R&D of Power Over Fiber in harsh environments and its novel application for the DUNE FD-VD Photon Detection System

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On behalf of DUNE collaboration

NuFact 2024
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Outline

Deep Underground Neutrino Experiment (DUNE)

- Far Detector Vertical Drift (FD-VD)

PoF Technology for DUNE FD-VD

- Laser unit box
- Optical fibers
- OPCs

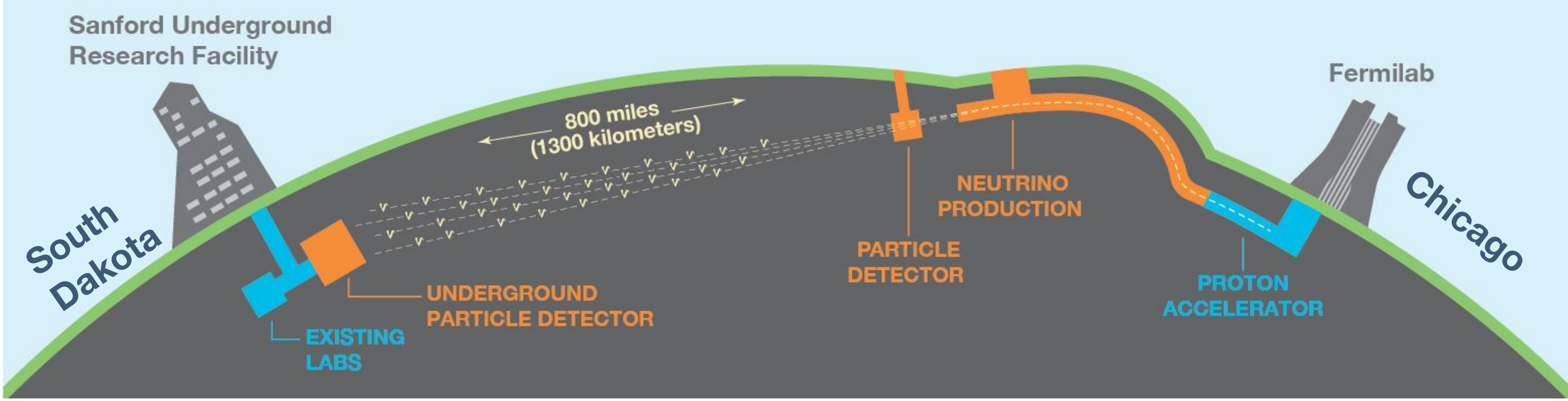
Prototype detectors at CERN neutrino platform

- PoF technology deployment

Deep Underground Neutrino Experiment (DUNE)

The Deep Underground Neutrino Experiment (DUNE) is the next generation long-baseline neutrino experiment.

Physics Goals: neutrino oscillations, CP violation, supernova physics, proton decay, BSM physics



DUNE will consist of two neutrino detector complexes:

- **Near Detector (ND):** Located ~ 60 m underground at Fermilab
- **Far Detector (FD):** Located ~1.5 km underground and ~1,300 km from the ND to the SURF in South Dakota.

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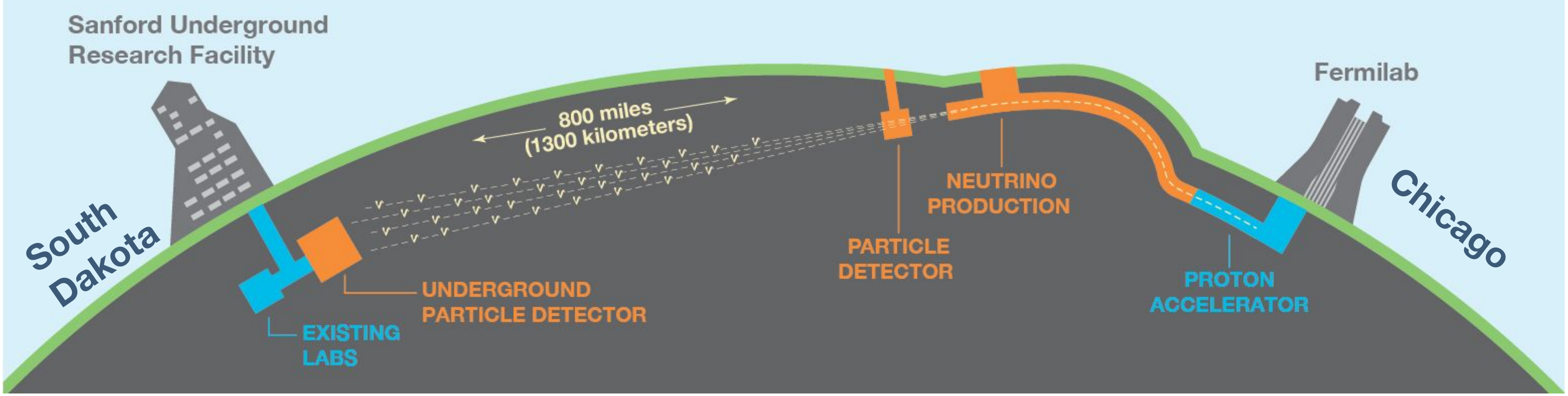

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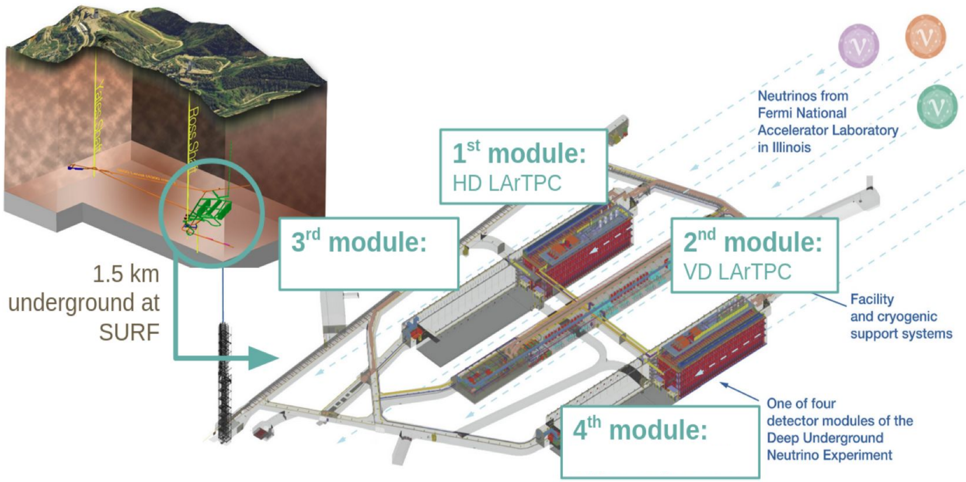
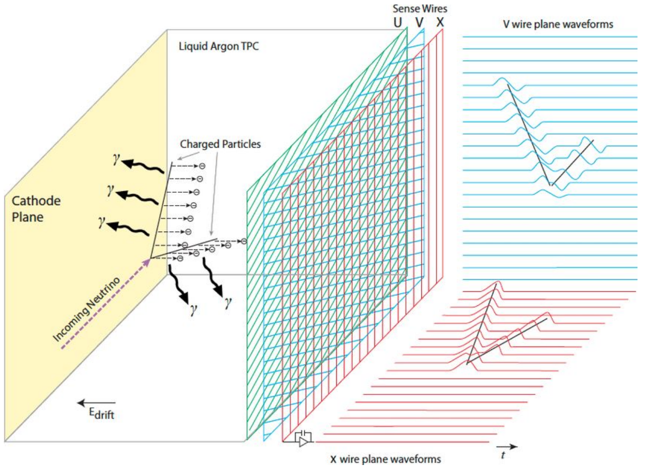
DUNE: Far Detector

The Far Detector (FD) will consist of four independent modules. The main detector technology will be a Liquid Argon Time Projection Chamber (LArTPC).





The second module (FD-VD) utilizes a vertical drift cathode arrangement that includes photon detectors (x-ARAPUCAs) embedded in the cathode at HV (~300kV). Because of the HV involved, conventional copper cables are not feasible for powering the PDS.

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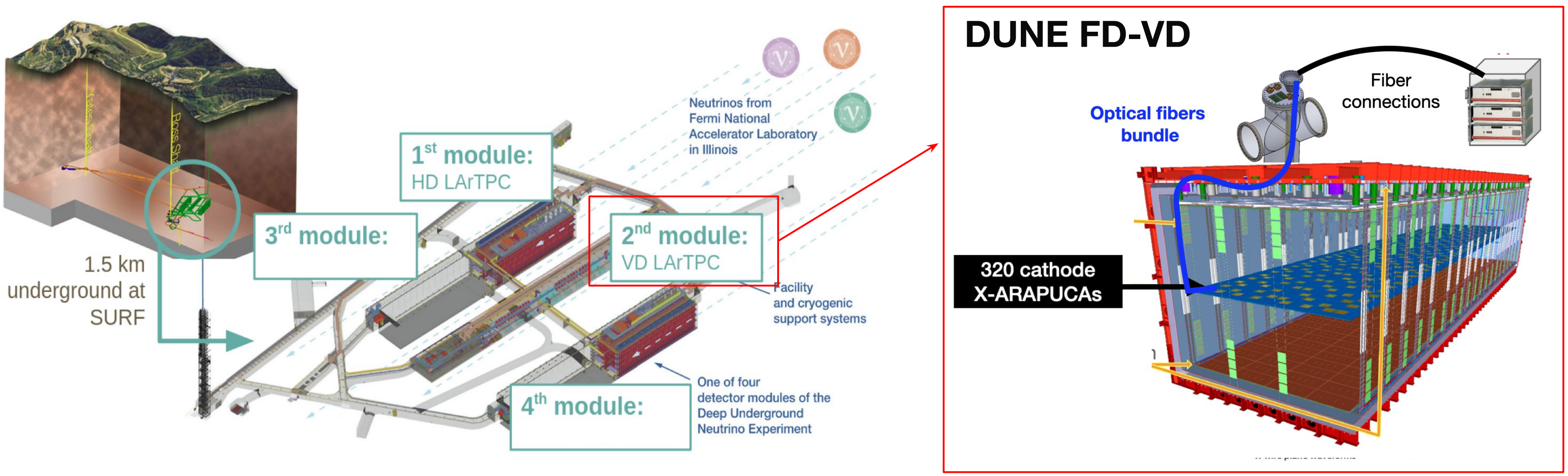

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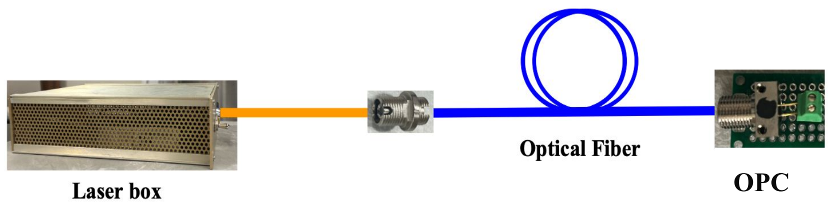
Power over Fiber (PoF) Technology

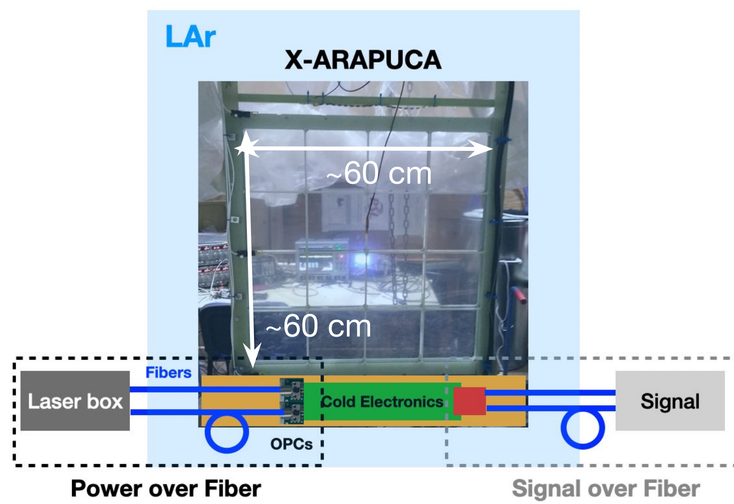
The PoF system is composed of three components: an infrared laser source, optical fibers to carry the optical power, and optical power converter (OPC) to convert optical power into electrical power.

- Offers superior noise performance and immunity to EMF
- PoF offers a reliable means of power transmission, leveraging optical fibers to transfer power with minimal system degradation

PoF technology components



PoF implementation for PDS (DUNE FD-VD)



As of today, DUNE FD-VD will be the first particle physics experiment employing PoF technology operating at cryogenic temperatures and HV environment to power supply the PDS (x-ARAPUCAs).

- Detailed R&D has been conducted to validate and optimize the performance of the individual components (arXiv:2405.16816v1)

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arXiv:2405.16816v1 [physics.ins-det] 27 May 2024

Characterization and Novel Application of Power Over Fiber for Electronics in a Harsh Environment

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Abstract

Power-over-Fiber (PoF) technology has been used extensively in settings where high voltages require isolation from ground. In a novel application of PoF, power is provided to photon detector modules located on a surface at ~ 300 kV with respect to ground in the planned DUNE experiment. In cryogenic environments, PoF offers a reliable means of power transmission, leveraging optical fibers to transfer power with minimal system degradation. PoF technology excels in maintaining low noise levels when delivering power to sensitive electronic systems operating in extreme temperatures and high voltage environments. This paper presents the R&D effort of PoF in extreme conditions and underscores its capacity to revolutionize power delivery and management in critical applications, offering a dependable solution with low noise, optimal efficiency, and superior isolation.

Keywords: Cryogenics, High voltage, Time Projection Chamber (TPC), Noble liquid detectors, High-power lasers, Optical fibers, Electronic detector readout concepts

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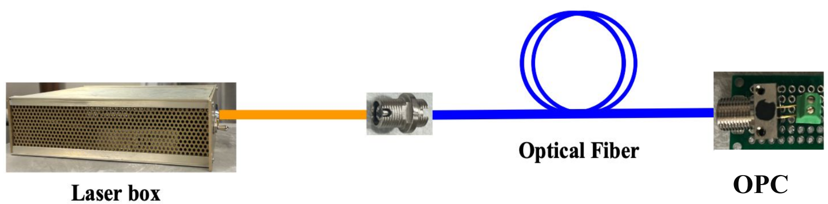
PoF technology components



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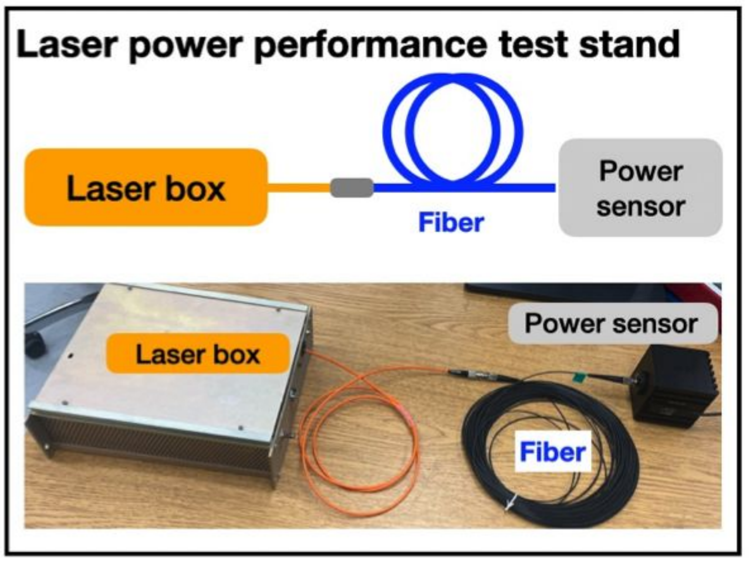
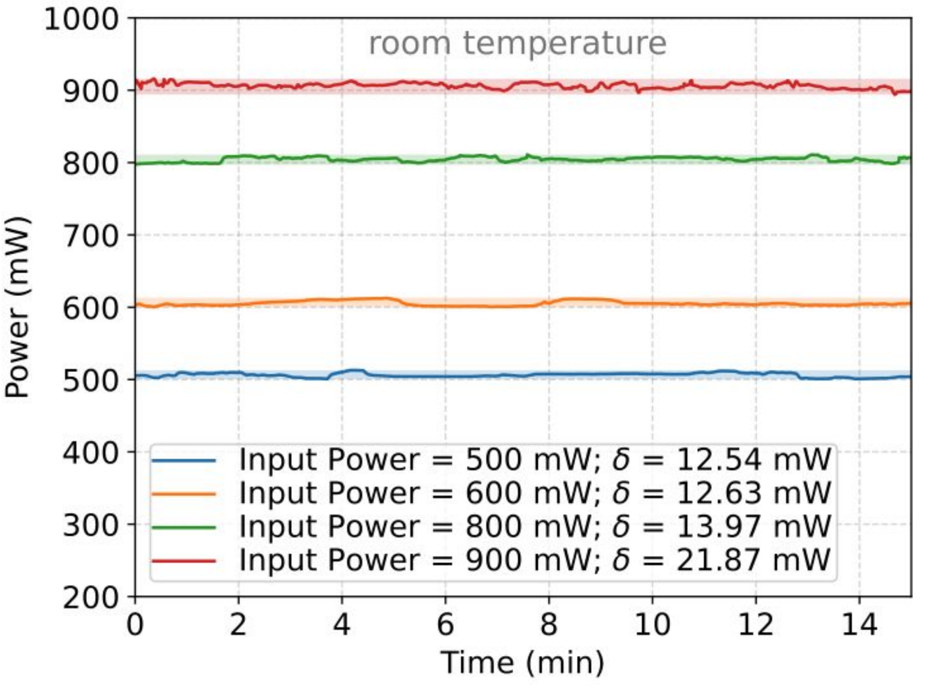
PoF Technology: Laser box units

The PoF laser box units contains a gallium arsenide (GaAs) 808-nm laser-transmitter module that transmits optical power through the optical fiber.

- A power stability test was conducted to monitor the output power of GaAs laser transmitter
    - This test, performed over an extended time period, allowed us to determine the power stability of the laser





- Power fluctuations are less than 3% wrt to the input powers

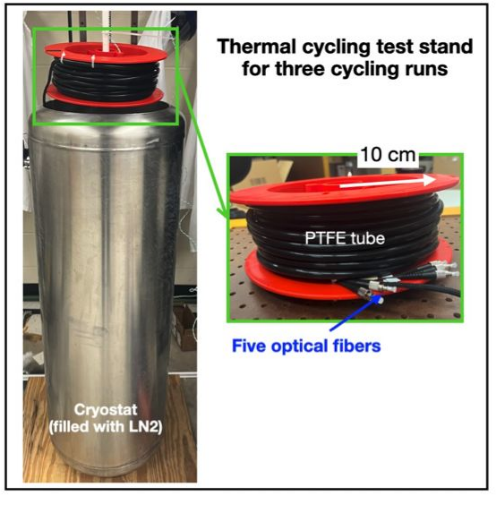
PoF Technology: Optical fibers (general description)

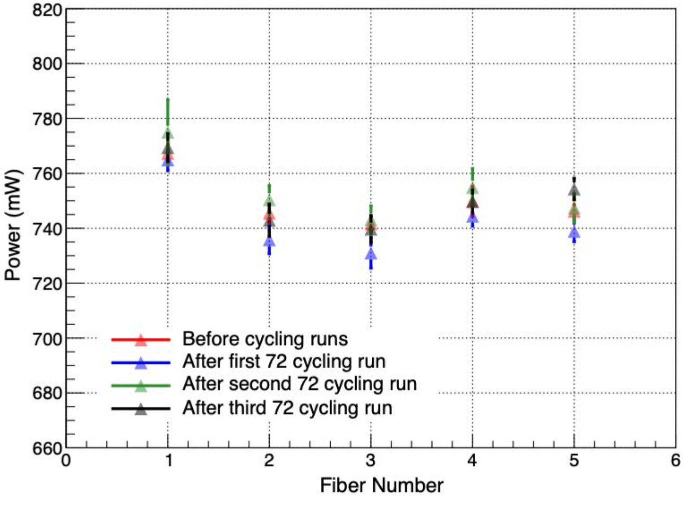
The selection of optical fibers for PoF technology took about 3 years. The selected optical fibers are unique and have large cladding, a double jacket (buffer + jacket) that helps to contain any light leakage.

MH-GoPower optical fibers	
Core diameter	62.5 um
Cladding diameter	200 um
Coating diameter	230 um
Buffer diameter	500 um
Black Jacket outer diameter	1.5 mm

The optical fibers have undergone a rigorous series of tests:

- *Light leak test:* verify that optical fibers don't have a light leakage
- *Thermal cycling test in LN2:* test results showed that thermal stress didn't affect the functionality of the fibers
- *Bending radius tests:* study of power loss as function of the bending radius

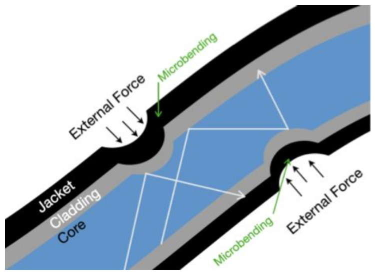


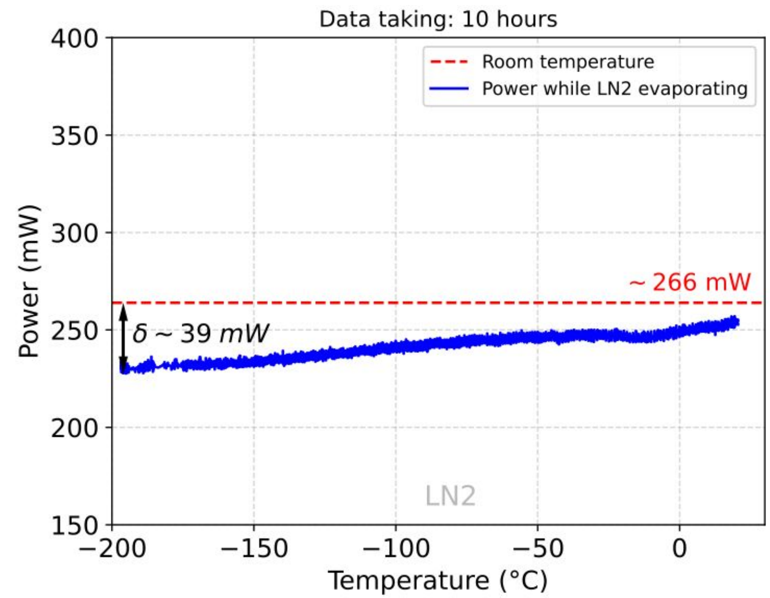


PoF Technology: Optical fibers (Power Loss at LN2)

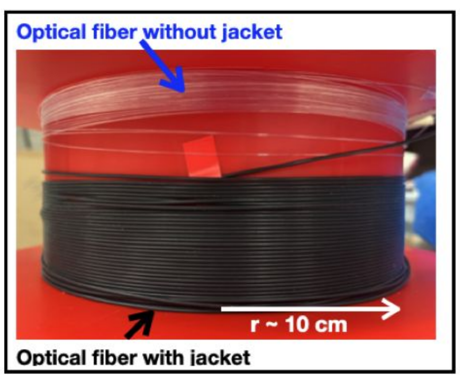
The PVDF jacket on the optical fibers provides chemical and radiation resistance, helping to prevent light leakage.

- Low temperatures can induce thermal contraction along the fiber, leading to microbending, which causes power loss





- Under LN2 temperatures, fibers with a PVDF jacket exhibit about three times higher power loss per meter than those without



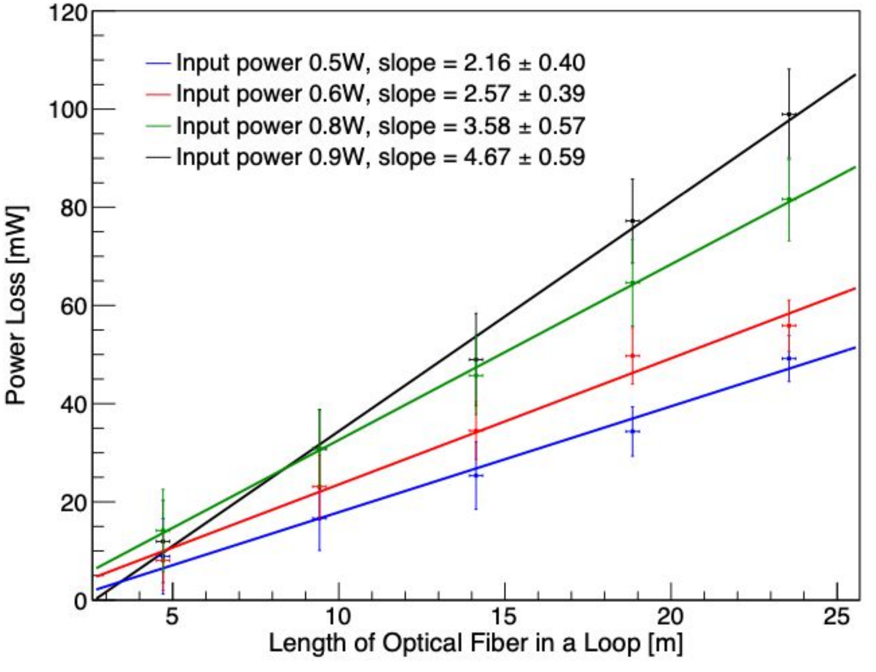
Fiber type	Input Power (mW)	Power loss per meter (mW/m)
With Jacket	500	1.74 ± 0.28
Without Jacket		0.56 ± 0.21
With Jacket	800	3.14 ± 0.51
Without Jacket		1.06 ± 0.48

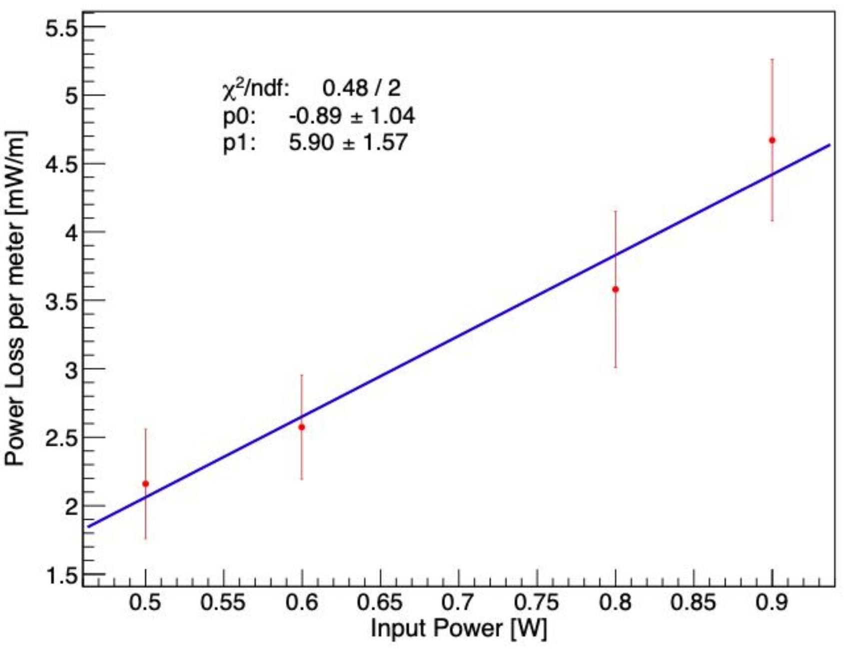
PoF Technology: Optical fibers (Bending radius)

Bending radius tests:

Power loss was characterized as a function of fiber length at LN2 temperatures, using a bending radius of 7.5 cm and five optical fibers.

- Five fiber lengths were evaluated 4.71 m, 9.42 m, 14.13 m, 18.84 m, and 23.55 m
- Four input power were used 0.5 W, 0.6 W, 0.8 W and 0.9 W



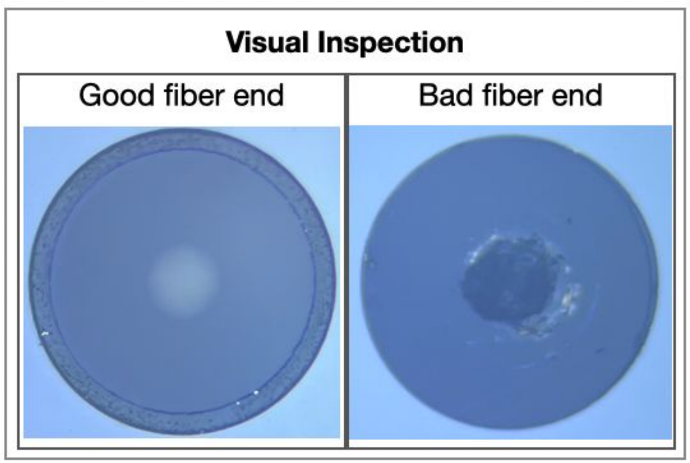


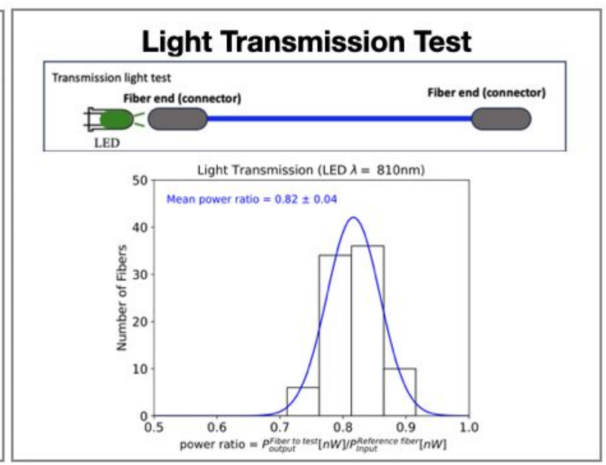
PoF Technology: Optical Fibers (QA/QC procedures)

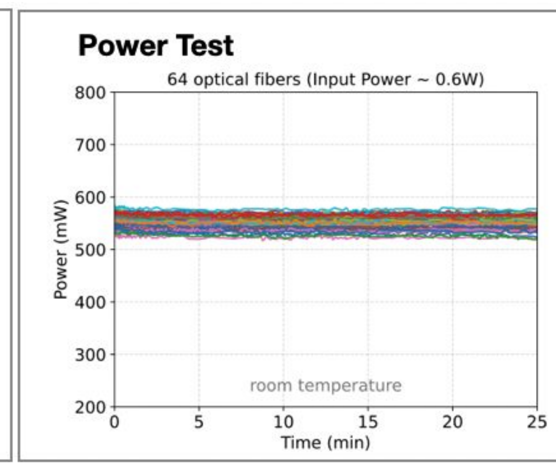
The optical fibers that are employed in PoF technology not only need to pass conventional tests (light transmission test) but also need to fulfill the emerging necessities of PoF technology demands.

We have developed a three-steps QA/QC that will be use in the qualification of optical fibers for cryogenic temperatures:

1. *Visual inspection:* Inspect fiber ends and jacket surface
2. *Light transmission test:* Measure light transmission to ensure fiber continuity
3. *Power test:* Power stability test to ensure power transmission through the fiber

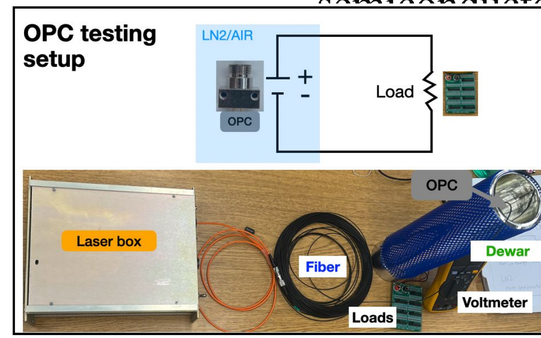






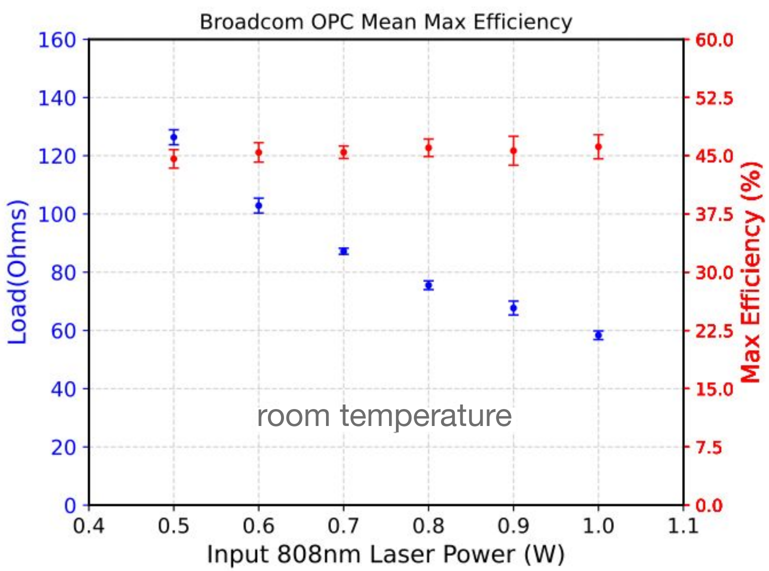
PoF Technology: Optical Power Converters (OPCs)

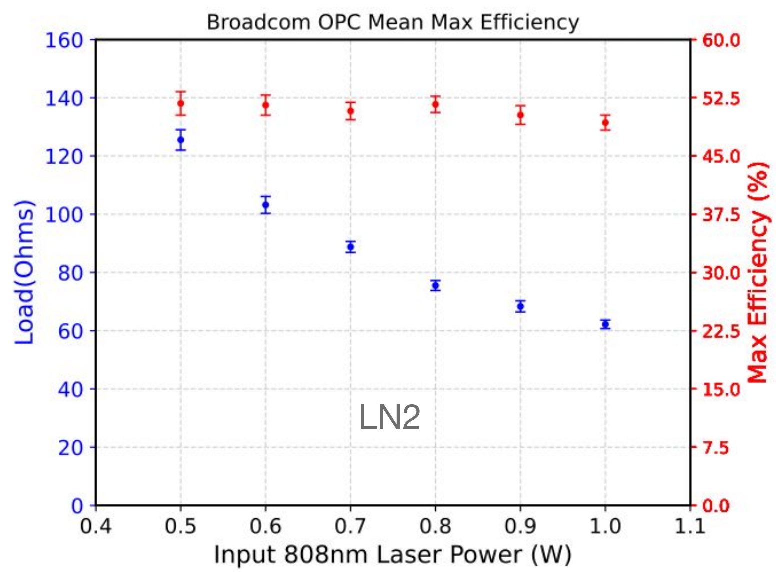
The OPC converts the optical energy of radiation into electric energy through the internal photoelectric effect in semiconductors.



- Two types of OPCs have been tested (Si and GaAs)
- Partnership between FNAL, Broadcom, UIUC to improve efficiency:
  - *UIUC*: Researching improved efficiency through semiconductor
  - *Broadcom*: Improved efficiency through packaging (Focal length, Material Size/Power Handling)
- A total of 12 Broadcom GaAs OPCs have been tested at LN2 and room temperatures.

$$\text{Efficiency} = \frac{P^{OPC}_{\text{max output}}(W)}{P^{Laser}_{\text{input}}(W)}$$

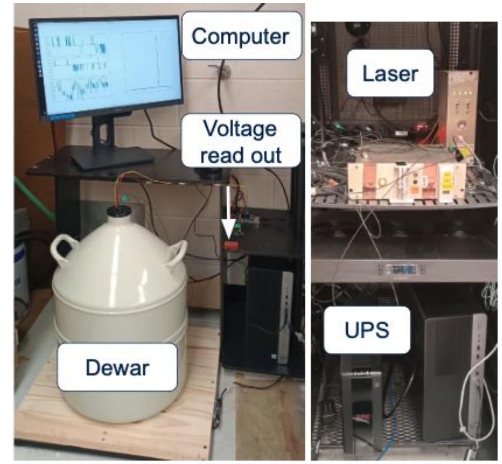


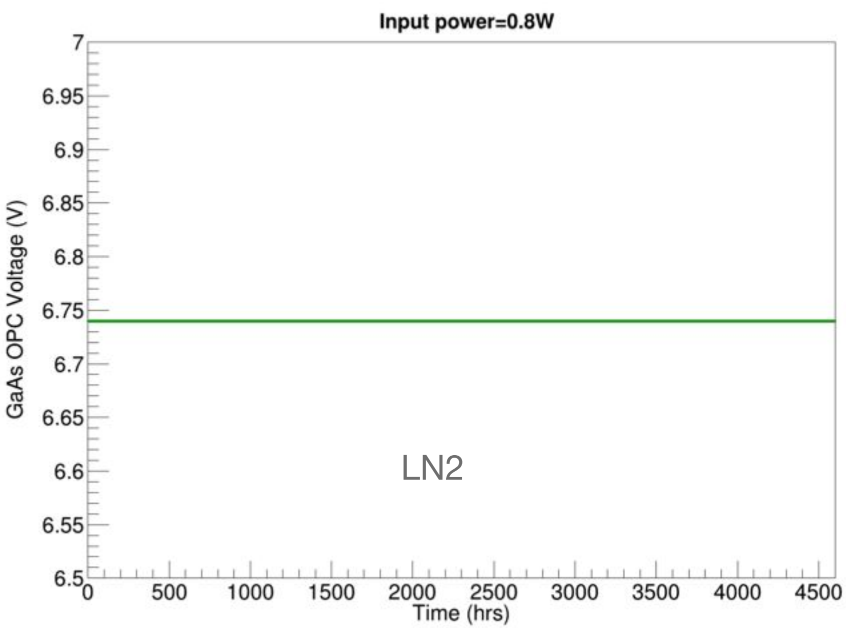


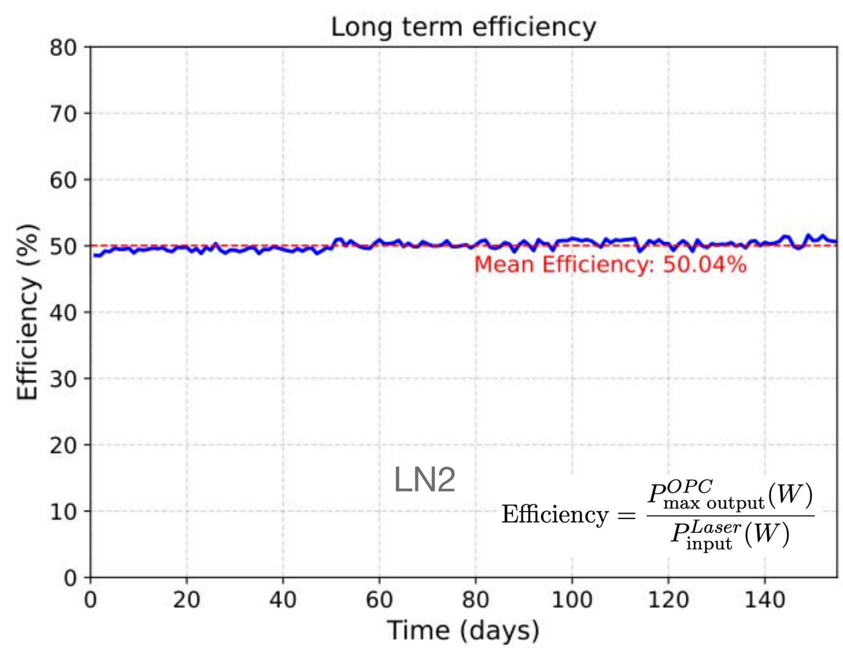
PoF Technology: Optical Power Converters (OPCs)

- The OPC is currently being tested in a long-term test stand at SDSMT, where the OPC's voltage output has been continuously measured for more than 6 months using an input power of 0.8W provided by the laser unit.

- We have measured the OPC efficiency at a 80-Ohm load for ~ 155 days.

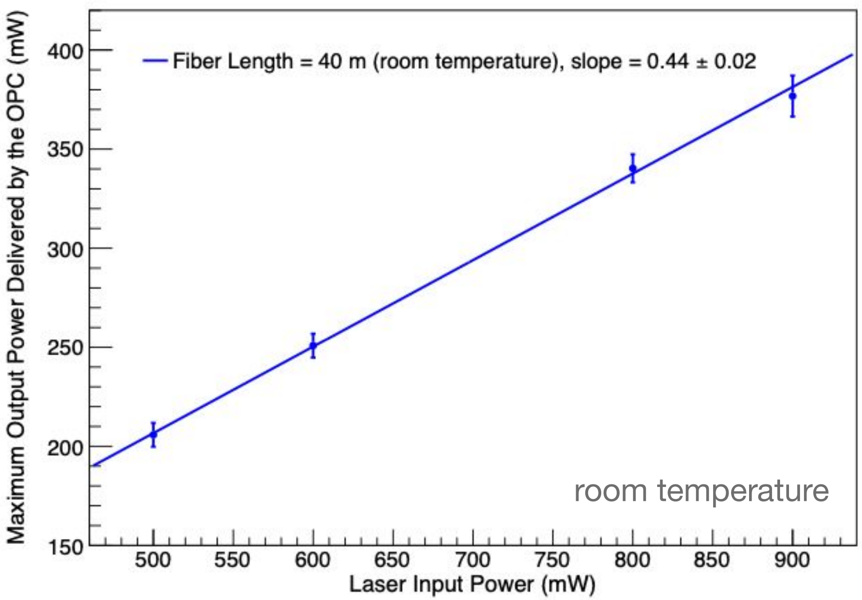


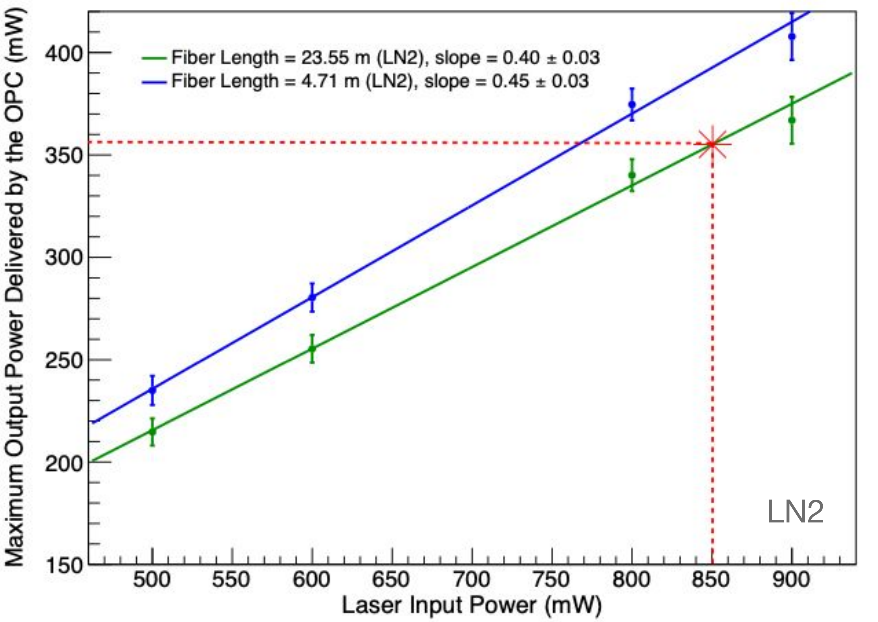




PoF Technology: Electrical Power Delivery

Characterization of PoF components (lasers, optical fibers, OPCs) helps to estimate the maximum electrical power delivered by OPC at specific lengths of optical fibers at room and LN2 temperatures





For the DUNE FD-VD, the cold electronics motherboard used to read out the photodetectors (X-ARAPUCAs) requires about 350-400 mW under cryogenic conditions and about 23 meters of optical fiber submerged in LAr.

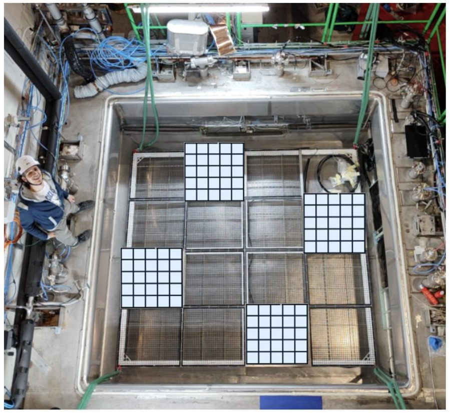
Prototyping detectors using PoF technology

After validating and optimizing the PoF components through multiple test stands, the PoF components have been installed in two prototypes Coldbox and ProtoDUNE VD at CERN.

- Coldbox at CERN
  - Successful integration of PoF to power four X-ARAPUCAs photodetectors located in high-voltage and LAr environment More details at Sabrina Sacerdoti's talk
  - PoF configuration utilizes per photodetector: two lasers-transmitter of 808nm, two optical fibers of 62.5um and PVDF jacket, and two GaAs OPCs (~6.5V in LAr)

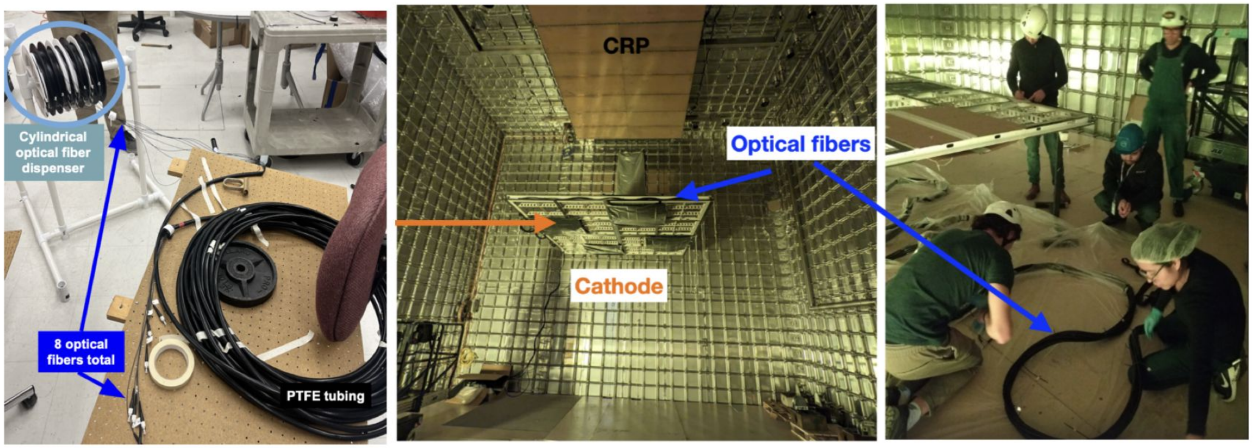
Coldbox runs at CERN marked the first successful instance of powering photodetectors at high voltage and in a cryogenic environment using PoF technology in HEP

CERN neutrino plataform

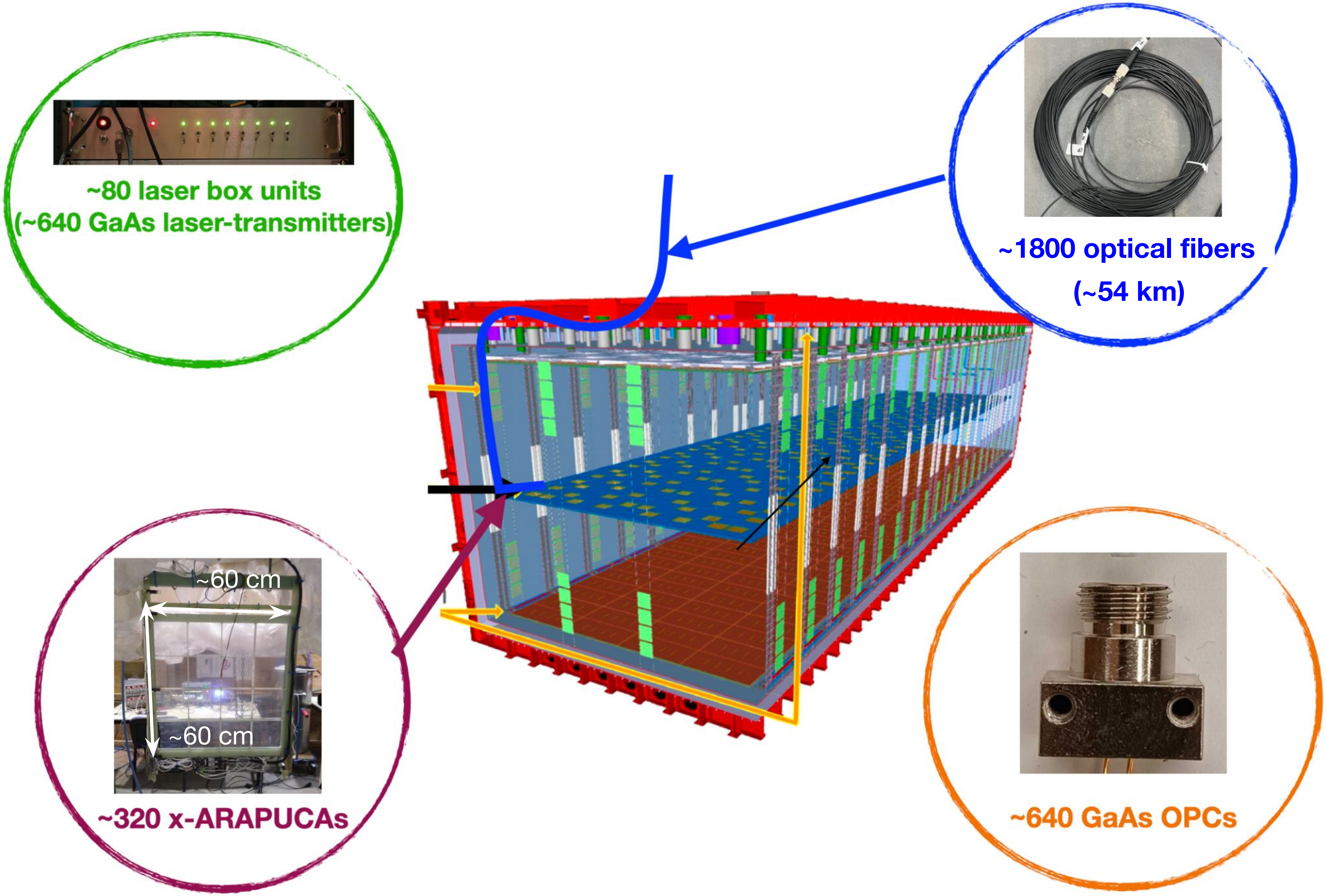


Volume ~ 0.22 x 3 x 3 m^3

Optical Fiber Assembly and ProtoDUNE VD Installation



PoF technology in DUNE FD-VD



Summary

- PoF technology offers a new opportunity for supplying electrical power to electronics operating in HV at cryogenic temperatures.
- Multiple tests of the individual components (lasers, optical fibers, and OPCs) have been performed over a period of ~3 years to validate and optimize this technology.
- Experience acquired with coldbox runs and ProtoDUNE VD at CERN will be critical in the application of PoF technology to power the PDS system located on the cathode plane for DUNE FD-VD.
- Further investigations are underway to continue improving the PoF technology.

This work is supported by the U.S. Department of Energy Office of Science.

Thank you!