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Development of a Digital Signal Readout System for Large TES Arrays

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Abstract We are developing a digital signal readout system for arrays of high-resolution gamma and fast-neutron detectors based on superconducting transition edge sensors (TESs). The readout system allows for real time data acquisition and analysis at count rates exceeding 100 Hz for pulses with several ∼ms decay times with minimal loss of energy resolution compared to optimum filtering. This digital signal processing system had originally been developed for gamma-ray analysis with HPGe detectors, and we have modified the hardware and firmware to accommodate the slower TES signals. Parameters of the filtering algorithm have been optimized to maximize either resolution or throughput. Here we present a summary of the digital signal processing hardware and discuss its initial performance.

Keywords Digital signal processor · Microcalorimeters · Detector arrays

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1 Introduction

Microcalorimeter gamma-ray and fast-neutron detectors based on superconducting Transition Edge Sensors (TESs) are being developed for fundamental science and

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nuclear non-proliferation applications because of their extremely high energy resolution [1–5]. This comes at the expense of a small pixel size and slow decay times. The small pixel sizes are being addressed by developing detector arrays [1, 4]. Here we address the count rate problem by developing Digital Signal Processors (DSPs) that allow higher throughput than traditional pulse processing algorithms.

Traditionally, low-temperature microcalorimeter pulses have been processed offline with optimum filtering routines based on the measured spectral characteristics of the signal and the noise [6]. These optimum filters rely on the spectral content of the signal being identical for all events, and therefore require capturing the entire pulse signal without pile-up. In contrast, the DSP algorithm being developed here is based on differences in signal levels before and after a trigger event, and therefore does not require the waveform to fully decay, or even the signal level to be close to the base line. Here we discuss the hardware and the filtering algorithm used in the Pixie-16 system built at XIA LLC for microcalorimeter analysis.

2 System Description

The DGF Pixie-16 is a scalable 16-channel data acquisition system based on the PCI standard used for nuclear physics and other applications requiring many channels. Originally developed as a digital spectrometer for gamma-ray analysis with high-purity Ge (HPGe) detectors, this system is now being adapted for use with superconducting microcalorimeters.

The output signal from each microcalorimeter pixel is read out with a separate channel of the Pixie-16 system. The incoming signal is first adapted for the analog-to-digital converter (ADC) with an analog signal conditioning unit that includes input termination and overvoltage protection circuitry, a user-defined offset adjustment, fixed gain, and a Nyquist filter. Since microcalorimeter pulses have time constants three orders of magnitude greater than HPGe, the ADC's Nyquist filter bandwidth was reduced to remove noise contributions from high frequencies. The signal is digitized using a 12 bit, 100 MHz ADC and read into the digital processing core of the system, which has three major components: (i) four field-programmable gate arrays (FPGAs) for filtering, (ii) a digital signal processor (DSP) for pulse height measurements, and (iii) a system interface FPGA (Fig. 1).

2.1 Filter FPGA

Digital data streams from four analog inputs are continuously processed by a single filter FPGA. For each channel of digitized data the FPGA continuously computes three energy sums (Σ_1, Σ_2 and Σ_3) over three user-defined time intervals τ_{peak}, τ_{gap}, and τ_{peak} (Fig. 2a). These boxcar sums provide the filtering, and for a step function input, they lead to a trapezoidal output with a peaking time τ_{peak} and a plateau of width τ_{gap}. The FPGA also computes two separate energy sums over intervals $\tau_{\text{peak,filter}}$ and provides a trigger signal whenever their difference exceeds a user-defined threshold.

To calculate the energy sums for microcalorimeter pulses with ∼ms decay constants, the range of the filter time constants was increased by modifying the Filter

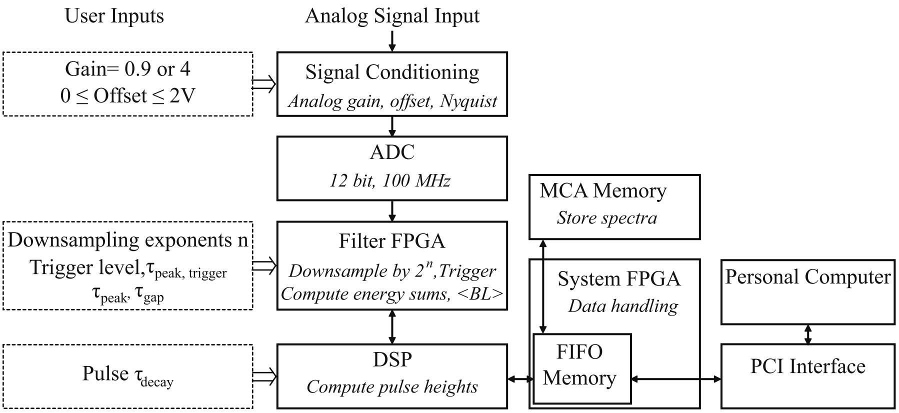

Fig. 1 Block diagram of the Pixie-16 system

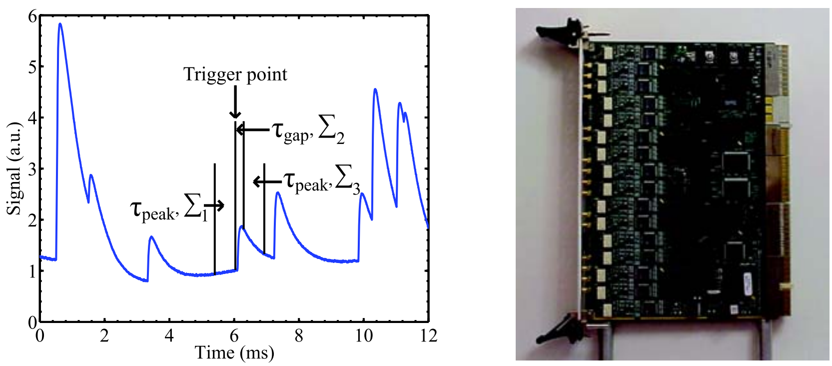

Fig. 2 (Color online) (**a** *left*) Typical gamma-ray microcalorimeter signal at high count rate and associated filter time constants. (**b** *right*) 16-Channel DSP Board (Pixie-16)

FPGA firmware and average up to 2^8 samples of the digital data stream from the ADC. This can reduce the effective sampling interval from 10 ns to 2.56 µs, and increase the range of filter time constants up to 5 ms. Occasionally, the FPGA measures the baseline level $\langle BL \rangle$ between pulses to monitor DC offsets and drifts. In addition, the FPGA performs pileup inspection and rejects pulses whose filter sums overlap. If desired, the FPGA uses on-chip FIFO memory to capture waveforms up to 10 ms (4000 samples) for offline analysis. When the trigger filter exceeds the threshold and the pulses are sufficiently spaced, a trigger signal is issued and the FPGA latches the energy sums to the data stream and issues an interrupt to the DSP.

2.2 Digital Signal Processor

Upon receiving the interrupt from the filter FPGA the DSP reads the energy sums and average baseline and computes the energy E as

$$E = c_3 \cdot \sum_3 - c_1 \cdot \sum_1 + c_2 \cdot \sum_2 - \langle BL \rangle. \tag{1}$$

Here the coefficients c_i use the definable pulse decay time constant τ_{pulse} to correct for both the decay of the measured pulse during τ_{gap} and any underlying decay from a previous pulse during τ_{peak}. When the system is not performing pulse height analysis, it periodically queries the FPGA for baseline measurements used for offset and drift corrections. In addition, the DSP applies time stamps, prepares data for output to the host computer, and sends the final pulse height values to the System FPGA for MCA histogramming. If desired, waveforms from the Filter FPGA's FIFOs can be read into DSP memory, and analyzed to compute rise times and other parameters to optimize system performance.

2.3 System FPGA

During a data acquisition run, the system FPGA receives pulse height values computed by the DSP for each event. The FPGA performs a read/increment/write operation on the MCA memory to build an onboard energy spectrum. The System FPGA responds to commands from the host computer to transfer the MCA memory through the PCI interface for analysis.

3 System Performance

The pulse processing algorithms are optimized for a given detector response by adjusting τ_{pulse} and τ_{gap}. The value of τ_{pulse} is used to compensate for the underlying decay of a pulse. This is particularly important for count rates above 100 Hz where pulses overlap frequently. Secondly, the gap time τ_{gap} must cover the entire rising part of the pulse. Microcalorimeters with a rising signal edge of the form $1 - \exp(-t/\tau_{\text{rise}})$ typically require $\tau_{\text{gap}} \geq 5\tau_{\text{rise}}$. Then, τ_{peak}, can be optimized to find the best tradeoff between energy resolution and throughput (Fig. 3a). The dead time τ_{dead} of the filter is approximately $\tau_{\text{dead}} = 2(\tau_{\text{gap}} + \tau_{\text{peak}})$, and for random Poisson-distributed pulses the output count rate (OCR) at a given input count rate (ICR) is [7]

$$\text{OCR} = \text{ICR} \cdot \exp(-\text{ICR} \cdot \tau_{\text{dead}}). \tag{2}$$

This gives a maximum $\text{OCR}_{\text{max}} = (\text{e} \cdot \tau_{\text{dead}})^{-1}$ at an input count rate of $\text{ICR}_{\text{max}} = 0.5(\tau_{\text{gap}} + \tau_{\text{peak}})^{-1}$. The optimum τ_{peak} for highest energy resolution is determined by the noise characteristics of the setup, and the throughput is inversely proportional to this value.

To characterize the performance of the Pixie-16 system, Gamma-waveforms from a ^{57}Co source that had produced an energy resolution of 75 eV FWHM by optimum filtering [2] were re-analyzed with the DSP algorithm. We found for these pulses with $\tau_{\text{pulse}} = 3$ ms, the optimum resolution of 85 eV FWHM at 122 keV is obtained for $\tau_{\text{peak}} = 1$ ms; The maximum output count rate at this setting was $\sim$100 Hz, an order of magnitude above the maximum rate of the optimum filter. Decreasing the peaking time to $\tau_{\text{peak}} = 0.2$ ms would allow count rates up to 260 counts/s while maintaining

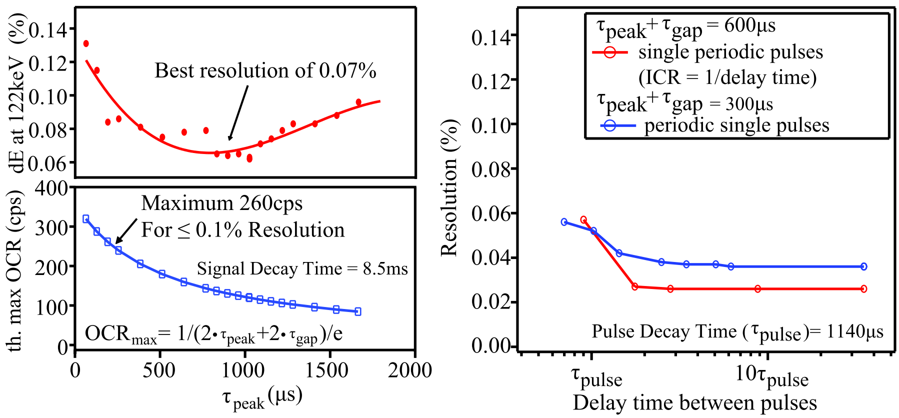

Fig. 3 (Color online) (**a** *left*) Trade-off between energy resolution and count rate. For pulses with a decay time $\tau_{pulse} = 3$ ms, the best resolution of 85 eV FWHM at 122 keV is obtained for $\tau_{peak} = 1$ ms. A resolution of 120 eV FWHM can be obtained at theoretical maximum rates up to 260 counts/s for $\tau_{peak} = 0.2$ ms. (**b** *right*) Pulses can be analyzed despite line overlap, although the resolution degrades when the time interval between pulses is shorter than the pulse decay time τ_{pulse}

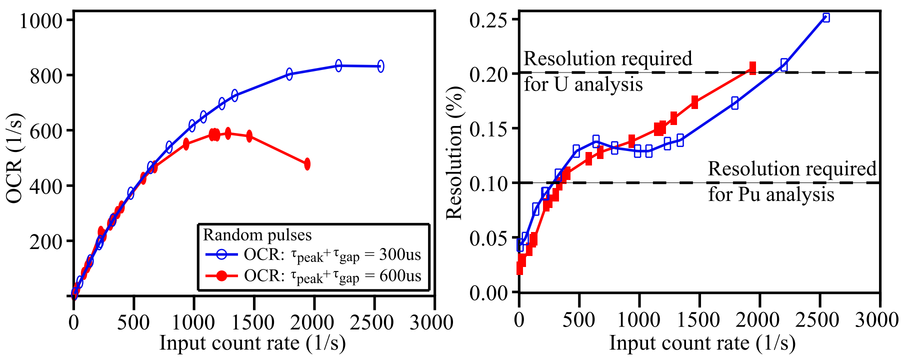

Fig. 4 (Color online) Shorter peaking times allow higher throughput (*left*), although generally at the cost of lower energy resolution (*right*). The DSP resolution decreases with increasing input count rate, but stays below the value required for certain national security applications such as Pu and U isotope analysis at 100 keV (*dashed lines*)

a resolution below 0.1% FWHM (Fig. 3a). To characterize the response of the system to pileup we used a series of idealized electronic pulses with systematically varying delay times. We found that the resolution remains at the highest level despite a delay time comparable to the pulse decay time. It remains below 0.1% even for significant pileup where $\tau_{delay} = 0.8\tau_{pulse}$ (Fig. 3b). The resolution remains below 0.2% for count rates exceeding several hundred counts per second (Fig. 4). Decreasing τ_{peak} allows for operation at higher count rates, although at the cost of lower energy resolution. For many applications in nuclear security, this is a very desirable trade-off [8].

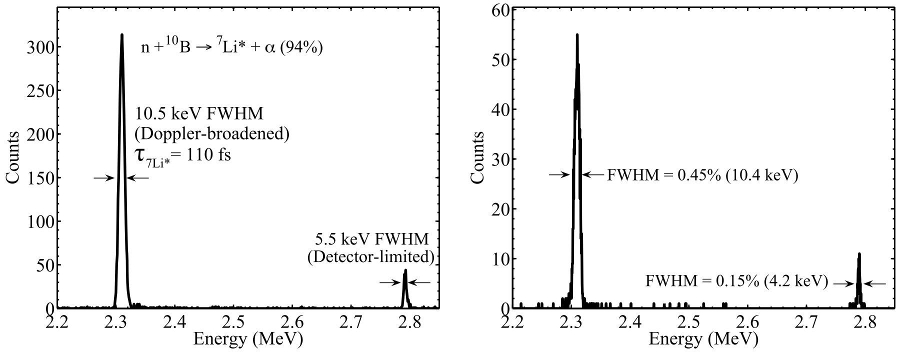

Fig. 5 Thermal neutron spectra of a TES with a TiB_2 absorber using an optimum filtering routine (*left*) and using the Pixie-16 algorithm (*right*). The 2.31 MeV line is Doppler-broadened by the decay of the $^7Li^*$ nucleus during thermalization

4 DSP Microcalorimeter Analysis

Pulses produced by a thermal neutrons incident on a TES with a TiB_2 absorber were used to directly compare the performance of Pixie-16 pulse processing algorithm and the optimum filter. Under certain circumstances (Fig. 5), we have observed an even better energy resolution with the DSP system then with the nominally optimum filter, possibly because the DSP system is less susceptible to small variations in the signal shape and pick-up. This suggests that DSP readout can provide an energy resolution comparable to the optimum filtering routines commonly used for microcalorimeter pulse analysis, while at the same time improving the count rate capabilities and thus the spectrometer sensitivity by an order of magnitude. Future improvements of the algorithms will address the degradation of energy resolution with count rate and non-ideal effects such as drifts and flux jumps upon cosmic particle absorption.

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