Evaluating Fast Multi-Channel Photosensors and Readout Electronics for Large Neutrino Detectors

Workshop on Geo-Neutrinos

University of Hawaii at Manoa

January 2–5, 2025

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Outline for the discussion
LLNL and OBD

- Recent R&D at LLNL (potential connection to OBD)
- Photosensors and Electronics — evaluation/design (most of this talk)
- New scintillators (liquid and plastic)
- Simulations/software (post-WATCHMAN, RATPAC 2, Livermore computing)
- Directionality (UH/LLNL studies)
- Engineering (optical modules, detector design)
- Bringing students

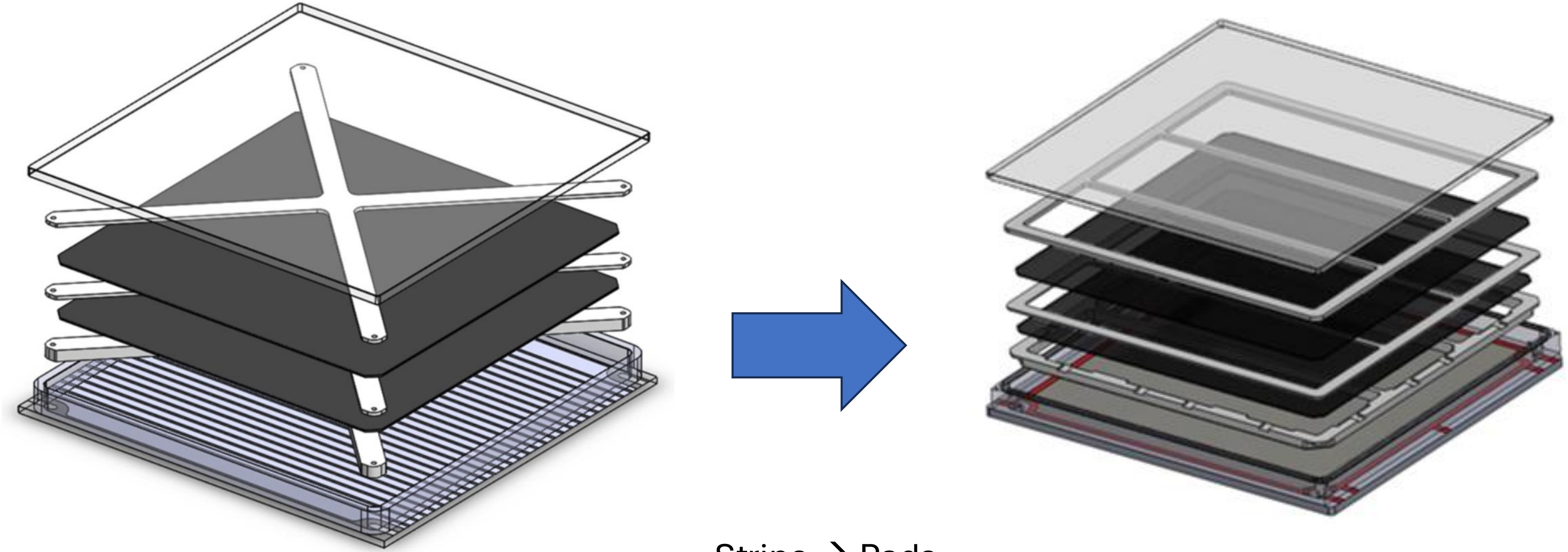
UTohoku / UH / LLNL need to coordinate the path forward.

Modern Large Neutrino Detector and advances by our LLNL group

- **Detection medium:**
  - **Plastic PSD Scintillator (**Performance of large-scale 6Li-doped pulse-shape discriminating plastic scintillators NIMA 1069 (2024) 169916)
  - **Liquid PSD (**6Li-loaded liquid scintillators produced by direct dissolution of compounds in diisopropylnaphthalene *NIMA* 1054 (2023) 168389**)**
  - **Water (**A long path-length optical property measurement device for highly transparent detector media *JINST* 18 (2023) 09, P09004, Exclusion and Verification of Remote Nuclear Reactors with a 1-kiloton Gd-Doped Water Detector *Phys.Rev.Applied* 19 (2023) 3, 034060**)**
  - **WbLS (**Pulse-shape discrimination in water-based scintillators *NIMA* 1036 (2022) **)**
- **Photosensor:**
  - **PMT** (Improvement in light collection of a photomultiplier tube using a wavelength-shifting plate *NIMA* 1040 (2022) 167207)
  - **MA MCP-PMT** (Studies of MCP-PMTs in the miniTimeCube neutrino detector, *AIP Adv.* 8 (2018) 9, 095003)
  - **MA MCP-PMT (LAPPD) (this talk)**
  - **SiPM** (A prototype for SANDD: A highly-segmented pulse-shape-sensitive plastic scintillator detector incorporating silicon photomultiplier arrays *NIMA* 942 (2019))
- **Electronics:**
  - **Feature-extraction (Q/T)** (Calibration of a compact ASIC-based data acquisition system for neutron/γ discrimination and spectroscopy with organic scintillators *NIMA* 1057 (2023) 168699)
  - **Full-waveform (this talk)**
- **Data analysis / simulations / ML:**
  - **GEANT4 / RAT-PAC (**Scalability of Gadolinium-Doped-Water Cherenkov Detectors for Nuclear Nonproliferation Phys. Rev. Applied **18**, 034059 , Physics-informed machine learning approaches to reactor antineutrino detection, Directional response of several geometries for reactor-neutrino detectors Phys.Rev.Applied 22 (2024) 5, 054030, Ratpac-Two v1.0.0 https://doi.org/10.11578/dc.20240620.8)
- **Deployment:**
  - **Underground/Underwater**

This talk is about recent advances made at LLNL and pros/cons of various systems.

LAPPD gen 1 and gen 2 — main difference

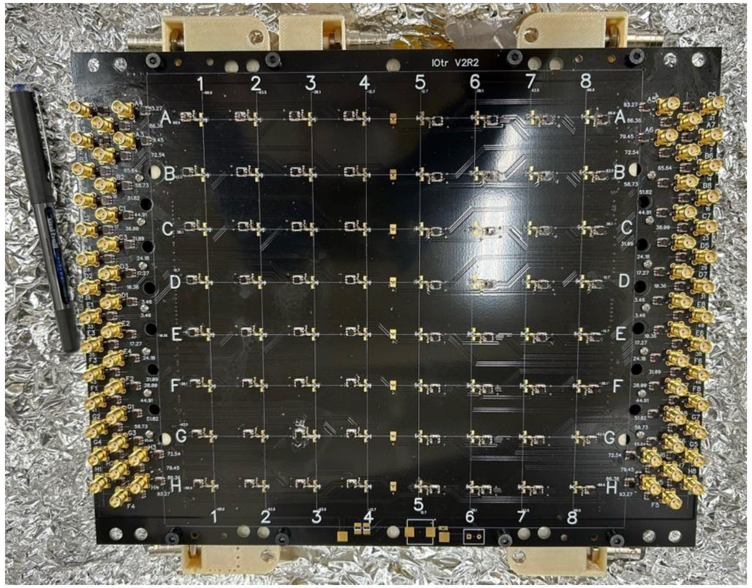


Strips → Pads
Cross → Ribs

The new design allows for custom size and shape of anodes (pixelization).

LAPPD gen 2 — first tests

- LAPPD #133 from Incom (8 X 8 anodes, each 1 inch X 1 inch)
- HV connection (5 is better than 2, but likely not 1)



64 SMA connectors at the back and 5 SHV connectors.

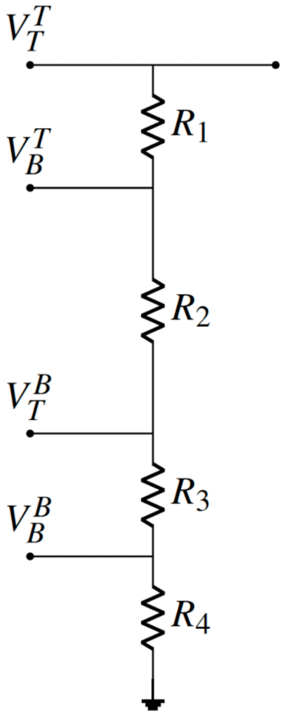
Intern James Foot holding LAPPD 133 after unpacking.

Incom sends an LAPPD with a detailed test summary.

Two methods of powering LAPPD

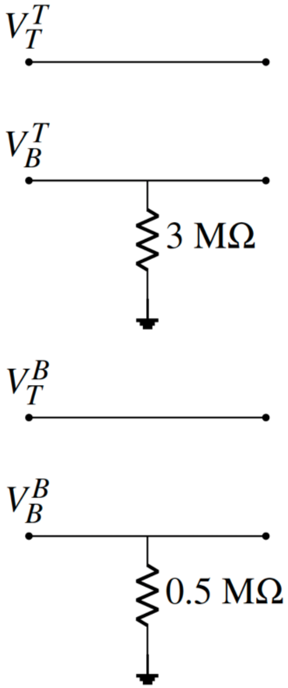
2 channels:

- *single HV for 2 MCPs*
- *photocathode*



5 channels:

- *2 MCPs (”entry” and “exit”)*
- *photocathode*

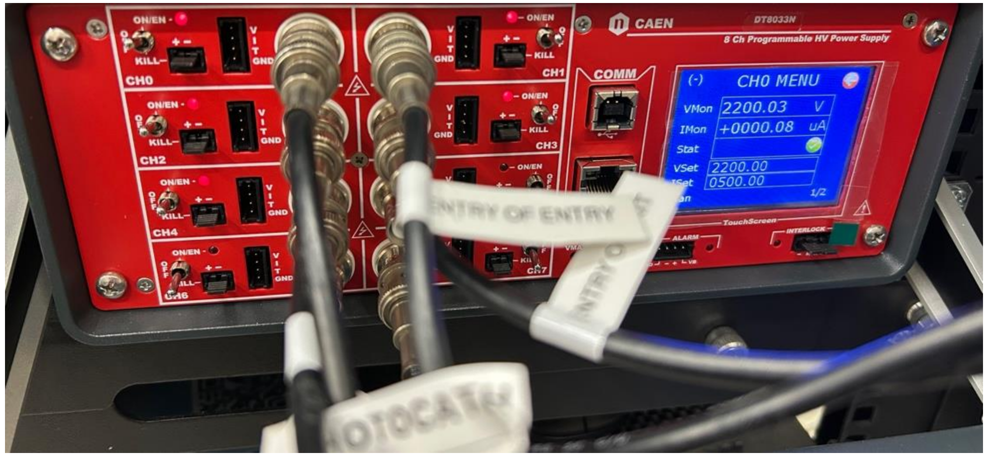


More channels lead to better control, but increase cost and complexity.

5 independent HV channels

- Photocathode
- Entry of entry MPC
- Exit of entry MCP
- Entry of exit MCP
- Exit of exit MCP

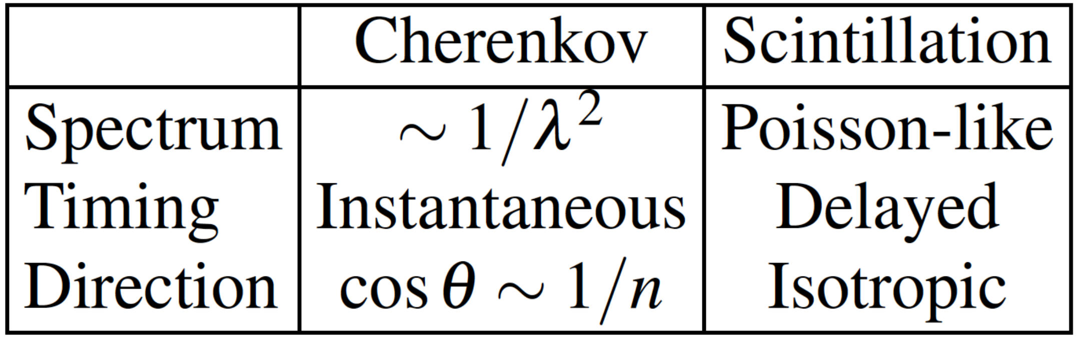
	Bottom MCP				Top MCP				Photocathode	
Step	V_B^B	I_B^B	V_T^B	I_T^B	V_B^T	I_B^T	V_T^T	I_T^T	V^{PC}	I^{PC}
1	-200	386.79	-600	15.07	-800	255.53	-1200	11.77	-1190	0.12
2	-200	379.19	-800	22.67	-1000	316.21	-1600	17.69	-1590	0.11
3	-200	371.52	-1000	30.36	-1200	376.63	-2000	23.63	-1990	0.08
4	-200	371.41	-1000	30.51	-1200	376.53	-2000	23.73	-2010	0.07
5	-200	371.36	-1000	30.53	-1200	376.51	-2000	23.75	-2200	0.07



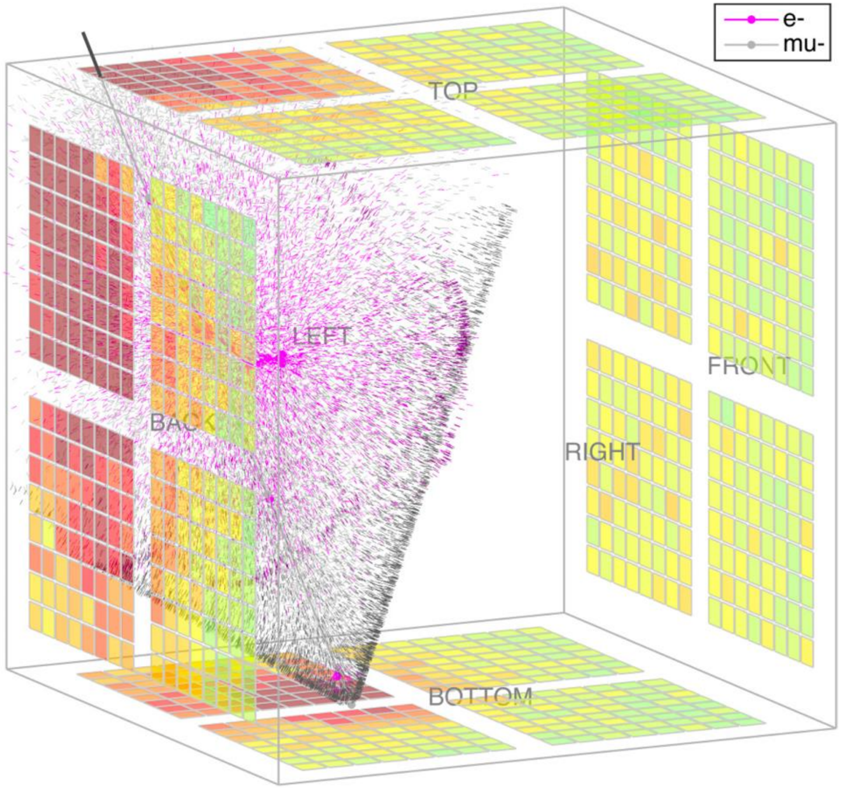
This method results in a more stable/controlled operation.

Fast-timing:
miniTimeCube era and why we need fast timing

- Fast-timing allows better track reconstruction
- Cherenkov and Scintillation light separation
- Trade-offs: pixel size, photocoverage, and cost



	Cherenkov	Scintillation
Spectrum	$\sim 1/\lambda^2$	Poisson-like
Timing	Instantaneous	Delayed
Direction	$\cos\theta \sim 1/n$	Isotropic

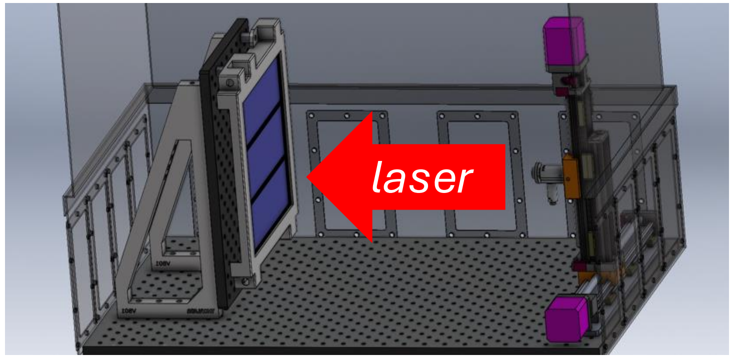


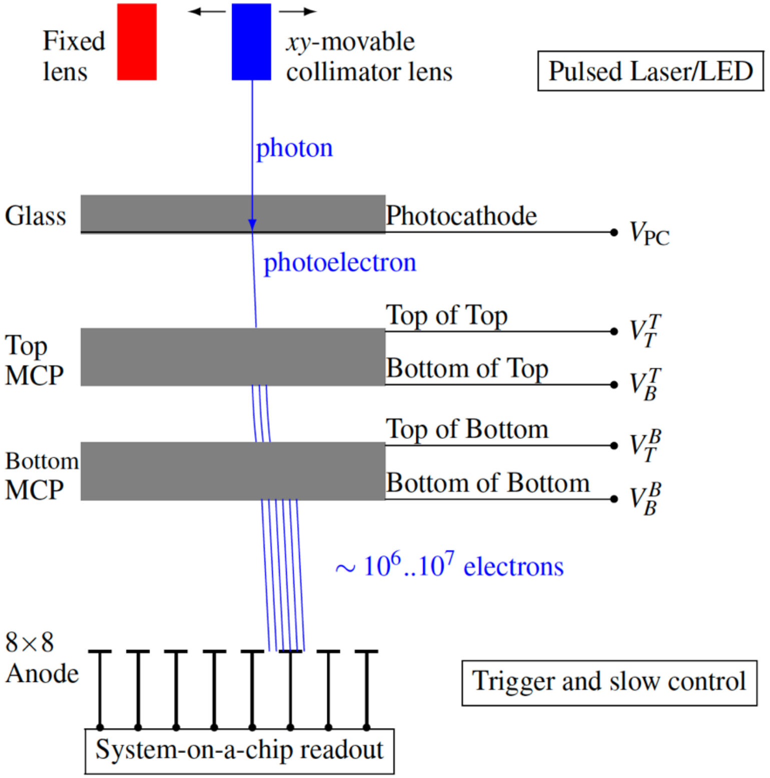
Cherenkov light in mTC (MA MCP-PMTs)

For pure liquid scintillator we likely don’t worry (scintillation dominant), but for WbLS it is valuable.

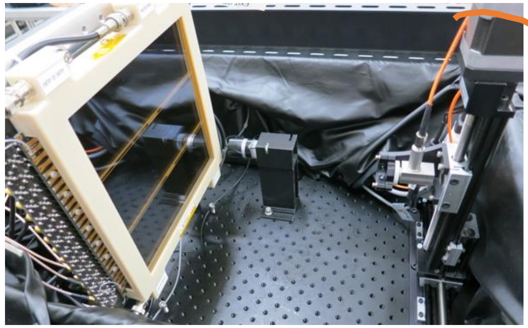
Test stand for LAPPD gen 2 at LLNL

- Picosecond laser
- Collimator
- XY stepper motor
- Automated scans
- LED and laser





from idea to implementation:



Laser fiber

The setup is robust and allows for X-Y alignment of the laser beam.

SPE pulses LAPPD gen 2 — estimating gain

Meas 1
Amplitude
μ': 378.9 μV

Meas 2
Area
μ': 18.67 pV*s

Meas 3
Amplitude
μ': 539.1 μV

Meas 4
Area
μ': 16.35 pV*s

Meas 5
Rise Time
μ': --
Low amplitude

Meas 6
Fall Time
μ': --
Low amplitude

Ch 1
Clipping
10 mV/div
50 Ω
1 GHz

Ch 2
Clipping
5 mV/div
50 Ω
1 GHz

Ch 3
1 V/div
50 Ω
1 GHz

Horizontal
2 ns/div 20 ns
SR: 50 GS/s 20 ps/pt (IT)
RL: 1 kpts 95%

Trigger
3 1.08 V

Acquisition
Auto, Analyze
Sample: 8 bits
56.727 kAcqs

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SPE pulse ~25 mV high and ~2 ns across.

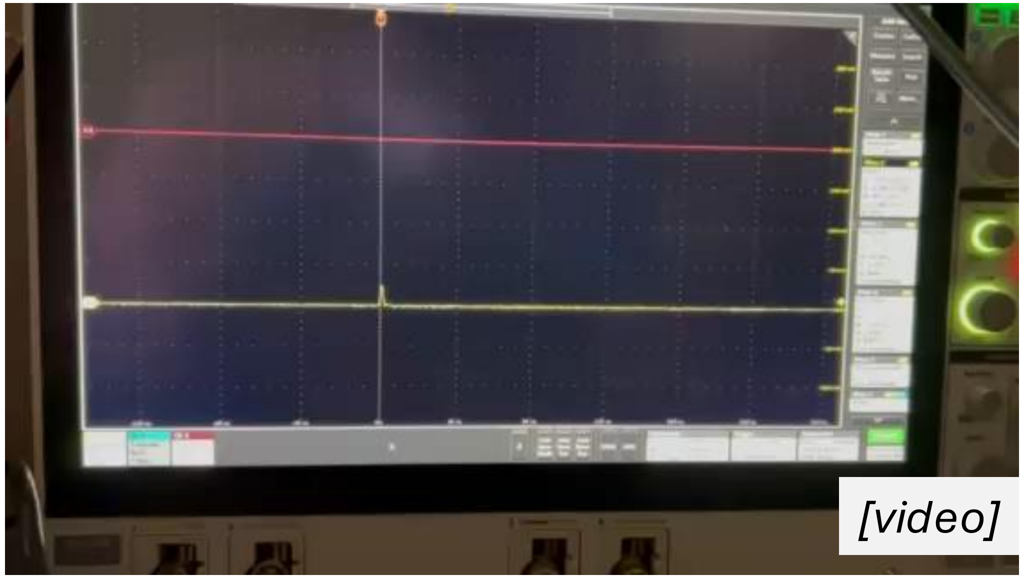
The SPE peak on the magenta histogram
(area under the cyan curve)
*is at about 60-70 mV * ns.*
*The baseline is at ~20 mV*ns.*
*subtracting the baseline, ~40 mV*ns*

*An estimate for the **gain**:*
*40e-12 / (1.6e-19 * 50) = **5e6***

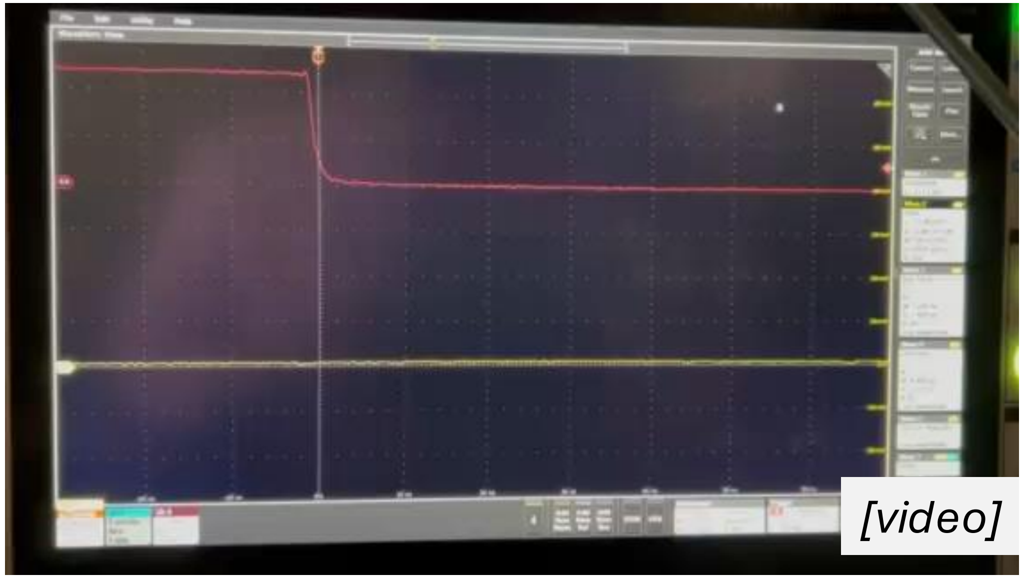
First data observed with
a Tektronix scope (connected to H1 pad).

SPE peak is rather broad.

SPE pulses LAPPD gen 2



Trigger on H1 pad (yellow trace).

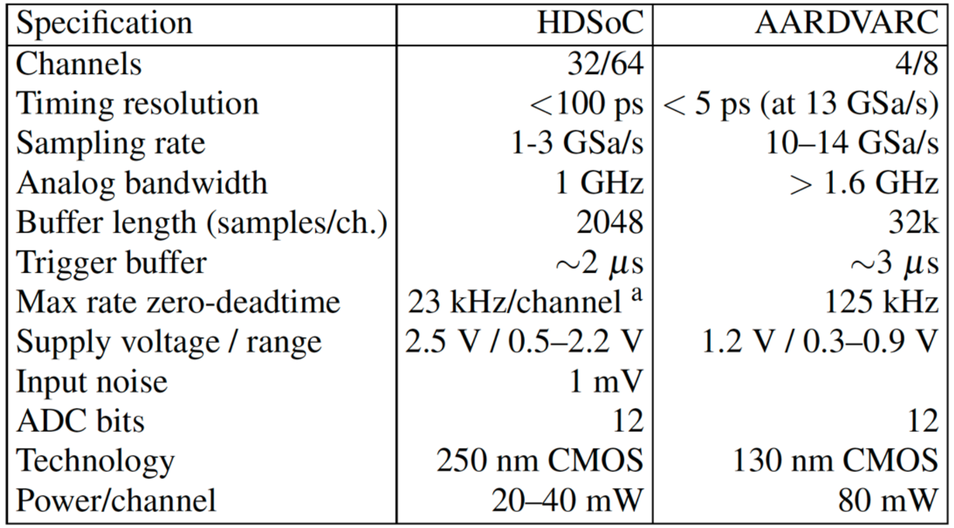


Trigger on delay generator/laser (10Hz, redtrace).

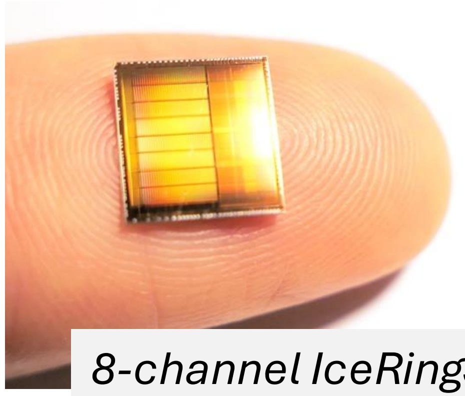
If triggering on the LAPPD, ringing is noticeable (~100 mVpp, ~100-ns, ~10-ns period).

Electronics

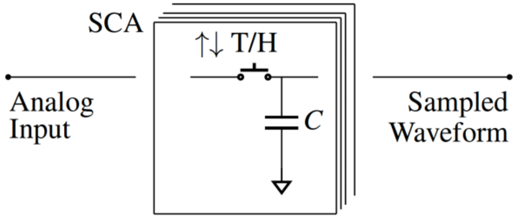
- Can we reach the $10/channel?
- How many channels?
- Readout *in situ*?



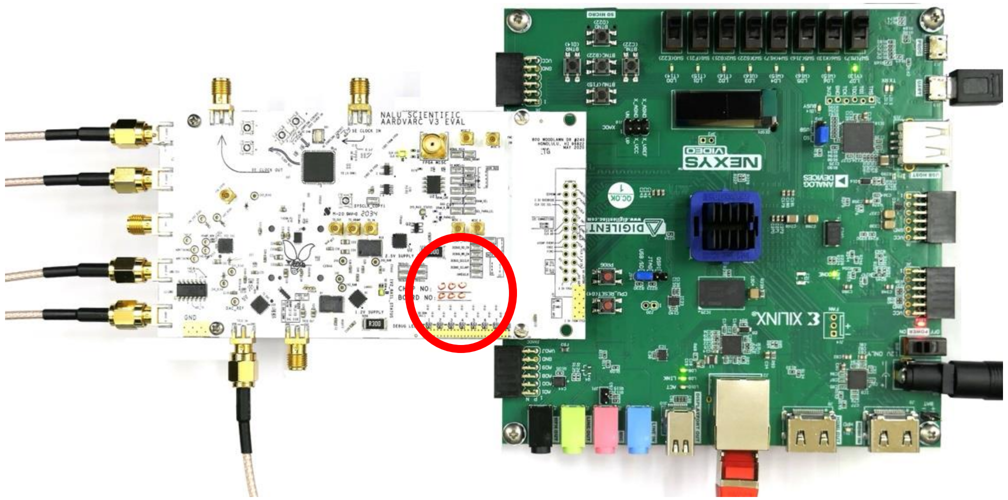
Specification	HDSoC	AARDVARC
Channels	32/64	4/8
Timing resolution	$<$100 ps	$<$ 5 ps (at 13 GSa/s)
Sampling rate	1-3 GSa/s	10–14 GSa/s
Analog bandwidth	1 GHz	$>$ 1.6 GHz
Buffer length (samples/ch.)	2048	32k
Trigger buffer	$\sim$2 μs	$\sim$3 μs
Max rate zero-deadtime	23 kHz/channel [a]	125 kHz
Supply voltage / range	2.5 V / 0.5–2.2 V	1.2 V / 0.3–0.9 V
Input noise	1 mV	
ADC bits	12	12
Technology	250 nm CMOS	130 nm CMOS
Power/channel	20–40 mW	80 mW



8-channel IceRingSampler



Track&Hold principle



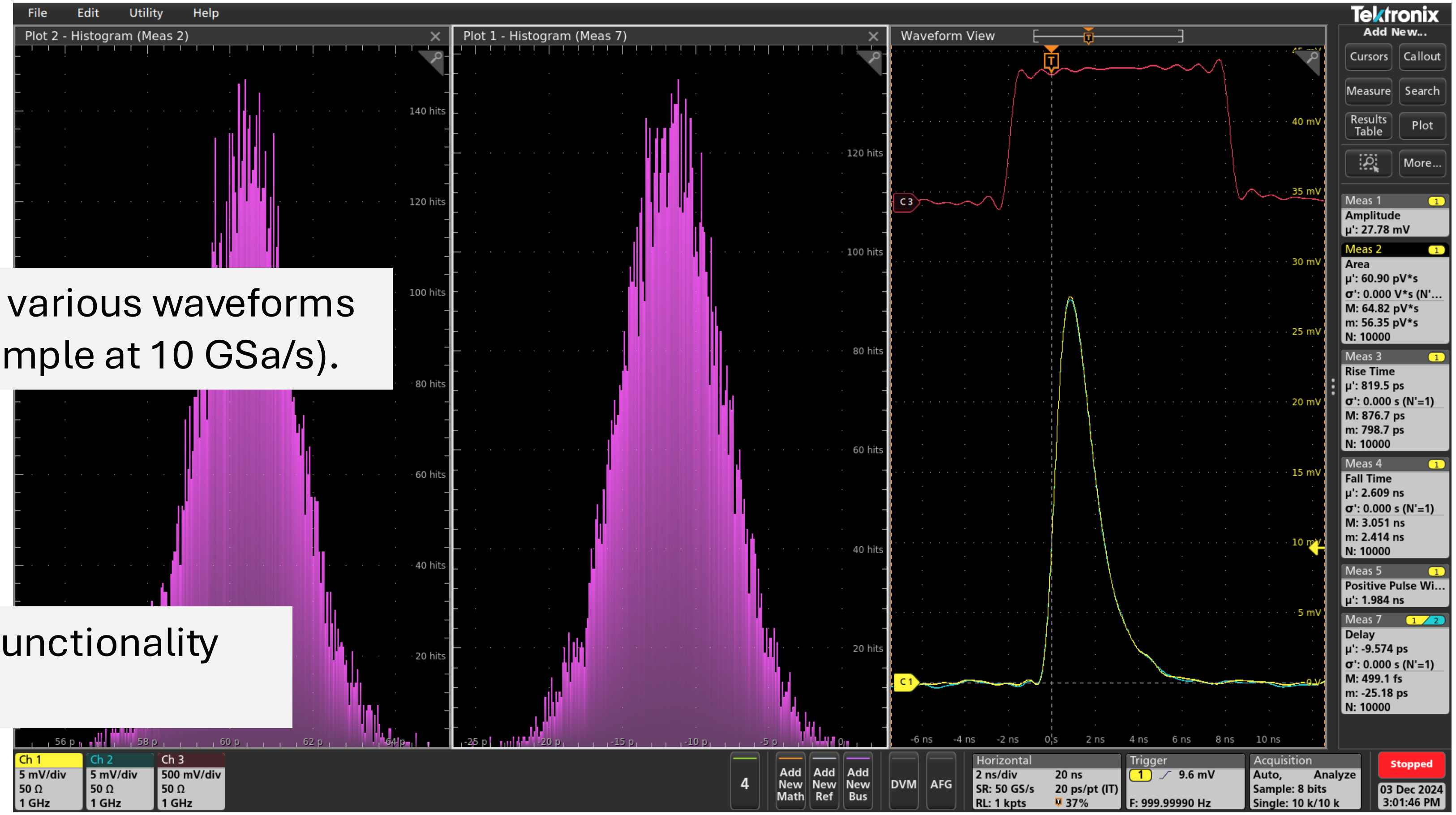
4-channel AARDVARC eval board (SN 000!)

Connection to UH: Prof. Gary Varner’s dream of “oscilloscope on a chip”.

Model electronic pulses

AWGs have a vast functionality to allow various waveforms (essentially load an array sample-by-sample at 10 GSa/s).

”Markers” at the back allow additional functionality (e.g. delayed trigger)



Meas 1
Amplitude
μ': 27.78 mV

Meas 2
Area
μ': 60.90 pV*s
σ': 0.000 V*s (N'...
M: 64.82 pV*s
m: 56.35 pV*s
N: 10000

Meas 3
Rise Time
μ': 819.5 ps
σ': 0.000 s (N'=1)
M: 876.7 ps
m: 798.7 ps
N: 10000

Meas 4
Fall Time
μ': 2.609 ns
σ': 0.000 s (N'=1)
M: 3.051 ns
m: 2.414 ns
N: 10000

Meas 5
Positive Pulse Wi...
μ': 1.984 ns

Meas 7
Delay
μ': -9.574 ps
σ': 0.000 s (N'=1)
M: 499.1 fs
m: -25.18 ps
N: 10000

Ch 1
5 mV/div
50 Ω
1 GHz

Ch 2
5 mV/div
50 Ω
1 GHz

Ch 3
500 mV/div
50 Ω
1 GHz

Horizontal
2 ns/div 20 ns
SR: 50 GS/s 20 ps/pt (IT)
RL: 1 kpts 37%

Trigger
1 9.6 mV
F: 999.99990 Hz

Acquisition
Auto, Analyze
Sample: 8 bits
Single: 10 k/10 k

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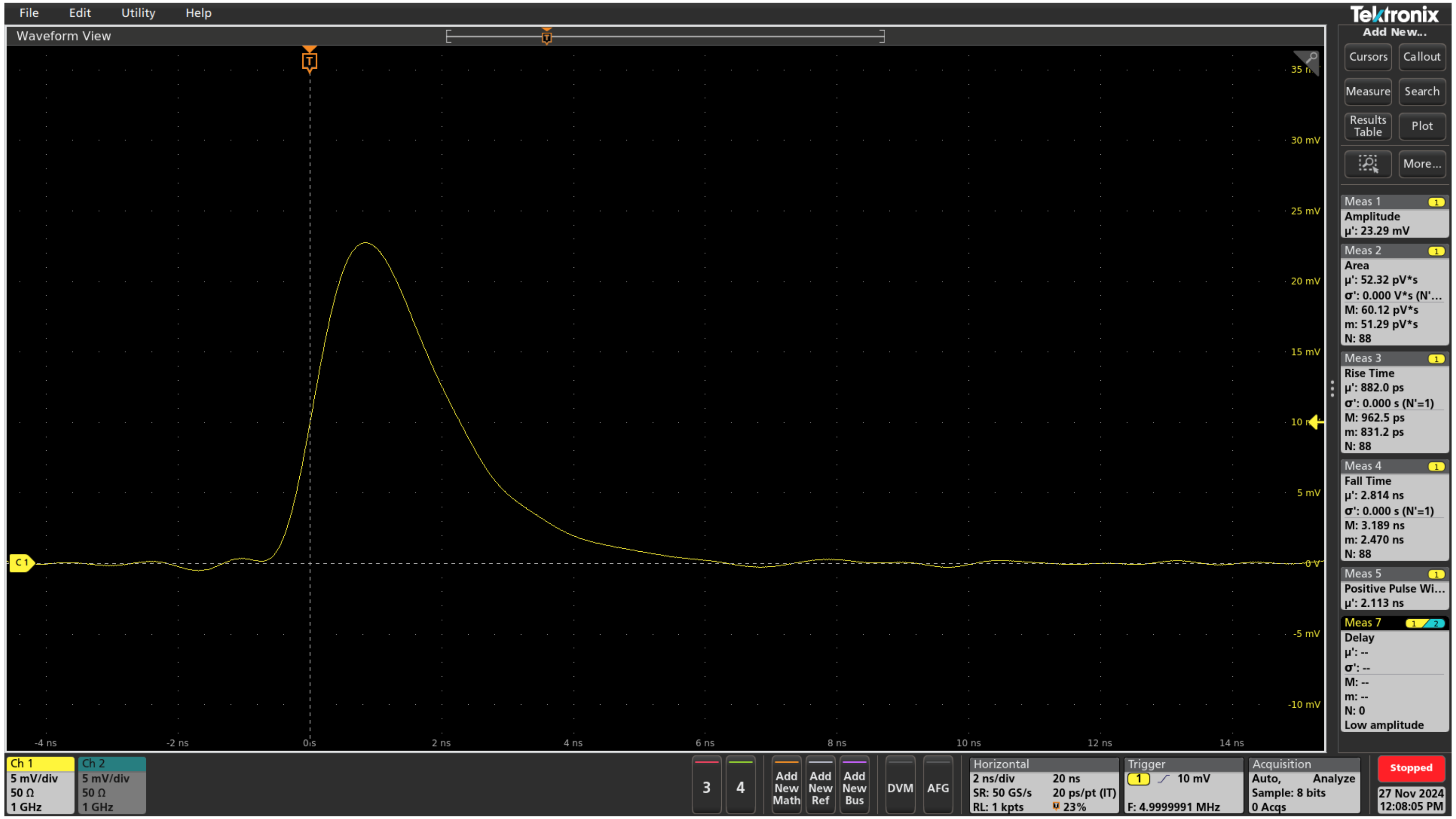
Unlike arbitrary “**function**” generators, arbitrary “**waveform**” generators are more versatile/stable.

Log-normal distribution



Meas 1
Amplitude
μ': 23.29 mV

Meas 2
Area
μ': 52.32 pV*s
σ': 0.000 V*s (N'...
M: 60.12 pV*s
m: 51.29 pV*s
N: 88

Meas 3
Rise Time
μ': 882.0 ps
σ': 0.000 s (N'=1)
M: 962.5 ps
m: 831.2 ps
N: 88

Meas 4
Fall Time
μ': 2.814 ns
σ': 0.000 s (N'=1)
M: 3.189 ns
m: 2.470 ns
N: 88

Meas 5
Positive Pulse Wi...
μ': 2.113 ns

Meas 7
Delay
μ': --
σ': --
M: --
m: --
N: 0
Low amplitude

Ch 1
5 mV/div
50 Ω
1 GHz

Ch 2
5 mV/div
50 Ω
1 GHz

Horizontal
2 ns/div 20 ns
SR: 50 GS/s 20 ps/pt (IT)
RL: 1 kpts 23%

Trigger
1 10 mV
F: 4.9999991 MHz

Acquisition
Auto, Analyze
Sample: 8 bits
0 Acqs

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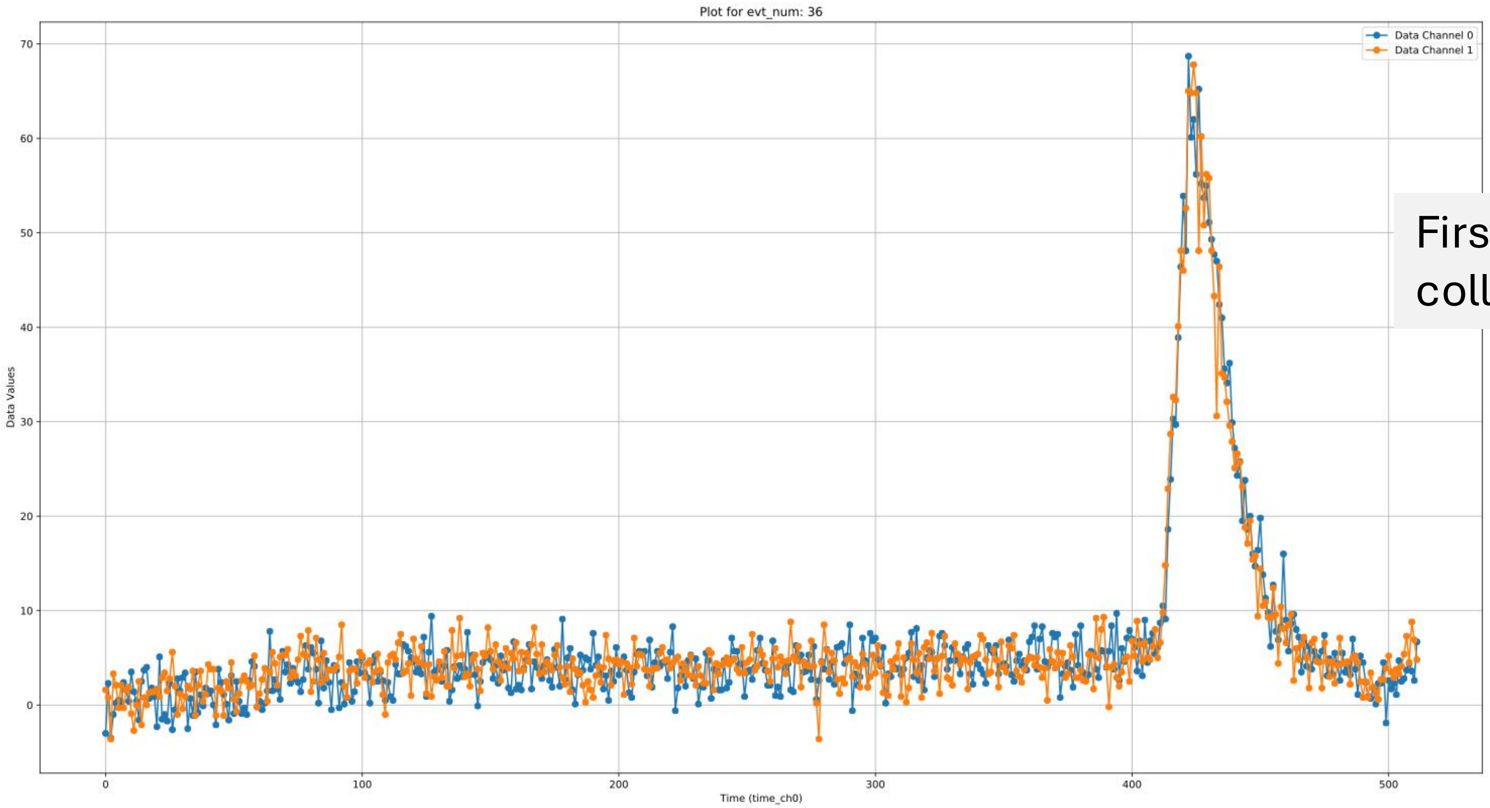
A clean pulse reproduced with using the AWG.

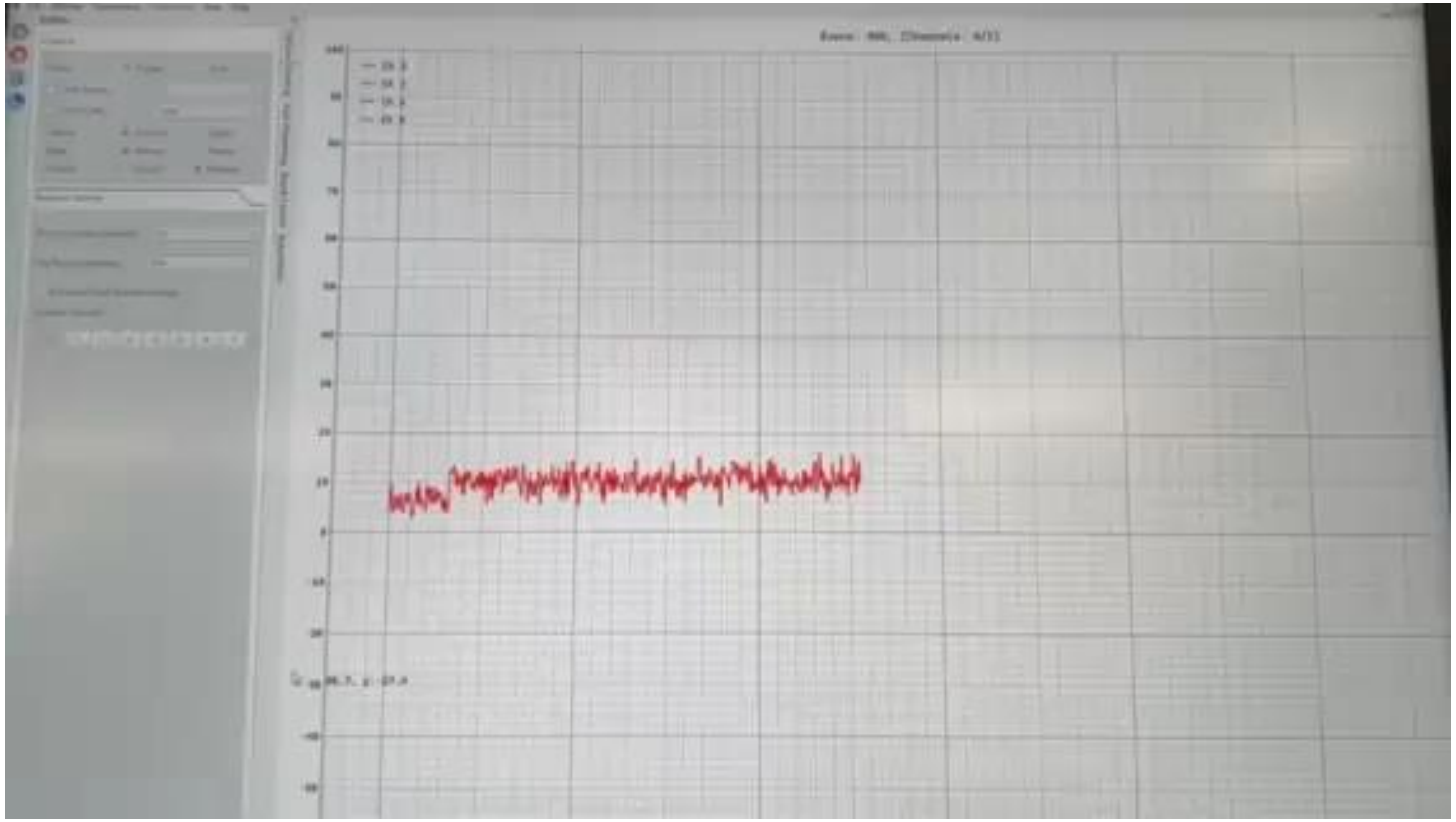
Nalu readout with a splitter



First fast artificial waveform 10GSa/s collected with Nalu AARDVARC

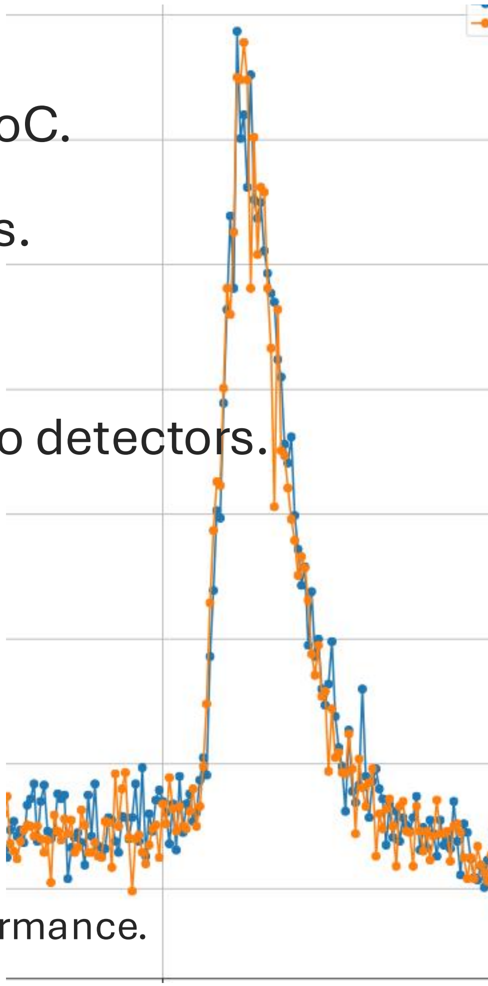
Data looks good.

SPE data with NaluScope (AARDVARC 000 SOC)



This is the first time LAPPD gen 2 has been readout with AARDVARC SoC.

Conclusion



- **First Readout of LAPPD Gen 2**: Successful integration with AARDVARC and HDSoC.
- **Initial Test Results**: Promising performance of new photosensors and electronics.
- **Future Development**: Significant R&D efforts anticipated for a final detector.
- **Ongoing Tests at LLNL**: Leveraging established infrastructure to advance neutrino detectors.

Looking ahead:

- **Exploration of New Ideas**: Focus on cost-effective underwater and ground detectors.
- **Development of Test Stands**: For photosensors, electronics, and detection media.
- **R&D Initiatives**: Investigating novel techniques, materials, and engineering solutions.
- **Utilization of Simulation and High-Performance Computing**: To enhance detector design and performance.

Photosensors and fast-timing electronics are advancing.

Back-up

For students: visit careers.llnl.gov to apply for undergrad and grad internships.