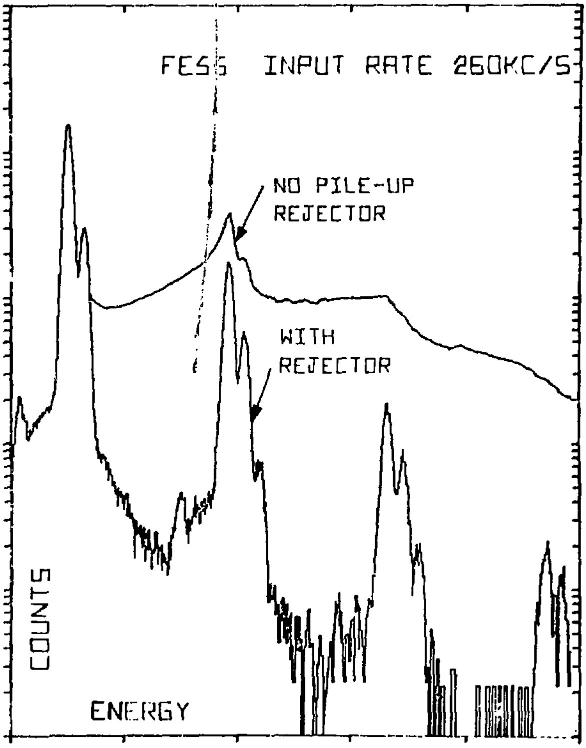

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Fig. 8 Illustrates the effect of a pile-up rejector on a Mn x-ray spectrum taken at an input rate of 260,000 counts per second.