Cryogenic Power over Fiber for fundamental and applied physics

Marta Torti

Consiglio di Sezione Milano Bicocca – 9 Luglio 2024

Overview

- **Cryo-PoF:** Cryogenic Power over Fiber
- Call “Grant giovani CSN5 2021”
- From 01 February 2022 to 31 January 2024
- PI: Marta Torti (MiB)
- INFN sections involved: MiB and Mi
- **Cryo-PoF’s main goal** is to power, at cryogenic temperature, both SiPM and cold amplifier, using a single Power over Fiber line and to tune SiPM bias with the laser power.
- This project arose from the **DUNE Vertical Drift** module, where the Photon Detection System has to be placed on the high voltage cathode surface.
- This technology can be used not only in DUNE, but for a wide range of application.

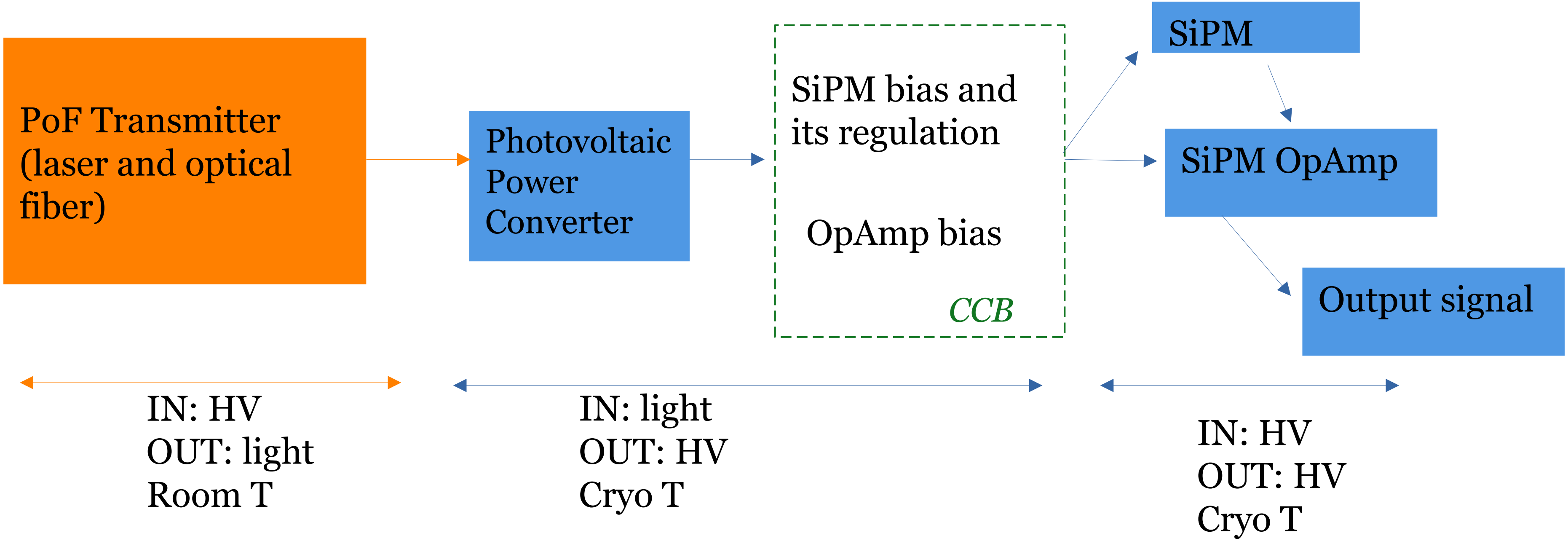
Power overe Fiber technology

- The **Power over Fiber** (PoF) technology delivers electrical power by sending laser light, through an optical fiber, to a photovoltaic power converter, in order to power sensors or electrical devices.
- Several producers of PoF systems are available on the market and this technology has been already employed in industry.

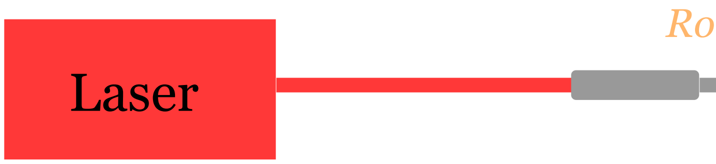
- PoF solution offers several **advantages**:
  - removal of noise induced by standard power lines,
  - robustness in a hostile environment,
  - spark free operation when electric fields are present,
  - no interference with electromagnetic fields.

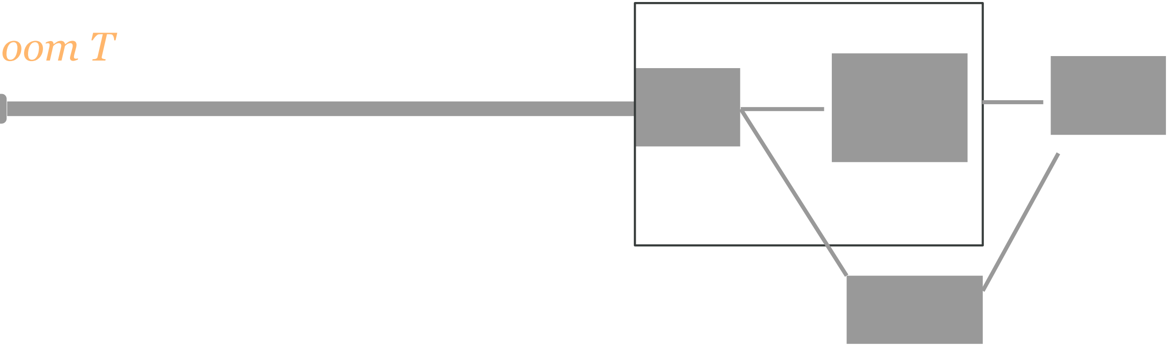
- Ideal solution where the environmental conditions are prohibitive for a copper-based power line.
- R&D for the application of PoF for the DUNE Vertical Drift (VD) detector was initiated at Fermilab for DUNE.

Project overview



Laser source

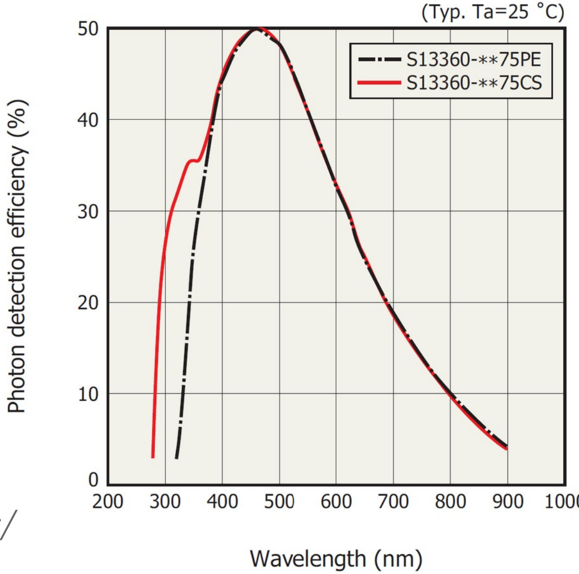




- **GaAs laser source**: 808 nm

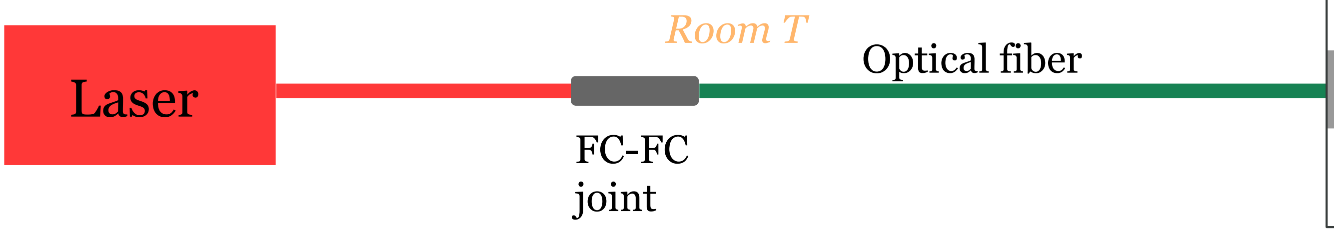
Why?

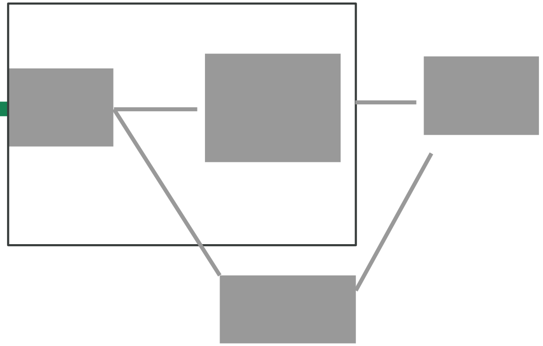
SiPMs photon detection efficiency has a peak around 500 nm
→ laser light should better be far from it!



https://www.hamamatsu.com/content/dam/hamamatsu-photonics/sites/documents/99_SALES_LIBRARY/ssd/s13360_series_kapd1052e.pdf

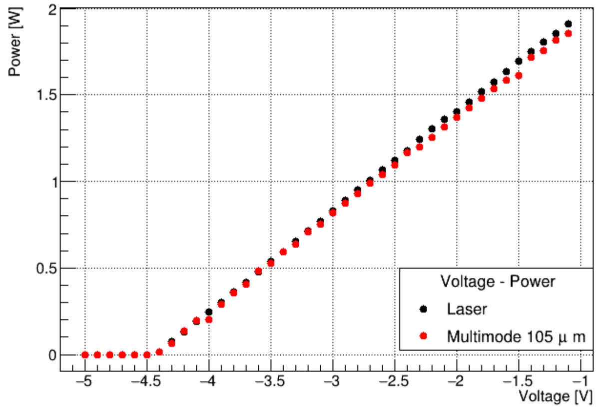
Laser source





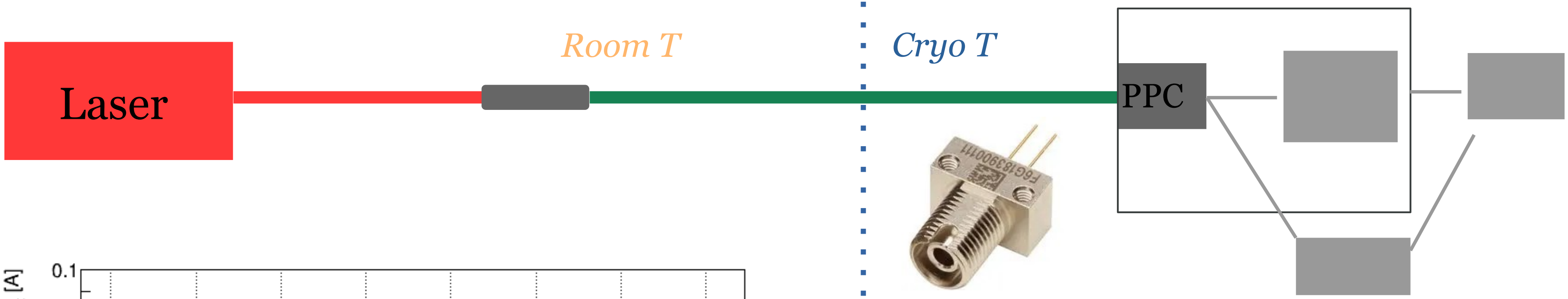
- **GaAs laser source,** 808 nm directly connected to a multimode optical fiber (62.5 µm core diameter) from Broadcom company.
- Characterization of the laser source in terms of:
  - linearity: output P tuned by input V V_{in} = [-5,0] V → P_{out} = [0,2] W
  - power loss connecting an **optical fiber**,
  - stability over time: max -min = 0.96 %.

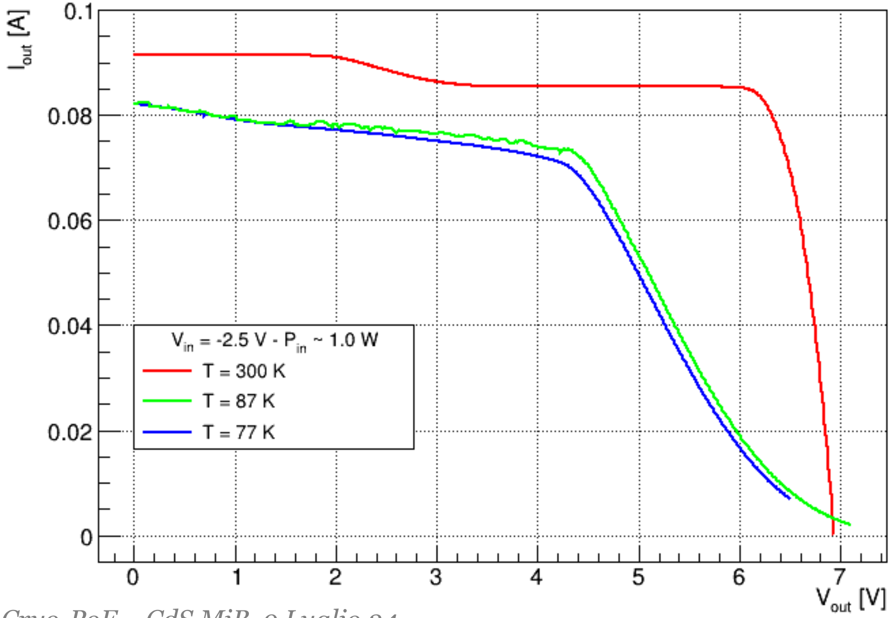
Multi mode optical fiber (core diameter 105 µm) with with black reinforced 3.8 mm tube.



~ 3.0 % power loss adding a FC/FC joint and an optical fiber.

Photovoltaic Power Converter





- **Photovoltaic power converter** is a commercial product from Broadcom company;
- IV curvers using a semiconductor analyser;
- Tested at different P_{in} .
- V_{max} at cryo T = ~ 6 V.

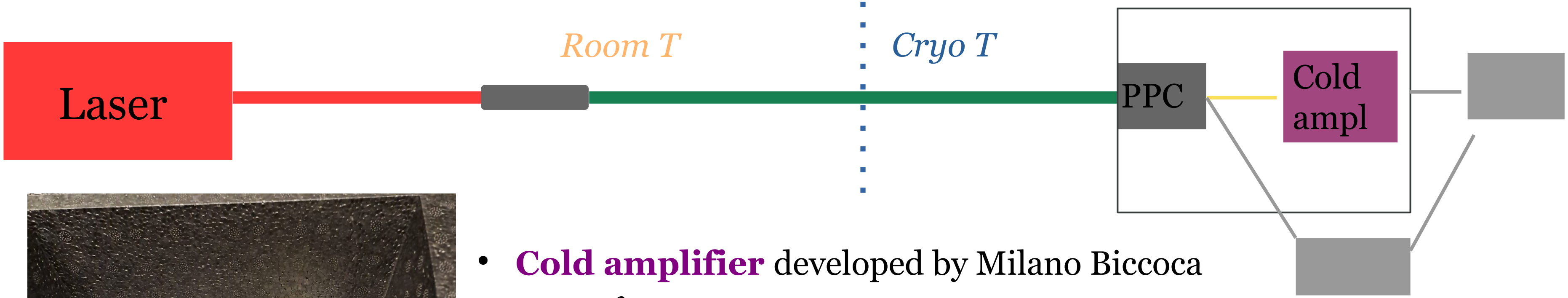
P_{in} ~ 1 W

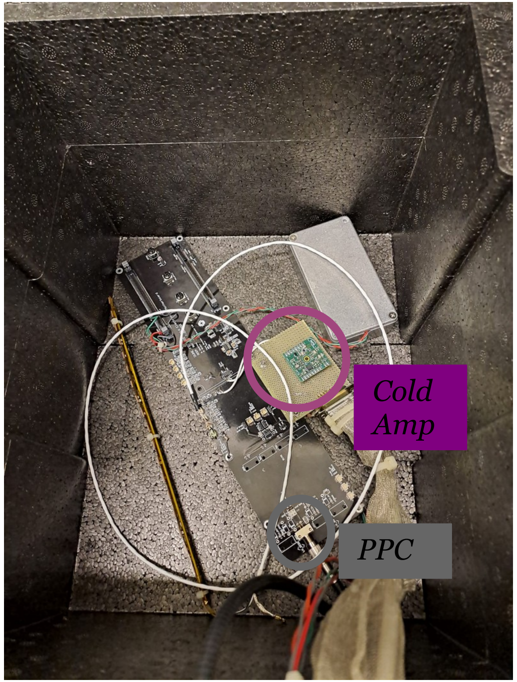
T = 300 K : P_{max} = 0.52 W , I_{max} = 91.4 mA

T = 87 K : P_{max} = 0.32 W , I_{max} = 82.5 mA

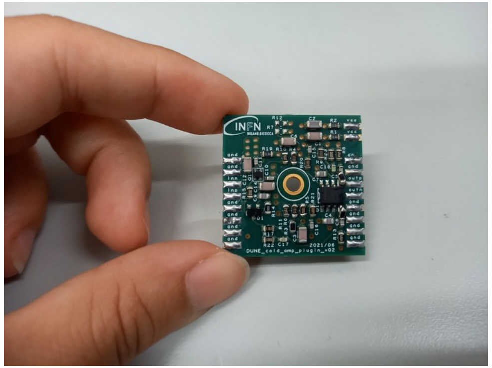
T = 77 K : P_{max} = 0.30 W , I_{max} = 82.2 mA

From laser to SiPM



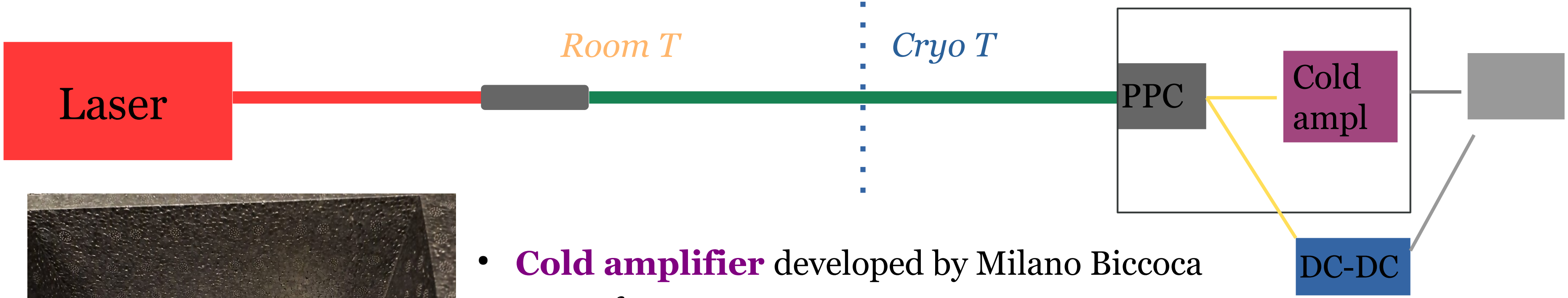


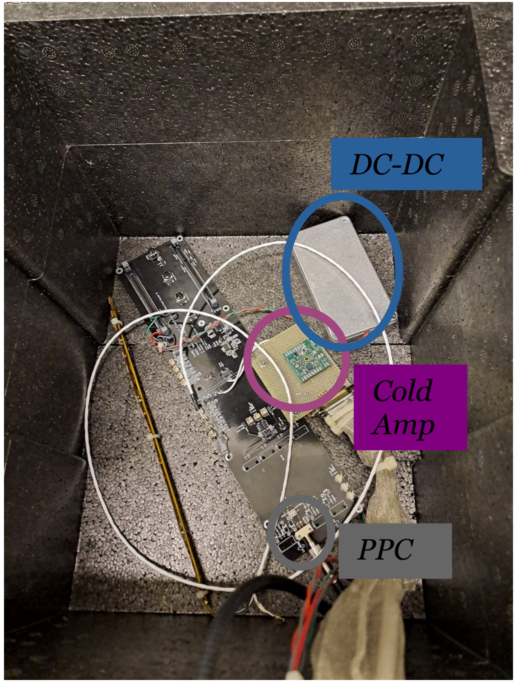
- **Cold amplifier** developed by Milano Biccoca group for DUNE $\rightarrow V_{in} = 3.3$ V



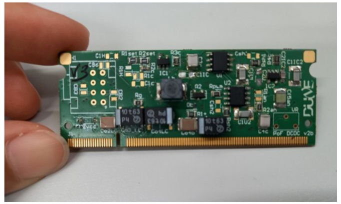
JINST (2020) 15 P01008

From laser to SiPM



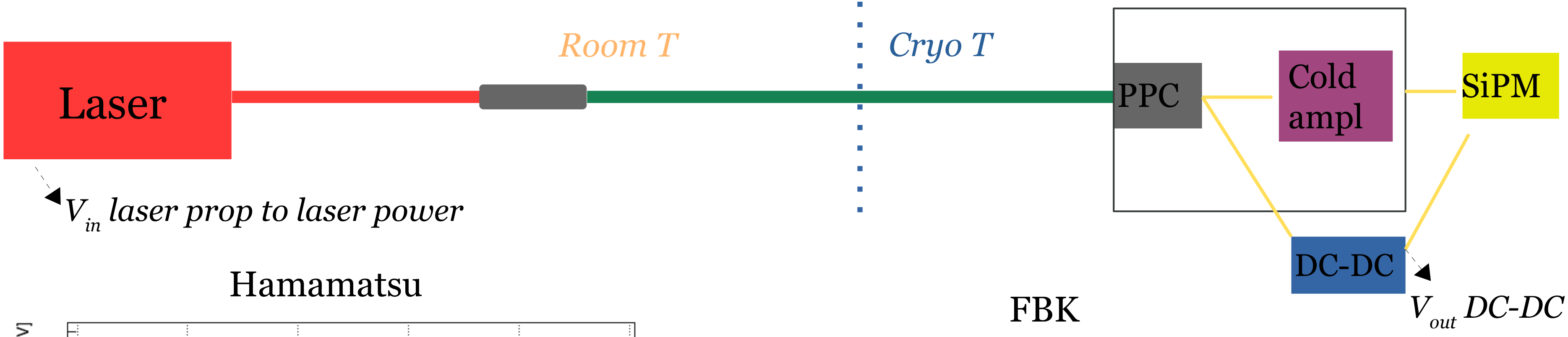


- **Cold amplifier** developed by Milano Biccoca group for DUNE → V_{in} = 3.3 V
- **DC-DC** boost converter developed by INFN Milano Statale group, → give bias to SiPMs;
  → V_{in} ~ 5 V; V_{out} ~ [40, 50] V for Hamamatsu SiPM
  → V_{in} ~ 5 V; V_{out} ~ [25, 35] V for FBK SiPM
  → placed in a metallic box to reduce noise.

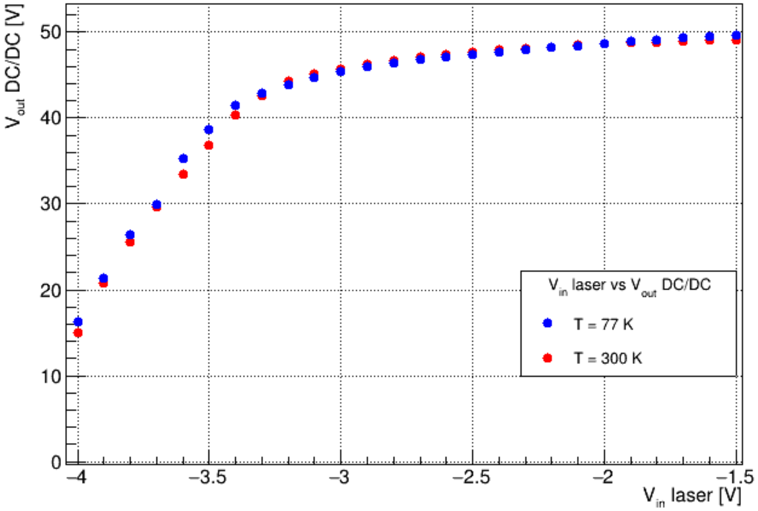


N. Gallice et al., 2022 IEEE I2MTC.

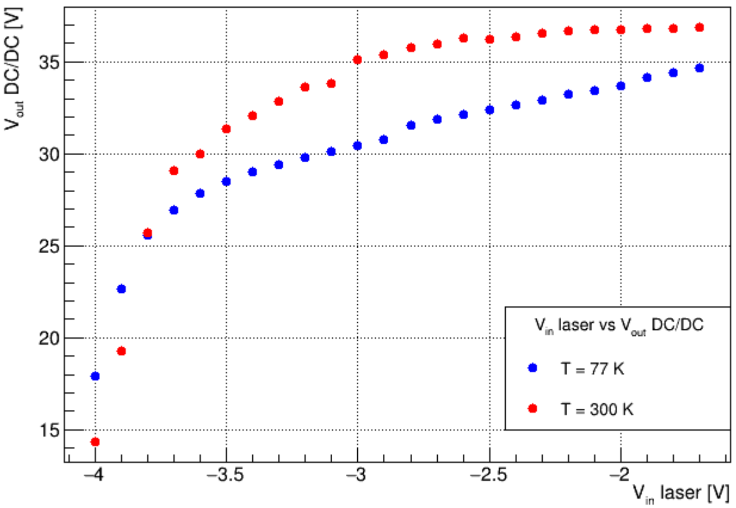
DC-DC boost converter



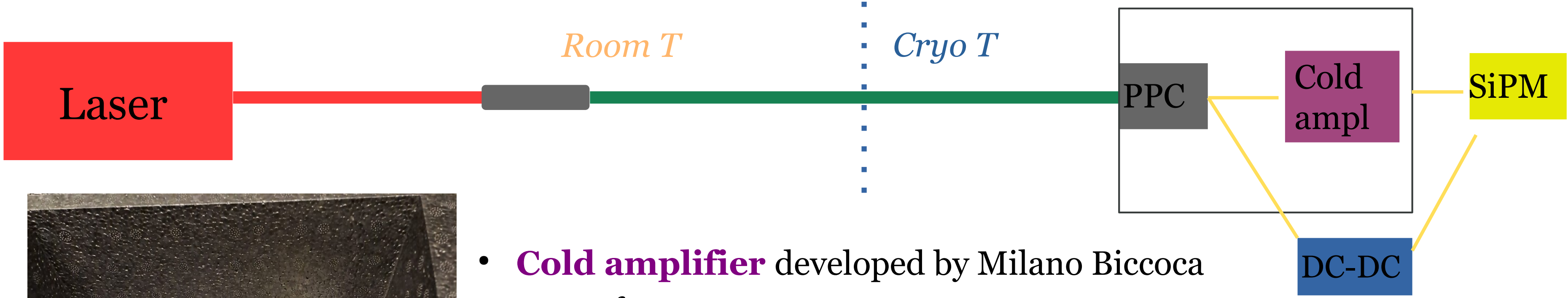
Hamamatsu

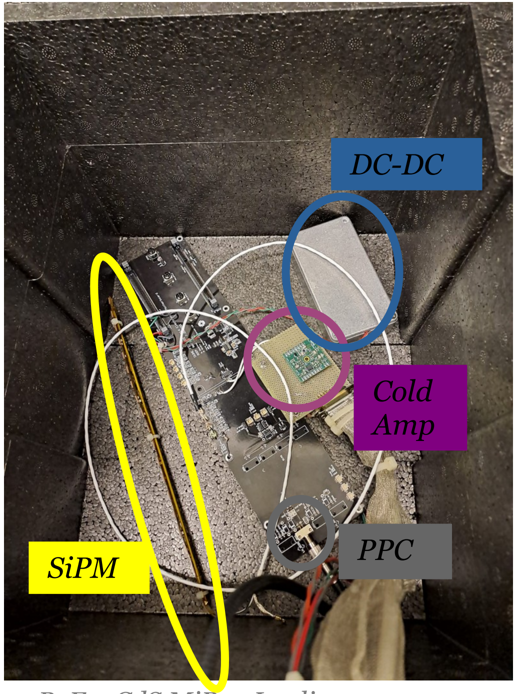


FBK

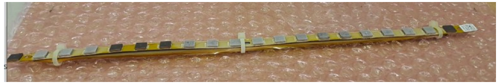


From laser to SiPM

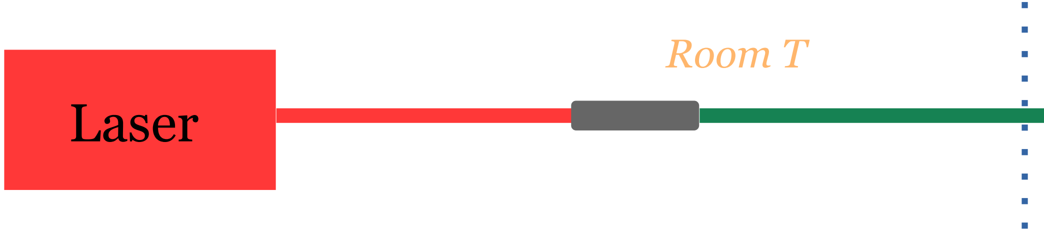


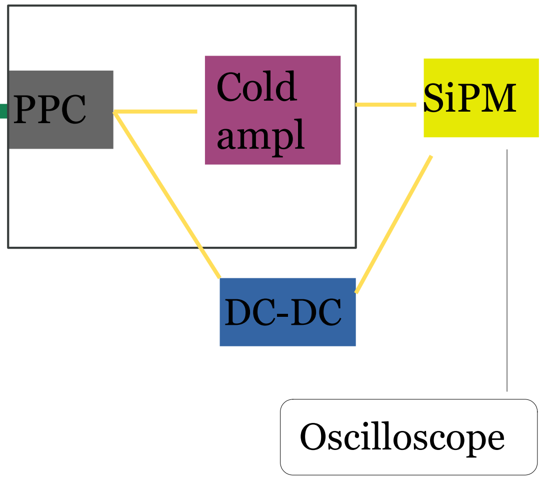


- **Cold amplifier** developed by Milano Biccoca group for DUNE → V_{in} = 3.3 V
- **DC-DC** boost converter developed by INFN Milano Statale group, → give bias to SiPMs;
  → V_{in} ~ 5 V; V_{out} ~ [40, 50] V for Hamamatsu SiPM
  → V_{in} ~ 5 V; V_{out} ~ [25, 35] V for FBK SiPM
  → placed in a metallic box to reduce noise.
- **SiPM**, developed by Hamamatsu and FBK for DUNE,
  → 1 flexi board with **20 SiPMs**,
  → V_{bd} = 42.0 V at 77 K for Hamamatsu
  → V_{bd} = 27.1 V at 77 K for FBK

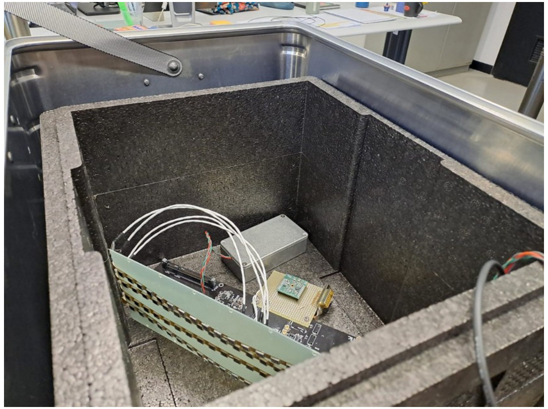


Results

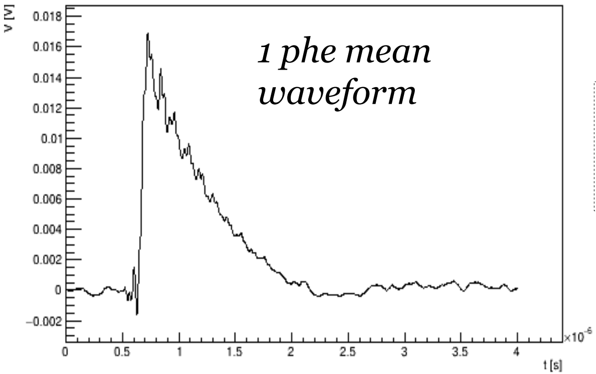




- Tests in **LN2** (T = 77 K);
- **20 SiPMs** (1 flexi board) and **80 SiPMs** (4 flexi, one acquisition channel);
- **three SiPM bias** tested :
  → 45 V, 46 V, 47 V for HPK;
  → 30.6 V, 31.6 V, 34.1 V for FBK;
- trigger with an external by LED source;
- evaluation of the **Signal to Noise Ratio** $SNR = \frac{\mu_1 - \mu_0}{\sigma_0}$
- comparison of the results: PoF vs copper line.



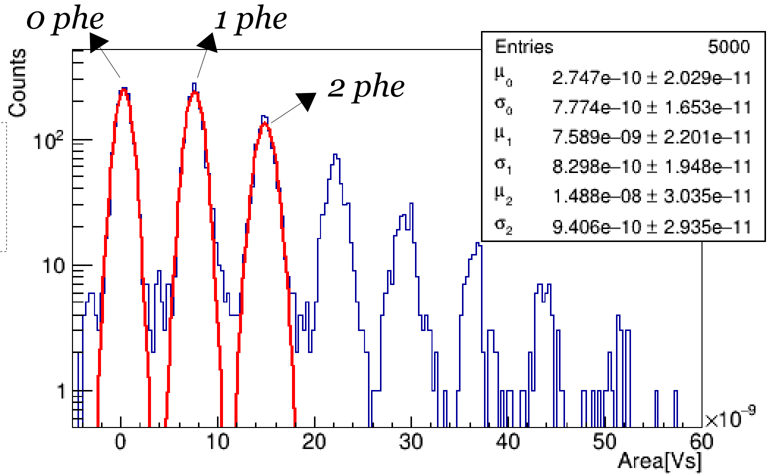
20 HPK SiPM test



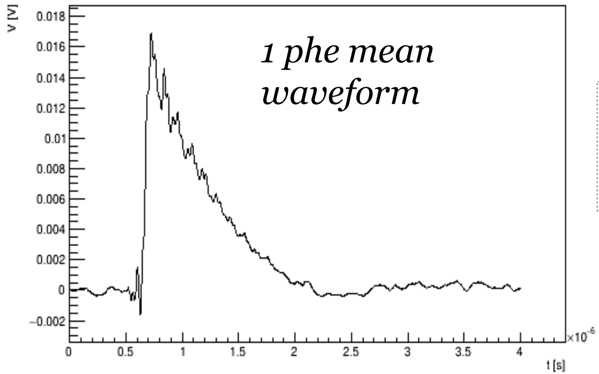
PoF

V_{in} laser = -2.61 V (~ 1 W)
V_{bias} = 47 V – 5 V ov

SNR = 11.070



20 HPK SiPM test



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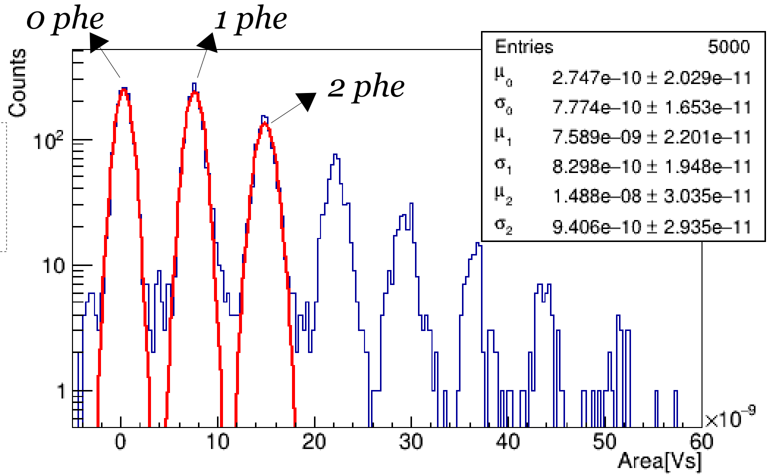
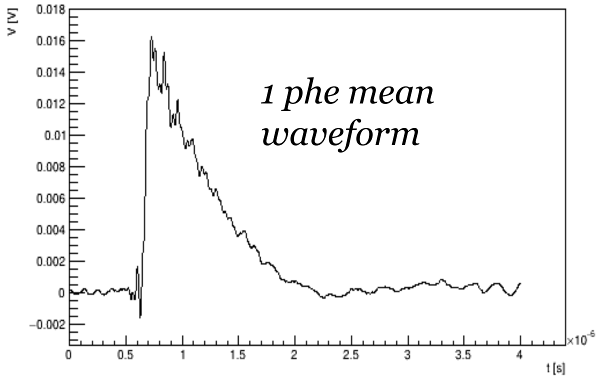
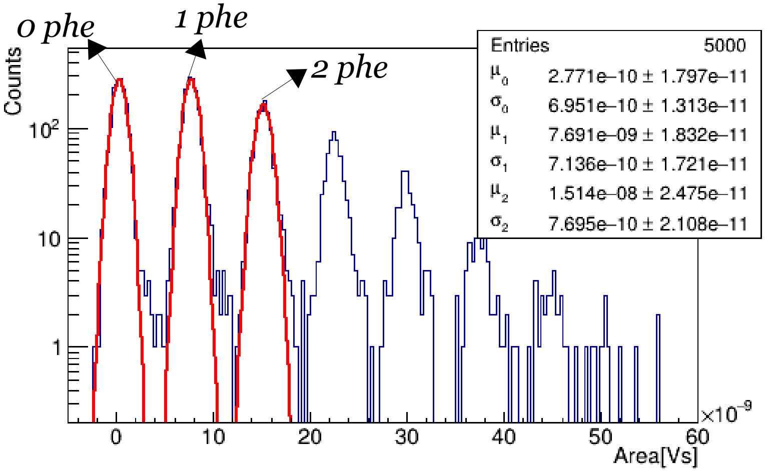




Copper cable

V_{bias} = 47 V – 5 V ov

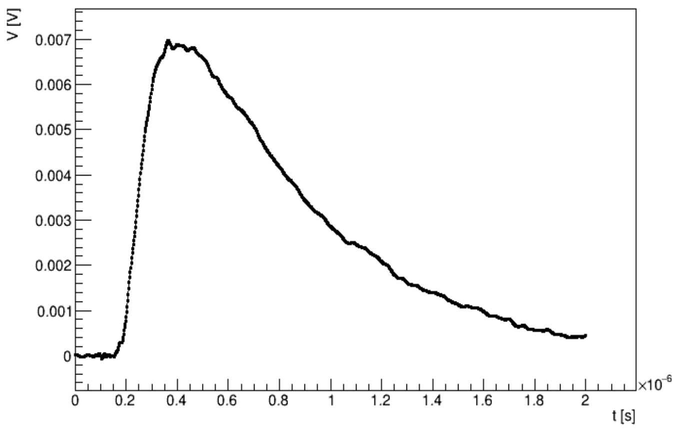
SNR = 13.004

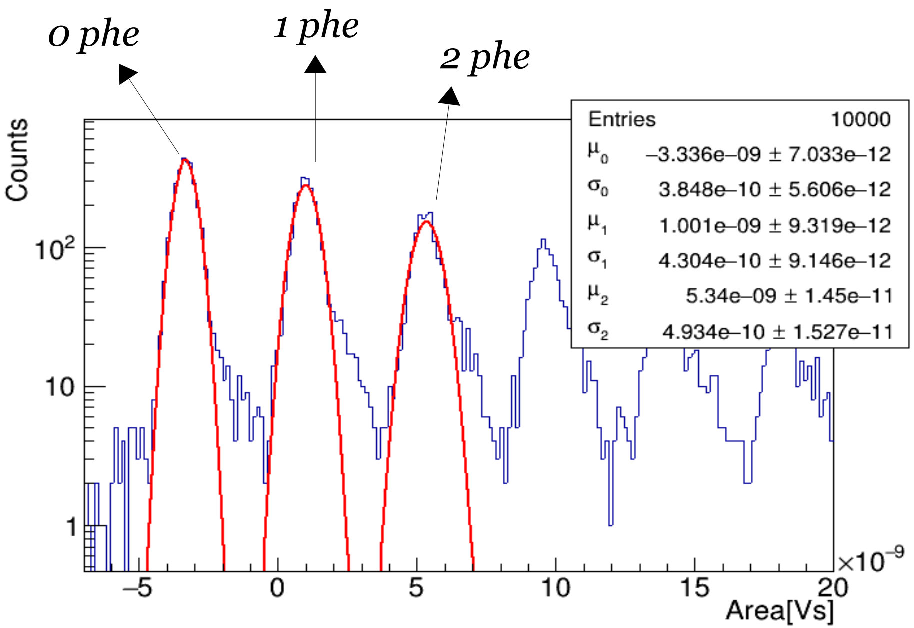


80 FBK SiPM test

V_{in} laser = -1.94 V (~ 1.3 W)
V_{bias} = 34.1 V – 7 V ov

1 phe mean waveform

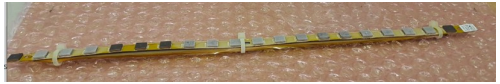




SNR = 11.270

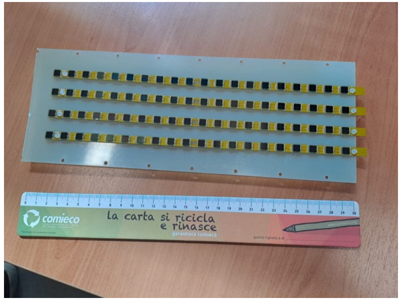
Summary of the SNR

HPK – 20 SiPMs



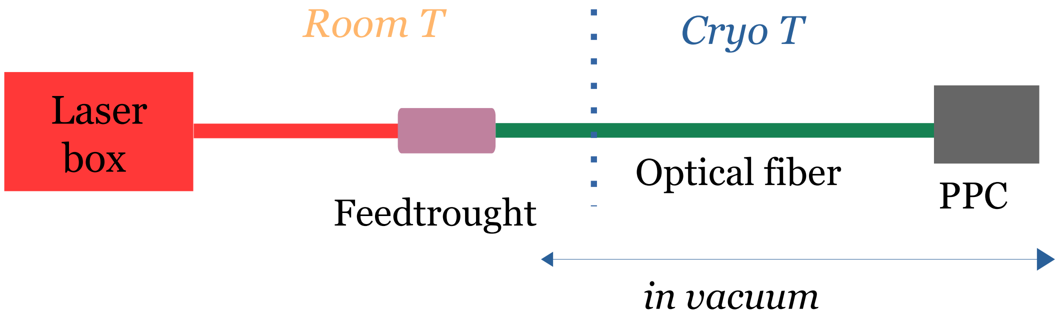
SiPM bias	*SNR Copper cable*	*SNR PoF*
45 V (40%PDE)	7.830	7.520
46 V (45%PDE)	10.665	9.409
47 V (50%PDE)	13.004	11.070

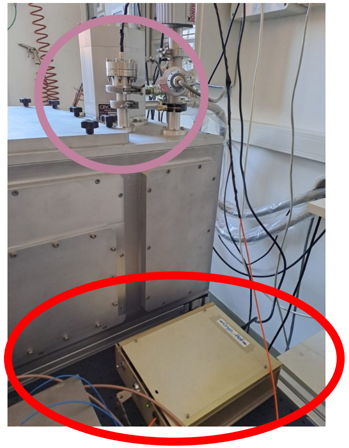
FBK – 80 SiPMs

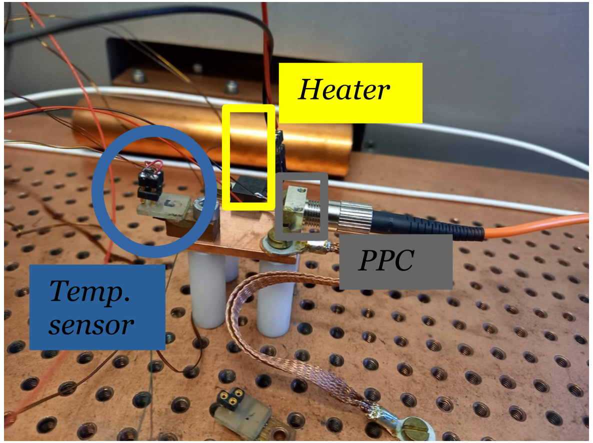


SiPM bias	*SNR PoF*
30.6 V (40%PDE)	6.027
31.6 V (45%PDE)	7.173
34.1 V (50%PDE)	11.270

Test at lower temperatures then LN (< 77 K) - Setup

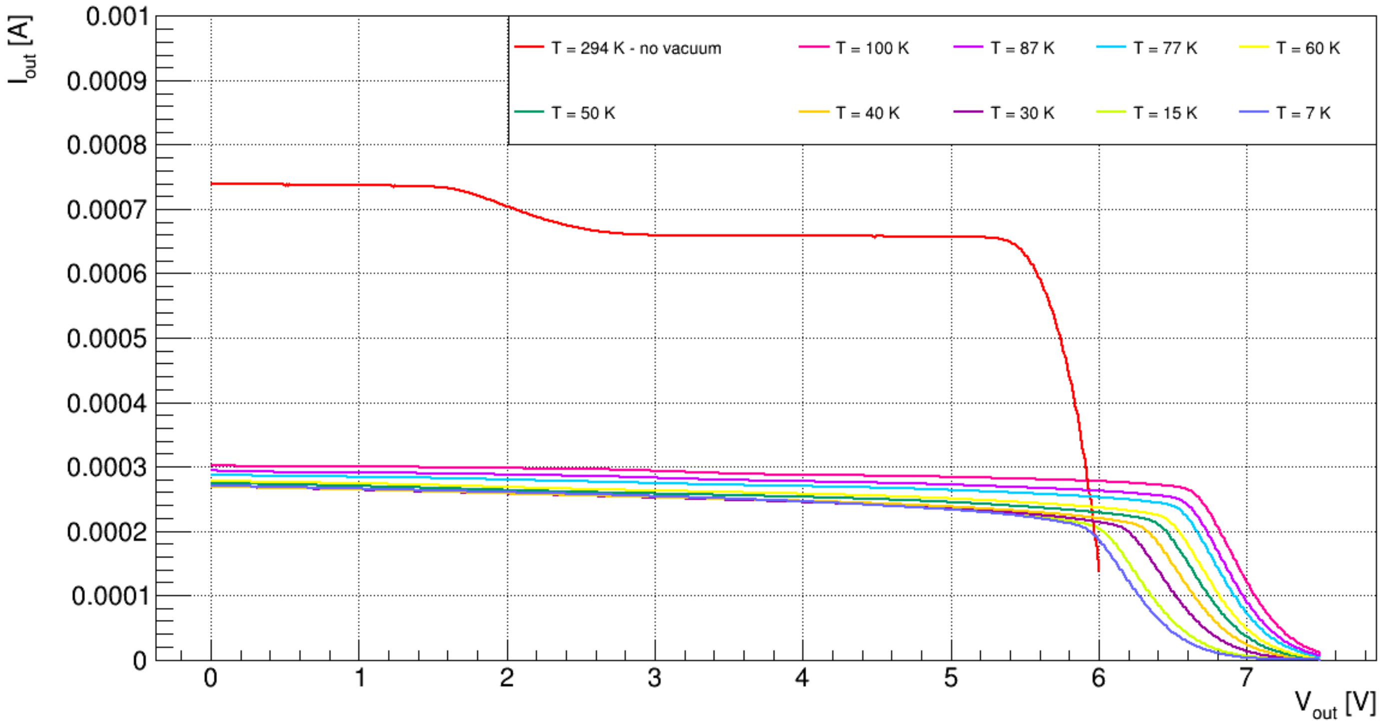






- We tested our setup (from laser to PPC) in a cryostat **till 7 K** and characterized the PPC output registering the I-V curves with the semiconductor analyzer.
- The system was in vacuum; the temperature was fixed and controlled by means of an heater and a termometer.
- There was a large power loss in the feedtrough (its core diameter smaller than the fiber core).
- The laser power at the PPC was ~ 5 mW.

Test at lower temperatures then LN (< 77 K) - Results



The device works till 7 K with P_{max} ~ 15 % P_{in} → Possibility to use this technology in other fields!

Milestones

Cryo PoF

2022

- Completamento della linea PoF ✔
- Scelta della lunghezza d’onda di lavoro e del laser ottimale ✔
- Qualificazione elettrica a temperatura ambiente della linea PoF + CCBv1 ✔
- Qualificazione elettrica in azoto liquido della linea PoF + CCBv1 ✔
- Verifica della dissipazione termica e dell’assenza di bubbling in argon o azoto liquido ✔

2023

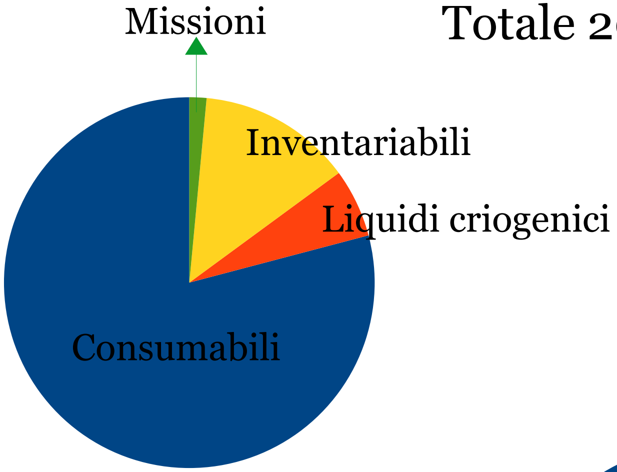
- Produzione di CCBv2 ✔
- Test dell’intera linea PoF con CCBv2 ed Amplitude Modulator in criogenia ✔
- Caratterizzazione dell’intera linea PoF per alimentare una tile in criogenia ✔
- Test dell’intera tile di SiPM posta sul catodo in alta tensione e in argon liquido (50%) ⇨

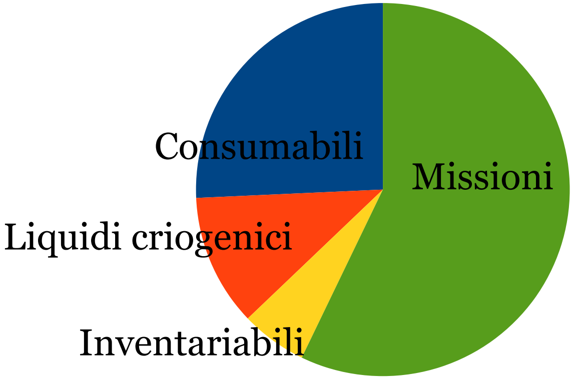
Anagrafica e finanziamento

Nome	FTE
Marta Torti (Resp Nazionale e Locale)	0.8
Claudia Brizzolari	0.1
Esteban J. Crostaldo Morales	0.4
Maritza J. Delgado Gonzales	0.3
Andrea Falcone	0.1
Francesco Terranova	0.1

Con il prezioso aiuto di C. Gotti e G. Pessina!

Totale 2022: 33.5 ke





Totale 2023: 35.0 ke

Publication,thesis, talks and posters

Publications

- M.Torti et al. *"Cryo-PoF: Cryogenic power over fiber for fundamental and applied physics at Milano-Bicocca"*, PoS TIPP23, to be published;
- M.Torti et al., *"Cryogenic power over fiber for fundamental and applied physics: results from the Cryo-PoF project"*, NIM Proceedind PM24, to be published;
- M.Torti et al. *"Development of a cryogenic power over fiber system for fundamental and applied physics"*, in preparation.

Thesis

L. Carminati *"L'utilizzo del power over fiber per i fotosensori criogenici di DUNE"* - tesi triennale UniMiB

Talks and Poster

- *"Cryogenic Power-over-Fiber for fundamental and applied physics"* – Talk at IFD2022, Bari;
- *"Cryo-PoF: Cryogenic power over fiber for fundamental and applied physics at Milano-Bicocca"* – Talk at TIPP23, Cape Town;
- *"Cryogenic power over fiber for fundamental and applied physics at Milano-Bicocca: the Cryo-PoF project"* – Poster at NuPhys23, London;
- *"Cryogenic power over fiber for fundamental and applied physics: results from the Cryo-PoF project"* - Poster at PisaMeeting 24, Isola d'Elba.
- *"Cryogenic power over fiber for fundamental and applied physics: results from the Cryo-PoF project"* - Poster at Neutrino24, Milano.
- "*Results from Cryo-PoF project: power over fiber at cryogenic temperature for fundamental and applied physics*" – Talk a ICNFP24, Creta

Cryo PoF : next steps

- Complete the missing tests on high voltage surface.
- Test with the new DC-DC boost converter with an active feedback (developed by INFN Mi).
- Test of the new PPC prototype delivered by the Broadcom company.
- Test on devices at very low temperature (quantum computing field).

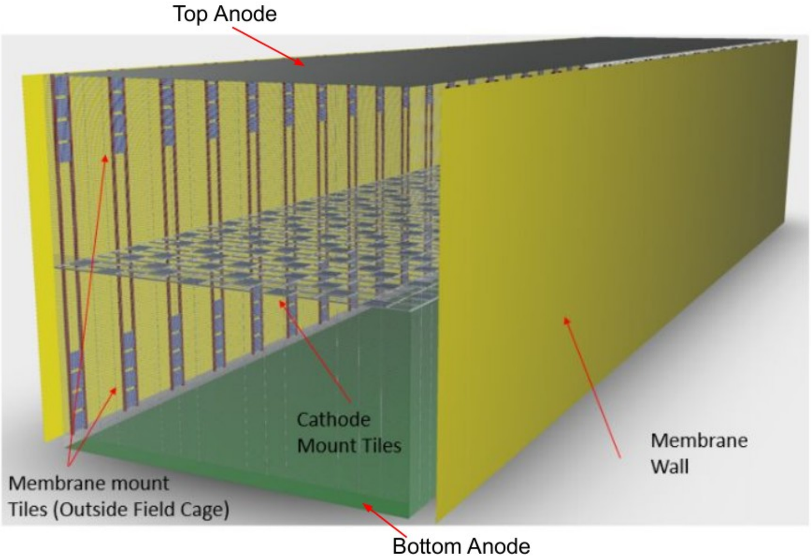
Thanks!

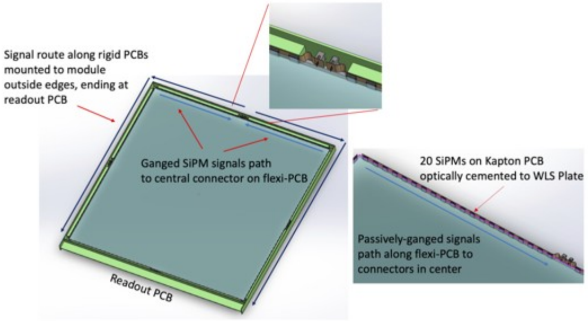
DUNE Vertical Drift

- **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 .

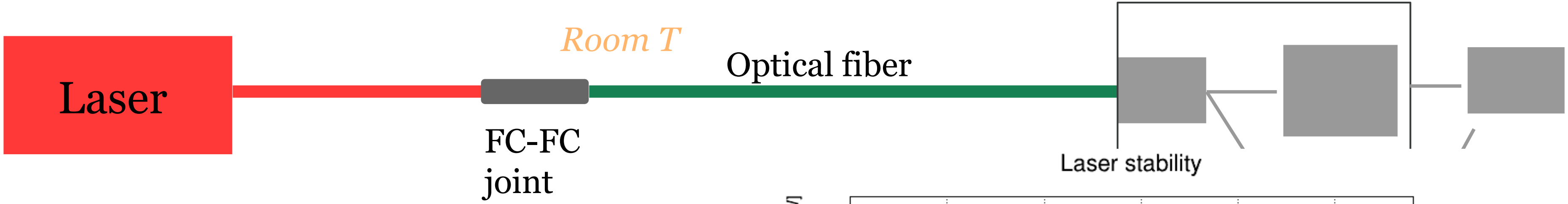


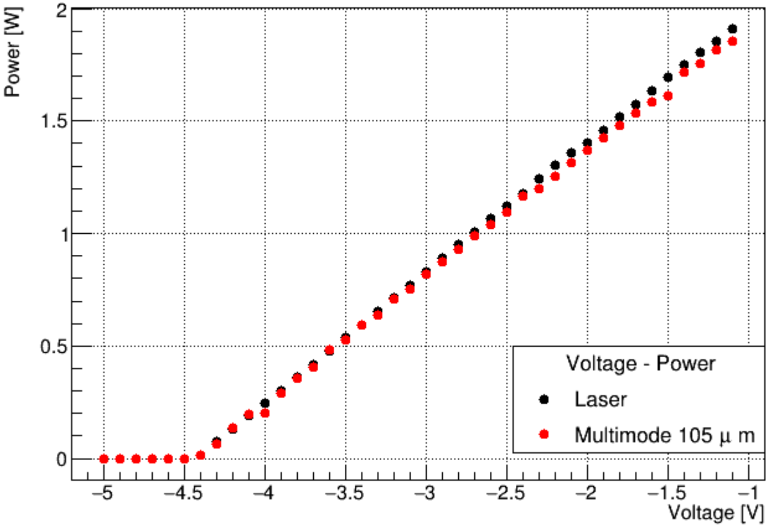


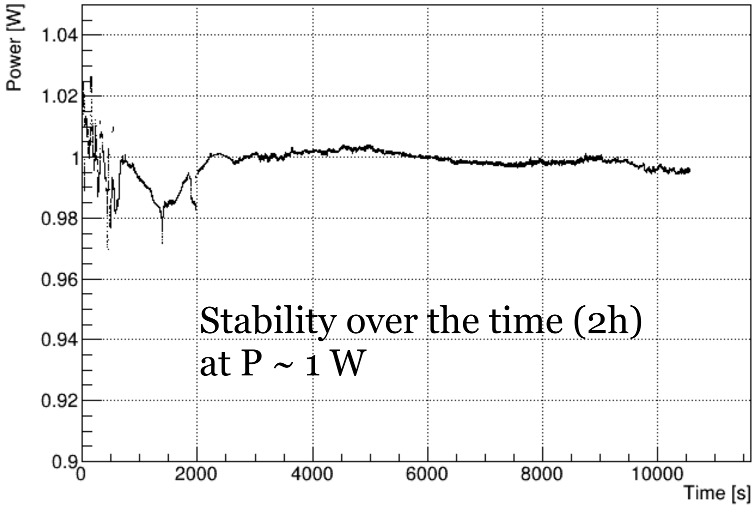
- The DUNE PD is the X-Arapuca: a light trap that used SiPMs as photosensors.

- Each X-Arapuca has 160 SiPMs and it is read by two acquisition channels.

Laser source







~ 3.0 % power loss adding a FC/FC joint and an optical fiber.

Max – Min ~ 5.7% - Mean(P_o – P_i) = 17.1 mW

Without the first 30 min:

Max – Min ~ 0.96% - Mean(P_o – P_i) = 15.9 mW