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The DGF Pixie-4 spectrometer – compact digital readout electronics for HPGe clover detectors

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Abstract

Large volume HPGe detectors are commonly used in applications that require good energy resolution and high detection efficiency, but are expensive and difficult to grow. Clover detectors consisting of four smaller crystals in a common cryostat are a possible alternative, but traditionally require complex readout electronics. In contrast, the DGF Pixie-4 is a compact, digital spectrometer providing on a single 3U CompactPCI/PXI card all the electronics required for clover detectors, including computation of addback spectra. This paper describes the DGF Pixie-4 system architecture, characterizes its energy resolution and throughput, and presents results of test measurements with a clover detector.

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1. Introduction

Radiation measurements with weak sources and low background requirements commonly use large volume HPGe detectors for their good energy resolution and high detection efficiency. Such applications include environmental monitoring, detection of low-level industrial radioactivity and bioassay. However, large HPGe crystals are difficult to manufacture and therefore expensive. Clover detectors, consisting of four smaller HPGe crystals arranged in a four-leaf clover geometry in a common cryostat [1], are a possible alternative to large single crystal detectors. Each crystal is read out independently, but coincident energies measured for each crystal can be summed by suitable readout electronics to reconstruct the full energy of gamma rays scattered from one crystal to the other. In this "addback" mode, clover detectors can reach detection efficiencies and peak-to-total ratios similar to a single large HPGe crystal. Besides being easier to grow and thus less expensive, the smaller crystals also have faster signal rise times and better energy resolution than large crystals. Especially important in large nuclear physics experiments, the smaller solid angle for incident radiation of each clover crystal compared to a single large detector also reduces the Doppler broadening of peaks [2].

Since they consist of multiple crystals, clover detectors require more complex readout electronics than a single large detector. Traditionally, a chain of shaping amplifier, pulse stretcher, analog-to-digital converter (ADC) and multi-channel analyzer (MCA) is used for each crystal. In addition, building the addback spectrum requires fast trigger circuits and logic gates for coincidence detection as well as a summing amplifier and an additional MCA. This not only amounts to a bulky setup with a large number of components, but also requires careful adjustment of the individual gains and other acquisition parameters. In

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contrast, the DGF Pixie-4 presented here is a compact digital readout module that combines all the electronics required for a 4-fold clover detector on a single 10 cm × 16 cm board and all parameters can be stored on file.

2. System architecture

The DGF Pixie-4 spectrometer (block diagram shown in Fig. 1) was designed as an industry standard CompactPCI/PXI module. Compared to the CAMAC or VME standards, CompactPCI/PXI has the advantages of a high data transfer rate (theoretical maximum 132 Mbytes/s) and a compact form factor (a Pixie-4 system with 20 channels can be as small as $20 \times 20 \times 30\ \mathrm{cm}^3$). The CompactPCI/PXI standard is widely used in the telecom industry and the data bus is directly compatible with the PCI architecture of common desktop PCs. Each of the four input channels of a Pixie-4 module accepts signals directly from the preamplifier of an HPGe detector, or from most other detector types such as scintillator/photomultiplier combinations. The incoming signals are adjusted for gain and offset, and then digitized at a rate of 75 MSPS with a 14 bit ADC. All further processing is performed on the digital data stream using the same algorithms and processing architecture as in the CAMAC based DGF-4C [3], but with higher speed: Triggering, pileup inspection and a trapezoidal energy filter are implemented in a field programmable gate array (FPGA) with user defined values of trigger threshold, filter rise and flat top time, etc. Whenever a valid event is detected, a digital signal processor (DSP) reads out the energy filter values from the FPGA, reconstructs the pulse height, and bins the energy in an MCA spectrum. The DSP can be programmed to perform a number of additional tasks, such as acquisition of pulse waveforms, rise time calculations or constant fraction timing, depending on the particular application. In this application with clover detectors, the DSP obtains the coincidence pattern of active channels in a given event from the FPGAs, and if more than one channel triggered within a user defined coincidence window, it computes the sum of pulse heights of these channels and bins the result in an additional addback spectrum.

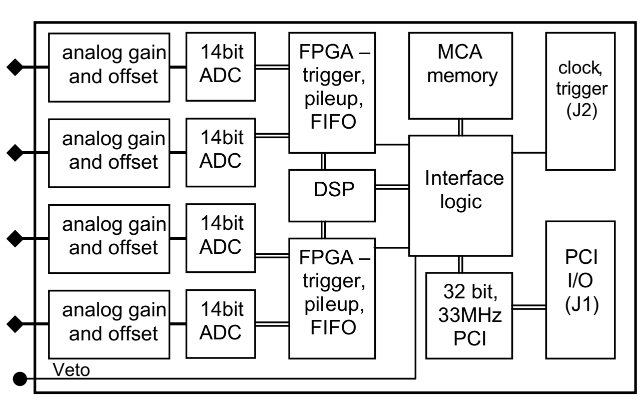

Fig. 1. Block diagram of the DGF Pixie-4 spectrometer.

The Pixie-4 spectrometer is controlled via a PCI interface by a host computer, which can be either an embedded CompactPCI/PXI computer residing in the same chassis or a desktop PC via a PCI-CompactPCI/PXI bridge. The data transfer rate of the PCI interface implemented in the Pixie-4 reaches over 100 MBytes/s. The Pixie-4 is operated via a graphical user interface that allows all settings, e.g. the analog gain and offset, filter parameters and trigger thresholds for each channel, to be stored in and recalled from files for easy switching between different experiments. This open source interface is based on Wavemetrics's Igor Pro, with the essential control functions implemented as a C library that can also be used to integrate control of the Pixie-4 into custom software. It is possible to operate several modules together in the same chassis, sharing trigger and run synchronization signals over the chassis backplane for applications with more than four channels, for example segmented clover detectors. Each card also has a Veto input which allows interactions in a Compton shield around the detector to lead to the suppression of events where gamma rays scatter out of the detector and only a fraction of their energy is deposited in the detector.

3. Experimental results

The performance of the Pixie-4 spectrometer was tested with a clover detector formerly part of the HBRIF CLARION array [4] as well as a random pulser and a single coaxial detector. Fig. 2 shows the addback spectrum using a ^{60}Co source obtained with the clover detector together with offline sum spectrum of all four channels, representing the performance of four individual small detectors or of one

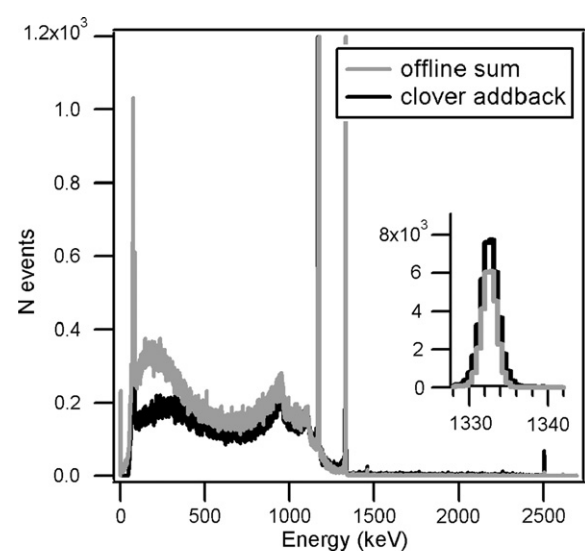

Fig. 2. ^{60}Co addback spectrum of clover detector acquired with the Pixie-4 and offline sum spectrum of the four individual clover spectra. The addback spectrum has lower Compton background and a larger number of counts in the peak areas than the offline sum.

small detector for four times the acquisition time. The low energy peaks (70–90 keV) are due to Bi X-rays from the BGO shield of the detector. Compared to the offline sum spectrum, the addback spectrum has a reduced Compton background at lower energies, which implies better counting statistics for low energy gamma rays measured in the presence of higher energy gamma-ray radiation. Furthermore, the addback spectrum has more counts in the peak areas, e.g. the number of counts in the 1.3 MeV peak is 1.43 times larger than in the offline sum. At the 2.5 MeV sum peak, the addback spectrum contains 47 times more counts than the offline sum, due to the higher probability of capturing both coincident ^{60}Co gamma rays in the clover detector, rather than in only one of the crystals. These results demonstrate the higher efficiency and peak to total ratio of the clover detector in addback mode compared to four individual detectors. The FWHM energy resolution of the 1.3 MeV peak is about 2.5 keV for the addback spectrum compared to about 2.1 keV for a single channel. As each channel has an electronic noise of about 1.5 keV in this setup, which adds in quadrature for events combined from two or more channels, the increase in FWHM for the addback spectrum is within the expected magnitude. Better resolution would require lowering the electronic noise.

The energy resolutions achieved with the Pixie-4 spectrometer were further studied with a smaller single HPGe detector at XIA. Fig. 3 shows the resolution for the ^{60}Co 1.3 MeV peak for two different values of dynamic range as a function of the input count rate (ICR). For these measurements, the rise time of the digital filter was set to 5.973 μs and the flat top time to 1.173 μs. The resolution is below 0.125% (1.67 keV) at low count rate for the smaller dynamic range, and increases to only about 0.135% at count rates of up to 25,000 counts/s. The resolution is slightly worse at the higher dynamic range as the 1.3 MeV pulse stretches over a smaller range of the ADC so that it is measured with less precision. In addition, at the lower gain of the higher dynamic range, the signal to noise ratio is reduced as well.

The maximum throughput of the Pixie-4 (output counts processed into the spectrum per second, OCR) as a function of input count rate is shown in Fig. 4. Theoretically, the OCR depends on the ICR according to the equation derived from Poisson statistics [5].

$$\mathrm{OCR} = \mathrm{ICR} * \exp(-2 * \mathrm{TD} * \mathrm{ICR}), \tag{1}$$

where the dead time TD is a function of the rise time and flat top time of the trapezoidal energy filter. However, the throughput is further limited by the processing speed of the spectrometer. In the measurements with a random pulser displayed in Fig. 4, the filter time constants were set to a rise time of 0.4 μs and a flat top time of 0.213 μs, small enough to make the processing speed the limiting mechanism for the throughput. Consequently, the throughput as a function of ICR does not follow the theoretical relation (1), but rather characterizes the maximum processing rate of the Pixie-4. When processing a single channel, the Pixie-4 can process up to 120,000 counts/s into the MCA spectrum. When processing four channels with coincident signals, the processing overhead per channel is reduced, and thus the Pixie-4 can process up to 100,000 counts/s for each channel, i.e. 400,000 counts/s overall. In a typical clover application where only some of the events are coincident, the maximum throughput will be an intermediate value.

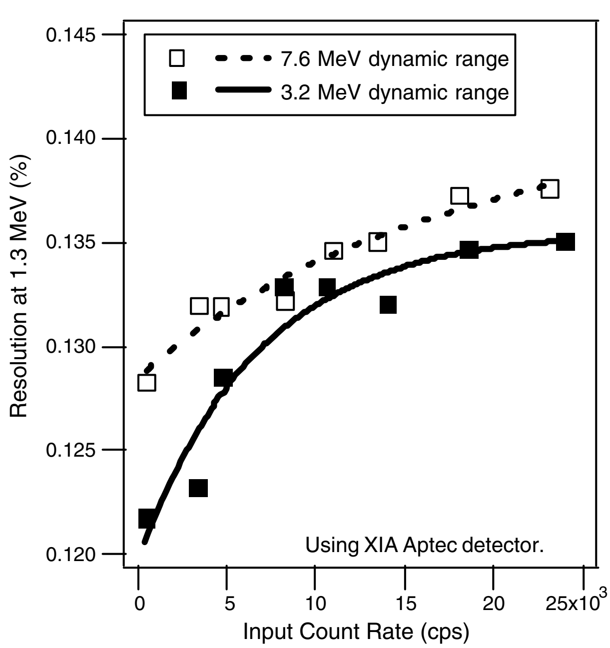

Fig. 3. Energy resolution of ^{60}Co as a function of input count rate measured with the Pixie-4 and a coaxial detector.

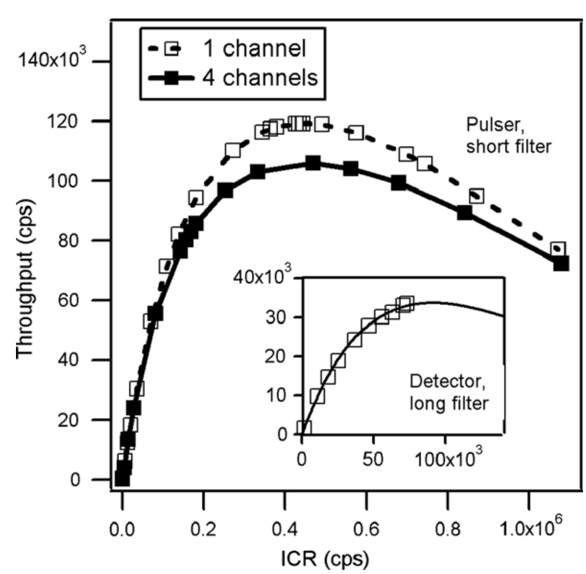

Fig. 4. Throughput per channel as a function of input count rate using a random pulser and short energy filter times to characterize the maximum processing rate of the Pixie-4. The inset shows the throughput at longer filter times using a coaxial detector where the throughput is limited by the filter dead time.

In a measurement with a HPGe detector and filter time constants set to values providing good energy resolution, the filter dead time TD will be the limiting factor for the throughput, which then follows Eq. (1). For example, shown in the inset of Fig. 4, with a rise time of 2.027 μs and a flat top time of 1.173 μs the throughput reaches about 33,500 counts/s at an ICR of about 74,000 counts/s, the maximum reached with available sources. The solid line in the inset is a fit with Eq. (1).

4. Summary

In summary, we developed a four channel digital readout module in the CompactPCI/PXI form factor that can compute on-line addback spectra for clover detectors. It achieves good energy resolution and high throughput in a compact design, making clover detectors a more feasible alternative to large HPGe detectors by simplifying the traditional complex readout electronics and providing the capability of storing all settings on file. The Pixie-4 module is also capable of instrumenting segmented clover detectors by sharing trigger and synchronization signals over the backplane. The results shown for the clover detector can be further improved by using a Compton shield around the detector to veto events with partially deposited energy.

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