Low Cost, High-Density Digital Electronics for Nuclear Physics

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SkuTek Instrumentation
SkuTek.com

Outline

- The company and its capabilities.
- Customers.
- Description of the Phase II project.
- Relevance to the NP program.
  - Our products are used at Fermilab, Oak Ridge, Los Alamos, MSU-NSCL, and LUX-Zepplin Dark Matter Search. All these were funded by the DOE.
  - We are focusing on collaborating with the ANL Physics Division.
- Example: The 40-Channel Digitizer and Its Performance With HPGe Detector.
- LUX-Zepplin DAQ Electronics.
- Plans.
- Questions for the NP community.

The company and its capabilities

- The team: two physicists, a junior electrical engineer, a senior software engineer, a part time engineering associate, and a manager.
- We worked with several interns listed on the Acknowledgement page.

Our focus:

Data acquisition (DAQ) for nuclear physics, high energy physics, and particle astrophysics.

We use digital techniques to acquire and process signals from nuclear radiation detectors.

Our capabilities:

- Electronic design.
- Firmware development for Field Programmable Gate Arrays (FPGA).
- Software development for embedded processors, especially Embedded Linux.
- Algorithms for pulse processing.
- Algorithm implementation in the FPGA (VHDL, Verilog) and in embedded processors (Pascal, Python, C).
- Processing data from nuclear detectors of any kind.
- Development of detector assemblies using scintillators, PMTs, or SiPMs.

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Our customers

UNIVERSITY of ROCHESTER

HOUGHTON COLLEGE

THE UNIVERSITY OF TENNESSEE KNOXVILLE

SFU SIMON FRASER UNIVERSITY ENGAGING THE WORLD

UNIVERSITÉ LAVAL

AUGUSTANA UNIVERSITY

Los Alamos National Laboratory

Fermilab

WIENER Plein & Baus, Corp.

Albert Einstein Center for Fundamental Physics

UNIVERSITÄT BERN

上海交通大學 SHANGHAI JIAO TONG UNIVERSITY

NSCL

National Superconducting Cyclotron Laboratory

BROWN

Brown University

Description of Phase II project

Problem or situation that is being addressed.

In Nuclear Physics there is need for cost effective, high density data acquisition (DAQ) systems with hundreds or even thousands of channels capable of signal acquisition and analysis.

How this problem or situation is being addressed.

We are developing digital DAQ modules with dozens of channels of waveform digitization, on-board FPGA, Ethernet, and USB interfaces, and running Linux on-board.

The deliverables.

- The products will range from simple table-top units to systems with thousands of channels.
- The table top units will serve small NP experiments, radiation detector development, or student labs teaching Nuclear Physics.
- Large systems will serve experiments conducted at DOE facilities, e.g., Facility for Rare Isotope Beams (FRIB), which is a new national user facility for Nuclear Physics.

Products for the NP Data Acquisition Systems

A modern digital DAQ is composed of digitizers and the Trigger / Logic modules. Both the digitizers and the Trigger/Logic are built around **ARM processors** and **Kintex-7**. The low density 10-channel digitizer is still using Spartan-6 (cost!).

High density digitizer: **40 channels**

Kintex-7

Low density standalone digitizer: **10 channels**

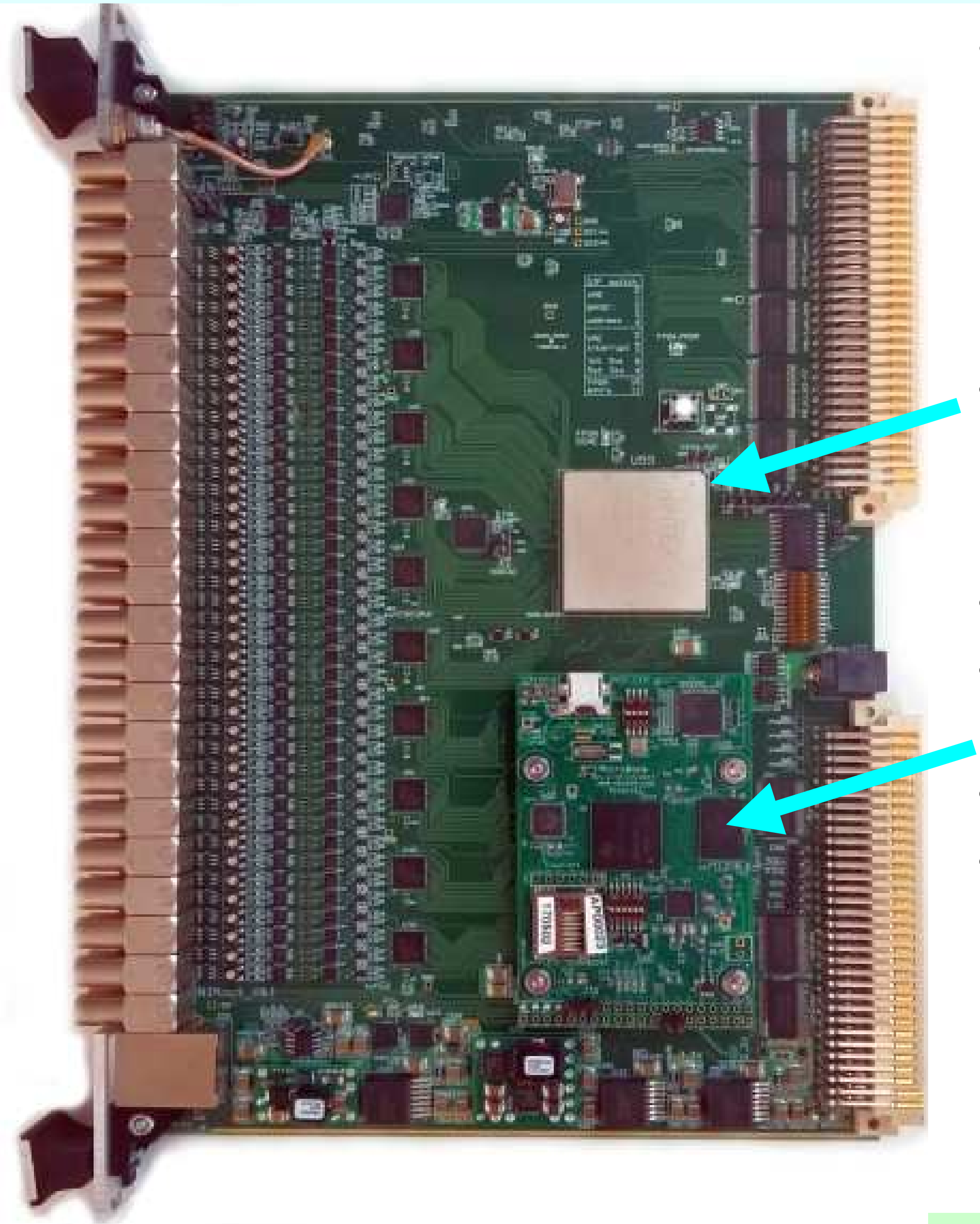
Spartan-6

LZ Trigger / Logic module

with ARM and Kintex-7

Kintex-7

Example: The DDC-40 Digitizer



- 40 ADC channels:
  - 100 MHz sampling rate
  - ADC chip resolution: 12, 14, or 16 bits
  - 2V input range
  - +/-1V adjustable baseline
- Kintex-7 Xilinx FPGA, two options:
  - XC7K325T: BRAM=1,780 kB (**228 μs/chan**)
  - XC7K410T: BRAM=3,180 kB (**407 μs/chan**)
- Temperature, voltage, current monitoring
- Embedded Linux Module with Ethernet, USB-2, and RS-232.
- Gigabit Ethernet with TCP/IP stack (Linux!).
- Remotely programmable:
  - Both the FPGA and the Linux Module
  - FPGA can be reprogrammed over Internet
  - Internal FPGA signals can be remotely accessed over Internet.

Performance of the 40-Channel Instrument With the HPGe Detector

GEM10P4-70; 10% Efficiency GEM Detector

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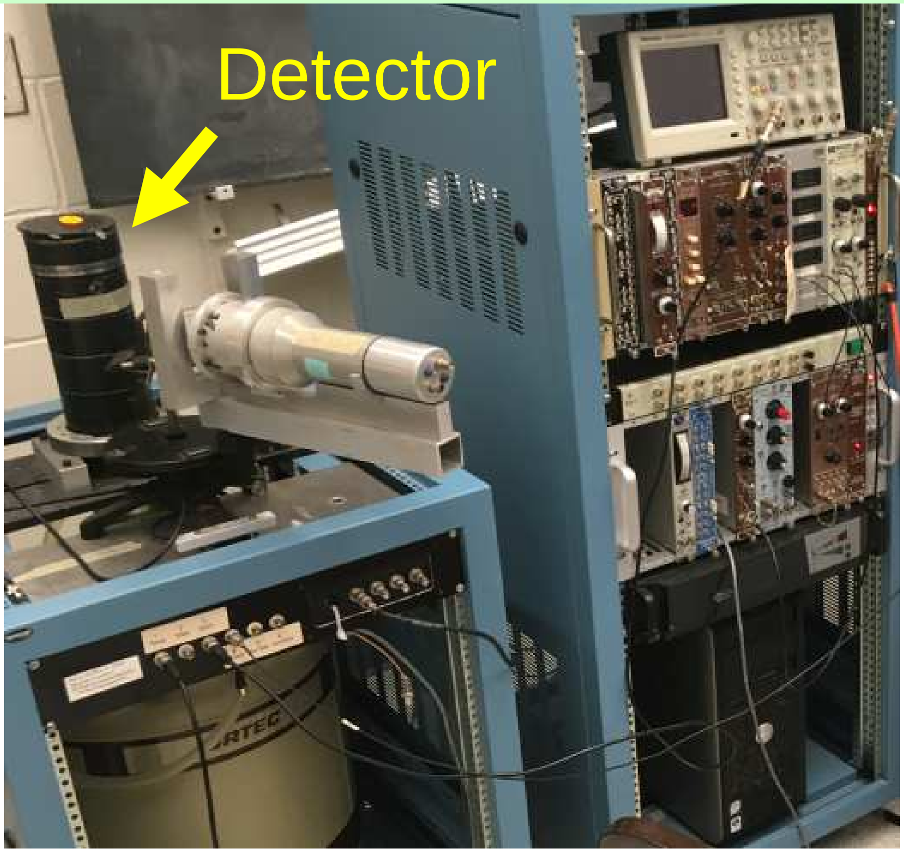


During the experiment the DDC-40 was operated in a standalone box and connected to a laptop with Ethernet.

The DAQ software was a standalone Python/Jupyter GUI running on the embedded ARM processor on board.

The event rate was kept low to avoid pileup.

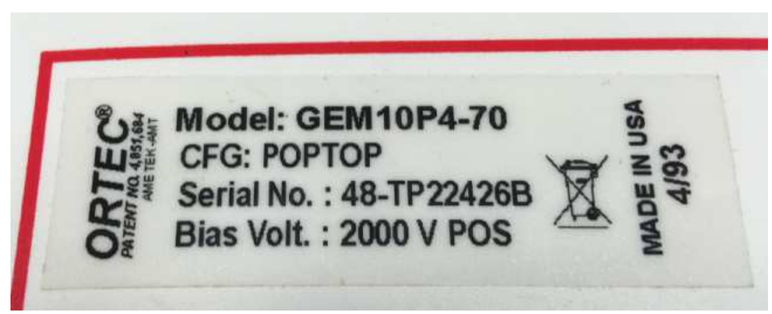
We recorded 2048 samples per event at ~400 events/s.

The events were written to the on-board SD card in binary “pickle” format by the Jupyter software.

The recording rate was ~1.6 MB/s. We captured ~54% of incoming triggers.

The preamp was connected directly to one of the DDC-40 inputs. Analog amplifier was used as a benchmark in the 2nd half of the experiment.

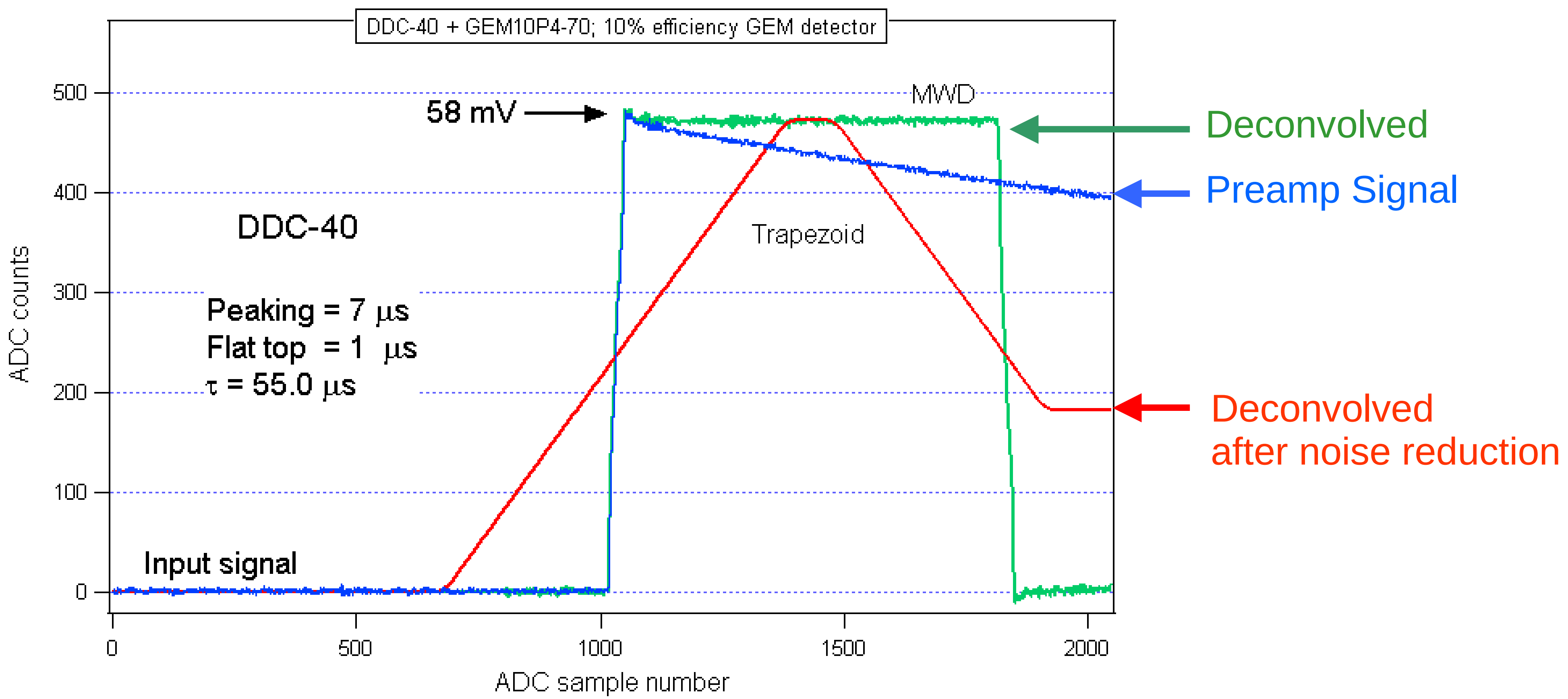
	Warranted	Measured	Amplifier Time Constant
Resolution (FWHM) at 1.33 MeV, ^{60}Co	1.93 keV	1.61 keV	6 µs
Peak-to-Compton Ratio, ^{60}Co	37:1	45:1	6 µs
Relative Efficiency at 1.33 MeV, ^{60}Co	9.0 %	9.9 %	6 µs
Peak Shape (FWTM/FWHM), ^{60}Co	1.90	1.83	6 µs
Peak Shape (FWFM/FWHM), ^{60}Co		2.41	6 µs
Resolution (FWHM) at 122 keV, ^{57}Co	880 eV	607 eV	6 µs



Offline Waveform Processing

- The RC-reset waveforms were processed with a Moving Window Deconvolution (MWD).
  - J. Stein et al, NIM B 113 (1996) 141
- The MWD signal was then shaped into a trapezoidal pulse to reduce noise.
- The pulse height was sampled within the flat part of the trapezoid.

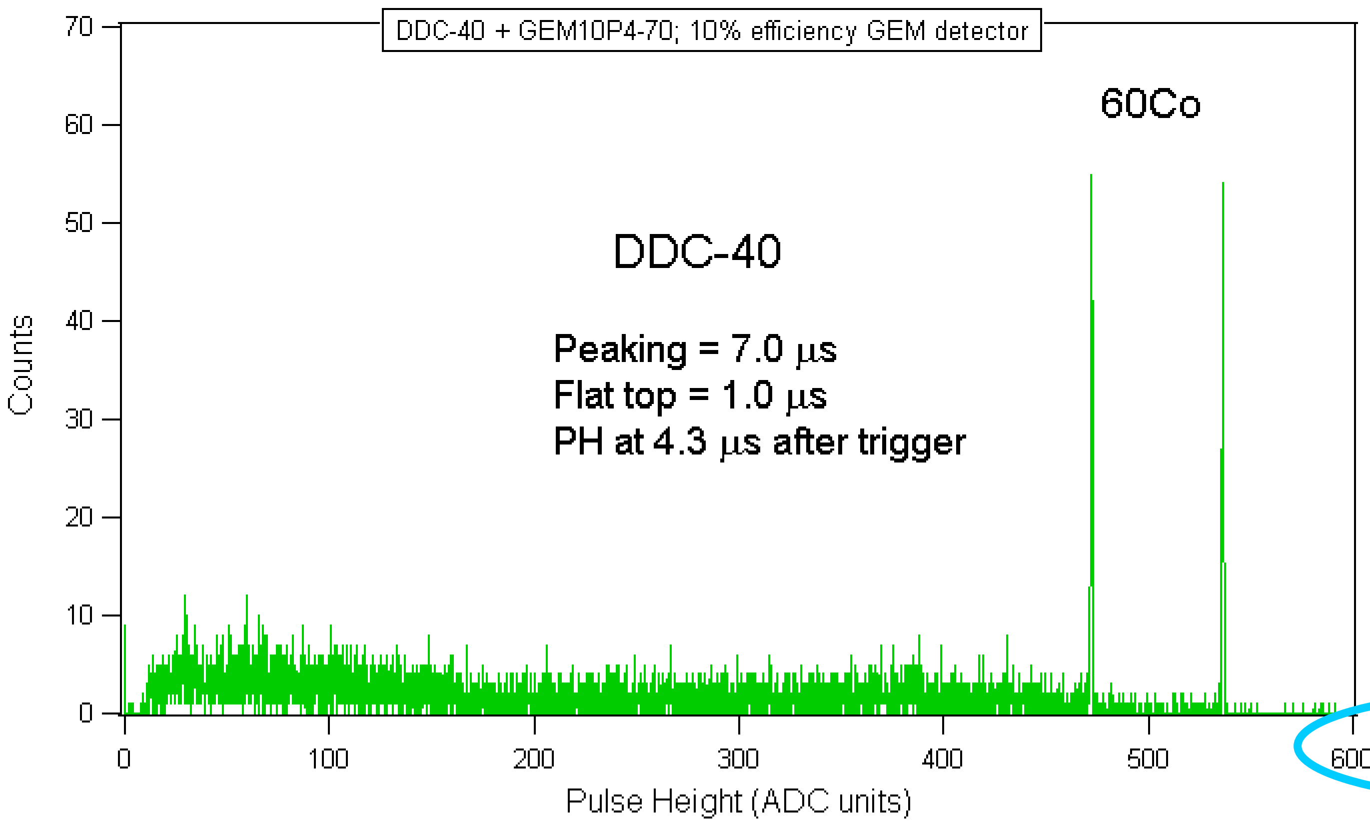
Fully Digital Signal Processing



^{60}Co Pulse Height Spectrum: Digital

- The pulse height (PH) histogram obtained from 10k digital waveforms is shown below.
- Notes:
  1. The preamp signal was digitized directly by the DDC-40.
  2. The dynamic range was **40.4 MeV** full scale.

Fully Digital Signal Processing



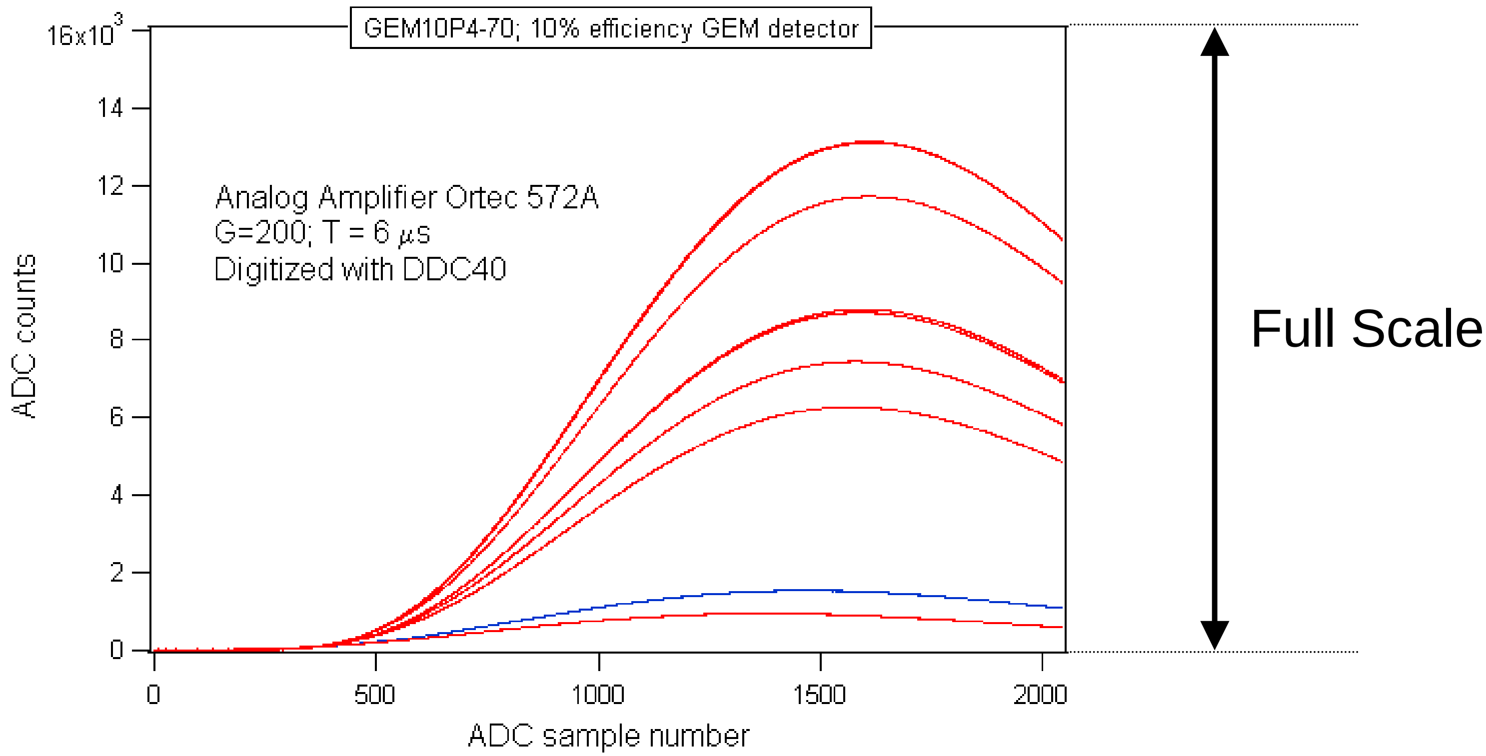
Full Scale
Is Far Away

3.7% of F.S.

Comparison With **Analog Pulse Shaping**

- Analog pulse shaping provided a benchmark: Ortec 572A Amplifier with nominal gain 200 and 6 µs shaping. The amplifier had an input impedance of 1 kΩ.
- Baseline was offset by -0.9 Volt (i.e., -7400 ADC counts) to maximize the dynamic range. The waveforms were numerically shifted back to zero for the offline display.
- The 1332 keV line was at ADC count 14,878 = 90.8% F.S. It means, that the 16k F.S. = **1.47 MeV**.
- The analog system was thus operated at the effective gain **27.5 times larger** than the digital system.
- We used DDC-40 as an ADC because we did not have access to any other “classic” ADC system.

Analog Signal Forming, Digitized With DDC-40



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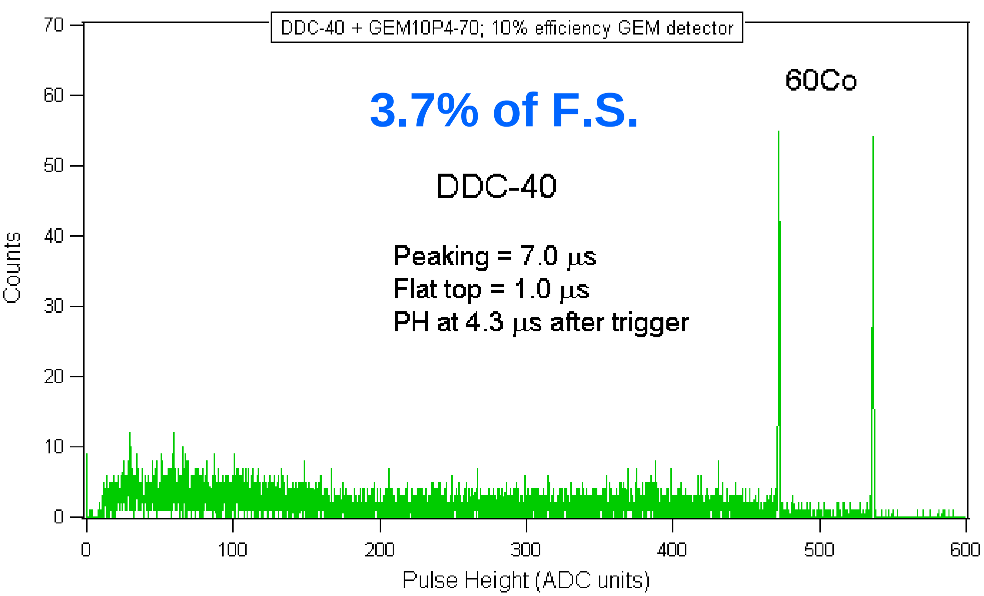
^{60}Co Pulse Height Spectrum: Analog

- The pulse height (PH) histogram obtained from 10k analog waveforms is shown below.
  1. The preamp signal was processed with Ortec 572A, nominal gain = 200, shaping = 6 μs.
  2. The 572A output was digitized with DDC-40 and recorded as waveforms.
  3. The 64-point smoothing was applied offline to suppress the remaining noise.
     - Such an averaging is not normally applied to peak sensing ADC results.
  4. The dynamic range was **1.47 MeV** full scale, smaller **27.5 times** than the digital system.
  5. Analog signal saturation is marked with an arrow.

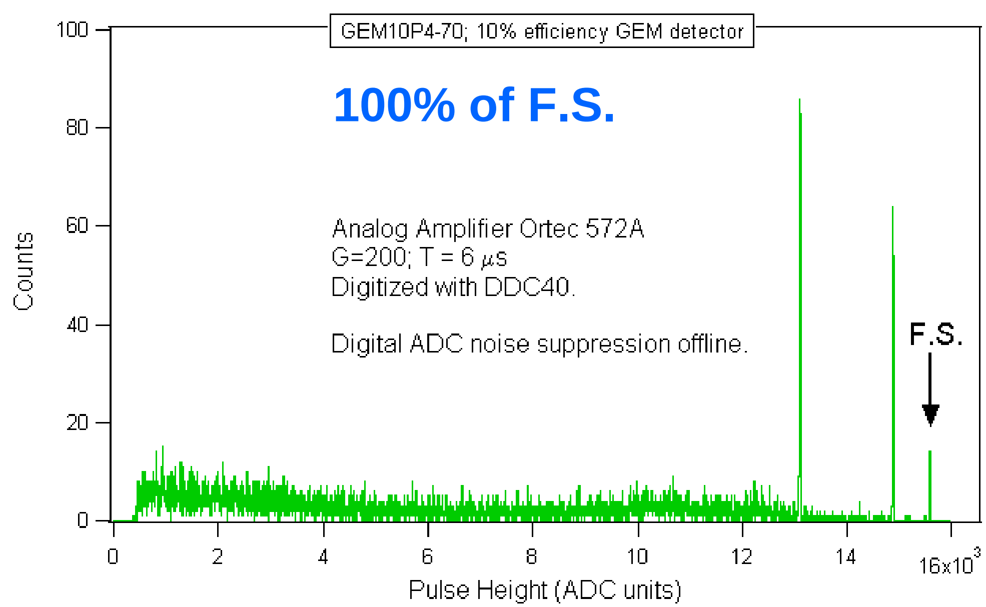
Fully Digital Signal Processing

Full Scale is **27x** this plot!



Analog Signal Forming

Full Scale covers the entire plot



Digital vs Analog Energy Measurement

- The digital FWHM of the 1332 keV peak was 3% worse than the analog FWHM.
- The analog results were obtained at 27.5 higher gain, and with an additional 64-point offline smoothing of the recorded analog waveforms.
- Such offline smoothing is never done with analog signals digitized with a peak sensing ADCs.
- We wanted to improve the analog resolution even beyond the capabilities of the Ortec amplifier.
- There is still room for improvement of our digital signal processing!

FWHM

γ-line	Digital @ **40.4 MeV** FS	Analog @ **1.47 MeV** FS
1173 keV	2.00 keV 11% worse	1.79 keV
1332 keV	2.04 keV 3% worse	1.98 keV

LUX-Zepplin DAQ Electronics Deployed at -4850’ This Summer

SkuTek DAQ Electronics for Dark Matter Search

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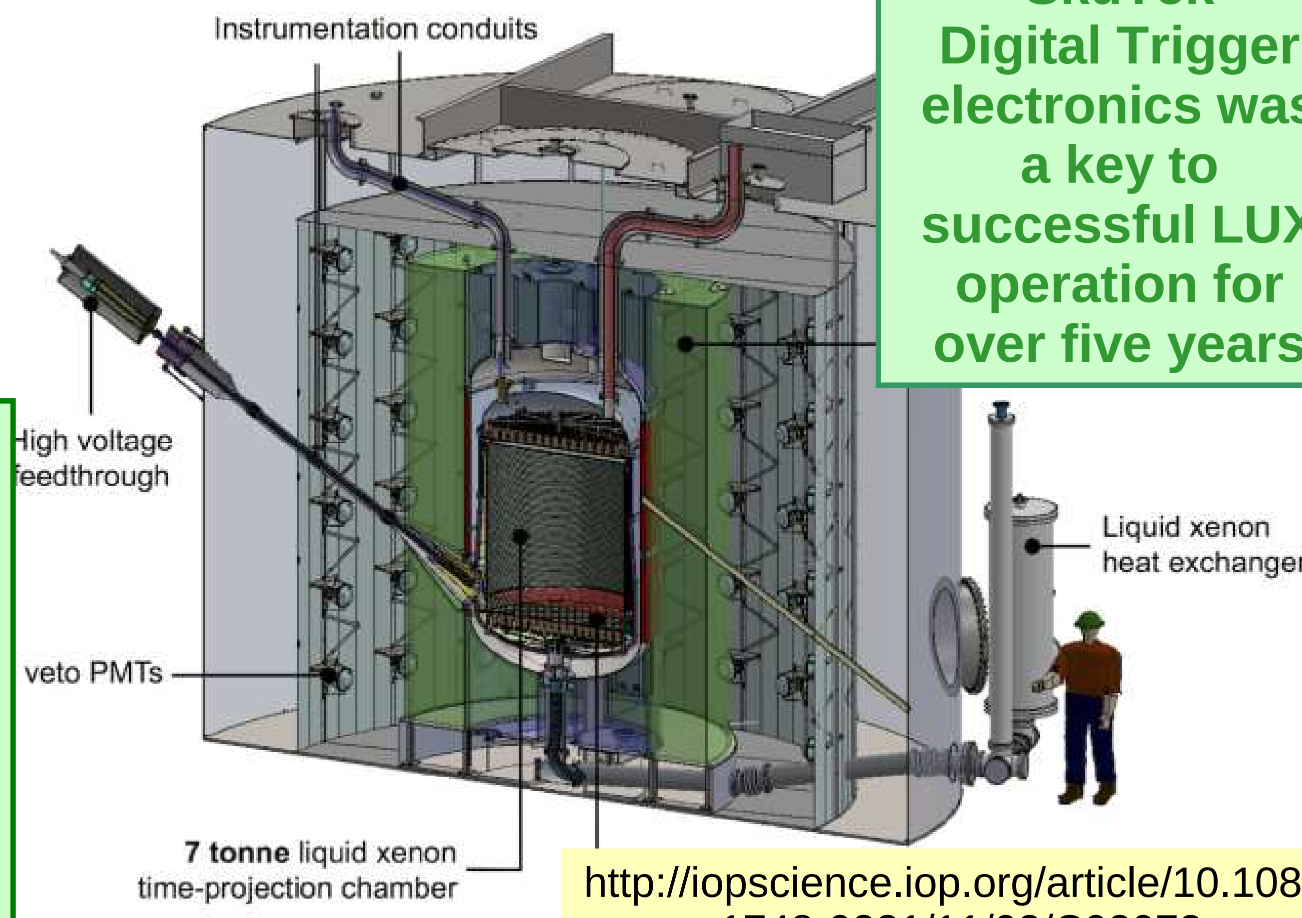
SkuTek collaboration with UofR Physics and Astronomy — UNIVERSITY of ROCHESTER

LUX-Zepplin is the "ultimate Dark Matter Search Detector". Together with UofR we are building the digital DAQ for LZ with **1,359** channels. (Non-SBIR funding!)

We delivered all the electronics to the LZ Collaboration (87 boards).

- Amount of Xenon: 5.6 tons fiducial
  - Drift time in Xenon: 700 μs.
- Number of PMTs: **745**
  - 614 with dual gain
  - 131 single gain
- Electronic channels:
  2*614 + 131 = **1,359**.

- **SkuTek DAQ electronics**
  - **Low noise**
  - **Flexible connection topology**
    - **GbE TCP/IP 40 MB/s**
    - **GbE UDP 109 MB/s**
    - **Fast Serial Links 400 MB/s**
  - **Powerful on board processing**
    - **FPGA**
    - **Embedded Linux**



SkuTek Digital Trigger electronics was a key to successful LUX operation for over five years

http://iopscience.iop.org/article/10.1088/1748-0221/11/02/C02072

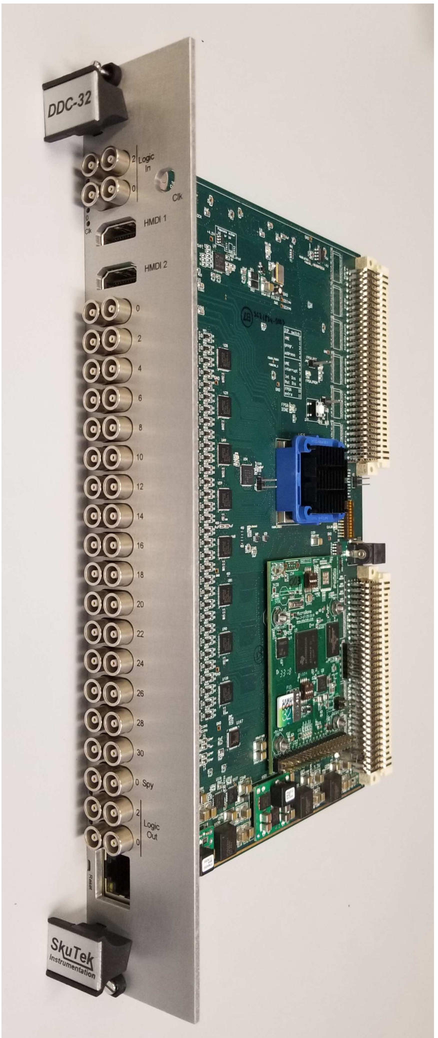
The Components of the LZ DAQ.

32-Channel Digitizer

Logic Board: Trigger Builder and Readout

Installation of the LZ DAQ at SURF.

DDC-32

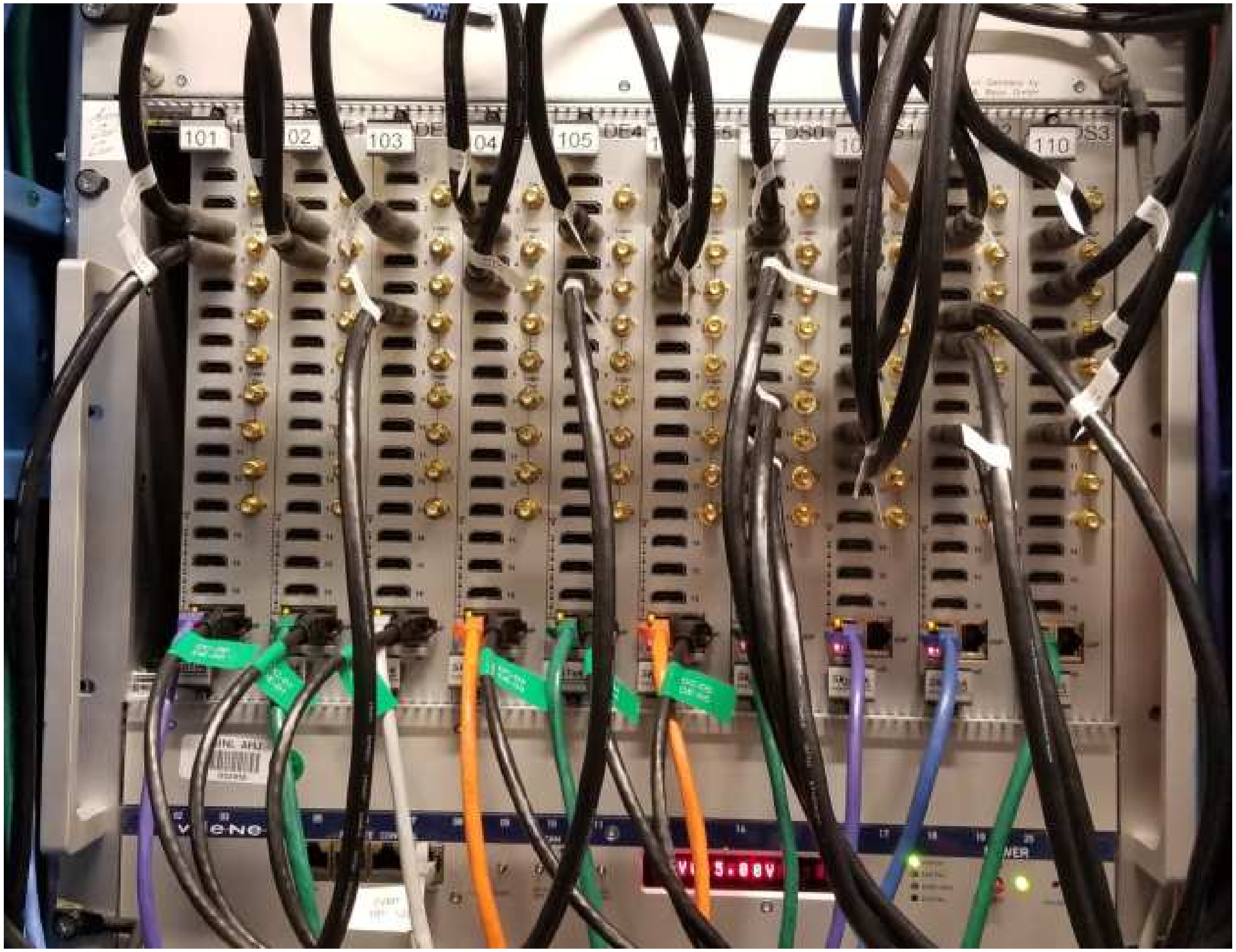


DDC-32 Boards being Installed in the SURF Lab Underground

Installation of the LZ DAQ at SURF.

Logic Board

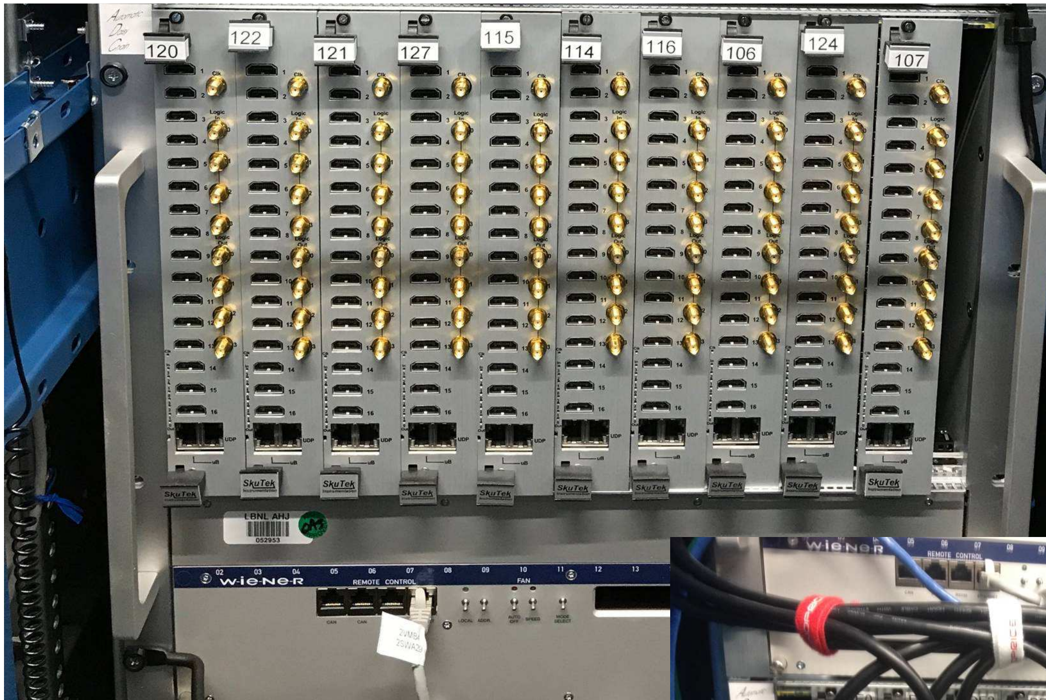
Logic Boards Installed in the SURF Lab Underground

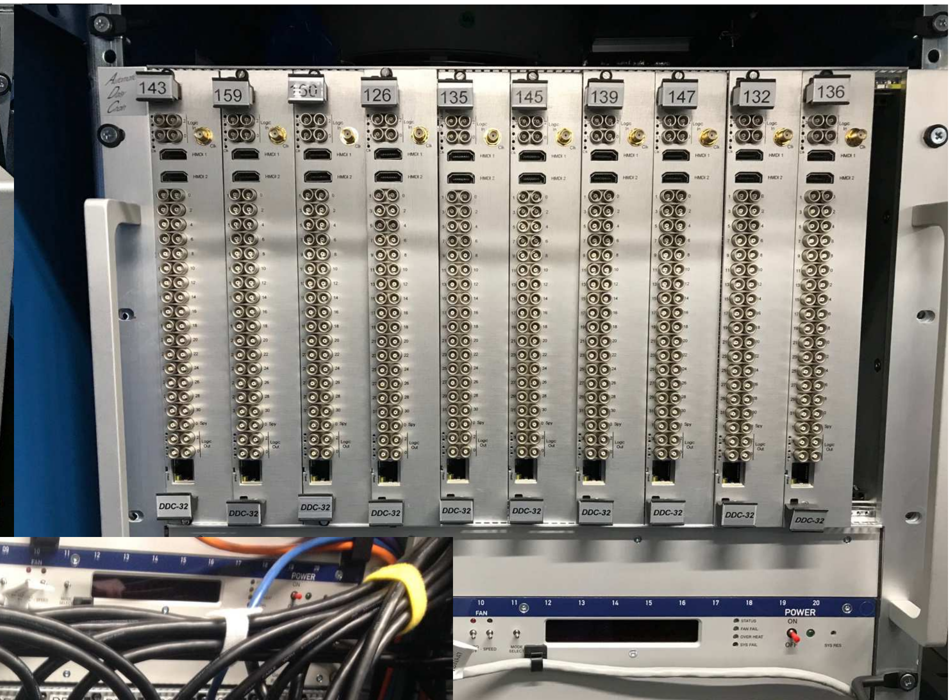


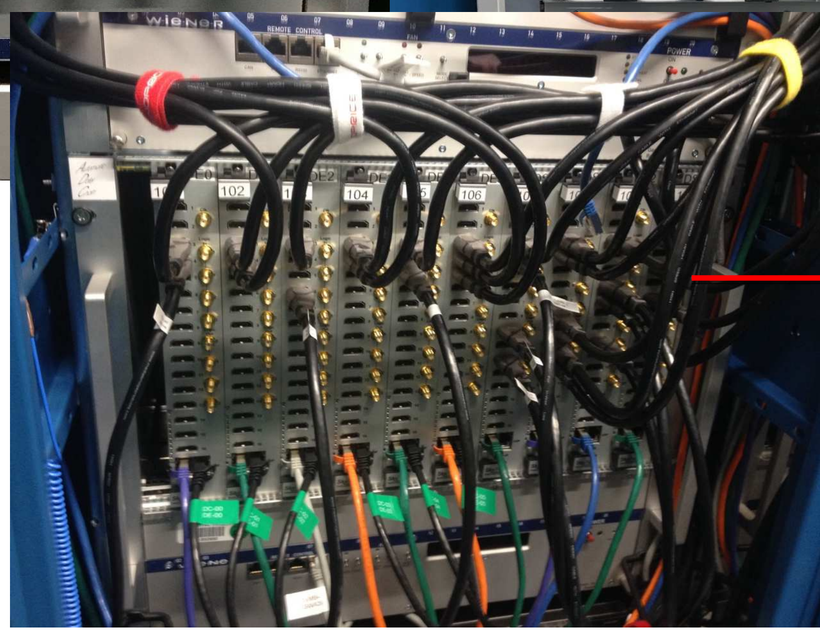
Installation of the LZ DAQ at SURF.

Logic Boards

Digitizers







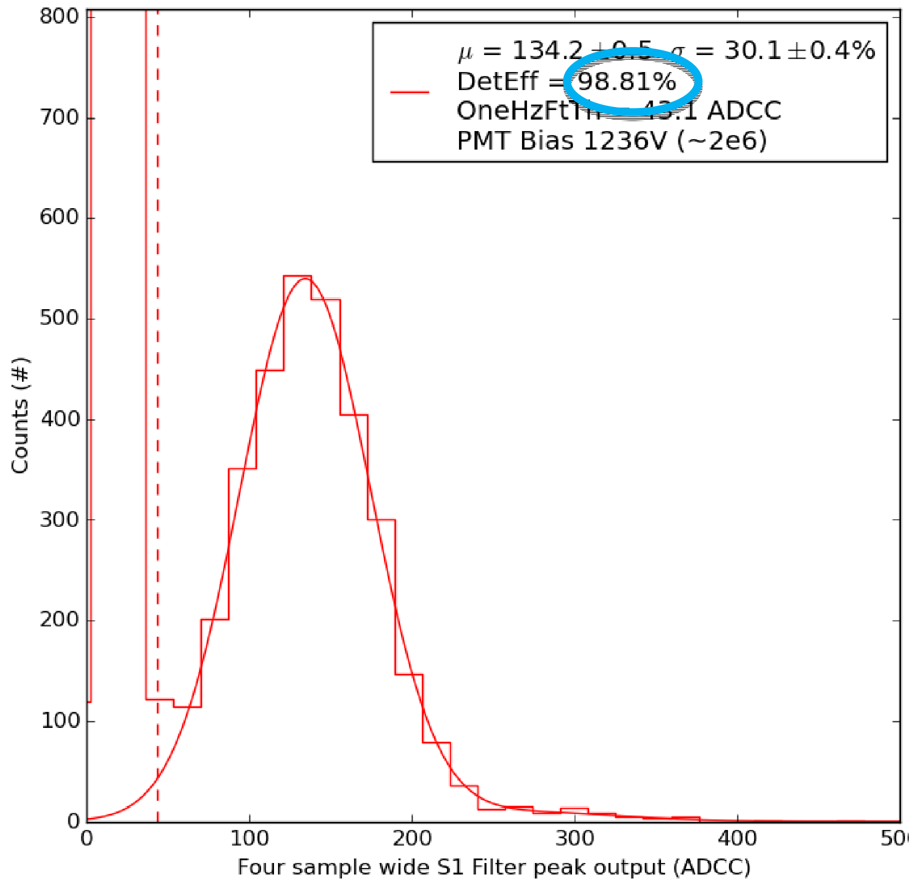
To Data Collectors.

Part of the DAQ was connected.

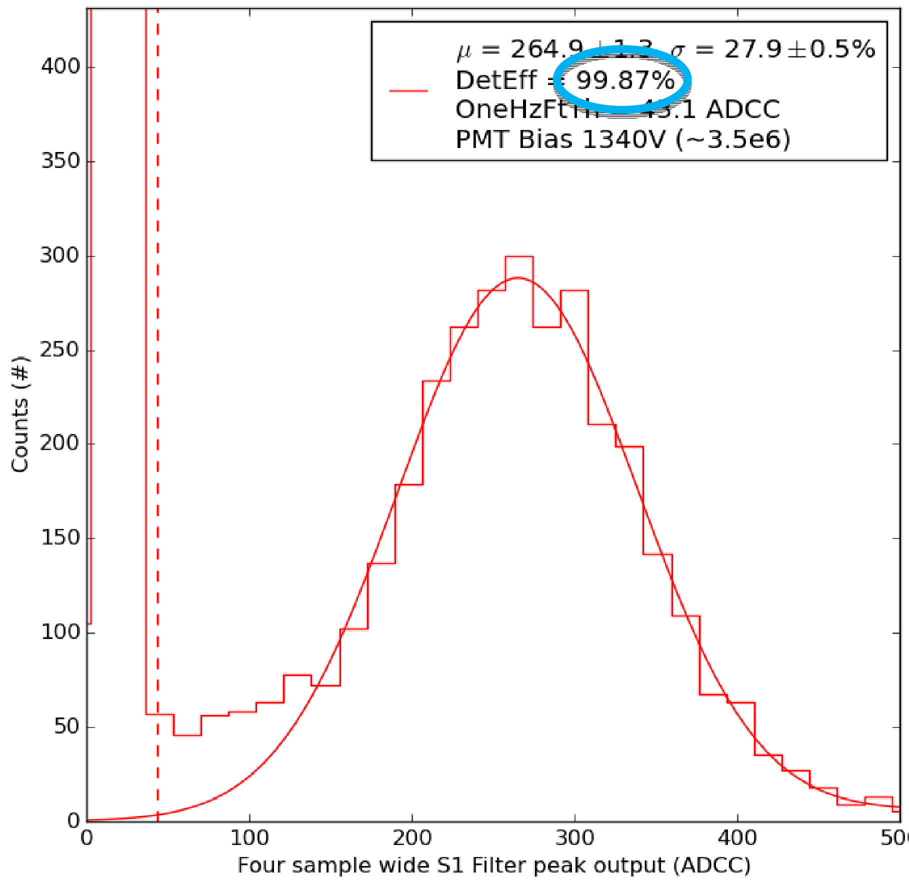
SkuTek Instrumentation Almost 100% Efficiency for SPHE From LZ PMTs.

- Very high efficiency for Single Photo Electron (SPHE) detection is crucial for LZ detector operation.
- Histograms of SPHE pulse height demonstrate an almost 100% detection efficiency of SPHE pulses. (The LZ detector efficiency will also depend on the PMT solid angle coverage.)
- Full Electronic Chain: PMTs (Hamamatsu) - Preamps (UC Davis) - Digitizers (SkuTek)

PMT gain = 2 x 10^6.



PMT gain = 3.5 x 10^6.



Summary of Technical Achievements

- We built two 40-channel prototypes and tested them with a HPGe detector.
- We achieved resolution similar to the analog electronics from Ortec.
  - Digital results were obtained at 27x larger dynamic range than analog results.
  - Digital: 1332 keV resolution was 3% worse than analog. The 1173 keV was 11% worse.
  - Taking into account the dynamic range, the digital result was very good. But there is room for improvements.
- We tested one of the 40-channel units in parallel with the Gretina digitizer at ANL.
  - We achieved equivalent pulse height resolutions of the DDC-40 and Gretina digitizers.
- We built and tested five 10-channel pre-prototypes. Three units were shipped to a customer.
- We then built the improved prototypes with the 100 MHz and 250 MHz sampling rates.
- We continue the firmware and software development using these units.
- **LUX-Zepplin electronics:**
- We used the DDC-40 know-how to design an LZ digitizer with 32 channels (separate funding).
- We also developed a Logic Module for the LZ experiment.
- The LZ DAQ electronics was delivered to LZ (87 boards total, 51 digitizers = 1,632 channels).
- Almost 100% SPHE pulse detection efficiency was demonstrated by the LZ customer.

Future Plans

- Continue development of firmware and software for our digitizers.
- Develop efficient readout over Gigabit Ethernet.
  - Currently we write data to networked disks using SAMBA.
  - It is not the most efficient method to use Gigabit Ethernet.
  - We are implementing the ZeroMQ method of data streaming.
- Develop protocols and interfaces compatible with the Nuclear Physics infrastructure.
  - We were awarded a Phase II grant for these developments.
- Stay in touch with the NP community concerning the DAQ needs, such as interfaces, data formats, and protocols.

Questions for the NP Community

- Can the community provide a set of guidelines and technical standards for the inter-DAQ communication and synchronization?
- Can the community recommend data formats which will be simple, efficient, general, and independent of particular analysis software?
  - Event files, waveforms, histograms, setup information.
  - Such formats could be used for electronics development, benchmarking, and testing.

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