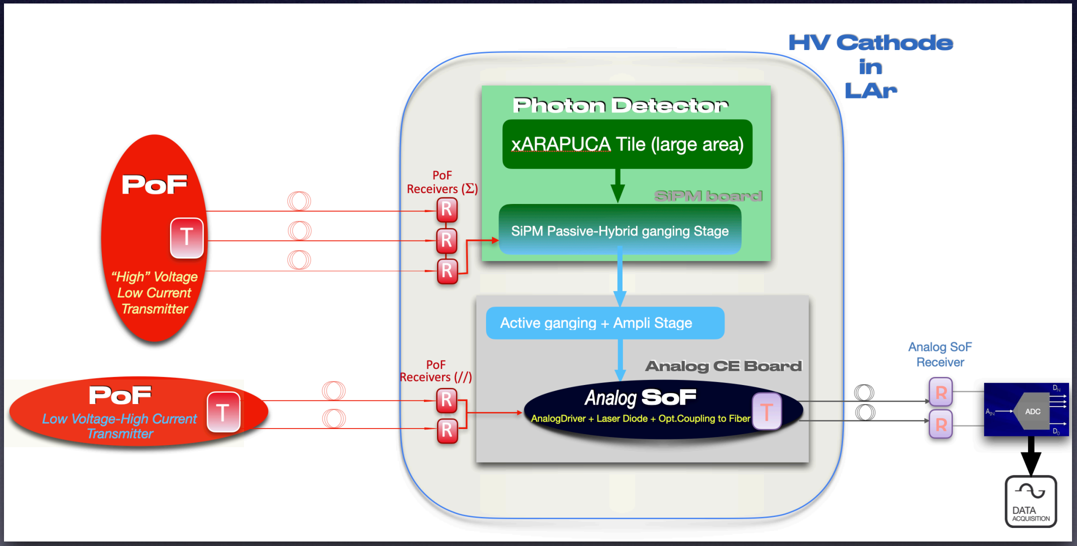
DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

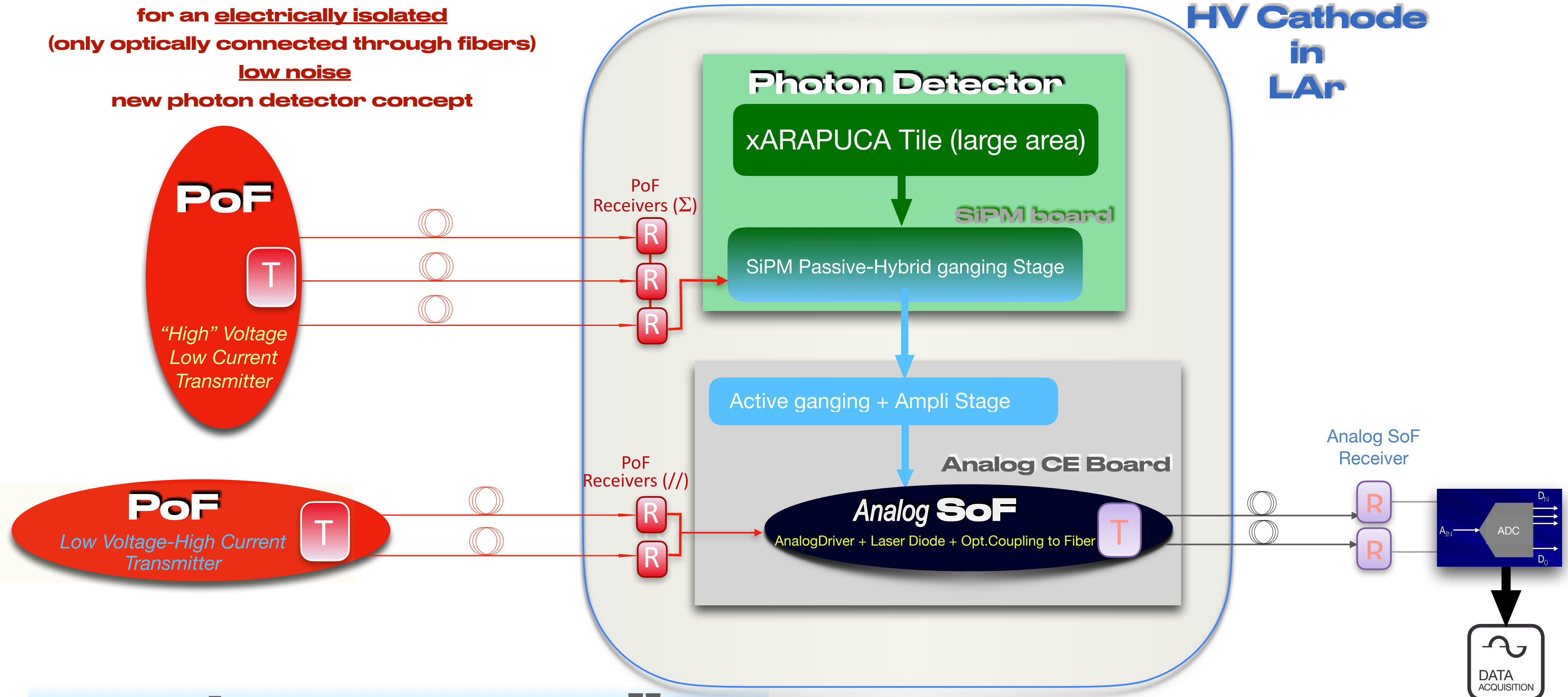
PoF and overall Detector Design, Development and Optimization



Fermilab

The VD LArPDS Development path

for an <u>electrically isolated</u>
(only optically connected through fibers)
<u>low noise</u>
new photon detector concept



... to success !!

3 + 1 main items on the VD PDS path for development & optimization:

- the **large area PD module**, based on the ARAPUCA technology, with 160 SiPM/channel in 8 groups of 20 passively ganged in a hybrid Series/Parallel solution (**SiPM ganging board**).

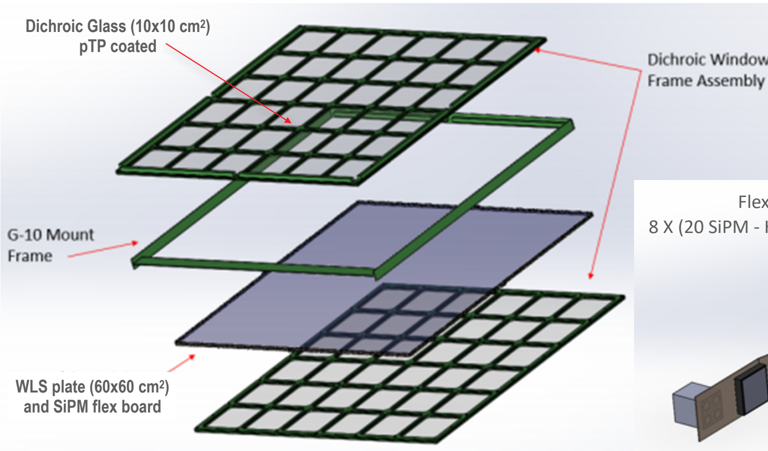
- the **PoF system** for power supply to sensors and to r/o electronics:
  - **HV-LC PoF** for SiPMs, that require $\mathcal{O}(<10\ \mu W)$ power output, at high voltage (30-50 V) and very low current (< 100 nA per sensor).
  - **LV-HC PoF** for OpAmps and other active analog electronics components, that require $\mathcal{O}(>10\ mW)$, at low voltage (3-5 V) and high current (> 10 mA per unit).

- the **FrontEnd Cold Electronics** (SiPM Active Sum and Amplification) + **SoF system** for signal transmission out of the Cathode (toward digitization and DAQ)

- the PDS layout on the Cathode (i.e. PD modules distribution on the Cathode, Power distribution to PD modules/CE boards): **Risk mitigation for HV cathode discharge and for long term operation** (30 yrs lifetime)

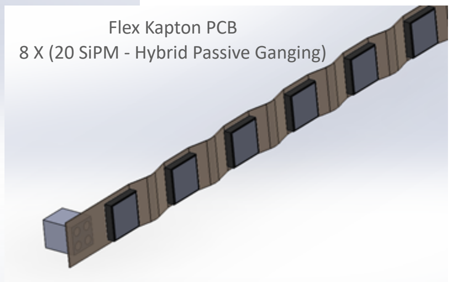
PhotoCollector concept

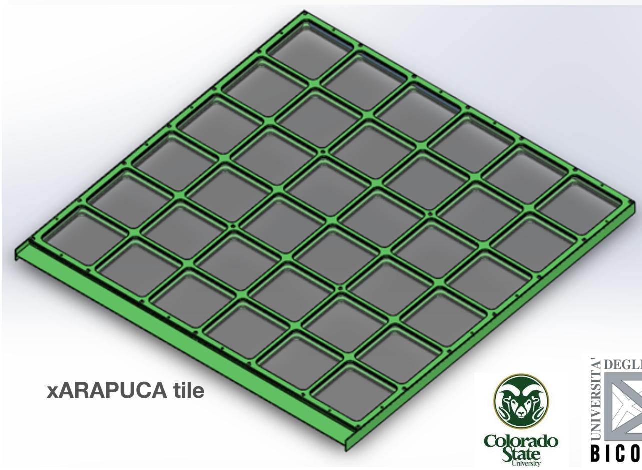
xARAPUCA technology - large detection Area, 2 r/o channels



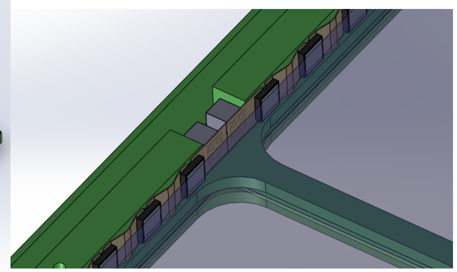
UCSB Fermilab

SiPM board





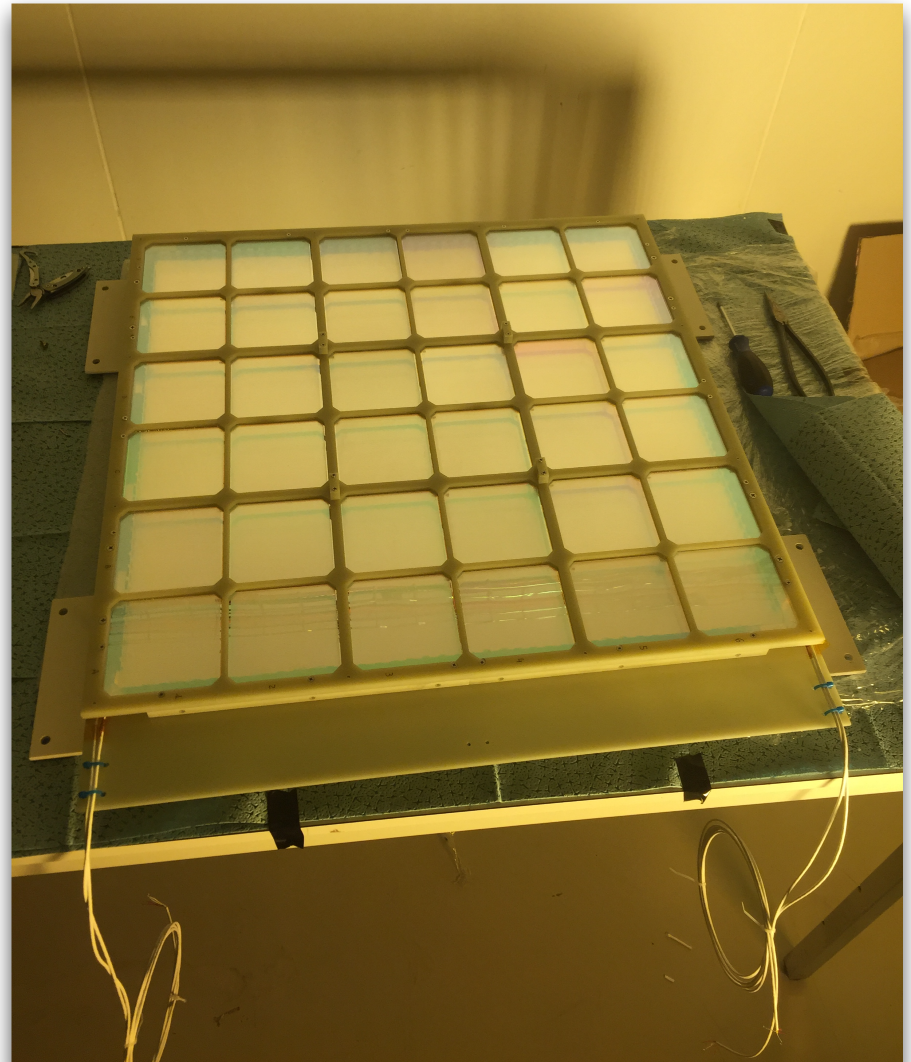
SiPM-WLS plate optical Contact



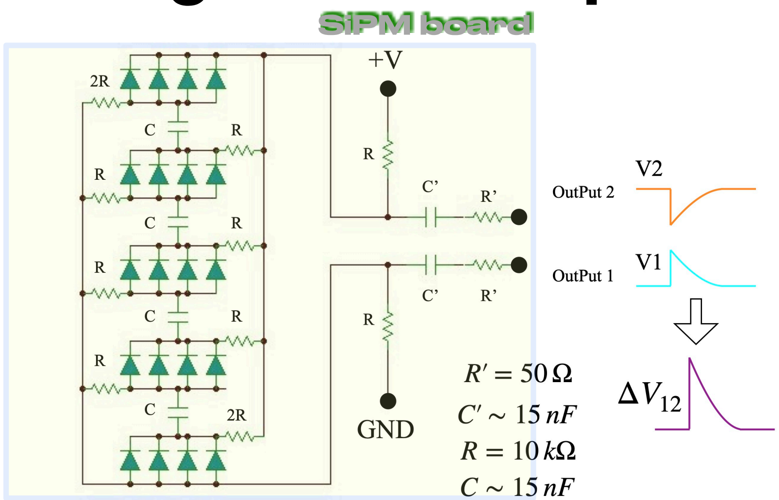
Colorado State University

UNIVERSITA' DEGLI STUDI DI MILANO BICOCCA

xARAPUCA tile assembled and cabled

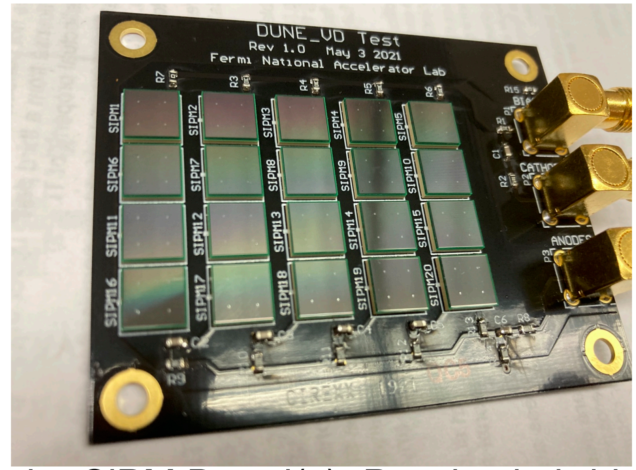


Analog SoF concept

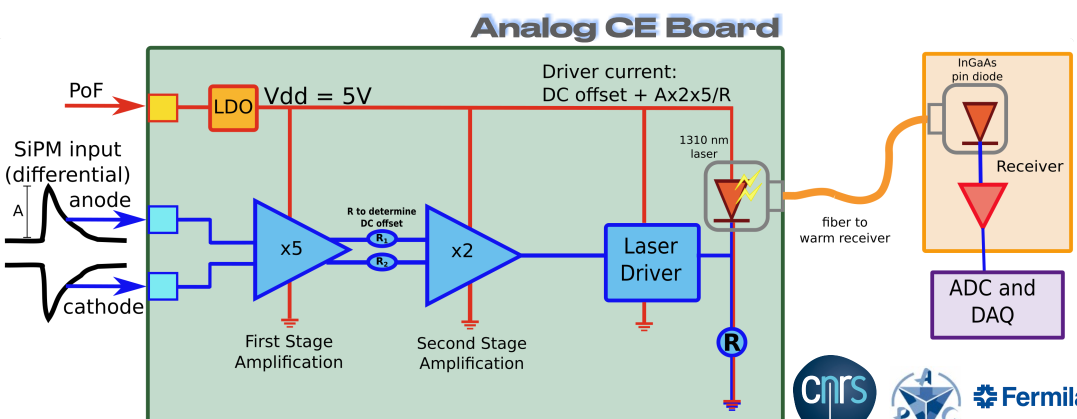


UCSB

Fermilab

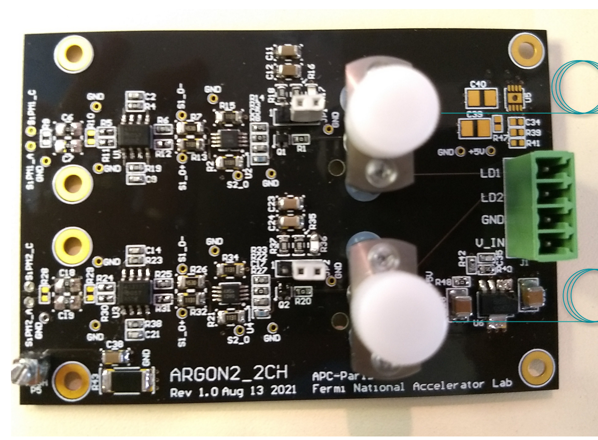


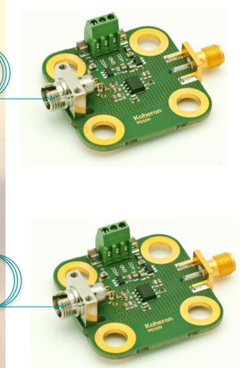
the SiPM Board(s)- Passive hybrid ganging



cnrs

Fermilab

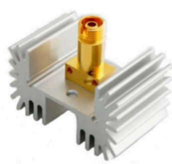




the Analog CE Board
Active ganging/Ampli & SoF

PoF concept

multimode fiber with FC connector

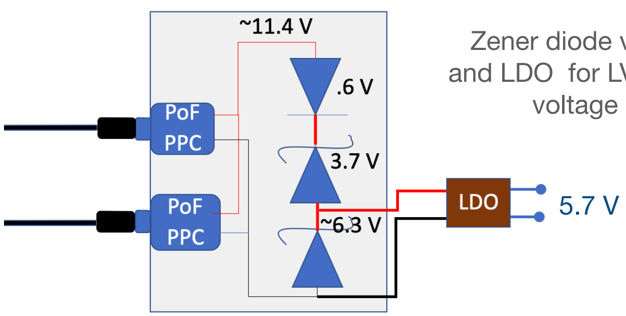


Si-based

PoF Transmitter
Photonic Power Module (PPM)
976 nm laser diode

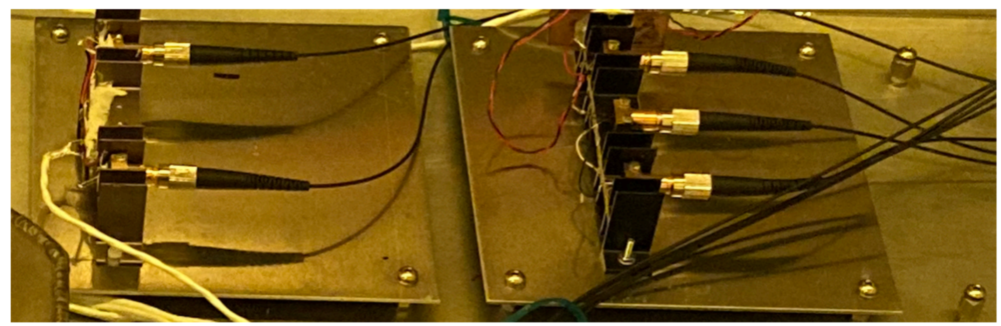
PoF Receiver high intensity
Photovoltaic Power Converter (PPC)
on heatsink

Fermilab/AD



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

PoF - Power housing unit *(5 warm Transmitter laser diodes)*



LV-HC PoF supply board
(2 cold Receivers on heatsink)

HV-LC PoF supply cold board
(3 cold Receivers on heatsink)

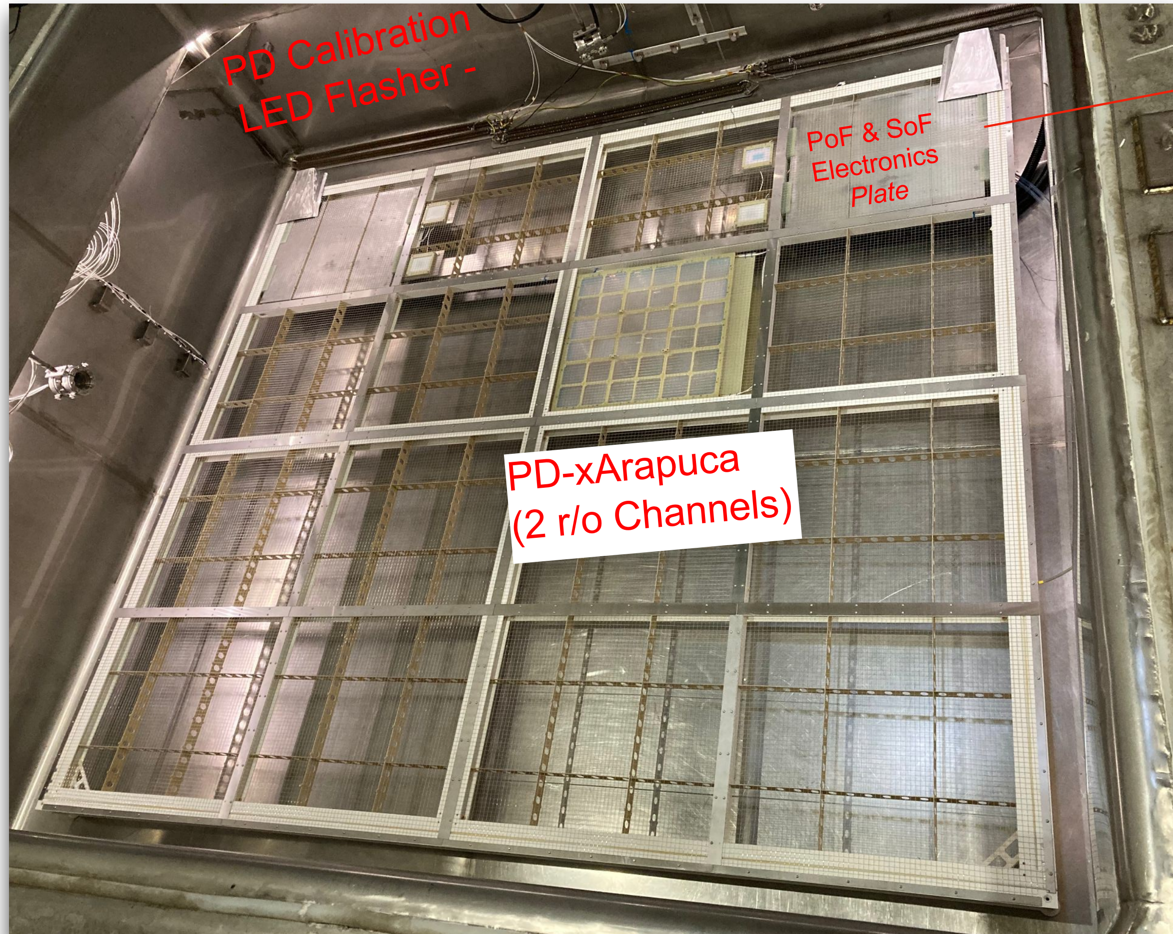
PoF technology was developed primarily for implementation in solar energy industry and small isolated electrical systems.

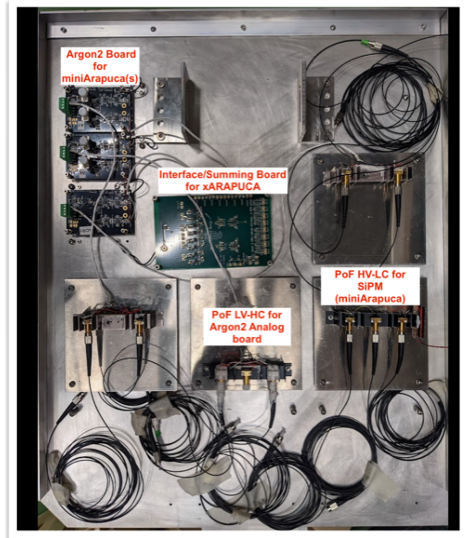
In our application, *the first in detector technology for HEP*, PoF supplies power to the active elements, *photo-sensors and cold electronics*, of a photon detection system immersed in LAr and lying on a HV surface.

The 976 nm, 3.5 W Si-based solution is demonstrated.
A new 808 nm, 3 W very high efficiency GaAs PPC units is under development/test.

The innovative cold PoF-SoF technology is immune from noise injection and signal distortion, and therefore adequate for low amplitude light signal collection and read-out

Validation Test at CERN - NP (ColdBox experiment)

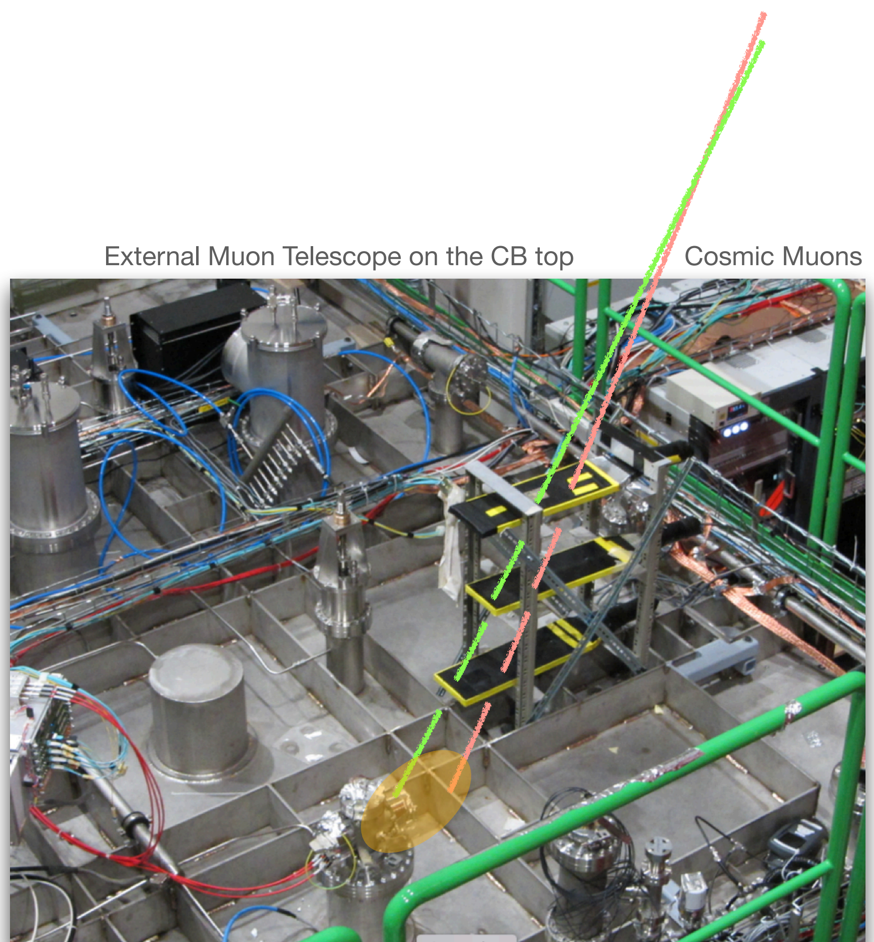




On Dec. 13
PDS on the Cathode + LED Calibration system installed in ColdBox at CERN Neutrino Platform

External Muon Telescope on the CB top

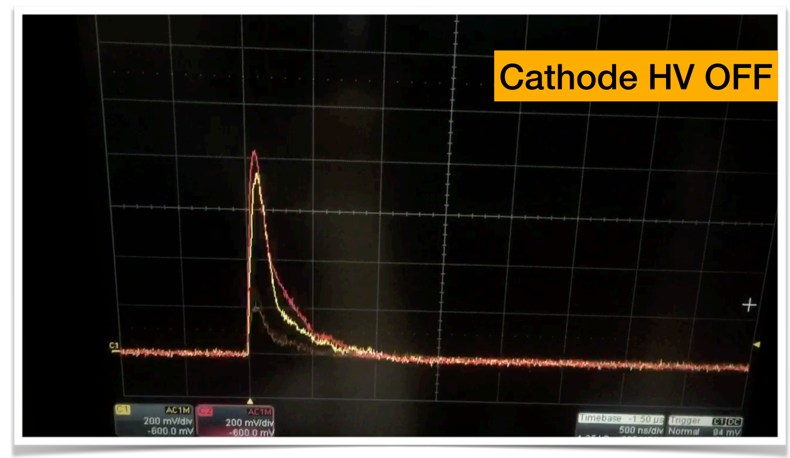
Cosmic Muons

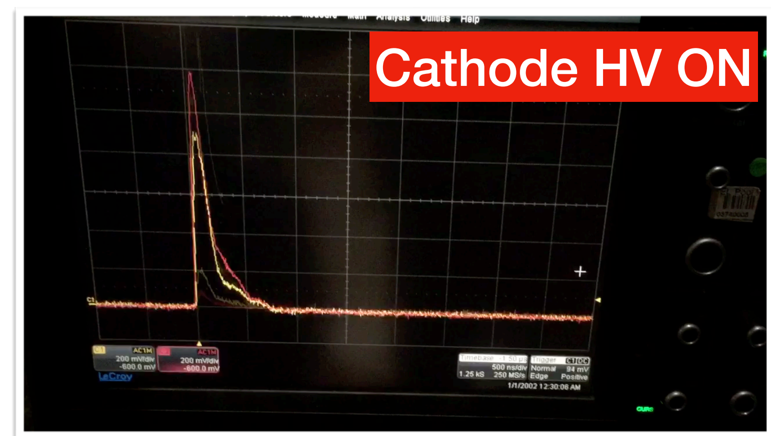


Milestone:

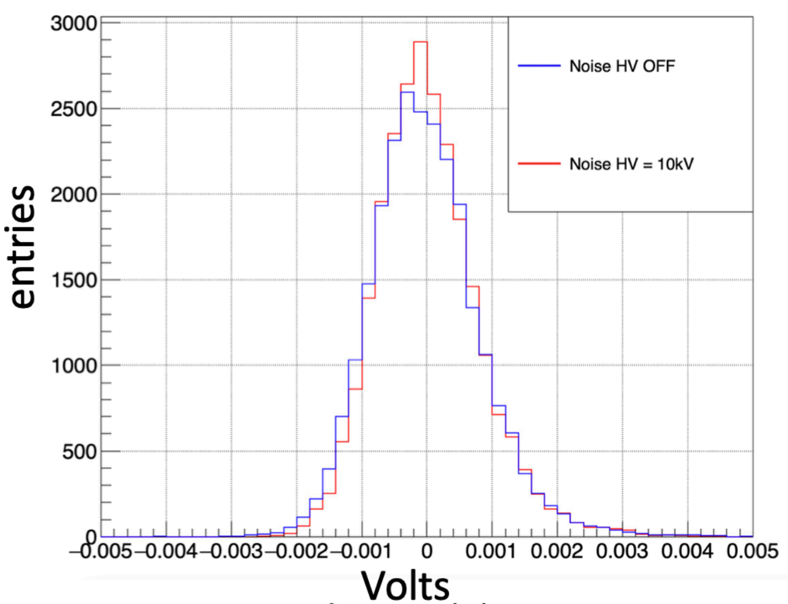
VD PDS signals with Cathode HV ON in LAr

PoF is turned ON on Dec. 15 at CERN - ColdBox Experiment. Clean signals immediately seen on scope





No noise increase or signal distortion when HV ON

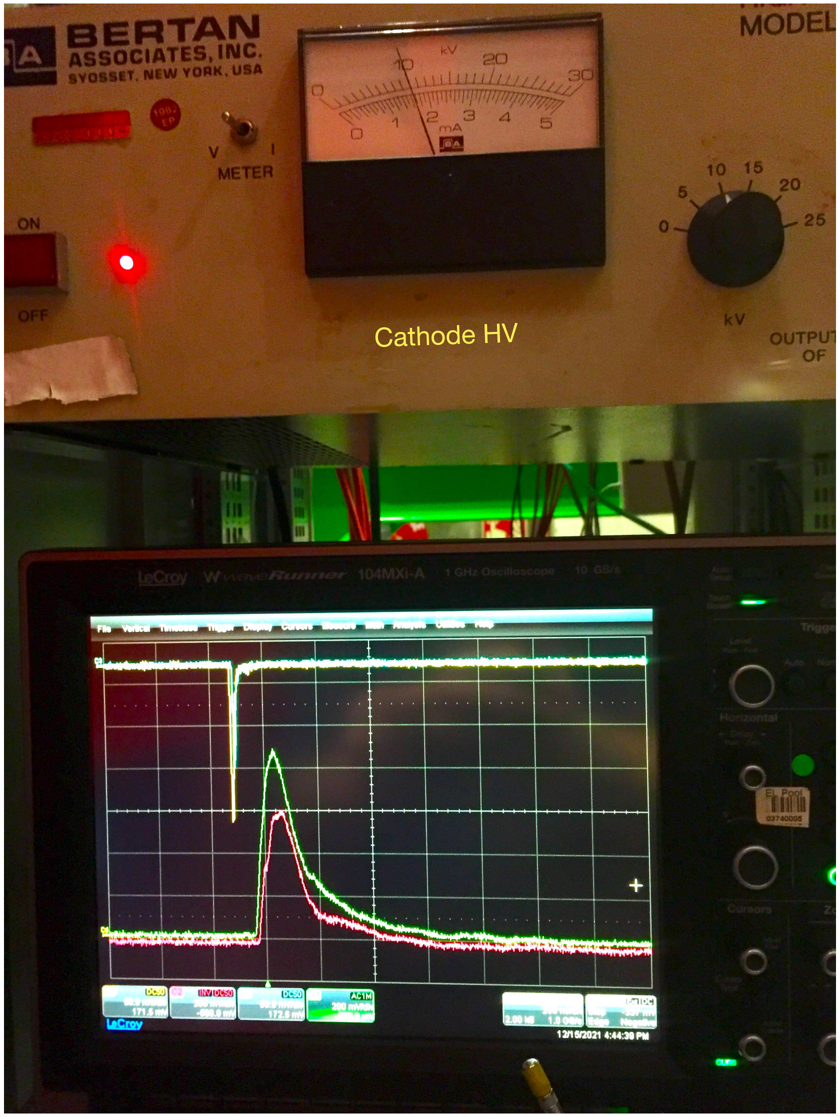


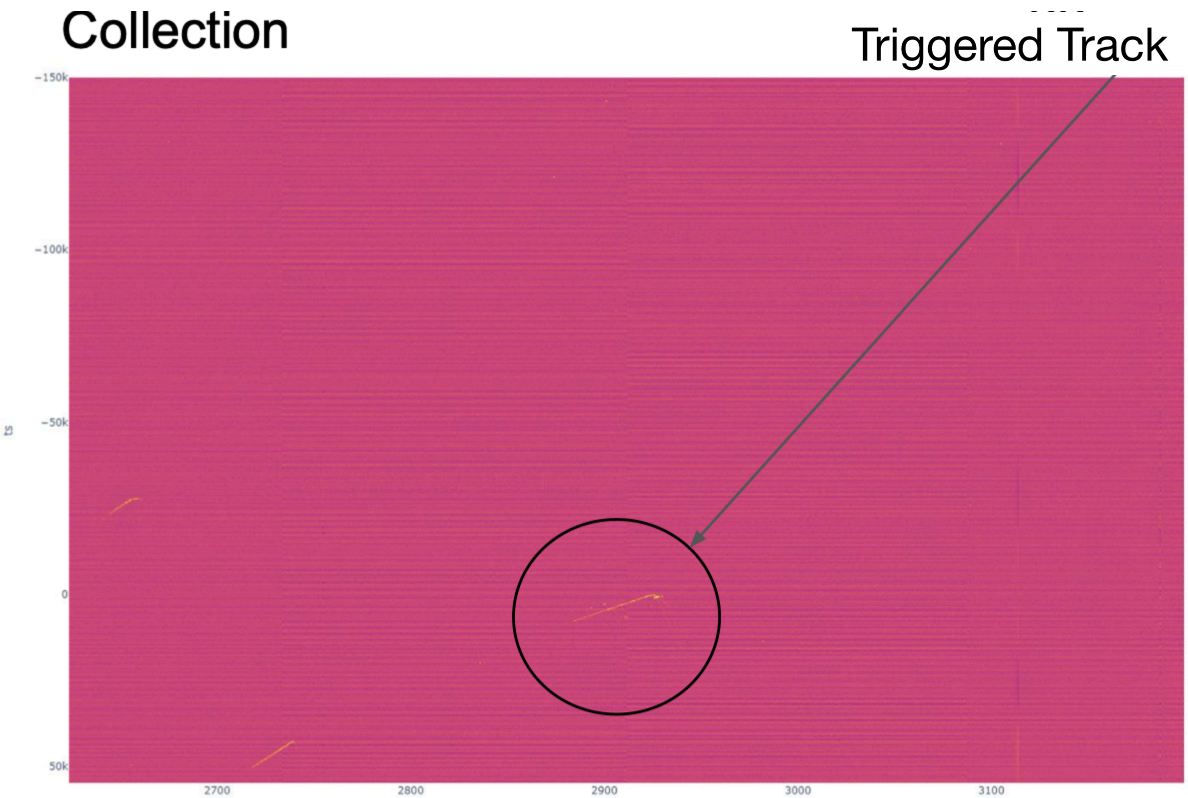
HV OFF:
Mean = -0.05 mV
Sigma =0.77 mV

HV = 10 kV
Mean =-0.02 mV
Sigma=0.71 mV

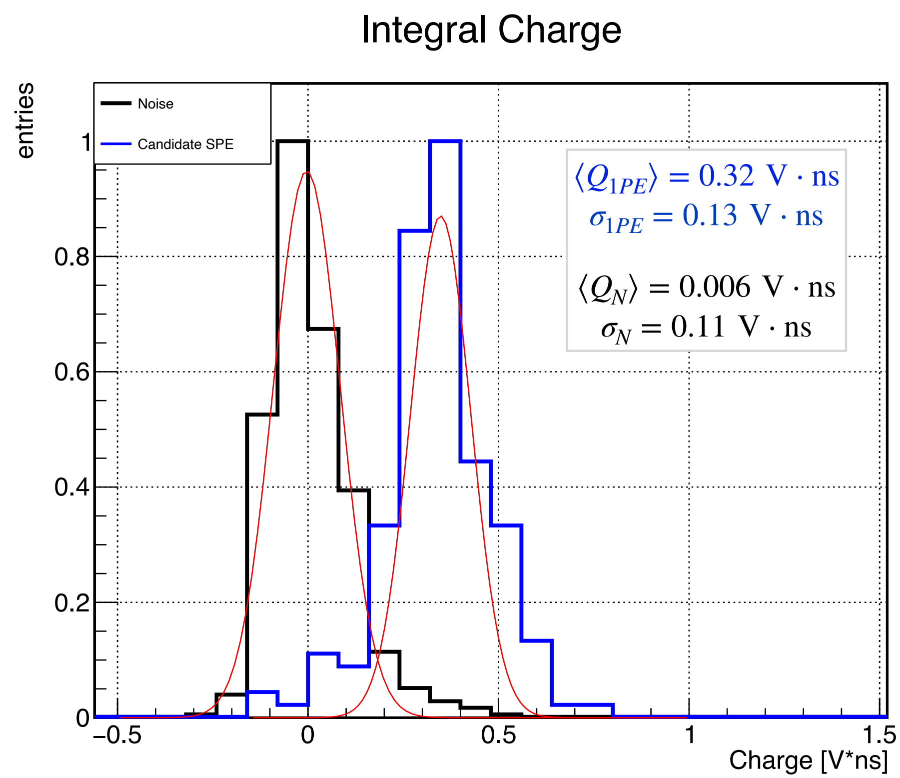
Milestone #2:

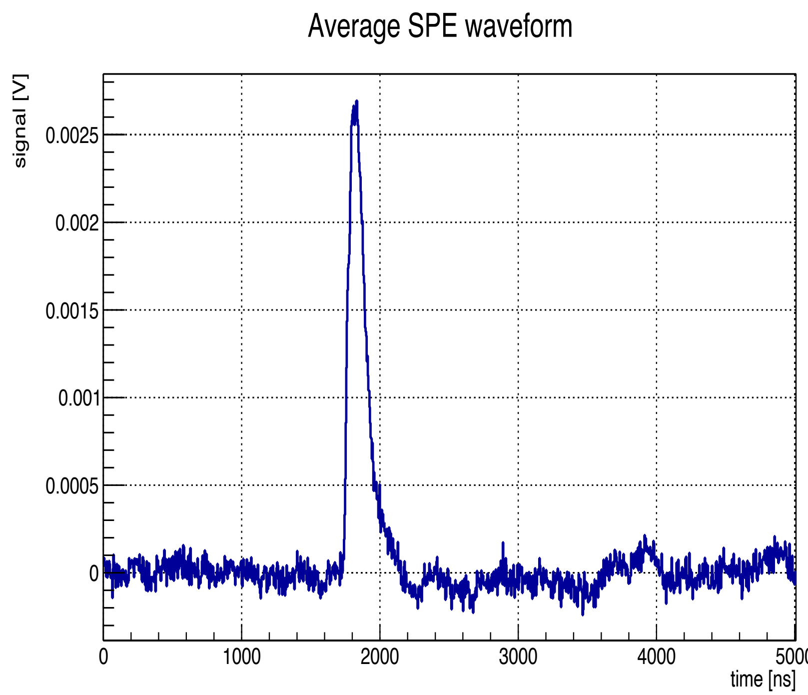
xARAPUCA on Cathode provide trigger to TPC DAQ and detect tracks in coincidence with Light Flash





Calibration Run

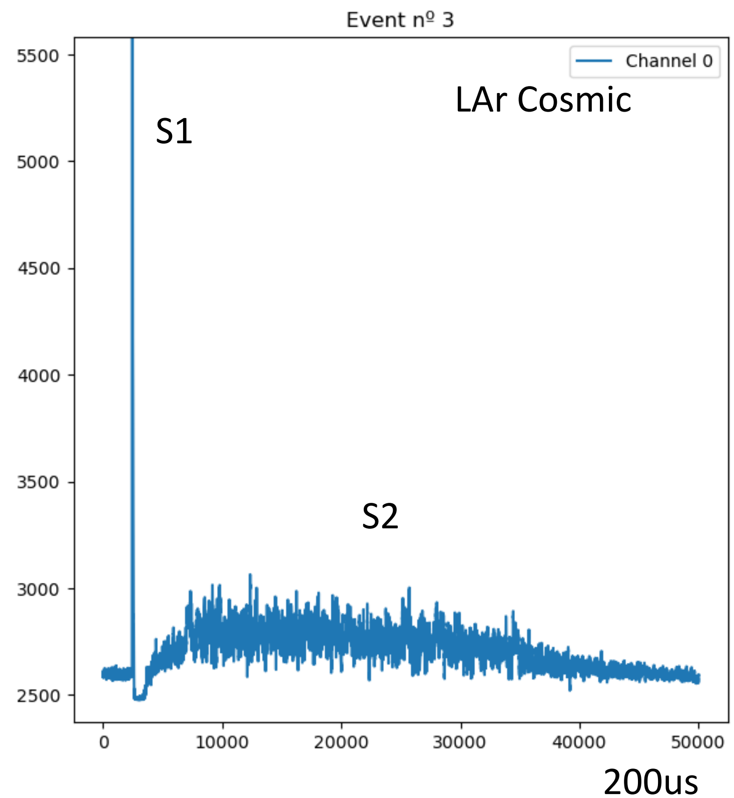




Noise (0-PE) and 1-PE Charge distributions (normalized)

X-Arapuca operated during the ARIADNE LarTPC test providing S1 and S2 light signal

- X-Arapucas work nicely !



… more on the PoF system:

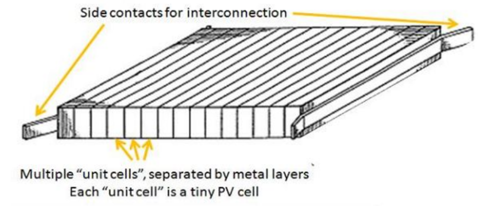
moving to 808nm GaAs PPC

by W. Pellico / FNAL

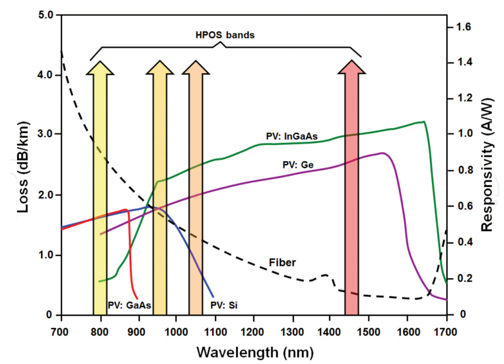
History

- From white board idea to VD baseline in ~2.5 years
- The use of PoF has been used in some application here at the lab (small and low power at 'room' temps)
  - Used to power electronics on RF modulator HV deck
  - Used to power some electronics on FNAL transformer yard
- High power outdoor systems being built for military systems
- This first of a kind PoF use of high power in a cryo environment
  - Not a big market
  - Not many vendors

We chose to focus on the Photovoltaic converter biggest concern was power/efficiency



- The VD cathode PD system has been a moving target
  - Power levels have change continuously –
    - We had digital Tx for a long time
    - Analog has moved to the front with power levels that have been drastically reduced
  - Layouts are still changing –
  - Initially we were also planning on FC mounted PD systems (may still happen….)
  - Localized heating – bubbles
- Our original power estimates were about a factor of 10 higher than now



Fibers and Lasers seemed less of a vulnerability –

We set up several vendor / university relationships to focus on

PC R&D partnerships

Proof of Principle

Desire to start with a low-cost option to start the investigation. We reached out to several vendors – only one was interested in participating in R&D of PoF

MH GoPower –

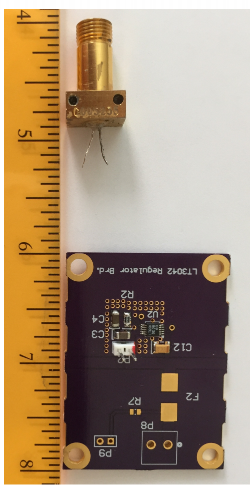
The company participated in initial testing at their site with nitrogen to see if it worked. We then started a series of tests with their Si based product.

The layout and components were tested over about 1.5 years.

The system of lasers, fibers and PC units has become our baseline design.

The president of the company visited and remain a source of expertise.

Si Based System



GaAs Based System

Initial focus on ~808nm based power systems

Broadcom

Boeing Spectrolab

UIUC Champaign Urbana

- The big vendors have extensive PC knowledge
  - Space Tech Use
- Manufacturing capabilities
- Wafer Options (2”, 4” and 6”)
- Fiber connectivity

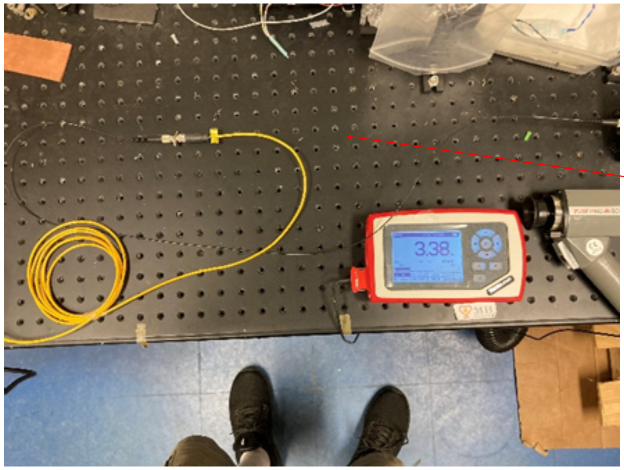
- Solar R&D Profs
- Students
- Cost
- Desire for R&D
- Accessible Lab
- Accessible Tech

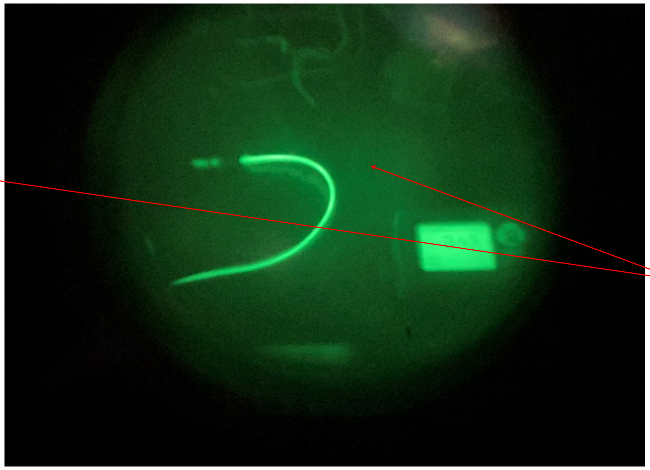
We have a testing program underway with South Dakota School of Mines and Technology led by David Martinez Caicedo Ph.D.

- This will allow FNAL to focus on R&D

Si Based PoF System

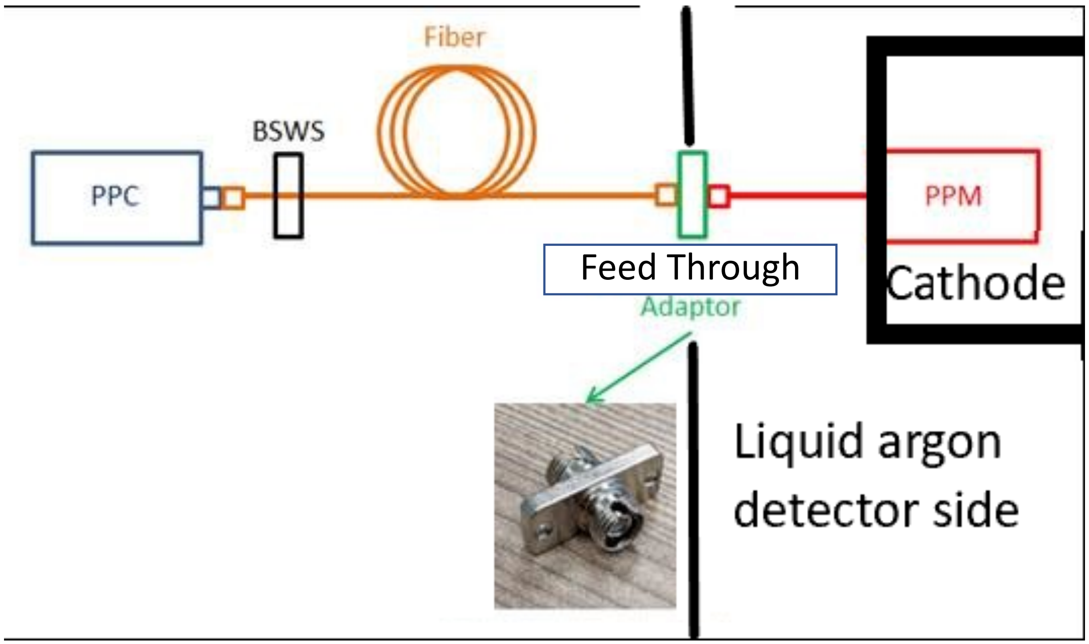
- We have had a lot of success with Si PoF but some growing pains
  - Lasers systems are fairly robust – but we have gone through 4 versions
    - Have had vendor modify some connectors – especially at pigtail
    - Interlocks needed upgrading
    - Simplification of dim connector – simplified unit
  - PPC cells have been good with only 10% loss during testing
    - Issues with stripping of connector teeth – quality issue
    - Light leakage from backside due to semi-opaque epoxy
  - Initial fiber jacket was not light tight





Pigtail fiber leaks So MUST Use: Black 1.5mm PVDF jacket, Black 1.8mm ETFE jacket

Si PoF System Proven to Meet VD PD Needs



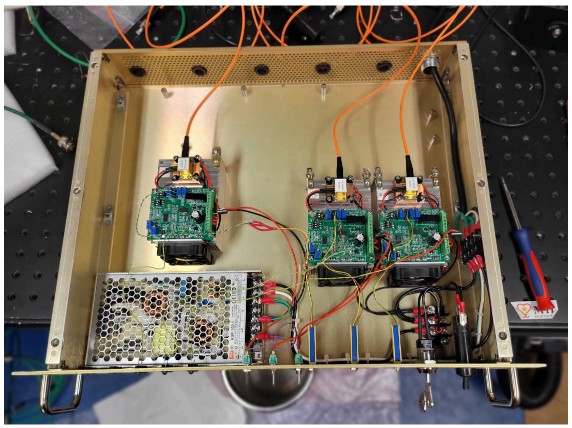
- Successful conclusion of CB1
- Proof of Principle
  - System proved to be low noise
  - Once system is installed it is reliable and repeatable
  - Simple to operate
  - Laser power was reduced
  - No bubbles
  - Not impacted by HV system

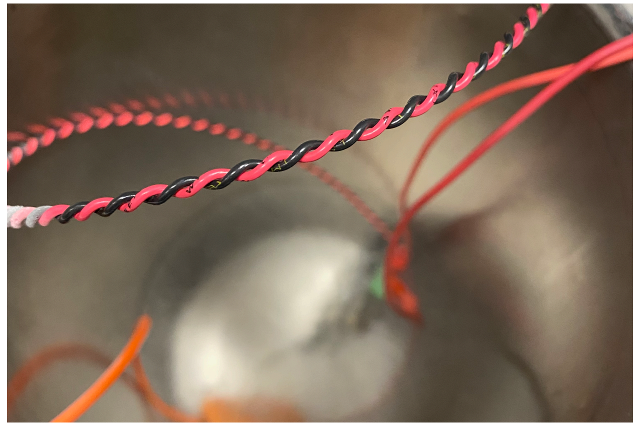
So Why Go Beyond what we did at CB1

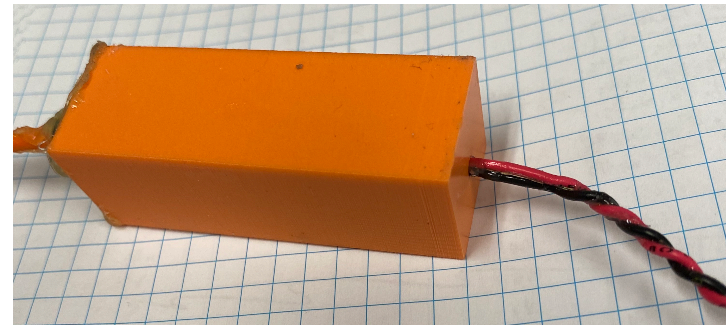
- The Si based system will have limited efficiency at cryo temps –
- Even at room temps Si is not the best option for high power
- The desire to reach efficiencies of >50%, maybe up > 85% possible

- Theory says for a single wavelength a GaAs system can reach ~90 % efficiency
- Lasers Systems are lower cost – (not a big driver)

First set of 808nm GaAs System Testing



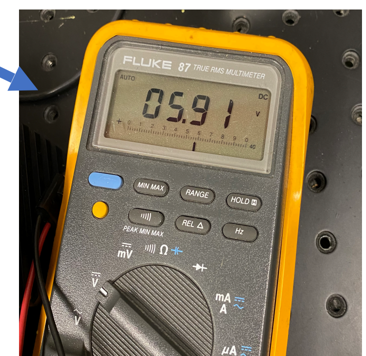




GaAs Unit powering an Argonx2 board.
PC inside small box filled with silicon sealant.
Running at 1.1 W laser power.
Slightly better than Si but room for improvement.

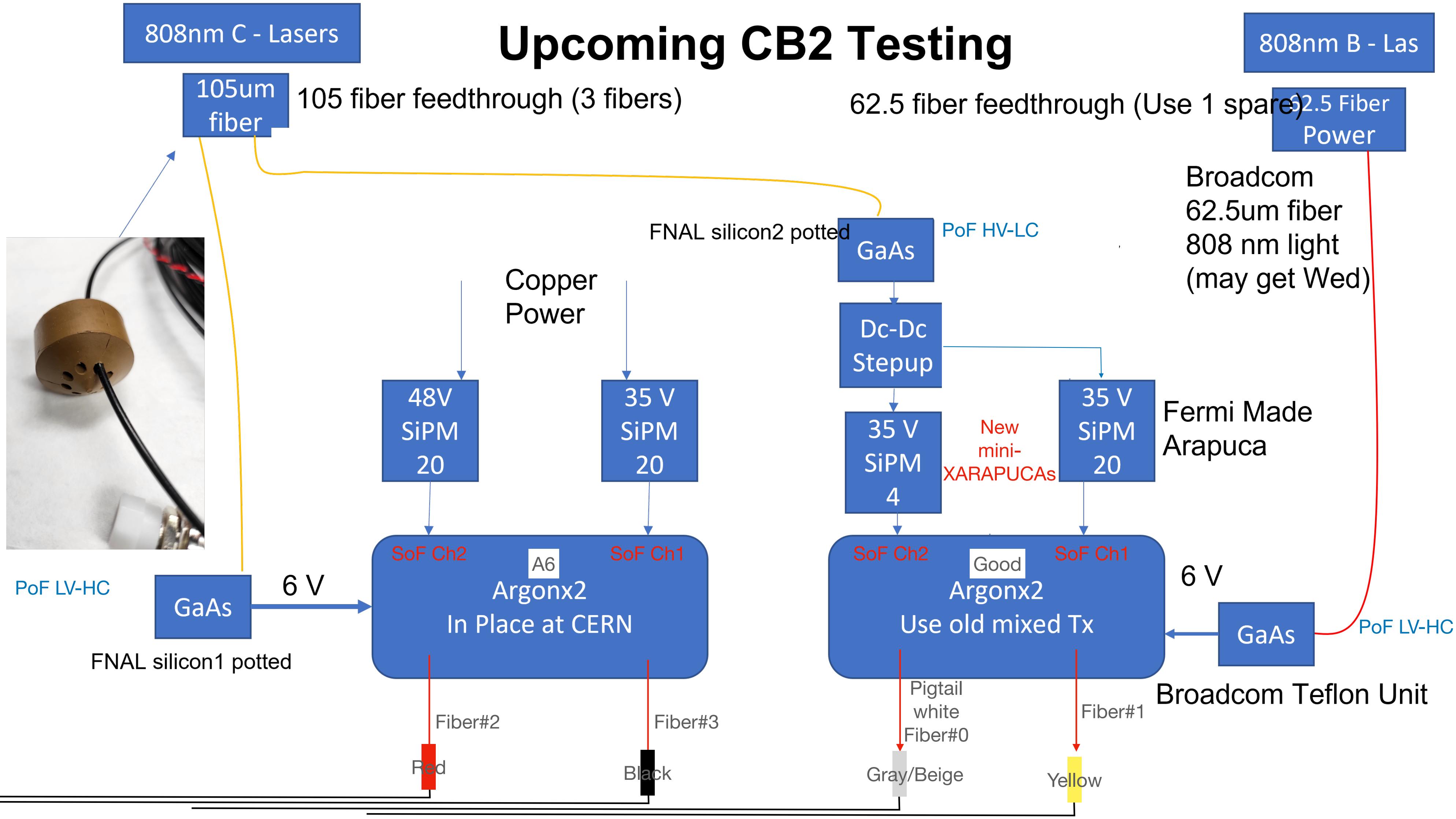
Clear low VOC Si sealant (-173c)

808 nm Laser Systems



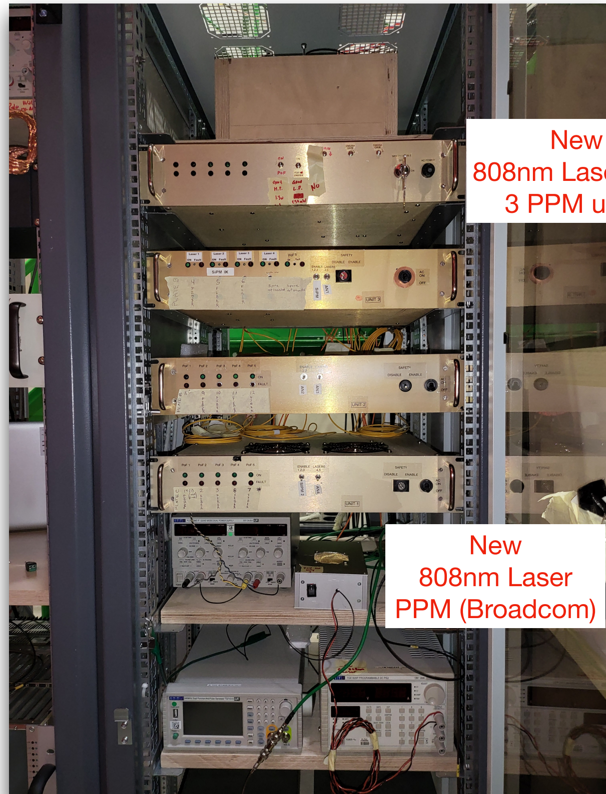
and new Laser and new converter (Teflon jacket) from Broadcom.

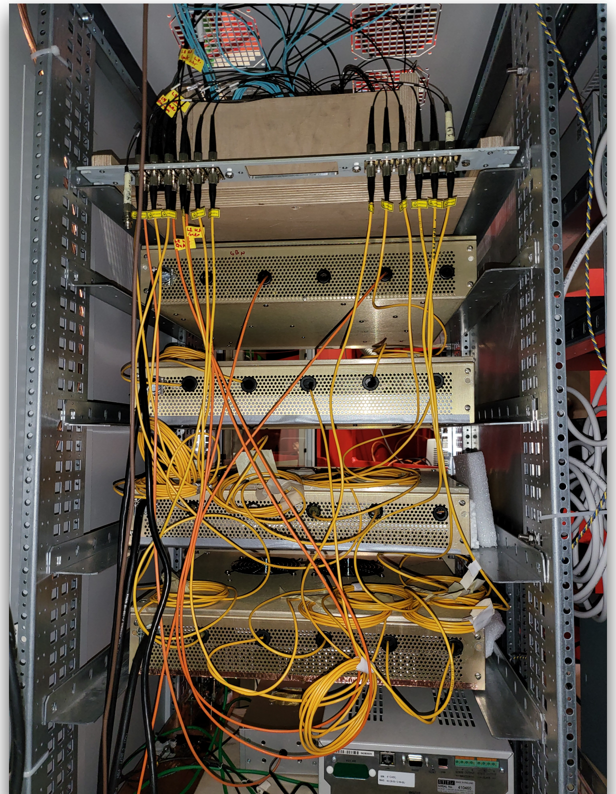
Upcoming CB2 Testing

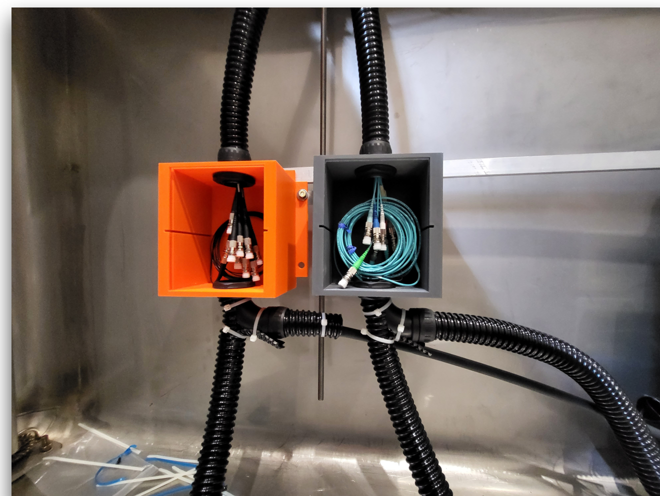


Installation completed on Apr.27
Ready for ColdBox#2

(LAr filling tbd - ~mid May)


New
808nm Laser Box
3 PPM units
New
808nm Laser
PPM (Broadcom)





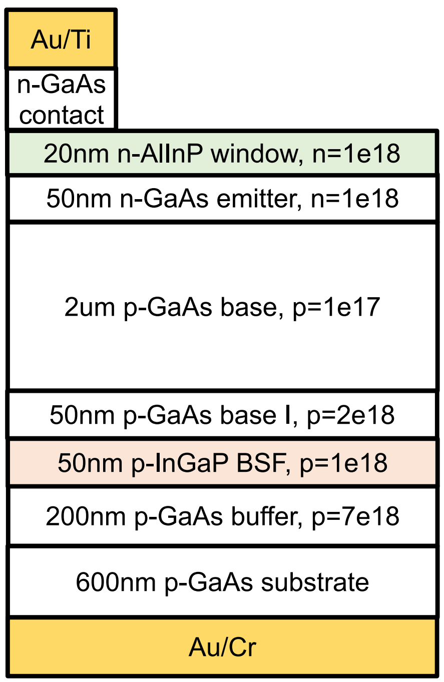
Next step in PoF system Optimization

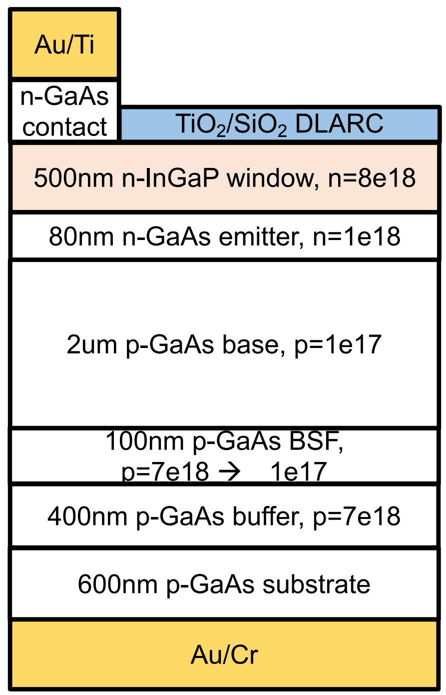
Upcoming PC R&D – At the Semiconductor Level

Looking to improve fill factor at cryo temps
Looking to reduce Rs
Looking to find a way to size up design/semiconductor
Present efficiency in cryo at ~51 % - Will do better

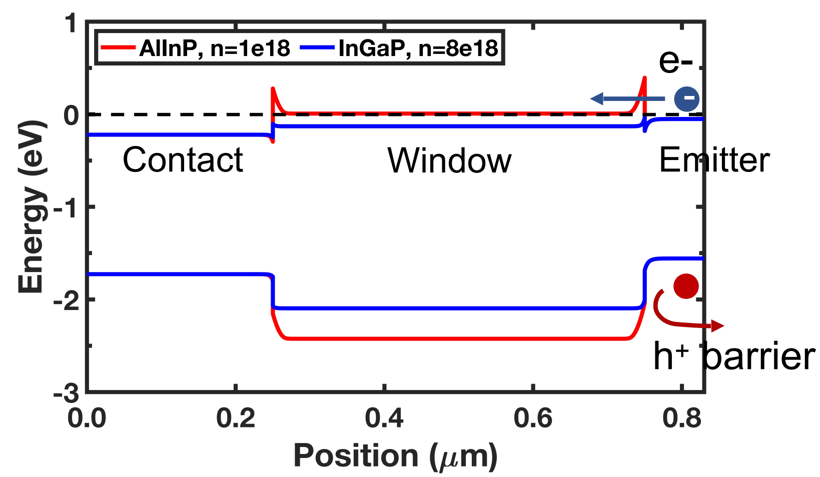
New LPC Design to Lower Series Resistance (R_S)

- **Design**
- #1 → #3





- **Aspects expected to be improved**
- Low R_S enabled by thick, n+-InGaP
  - Suppressed majority carrier blocking



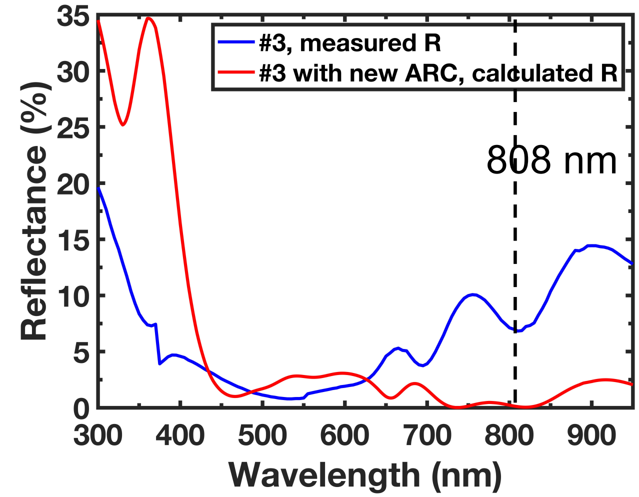
  - Low R_{sheet} (33-35 ohm/sq)
- EQE enhancement by DLARC

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

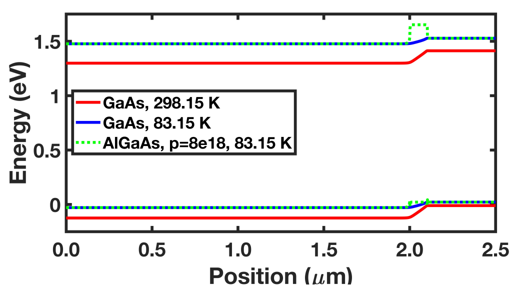
- **EQE boost with optimized ARC**
  - Simply, with optimum ARC, efficiency at 190˚C will be ↑ to -54%.

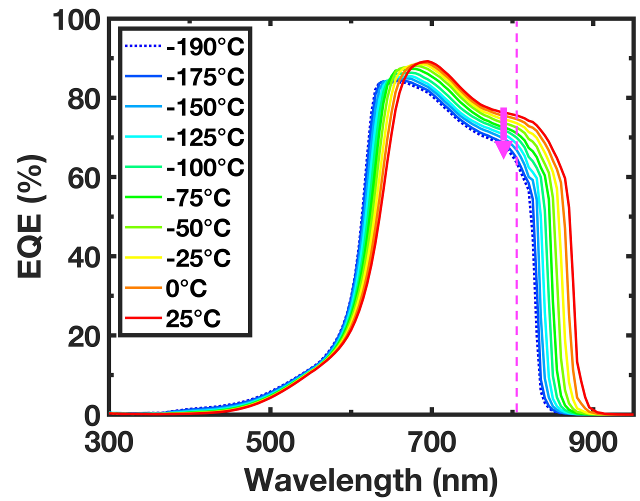
ID	$R_{808\ nm}$ at RT	$EQE_{808\ nm}$ at RT	$EQE_{808\ nm}$ at -190˚C
#3	7.0%	75.4%	62.2%
#3 with optimum ARC	0.2%	80.9%*	66.8%*

(* expected values)



- **p+$Al_{0.1}GaAs$ BSF**
  - Diffusion length ↑, barrier for minority carrier
  - → suppress decrease in EQE at low T





Following the successful Validation Test at CERN ColdBox#1 in Dec.21 and the continued operation during the ARIADNE ColdBox test in Feb/Mar 22

PDS with PoF&SoF is now baselined for DUNE FD2

PDS with PoF&SoF is currently in its optimization phase (2022-23)

ProtoDUNE-VD Module-0 Integration Test (2023) milestone for final approval

PDS Construction phase expected starting in 2024.

A large international community of groups/institutions from DUNE PD Consortium engaged for PDS realization

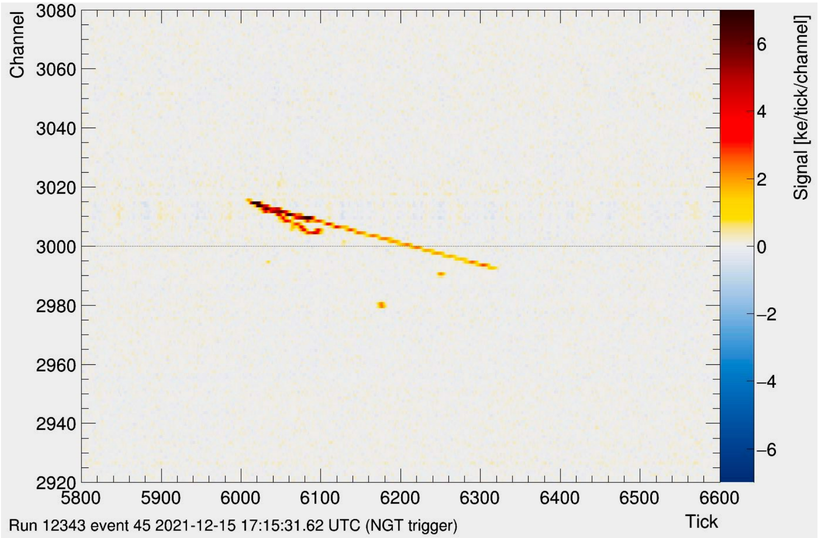
PDS ColdElectronics primary scope for US/DoE

+ important contributions from EU groups

FERMILAB leading institution, with Project management responsibility

CE optimization and Detector design finalization on the critical path

BackUp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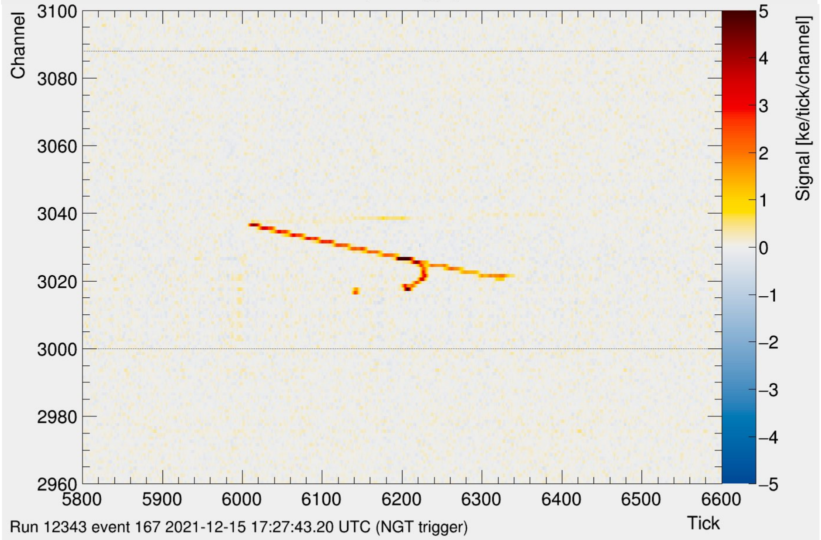
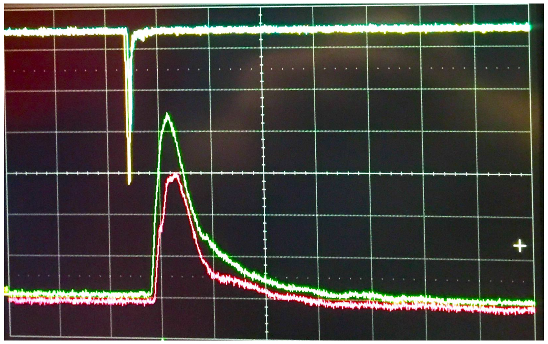
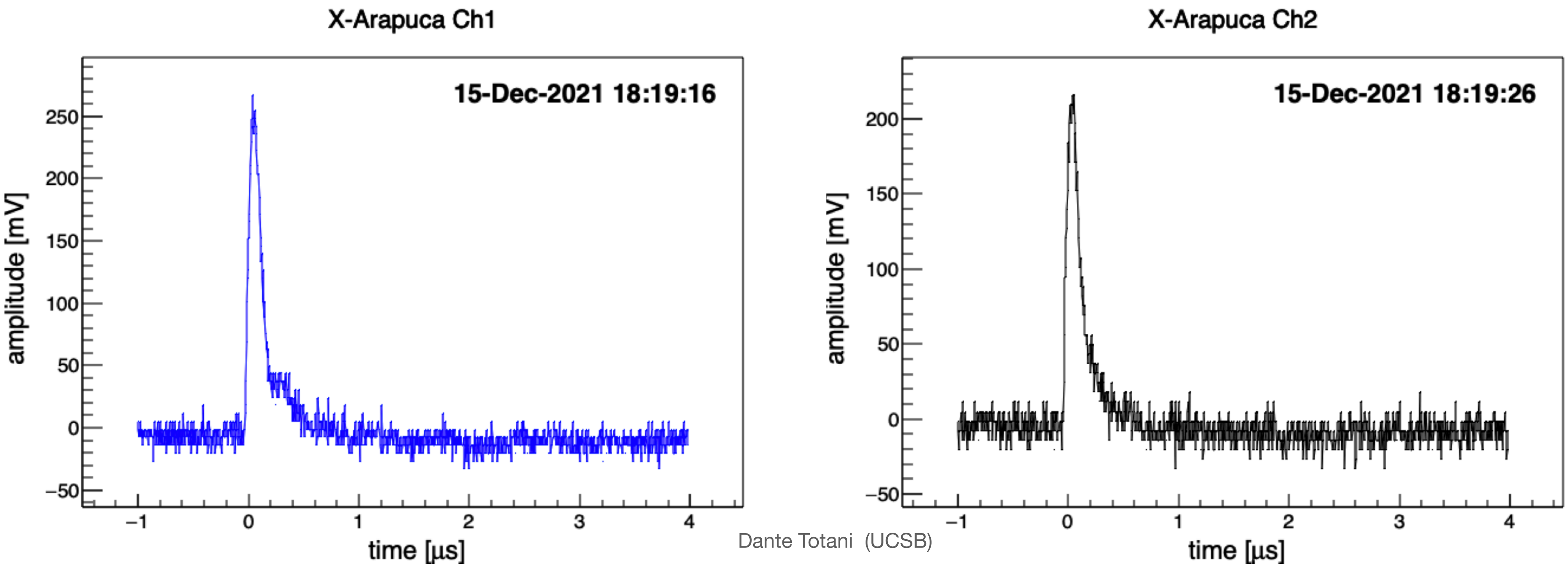
Signal [ke/tick/channel]
Tick
Run 12343 event 45 2021-12-15 17:15:31.62 UTC (NGT trigger)


Channel
Signal [ke/tick/channel]
Tick
Run 12343 event 167 2021-12-15 17:27:43.20 UTC (NGT trigger)



Cosmics Run

Example of signals triggered on CRT + X-Arapuca



Dante Totani (UCSB)