General Purpose Pulse Shape Analysis
Firmware for Mixed Field Radiation
Introduction

In some radiation detectors, analysis of pulse waveforms can provide additional information besides commonly obtained MCA pulse height spectra. Neutron/gamma pulse shape discrimination (PSD) is one form of such pulse shape analysis (PSA). It employs the observation that in certain liquid scintillators light pulses display different pulse decay characteristics depending on whether the energy deposited originates from a neutron or photon. Other PSA applications include particle discrimination, phoswich detectors, and determining points of interactions in a detector.

Capturing waveforms and applying offline PSA becomes increasingly cumbersome and time consuming as event rates increase. At some juncture it becomes advantageous to incorporate the analysis within the data acquisition system. Though the precise reduction in processing time going from online to offline processing is algorithm-dependent, reduction factors of 10-100 are possible, resulting in corresponding increases in throughput. Neutron/gamma PSD is one analysis that can be readily incorporated into firmware, but many other applications can be served with the same or similar algorithms.

XIA’s Pixie spectrometers feature an on-board DSP for its standard pulse processing for energy reconstruction. The DSP code can be customized by the end user and is capable of extracting pulse characteristics from recorded waveforms. A user DSP template for pulse shape analysis has been developed for the Pixie-500 and Pixie-500 Express, specifically targeting PSA for fast scintillators using waveforms captured at 500 MHz. We show results from several applications of the PSA, including a pulser, a phoswich detector, a CLYC scintillator, a liquid organic scintillator, and crystal stilbene. All analyses were performed using the same generic algorithms with application-specific optimized PSA parameters.

PSA definitions and approach

![PSA parameters and results.](image)

The PSA algorithms implemented on the Pixie spectrometers are a version of the digital charge comparison method, in which 2 sums are accumulated over characteristic regions of a scintillator pulse. Figure 1 defines four input values (black) that are specified by the user prior to the start of a run. In this figure the DSP parameters S0 and S1 refer to the starting point of the sums referenced to the trigger T and L0 and L1 are their lengths. Figure 1 also shows the output values (red): PSA sums Q0 and Q1, a baseline sum B, and the amplitude A. For the Pixie-500, the DSP additionally computes the 10-90% rise time RT of the pulse. For both Pixie-500 and Pixie-500 Express, the DSP also computes a PSA ratio R1 = Q1/Q0.
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(or other appropriate quantity) to which expresses the difference of the pulse shapes from the scintillator. These values are stored, together with timestamps and the overall pulse height E from the digital filter as part of the list mode data header in on-board memory (storage of the full waveform is optional).

The key difference between the PSA implemented in the Pixie-500 and the Pixie-500 Express is that the Pixie-500 exclusively uses its DSP to process the waveforms, whereas in the Pixie-500 Express, time consuming operations like finding maxima and accumulating sums are performed in an FPGA. This allows much higher throughput for the Pixie-500 Express, as the basic PSA values are available “as the pulse comes in”. The DSP only performs the more complex math on the intermediate results, such as computing the ratio R1.

The Pixie Viewer software was expanded to show control fields to specify the PSA input parameters. During the data acquisition, the PSA results are stored in the binary list mode data file, and can be extracted as a text file. To facilitate user analysis, a number of utilities have been added to the Pixie Viewer to list parameters, to compare them with offline computations from captured waveforms, and to plot one parameter against another. These utilities have been used to generate the plots below. They can be easily customized by the end user.

DSP based PSA in the Pixie-500

PSD - XIA PDM programmable pulser

As a first test, a mixed neutron-gamma field was simulated by programming the FPGA of an XIA PXI-PDM to produce randomly triggered pulses with differing rise and decay times but identical amplitudes. A typical waveform is shown in the inset of the PSD plot – disparate decay times were chosen to test the robustness of the analysis. List mode data was acquired and PSA parameters were computed in the DSP then plotted using IGOR software.

The PSD plot is a scatter plot of the pulse rise RT vs. R1 = Q1/Q0 for ~200,000 PDM pulser events. The events are cleanly separated by RT and PSA value, with the slower pulses giving the higher PSA value, as expected. The second cluster of points below RT of 300 with the higher PSA values represent overlapping pulses where PSum is augmented by the presence of the short decay time pulse.

Neutron/gamma discrimination with CLYC

In studies with the scintillator Cs₂LiYCl₆:Ce (CLYC), a CLYC crystal was illuminated with an AmBe source producing a mixed neutron-gamma radiation field. Paraffin blocks were used to moderate the fast neutrons. CLYC detects thermal neutrons through the interaction with Li, which imparts ~4.8 MeV to the reaction products. The scintillator light output is equivalent in magnitude to a 3.2 MeV photon.

Figure 3 shows a scatter plot from the CLYC measurements plotting the ratio of R2 = Q0/E, colored by the rise time. Neutrons appear with a defined energy in the plot, separating both in RT and R2 from the horizontal band of photons with varying energy. A third major type of pulse shape, ascribed to Core-to-Valence-Luminescence events, forms a group of fast rising pulses with low E.

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Fig. 3: (inset) Waveforms from CLYC Scintillator. (main) Scatter plot of $R2=Q0/E$ vs $E$, colored by rise time $RT$.

**XIA PhosWatch PSA**

A third application is XIA’s PhosWatch detector. It is a Plastic/CsI phoswich detector, designed for detection of beta/gamma coincidences from radioxenon. Interactions in the CsI scintillator create pulses with a slow rise time and a slow decay. Interactions in the plastic scintillator create fast pulses. Simultaneous interactions in both scintillators, corresponding to beta/gamma coincidences from radioxenon, create mixed pulse shapes. For the PSA studies we illuminate the phoswich detector with an externally placed $^{137}$Cs gamma-ray source.

Fig. 4: (inset) Waveforms from XIA PhosWatch. (main) Scatter plot of $Q0$ vs $E$, colored by rise time.

Figure 4 shows a scatter plot of $Q0$ vs $E$ from these measurements, colored by RT. Most events are interactions only in the CsI. For this pulse shape, there is a fixed proportionality of $Q0$ vs $E$ and in the
scatter plot the events fall on a straight line that also has a large rise time. Another set of events interact only in the plastic scintillator. These pulses have a different proportionality of $Q_0$ vs $E$ and fall on a straight line with a different slope (and short rise time). Compton events that deposit energy in both the plastic and CsI have a short rise time also, but no fixed proportionality between $Q_0$ and $E$, since they are a linear combination of the pure event pulse shapes. Thus they fall on the region in between the pure events. A broad diagonal line is recognizable which corresponds to a fixed energy of 662 keV distributed between plastic and CsI by Compton scatter. This analysis can be extended further to extract the energy deposited in each Scintillator and plot them in separate histograms.

**Neutron/gamma discrimination with liquid scintillator**

Liquid organic scintillators are increasingly studied for neutron/gamma PSD applications. In our tests, a liquid scintillator has been exposed to an AmBe source. The results are shown in Fig. 5. The Pixie-500 PSA brings out the subtle differences in pulse shape between neutron and gamma interactions, resulting in two distinct groups in a plot of $R^2 = Q_0/E$ vs $E$. For clarity, the scatter plot has been converted into a 2D histogram with 256 x 256 bins where each bin is colored by the (log) of the number of counts.

![scatter plot](image)

*Fig.5: (inset) Waveforms from liquid scintillator. (main) 2D histogram of $R^2 = Q_0/E$ vs $E$, colored by intensity.*

**FPGA based PSA in the Pixie-500 Express**

**Alpha/gamma discrimination with Stilbene**

A material more recently developed for pulse shape analysis is crystal Stilbene. While the main purpose of the materials development is neutron/gamma discrimination, in our work we explored it as a gamma/alpha discriminator. Being a solid rather than a liquid, it requires no container, and so an alpha source ($^{241}$Am) is easily brought in close enough contact with the scintillator. A $^{137}$Cs source was added to increase the photon rate.
Fig.6: 2D histograms of Q1/Q0 vs E for crystal Stilbene, colored by intensity, for online and offline processing of the same data.

PSA scatter plots for online and offline computations are shown in Fig.6. Alphas excite more of the slow scintillation process and therefore have relatively higher Q1, populating the upper group of events in the scatter plots. Online and offline scatter plots for the Pixie-500 Express (using the same data) look almost identical. The Figure of Merit of the separation (FoM)\(^1\) is 2.323 for the Pixie-500 Express online computation, and 2.318 for the Pixie-500 Express offline computation.

**Alpha/beta/gamma discrimination with Stilbene/Csl phoswich**

Fig.7: Waveform examples from a Stilbene/Csl phoswich detector for four different event types. Waveforms are smoothed after 1.1us for clarity (thin lines show original data). Note the slower decay of the alpha waveforms (purple) than the beta (green).

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\(^1\) FoM = (distance of centroids) / (sum of widths)
A phoswich was assembled with a 1 mm thick crystal Stilbene disc optically coupled to a 2” CsI(Tl) crystal. The Stilbene is one end of an otherwise Aluminum cell holding radioactive gas samples. Filled with a Rn source (including daughters), we observe 4 types of signals from this detector (Figure 7):

1) gammas interacting in the CsI, generating a slow rising pulse with ~1 us decay
2) betas (or gammas) interacting in the Stilbene, generating a fast rise followed by a fast decay
3) alphas interacting in the Stilbene, generate fast rise and a slightly slower decay
4) gamma/beta coincidences in CsI and Stilbene (or gammas scattering between CsI and Stilbene) generating a mixture of the respective pure pulses, the relative contribution proportional to the deposited energy in each scintillator.

The ratios Q0/E and Q1/E were computed offline and are plotted in Figure 8 (left). The 4 event types fall into well separated groups, with CsI/Stilbene coincidences connecting the groups of pure CsI events and pure Stilbene beta (or gamma) events. In contrast, exposing the detector to an external Cs source (no alphas) results in a similar plot, but without the alpha events, see Figure 8 (right). The detector and PSA thus allow a 2-layer phoswich to detect alphas, betas and gammas, while in the past 3 layers have been used for such purposes.

Summary

The measurements and analysis described above demonstrate the online PSA capability for the Pixie-500 and Pixie-500 Express using a general purpose code – adaptation to the different applications is limited to tuning input parameters and selection appropriate PSA ratio. This demonstrates that a general purpose PSA FPGA implementation is feasible and readily adaptable to other fast scintillators, while allowing 1-2 orders of magnitude higher throughputs. Implementation in the DSP is comparatively easier, since sequential programming is used, but processing is slower, especially where sample by sample operations on buffered waveforms are performed. Implementation in the FPGA is more complex and requires great care to debug errors and adapt to device limitations, but is much faster as data can be processed in true real time. In practice, a combination of FPGA, DSP and offline processing seems to be the most rewarding – the FPGA performing the simpler, but time consuming operations such as summing and finding maxima, while computation of ratios and acceptance decisions can be performed by a DSP or offline. This also allows more flexibility for varying criteria in different applications.

One simple extension of this work would be the introduction of a threshold for accepting events (e.g., those above a certain PSA ratio threshold) and building neutron and gamma histograms by the DSP in on-board memory.
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