# CRYO-PoF: Cryogenic Power-over-Fiber for fundamental and applied physics

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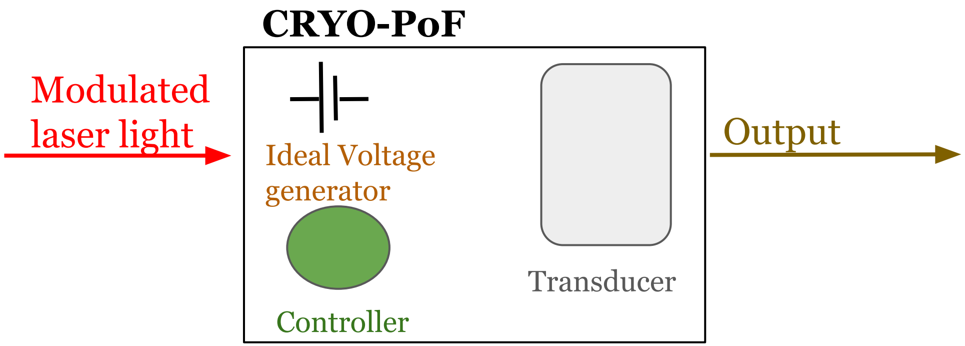
# Project overview

- CRYO-PoF is aimed at designing and validating the first cryogenic system solely based on optoelectronic devices to power analog and digital electronics.




It is based on a core concept: a cryogenic Power over Fiber system must suit all applications where the environmental conditions are prohibitive for a copper-based power line.

- This solution is inspired by the needs of the DUNE Vertical Drift detector, where Photon Detection System must have ideal galvanic isolation to the source. **The idea I proposed in the Project has a much broader suite of applications, both for science and industry.**

# Power over fiber

- The miniaturization of semiconductor-based lasers and the extreme data transfer rate that can be achieved by transforming an electrical signal into a light pulse.
- Power over Fiber (PoF) is a novel power delivery technology that delivers electrical power by sending laser light through lightweight, non-conductive fiber optic cable to a remote photovoltaic receiver or photovoltaic power converter (PPC) to power remote sensors or electrical devices.
- This innovative solution provides noise immunity, voltage isolation, and spark-free operation.
- Several producers of PoF systems are available on the market and this technology has been already ported at the industrial level.
- No attempt has been done to port the technique at the cryogenic level even if the applications would be very rewarding. The reason is that optoelectronic components and standard electronic components are certified down to 233 K (-40° C) and full development of cryogenic electronics cannot be afforded by potential users.

# CRYO-PoF: a breakthrough in fundamental and applied physics

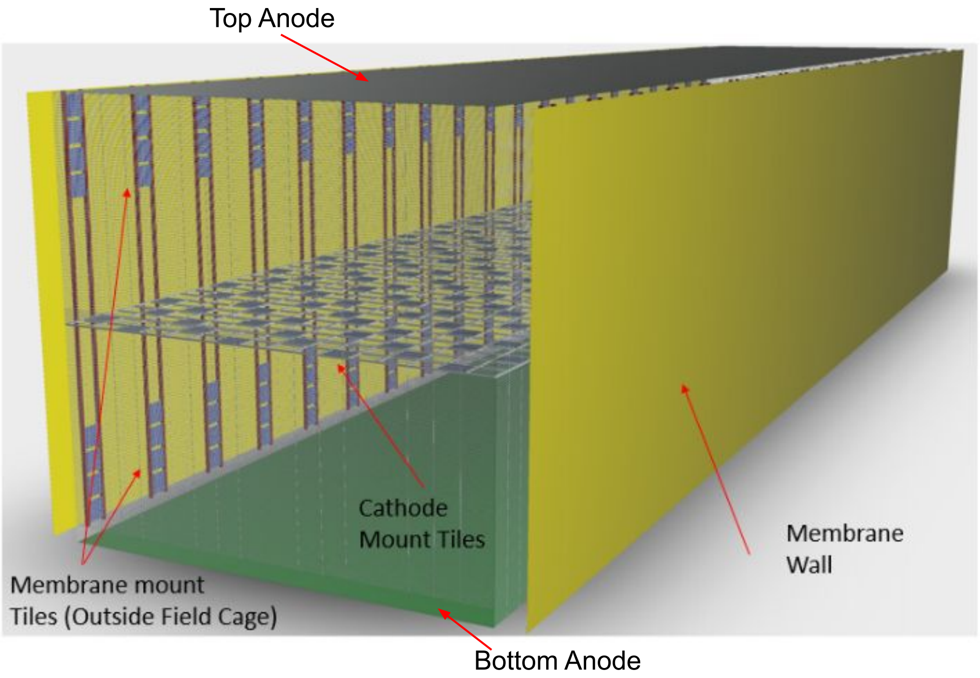
The innovative technology developed in this proposal can benefit a broad class of applications: all systems that rely on remote powering of electronics circuits operating in harsh environments, and, particularly, systems operating below the minimum temperature for certified electronics (233 K).

- all liquified noble gas experiments searching for dark matter and rare events;
- liquid argon neutrino experiments: DUNE;
- solid-state research and quantum computing (e.g. with dilution refrigerator);
- ultra low noise signal transmission.

**CRYO-PoF is a Comm. 5 project that will benefit many science fields of relevance for INFN and foster industrial applications.**

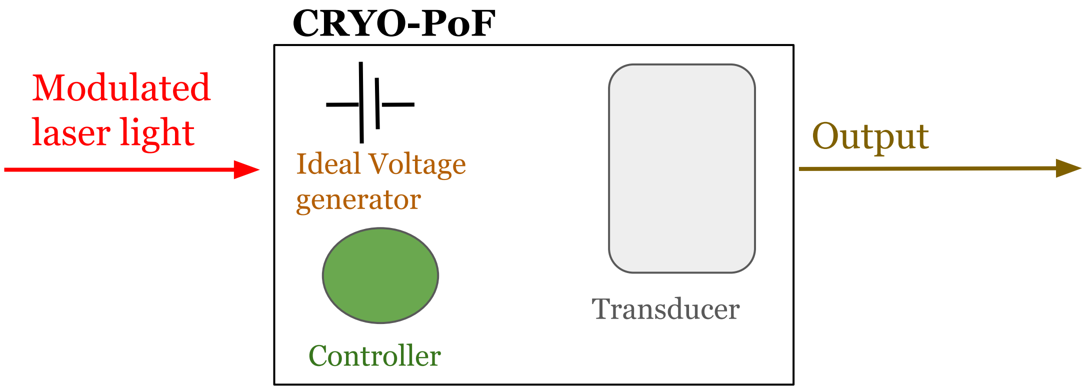
# vertical drift

- DUNE Vertical Drift (VD) module: LAr TPC in which electrons drift toward the anodes placed on top and bottom of the detector. Anode planes will be made by PCBs, so light opaque.
- The grid **cathode** is at half height and **operated at 320 kV**.
- Photon Detection System (PDS) can be placed or on the cathode or outside the field cage with much lower photon collection efficiency.




- **Thanks to CYO-PoF, we can install the PDS in the cathode, even if the ground is at 320 kV.**

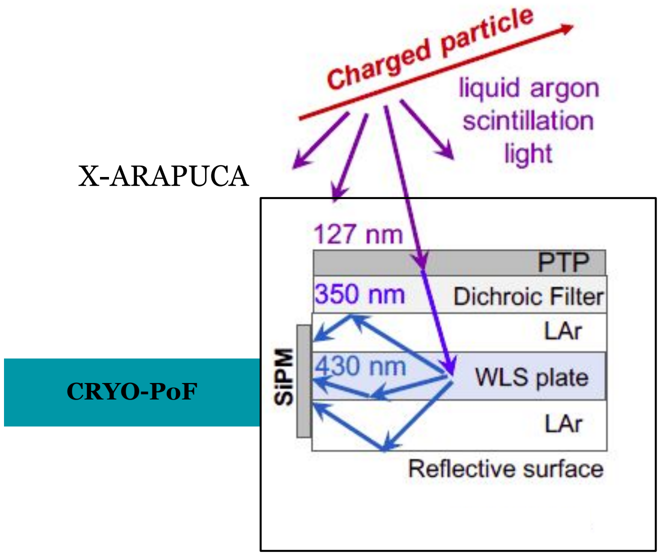
# The cryo-PoF module and an example of application




Controller and transducer have to suit the various applications.

DUNE: CRYO-PoF

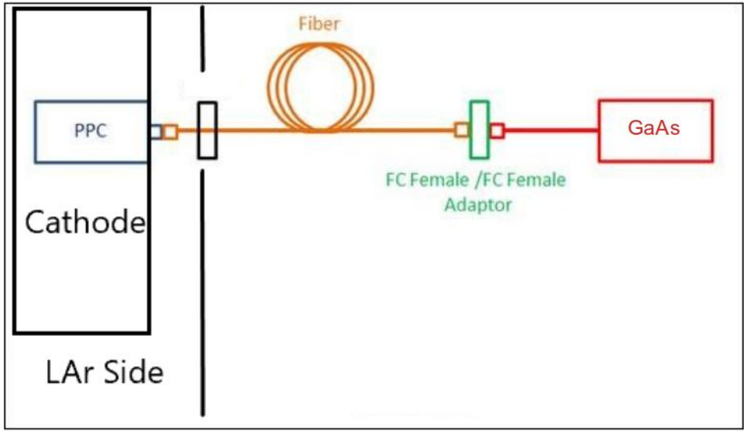
- Controller → SiPM bias
- Transducer → SiPM
- Output → SiPM signal



# Basic unit

<u>DUNE</u>:

- power from silicon diode lasers (commercial products);
- control of electronics (setting, slow control etc.) through a dedicated line.




<u>CRYO-PoF</u>:

- The key component of CRYO-PoF is the exploitation of gallium arsenide (GaAs) laser: power efficiency (GaAs), longer wavelength (InGaAs), reduction of background photons;
- the control of the electronic is done by amplitude modulation of the laser source.

SiPM bias

Cryogenic Control Board (CCB)

Laser light

# SiPM bias

- The SiPMs require a DC bias ranging from 25 V (87 K) to 45 V (300 K) with a stability of 1%.
- Voltage multiplication and trimming are performed by a CCB inherited by the DAPHNE board of DUNE and sourced by the PoF.
- Unlike conventional solutions, CRYO-PoF does not need a dedicated control line but the bias level for the SiPMs is directly driven by the tunable power of the GaAs laser: an amplitude modulation of the current will pilot the board to deliver the voltage in the range suited for the SiPMs and perform fine-tuning during data taking.
- Amplitude modulation, thus replace completely a dedicated digital transmission and control line.

# Cryogenic Control Board

- The cold amplifier is powered by the CCB at a fixed voltage and is based on a SiGe transistor downstream of a transimpedance amplifier. While the cryo-reliability of these components has been assessed, modification of the gain and bandwidth must be compliant with the whole system.

- The CCB will be developed by the electronic engineers (E. Cristaldo and M. Lazzaroni) of CRYO-PoF and employ discrete components. It is distributed in a 5x5 $cm^2$ surface and connected with the heat dissipation system of the VD tile. We aim at designing the CCB to reach a safe limit in the local heat dissipation, well below the bubbling limit of the liquid argon.

# Laser light

- The main drawback of GaAs lasers is the operating wavelength. An AlGaAs system for telecommunication generally operates at 980 nm for optical amplifiers. AlGaAs at 1064 nm is a classical choice for optical communication and InGaAs reaches a longer wavelength (1310 nm), again for fiber optics communications.

- All these wavelengths are outside the nominal sensitivity of the NUV-HD-CRYO FBK photosensors, which is negligible above 550 nm. However, there are no direct measurements in the deep infrared and even a $10^{-4}$ photon detection efficiency (PDE) can jeopardize the operation of the PDS.

- CRYO-PoF will therefore deliver a screening system that decouples the optical power lines at $10^{-5}$ limit and test them in liquid argon.

- If conventional AlGaAs lasers turn out to be mandatory for power efficiency and cryo-reliability, CRYO-PoF will provide the corresponding PDS design to eliminate any light leakage originating from the PoF.

# CRYO-PoF team

6 Post-Docs

2 PhD students

3 Seniors

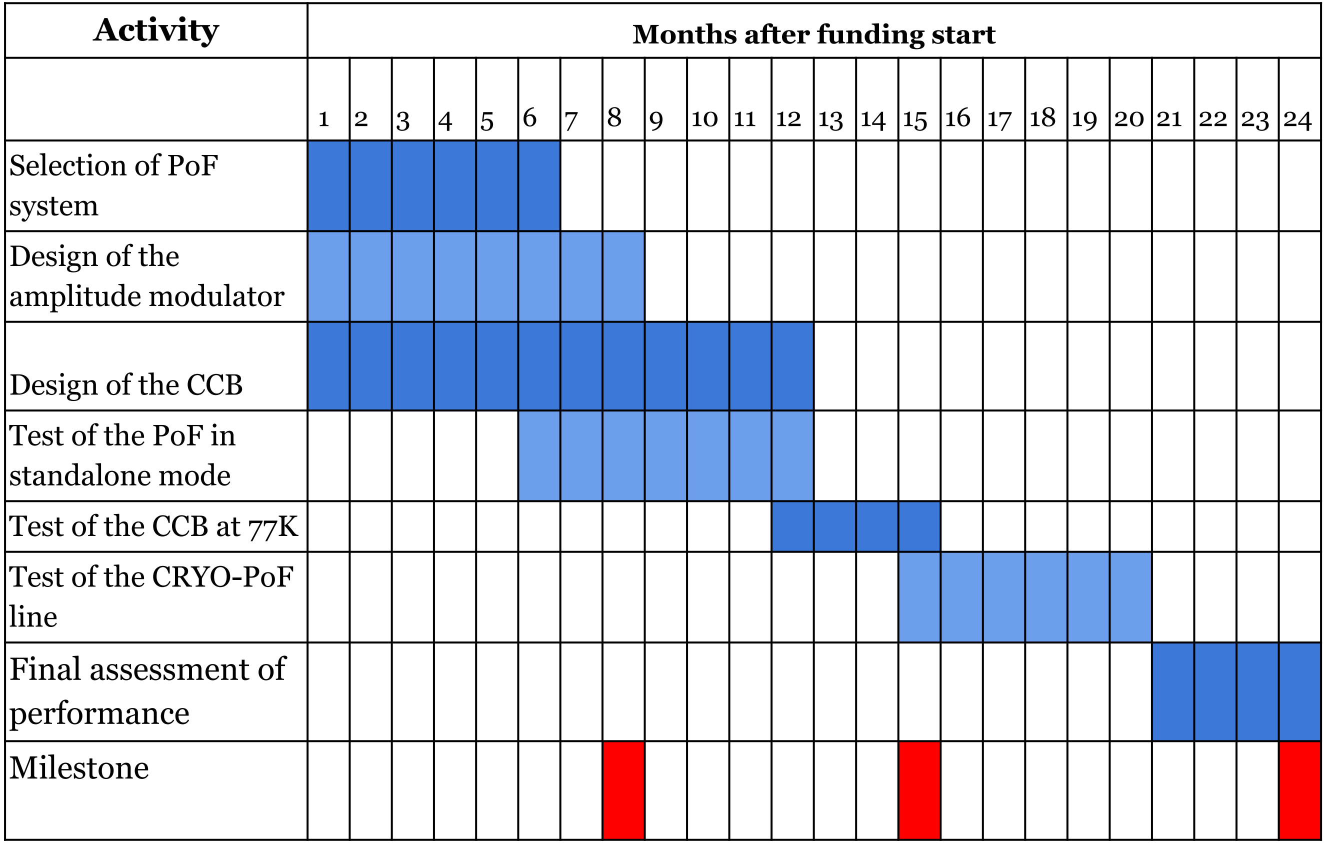
| *Name* | *FTE* |
| --- | --- |
| **MiB** | |
| Marta Torti | 0.8 |
| Claudia Brizzolari | 0.1 |
| Esteban J. Cristaldo Morales | 0.4 |
| Maritza J. Delgado Gonzales | 0.3 |
| Andrea Falcone | 0.1 |
| Maura Spanu | 0.2 |
| Francesco Terranova | 0.1 |
| **Mi** | |
| Massimo Lazzaroni | 0.1 |
| Niccolò Gallice | 0.1 |
| **Fermilab** | |
| Flavio Cavanna | 0.2 |
| Dante Totani | 0.2 |

# CRYO-PoF facilities

Four facilities are available:

- INFN-MiB electronic laboratory (resp. G. Pessina)
- INFN-MiB DUNE/GERDA laboratory (resp. C. Cattadori)
- Liquid argon laboratory at CERN (resp. F. Pietropaolo)
- DUNE production center (UniMib Bld U19, resp. F. Terranova): available in 2023.

# CRYo-PoF timeline



**Funding start**

6

*Selection of PoF system (MiB, Fermilab)*

Selection of commercial PoF systems from industrial partners, starting from the baseline system from MH-Gopower based on InGaAs and considering the AlGaAs options.

- Check operation and stability at 77 K  of InGaAs.
- Identification of commercial modules that can operated with AlGaAs .
- Tests of these commercial modules with the optocoupler at low temperature.
- Final selection.

**Funding start**


*Design of the amplitude modulator (Mi, Fermilab)*

- Procurement of the amplitude modulator.
- Selection of the optolink receiver for the amplitude demodulation.

**Funding start**


*Design of the CCB (Mi, MiB)*

Design of the cryogenic control board using discrete components and test of components not validated yet at 77 K.

- Design of the CCB input source line at 12 V, the CCB output source line for the cryogenic amplifier, and the SiPM bias.
- Design and test of the trimmer of the bias driven by the amplitude modulated system.
- Implementation using pre-selected components from the DUNE database and test of cryo-reliability of new components (if needed).

**Funding start**


*Test of the PoF in standalone mode (MiB, Mi, Fermilab)*

Test of the Power-over-Fiber in standalone mode and light leakage reaching the SiPMs (at this stage SiPMs are biased with standard copper lines).

- Stability of current output at the input of the CCB.
- Tests of signal fidelity in amplitude modulation.
- Readout of the SiPMs in the final chassis for light tightness tests .
- Test of PDE at the operating wavelength of the laser (if needed).
- Measurement of the PoF power efficiency.

**Funding start**


*Test of the CCB at 77K (Mi, MiB)*

Test of the CCB at 77 K with amplitude-modulated signals. Optimization of the modulation bandwidth for setting and trimming of the SiPM bias. Test of the CCB copper power line to SiPMs and the cryogenic amplifier.

- Test of the stability of the SiPM bias and fine-tuning of the passive filter (if needed).
- Test of stability of the power lines for the cold amplifier.
- Measurement of the CCB power consumption.
- Test of the voltage trimming: decoding of the modulated signal, tests of the response of the SiPMs.

**Funding start**


*Test of the CRYO-PoF line (MiB, Mi, Fermilab)*

Test with the ground of CRYO-PoF at HV with the trimmer for bias tuning. Check of power dissipation and liquid argon stability (microbubbling).

- Test of the system stability and the full chain of the SiPM voltage regulator.
- A complete estimate of power consumption.
- Test with the ground at HV using the DUNE test setup at CERN.
- Optical inspection of microbubbling using the DUNE test setup at CERN.

**Funding start**


*Final assessment of performance (MiB, Mi, Fermilab)*

Contingency and analog output analysis in term of stability, linearity, and PoF induced dark count rate.

- SiPM analysis of single photoelectron response, dynamic range, signal-to-noise at single photoelectron.

- SiPM dark count rate as a function of the injected light power.

- Diagnostics of the PoF optocoupler and the voltage splitters and regulators.

**Funding start**


*Milestones*

Three main publications regarding:

- choice of the laser technology;
- design and performances of the CCB;
- validation of the full system.

# CRYO-PoF budget request

The cost drivers are the procurement of the power laser, the modification of the cryogenic setup available at MiB.

| ***Item*** | ***Description*** | ***Cost (€)*** |
|---|---|---|
| Equipment Project | hardware component | 73'770 |
| Consumption | Cryogenic liquids | 6'000 |
| Travel expenses | Travels | 27'500 |
| Total | | 107'270 |

| ***Year*** | ***Cost (€)*** |
|---|---|
| First | 60'770 |
| Second | 46'500 |

# CRYO-PoF risk factors

| Risk | Likelihood | Mitigation |
|---|---|---|
| SiPM | Low | Use of commercial SiPMs already tested at 77 K (e.g. HPK S14160 in HWB technology) |
| GaAs procurement | Low | Alternative vendors identified |
| InGaAs and InGaAsP procurement | Medium | Alternative vendors identified |
| Malfunctioning of non-GaAs receiver | High | Use of GaAs receiver |
| Overconsumption of the CCB | Medium | Increase by one unit the PoF receivers |
| Malfunctioning of the amplitude modulation | Low | Use of a dedicated optical line to pilot the CCB |
| HV discharge | Low | Modification of the chassis |
| Delay in the design and commissioning of CCB | Medium | Test the system where the trimming and bias is performed in traditional mode while waiting for the completion of the CCB |
| Oversensitivity of the selected SiPM to PoF light leakage | Medium | Improve the shielding design |
| Delays in the delivery of the customized receiver once the laser is chosen | Medium | Use of GaAs receiver or delay the final test (marginal extra-cost) |
| Excess of power dissipation by the PoF unit | Low (except for non-GeAs where is Medium) | Increase by one unit the PoF receivers and improve the heat dissipation system increasing the surface of the Housing Unit |

# The CRYO-PoF deliverables and goals

- The selection of a commercial PoF system that can be operated at 87 K.

- The design of the light transmission system and the study of possible interference with the detection of the scintillator photons in liquid argon.

- The replacement of the component that jeopardizes cryo-reliability, uniformity and stability.

- A full test at 0V where power conversion efficiency, stability, power delivery to the cold amplifier, and power dissipation will be validated.

- A test at high voltage, which includes standard and emergency operation modes (HV discharge in VD, leaks in the light transmission line or converter).

# Conclusions

- CRYO-PoF will demonstrate that electronics of detectors will be fully optical alimented at cryogenic temperatures.

- The CRYO-PoF system is the only system that can pilot the VD DUNE PDS without dedicated communication lines, which reduces complexity and the need for a digital optolink.

- Innovation in CRYO-PoF, thus, resides not only in the core idea: the use of a cryogenic Power-over-Fiber system to operate a VUV photon detector at low temperature. It also addresses very specific challenges: power conversion efficiency, heat dissipation, control of active electronic components through the CCB, and light leakage.

- CRYO-PoF is a Comm.5 project that will benefit many science fields and industrial applications.

Thanks!