(Cryogenic) Signal and Power transmission over Fiber in the DUNE Far Detector

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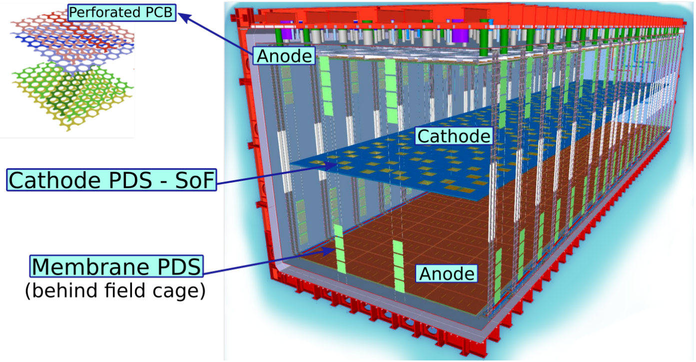
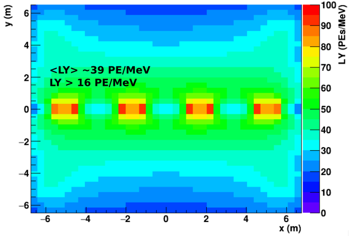
The Vertical Drift Photo-Detection System (PDS)

14m x 14m x 60m



- 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

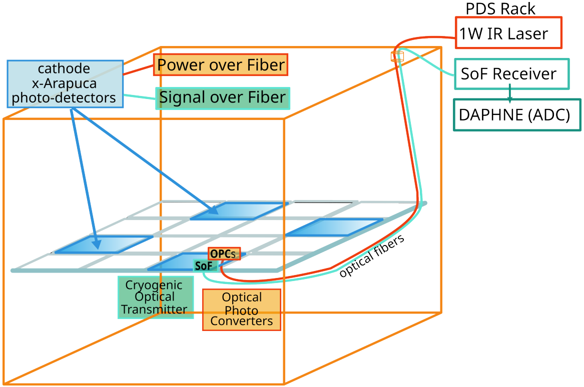


DUNE FD2 TDR

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

PDS on the High Voltage cathode

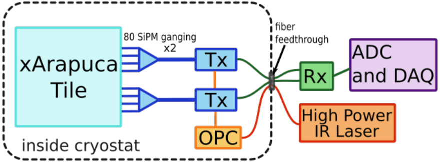
Each cathode structure is 3 × 3 m^2 and contains 4 xArapuca modules



xArapuca:

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

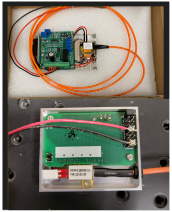
Signal transmission and powering schematic



*See Patricia Sanchez's slides for details on the photo-detectors

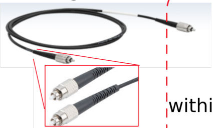
Powering on a high voltage surface

- High power IR laser (> 1 W, 808 nm) for power:
  - set at $\sim$ 800 mW
  - potential to increase power during detector lifetime if needed
- Multi-mode optical fibers, 62.5 um core, with FC connectors
  - protected with meshes and tubing
  - metal connectors and black covers to diminish light leakage
- IR light leakage:
  Although 808 nm is far from the SiPM's peak sensitivity, the laser power is very high and the placement of connectors and fibers is very close to the sensors, so that a high count of PE can be detected.



IR lasers: housed in PDS rack

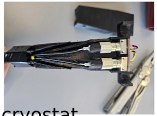
40 m long fibers



FC metal connectors

OPC receiver

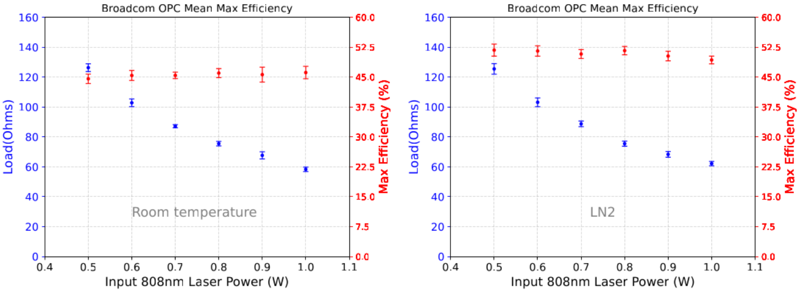
within IR light-tight enclosure



inside cryostat

Cryogenic Optical Photo Converters

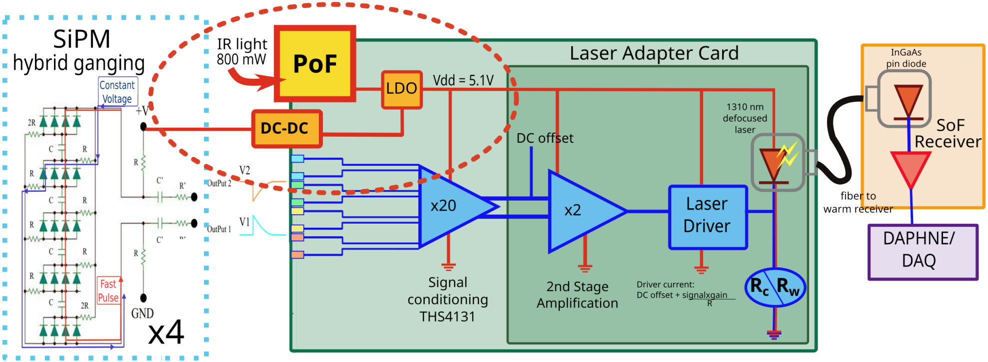
- High efficiency (optimized for cold operation) InGaAs Optical Power Converters
  - OPC voltage output depends on load (blue)
  - Power conversion efficiency is constant as a function of laser power (red)
  - a single OPC can provide $> 265\ mW$ necessary to power the readout/bias electronics in cold
  - with two OPCs power is enough for the warm commissioning of the detector ($> 550\ mW$)



Maximum efficiency obtained and corresponding load.

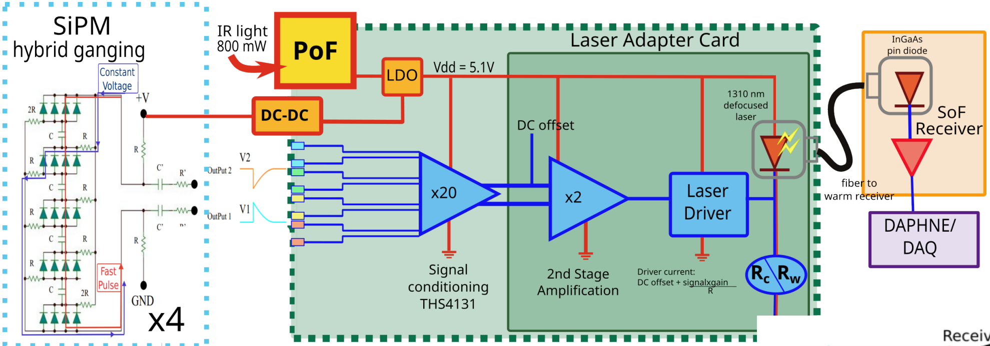
*JINST 19 (2024) 10, P10019

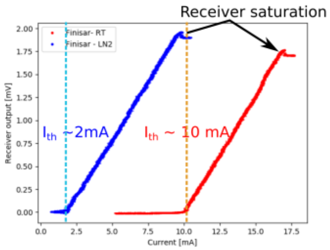
Signal Transmission over Fiber - SoF



- **Power/Bias scheme**:
  - PoF receiver output is 5-6 V depending on the load
  - $\sim$45 V SiPM bias generated with an in-house designed DCDC circuit (low noise, $<$200 μV)
- **SiPM hybrid ganging** allows to bias and read-out signal through the same differential pair

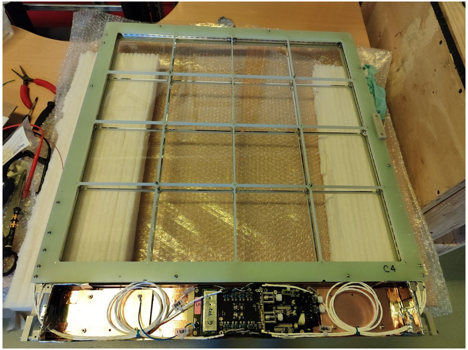
Signal Transmission over Fiber - SoF

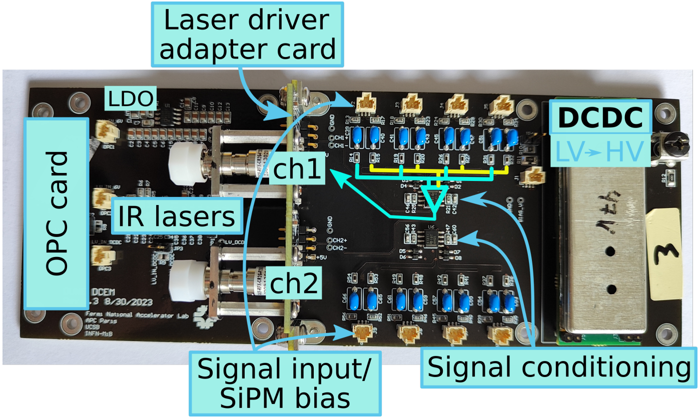




- Cryogenic Analog Optical transmitter:
  - Signal gain: compromise between SNR and dynamic range
  - Laser driver: signal conversion from voltage to current - IR laser
  - A constant DC offset current keeps the laser above its lasing threshold
- Warm electronics: an in-house designed optical receiver and the PDS custom digital electronics, DAPHNE

xArapuca module with SoF electronics inside open electronics enclosure

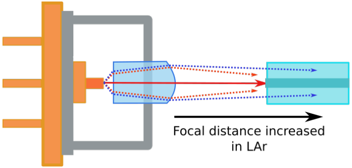




SoF - cold electronics - R&D

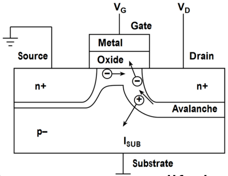
Defocused Lasers

- 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"

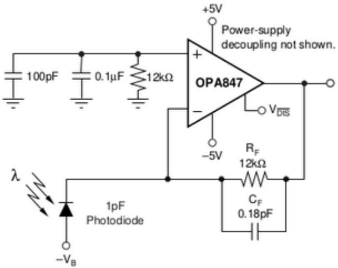


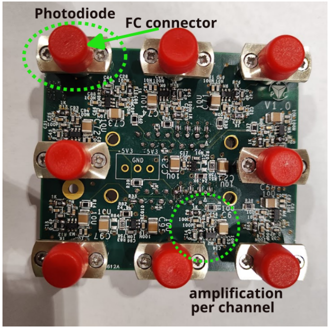
- Solution: validate component lifetime or use pure bipolar components

SoF - warm electronics

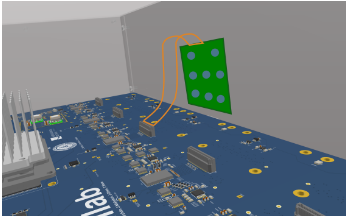
Analog Optical Receiver

- 8-channel mezzanine booard, connected onto the DUNE PDS digitization module DAPHNE - benchmarked against commercial solution.
- InGaAs IR diode - high bandwidth, low noise, $\sim$ 9 A/W
- Fast low noise TIA amplifier $>$ 1 kV/A amplification
- Large dynamic range

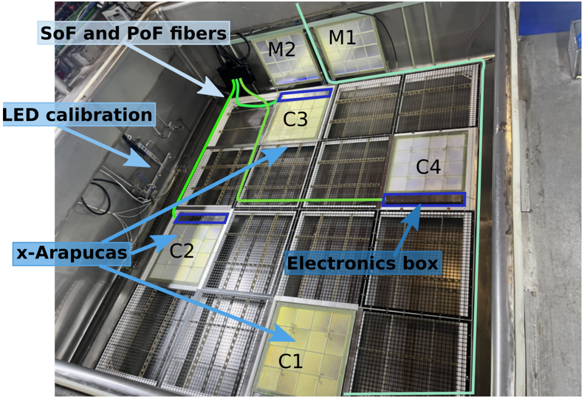




SoF receiver in digital electronics enclosure



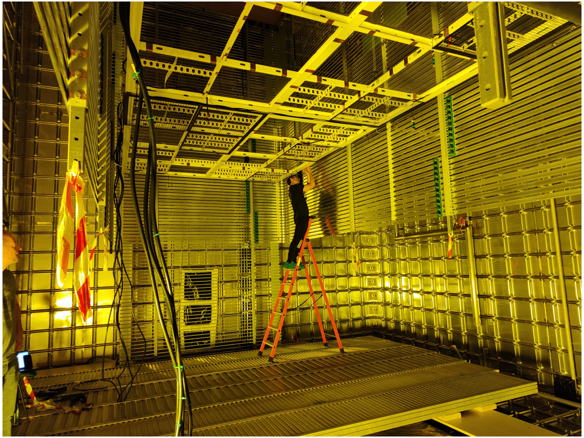
Prototype Testing at CERN - Coldbox



Cathode inside the open coldbox - Four xArapucas read-out with fibers.

- 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) $\rightarrow$ close conditions to real detector with fast turnaround
- Cosmic muons are detected with both PDS and TPC
- A UV LED flashing system allows to take performance/calibration runs
- $>$ 15 runs since November 2021!

Prototype Testing at CERN - ProtoDUNE-VD



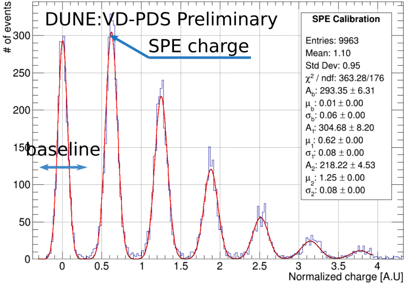
Assembly of the cathode PDS during ProtoDUNE construction - June 2024.

- Kiloton-scale prototype construction
- 8 cathode modules installed, with prior testing in cryogenic conditions
- After a long wait, beam data-taking started yesterday!! woohooo!!!

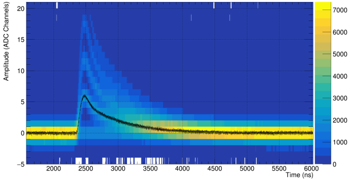
Evaluation of PDS performance: LED calibration

- 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

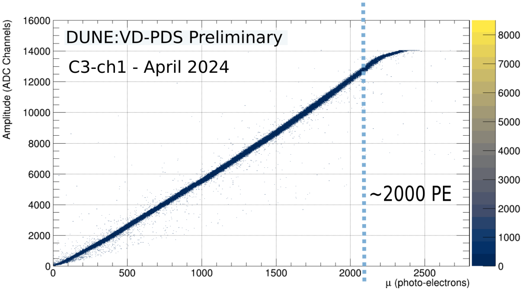
- Four cathode modules (8 channels) tested
- All modules achieved good performance and met DUNE requirements

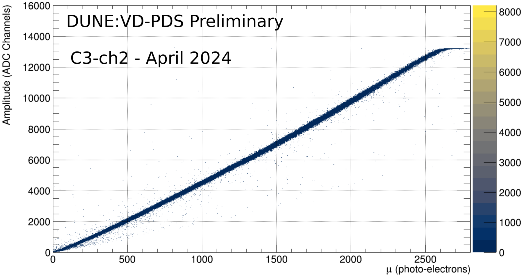
Evaluation of PDS performance: dynamic range

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

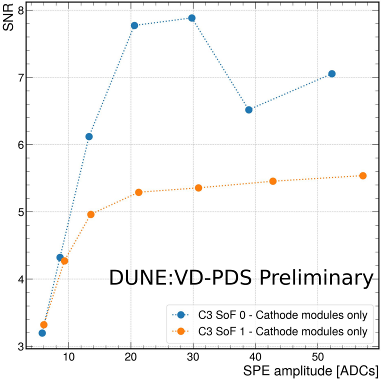
The SoF cold electronics evaluated in the prototype run of April 2024 demonstrated a dynamic range between 1600 and 2000 PE and met DUNE requirements.

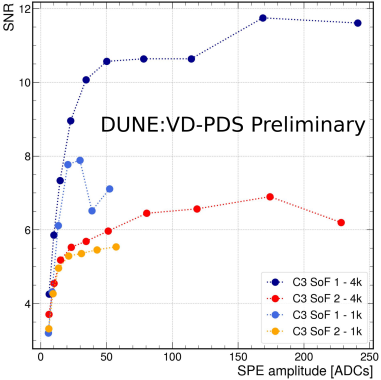




Warm Electronics

- 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.

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 4 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 VD-PDS readout scheme has reached a stable design, we're eagerly waiting for ProtoDUNE-VD data!

Thank you for your attention!

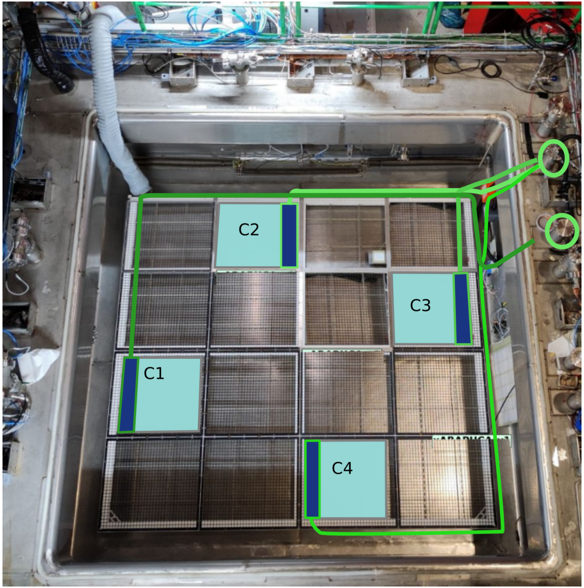
Back Up

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

Prototype Testing at CERN



Hot Carrier Effect

- Carriers accelerated by the E field, reaching high velocities (hot) that are maximum at the drain, and can generate e-h pairs
- The generated charges can then get trapped in the oxyde
- As a consequence, the device performance degrades and substrate current is increased