Digital Pulse Processing: New Possibilities in Nuclear Spectroscopy†

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Abstract

Digital pulse processing is a signal processing technique in which detector (preamplifier output) signals are directly digitized and processed to extract quantities of interest. This approach has several significant advantages compared to traditional analog signal shaping. First, analyses can be developed which take pulse-by-pulse differences into account, as in making ballistic deficit compensations. Second, transient induced charge signals which deposit no net charge on an electrode can be analyzed to give, for example, information on the position of interaction within the detector. Third, deadtimes from transient overload signals are greatly reduced, from 10's of μs to 100's of ns. Fourth, signals are easily captured, so that more complex analyses can be postponed until the source event has been deemed "interesting". Fifth, signal capture and processing may easily be based on coincidence criteria between different detectors or different parts of the same detector.

XIA's recently introduced CAMAC module, the DGF-4C, provides many of these features for four input channels, including two levels of digital processing and a FIFO for signal capture for each signal channel. The first level of digital processing is "immediate", taking place in a gate array at the 40 MHz digitization rate, and implements pulse detection, pileup inspection, trapezoidal energy filtering, and control of an external 25.6 μs long FIFO. The second level of digital processing is provided by a digital signal processor (DSP), where more complex algorithms can be implemented.

To illustrate digital pulse processing's possibilities, we describe the application of the DGF-4C to a series of experiments. The first, for which the DGF was originally developed, involves locating gamma-ray interaction sites within large segmented Ge detectors. The goal of this work is to attain spatial resolutions of order 2 mm σ within 70 mm x 90 mm detectors. We show how pulse shape analysis allows ballistic deficit to be significantly reduced in these detectors. A second experiment involves studying exotic nuclei by observing their 1 MeV direct proton decays following implantation in a Si crossed stripe detector at 35 MeV. Whereas the implantation paralyzes analog electronics for almost 10 μs, the DGF allows the study of decay times as short as 1 μs. Initial energy and time resolution results are presented. Finally, we show how the DGF's precise timing and coincidence capabilities lead to significant experimental simplifications in dealing with phoswich detectors, low background counting work, and trace Pb detection by coincident photon detection.

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1. The digital approach to spectroscopic pulse processing

1.1. Pulse processing goals in spectroscopy

At the conceptual level, digital and analog signal processing share several common goals, which include: 1) to extract information of interest (pulse height, pulse shape, arrival time, etc.) from an incoming data stream; 2) to suppress non-essential information (i.e. "noise"); 3) to reduce the incoming data stream to a manageable level; and 4) to sort or present the extracted data in a manner that makes it intelligible. Each of these functions is present in all spectrometers, whether one is dealing with a single, simple γ-ray detector used in a counting experiment or with an array of 100's of detectors with anti-Compton shields in a large nuclear physics experiment.

1.2. Comparison: digital to analog

The typical modern analog spectrometer simultaneously processes the preamplifier signal using a fast channel and a slow channel. The fast channel detects pulses and provides pileup inspection while the slow channel provides energy resolution. When a valid pulse is detected, the slow channel peak is captured, stretched and digitized by an analog-to-digital converter (ADC) and binned by a multichannel analyzer (MCA) for inclusion in a spectrum. Topologically, a digital pulse processor (DPP) is similar. The major difference is that, after signal conditioning, the preamplifier signal is digitized immediately and all fast and slow channel operations are carried out in digital filters.

This distinction provides several immediate benefits. First, all channels are working with identical copies of the signal, whose fidelity can be maintained indefinitely. Second, there is no deadtime penalty incurred by the digitization step, as there is in the analog case. Third, pulse shapes are easily captured and stored for analyses, immediate or delayed, which are difficult or impossible to implement in analog circuitry. Finally, if the system is overloaded, it recovers with the speed of the signal conditioning circuit, rather than of the slow energy filtering circuit.

A second distinction is that DPPs have an enhanced ability to delay signals while accurately preserving time information between different filtering operations. A digital delay line, for example is just a first-in-first-out (FIFO) memory which can easily be 10's on µs long with perfect signal fidelity. Time information can be preserved because all filters run synchronously on a common clock and require a fixed number of cycles to execute. For example, since the time between the firing of a fast channel discriminator and the arrival of the signal peak in the slow channel is a known number of clock cycles, "peak capture" in the DPP is simply implemented using a register gated by a counter.

Several approaches for DPP implementation have been developed. The earliest was to stream data through a FIFO and, when a pulse was detected, to load the FIFO contents into a digital signal processor (DSP) to apply the desired filtering algorithms. This approach is capable of the highest resolution but is inherently slow due to the number of processing operations required per pulse. A second approach was to implement all digital filtering in hardwired logic, using, for example, digital multiplier chips to implement the filters. This approach is capable of very high throughput rates but the required circuits were complex, expensive and extremely power hungry. XIA's patented approach, developed to provide high throughputs at low cost in multichannel applications, divides the filtering into two steps. In the first step, a Real Time Processing Unit (RTPU) implemented in combinatorial logic, processes the preamplifier signal at the ADC data rate using no operations more complex than addition or subtraction. In the second step, signal values output by the RTPU are captured and refined at the event rate by a DSP to produce good energy values. In its present state, this approach is comparable to the best analog amplifiers in energy resolution and capable of output count rates in excess of 500,000 cps.

A final advantage to digital pulse processing is flexibility. In the XIA case, for example, the RTPU is implemented using a field programmable gate array (FPGA) whose firmware is loaded at startup, as is the DSP's software. This means that digital processing algorithms in either the firmware or software are readily modified, so that enhancements can be added or special applications accommodated without any hardware reconfigurations or rework.

1.3. Areas of new capability

As a result of these development, several areas of new capability are now available. These include the following, whose uses will be examined in greater detail in the following sections on applications.

1) Pulse specific corrections to provide ballistic deficit correction and particle identification.
2) Transient signal analysis to analyze induced charge signals to provide photon interaction location information.
3) Improved transient response to eliminate slow filter overload responses.
4) Hierarchies of processing complexity which readily supports simple-fast vs. complex-slow decision making on an event by event basis.
5) Complex coincidence criteria are readily supported so that criteria for capturing and/or processing data can be immediate or delayed.
6) Digital communication enhances operating convenience by allowing remote operation, instrument self calibration, and restoration of previous setups from files.

2. The DGF-4C as an illustrative instrument

2.1. Development history

The DGF-4C (or DGF) was developed under a DOE SBIR Phase I grant to provide instrumentation support for the GRETA (Gamma-Ray Energy Tracking Array) project at Lawrence Berkeley National Laboratory (LBL). (Deleplanque, 1998, Fallon, 1998) This project's goal is to improve efficiency in large Ge detector arrays by reducing Compton scattering losses. Its approach was to capture and analyze induced charge signals (Raudorf, 1982) on multi-electrode large Ge detectors to locate Compton scattering interaction points. Figure 1 shows the schematic of such a detector. An interaction occurs within the detector at radius R, angle θ, and axial position z. A "collection cathode" captures the generated charge, while its nearest neighbor "spectator cathodes" see transient induced charge signals which can be used to determine θ and z. Figure 2, for example, shows model curves for induced charge versus time on the spectator anode S_Z, showing how the shape of these

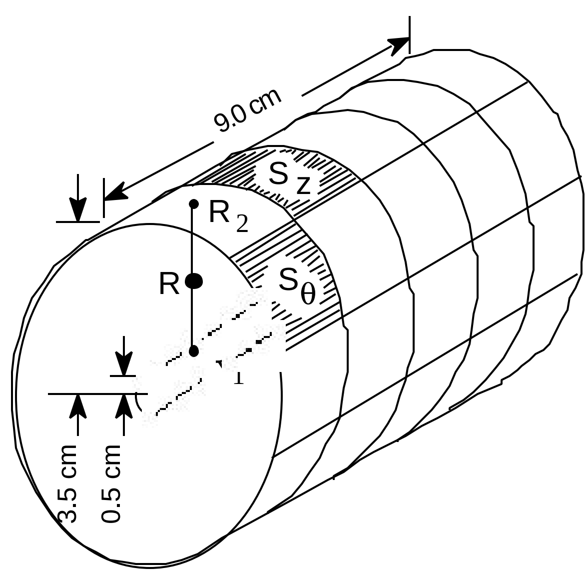

Fig. 1: GRETA detector schematic.

curves carries clear, if complex, information regarding the interaction radius R, which labels the curves. Modeling results including noise estimates showed that it should be possible to locate single event interaction sites within large detectors to within about 2 mm rms.

The complexity of the induced charge curves makes this a challenging project with a final requirement of being able to identify coincidence events across many detectors, meas

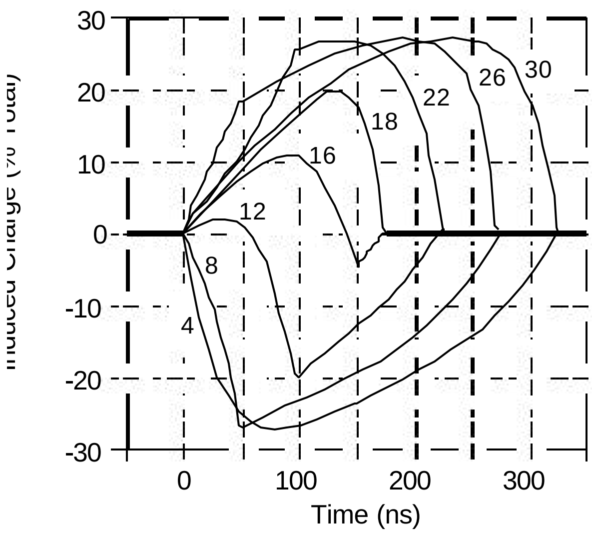

Fig. 2: Induced charge signals on spectator anode S_Z as function of depth of interaction R.

ure their energies, capture induced charge traces on both collection and spectator electrodes, and extract event locations, preferably within the instrument at event rates. However, initially, to help the physicists develop and test the required analysis algorithms, the requirement is much simpler: to provide multiple channels that can detect and measure energy events, communicate with other modules and capture signal traces for off-line analysis.

2.2. Functional design

Figure 3 shows the resultant DGF design. (Hubbard-Nelson, 1999) A single width CAMAC module, it contains 4 high speed processing channels, acquisition and control logic, a single DSP, and a CAMAC interface. Shared data buses allow parameters and signal traces captured by the processing channels to be passed to the DSP for local analysis or sent to the host computer for off-line analysis. The structure of one high speed processing channel is shown explicitly, including analog signal conditioning (with 16 bit offset and gain control), a 12 bit, 40 MHz ADC, a RTPU implemented in a FPGA, and a long FIFO acting as a 25.6 µs circular buffer.

Figure 4 shows the RTPU, which is the heart of the DGF unit. The RTPU is functionally divided into a fast channel (fast filter, pulse detection, pileup inspection, and event trigger logic), a slow channel (decimator and slow filter), and a set of output buffers for capturing slow filter

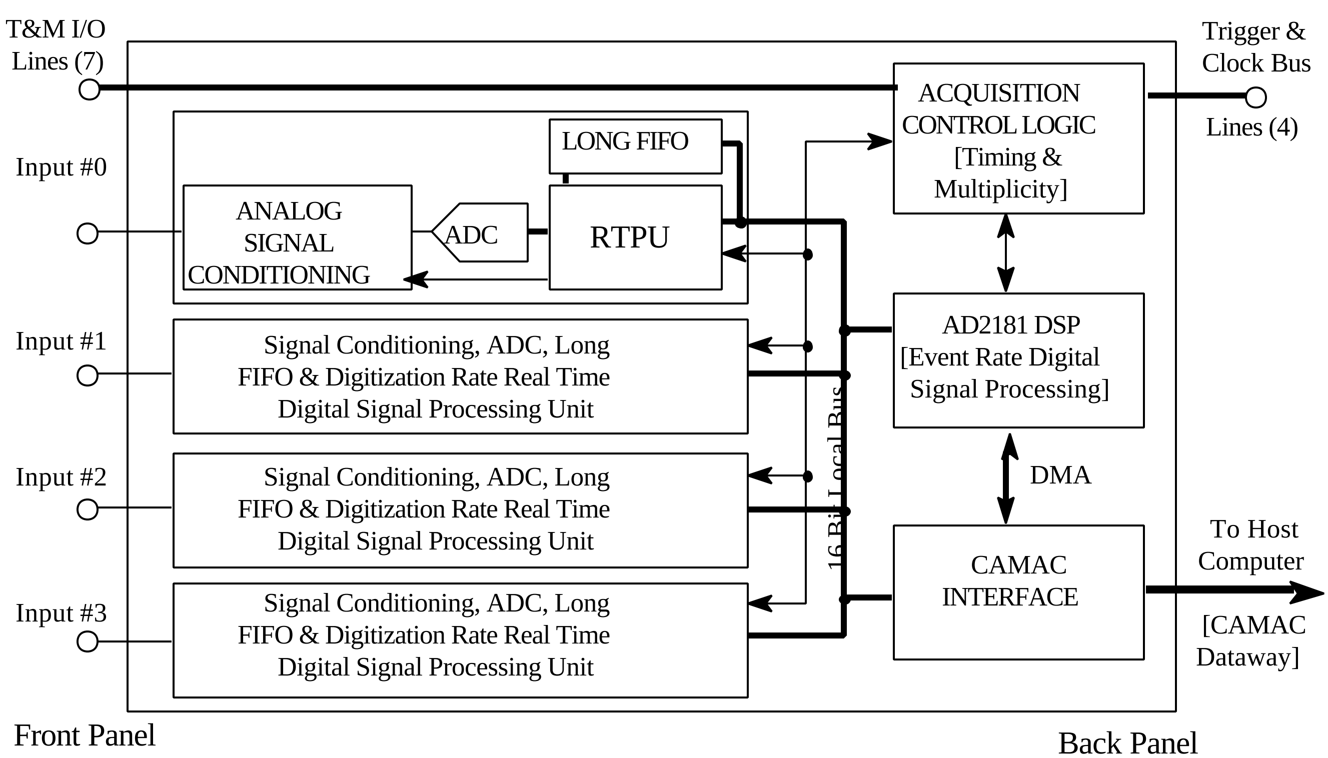

Fig. 3: Block diagram of the DGF-4C module, including an expanded view of one of the four signal processing blocks.

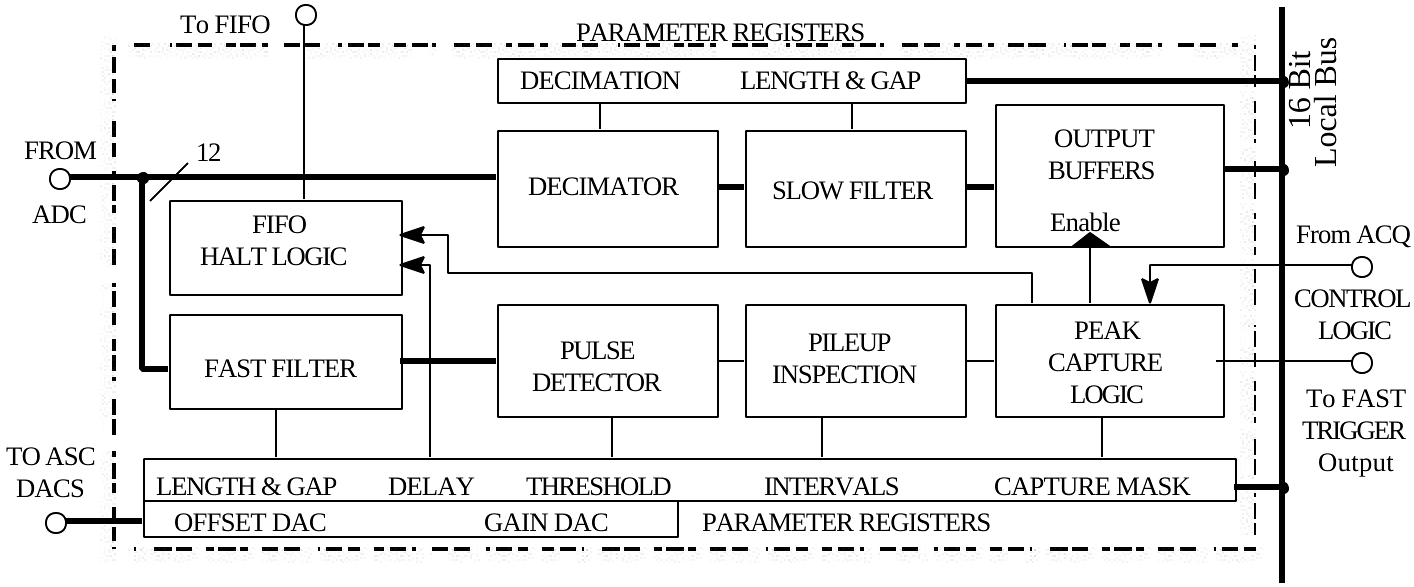

Fig. 4: Block diagram of the real time processing unit (RTPU), which in implemented in a field programmable gate array.

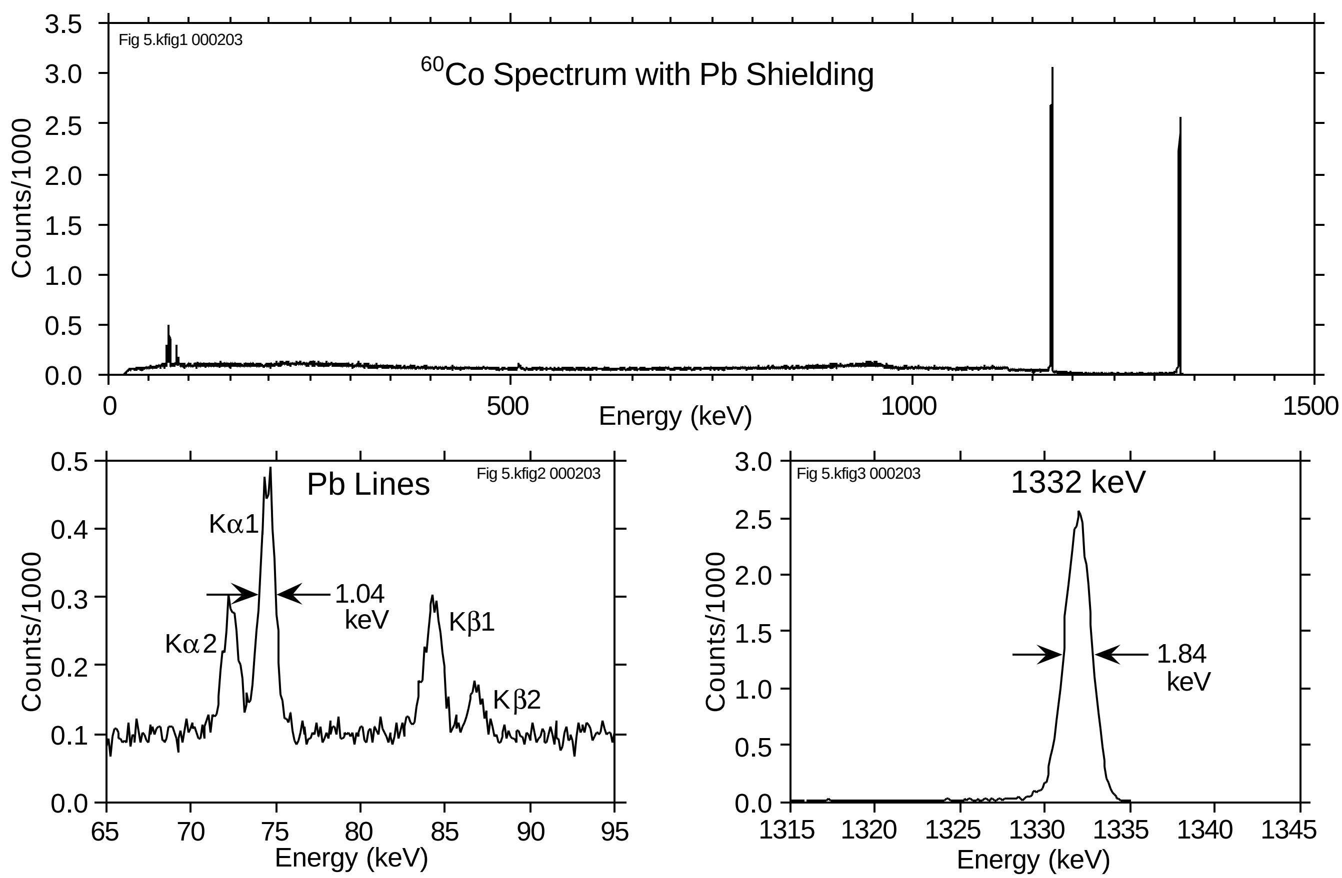

Fig. 5: ^{60}Co spectrum with Pb shielding. Pb line and 1332 keV line expansions show how resolution varies with energy.

values. The peak capture logic (which also halts the long FIFO either immediately or after a fixed delay) includes inputs both from the fast channel and from external control logic. This allows, for example, traces to be captured even if there is no local event detected. The logic also emits a signal for use by outside multiplicity logic to determine if event capture should occur.

XIA also produces a single channel module, the DXP-G12P, primarily for stand-alone, single detector applications. Its major differences from the DGF are that intermodule coincidence signaling is greatly reduced, a 2 MB SRAM memory allows for spectral storage, and its I/O structure is more flexible, with both enhanced parallel port (EPP) communications, gate and sync lines, and 24 bi-directional TTL lines for generalized control purposes.

2.3. Capabilities

The general specifications of the DGF may be found in its data sheet. Of particular interest are the following.

1) All parameters are programmable: gains, offsets, filter times, thresholds, trigger criteria, coincidence masks, etc.
2) Peaking time ranges: 25 - 725 ns in the fast channel and 0.15 - 48 µs in the slow channel.
3) FIFO's for capturing signal segments up to 25.6 µs.
4) All events time-stamped to 25 ns granularity.
5) Large MCA spectral range (15 bit accuracy, 8K in the DSP , up to 32 K in optional memory).
6) High throughput capability: over 500,000 cps OCR in DXP-G12P. The DGF OCR is limited by the complexity of any required analysis.
7) Time resolution: 25 ns in RTPU, 4 ns in DSP analysis.
8) Data capture on Global First or Second Level Triggering simplify DGF use in large data collection system.

Figure 5 is a ^{60}Co spectrum which highlights the DGF's spectrometric performance. The full 65,000 channel range is 1.5 MeV. The 1.3 MeV peak has an energy resolution of 1.84 keV. The ^{60}Co gammas scatter from the lead shielding, so Pb-K x-rays are also generated. The expansion shows that the K lines are resolved, with an energy resolution of 1.04 keV.

2.4. Energy resolution with larger detectors

The problem of obtaining good energy resolution in large Ge detectors has been much studied and is currently known to be limited by ballistic deficit effects, which arise due to charge collection time variations between events from different locations within the detector. Both field and geometry variations can produce risetime variations of 150 ns or more. When filtered, these variations remain as fluctuations in extracted energy. Trapezoidal filtering corrects this to the 0.2% level, but 0.2% of 1 MeV is 2.0 keV. Ballistic deficit (BD) errors are linear in gamma ray energy and become larger as detector size increases and risetimes become longer.

The advent of pulse shape analysis, however, allows additional corrections to be made. Figure 6 shows preliminary results from an older, leased detector of intermediate volume (approximately 5 cm diameter) using the DGF. The ^{60}Co line at 1.3 MeV has a resolution of 3.13 keV without BD correction, which is improved to 1.95 keV with correction. Similar work with the ^{208}Tl line at 2.6 MeV shows

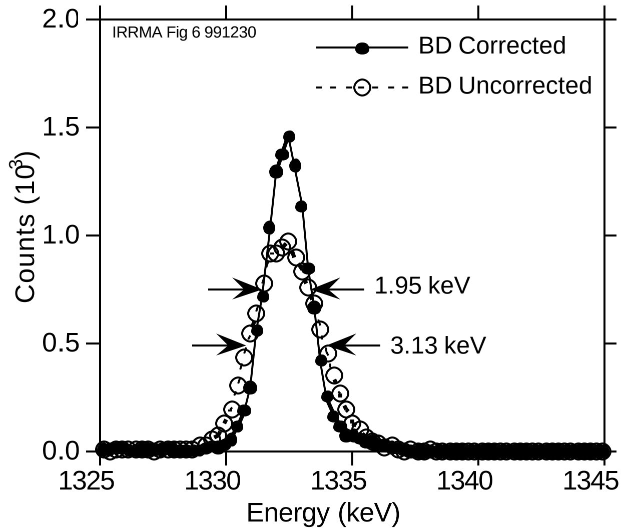

Fig. 6: Effect of ballistic deficit correction at 1332 keV.

an even larger effect. The uncorrected line has a resolution of 5.9 keV, which corects to 2.8 keV. The uncorrected resolutions are thus primarily limited by BD effects while the corrected resolutions become primarily limited by charge generation (Fano) fluctuation effects. Improvements of this kind should therefore produce significant increases in detection sensitivity in the region above 1 MeV.

3. Application #1: Radioactive ion decay studies

This class of nuclear physics experiments seeks to study short lived radioactive ions that decay by proton emission. (Batchelder *et al.*) Experimentally, the radioactive ions are collected from an accelerator target and implanted into a Si stripe barrier detector, where some of them decay by proton emission. The detector output, then, is a large pulse of from 18 to 30 MeV from the implantation, followed by a pulse from the proton emission at about 1.0 MeV. The decay time depends upon the specific ion under study. Using analog electronics, it had been possible to capture decay events down to about 10 µs, since overload from the implantation pulse precluded detecting proton decay pulses at shorter times.

Figure 7 shows a decay event captured by the DGF-4C. The upper panel shows the implantation at 18 MeV, followed by the fast proton decay at 0.5 MeV, or about 2.5% of the implantation. The lower panel is an enlargement of the trace in the vicinity of the pulses, showing the signal to noise ration attainable. The proton pulse is clearly resolved only 1.5 µs after the implantation. The slow settling time of the preamplifier can be seen following the implantation. However, since the entire waveform is captured, this can be accounted for using deconvolution techniques. We therefore anticipate that, with further

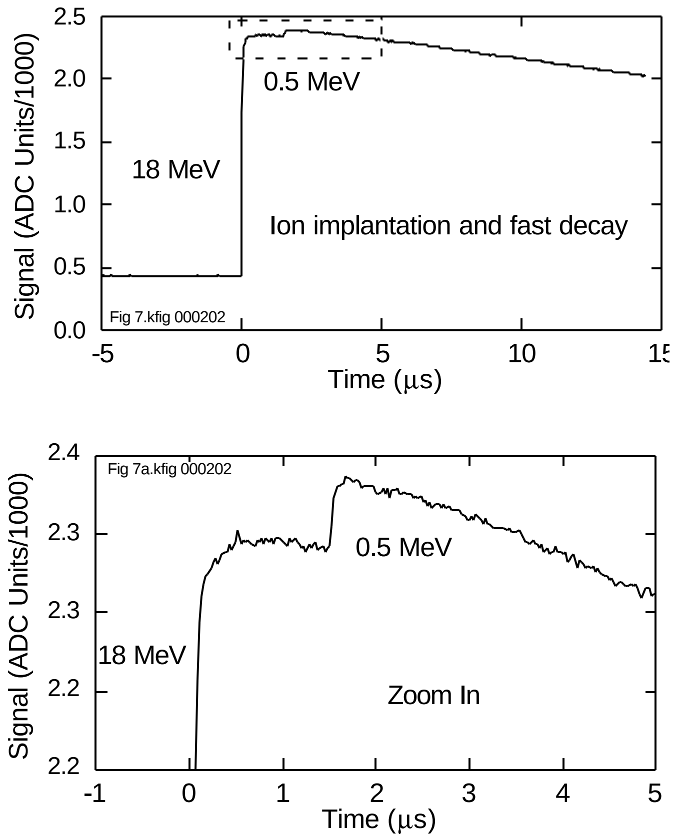

Fig. 7: Preamp signal of ion implantation followed by fast proton decay, with enlargement of fast decay region.

work on the preamplifier electronics, it should be possible to study decay times well into the sub-microsecond regime, which is a factor of ten better than could be achieved before.

An interesting feature of this experiment is the reversal of the DGF's usual pulse pileup inspection to specifically capture this sort of event. Normally the pileup inspection circuitry is set to *reject* pulses which follow too closely in succession. In our first runs this was turned off and all pulses were recorded and a computer program used to screen the thousands of captured pulses for those with both implantation and decay pulses. We have since produced a modified RTPU which *accepts* only pulses which occur within a fixed time interval of each other. Now only implantations followed by a decay are recorded, greatly reducing offline analysis time. This is a nice illustration of the ability to reprogram digital pulse processors mentioned earlier.

4. Application #2: Particle identification-phoswich detectors

The general approach to particle identification is to construct detectors which produce different responses to different particles of the same energy. One common approach is to construct the detector out of films of different phosphors with different characteristics and tailor their thicknesses so each captures a different type of particle. These are called phoswich (phosphor sandwich) detectors and are particularly good for separating particles like alphas, betas and gammas. Another approach is to use materials with multiple decay components whose response is inherently different for different particle types. CsI(Tl) is such a material, having a short lifetime component τ_1 of 0.4-1.0 µs and a long lifetime component τ_2 of about 7 µs. Both the value of τ_1 and its intensity relative to that of τ_2 depend upon particle type. (Masuda, 1992, Moszynski, 1993) Figure 8 shows how this class of output looks when only the intensity of the τ_1 component changes. A common approach to determining particle type in this case has been to use two gated integrators, one which captures a region near the pulse peak and a second to capture a region after the short component has died away. To make a complete spectroscopy system also requires a pair of ADCs and a data capture system to work with the pair of captured values.

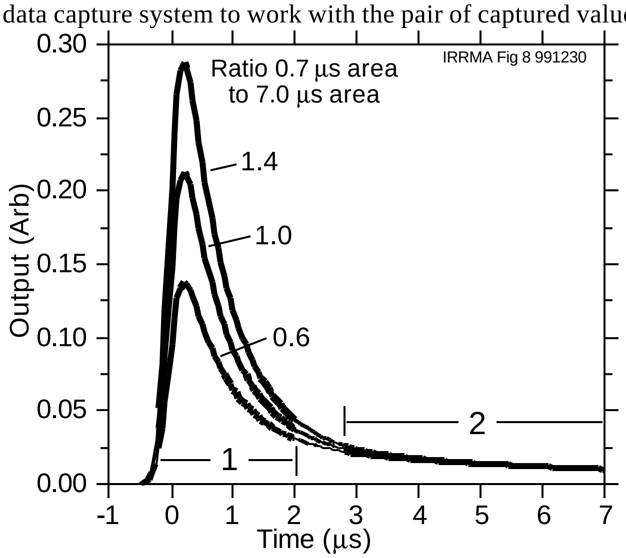

Fig. 8: CsI(Tl) pulses with different τ_1 to τ_2 ratios, showing digital sum regions to give particle ID.

A single channel DGF, such as the DXP-G12P, however, can handle this class of experiment all by itself. The RTPU is programmed to capture the values of two digital running sums (shown in bold in Fig. 8) having the correct duration and delay following the pulse's leading edge. Because both filters share a common clock, both their relative timing and absolute durations will be precisely held. Once they are captured, the DSP can perform any required analyses to determine both the particle's identification and its energy. If desired, either a 3-D scatter plot (number vs. energy vs. amplitude ratios) or individual spectra for the particles can be produced. Using more complex filters it should also be possible to determine τ_1 for each event as well, even extending to the method of Miller & Berliner, who capture full traces and decompose the spectra using known basis functions.(Miller and Berliner, 1993) Further digital refinements are also possible: e.g. supplying temperature information to the DSP so that it can correct for known variations of τ_1 and relative yield with temperature.

5. Application #3: Low background counting

Figure 9 is an application showing the flexibility of the DXP-G12P, wherein a single spectrometer is used to monitor a large number (here 8) of proportional counters all working at low rates as ^3H monitors. Since amplifier noise is not limiting, all the signals are summed and fed to the spectrometer. Then, to assign each pulse to its source counter, low cost discriminators are attached to the preamplifiers and their outputs connected to the DXP-G12P's TTL input lines. When the DSP finds a pulse in its input data stream, it reads the TTL lines to learn its "address" and can then bin it in a spectrum associated with the correct counter. In this manner it produces a unique spectrum for each counter.

Since it is further required to provide anti-coincidence rejection of background and cosmic ray events, a background shield counter is added. The output of its preamplifier is discriminated and inverted and attached to the DXP-G12P's Gate input, which must be HIGH to allow counting. In this configuration, each background count produces a LOW pulse to the gate, which effectively vetoes any counts arriving from the proportional counter array.

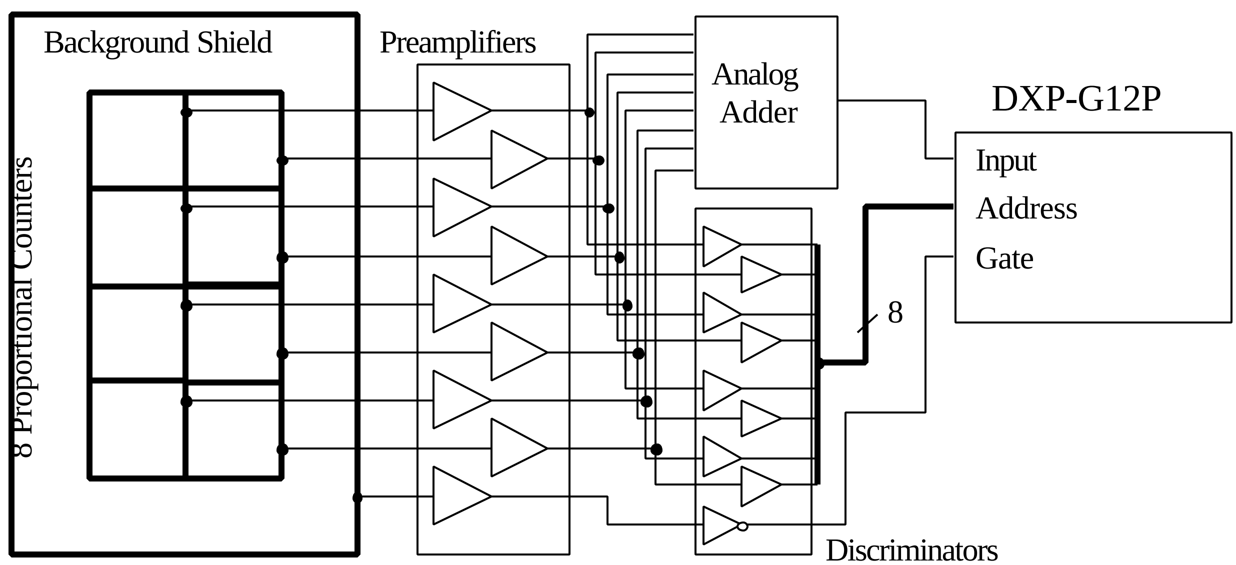

Fig. 9: Schematic for method for using a single DXP-G12P to service 8 low count rate proportional counters.

6. Application #4: Coincident photon Pb detection

Figure 10 shows a proposed approach for using a DGF module for detecting low concentrations of lead in bone using coincidence detection of Pb-K and Pb-L x-rays. The bone is irradiated with a monoenergetic x-ray or gamma ray source whose energy lies above the Pb K absorption edge. The preferred source would have a single excitation line and would not also stimulate the L absorption edge, as does ^{109}Cd. The straight- forward approach is to examine the bone with two detectors, for the Pb-L x-rays using a relatively thin Si(Li) detector, to minimize Pb-K x-ray sensitivity and using a thicker Ge detector for the Pb K x-rays. Both would be attached to a DGF-4C.

Since the goal of the experiment is to detect both a Pb-K and Pb-L x-ray from the same decay cascade, the DGF-4C would make a primary coincidence inspection between fast trigger signals generated by the two RTPU circuits using a window of perhaps 25 to 100 ns. Finding such a coincidence, which already eliminates the vast majority of singles events from Compton scattering, the DGF would then examine the energy from the Si(Li) detector to see if its energy matches any preselected Pb L x-ray energy. To enhance efficiency, any of the allowed L energies might be included in this test, depending upon their signal to noise ratios. When an L energy match is found, then the energy in the other detector is binned into a spectrum. The areas under the Pb K lines in this spectrum can then be used as a measure of the Pb concentration in the bone.

It is worth noting that a 4 channel DGF-4C can easily accommodate up to 4 detectors in this experiment, looking for coincidences between any pair. To further increase sensitivity, thin windowed Ge detectors could be used for all detectors and the Pb-L x-ray test could also be modified to include escape peak areas if these have significant areas. Since either a K or an L x-ray can now be found in any de

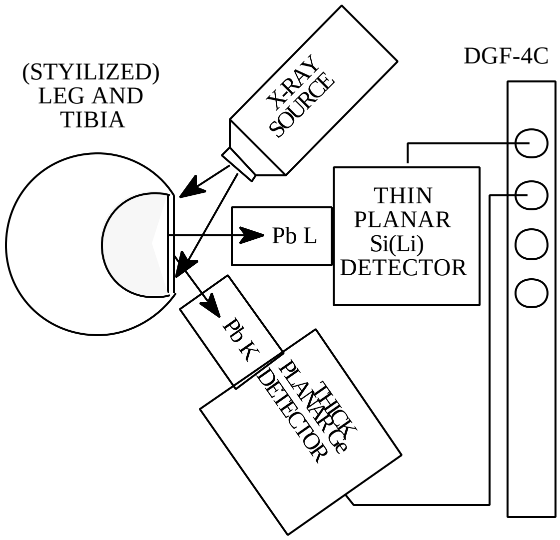

Fig. 10: Using the DGF to detect Pb-K and Pb-L x-rays in coincidence mode to reduce Compton background.

tector, the efficiency of N detectors will be increased N(N-1) compared to the simple Si(Li)/Ge detector case. This example shows how the DGF's coincidence and spectral test abilities may be used to significantly enhance an experiment.

7. Conclusions

While developed specifically for a multi-electrode nuclear physics detector problem, the DGF digital spectrometer is a sufficiently general instrument that it can be used to explore digital processing approaches to a variety of nuclear detection problems. In this paper we have explored ways in which its capability to capture and analyze waveforms and perform coincidence triggering might benefit a variety of detection applications beyond detecting events in large multielement detectors and capturing induced charge signals from them. These included making accurate ballistic deficit corrections, doing radioactive ion decay measurements, instrumenting phoswich detectors, multiplexing low background measurements, and detecting low environmental Pb concentrations using coincident photon detection.

8. Acknowledgments

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9. Presentation

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