Light detection with power and signal transmission over fiber

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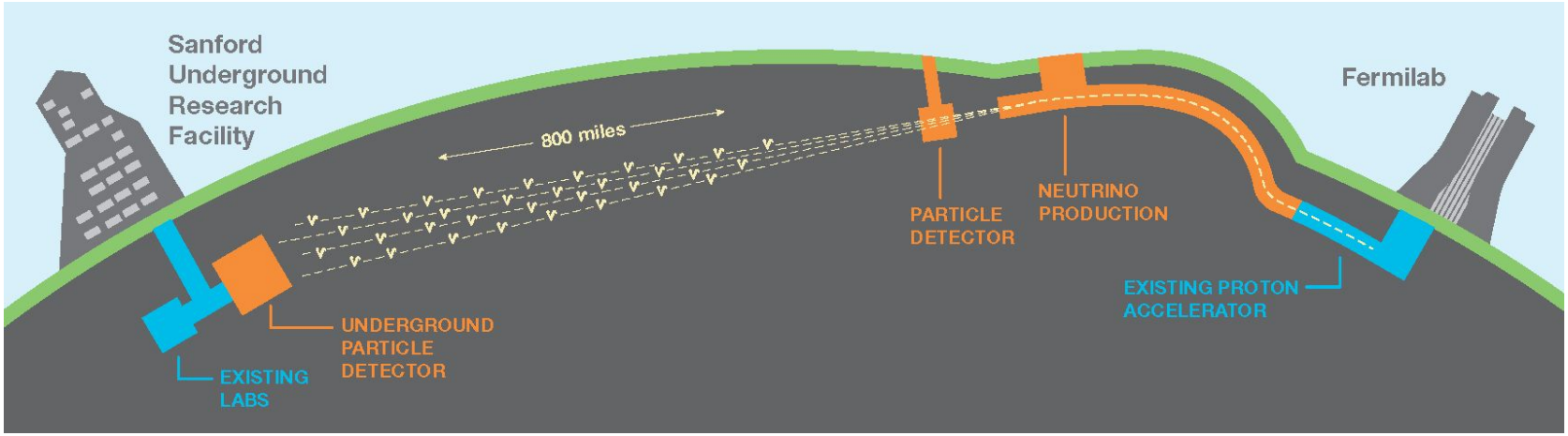
LIDINE 2022: LIght Detection In Noble Elements

September 23, 2022

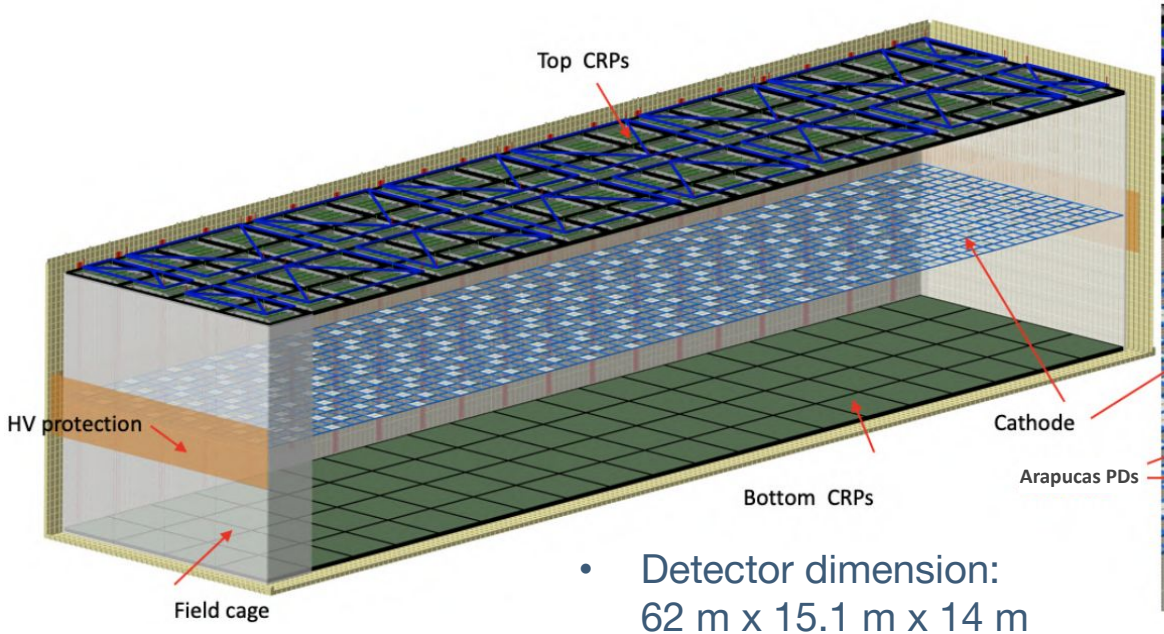
Deep Underground Neutrino Experiment (DUNE)

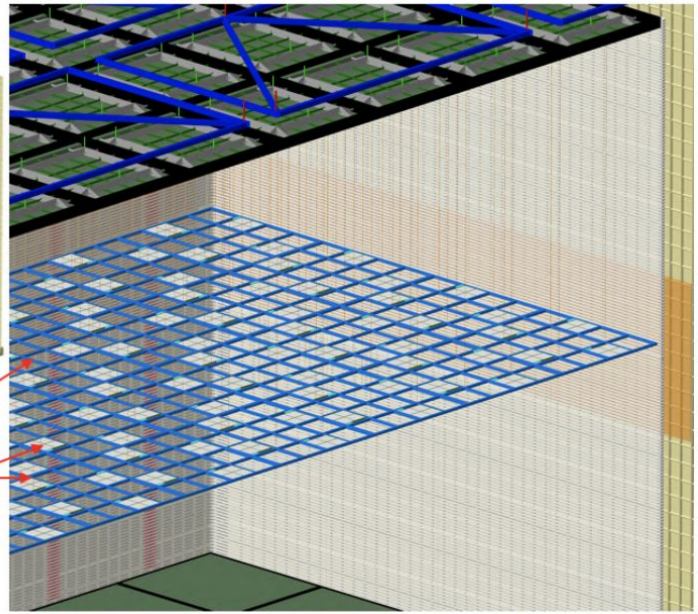
- Massive neutrino detector
- Four **Far Detector (FD) modules** of 17 kt each using Liquid Argon Time Projection Chambers (**LArTPC**)
- Neutrino **beam physics**, **supernova neutrinos**, **proton decay** and **solar and atmospheric neutrinos**
- The experiment search to answer open question in the field of particle physics, astronomy and cosmology (**CP violation phase** in the leptonic sector, octant of θ_{23}, **mass hierarchy**, etc.)
- Baseline of **1300** km and neutrinos energy from **0.1 to 10 GeV**



LArTPC: Vertical Drift (VD) module

- Charge-readout planes (CRP) (anode) on top and bottom.
- Cathode in the center at -300 kV
- 6,5 m drift distance
- Fiducial mass ~14.7 kt



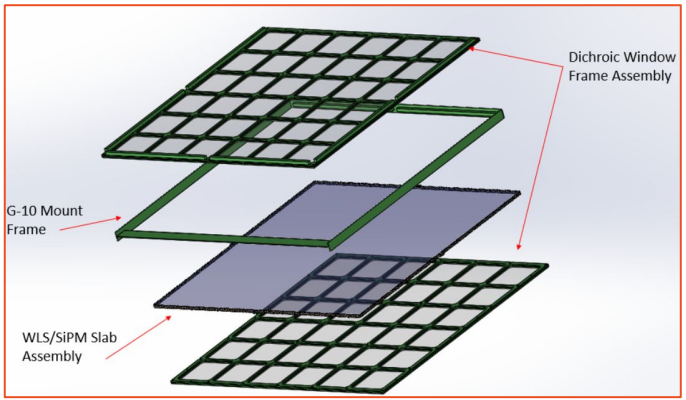


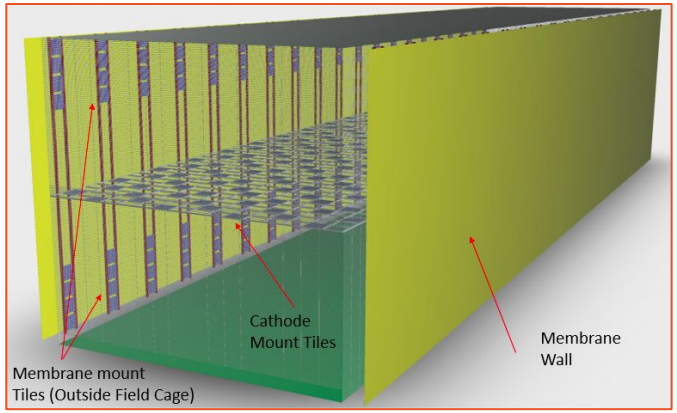
- Detector dimension:
  62 m x 15.1 m x 14 m

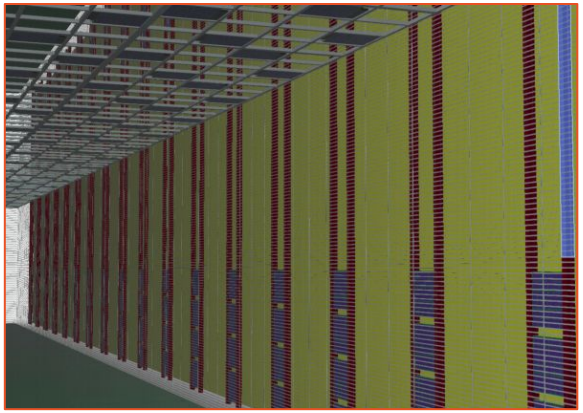
Challenge: photon detection system (PDS)

One of the new challenges to build such a technology is the PDS:

- The PDS is based on the X-Arapuca device.
- A total of 2x80 Silicon Photomultipliers (SiPMs) need to be biased and read out.
- These devices are installed on the Cathode at -300 kV
  - Power supply and signal must be transmitted over non-conducting materials

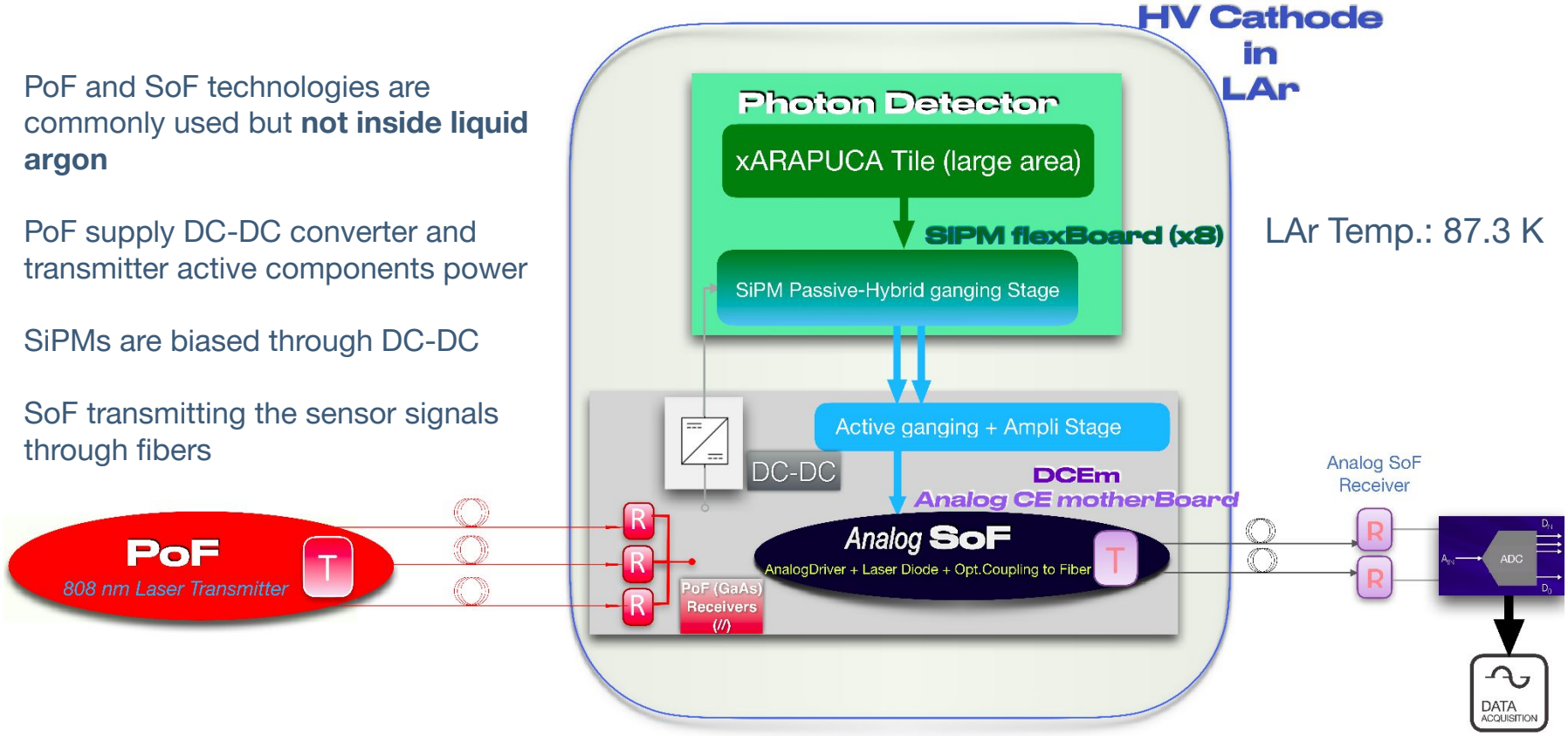






PDS: Power and Signal over Fiber

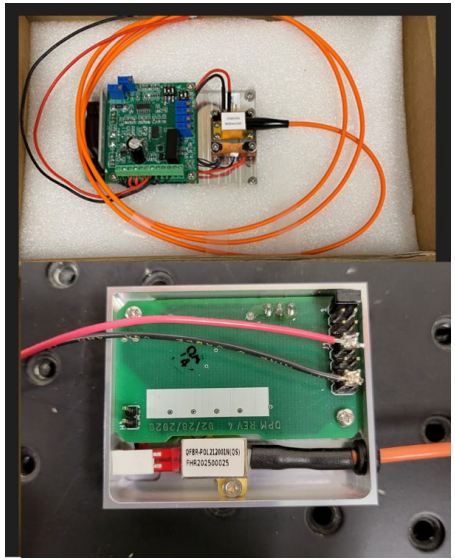
- PoF and SoF technologies are commonly used but **not inside liquid argon**
- PoF supply DC-DC converter and transmitter active components power
- SiPMs are biased through DC-DC
- SoF transmitting the sensor signals through fibers



Power over fiber

Low voltage (5 V) and high current PoF for DC-DC converter, OpAmps and other active analog electronics components.

Three receivers in parallel with efficiency >65%



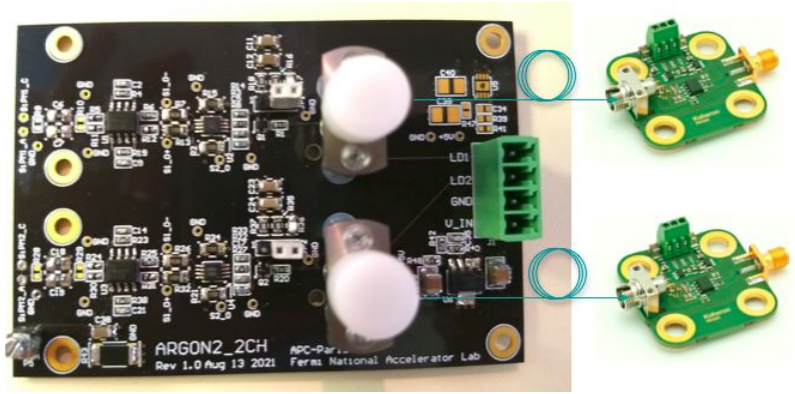
Multimode fiber with FC connector

PoF transmitter
806 nm 3 W laser

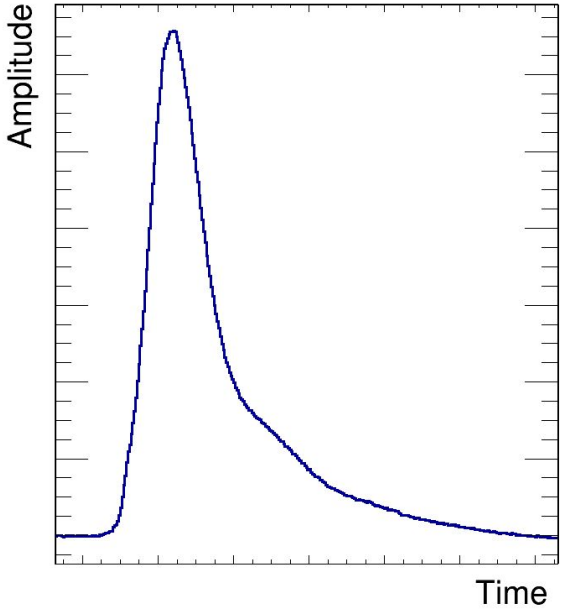
PoF Receiver
Gallium arsenide (GaAs)
Photovoltaic Power Converter (PPC) on heatsink

Signal over fiber

- **Board requirements**
  Efficiently transmit **single photo-electron** signals (also the signals from LAr scintillation, but this is mostly limited by the dynamic range)



First prototype

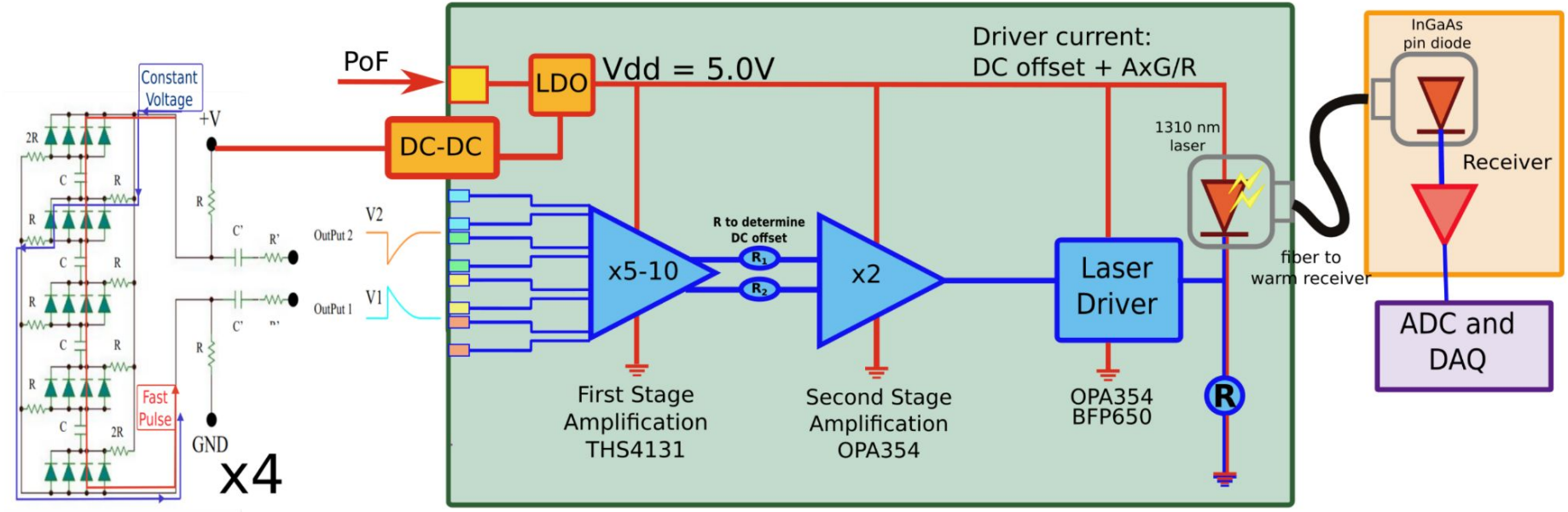


Amplitude ~ 50 - 100 μV
Rise time ~ 20 to 80 ns
Discharge time constant ~ 100 to 300 ns

Bandwidth ~ 30 MHz
Signal-to-noise ratio > 4
Dynamic range ~ 1000 photo-electrons

Signal over fiber

- DCem board (2 channels/board)
  - Fabry Perot 1310 nm lasers FC connector
  - Voltage gain ~x20 to x40
  - Laser optical power output ≲ 2 mW
- Integrated Photovoltaic Power Converter (PPC)
- Integrated DC-DC converter
- NTC resistor to enable warm and cold operation
- Low-Drop Out Voltage Regulator (LDO)



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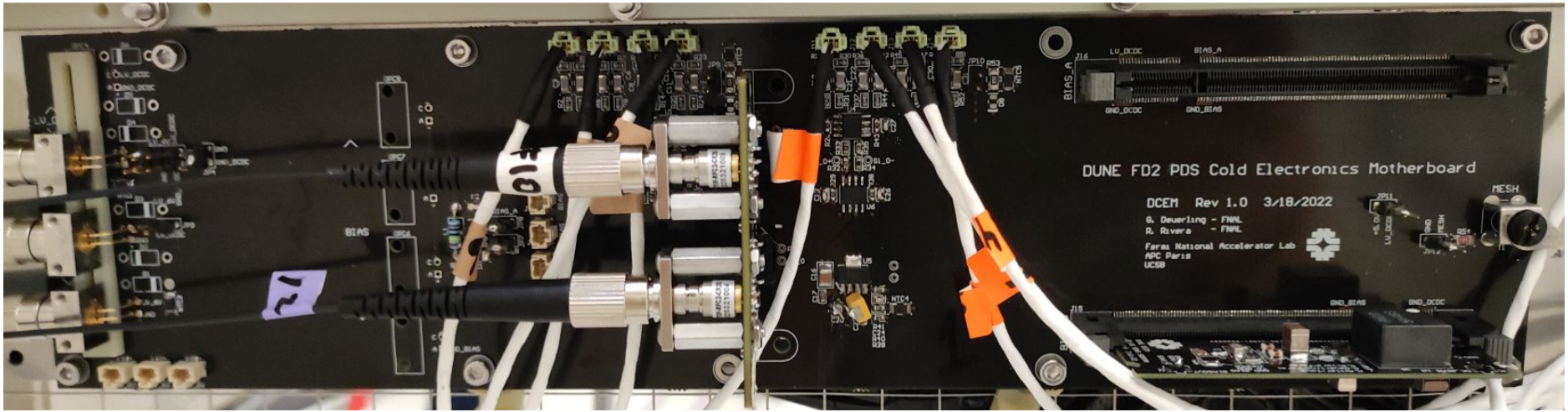
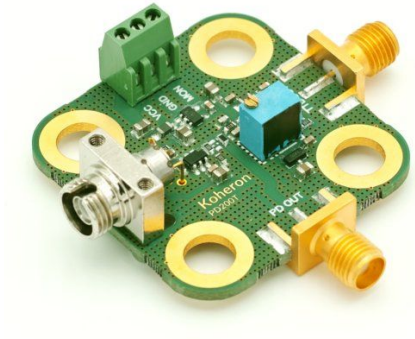
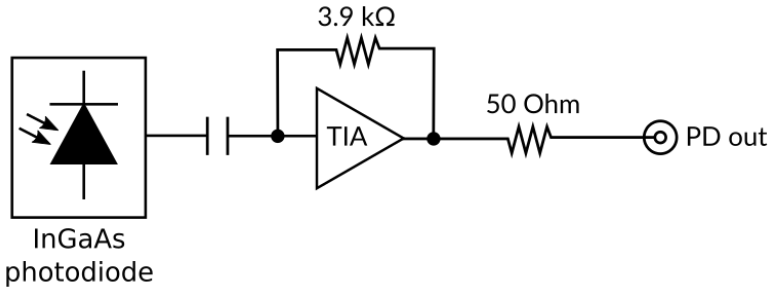


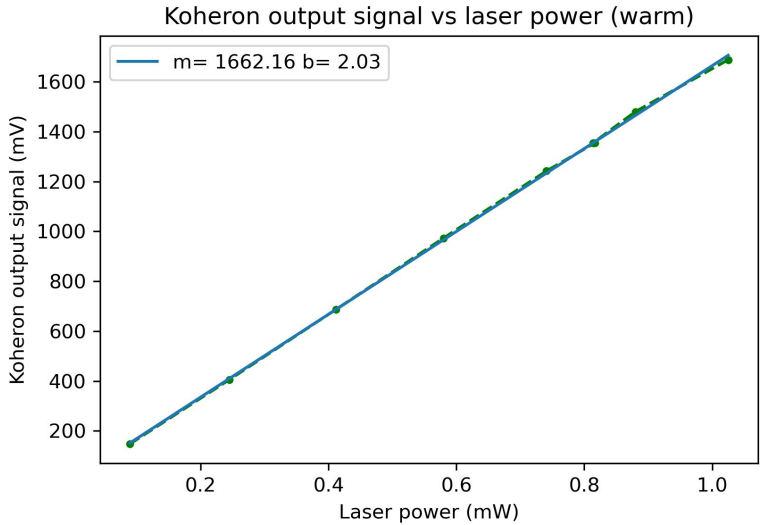
Signal over fiber

Koheron PD100 low noise photodiode

- single channel commercial solution - found early 2021
- Indium gallium arsenide (InGaAs) photodiode
- DC-coupled
- 0.9 A/W - 3.9 kV/A amplification
- 600 µW maximum input at 100 MHz
- ± 6V bias, ~40mA







PoF and SoF operation

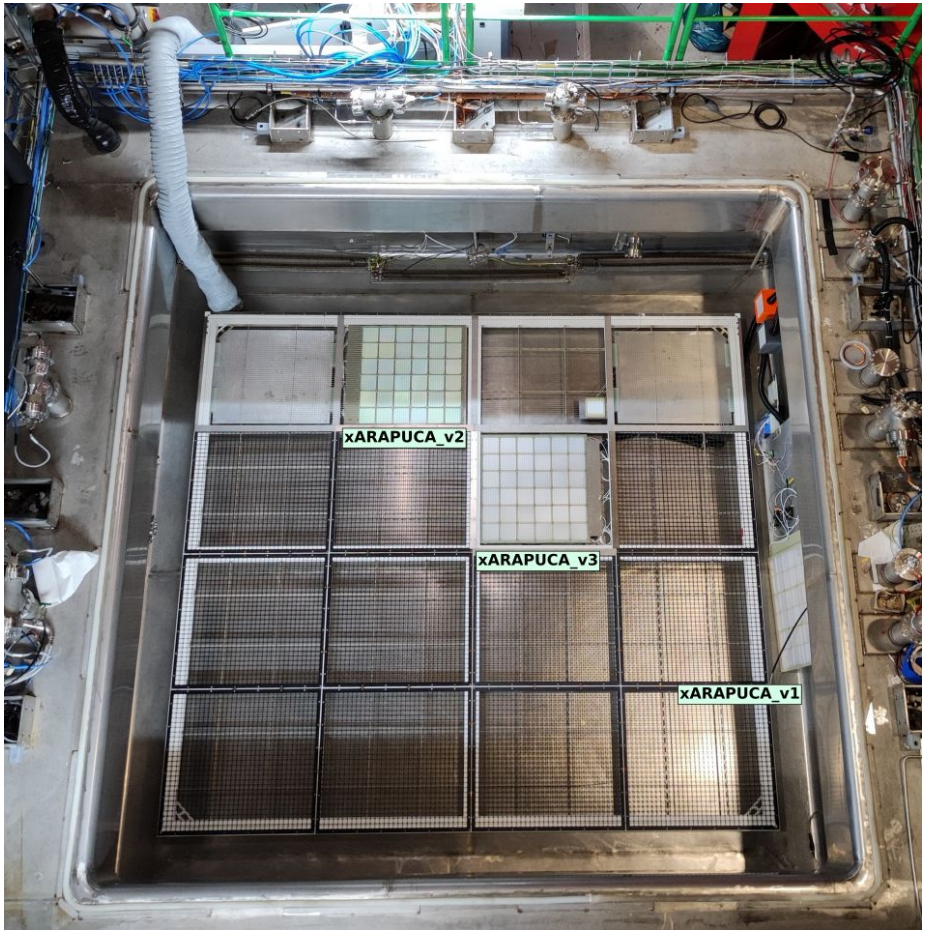
CERN Neutrino Platform **coldbox**:

3×3×1 m^3 cryostat for LAr tests

Cathode placed on feet, TPC is mounted on the coldbox cover (23 cm drift distance)

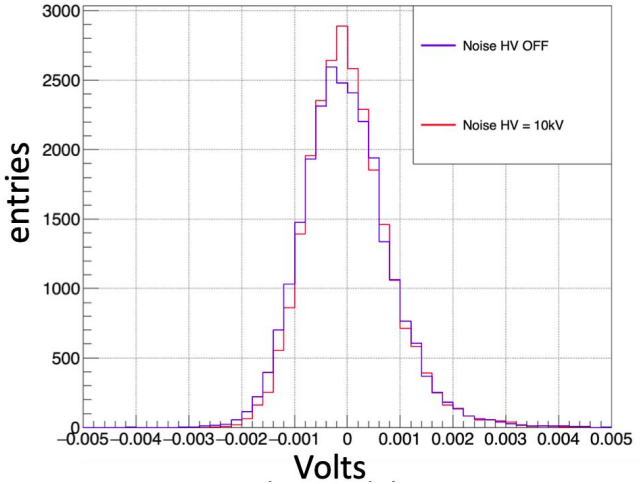
Target: operation of PDS system in LAr

PD with signal and power transmission through fiber, operating on an HV surface



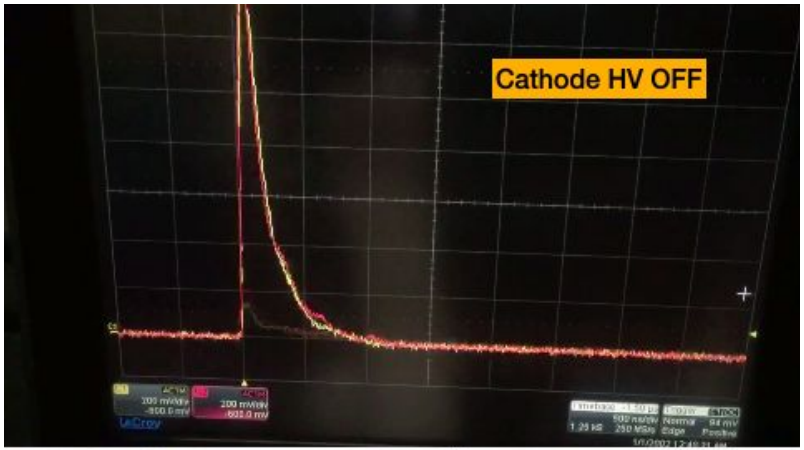
PoF and SoF operation

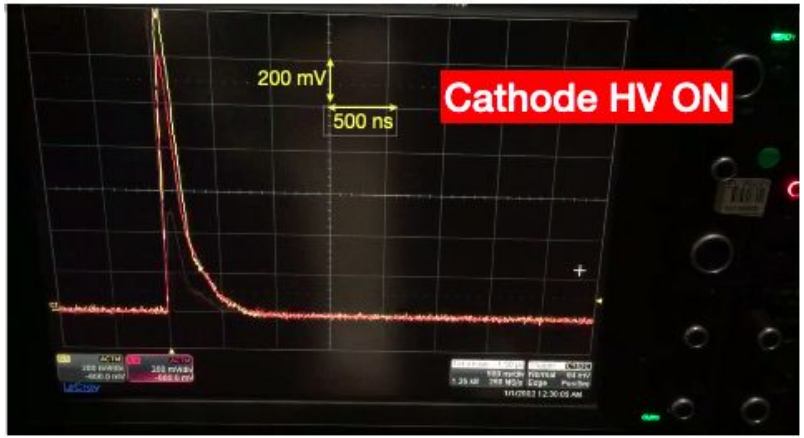
- Photon Detection System principle successfully demonstrated
  - Power and readout done through fiber only at liquid argon
  - Operation stable with High Voltage on and off
  - No interference in the TPC performance



HV OFF:
Mean = -0.05 mV
Sigma =0.77 mV

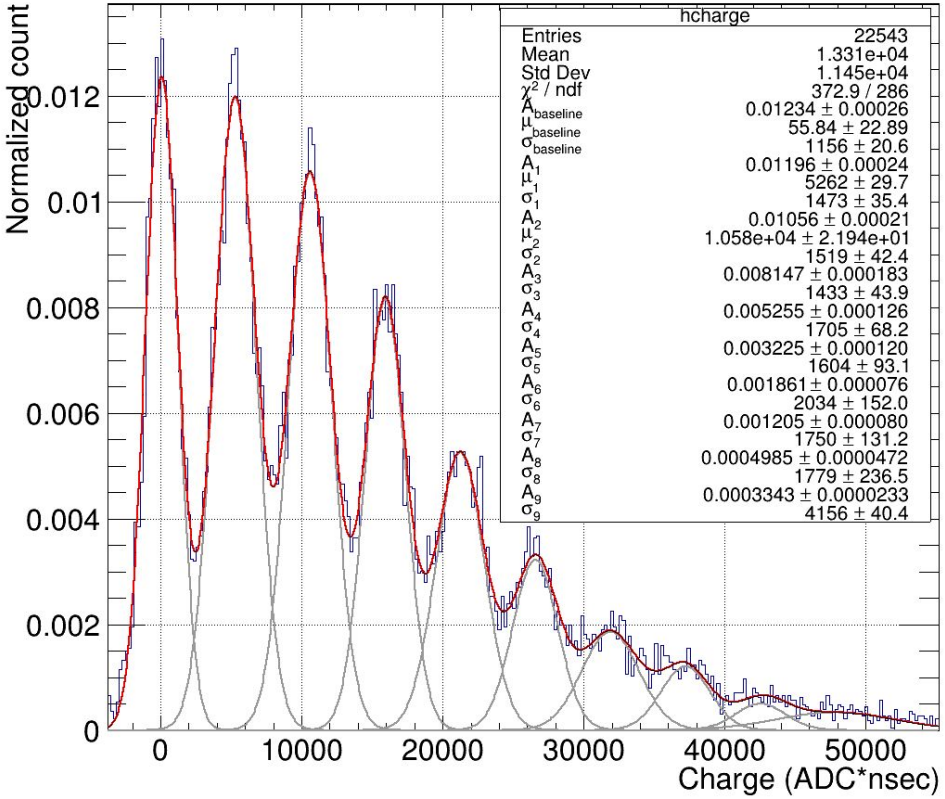
HV = 10 kV
Mean =-0.02 mV
Sigma=0.71 mV





SoF operation

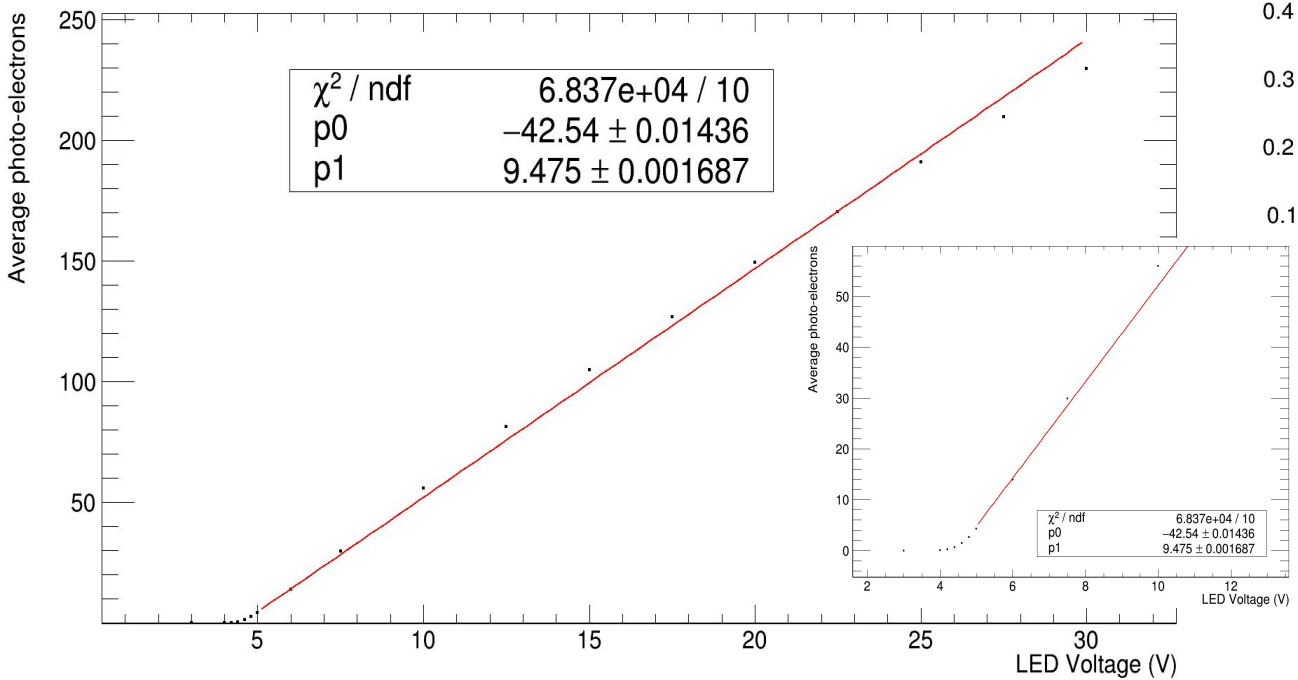
- LED flashes also made possible for single photo-electron calibration

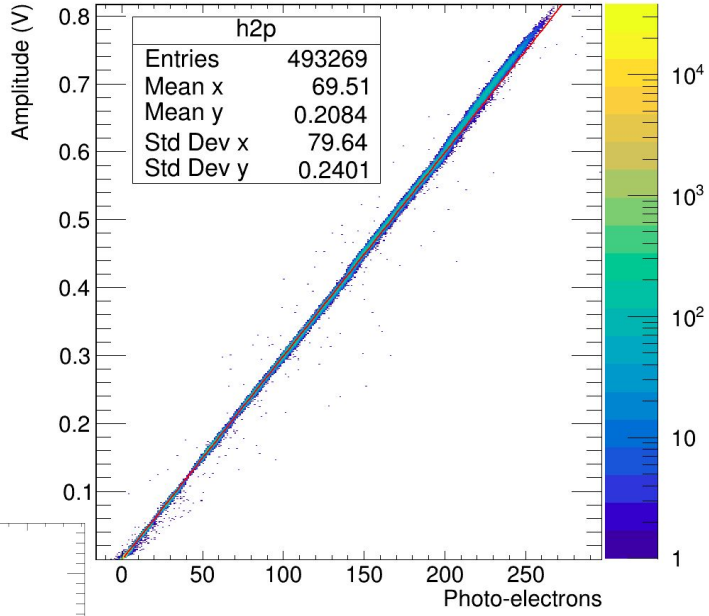


- Arapuca detector in the LArTPC membrane
- 20 SiPMs hybrid ganged
- Bias through copper (37V)
- Argon2x2 board (namely A1)
- Signal-to-noise ratio ~ 4.9

PoF and SoF operation

- Full chain linearity up to ~ 250 – 300 PE using LED calibration light





- Light output regulated through voltage (up to 30V) or pulse width
- SPE charge 0.3 Vns (measured)

Conclusions

- Power and Signal over Fiber successfully tested in December 2021 in a 23 cm drift distance LArTPC.
  - Stable performance when cathode operated at 10 kV (~430 V/cm)
  - Dedicated measurements have shown a linear response of the device
  - No interference on the functioning of the TPC

- Reliable system, operated through 5 different runs.

- Research and Development still in progress, with tasks such as:
  - Improve and verify circuit stability for the ~30 years long experiment
  - Prove dynamic range to cover the required ~1000 photo-electrons
  - Improve fiber connections to enhance light transfer in LAr

Thanks!

- Thanks to the APC group, specially to Sabrina Sacerdoti, Jaime Dawson, Ariel Cohen and Davide Moretti who without their great effort this work could not be possible.

- To the DUNE collaboration, in special to Flavio Cavanna and William Pellico for the feedbacks and the FD VD working group

- To the conference committee for the opportunity to present this work

Liquid Argon Time Projection Chamber (LArTPC)

Analogous to the concept of the bubble chamber: readable tracks from particles allow the three dimensional reconstruction of the event.

Particle detection

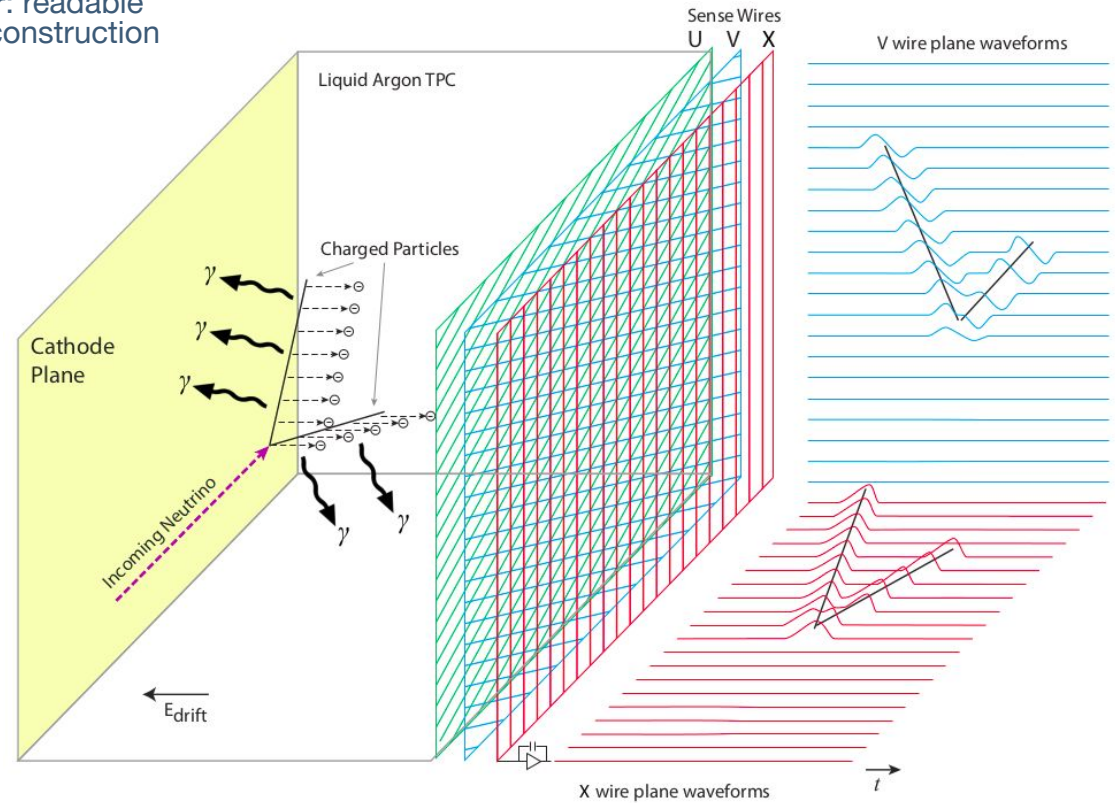
Ionization:

- Event reconstruction through ionization electrons.
- Requires an intense and uniform electric field

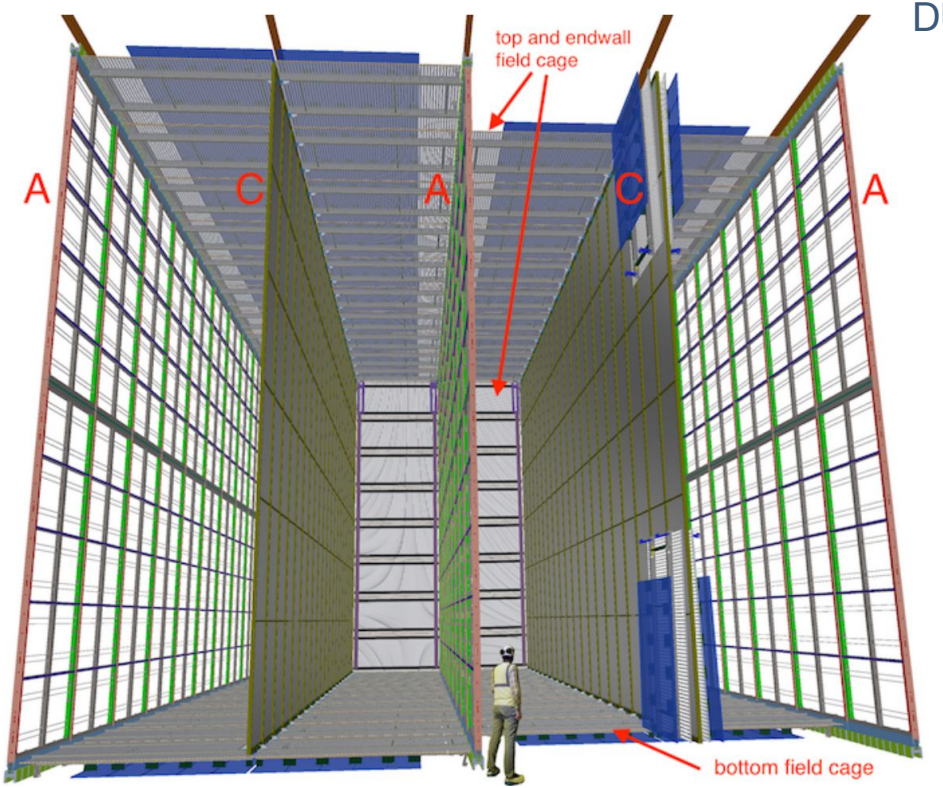
Scintillation:

- Electron recombination or self-excitation produce scintillation light
- Light measurements contribute to event reconstruction and calorimetric measurements

Three wire planes for disambiguation
External trigger or light: depth info
Max. e drift vel.: 1.59 mm/μs

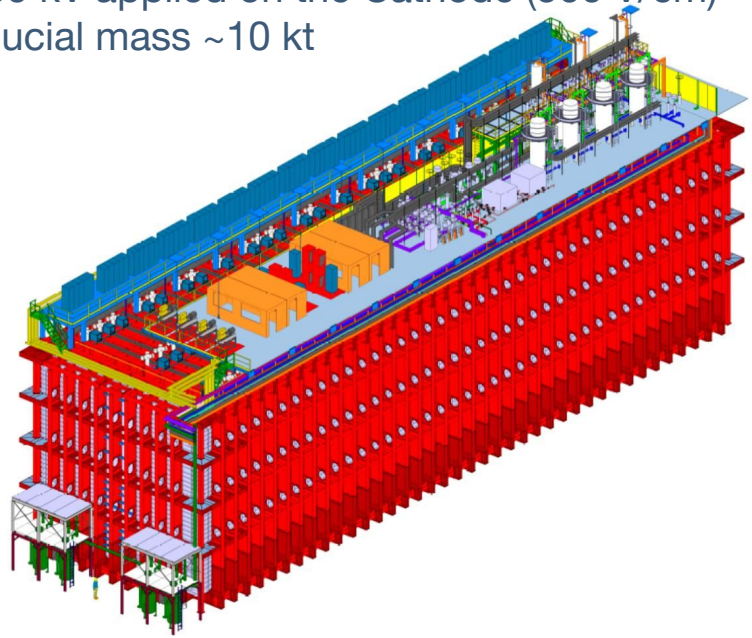


LArTPC: Horizontal Drift (HD) module

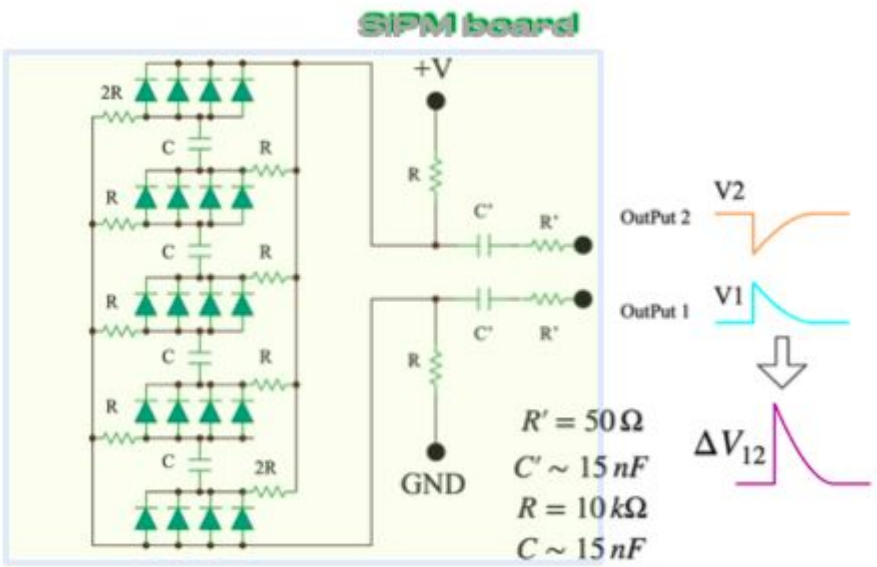


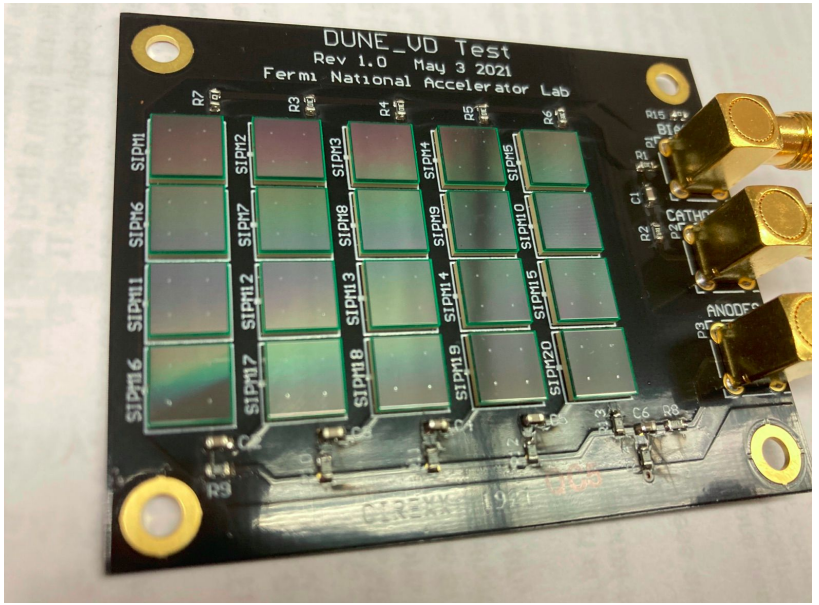
DUNE HD FD module:

- 12.0 m ×14.0 m × 58.2 m
- 3.5 m drift distance
- -180 kV applied on the Cathode (500 V/cm)
- Fiducial mass ~10 kt



Backup slides





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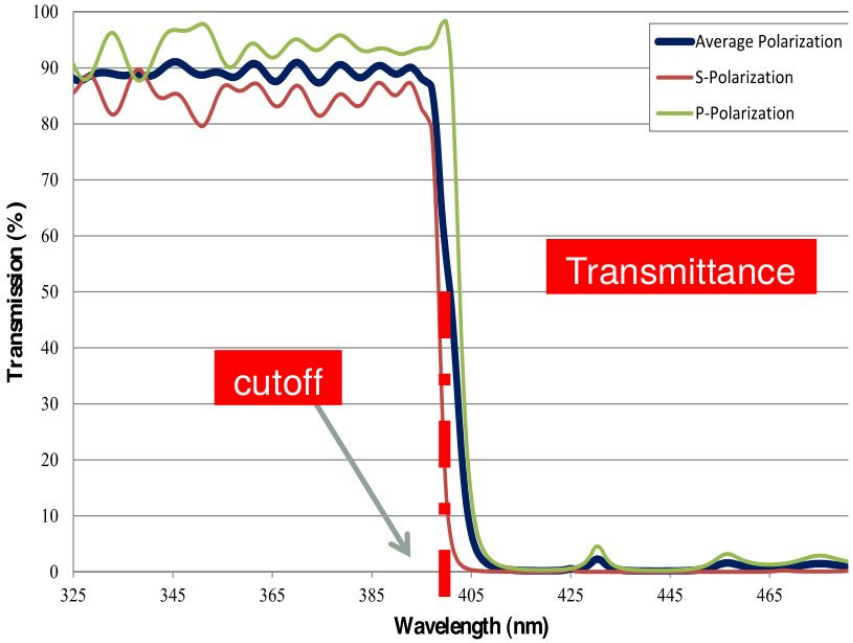
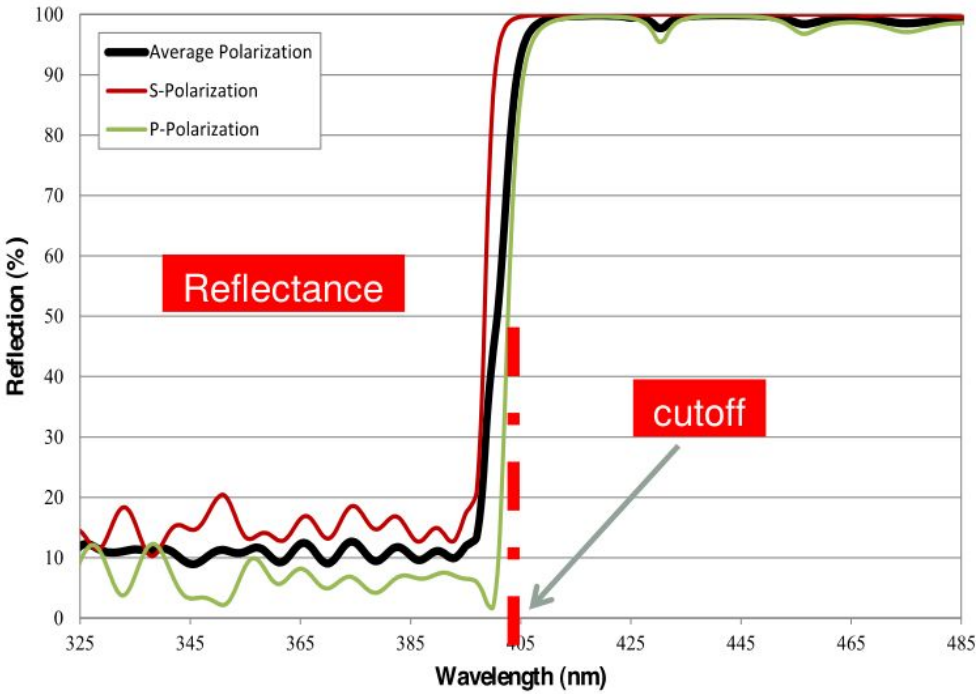
X-Arapuca



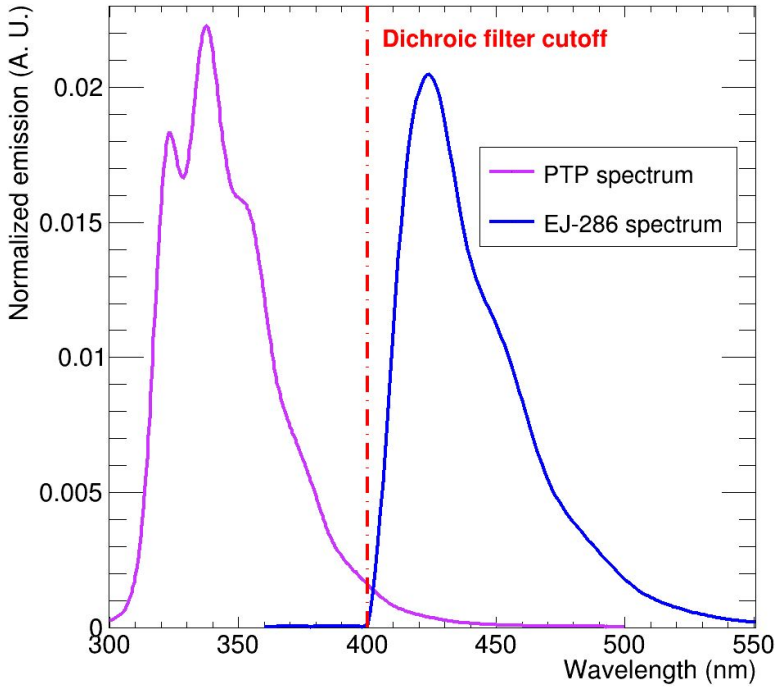


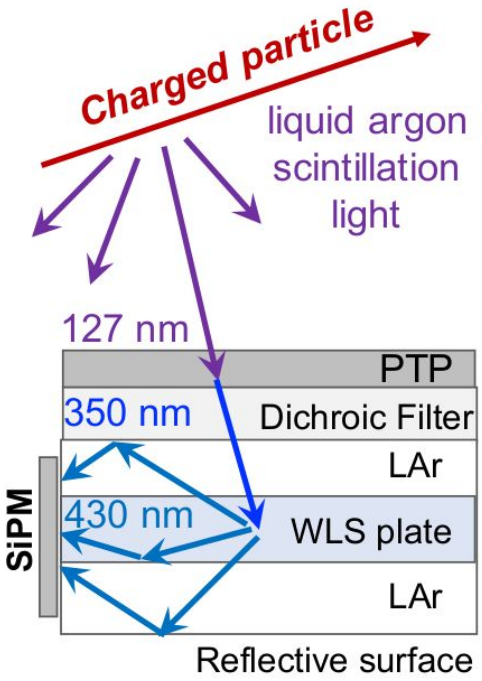
The device makes use of a dichroic filter in combination with two wavelength shifters (WLS)

Backup slides

PTP → p-Terphenyl
SiPM → Silicon photomultiplier

X-Arapuca





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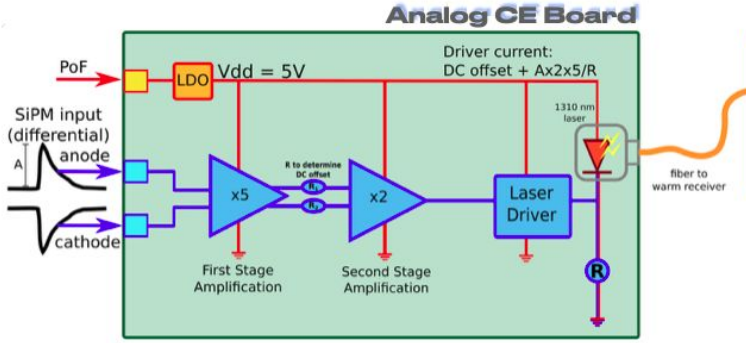
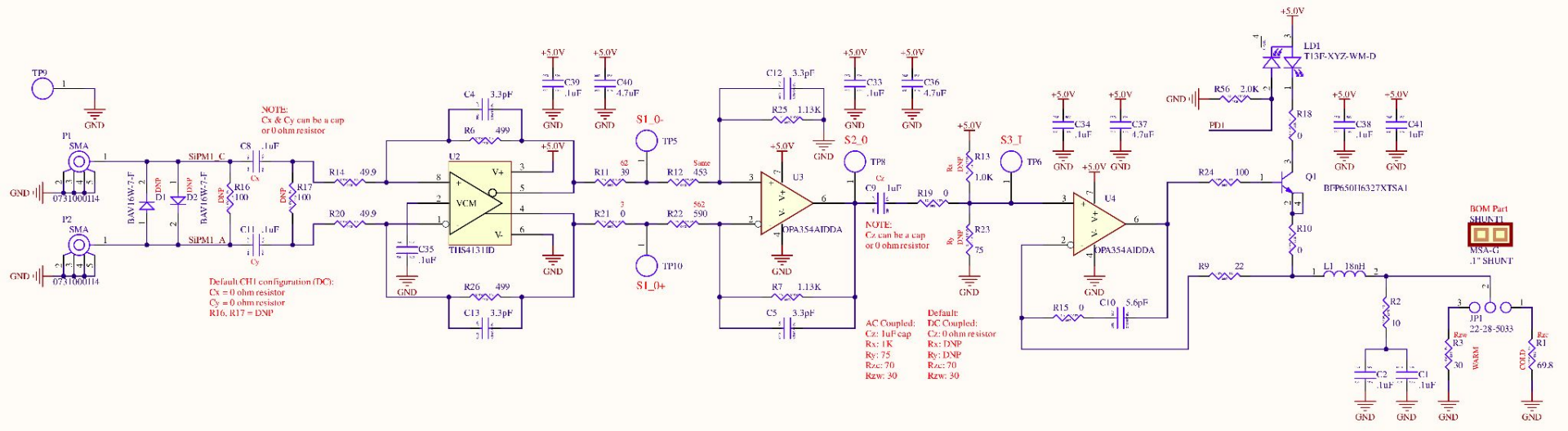
Backup slides

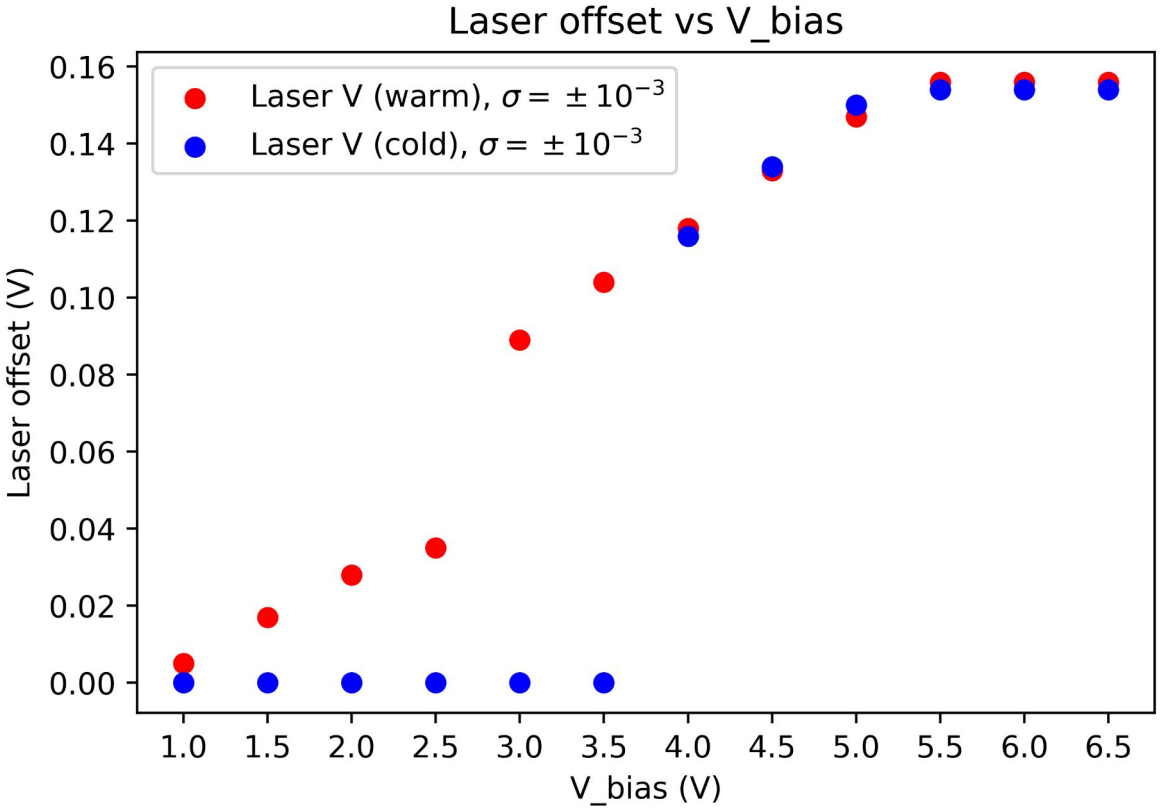
- ARGON2x2 (2 channels/board)
  - V = 5.1V, I < 35 mA (< 100 mW/ch)
  - FP 1310 nm lasers FC connector
  - Voltage gain ~20
  - Optical power ≲ 0.1 mW at receiver





Backup slides

Laser offset in warm and cold



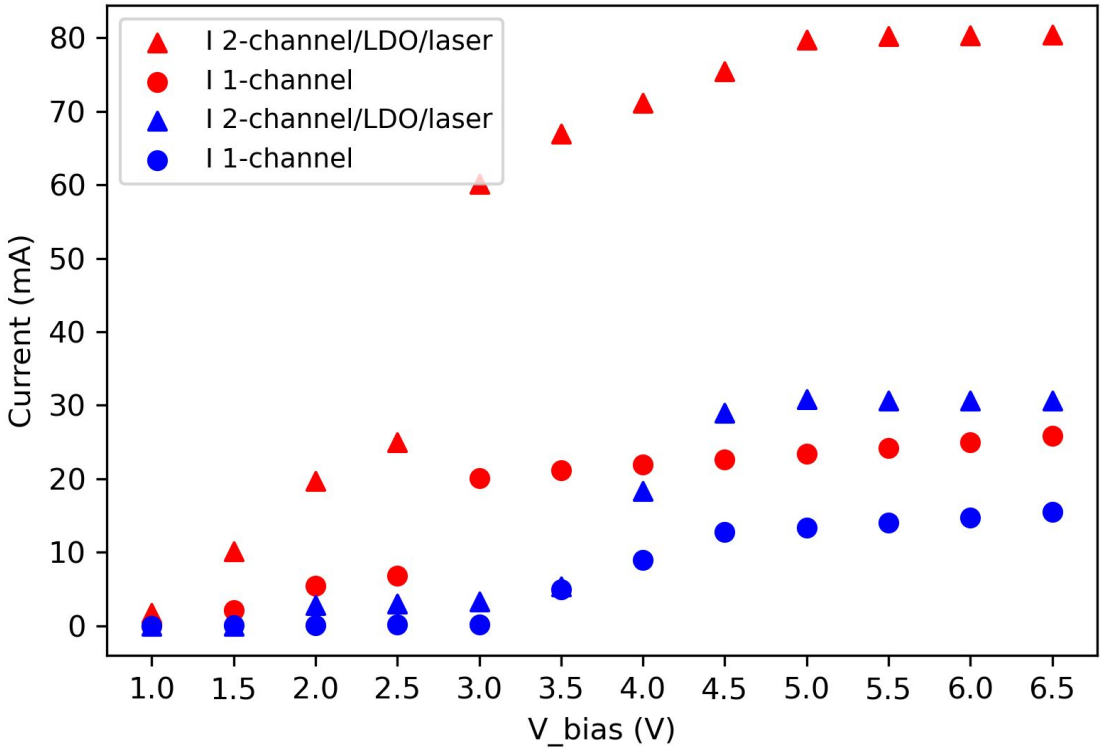
- Reminder: DC offset for laser to be in linear regime
- For V_bias > 4V, the laser DC offset values are the same

→ circuit DC behaviour is the same

- LDO keeps Vdd constant after 5.2V
- Points below 3V and 4V: bias not enough for amplifiers to work (OPA354 min bias specs is 2.5V).

Laser's nominal offset (156 mV) → 3.12 mA (cold), 14.2 mA (warm)

Backup



Full circuit in cold (2 channels - 2 lasers -LDO) ~35 mA

- Measurement for two boards, one with 2 channels + LDO + 1 laser, the other with just 1 channel

-The consumption in cold is lower than in warm:

- the circuit itself (40% less)
- laser current ~15mA vs ~3mA

- Difference between the working start point for the Op. Amp. in both boards

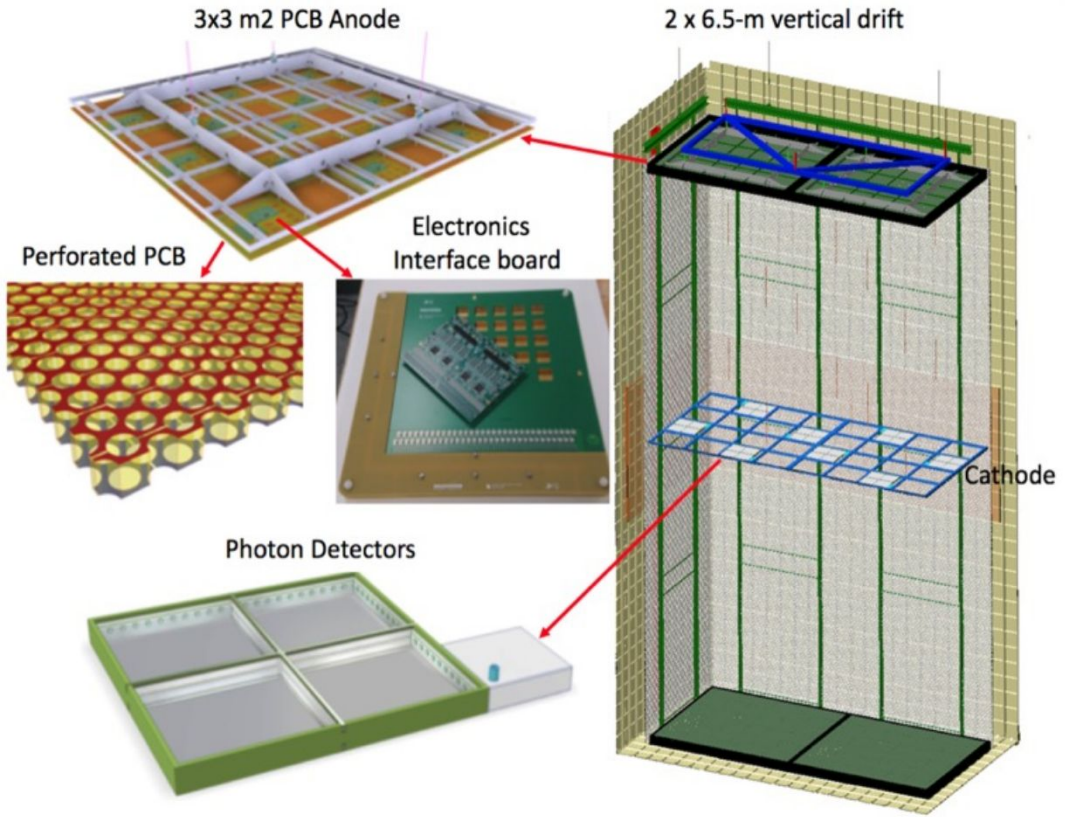
-LDO works well in cold, regulating the voltage at a similar value (to 5.23 V measured in warm; PoF is at 5.6V)

Vertical drift: but why?

- Tests with DUNE's prototypes (ProtoDUNE) shows **outstanding LAr purity**
  - **Drift distance** of 6 - 7 m allowed.

- **Vertical drift layout is simpler** to construct
  - More efficient use of LAr volume
  - Reduce schedule and financial risks
  - Lightweight CRP, no broken wires, easier installation, etc.

- Photon Detection System (PDS) installed on the TPC walls AND cathode allows **higher coverage, light uniformity, energy & position resolution and detection threshold.**



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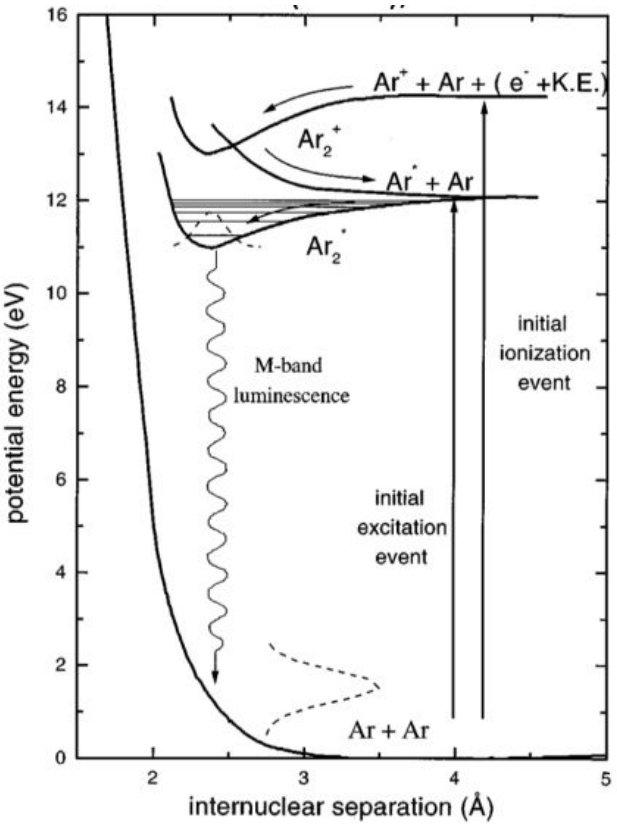
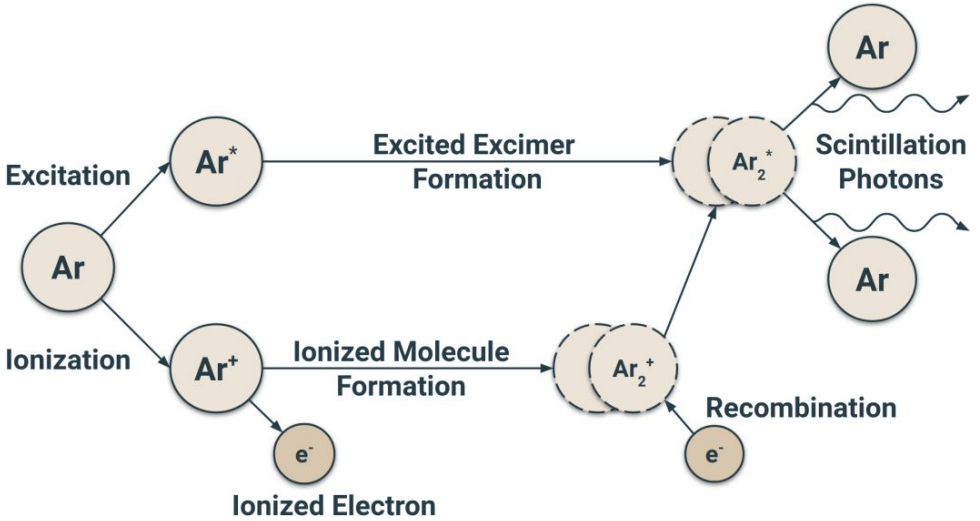
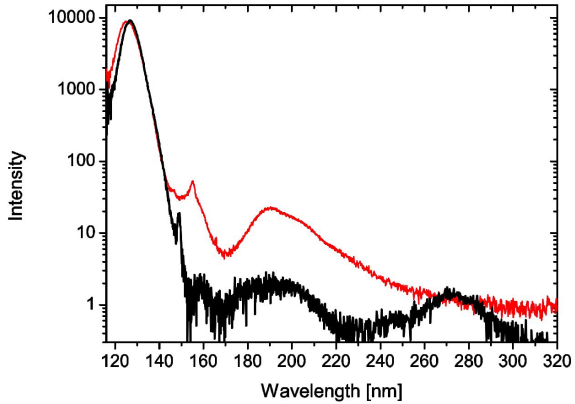
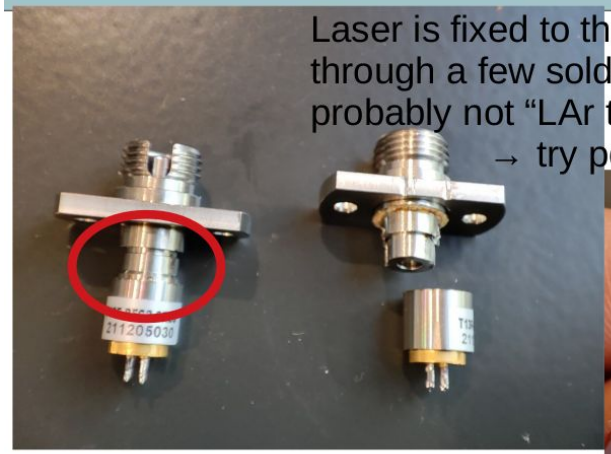






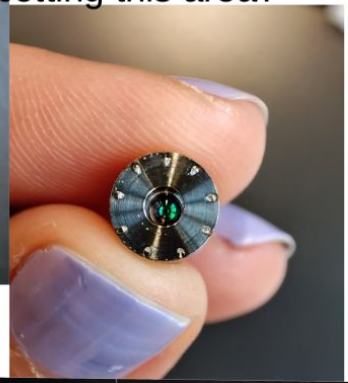
Backup slides

Lasermate FC connector



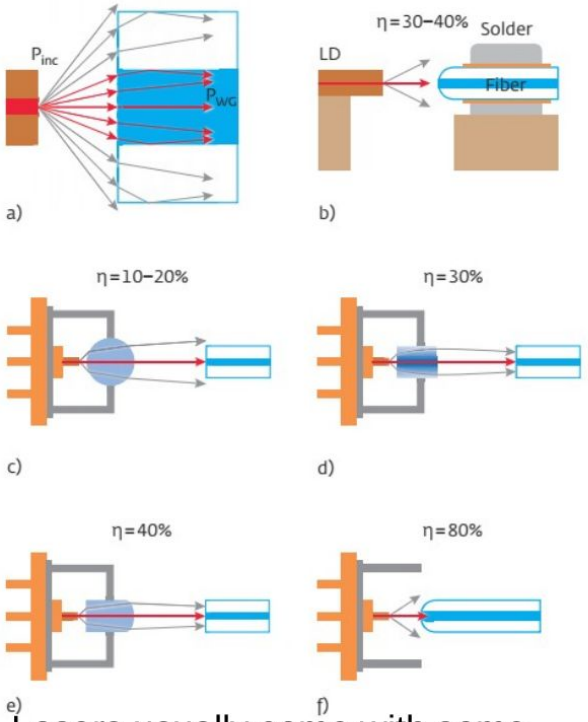
Laser is fixed to the FC connector through a few solder points: probably not “LAr tight”

→ try potting this area?



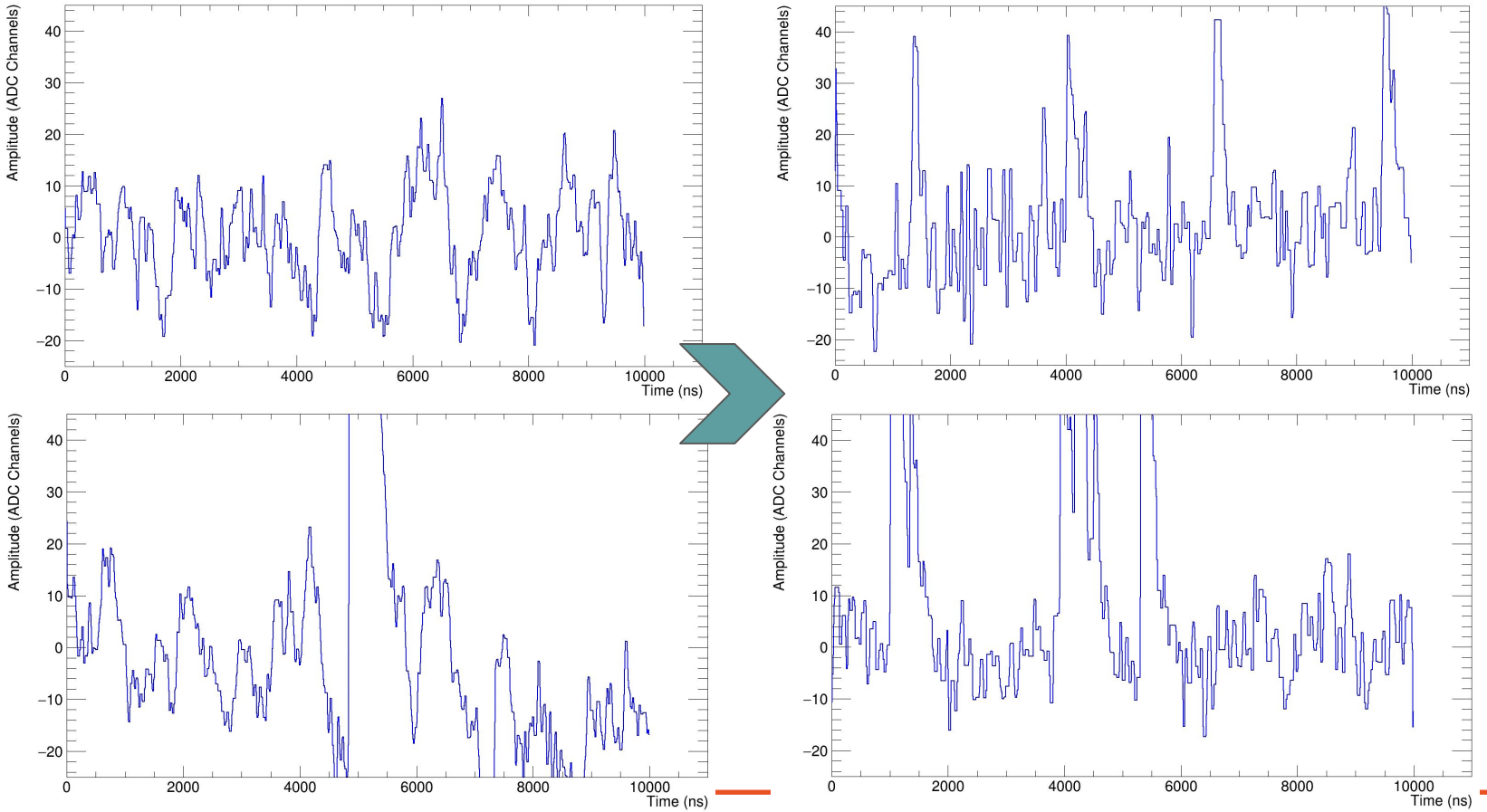
* There seems to be a lens inside → usually the laser beam has a focus point ~few mm from lens

* By fully potting a pigtailed laser we did not see the power output drop
* potting is not trivial



Lasers usually come with some kind of lens → not clear how LAr affects the focus

Backup slides



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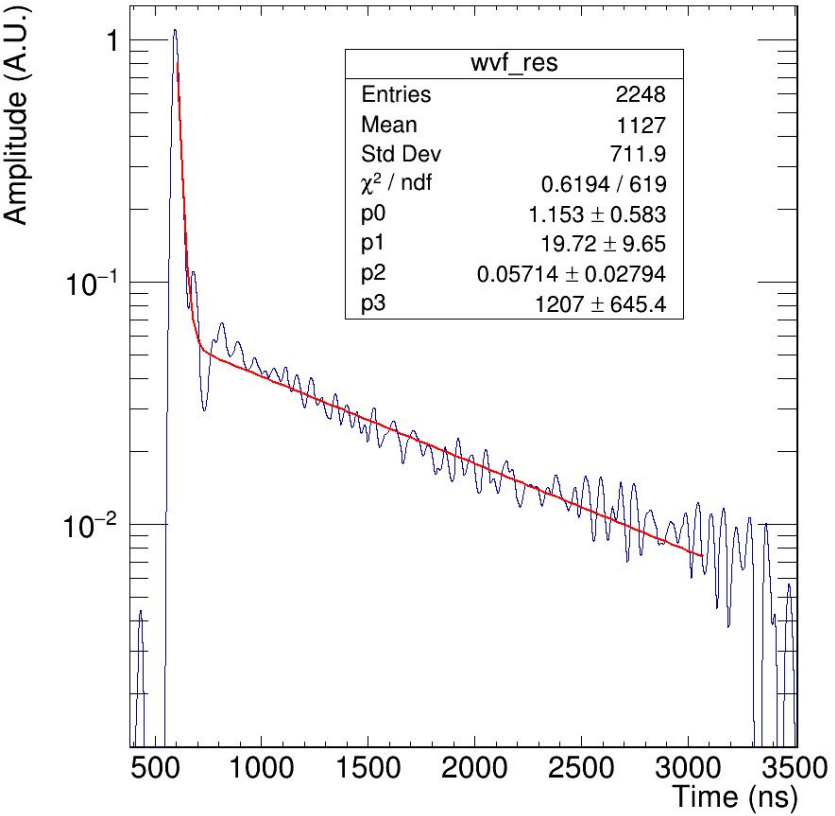

Scaling factor = 60.4
; would mean 60% of light
with 10 kV (430 V/cm)