The DUNE FD2 Photon Detection System: Implementing novel concept of signal over fiber and power over fiber transmission

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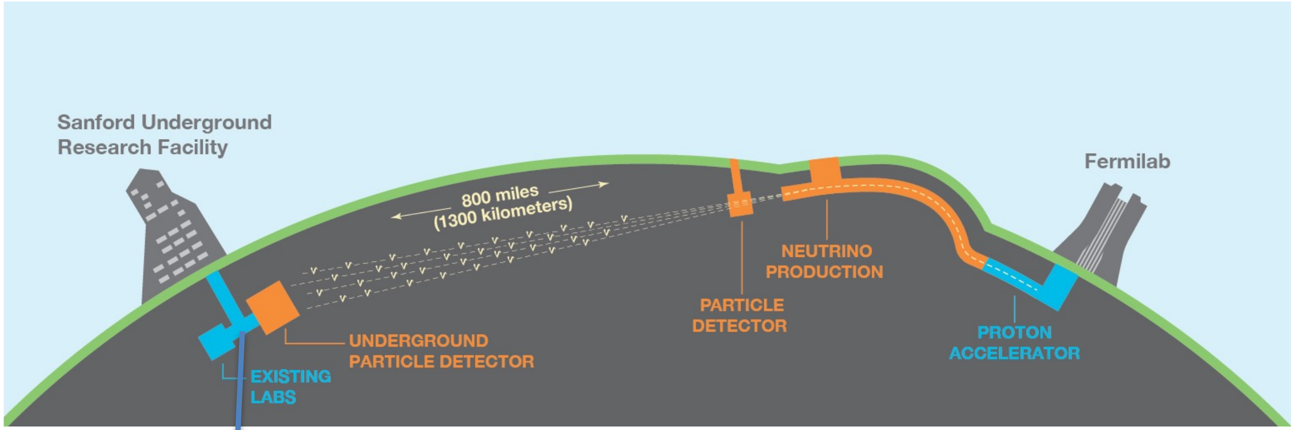
On behalf of the DUNE collaboration

CPAD Workshop 2023 (Nov 7-10) SLAC National Accelerator Laboratory

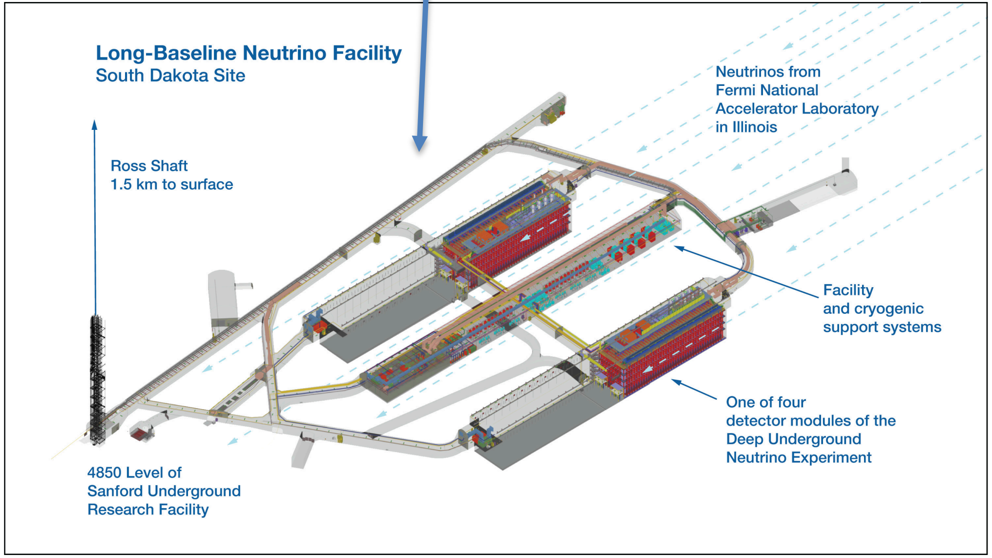
Outline:

- Deep Underground Experiment (DUNE)
- Photon Detection System for DUNE FD2
- X-ARAPUCA technology
- Power over Fiber (PoF)[mini-talk]
- Signal over Fiber (SoF)
- PoF, SoF concept validation through prototypes

Deep Underground Neutrino Experiment



Physics goals: neutrino oscillations, CP violation, proton decay, supernova neutrinos.



- (2 + 2) 17kt modules
- 1300 km away
- 1.5 km underground
- 1st module →Horizontal drift LArTPC
- 2nd module →Vertical drift LArTPC
- 3rd and 4th modules to be built in Phase II, proposals and R&D ongoing

LArTPC concept (HD design):

- Cathode at high voltage (few 100s of kV)
- Wired charge readout planes
- Uniform electric field between cathode and anode (~500 V/cm).
- To make the Efield uniform field cage is installed covering the remaining TPC faces.
- A charged particle produces ionization electrons and scintillation light as it pass through the detector.
- Charge read by APA, and light detected by PDS

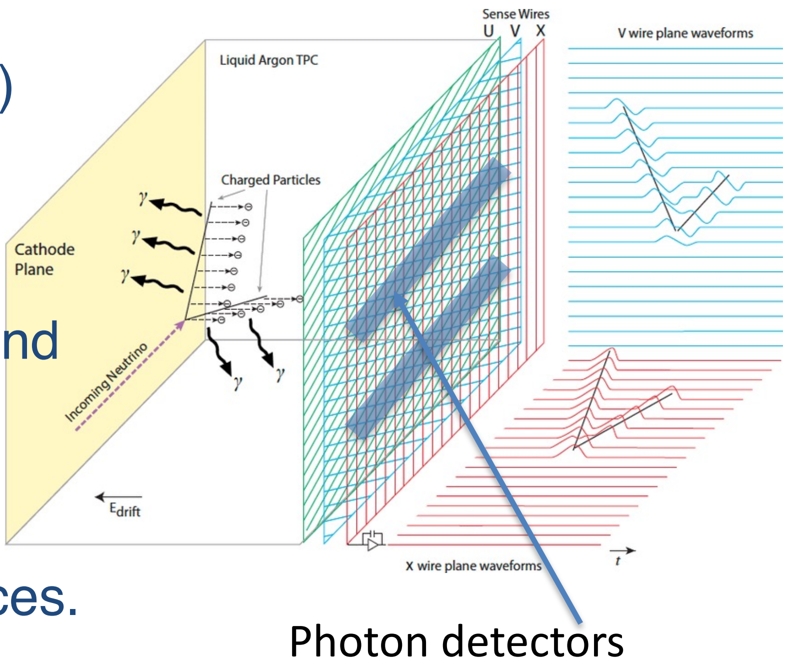
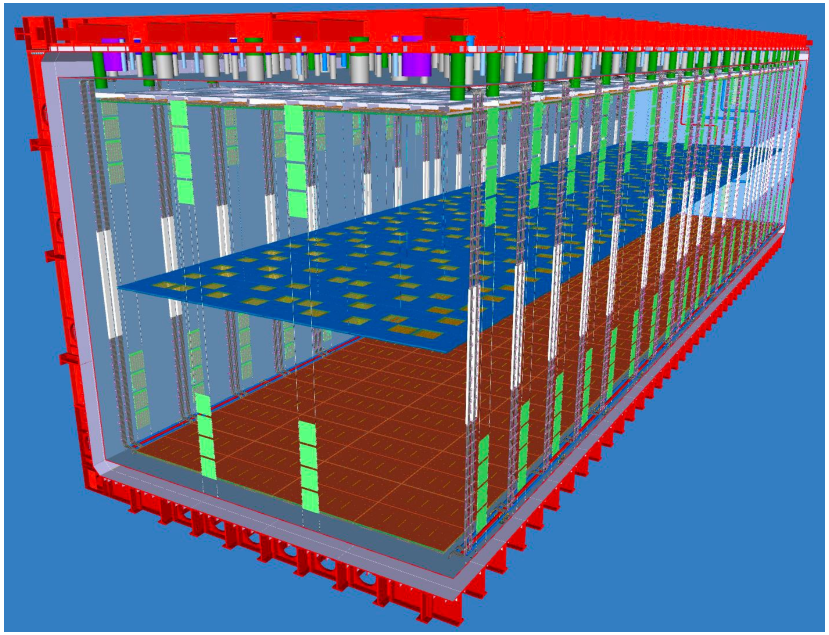


Fig: LArTPC working principle*

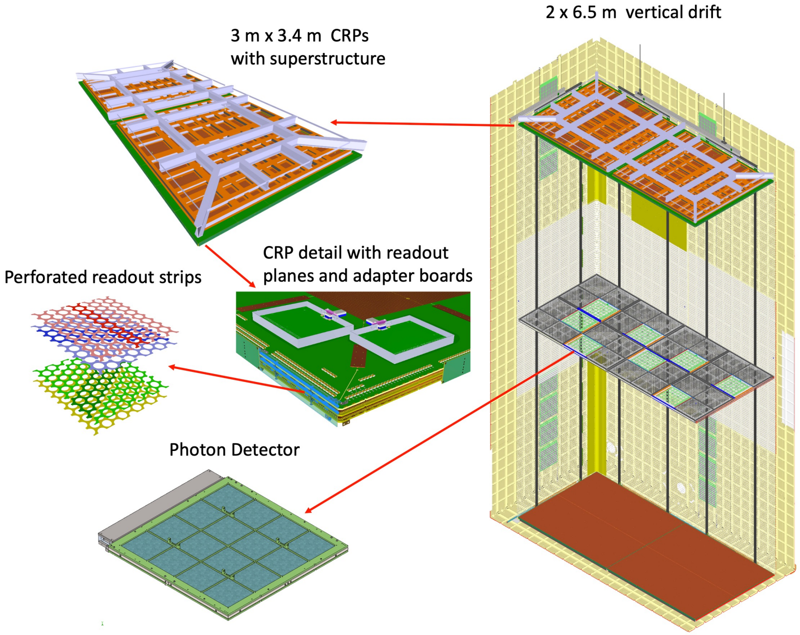
*JINST 13 (2018) 07, P07006.

DUNE FD2 LArTPC:

- Charge readout plane (CRP) technology used
- CRPs have low transparency. Placing PDS behind CRP results in low light collection efficiency.
- Initial design field cage also had very low transparency.
- Placing the PDS on HV cathode surface (~300kV) allows higher light collection
- In the final design PDS placed behind field cage as well, and reflective CRP surface; makes the detector coverage of ~4π

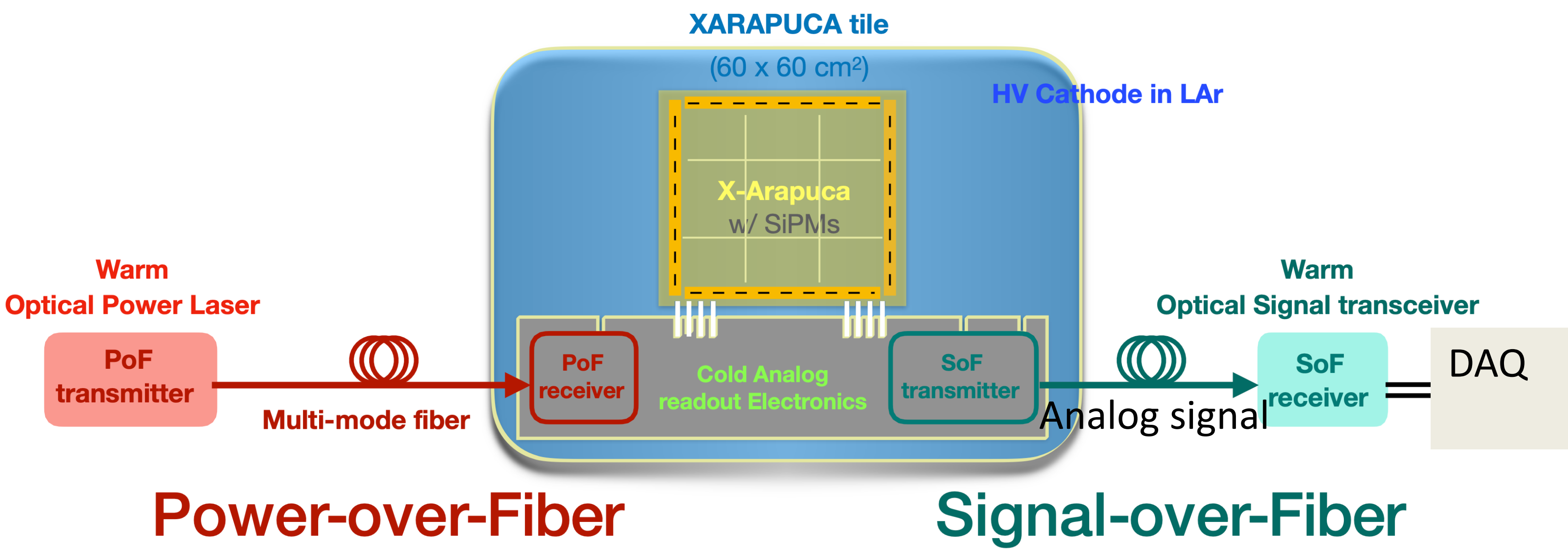


Active volume dimensions: 60 x 12 x 13 m^3



Power over Fiber (PoF), Signal over Fiber (SoF) and X-ARAPUCA:

PDS on HV surface brings up challenges; solutions are PoF and SoF:
→provides voltage isolation in both signal reception and transmission.
→PoF and SoF are a well-established technology, but extensive use in a cryogenic detector is a new application.

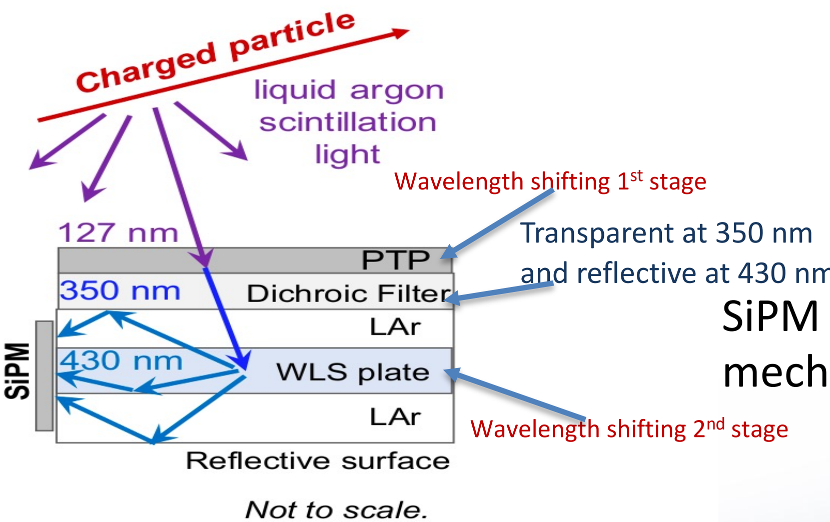


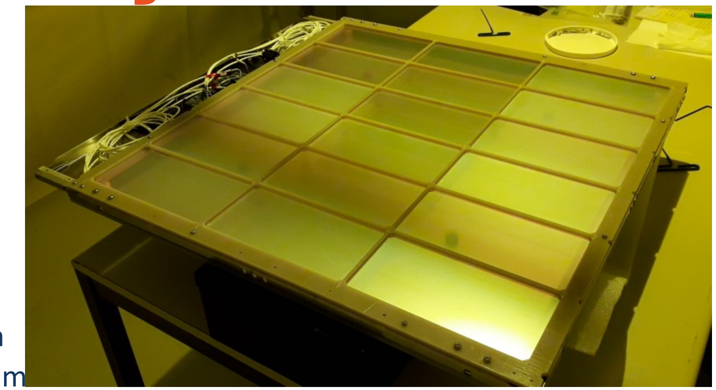
Working principle of PoF and SoF solution

DUNE FD2 PDS SYSTEM COMPONENTS

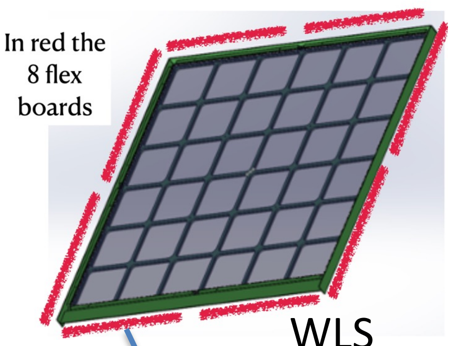
Photon Detection System:

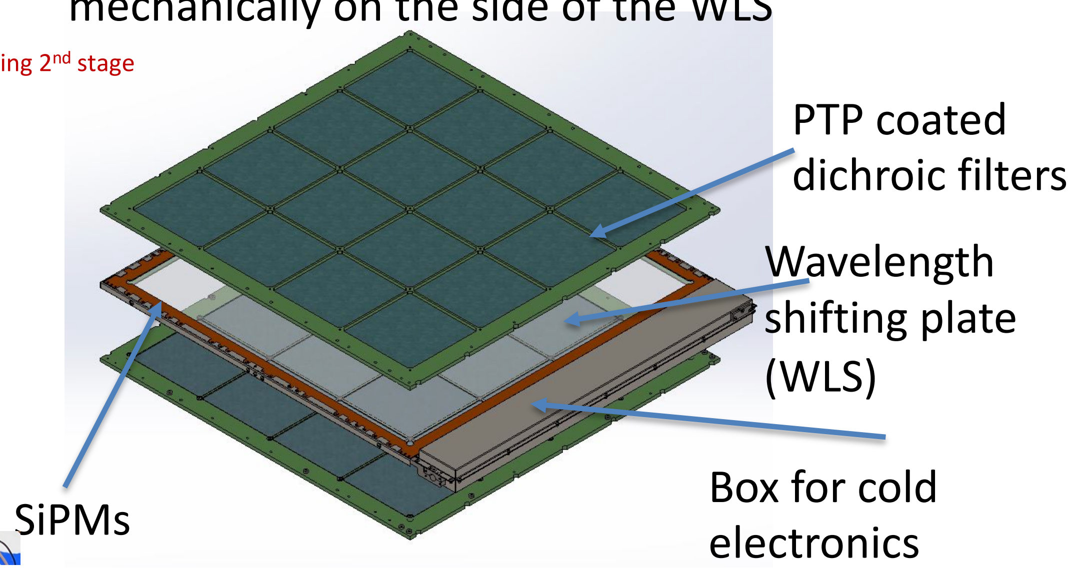
X-ARAPUCA concept:





SiPM are the photosensors used, attached mechanically on the side of the WLS





SiPM ganging:

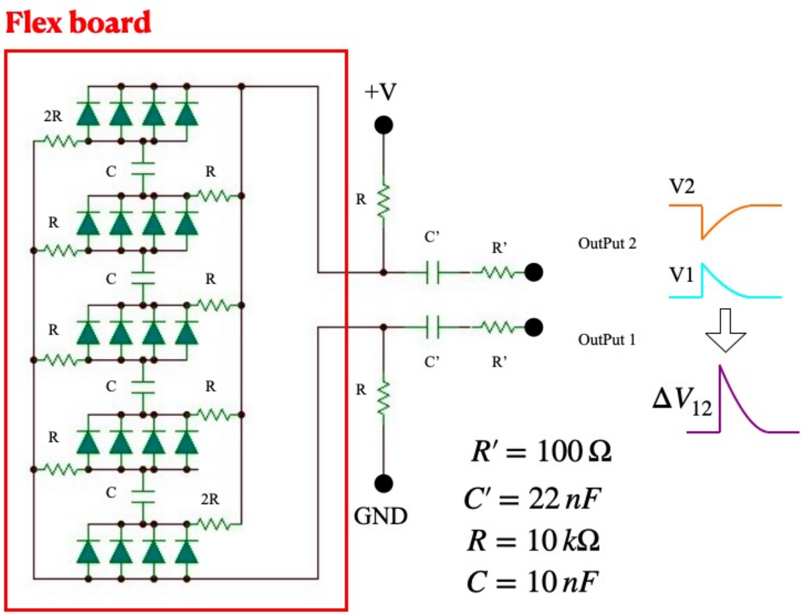
→Each flex has 20 SiPMs passively ganged.

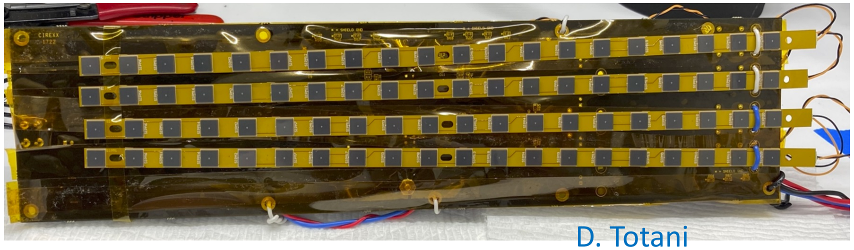
→4 such flexes are actively ganged and connected to a single front-end amplifier.

→In the hybrid ganging scheme, 80 SiPMs (20x4) have been successfully read by a single readout channel.

→each X-ARAPUCA has 2 electronics channels with 4 flexes each.

Advantages:
→Same bias voltage as for a single SiPM.
→Small capacitance-->Short recovery time.





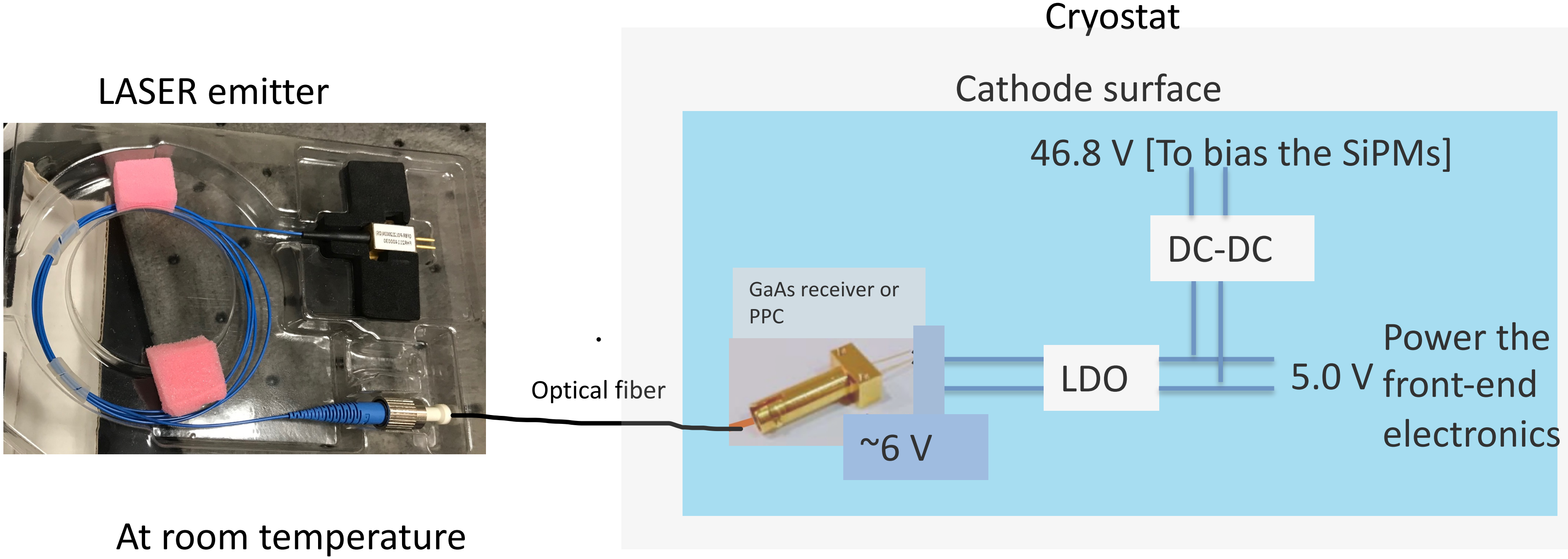
4 Flexes used for bench tests at UCSB

Power over Fiber (mini-talk)

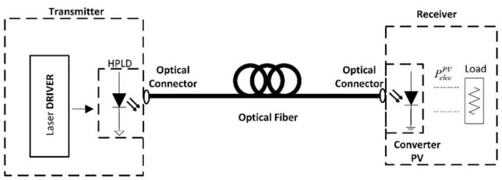
Power over Fiber (PoF)

Delivers electrical power by sending laser light through optical fibers to a remote photovoltaic receiver or photovoltaic power converter (PPC)

Benefits: (1) noise immunity, (2) voltage isolation, and (3) spark-free operation.



Power over Fiber



So far implemented in solar energy industry,

now developed (at FNAL, 2020-23) and applied *in detector technology for HEP:* PoF supplies power to the active elements, *photo-sensors and cold electronics,* of DUNE FD2 photon detection system immersed in LAr and lying on a HV surface.

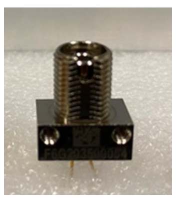
three major benefits:

(1)noise immunity,

(2)voltage isolation,

(3)spark free operation

partnership between FNAL, Broadcom, UIUC and GoPower



Optical Power (Laser) Transmitter

- OTS products

BROADCOM AFBR-POL2120

Laser Module, 808 nm, 2 W, 1.85 V, 2.4 A

(laser capable of 2x operating point)

laser chip, operating at 808 nm wavelength at a case temperature of 25°C in hermetically sealed package, with a pigtail fiber and an FC/PC optical connector.

Stability: Better than 10% power flatness

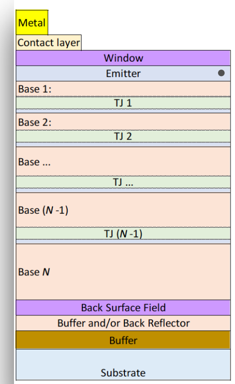
Lifetime: >10 year lifetime at full power

Laser-Optical Receiver&Converter into Electrical Pwr

- OPC (in cold) converts optical energy of radiation into electric energy by internal photoelectric effect in semiconductors (0.2–0.3 mm thickness):

808 nm, 2 W multi-junction GaAs

- Opt-to-Elec Conversion - Higher efficiency at cryo temps
- $\epsilon \ll 1$[typical20% →~ 55%(currentdevelopment) →~ 80%(finalgoal)]
- Practically unlimited service life
- Individual photovoltaic cells/OPC may be interconnected in series or in parallel.
  Series-connected cells generate small currents at high voltages; Parallel-connected cells generate large currents at low voltages



improve from off the shelf:

– At UIUC – Researching improved efficiency through semiconductor

– At Broadcom – Improved efficiency through packaging

  - Focal length, Material Size/Power Handling

Fiber type	Item	Description
MM	Numerical Aperture (NA)	0.27
	Index Profile	GI
	Core Diameter	62.5 ± 3 μm
	Cladding Diameter	200 ± 4 μm
	Coating Diameter	230 ± 10 μm
	Diameter of Buffer	500 ± 50 μm
	Fiber Attenuation	< 3.5 dB/km (@980nm)

Optical Fiber OTS producer GoPower

Why is this fiber unique?

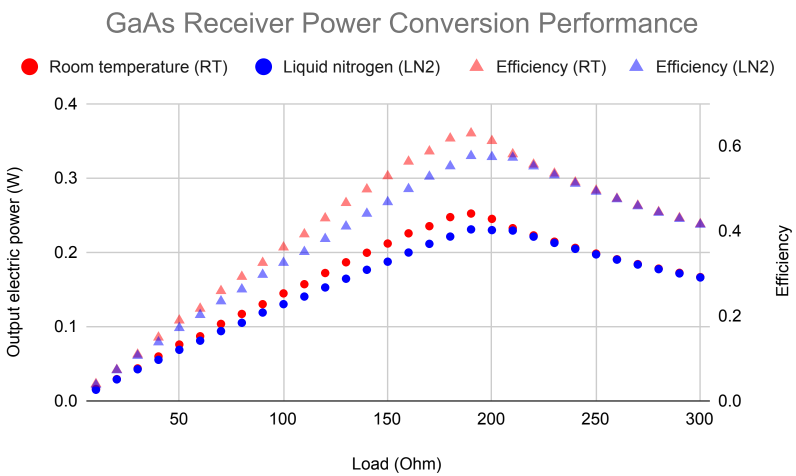
Power handling: Not a concern at our level of Pwr transmission

Cryogenic Compatibility: Jacket

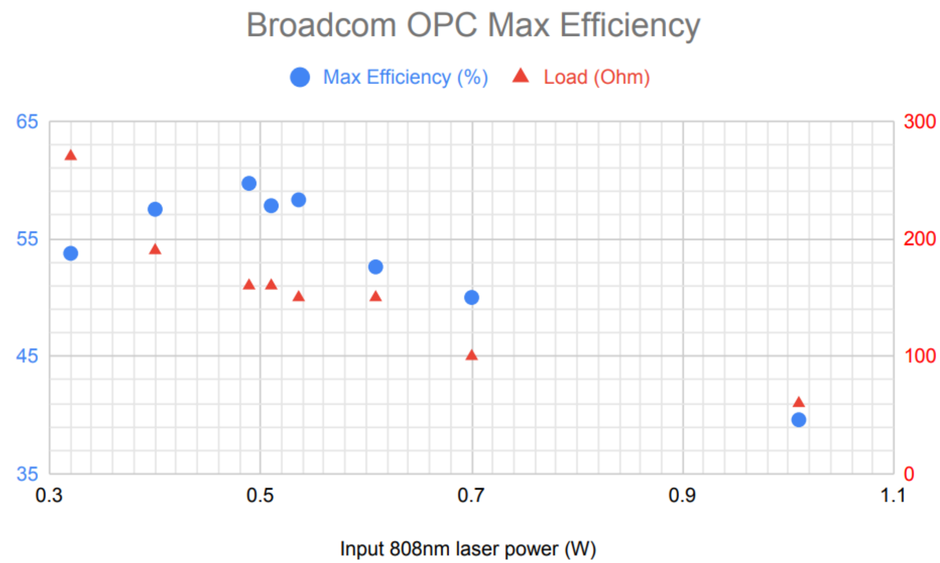
It has a large 200 um cladding – helps contain light leakage

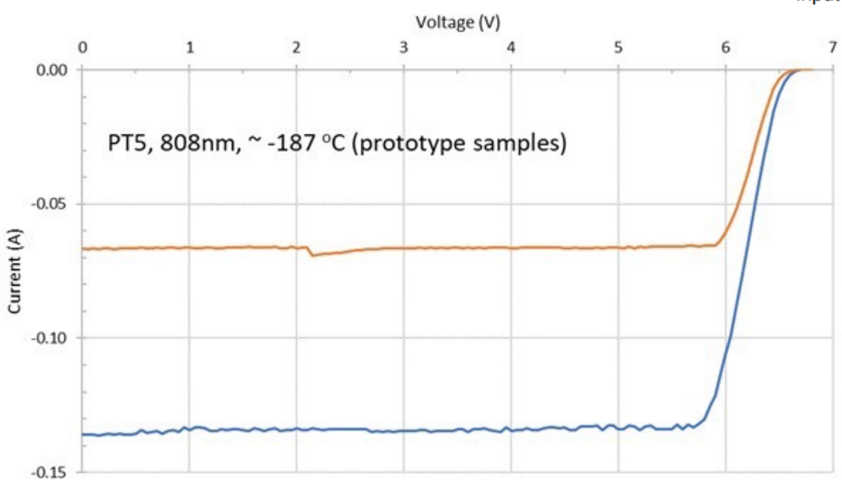
It has a double jacket – 500 um and 1.5 mm – again for better light containment.

Power, Efficiency, Leakage (I-V curves across loads)



Input 808nm Laser@ 400mW

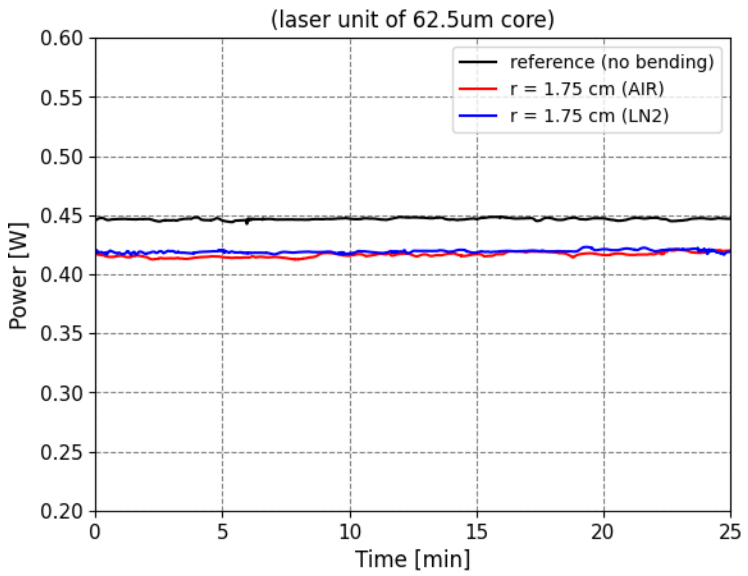


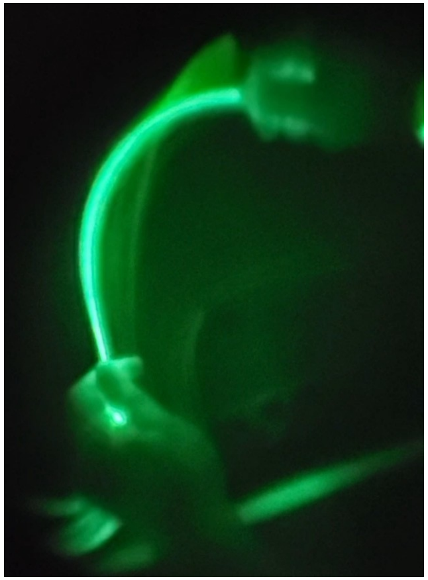


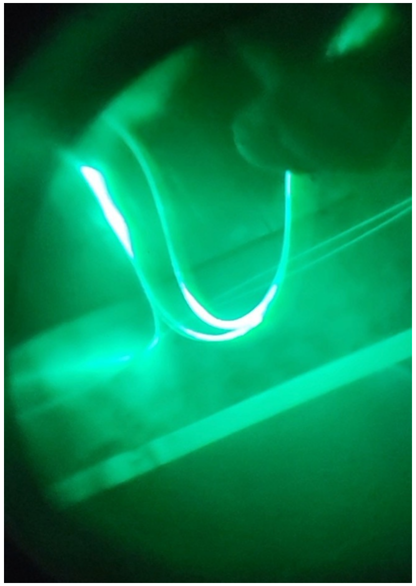
New OPCs have slightly higher current and voltage capability

Fiber tests:

- Bending stress testing
- Light leakage
- Thermal cycling
- Loss measurement



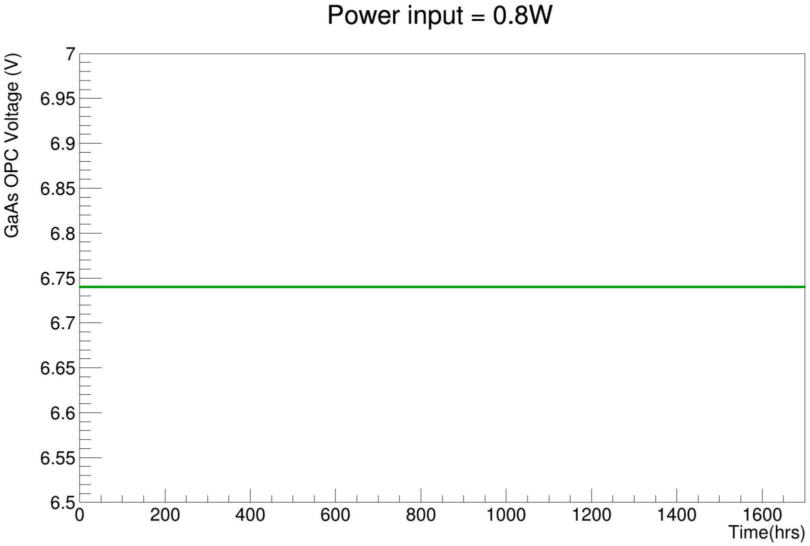


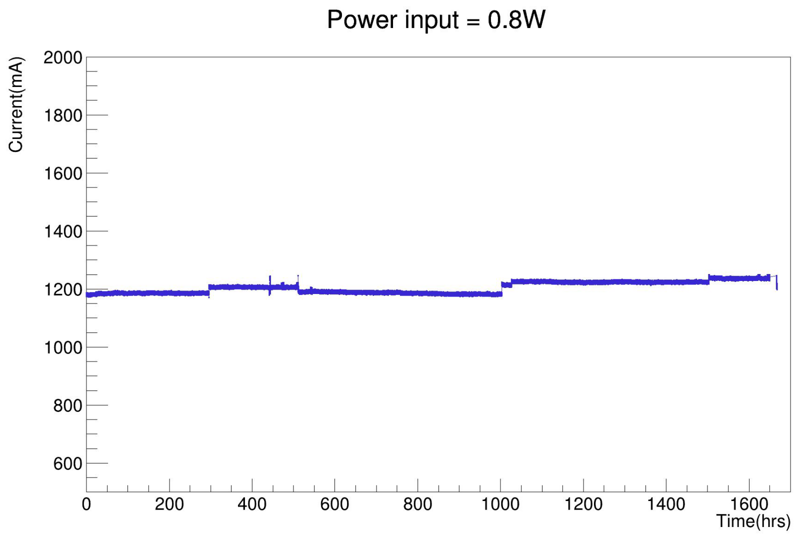


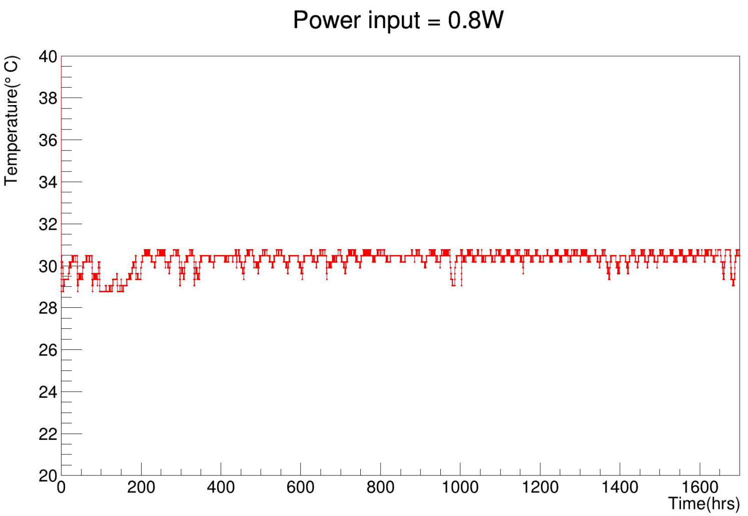
Bend test power

Long term stability tests [at SDSMT]

The long-term test stand is in full operation:
→continuous recording of OPC voltage, current, and temperature for the laser unit for nearly two months without interruption.







Fermilab DUNE

To summarize the PoF section:

- PoF has proven to deliver clean power at required levels to an isolated cryogenic system (DUNE FD2 PDS).

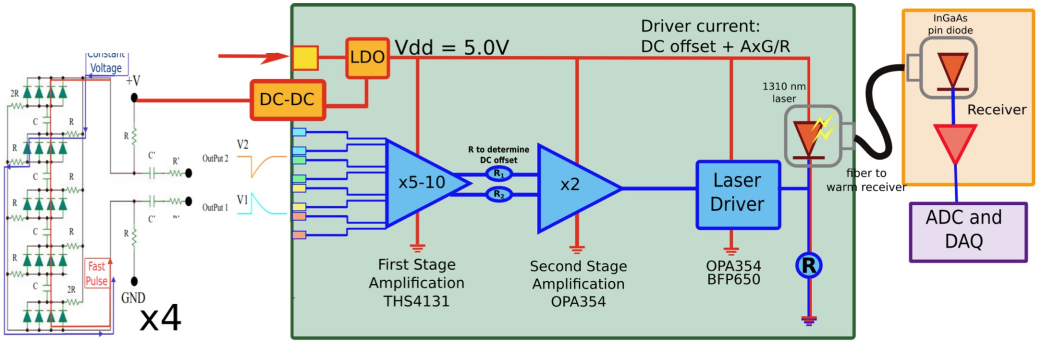
- Work moved from concept to optimization stage, to deployment in full scale HEP detectors in ~2 yrs through significant FNAL effort, DoE support, and Universities and industrial partnerships.

- PoF may find wide range of applications in detector technology for HEP beyond this first one.

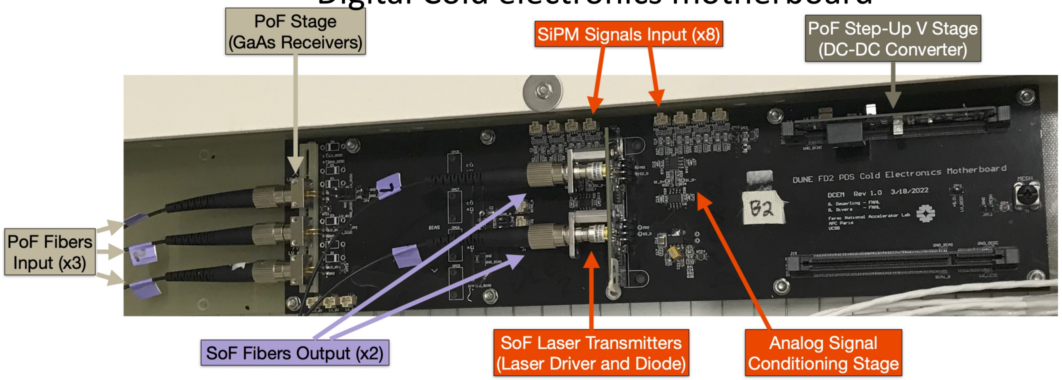
- With proper packaging class 4 lasers to class 1 lasers.

Readout electronics and Signal over Fiber

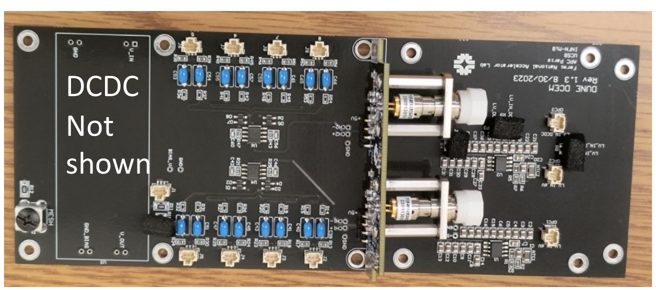
Integrated motherboard:



Digital Cold electronics motherboard



Digital Cold electronics motherboard most recent version



- 2 readout channels per X-ARAPUCA
- 4 SiPM flexes per channel
- 1st stage: Active ganging and amplification→ Summing multiple channels preserving signal shape. Tuning signal amplitude.
- 2nd Stage: Full differential to single ended
- 3rd stage: current source to drive the laser emitter.

Fermilab DUNE

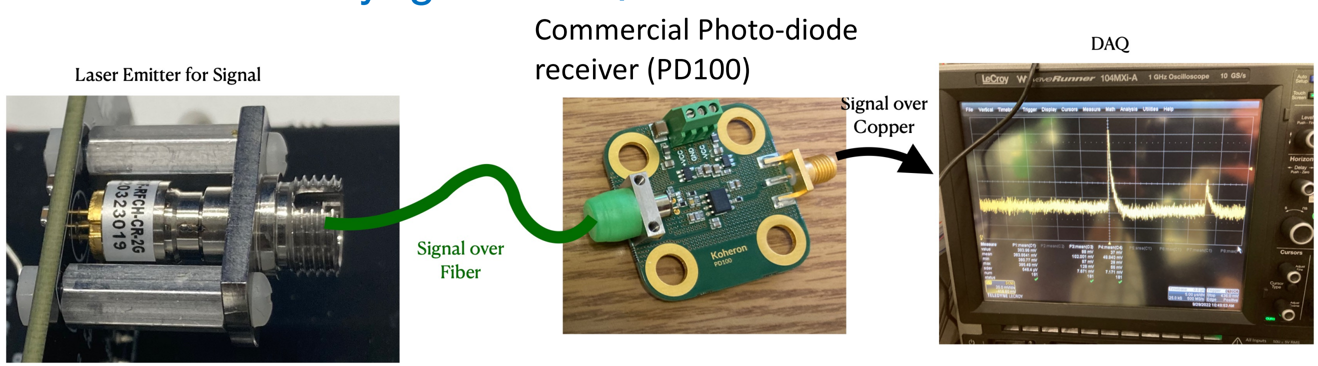
Signal over Fiber (1):

Analog Optical signal transmission:

Accurate conversion of the electrical pulse into optical on front-end preserving pulse shape and current-modulation of a laser (modulating optical power or optical signal amplitude).

Challenges:

- Little industry experience in extreme temperatures and in highly-refractive media.
- Higher signal-to-noise ratio requirements
- Transfer function must be well characterized to insure extraction of original signal
- During the initial R&D, off the shelf 1310 nm Fabry- Pérot laser diode was found to work well at cryogenic temperature.



Presentation by Alex Kish (Analog Optical signal transmission for HEP experiments; RDC 2 11/8/23, 5:00PM).

Signal over Fiber (2):

- However, almost complete loss of optical power was observed when the laser diode was placed at depth in cryogenic liquid (>16 inch)
- The problem was identified to be a change in the refractive index of the medium, which results in changes to the focal length of the length and the angle at which the rays enter the receiving fiber stub.

Engineered solutions:
Customization of the laser diode assembly:
1.Implementation of venting holes for the cryogenic liquid to easily fill the interior
2.Adjust lens-to-fiber stub distance for the change in rays' path (focal length and angular distribution)

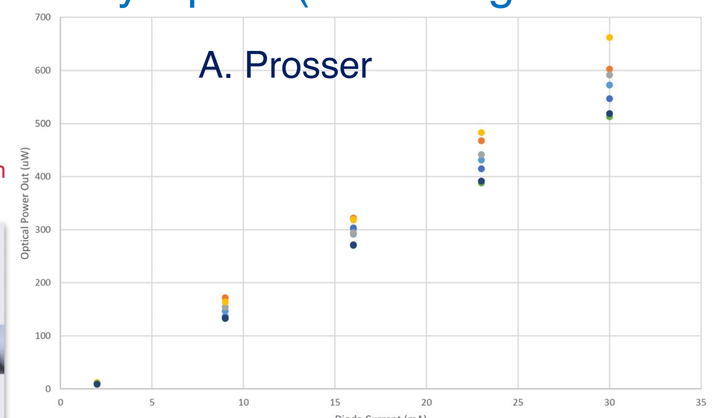
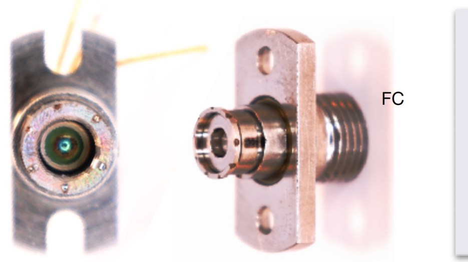


Fig: Linearity of response for a sample of six Lasermate Fabry–Pérot laser diodes in LAr at Fermilab

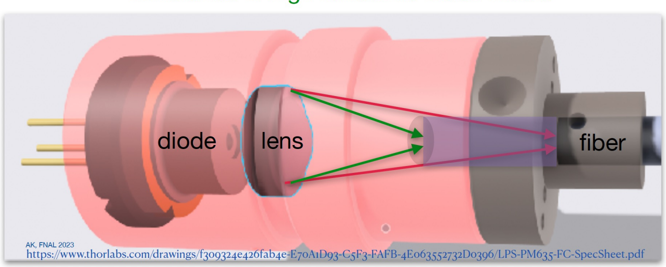
Laser diode components

Component 1:
Emitter with a lens

Component 2:
Receiver with a fiber stub



Focal length and angular distribution in air/vacuum
Difference in high refractive index media



A. Kish

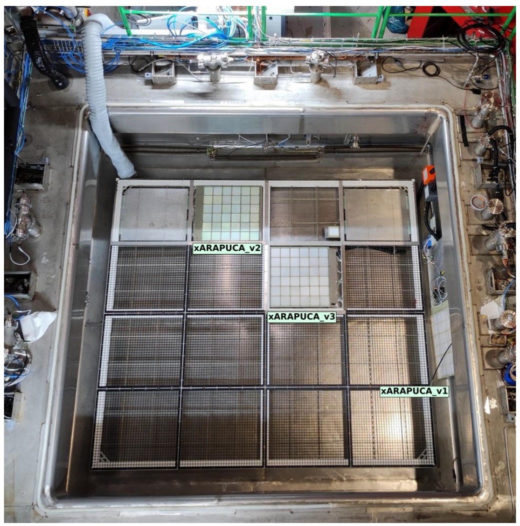
Fermilab DUNE

Prototyping detectors using PoF-SoF technology

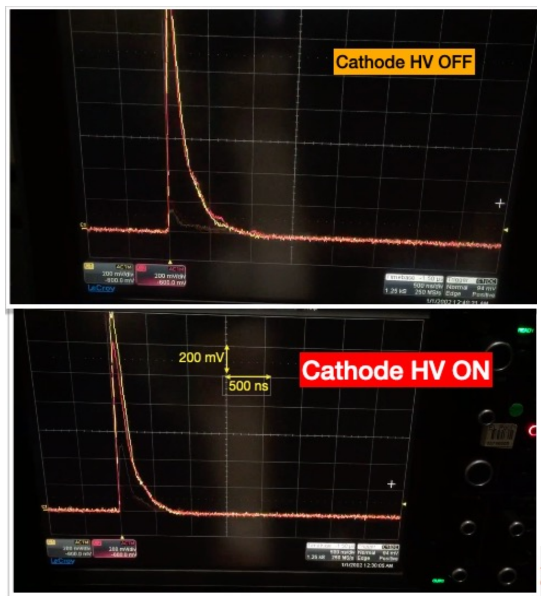
Prototyping the DUNE FD2 PDS system:

- Besides test bench studies in various institutes, a large-scale prototype implementing PoF and SoF technology was built at the CERN neutrino platform. This has been used as a test bed for validating the improvements.

- series of tests were condutced beginning Dec 2021

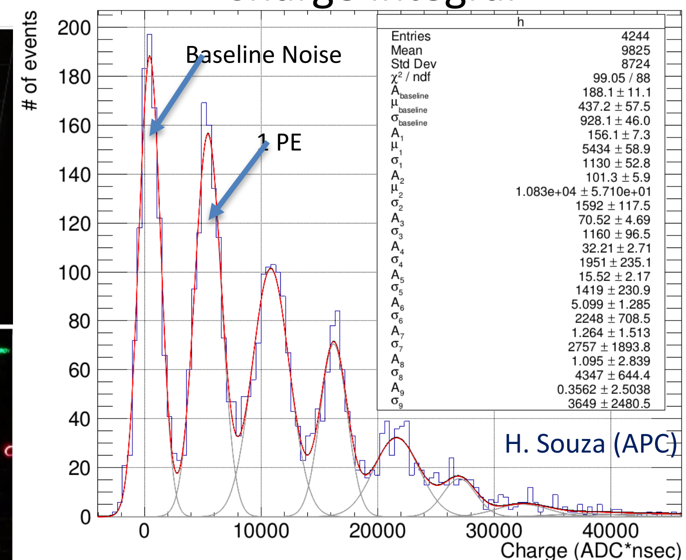


Top view with CRP not shown. Dimensions of the active volume ~ 0.22 x 3 x 3 m^3



Pictures from first tests in Dec 2021

Charge integral



Feb 2023 run, shows a SNR of 5.9

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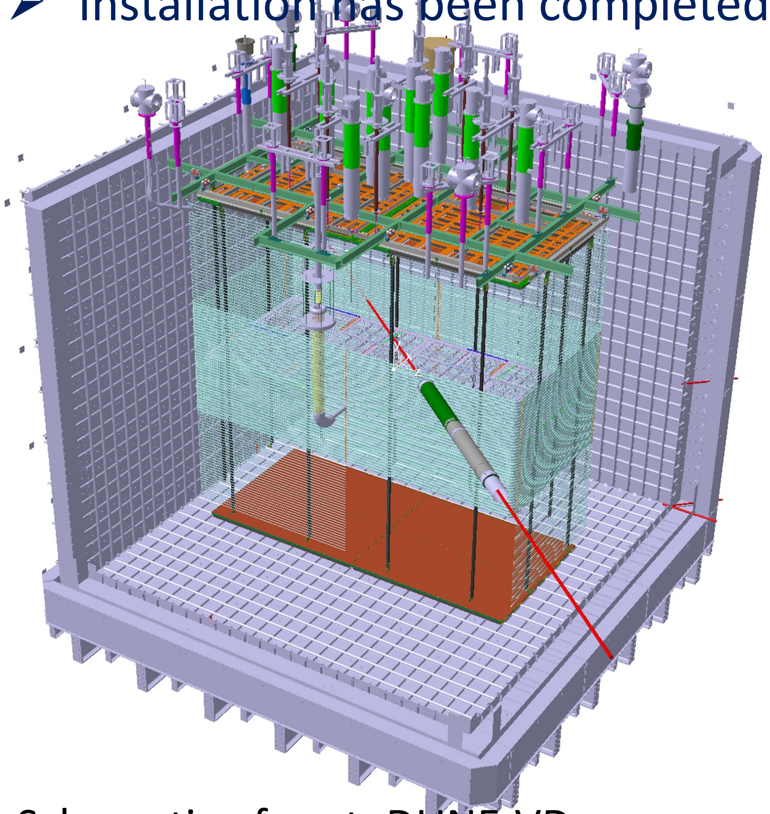
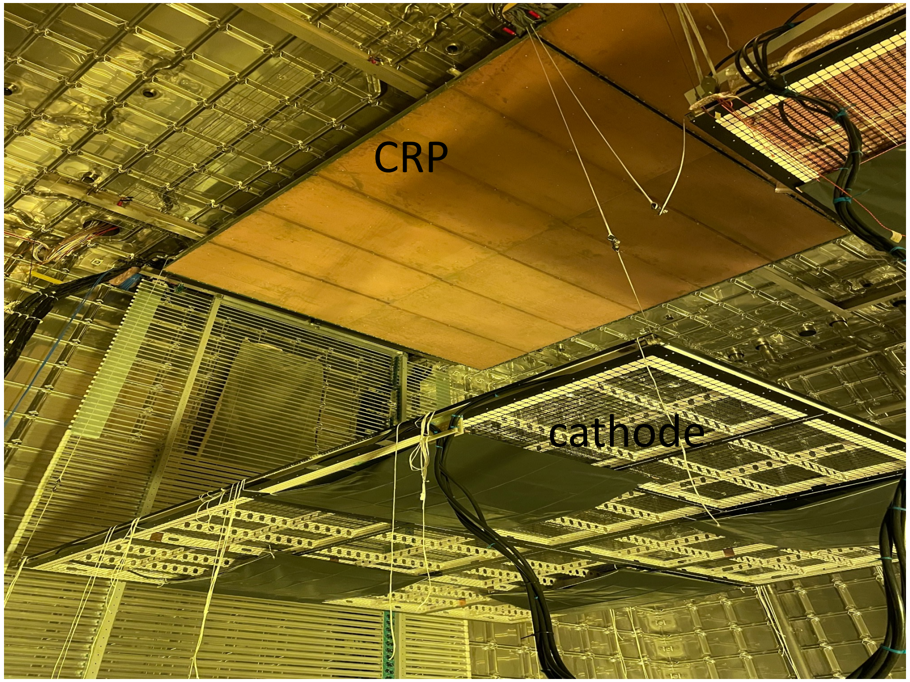
Larger scale prototype→ProtoDUNE-VD:

- 8 double-sided X-ARAPUCA modules on the cathode [using PoF and SoF technology]
- 8 single-sided X-ARAPUCA modules behind the field cage [using copper cables]
- Installation has been completed; operation planned in 2024→Stay tuned



Schematic of protoDUNE-VD



Picture taken during installation

Summary:

- PoF and SoF technology will be used as a part of the DUNE FD2 Photon Detection System.
- The technology have been demonstrated successfully in prototype detectors.
- A larger scale prototype (ProtoDUNE-VD) is ready to operate in 2024.
- The technology allows the PDS coverage to be increased significantly and making light collection uniform, potentially enhancing the physics study capabilities of the detector.