Amptek Silicon Drift Diode (SDD) at High Count Rates

A silicon drift diode (SDD) is functionally similar to a SiPIN photodiode but its unique electrode structure reduces the electronic noise at short peaking times[1]. Under optimal conditions, the SDD gives somewhat better energy resolution than a comparable SiPIN, but its biggest advantage is that it can be operated at a much higher count rate for the same energy resolution. This note will show the performance of an SDD at high count rates and then discuss how to optimize the system configuration to run at high rates.

Typical Performance

Figure 1 shows the energy resolution (measured at the 5.9 keV Mn K_α peak) versus input count rate (R_{in}) for several different peaking times. Also shown is the R_{in} at which the output count rate (R_{out}) is a maximum. Increasing R_{in} past this is not recommended. The first key point from this plot is that the energy resolution is flat, to within measurement uncertainty, from very low rates up to the maximum and beyond. The second key point is the relation between energy resolution and maximum rate: to operate at a high count rate, one needs a short peaking time, and this leads to degraded energy resolution. There is a trade-off between peaking time and maximum count rate.

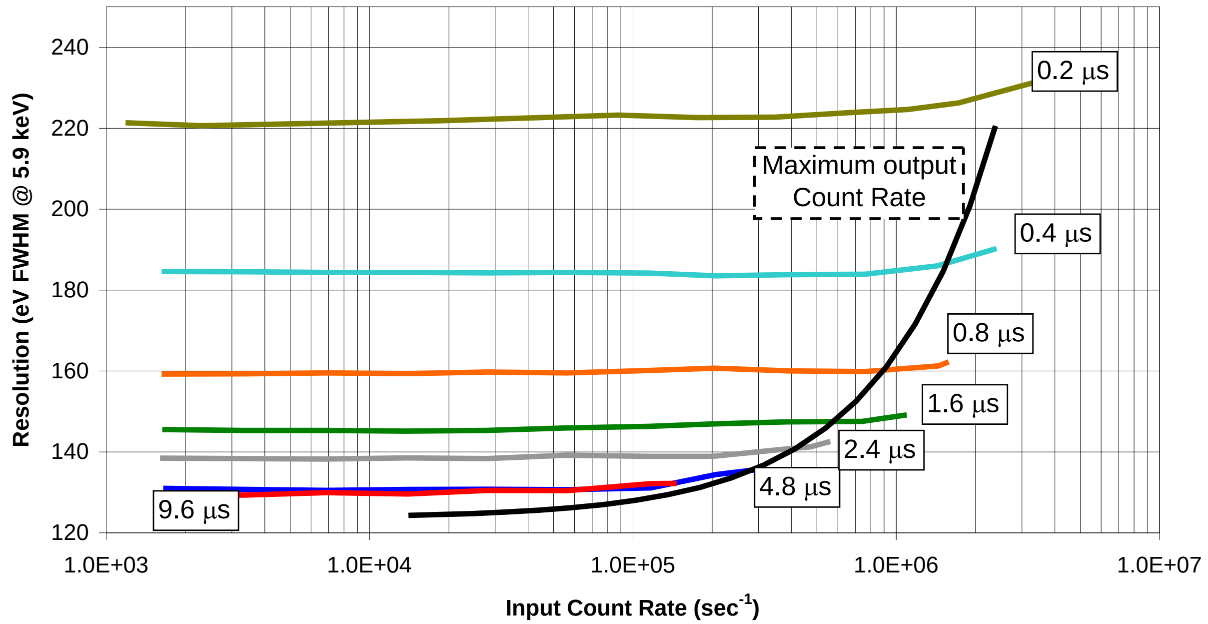


Figure 1. Plot showing the energy resolution (measured at 5.9 keV) versus input count rate at several peaking times. Also shown is the input count rate at which the output count rate peaks.

Figure 2 shows the measured throughput, R_{out} as a function of R_{in}, for several different peaking times. The curves show computed values while the dots show measured values. Data for the fast channel are shown in red. The slow channel data were obtained with pile-up rejection enabled. Figure 2 clearly confirms that, for each peaking time, there is a maximum in R_{out}, at a specific R_{in}. This plot also shows that the theoretical throughput curves are in excellent agreement with the data. The maximum R_{out} is 7×10^5 cps, obtained for T_{peak}=0.2 µsec and R_{in} of 2×10^6 cps.

[1] For more information on silicon drift diodes (SDDs), refer to Amptek's Application Note AN-SDD-03. For a comparison with SiPIN detectors, refer to AN-AMP-005.

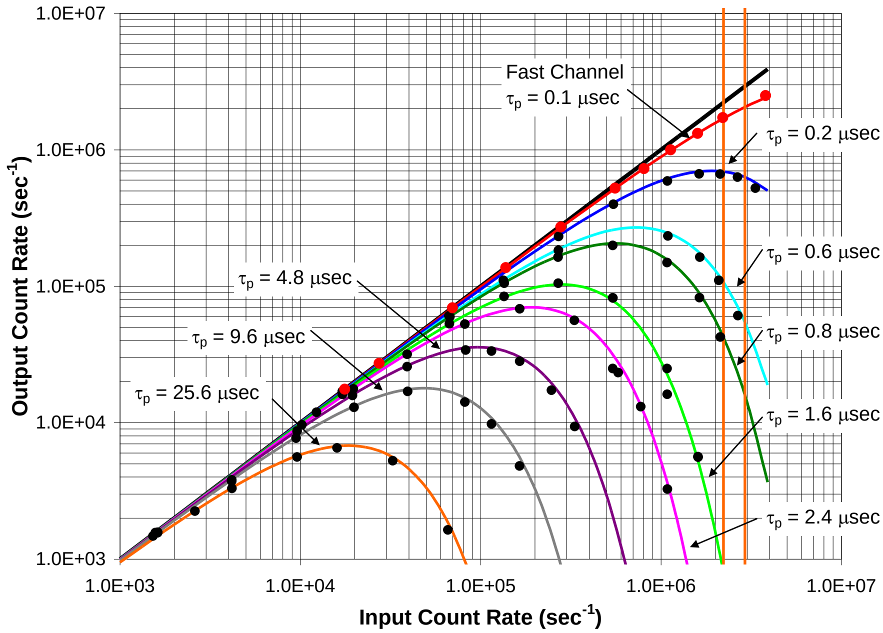


Figure 2. Plot showing the throughput, R_{out} as a function of R_{in}, at several peaking times.

Representative Spectra

Figure 3 shows spectra illustrating the performance of the 25 mm^2 SDD with DP5 at high count rates. These spectra were measured using a 99.99% pure Mn target, excited with Amptek's Mini-X X-ray tube. These spectra were taken with T_{peak}=0.8 µsec, for R_{in} from 1 kcps to 0.8 Mcps. There is very little change in the spectrum over this count rate range. The baseline shifted by a maximum of 15 eV (0.25%) when operating below the R_{out} maximum (37% throughput).

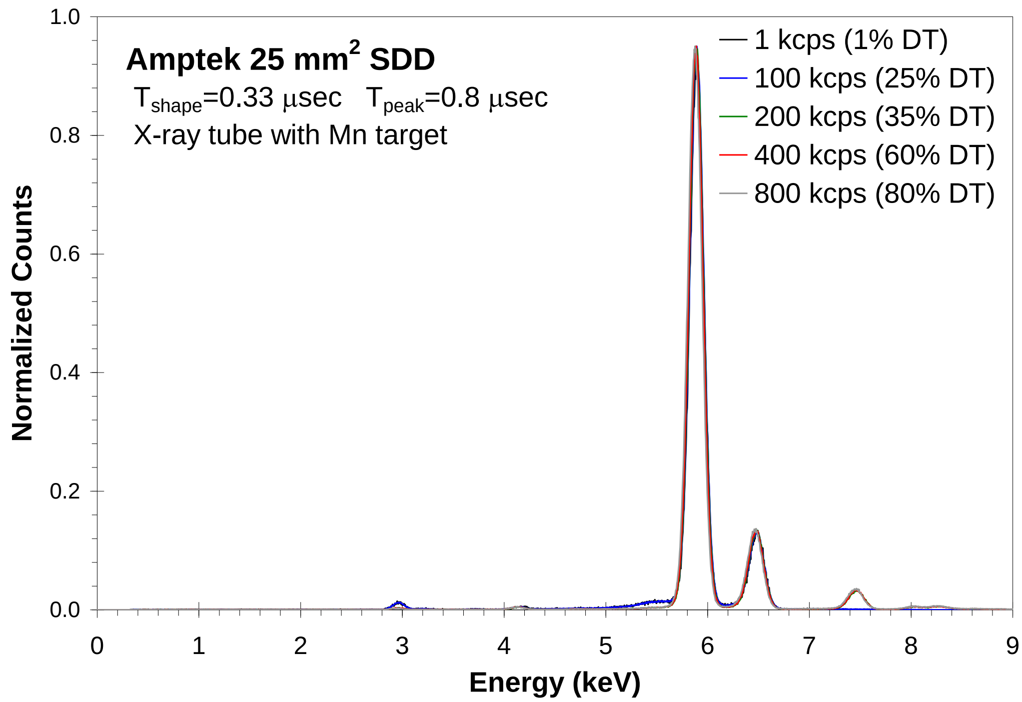


Figure 3. Spectra from a pure Mn target, taken using an SDD with DP5 at T_{peak}=0.8 µsec peaking time. The data were taken at R_{in} of 1 kcps (99% throughput), 400 kcps (40% throughput, near the peak of the R_{out} curve), and 800 kcps (20% throughput, past the peak of the R_{out} curve). The resolution was 160 eV FWHM.

Deadtime Correction

All nuclear spectroscopy systems exhibit a dead time associated with each radiation interaction. Following any interaction, there will be a time period during which subsequent pulses cannot be detected and will not contribute to the output counts. Because the timing of pulses is random, there is always some probability that pulses will occur in these dead time intervals, and therefore the output count rate (R_{out}) measured by a system is always lower than the input count rate (R_{in}). The measurement goal is to determine the incident spectrum and count rate, which requires correcting for these losses.

Theory of Deadtime Losses

The theory of deadtime losses is discussed in many references[1,2]. From this theory, the DP5 should exhibit a paralyzable dead time, which implies that

$$R_{out} = R_{in} e^{-R_{in} T_{DEAD}} \qquad (1)$$

where R_{in} is the true input count rate, R_{out} is the measured count rate, and T_{DEAD} is the dead time. This equation applies to both the fast and slow channels. For the fast channel, T_{DEAD} is approximately equal to the fast channel peaking time, T_{Fast}. For T_{Fast} =0.1 μs, the fast channel T_{DEAD} =0.12 μs. For $R_{in} \leq$ 500 kcps, the throughput of the fast channel is $\geq$95%.

The throughput of the slow channel is much lower and understanding its dead time is very important. For the slow channel,

$$T_{DEAD} = (N)(1 + F_{PD})(T_{Peak} + T_{Flat}) \qquad (2)$$

In Equation (2), N equals 1 if pile-up rejection is disabled or 2 if enabled. T_{Peak} is the time to peak and T_{Flat} is the duration of the flat top. F_{PD} is the time need by the peak detect logic to identify that a pulse peaked. If the slow threshold is set to channel C_{LLD} and the pulse peaks in channel C_{peak}, then $F_{PD}=C_{LLD}/C_{peak}$. For a spectrum, one can find the mean value <FP> and use this for a mean dead time per pulse. In most application, the slow threshold is low (on the order of a percent of the peak heights) so this represents a small correction.

The peak of Eqn [1], the maximum value for R_{out}, occurs for $R_{in}=1/T_{DEAD}$ and corresponds to R_{out}/R_{in}=43%. Equations (1) and (2) were used to compute the curves shown in Figure 2, which is in excellent agreement with the data.

Deadtime Correction

Given these losses, what is the best way to determine the R_{in}, the true input count rate? Most analog spectroscopy systems use a “livetime clock”. The shaped pulses are sent to an MCA, which detects the peaks and records the rate of peaks detected. This is R_{out}. The livetime clock is disabled when the system is processing a pulse, and it can be shown that R_{in} equals R_{out} divided by this livetime. The livetime clock requires for its input only the slow, shaped pulse and can accommodate any pulse shaping, any spectrum, etc. The dead time of an analog system is a strong function of the pulse shaping, can depend on the spectrum, and is usually dominated by the conversion time of the ADC. In these circumstances, the livetime clock usually works well, though for sufficiently high losses there are errors in the clocks. In the high rate and high resolution analog systems, such as HPGe in γ-ray spectroscopy, the slow pulse is used to measure the spectrum while a faster shaping amplifier is connected to a counter to directly measure R_{in} [3]. In analog counting systems, as opposed to MCAs, if the signal is well above the noise then the dead time per pulse is very well known so a “manual correction” may be applied, by computing the fraction of counts lost [2].

Amptek’s system, the SDD with a DP5 digital processor, does not rely on the livetime clock but uses better solutions available with digital processing to determine R_{in}. First, while an analog MCA has only one analog signal, the slow signal, the DP5 has a very high performance fast channel. Pulses can be counted in this fast channel, so R_{in} can be directly measured. Second, because the shaping and MCA are not distinct but elements in a single signal processor, it need not handle any and every pulse shape. It processes only trapezoidal pulses, and these have a well defined duration, with a finite impulse response. Third, the digital processor has zero conversion time, and with the SDD’s low noise threshold, the dead time per pulse is effectively constant. These fundamentally different characteristics of the digital processor lead to better results than can be obtained with a livetime clock [4].

The DP5 uses the measured fast channel count rate, R_{fast}, to determine R_{in}. The ADMCA software reports the measured R_{fast} with no corrections. For R_{in} < 100 kcps, which covers a great many application, the error with this method is less than 1%. At higher rates, the user can apply a "manual method", computing a correction factor for R_{fast} . A first order estimate can be obtained from the simple equation for a nonparalyzable dead time,

$$R_{est} = \frac{R_{fast}}{1 - R_{fast} T_{Fast}} \qquad (3)$$

This correction method is good to 0.5% for $R_{in} \leq 500$ Mcps. One could invert Eqn (2) to do the full correction for a paralyzable dead time, but there is no analytic expression for this inversion, so it must be done numerically. With this method, the error is less than 1% for R_{in} < 2.2 Mcps. Figure 4 compares the performance of the three methods.

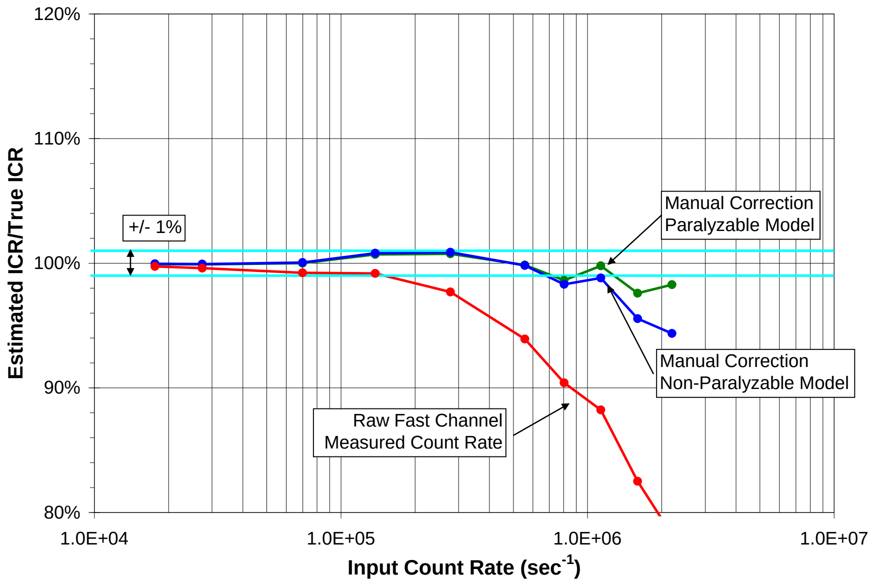


Figure 4. Plot comparing the SDD/DP5 deadtime correction methods.

Amptek ADMCA and DPPMCA software

Amptek's ADMCA and DPPMCA software displays uncorrected fast and slow counts in the "Information Pane", on the right. The line labelled "Counts" represents the total number of slow counts, the number of times a valid peak was detected during the accumulation interval. A valid peak must be (a) above the slow threshold, (b) below the upper limit of the MCA, (c) separated from an overlapping peak by at least T_{DEAD} and (d) if PUR is enabled, not rejected by the logic. Dividing "Counts" by "Real Time" gives R_{out}.

The "Input Counts" line represents the total number of fast counts, the number of times the fast channel had a pulse exceeding the fast threshold during the accumulation interval. The "Total Rate" equals "Input Counts" divided by "Real Time". Thus "Total Rate" represents the first deadtime correction method.

Note that there is only a lower threshold for the fast channel but both upper and lower thresholds for the slow channel. If the gain is set such that count are out of range of the spectrum, they will not be counted in the slow channel but will be counted in the fast channel.

The "Dead Time" shown in the information pane is computed from R_{in} and R_{out}. It is not measured using a clock but is estimated from the number of lost counts. This estimate is valid as long as the slow threshold, upper limit of the spectrum, and fast channel are all set appropriately. The meaning of this is discussed below, but if a threshold is too low (such that it triggers on noise) or is set too high (such that counts are missed), then a misleading dead time calculation can result.

Configuring the DP5 for high count rates

There are a few key considerations in configuring the DP5 to obtain good performance at high rates and an accurate estimate of R_{in}. Amptek's ADMCA software is provided with default configurations which provide a good starting point for most users in most applications. Tuning these parameters is necessary to get the best performance at high rates. The following notes provide Amptek's recommendations for operating at input count rates below 800 kcps. Operation at or above 1 Mcps is certainly possible but several additional effects become important. Contact Amptek for further information.

Pulse Shaping Times

First and foremost, the user needs to select the correct peaking time. The best peaking time depends on (1) what energy resolution is required for your particular application and (2) what count rate you need. A fast peaking time permits higher count rates but with degraded energy resolution. Use Figure 1 and Figure 2 of this note to determine what peaking time you need. At the count rates of interest here, up to 800 kcps, a peaking time of 0.6 μs or longer is suggested. We recommend a flat top duration of 0.2 μs or longer and a fast channel peaking time of 0.1 μs or longer. The DP5 can be used with shorter pulse times but varying charge collection times in detector, preamplifier risetimes, and other phenomena can lead to spectral artifacts and make optimizing the configuration complicated. The shorter pulse times are not needed for operation <500 kcps.

Gain

Second, in all X-ray spectroscopy applications, the gain should be adjusted so that the maximum energy of interest occurs somewhat lower than the peak channel. If one is measuring Ag, for example, the gain should be adjusted to give about 30 keV full scale, for low rate applications. At high rates, it is often useful to see the sum peak, in this case 50 keV. With the highest rates and very energetic spectra, it may be useful to reduce the gain further, to avoid pile-up in the analog circuitry which leads to distorted spectra.

Slow and Fast Thresholds

Third, the thresholds must be set properly. Improperly set threshold are the most common error in configuring the DP5 for high rates. The simplest way to set the thresholds is to use the "Tune Fast/Slow Thresholds" button on the ADMCA toolbar (please note that the source must be removed first). This will set both fast and slow thresholds just above the noise.

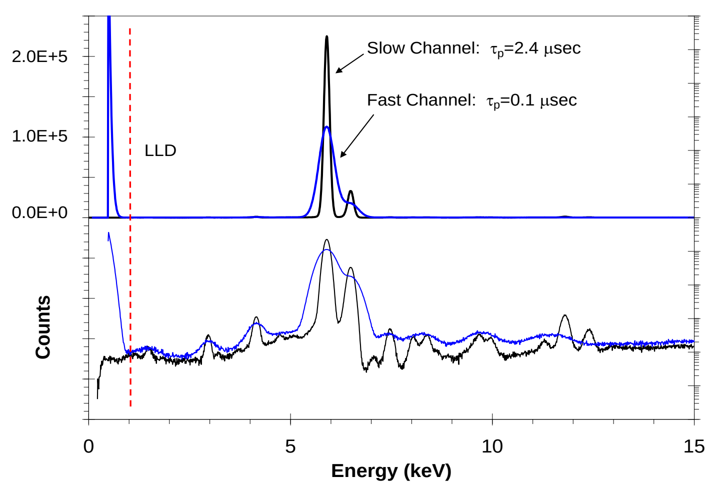


Figure 5 Plot showing spectra measured for the slow channel, at 2.4 μsec and 0.1 μsec T_P for the slow and fast channels, respectively. The same data are depicted in linear (top) and log (bottom) scales. Also shown is the LLD for the fast channel.

Figure 5 shows a typical Mn spectrum, measured with the slow channel (at T_{peak}=2.4 μsec) and with the fast channel (T_{fast}=0.1 μsec). The fast channel will count all events which exceed the fast threshold, which are separated in time by more than 120 nsec. In this case, the threshold should be set to about 1 keV. If the threshold is set too low, then the fast channel will trigger on noise. That is, a noise fluctuation in the baseline may exceed the threshold, and the DP5 records this as an interaction. This causes two problems:

1. R_{fast} is too high. Since R_{fast} is used to estimate R_{in}, the estimate will be too high. Moreover, since the dead time is estimated from the R_{fast} to R_{slow} ratio, the reported dead time will be erroneously high. If there are really 100 counts per second, then the dead time is near zero. But if the fast channel is counting noise 900 times per second, it will report a 90% deadtime and a “True Rate” of 1 kcps.
2. The pile-up reject (PUR) will discard valid events. If the fast channel triggers on the noise, then noise will veto valid slow channel events. If the threshold is low enough, then it will reject everything, thus no spectrum is acquired.

The slow channel will record events in which (1) the pulse peaks above the slow threshold, (2) the pulse peaks below full scale, and (3) the system did not detect two fast channel pulses within the pile-up inspection time, roughly T_{DEAD}. The slow channel generally has much lower electronic noise than the fast channel; therefore its threshold is much lower. In the example above, its threshold is around 300 eV. X-rays depositing 500 to 700 eV will be counted by the slow channel but not the fast channel so will not contribute to the estimate of R_{in} from the fast channel. These events are rare, due to the Be window. If the gain of the system is set very high, then there may be many events which exceed full scale. These are not recorded in the spectrum so are not included in “Counts”. In this case, the “Counts” value does not well represent the actual counts which are present. “Input Counts” will still return a valid number, but the “Dead Time” fraction will be erroneously high.

Our advice to the user is: be mindful of these thresholds. Note the counts carefully, and if R_{in} or the deadtime appear excessively high, check the thresholds. Use an oscilloscope (or ADMCA’s oscilloscope mode) to trigger on ICR (which is the fast channel logic input to the fast channel counter) and view the decimated input, the slow channel, and the fast channel.

Baseline Restorer

The baseline restorer (BLR) keeps the centroid from shifting with count rate. There are two parameters: Up and Down. These essentially set the slew rate of the BLR. If you observe that the centroid is shifting down as count rate increases, then you can increase the “Up” setting or reduce the “Down” setting. We have found that the optimum setting varies considerably with spectrum, gain, count rate, etc.

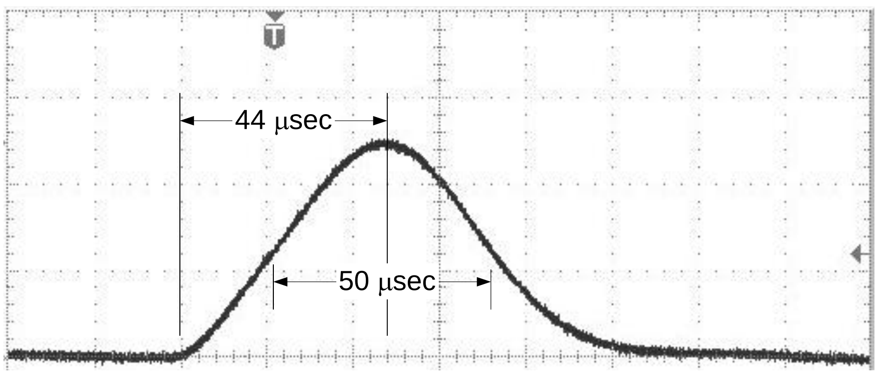
Reset Interval

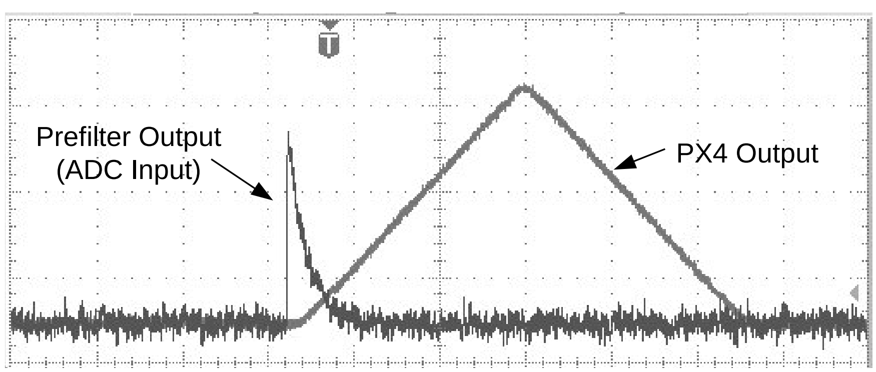
There is a “Detector Reset Lockout Period” which should be set to 410 μsec (typically) for the SDD. The preamplifier resets whenever enough charge has been integrated on the feedback capacitor, causing a large anomaly in the preamp output. Signal processing needs to be stopped for some time after such resets, to let the system return to normal. At high count rates, the current across the capacitor is much larger, so the reset rate is much larger, and acquisition is stopped for a large fraction of the time. When this occurs, the accumulation time in ADMCA integrates by significantly less than a second for each update. When this is observed, reduce the reset interval.

Additional Information

Peaking time and shaping time

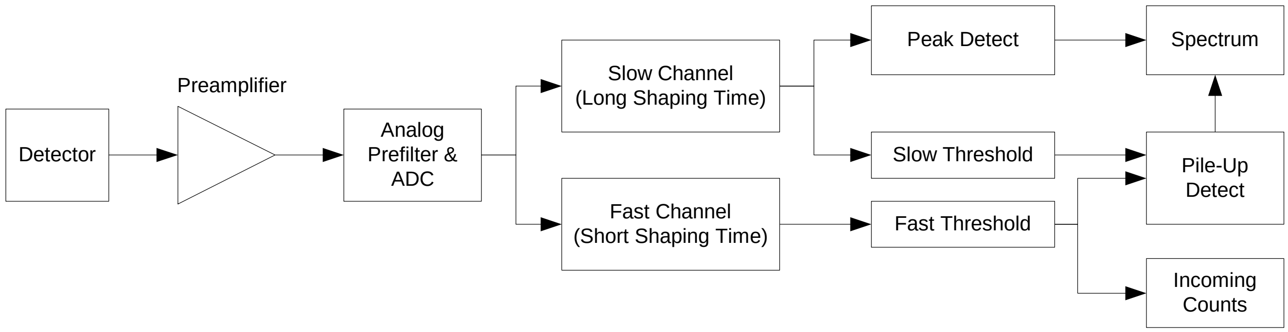
This is the source of much confusion, in both analog and digital pulse processing. Analog shapers usually specify the "shaping time constant" τ. The time for an analog pulse to reach its peak value is roughly 2.2τ (it depends on the shaping amplifier design). Digital processors specify the "peaking time" and will have performance a bit better than a pseudo-Gaussian analog shaper of the same peaking time. Shown below are oscilloscope traces of (top) a quasi-triangular pulse from an analog shaper, an Amptek PX2, and (bottom) a digitally shaped trapezoidal pulses. The analog pulse used $\tau = 20$ μs, with a time to peak of 44 μs, or 2.2τ. The pulse is slightly asymmetric, with a settling time slightly longer than its rise time, and a FWHM of 50 μsec. The digital pulse was set to T_{peak}=51.2 μs and T_{flat}=0.4 μs. The pulse is triangular, so is symmetric and has duration 51 μsec (FWHM). For more information on the difference between analog and pulse shaping, please see Amptek's application note AN-DPP-001.PDF, "Digital pulse processors: Theory of operation".





The "fast channel" and the "slow channel"

The "fast" and "slow" channels are two parallel signal processing paths inside the DP5, operating at different shaping times. They are optimized to obtain different data about the incoming pulse train. The "slow" channel, which has a long shaping time constant, is optimized to minimize electronic noise, to obtain an accurate pulse height. The "fast" channel, which has a short shaping time constant, is optimized to detect pulses which are closely spaced in time and so overlap (or pile up) in the slow channel. For most detectors, electronic noise is minimized at a fairly long shaping time constant. The slow channel is operated at this long time constant, and its output is connected to the peak detect circuit and used to obtain the energy spectrum.



Since radiation interacts in the detector at random intervals, it is possible to have two interactions occur within the processing time of the slow channel. Even at low count rates this will occur occasionally and in most applications, it is useful to operate at a high count rate to minimize data acquisition time. Two problems occur when the pulses overlap in time: only a single pulse is recorded rather than two, and the detected peak has incorrect amplitude. To address this, there is a fast channel with a short peaking time. Pulses which overlap in the slow channel but not in this fast channel may be rejected from the spectrum, to minimize the distortions. If pile-up reject (PUR) is turned on, then they are rejected. Further, the fast channel is used to measure the true incoming count rate (ICR), where far fewer pulses are rejected.

Note that separate thresholds are used in the fast and slow channels. Since the fast channel is usually operated further from the noise corner, it has a higher noise level and so the threshold must be higher. The “counts” recorded by the DP5 are those detected in the slow channel. The “incoming counts” recorded by the DP5 are those detected in the fast channel, where the dead time is much less.

Acquisition Time

The DP5 measures the “acquisition time”. This is the real elapsed time during which data are being acquired. The real time clock is turned off during certain events, including data transfers over the serial bus and also including reset intervals. If a reset preamplifier is used, and the DP5 is configured for a certain reset time period, then acquisition is shut down during the reset period and the acquisition clock is stopped. This acquisition time is measured using a 100 ppm crystal oscillator so is quite accurate. The true count rate should be computed using the actual acquisition time.

Data transfers occur based on an approximate real time clock in the PC. For example, one might configure ADMCA or DPPMCA to update every second. When the data transfer occurs, the acquisition time is shown and this will probably differ from the nominal “1 second”, due to the approximate clock and also due to reset losses. A typical value is 1.05 second. At high count rates, a reset preamp resets more often, and so there is less acquisition time per transfer. In this case, the acquisition time might become 0.85 seconds.

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[1] G.F. Knoll, *Radiation Detection and Measurement*, 3rd ed, J. Wiley & Sons, 2000, pp 119-127 and pp 632-643

[2] R. Jenkins, R.W. Gould, D. Gedcke, *Quantitative X-ray Spectrometry*, 2nd Edition,, Marcel Dekker, Inc., 1995. 2, pp 147 - 207.

[3] A.J. Dent, G.E. Derbyshire, G. Derst, R.C. Farrow, *Dead-time correction and normalization in germanium solid-state detector systems using an incoming count rate monitor*, Rev. Sci. Instrum. 66 (2), Feb 1995, p 2306

[4] Redus, R.H., A.C. Huber, D.J. Sperry, *Dead time correction in the DP5 digital pulse processor*, IEEE Nucl. Sci. Symp. Conf. Rec., Oct 2008, pp 3416 - 3420 (2009).