

## 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. 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 high 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  $K_{\alpha}$  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.

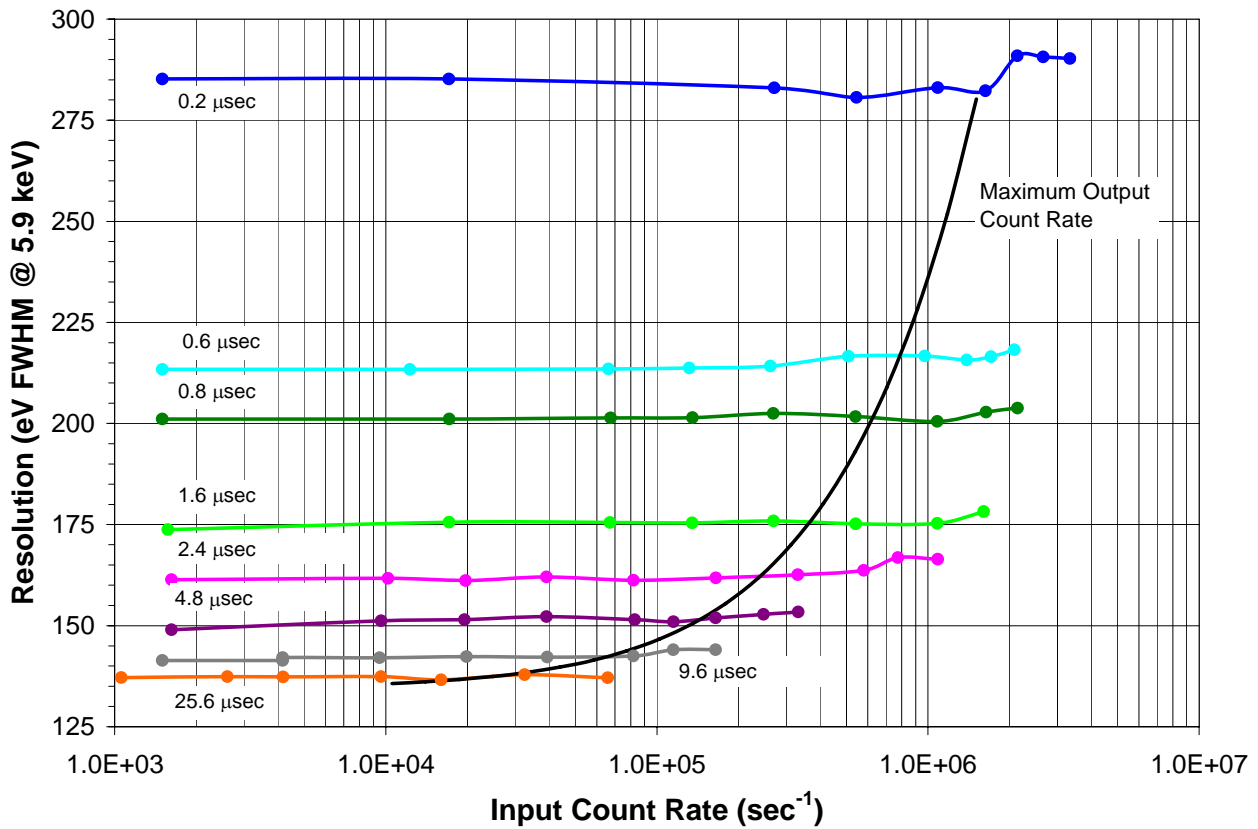


Figure 1. Plot showing the energy resolution (measured at 5.9 keV) versus input count rate at several peaking times. Also shown is the input count rate at which the output count rate peaks.

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  $7 \times 10^5$  cps, obtained for  $T_{peak} = 0.2 \mu\text{sec}$  and  $R_{in}$  of  $2 \times 10^6$  cps.

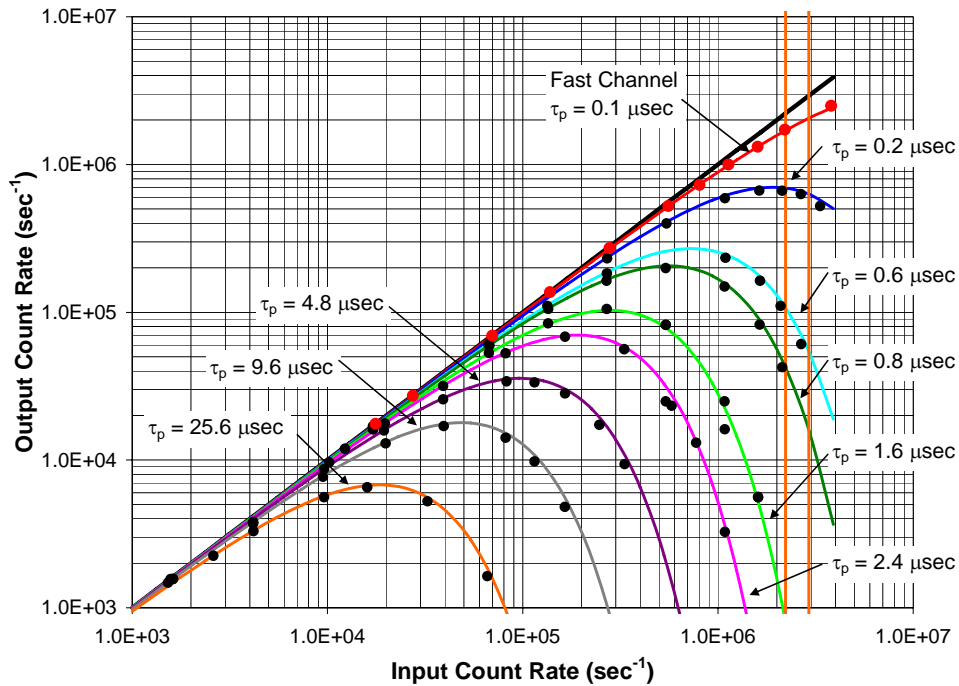
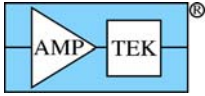


Figure 2. Plot showing the throughput,  $R_{out}$  as a function of  $R_{in}$ , at several peaking times.

### Representative Spectra

Figure 3 and Figure 4 show spectra illustrating the performance of the 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. Peaking times were 9.6 and 0.8  $\mu\text{sec}$ , for  $R_{in}$  from 1 kcps to 1 Mcps. There is very little change in the spectrum over this count rate range. The sum peaks are visible in both cases, as expected. The baseline shifted by a maximum of 15 eV (0.25%) when operating below the  $R_{out}$  maximum (37% throughput).

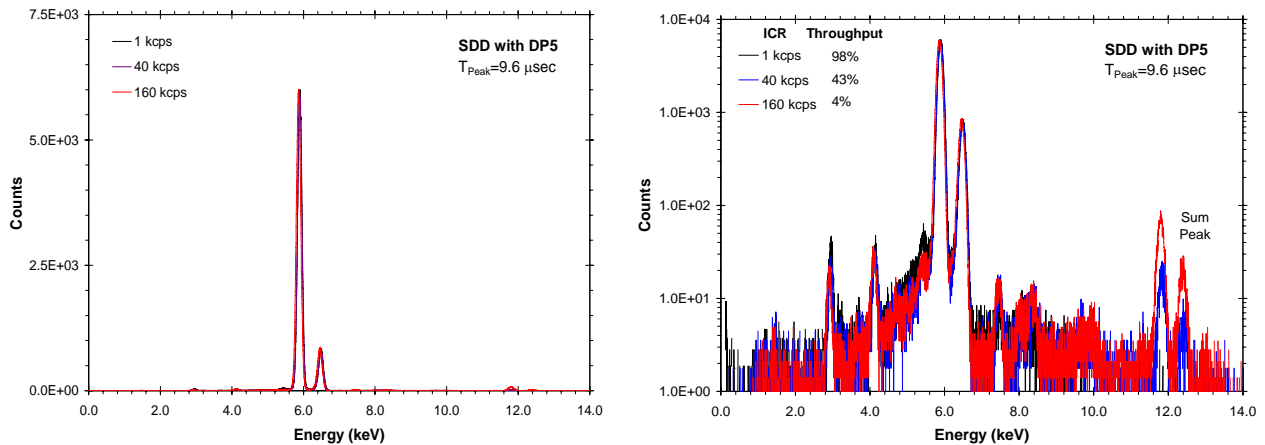


Figure 3. Spectra from a pure Mn target, taken using an SDD with DP5 at 9.6  $\mu\text{sec}$  peaking time. The data were taken at  $R_{in}$  of 1 kcps (98% throughput), 40 kcps (43% throughput, near the peak of the  $R_{out}$  curve), and 160 kcps (4% throughput, far past the peak of the  $R_{out}$  curve). The resolution was 142 eV FWHM.

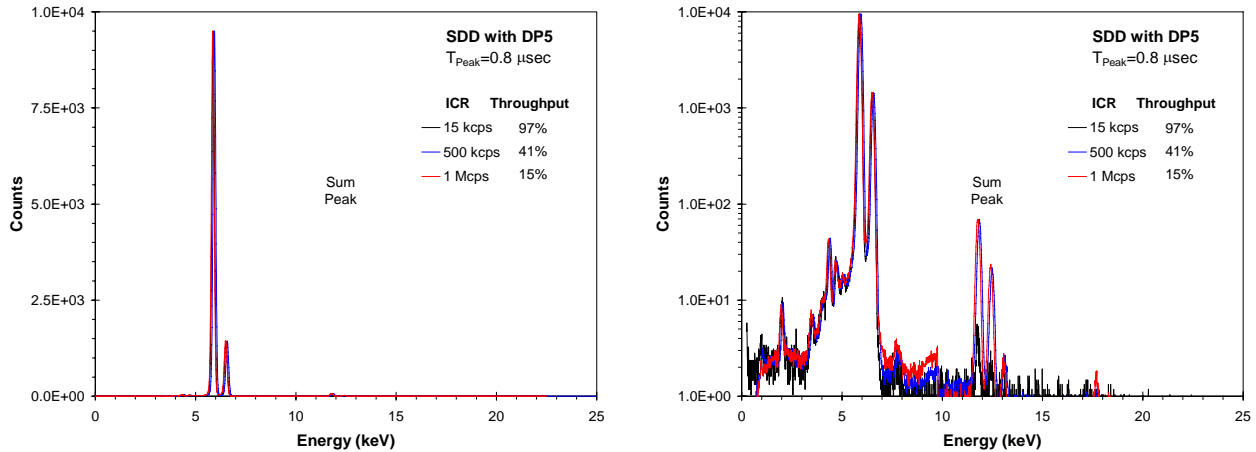
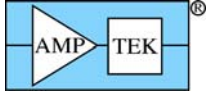


Figure 4. Spectra from a pure Mn target, similar to Figure 3 except taken at a peaking time of 0.8  $\mu$ sec. The highest rate data were taken at  $R_{in}$  of 1 Mcps. The energy resolution was 201 eV FWHM.

### 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]. The dead time characteristics of the DP5 have been presented in a recent publication [3]. The output count rate of the DP5 is given by

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

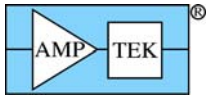
where  $R_{in}$  is the true input count rate,  $R_{out}$  is the measured count rate, and  $T_{DEAD}$  is the dead time,

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

In Equation (2),  $N$  equals 1 if pile-up rejection is disabled or 2 if enabled.  $T_{Peak}$  is the time to peak,  $T_{Flat}$  is the duration of the flat top, and  $F_{PD}$  is a time for the peak detect to identify that the pulse peaked. It equals the threshold,  $E_{th}$ , divided by the mean pulse height  $\langle E \rangle$  and is about 0.05 in these data. The peak of  $R_{out}$  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. The dead time per pulse represented by equation (2) is much less than that of an analog system with comparable resolution: there is no MCA associated conversion time and the shape associated dead time is less than half. The dramatic improvement in throughput is a key advantage of digital pulse processing.

#### Deadtime Correction

Given these losses, what is the best way to determine the  $R_{in}$ , the true input count rate? Most traditional analog spectroscopy systems use a "livetime clock" but the SDD with a DP5 digital processor uses better solutions available with digital processing to determine  $R_{in}$ . The DP5 uses the measured fast channel count rate to determine  $R_{in}$ . There are three approaches which the user can choose to implement. First, one can simply use  $R_{fast}$  as an estimate of  $R_{in}$ . For  $R_{in} < 100$  kcps, the error with this method is less than 1%. Second, one can apply a "manual method", computing a correction factor for  $R_{fast}$  using the simple equation for a nonparalyzable dead time,



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

where  $T_{fast}$  is the dead time of the fast channel, 120 nsec for the SDD with DP5. This approach has an error less than 1% for  $R_{in} < 1$  Mcps. Third, one can invert Eqn (2) to do the full correction for a paralyzable dead time. 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.

In Amptek's ADMCA software, both the fast and slow counts are displayed. The "Information Pane", on the right, has a line for "Counts". This represents the total number of slow counts, the number of times a valid peak was detected during the accumulation interval. 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. It is a measurement of  $R_{fast}$ , and for Total Rate  $< 100$  kcps is accurate to 1%. To apply the manual method, one must use the "Total Rate" in Eqn (3) or to invert Eqn (2). 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.

### 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  $R_{in}$  measurement. Amptek's ADMCA software is provided with default configurations, which are intended to provide a good starting point for most users in most applications. Tuning these parameters is necessary to get the best performance at high rates.

#### Peaking Time

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. To handle the highest count rates, the energy resolution is degraded. Use Figure 1 and Figure 2 of this note to determine what peaking time you need.

#### Gain

Second, the gain should be adjusted. In all X-ray spectroscopy applications, you want the gain 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.

At the very highest rates, where the peaking time is short, the gain may need to be reduced further. The preamp output passes through an analog prefilter, where it is digitized. The ADC has a range of 0 to 2V. At a sufficiently high count rate and high gain, the pulses pile-up into the ADC. This creates distorted pulses and causes several spectral anomalies. To check for this, set the DAC output to "decimated input" and either connect an oscilloscope or use ADMCA's oscilloscope mode. Look for signals hitting the rail. If these are seen, the gain should be reduced.

#### 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 "Autotune" button on the ADMCA toolbar. This will set both fast and slow thresholds just above the noise.

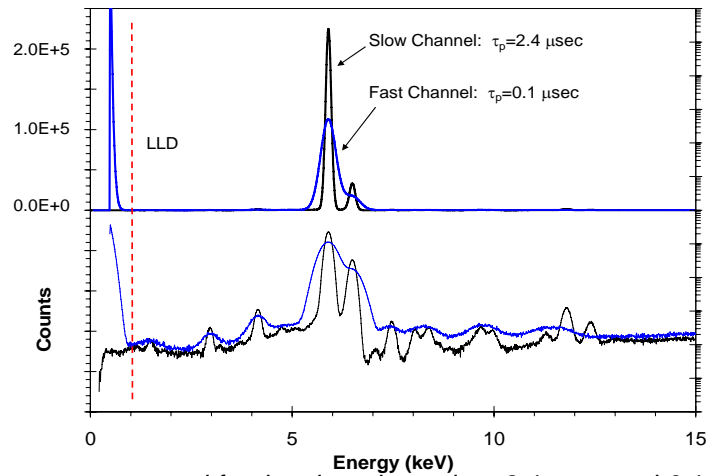
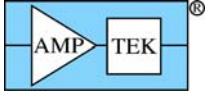


Figure 5 Plot showing spectra measured for the slow channel, at 2.4  $\mu\text{sec}$  and 0.1  $\mu\text{sec}$   $T_p$  for the slow and fast channels, respectively. The same data are depicted in linear (top) and log (bottom) scales. Also shown is the LLD for the fast channel.

Figure 5 shows a typical Mn spectrum, measured with the slow channel (at  $T_{\text{peak}}=2.4 \mu\text{sec}$ ) and with the fast channel ( $T_{\text{fast}}=0.1 \mu\text{sec}$ ). 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:

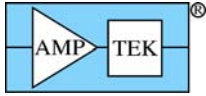
1.  $R_{\text{fast}}$  is too high. Since  $R_{\text{fast}}$  is used to estimate  $R_{\text{in}}$ , the estimate will be too high. Moreover, since the dead time is estimated from the  $R_{\text{fast}}$  to  $R_{\text{slow}}$  ratio, the reported dead time will be erroneously high. If there are really 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  $T_{\text{DEAD}}$ . 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  $R_{\text{in}}$  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 not 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  $R_{\text{in}}$  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  $\mu\text{sec}$  (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.

### Pile-Up Rejection and Risetime Discrimination

The operation of Pile-Up Rejection (PUR) is illustrated in Figure 6 and Figure 7. Figure 6 (left) shows two pulses which are well separated in time. Both are counted and accurate pulse heights are detected. Figure 6 (middle) shows two pulses separated by a little more than  $T_{\text{peak}}$ . The pulses overlap in the slow channel but the separation is large enough that the peak amplitudes are unaffected. Both are counted and accurate pulse heights detected for each. Figure 6 (right) shows two pulses separated by less than  $T_{\text{peak}}$ . The peak amplitude is a sum of the two and does not accurately represent either interaction. With PUR disabled, the slow channel records a single pulse with incorrect amplitude. The fast channel records both pulses. With PUR enabled, the fast channel still records two pulses, but the PUR logic recognizes that the events are closely spaced in time and so the peak is rejected. Nothing is recorded in the spectrum or the slow counts.

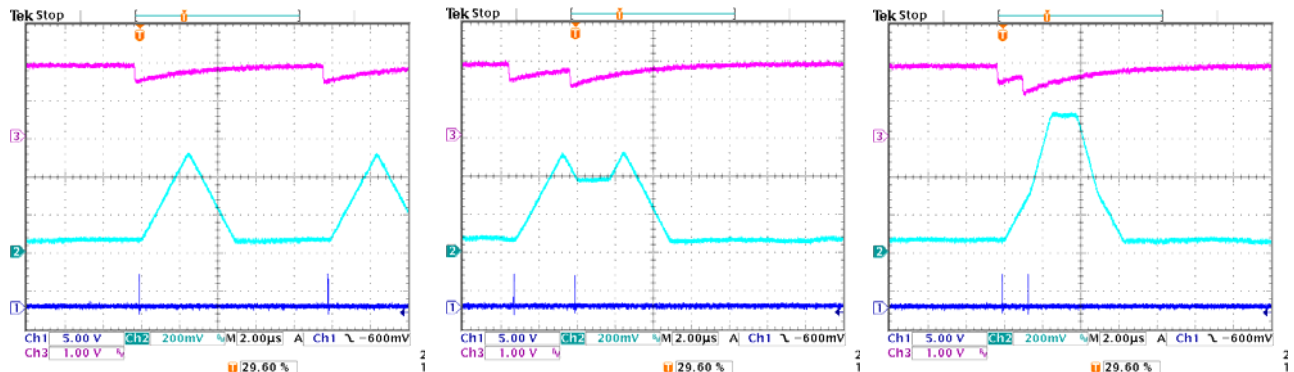


Figure 6. Oscilloscope traces demonstrating pulse pile-up. The pink trace is the ADC input. The light blue trace is the shaped output (here set to a peaking time of 2.4  $\mu\text{sec}$ ). The dark blue trace is “ICR”, the logic signal indicating that a pulse was detected in the fast channel.

Figure 7 shows the fast channel operation, for pulses very close in time. Figure 7 (left) shows pulses separated by 240 nsec, with no overlap in the fast channel. Figure 7 (middle) shows pulses separated by 120 nsec. They overlap in the fast channel, but there are distinct peaks so the fast channel logic recognizes the distinct events. Both events are counted in the fast channel and the pile-up reject logic discards the sum event in the slow channel. Figure 7 (right) shows pulses separated by less than 100 nsec. They are recorded as a single event in the fast channel and are not rejected by PUR. Since these two occur at nearly the same time, the amplitude in the slow channel will be very nearly equal to the sum of the two discrete amplitudes, giving rise to the sum peak.

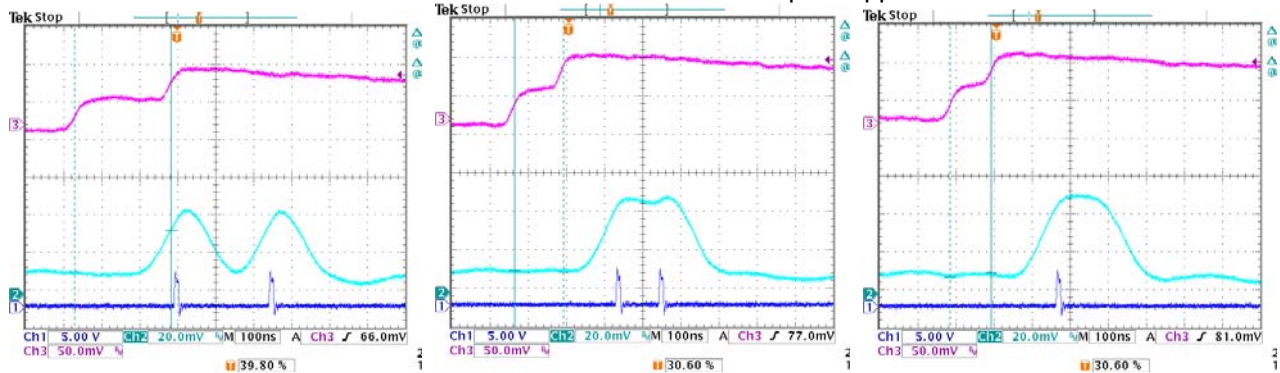
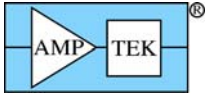
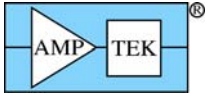


Figure 7. Oscilloscope traces demonstrating fast channel operation. The pink trace is the ADC input. The light blue trace is the fast output (peaking time of 0.1  $\mu$ sec). The dark blue trace is “ICR”, the logic signal indicating that a pulse was detected in the fast channel.

Events such as those in Figure 7 (right), though not identified by PUR logic, still have a recognizable signature. Note that the sample of the fast channel pulse is considerably different from that in Figure 7 (left). The long duration pulse in the fast channel is what one expects for a slow input current. Essentially, this looks to the signal processor like a single event with an input current duration of 100 nsec. The preamplifier output looks like that from a slowly rising pulse. Therefore, risetime discrimination can be used to reject such events. The DP5 does include a risetime discriminator, but the settings need to be tuned for any application. Turn the system on at a low count rate, and record the rates. Turn the RTD on, and set the “Threshold” and “HWHM” to their maximum values. At this setting, nothing should be rejected; record counts to verify. Then begin reducing the “threshold” until the slow count rate begins to fall. The system is now at the threshold of rejecting valid events as “too long”. Increase the “threshold” slightly, until you recover the initial rate. The system will now reject many events which are missed by PUR, reducing the sum peak considerably.

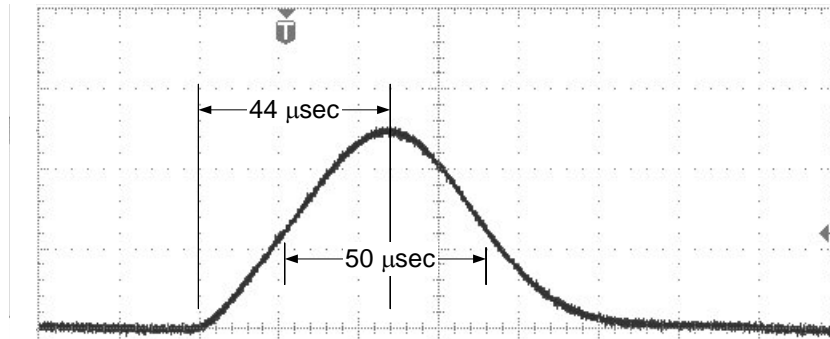


### Additional Information

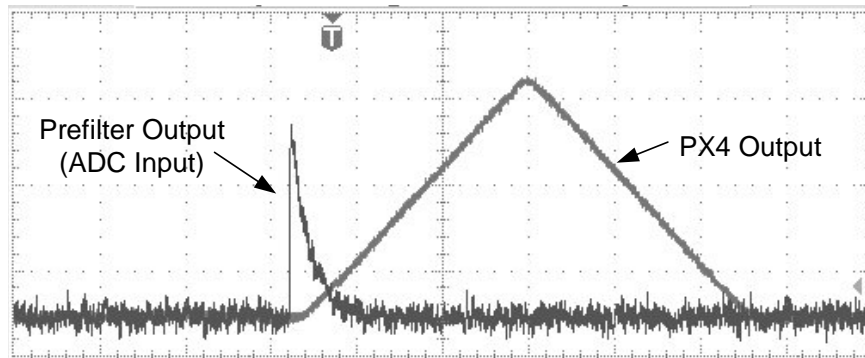
#### Peaking time and shaping time

This is the source of much confusion, in both analog and digital pulse processing. Analog shapers usually specify the “shaping time constant”  $\tau$ . The time for an analog pulse to reach its peak is roughly  $2.2\tau$  (it depends on the shaping amplifier design). Digital processors specify the “peaking time” and will have performance comparable to a pseudo-Gaussian analog shaper of the same peaking time. The DP5 with  $T_{\text{peak}}=2.4 \mu\text{sec}$  has resolution and such comparable to an analog shaper with  $1 \mu\text{sec}$  shaping time constant.

Shown below is an oscilloscope trace of a quasi-triangular shaped pulse from an analog pulse shaper, an Amptek PX2, with  $\tau = 20 \mu\text{sec}$  (the horizontal axis is  $20 \mu\text{sec/div}$ ). This is considered the shaping time it is the real component of the poles of the transfer function. The risetime is  $44 \mu\text{sec}$ , or  $2.2\tau$ . The pulse is slightly asymmetric, with a settling time slightly longer than its rise time. The FWHM is about  $50 \mu\text{sec}$ .

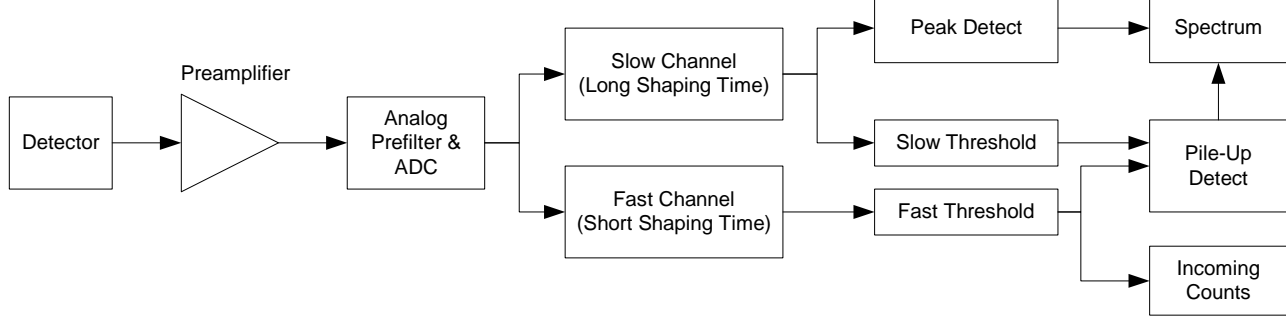
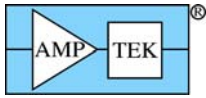


An oscilloscope trace of a digitally shaped pulse is shown below ( $20 \mu\text{sec/div}$ ). The risetime is well defined at  $51 \mu\text{sec}$ . The pulse is triangular, so is symmetric and has duration  $51 \mu\text{sec}$  (FWHM).



#### 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 peaking time of 0.4  $\mu$ sec. 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 much higher noise level and so the threshold must be higher. The “counts” in recorded by the DP5 are those in the spectrum, 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 typical 20 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. For example, one might configure the DP5 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. On the screen, this time is displayed along with the fast counts and the slow counts during the same interval.

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

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

<sup>3</sup> R.H. Redus, A.C. Huber, D.J. Sperry, “Dead time correction in the DP5 digital pulse processor”, presented at the 2008 IEEE Nucl. Sci. Symp. and submitted to the proceedings (2008).