

A Versatile Multichannel Digital Signal Processing Module for Microcalorimeter Arrays

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Abstract: Different techniques have been developed for reading out microcalorimeter sensor arrays: individual outputs for small arrays, and time-division or frequency-division or code-division multiplexing for large arrays. Typically, raw waveform data are first read out from the arrays using one of these techniques and then stored on computer hard drives for offline optimum filtering, leading not only to requirements for large storage space but also limitations on achievable count rate. Thus, a read-out module that is capable of processing microcalorimeter signals in real time will be highly desirable. We have developed a multichannel digital signal processing electronics that is capable of on-board, real time processing microcalorimeter sensor signals from multiplexed or individual pixel arrays. It is a 3U PXI module consisting of a standardized core processor board and a set of daughter boards. Each daughter board is designed to interface a specific type of microcalorimeter array to the core processor. The combination of the standardized core plus this set of easily designed and modified daughter boards results in a versatile data acquisition module that not only can easily expand to future detector systems, but is also low cost. In this paper, we first present the core processor/daughter board architecture, and then report the performance of an 8-channel daughter board, which digitizes individual pixel outputs at 1 MSPS with 16-bit precision. We will also introduce a time-division multiplexing type daughter board, which takes in time-division multiplexing signals through fiber optic cables and then processes the digital signals to generate energy spectra in real time.

Keywords: *Digital signal processor, real time processing, multiplexing, microcalorimeter arrays*

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1. INTRODUCTION

Microcalorimeters are cryogenic radiation detectors that measure the energy of incident photons or neutrons by the temperature increase of a thermal sensor. The thermal sensor is typically either a thermistor or a superconducting transition edge sensor (TES), operating at temperatures of $\sim 0.1\text{K}$. Microcalorimeters can be used

as very precise detectors for electromagnetic radiation from the near infrared to gamma rays. However, microcalorimeters are typically individually tiny, and thus large arrays are often needed to provide adequate detection efficiency. Different techniques had been developed for reading out these microcalorimeter arrays: individual outputs for small arrays and time-division or frequency-division or code-division multiplexing (TDM or FDM or CDM) for large arrays. In past data acquisition systems, triggered waveform data were often read out from the arrays using one of these techniques before undergoing offline optimum filtering to generate energy spectra. Such read out systems not only require huge disk storage space but also limit the achievable count rate. Read out electronics capable of on-board real time processing microcalorimeter signals would therefore be greatly advantageous.

Optimal filtering based real time pulse processing for microcalorimeters has been reported in various systems [1]. Such systems are typically designed for a particular type of microcalorimeters and thus they are constrained by a particular read out technique and not easily adaptable to other ones. Therefore, a read out system that can interface to any read out technique should become popular, not only allowing flexibility in instrumenting microcalorimeters with existing or even to-be-developed read out techniques but also lowering costs by economy of scale in production. Based on the fact that the underlying physical principle remains the same for different read out techniques, i.e., thermal rebalance following heat absorption in the thermal sensor, we have developed a “two-board” solution using digital signal processing technology. The first board of this “two-board” solution is the so-called daughter board, variants of which can be designed to interface to a particular type of read out technique, and the second board is the core processor board or main board. For microcalorimeter arrays with individual outputs, the daughter board both digitizes the analog inputs using on-board high precision ADCs and then presents the resulting data to the main board in a standardized format. For microcalorimeter arrays that already produce digital multiplexed data stream, the daughter board’s job is simply to convert that data stream into the standardized format. Because the data format is standardized, the same core processor can process the data in real time, irrespective of the type of microcalorimeter array that produced it.

In this paper, we will first describe the hardware development of the main board and two variants of daughter board, one is an 8-channel daughter board, which digitizes individual pixel outputs at 1 MSPS with 16-bit precision, and the other is a TDM type daughter board, which accepts time-division multiplexing signals through fiber optic cables and then outputs the data as electrical signals to the main board. We will then report the performance of the 8-channel daughter board.

2. HARDWARE DEVELOPMENT

2.1 Main Board

The core processor board or main board is a 3U CompactPCI/PXI module. The modular architecture allows multiple modules to be assembled into larger data acquisition systems. Its main components are: a FPGA (Xilinx Spartan-3A DSP), a 32 Mega deep by 16-bit wide DDR SDRAM, a PCI Interface (PLX9054), board-to-board connectors for interfacing to daughter boards, and backplane connectors. Fig. 1 shows the block diagram of the main board (left) and its top view (right). The FPGA acts as the “heart” of the main board by performing the following tasks: 1) communicating to the daughter board for booting its FPGA, configuring control registers and accepting digital data for processing; 2) processing pulse data from daughter board in real time using algorithms that we developed earlier [3,4]; 3) reading or writing list mode and histogram data to the DDR SDRAM; and 4) communicating to the host PC through the PCI interface. The main board FPGA runs at 100 MHz, and that allows it to process data from multiple microcalorimeter pixels through an interleaving mechanism.

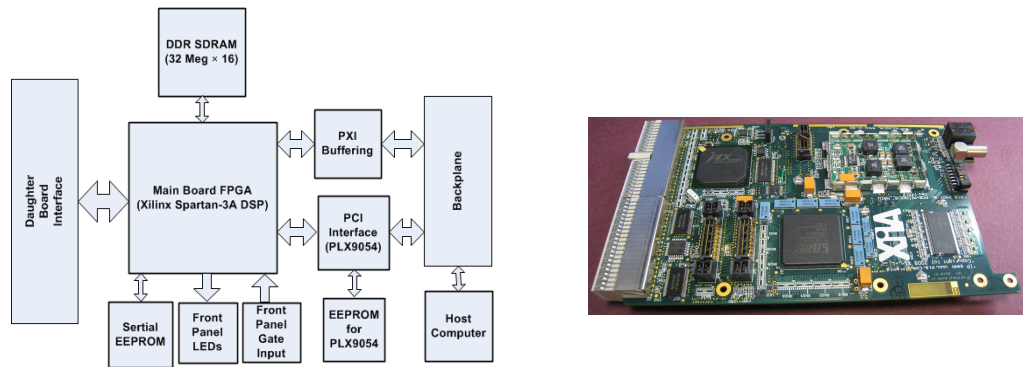


Fig. 1. (a left) Block diagram of the main board. (b right) top view of the main board.

2.2 An 8-channel daughter board (MicroCAL-A8)

The first daughter board variant that we developed is an 8-channel board for interfacing to microcalorimeters with individual analog outputs, the MicroCAL-A8. A block diagram of this daughter board is shown in Fig. 2. Each channel is equipped with one 16-bit ADC with the digitization rate of 913 kHz. The digitization rate can also be divided by a factor of 2^N , where N varies from 0 to 9, allowing digitization rates from 913 kHz to 1.78 kHz. The input voltage range of the ADC is 0 to +5V. Each board has two gain stages. The first, in the analog signal conditioning stage, has a fixed gain of 3.65. The second is in the ADC itself, whose reference voltage can be adjusted through a 12-bit Gain DAC. The Gain DAC provides two independent reference voltages: one used for channels 0, 2, 4 and 6 and the other for channels 1, 3, 5 and 7. The final gain is the product of these two gains stages and has a range of 3.65 to 14.61. Four dual Offset DACs provide a total of eight independent offsets that can be adjusted from -5V to +5V in 65536 steps. The input impedance of each channel can be set to either 50 Ohm or 1.37k Ohm through on-board jumper switches.

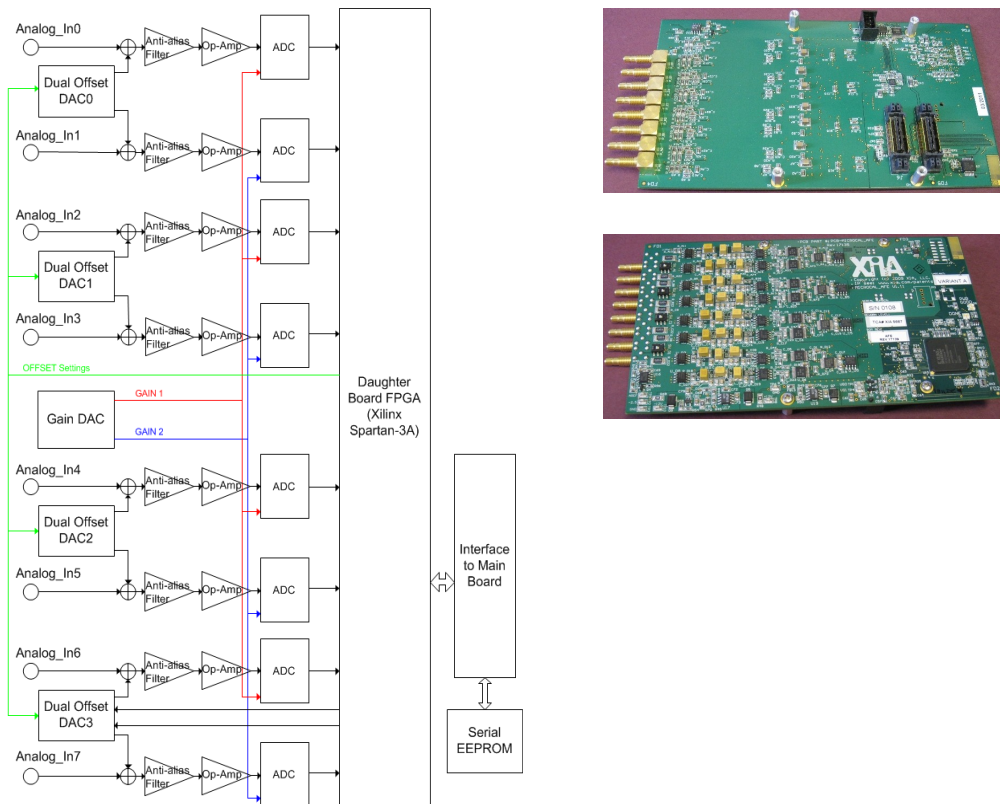


Fig. 2. (a left) Block diagram of the MicroCAL-A8. (b right) top and bottom views of the MicroCAL-A8.

This daughter board, when coupled with a main board to form a single-slot wide 3U PXI card, supports recording raw pulse records to disk, either in triggered mode or free running mode. Each of the 8 board channels has a 2 Mega-word block (16-bit wide) in the DDR SDRAM for storing pulse records that, at the highest ADC sampling rate of 913 kHz, translates into about 2.3 seconds of storage space for each channel. Because the main board supports reading previous pulse records from the memory to host computer while new pulses are being recorded, continuous data acquisition is possible.

2.3 A TDM type Daughter Board (MicroCAL-T128)

The second daughter board variant that we developed, MicroCAL-T128, interfaces to a digital feedback board (DFB), which is a time-division multiplexing read out board developed by NIST [2]. A multiplexed data stream is sent out by the DFB via a fiber optic cable and is received by one of the six optic receivers on the MicroCAL-T128. Fig. 3 shows the block diagram of the MicroCAL-T128 and a picture showing the combination of a MicroCAL-T128 and a main board in a 3U PXI crate. In the picture, test signals from two on-board optic transmitters are being fed back to two front panel optic receivers for self-testing. Depending on the number of microcalorimeter pixels that are multiplexed on each fiber optic cable from the DFB, each MicroCAL-T128 can accept data from up to 5 optic cables (the sixth one is used for synchronization between the DFB and daughter board), up to a maximum of 128 multiplexed channels.

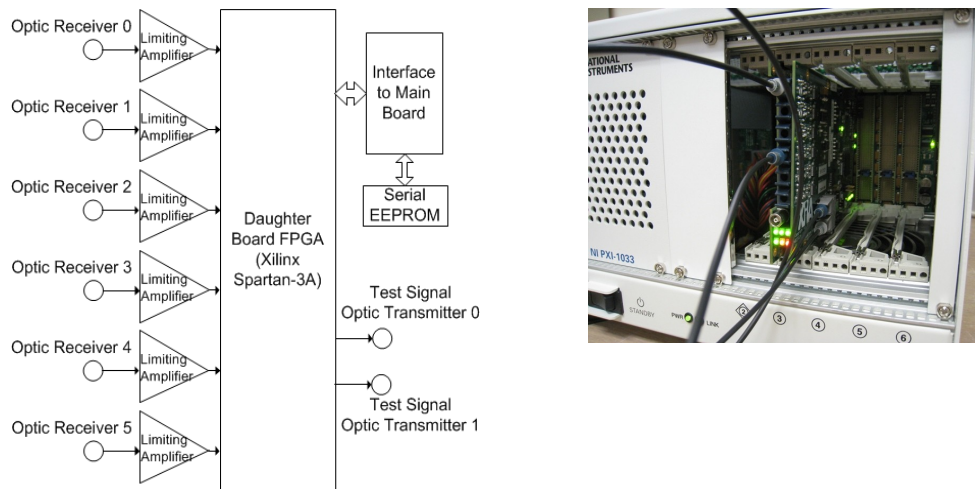


Fig. 3. *(a left)* Block diagram of the MicroCAL-T128. *(b right)* MicroCAL-T128 coupled to a main board and installed in a 3U PXI crate.

3. MicroCAL-A8 PERFORMANCE EVALUATION

We report here the performance of the MicroCAL-A8 coupled to a main board, including its intrinsic noise, nonlinearity, and energy resolution. The performance of the MicroCAL-T128 will be reported elsewhere.

3.1 Intrinsic Noise Characterization

With no input signals connected, we took 10 ms ADC data on all 8 channels simultaneously at the digitization rate of 913 kHz. Fig. 4 shows the captured ADC data, which essentially illustrate the DC level noise of these 8 channels. A way to measure this DC level noise is to histogram the captured ADC data, and the 8 histograms for the 8 channels are shown in Fig. 5. The histograms demonstrate that the DC level noise of all 8 channels is equivalent to 6 ADC steps or less (peak-to-peak), with a majority of channels having a FWHM of only 2 to 3 steps. The data illustrate the extremely low intrinsic noise of the MicroCAL-A8, since 3 steps of a 16-bit 5V full range ADC only correspond to 229 μ V noise peak to peak.

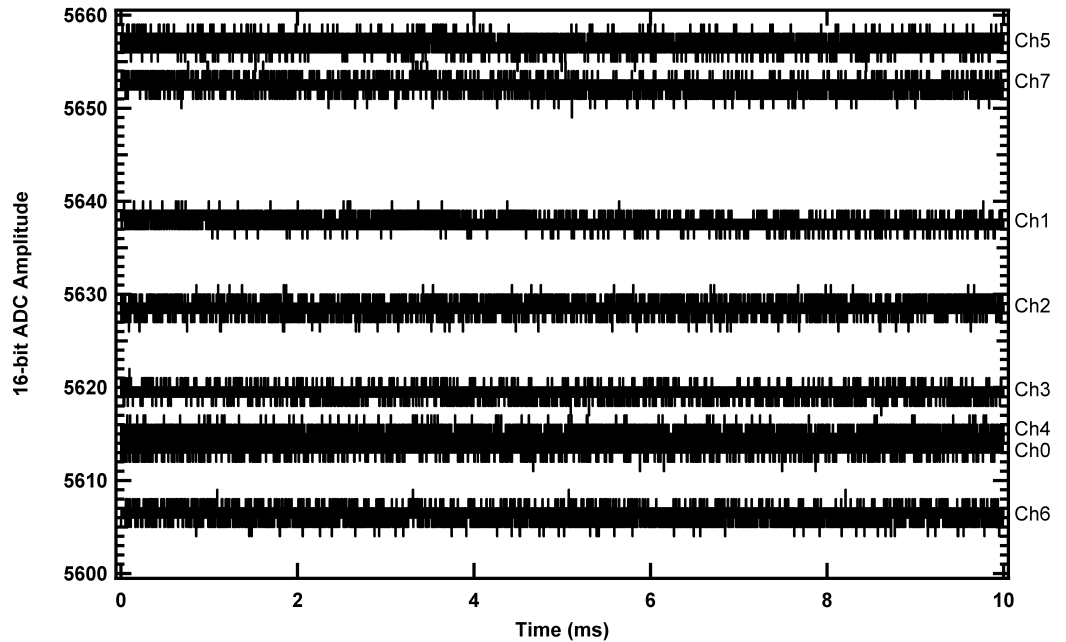


Fig. 4. ADC data captured on the MicroCAL-A8 when no input signal is connected.

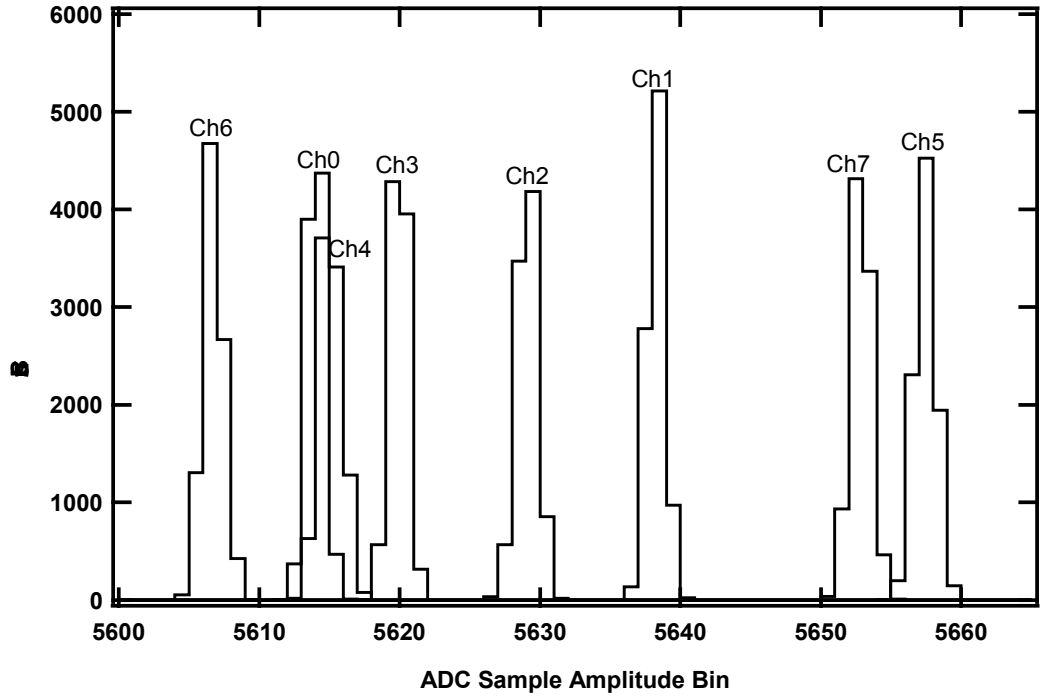


Fig. 5. Histograms of the captured ADC data for the MicroCAL-A8.

3.2. Nonlinearity Measurement

Microcalorimeter-like test pulses generated by an Agilent 3320A Arbitrary Waveform Generator (Fig. 6) were used to characterize the nonlinearity of the MicroCAL-A8 by adjusting the amplitude of the test pulses and measuring the resultant peak positions in the MCA histograms for all 8 channels. After plotting measured peak position versus input signal amplitude, linear fits were performed. Both the linear fits and their residuals are shown in Fig. 7, where we find that the MicroCAL-A8 has excellent linearity, with the residuals typically below $\pm 0.1\%$.

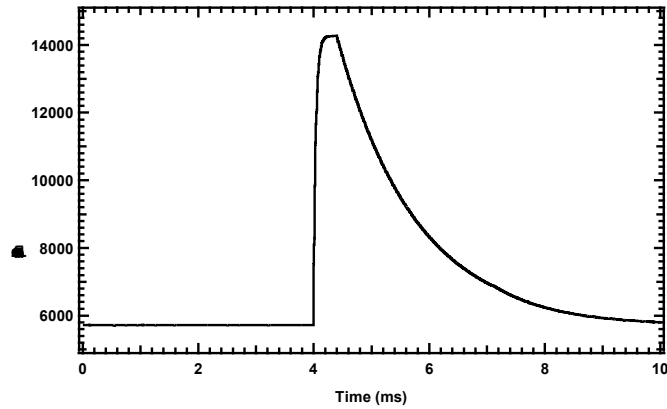


Fig. 6. Microcalorimeter-like test pulse generated by an Agilent 3320A Arbitrary Waveform Generator.

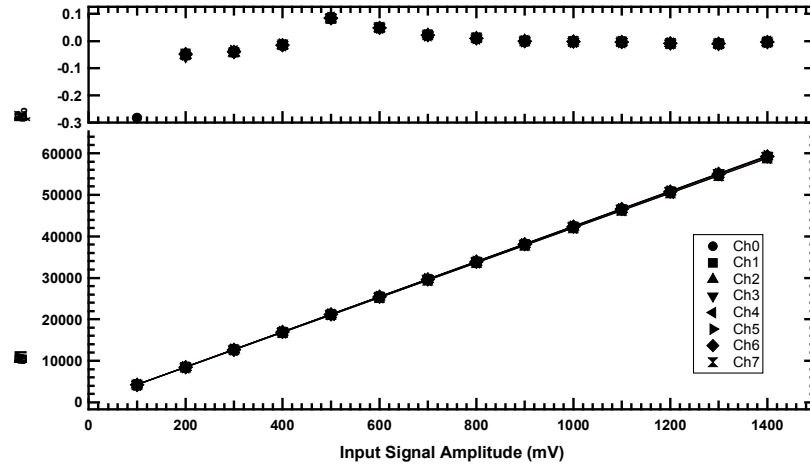


Fig. 7. (bottom) Measured peak positions versus input signal amplitudes for all 8 channels, (top) residuals of linear fits.

A further test of the ADCs' nonlinearity was conducted by using a fixed-amplitude input test pulse whose amplitude spanned $\sim 30\%$ of the 5V ADC range and moving its DC offset level. The measured peak position versus the ADC DC offset or baseline level for one of the 8 channels is presented in Fig. 8. It shows that as the input test pulse moved up towards the upper limit of the ADC range, the measured peak position gradually shifted downwards. However, the downward shift is less than 0.1% at all baseline levels, again illustrating the MicroCAL-A8's excellent linearity.

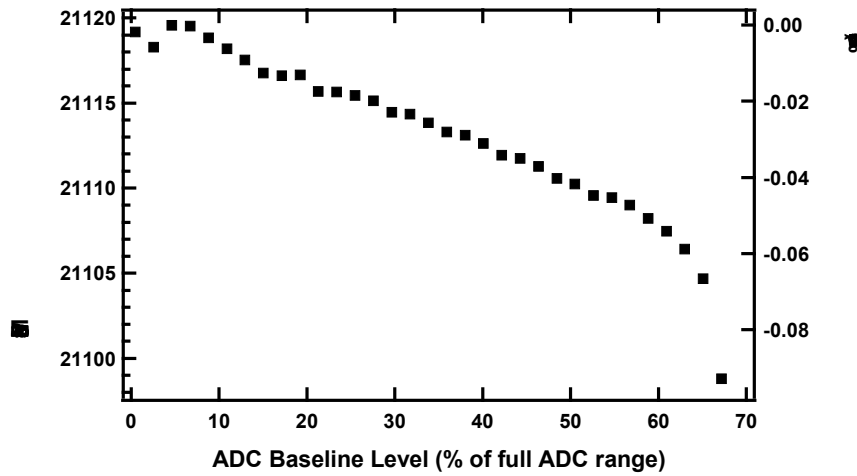


Fig. 8. Measured peak position versus ADC baseline level.

3.3 Energy Resolution

The MicroCAL-A8's energy resolution was also measured with test pulses. Fig. 9 shows 8 MCA histograms accumulated in real time in the main board from the 8 channels and their respective energy resolutions after Gaussian fits on the energy peaks. All 8 channels showed excellent energy resolution at $\sim 0.0085\%$ FWHM. The slightly different peak positions can be attributed to the channels' slightly different gains. In order to better match gains between channels, we are developing a digital gain correction function in the main board FPGA, which can digitally correct for the small gain difference between channels so that all of their MCA spectra can be directly added into a sum spectrum for better statistical analysis.

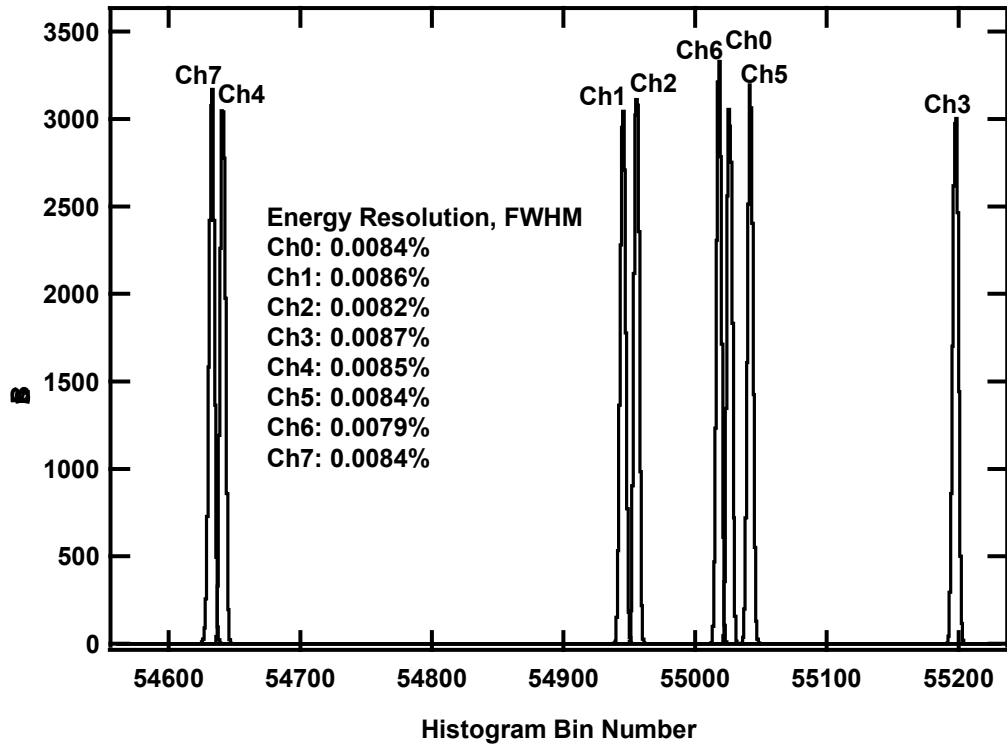


Fig. 9. Measured MCA histograms and their fitted energy resolution with test pulses.

We further characterized the energy resolution by measuring resolution as a function of the input test pulse amplitude. The results are shown in Fig. 10. As the test pulse amplitude increases, the energy resolution improves, as expected from the increased signal to noise ratio at the source. The improvement is seen to start saturating above about 400 mV, which suggests that the measurement was

approaching the energy resolution limit of the MicroCAL-A8 as a result of its intrinsic noise.

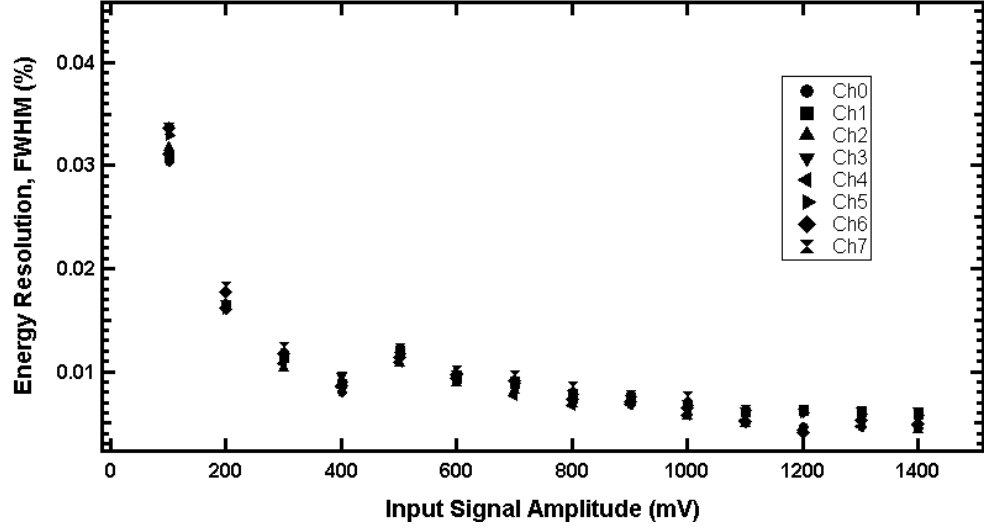


Fig. 10. Measured energy resolution versus input signal amplitude.

4. CONCLUSIONS AND OUTLOOK

We have presented a versatile digital signal processing module for instrumenting both small and large microcalorimeter arrays. The module consists of a main board where all digital signal processing occurs and a daughter board which can be designed to interface to a particular type of microcalorimeter read out system. Multiple modules can be combined into larger systems for microcalorimeter arrays with many channels. We characterized the performance of MicroCAL-A8, an 8-channel daughter board, which demonstrated extremely low intrinsic noise, excellent linearity and energy resolution from tests with a pulser. Our next step is to test this module with real microcalorimeter detectors.

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