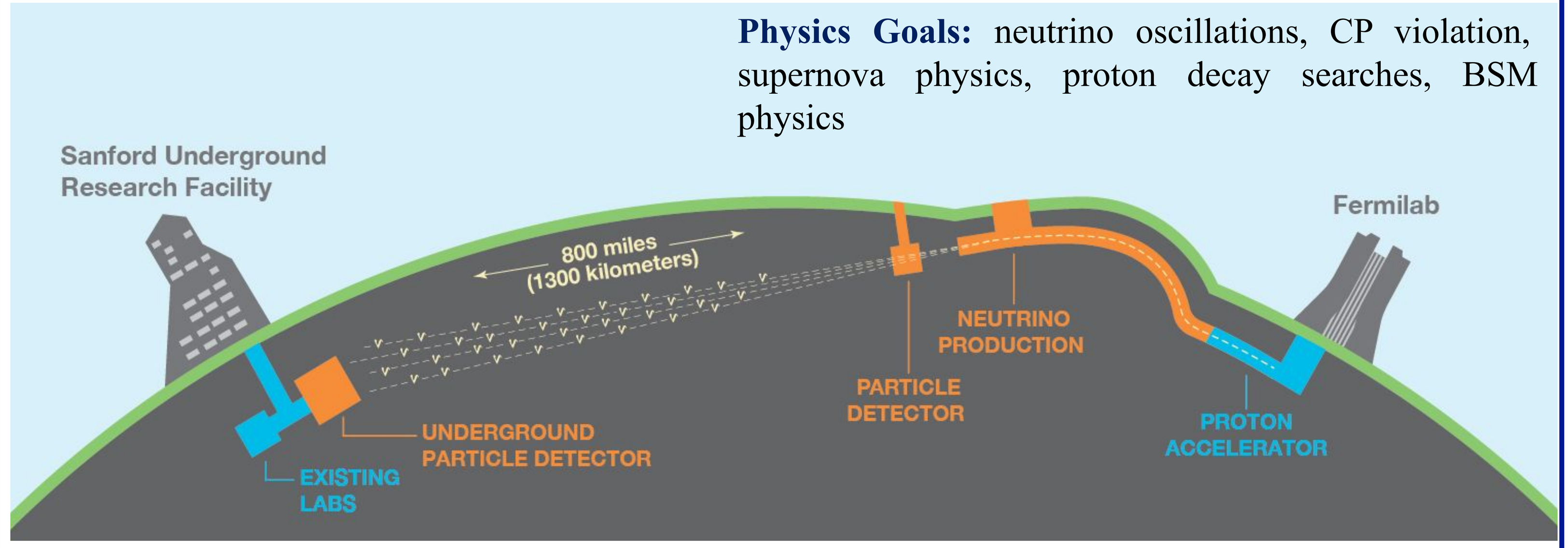
R&D of Power Over Fiber in harsh environments and its novel application for the DUNE Photon Detection System

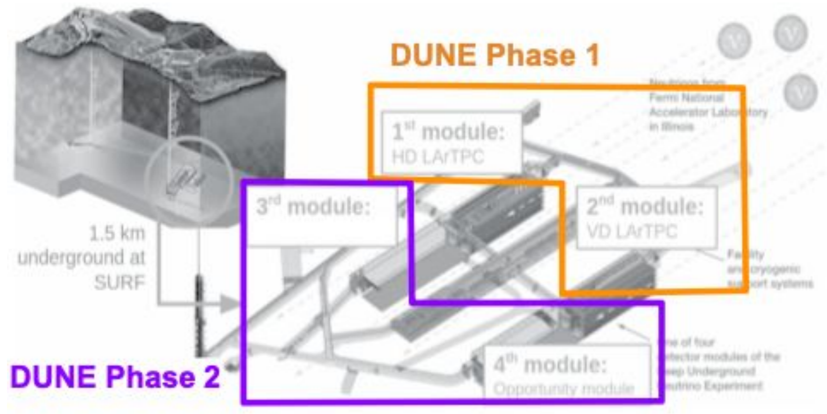
David Martinez Caicedo on behalf of the DUNE Collaboration – South Dakota School of Mines and Technology

The Deep Underground Neutrino Experiment



- **Near Detector (ND):** Located ~574 m from neutrino beam target and ~60m underground at Fermilab.
- **Far Detector (FD):** Located ~1.5 km underground and ~1,300 km from the ND to the SURF in South Dakota. DUNE far detector will utilize 17 kt LArTPC modules.

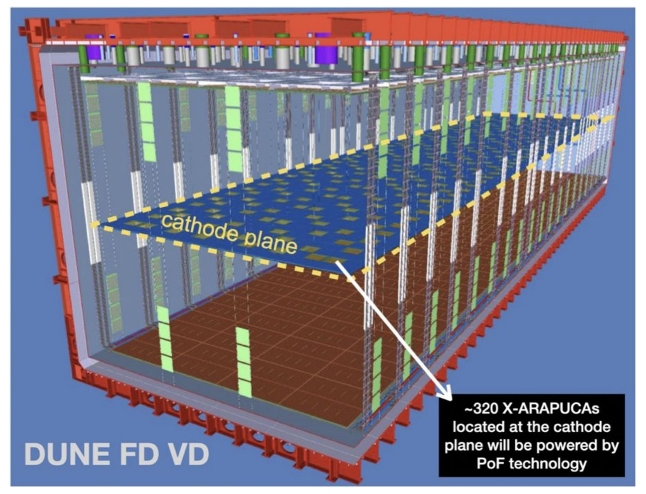
Far Detectors and Motivation

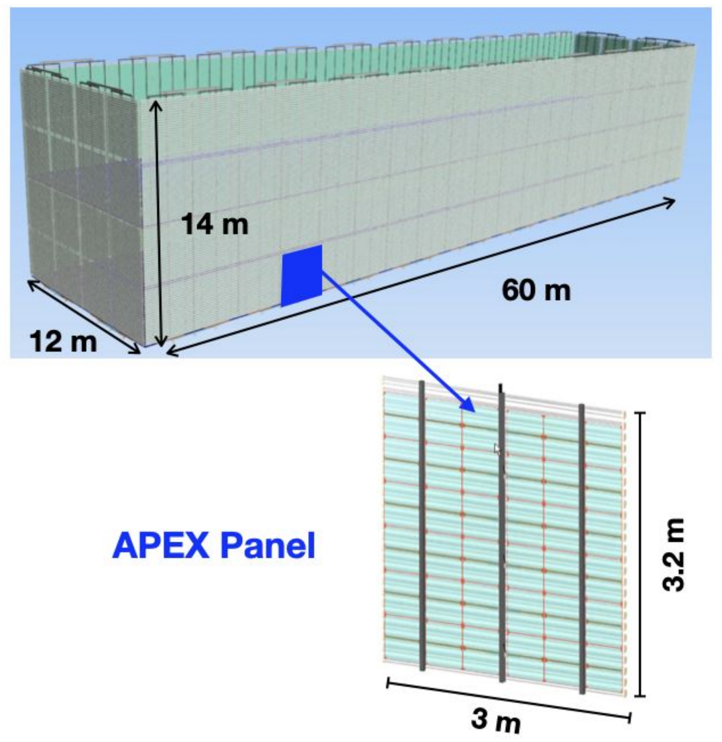


DUNE will be implemented in two phases: Phase I comprises the first two Far Detector modules (FD-HD and FD-VD), followed by FD3 and FD4 (Module of Opportunity) in Phase 2.

DUNE FD Phase 1 (FD-VD):

- The DUNE FD-VD will utilize a vertical-drift liquid argon TPC with X-ARAPUCA photon detectors embedded in the high-voltage cathode (~300 kV) and membrane.
- Cryostat under construction at SURF





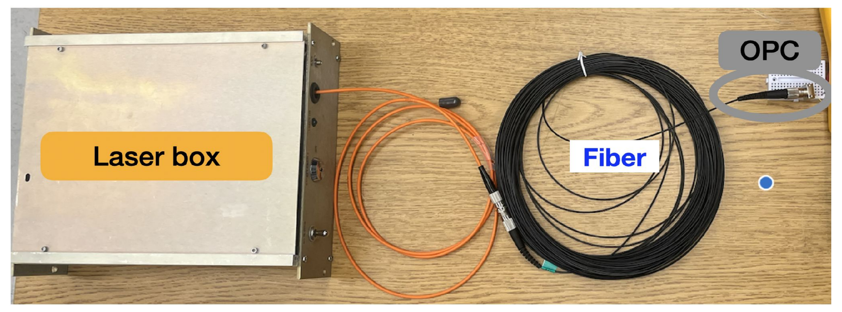
DUNE FD Phase 2 (FD3/APEX):

- The proposed APEX photon detection system integrates X-ARAPUCA photon detectors into aluminum field-cage panels, transforming the field cage into an active photon-detection system.
- X-ARAPUCAs integrated into the field cage aim to provide ~60% optical coverage.

Motivation: Photon detectors will be installed on high-voltage cathode and field cage structures, conventional copper cables are not feasible.

Power over Fiber Technology (PoF)

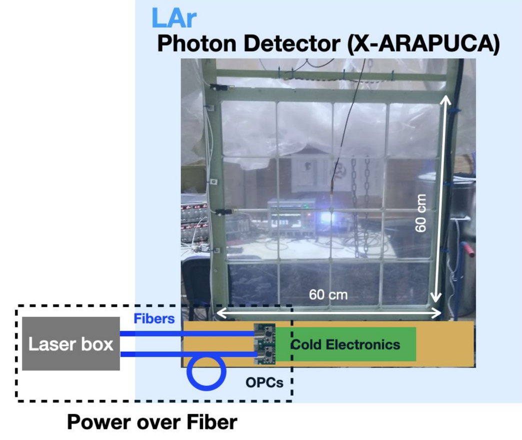
The PoF system is composed of three components: an infrared laser source, optical fibers to carry the optical power, and optical power converter (OPC) to convert optical power into electrical power.



Warm Side PoF requirements:
- Designed for maintainability
- Minimize production cost
- Control laser temperature stability

Cold Side PoF requirements:
- Designed for reliable operation with a 20-year viability
- Built-in system redundancy
- Low noise performance

PoF implementation for Photon Detector System



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 photon detection system (PDS).

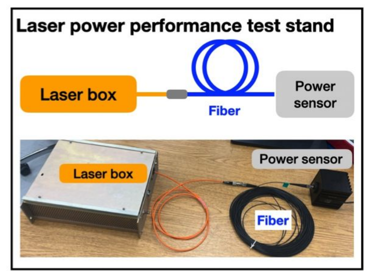
JINST publication summarizes the FD-VD PoF R&D program and the first successful deployment of PoF technology in photon detector prototypes at CERN.

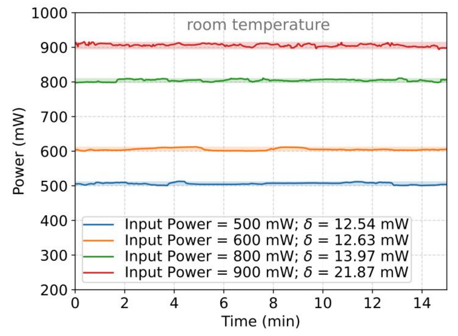
JINST **19** P10019

PoF for DUNE FD-VD

Lasers Transmitter Modules

PoF laser units use 808-nm GaAs laser transmitters to deliver optical power through optical fibers, with power fluctuations below 3%.

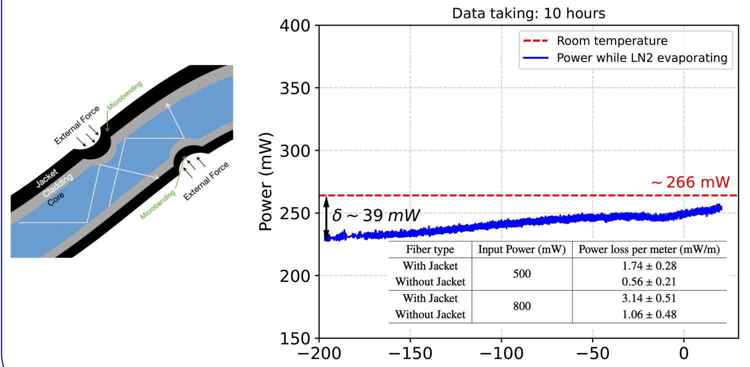




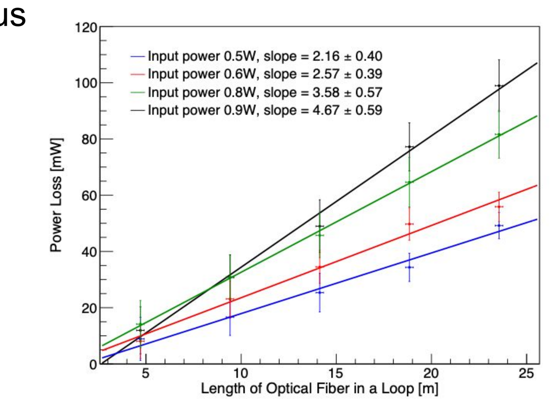
Optical Fibers

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 light leakage.

LN2 tests: Thermal contraction can induce fiber microbending, which causes power loss.



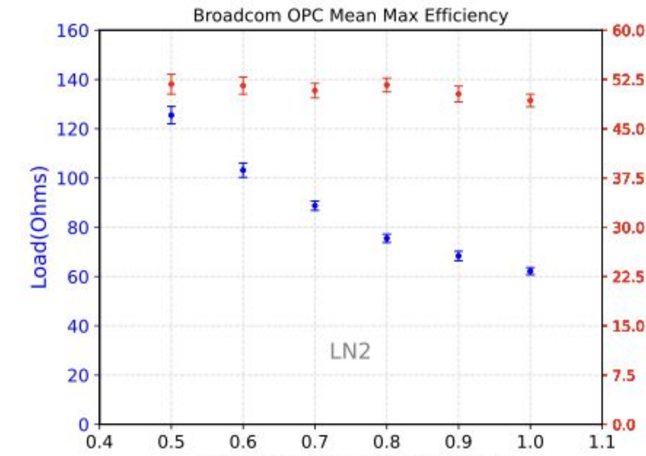
Bending radius tests: study of power loss in the optical fiber as function of the bending radius

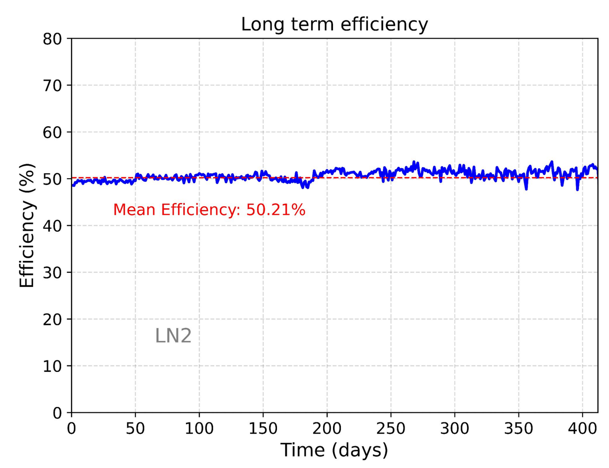


GaAs Optical Power Converters

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

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





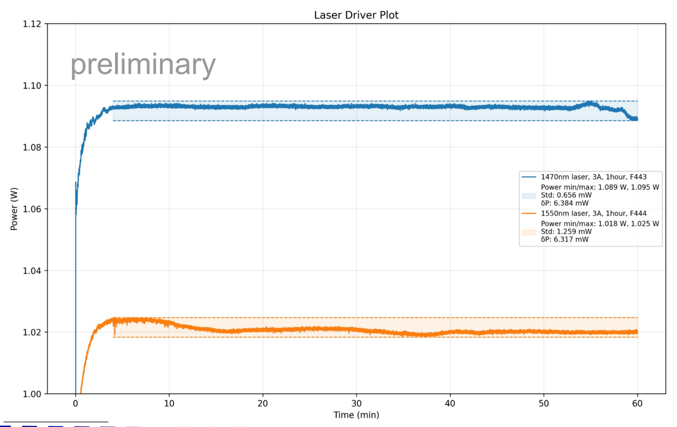
A maximum optical-to-electrical power conversion efficiency of ~ 51% was measured in LN2

PoF for DUNE FD3

The FD3 PoF system builds upon the DUNE FD-VD design, focusing on next-generation lasers, optical fibers, and optical power converters to improve optical to electrical conversion efficiency, reduced light leakage, and enhance the reliability in cryogenic environments.

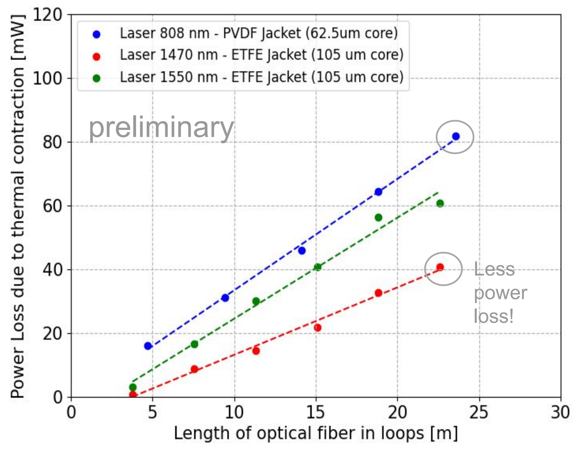
Lasers Transmitter Modules

- Minimize light leakage by evaluating 1470 nm and 1550 nm lasers. Preliminary results show power fluctuations below 1%.



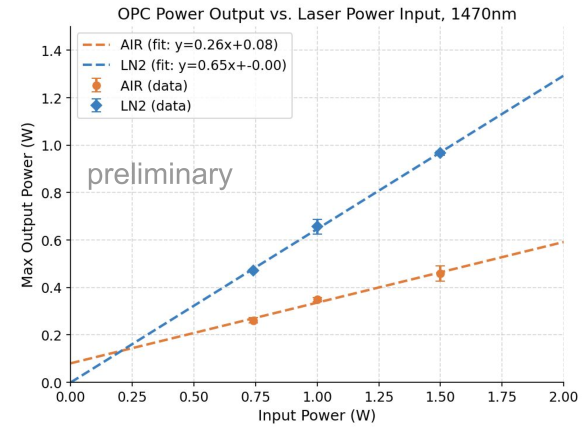
Optical Fibers

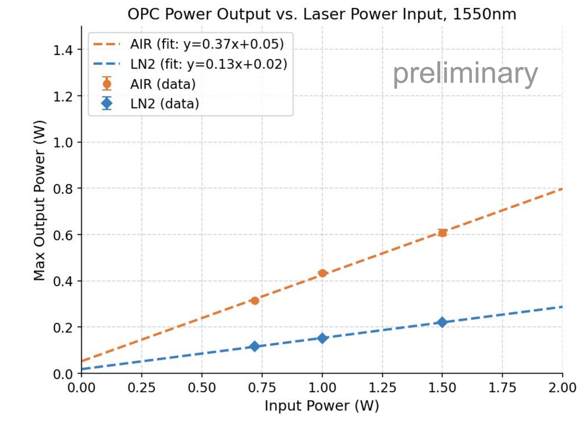
- Preliminary tests using fibers with 105 um core and ETFE jacket shows lower power loss at LN2 temperature (0.8 W laser input) relative to the 62.5 um core and PVDF jacketed fibers selected for FD-VD.



InGaAs Optical Power Converters

- Ongoing studies evaluate InGaAs OPCs under cryogenic conditions with 1470 nm and 1550 nm lasers.

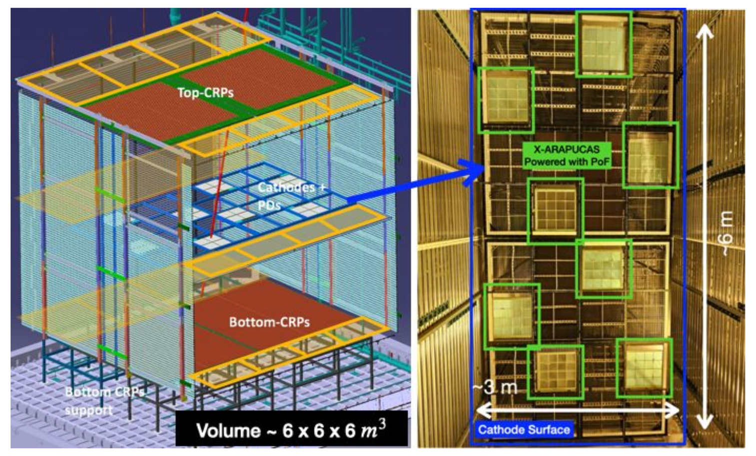




- Measured maximum optical-to-electrical power conversion efficiencies of ~65% (1470 nm) and ~13% (1550 nm) in LN2.

Summary

DUNE FD Phase 1: PoF has been successfully validated for operation in high-voltage and cryogenic environments through extensive R&D and deployment in Coldbox and ProtoDUNE-VD at CERN, establishing the baseline for DUNE FD VD.



DUNE FD Phase 2: The proposed DUNE FD3 design will build upon the vertical-drift technology developed for DUNE FD-VD.

- Preliminary results of R&D on infrared lasers, low-loss optical fibers, and high-efficiency InGaAs optical power converters are promising and show the potential advance of the next generation of PoF technology for FD3.

[1] M.A. Arroyave *et al.* "Characterization and novel application of power over fiber for electronics in a harsh environment "*JINST* **19** P10019 (2024)
[2] https://www.dunescience.org
[3] http://neutrinos.ciemat.es/es/dune-es
[4] Abi, Babak, et al. "Volume I. introduction to DUNE." *Journal of instrumentation* 15.08 (2020)
[5] https://ep-news.web.cern.ch/content/dune-prototype-activities-neutrino-platform
[6] F. Marinho on behalf of the DUNE collaboration, *JINST* 20 C05029 (2025)
[7] W. Shi, DUNE FD3 APEX Physics Prospects and Prototyping Status, NuFact 2024

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Neutrino 2026: XXXII International Conference on Neutrino Physics and Astrophysics, UCI, CA.

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