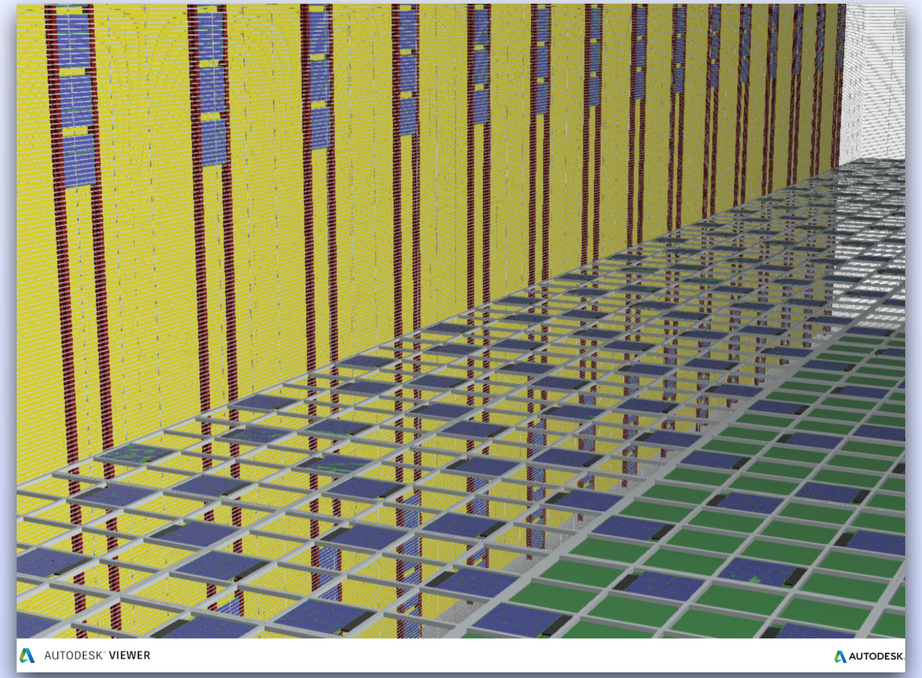
FD2 VD Photon Detector System:

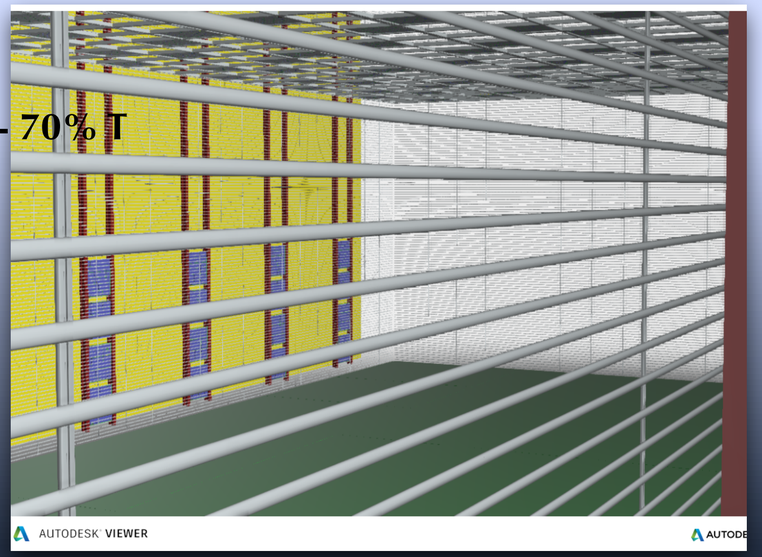
Cold Electronics (PoF and SoF) Progress, Status and Path forward

View from inside the Upper Volume with PD instrumented Cathode (below) and PD instrumented Membrane behind the FC



modified FC - 70% T

View of the Lower Volume from behind the FC, as seen by the Membrane PD modules



FD2 PD Cold Electronics Workshop
Brookhaven National Lab

The idea for a Photon Detector System with Power-over-Fiber (PoF) and Signal-over-Fiber (SoF) for voltage isolation and noise immunity was first presented at the DUNE *Module of Opportunity Conference* at BNL in fall 2019 (B.Pellico and FLC).

First PoF development at FNAL-AD in early 2020 and first tests at CERN in fall 2020 *(6 months lockdown in between)*

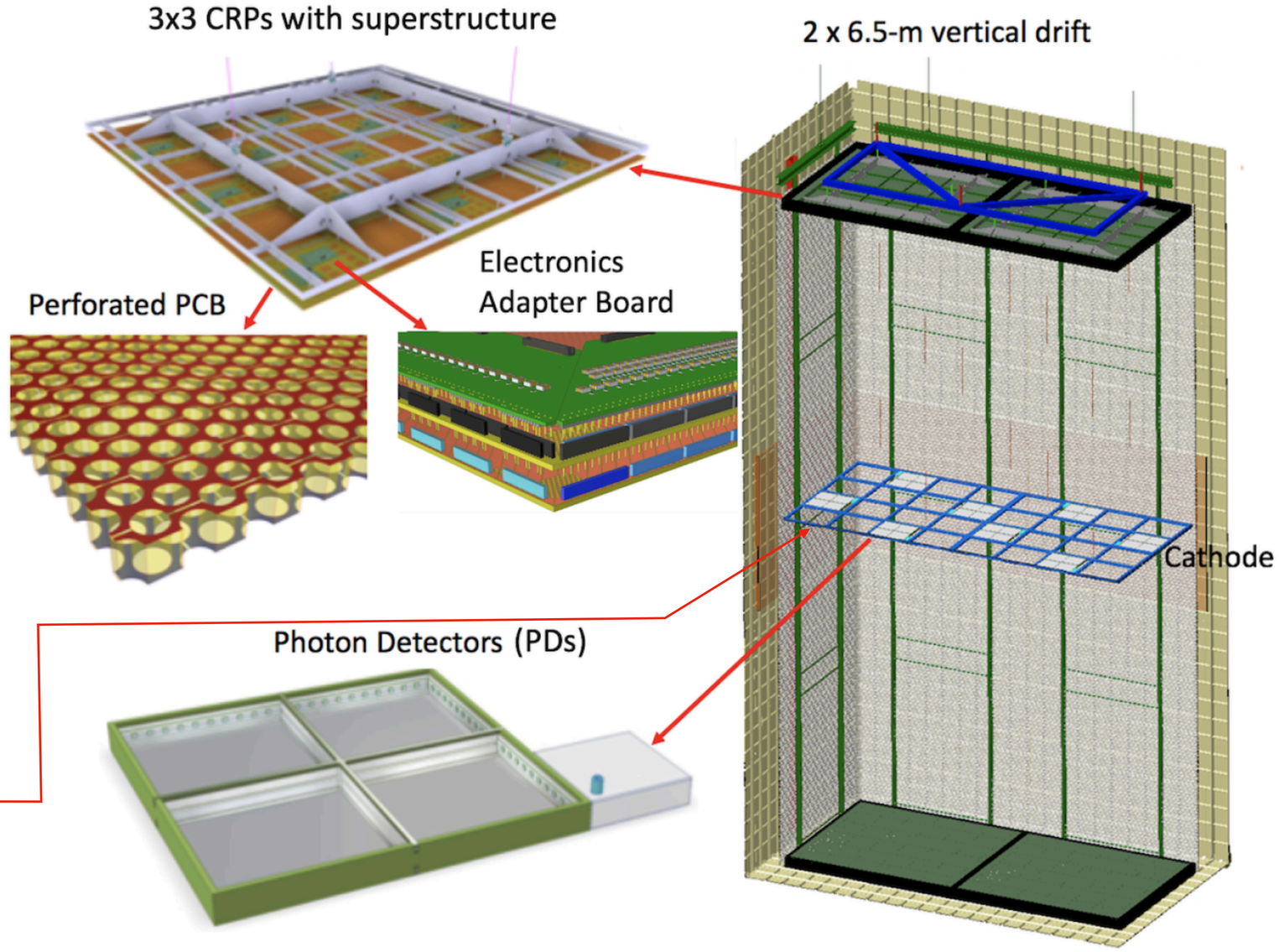
In the meantime the "Vertical Drift" TPC design based on perforated PCB - Charge Readout Plane was proposed for DUNE FD 2 …

but "*we need a PD, and we need it on the Cathode…* "

⇒ **PoF-SoF based PDS concept proposed by FNAL was taken as candidate for FD2 PDS**

A new Photon Detector for the new DUNE FD2 VD Module

- Energy deposition in liquid argon yields two signals:
  - ***free charge*** from ionization
  - fast ***scintillation light***.
- **TWO DETECTORS in one LAr Volume**: LAr-TPC and LAr-PDS complementary for improved Detection Efficiency, enhanced Energy Resolution and max LiveTime
- PDS particularly important for detection & reconstruction of low energy underground events and background rejection
- PDS Optical coverage: 14% of Cathode and 8% (behind) FC walls provides high & uniform Light Yield



Operating PD on HV surface (Cathode) requires

electrically floating *Photo-sensors* and *r/o Electronics*

⇒ Power (IN) and Signal (OUT) transmitted via non-conductive cables (i.e. optical Fibers)

Existing PoF and SoF *(optolinks)* technologies are employed for voltage isolation between source/receiver and embedded electronics in high voltage or high noise environments.

however:

none of the commercially available technologies are rated to operate in Cold (at LAr Temperature)

⇒ A highly specialized R&D has been launched (mid Mar '21)

to customize and develop PoF and SoF technologies for Cold applications

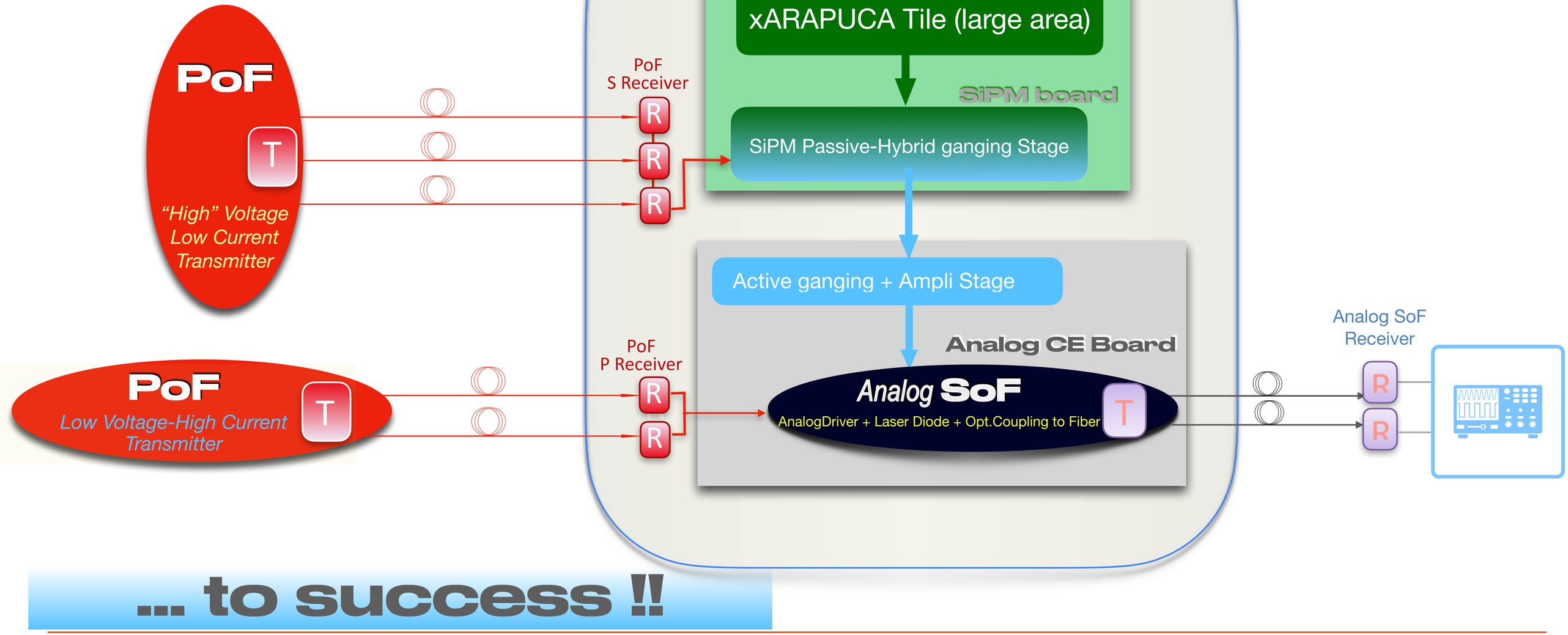
the challenge:

the timeline of the Project required PoF and SoF R&D to be completed it in ~6 months.

(with demonstration and validation of the new technology by fall '21)

The VD R&D 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**).

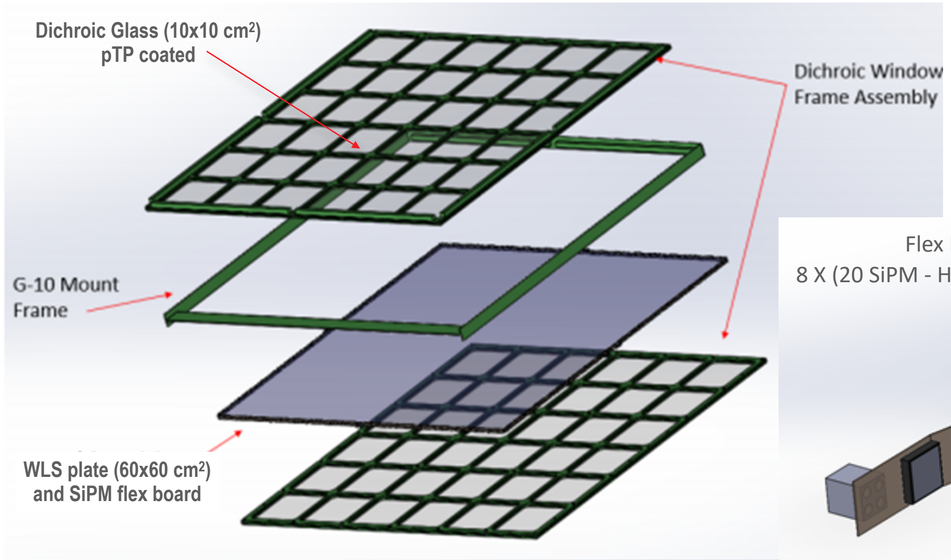
- the **PoF system** for power supply to sensors and to r/o electronics:
  - ☆ **HV-LC PoF** for SiPMs, that require $\mathcal{O}(< 10\ \mu\mathrm{W})$ power output, at high voltage (30-50 V) and very low current (< 100 nA per sensor).
  - ☆ **LV-HC PoF** for OpAmps and other active analog electronics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

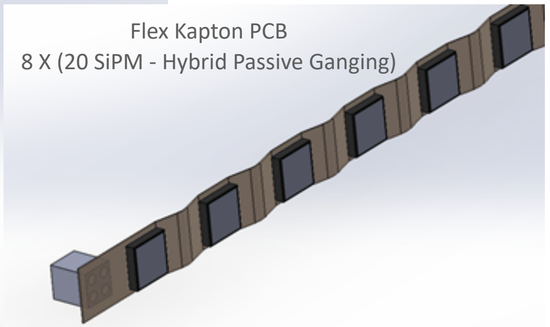
PhotoCollector concept

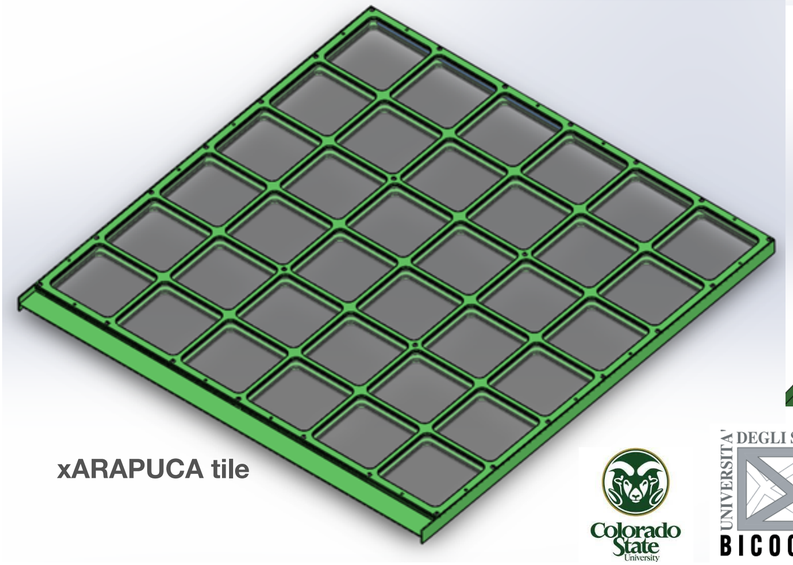
xARAPUCA technology - large detection Area, 2 r/o channels



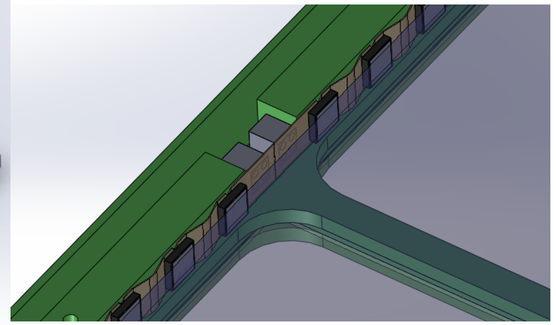
UCSB Fermilab

SiPM board





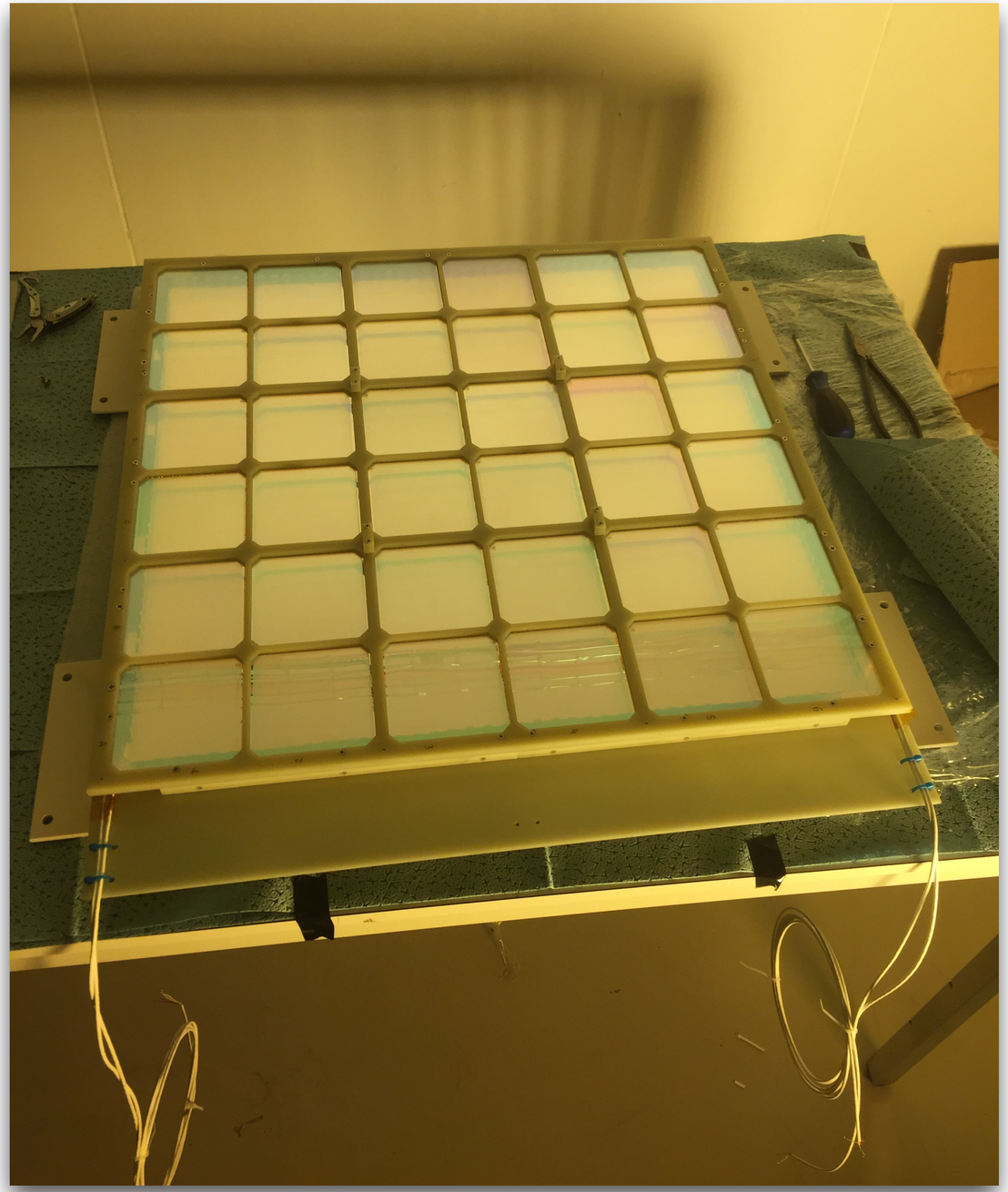
SiPM-WLS plate optical Contact



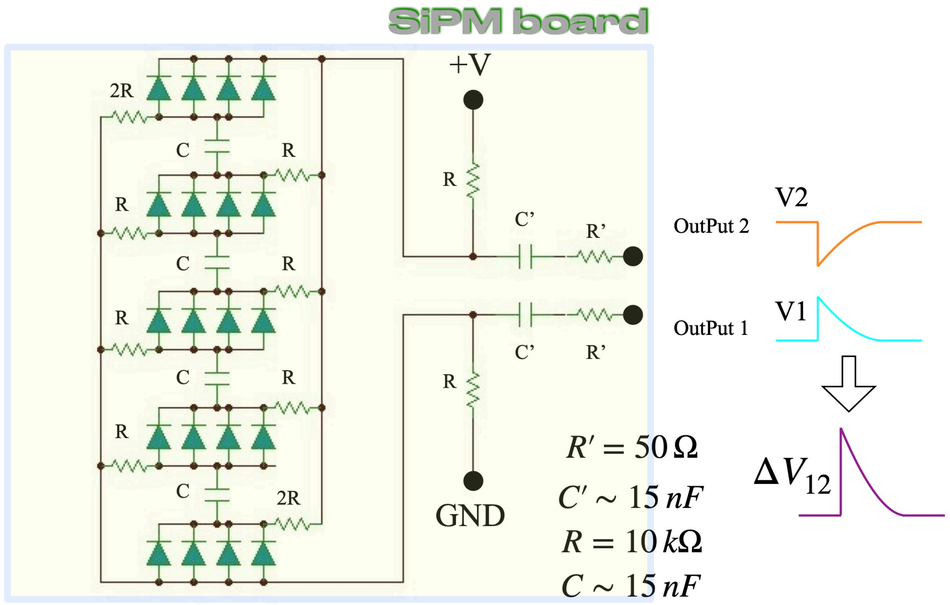
Colorado State University

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

xARAPUCA tile assembled and cabled



Analog SoF concept



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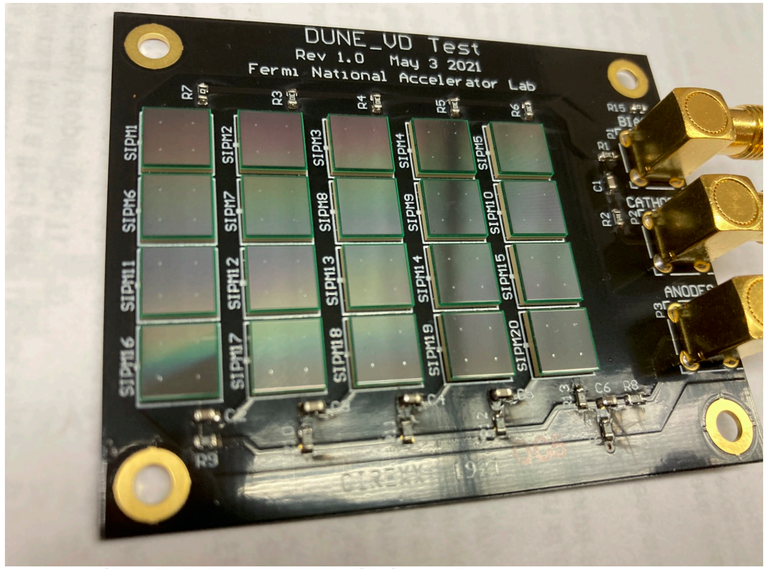
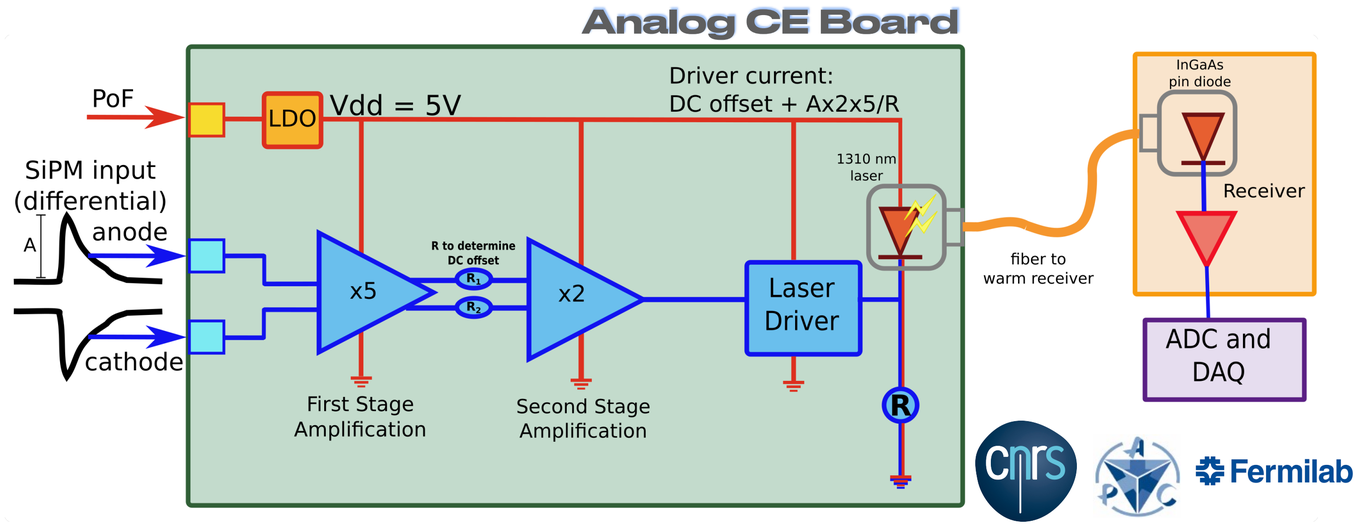
Fermilab

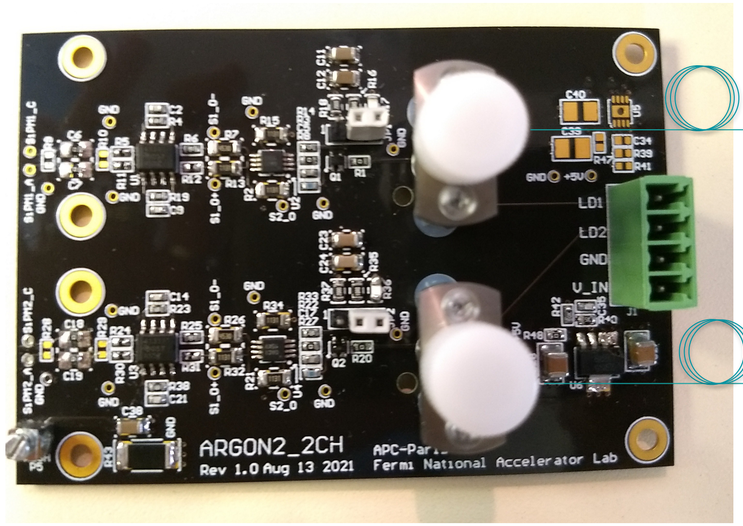


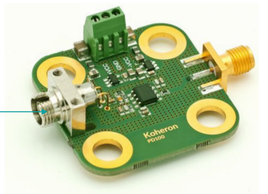
the SiPM Board(s)- Passive hybrid ganging

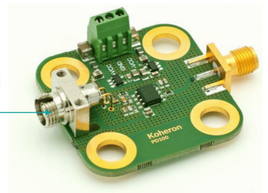


cnrs

Fermilab







the Analog CE Board
Active ganging/Ampli & SoF

Fermilab DUNE

PoF concept

multimode fiber with FC connector

PoF Transmitter

Photonic Power Module (PPM)

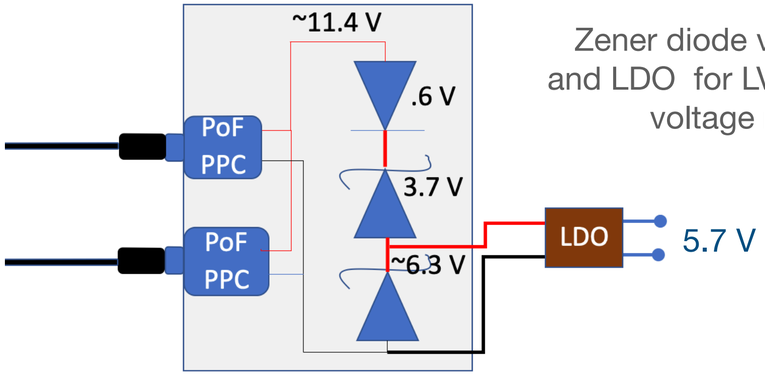
976 nm laser diode

Si-based

PoF Receiver high intensity

Photovoltaic Power Converter (PPC)

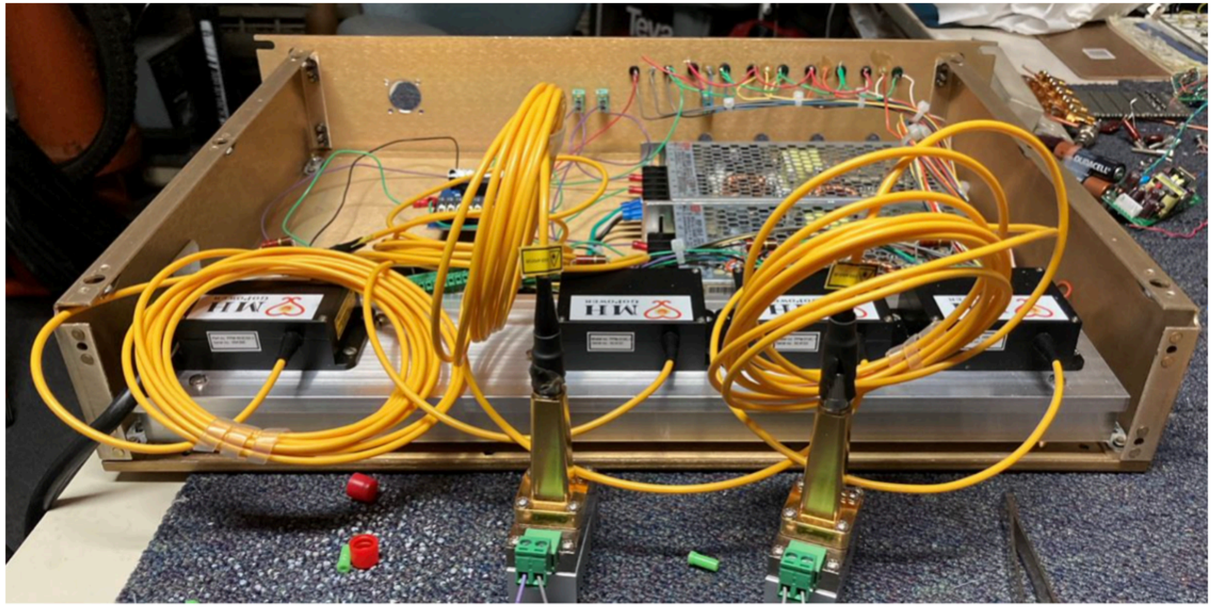
on heatsink

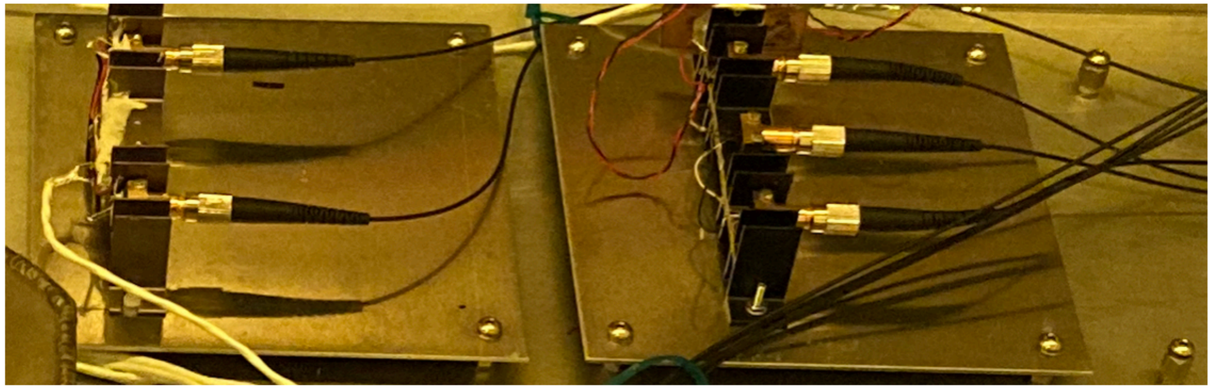


Zener diode voltage divider and LDO for LV-HC PoF output voltage regulator

Fermilab/AD

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.

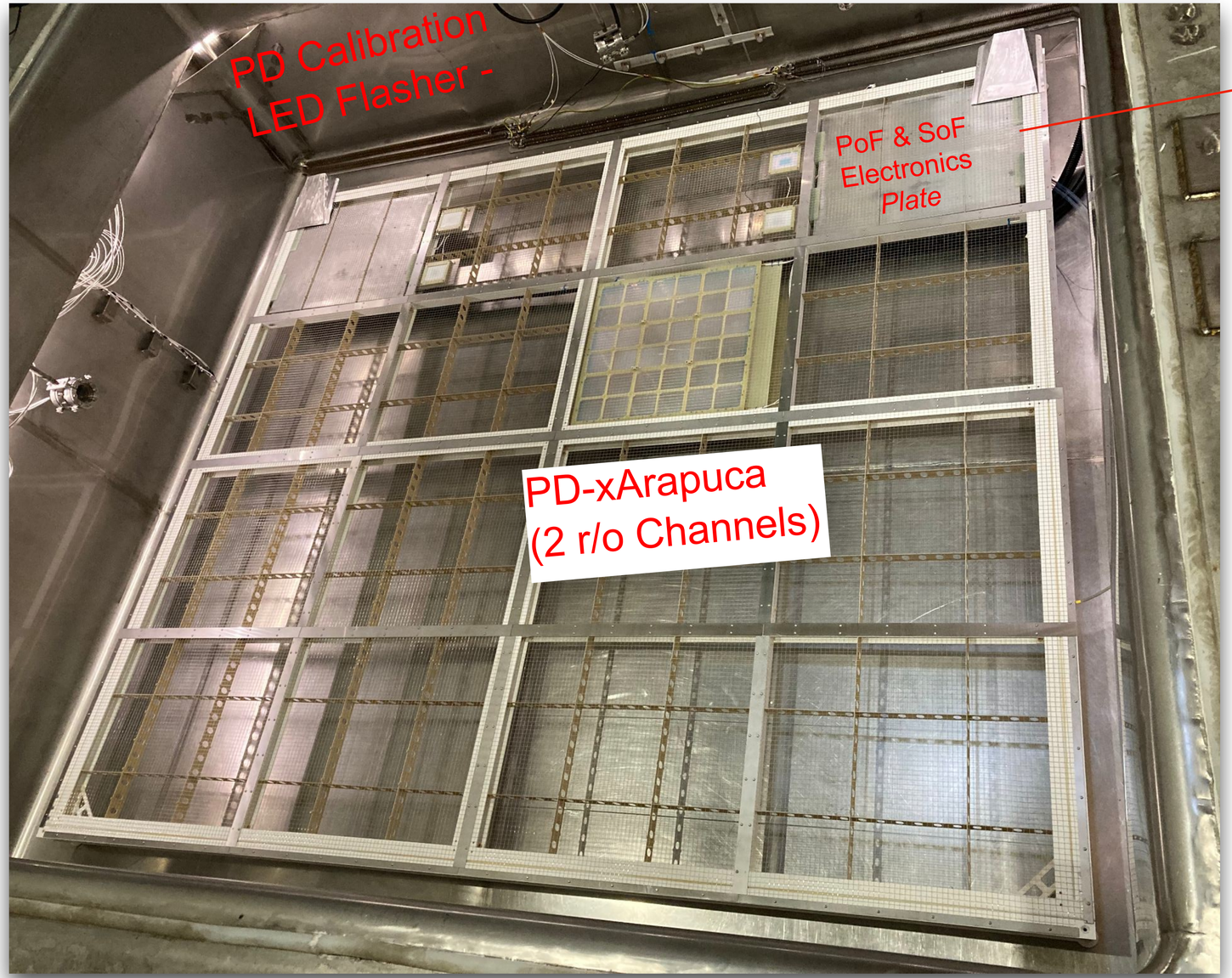
In our application, ***the first in detector technology for HEP,*** PoF supplies power to the active elements, *photo-sensors and cold electronics*, of a photon detection system immersed in LAr and lying on a HV surface.

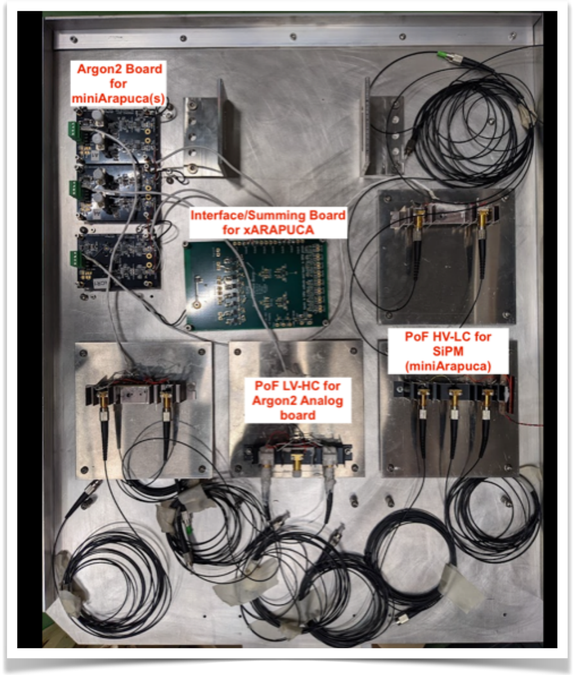
The 976 nm, 3.5 W Si-based solution is demonstrated.

A new 808 nm, 3 W very high efficiency GaAs PPC units is under development/test.

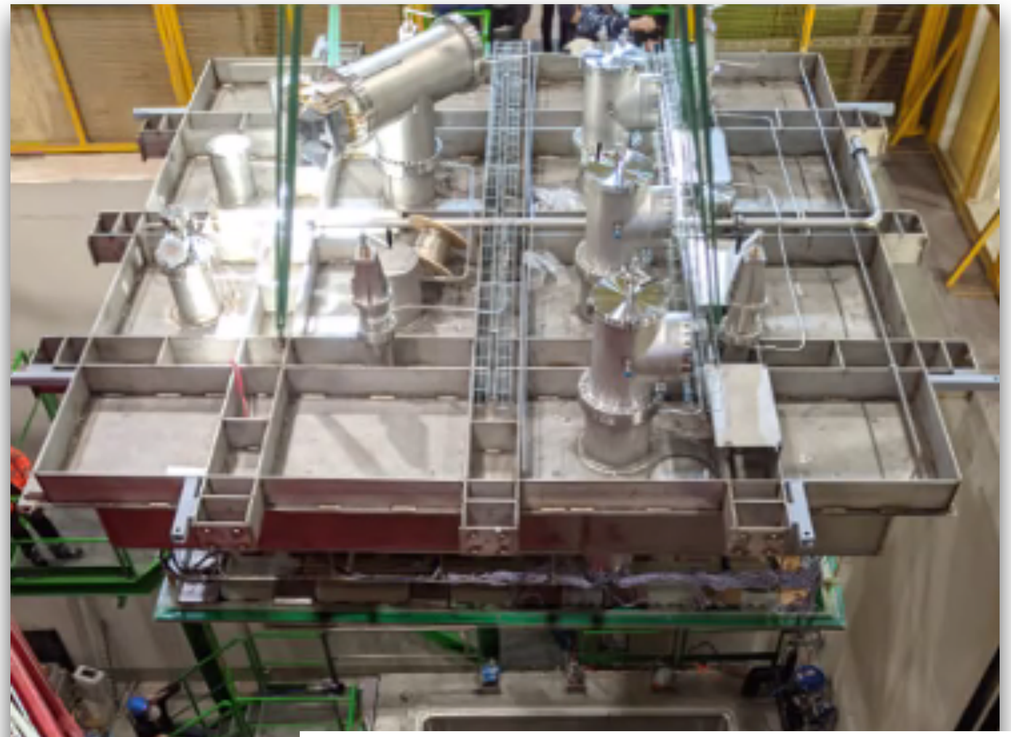
The innovative cold PoF-SoF technology is immune from noise injection and signal distortion, and therefore adequate for low amplitude light signal collection and read-out

Validation Test at CERN - NP (ColdBox experiment)





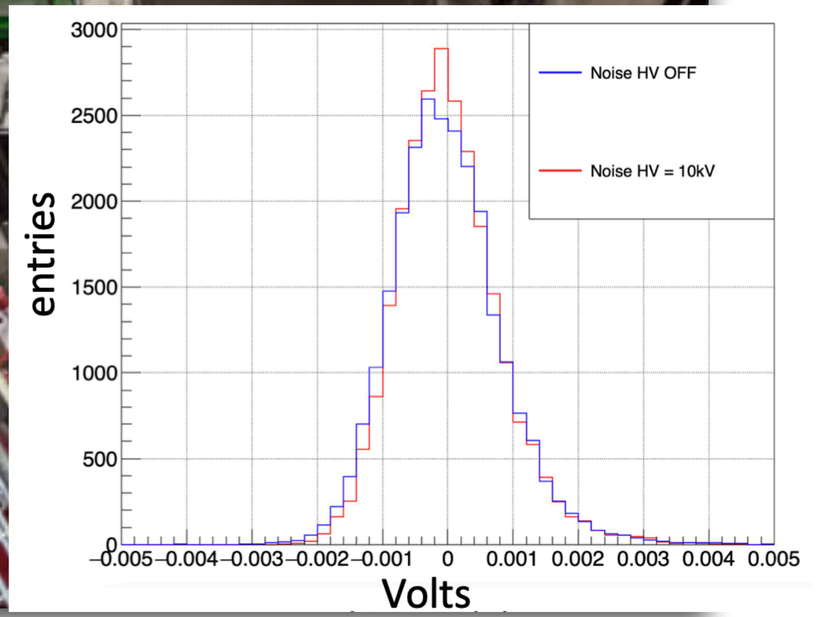
On Dec. 13
PDS on the Cathode + LED Calibration system installed in ColdBox at CERN Neutrino Platform



Milestone:

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

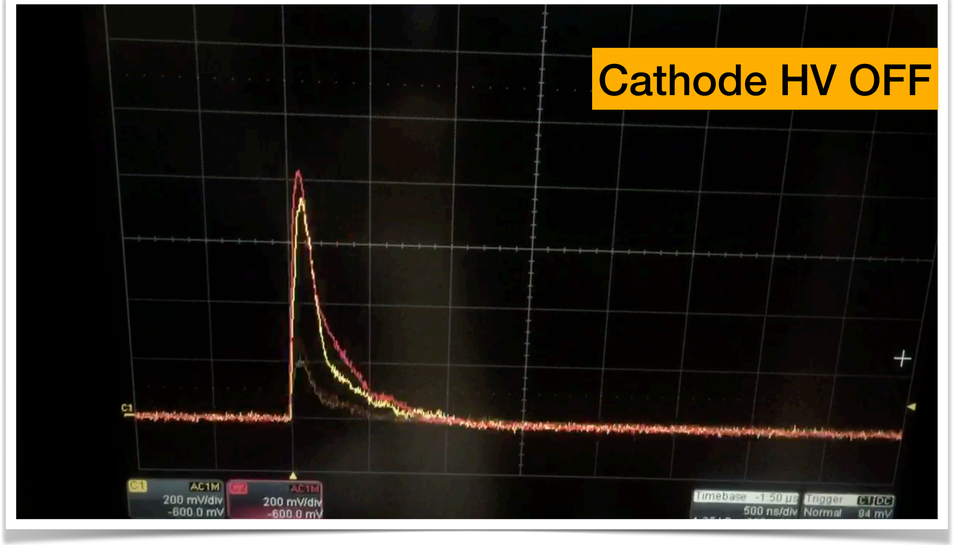
No noise increase or signal distortion when HV ON

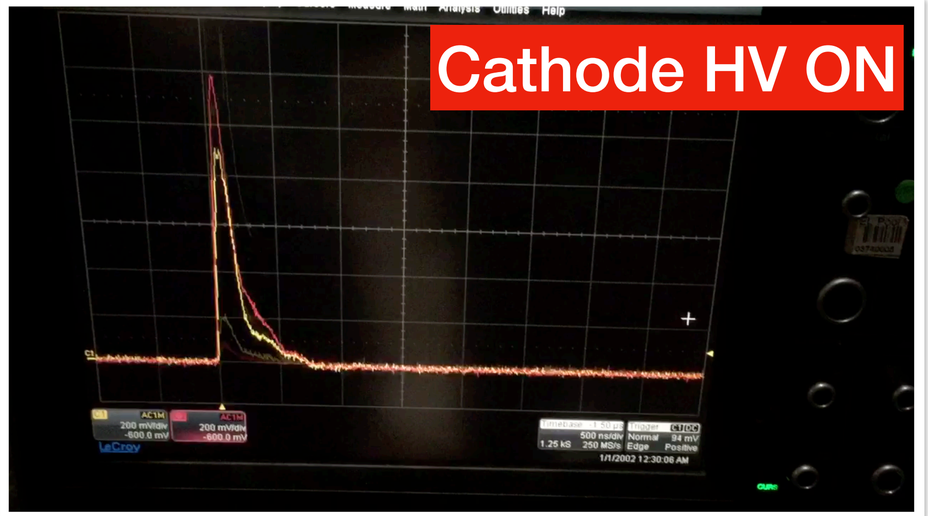


HV OFF:
Mean = -0.05 mV
Sigma =0.77 mV

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

VD PDS signals with Cathode HV ON in LAr





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

Role of this Workshop:

focus on critical decisions, define strategy/choice and responsibility sharing

on the critical path:

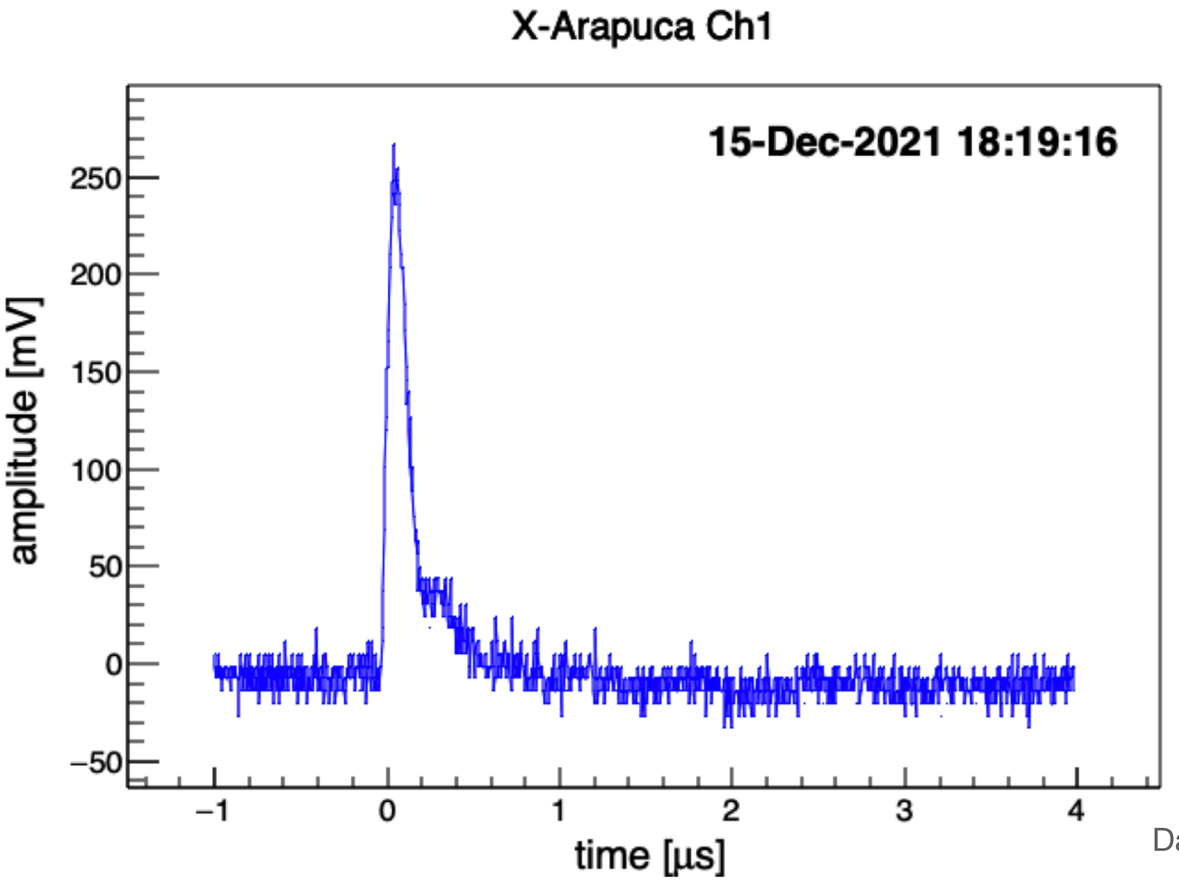
- complete design of PoF system for power distribution (GaAs PoF & optical-to-electrical conversion efficiency, optical fiber selection, voltage/current regulation)
- optimize design of Analog SoF (laser driver, amplification gain, S/N)
- PD layout on the Cathode, implementation of HV discharge risk mitigation (shield for EM fields/electric charge, inductance,…)
- 30yrs lifetime qualification: all electronic component should be qualified through endurance test, risk mitigation for long lifetime failures

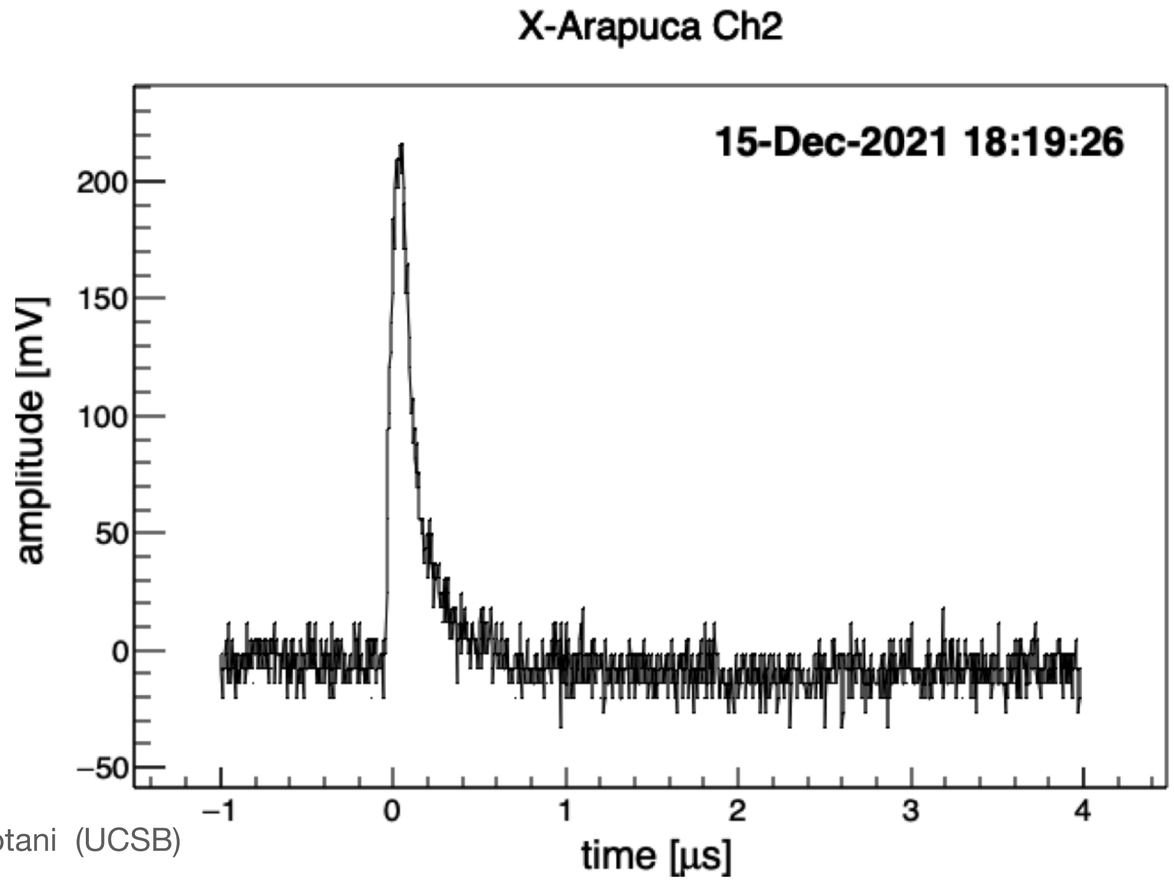
BackUp

Flavio Cavanna
April 13, 2022

Cosmics Run

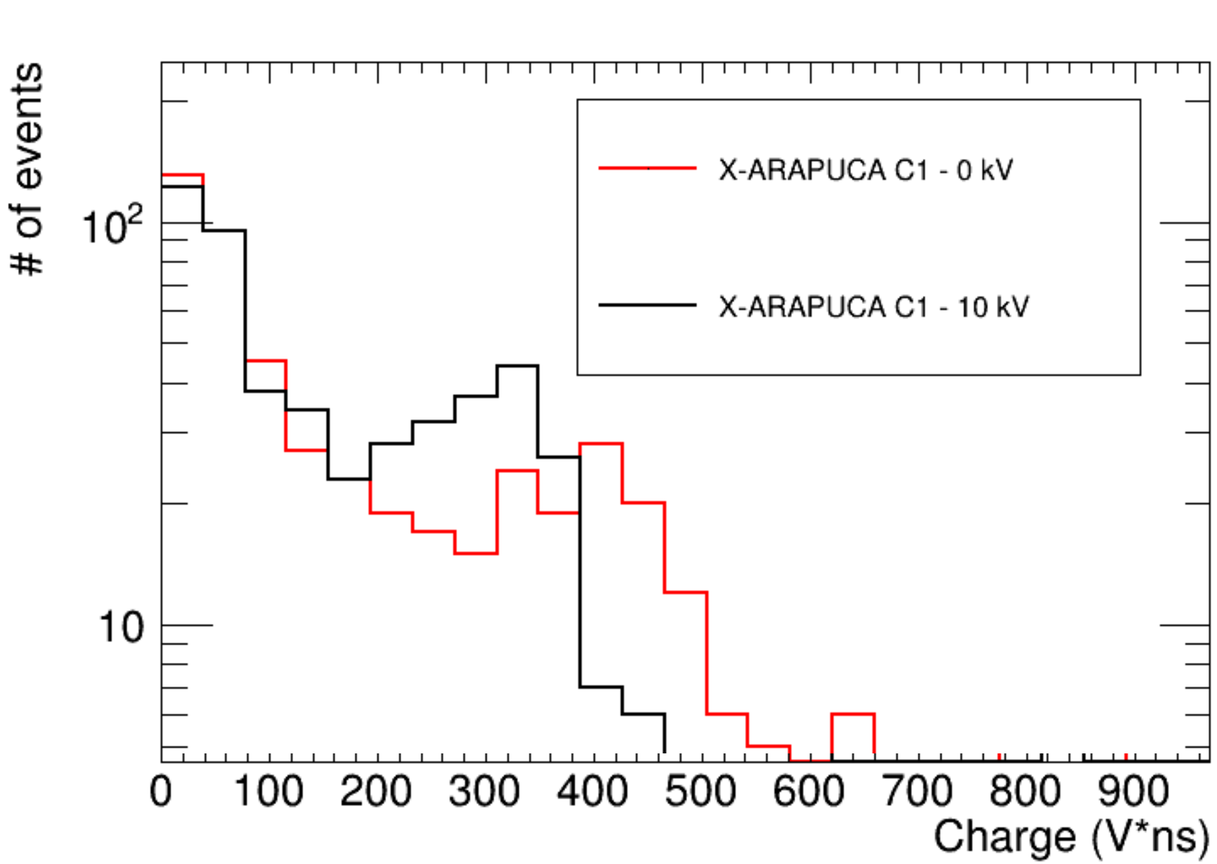
Example of signals triggered on CRT + X-Arapuca

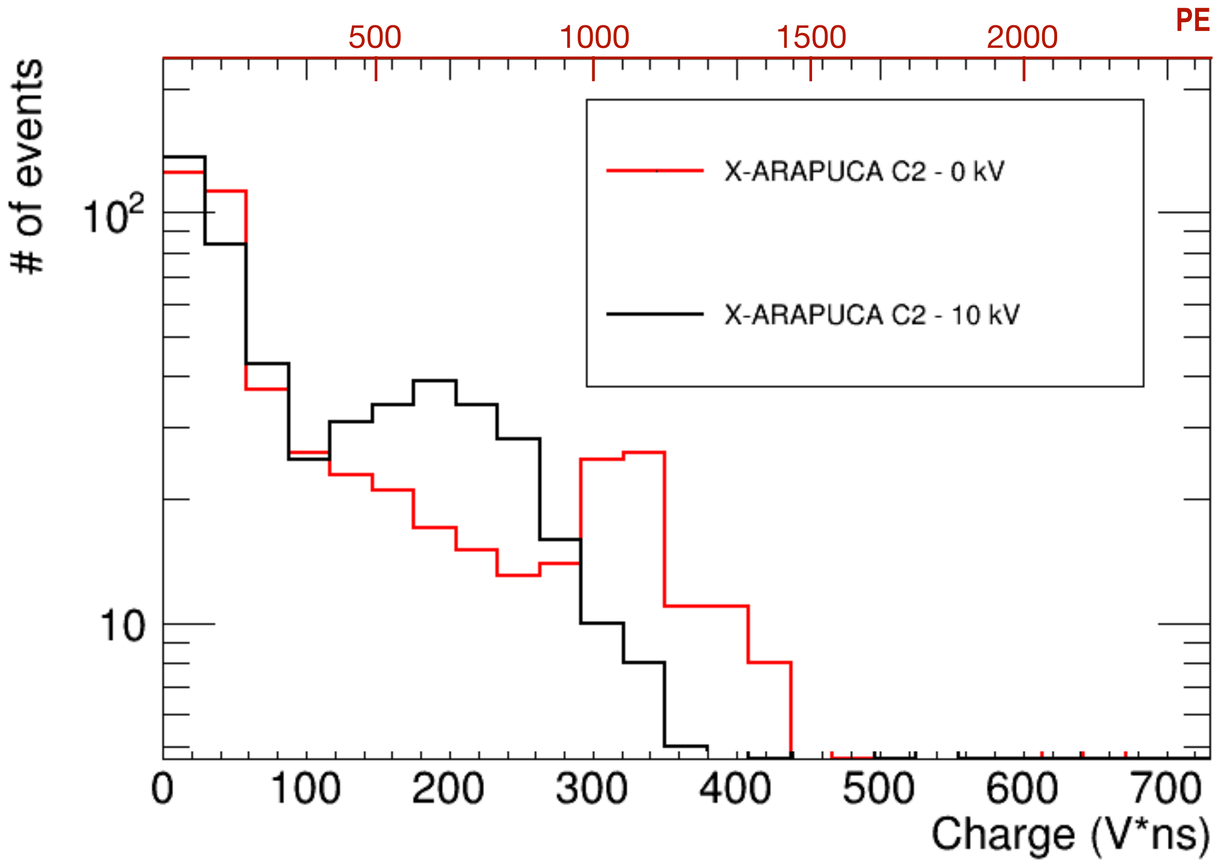




Dante Totani (UCSB)

Light Signals from Cosmic Tracks (external CR Telescope trigger)





1 PE ≃ 0.3 V*ns
(see next slides)

EF-ON vs EF-OFF: light spectra change due to recombination

Henrique Souza (APC)
Sabrina Sacerdoti (APC)

Calibration Run

X Arapuca Channel 1:

Scanned	Prediction from Poisson statistics
Total events = 500	----------
Noise events = 327	$\lambda_P = 0.425$
Single PE=130	138.8
2 PE = 36	29.5
3 PE = 5	4.1

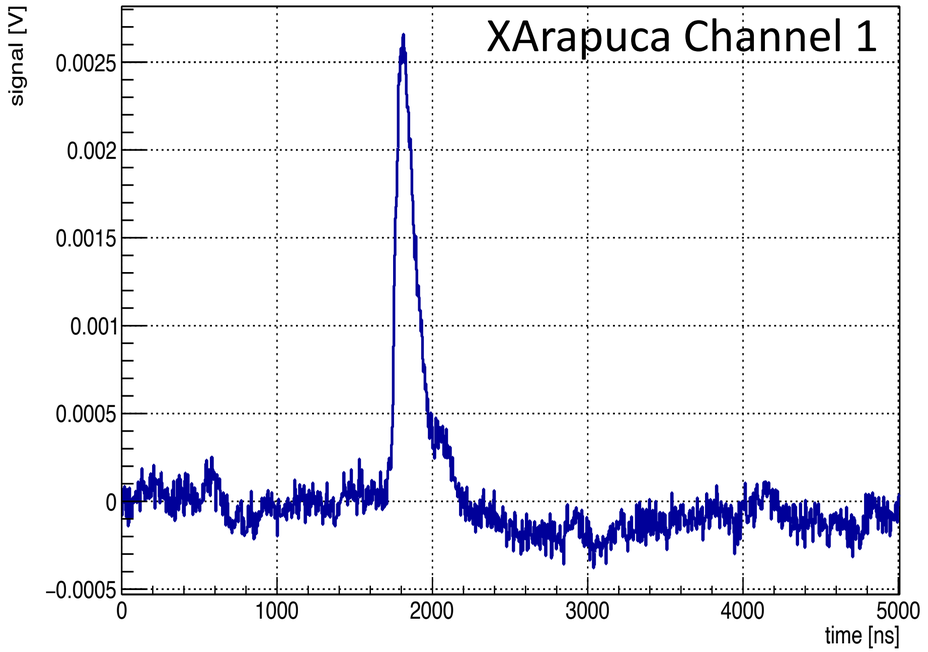
Note: some after-pulse and X-talk contribution to 1-2-3..-PE counts is expected - probably a number of SPE are in the noise (0-PE sample)

X Arapuca Channel 2:

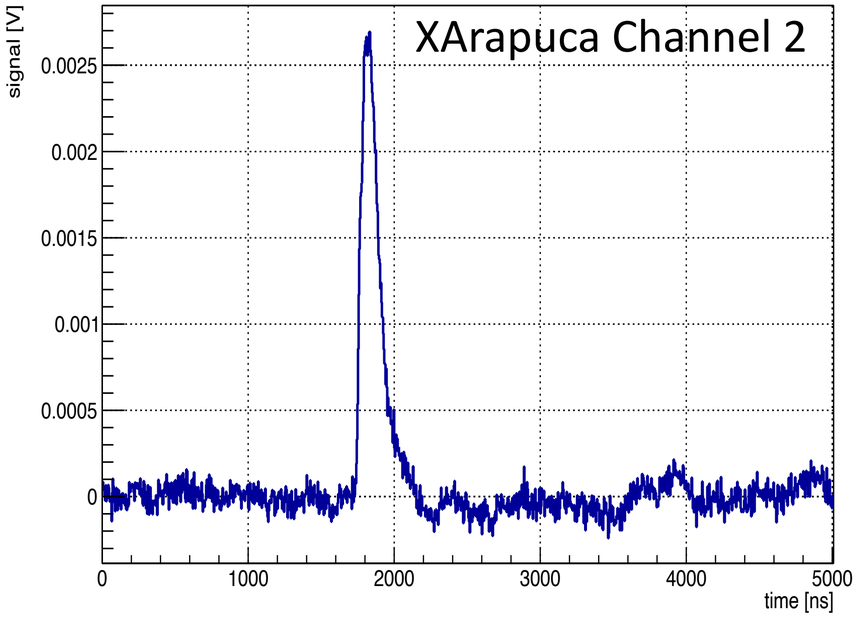
Scanned	Prediction from Poisson statistics
Total events = 500	----------
Noise events = 325	$\lambda_P = 0.430$
Single PE=143	140.0
2 PE = 26	30.1
3 PE = 5	4.3

Analysis is in progress - with more extended statistics

Average SPE waveform

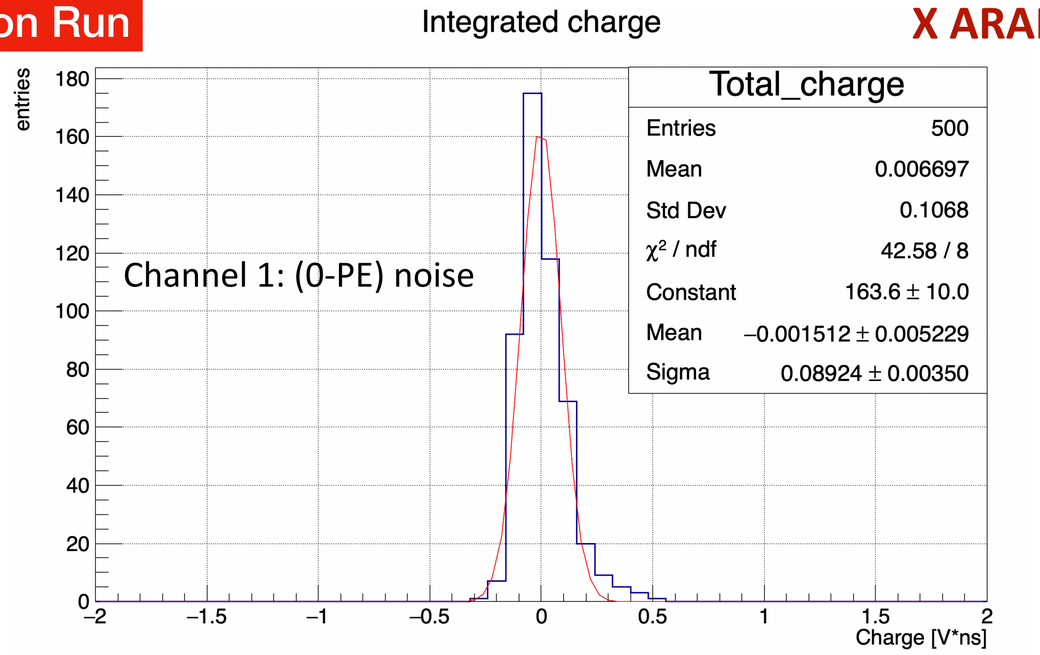


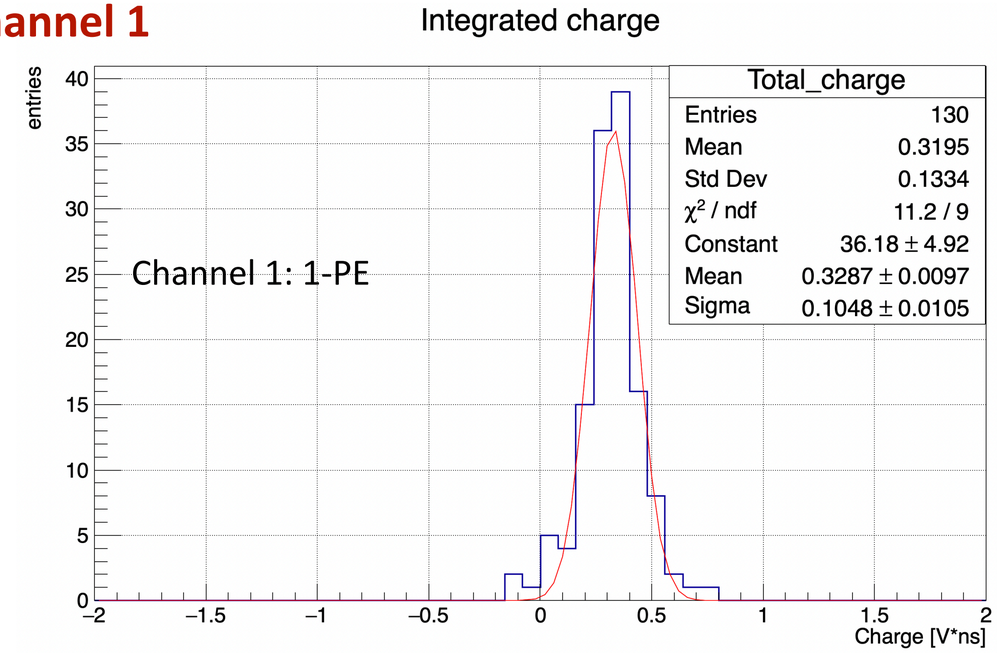
Average SPE waveform



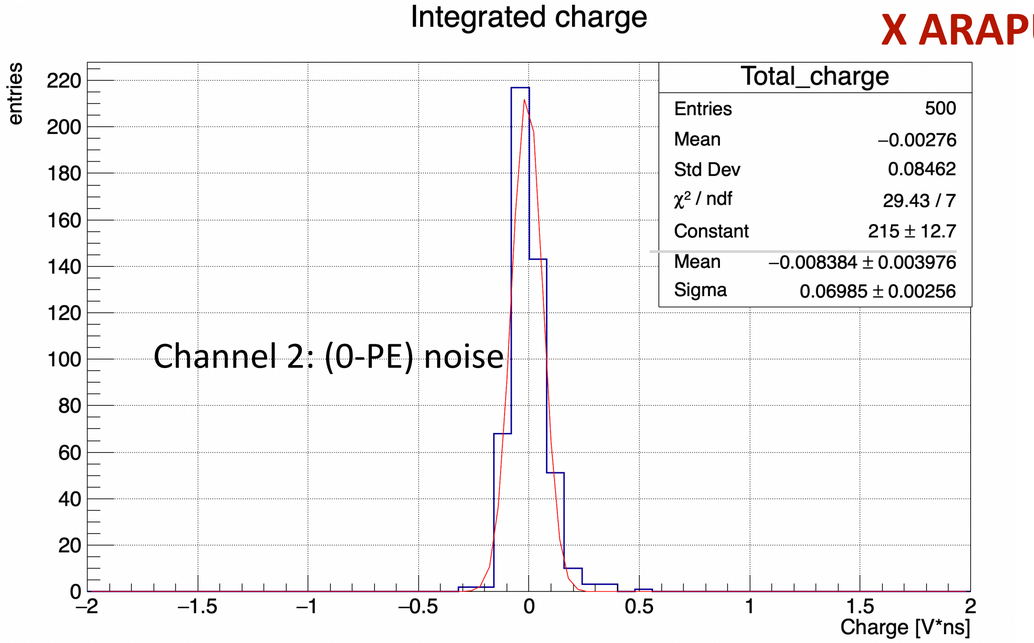
Calibration Run

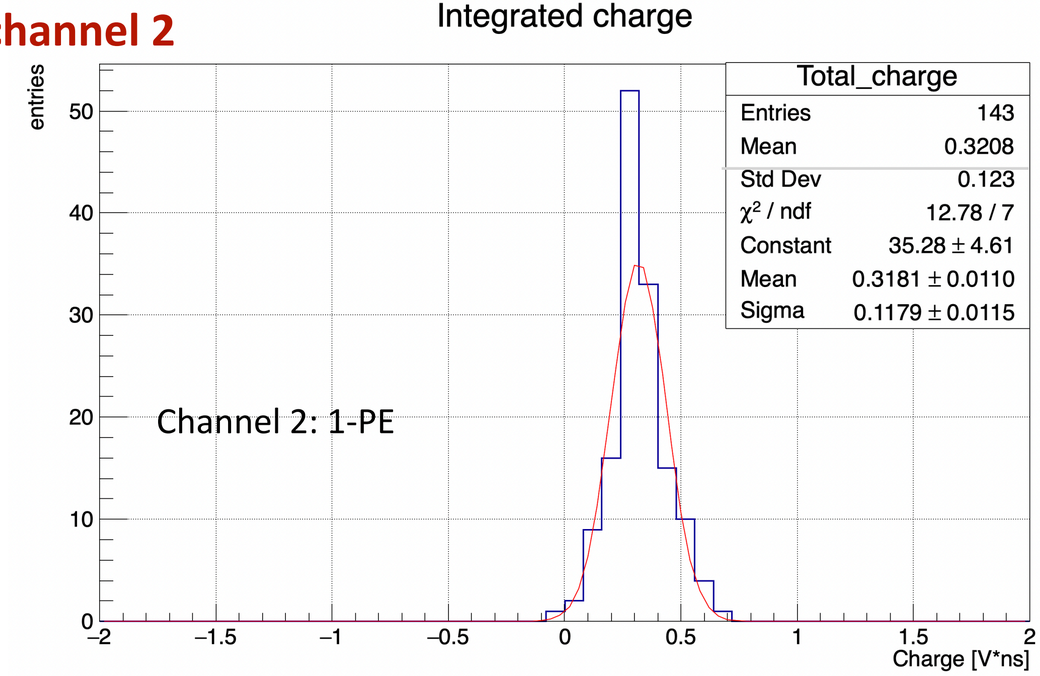
X ARAPUCA channel 1



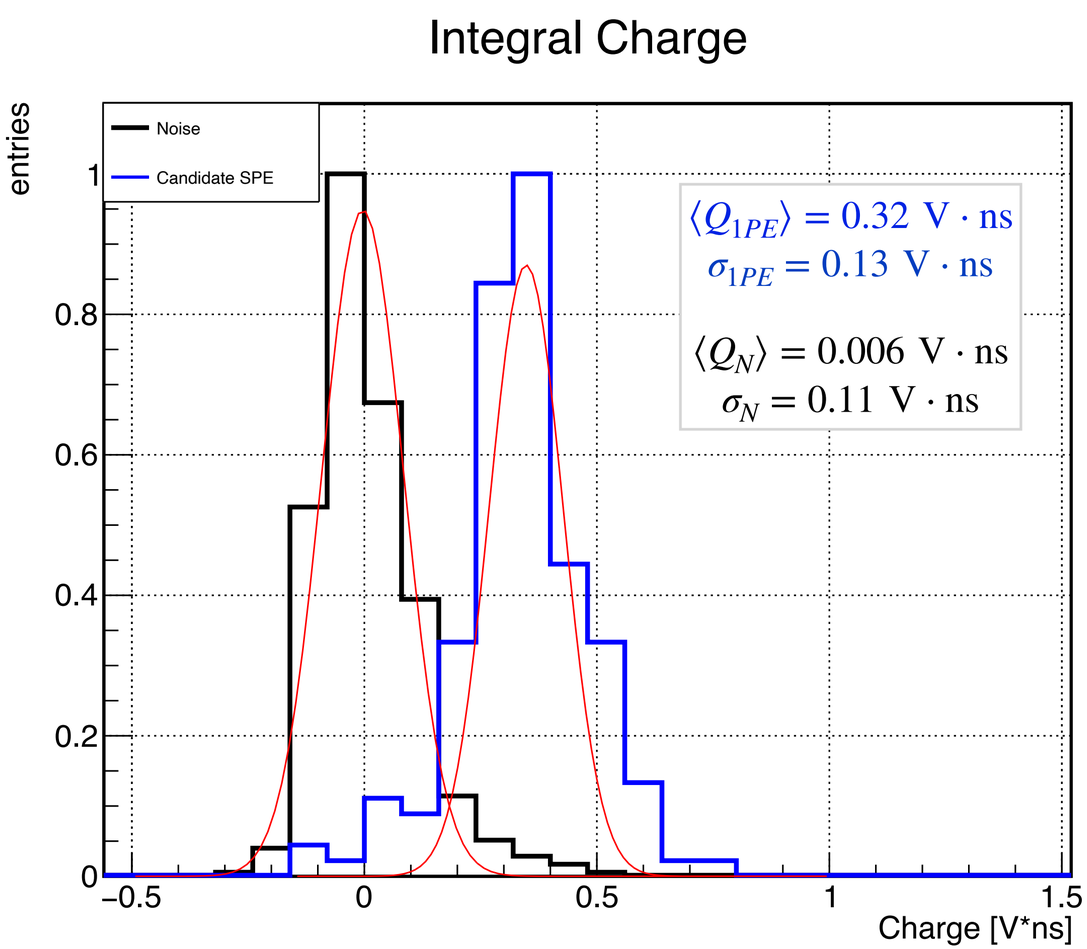


X ARAPUCA channel 2

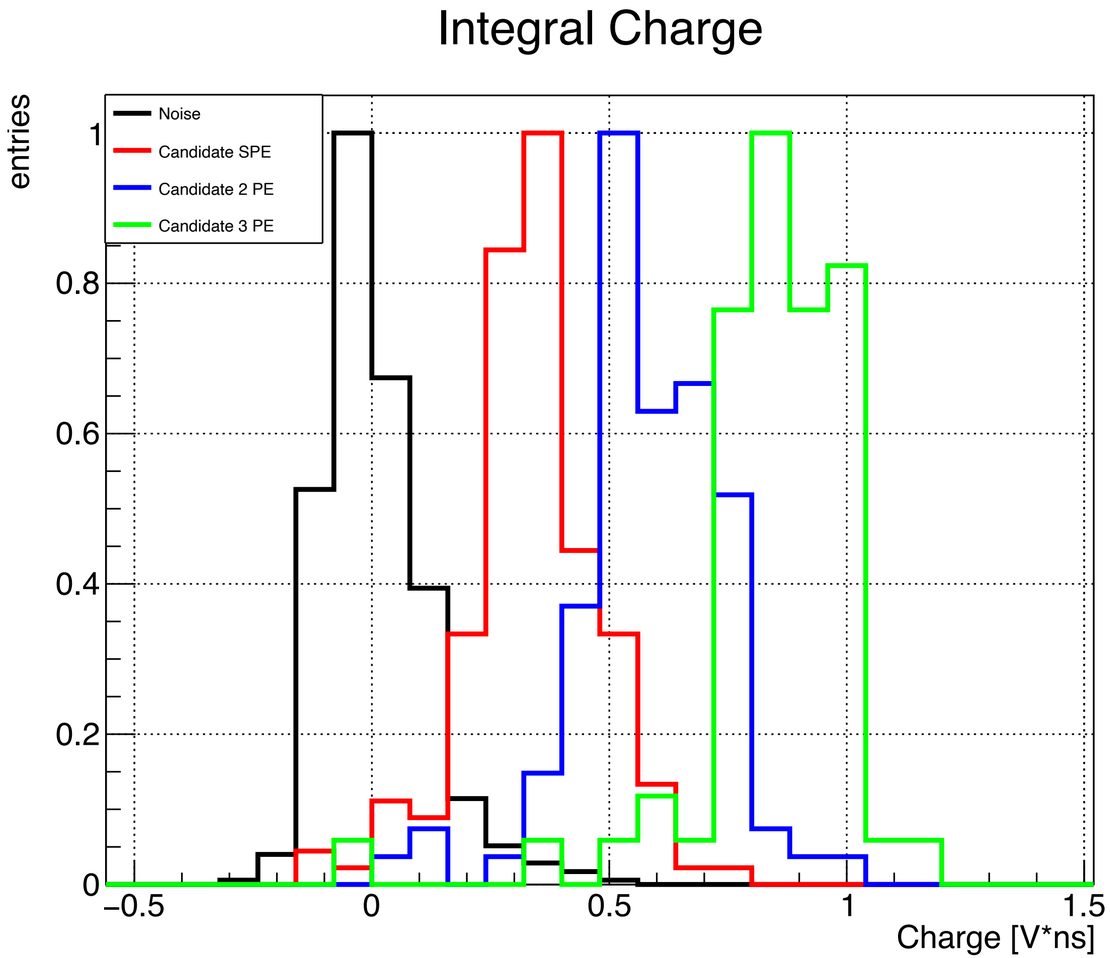




Calibration Run



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



and here adding 2-PE and 3-PE Charge distributions (normalized)