Power and signal transmission over optical fiber for the DUNE FD2 detector

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ND All Hands
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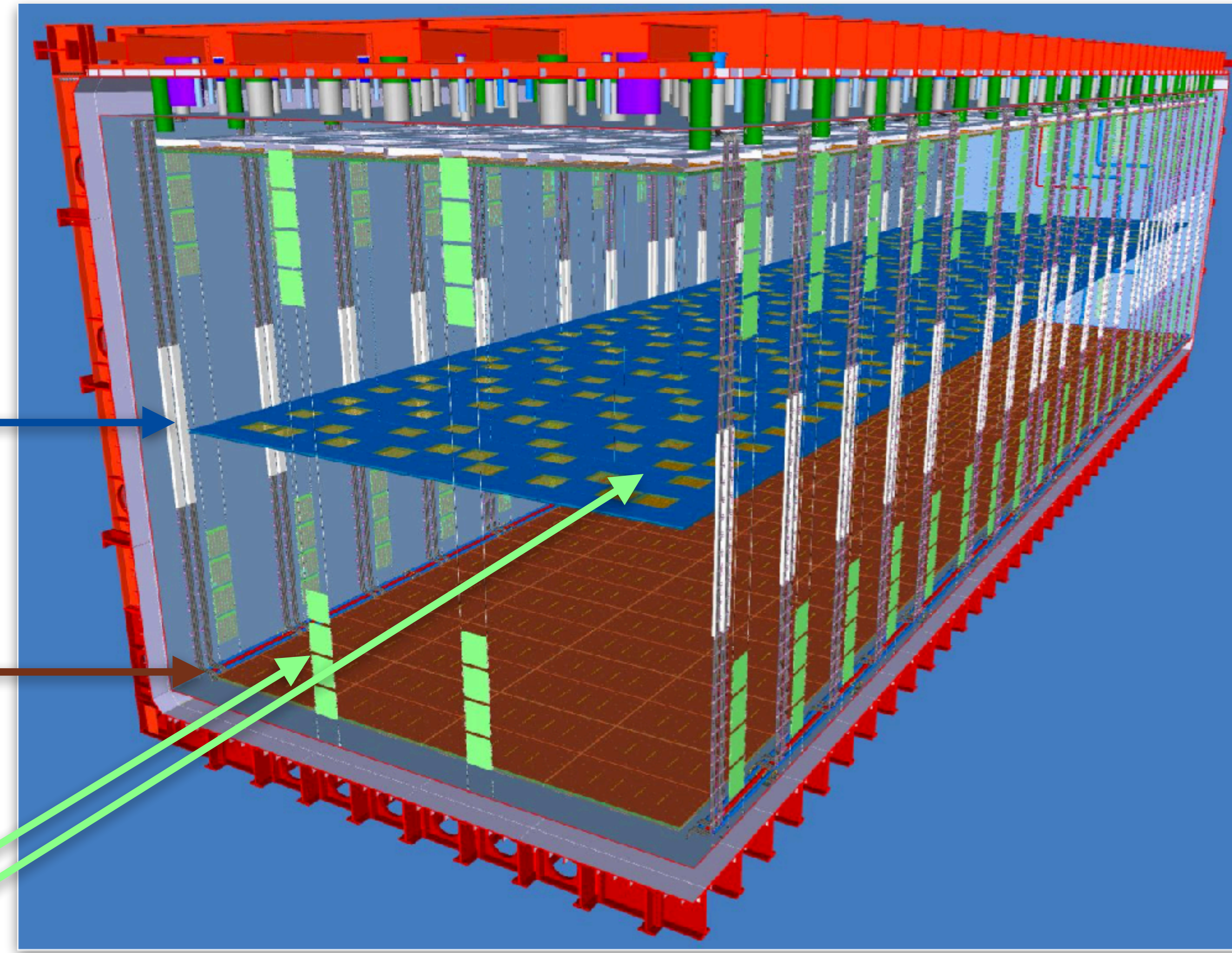
Vertical Drift Single Phase Liquid Argon TPC

DUNE Far Detector 2 – single phase TPC

Two volumes of $13.5 \times 6.5 \times 60$ m^3

Vertical drift of ionization charge

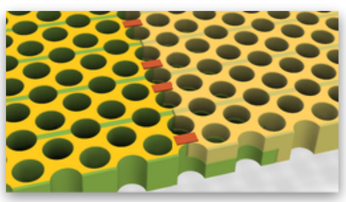


Cathode

- resistive mesh at the mid-height of the detector volume

Anode

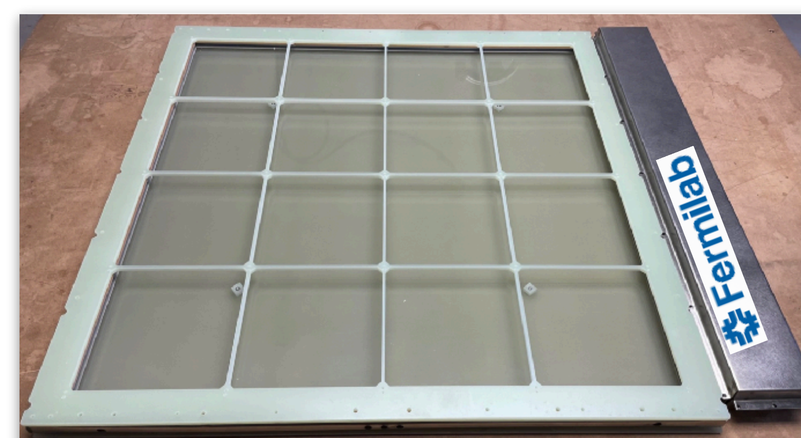
- two planes (perforated PCBs) at the top and bottom
- opaque to LAr scintillation light

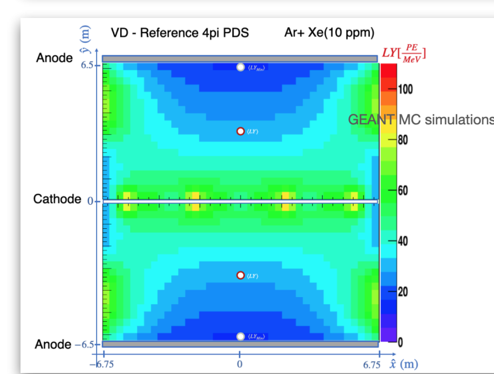


Photodetection system

- uniform light yield with 4π coverage, fast signal
- improved reconstruction of event vertex and deposited energy
- low energy threshold, O(10)MeV

→ enable low energy physics measurements, e.g. supernova neutrino bursts, diffuse supernova neutrinos)



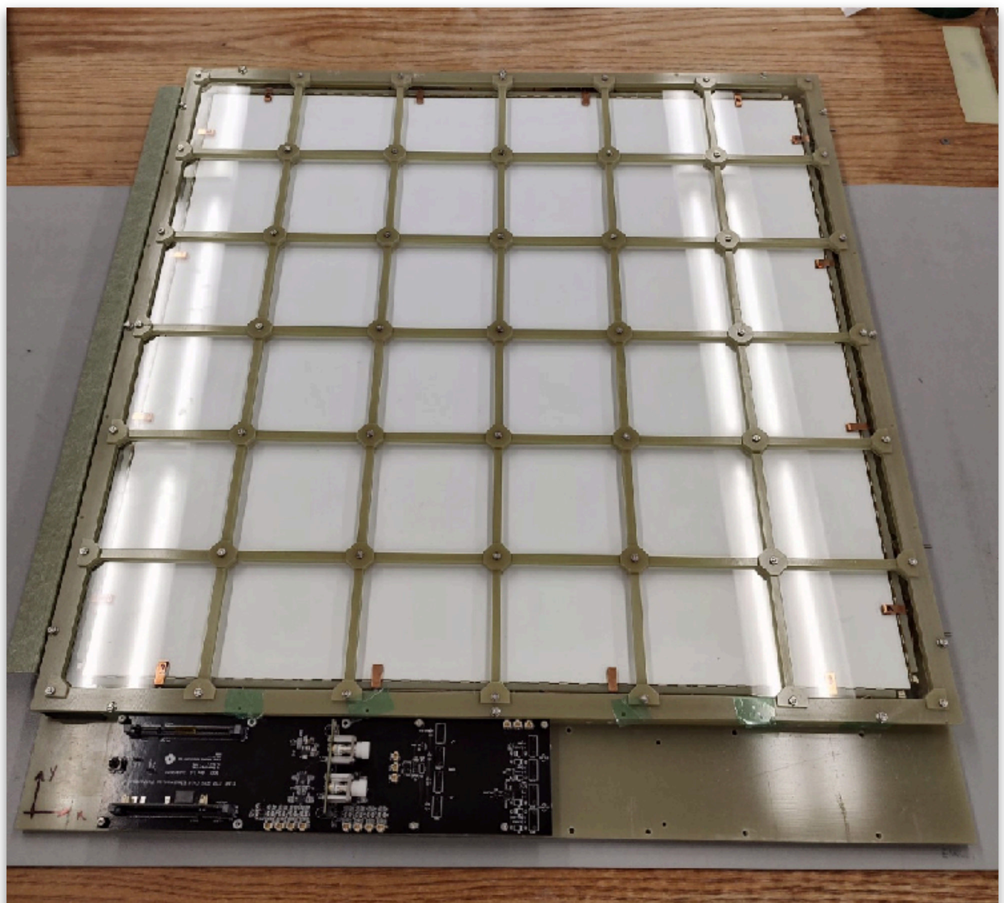


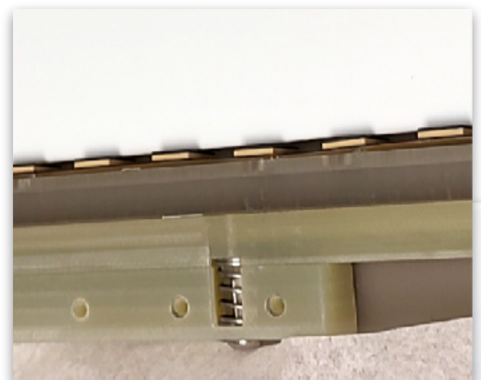
Photodetectors

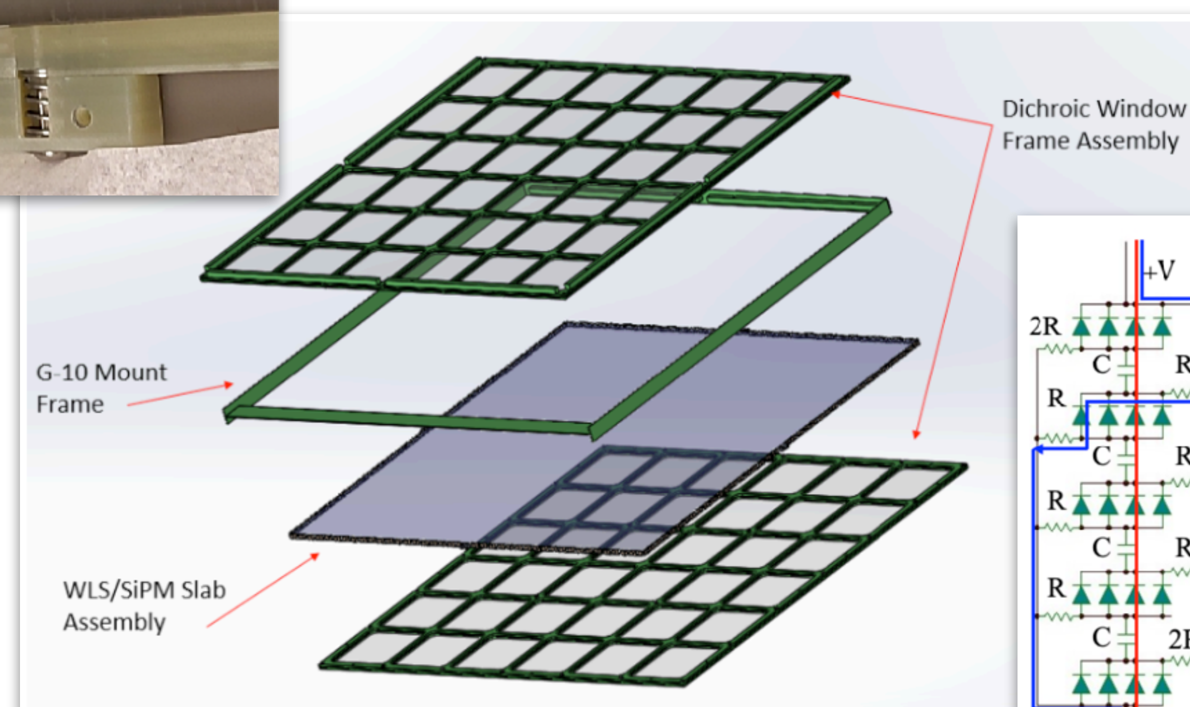
X-Arapuca: 60 × 60 cm^2 active area light ‘trap’ with dichroic filters and wavelength shifter

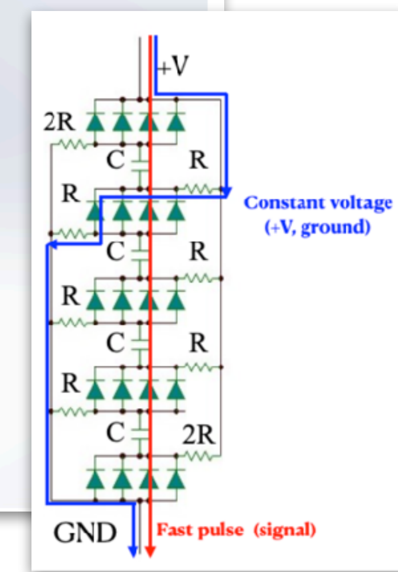
Double-sided on the cathode, single-sided on the field cage

160 SiPMs (6×6mm^2) are distributed along the four sides, grouped in 8 flexible boards





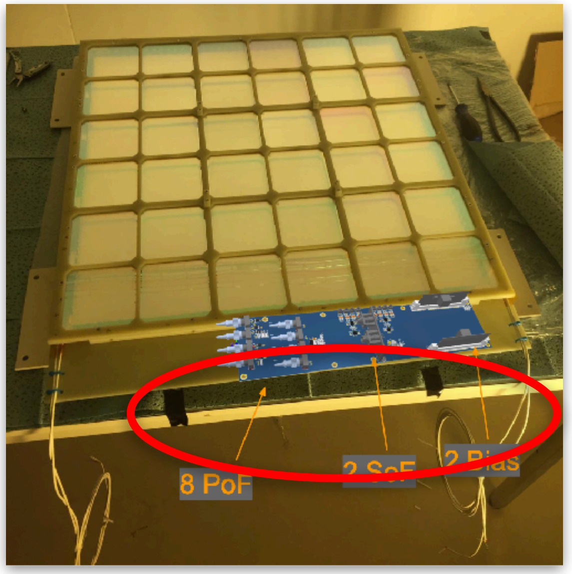




Cathode is a high-voltage environment. Not possible to use conventional wires to to supply power to the photosensors and front-end electronics, and to transmit signal from the detector.

New technologies have been developed at Fermilab:
Power over Fiber (PoF), Signal over Fiber (SoF)

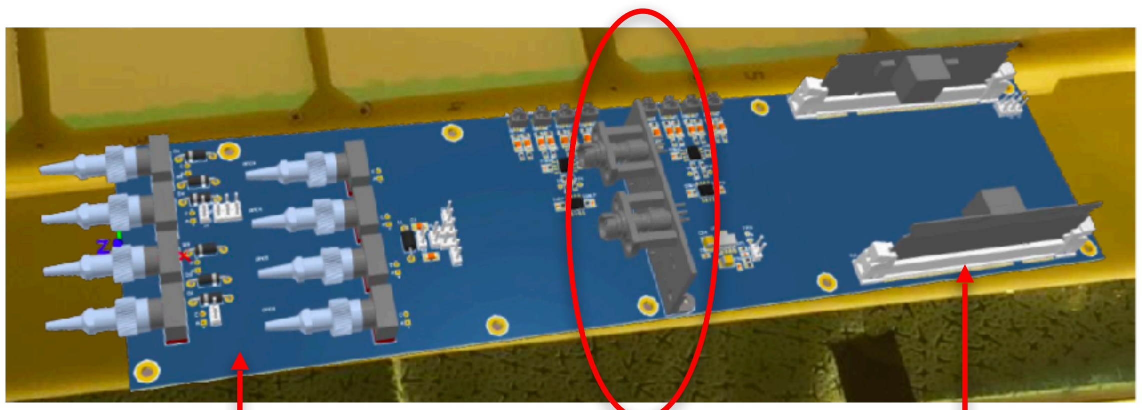
Cold (front-end) electronics



The DUNE Cold Electronics Motherboard (DCEM) integrates:

- PoF receivers
- DC/DC bias voltage generators
- SiPM signal amplification and laser diodes for optical transmission

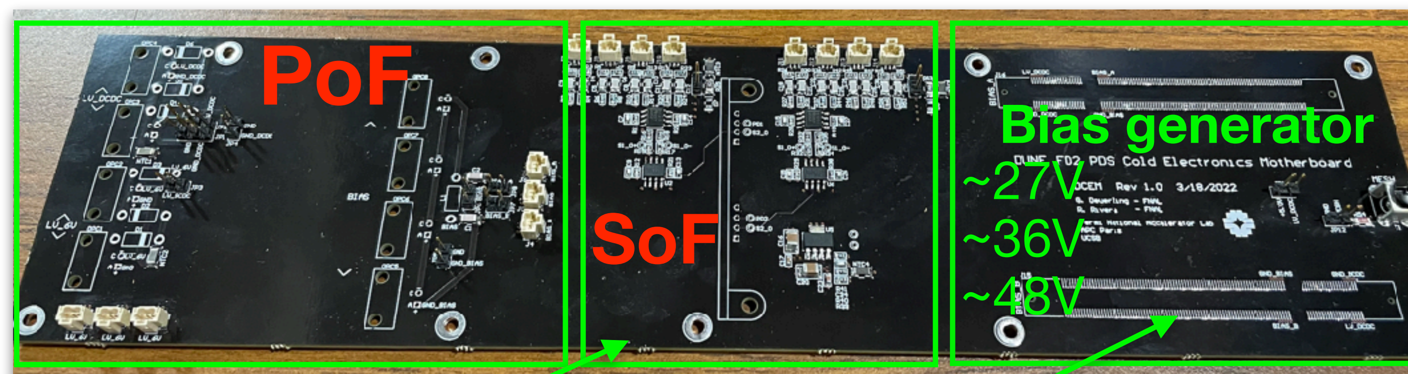
DCEM is installed at the edge of X-Arapuca, shielded with a copper cage

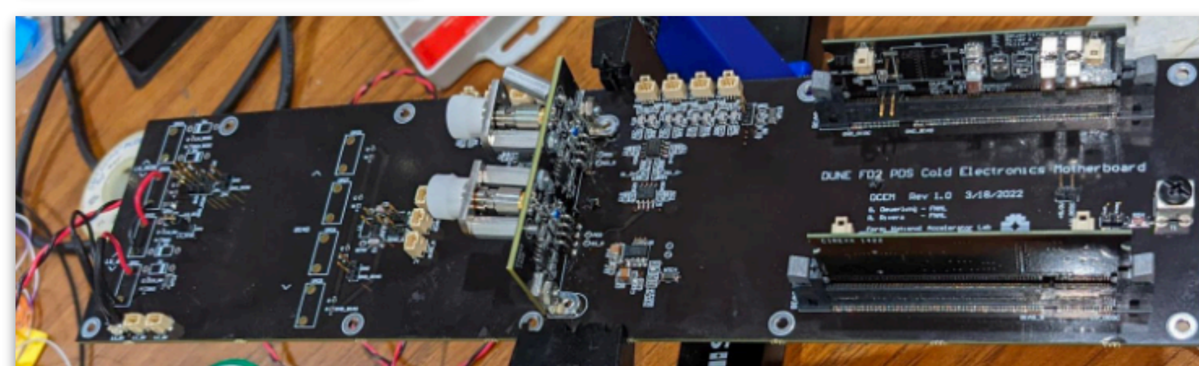


Up to 8 PoF Photovoltaic receivers (silicon or Gas)

Analog optical transmitter with lasers & laser driver on daughter card

DC/DC converters in SIMM connectors (BIAS_SODIMM)





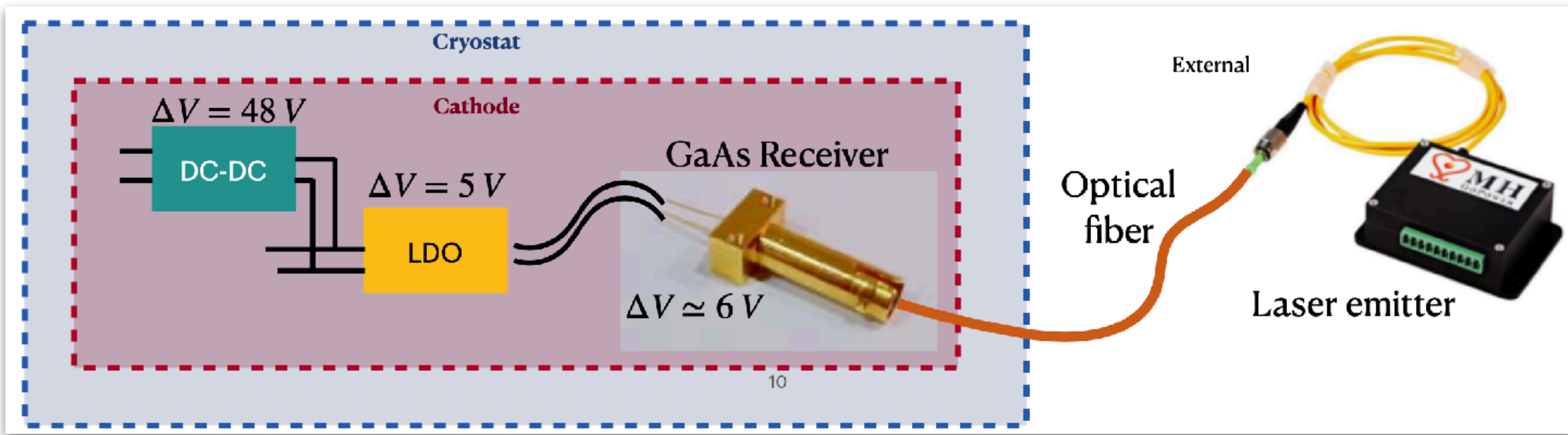
Power over Fiber (PoF)

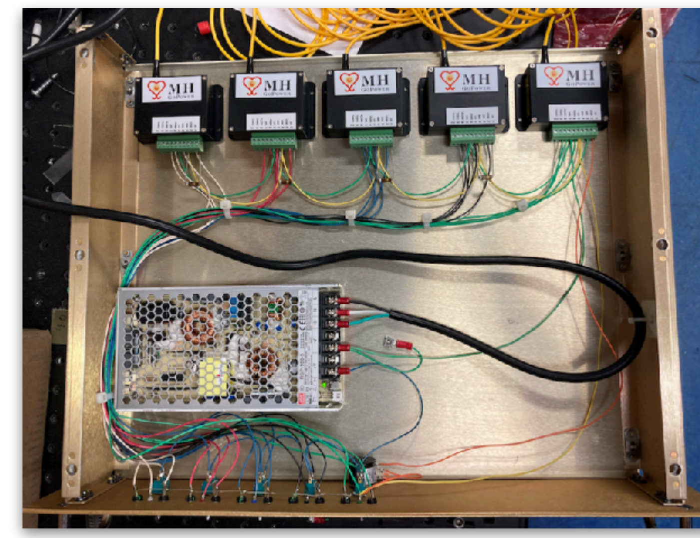
Power target 0.4W

Emitter: Eight 2W power-capable gallium arsenide (GaAs) lasers, 808 nm wavelength

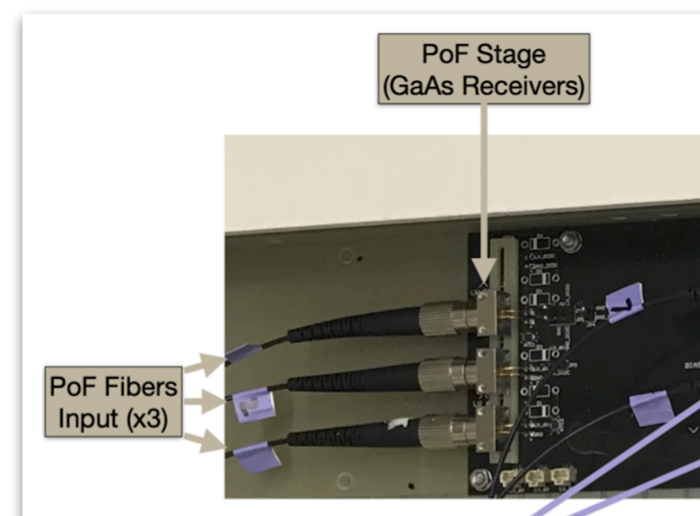
Transmission: 62.5µm fused silica fibers

Receiver: GaAs (3 in parallel, 1.5W capable), convert optical power to I-V power





Voltage stabilization with a low-dropout regulator (LDO, 5V)



Front-end electronics:
Low voltage / High current (5V, <100mA)

SiPMs:
High voltage / Low current (~50V, µA), DC/DC converter

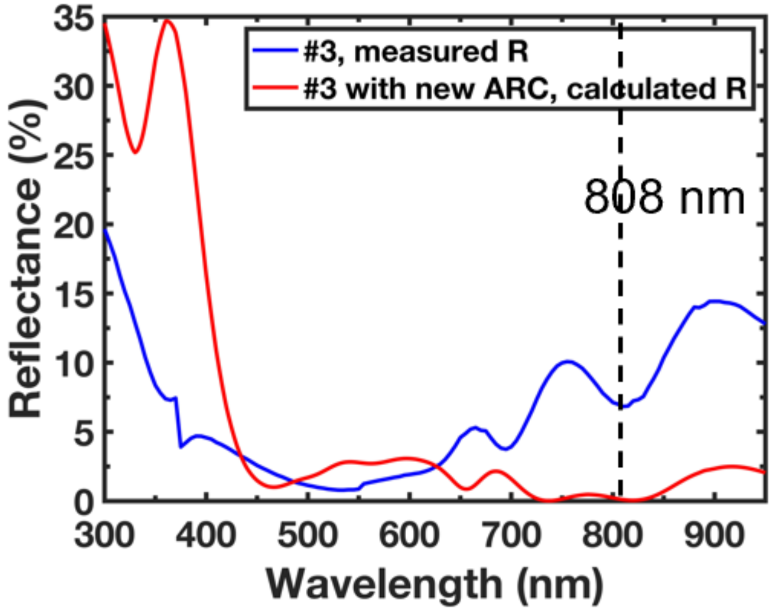
Major benefits for HEP experiments:
voltage isolation, spark-free operation, noise immunity

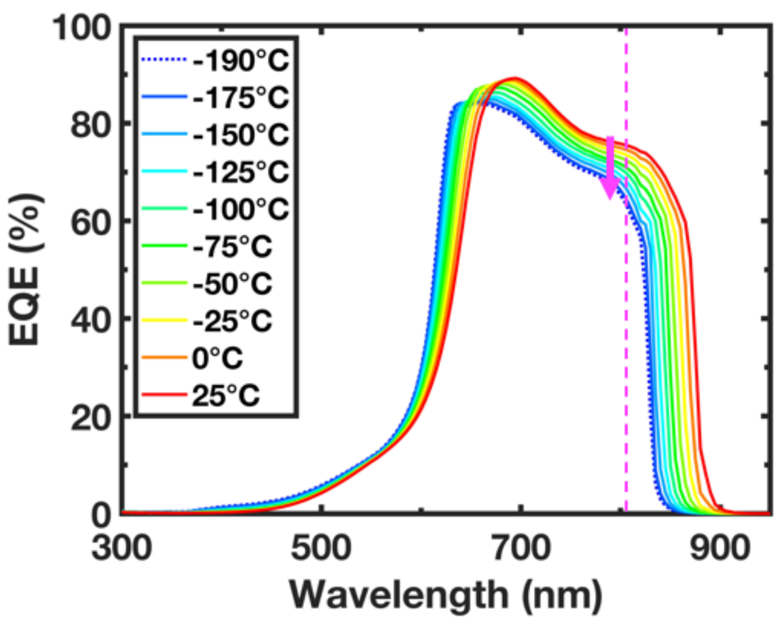
Near-Term Roadmap for 60+% Efficiency GaAs LPC at Low T

- **Optimized OPC – several tech updates**
  - Simply, with optimum anti-reflective coating, efficiency at 190˚C will be ↑ to 54%.
- **Larger Surface Area**
  - **2x2 mm to 2.4x 2.4mm**
- **Adding metal to the tunnel junction**
  - **p+$Al_{0.1}$GaAs BSF**
    - Diffusion length ↑, barrier for minority carrier

Device	Power	$EQE_{808\ nm}$ at RT	$EQE_{808\ nm}$ at -190˚C
H1 BC Unit	300mW	52%	28%
H2 BC Unit	300mW	54%	37%
F1 BC Unit	500mW	58%	45%
F2 BC Unit	600mW	65.4%*	62.2%*
#3 with optimum ARC	0.2%	80.9%**	66.8%**

- *TBD Feb 2023
- **TBD Fall 2023



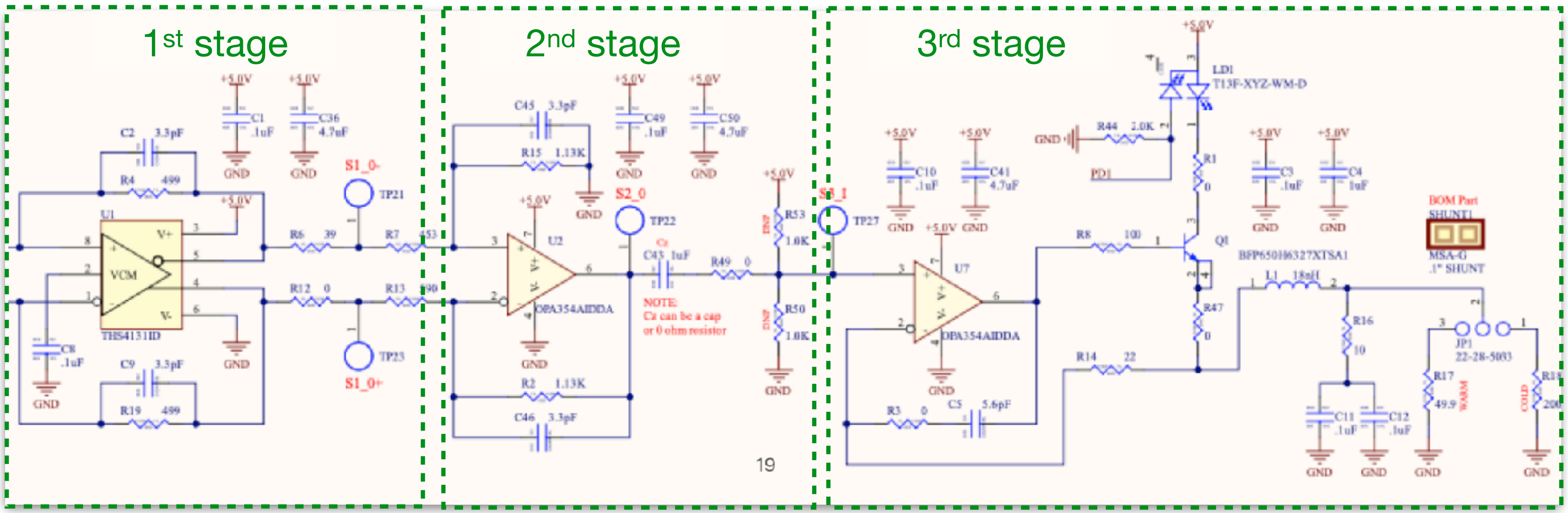


Signal over Fiber (SoF)

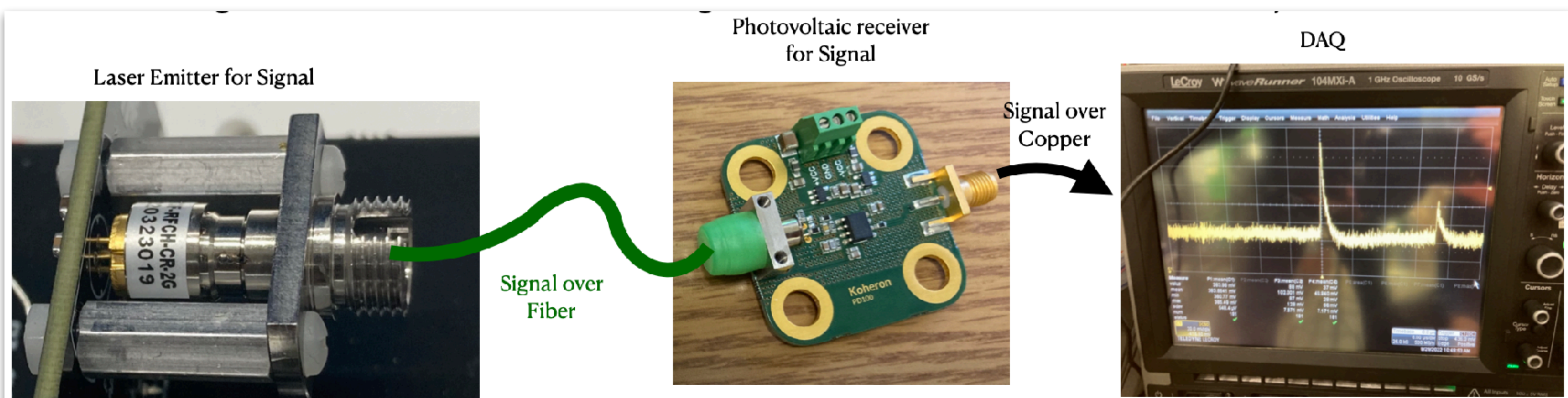
First stage pre-amplification

Second OpAmp stage to convert from full-differential to single-ended signal

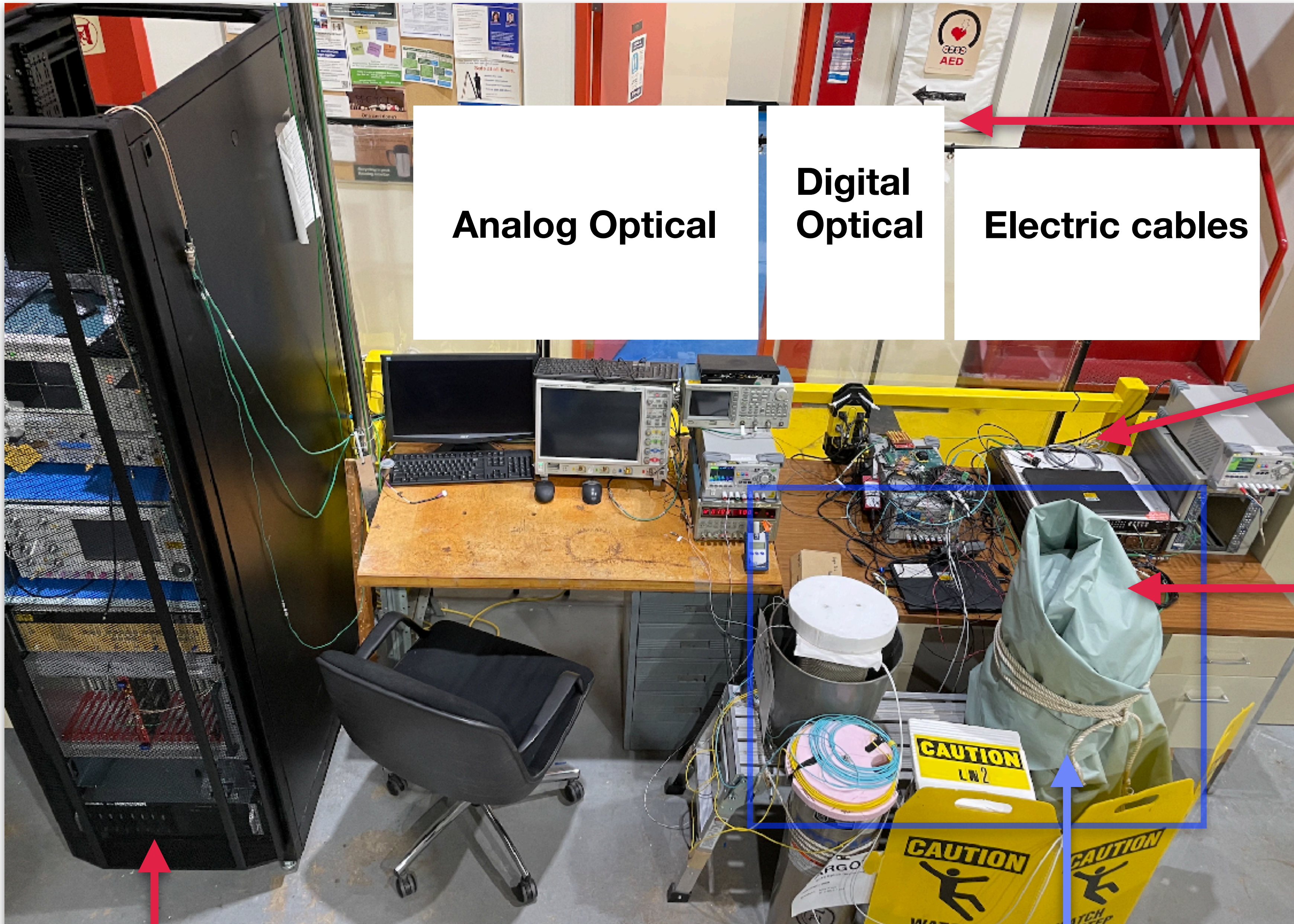
Third OpAmp (combined with a transistor) to drive the laser diode emitter



Fabry-Perot laser diode for data communication: 1310nm (RT) / 1255nm (LAr)



Cold test setup at the Proton Assembly Building (PAB)



(D) DAQ2
(FPGA at room temperature, ADC in LAr)

(C) DAQ1
(differential input, SiPM direct measurements)

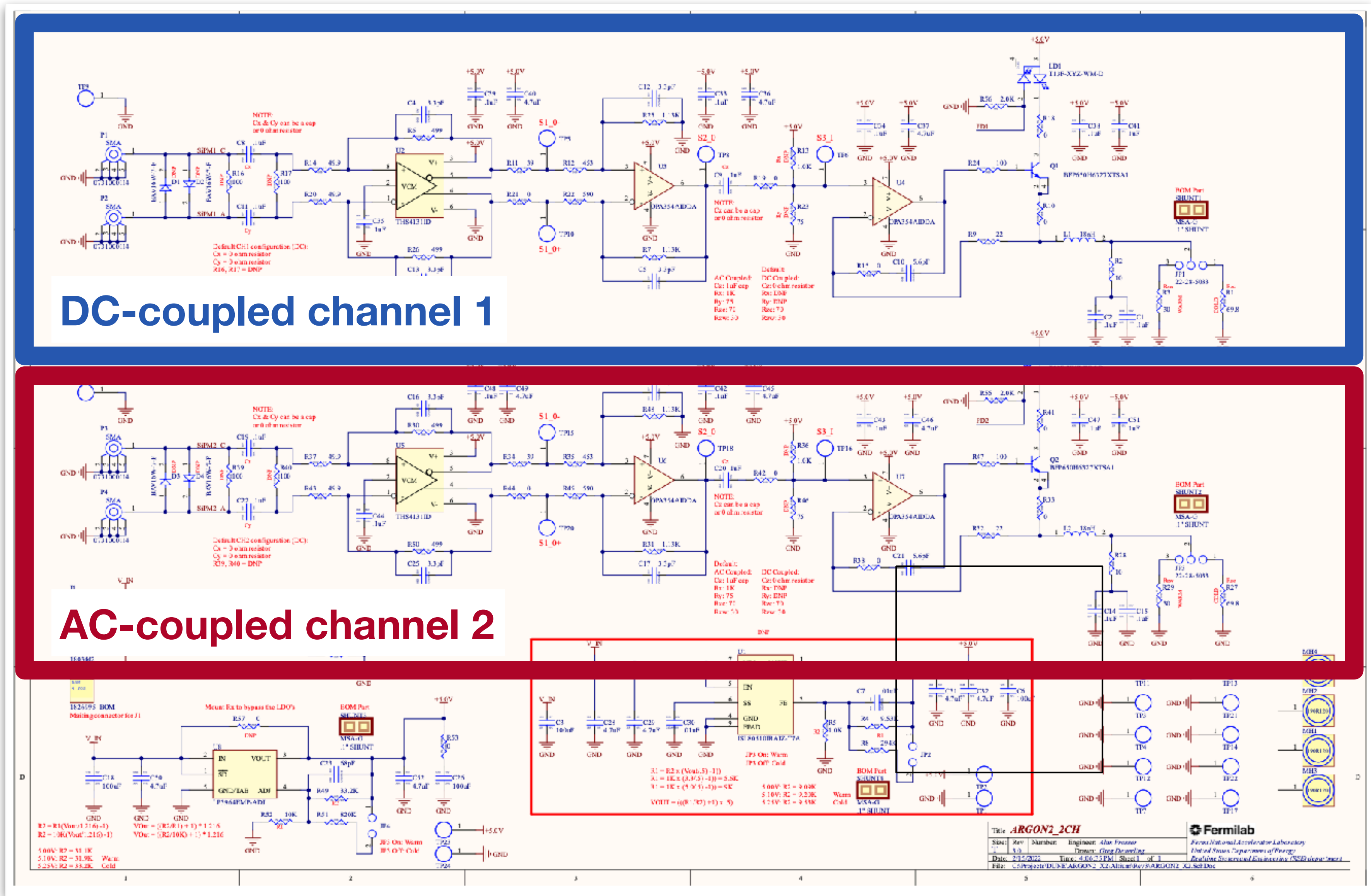
(B) SiPM board
in dark environment
with LED pulser
(400 Hz)

(E) DAQ3
(single-ended input,
measurements with optical receiver)
Data storage and analysis server

(A) open-mouth dewars with LAr and LN2
– two shallow, two tall (up to 25” of cryogenic liquid)
– fast turn-around and iteration, side-by-side tests

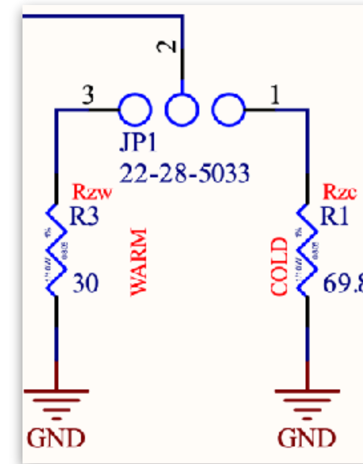
* LAr delivery and external storage in 180L/350PSI cylinders, transfer walking with a gallon insulated bottle

Cold analog optical signal transmission R&D

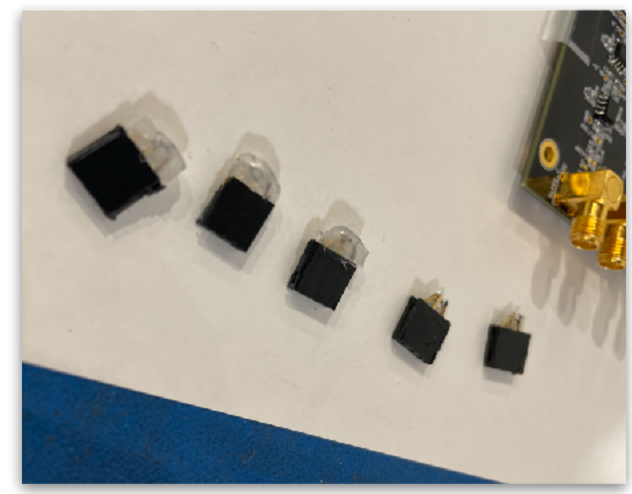


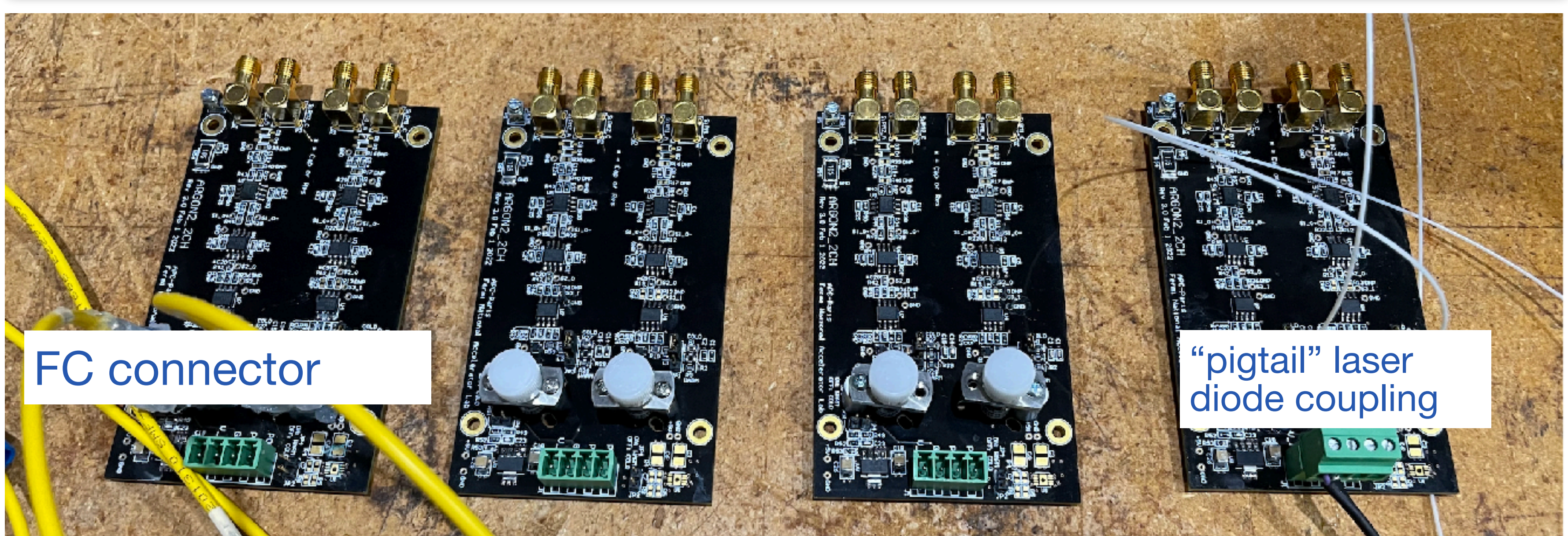
Warm/cold operation jumper passive switch with NTC resistor

Warm



Cold (less power required for laser diode)





Several modifications:

– same topology
– varying gain, feedback circuit, etc.)

→ optimization of S/N ratio, power consumption

xArapuca cold test in the Iceberg cryostat

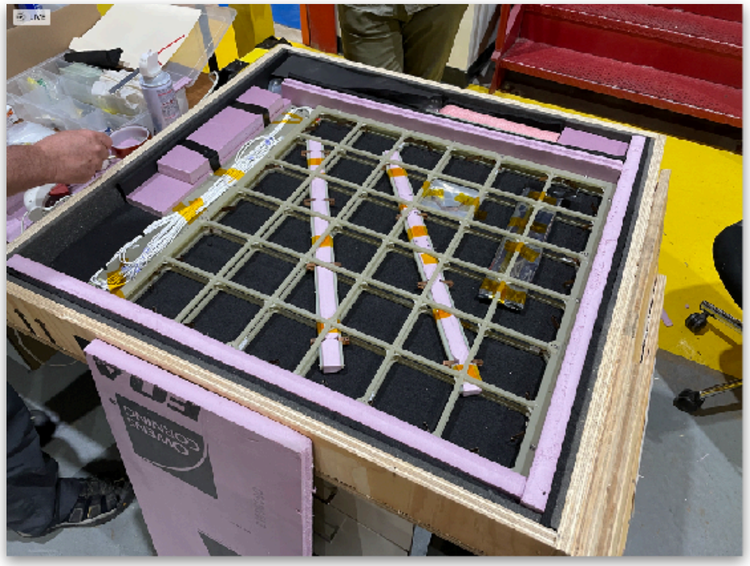
The first full-size V2 “xArapuca” module (with dummy WLS and dichroic filters) assembled first and equipped with cold electronics (DUNE Cold Electronics Motherboard). 7kg weight

Integration at Fermilab PAB
Very tight schedule to be tested and arrive at CERN

Operation at 6psig overpressure (emulation of an immersion test at ~1.2m of LAr)

Performed tests:

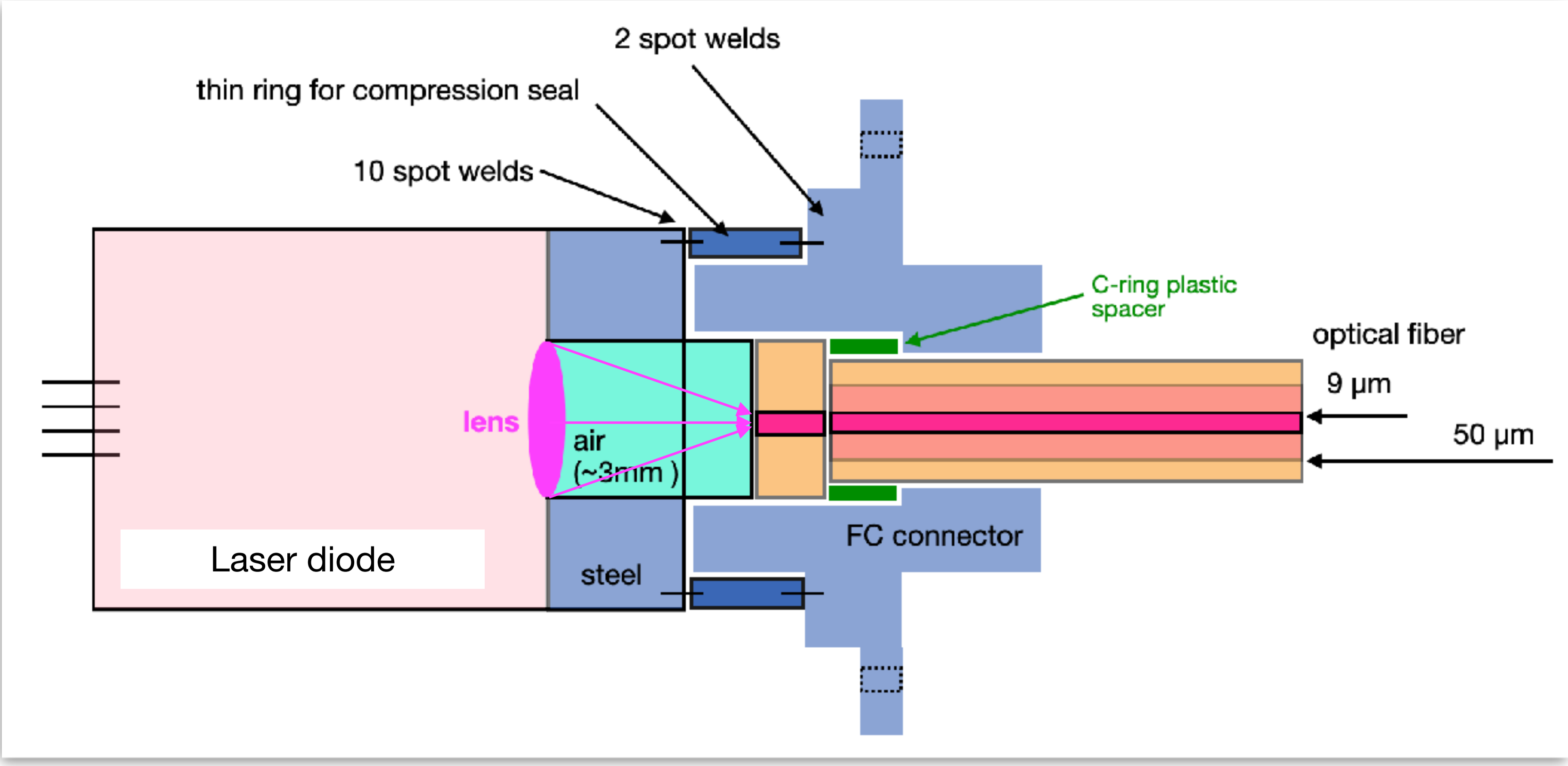
– mechanical integrity, cool down and operation
– emulation of a depth of ~1.2m in LAr with 6 psi overpressure
- power over fiber (PoF) delivery
- power distribution and voltage regulation on DCEM
- laser adapter card functionality (signal over fiber, SoF)
- optical transmission chains
- warm part of the electronics/DAQ chain

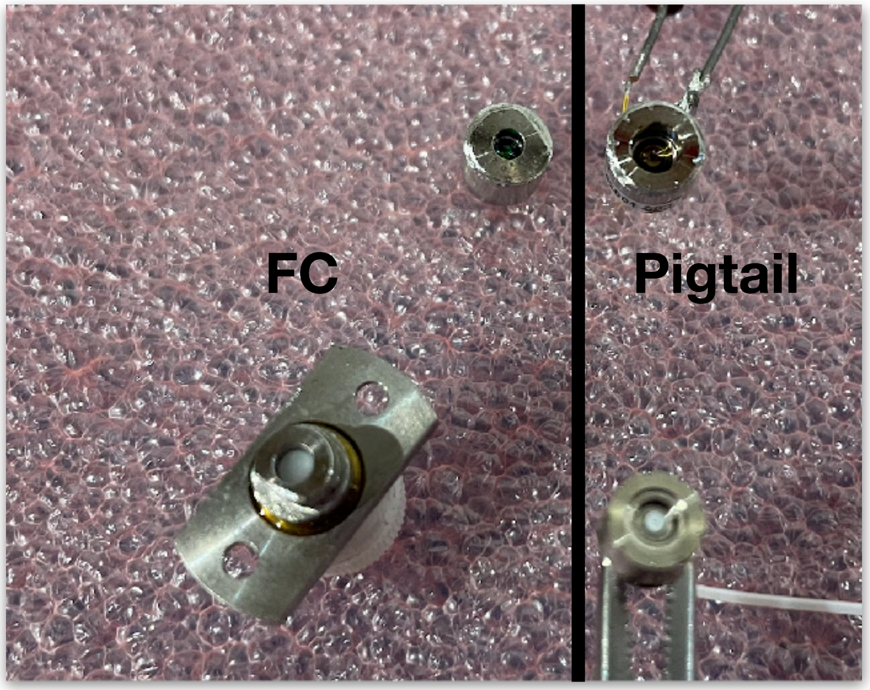


Signal communication with laser diodes in liquid argon

Laser operation is stable in shallow-depth cryogenic liquid, but optical power is lost under 12-15” of LAr/ LN2

Confirmed hypothesis: LAr entering the air cavity where light from the diode is focused into the optical fiber, changing the focal length





Explored and the definite solution:

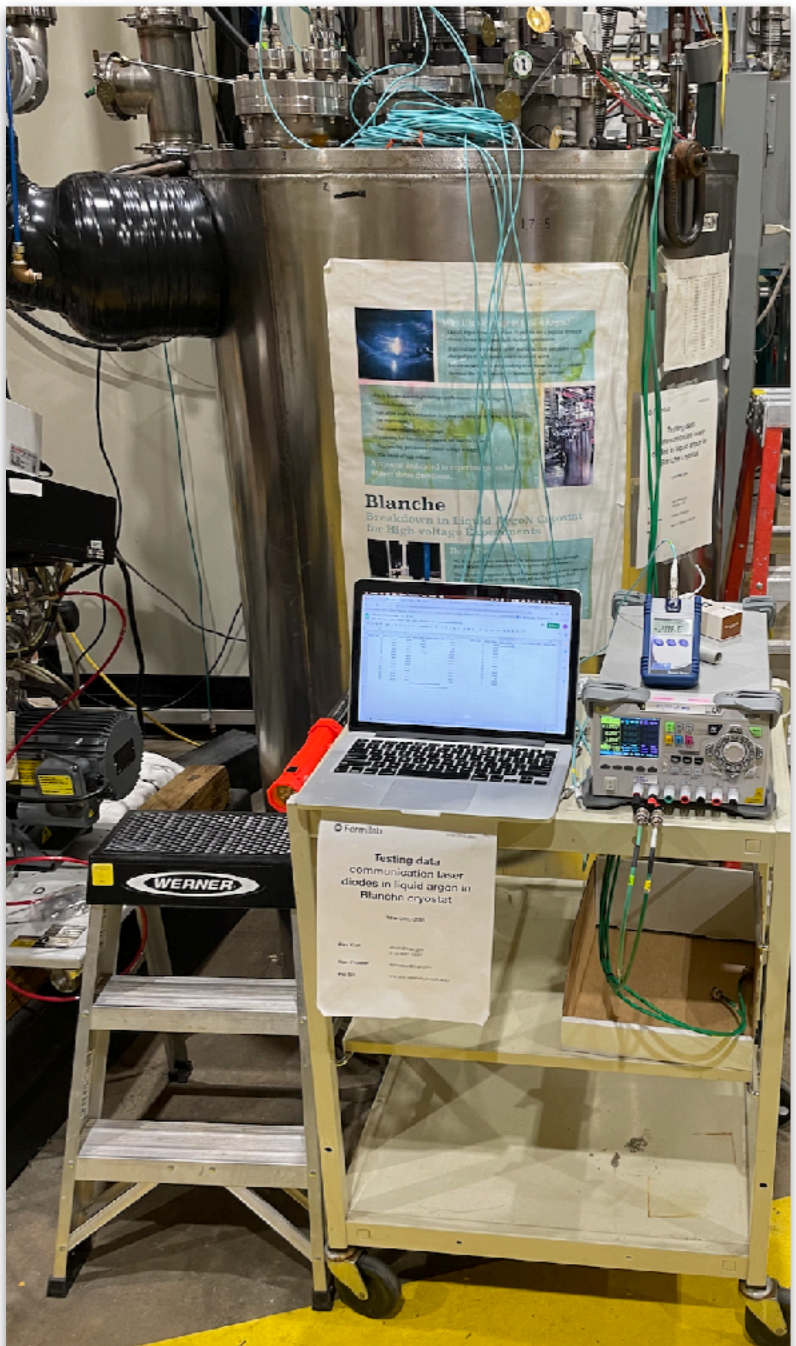
Potting the laser assembly with cryogenic epoxy or silicon
Hermetically-sealed laser diodes
Filling the air cavity with an index-matching material
Adjustment of the focal length for LAr (‘defocusing’) with a penetration for the liquid argon to easily enter the assembly
Large-core fiber to maximize light collection in LAr

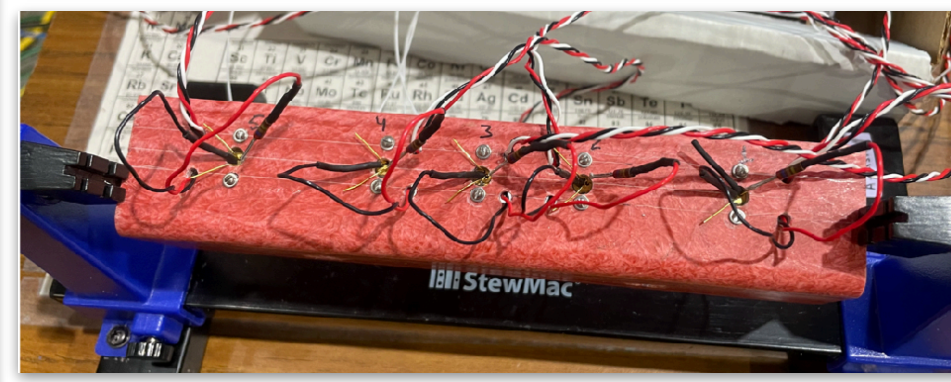
Data communication laser diodes in the Blanche cryostat

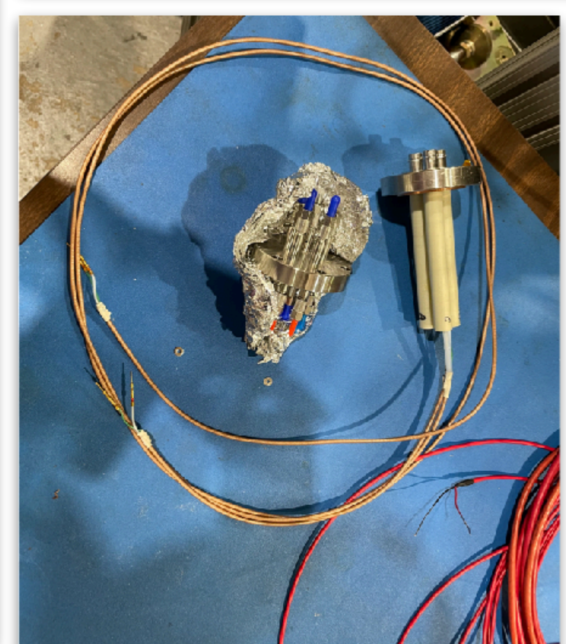
In DUNE, the laser diodes will be submerged in several meters of liquid argon, being a subject to a hydrostatic pressure of ~1bar

Open bath tests provide just ~30-50mbarg pressure

“Deep immersion tests” are being emulated in a closed-loop system in the Blanche cryostat by changing the condenser set point and increasing vapor pressure (1barg ~ 6m LAr)

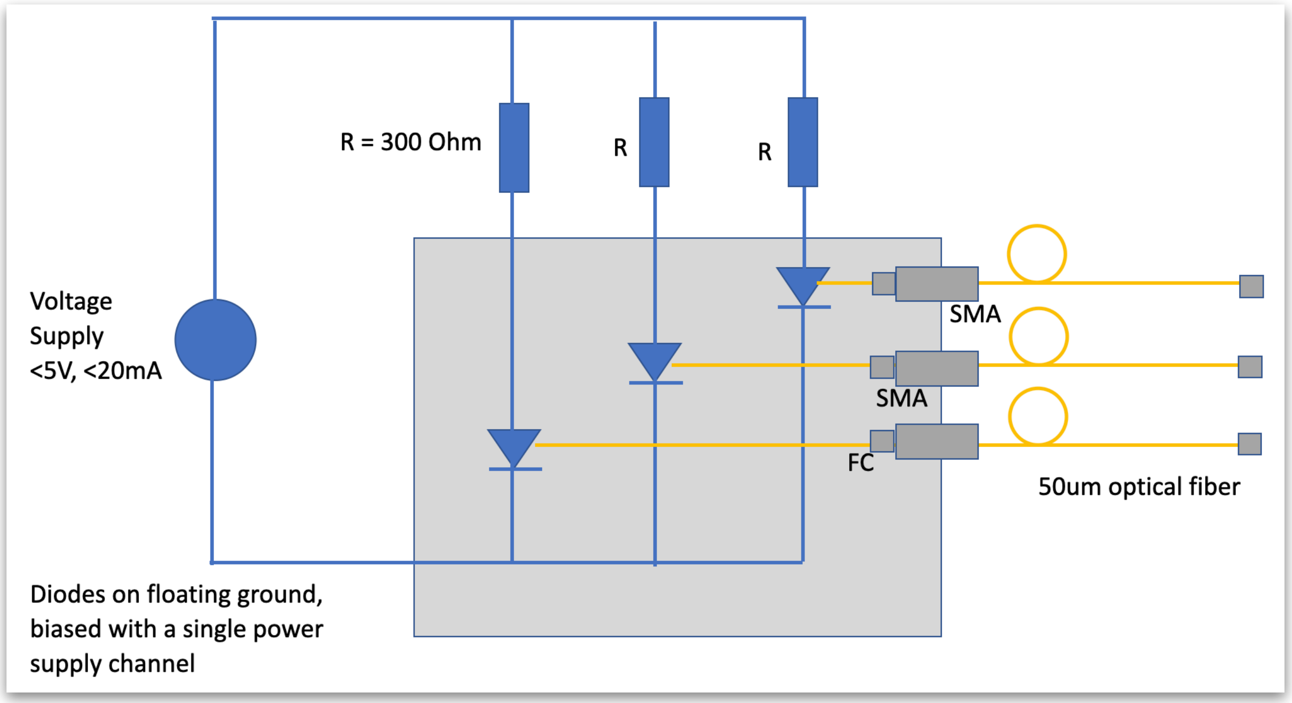






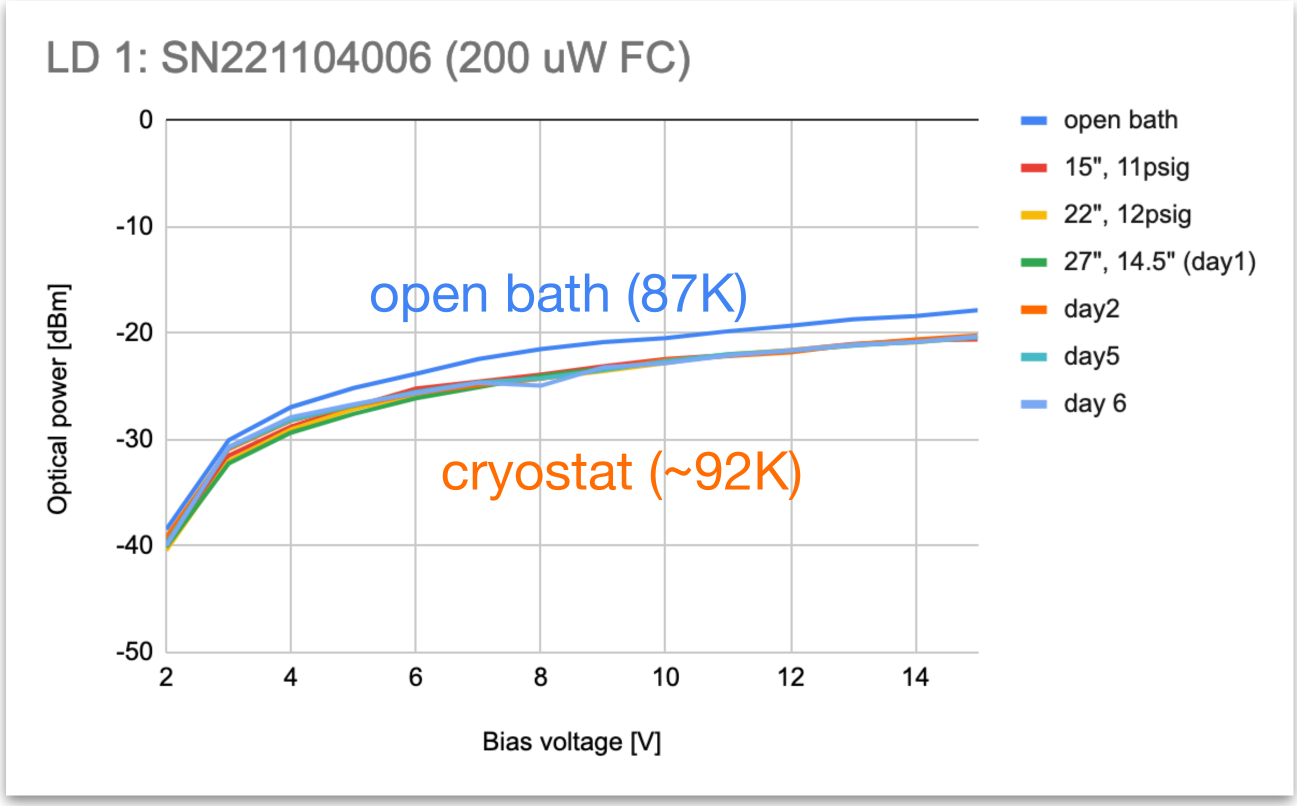
Data communication laser diodes in the Blanche cryostat

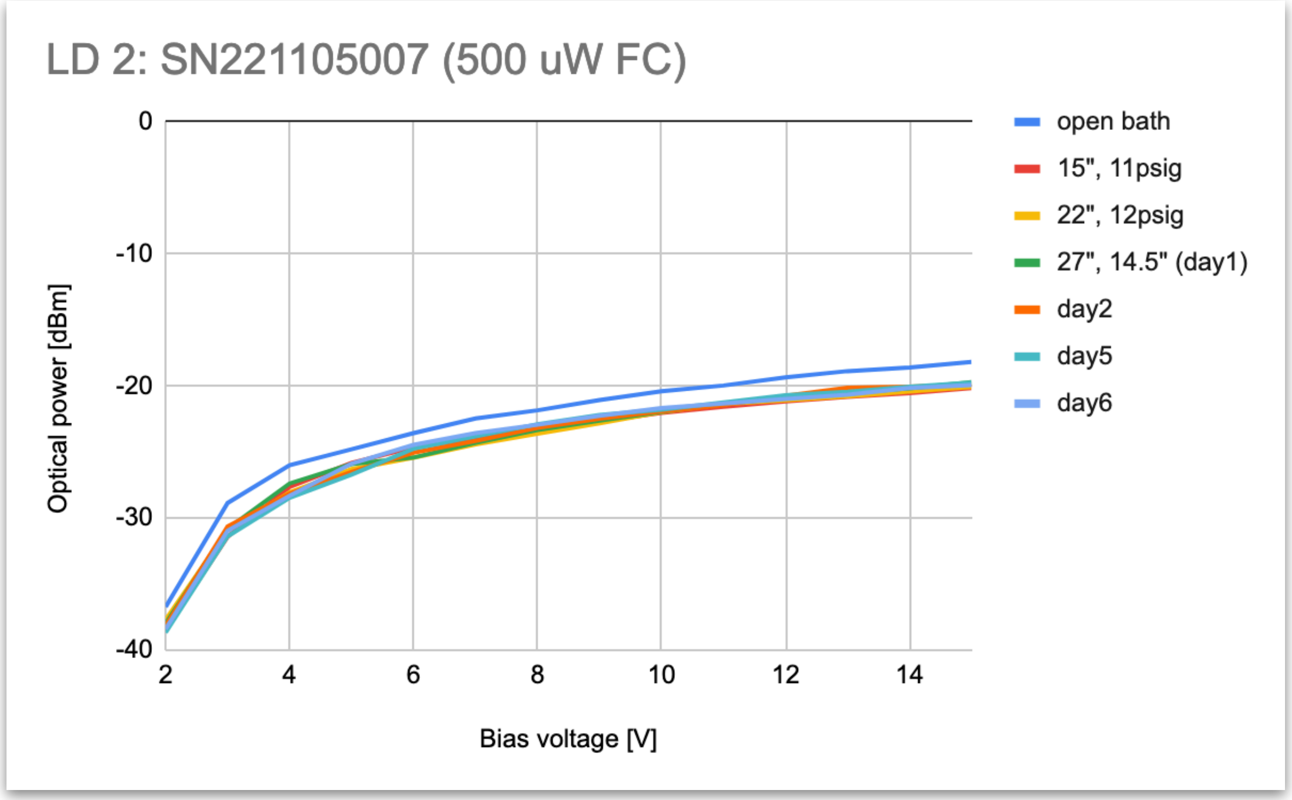
The laser diodes are operated continuously, and a scan of the optical power is regularly taken with a hand-held optical power meter



The one-week run so far shows a remarkable stability of the optical power

Observed temperature dependence between 87K and 92K (will be quantified later and with additional tests)

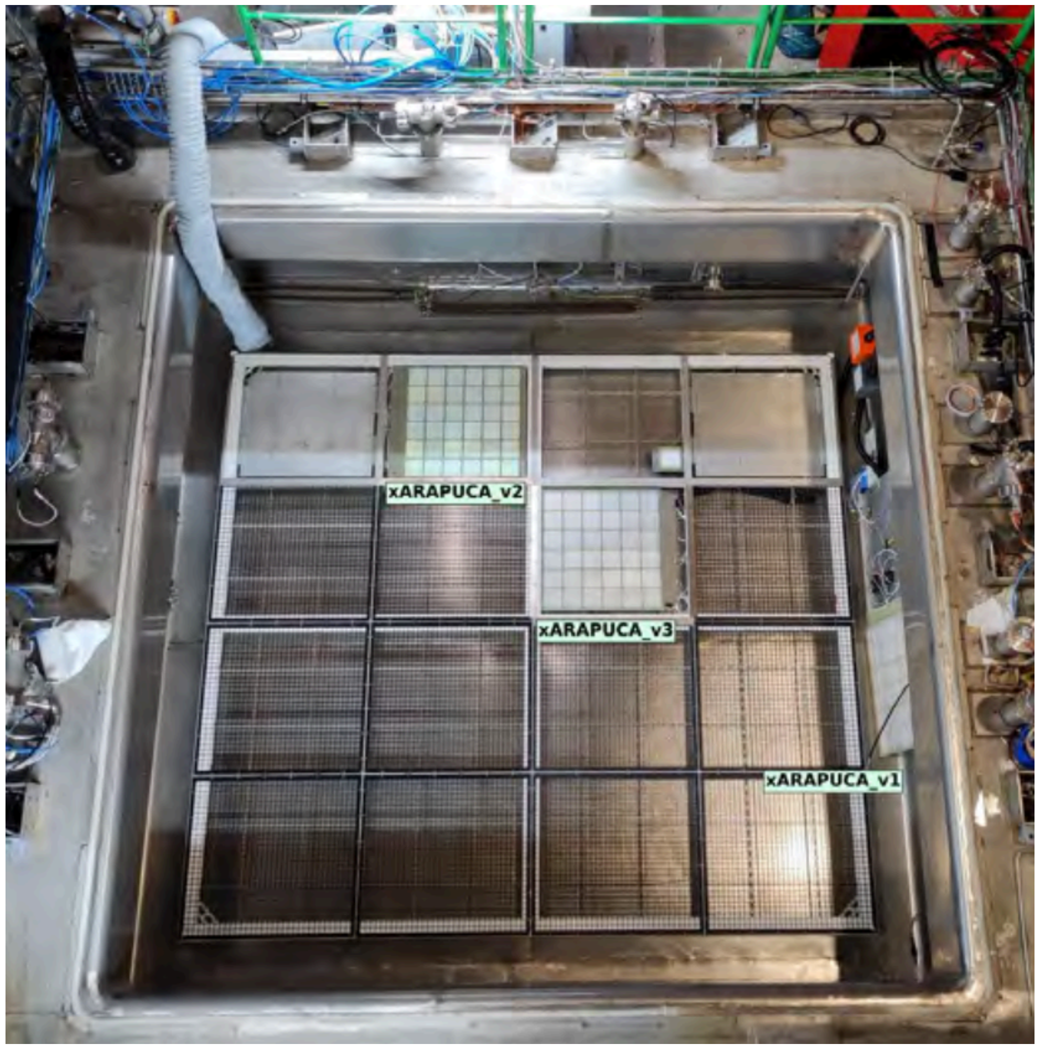


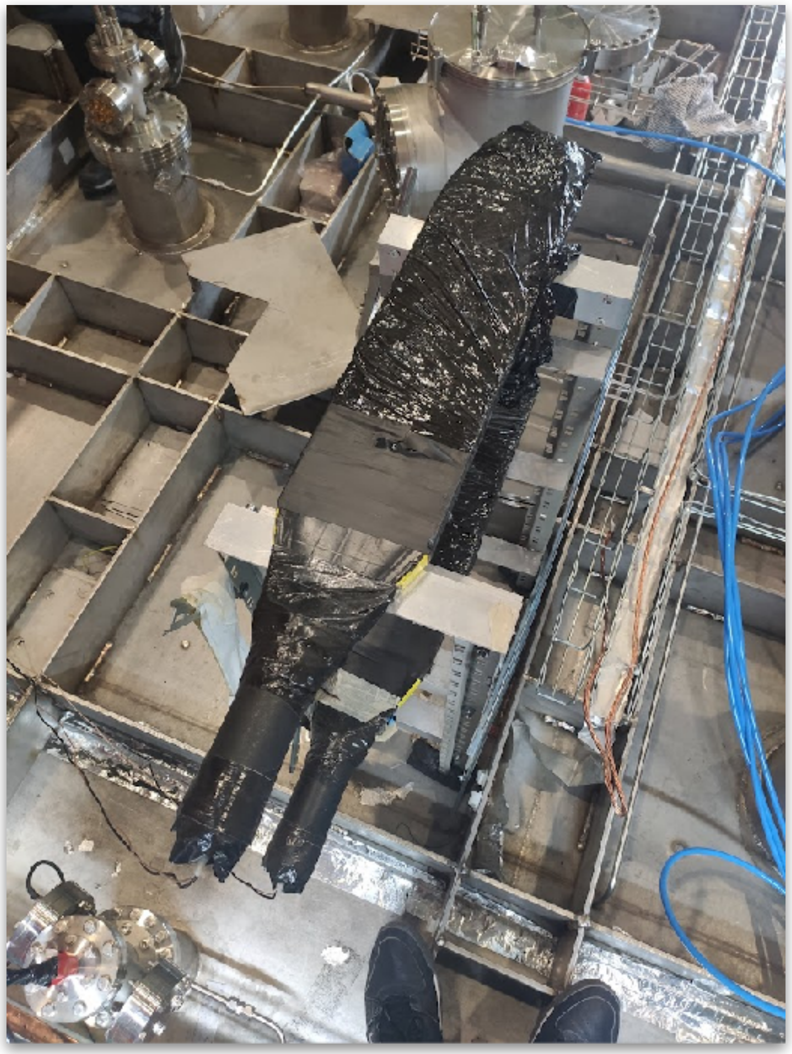


Cold box tests at CERN

The developed and tested cold electronics is delivered to CERN for tests in liquid argon with electric field in a large cryostat (cold box)

Several versions of X-Arapuca and cold electronics boards





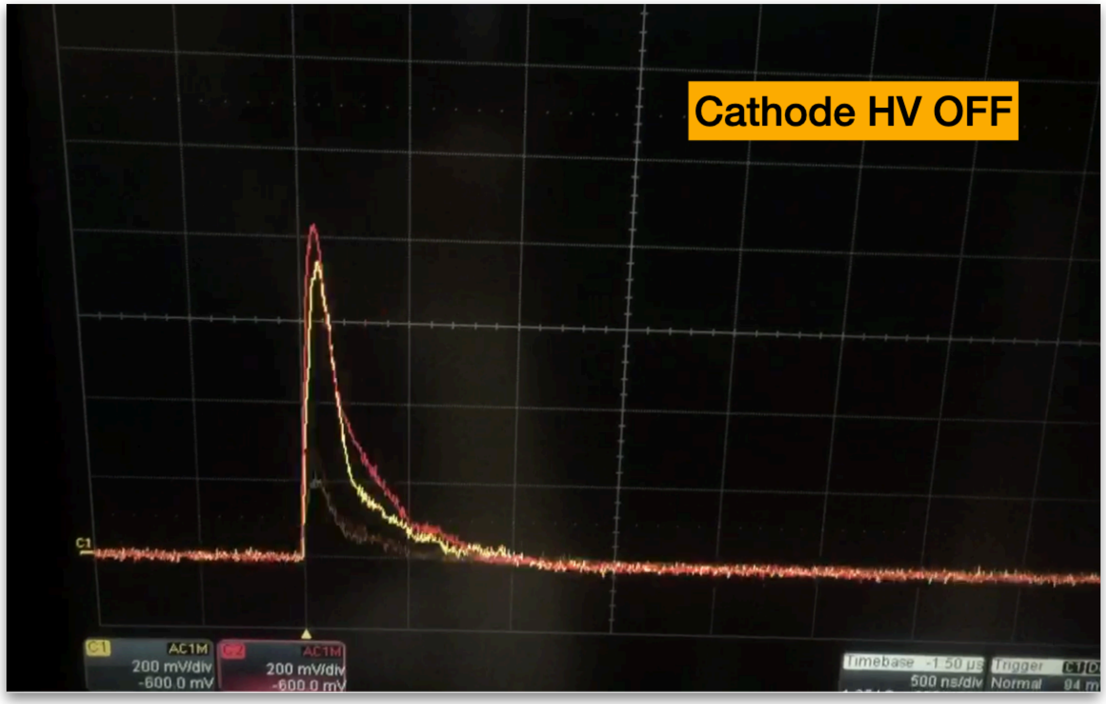
Cosmic ray tagger on the top

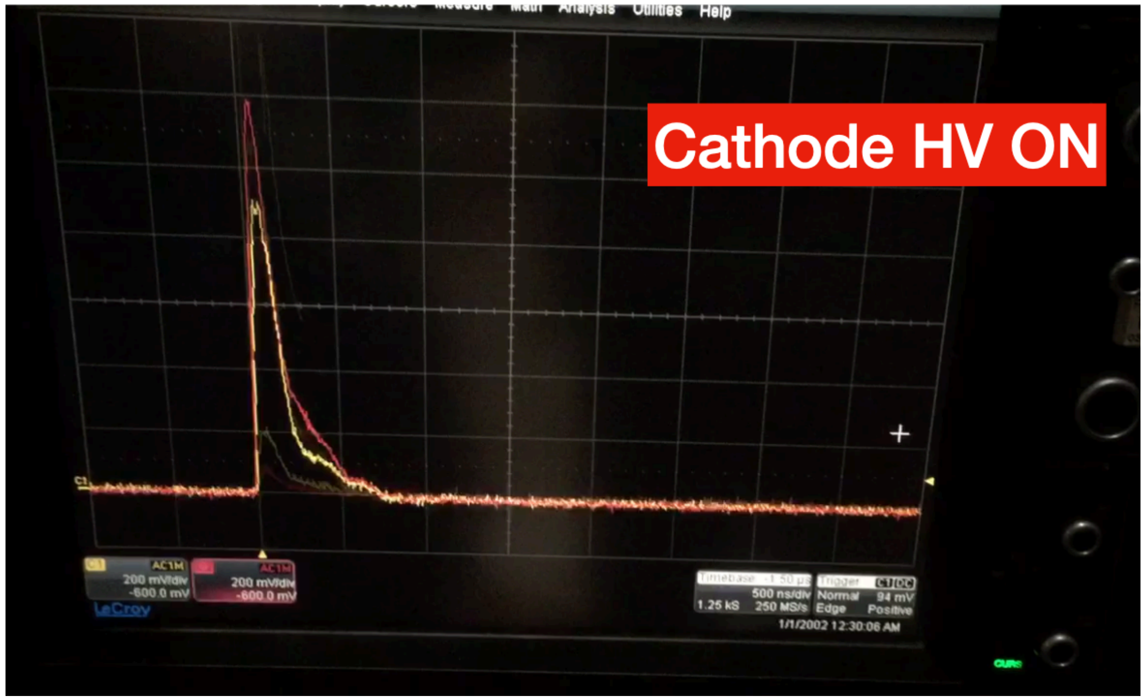
Latest run just finished, the next one is being prepared for February. Then:

March – final design review
April – module-1 design workshop
July – CERN cold box run

DUNE Vertical Drift TPC

Recorded cosmic ray signals. No difference (absence of noise) with the biased electrodes





Resolution on single photoelectron better than 20%, signal-to-noise ratio better than 4

Signal linearity up to ~1000 PE