High Density Low Cost Readout Electronics for Large Scale Radiation Detectors

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DOE Office of Science, Office of Nuclear Physics

Presenter: Dr. Stephen Asztalos, XIA LLC
Motivation

• Large scale nuclear physics experiments with hundreds or thousands of detector channels
  – Existing off-the-shelf readout electronics prohibitively expensive
  – Need for high density, low cost readout electronics with good linearity, timing and energy resolutions

• Recent improvements in the design of commercial ADCs have resulted in a variety of multi-channel ADCs that are natural choice for designing such high density readout modules
  – 4 or 8 channels integrated on a single chip
  – 10 to 16 bits and 40 to 250 MSPS sampling rates
  – Consume power as low as ~50 mW per channel
Large Scale NP Detectors

- **Booster Neutrino Experiment (BooNE) at Fermilab**
  - Investigate the question of neutrino mass by searching for oscillations of muon neutrinos into electron neutrinos
  - MiniBooNE, the first phase of BooNE, uses a single detector which is a large tank of 800-ton mineral oil liquid scintillator and viewed by 1280 photomultiplier tubes >1280 readout channels needed

- **Absolute Luminosity For ATLAS (ALFA)**
  - Each detector module consists of ten layers of two times 64 scintillating fibers each
  - The fibers are coupled to 64-channel Multi-Anodes PMTs
  - The total number of channels is about 15000

- **GRETINA, the first stage of a full Gamma-Ray Energy Tracking Array (GRETA)**
  - A large number of auxiliary detectors are planned for GRETINA, e.g. silicon and scintillation particle detectors and gas counters
SBIR Project objective is to develop a high channel count, low cost, and versatile digital readout module for large scale nuclear physics radiation detectors

- "Pixie-32": a 32-channel digital gamma-ray spectrometer
- Target price per channel will be only $200-$300 while it will still be a true spectrometer
- Implement a PCI Express interface (up to 1 GB/s) on Pixie-32 modules (versus the regular 100 MB/s PCI interface on Pixie-4 and Pixie-16)
## Technical Approach

<table>
<thead>
<tr>
<th>SBIR Phase</th>
<th>Tasks</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Verify capability of modern FPGAs to receive Gbit/s data streams from a multichannel ADC</td>
<td>Done</td>
</tr>
<tr>
<td>I</td>
<td>Estimate costs for different board architectures</td>
<td>Done</td>
</tr>
<tr>
<td>I</td>
<td>Verify multichannel ADCs for spectroscopy quality</td>
<td>Done</td>
</tr>
<tr>
<td>II</td>
<td>Finalize architecture for the Pixie-32 spectrometer</td>
<td>Done</td>
</tr>
<tr>
<td>II</td>
<td>Draw design schematics and layout printed circuit boards</td>
<td>Done</td>
</tr>
<tr>
<td>II</td>
<td>Manufacture a small number of prototype boards</td>
<td>Done</td>
</tr>
<tr>
<td>II</td>
<td>Develop Pixie-32 FPGA firmware</td>
<td>Done</td>
</tr>
<tr>
<td>II</td>
<td>Develop PCI Express driver and API library</td>
<td>90%</td>
</tr>
<tr>
<td>II</td>
<td>Develop a user interface that can be used for 100’s or even 1000’s of data acquisition channels</td>
<td>In Progress</td>
</tr>
</tbody>
</table>

No-cost extension until November 2015
Integral Nonlinearity (INL) Tests of Multichannel ADC

- AD9432
- AFE5801 Ch0
- AFE5801 Ch1
- ADS6425 Ch0
- ADS6425 Ch1
- AD9222 Ch0
- AD9222 Ch1

Energy (keV)

Fitting Residual (keV)
Multichannel ADC Tests

Differential Nonlinearity (DNL) Tests of Multichannel ADC
8-Channel Variable-Gain Amplifier (VGA) With Octal High-Speed ADC

Eight Variable-Gain Amplifiers (VGA)
Variable Gain, –5dB to 31dB With 0.125dB or 1dB Steps
Digital Gain Control

Third-Order Antialiasing Filter With Programmable Cutoff Frequency (7.5, 10, or 14MHz)

Analog-to-Digital Converter (ADC)
Octal Channel, 12Bit, 65MSPS
Pixie-32 Prototype

- Analog inputs connector
- Mezzanine board connector
- DSP
- PXIe backplane connector
- AFE5801
- Artix-7 FPGA
- SDRAM
- PCIe
- PXIe backplane connector
Pixie-32 System Diagram

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Pixie-32 Prototype

32 single-ended analog signal inputs to the Pixie-32 front panel

Other types of cabling solutions are possible, e.g. ribbon cable connections to detector outputs

Pixie-32 in a PXIe chassis
Main Processor FPGA

• Utilized the latest FPGA technology, a 7-series Artix-7 FPGA from Xilinx, which offers low power, low cost and yet high performance, when compared to existing FPGA technology

• Firmware runs inside this Artix-7 FPGA
  – deserialize high speed serial data from ADCs
  – trigger and compute detected pulses' energy, time of arrival, and record raw waveforms for offline pulse shape analysis
  – communicate to host computer through a up to 800 MB/s PCI-express interface
32-Chan Logic in Artix-7 FPGA

- Four 8-chan groups of logic indicated by the four colored regions in the Artix-7 FPGA

- Slices utilization percentage is only 23% for 32 channels
DSP Slices in Artix-7 FPGA

• Utilized DSP slices in Artix-7 FPGA to compute pulse energy

• DSP slices have 25 x 18 multiplier, 48-bit accumulator, and pre-adder
Pixie-32 Test Software

- Software for booting up Pixie-32 boards
- Direct FPGA register read/write
- Data acquisition and display

Sample trace captured by Pixie-32
Phase II Remaining Tasks

- Complete the development of PCI Express driver and API library and the user interface software

- Test & Characterization
  - Characterize gamma-ray spectroscopy performance
  - Test Pixie-32 at collaborating laboratories
Characterized spectroscopy performance of multichannel ADCs

Finalized Pixie-32 board architecture

Designed and manufactured Pixie-32 prototype boards

Working to complete the development of firmware and software for the Pixie-32

Ongoing efforts to commercialize Pixie-32 as early as possible (orders already pending!)
## Multichannel ADC Tests

<table>
<thead>
<tr>
<th>ADC</th>
<th>#Chan</th>
<th>Rate (MSPS)</th>
<th>Bits</th>
</tr>
</thead>
<tbody>
<tr>
<td>AD9222</td>
<td>8</td>
<td>65</td>
<td>12</td>
</tr>
<tr>
<td>ADS6425</td>
<td>4</td>
<td>125</td>
<td>12</td>
</tr>
<tr>
<td>AFE5801</td>
<td>8</td>
<td>65</td>
<td>12</td>
</tr>
<tr>
<td>AD9432</td>
<td>1</td>
<td>100</td>
<td>12</td>
</tr>
</tbody>
</table>

Energy spectra from a 40% coaxial HPGe Detector and multiple radiation sources

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# Multichannel ADC Tests

## HPGe energy resolution (keV, FWHM)

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>AD9222 Ch0</th>
<th>AD9222 Ch1</th>
<th>ADS6425 Ch0</th>
<th>ADS6425 Ch1</th>
<th>AFE5801 Ch0</th>
<th>AFE5801 Ch1</th>
<th>AD9432</th>
</tr>
</thead>
<tbody>
<tr>
<td>122</td>
<td>0.92</td>
<td>0.92</td>
<td>0.98</td>
<td>1.08</td>
<td>1.15</td>
<td>1.16</td>
<td>0.84</td>
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<tr>
<td>661.6</td>
<td>1.34</td>
<td>1.36</td>
<td>1.36</td>
<td>1.43</td>
<td>1.55</td>
<td>1.55</td>
<td>1.28</td>
</tr>
<tr>
<td>1332.5</td>
<td>1.78</td>
<td>1.80</td>
<td>1.84</td>
<td>1.82</td>
<td>1.96</td>
<td>1.96</td>
<td>1.72</td>
</tr>
<tr>
<td>2614.5</td>
<td>2.39</td>
<td>2.44</td>
<td>2.47</td>
<td>2.52</td>
<td>2.64</td>
<td>2.63</td>
<td>2.36</td>
</tr>
</tbody>
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Multichannel ADC Tests

Timing resolution measured using a single LaBr$_3$/PMT detector and a $^{137}$Cs source. The output of the LaBr$_3$/PMT was split into two branches and then fed into two ADC channels.