EXAMPLE: ACQUISITION TIME, LIVE TIME, AND ALL THAT

What is the difference between "real time", "accumulation time", and "live time" in Amptek's DPPs? How do you measure "dead time"? How do you measure "live time"? These questions are very frequently asked. Many users are accustomed to methods traditionally used in analog MCAs to measure these quantities. There are fundamental differences to the way these are measured in Amptek's digital processors.

Amptek has an application note entitled "Understanding acquisition time, live time, and all that" which defines and explains the various quantities. This application note gives two specific examples to illustrate how to accurate correct for deadtime, pulse pile-up, etc. The first application is a 13mm^2 SiPIN detector, used at 6.4 µs peaking time and count rates up to about 30 kcps. The second application is a 25mm^2 FastSDD, used from 4 to 0.1 µs peaking time and count rates up to 2 Mcps. A third section of this note provides examples and additional information to illustrate pile-up rejection, sum peaks, and other timing and counting related phenomena.

1. SiPIN example

The table below shows several important count rate related quantities, measured using a 13 mm^2 SiPIN detector and a Mn target, excited by a Mini-X X-ray tube. The tube had an Ag anode and was used with a W/Al filter and operated at 30 kVp. The beam current varied from 5 to 132 mA. We first present the table, then discuss and define the quantities. The other application note has more detailed definitions.

Raw Measurements						Uncorrected count rates			
Accum Time	Real Time	Total Cts	Input Cts	Net Cts	Sum Cts	Fast Rate	Total Rate	Net Rate	Sum Rate
189.98	**190.82**	**251,886**	**253,593**	**151,308**	**155**	**1,334.8**	**1,325.9**	**796.4**	**0.8**
44.09	44.61	253,498	272,253	149,634	255	6,174.9	5,749.6	3,393.8	5.8
25.82	26.36	267,427	311,735	157,909	778	12,073.4	10,357.4	6,115.8	30.1
16.58	17.24	287,497	393,787	166,452	1,328	23,750.7	17,340.0	10,039.3	80.1
13.49	14.19	277,012	419,204	160,551	1,515	31,075.2	20,534.6	11,901.5	112.3
185.65	**186.47**	**247,703**	**248,552**	**148,462**	**0**	**1,338.8**	**1,334.2**	**799.7**	**0.0**
45.10	45.63	258,435	276,938	153,868	466	6,140.5	5,730.3	3,411.7	10.3
25.82	26.36	267,354	311,350	157,032	1,175	12,058.5	10,354.5	6,081.8	45.5
17.10	17.79	293,079	400,717	168,012	2,278	23,433.7	17,139.1	9,825.3	133.2
13.48	14.19	272,465	412,476	153,810	2,932	30,599.1	20,212.5	11,410.2	217.5

Corrected & model count rates									
Fast correction	Input Rate	Live Time Fraction	Dead Time Fraction	Dead Time Correction	Model Dead Time Correction	Model Total Rate	Corrected Total Rate	Corrected Net Rate	Model Sum Rate
1.0007	**1,335.7**	**99.26%**	**0.74%**	**1.007**	**1.019**	**1,311.2**	**1,350.6**	**811.3**	**0.3**
1.0031	6,194.1	92.82%	7.18%	1.077	1.090	5,684.5	6,265.0	3,698.1	6.3
1.0061	12,146.7	85.27%	14.73%	1.173	1.183	10,264.6	12,256.4	7,237.1	22.1
1.0120	24,036.2	72.14%	27.86%	1.386	1.395	17,226.0	24,195.3	14,008.3	70.3
1.0158	31,565.6	65.05%	34.95%	1.537	1.549	20,380.3	31,804.6	18,433.4	109.7
1.0012	**1,340.4**	**99.54%**	**0.46%**	**1.005**	**1.020**	**1,313.5**	**1,361.6**	**816.1**	**0.6**
1.0056	6,174.7	92.80%	7.20%	1.078	1.098	5,624.3	6,291.0	3,745.6	11.5
1.0110	12,190.8	84.94%	15.06%	1.177	1.202	10,138.7	12,450.4	7,312.8	40.0
1.0215	23,938.6	71.60%	28.40%	1.397	1.436	16,668.8	24,614.0	14,110.4	124.8
1.0283	31,465.6	64.24%	35.76%	1.557	1.609	19,553.1	32,526.8	18,361.8	188.6

Directly measured quantities

The table lists some key directly measured quantities. These can all be read from the DPPMCA display.

- The **real time** is the time that elapsed between starting and stopping this data acquisition. It is what you would measure with a clock.
- The **accumulation time** is the time that the system was actually acquiring data; acquisition is gated off during preamp resets, data transfers, and other events. This is the meaningful time for determining count rates.
- The **input count value** is the number of pulses which exceeded the fast threshold while data were accumulated. The input counts are directly measured.
- The **total count value** is the number of pulses recorded in the spectrum. The total counts are directly measured.
- The **net counts** in the photopeak are not directly measured. The software does a linear fit to the background across a region of interest and then computes the difference between the gross counts in the ROI and the background counts in the ROI. These are net counts. For this example, we found net counts in the Mn K_α photopeak and in the sum peak.

Raw Count Rates

The raw count rates are obtained by dividing the directly measured raw counts by the directly measured accumulation time.

- The **fast count rate** is given by the input counts divided by accumulation time. It represents the raw count rate measured in the fast channel, where pile-up is minimal and there is only a lower threshold. It is not displayed in DPPMCA.
- The **total count rate** is given by the total counts divided by accumulation time.
- The net photopeak counts the net sum peak are found by dividing the appropriate net counts by accumulation time.

Input Counts

The input count rate is estimated from the fast count rate by making a small correction to account for dead time in the fast channel. The input count rate is given by

$$R_{input} = R_{Fast}\left(\frac{1}{1-R_{Fast}T_{Fast}}\right) \qquad [1]$$

where T_{Fast} is the pulse pair resolving time in the fast channel. This is approximately equal to the sum of the fast channel peaking time (which can be commanded to several values) and the typical pulse risetime, which depends on the detector. For the SiPIN here, we used fast channel peaking times of 0.4 and 0.8 µs and a risetime of 0.1 µs.

The fast channel correction factor is the term in parentheses in Eqn. [1]. Amptek strongly recommends that the fast channel peaking time be much shorter than the slow channel peaking time. We also recommend that the dead time in the slow channel be <70%. Under these conditions, the correction factor will generally be quite small, a few percent. This is why the raw fast channel count rate is a very good approximation to the true input count rate. The correction factor and the input rate are shown in the first two columns of the corrected and model results table.

DPPMCA implements the correction in Eqn. [1] and this is displayed as **input rate** but uses a fixed value of T_{Fast}, 0.1 µs for 80 MHz ADC clock (0.4 µs for 20 MHz). If you command the fast channel to a different value of T_{Fast}, the value displayed in DPPMCA is incorrect. DPPMCA also does not include the pulse risetime, which depends on the detection. If the correction factor is significant, we recommend computing the value directly, using the raw count rates.

Livetime and Deadtime

The livetime and its conjugate deadtime are computed from the difference between the input and total count rates. This is fundamentally different from an analog MCA, in which the total counts and livetime are directly measured and the input rate derived; in Amptek's DPPs, the count rates are directly measured and the livetime derived. This is because the count rates are the quantities of primary interest; livetime is only used in an analog MCA to obtain input count rates.

The livetime fraction is just the fraction of input counts which are in the spectrum. The deadtime fraction is one minus the livetime fraction. The deadtime correction factor is one over the livetime fraction. This deadtime correction factor is very important because it can be applied to any raw count rate.

$$F_{live} = \frac{R_{Total}}{R_{Input}} \qquad F_{dead} = \frac{R_{Input} - R_{Total}}{R_{Input}} \qquad F_{correction} = \frac{R_{Input}}{R_{Total}} \qquad [2]$$

The deadtime correction factor can be predicted theoretically as

$$F_{correct} = \exp\left(2 R_{input} T_{slow}\right) \qquad [3]$$

where T_{slow} is the deadtime per pulse in the slow channel. This will be given by

$$T_{slow} = \left(T_{peak} + T_{flat} + T_{rise}\right)\left(1+\delta\right) \qquad [4]$$

where T_{peak} is the peaking time in the slow channel, T_{flat} is the flat top in the slow channel, and T_{rise} accounts for the risetime of the detector signal. The term $(1+\delta)$ accounts for the fact that the pulse must fall from its peak before the peak detect counts a pulse. The value δ is the ratio of the slow threshold to the peak of the pulse, e.g.a slow threshold of 2% and a photopeak at ¼ full scale gives δ of 0.1.

The columns in the chart below labeled "Dead Time Correction" and "Model Dead Time Correction" are comparing the value found from Eqn [2], using actual counts, and that predicted by Eqn [3]. The agreement is quite good, which indicates that the pulse losses are well understood and predicted by theory.

Note that the correction factor increases rapidly as the livetime fraction falls. What this implies is that one must rely on the correction to obtain accurate results at high count rates. There will be errors and uncertainties in any correction, which is why keeping the livetime high is usually helpful.

Corrected total and net count rates

The corrected total and corrected net rates in the table below are found by multiplying the raw or uncorrected rates by the correction factor, using Eqn. [2]. DPPMCA uses Eqn. [2] to compute the net count rate in an ROI but notice that Eqn. [2] uses the input count rate, i.e. Eqn. [1]. Since DPPMCA uses a fixed value for T_{fast}, this correction is only approximate.

Model sum peak count rate

The sum peak rate is the probability of two photopeak counts occurring with the fast channel pulse pair resolving time, T_{Fast}. The true sum peak rate is the square of the true photopeak net rate but the sum peak rate actually measured must be scaled by the deadtime correction factor, which will apply to the sum peak. The model predicts this rate to be given by the equation below. The table below indicates pretty good agreement between the theory and the observations. It appears that the resolving time is slightly longer than the predicted value.

$$R_{sum\_m} = \left(R_{Net\_corr}\right)^2 \frac{T_{Fast}}{F_{correct}} \qquad [5]$$

2. FastSDD example

As a second example, another set of Mn spectra were taken but using a 25mm^2 FastSDD as the detector. This permits count rates up to several Mcps. A 30 kV Ag anode Mini-X was also used, but with no filter to obtain higher count rates. Spectra were recorded at beam currents from 1 to 130 mA, giving input count rates from about 10 to 1200 kcps. The peaking time, flat top duration, fast channel peaking time, and other parameters were varied and spectra taken over the range of current. In each case, the system data were acquired until 30,000 counts were recorded in the peak channel, so the acquisition times varied significantly.

The tables below show the direct counts, raw rates, corrected rates, and modeled rates for T_{Peak}=1.0 µs, F_{flat} = 0.2 µs, T_{Fast} = 0.05 µs, and a pulse risetime of 0.05 µs. These were computed using the same formulas as above. Similar data were taken for a variety of peaking times, flat tops, and fast channel times and are shown in the plots which follow.

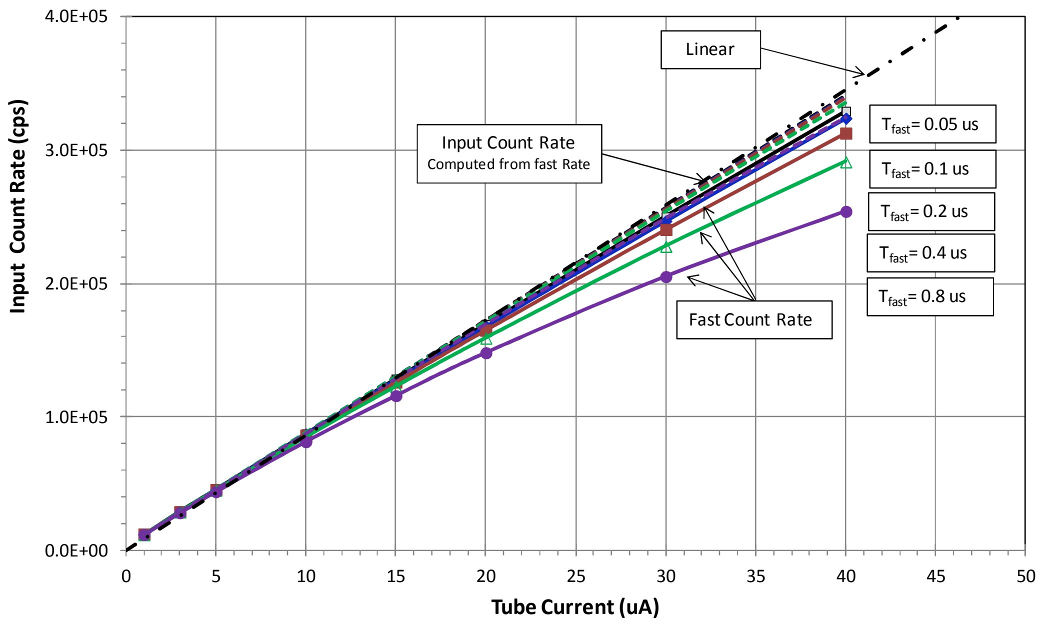
Raw measurement values				
Accum	Total Cts	Input Cts	Net Cts	Sum Cts
45.25	576,693	597,847	437,975	315
19.82	576,761	627,553	437,542	751
13.27	578,445	659,655	438,164	1,210
7.91	583,255	749,955	440,251	2,243
6.10	586,078	848,874	440,480	3,340
5.28	592,909	967,408	442,420	4,156
4.56	594,201	1,231,405	441,410	6,470
4.46	605,053	1,583,289	445,189	9,054
5.05	628,645	2,635,677	451,908	13,997
6.26	640,644	4,269,638	454,697	18,830
8.55	675,275	7,167,289	471,711	24,820
15.17	740,462	16,370,648	499,914	35,476

Raw count rates			
Fast Rate	Total Rate	Net Rate	Sum Rate
13,212.1	12,744.6	9,679.0	7.0
31,662.6	29,099.9	22,075.8	37.9
49,710.2	43,590.4	33,019.1	91.2
94,811.0	73,736.4	55,657.5	283.6
139,159.7	96,078.4	72,209.8	547.5
183,221.2	112,293.4	83,791.7	787.1
270,045.0	130,307.2	96,800.4	1,418.9
354,997.5	135,662.1	99,818.2	2,030.0
521,916.2	124,484.2	89,486.7	2,771.7
682,050.8	102,339.3	72,635.3	3,008.0
838,279.4	78,979.5	55,170.9	2,902.9
1,079,146.2	48,810.9	32,954.1	2,338.6

Corrected and model rates								
Fast correction	Input Rate	Live Time Fraction	Dead Time Fraction	Dead Time Correction	Model Total Rate	Corrected total rate	Corrected Net Rate	Model Sum Rate
1.0013	13,229.6	96.33%	3.67%	1.036	12,767.5	13,205.9	10,029.3	9.7
1.0032	31,763.2	91.62%	8.38%	1.089	29,164.3	31,693.1	24,043.0	53.1
1.0050	49,958.6	87.25%	12.75%	1.144	43,681.8	49,854.1	37,763.8	124.7
1.0096	95,718.5	77.03%	22.97%	1.293	74,007.6	95,367.7	71,985.2	400.7
1.0141	141,123.5	68.08%	31.92%	1.461	96,579.5	140,391.3	105,514.2	761.9
1.0187	186,640.9	60.17%	39.83%	1.651	113,022.7	185,436.4	138,369.9	1,159.4
1.0278	277,539.8	46.95%	53.05%	2.108	131,640.7	274,728.5	204,085.6	1,975.6
1.0368	368,063.7	36.86%	63.14%	2.689	136,877.3	364,796.1	268,411.5	2,679.2
1.0551	550,655.9	22.61%	77.39%	4.392	125,364.1	546,790.7	393,066.2	3,517.4
1.0732	731,975.2	13.98%	86.02%	7.151	102,366.9	731,778.0	519,379.3	3,772.5
1.0915	914,980.3	8.63%	91.37%	11.693	78,248.8	923,525.5	645,125.5	3,559.2
1.1210	1,209,689.4	4.03%	95.97%	25.817	46,856.0	1,260,161.0	850,782.5	2,803.7

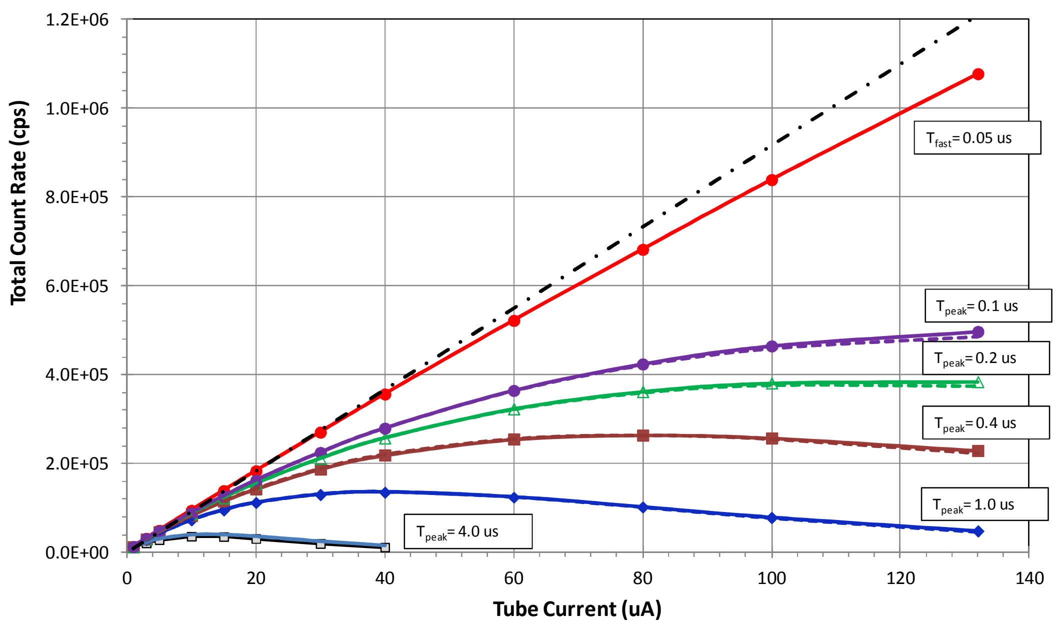
Fast channel count rate and correction

The plot below shows, in the solid lines, the raw fast count rate (fast counts divided by accumulation time) as the solid curves for T_{Fast} from 0.05 to 0.8 µs. The dashed curves show the input count rate, computed from the fast count rates using Eqn. [1]. The black dash-dot shows a linear extrapolation from low count rates. This shows the accuracy of the correction in Eqn. [1].

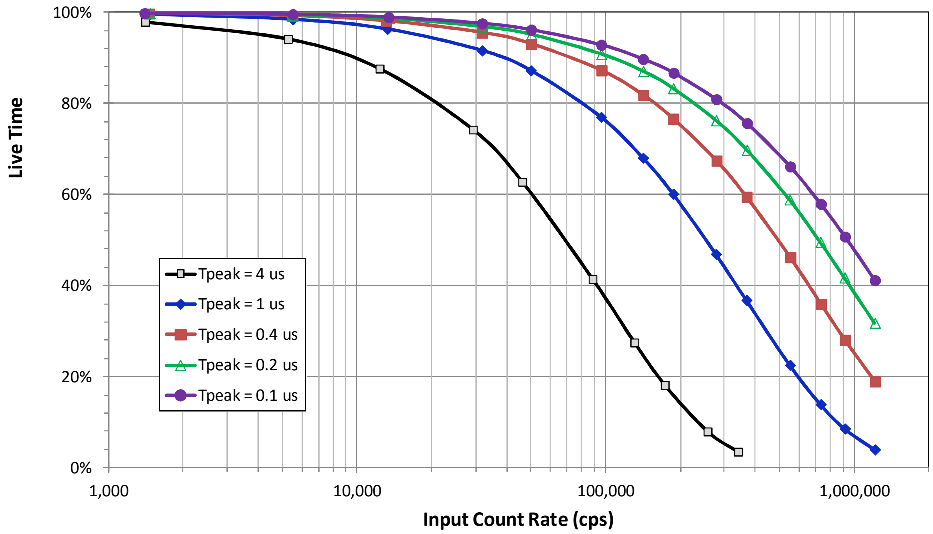


Total count rate correction and model

The plot below shows the raw total count rate as the solid lines, for T_{peak} from 0.1 to 4.0 µs. The dashed curves show the model total count rate, the inverse of Eqn. [3].The red line shows the raw fast rate and the dash-dot a linear extrapolation from low rates. The excellent agreement indicates the accuracy of Eqns. [3] and [4] and also indicates that the dead time characteristics are well understood.

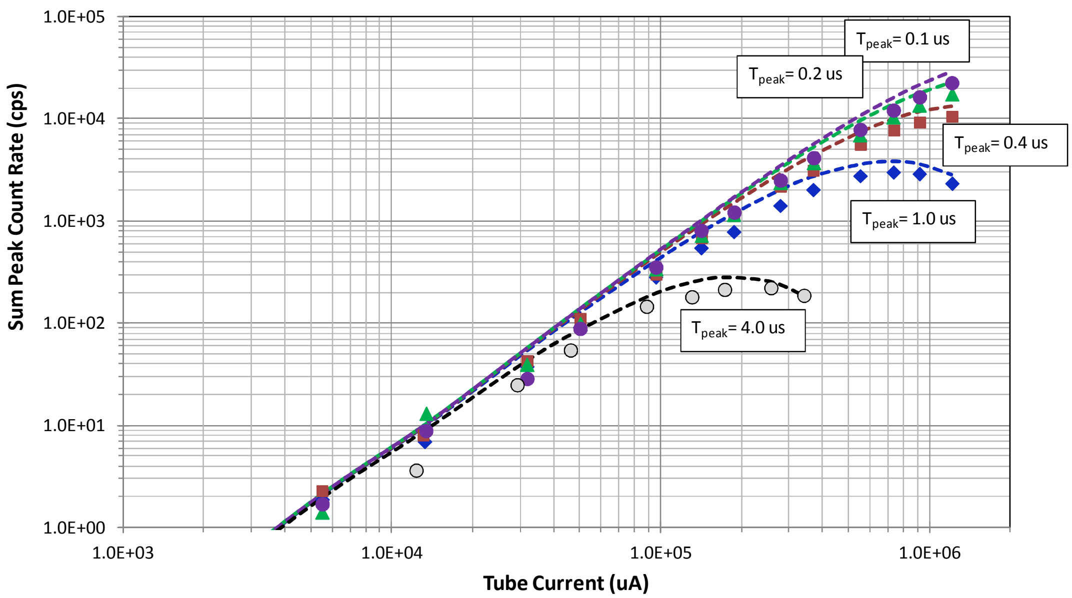


The plot below shows the live time fraction versus input count rate for the various peaking times corresponding to the data in the chart above.



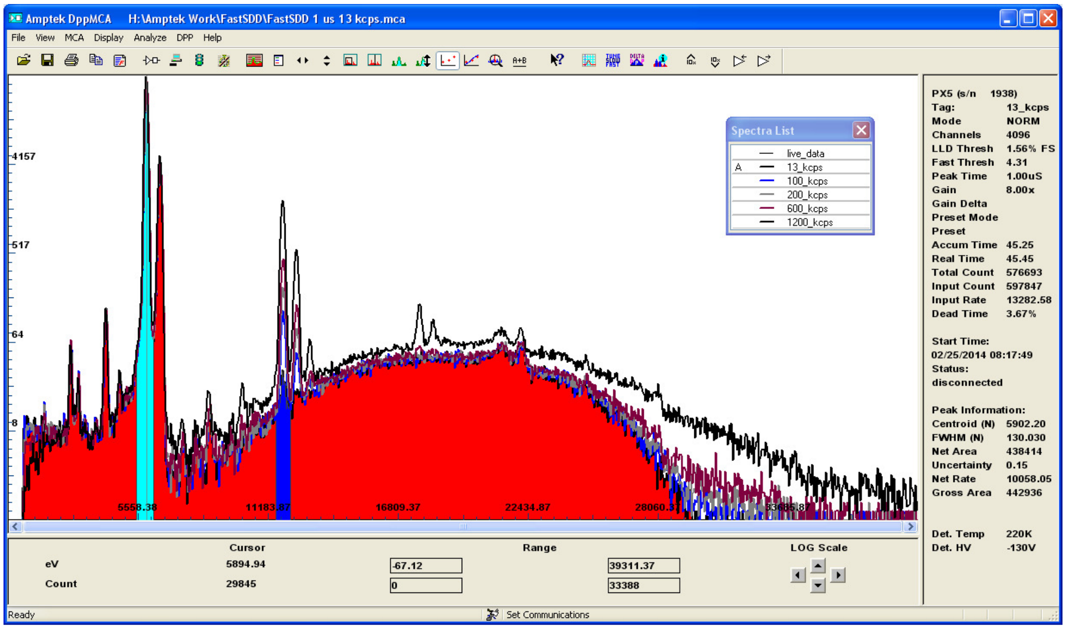
Sum peak intensity

The plot below compares the measured sum peak intensity with that computing using Eqn. [5], again showing good agreement. This implies that the sum peak properties are well understood. It also shows that Eqn. [5] can be used to accurately estimate the sum peak intensity, for corrections in analytical software.

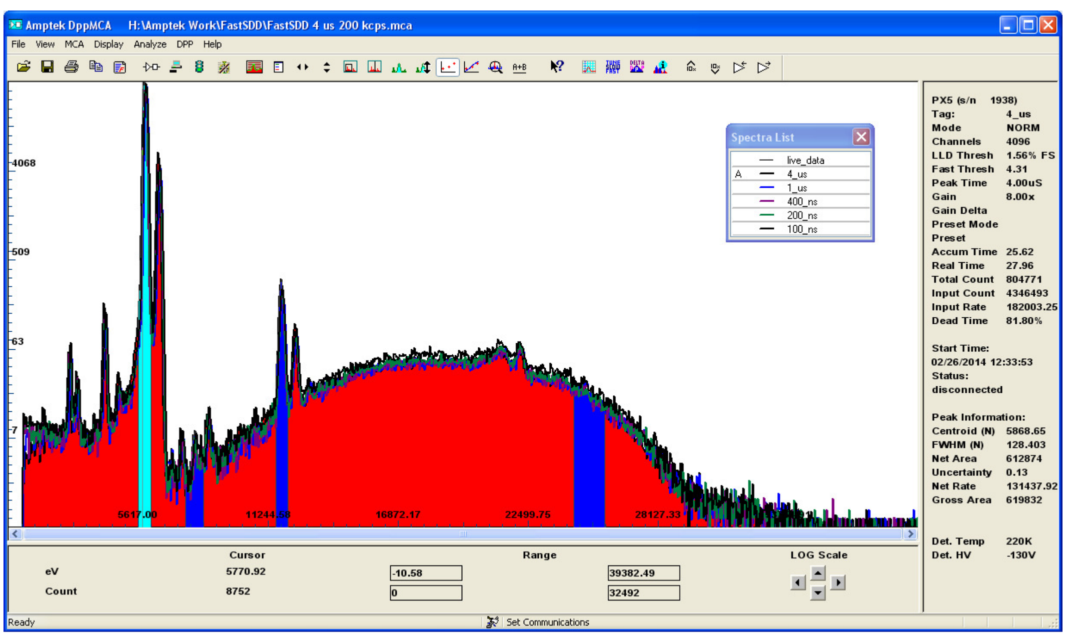


3. Spectra

The plot below shows spectra taken with the FastSDD at a T_{peak} of 1.0 µs, at input count rates from 13 to 1200 kcps. These are the spectra from which the tables above are derived. Data were recorded to a fixed number of counts in the peak channel. As the count rate increases, up to 1 Mcps, the only changes in the spectrum are an increase in the intensity of the sum peak and the continuum sum (this causes the tail above 30 keV). Above 1 Mcps, i.e. 95% dead time, the triple sum peak is visible.



The plot below shows spectra taken at 200 kcps with the FastSDD, with peaking times from 0.1 to 4.0 µs with a fixed T_{Fast} of 50 ns . Note that there is negligible change to the overall spectrum, and in particular, that the sum peak intensity is constant. The only changes are in the resolution of the photopeak and also in the acquisition time (not shown in the plot but the data were taken to fixed photopeak counts and thus for accumulation times from 4.5 to 25 sec).



The plot below illustrates some subtleties in the sum peak. These data were all taken with the FastSDD at T_{peak}=4.0 µs, T_{flat}=0.2 µs, and an input count rate near 50 kcps. The black trace shows pile-up rejection disabled. The continuum, a straight line from the primary peak to the sum peak, is arises because the pulse sums two trapezoids with a variable delay. The peak of the summed shape is proportional to the delay, due to the linear rise of the trapezoid. The "bump" at the sum peak arises from the flat top.

The filled red trace shows standard pile-up rejection parameters, with T_{fast} = 0.1 µs. Pulses which occur within the fast channel resolving time show up in the sum peak, as expected. The blue trace shows the spectrum for T_{fast} =0.4 µs, while the green trace shows T_{fast} =0.8 µs. The sum peak intensity increases, as one expects from Eqn. [5]. But is also broadens and becomes non-Gaussian with a tail to lower amplitudes. This occurs because the $T_{fast} > T_{flat}$. With this condition, the summed pulse can fall from its peak value and yet be within the pulse pair resolving time of the fast channel. The amount that it falls depends on T_{fast}, and T_{flat}, and also on T_{peak}. We recommend using $T_{fast} \leq T_{flat}$ to obtain a more symmetric sum peak. Note that the FWHM of the sum peak is about √2 the width of the primary peak, since this is essentially a single X-ray deposition with twice the energy.