Photon Detection implementation in the DUNE Far Detector

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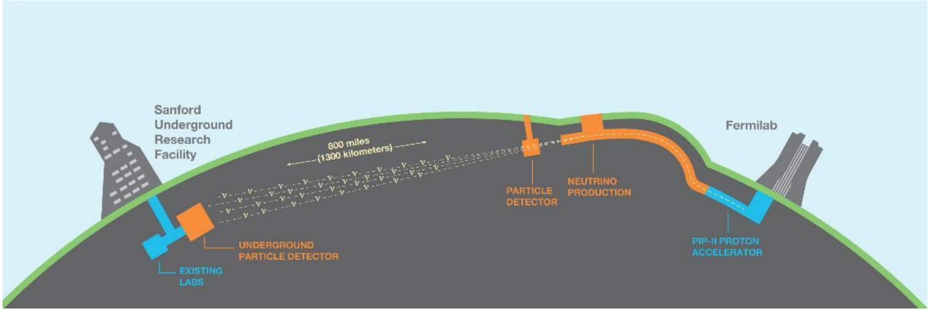
The Deep Underground Neutrino Experiment



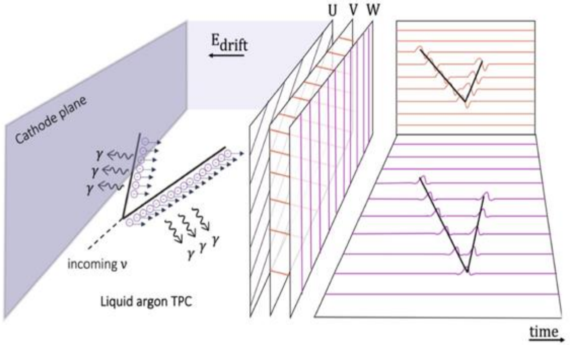
DUNE TDR Volumes:
JINST 15 (2020) 08, T08008
JINST 15 (2020) 08, T08009
JINST 15 (2020) 08, T08010
JINST 19 (2024) 08, T08004
ND CDR : Instruments 5 (2021) 4, 31

DUNE is a long baseline neutrino oscillation experiment with unique features:

- A **1.2 MW proton beam** (upgradeable to $>$ 2 MW) will be produced at Fermilab, generating a neutrino beam aimed towards the Sanford Underground Research Facility (SURF)
- **1300 km baseline** between Near and Far Detector sites
- A far detector placed on-axis, with a **1.5 km overburden** and four modules totalling **70 kton LAr**

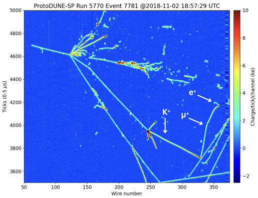
The LArTPC technology

At least 3 of the DUNE Far Detectors will be Liquid Argon Time Projection Chambers:

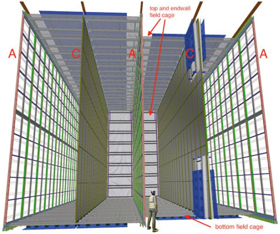


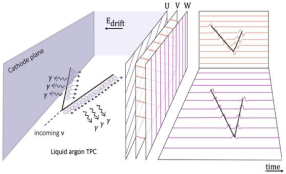
- LAr is (relatively) cheap, dense and transparent to its own scintillation light.
- Signals from:
  - ionization electrons → 2D image of the event
  - scintillation photons → timestamp to reconstruct event depth

- First proposed by Carlo Rubbia in the 70s
- Well understood and tested technology
- Implemented in experiments like MicroBoone and Icarus
- But never at the kiloton scale!

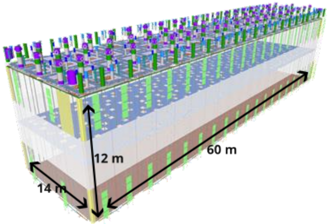


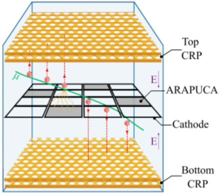
Horizontal Drift





Vertical Drift





- Four drift volumes, 3.6 m drift → -180 kV
- Anodes are wire plane assemblies (APA)
- PD embedded in anodes

- Two drift volumes, 6.25 m drift → -300 kV
- Anodes are printed cricuit boards (PCB)
- They are opaque → different PD placement
  - 340 on cryostat membrane
  - 320 on cathode HV surface

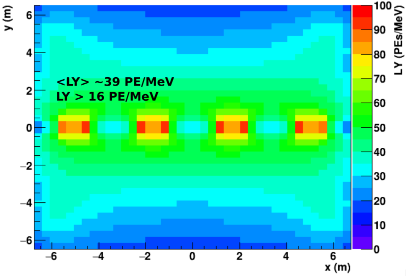
Different detector geometries require different implementations of PDS.

Photon Detection in the DUNE FD

- Uses of PDS:
  - timestamp for neutrino interactions ($\sigma_t \sim$ ns)
  - low energy sensitivity ($\sim$ 10 MeV)
  - calorimetry
- LAr scintillation is VUV (128 nm)

PDS requirements

- Average light yield $>$ 20 PE/MeV,
- Minimum light yield $>$ 0.5 PE/MeV
- Time resolution $<$ 100 ns
- Dynamic range: less than 20 % simultaneous detector saturation



VD-PDS: PDs on cathode increase LY uniformity

The xArapuca photon collector

"A trap for photons"

Challenge: detect VUV light using SiPMs (maximum sensitivity in visible range) with high efficiency

- conversion of photon's λ, from 128 nm to visible
- optimization of coupling between SiPM and WLS
- efficiency optimisations: depends on geometry, materials, etc

arxiv: 1804.01407

An arapuca is a type of bird trap in tupi-guarani language

The xArapuca photon collector

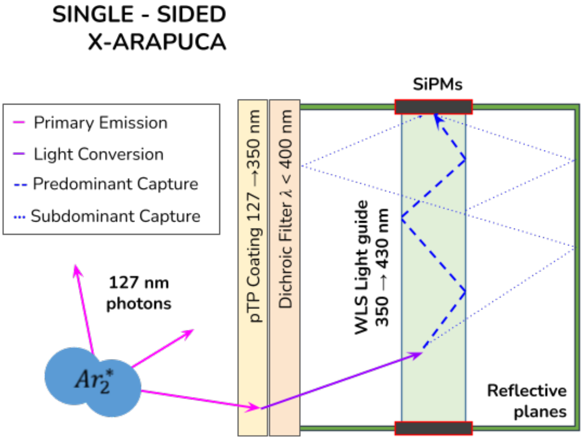
xArapuca structure:

PTP (P-terphenyl layer):
Converts the LAr scintillation light
($\lambda = 128$ nm $\rightarrow \lambda = 350$ nm)

Dichroic filter:
Transparent to light with $\lambda < 400$ nm $\rightarrow$ pTP converted light can enter
Reflective for $\lambda > 400$ nm $\rightarrow$ traps converted light

Wavelength shifter bar (WLS): Converts incoming light to $\lambda = 430$ nm
$\rightarrow$ light is trapped by DF
$\rightarrow$ physical support of xArapuca

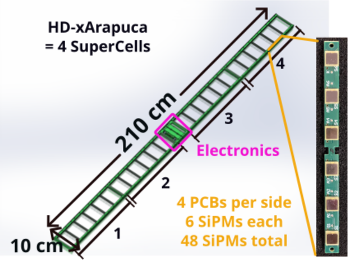
Silicon PhotoMultipliers (SiPM): Light detection
Absolute Photon-Detection Efficiency: 3-4.5%

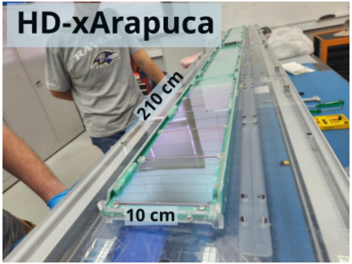


Note: efficiency measurements showed that removing the dichroic filter increased efficiency

arxiv: 2511.12328v2

The Horizontal Drift Photo-Detection System (PDS)

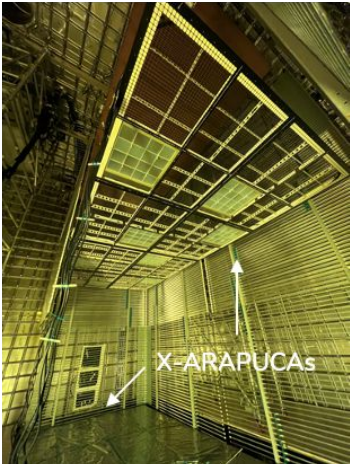




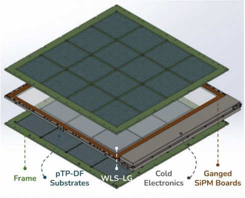
PDS installation in ProtoDUNE-HD at the CERN Neutrino Platform

- Anodes are wire-planes
- 10 xArapucas embedded within wires
- Each supercell:
  - $50 \times 10\ \mathrm{cm}^2$
  - one channel for 48 SiPMs
- 4 supercells per PD
  $\rightarrow$ 4 analog amplifiers

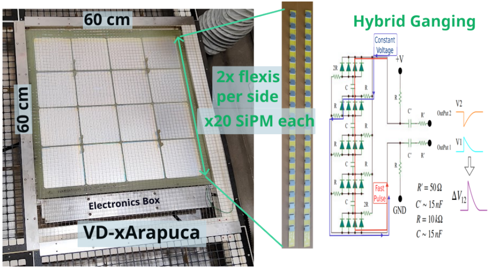
The Vertical Drift Photo-Detection System (PDS)



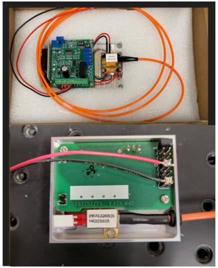
PDS installation in ProtoDUNE-VD



- Anodes are opaque PCBs conditions PD placement:
  $\rightarrow$ on membrane, behind fieldcage
  $\rightarrow$ on cathode, at HV (4 per 3×3 m^2)
- Each megacell:
  - 60×60 cm^2
  - 2 channels, 80 SiPMs each
- PDS on cathode helps increase the light-yield and improve uniformity



Power Over Fiber: powering on a high-voltage surface



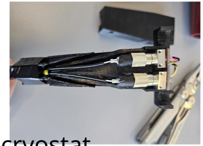
IR lasers: housed in PDS rack

40 m long fibers

FC metal connectors

OPC receiver

within IR light-tight enclosure

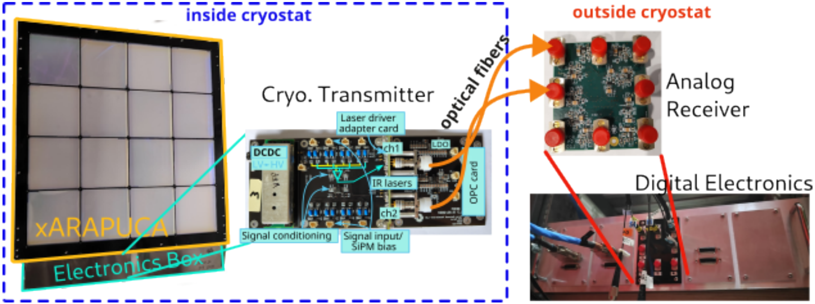


inside cryostat

- High power (1 W) IR laser for power (outside cryostat)
- Multi-mode optical fibers, 62.5 um core, with FC connectors (protected with special tubing)
- High efficiency (optimized for cold operation) InGaAs Optical Power Converters (efficiency $> 50\% \rightarrow > 265\ mW$)

arxiv: 2412.10177

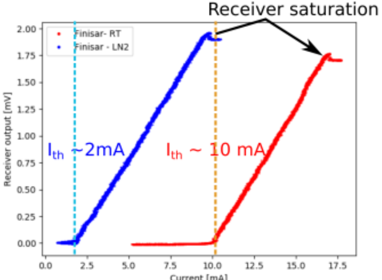
Signal Over Fiber



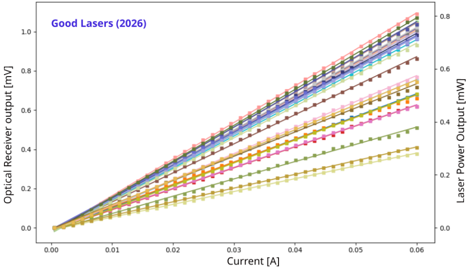
- Cryogenic analog optical transmitter placed on HV surface
- Defocused IR laser for signal transmission through optical fibers
- Outside the cryostat, 8-channel analog optical receiver
- PDS DUNE-specific digital electronics

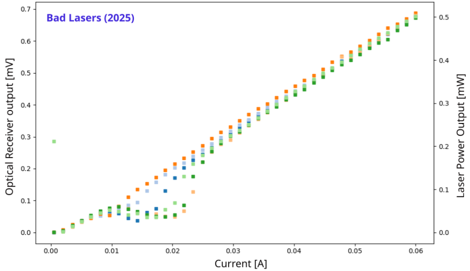
Lasers in Cryogenic conditions

- IR (1310 nm) laser: commercially available and far from SiPM sensitivity
- Low (2.7 mA) lasing threshold current in LAr
- Defocusing: LAr diffraction index is higher than for air, and affects the laser-fiber coupling.
  $\rightarrow$ increasing the FC-connector length improves coupling efficiency.



Issues with lasers in LAr: noise and non-linearities

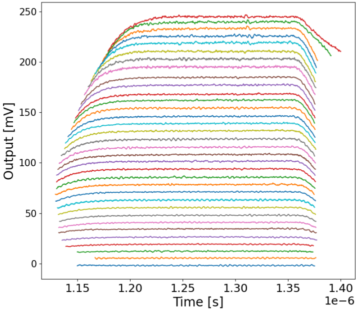




Lasers in Cryogenic conditions

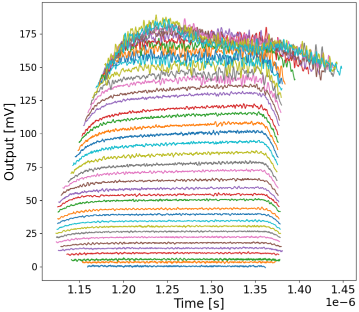
Measured non-linearity is not a feature of setup but caused by low temperature

Good Laser



- increase in power output is uniform
- same noise level for all pulse amplitudes

Bad Laser



- spacing between output changes depending on current
- increased noise level at higher current

Mode-hopping could be a potential explanation

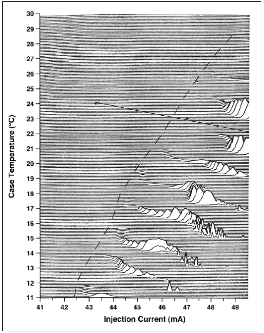


Figure 7. Laser Stability Map. Plots of ac voltage vs. current taken at different temperatures are plotted in an offset, hidden-line fashion. The solid line shows conditions for constant 2 mW laser output.

Mode Hopping in Semiconductor Lasers

DUNE SiPMs

DUNE Phase-I requires a huge number of SiPM: $\sim$300k for HD and $\sim$100k for VD

Two different vendors for both detectors:

- HAMAMATSU
- FBK

Different SiPM technologies/models proposed and tested before down-selection.

DUNE-SiPMs are not commercial models, with 6×6 mm^2 surface.

Every SiPM is characterized before installation in the detector:

- Breakdown voltage
- Quenching resistance
- Dark Count Rate (DCR), after pulses (AP), crosstalk (XT)

Testing procedures:

- IV curves
- Dark measurements

JINST 19 (2024) T01007

All SiPMs will be tested in dedicated facilities for DCR, AP and XT - both before and after thermal stress to check reliability in LAr.

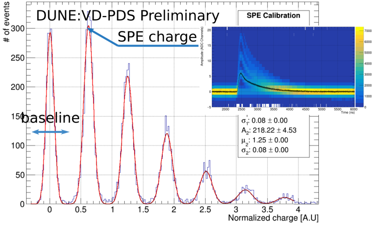
DUNE SiPM mass-testing

Cryogenic Apparatus for Control Tests Upon SiPMs

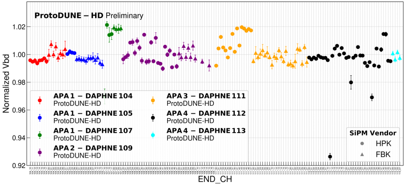
- SiPMs tested at RT and in LN_2, with automatic LN refill
- Custom, low noise readout electronics connected to FPGA
- 5 testing sites, total 2400 SiPMs tested per month

PDS performance summary

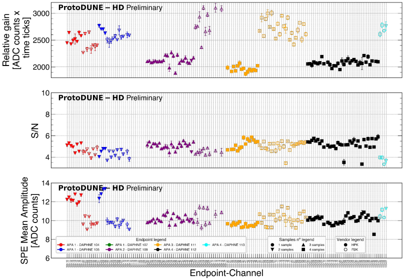
Signal-to-Noise is measured through a charge histogram



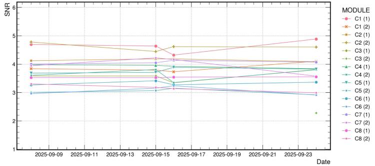
V_{bd} measured in ProtoDUNE-HD is stable

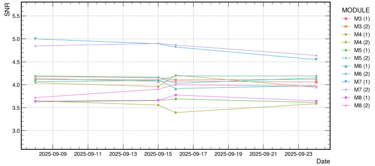


Performance of HD-PDS



Performance of VD-PDS





ProtoDUNE-VD run is ongoing, with studies of:

- Xe doping of LAr
- Detection of neutrons (using PNS)

Conclusions

- Photon-Detection in the DUNE Far Detector is necessary to reach DUNE's physics goals
- Different detector geometries in each Far Detector module $\rightarrow$ different implementation of PDS
- Based in same photon-collection technology: xArapuca, and on SiPMs
- Different cryogenic readout electronics
- Successful demonstration of PDS implementation in kiloton-scale prototypes at CERN:
  - integration to rest of detector
  - performance

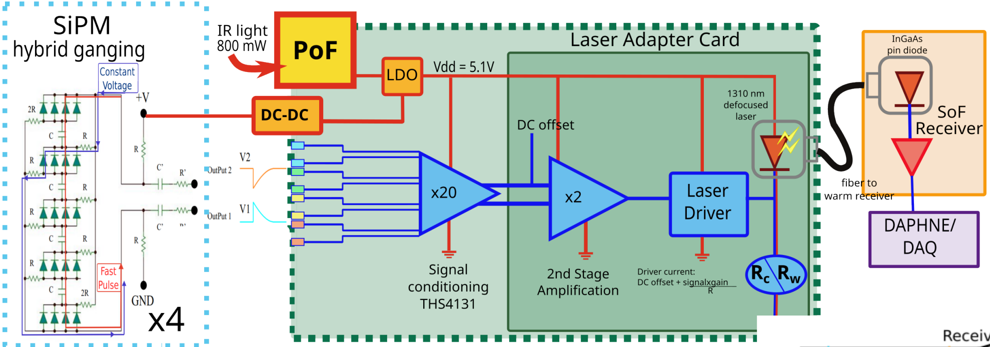
Thank you!

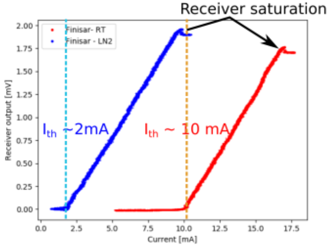
Back up

SiPM

Parameter	Value	Note
SiPM dimension and packaging	$6 \times 6\,mm^2$, SMT (Surface Mount Technology)	Compatible with the PDS module final design
Cell pitch	50–150 μm	As large as possible in the range allowed
PDE at nominal voltage (Vop)	> 35% at 430 nm	At room temperature
Window material	Siliconic or epoxidic	Cryogenic reliable
DCR	$< 200\,mHz/mm^2$ at Vop	At 77 K
Cross-talk probability	< 35% at Vop	At 77 K
After-pulsing probability	< 5% at Vop	At 77 K
Gain	2 to $8 \cdot 10^6$	Not critical
SiPM recovery time	200–1000 ns	Optimal for cold electronics
Breakdown voltage (Vbd) spread	< 200 mV (max-min)	Per group of 240 SiPMs (one PDS module)
Maximum Vbd voltage spread	< 2 V (max-min)	Global spread
Thermal cycles	> 20	Tested at 77 K by the Consortium
Signal to noise ratio in ganging	> 4	ganging of 48 SiPMs (1 DAQ channel)

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