OPERATING THE DP5 AT HIGH COUNT RATES

The DP5 with the latest firmware (Ver 6.02) and Amptek's new 25 mm^2 SDD are capable of operating at high rates, with an OCR greater than 1 Mcps. Figure 1 shows a spectrum measured at an ICR of 1.1 Mcps, about 50% dead time, with a resolution of 250 eV FWHM. With other settings, an OCR of $1x10^6$ cps was measured at 350 eV FWHM, and an OCR of $4x10^5$ cps at 220 eV FWHM. Figure 2 shows the measured and computed throughput and the resolution versus input count rate. The throughput matches the calculation very well and the resolution is very stable.

But there are some subtleties which show up at these high rates, starting at an ICR around 1 Mcps. This note was written to provide advanced users with the information necessary to understand these effects and optimize a complete system. This note complements another Amptek application note, AN-SDD-001, which describes operation below 1 Mcps. Most of the subtleties arise from the fact that, at a high rate, one needs very short pulse shapes. When T_{peak}, T_{flat}, and T_{fast} are on the order of the charge collection time in the detector, preamplifier risetime, and the signal processor's clock rate, some specific effects arise, including: (1) Ballistic deficit, a variation in peak amplitude seen if the charge collection time is variable and longer than the pulse flat top. (2) An increase in dead time due to non-zero risetimes. (3) Changes in the shape of the sum peak (due to pulse pile-up) when the flat top of the slow pulse is shorter than the pulse pair resolution in the fast channel. (4) Pulse pile-up into the ADC exceeding the ADC input range.

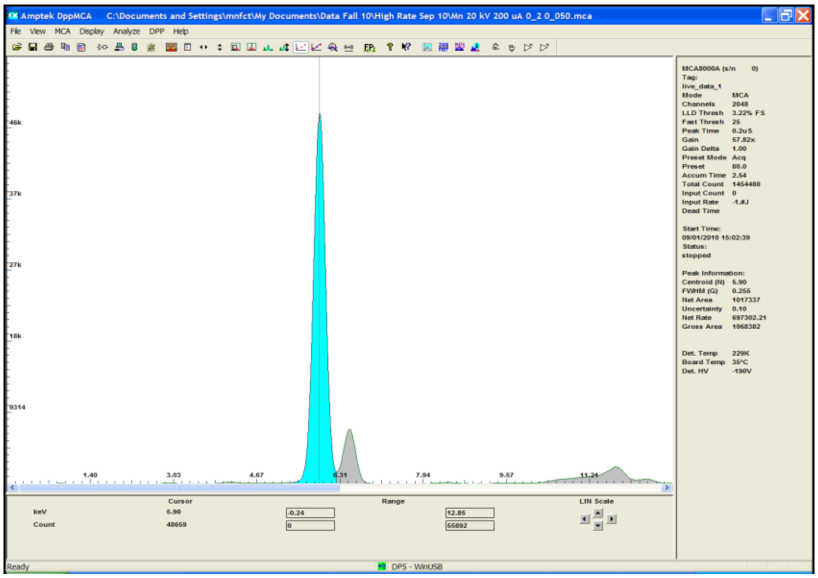

Figure 1. Spectrum taken at an ICR of 1.1 Mcps, and an OCR of 580 kcps, at 250 eV FWHM.

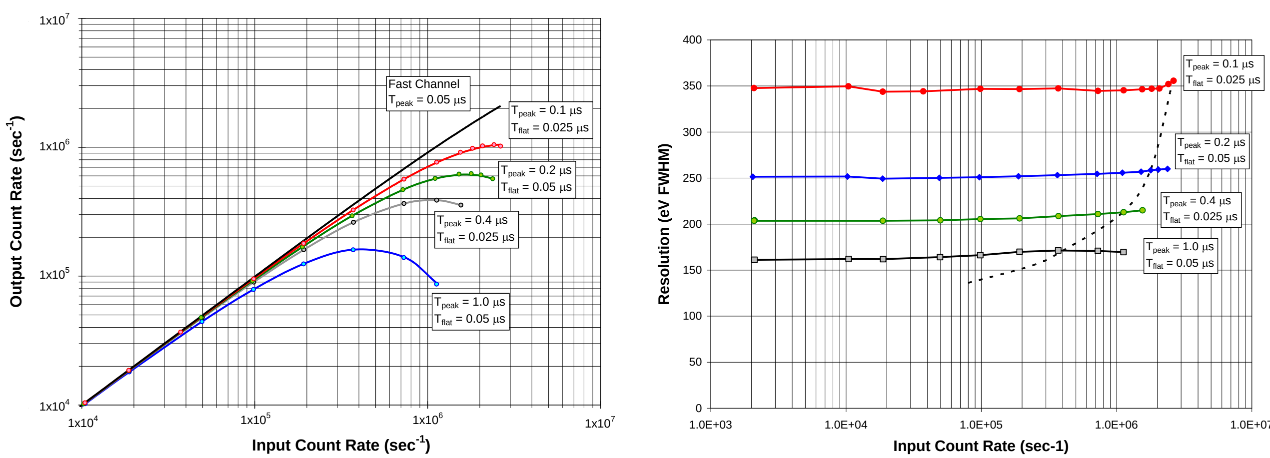

Figure 2. Plot of computed and measured throughput at the highest rates (left) and of resolution versus ICR (right). Data were taken with a collimated Amptek 25 mm^2 SDD and the DP5 with FW 6.02.

Ballistic Deficit

Every X-ray detector has a non-zero charge collection time and exhibits variations in this charge collection time, but the pulse shaping time is often long enough that one can ignore the charge collection time. In a planar detector, e.g. Amptek's 6 mm^2 silicon detector, the electrons (holes) take 0.1 (0.3) μs to cross the 500 μm depleted region. Depending on the depth of X-ray interaction, the transient current into the preamplifier ranges from 0.1 to 0.3 μs. If one uses a pulse shape with a T_{flat} <0.3 μs, only a portion of the charged is integrated and thus measured. The pulse height defect is termed ballistic deficit. In a silicon drift detector (SDD), there is also a variation in charge collection time. The physical mechanism responsible is different from that of a planar detector[1], and the risetime depends on the details of the electrode structure, bias voltages, etc. but all SDDs will exhibit varying charge collection times. Figure 3 shows oscilloscope traces taken with Amptek's drift detector. The green trace shows the pream, with risetimes from 40 to 200 ns (the slowly rising pulses originated near the outer edge of the electrically active area).

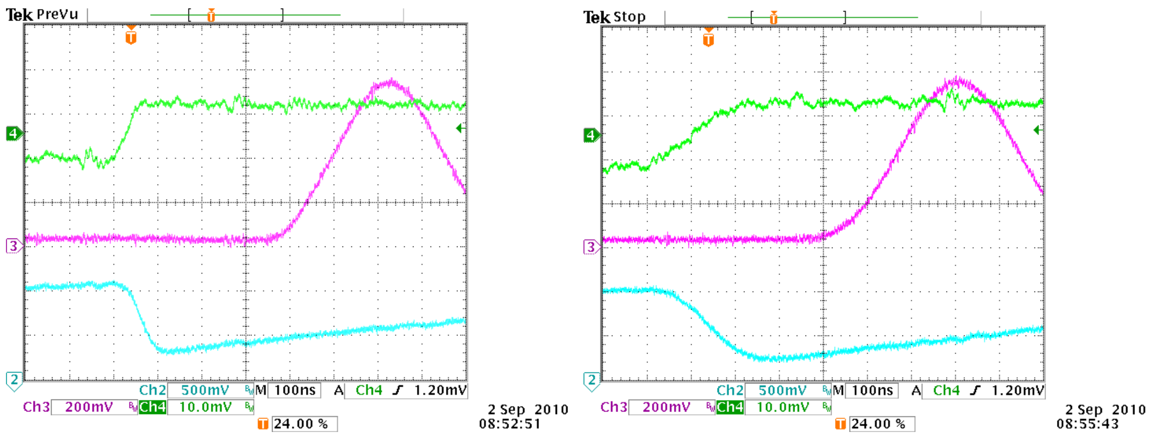

Figure 3. Oscilloscope traces illustrating risetime variations. The green traces show the preamplifier output, while the blue traces show the ADC input and the pink traces show the slow channel for a 100 ns peaking time and 50 ns flat top. The detector was uncollimated and an Ag target was used.

Figure 4 illustrates the effect of ballistic deficit on spectra. These plots were taken using a ^{55}Fe source at low rate and no external collimation. The plot on the left was taken at T_{peak} = 0.1 μs and T_{flat} from 0.025 to 0.2 μs. A longer T_{flat} leads to a narrower peak. The plot on the right was taken at T_{peak}=0.4 μs and the same range of T_{flat}. At the longer T_{peak}, even the short T_{flat} led to less ballistic deficit.

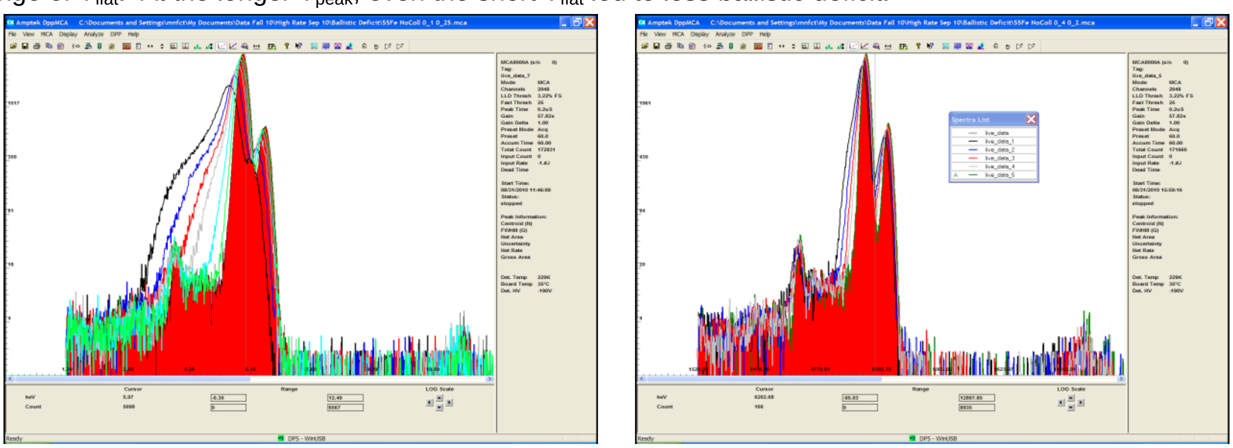

Figure 4. Spectra taken at T_{peak}=100 ns (left) and 400 ns (right) with a DP5 and a 25 mm2 Amptek SDD.

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[1] One need not understand the mechanism for what follows, but for those who are interested, the carriers drift radially towards the signal anode from the point of interaction. For events near the outer edge of the active area, the drift time can be quite long, due to the long path and weak radial field. However, the preamp does not measure this drift time: the inner drift electrode is a virtual ground, so that transient current is induced into the signal anode only after the carriers pass this inner electrode, and this transit time is independent of the initial position. As the carriers drift, however, the charge cloud spreads. It is this spread in the charge cloud which leads to the charge collection time and its variation.

To test the operation of the electronics and take the data in Figures 1 and 2, an external collimator of 1 mm radius was used. This reduced risetime variations to a range of 30 to 80 ns. This has an open area about 1/5th that of the 17 mm^2 area of the internal collimator so rejects 80% of the incident flux.

What can a customer do about ballistic deficit?

- Lengthen T_{peak} and T_{flat}. This will improve resolution but reduce maximum count rate. At $T_{peak} \geq 2$ µs, Amptek recommends $T_{flat} \geq 0.2$ µs because it does not have much effect on throughput.
- Increase the bias voltage. As a rule of thumb, the bias voltage must be doubled to cut the risetimes in half.
- Use an external collimator. If the flux is high enough, this is feasible: using an Amptek Mini-X, and ICR of 2 Mcps was achieved with a 1 mm collimator.
- In principle, one can use RTD to reject slow events. This is really electronic collimation because you are effectively reducing the active area.
- Use spectrum processing software which is tolerant of ballistic deficit, i.e. an assymetric tail.

Dead Time

Fast Channel

The fast channel can now be set to a minimum peaking time of 50 ns (no flat top) rather than 100 ns. But the actual pulse is longer because the input signal has non-zero risetime. The actual dead time for the fast channel will be longer than T_{fast}. The figure on the left below shows oscilloscope traces measured using an Amptek 25 mm^2 SDD and a DP5, where the black trace is the fast pulse for T_{fast} =50 ns and the pink trace is the fast pulse for T_{fast} =100 ns (the dark blue trace is the ICR output). The actual time it takes the pulses to rise are more like 100 and 150 ns. With T_{fast} set to 50 (100) ns, the pulse pair resolution was 100 (150) ns.

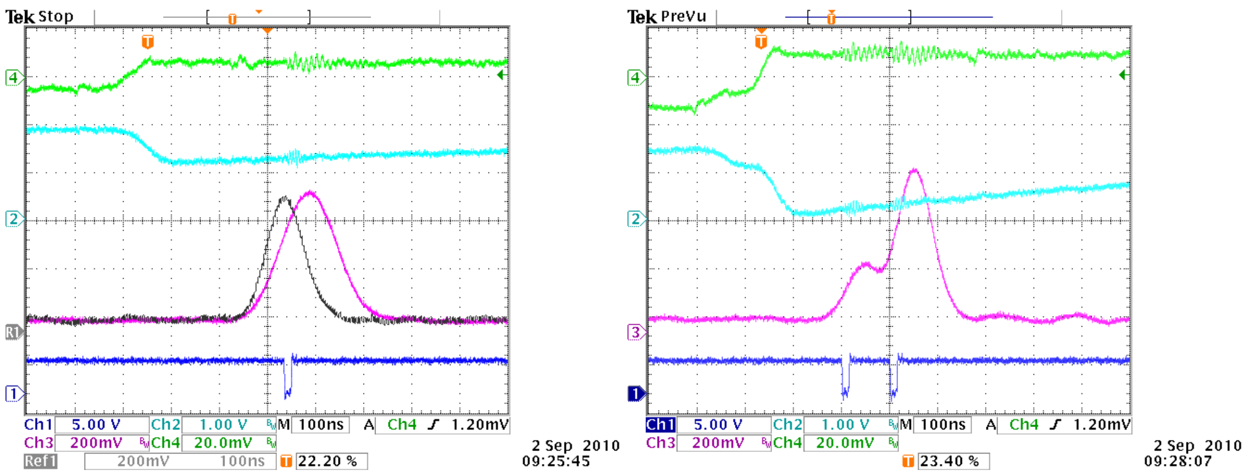

Figure 5. Oscilloscope traces showing fast channel operation. The green trace is the preamp output, the light blue trace is the ADC input, and the dark blue trace is ICR. On the left, the black (pink) trace shows the fast pulse for 50 ns (100 ns) T_{fast}. On the right, the pink trace is the fast output for T_{fast} of 50 ns.

Slow Channel

Eqn [2] of AN-SDD-001 describes the dead time in the slow channel, where F_{PD} is usually approximated as 0.05. This approximation requires two corrections to obtain the fit shown in Fig 2 above.

1. The F_{PD} value is no longer negligible. This value arises because the logic must wait for the shaped pulse to drop from its peak by a value equal to the slow threshold. At short peaking times, the noise can be a significant fraction of the pulse height. This correction was as much as 20% in Fig 2.
2. There is actually a third factor T_L, added to T_{peak} and T_{fast}. The logic takes two clocks (25 ns) after the peak to prepare for a subsequent pulse. This is negligible for longer peaking times, but with a peaking times and flat tops of a few clocks, it is not.

Pile-Up Rejection

There are a few issues surrounding pile-up rejection (PUR). First, PUR only functions if $T_{fast} < T_{peak}$. Second, if T_{fast} is slightly less than T_{peak}, it will not reject very much. For example, with T_{peak}=100 ns and T_{flat}=12 ns, the actual dead time is ~140 ns. With T_{fast}=50 ns, the fast channel pulse pair resolution is ~100 ns. In this case, PUR only rejects pulses which are between 100 and 140 ns apart.

Third, if $T_{flat}<T_{fast}$, the "sum peak" is not really a peak but exhibits a rather complex shape. Figure 5 illustrates the effect. All of these were taken with T_{peak}=0.4 μs and at an ICR of 1 Mcps. The orange trace shows PUR disabled, for T_{flat}=0.1 μs. On an oscilloscope, the pulse shape is the sum of two trapezoids, offset in time (this is actually shown in Fig 9 below). If the two events are separated by more than the flat top duration, then the peak amplitude depends linearly on the delay between the events, yielding an almost flat continuum. If the delay is less than the flat top duration, a true sum peak results. This orange trace yields the shape one expects for PUR disabled. The filled gray trace shows PUR enabled for T_{flat}=0.2 μs. The pile-up peak has the expected shape for a sum peak with no continuum.

The blue trace is for T_{flat}=75 ns and yields part of the continuum. When the flat top duration is shorter than the pile-up inspection interval, then pulses can pile-up but not give a sum peak. The green and red traces are for T_{flat}=25 and 50 ns. Spectrum analysis software is usually designed to correctly remove sum peaks but this partial continuum may not be handled quite so well. To get the nice sum peak, one needs to extend the flat top, which of course reduces throughput somewhat.

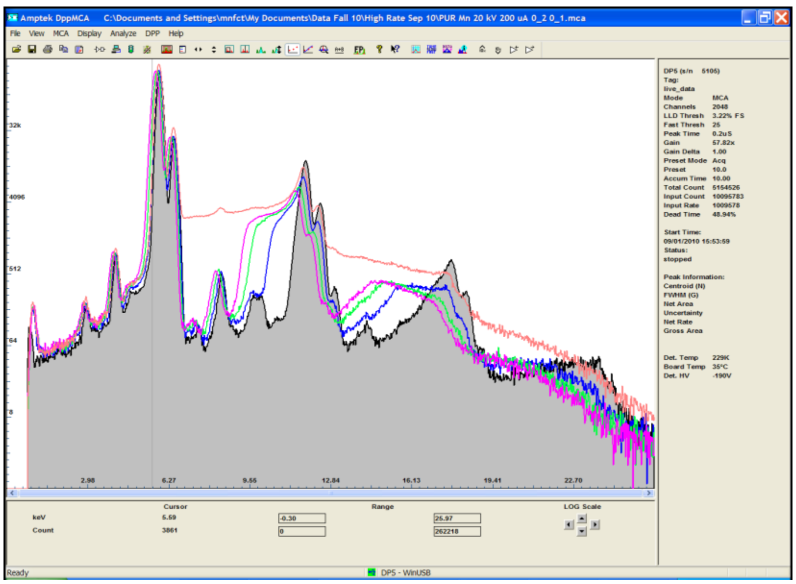

Figure 6. Spectra showing the effects of flat top duration on the shape of the pile-up events. The data were all taken for T_{peak}=0.4 μs and at an ICR of 1 Mcps. The orange trace is with PUR disabled. The filled spectrum is with T_{flat}=0.2 μs. The other traces are for shorter T_{flat}.

The ballistic deficit problem was best addressed by using T_{flat}>100 ns and this also helps reduce the pile-up artifacts. Amptek recommends T_{flat}>100 ns, and to use T_{flat}>200 ns for T_{peak}>2 μs or so, to help both of these effects. The customer may use other settings but should understand the consequences.

Thresholds

AN-SD-001 has a discussion of thresholds. The basic issues are the same for the fastest pulse shapes but "more so". At T_{fast}=0.05 μs, the fast threshold must be quite high due to the series noise. Ballistic deficit is also exceedingly important. Understanding and setting the fast and slow thresholds must be done with great care with the shortest pulse shapes.

Pile-Up into ADC

There is another spectral artifact which appears at the very highest count rates when high energy events are present. Figure 7 shows oscilloscope traces taken under normal operation, at a moderate count rate. The green trace is the preamp output and exhibits a series of steps. The blue trace shows the ADC input, measured at AMP3OUT on the DP5. The ADC has a nominal input range of 0 to 2V. With an SDD (positive polarity input signal), AMP3OUT has a baseline of ~1.9V, negative going pulses, which recover with a 3.2 μs time constant (a high rate configuration uses a 1.6 μs time constant). The pink trace shows the shaped pulses with a T_{peak}=0.4 μs. These data were taken using an Ag target at 30 kcps.

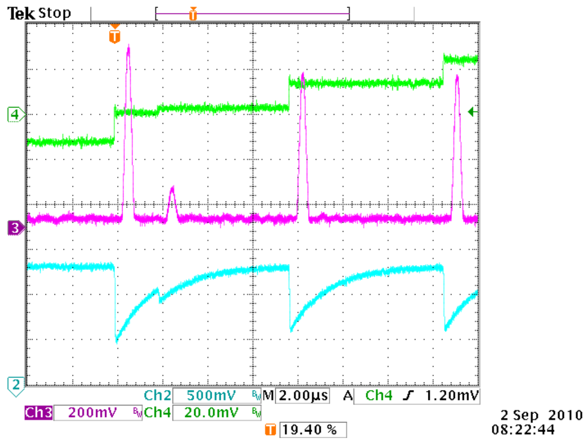

Figure 7. Plot showing normal DP5 operation. The green trace is the preamp output, the blue trace is the ADC input, and the pink trace is the shaped output.

Figure 8 shows what happens at higher rates. In the plot on the left, AMP3OUT has shifted more negatively. The signal never really returns to its baseline and goes negative during the largest pulses, but the signal processor handles this. In the plot on the right, AMP3OUT has shifted even more negatively. When the blue trace falls more than a diode drop below ground, the ADC input is clamped and this leads to the distorted shape in the pink trace and a strange artifact somewhere near the middle of the spectrum.

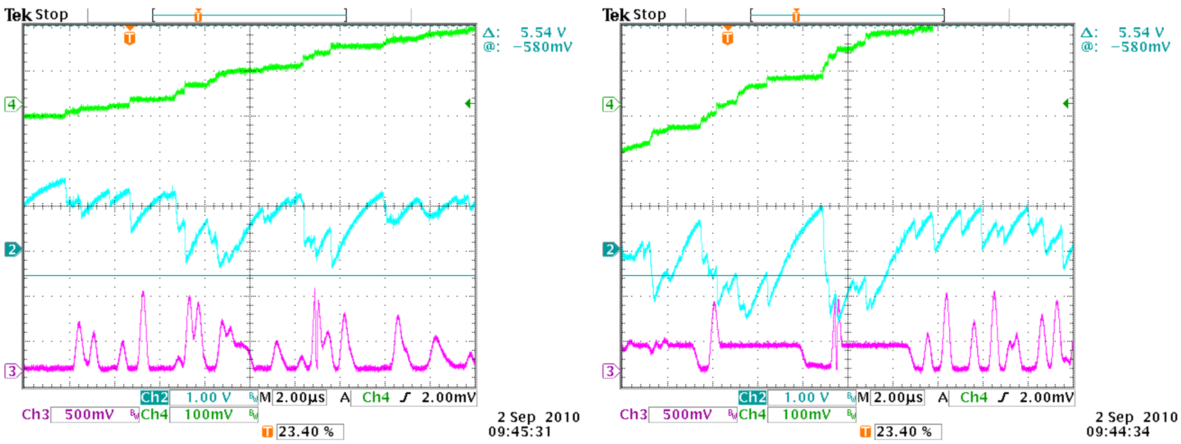

Figure 8. Plot showing the condition under which artifacts occur at high count rates.

Amptek's advice to the user is to be mindful of this. If artifacts begin to appear, use an oscilloscope to measure AMP3OUT. If this ever goes more than a diode drop negative, you will get artifacts. The simplest solution is to reduce the coarse gain. But be aware that it is not simply the count rate which causes this artifact, but the combination of large pulses and high count rates. If you see this effect and reduce the amplifier gain, it goes away. If you see this effect with the tube at 40 kVp and reduce the energy to 20 kVp, it goes away.

Pulse Shape Discrimination

Pulse shape discrimination (PSD) has two possible applications at these high rates. First, it can be used to improve pileup rejection. The standard PUR logic rejects pulses which overlap in the slow channel but are separated in the fast channel. As noted above, when T_{peak} is close to T_{fast}, this does not reject many piled up pulses. However, this condition will lead to a long duration pulse in the fast channel. Pulse shape discrimination can be used to reject these pulses, which look like they have a slow risetime. Second, interactions near the outer edge of an SDD give a long transient current, which results in ballistic deficit at short T_{flat}. These pulses will have a slow risetime, so pulse shape discrimination can reject them.

The biggest challenge in using PSD is that it will reject both pulses overlapping in time and pulses from the outer edge of the device. If one uses PSD to improve PUR, then one might also be rejecting valid events from a portion of the detector volume. PSD offers the possibility of improving performance but the user must be careful.

Pile-Up Rejection via Pulse Shape Discrmination

The operation of Pile-Up Rejection (PUR) is illustrated in Figure 9. Figure 9 (left) shows two pulses which are well separated in time. Both are counted and accurate pulse heights are detected. Figure 9 (middle) shows two pulses separated by a little more than T_{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 9 (right) shows two pulses separated by less than T_{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.

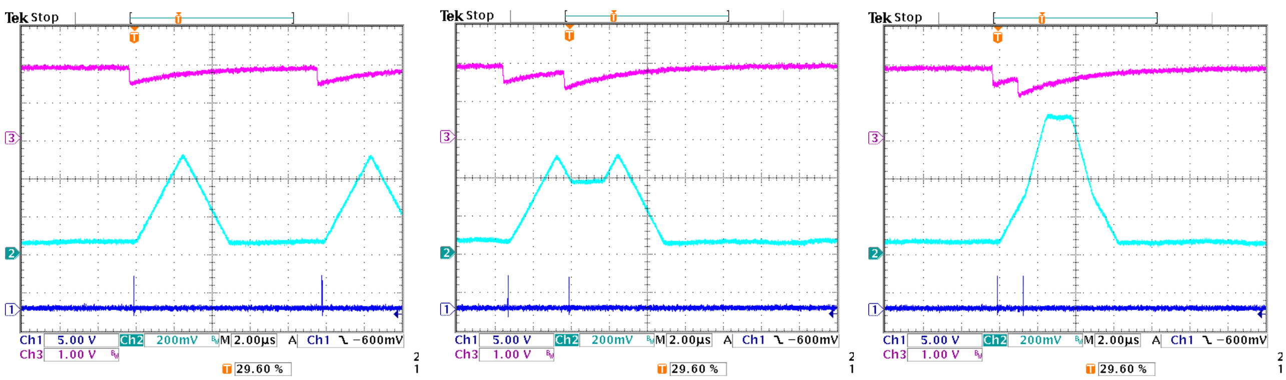

Figure 9. Oscilloscope traces demonstrating pulse pile-up. The pink trace is the ADC input. The light blue trace is the shaped output (here set to a peaking time of 2.4 µsec). The dark blue trace is "ICR", the logic signal indicating that a pulse was detected in the fast channel.

Figure 10 shows the fast channel operation, for pulses very close in time. Figure 10 (left) shows pulses separated by 240 nsec, with no overlap in the fast channel. Figure 10 (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 10 (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.

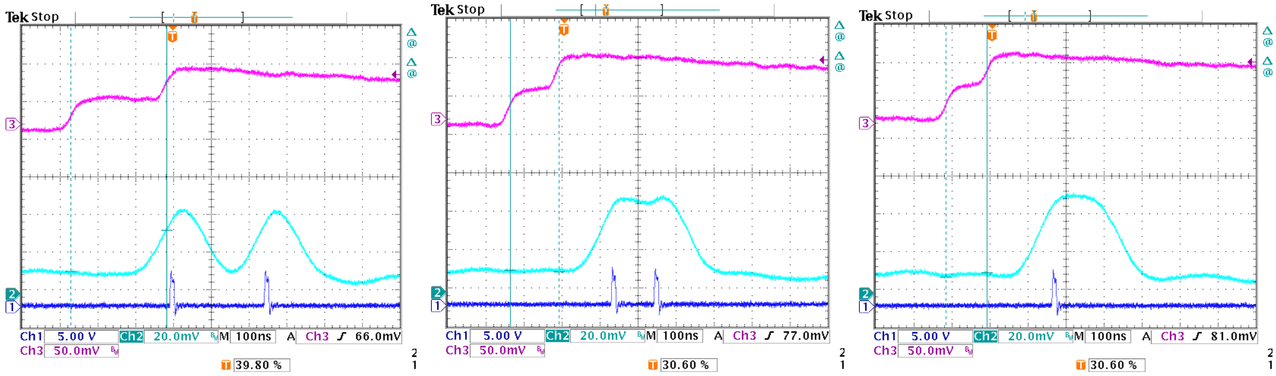

Figure 10. Oscilloscope traces demonstrating fast channel operation. The pink trace is the ADC input. The light blue trace is the fast output (peaking time of 0.1 μsec). The dark blue trace is “ICR”, the logic signal indicating that a pulse was detected in the fast channel.

Events such as those in Figure 10 (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 10 (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 “sensitivity” to their maximum values. At this setting, nothing should be rejected; record counts to verify. Then begun reducing the “sensitivity” until the slow count rate begins to fall. The system is now at the threshold of rejecting valid events as “too long”. Increase the “sensitivity” slightly, until you recover the initial rate. The system will now reject many events which are missed by PUR, reducing the sum peak considerably.