Signal and Power transmission over Fiber in the DUNE Far Detector

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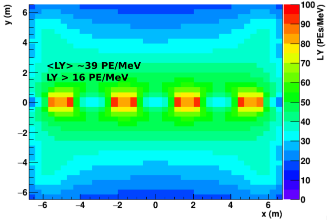
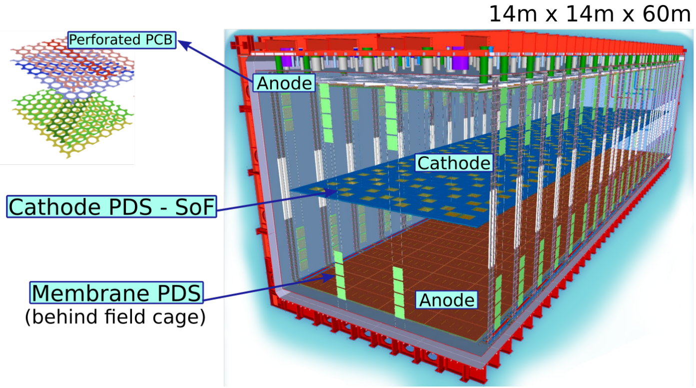
The Vertical Drift Photo-Detection System (PDS)

- 6.5 m drift length, -300 kV bias
- Opaque top and bottom anodes (PCB)
- PDS on cathode helps increase the light-yield and improve uniformity



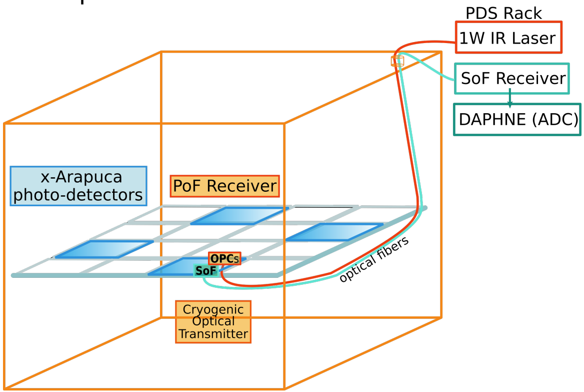


Two types of PDS modules:
membrane PDS powered and read-out with copper wires,
and **cathode PDS** powered and read-out using optical fibers.

*General description of the Vertical Drift detector in José Soto's talk

PDS on the High Voltage cathode

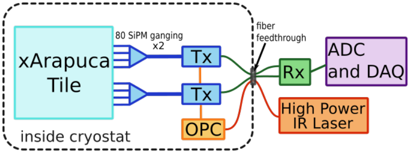
Each cathode structure is 3 $\times$ 3 m^2 and contains 4 xArapuca modules



xArapuca:

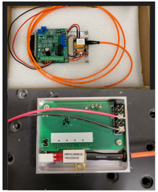
- Wavelength shifting (WLS) plate, 60 $\times$ 60 cm^2
- 160 SiPMs, in groups of 20 on flex circuit boards
- Double sided: light collection from both sides $\rightarrow$ signal matching to membrane modules to determine drift volume

Signal transmission and powering schematic



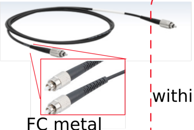
Powering on a high voltage surface

- High power (1 W) IR laser for power:
  - set at $\sim$ half power for safety
  - potential to increase power input during detector lifetime if needed
- Multi-mode optical fibers, 62.5 um core, with FC connectors
  - metal connectors and black covers to diminish light leakage
  - also protected with meshes and tubing
- High efficiency (optimized for cold operation) InGaAs Optical Power Converters
  - a single OPC can provide $> 265\ mW$ necessary to power the readout/bias electronics in cold
  - with two OPCs power is enough for the warm commissioning of the detector ($> 550\ mW$)



IR lasers: housed in PDS rack

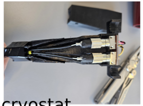
40 m long fibers



FC metal connectors

OPC receiver

within IR light-tight enclosure

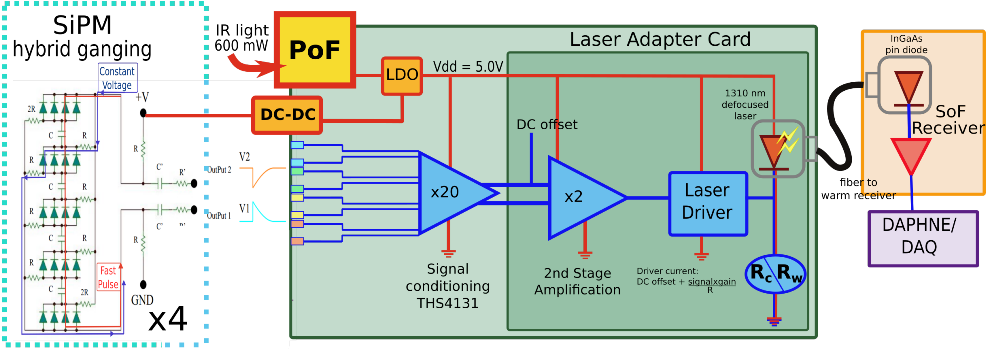


inside cryostat

IR light leakage:
Although far from the SiPM's peak sensitivity, the laser power is high and the loss point very close to the sensors, so that a high count of PE can be detected.

*Detailed description of Power-over-Fiber system and R&D in Diana Leon's talk

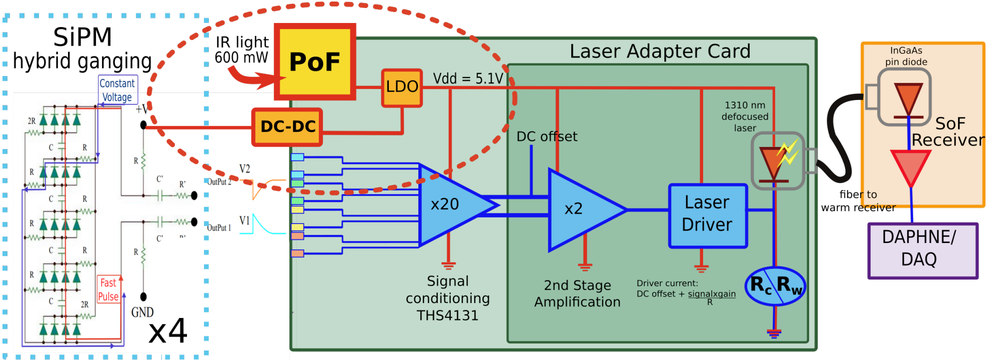
Signal Transmission over Fiber - SoF



SiPM hybrid ganging:

- Each flex board contains 5 groups of 4 SiPMs in parallel, with bias and readout over the same lines
- a differential signal is extracted, decoupled from bias with a 0.1 uF capacitor
- four flexis are added together with an operational amplifier, minimizing the signal deformation

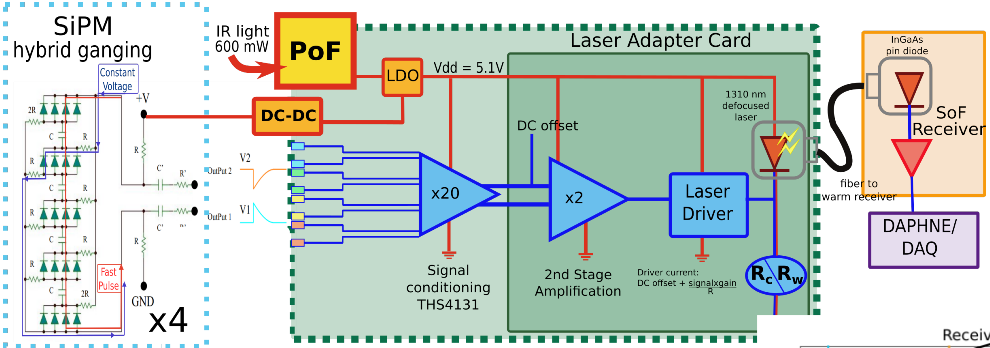
Signal Transmission over Fiber - SoF



Power/Bias scheme:

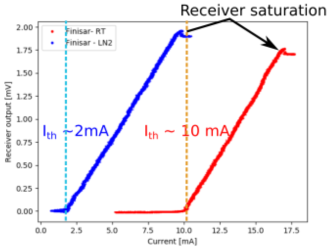
- The PoF receiver outputs between 5 and 6 V depending on the load
- a voltage regulator ensures a V_{dd} of 5.1 V for the transmitter and the DCDC
- an in-house designed DCDC circuit generates the SiPM bias, with different output in LAr and room temperature

Signal Transmission over Fiber - SoF

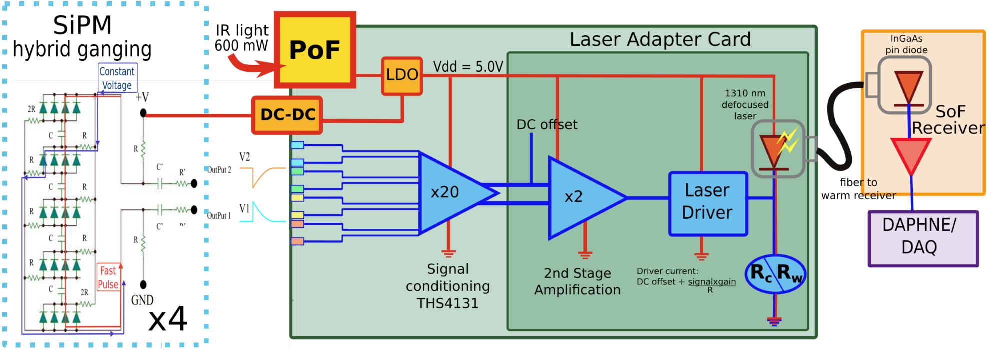


Cryogenic Analog Optical transmitter:

- Signal gain is tuned to optimize SNR within the available voltage range
- Laser driver: signal conversion from voltage to current
- A constant DC offset current keeps the laser above its lasing threshold
- An NTC resistor automatically switches between RT and LAr operation



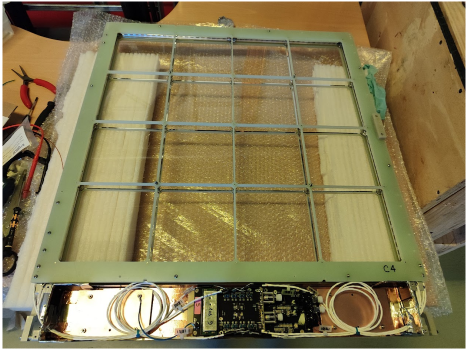
Signal Transmission over Fiber - SoF

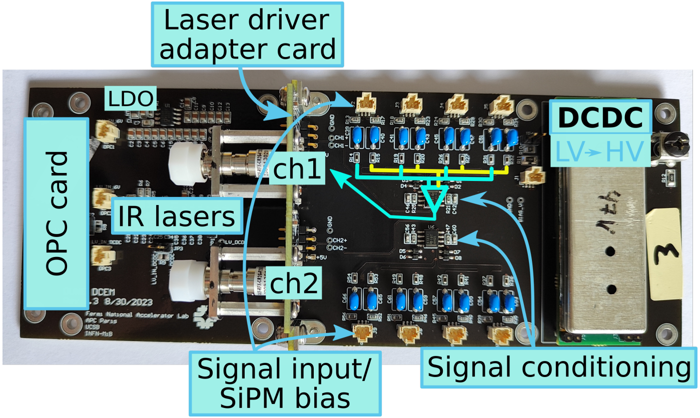


Warm receiver/digitization:

- Optical signals are transmitted through fibers outside of the cryostat.
- An in-house designed optical receiver converts them to analog signals, and is connected to
- the PDS digital electronics board (DAPHNE)

xArapuca module with SoF electronics inside open electronics enclosure

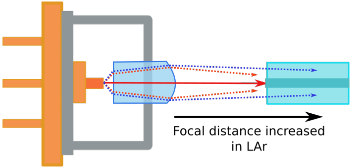




SoF - cold electronics - R&D

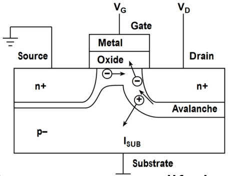
Defocused Lasers

- IR (1310 nm) laser: commercially available and far from SiPM sensitivity
- Low current: 2 mA lasing in cold
- LAr diffraction index being different from air, fiber-laser coupling is affected
- FC connector structure was modified so that the focus point is closer to the fiber tip when submerged in LAr.



Component Selection and Longevity

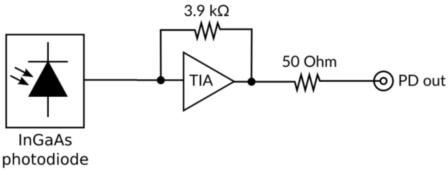
- Most active electronic components won't work in cryogenic temperatures unless designed to do so
- Some, however, do: like some bipolar and many CMOS components
- Most known failure mechanisms (electromigration, stress migration, thermal cycling) are mitigated by operating in cold
- Only identified degradation mechanism, affecting MOS components, is the "Hot Carrier Effect"

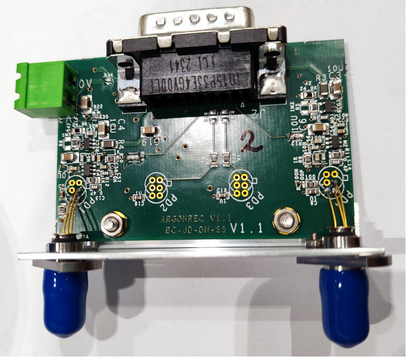


- Solution: validate component lifetime or use pure bipolar components

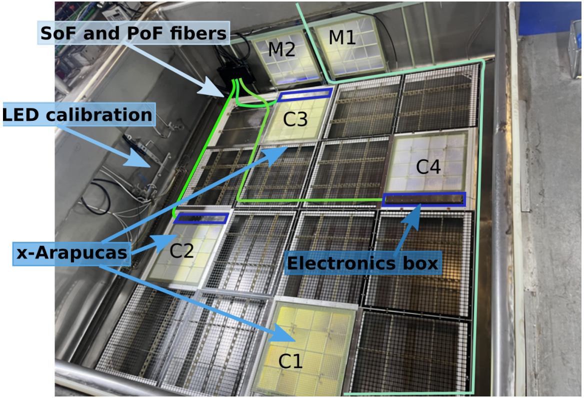
Analog Optical Receiver

- InGaAs IR diode - high bandwidth, low noise, $\sim$ 9 A/W
- Fast low noise TZ amplifier $>$ 1 kV/A amplification
- Large dynamic range
- Until now using a commercial, 1-channel optical receiver and a CAEN 14b digitizer
- Under development: in-house design: 8-channel mezzanine board connected into the DUNE PDS digitization module DAPHNE - benchmarked against commercial solution.





Prototype Testing at CERN

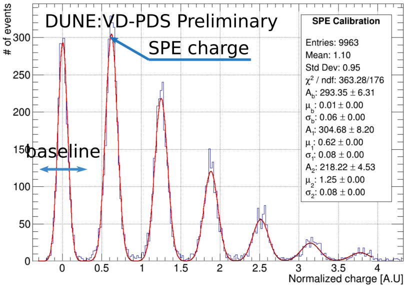


- The "coldbox" is a $3 \times 3 \times 1\ m^3$ cryostat located at the CERN Neutrino Platform
- Here the PDS can be tested alongside the TPC components (bias voltage up to -30 kV) $\rightarrow$ closest conditions to real detector
- Cosmic muons are detected with both PDS and CRP
- A UV LED flashing system allows to take performance/calibration runs
- $>$ 15 runs since November 2021!

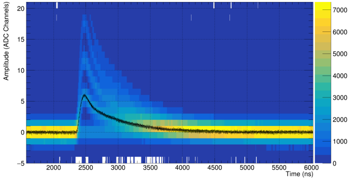
Evaluation of PDS performance: LED calibration

- Data generated with a 275 nm LED set to a minimal light output allows to uniquely identify few-photon signals
- The integrated charge of the small signals is plotted
- The Signal-to-Noise Ratio (SNR) is computed as

$$SNR = \frac{\text{SPE average charge}}{\text{baseline RMS}}$$



Signals of 1, 2 and 3 PE - April 2024



MODULE	channel	type	SPE amplitude (mV)	Baseline RMS (mV)	SNR
C1	ch1	CMOS	0.9	0.49	8.8
	ch2		0.8	0.48	7.9
C2	ch1	CMOS	0.8	0.55	6
	ch2		0.6	0.49	6.2
C3	ch1	SiGe	0.7	0.45	10.1
	ch2		0.7	0.60	6.1
C4	ch1	SiGe	0.5	0.45	5.9
	ch2		0.8	0.65	5.3

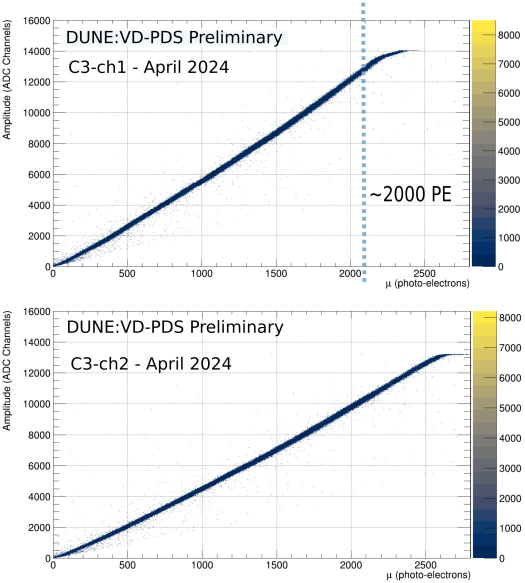
- Four cathode modules (8 channels) tested
- All modules achieved good performance

Evaluation of PDS performance: dynamic range

The dynamic range of the full SoF readout chain results from the interplay between:

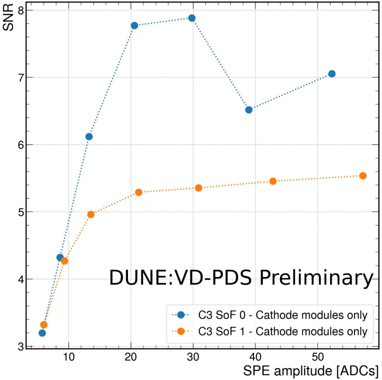
- The SiPM signal size at the output of the xArapuca (related to bias over-voltage)
- the cold transmitter's maximum signal output (related to V_{dd})
- the warm receiver's maximum input
- the ADC's range

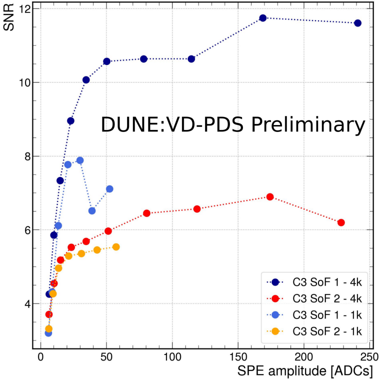
The SoF cold electronics evaluated in the prototype run of April 2024 demonstrated a dynamic range between 1600 and 2000 PE.



Warm Electronics

- The gain of the receiver can be configured to values above 1 k
- DAPHNE provides amplification and attenuation within its digitization chip, that can be selected independently
  $\rightarrow$ Both gains need to be chosen coherently to achieve an optimal SNR and dynamic range
- A first study of the warm-stage performance was done in April 2024





Varying the gain withing DAPHNE modifies the amplitude of the SPE, and affects the SNR.

Building ProtoDUNE-VD

- The installation procedure of the VD-PDS implies that all PD modules are tested in LAr prior to installation.
- A setup was built at CERN to this purpose; all 8 cathode modules installed in ProtoDUNE-VD were tested in June 2024.
- This constitutes additional data from 16 channels.

MODULE	channel	type	SPE amplitude (mV)	Baseline RMS (mV)	SNR
C1	ch1	SiGe	1.0	0.47	6.7
	ch2		0.8	0.51	5.4
C2	ch1	SiGe	0.8	0.45	5.5
	ch2		0.9	0.48	6.2
C3	ch1	SiGe	1.1	0.46	7.9
	ch2		1.0	0.56	6.8
C4	ch1	SiGe	1.0	0.46	7.9
	ch2		0.8	0.46	6.1
C5	ch1	CMOS	0.6	0.46	4.9
	ch2		1.0	0.47	7.5
C6	ch1	CMOS	1.5	0.48	8.1
	ch2		1.0	0.46	7.8
C7	ch1	CMOS	0.8	0.49	6.3
	ch2		0.5	0.49	4.3
C8	ch1	CMOS	1.2	0.45	7.9
	ch2		0.9	0.55	4.8

Conclusions

- The geometry of the Vertical Drift LArTPC detector presented a challenge for the placement of the PDS sensors.
- Simulation studies showed that placing PD sensors on the cathode greatly enhances the light detection within the VD detector.
- Technologies to power and transmit the signals of these detectors over fiber were developed and optimized over the past 3 years.
- Prototype runs at CERN were fundamental to test the SoF readout and allowed to optimize the design in accordance with the rest of the PDS components.
- A maximum of 8 channels has been tested simultaneously, demonstrating that the system meets the performance requirements.
- In addition, 8 modules (16 channels) have been tested in LAr, showing consistent performance.
- The cold electronics have reached a stable design; the warm stage tuning is on-going with a new version of DAPHNE soon available.

Thank you for your attention!

Back Up

Prototype Testing at CERN