Cross-strip HPGe Imaging Detector – Processing Electronics for Operation at 10^6 cps

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***Abstract*–We describe the development of an HPGe cross-strip detector with energy resolution intended for mouse heart imaging. The detector is designed with 2 mm wide strips, but is intended to achieve 300 μm spatial resolution by processing spectator strip signals. We review the design requirements that this implies and then describe in detail the 16 channel, 12 bit, 100 MHz digital spectroscopy module that we have developed to achieve these goals.**

I. Introduction

MURINE (mouse) models are widely used in cardiac research, with hundreds of studies funded by the NIH each year alone, and a popular both because mice can be provided with carefully controlled genetic backgrounds and also because, being short lived, they can provide useful information on a convenient time scale. Physiological parameters of interest include heart wall thickness, chamber clearing time, and responses to various drug treatments. Measurements are typically made by injecting a bolus of radioactive tracer into a vein and then imaging this material as it is pumped into and out of the heart.

From an experimental point of view, however, imaging beating mouse hearts in real time is a non-trivial issue. The typical mouse heart is approximately 3 mm across and beats at about 10 Hz. Therefore, in order to make useful observations, it is necessary to form images with approximately 100 μm spatial resolution at about 10 ms/frame (i.e. 10 frames/beat). Estimating that it will take at least 10,000 photons to produce an adequate image, this implies that our detector electronics need to be able to process counts at nearly 10^6 counts/sec.

Our proposed experimental approach is therefore as follows: first, we propose to image the heart using a pinhole camera operating in magnifying geometry, which relaxes the detector resolution requirement to between 200 and 300 μm; second, we propose to design the detector to operate using 35 keV x-rays from various Iodine radiotracers; third, we will design our detector to operate with reasonable energy resolution and use the signals on nearest neighbor spectator strips to achieve resolution that is smaller than the width of the detector strips. The reasoning behind these choices is to minimize the contribution of Compton scattering in our images, which will allow us to achieve good signal to noise with the smallest number of processed counts. In particular, by operating at 35 keV we significantly reduce Compton scatter in both the mouse being imaged and in our detector as well. Then, by applying energy cuts on detected photons, we can remove those Compton scattered photons that do occur.

In the remainder of this paper we will describe our progress in developing this detector system. In Section II we will describe the detector, its mode of operation, and the signals it generates. In Section III we will examine the requirements the detector signals pose for the processing electronics and describe the electronics that we have produced to condition the signals for downstream digital processing. In Section IV we will then describe the 16 channel "Pixie-16" digital processing modules that we have produced to instrument the detector and whose operation is this paper's primary focus.

II. Crossed Strip HPGe Imaging Detector

Fig. 1 shows our detector, which is 1 cm thick HPGe, fabricated for us by Paul Luke's group at LBNL. The front end FETs, feedback capacitors and isolation capacitors may also be seen on the PC boards attached to the frame of the detector's cryostat holder. The 10 strips, 2 mm by 25 mm with 500 μm spaces, are the active area and are surrounded by a

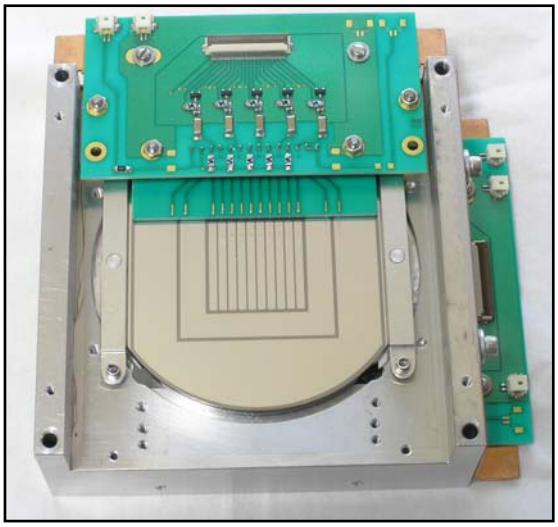

Fig. 1. Crossed strip HPGe imaging detector in its cryostat holding frame and showing the front end electronics with wirebonds to the detector.

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guard ring. The contacts on the rear are identical but rotated by 90°. Operating temperature is about 85°.

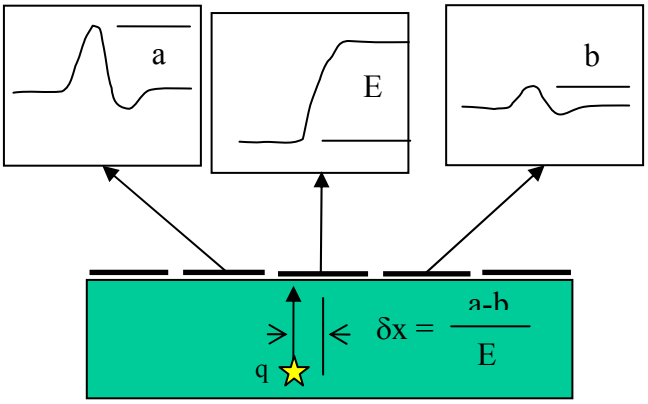

Fig. 2. Charge collection in the crossed strip HPGe imaging detector, showing how spectator strip signals are used to interpolate photon location.

Fig. 2 shows the signals that are induced on the detector's strips by the charge generated by a photon absorbed under the left hand side of the central strip electrode. The amplitude of the preamplifier output signal from this strip is proportional to the photon energy. Transient signals are generated in that strip's nearest neighbors that last only for the duration of the charge collection process, about 40 - 50 ns. The difference of the amplitudes of the two signals, scaled by the energy, can be shown to be proportional to the location of the photon, measured from the center of the strip [1]. The maximum amplitude of these signals is about 30% of the energy value (i.e. 12 keV at 35 keV) and they must be measured to the same accuracy as the desired interpolation – 10% if 200 μm resolution from 2 mm strips. Taken together, this implies that the spectator signal noise must be less than 1 keV, which lead to our preamplifier design using cooled front end FETs.

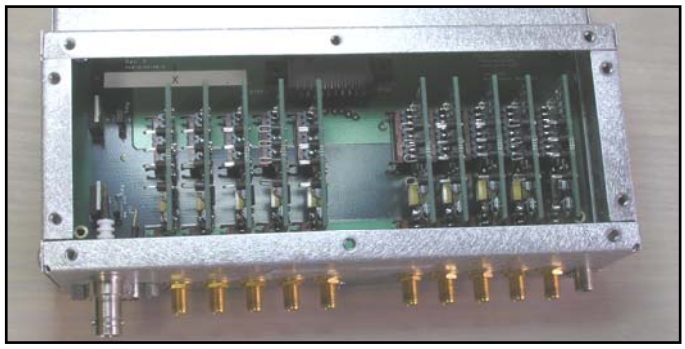

Fig. 3. Preamplifiers for one side of the detector, in shielded enclosure.

Our preamplifier design therefore separates the front end FET, feedback capacitor and resistor and AC coupling capacitor from the body of the preamplifier, which is fabricated using discrete components on small PC cards that measure approximately 2.5 cm by 4.0 cm. Fig. 3 shows the set of 10 preamplifiers required for one side of the detector, mounted in a shielding enclosure. These preamplifiers have a risetime of about 7 ns and have a measured noise of 1.1 keV, very close to our design goal. Figure 4 shows the detector, behind its IR shielding and inside its vacuum housing, with the two preamplifier enclosures mounted directly outside. Signals are routed from the cooled front ends to the preamplifier cards using flat, shielded ribbon cable, as shown.

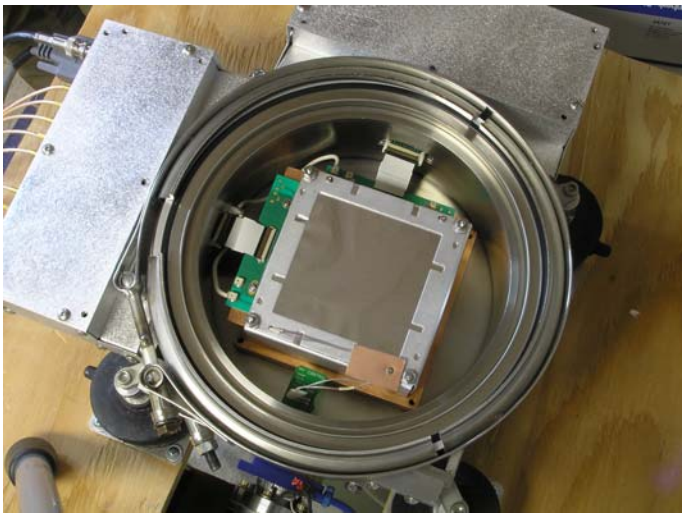

Fig. 4. Charge collection in the crossed strip HPGe imaging detector, showing how spectator strip signals are used to interpolate photon location.

We are currently engaged in initial experimentation with our first detector, which does not appear to deplete properly and so has not yet produced any real spectator signals. We are postponing the design of our spectator signal processing electronics until we are actually able to view these signals, since our options may be constrained by their speed and amplitude. Since we are expecting their total duration to be 50 ns or less, we cannot digitize them directly at 100 MHz and hope to capture their maxima accurately enough for our requirements. We are presently contemplating two possible approaches. The first is to reduce their bandwidth by filtering, which may be able to stretch them far enough for our peak capture needs. This filtering will further reduce their amplitudes, but may also reduce their noise enough to compensate. In this case the difference $(a-b)$ would be formed digitally after digital peak capture. The second is to build a preprocessing circuit that will take the difference of nearest neighbor signals and then implement a resettable peak capture and hold circuit (i.e. the value $(a-b)$ shown in Fig. 2. Some experimentation will be required to devise the optimum approach.

III. Digital Processing Requirements

The system's digital processing requirements fall into three general areas: signal capture, data extraction, and image generation. Our design approach was to develop a single processing module that, using a single set of hardware, but with appropriately modified firmware, could do all three.

A. Signal Capture

Assuming that we implement the analog peak capture and hold circuit for capturing spectator signal differences, then we

will need 40 channels of processing electronics – 20 for capturing and processing energy values and 20 for capturing and processing spectator peak difference values. Further, because x and y position information are carried by different sides of the detector, and also because of the possibility of charge sharing between neighboring strips, data capture must occur in coincidence mode so that all traces belonging to the same event are correctly identified and labeled as such. Because of the high contemplated data rates, the most preferable approach is for the coincidence detection to occur in real time and for the electronics to produce a single record per event, including measured energies from top and bottom strips and their associated spectator amplitude differences, and thereby eliminating any need for later data sorting.

B. *Data Extraction*

While the electronics might capture traces for all events and save them for later processing, this approach is not acceptable at 10^6 counts/sec. Our electronics will therefore provide digital filters to immediately extract energy values (E_x, E_y) and times of arrival (t_x, t_y) (to measure of interaction depth) from the strip signals and amplitude differences $(\Delta A_x, \Delta A_y)$ from the spectator signals. Since these values will typically be generated in different processing modules, the data collection system also requires the capability of assembling them into a single event record $(X, E_x, t_x, \Delta A_x; Y, E_y, t_y, \Delta A_y)$ for image processing, where X and Y identify the locations of the central, charge collecting strips.

C. *Image generation*

It would also be useful to be able to use the event records to generate images in real time. This involves the following steps/ First: validating the event by comparing the x and y energies $(E_x; E_y)$, which should be equal. Second, using $(X, \Delta A_x; Y, \Delta A_y)$ to compute the interpolated event location $(X + \Delta X; Y + \Delta Y)$. Third, generating images in memory. We expect the images to be relatively small – 64x64, with 200 μm pixel dimensions, which is about 8 KB/energy slice. This will be a novel feature of the detector, producing images whose photon energies lie within specific energy regions. Since our energy resolution is expected to be about 1 keV, this is a good starting estimate for the energy slice width ΔE. Assuming 32 energy slices, the total memory required for image storage is 256 KB. To output the entire image in real time at the expected rate of 100 frames/sec then requires a data transfer rate of 25 MB/sec.

IV. PIXIE-16 PROCESSING MODULES

A. *Module characteristics*

To meet the requirements laid out in Section III, we have designed and produced a 16 channel PXI module in a 6U format that we have dubbed the "Pixie-16". The major characteristics of the module include: fixed channel gain, 100 MHz 12 bit ADCs, considerable on board digital processing power through the use of large field programmable gate arrays

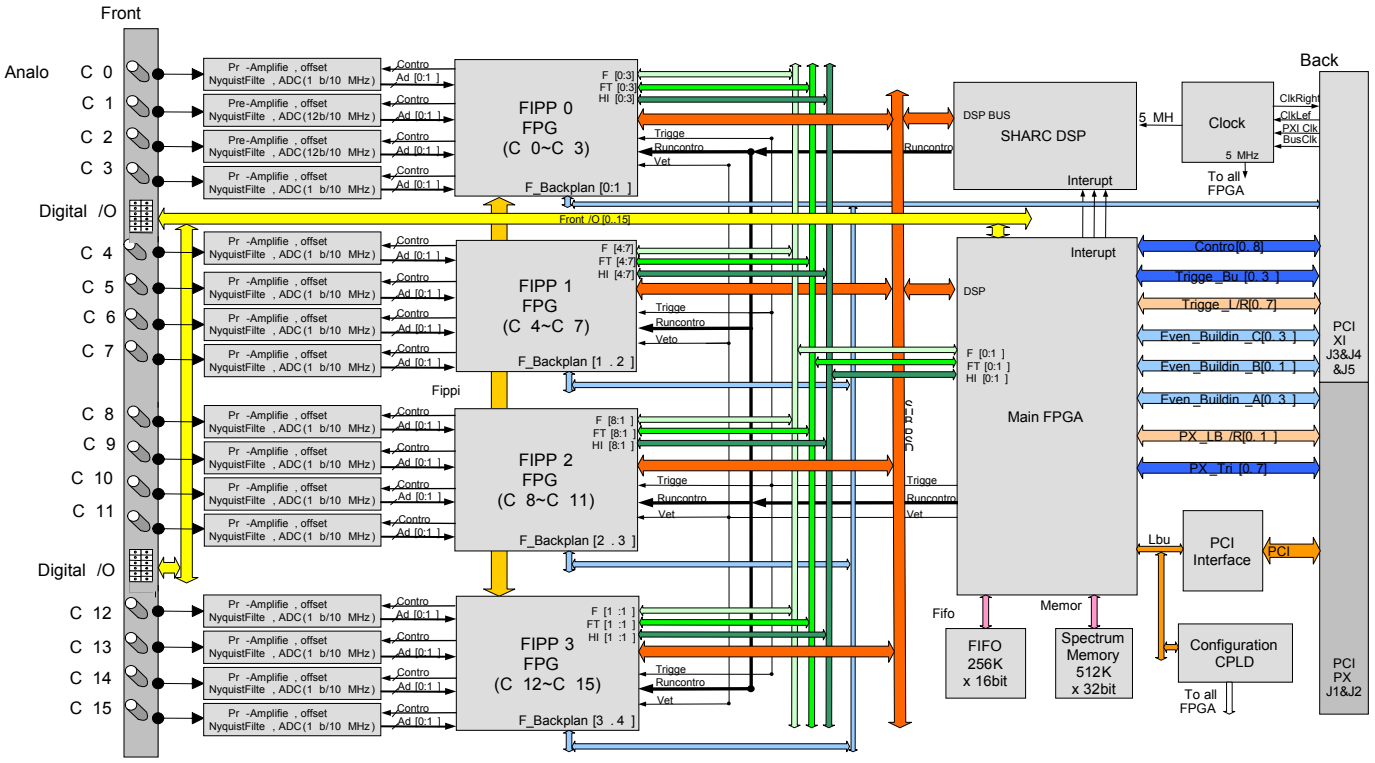

Fig. 5. Pixie-16 block diagram.

(FPGAs), and significant backplane resources for inter-module communication.

B. FiPPI Operation

As may be seen from Fig.5, the analog front ends and ADCs are arranged in groups of four per front end processing FPGA. As shown in the block diagram in Fig. 6, these "FiPPI" units contain fast filters with discriminators to identify the presence of pulses, energy filters, timing CFDs, and FIFOs to capture traces if need be. They internally inspect for pulse pileup and connect to each other and to the backplane via the Main FPGA so that they can use coincidence logic to decide whether or not to capture and store values in response to event detection. Baseline energy correction is implemented through the use of a separate baseline filter whose values are captured from time to time and used to estimate the baseline of the energy filter. In looking at the FiPPI operation, it is important to note that all the filters run continuously and that their output values may be captured in response to the event logic, which may respond to either local or external triggers.

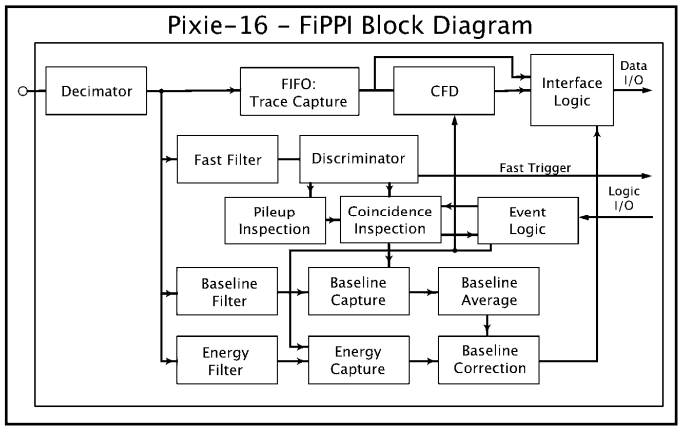

Fig. 6. Front end FPGA ("FiPPI") block diagram of a single channel.

C. FiPPI Timing

In our proposed operation, we will use the same modules both to capture energy values directly from the preamplifier outputs and also to capture spectator amplitude differences from differencing peak-capture-and-hold amplifiers. In this mode of operation, the channels that look directly at the strip outputs will act as masters and the channels that look at the spectators will act as slaves, only capturing values in response to triggers from the masters. Fig. 7 shows their respective signals.

In Fig. 7, "Trace" shows the signal arriving from a strip that is collecting charge, with "DISC" showing the FiPPI fast filter output. When this signal crosses threshold, a pulse is generated as shown and, a fixed time later a capture trigger is produced, as shown in "Pulse" and "Capture", respectively. The "E Filter" trace shows the energy filter's output. When sampled at the point of capture, its value is its length L times the amplitude A of the charge trace.

Meanwhile, the strip's neighboring spectators are producing the signals marked "Spec 1" and "Spec 2" and the output of the differencing peak-capture-and-hold is producing the "Δ Spec" trace. We note that, topologically, the signals "Trace" and "Δ Spec" are very similar and produce similar looking outputs "E Filter" and "Spec Max" from the FiPPI energy filters. Thus, if the slave module captures the output of "Spec Max" in response to the "Capture" trigger, we will obtain a value equal to L times the desired amplitude ΔH. Thus, simply by implementing appropriate triggering logic, we can use exactly the same modules to capture both energy and position data.

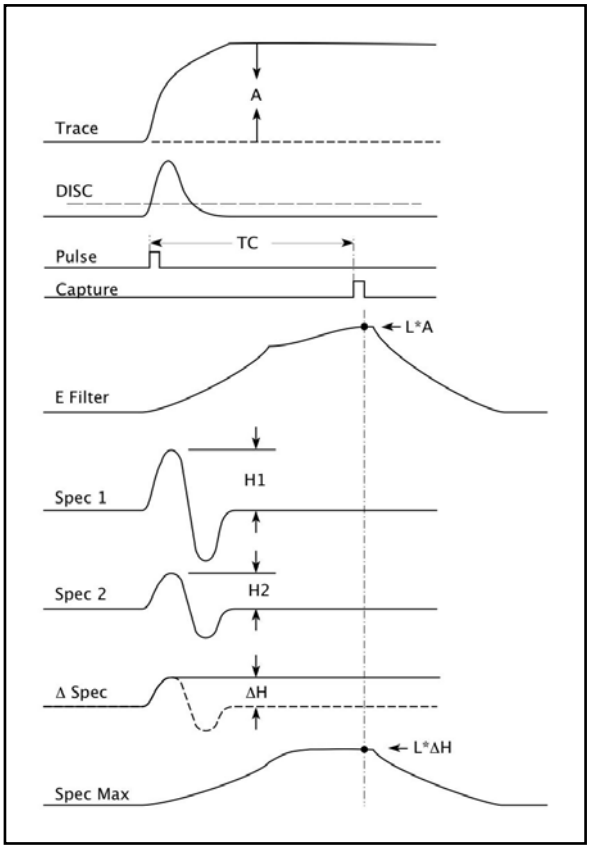

Fig. 7. FiPPI energy and spectator signals.

D. Data Collection System Organization

Using the Pixie-16s as the core of our data collection system leads to a detector system as shown in the block diagram in Fig. 8. Each detector strips, on both the top and bottom sides of the detector are attached first to their cold front end circuit and then to a preamplifier. The preamplifier outputs are fed into both a pair of "master" Pixie-16s that will process energy pulses and into a differencing peak-capture-and-hold module. The output of these modules are fed into a second pair of "slave" Pixie-16s that will capture these peak values under control of their associated master modules. The master and slave modules are collected via the backplane, which not only shares trigger signals between masters and slaves but also allows the masters to determine whether they are seeing events in coincidence and whether it is valid to generate capture signals. Following capture, the spectator amplitudes can be passed over the backplane to their masters,

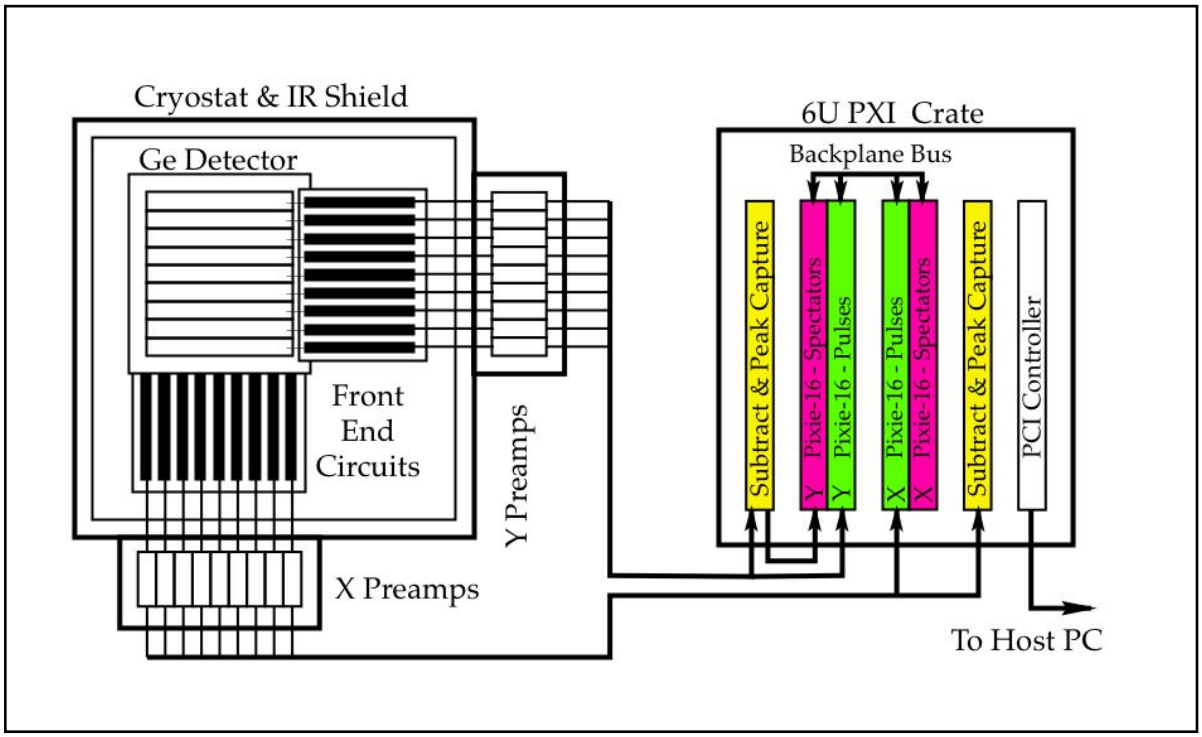

Fig. 8. Block diagram of the data collection modules for the complete detector system.

which can then assemble records of $(X, E_x, \Delta A_x)$ or $(Y, E_y, \Delta A_y)$ from the detectors top or bottom, respectively.

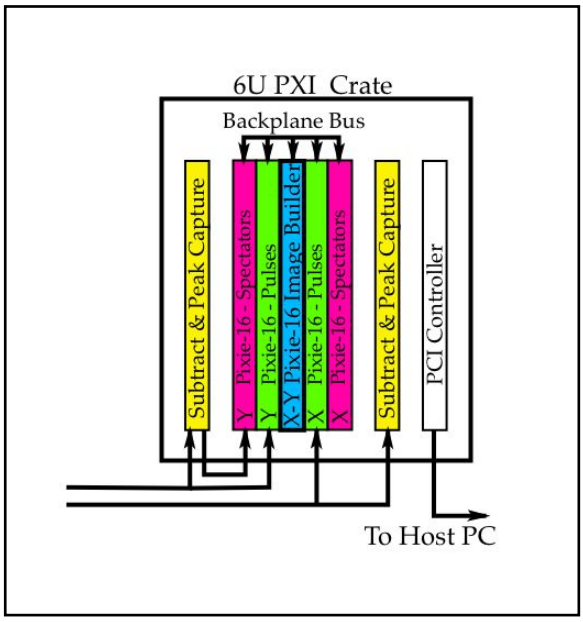

Fig. 9. Processing electronics with image building added.

In order to add image building capability, we need add only a single additional Pixie-16, as shown in Fig. 9. This module would not use its front end electronics and FiPPIs at all, but would have specialized firmware implemented in its Main FPGA to gather $(X, E_x, \Delta A_x; Y, E_y, \Delta A_y)$ data sets from its neighboring master modules over the backplane bus and then use its internal SHARC processor to compute image parameters and build the image using the onboard 512K spectrum memory (see Fig. 5). Since the PCI controller is capable of making block data transfers to the host at rates in excess of 100 MB/sec, the system will be fully capable of passing images to the host computer at the full 100 Hz frame rate.

V. Conclusions

Capturing energy resolved, single photon counting images at 10^6 cps and 100 Hz frame rates is a challenging proposition. To meet this challenge we have designed and constructed a 16 channel PXI digital spectrometer/data processing card. This card has 1) the capability of capturing pulse parameters in real time; 2) a rich set of trigger logic and inter-module communication features; and 3) sufficient computation resources; so that, with appropriate firmware implementations, it can satisfy all the needs of our high speed imaging system.

References

[1] W.K. Warburton, "An approach to sub-pixel spatial resolution in room temperature x-ray detector arrays with good energy resolution" in *Semiconductors for Room Temperature Radiation Detector Applications II*, Eds. R.B. James *et al.*, Materials Research Symp. Proc. **487**, 531-535 (1998).