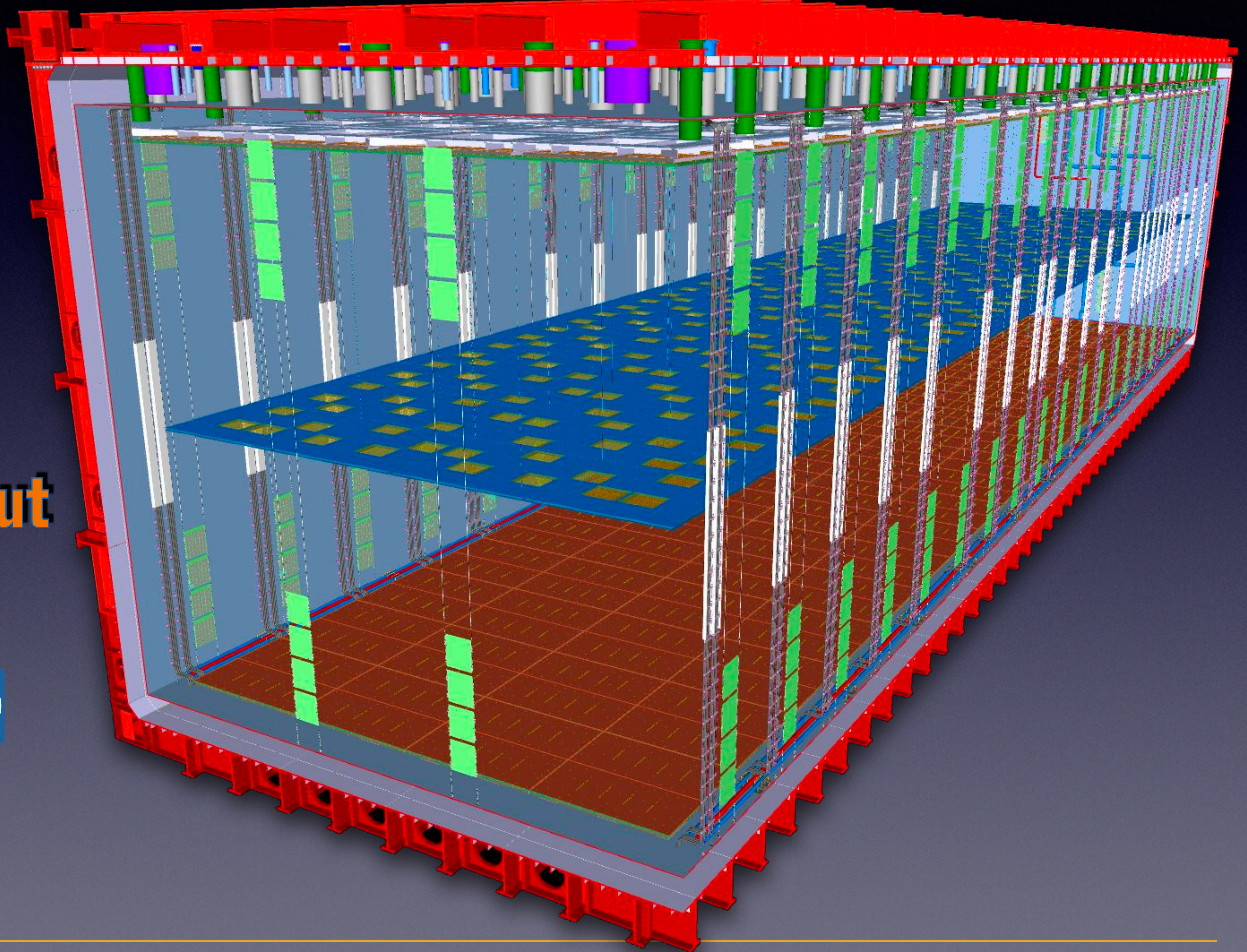
DEEP UNDERGROUND
NEUTRINO EXPERIMENT

The new Photon Detection System for DUNE [FD#2 Vertical Drift Module]

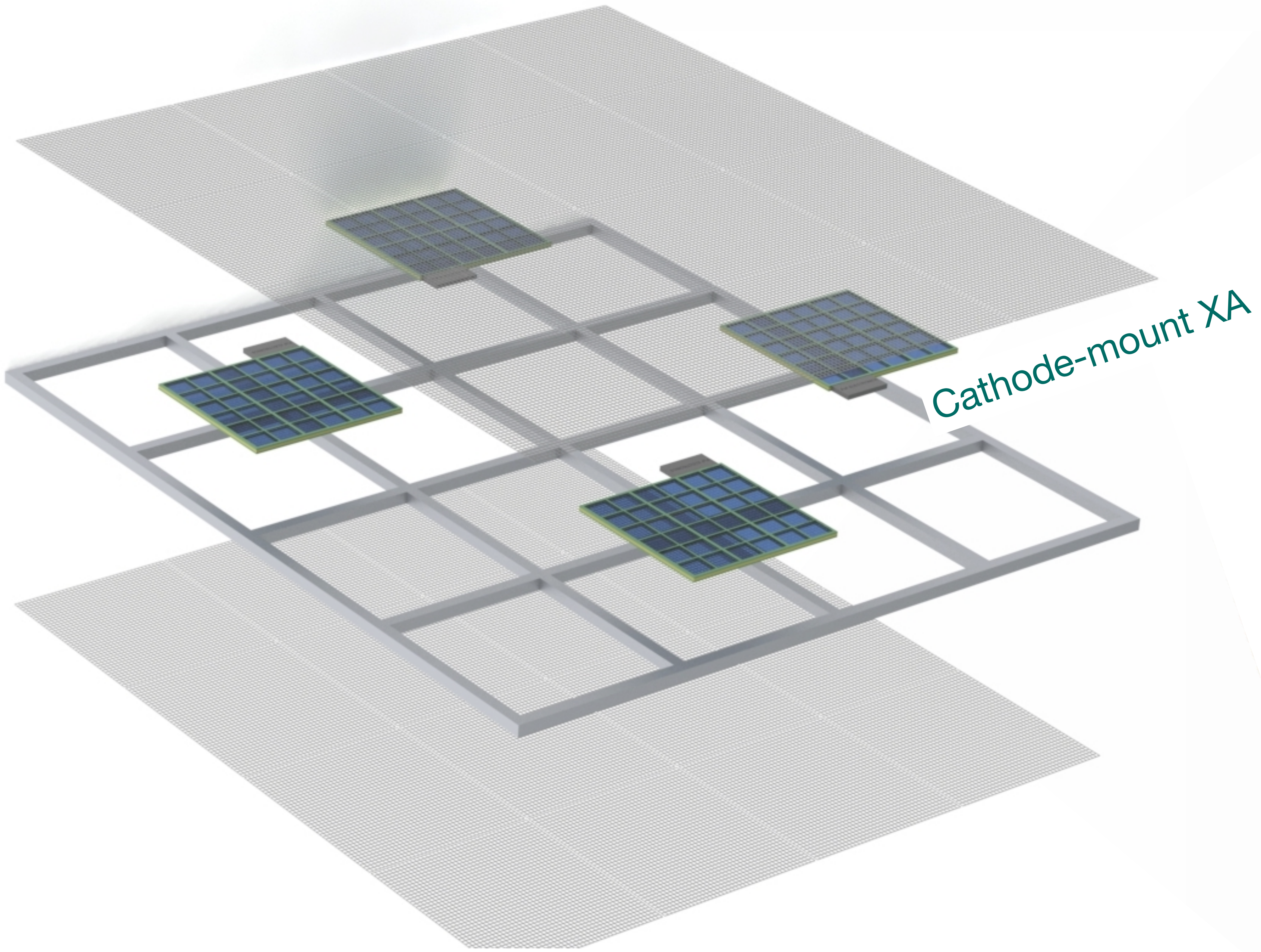
X-Arapuca with PoF and optical readout

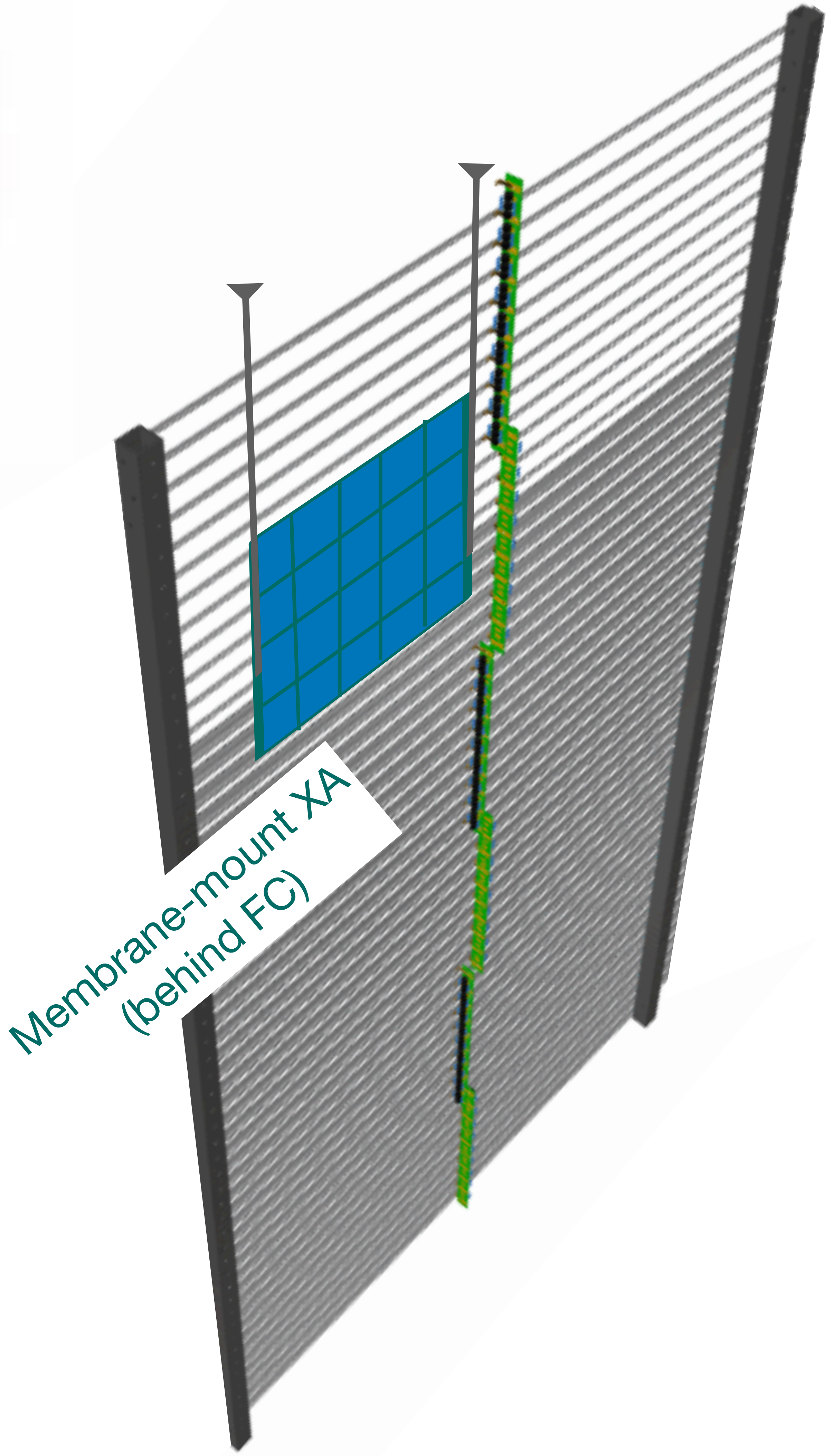


PDE measurement of X-Arapuca VD
Workshop in Naples

April 20-21, 2023

F. Cavanna
Fermilab


Cathode-mount XA


Membrane-mount XA
(behind FC)

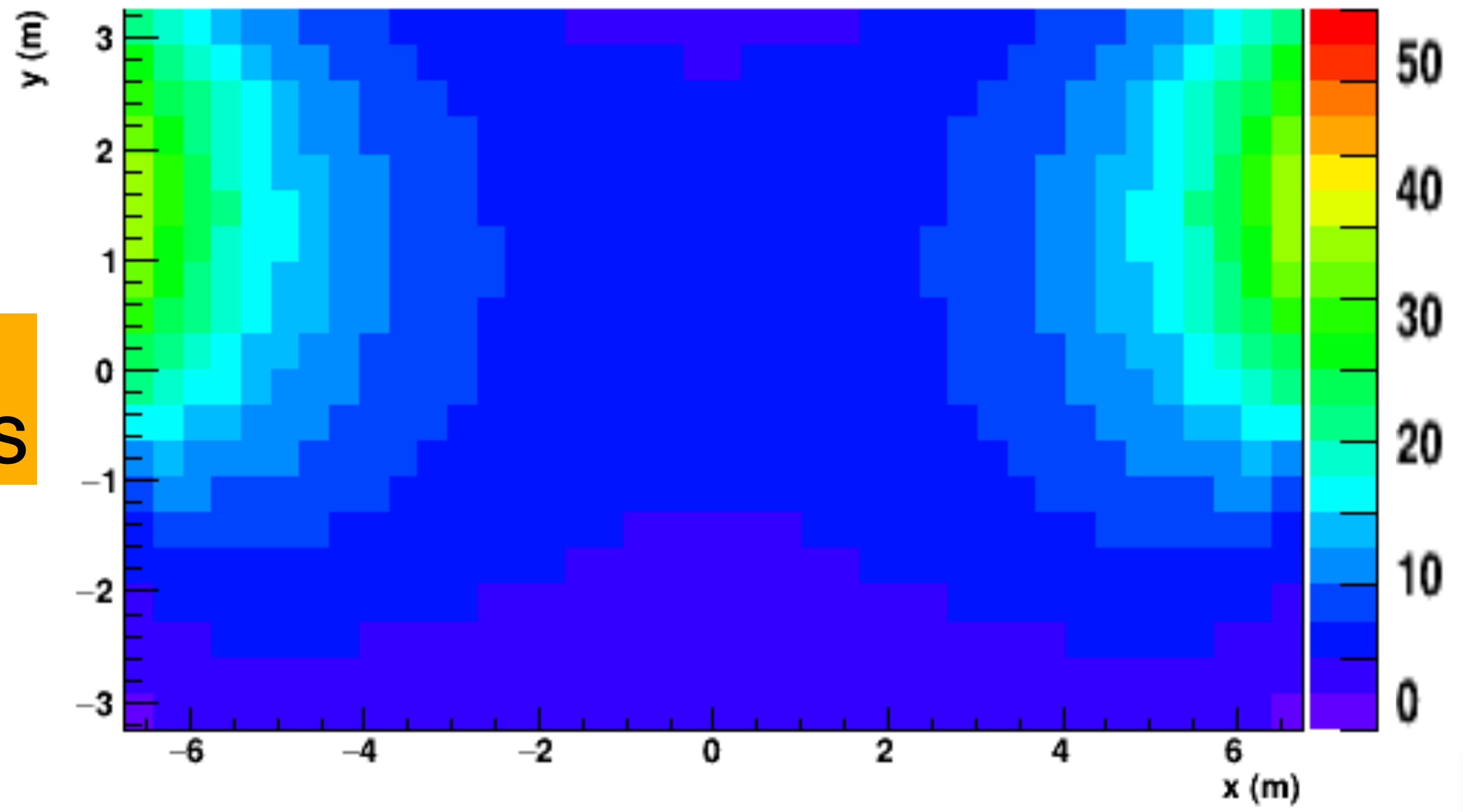
LY [PE/MeV] & LY uniformity Metrics for PD Layout Design

Light Yield maps [***upper volume, above cathode*** - transverse (x,y) plane at z=0, detector mid length] from MC simulation.

Ref.: DUNE FD2 -VD Technical Design Report
FD2-VD TDR v.2
FD2 PDS Characterization by G4 Simulation

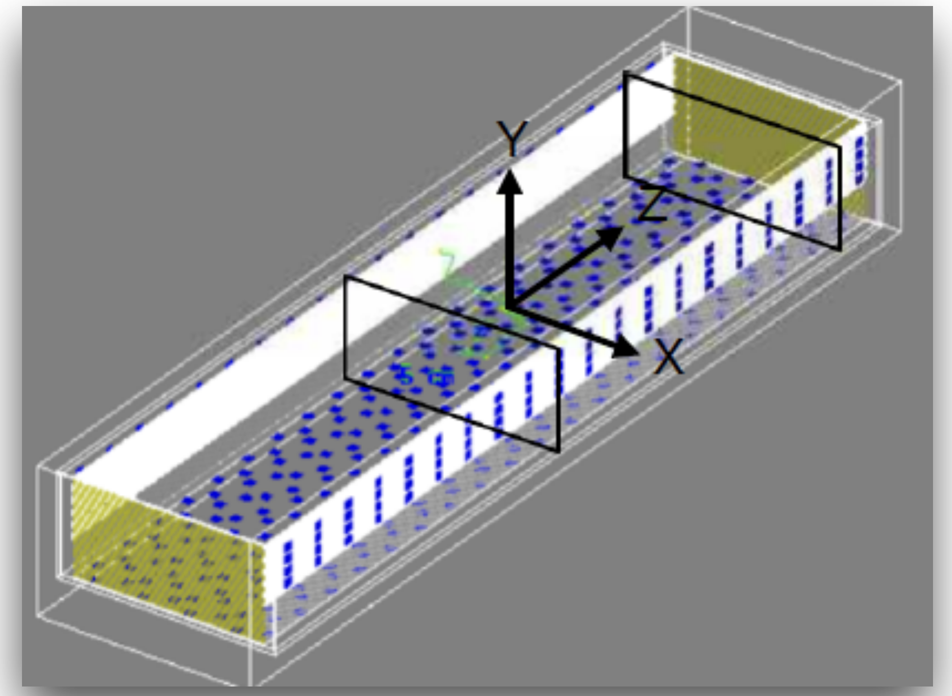
All-Membrane mounted PDS

$\langle LY \rangle \simeq 9$

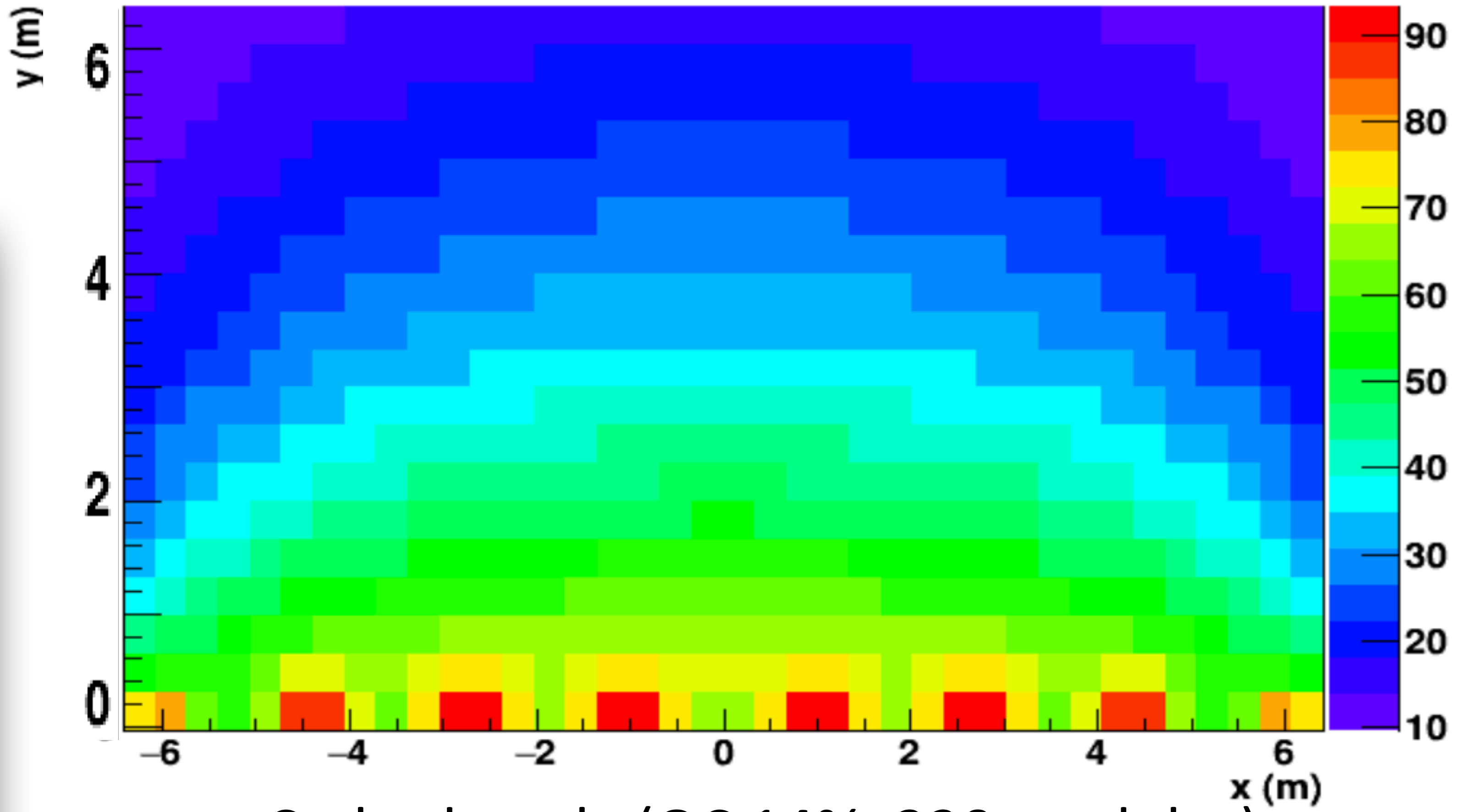


Membrane only [OC 7%, 320 modules]

upper volume, above cathode



$\langle LY \rangle = 36.2$



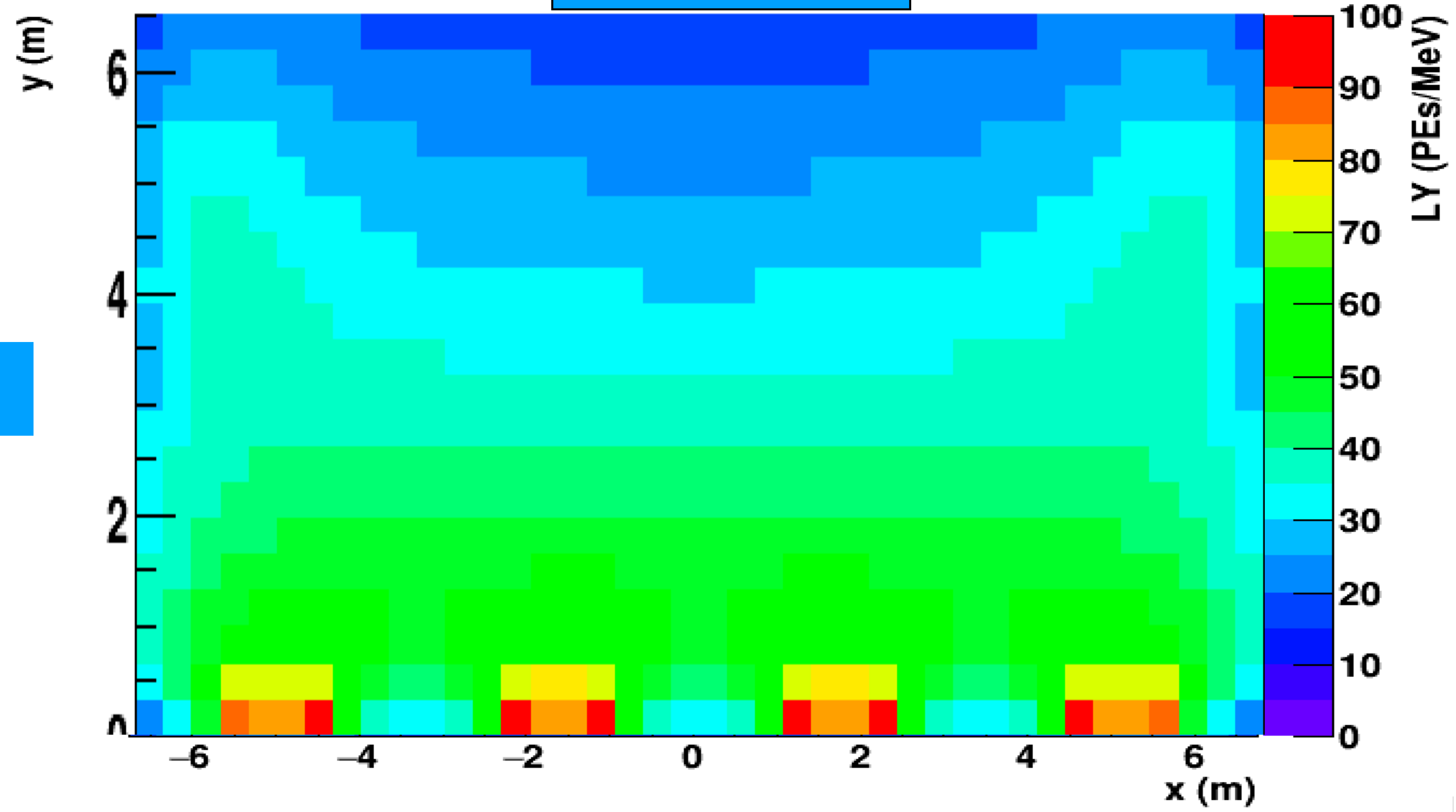
Cathode only (OC 14%, 320 modules)

[Cathode OC 14%, 320 modules &

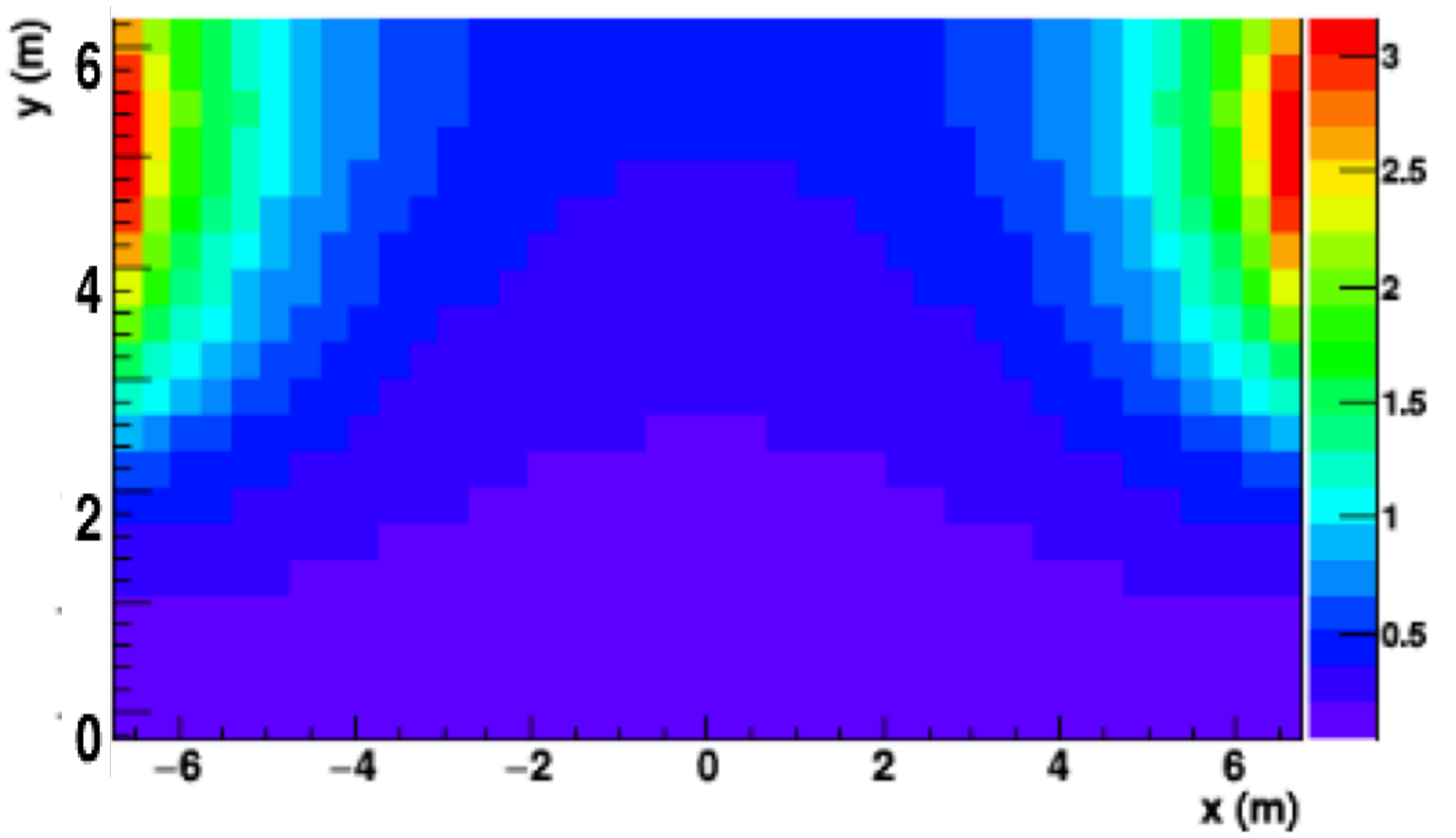
Membrane OC 7%, 352 modules]

(~4pi) Reference Design

$\langle LY \rangle = 39$



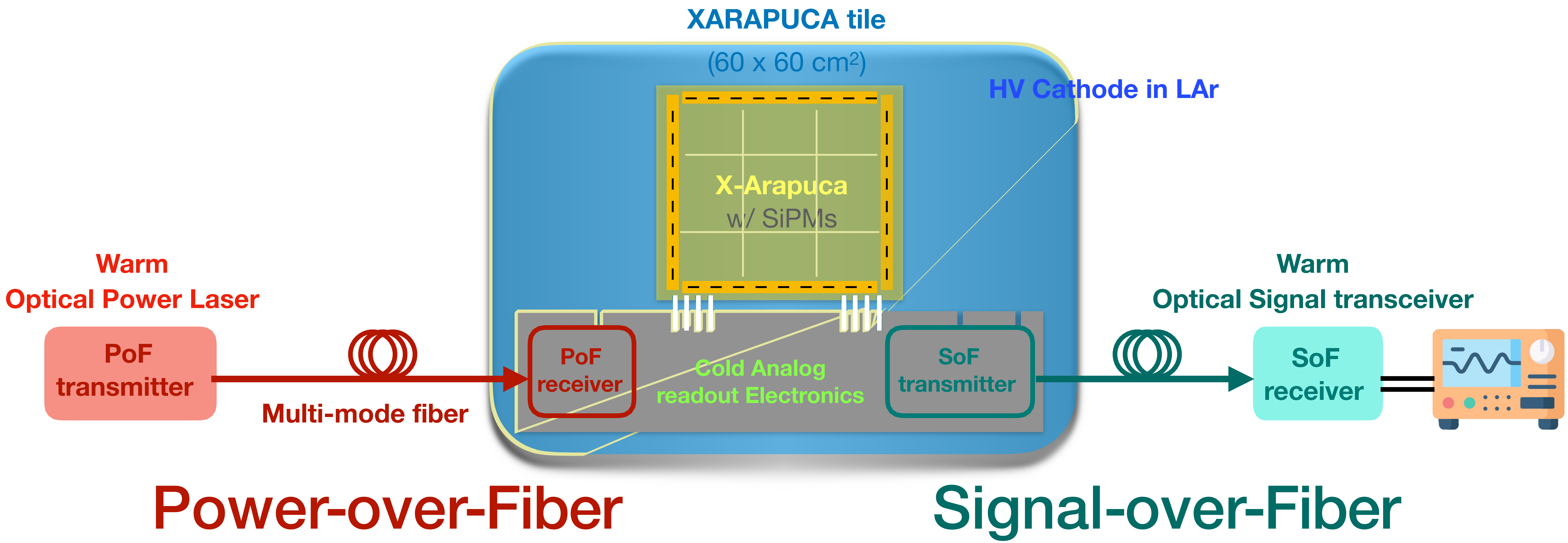
LY ratio: lateral membrane-mount LY over cathode-mount LY



The electrically isolated
(only optically connected through fibers)
low noise

FD2 Photon Detector Concept

in a nutshell



The novelty elements in the FD2 VD PDS Design

- Large number of SiPMs per Electronic Channel (80): 2 ganging stages [hybrid Passive, Active sum/ampli in Cold]
- Large(st) photo-detector sensitive area (60 x 60 cm^2): XARAPUCA large form-factor with new WLS plates, new dichroic glasses.
- PoF (electrical isolation, noise immunity, spark-free operation) never operated in HEP, existing technology to be validated in Cold (at LAr T) SoF (electrical isolation) develop Cold custom technology
- Optical Fibers (instead of copper cables)
- Interface w/ Cathode System
- Onset of Optical Noise (way less familiar than Electrical Noise)

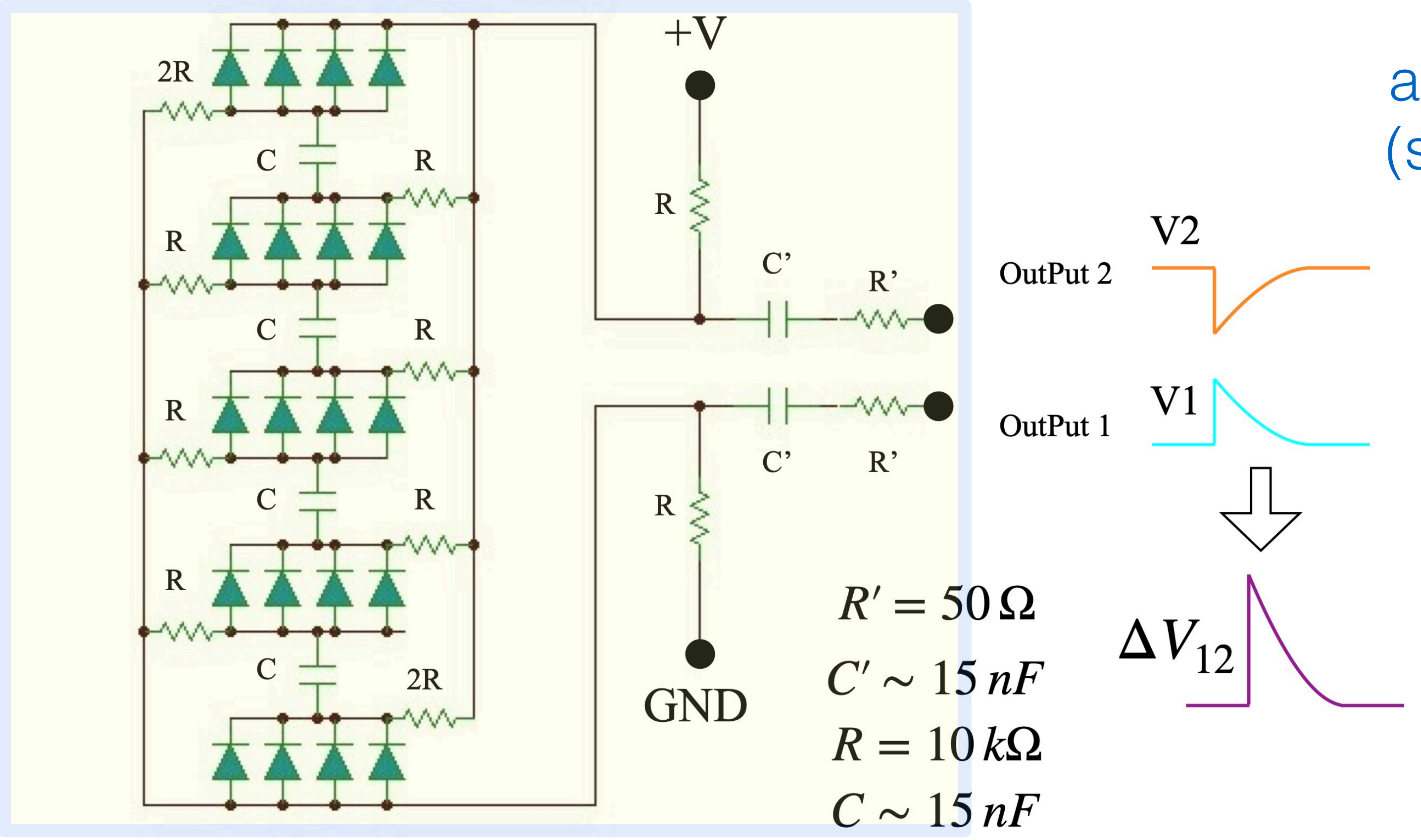
The VD LArPDS Design and Development path

for an **electrically isolated**
(only optically connected through fibers)
low noise
new photon detector concept

•Validation Milestones

Concept & Prototypes: *Cold Box tests at CERN 2021*

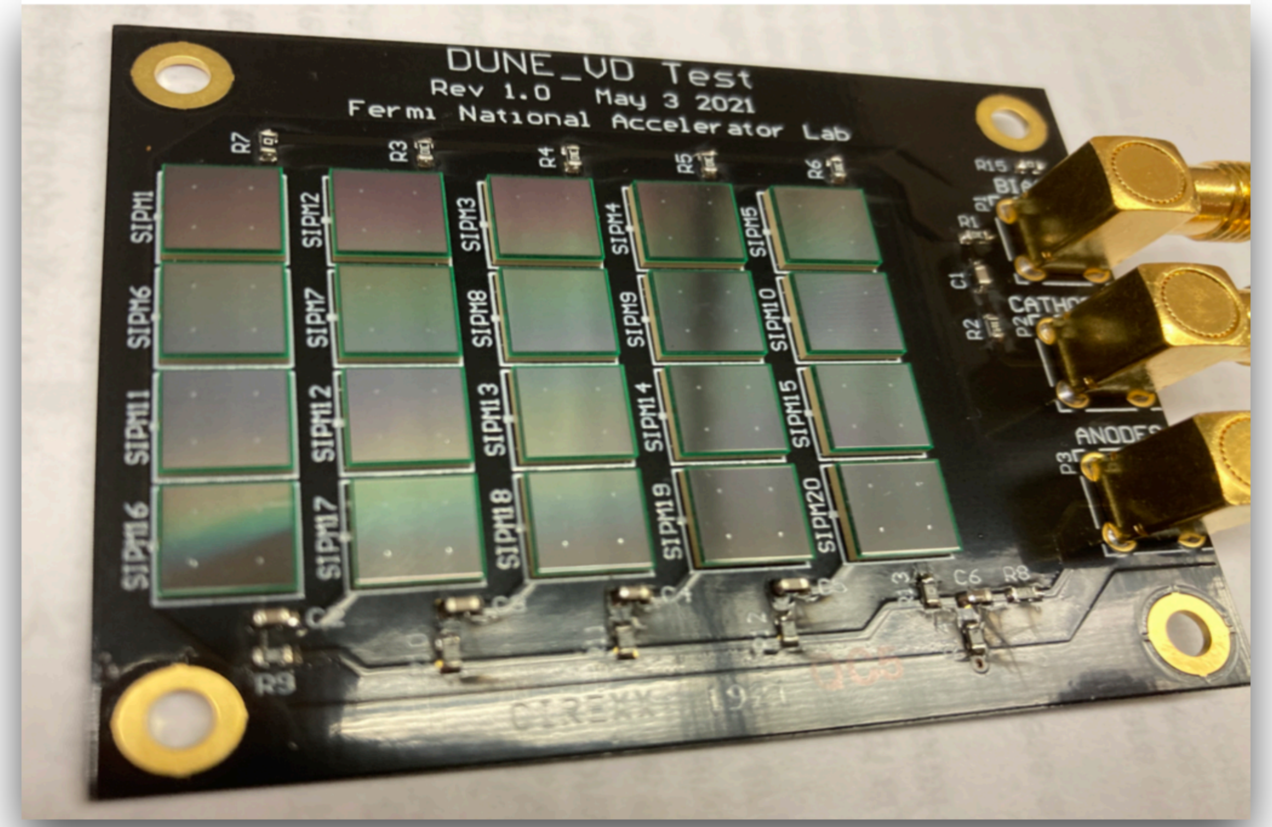
SiPM board



Series connection for signal and parallel connection for bias (similar to MEG-II)

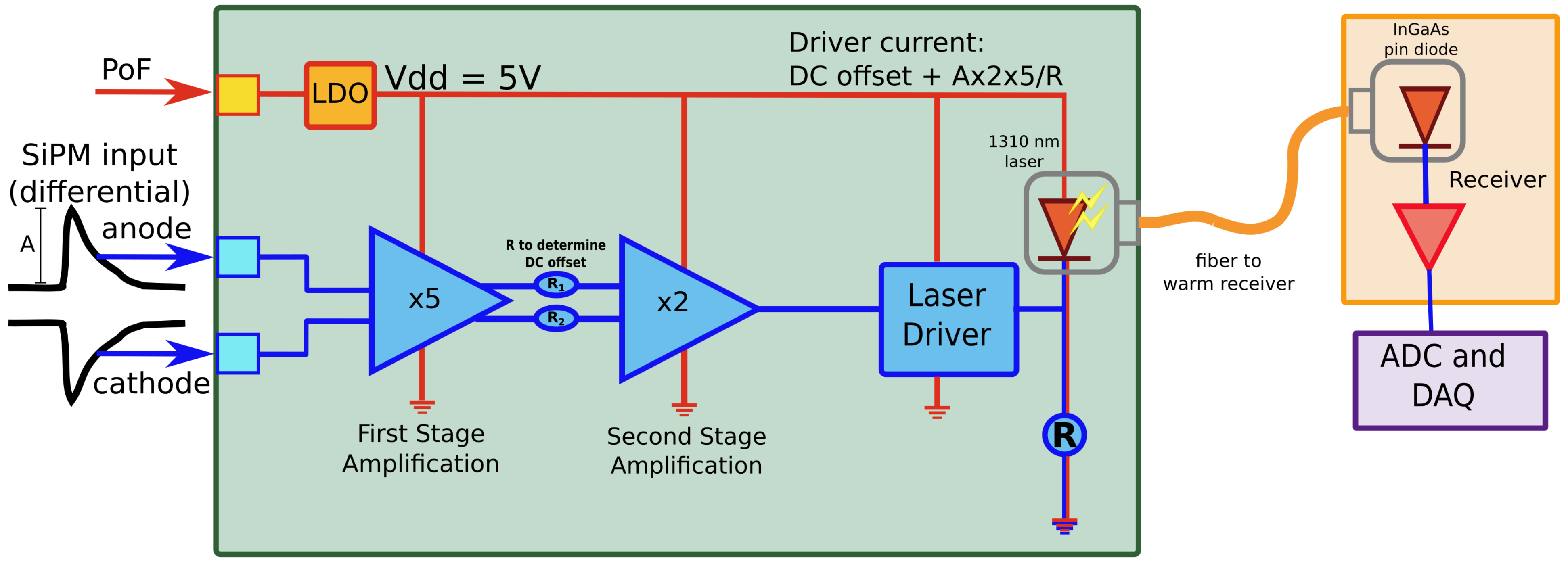
the prototype SiPM Board - Passive ***hybrid*** ganging

UCSB
Fermilab



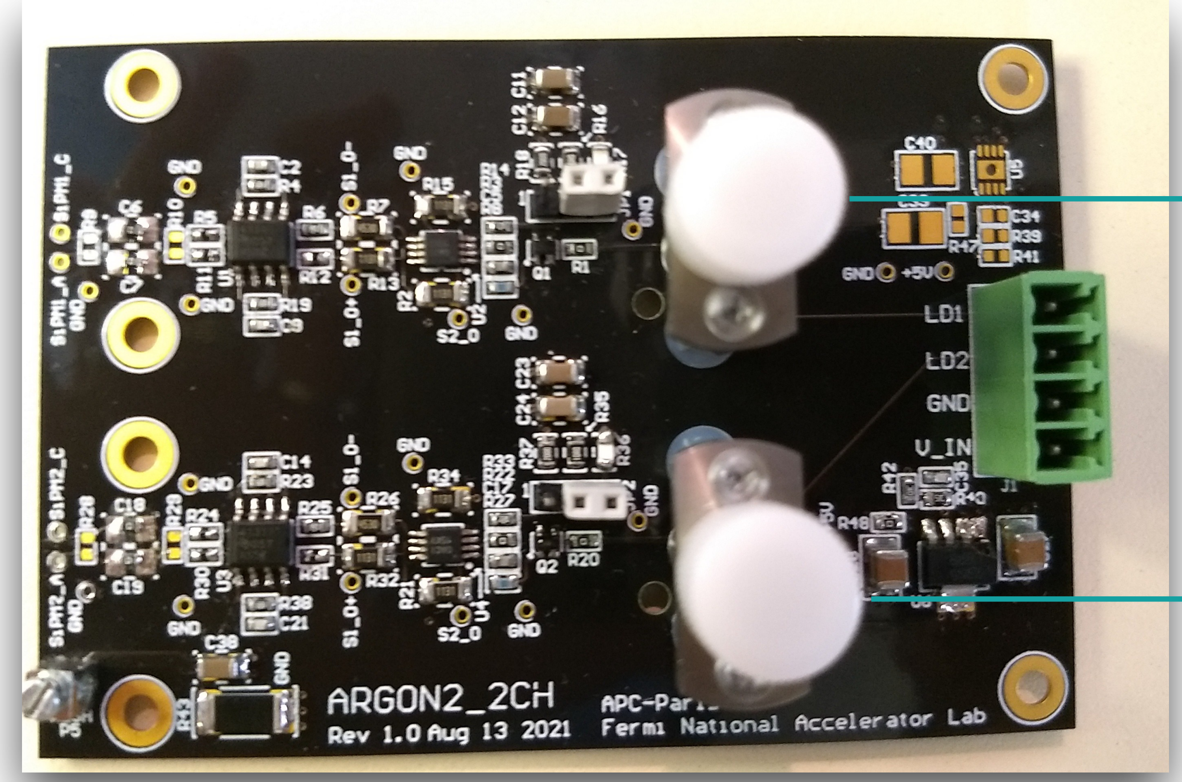
Hamamatsu MPPC S14160-6050HS

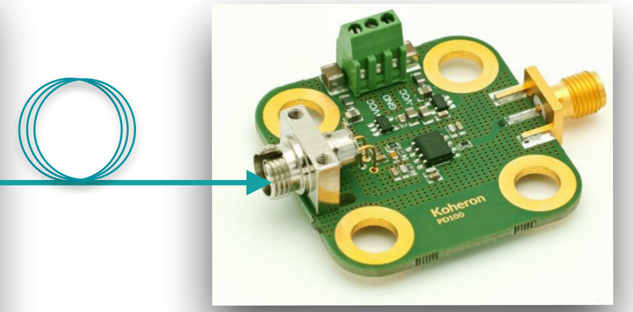
Analog CE Board



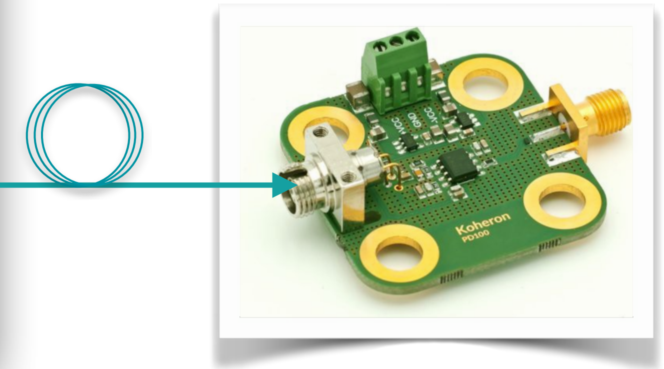
the Analog CE Prototype Board - Active ganging/Ampli & SoF

cnrs
Fermilab
UCSB



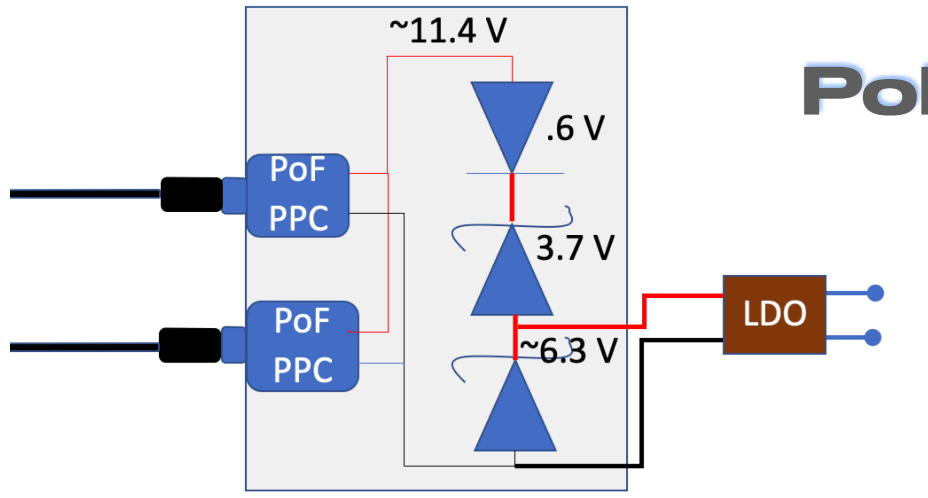


SoF Warm Receivers



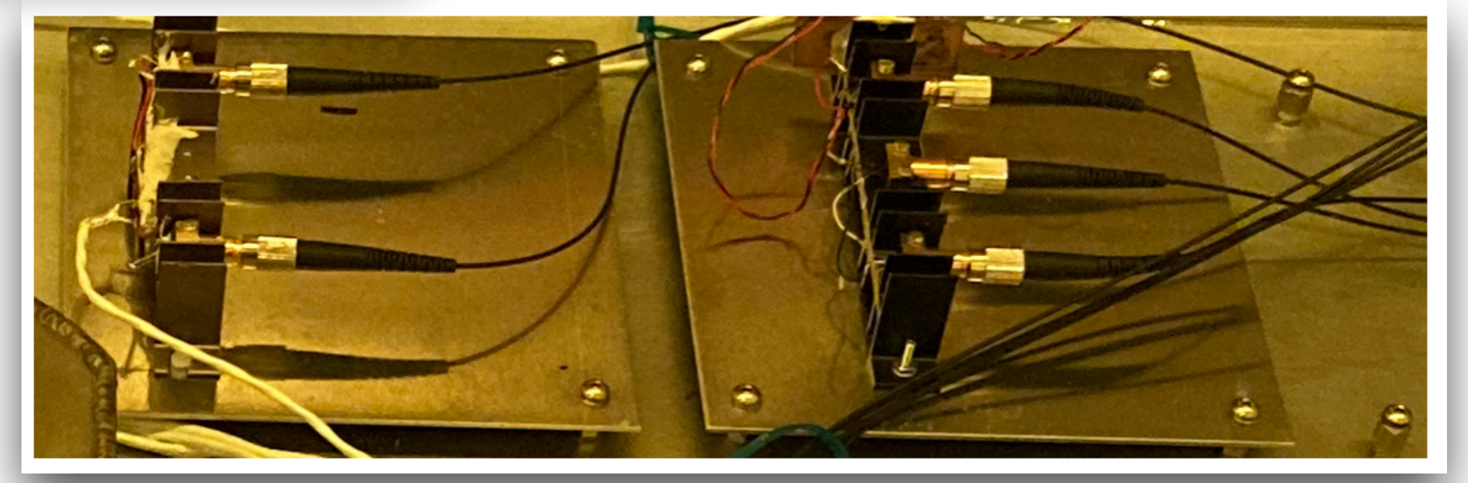
cnrs

PoF Si-OPC Board



Zener diode voltage divider and LDO for LV-HC PoF output voltage regulator

Fermilab



PoF Operating Guidelines

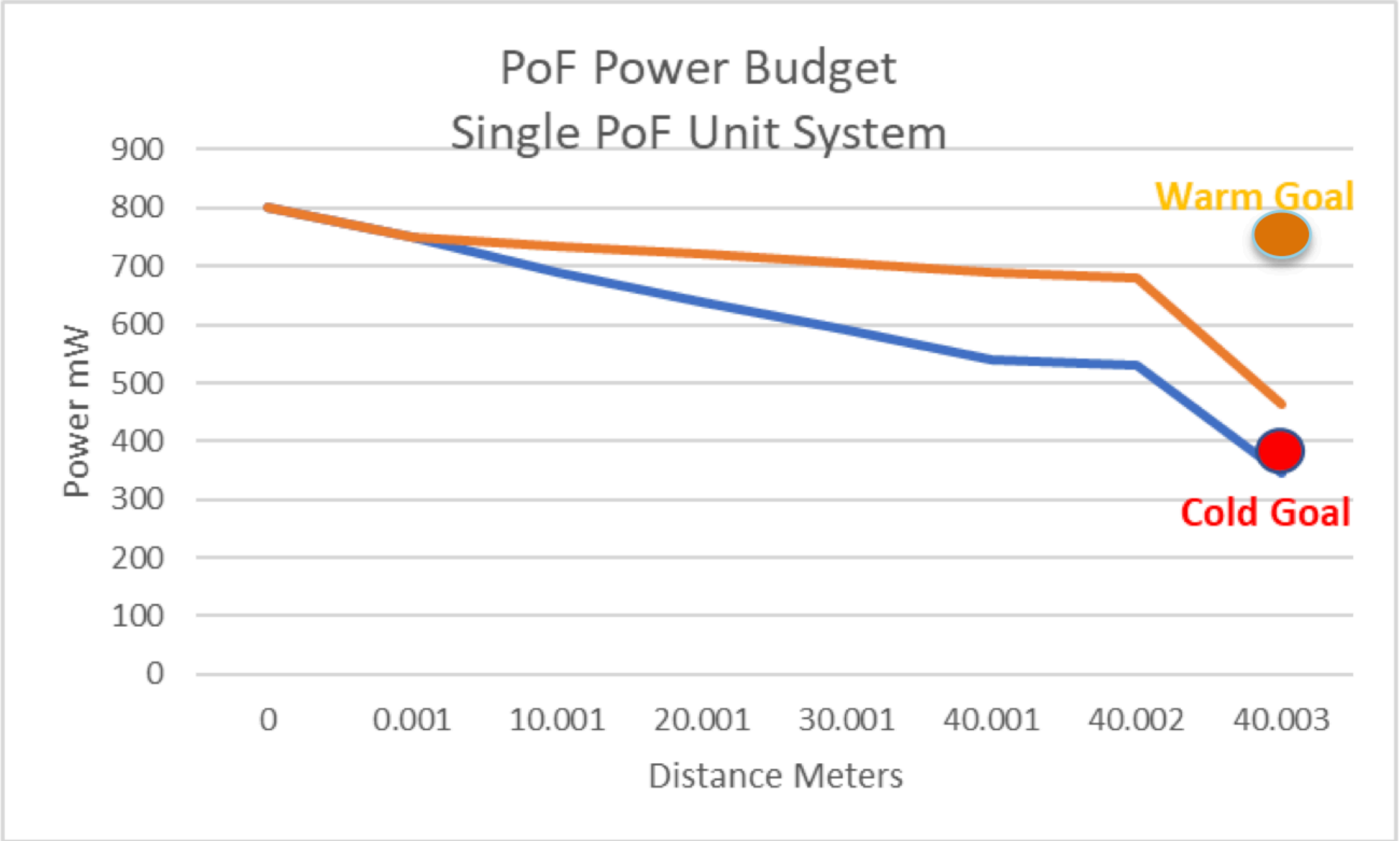
PoF System

COLD SIDE POWER NOTES

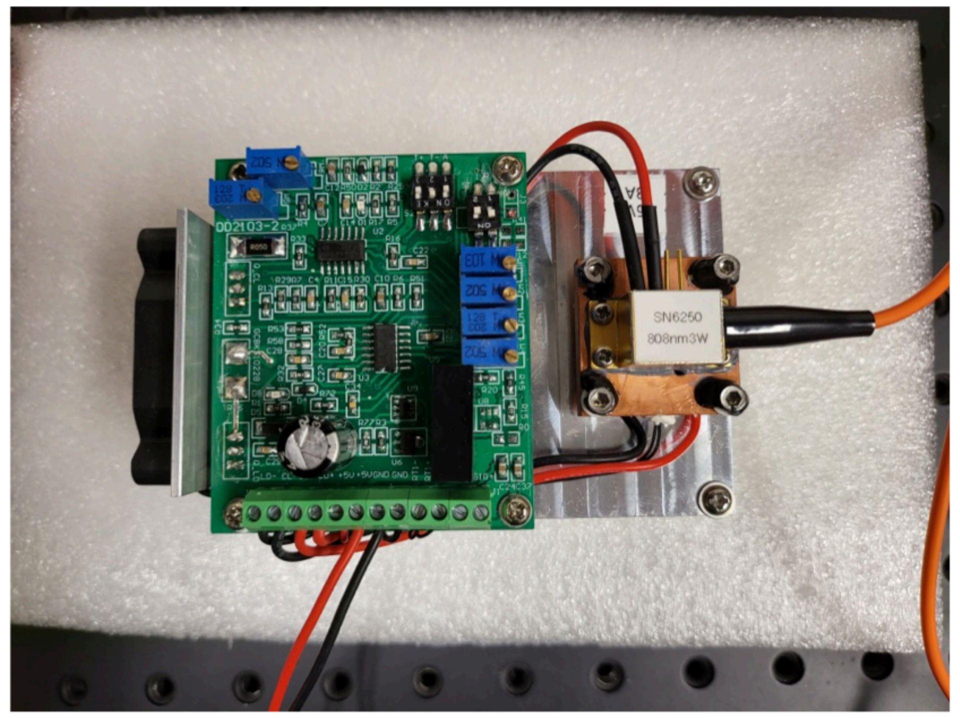
- Designed to above required/unit for 30-year viability
- To have redundancy the system is designed to be capable of >2x/unit
- Noise – < 1 PD per 10us
- Safety – meets DUNE/FNAL ES&H
- Contamination - mostly previously used

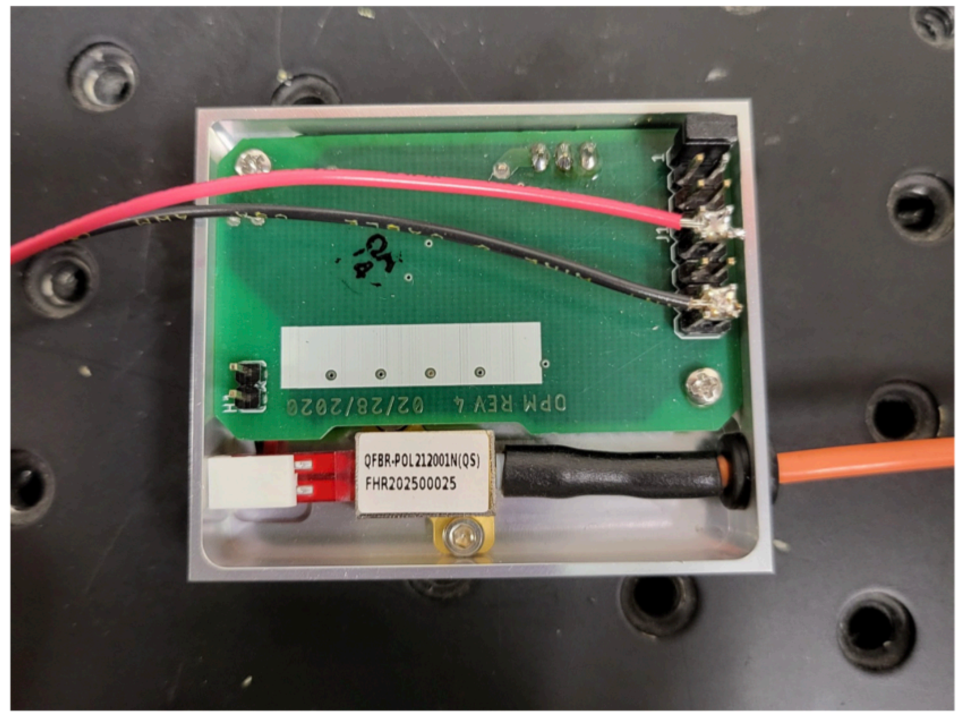
WARM SIDE POWER NOTES

- Safety – Class 4 to Class 1 conversion
- Capability – Cold plus system loss budget
- Cost – OTS products as much as possible
- Viability – Designed to be repairable



Laser Power	OPC (Optimum)	Fiber
2 W/unit Max	400 - 700 mW	6 W
800 mW Op Pt	600 mW Op Pt	600-800 mW





808 nm cw lasers.

– Power: Wanted a laser capable of 2x operating point

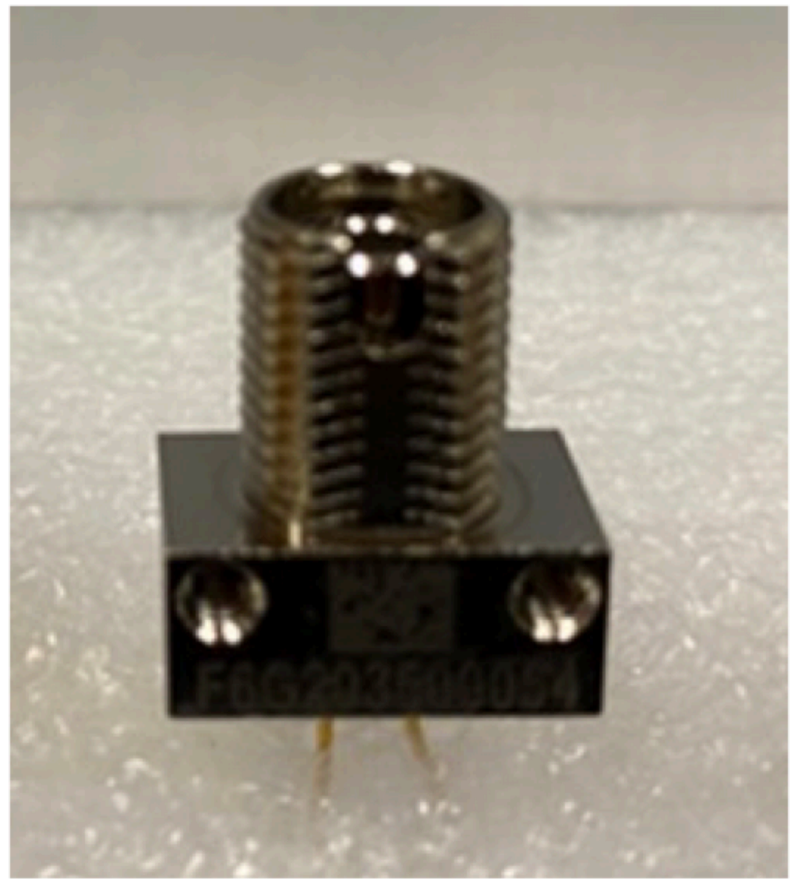
– Stability: Better than 10% power flatness

– Cost: Commercial unit with limited features required

– Lifetime: >10-year lifetime at full power

GaAs
Achieved power needs, regulation and relibility

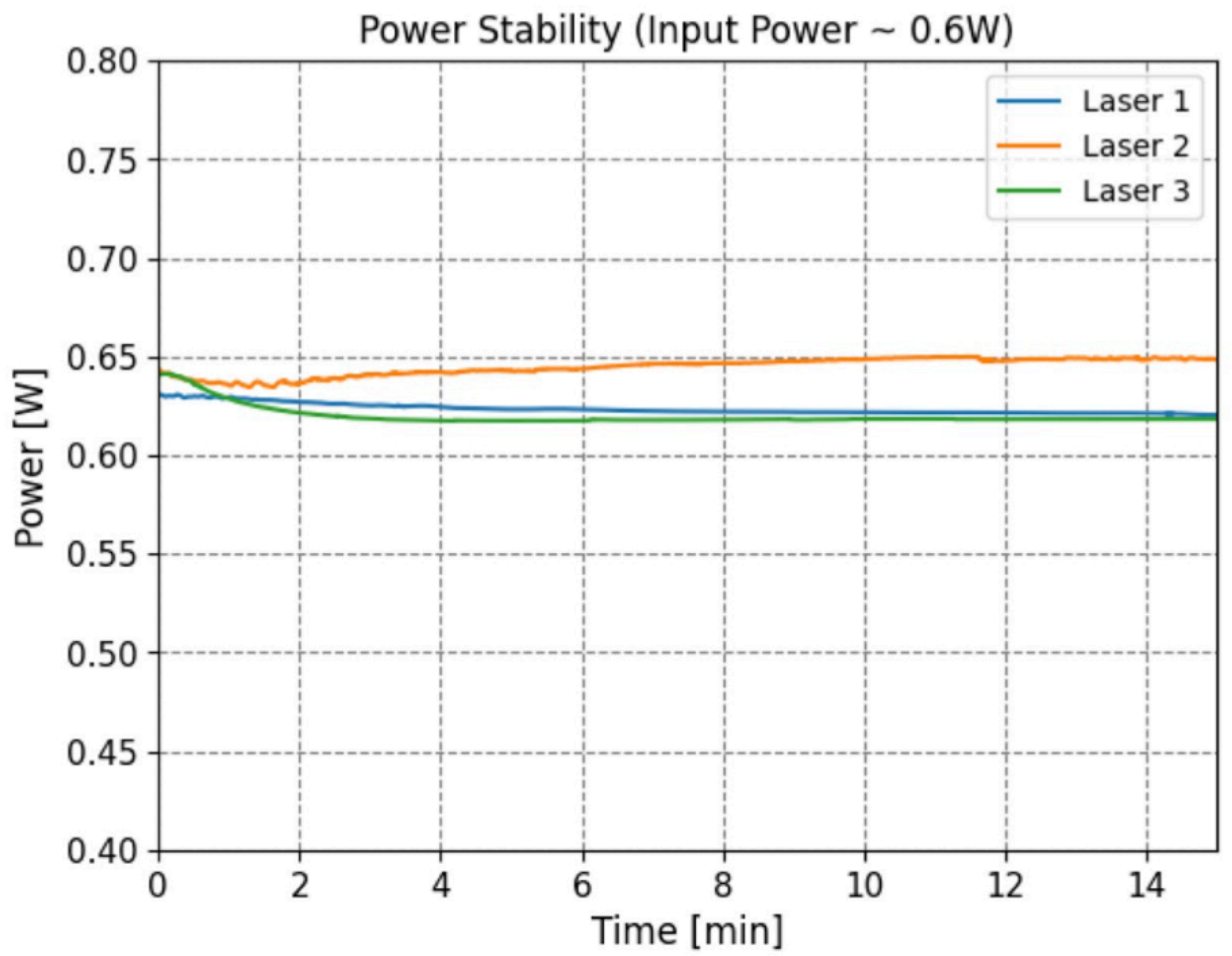
- During the development of the GaAs cryo use – additional R&D was/is desired.
  - A contract with University of Illinois school of engineering was started
    - GaAs potential at cryo temps was not fully investigated
      - Carrier freeze out was evident
      - Tunnel junctions at cold temp became more resistive
    - Build units that meet VD PD specification
      - Extreme low temp ops with efficiencies of room temp devices
      - No contaminants
      - Use of approved material – namely epoxies/sealants



In the end a partnership between FNAL, Broadcom, UIUC and GoPower

The final version (V4) has undergone several noteworthy improvements to achieve the higher efficiency at cryo Temps and to reduce impact of cryo on optics.

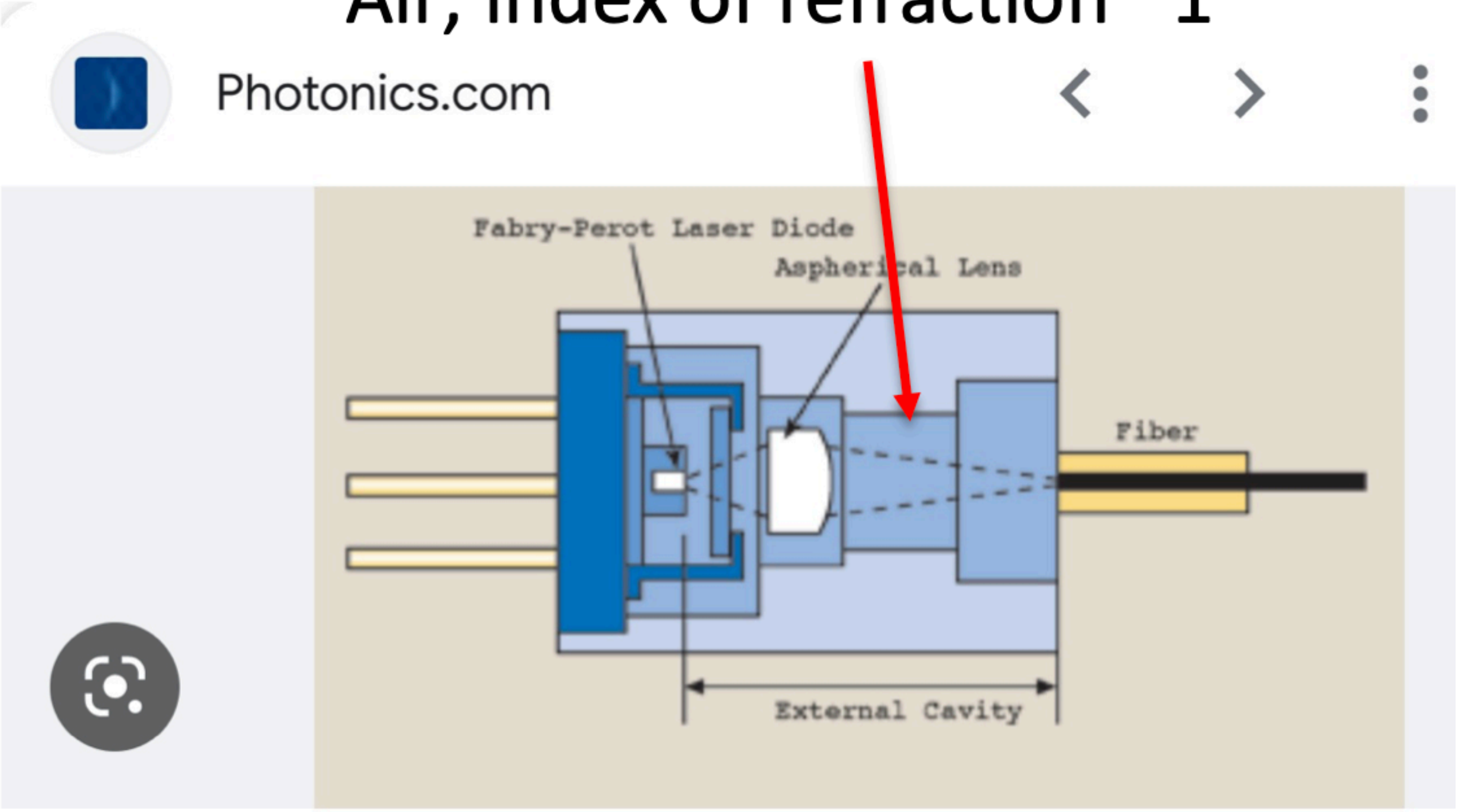
The work will continue outside of the VD project to test new ideas – 1500 nm, Rs reduction etc.….

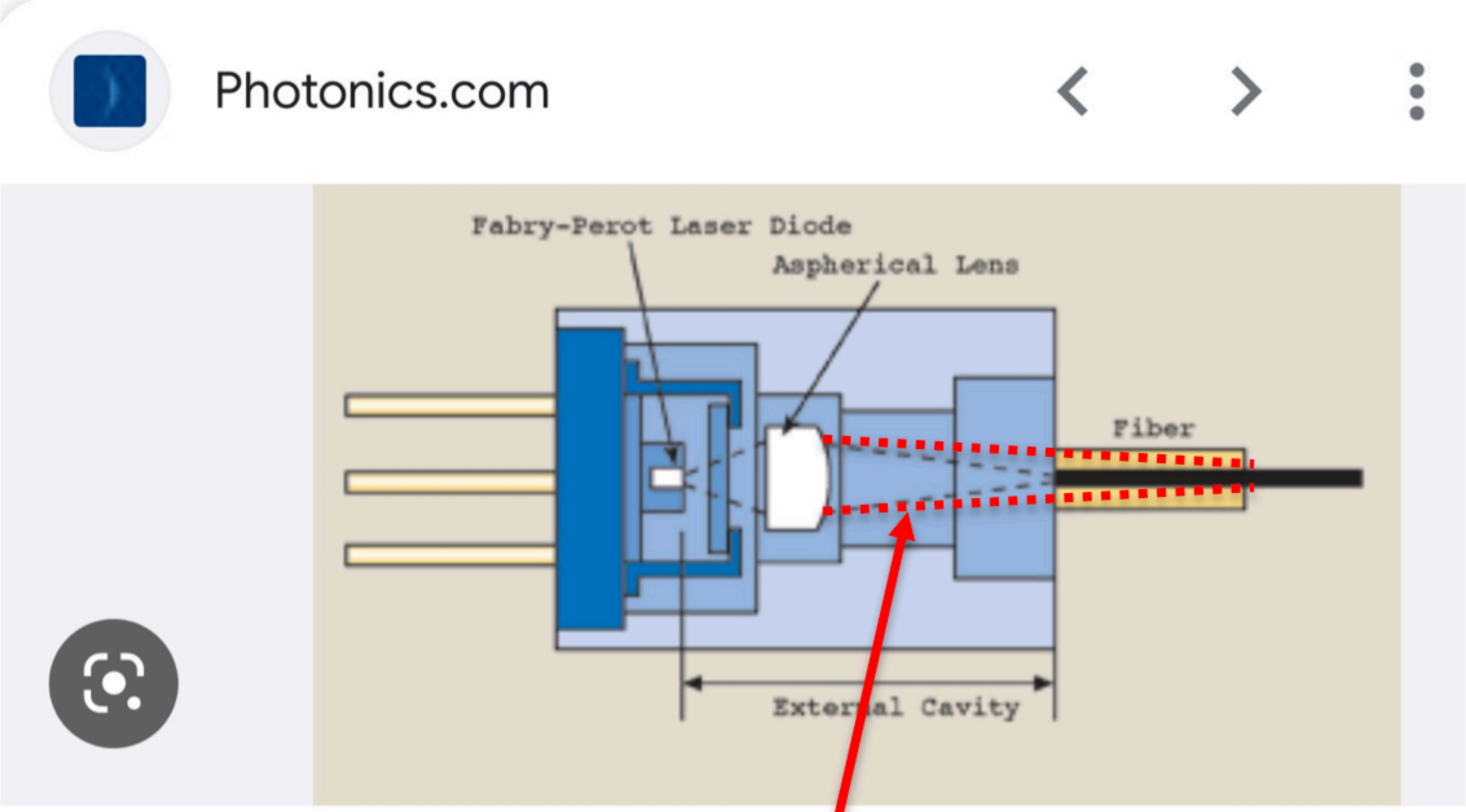


Signal-over-Fiber

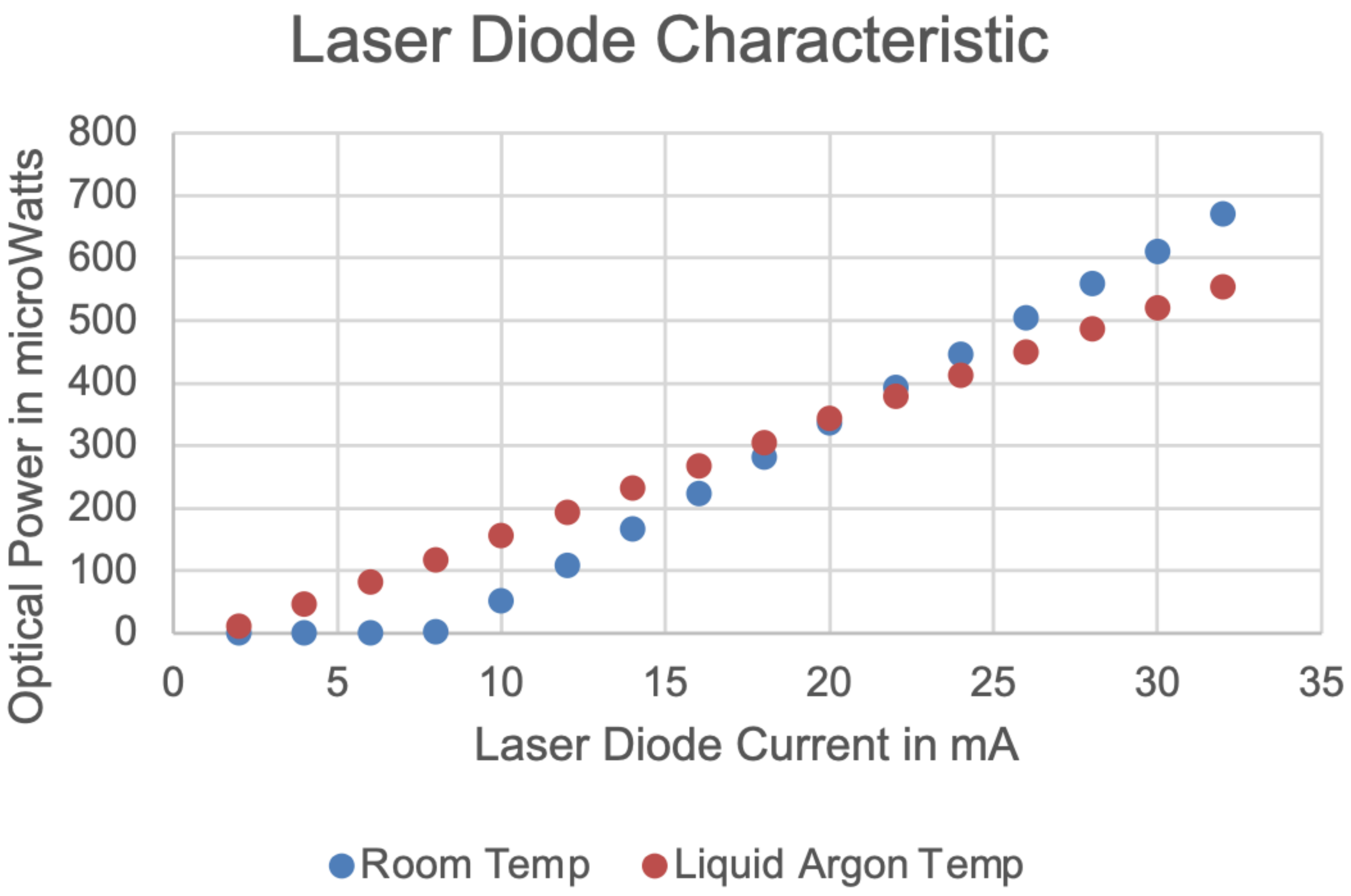
- The first FC LDs that we got from Lasermate produced much less light in the NP02 cold box run in Dec 2021 than in our tests with (shallow) LN2.
- The next batch of LDs from Lasermate produced essentially no light in a subsequent cold box run.
- We eventually understood that the problem was that the LD package became flooded with liquid argon.
- This changed the optics such that much less light was captured in the (very fine) single mode fiber used in the package.
- In response to a question, Lasermate said that they had changed the lens type between orders.

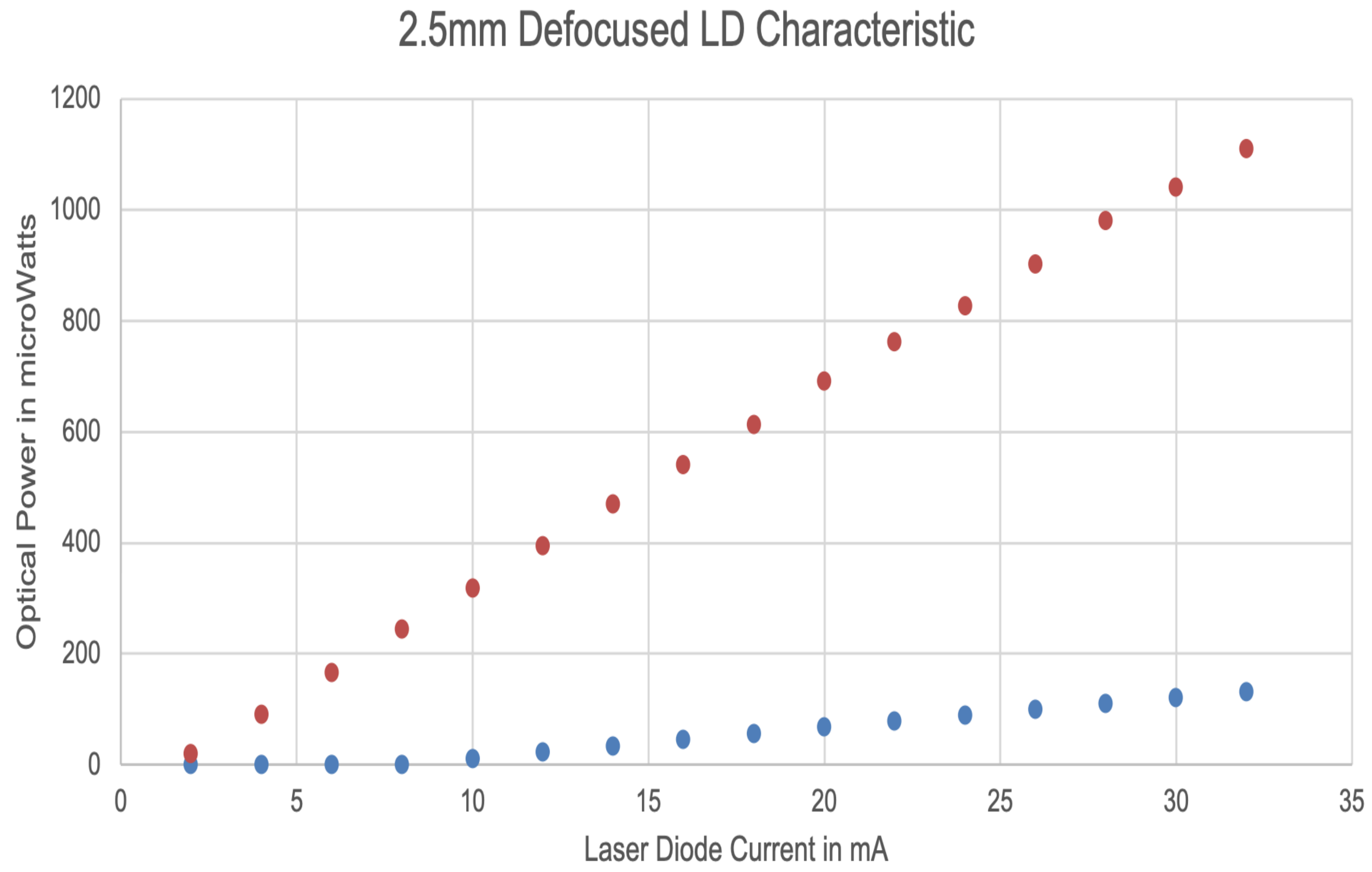
Air; index of refraction ~1





LAr; index of refraction ~1.23 @1220 nm

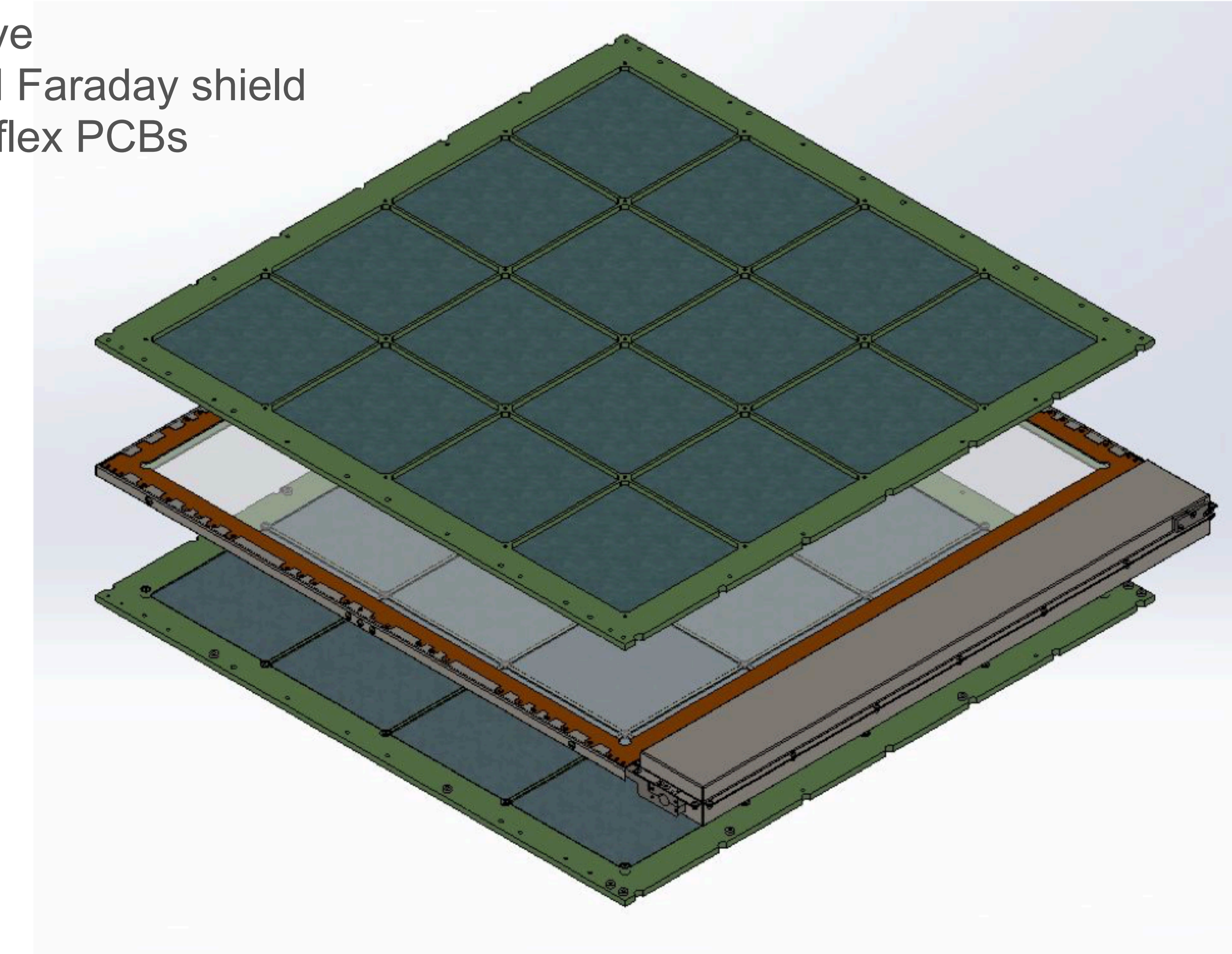


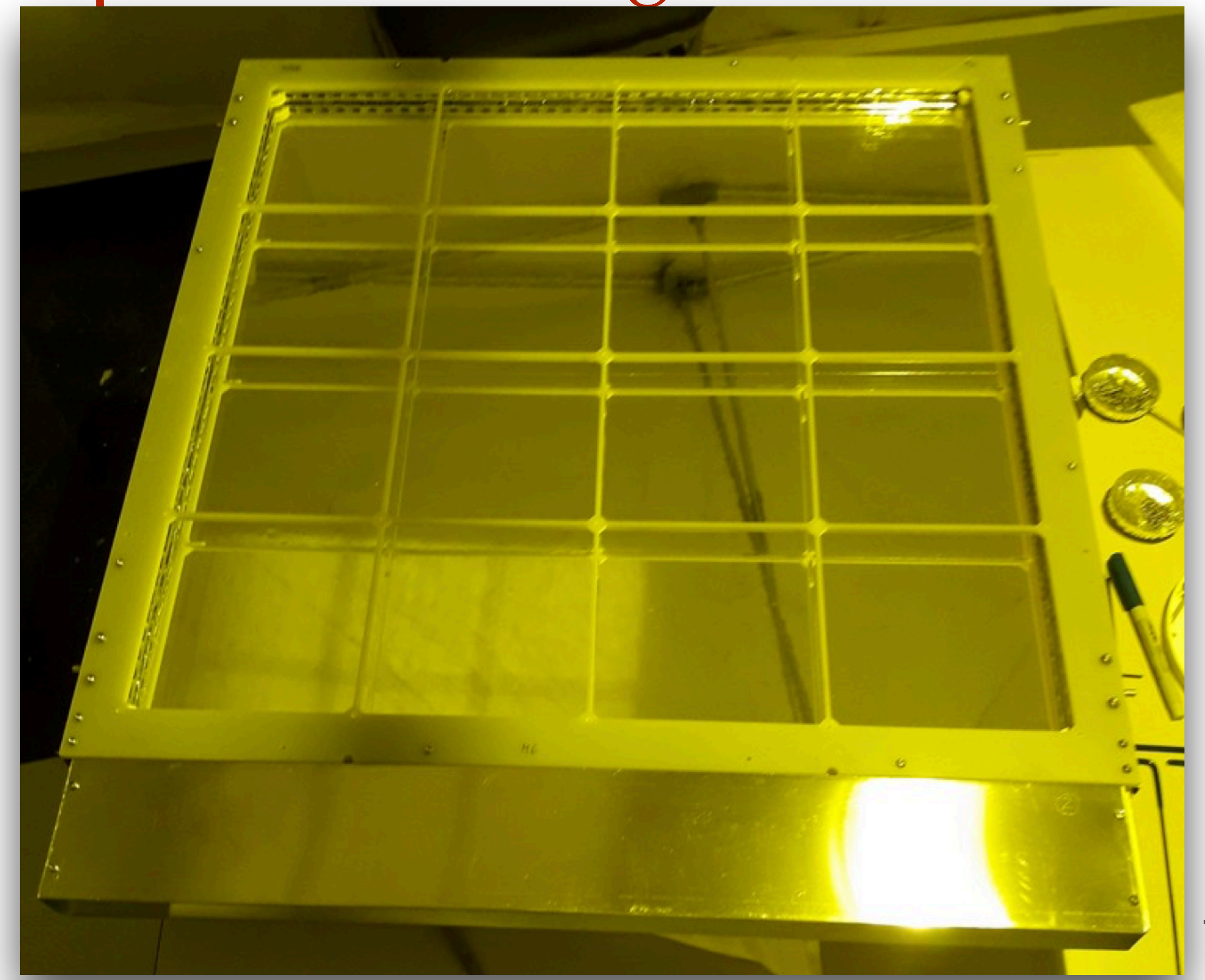


Design Optimization 2022 & Milestones

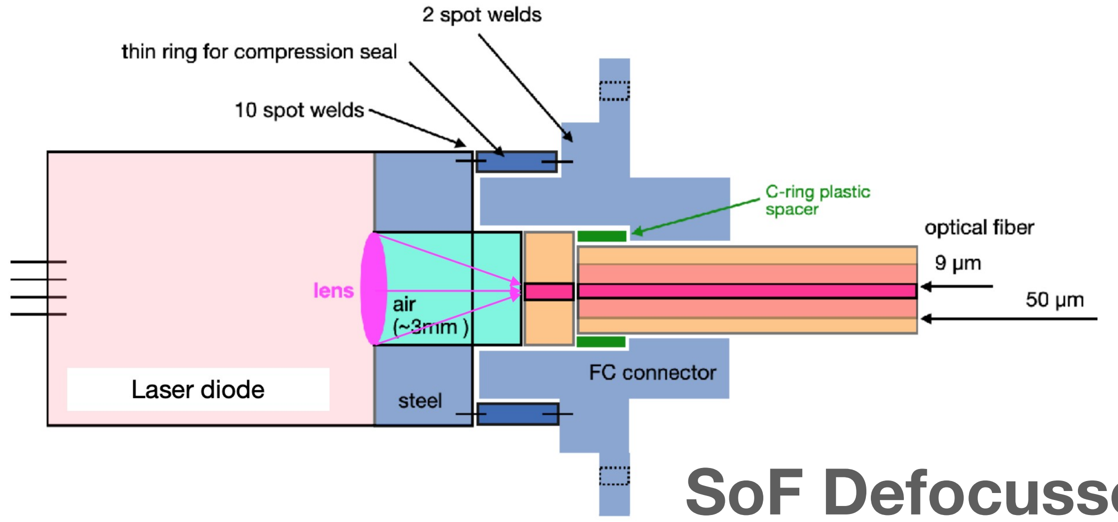
xARAPUCA optimized design

Conductive
C-shaped Faraday shield
for SiPM flex PCBs

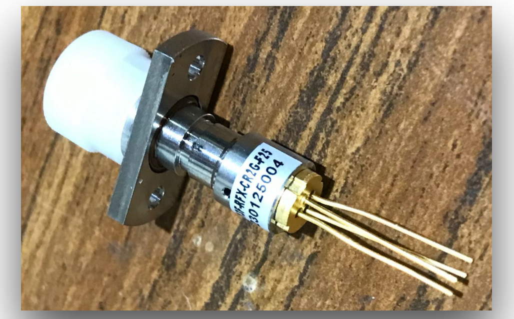




LAr optimized
dichroic filters



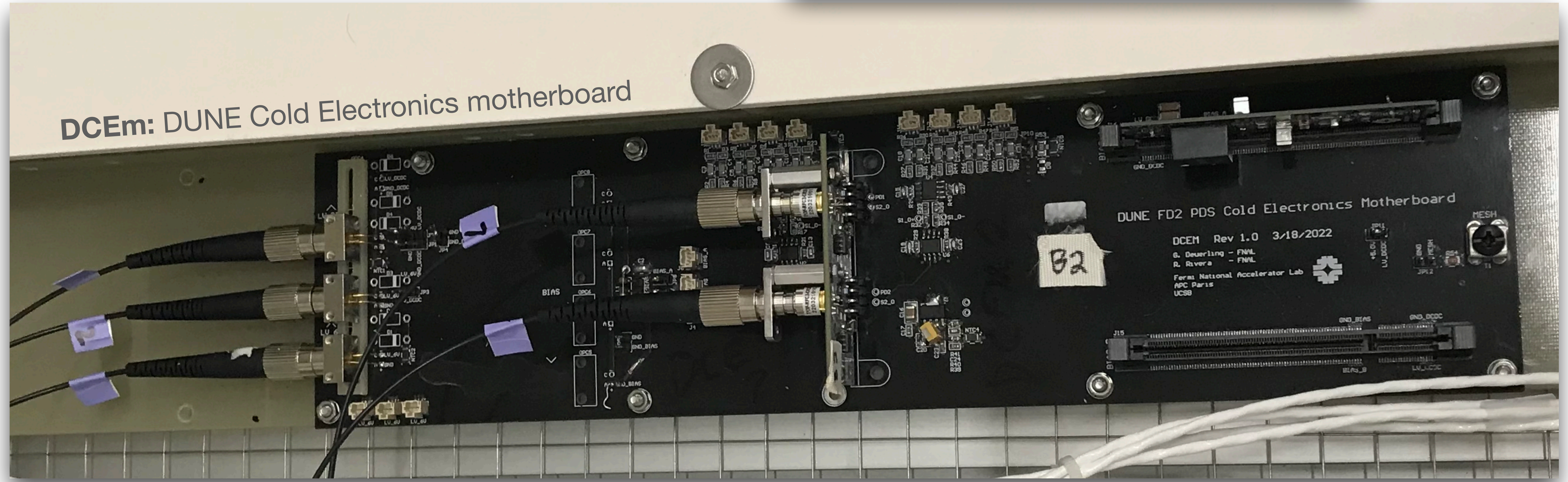
SoF Defocussed FP Laser Diode



Light tight Faraday box
for electronics

PoF High Efficiency GaAs OPC

PoF Fiber



SoF Fiber

V StepUp Cryo DC-DC Converter

Design optimization 2022 & Cold Box tests progression

for an electrically isolated
(only optically connected through fibers)
low noise
photon detector system

Electrical Noise and (single) Photon Background ("Optical Noise")

Two sources of baseline fluctuations in recorded waveforms found in ColdBox runs:
electrical noise and background photons (dubbed "optical noise")

Q1 from LBNC PDS briefing

Electrical noise:

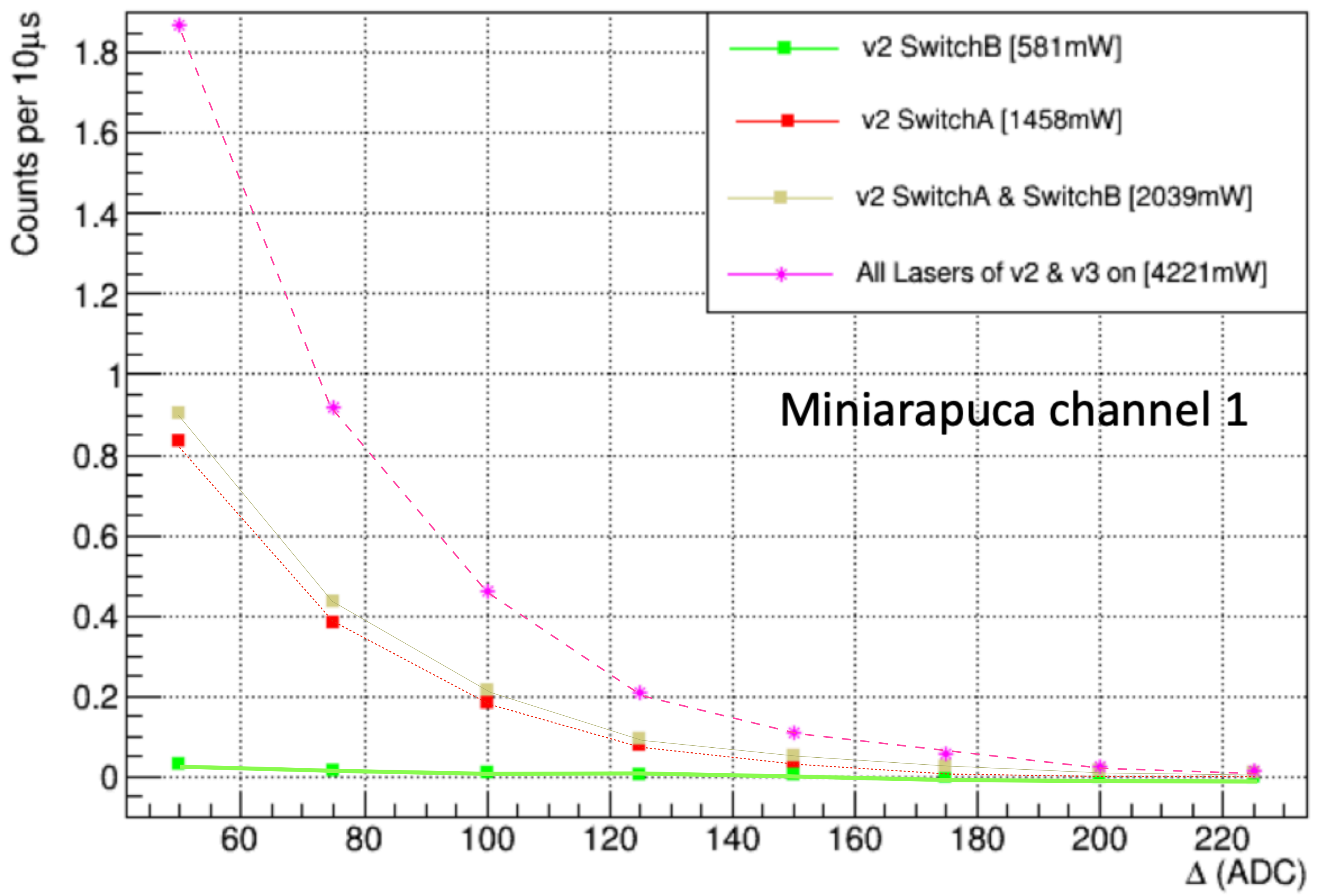
Low-frequency O(100kHz) observed in December-March ColdBox runs mitigated/solved by improving the grounding and shielding connections.

Background photons:

Single photons from (uncontrolled) origins generate small amplitude signals (SPEs/multiplePEs).
When the rate is high → large-amplitude fluctuations in the recorded waveform ("optical noise").
Sources of background photons identified (by miniARAPUCA on Wall - SoF, ~~PoF~~):

- *Ambient light leaking into the ColdBox*
- *IR light (808 nm) escaping PoF fibers&connectors and PV receivers (and reflections from walls)*

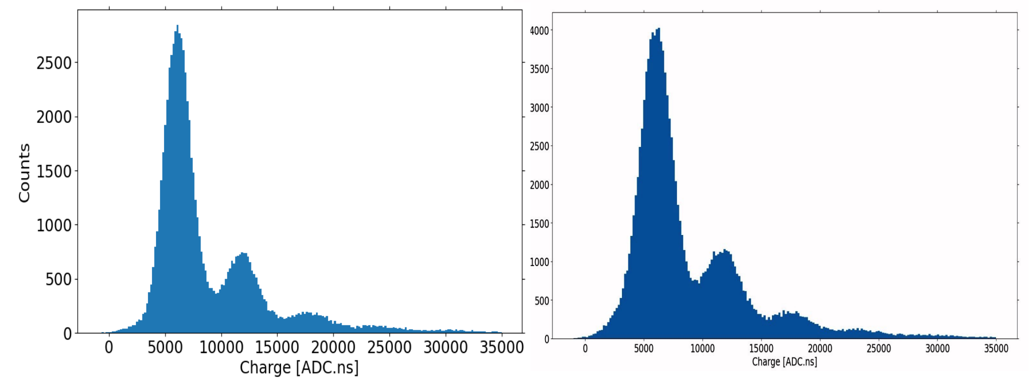
Pulse height (ADC) counts above threshold in 10μs window at increasing PoF units ON (up to max deliverable power)



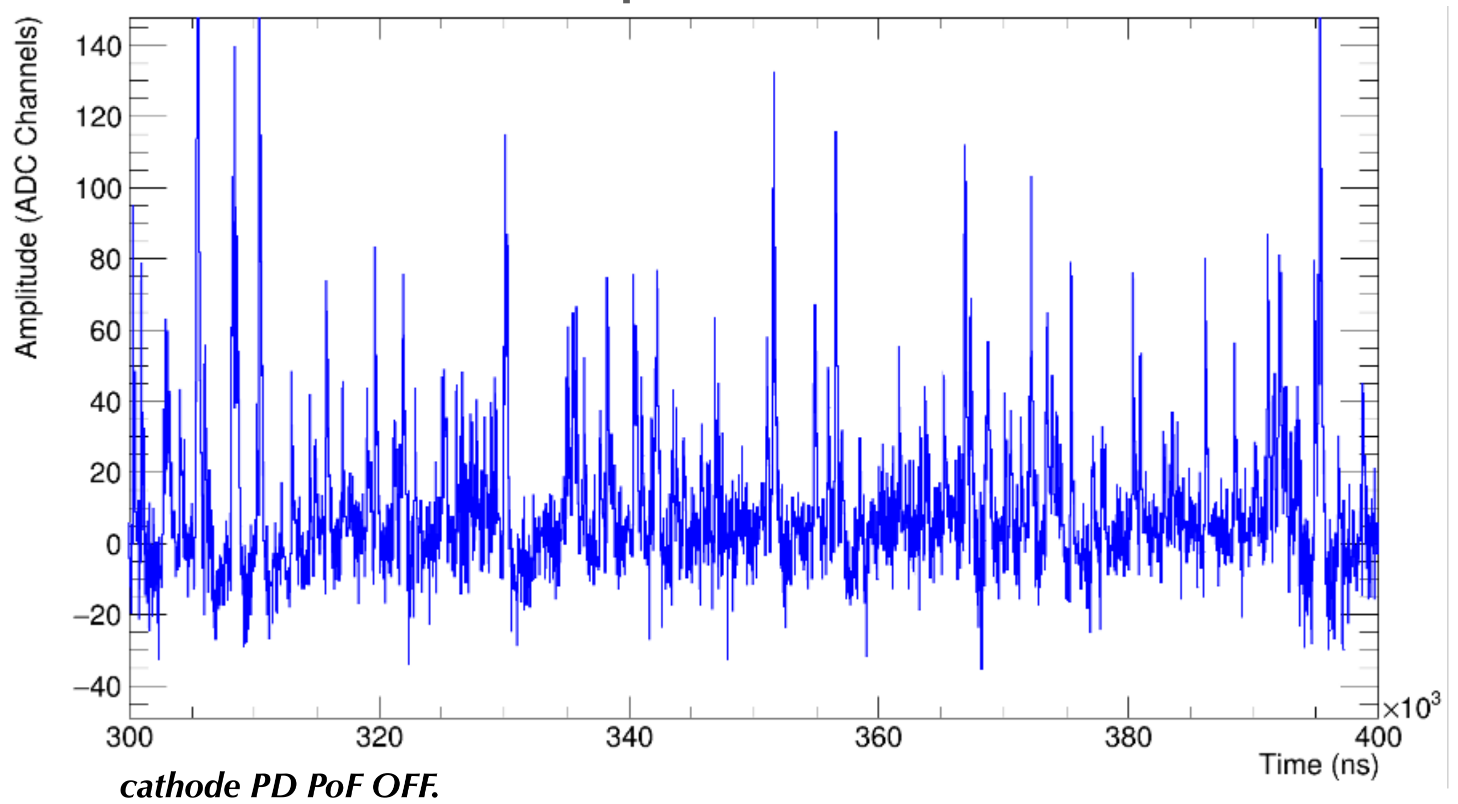
Pulse Rate (above-threshold):

	Ambient Light PoF OFF (Fig.1)	*Reduced Ambient Light PoF OFF (Fig.2)*	*Reduced Ambient Light PoF ON (Fig.3)*
Pulse Rate (10x10 cm² miniARAPUCA)	396 kHz	74 kHz	222 kHz
Avg. N. of Pulses in 10μs window	4	< 1	~2
Avg. time btw pulses	2.5 μs	13 μs	~4 μs
SiPM BCR*	0.9 kHz/mm²	0.1 kHz/mm²	0.3 kHz/mm²

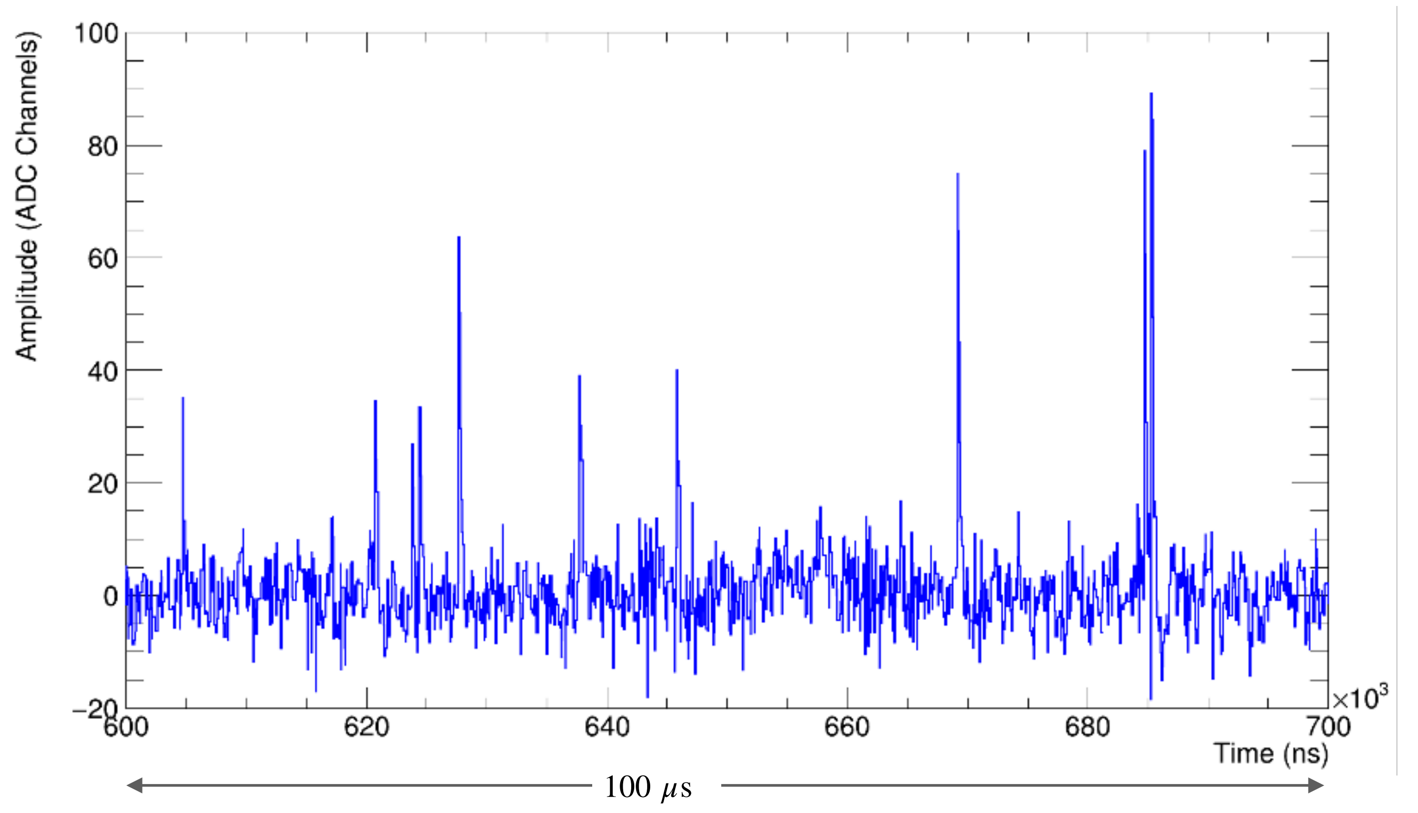
Pulse Charge Distribution: (first peak)
1PE $\simeq$ 6000ADC $\times$ ns



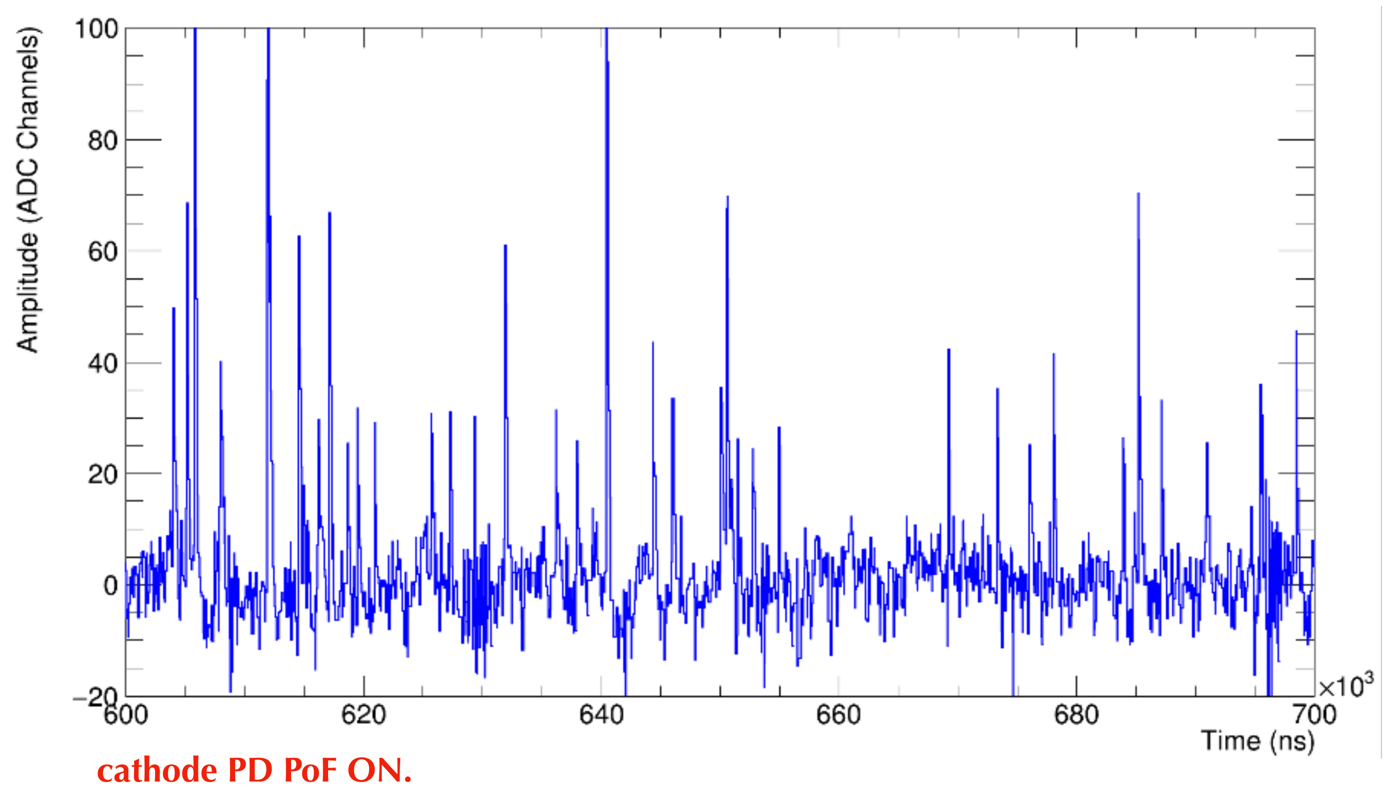
◉ mini-Arapuca on the Wall



cathode PD PoF OFF.
Before Ambient light leakage mitigation



cathode PD PoF OFF.
After Ambient light leakage mitigation
[optical noise/ambient light - SPEs/multiplePEs rate significantly reduced]



cathode PD PoF ON.
[optical noise/IR light from PoF- SPEs/multiplePEs rate increased]

Pulsed neutron source for PDS calibration:

- Study for detector LY calibration
  - Neutron capture on Ar-40 produces 6.1 MeV gamma cascade
    - Well defined energy deposition ideal for energy scale calibration
  - Neutrons can travel large distances in LAr before being captured, which gives good coverage with fewer neutron generator

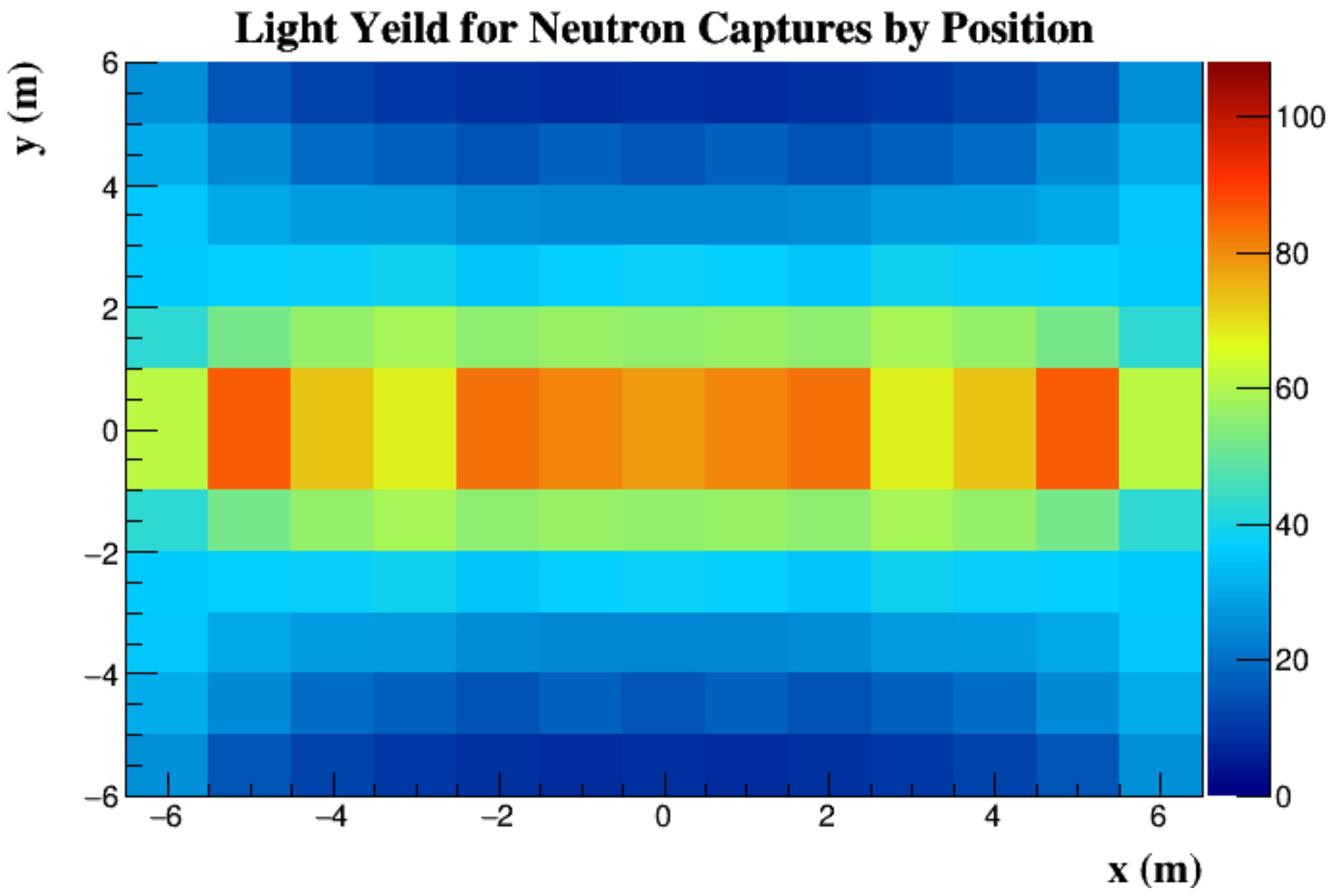


Fig: LY from neutron capture in LAr using Geant4 standalone simulation for DUNE VD

- Simulation of light from neutron capture events ongoing
- First Geant4 stand-alone simulation has been performed and LY map has been made (left plot)
- The overall features of LY map from neutron capture is similar to the LY map from a point source (there are slight differences near the edges which is being understood).
- More realistic simulation by introducing uncertainty in the knowledge of position of neutron capture is being worked on.