



**SOUTH
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MINES**

R&D on Next-Generation of Power-over-Fiber for HEP Detectors

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Outline

- **Power-over-Fiber Technology in HEP**
 - Laser characterization and driver development
 - InGaAs OPC characterization at cryogenic temperatures
 - Optical fiber attenuation and projected power delivery
 - SiPM response to light leakage at 808, 1470, and 1550 nm
 - Applications of Next Generation PoF system
- **Summary**

Power-Over-Fiber Technology (PoF) in HEP

From the concept to detector prototype operation and next generation of PoF system

Concept and Feasibility Studies (2018 - 2020)

Proposed a novel application of PoF technology to supply power to cathode-mounted photon detectors electronics in the DUNE by Fermilab team.

Evaluation of silicon-based PoF systems.

PoF Development and Validation (2020 - 2023)

Developed 808 nm GaAs-based PoF system for cryogenic temperatures.

Characterization of lasers, optical fibers and optical power converter in room, LN₂ and LAr.

Achievement possible through efforts at Fermilab, industry, and Universities.

PoF integration and Operation in DUNE prototypes (2023 - 2025)

First successful operation of 808 nm PoF system powering photon detectors in LAr at high voltage (10 kV) in the CERN Coldbox.

Successfully powered and operated eight X-ARAPUCA photon detectors using 808 nm PoF in ProtoDUNE Vertical Drift (~175 kV, ~800 tons of LAr) since 2025.

Published PoF R&D results in [JINST 19 \(2024\) P10019](#).

Presented PoF R&D at [CPAD 2024](#) and ProtoDUNE-VD operation at [CPAD 2025](#).

Next-generation PoF R&D (2024 - present)

Ongoing R&D on next-generation PoF systems for potential applications in future large-area photon detectors, including the proposed APEX photon detection system for DUNE Phase II.

Today's Talk:

Characterization of next-generation 1470 and 1550 nm PoF systems, focusing on power conversion efficiency, optical losses, and light leakage under cryogenic conditions.

Motivation for 1470 nm and 1550 nm PoF

Building on the success of the 808 nm PoF system and the lessons learned from its development, this R&D focuses on:

A PoF system is composed of three key components:

- Infrared laser source to generate optical power.
- Optical fiber to transmit the optical power.
- Optical power converter (OPC) to convert the received optical power into electrical power.



Reduce infrared light leakage:

- Evaluate 1470/1550 nm lasers to reduce infrared light leakage.
- Investigate the impact of infrared light leakage on SiPM response.

InGaAs optical power converters (OPCs):

- Characterize voltage output and optical-to-electrical conversion efficiency at cryogenic temperatures.

Optimize optical fiber performance:

- Minimize optical power loss and light leakage under cryogenic conditions.

Enable future applications:

- Provide electrically isolated, low-noise power delivery to electronics and sensors operating in high-voltage and cryogenic environments.

Next-generation PoF could enable electrically isolated, low-noise power delivery for DELTA, with the proposed APEX photon detection system for DUNE Phase II as a potential DELTA application, while opening opportunities for other high-voltage and cryogenic applications.

Laser and InGaAs OPC Candidates

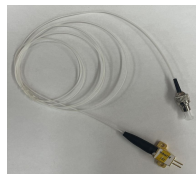
Laser of 808 nm - DUNE Far Detector Vertical Drift

- Max output power: 2.0 W
- Core diameter: 62.5 μm
- Working current: 0.4 - 2.7 A
- Working voltage: ~ 1.8 V



Candidate 1: Laser of 1470 nm

- Max output power: ~ 2.5 W
- Core diameter: 62.5 or 105 μm
- Working current: 0.5 - 9.0 A
- Working voltage: 1.8 V



Candidate 2: Laser of 1550 nm

- Max output power: ~ 2 W
- Core diameter: 62.5 or 105 μm
- Working current: 0.5 - 6.0 A
- Working voltage: 1.5V



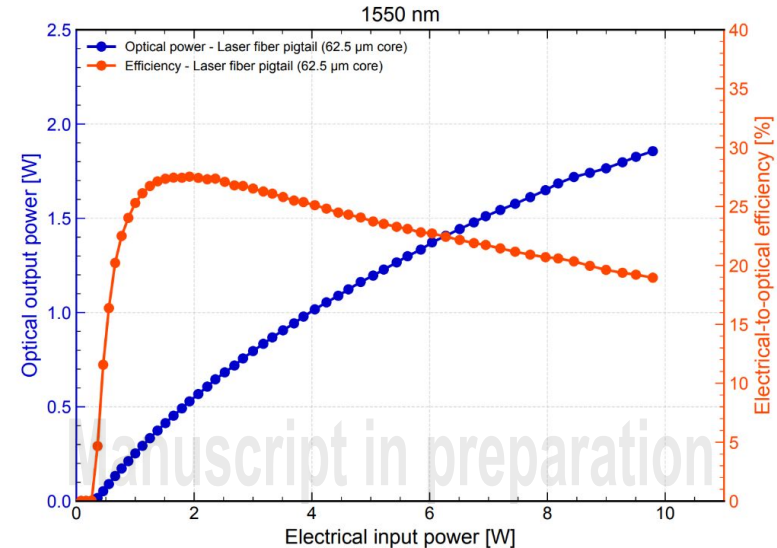
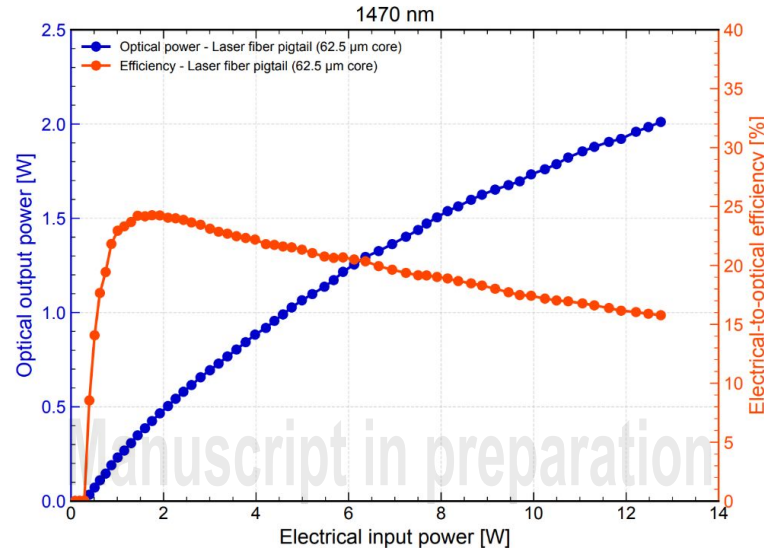
Optical Power Convertors (OPC)



- Max input power: 1.5 W
- Core diameter input fiber: 9 μm - 400 μm
- NA input fiber: 0.22 (Max. output)
- Optimized for:
 - 1450 - 1500 nm
 - 1500 - 1550 nm

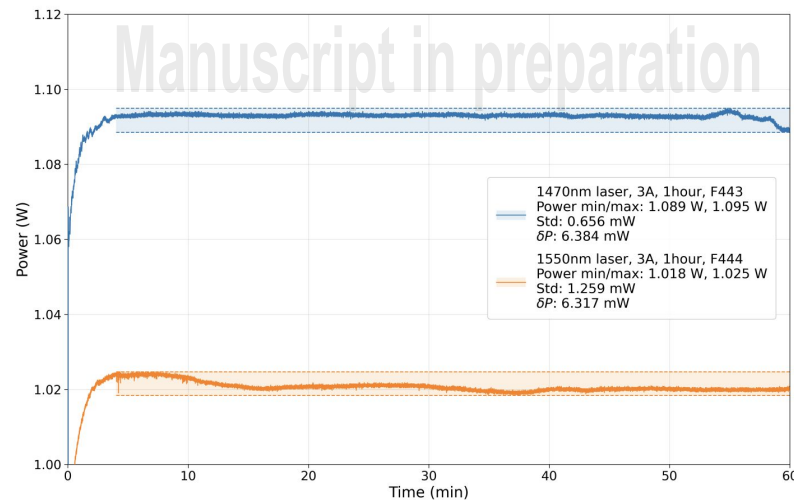
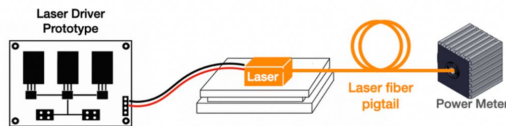
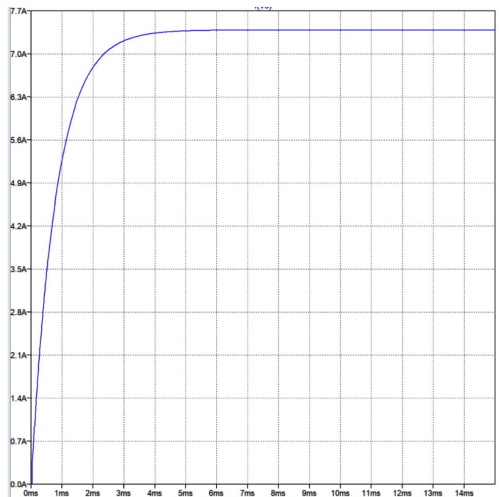
1470 and 1550 nm Lasers: Electrical-to-Optical Efficiency

- The optical output power increases with the electrical input power for both laser transmitters.
- Measured maximum electrical-to-optical efficiencies of approximately 24% at 1470 nm and ~28% at 1550 nm.
- The laser operating point can be selected based on the required optical output power and the corresponding optical-to-electrical conversion efficiency.



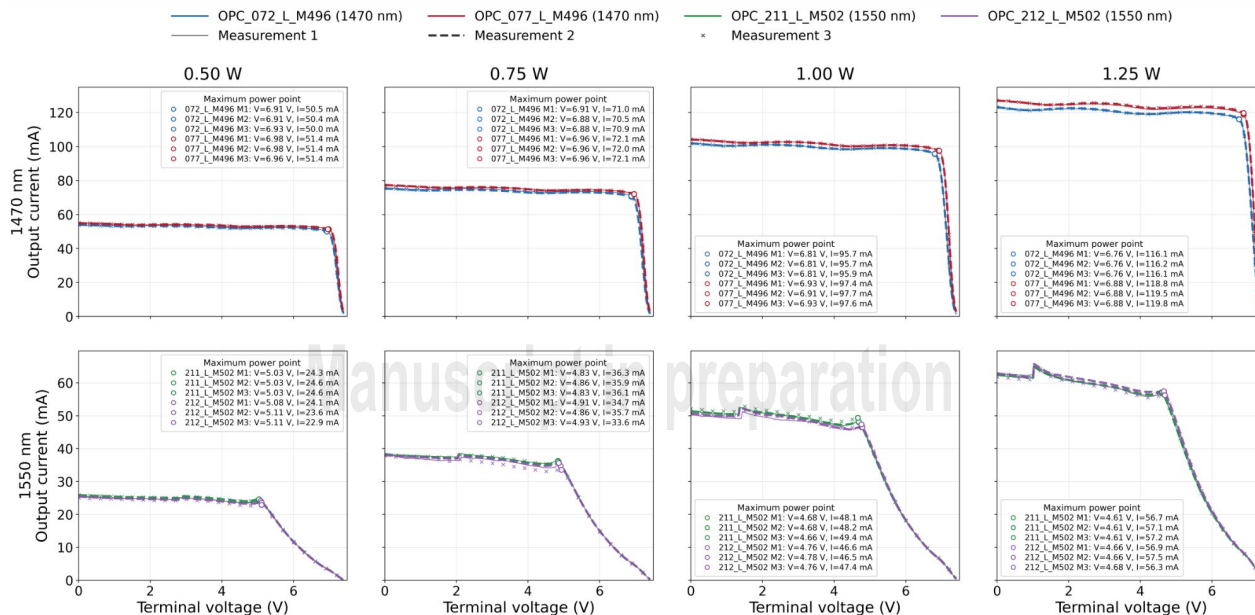
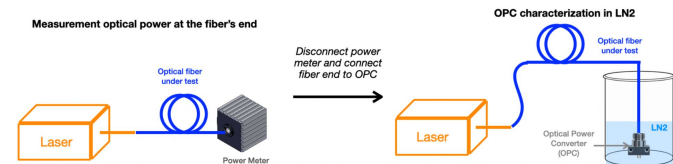
Laser Driver Prototype and Optical Power Stability

- Laser-driver prototype
 - A laser-driver prototype was developed for the 1470 and 1550 nm laser transmitters.
 - Prototype driver tests reached up to ~ 7.3 A, with a measured laser optical output power of up to ~ 2.6 W.
- Power output stability
 - Both lasers transmitters were operated continuously at 3 A for one hour.
 - After the initial stabilization period (~ 4 min.), laser optical-power fluctuations remained around 1%.
 - Planned long term operations of lasers and design of an optimal cooling system



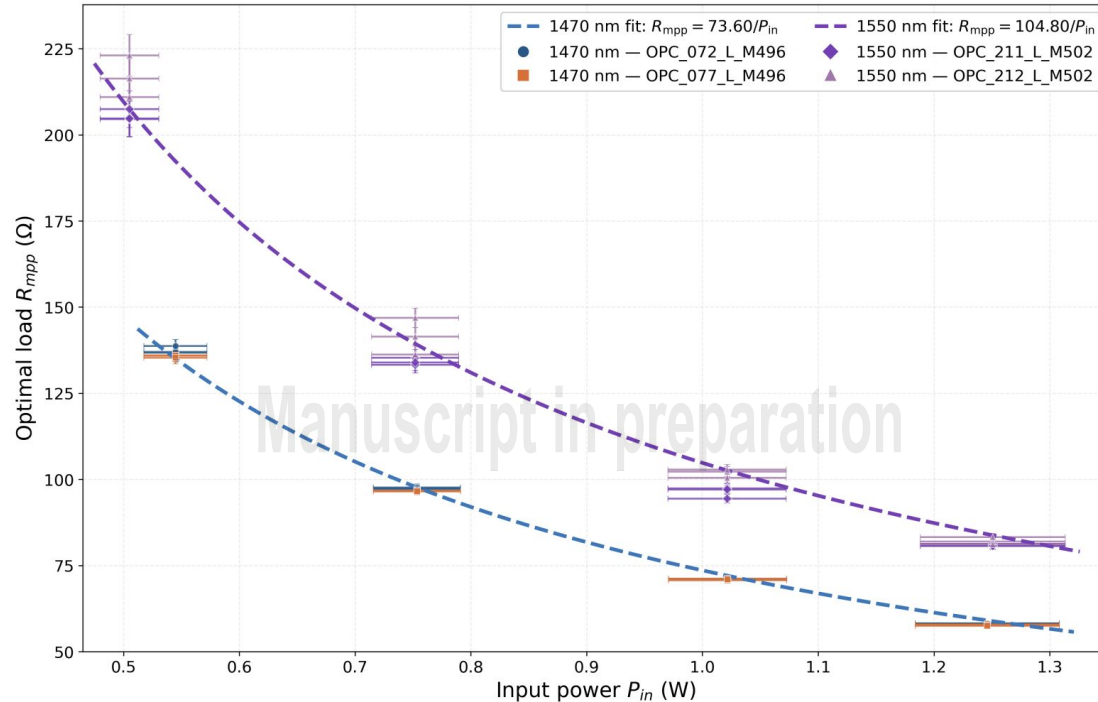
InGaAs OPC Characterization for 1470 nm & 1550 nm Lasers

- Two InGaAs OPCs were characterized at each wavelength in LN₂.
- I-V measurements were performed at optical input powers from 0.5 to 1.25 W.
- The maximum power point (MPP) was identified from the measured I-V curves.



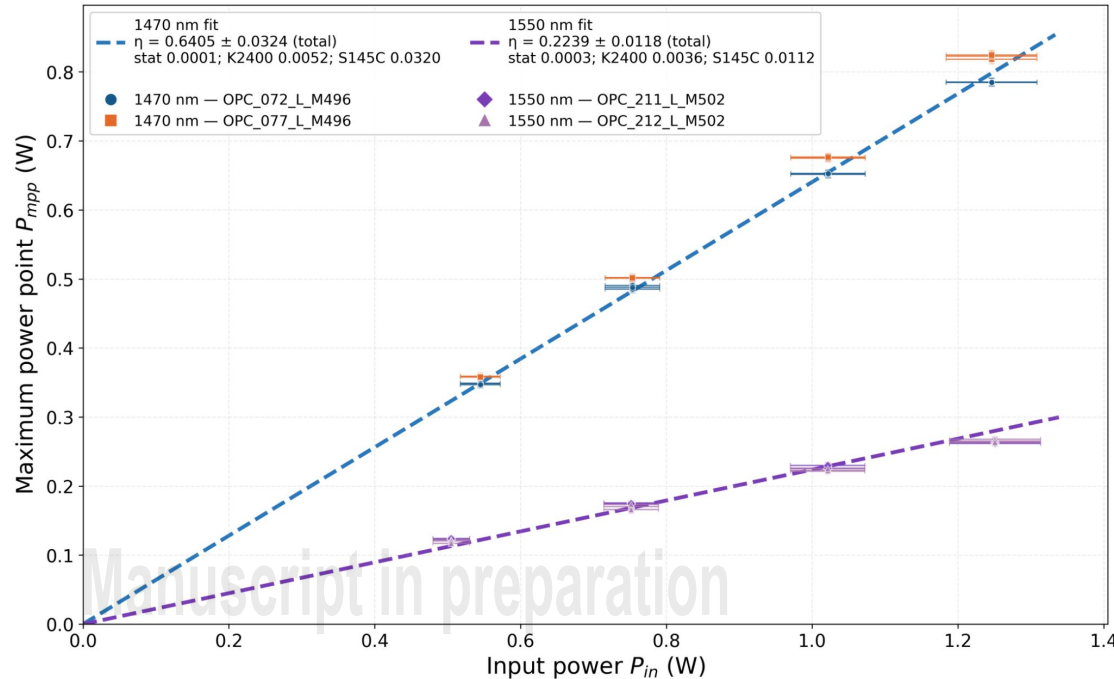
Optimum Load Resistance of InGaAs OPCs

- The optimum load resistance, (R_{mpp}), was obtained from the maximum power point of each I-V curve.
- For both wavelengths, the optimum load resistance decreases as the optical input power increases.
- Typical load at 20°C $\approx 50.8 \Omega \cdot W/P_{in}$



InGaAs OPC Characterization for 1470 nm & 1550 nm Lasers

- Optical-to-electrical power conversion efficiencies were obtained from linear fits of Maximum Power Point(P_{mpp}) versus optical input power.
- Measured efficiencies at cryogenic conditions:
 - 1470 nm: $(64.05 \pm 3.24)\%$; 1550 nm: $(22.39 \pm 1.18)\%$

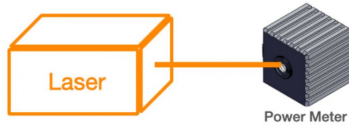


Optical Fiber Attenuation at Room and Cryogenic Temperatures

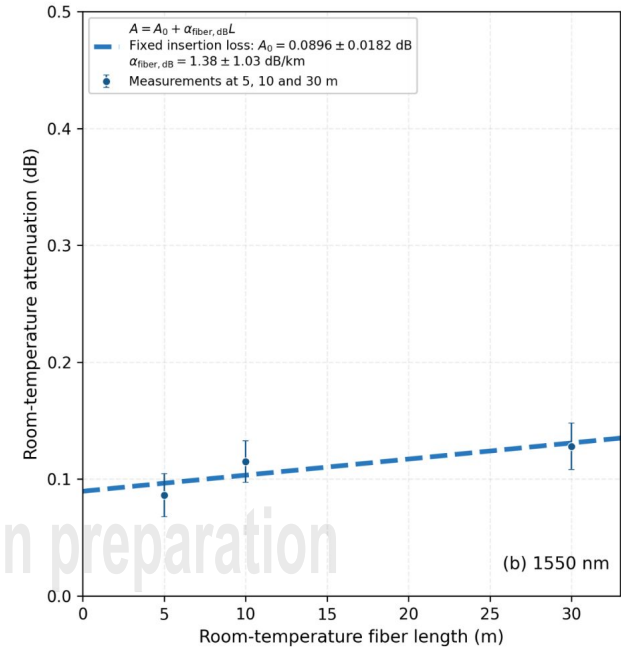
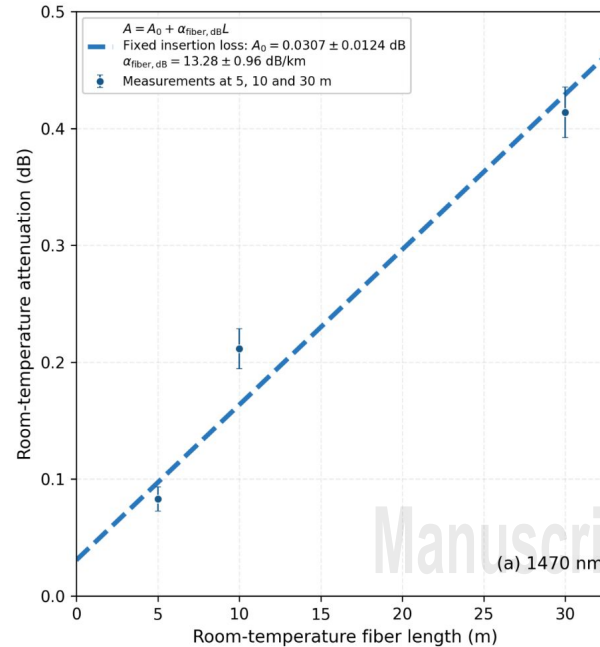
- Room-temperature optical losses were measured using 5, 10 and 30 m fibers with 1470 and 1550 nm lasers.

$$A_0 + \alpha_{\text{fiber,dB}} L$$

Laser reference power measurement



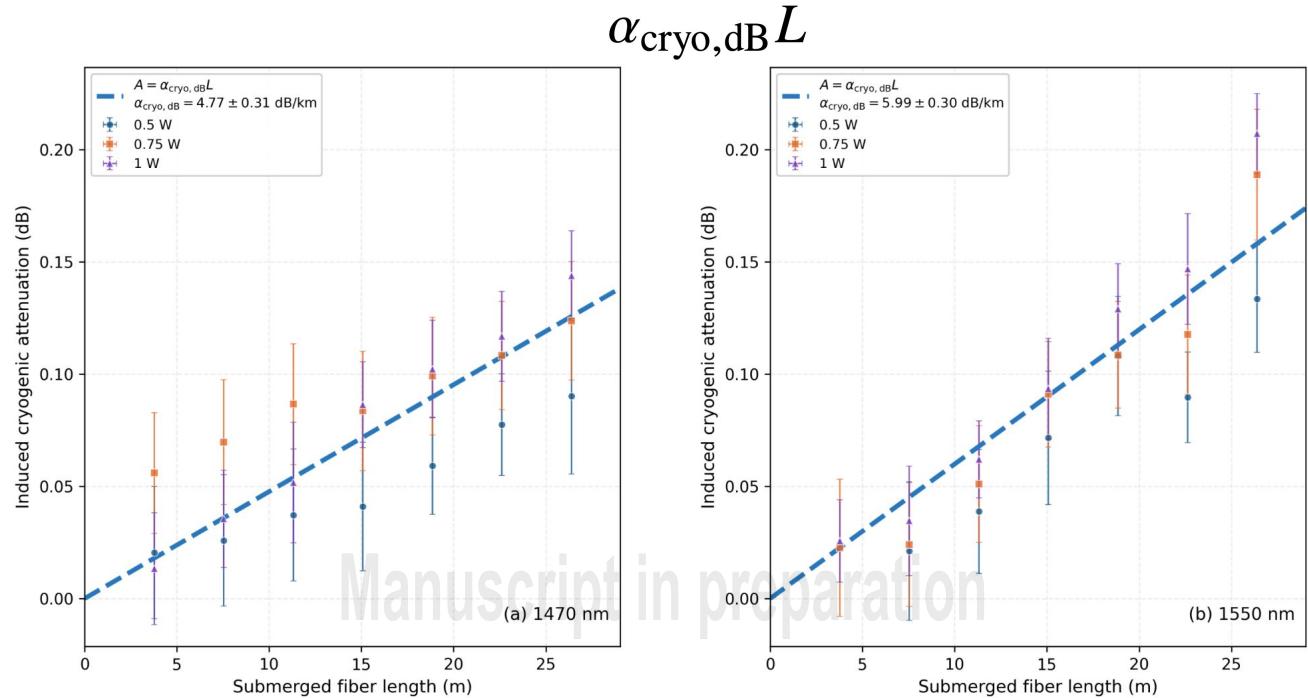
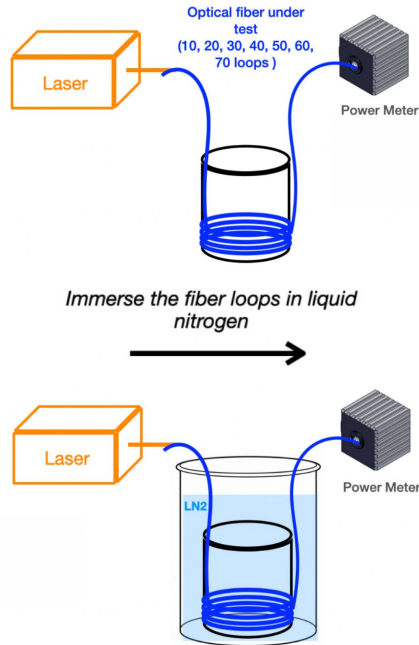
Fiber under test
connected
between the laser
transmitter and the
power meter



Parameter	1470 nm	1550 nm
A_0 [dB]	0.03 ± 0.01	0.09 ± 0.02
$\alpha_{\text{fiber,dB}}$ [dB/km]	13.28 ± 0.96	1.38 ± 1.03

Optical Fiber Attenuation at Room and Cryogenic Temperatures

- Cryogenic attenuation was evaluated using different lengths (from 3.7 m to 26.4 m) submerged in LN₂ with 1470 and 1550 nm lasers.



Parameter	1470 nm	1550 nm
$\alpha_{\text{cryo,dB}}$ [dB/km]	4.77 ± 0.31	5.99 ± 0.30

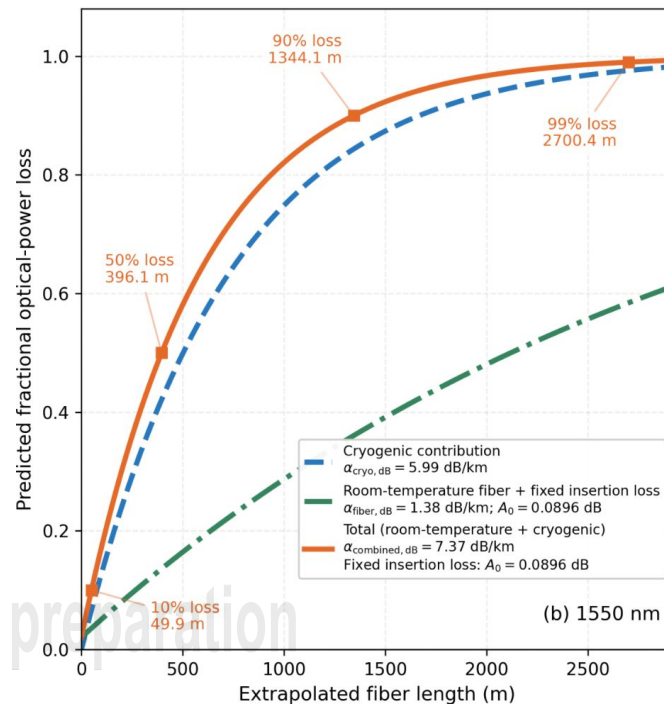
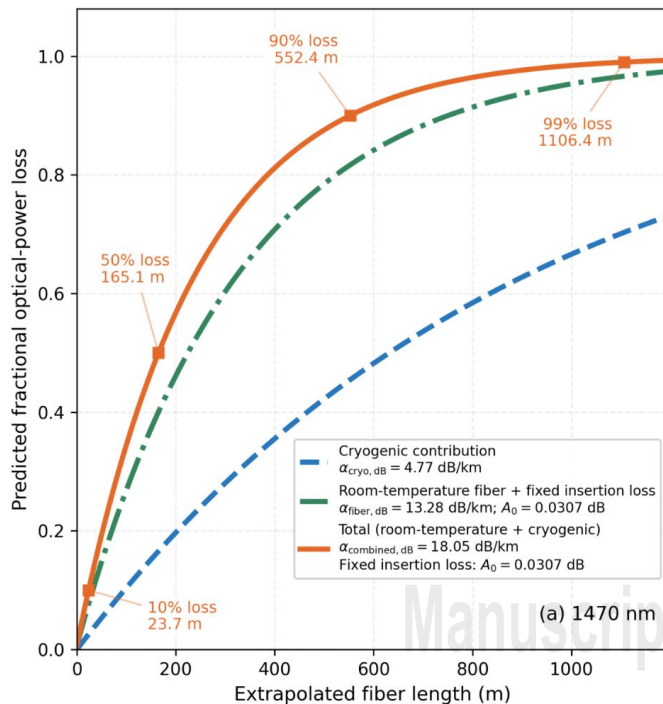
Projected Optical Power Losses over Longer Fiber Lengths

- The measured attenuation coefficients were used to estimate optical power losses over fiber lengths beyond the measured range.

$$A_{\text{total}}(L) = A_0 + (\alpha_{\text{fiber,dB}} + \alpha_{\text{cryo,dB}}) L$$



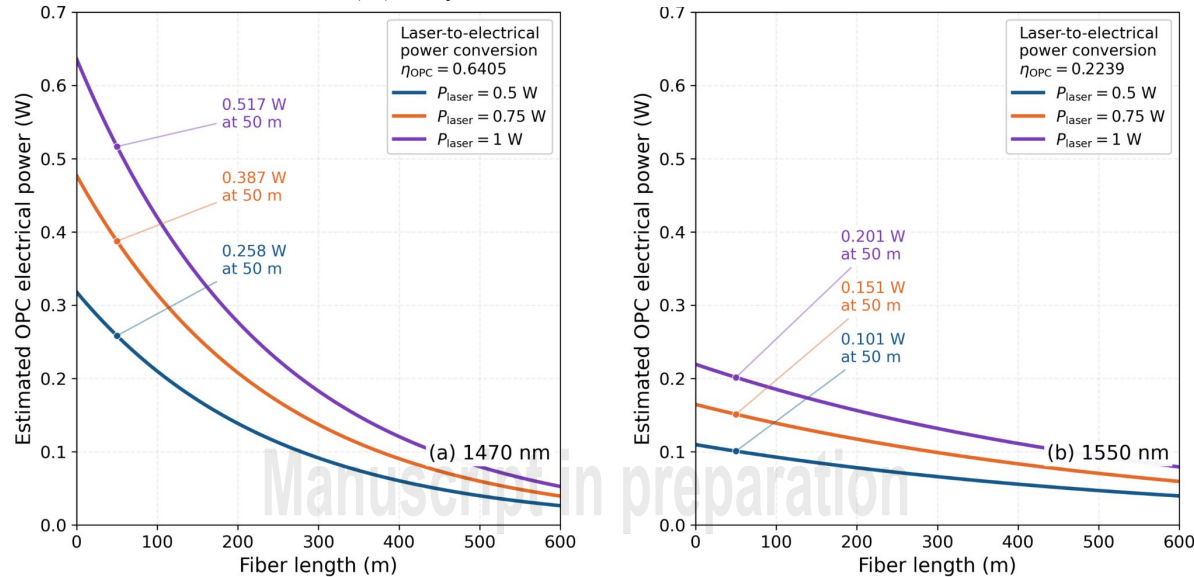
$$f_{\text{loss}}(L) = 1 - \frac{P_{\text{out}}(L)}{P_{\text{ref}}} = 1 - 10^{-A_{\text{total}}(L)/10}$$



Applications of Next Generation PoF System

- Projected electrical power delivery combines measured optical fiber attenuation with the cryogenic OPC optical-to-electrical power conversion efficiency.

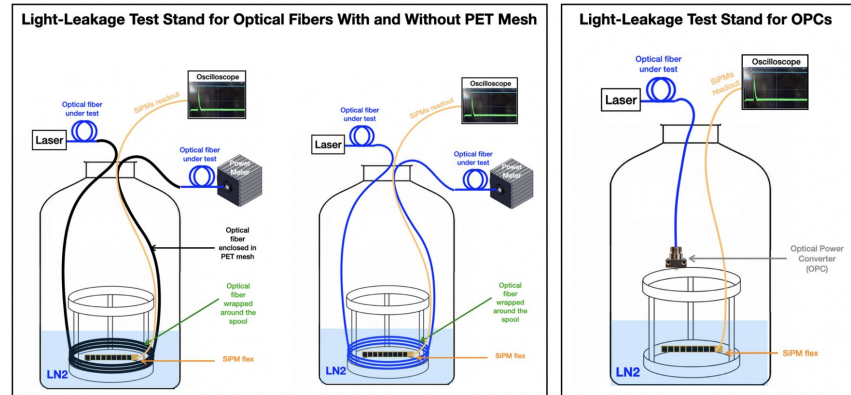
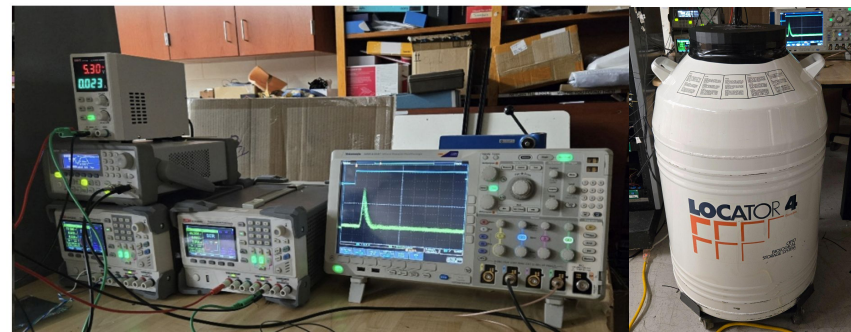
$$P_{\text{out}}(L) = \eta_{\text{OPC}} P_{\text{laser}} 10^{-[A_0 + (\alpha_{\text{fiber, dB}} + \alpha_{\text{cryo, dB}})L]/10}$$



- Results provide a foundation for the development of next-generation PoF systems capable of powering electronics and electrical systems operating in cryogenic conditions.
- Next-generation PoF could enable electrically isolated, low-noise power delivery for DELTA, with the proposed APEX photon detection system for DUNE Phase II as a potential first DELTA application.

SiPM Light-Leakage Measurement Setup

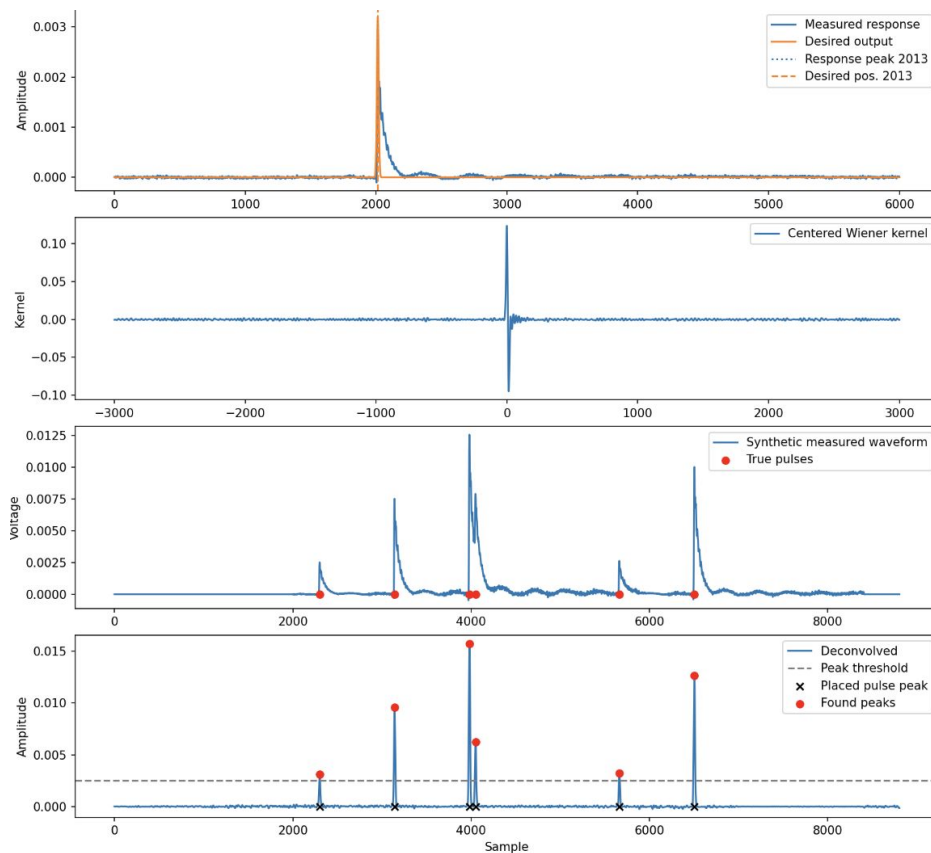
- A light-tight LN₂ dewar and a flex circuit containing 20 Broadcom SiPMs were used to measure the response to light escaping from PoF components.
- Two test configurations were evaluated:
 - Optical fibers wrapped around a spool, with and without protective PET mesh.
 - Exposed OPC connected to optical fibers.
- SiPM signals were amplified then recorded with an oscilloscope.
- Measurements at 1470 and 1550 nm were compared with an 808 nm reference to evaluate the reduction in SiPM response.



SiPM Signal Response for Light-Leakage Measurements

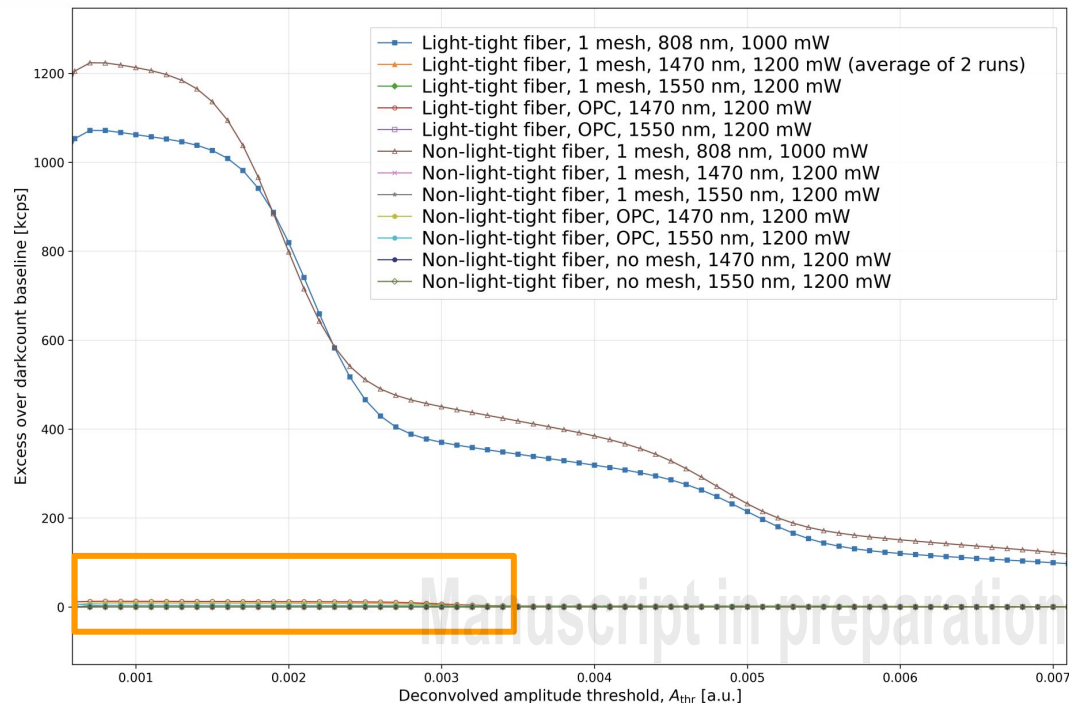
- A single-p.e. response template and a noise spectrum were obtained from dedicated measurements.
- Wiener deconvolution was applied to obtain narrower pulse (sharp gaussian) responses and improve the separation of overlapping signals.
- Peaks were identified over a wide range of deconvolved amplitude thresholds in both PoF and dark-count measurements.
- The excess SiPM count rate was determined by subtracting the dark-count-rate (DCR) reference from the PoF count rate.

$$R_{\text{excess}}(A_{\text{thr}}) = R_{\text{PoF}}(A_{\text{thr}}) - \bar{R}_{\text{DCR}}(A_{\text{thr}})$$



Light Leakage: 1470 nm and 1550 nm Comparisons

- A clear increase in the SiPM count rate above the DCR reference was observed during 808 nm PoF operation.
- The excess count rates measured at 1470 and 1550 nm were substantially lower across the tested amplitude thresholds (orange box).
- It was observe a reduction of about 2 orders of magnitude or more respecting the 808 nm tests.



Summary

- **Laser and driver prototypes:** Measured electrical-to-optical efficiencies of approximately 24% (1470 nm) and 28% (1550 nm)
 - The laser driver prototype operated during one hour with a current of 3 A and delivered up to 1 W of optical power with optical power fluctuations below 1%
- **Optical fibers:** Measurement of the attenuation of the optical fiber in both room and cryogenic temperatures resulted in the obtaining the following attenuation coefficients: 8.05 dB/km (1470 nm) and 7.37 dB/km (1550 nm)
- **InGaAs OPCs:** Cryogenic optical-to-electrical power conversion efficiencies of approximately 64% (1470 nm) and ~22% (1550 nm).
- **SiPM light leakage:** Excess count rates were reduced by approximately two orders of magnitude or more when using 1470 and 1550 nm relative to the 808 nm reference under the tested conditions.
- **Applications of next generation PoF system:** Promising results provide a foundation for the development of next-generation PoF systems capable of powering electronics and electrical systems operating in cryogenic conditions.
- **Future: Deployment of the next generation of PoF system presented in this work in DUNE phase II prototypes could be expected at CERN on DUNE prototypes before the end of this decade.**

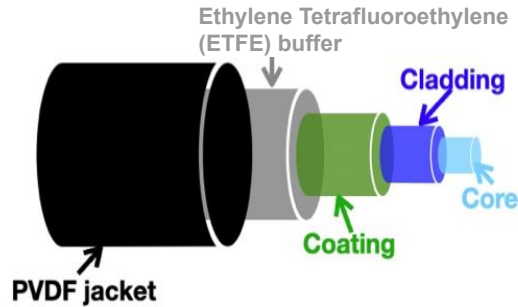
Paper describing the work in lasers, optical fibers, OPC, light leakage and applications of next generation PoF soon on ArXiv!

Backup

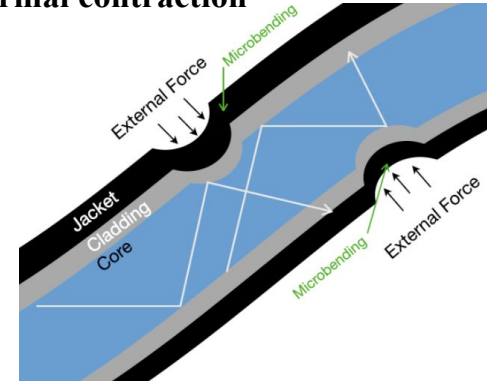
R&D on Optical Fibers: Power loss due to fiber bending in LN2

- Based on the optical fiber down selection for FD-VD, we have been testing different optical fibers to characterize power losses due to thermal contractions but using the 1470 and 1550 nm lasers.

DUNE FD-VD's fiber



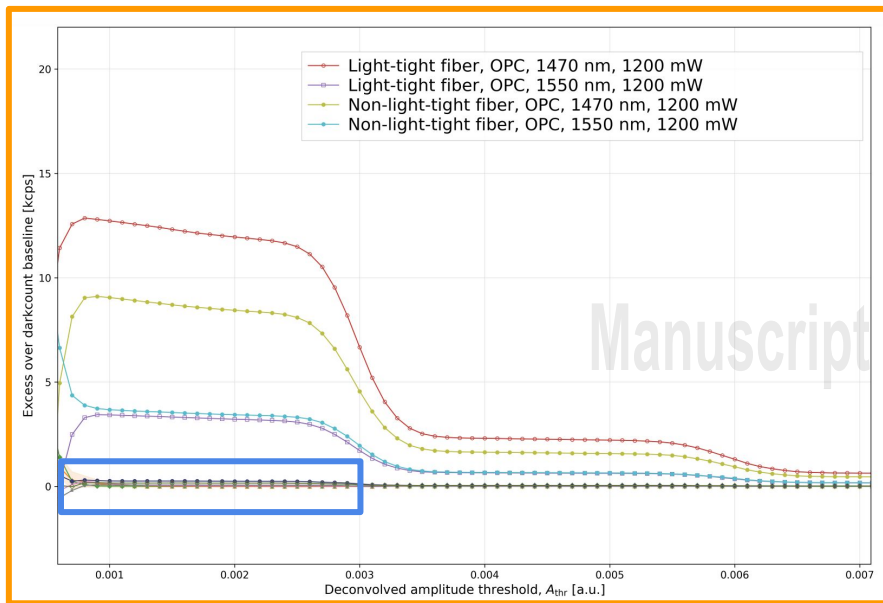
Thermal contraction



- At LN2 temperatures the jacket material induce thermal contraction along the fiber, leading to microbending, which causes power loss.

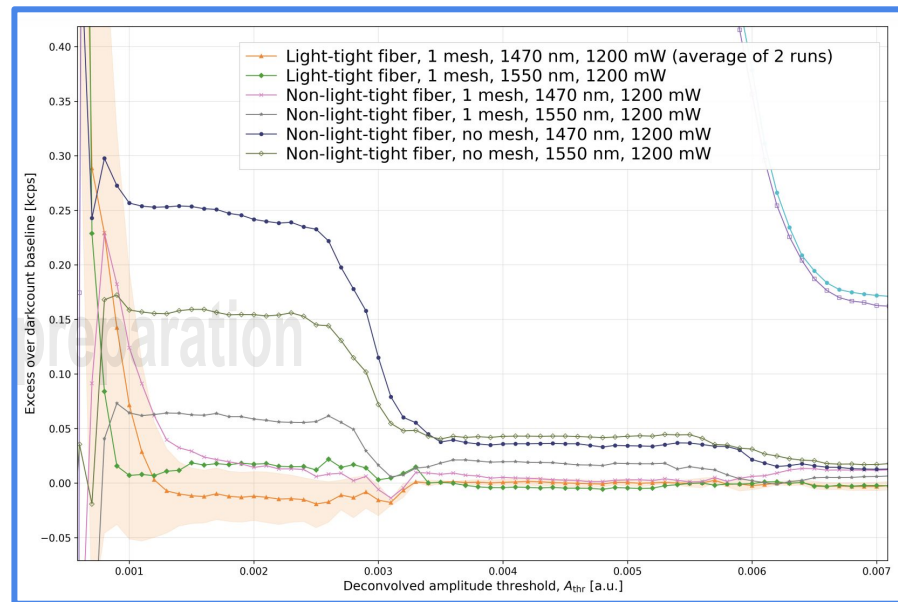
Light Leakage: 1470 nm and 1550 nm lasers

- A reference of expected optical flashes on the PDS due to radiological model (DUNE TDR): 800 counts for 4 ms windows.
- Noticeable improvement regarding leakage from OPC and fibers when compared with our 808 nm laser test (about 2 orders of magnitude or more).



Tests OPC: ~15 - 60 counts / 4 ms

Jairo Rodriguez | CPAD 2026



Tests fiber with(wo) mesh: ~0.2(~1) counts / 4 ms