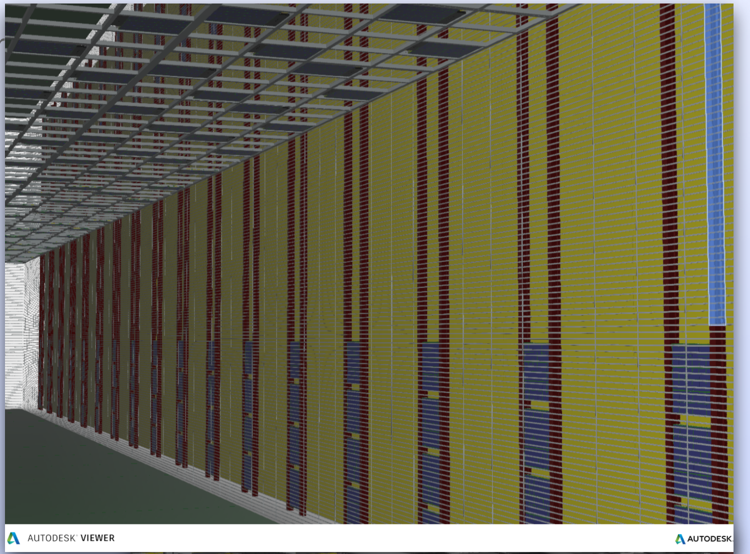
Final Design Review

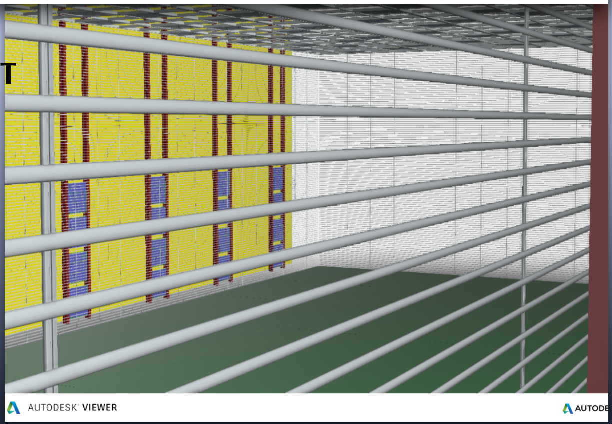
FD2 -PDS
The Design Path:

Requirements, Milestones, Developments, Baseline

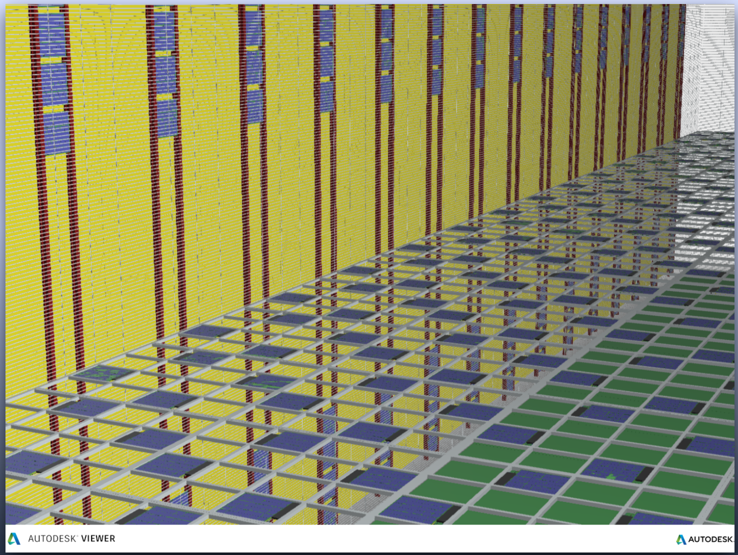
View from inside the Lower Volume with PD instrumented Cathode (above) and PD instrumented Membrane behind the FC



modified FC - 70% T



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



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

DEEP UNDERGROUND NEUTRINO EXPERIMENT

Overview of FD2 PDS technical design and Physics performance

- Requirements: FD2 PDS Physics program driven through the engineering requirements at the component/subsystem level.
- Overview of FD2 PDS validation milestones and baseline design
- Justification for expected performance exceeding the requirement specs, for the overall layout, and how+why the layout has evolved (cathode, sidewalls, endwalls, number of modul, fall-back solution retired)
- Status of each (main) Requirement: either achieved and documented, or planned when (before PRR) => Critical path analysis and float

(FD2) Vertical Drift proposal - Dec 2020

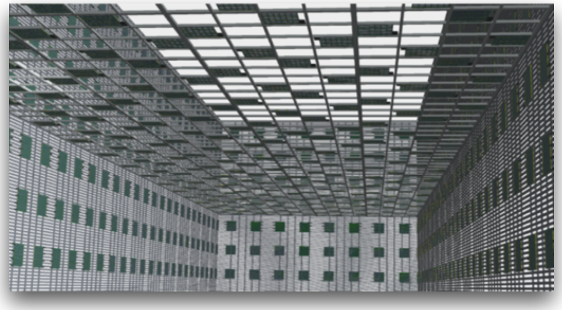
Next-generation LArTPC Detector Technology for the Deep Underground Neutrino Experiment: a Vertical Drift Single-phase Solution with Perforated PCB Anode

First presented at LBNC Review on Dec.7 2020

In the Vertical Drift LArTPC layout, the readout plane structure, even though it is perforated, is not transparent to light and therefore does not allow for PD installation at the anode (ground) side of the TPC volume. This has the consequence that the photon detectors can only be instrumented on the cathode plane or on the field cage walls, and **therefore need to operate on surfaces at voltages** up to the full cathode voltage**.** To meet this challenging constraint, **the PDs are powered using non-conductive power-over-fiber (PoF) technology, and the output signals are transmitted through non-conductive optical fibers, thus providing voltage isolation in both signal reception and transmission.**

The optimization of the PDS in terms of detection coverage, detection efficiency and timing capabilities would allow to enhance the LAr physics reach beyond the minimal scientific requirements: triggering on galactic SNB events, determination of the drift position of proton decay signals and correction for charge lost due to electron capture and other transport effects in the TPC.

Improving the uniformity of the response would increase the trigger efficiency and increase the light yield of the detector, which could enable enhanced calorimetric measurements based on the light emitted by the ionizing particles. The improvement of the signal to noise ratio in the PDS will allow to lower the event energy threshold, which is limiting the detection of low energy events like solar and supernova neutrinos. An enhanced PDS can also provide a better particle identification and a more precise energy measurement.



The ~4π PDS Concept
with Cathode and FieldCage Coverage

The novelty elements in the FD2 VD Design

- Large(st) number of SiPMs per Electronic Channel: 2 ganging stages [hybrid Passive, Active sum/ampli in Cold]
- Large(st) photo-detector sensitive area (60 x 60 cm^2): new XARAPUCA form-factor with new WLS plates
- 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

Boundary Conditions (subject to variations):

Time constraints of DUNE Project [Milestones and Baseline decisions]: <2.5 yr from Concept to FinalDesign (and Module-0)

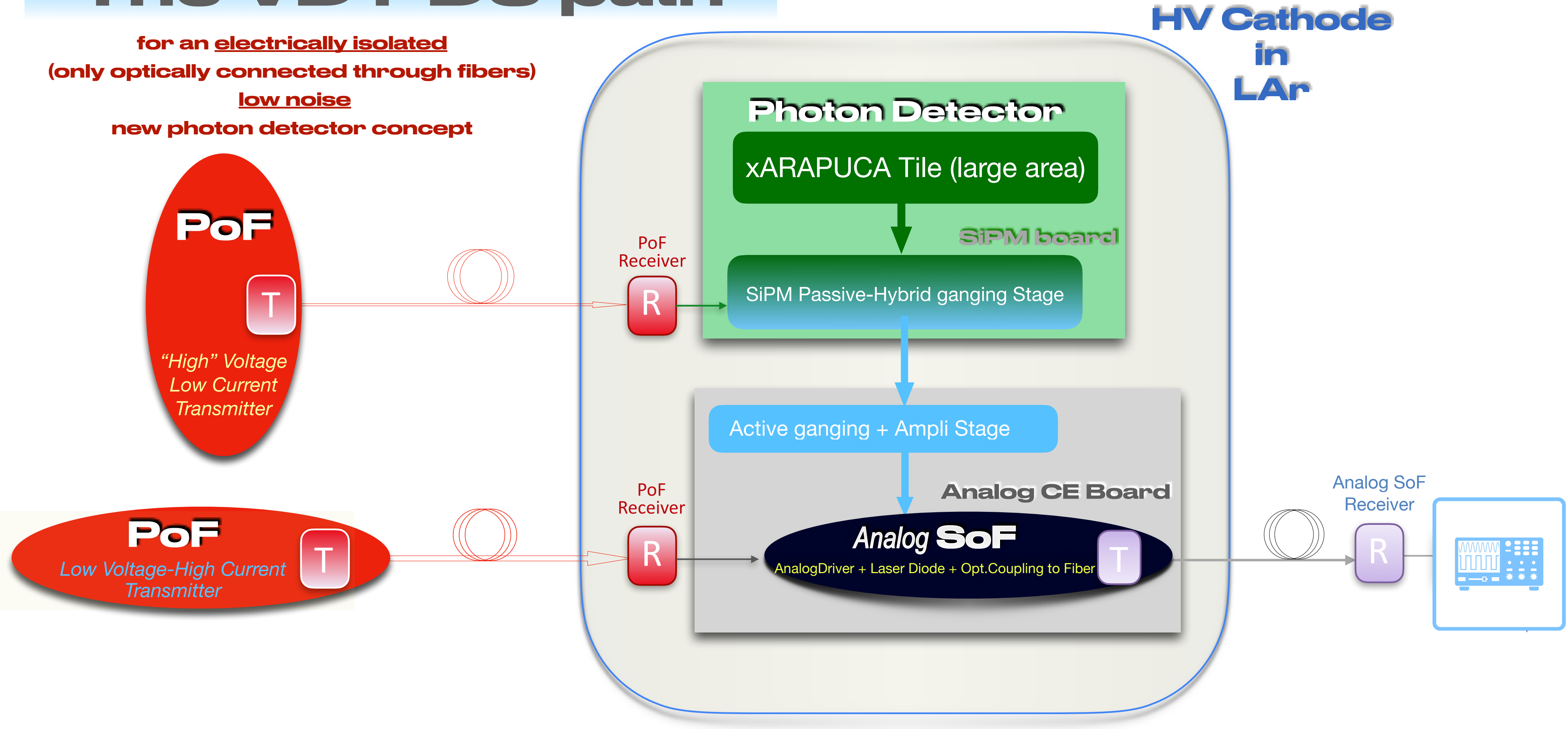
Budget Cap: fixed limit < FD1 Budget for Project Costs available for FD2 design and Project scope sharing DoE/International

Demonstration Requirements: validation tests at CERN (ColdBox in sync with CRP/TPC)

Project Risks Mitigation: backup solution in case of R&D failure

The VD PDS path

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

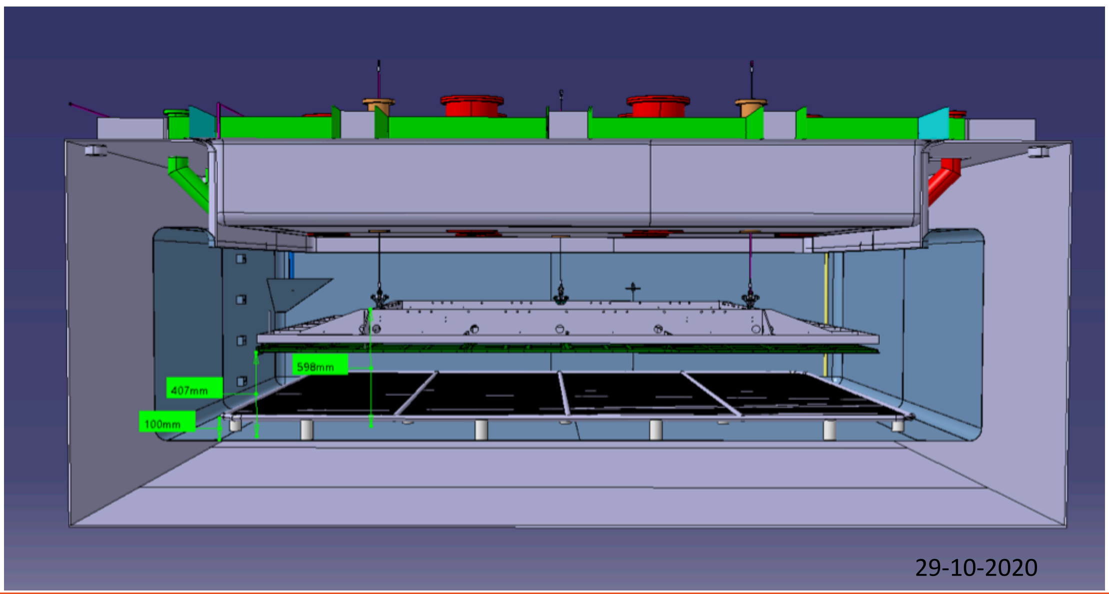


VD Photon Detector Project

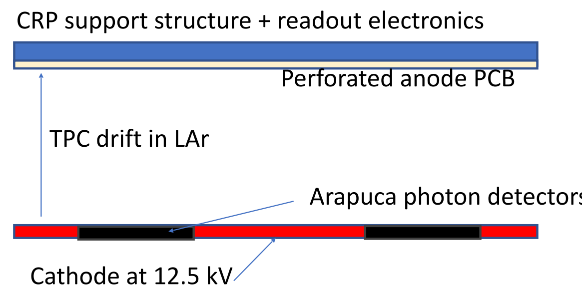
Feb. 25, 2021 Start of Project funded VD PD Prototype Phase

	2020	2021	2022	2023	≥2024
Concept (Proposal)					
Prototype (ColdBox Test & Concept Validation)					
Optimization (Final Design)					
Production (protoDUNE-VD & FD2)					

Schedule Updated in 2022



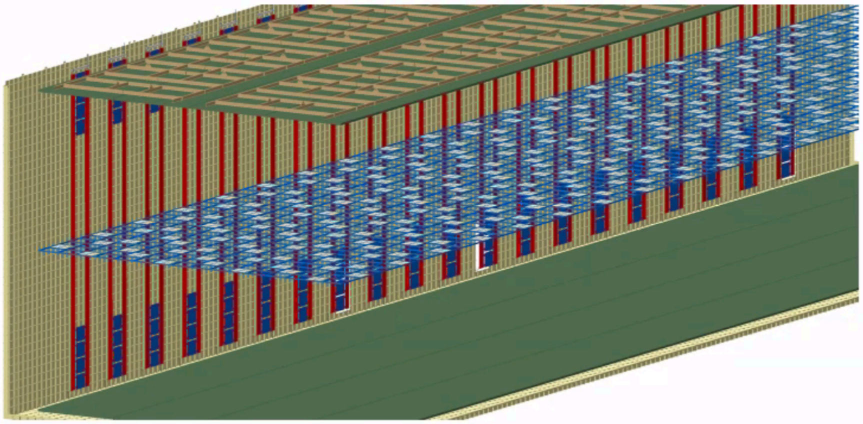
2021 VD demonstrator



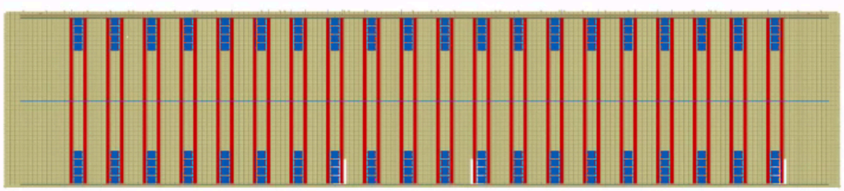
✓ test the light readout detector concept (on HV surfaces) at large scale

VD PDS Options (risk mitigated):
Reference ~4pi Design and Backup Design

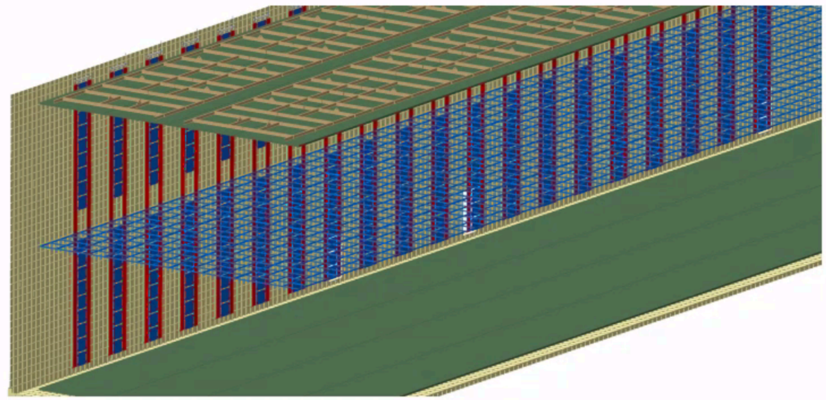
Reference Design (Cathode & Membrane mounted PDS ⊕ Xe doping)



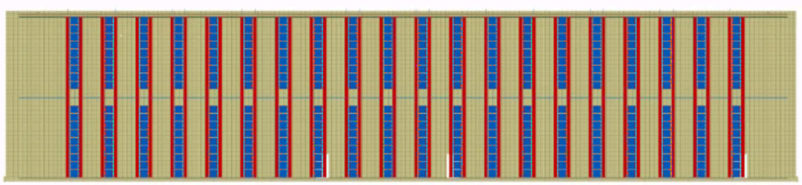
4 pi layout :
- Full trigger capabilities down to 10 MeV
- Energy, Position and T0
- xArapucas 60x60 on the cathode, 115 mq, analog readout
- xArapucas 60x60 on the cryo membrane, ~3m from Cathode



Backup Design (All-Membrane mounted PDS ⊕ Xe doping)



Minimal layout:
- Trigger via charge TPC readout down to 10 MeV
- T0, (Energy)
- xArapucas 60x60 on the cryo membrane, 20 columns, each column 18 xArapucas, SPHD readout



VD Photon detectors scenari

6 Apr. 2021 S.K, M.Ne.

Decision process

- 4 pi Option can be adopted just before Module 0 if
  - ✓ R&D on PoF positive and reviewed
  - ✓ R&D on SoF Readout positive and reviewed
  - ✓ All physics simulation done and reviewed
  - ✓ Partners support the required additional funding?

- Milestones
  - ✓ September 2022 decision on reference vs. 4pi option
  - ✓ October 2022 final design review
  - ✓ Jun 2023 module 0 components ready
  - ✓ Aug 2024 to Dec 2026 mass production and delivery to Su
  - ✓ PDs installed Dec 2027

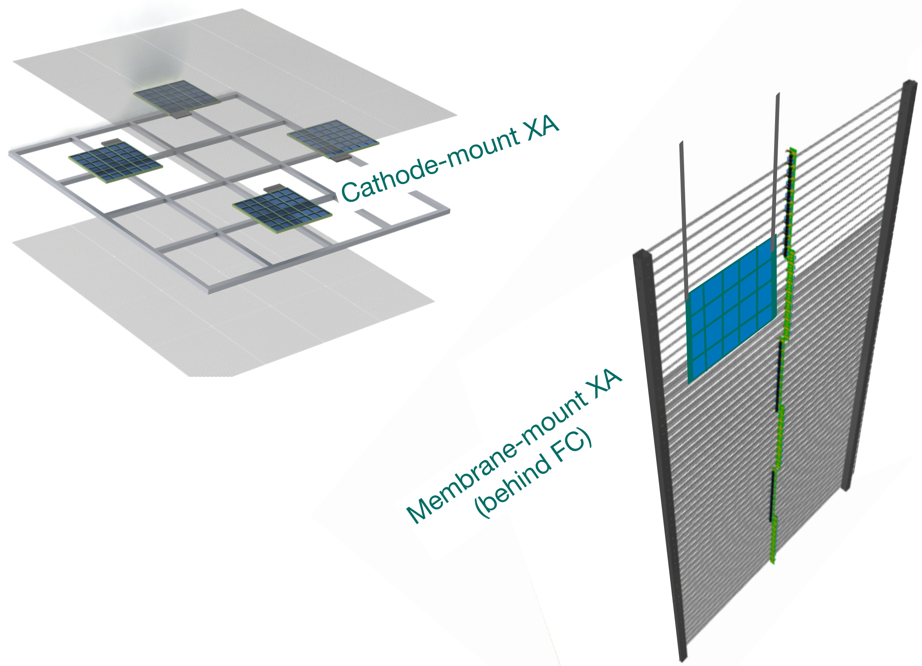
- FD2 PDS Requirements and Boundary Conditions

EB-held requirements

Specification	Detector components shall be sufficiently reliable so as to ensure that dead channels do not exceed 1% over the lifetime of the experiment.	Detector needs to operate over a 20-30 year lifetime with components that will be inaccessible post-installation, so components must be robust against damage during installation/cooldown and have long-term stability.	ProtoDUNE will identify infant mortality rates for the current detector components. Additional cosmic-ray operation will validate longer-term stability.

to be adopted as TB-held requirements

Requirement	VD PD layout	Photon Detector modules located on the Cathode plane should be electrically isolated	No copper cable connection to/from TPC cathode (at HV) should be established serving PD modules
Requirement	VD Membrane-mount modules position behind Field Cage	Membrane-mount modules must be positioned at vertical distance from cathode plane, behind field cage with enhanced 70% transparency	> 2.5 m vertical distance from cathode plane
Specification	VD Membrane-mount modules layout	PD coverage should be extended to all 4 membrane sides behind FC (two long and 2 short membrane sides)	Optimize LY uniformity with minimal number of membrane-mount modules on short membrane wall.
Requirement	VD Cathode-mount modules position on the cathode plane	No cathode-mount modules must be positioned at the edges of the cathode plane to minimise risk of damage in case of cathode HV discharge	>60cm clearance from cathode edges (and any other significant value from discharge Models)
Requirement	Ground mesh in front of VD membrane-mount modules	Ground mesh must be positioned in front of membrane-mount modules	mesh should make no EF> 30kV/cm



Consortium-held requirements

General						
Cathode-mount PD Module						
			1	R	Electric Isolation	Cathode-mounted modules must be electrically isolated - no copper cable connection to/from TPC cathode (at HV)
			2	R	Double sided	Light sensitive areas facing up and facing down must be provided for light collection from upper LAr volume above central cathode and from lower Volume below cathode
Membrane-mount PD Module						
			1	R	Electric Isolation is NOT required for membrane modules	Membrane modules can be connected with copper cables.
			2	R	Single sided	Light sensitive areas facing inward to the active LAr volume of the TPC - through Field Cage
	Photosensors					
			1	S	Same photosensors (Silicon based) as for FD1 PDS	FD1 PDS - SiPM optimisation carried out by FD1-PDS with industry is immediately available and applicable to FD2. Selecting the same SiPMs allows us to leverage this experience and reduce cost and risks.

Electronics (including Fibres and Cables)						
			1	R	Heat dispersion (and macroscopic bubble generation) by cathode-mount electronics	The cathode-mount electronics must minimise and disperse excess heat in such a way as to prevent (macroscopic) bubble generation at the cathode (~6m depth in LAr)
			2	R	Faraday shield boxes for Cold electronics boards	Electrical noise diffusion by electronics active components of cold electronics boards must be minimised - Cold electronics boards must be housed in Faraday shield boxes
			3	S	Fiber bending, protective black tubes for fibres and light tight boxes for fiber connectors	Optical noise from fiber and connector light leakage must be minimised - Fibres must be protected in black tubes and connectors on CE boards housed in light tight boxes. Power and signal optical fiber must not leak light of wavelengths and intensity that can impact X-ARAPUCA efficiency or other subsystems.

Design				

	PD Modules					
			1	S	Material selection - cryo-resilient	All materials must be cryo-resilient. All materials already selected for FD1 PD modules (XARAPUCA super-cell) should be used for FD2 PD modules (XARAPUCA mega-cell) where possible. Main components: mechanical frame, dichroic filter, WLS-1 film, WLS-2 plate, plastic reflector foils, SiPM photosensors.
			2	R	XARAPUCA mega-cell design and max photo-collection efficiency	New XARAPUCA mega-cell design should maximise photo-collection efficiency. Minimal dead space or shadow by mechanical frame, maximal exposed surface of dichroic filter area and WLS plate, maximal coverage of reflective area should be pursued at design level, optimal optical contact SiPM-WLS.

Electronics (including Fibres and Cables)						
			1	S	Cold El. Motherboard	Dedicated CE motherboard with PoF-SignalConditioning-SoF stages for cathode-mount modules (no PoF and SoF stages are required for membrane-mount modules)
			2	R	S/N > 4	S/N of CE must be high enough for single PE sensitivity (in the whole waveform)
			3	S	Dynamic range of CE	Dynamic range of CE must be sufficiently extended to collect large signals (and reduce fraction of saturation to minimal). Beam events in the proximity of Cathode plane may generate very large signals. Fraction of beam events with over-range ADC limited to <20%
			4	R	Timing resolution of SiPM + CE r/o system	<< 100 ns for low-PE signal time determination
			1	S	Cryo-reliability of component	discrete component resilient to temperature change and long term operation at 87 K

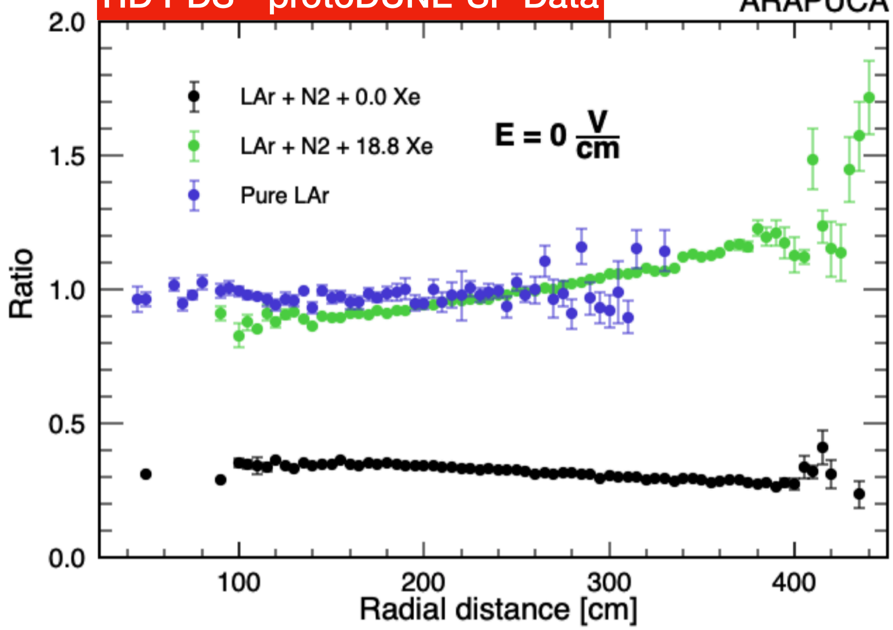
Design Goals
(Physics program driven through engineering requirements)

Detector Component/Feature	Parameter	Demonstration
Scintillation medium composition	Ar+Xe(10 ppm) (Ar Slow-component full transfer to Xe)	*protoDUNE-SP and -DP*
X-ARAPUCA Technology Choice SiPM + Electronics read-out X-ARAPUCA efficiency PoF - Power Transmission SoF - Signal Transmission	 S/N ≥ 5 ϵ_D=3% Conversion Effic. 22% $\rightarrow$ 70% Usable Pwr: 4 W/PoF-Unit stability, noise at $V_{out} \sim$ 50V	 *protoDUNE + prototype Tests* *+ ColdBox Tests 2021-23* *+ Module0 Tests 2023*
PDS Light Yield	$\langle$LY$\rangle \simeq 45$ LY$_{min} \simeq 25$	*from MC study* *from MC study*
Spatial resolution Energy resolution Time resolution	$\sigma_r \leq 0.7$ m $\quad (E_{dep} \geq 5$ MeV) $\sigma_E/E \leq 10\%$ $\quad (E_{dep} \geq 5$ MeV) ≤ 20 ns	*from MC study* *from MC study* MC study + (protoDUNE-SP)

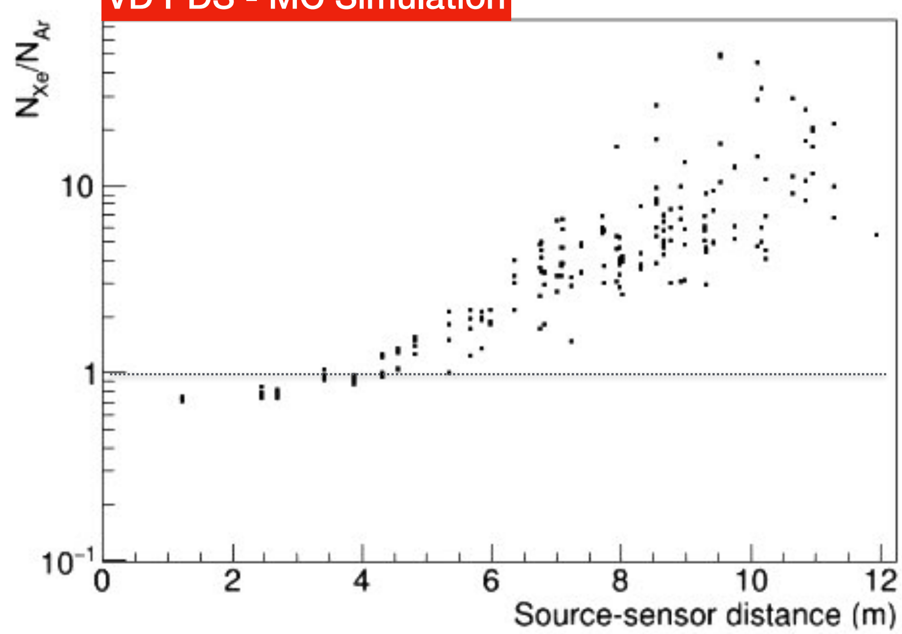
Xe doping as baseline solution

The collected light is found to be larger for Xe-doped Argon, due to the effect of the longer Rayleigh scattering length enhancing collection probability for light emitted at longer distances from the photon-detectors (+30% in VD - from MC simulation)

HD PDS - protoDUNE-SP Data



VD PDS - MC Simulation



This justify the baseline solution of Xe-doped Ar as scintillation medium in VD

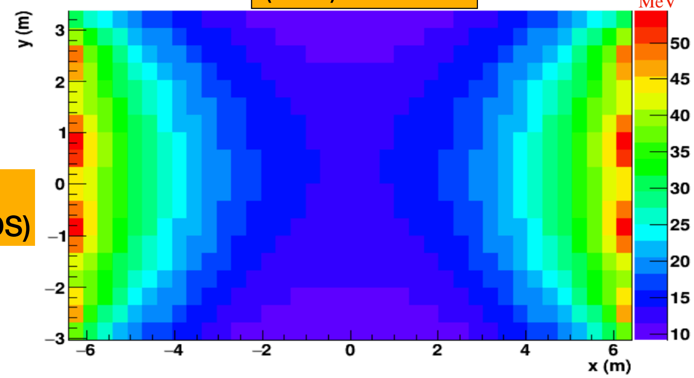
LY [PE/MeV] & LY uniformity Metrics for PD Layout Design

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

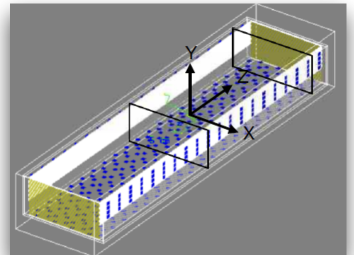
Ref.: DUNE FD2 -VD Technical Design Report
[FD2-VD TDR v.2]
[FD2 PDS Characterization by G4 Simulation]

Backup Design (All-Membrane mounted PDS)

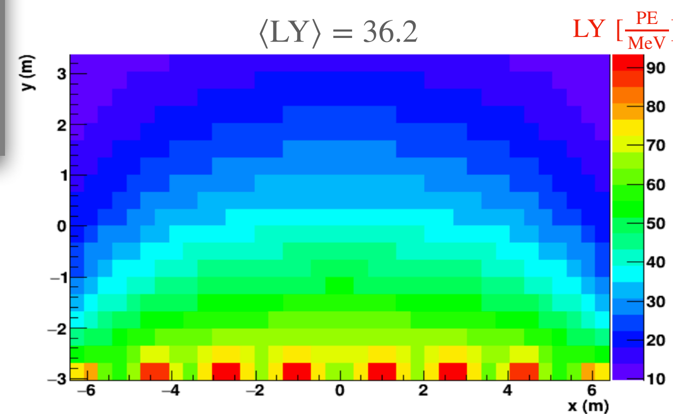
$\langle LY \rangle = 21.0$



Membrane only [OC 14%, 704 modules]



$\langle LY \rangle = 36.2$

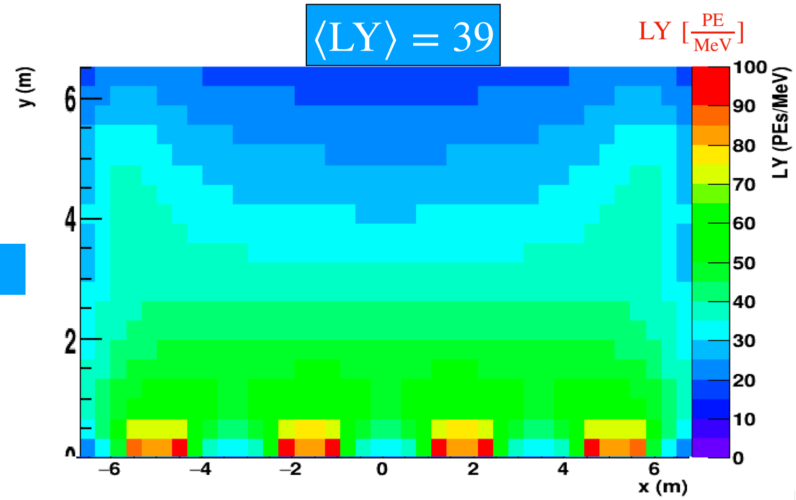


Cathode only (OC 14%, 320 modules)

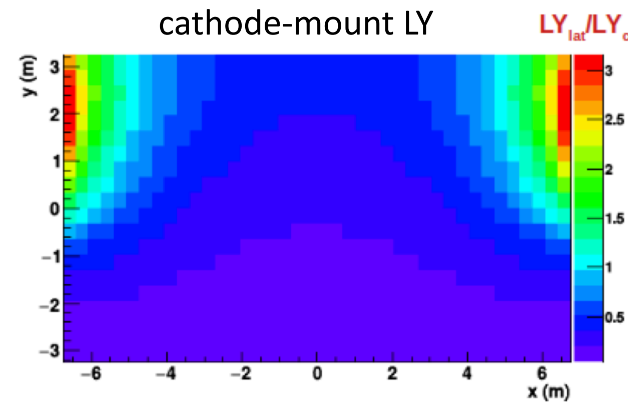
[Cathode OC 14%, 320 modules & Membrane OC 7%, 352 modules]

Baseline Design (~4pi)

$\langle LY \rangle = 39$



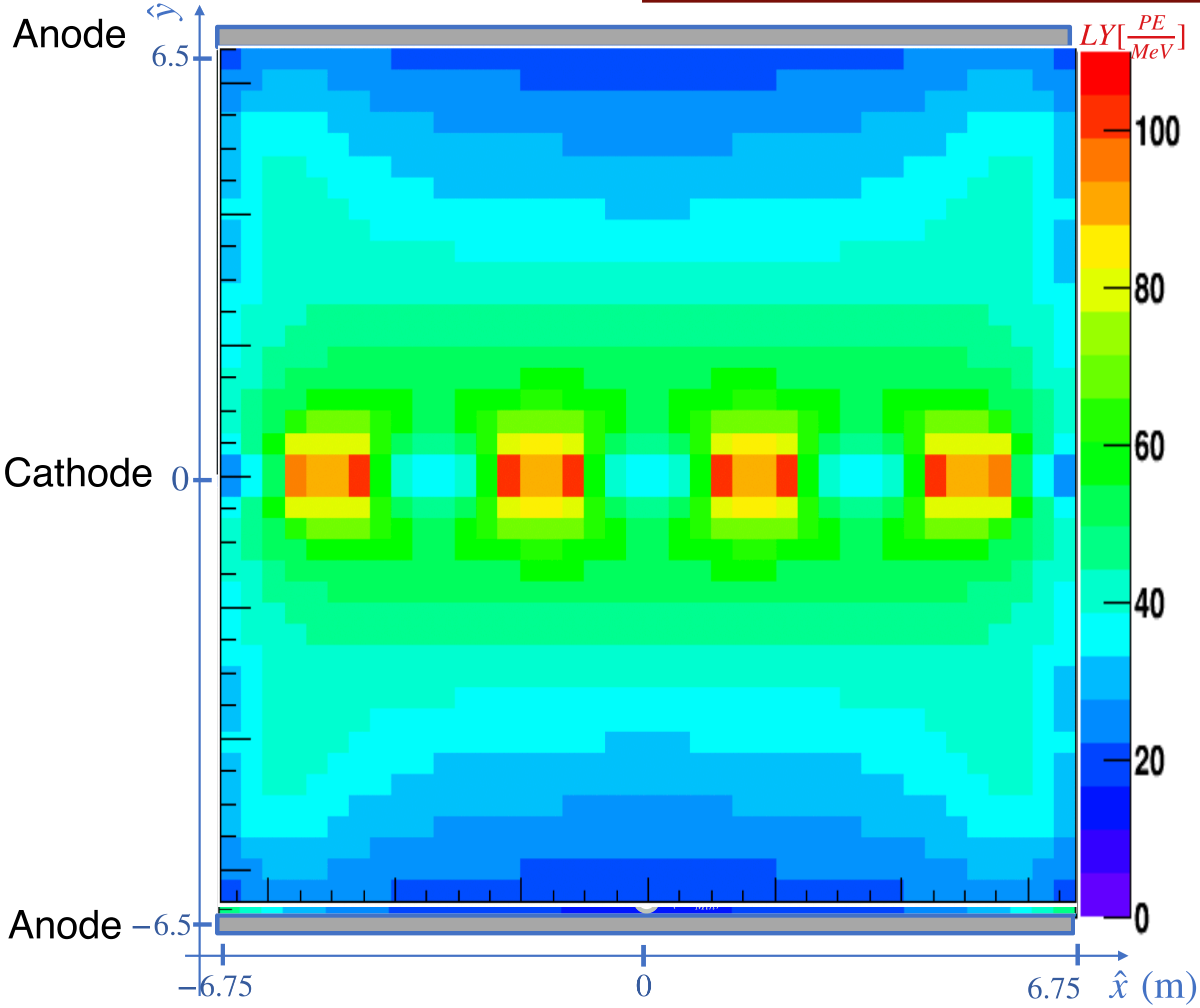
LY ratio: lateral membrane-mount LY over cathode-mount LY



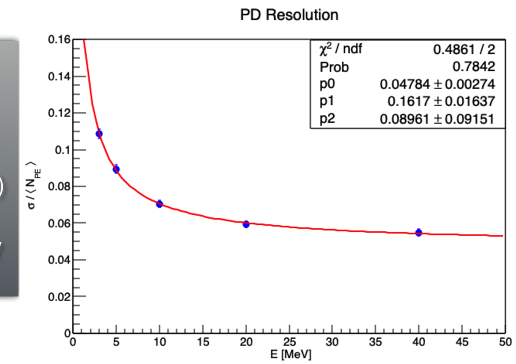
VD - Baseline 4pi PDS

Light Yield

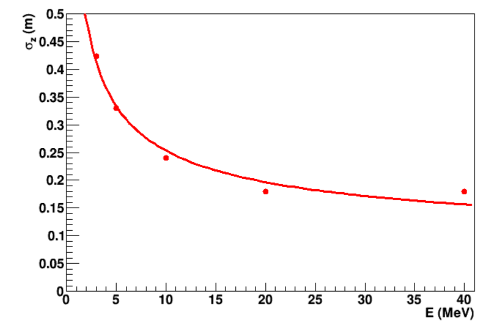
Calorimetric Energy and Position Resolution from detected photon counting



Energy Resolution from statistical fluctuation (p1) on detected PEs, electronics noise (p2) and uncertainty on energy calibration (p0)



Position Resolution from detected PEs barycenter determination.

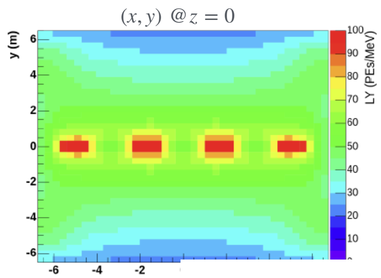


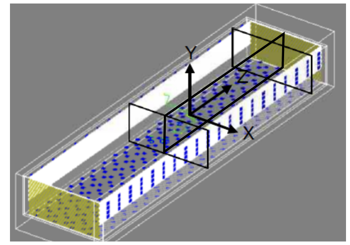
- $\langle LY \rangle = 39$ PE/MeV
- $\langle LY_{Min} \rangle = 17$ PE/MeV

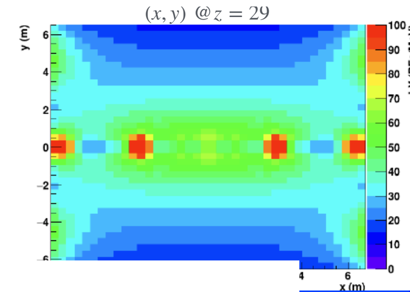
• VD PDS Baseline:

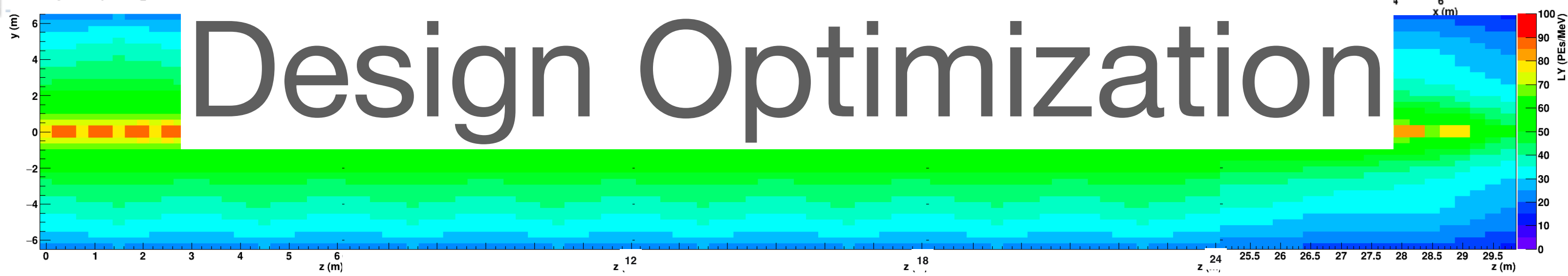
- PDS layout (Membrane-mount): LY performance improvement/risk mitigation

Design Optimization

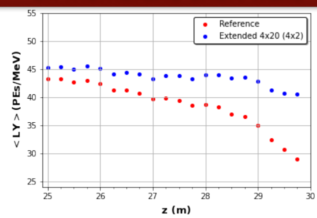


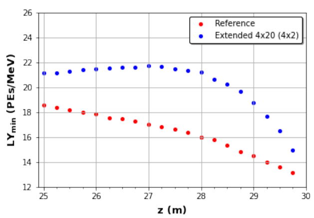


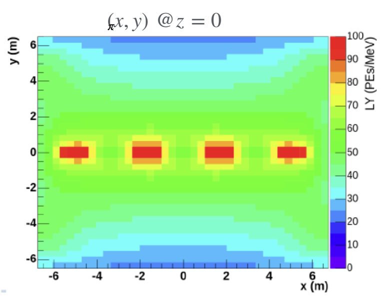


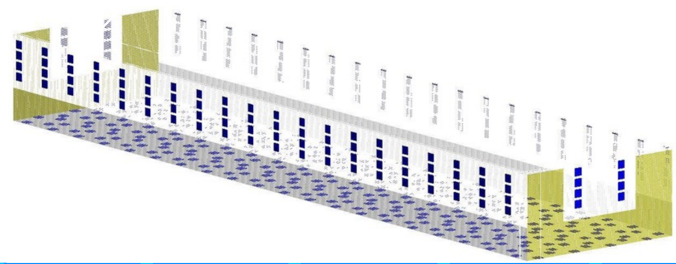


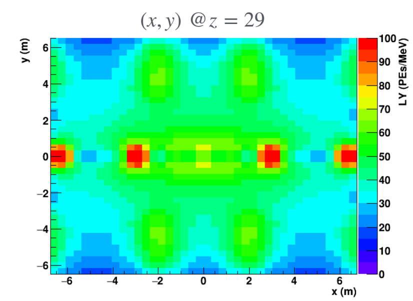
addition of X-Arapuca modules
(32 modules, +5% of total)
on membrane short walls

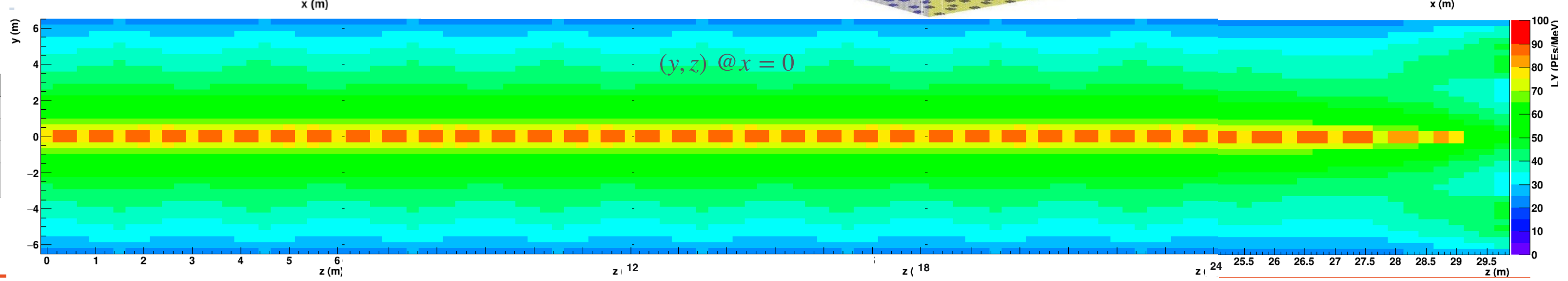










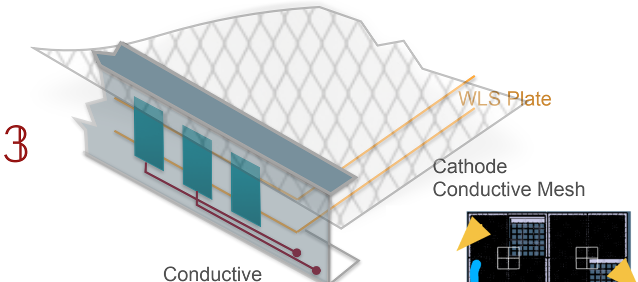


	n. of PD Modules	Opt. Coverage (%)	Layout
Cathode Side	320	14% - Active	Chess-board
2 FC Long Sides	320	~7% - Active	Grid
2 FC Short Sides	32	~3% - Active	Grid
Anode Side	0	45% - Passive	R = 0.4 @ wl 178 nm R = 0.2 @ wl 128 nm

The addition of a modest active OC on the FC Short sides (re)establish the ~4 PDS concept significantly improving LY uniformity along the z-axis.

•VD PDS Baseline:
PDS layout (Cathode-mount): HV discharge risk mitigation

3

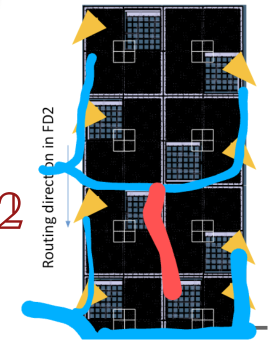


Cathode HV Discharge Impact on design

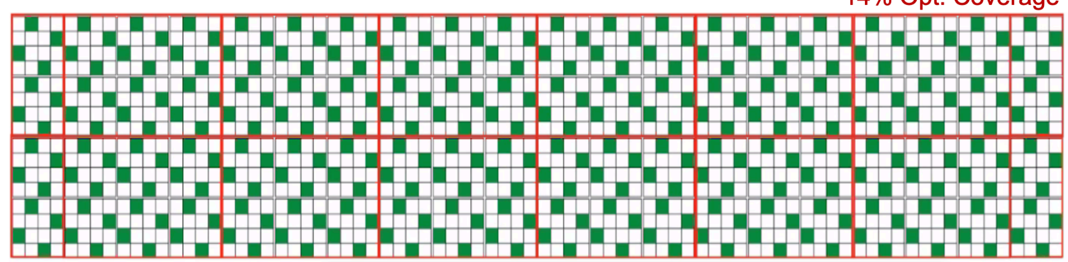
- Will cathode discharges happen? (answer: assumption - Yes
- Can a discharge impact the cathode-mounted PD modules? (answer: potentially - Yes
- Car
  - Design Risk Mitigation
    - 20-125 A
    - 0.2-1.25 μC

Stored Charges moving across the Cathode Conductive Mesh in fast transient after HV discharge

2



14% Opt. Coverage



1.During a discharge, there is some risk (worse at the cathode edges) to an X-ARAPUCA with **independent power**, but it is reasonable to expect that a conservatively **X-ARAPUCA module shielded design** would survive at any location on the cathode.

2.During a discharge, there is more risk (still worse at the cathode edges) to X-ARAPUCA with shared/distributed power and signal, but it is reasonable to expect that a conservatively shielded design, with **conductive conduits and Balun Box break** would survive in the central cathode modules.

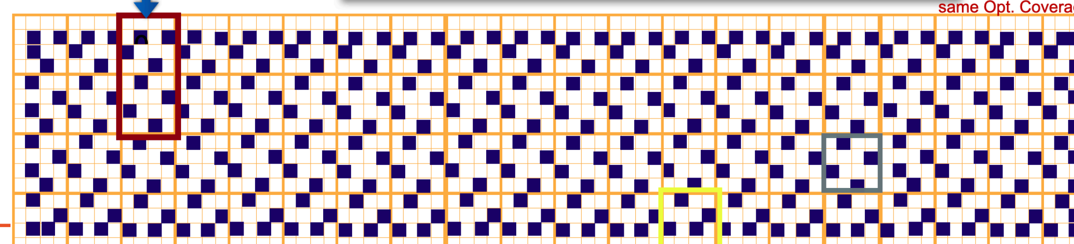
3. Action items 1,2,3

Cathode in protoDUNE Module-0

48 PD modules on the edge moved (60 cm) inward

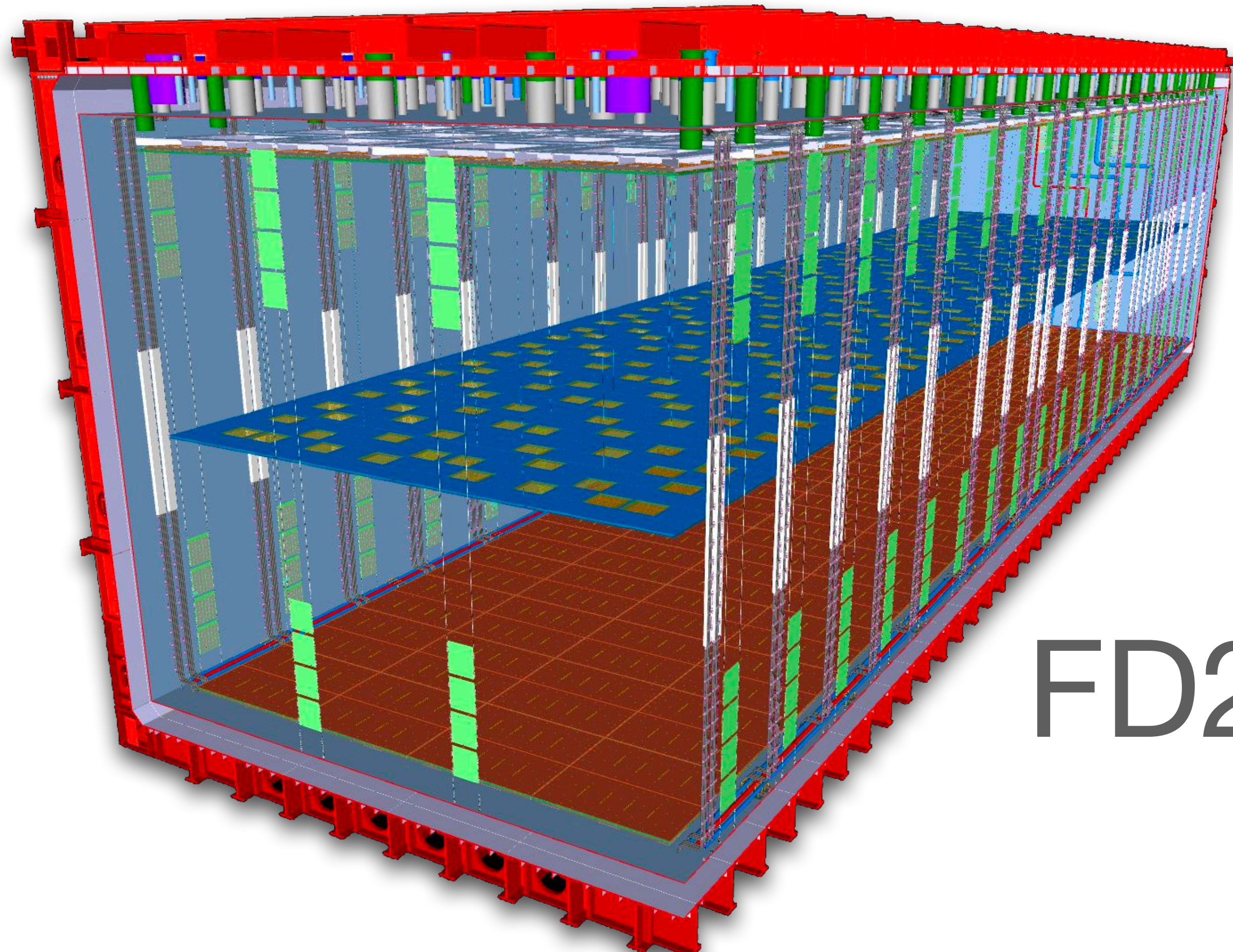
same Opt. Coverage

1



(two main cathode layouts: Outer Layout and Inner Layout)

- Two independent simulation studies
  - **BNL**: Sergio Rescia, Veljko Radeka, Bo Yu, Hucheng Chen, et. al.
  - **Fermilab**: Paul Rubinov, Sergey Los, et. al. Full 3D ANSYS discharge simulation



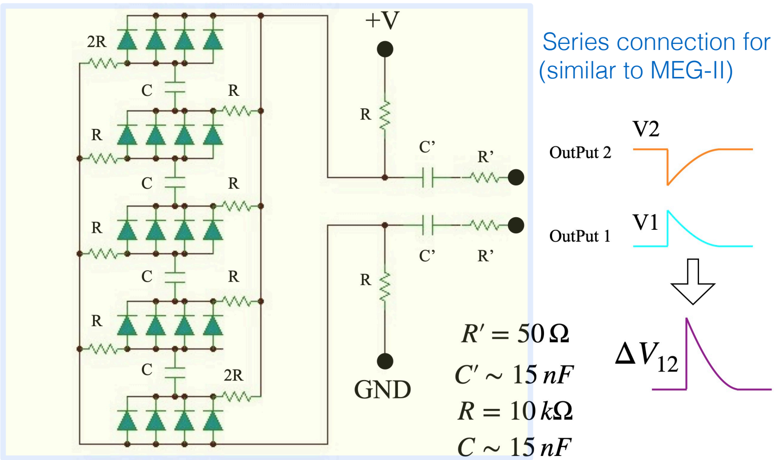
FD2-PDS Desig
Baselined

•PDS Demonstration

Cold Box tests at CERN 2021

SiPM board and Signal-over-Fiber

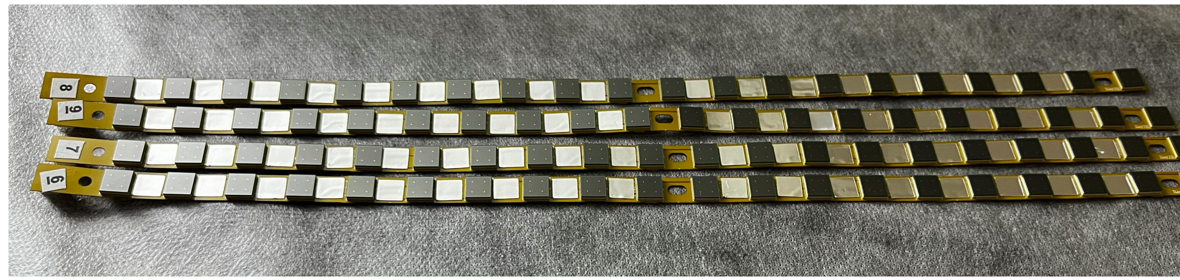
SiPM board



UCSB
Fermilab

the SiPM Flex Board(s)- Passive ***hybrid*** ganging

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

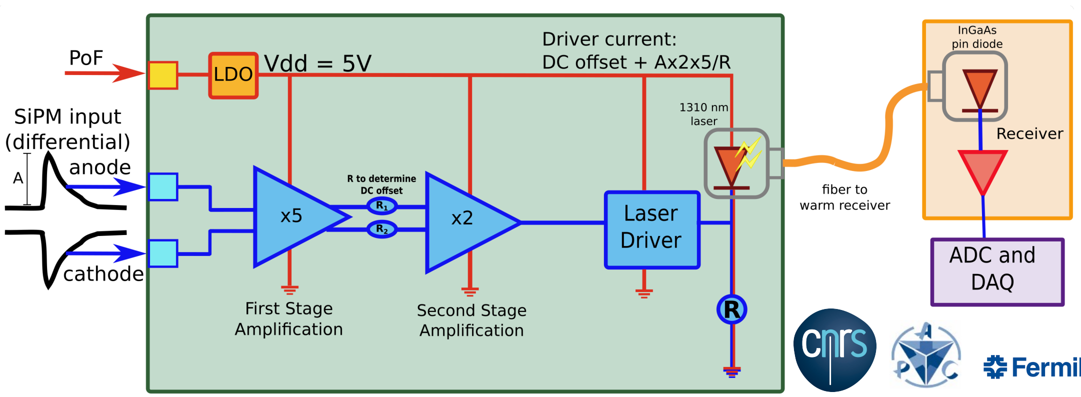


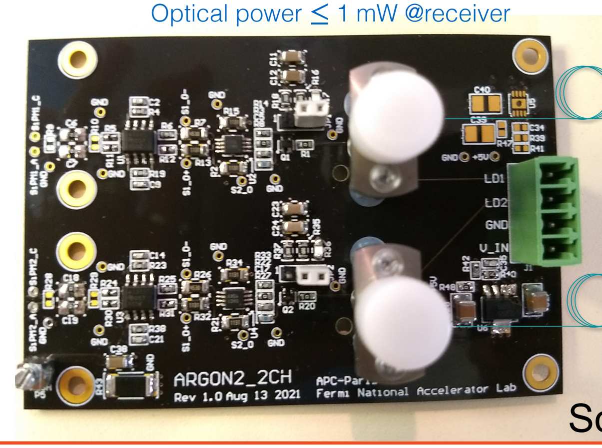
Hamamatsu MPPC S14160-6050HS [$V_{BD} = 32\ V$ at LAr T]

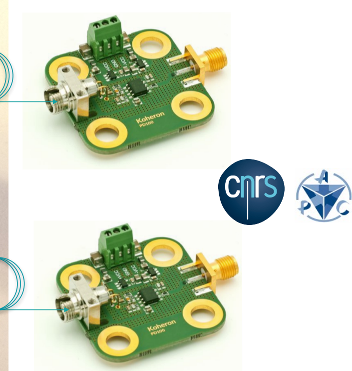
the Analog CE Board - Active ganging/Ampli & SoF

ARGON2x2(2 channels/board): 5.1V, < 35 mA (< 100 mW/ch), FP 1310nm lasers FC connector, Voltage gain ~20
Optical power $\leq$ 1 mW @receiver

Analog CE Board





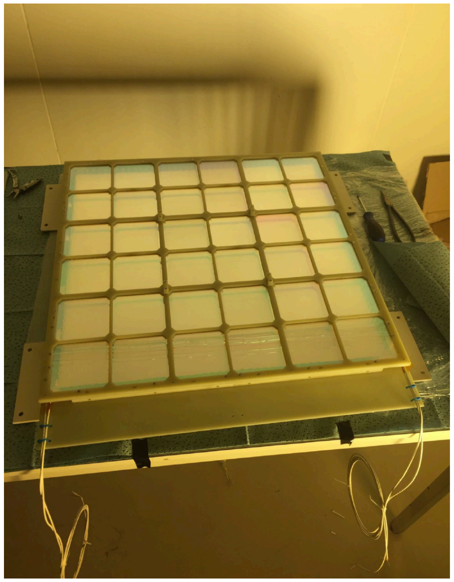


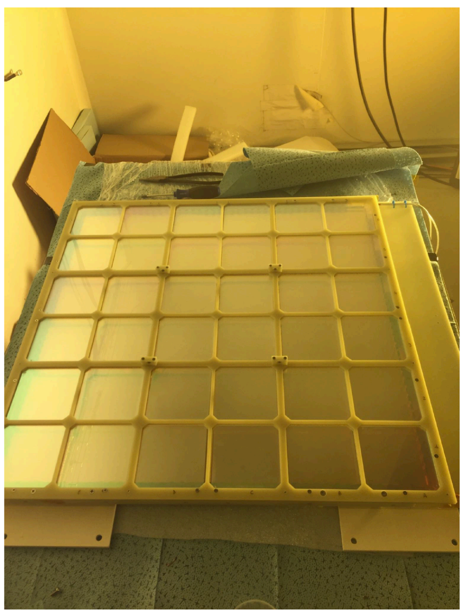
SoF Warm Receivers

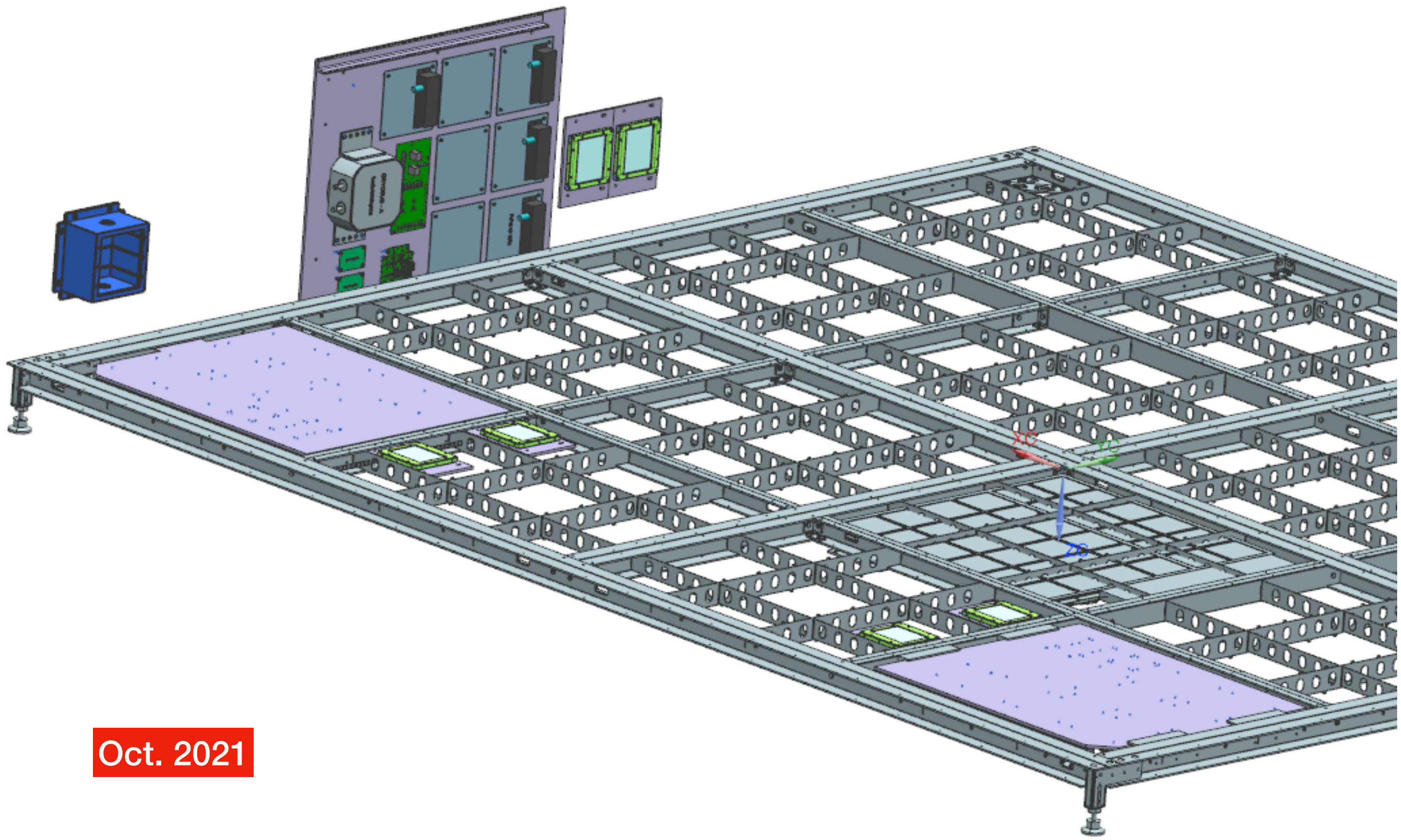
Fermilab

Cold Box 1 Topology

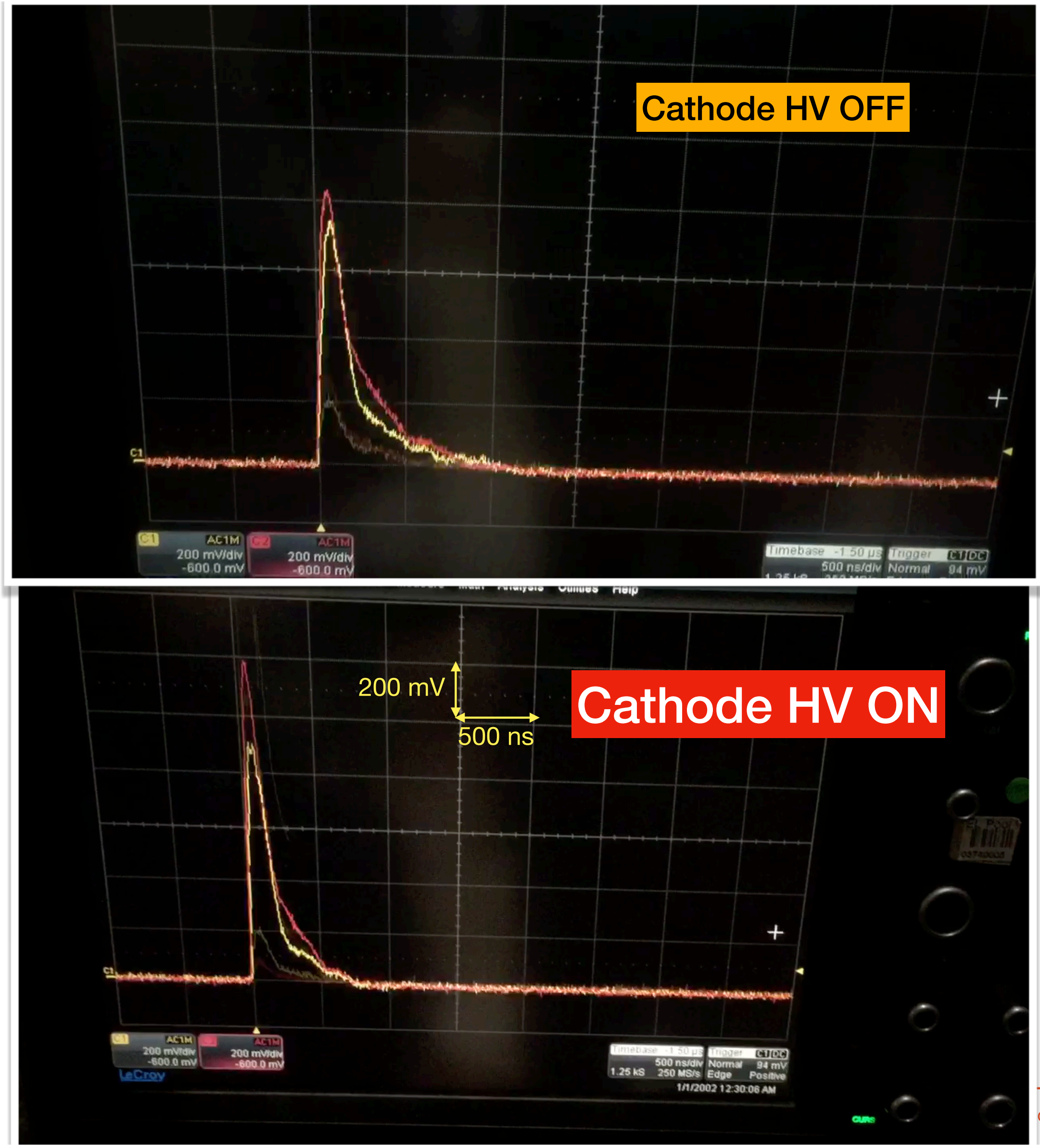
- 6 mini-ARAPUCA
- 1 xARAPUCA



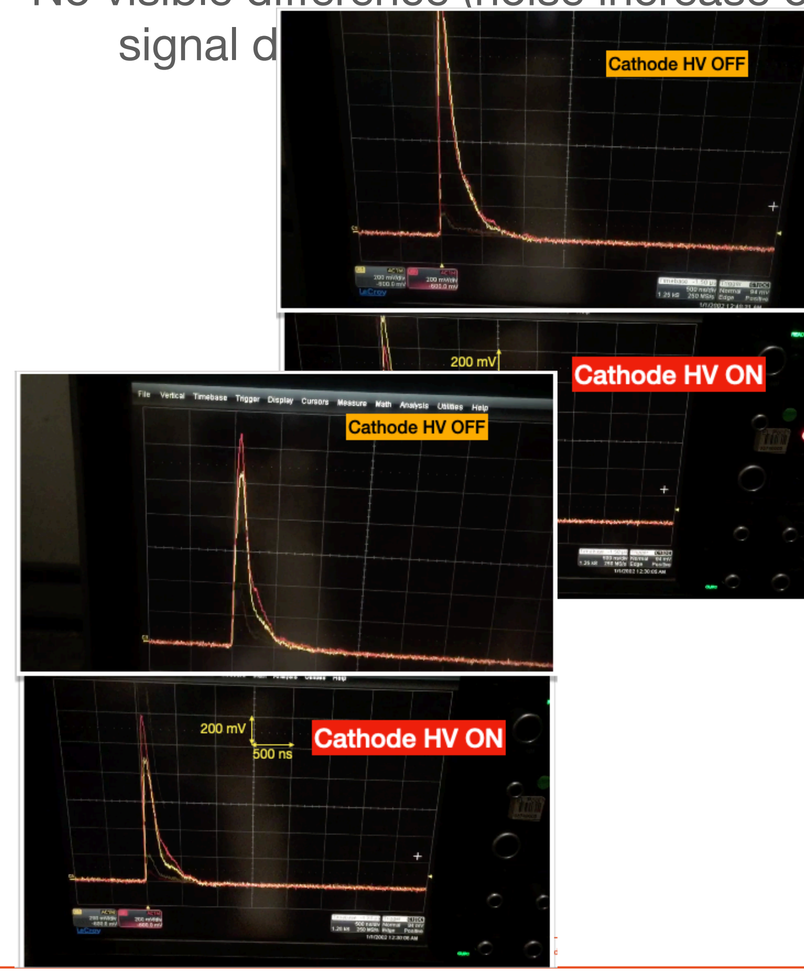


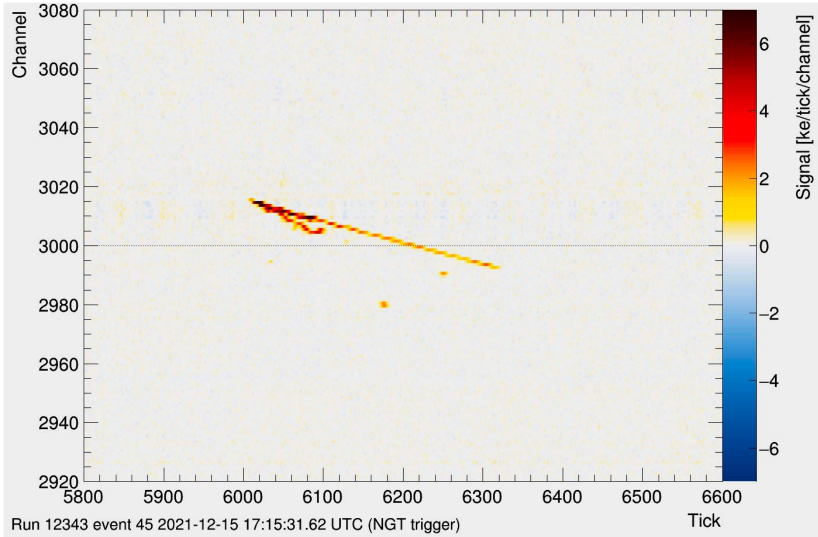


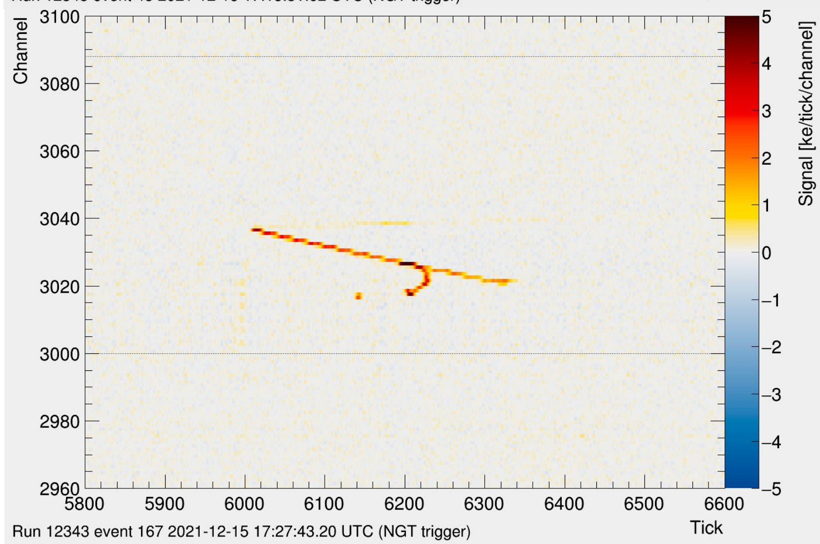
Oct. 2021

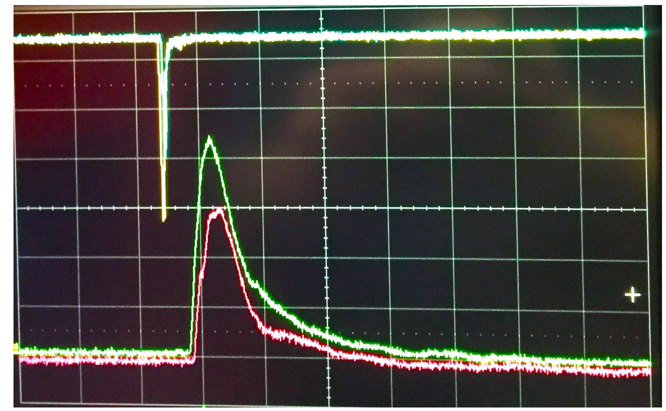


No visible difference (noise increase or
signal d





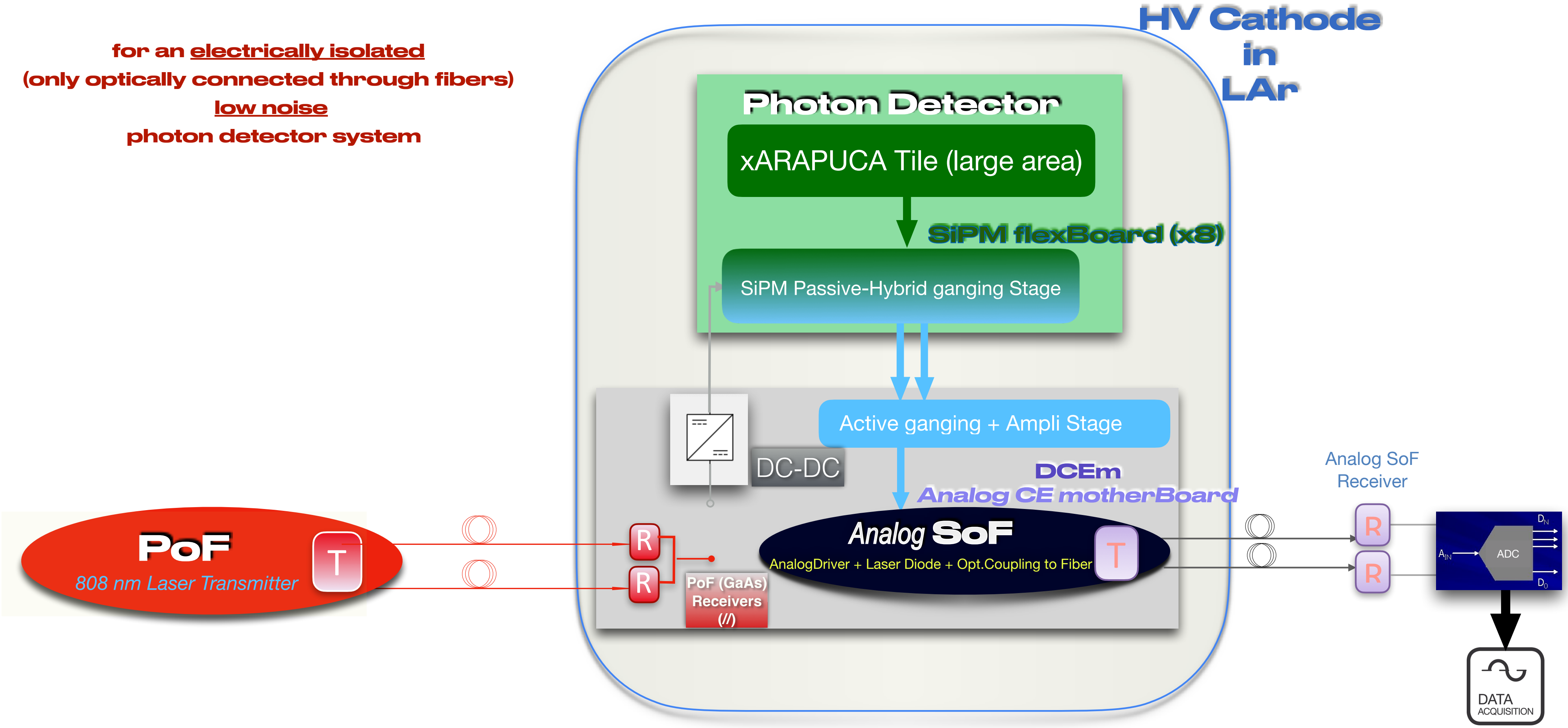




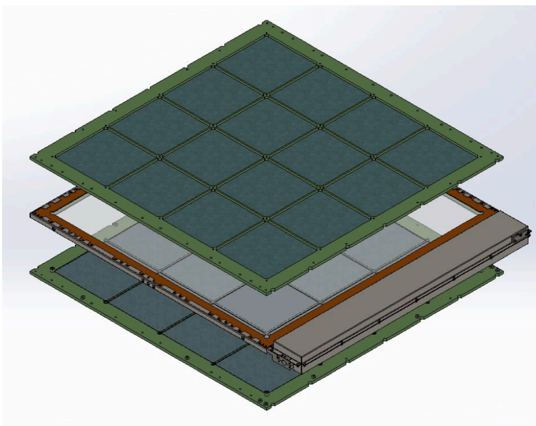
Dec. 2021 - ColdBox Validation

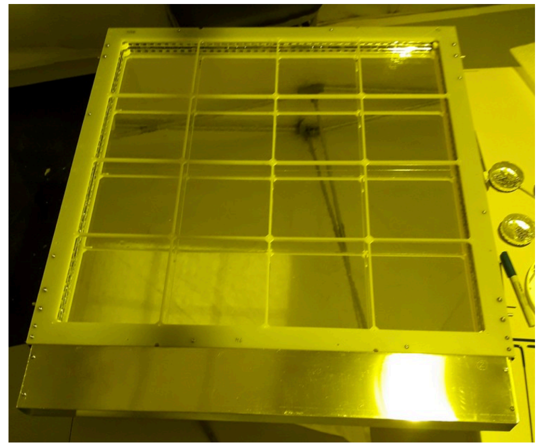
- **PDS Demonstration**
  - **Cold Box tests progression 2022 - design optimization:**

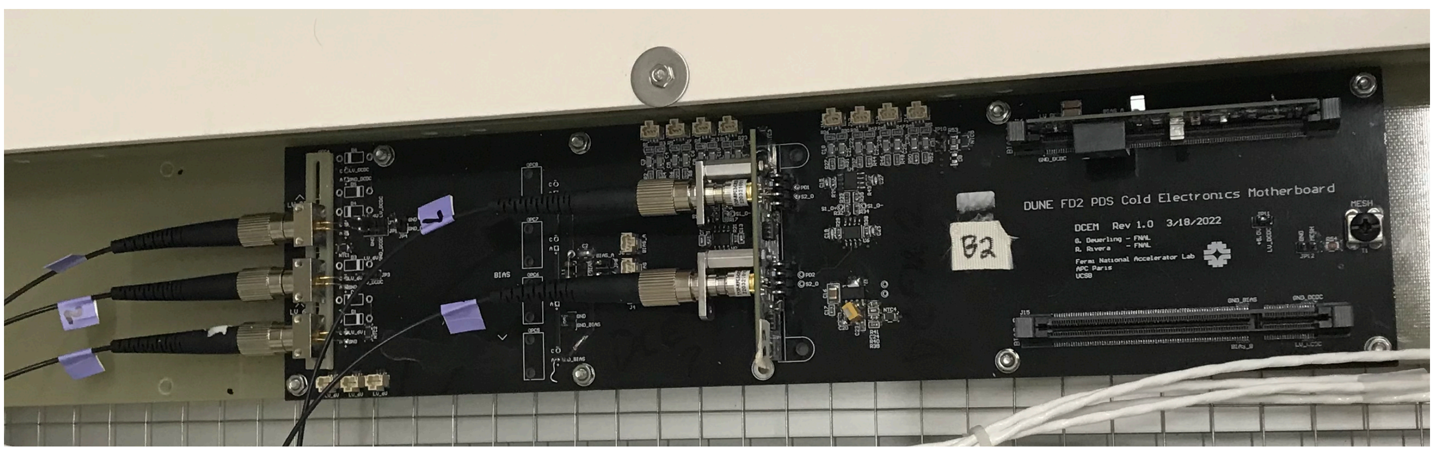
for an electrically isolated
(only optically connected through fibers)
low noise
photon detector system



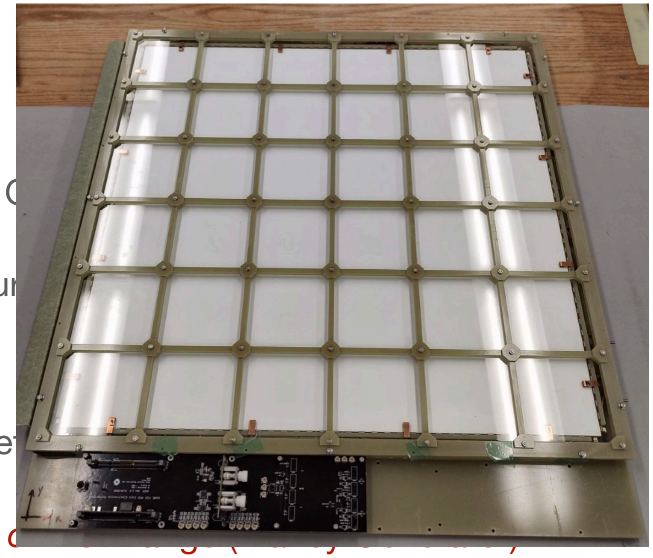
Optimization: 2022







Optimization: 2022 in flow



- LArPDS Simulation from stand-alone G4 into standard LArSoft G4 + Neutrino event C
- MC Tuning of Scintillation Light emission processes and parameters for Ar+Xe mixtur doping tests [second round of tuning completed, but still lot to understand]
    - propagation in LAr volume (attenuation from Rayleigh and Absorption) and re
- MC production (high stats, 100 k-evt) in progress for SN Neutrino events in the *tens* c
    - LArPDS-based energy resolution for SN Neutrino events - and comparison to LArTPC [preliminary results]
    - LArPDS-based SNB trigger efficiency as a function of neutrino energy and SN distance

- Detector Layout optimization
    - PD Modules on the Cathode: layout modification for HV discharge effects mitigation
    - PD Modules on Membrane Walls: layout modification for LY Uniformity improvement
    - Calibration system for LY monitoring - *to be defined*

electrical isolation, low noise

No noise increase or signal distortion when Cathode HV ON

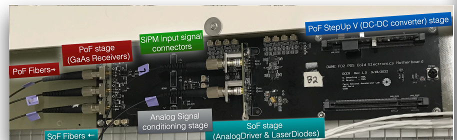
LAr light flash matching TPC crossing muon track

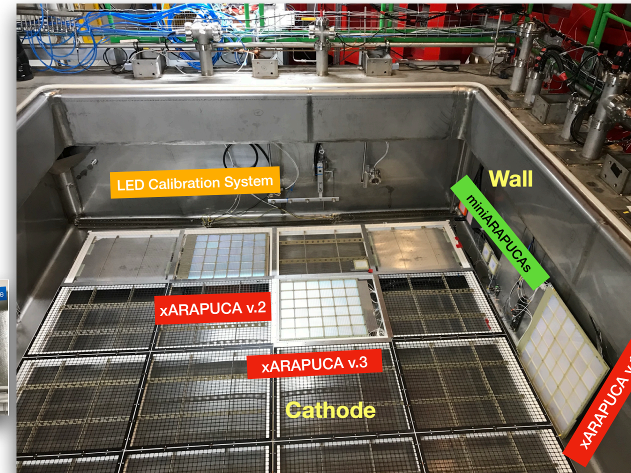
- VD PDS Demonstration
  - ***Cold Box tests at CERN - 2021***
    - ☑ validation of design foundations and high level goals achievement

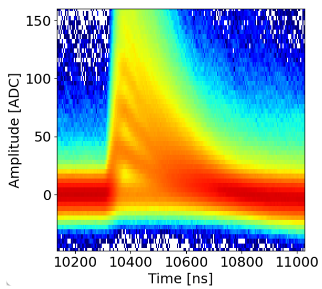
No noise from PDS detected on Top/Bottom CRP Electronics

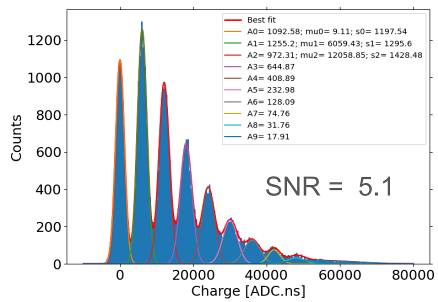
  - ***Cold Box tests progression - 2022 design optimization***
    - ☑ HighEfficiency GaAs PoF
    - ☑ Integrated PoF/Analog CE/SoF DCEm board
    - ☑ xARAPUCA design improvement

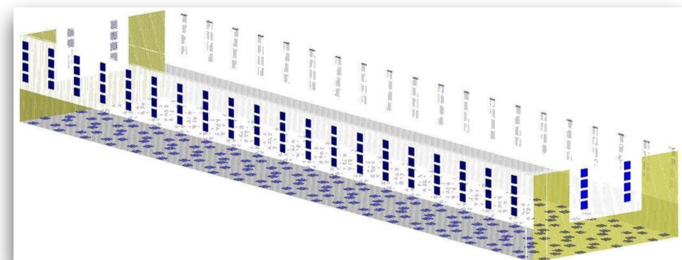
      (SiPM-WLS optical contacts, frame mechanics, LAr optimized dichroic filters)
    - ☑ Single PE Sensitivity (from last ColdBox Run - Sept.2022)



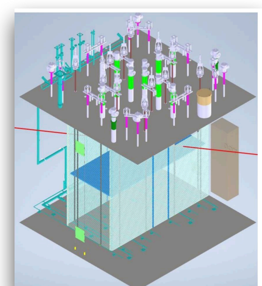








- VD PDS Baseline:
  - PDS layout (320 Cathode-mount) optimization: HV discharge risk mitigation
  - PDS layout (320+32 Membrane-mount) optimization: LY performance improvement from short side wall coverage



- Plan for 16 PD modules production and installation in protoDUNE-VD (Module-0)
- Feasibility study for detector LY Calibration (in progress)

- Status of each (main) Requirement: either achieved and documented, or planned when (before PRR)
  => Critical path analysis and float (bridge into Ryan’s talk)