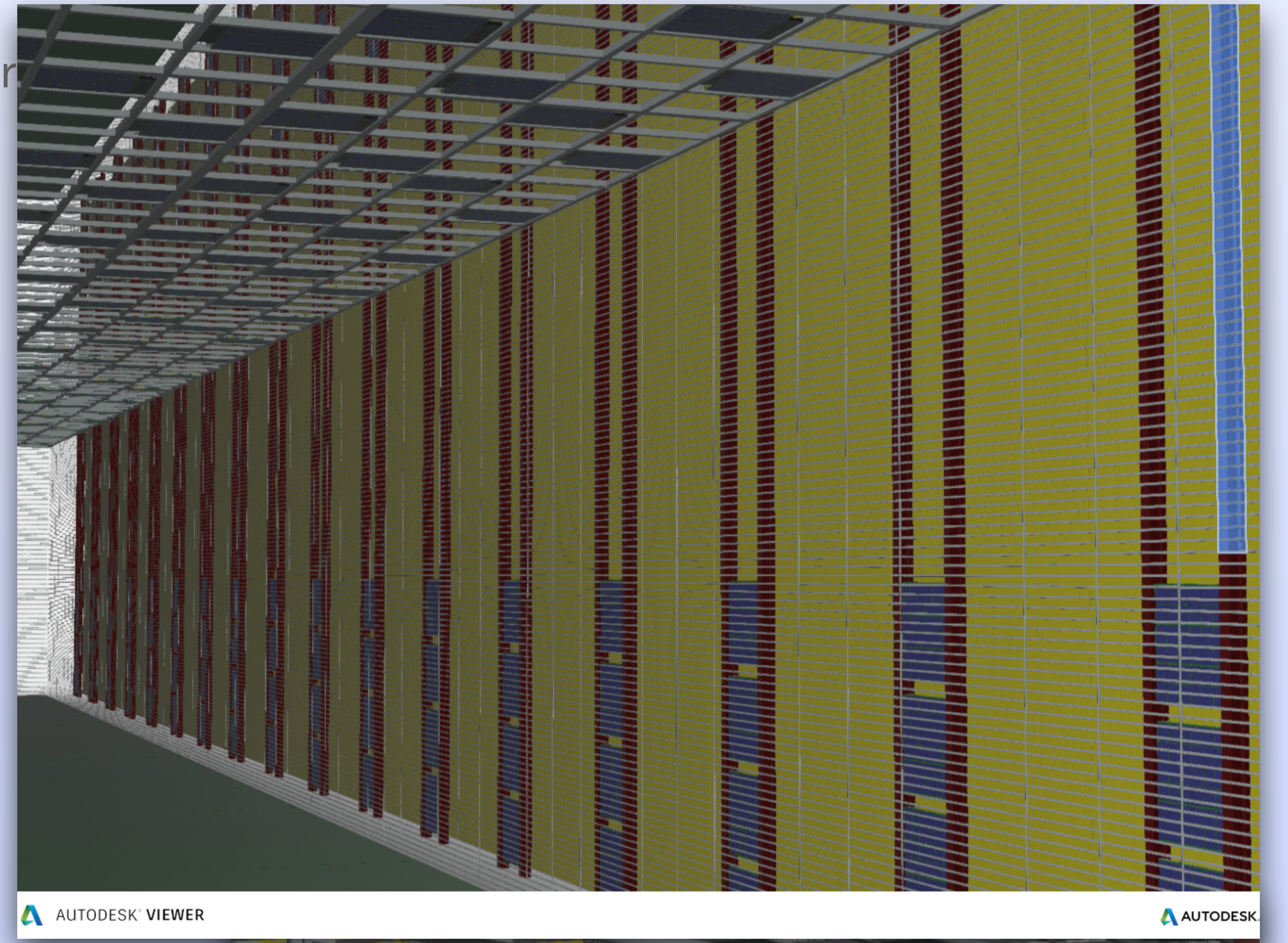
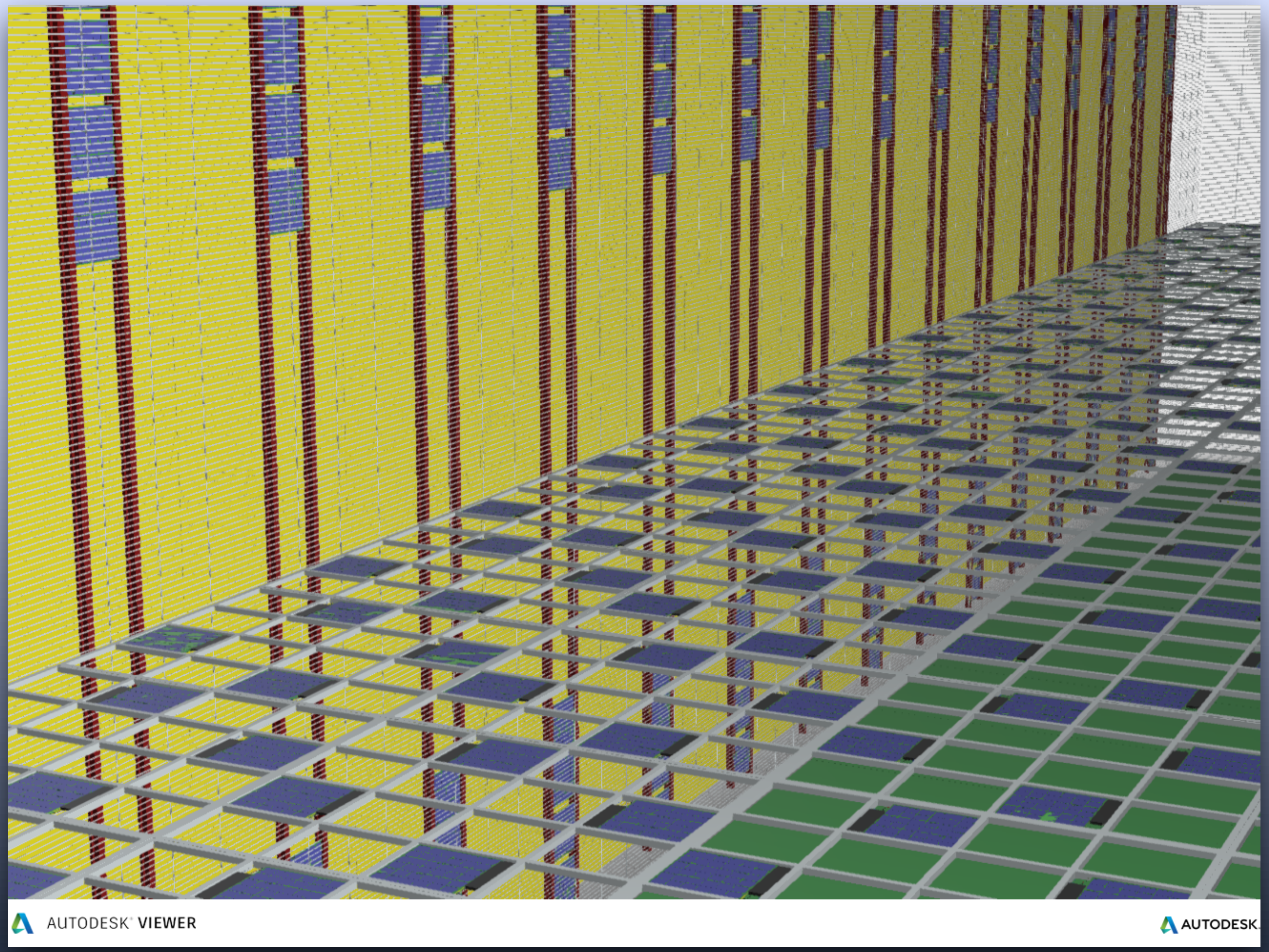
FD2 -PDS
The Design Path:

Requirements, Milestones, Developments, Baseline

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

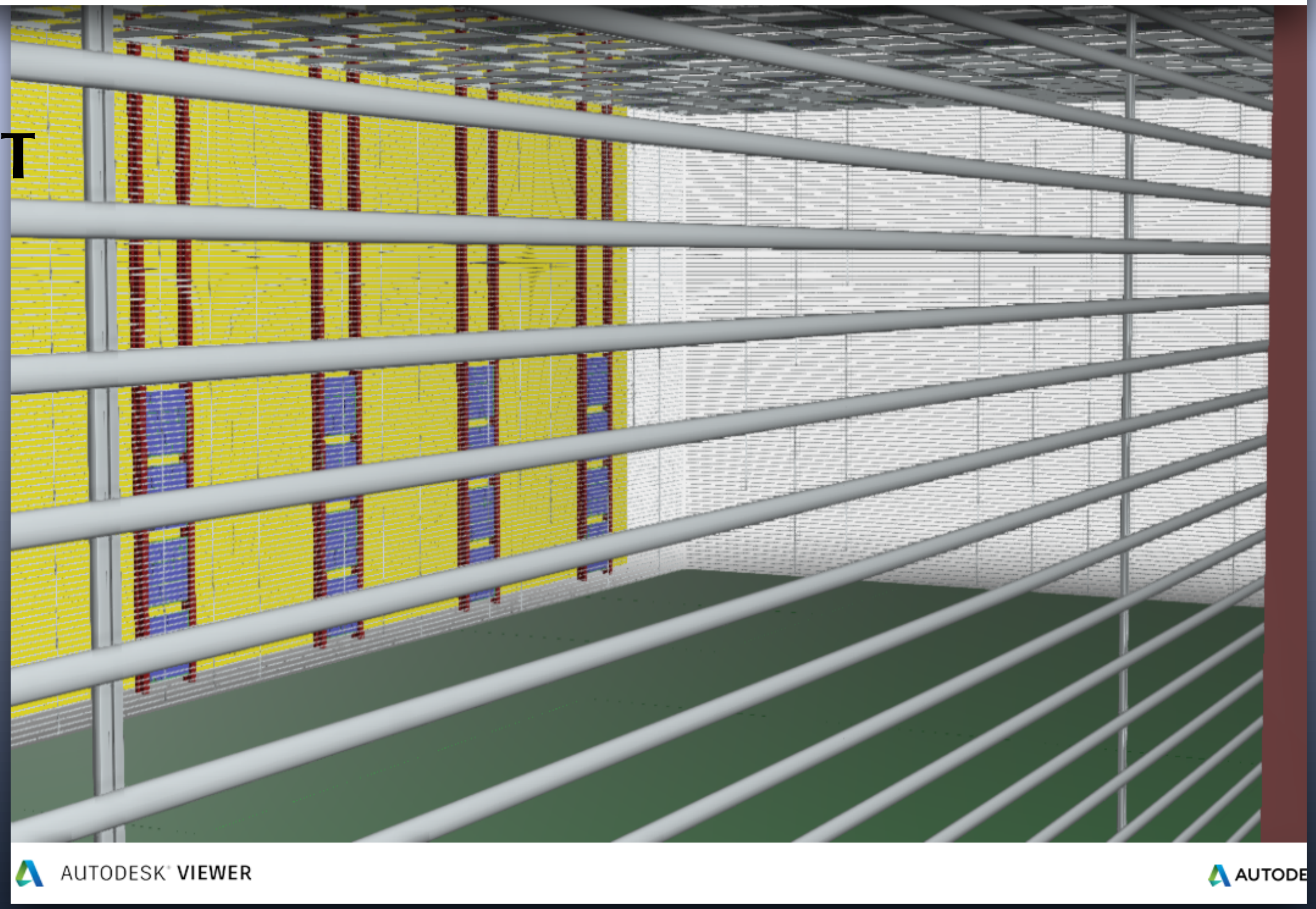


View from inside the Upper Volume with PD instrumented Cathode (below) and PD instrumented Membrane behind the FC



modified FC - 70% T

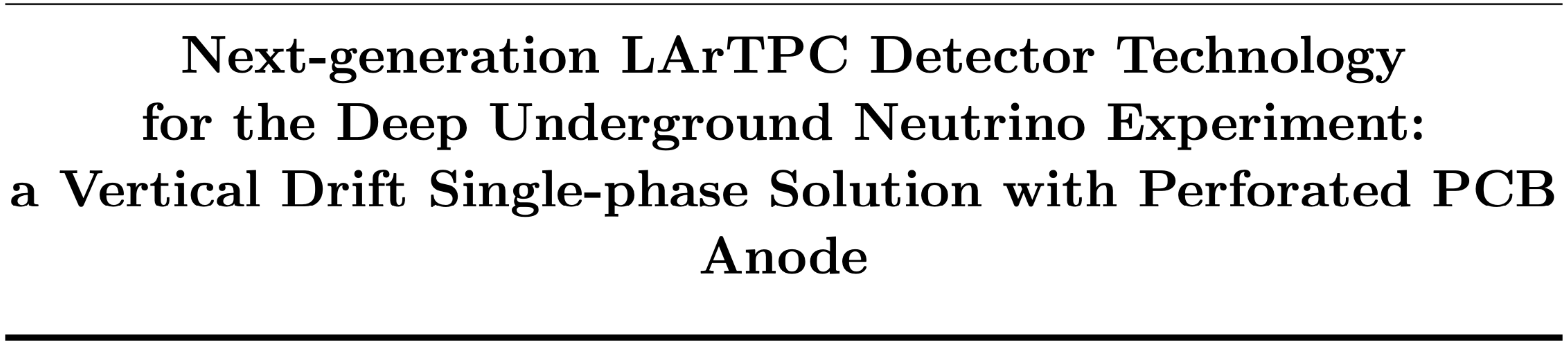
View of the Lower Volume from behind the FC, as seen by the Membrane PD modules



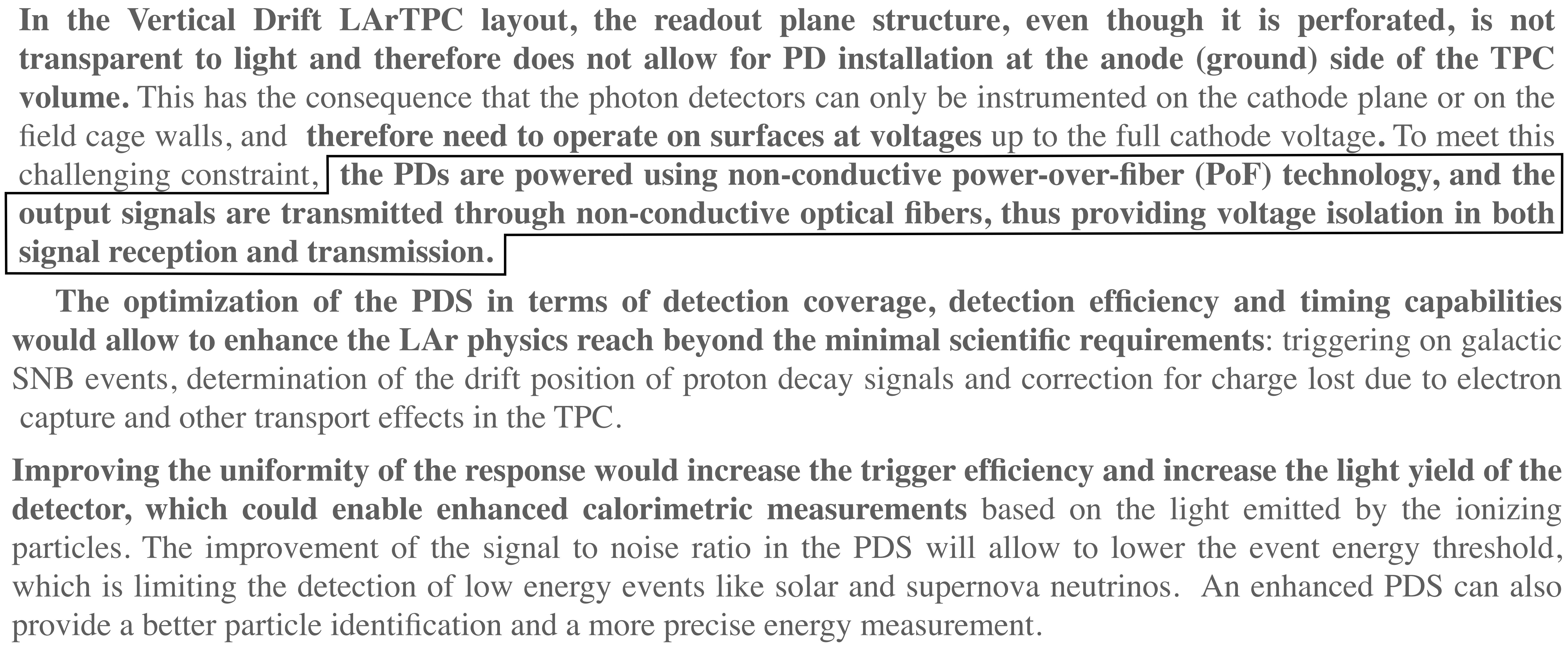
Overview of FD2 PDS technical design and Physics performance

- 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 modules, fall-back solution retired)
- Status of each (main) Requirement & Milestones: 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

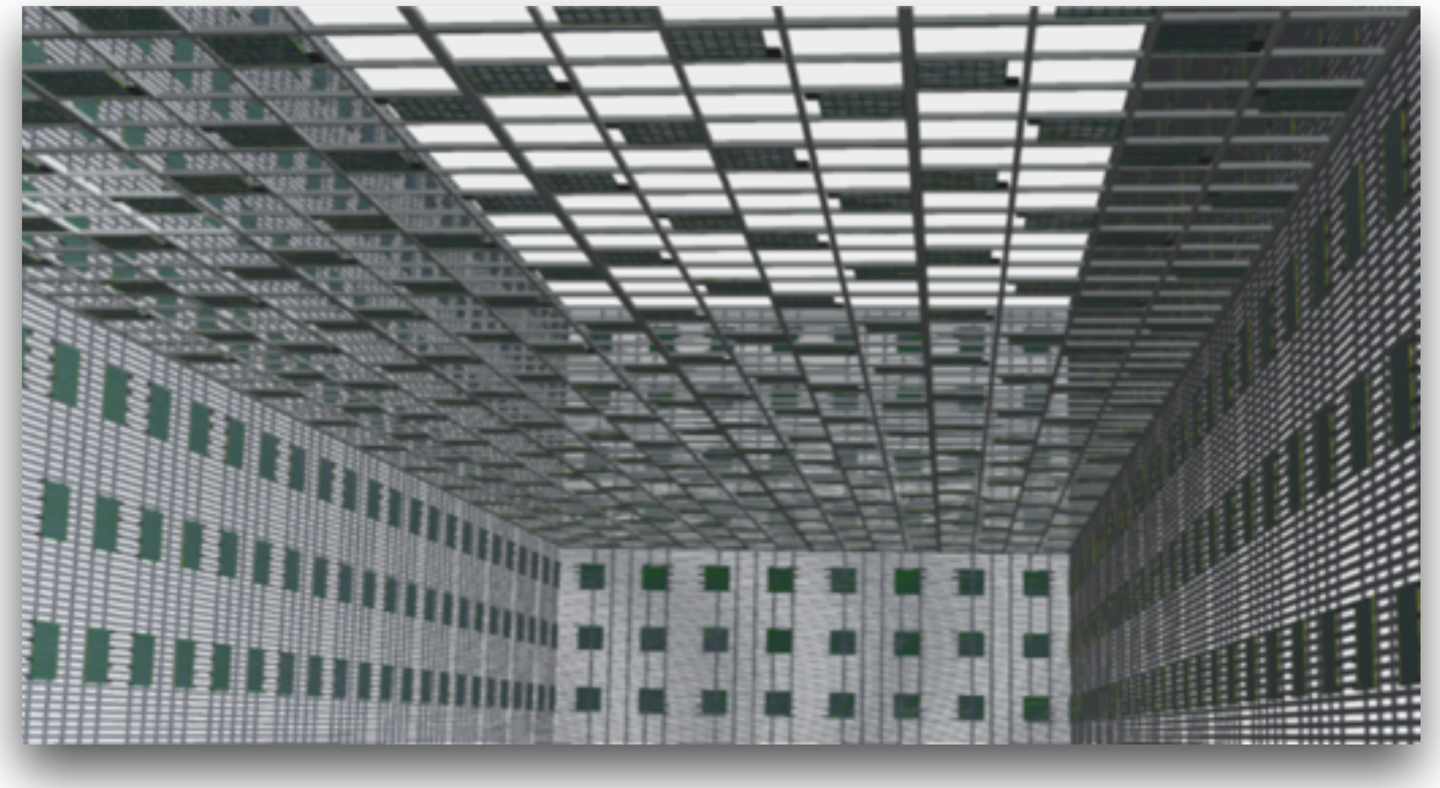


In the Vertical Drift LArTPC layout, the readout plane structure, even though it is perforated, is not transparent to light and therefore does not allow for PD installation at the anode (ground) side of the TPC volume. This has the consequence that the photon detectors can only be instrumented on the 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.

Dec.7 2020:
First presented at Director's Review & LBNC Review

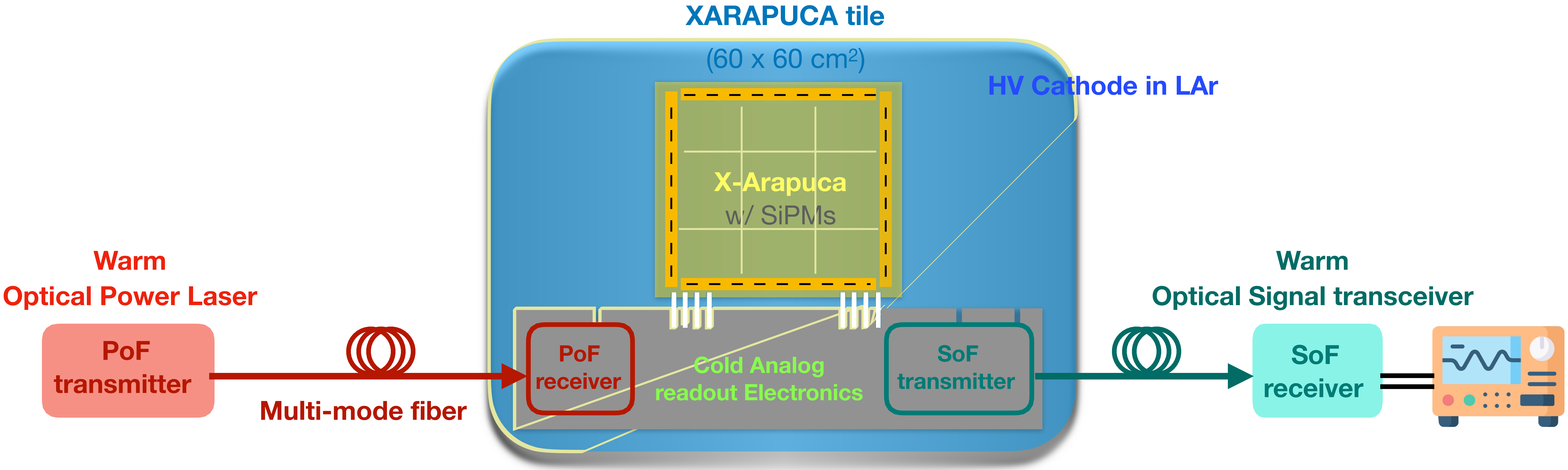


The ~4π PDS Concept
with Cathode and FieldCage Coverage

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

FD2 Photon Detector Concept

in a nutshell



Power-over-Fiber

Signal-over-Fiber

The novelty elements in the FD2 VD PDS Design

- Large(st) number of SiPMs per Electronic Channel: 2 ganging stages [hybrid Passive, Active sum/ampli in Cold] → Ref. *Dave C talk*
- Large(st) photo-detector sensitive area (60 x 60 cm^2): XARAPUCA large form-factor with new WLS plates → Ref. *Dave W, Carla, Kurt talks*
- PoF (electrical isolation, noise immunity, spark-free operation) never operated in HEP, existing technology to be validated in Cold (at LAr T) → Ref. *Bill talk*
- SoF (electrical isolation) develop Cold custom technology → Ref. *Dave C, Sabrina talks*
- Optical Fibers (instead of copper cables) → Ref. *Diana talk*
- Interface w/ Cathode System → Ref. *Dave W, Anselmo, Ryan talks*

Boundary Conditions (subject to variations over time):

- 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 ← Ref. *Ettore,* → *Francesco talks*

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

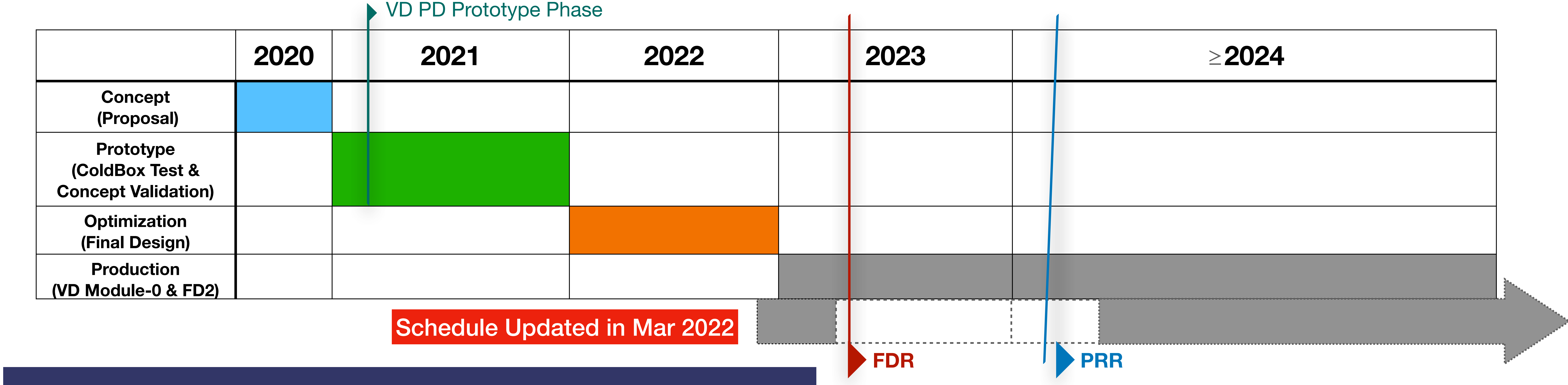
- Demonstration Requirements:

* validation tests at CERN (ColdBox in sync with CRP/TPC) → Ref. *Sabrina talk*

* production and installation in VD Module-0 at CERN → Ref. *Anselmo talk*

Schedule Feb. 25, 2021

VD Photon Detector Project



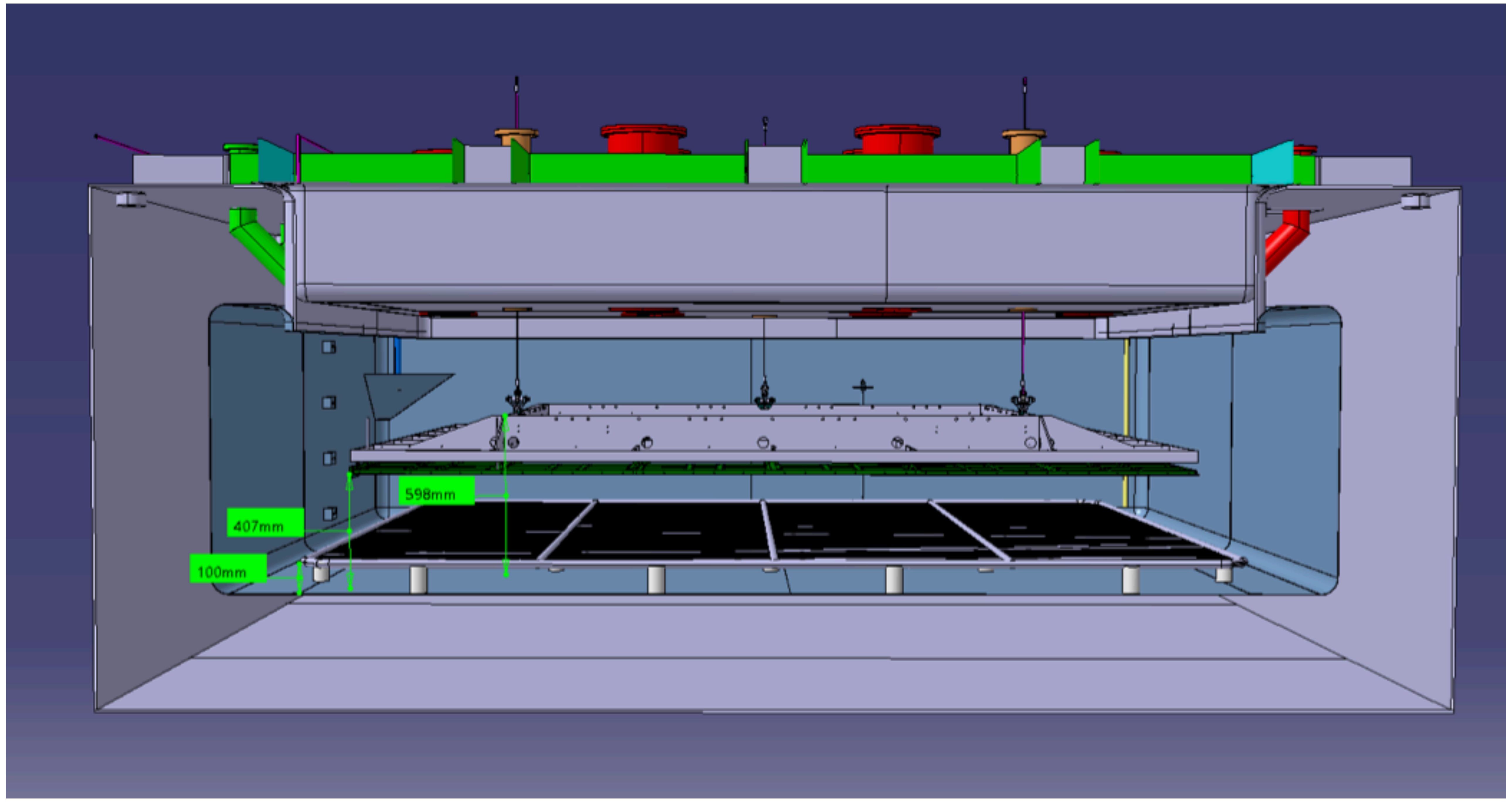
Start of Project funded
VD PD Prototype Phase

	2020	2021	2022	2023	≥2024
Concept (Proposal)	🟦				
Prototype (ColdBox Test & Concept Validation)		🟩			
Optimization (Final Design)			🟧		
Production (VD Module-0 & FD2)				⬛	⬛

Schedule Updated in Mar 2022

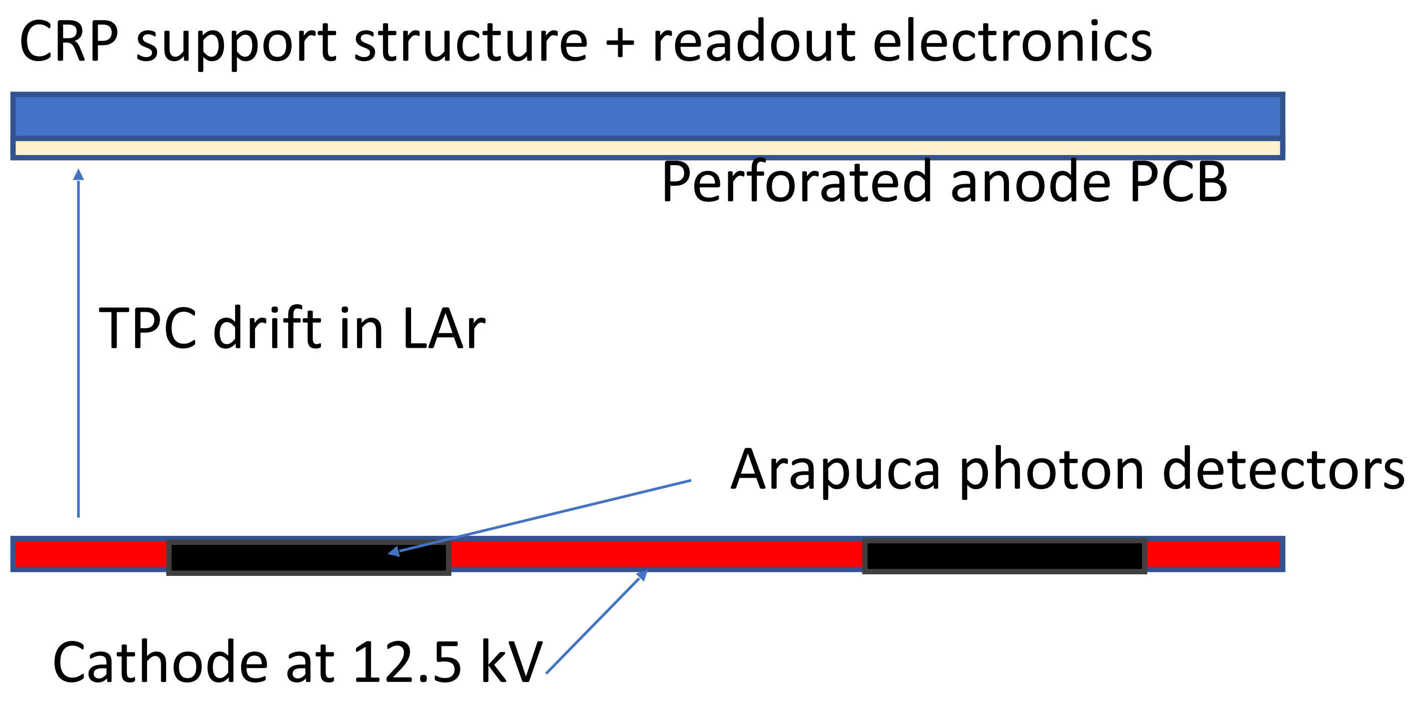
FDR

PRR



2021 VD demonstrator

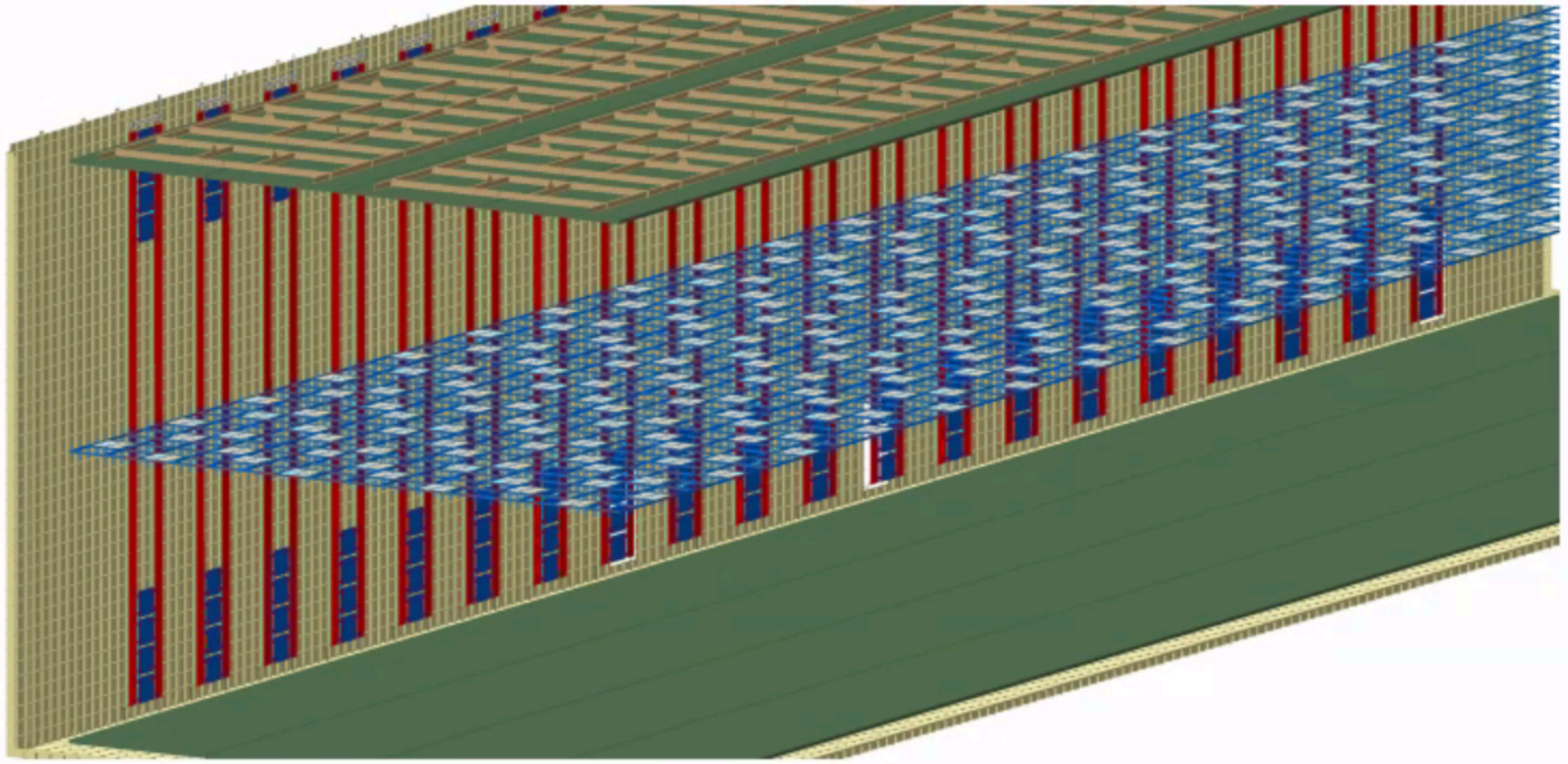
29-10-2020



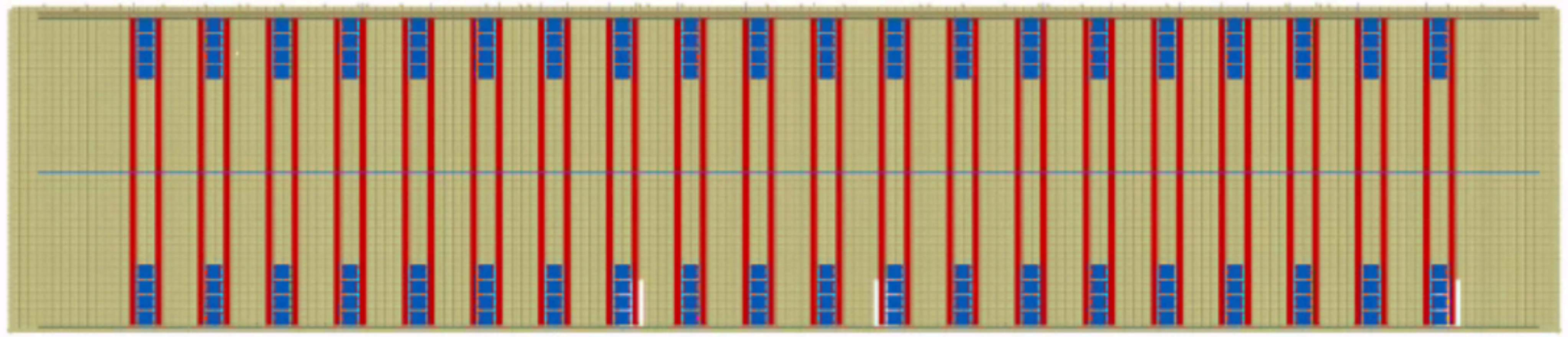
- ✓ test the light readout detector concept (on HV surfaces) at large scale

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

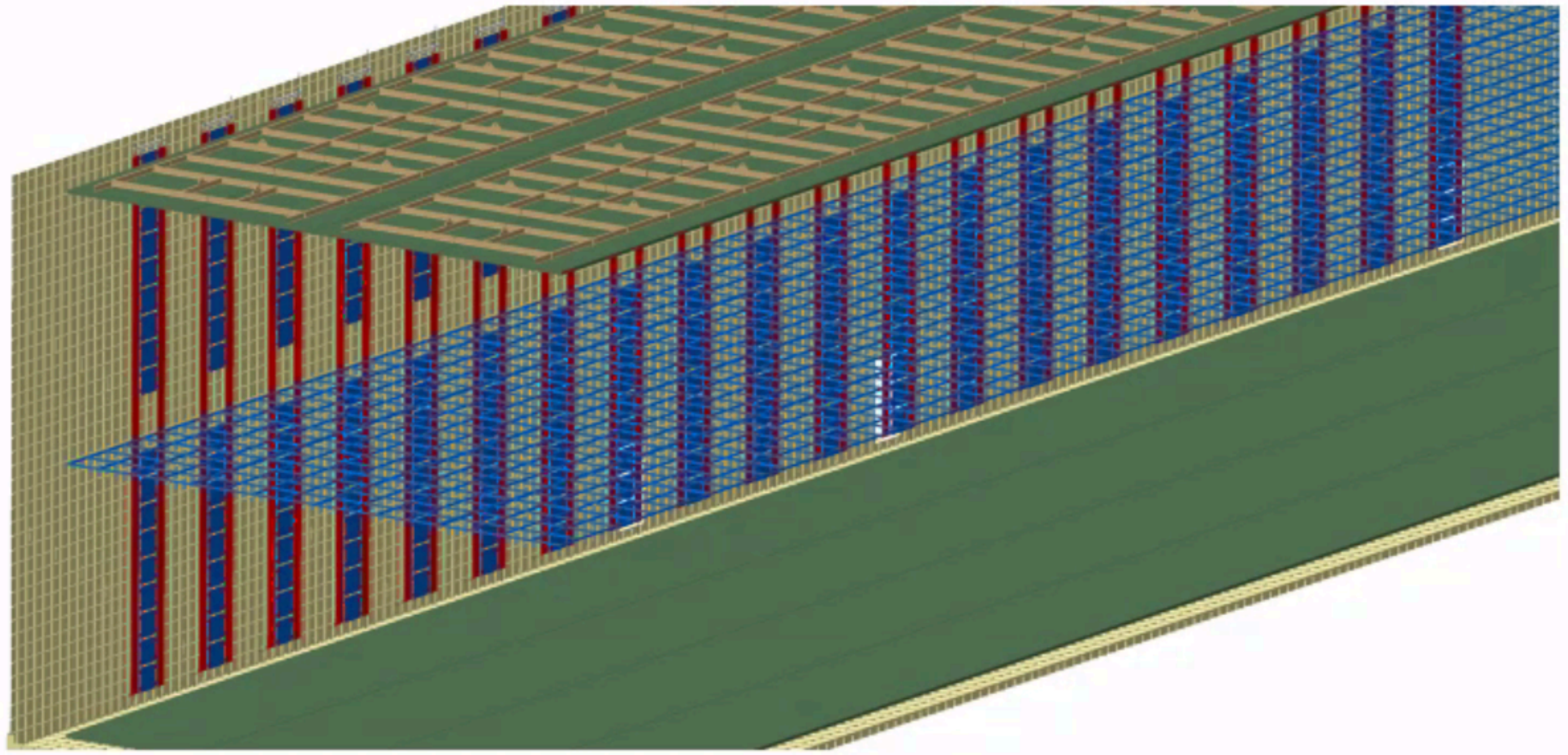
Reference Design (Cathode & Membrane mounted PDS ⊕ Xe doping)



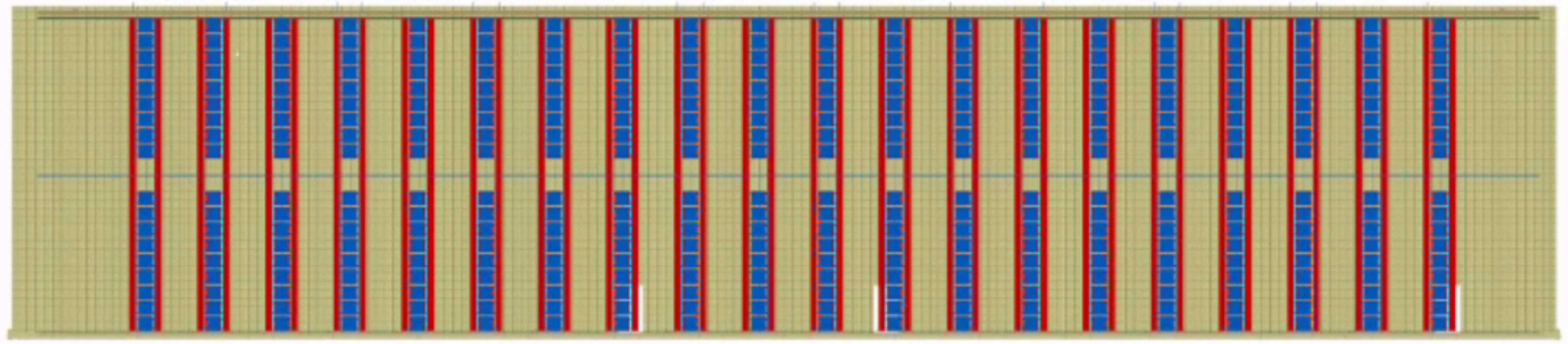
4 pi layout :
- Full trigger capabilities down to 10 MeV
- Energy, Position and T0
- xArapucas 60x60 on the cathode, 115 mq, analog readout
- xArapucas 60x60 on the cryo membrane, ~3m from Cathode



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 Surf
  - ✓ PDs installed Dec 2027

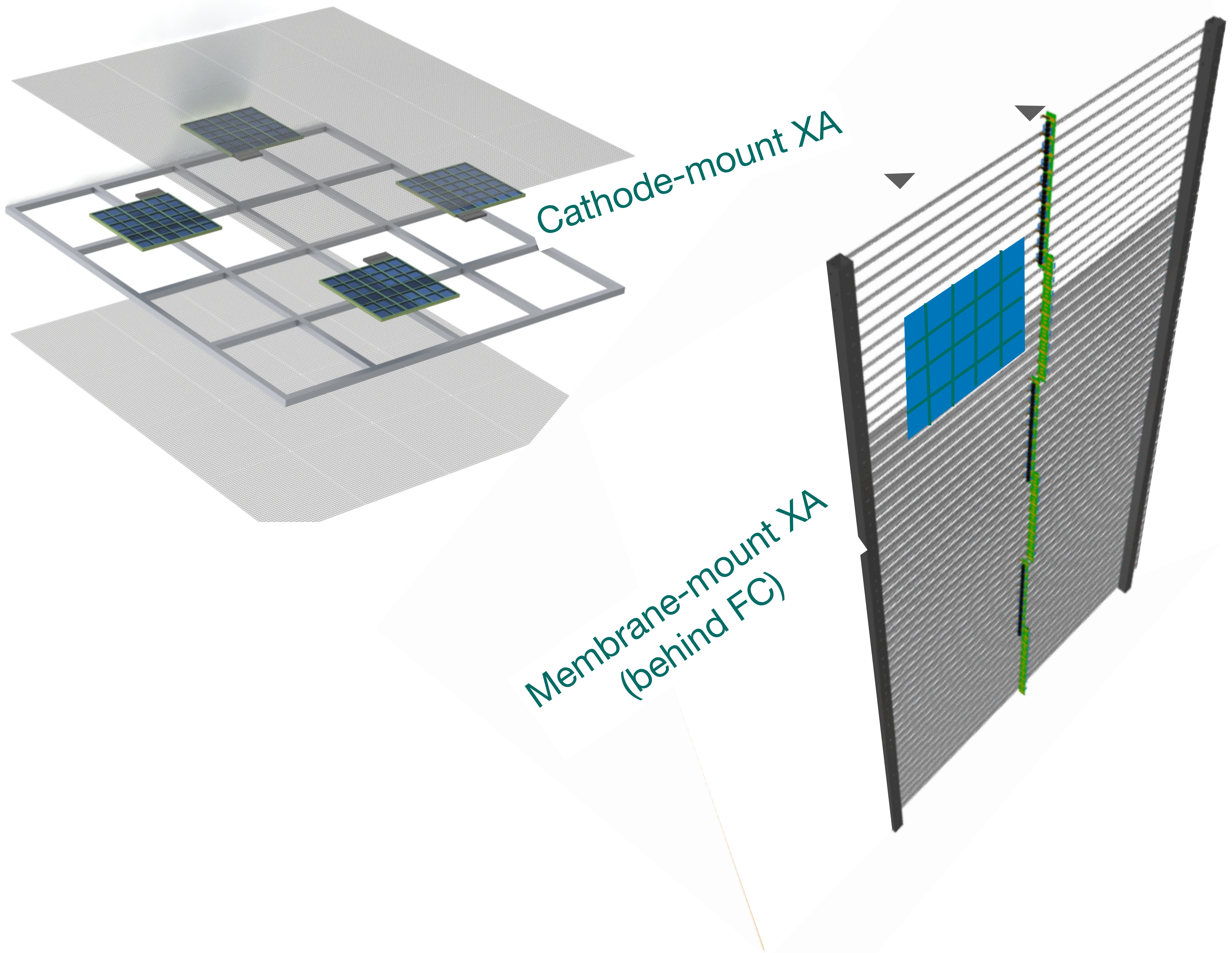
• FD2 PDS Requirements and Boundary Conditions

EB-held requirements

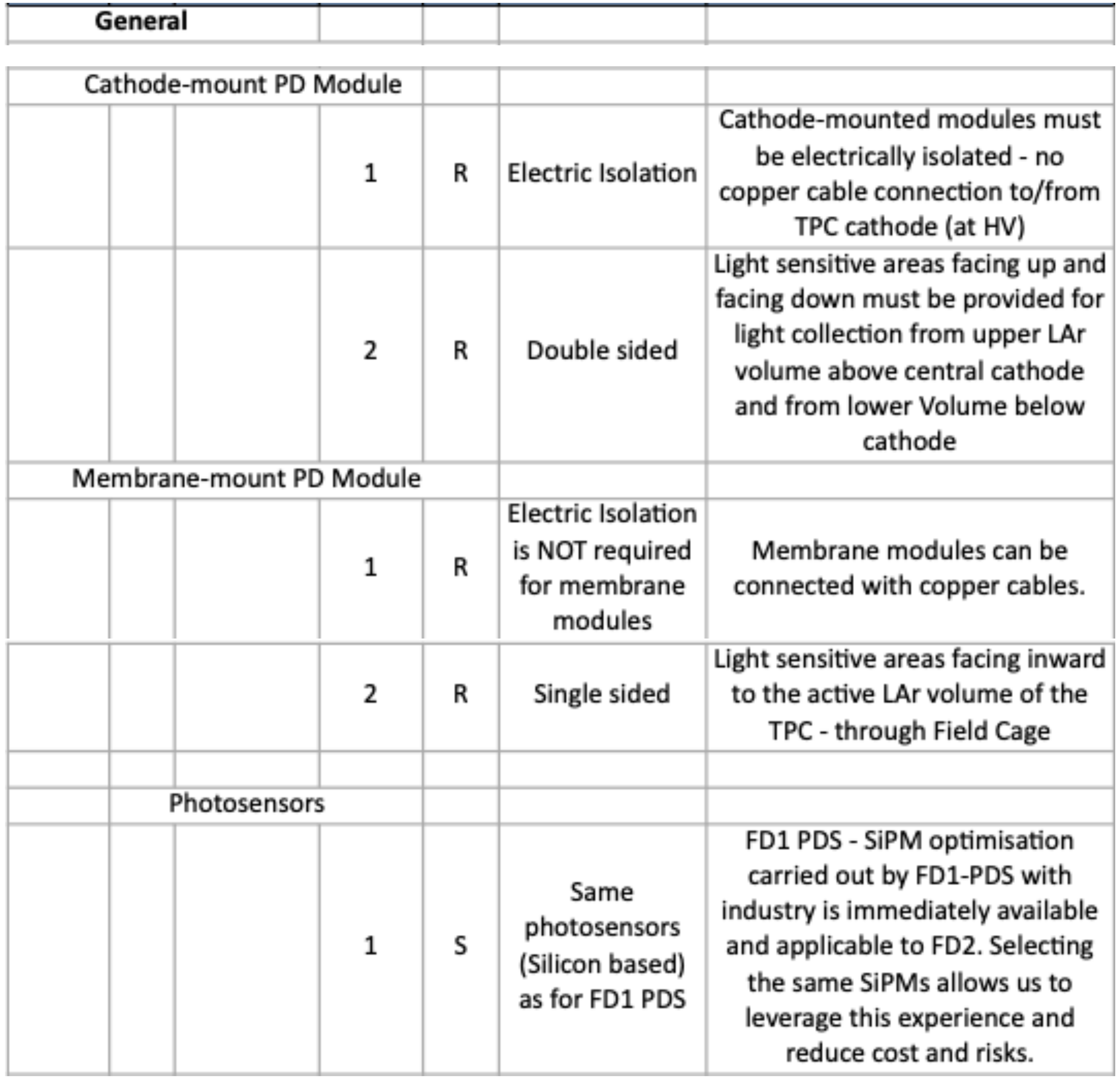
Specification	Detector components shall be sufficiently reliable so as to ensure that dead channels do not exceed 1% over the lifetime of the experiment.	Detector needs to operate over a 20-30 year lifetime with components that will be inaccessible post-installation, so components must be robust against 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.
Specification	Light yield	The average light yield (LY) shall be high enough to reach similar calorimetric energy resolution with the PDS for low energy supernova neutrinos as with the TPC. The average LY shall also be sufficient to enable triggering on neutrinos from supernova bursts. The minimum LY in the active volume shall be sufficient to correctly associate scintillation light with events with energy >200 MeV with efficiency >99%.	**LY >20 PE/MeV (avg),** **LY >0.5 PE/MeV (min)**

to be adopted as TB-held requirements

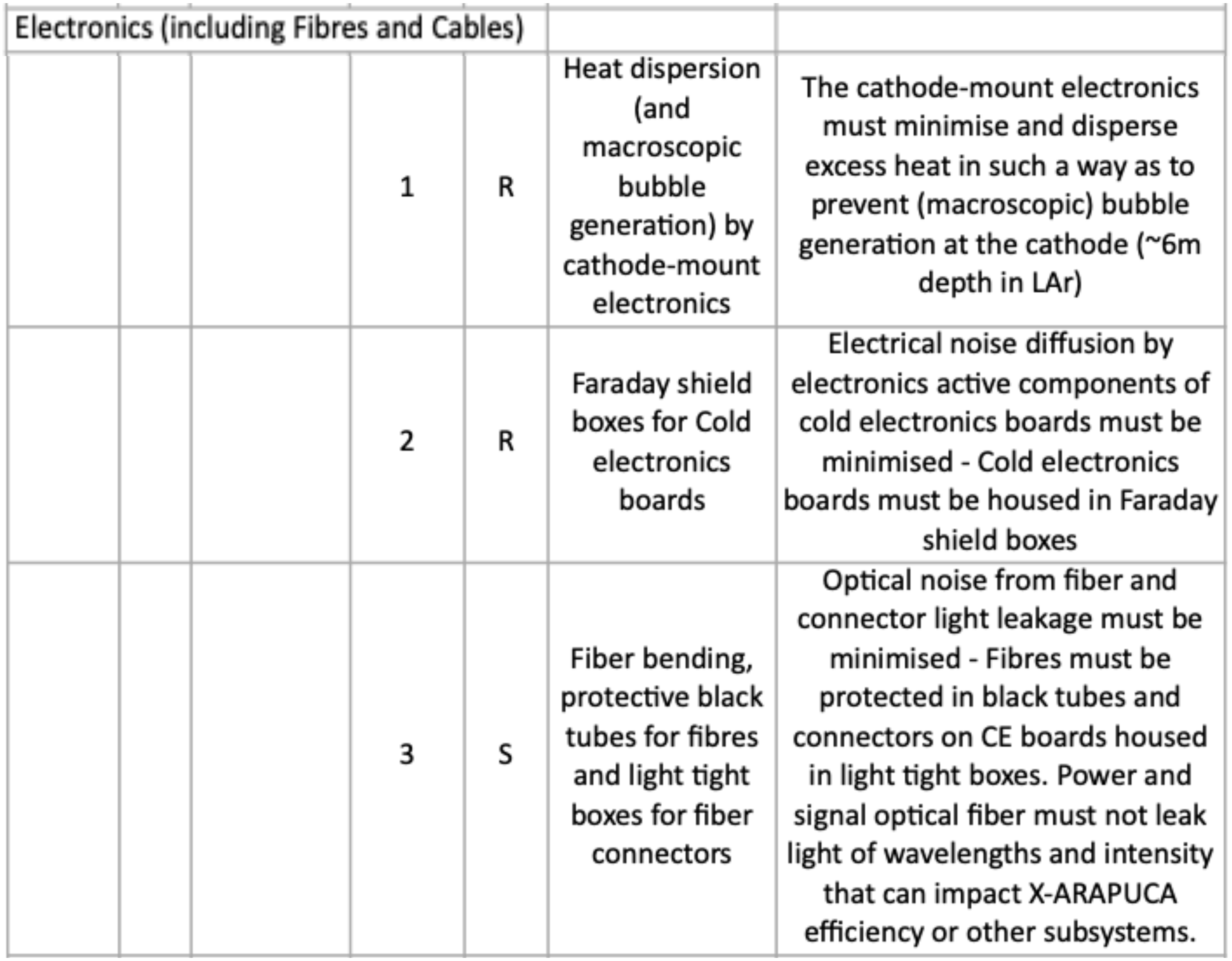
Requirement	VD PD layout	Photon Detector modules located on the Cathode plane should be electrically isolated	No copper cable connection to/from TPC cathode (at HV) should be established serving PD modules
Requirement	VD Membrane-mount modules position behind Field Cage	Membrane-mount modules must be 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

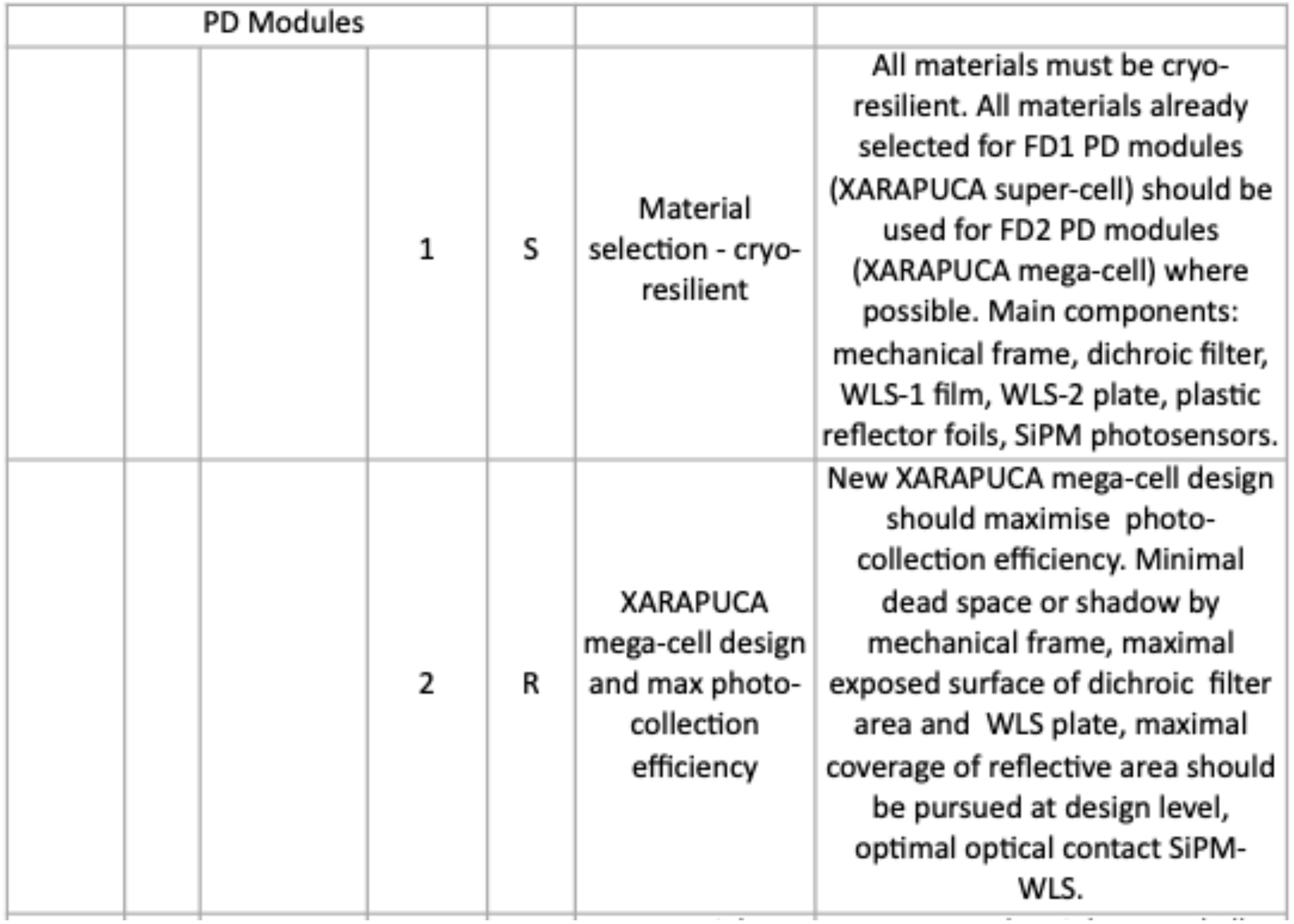


General						
Cathode-mount PD Module						
			1	R	Electric Isolation	Cathode-mounted modules must be electrically isolated - no copper cable connection to/from TPC cathode (at HV)
			2	R	Double sided	Light sensitive areas facing up and facing down must be provided for light collection from upper LAr 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.

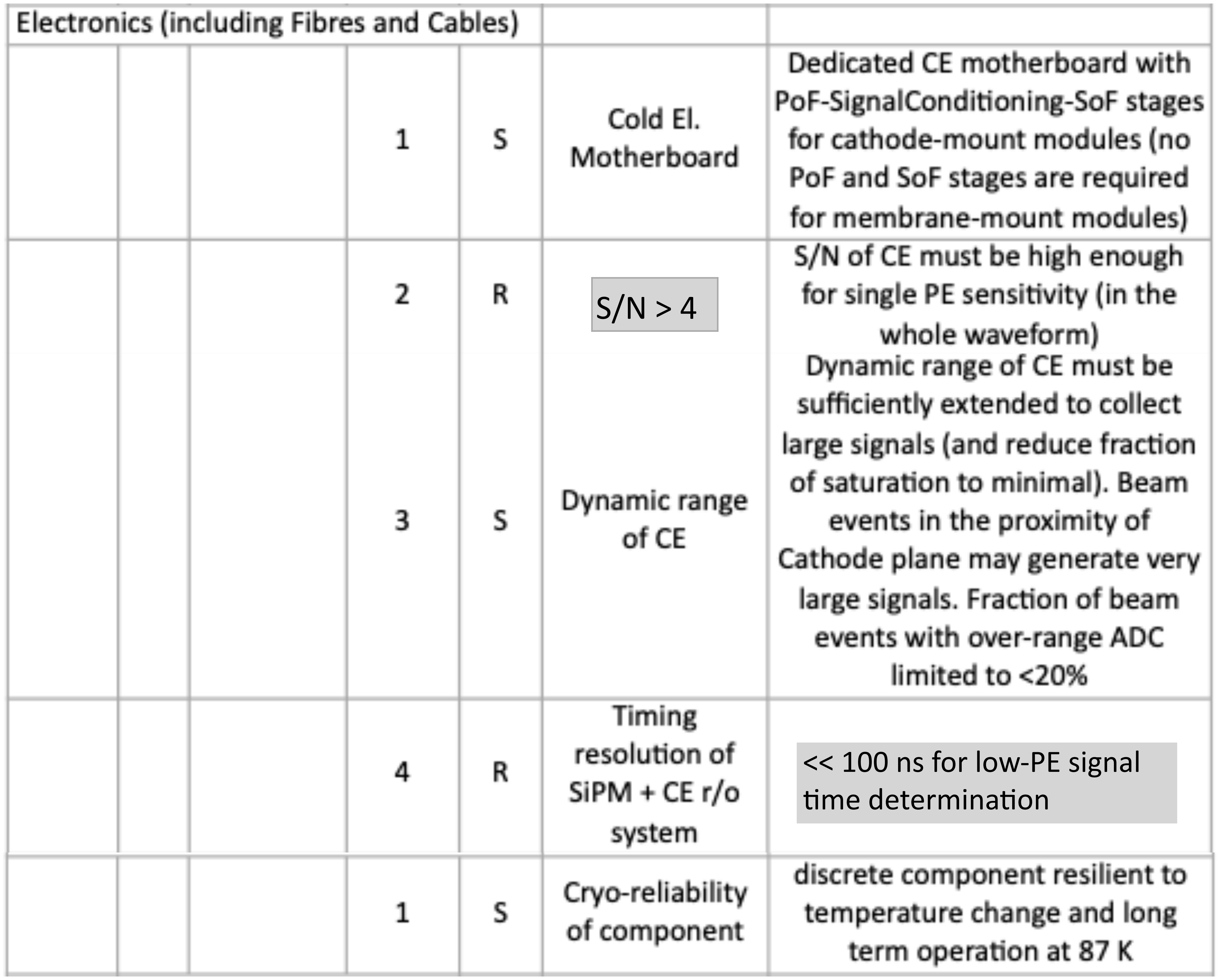


Electronics (including Fibres and Cables)						
			1	R	Heat dispersion (and macroscopic bubble generation) by cathode-mount electronics	The cathode-mount electronics must minimise and disperse excess heat in such a way as to prevent (macroscopic) bubble generation at the cathode (~6m depth in LAr)
			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

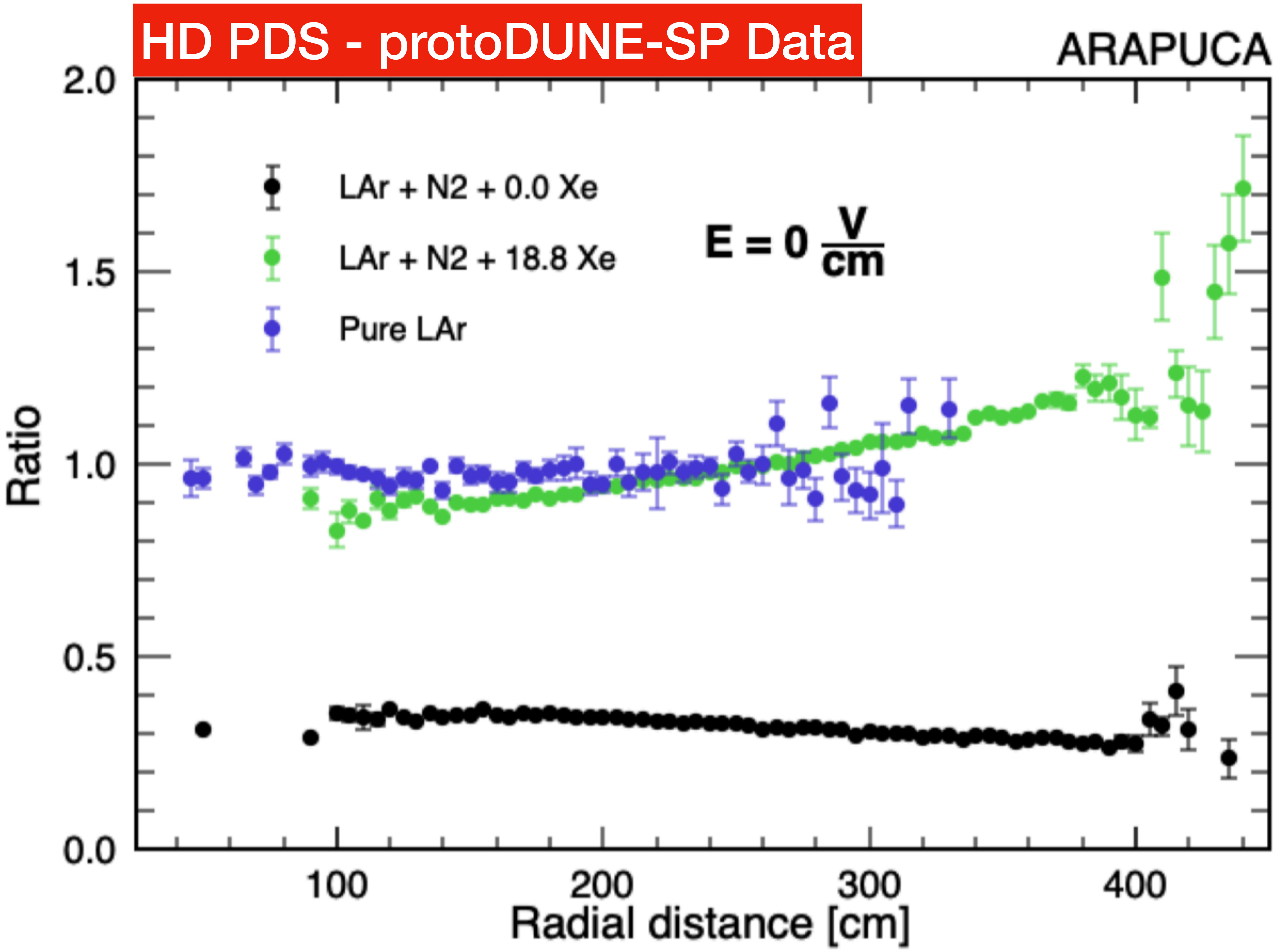
Design Goals
(Physics program driven through engineering requirements)

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	S/N ≥ 5	*protoDUNE + prototype Tests*
X-ARAPUCA efficiency	ϵ_D=3%	*+ ColdBox Tests 2021-23*
PoF - Power Transmission	Conversion Effic. 22% → 70%	*+ Module0 Tests 2023*
	Usable Pwr: 4 W/PoF-Unit	
	stability, noise at $V_{out} \sim 50$V	
SoF - Signal Transmission		
PDS Light Yield	$\langle \mathrm{LY} \rangle \simeq 40$ $\quad$ $\mathrm{LY}_{min} \simeq 20$	*from MC study* *from MC study*
Spatial resolution	$\sigma_r \leq 0.7$ m $\quad (E_{dep} \geq 5$ MeV)	*from MC study*
Energy resolution	$\sigma_E/E \leq 10\%$ $\quad (E_{dep} \geq 5$ MeV)	*from MC study*
Time resolution	≤ 20 ns	MC study + (protoDUNE-SP)

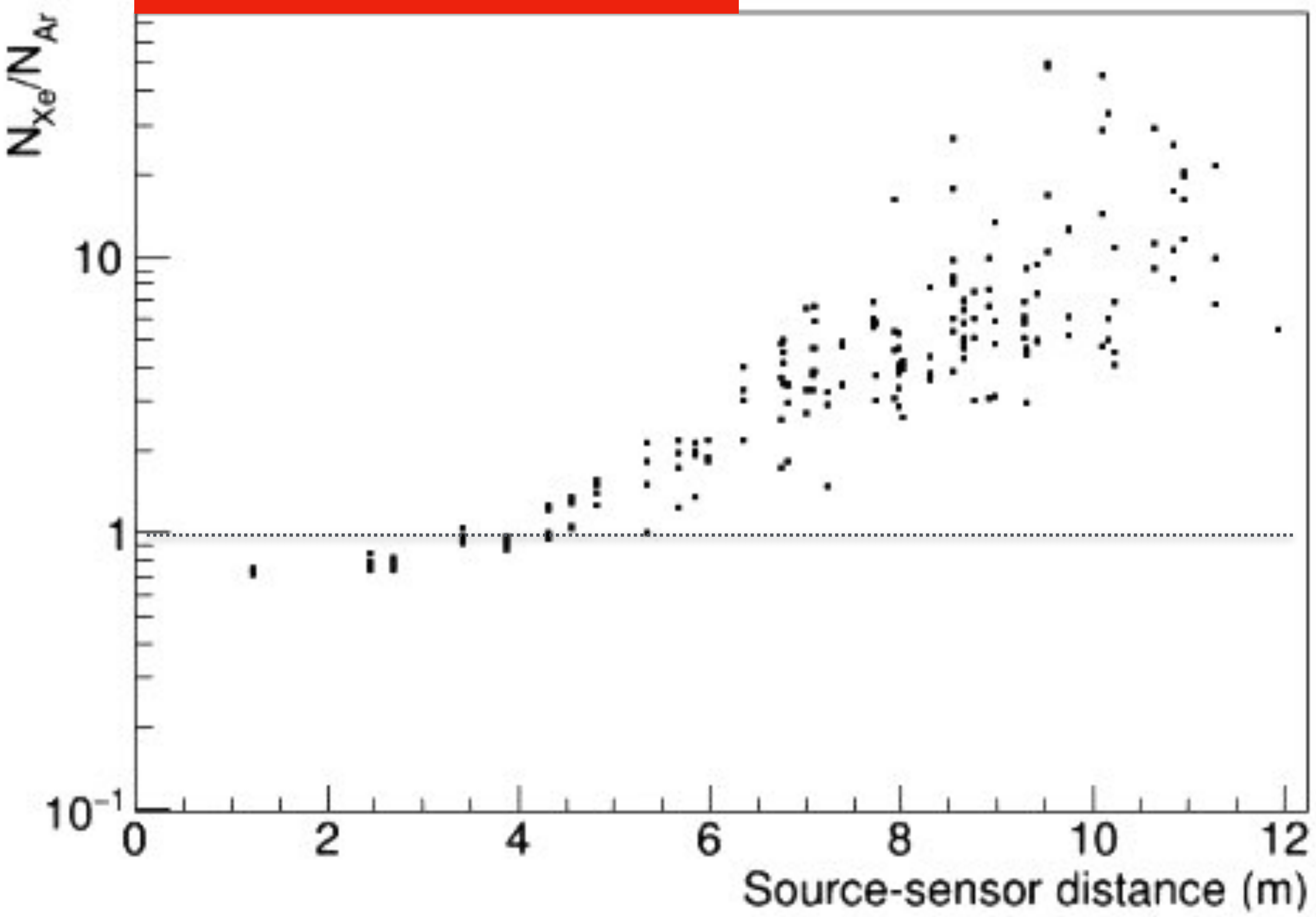
Xe doping as baseline solution

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



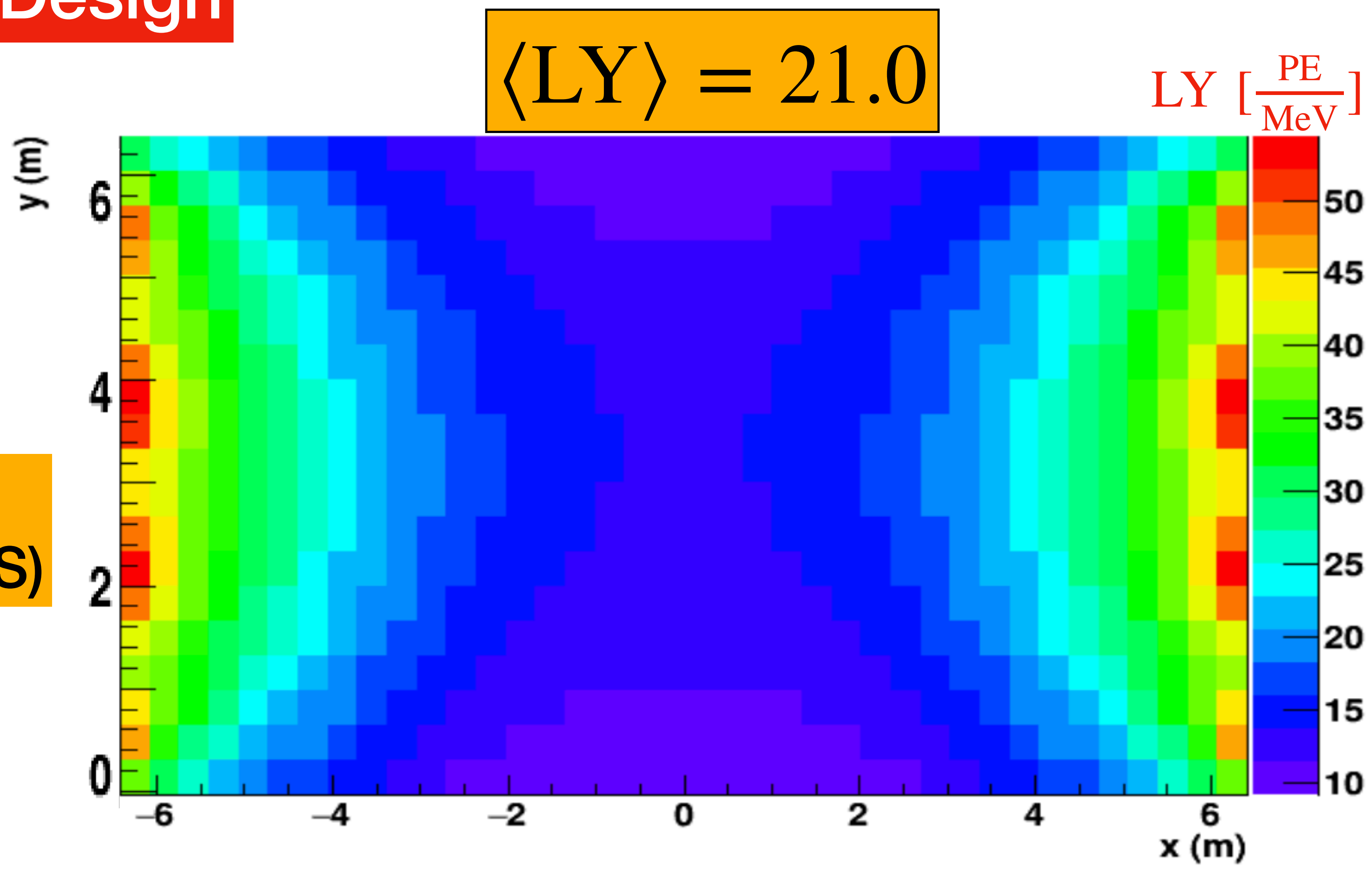
This justify the baseline solution of Xe-doped Ar as scintillation medium in VD

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.

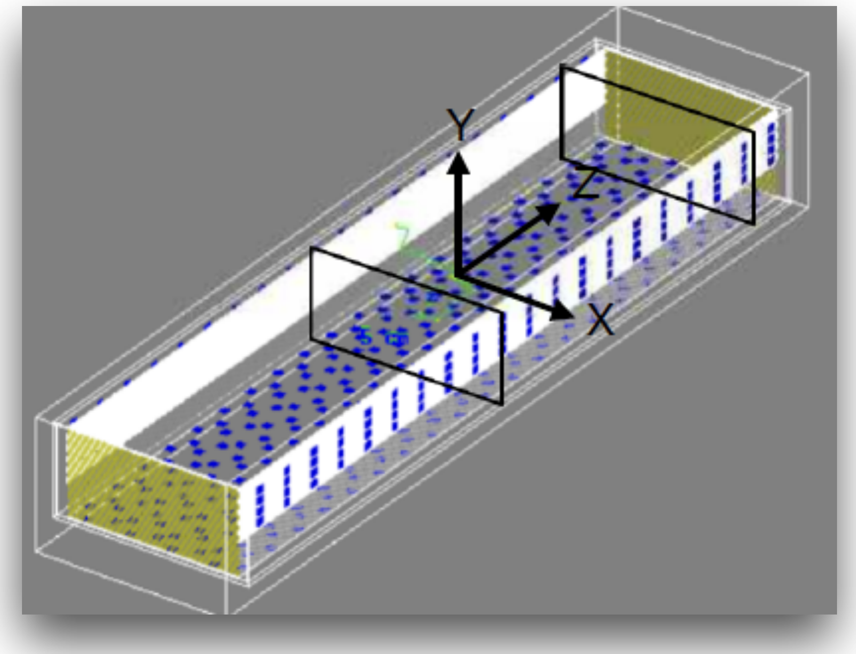
Ref.: DUNE FD2 -VD Technical Design Report
FD2-VD TDR v.2
FD2 PDS Characterization by G4 Simulation

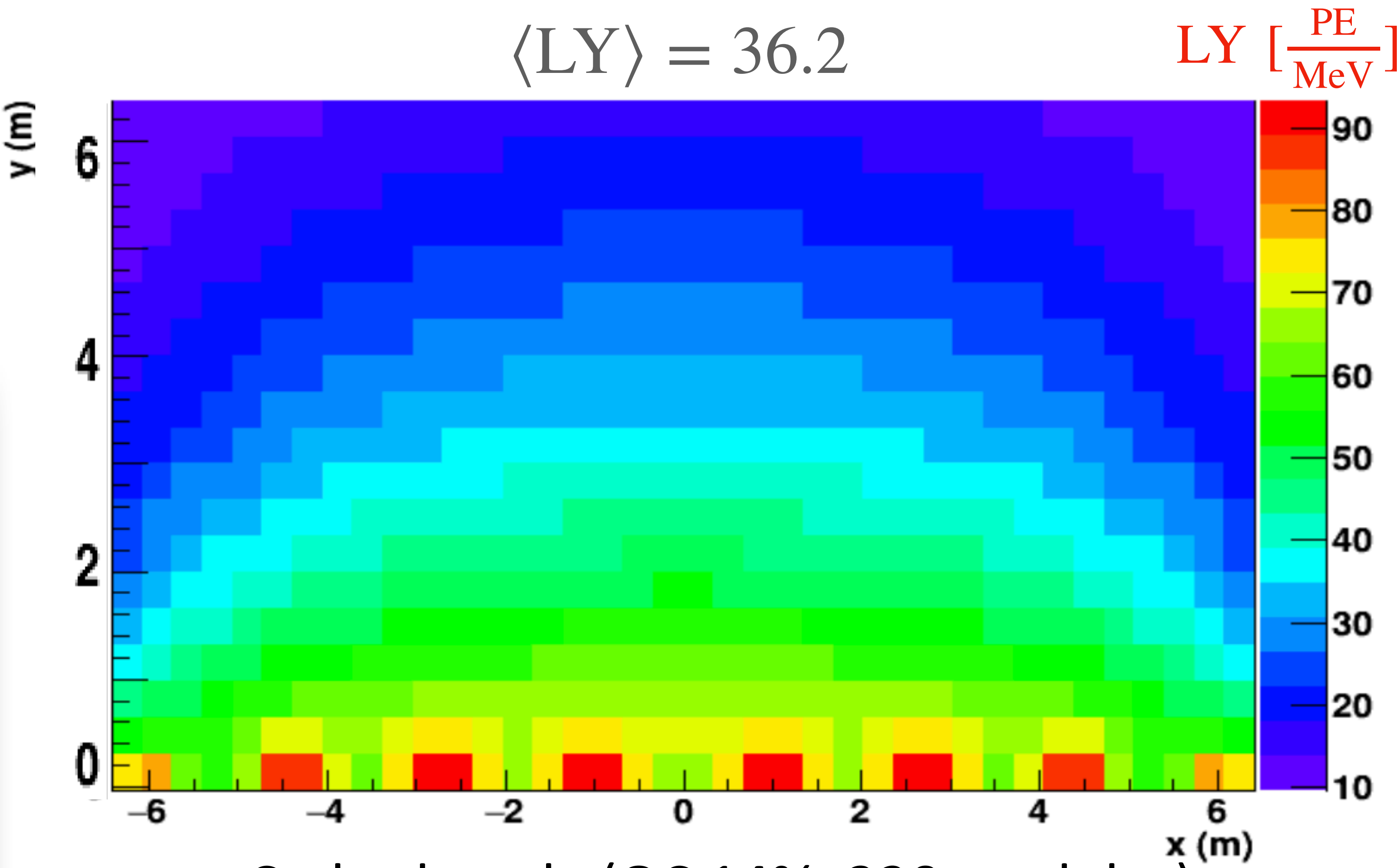
Backup Design
(All-Membrane mounted PDS)



Membrane only [OC 14%, 704 modules]

upper volume, above cathode



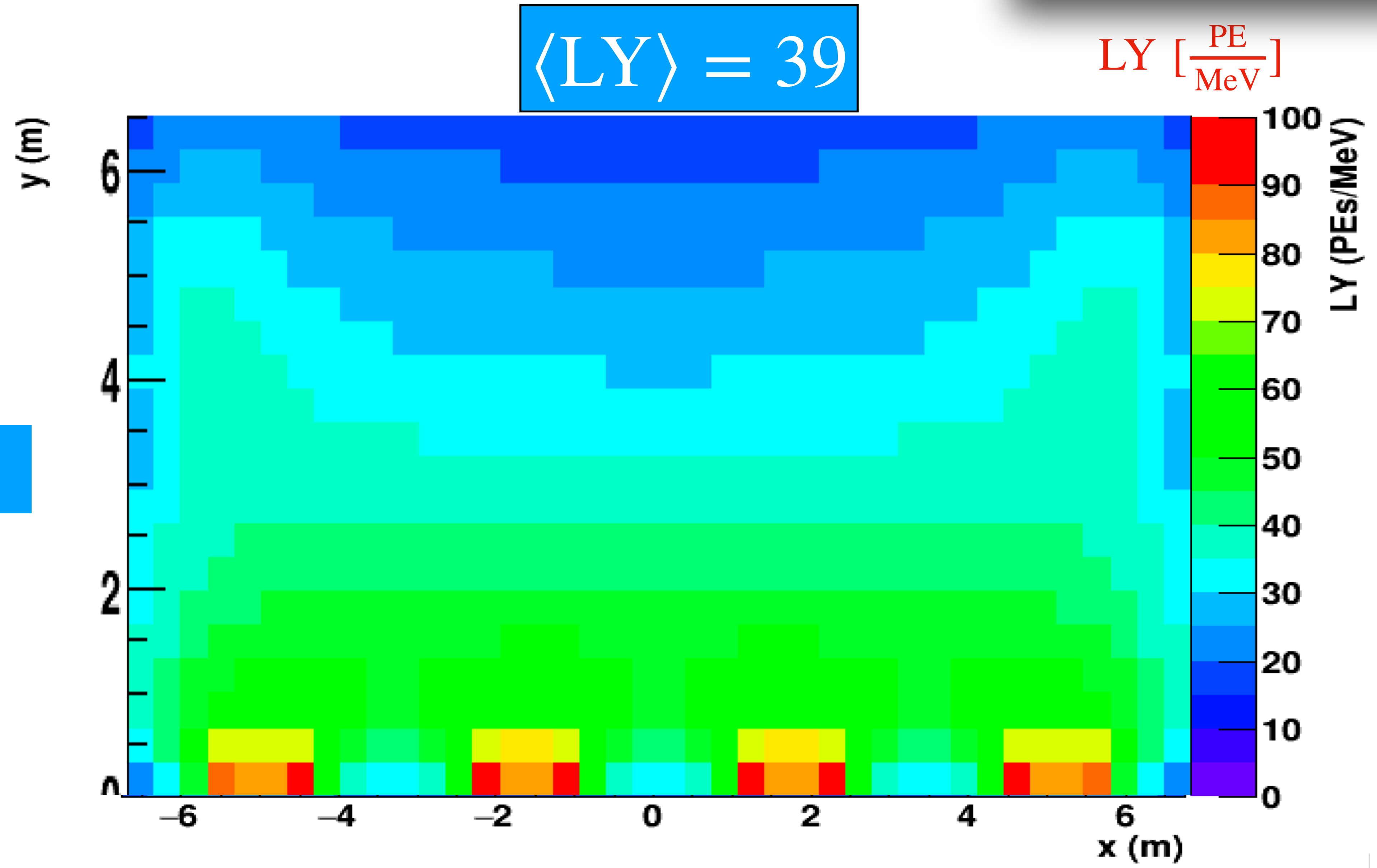


Cathode only (OC 14%, 320 modules)

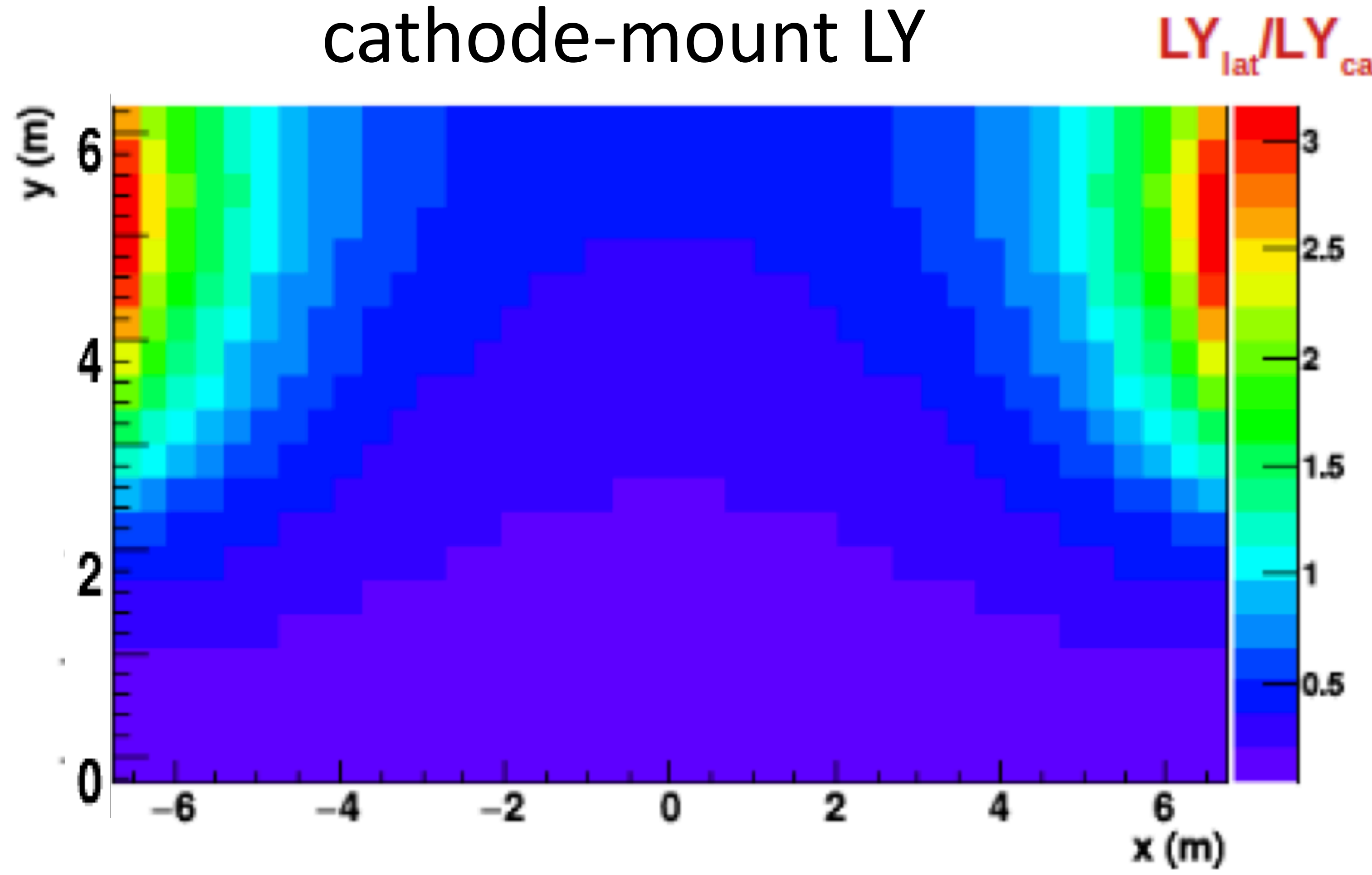
[Cathode OC 14%, 320 modules &

Membrane OC 7%, 352 modules]

(~4pi) Reference Design



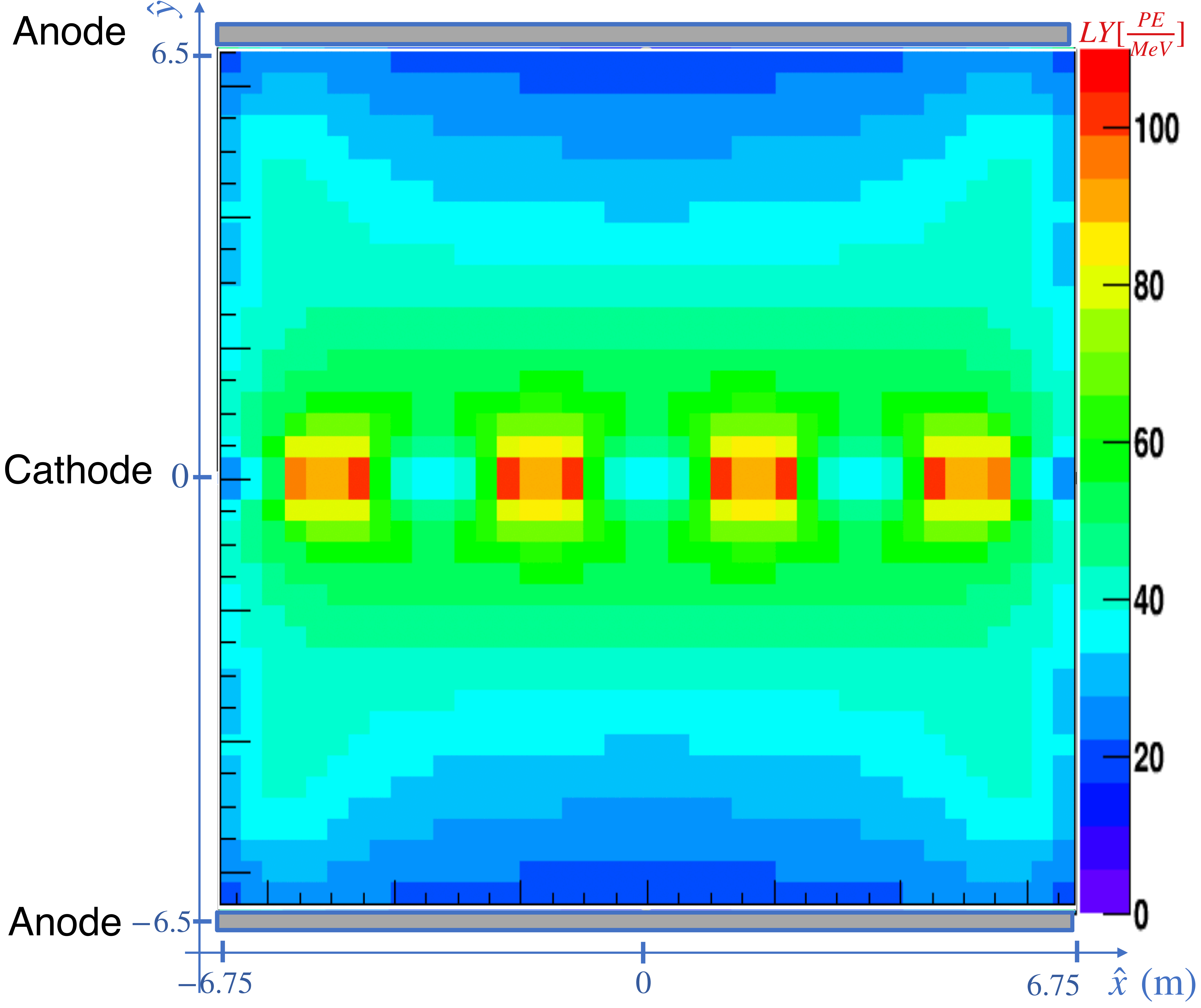
LY ratio: lateral membrane-mount LY over cathode-mount LY



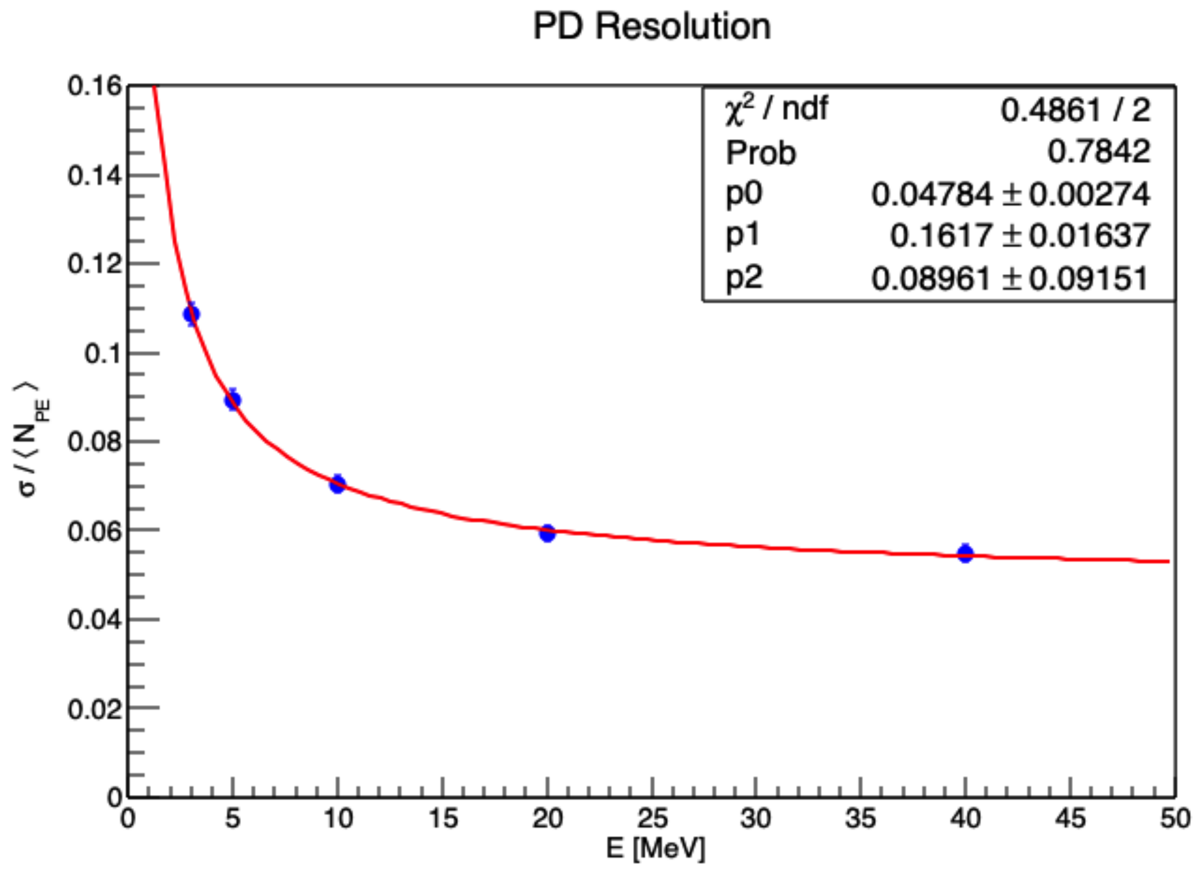
VD - Reference 4pi PDS

Light Yield

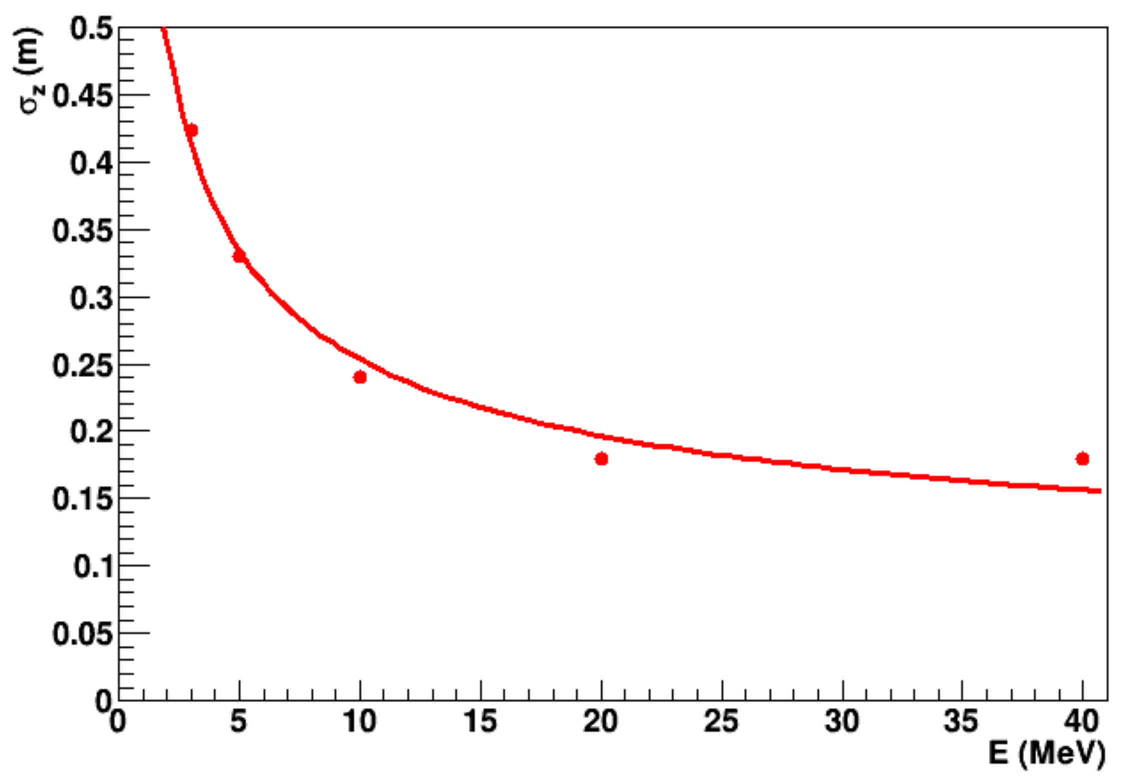
Calorimetric Energy and Position Resolution from detected photon counting



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



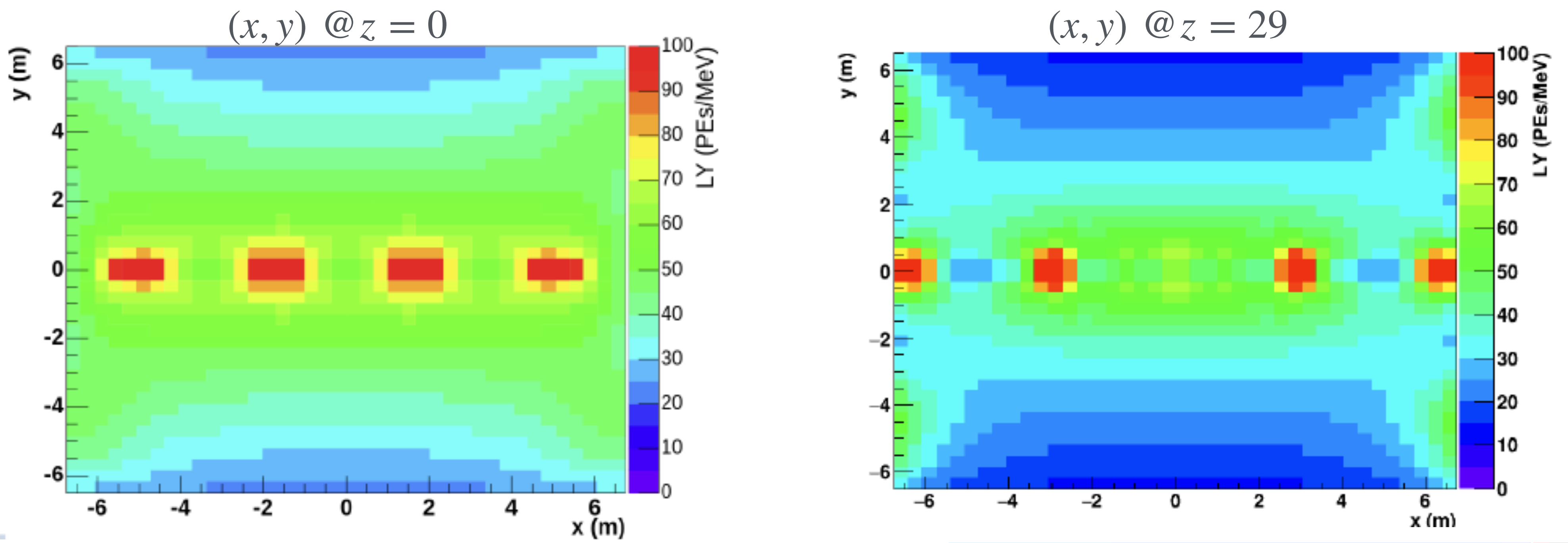
Position Resolution from detected PEs barycenter determination.

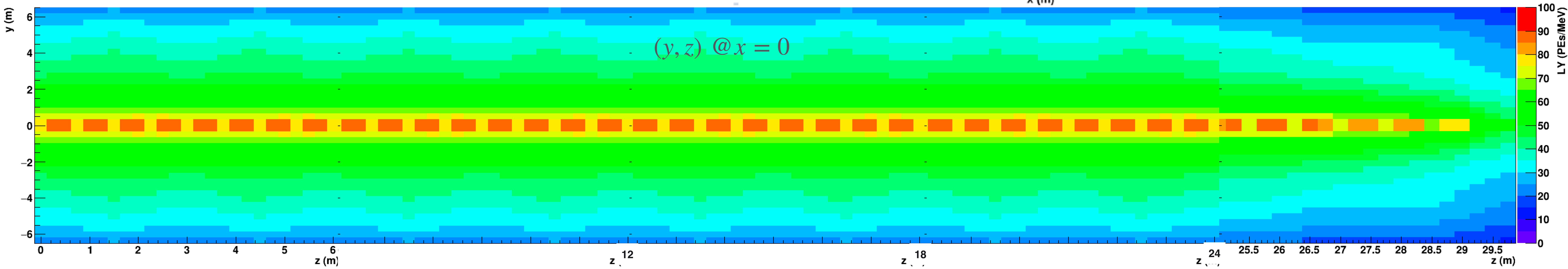


○ $\langle LY \rangle = 39$ PE/MeV

○ $\langle LY_{Min} \rangle = 17$ PE/MeV

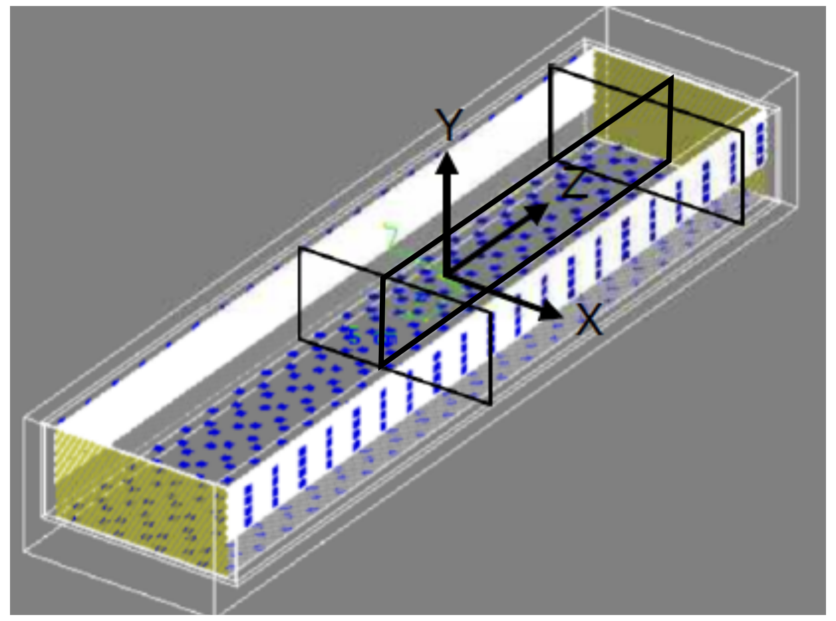
Design Optimization

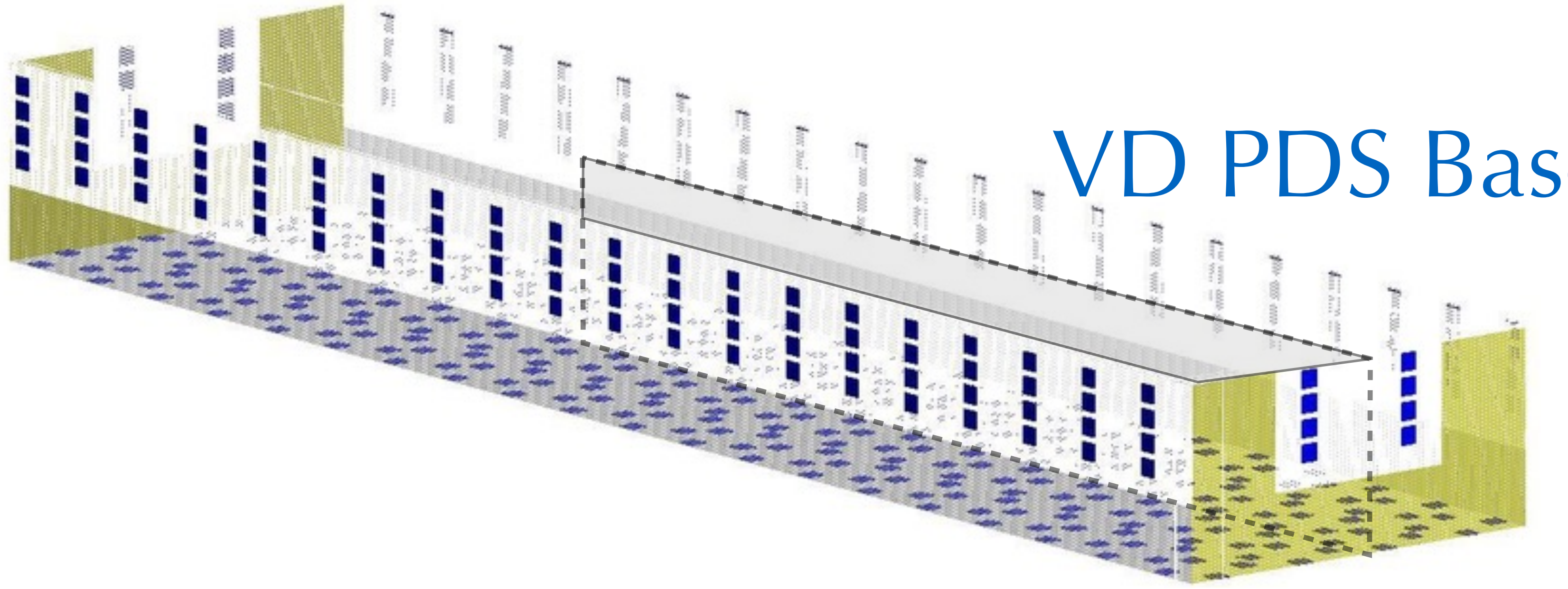




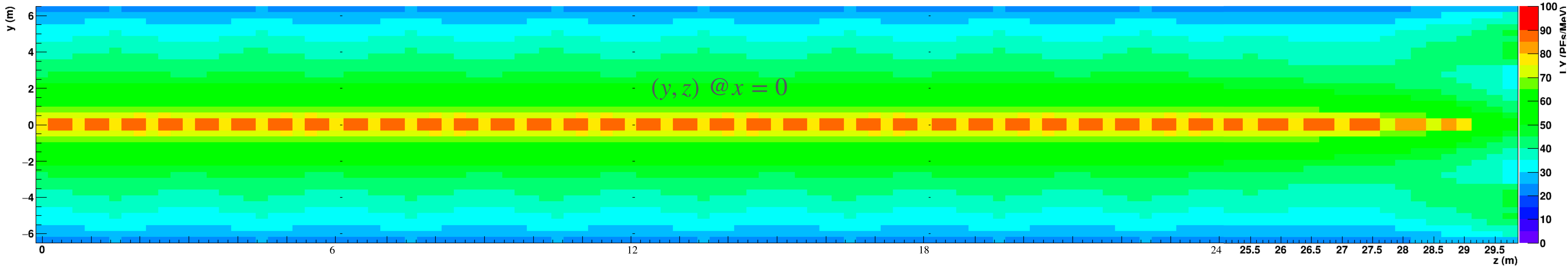
addition of X-Arapuca modules
(32 modules, +5% of total)
on membrane short walls

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





VD PDS Baseline



Design Risk Mitigation

HV discharge risk

- The worst case X-ARAPUCA (1m) fast component (10ns)
  - 100 KV/m
  - 20-125 A
  - 0.2-1.25 μC

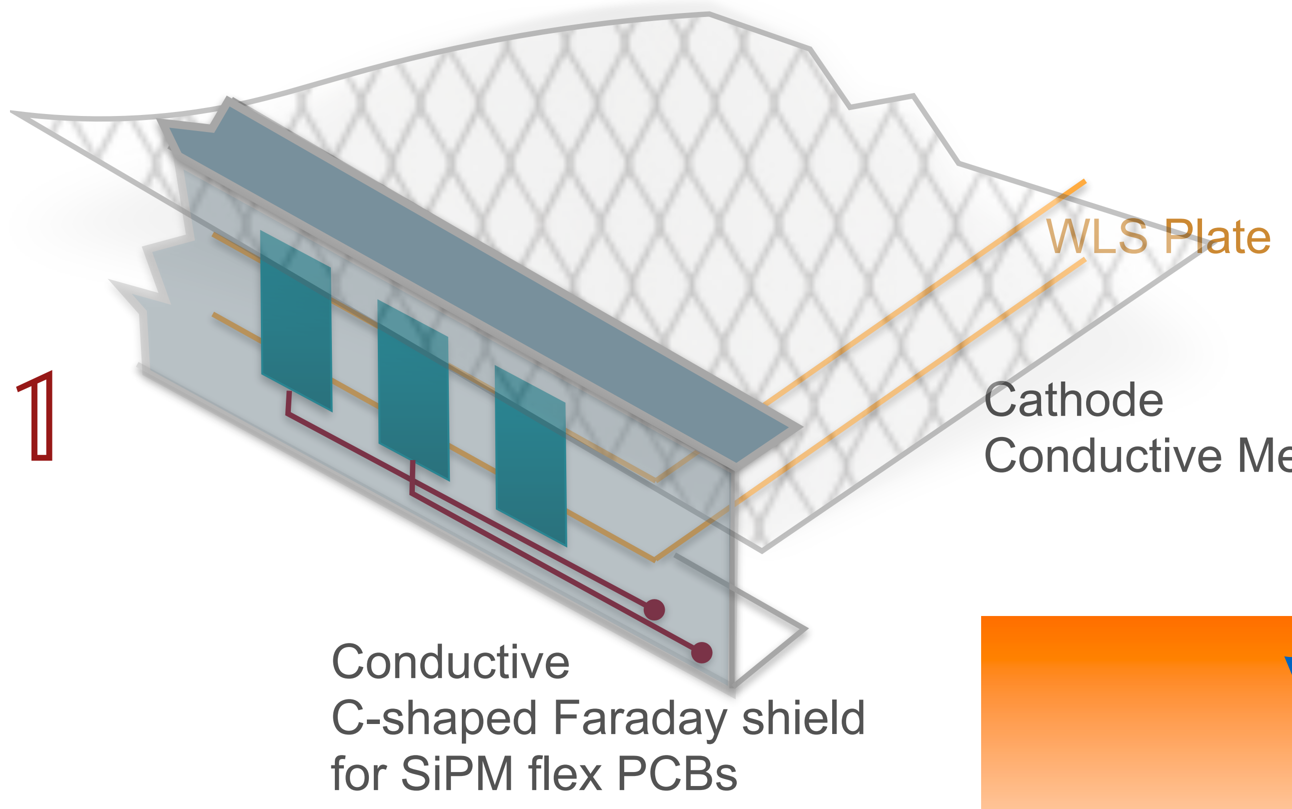
Stored Charges moving across the
Cathode Conductive Mesh in fast transient
after HV discharge

- 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

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.

3. Action items 1,2

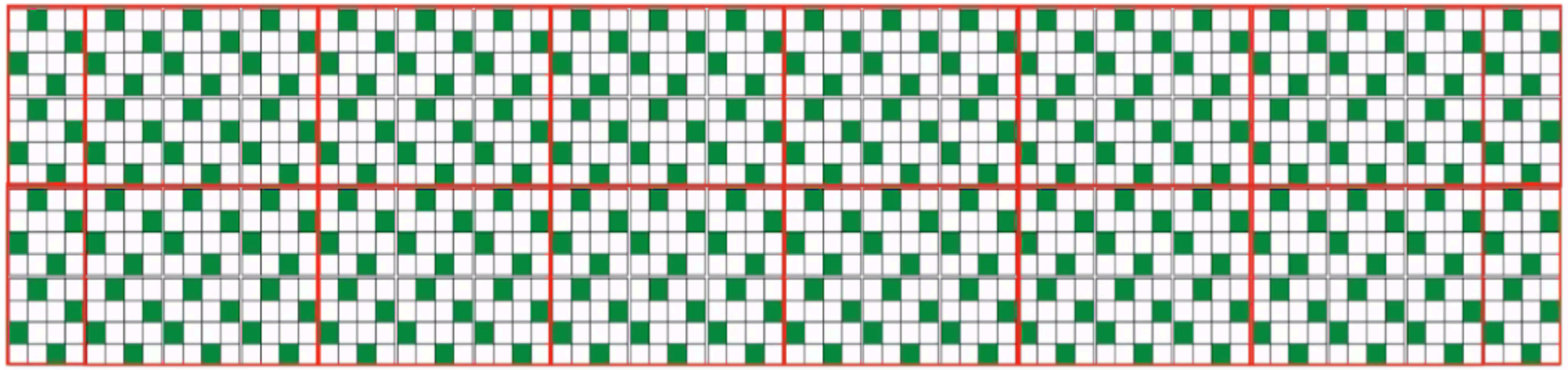
1



VD PDS
Baseline Layout

2

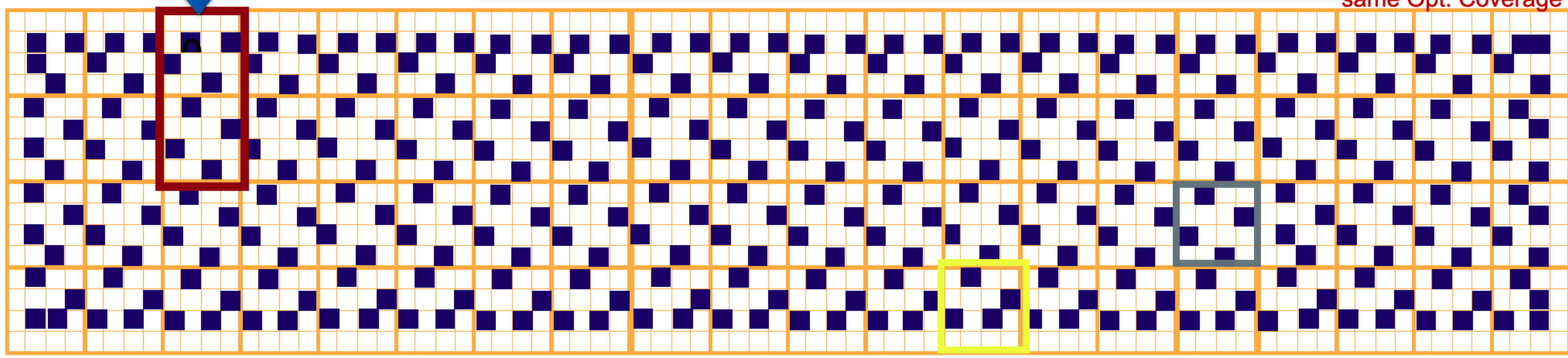
14% Opt. Coverage



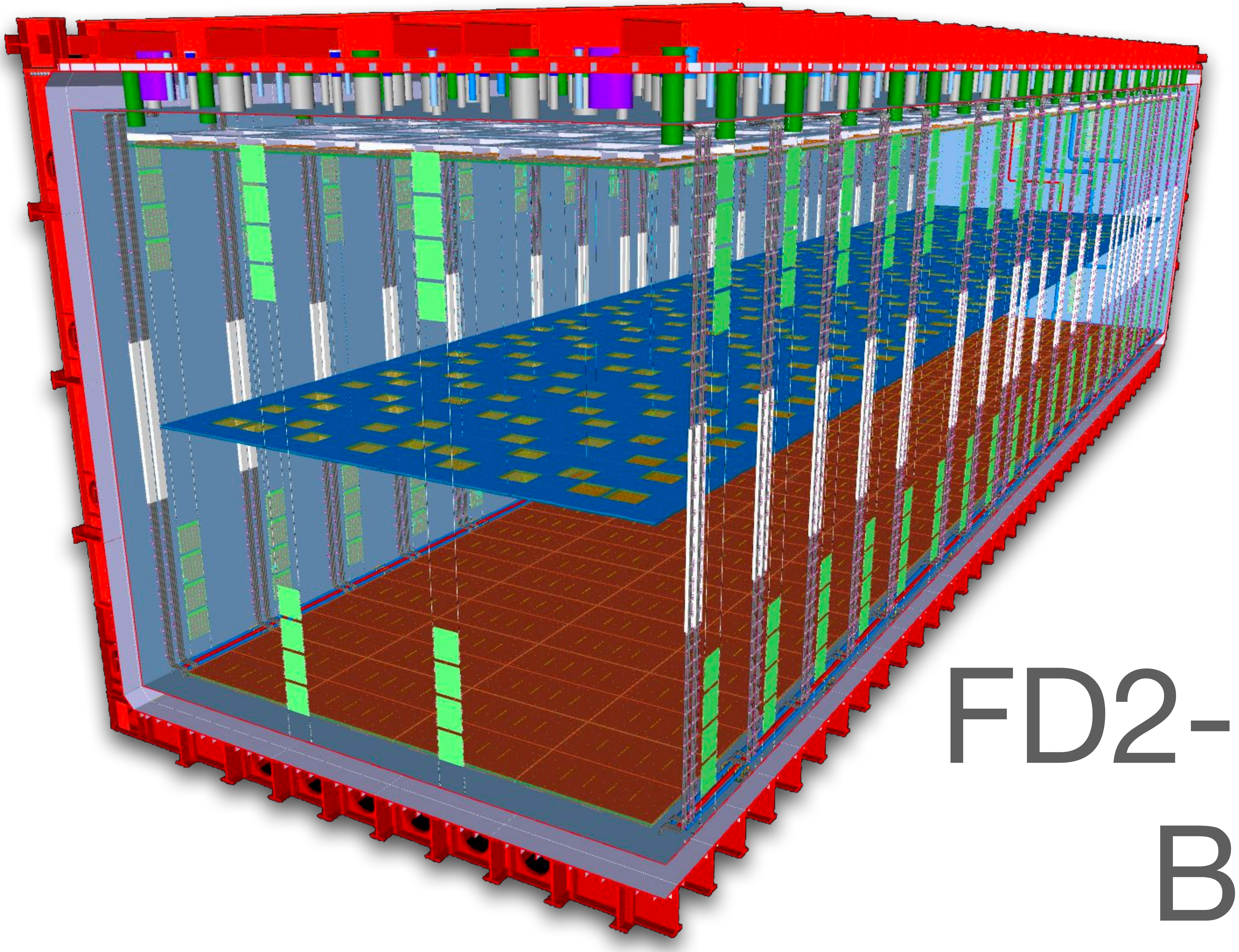
Cathode in protoDUNE Module-0

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

same Opt. Coverage



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



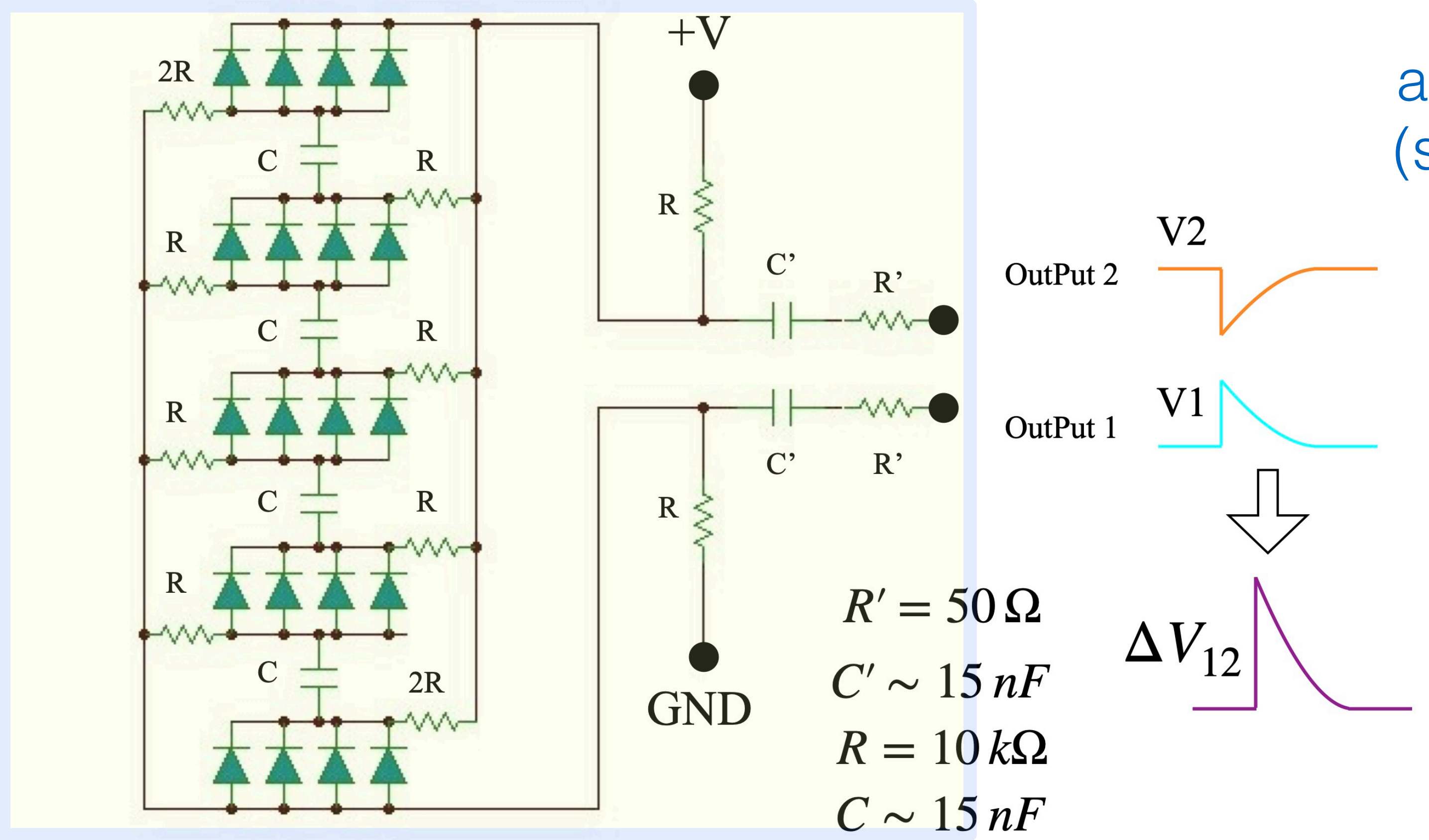
Milestone
by End'22

FD2-PDS Layout Baselined

•Validation Milestones

Concept & Prototypes: Cold Box tests at CERN 2021

SiPM board

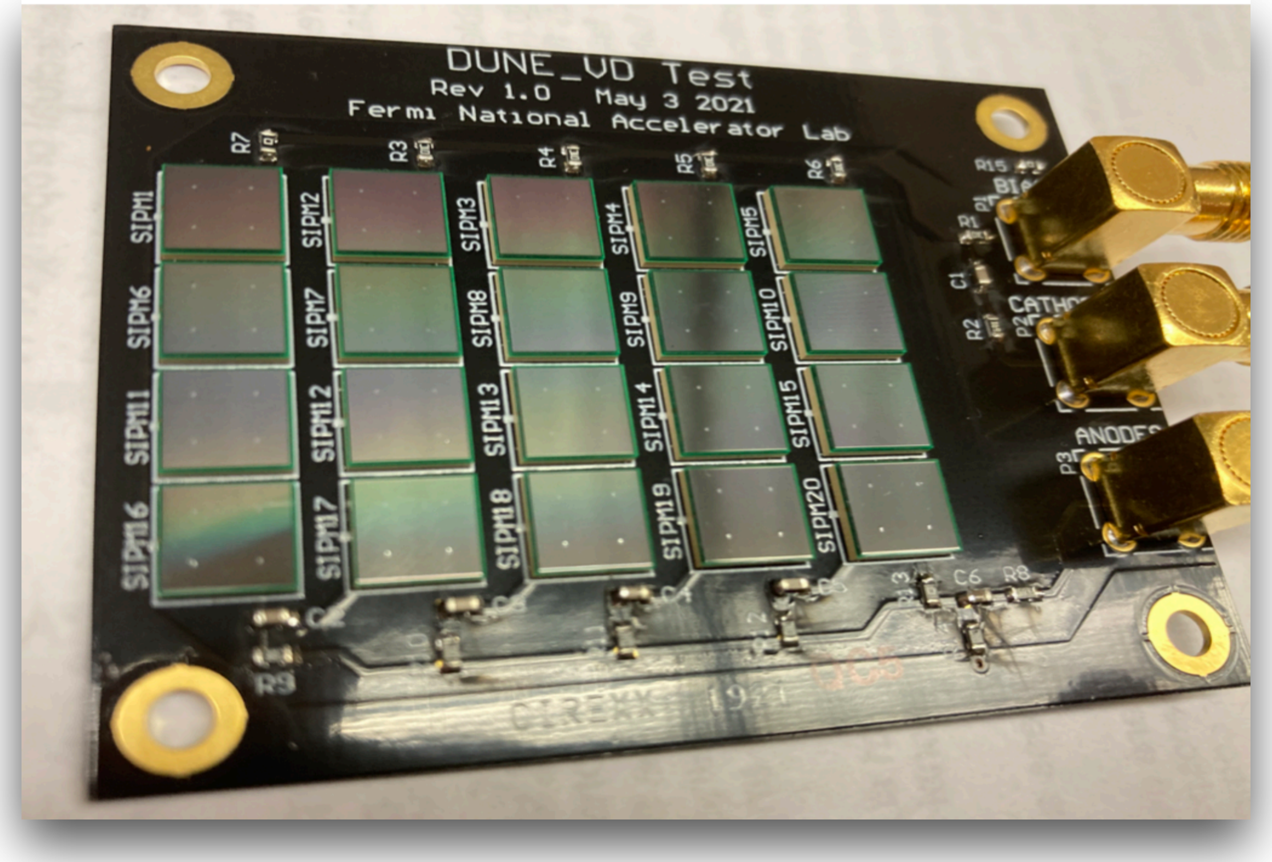


Series connection for signal and parallel connection for bias (similar to MEG-II)

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

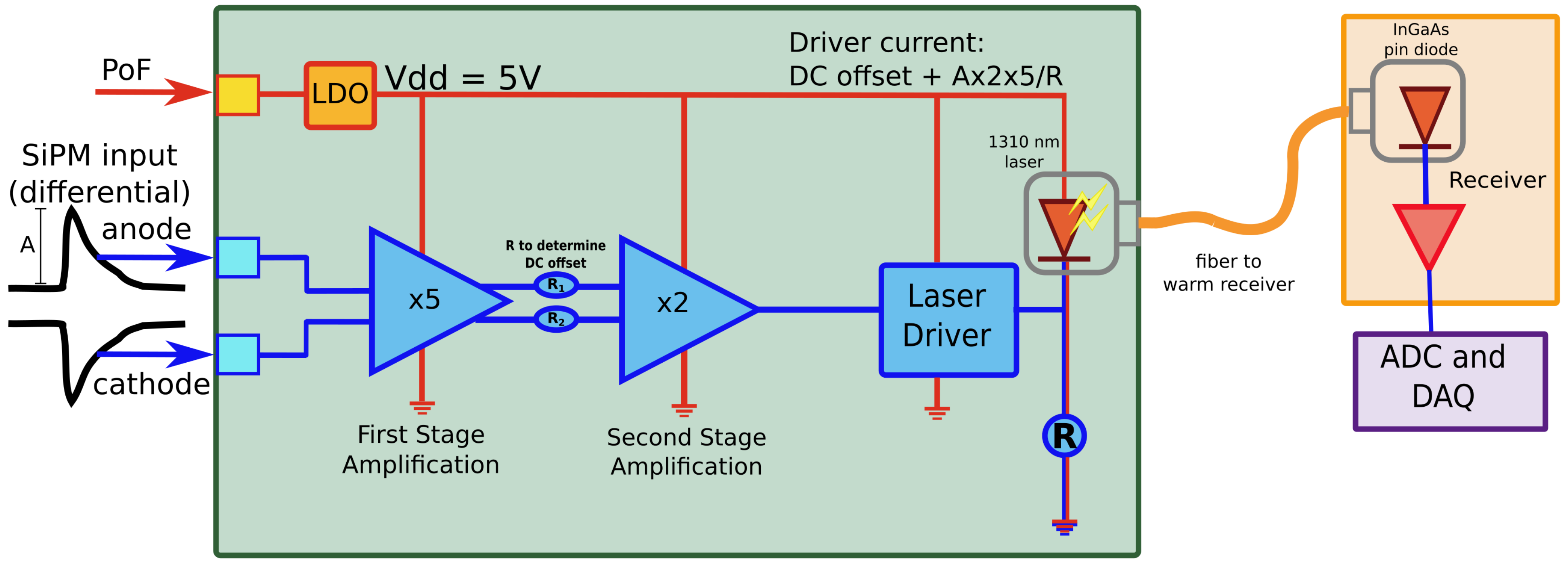
UCSB

Fermilab



Hamamatsu MPPC
S14160-6050HS

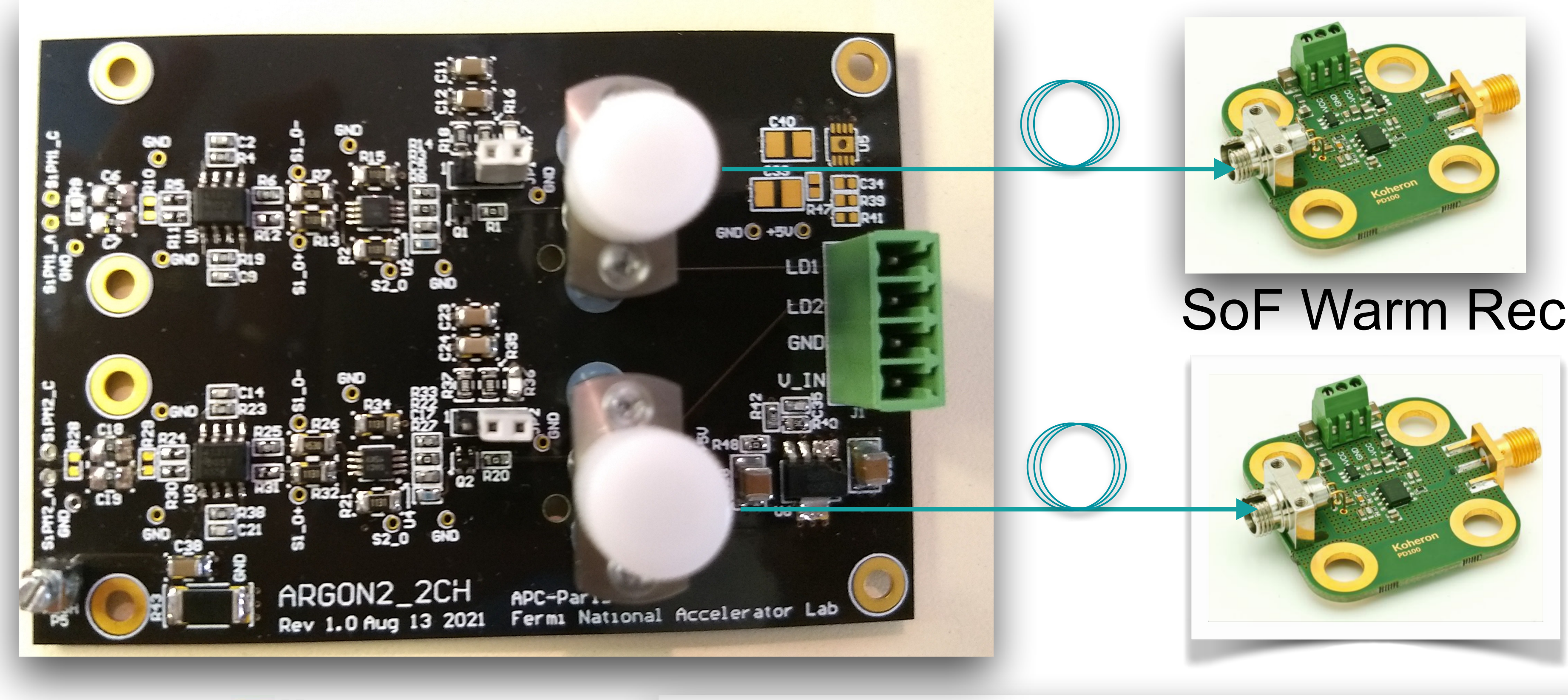
Analog CE Board



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

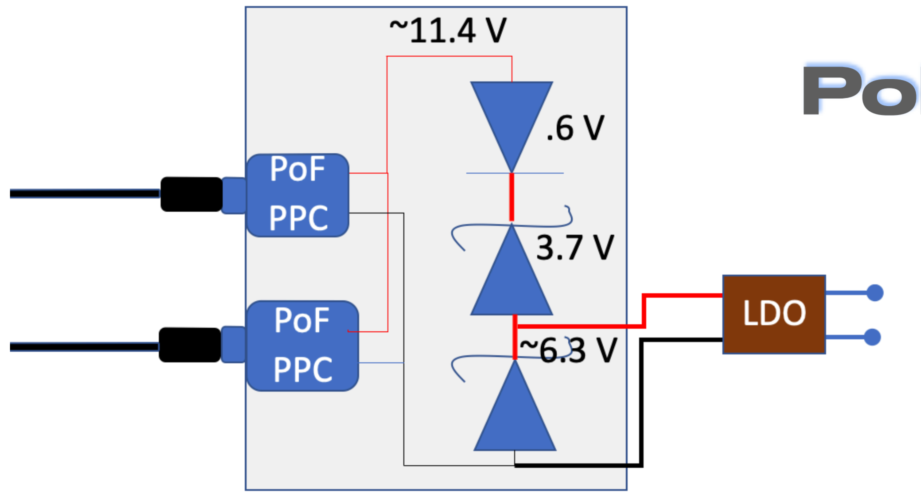
Fermilab

UCSB



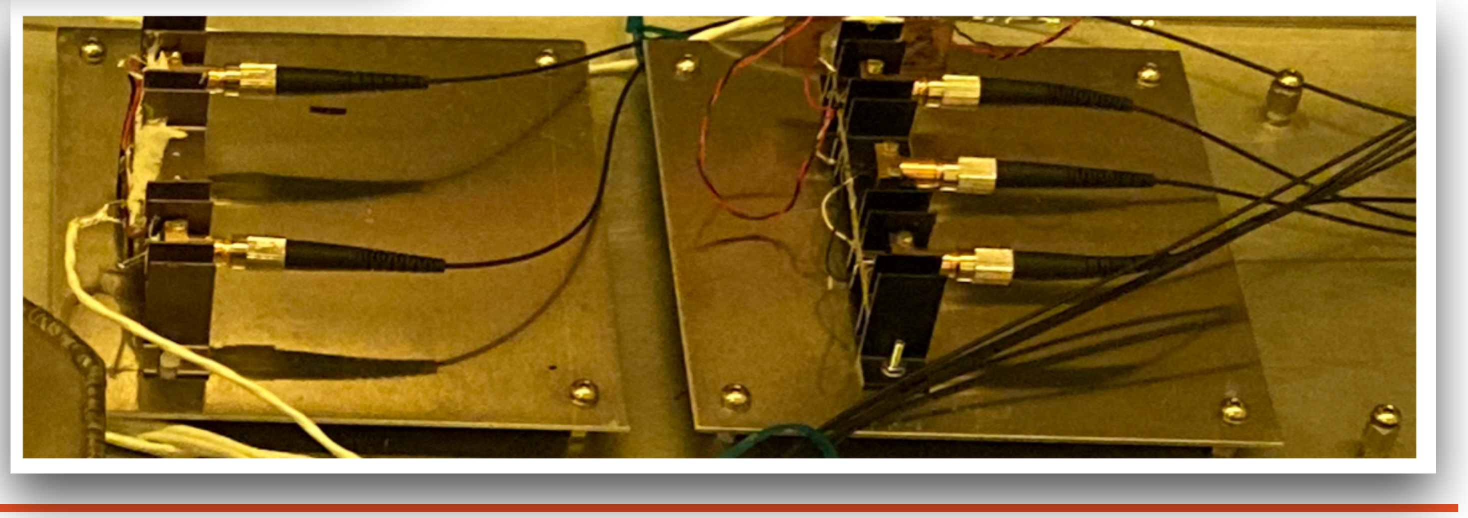
SoF Warm Receivers

PoF Si-OPC Board



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

Fermilab

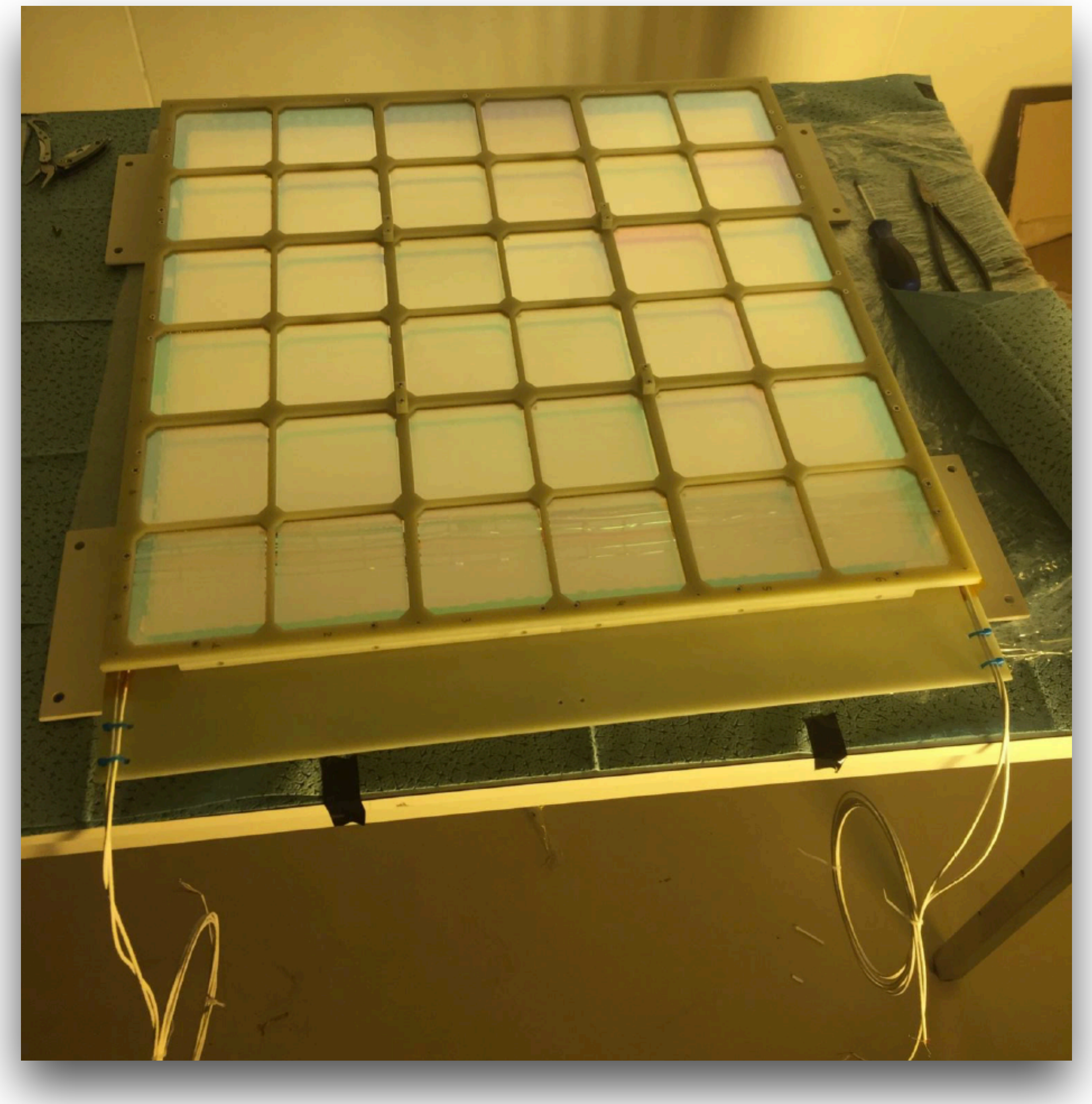


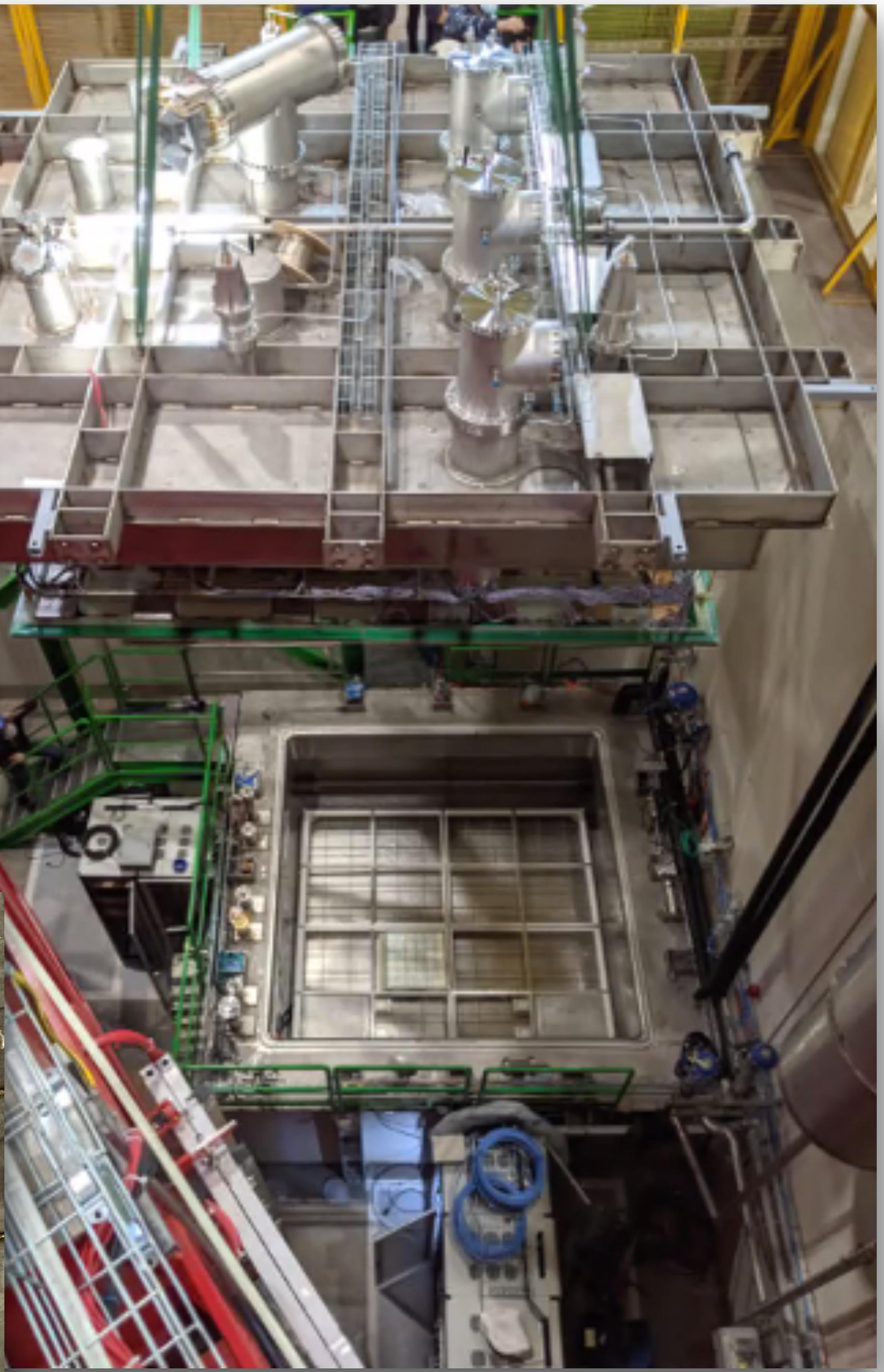
Dec. 2021

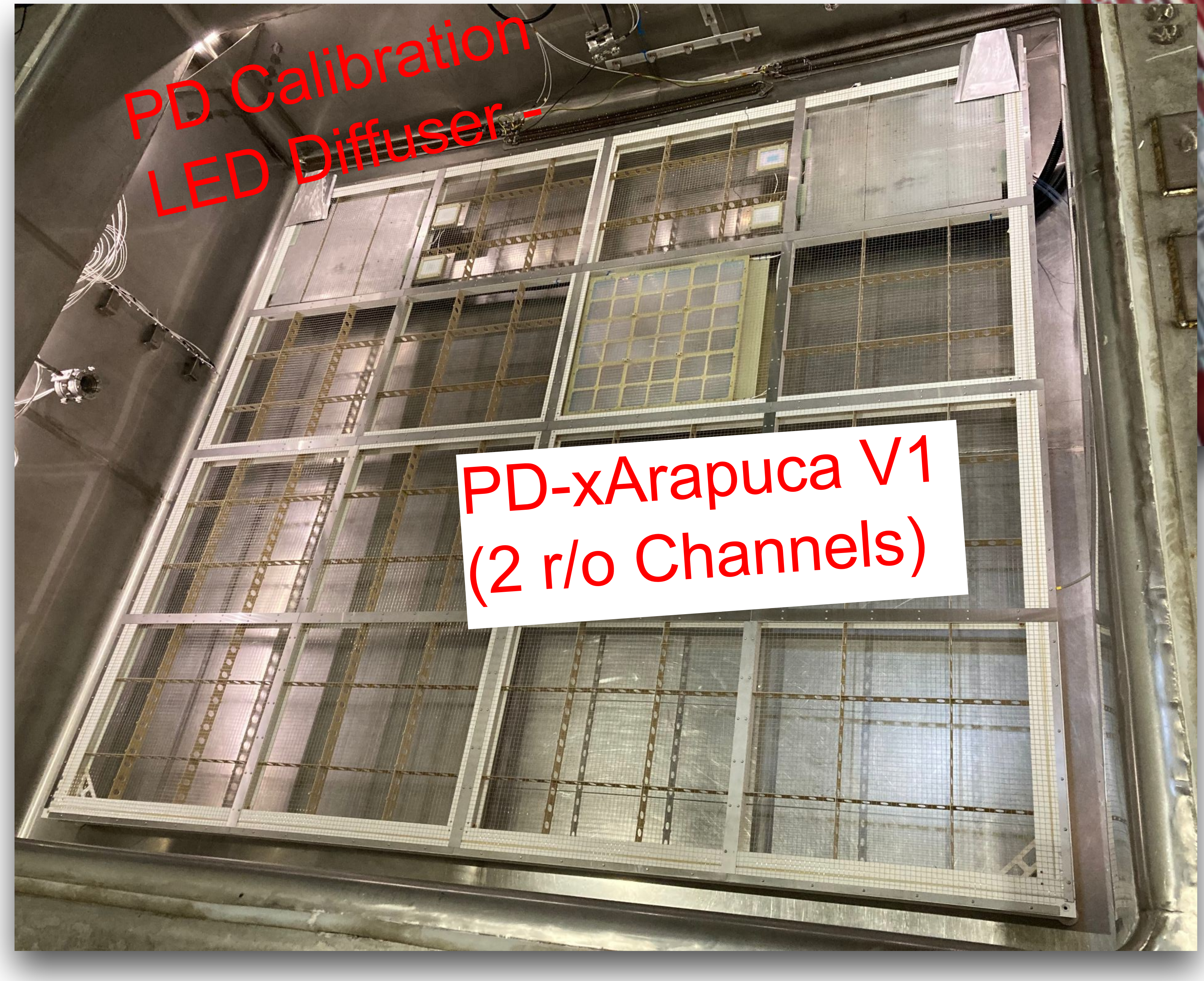
LAr-PDS on the Cathode (xARAPUCA+PoF+SoF)

+ LED Calibration system

installed in “ColdBox” at CERN Neutrino Platform



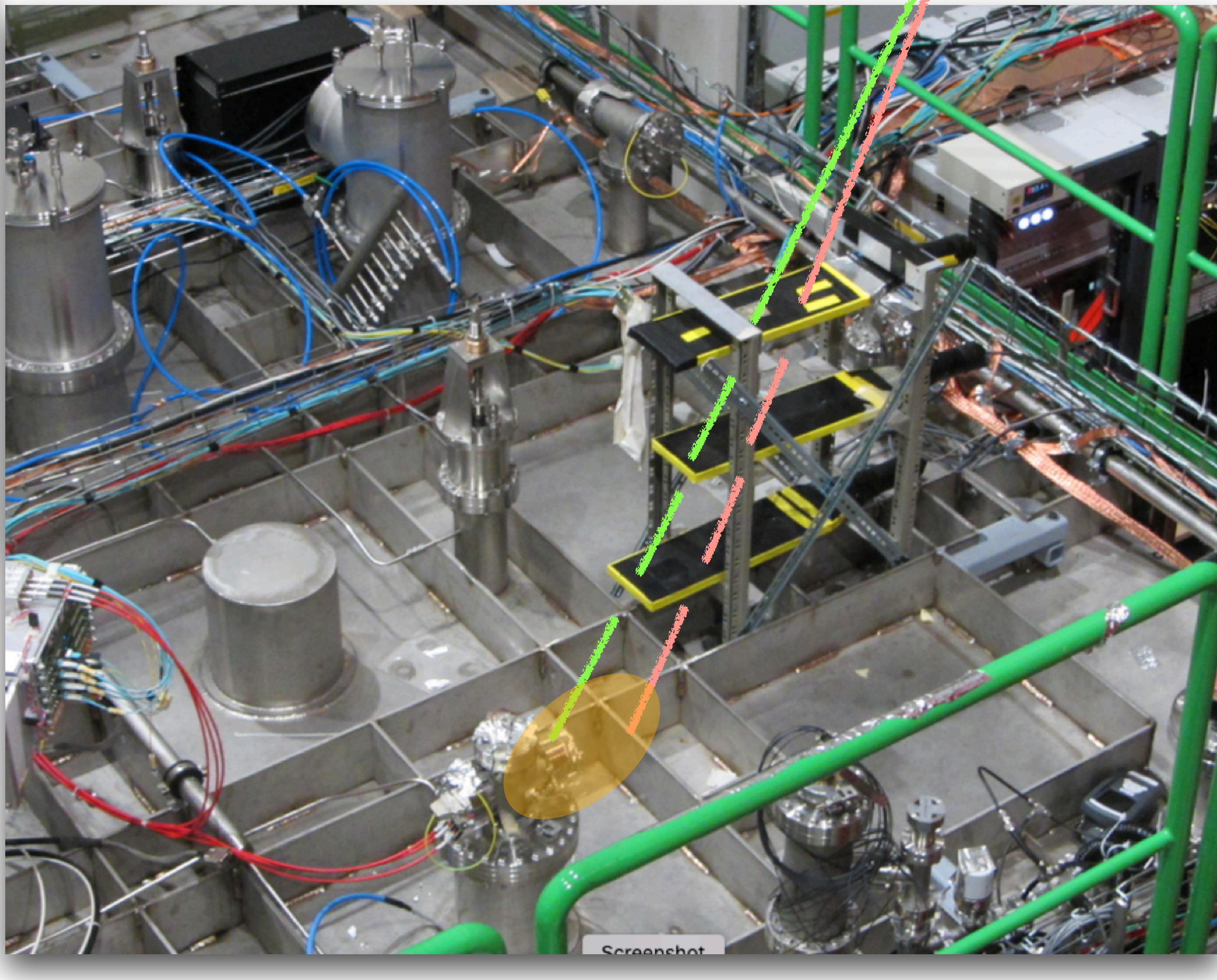




and operated in sync with LArTPC (CRP module))

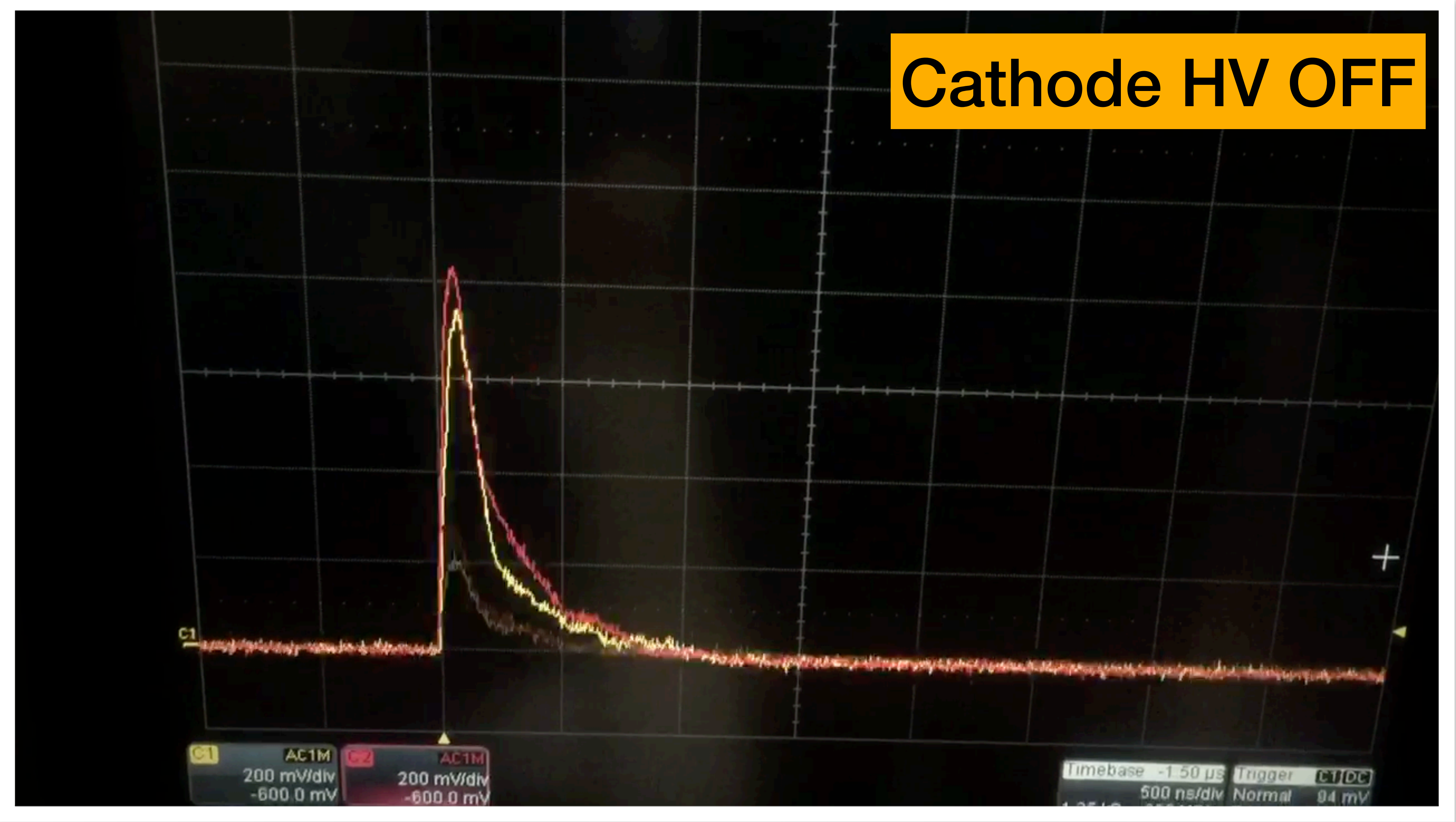
External Muon Telescope on the CB top

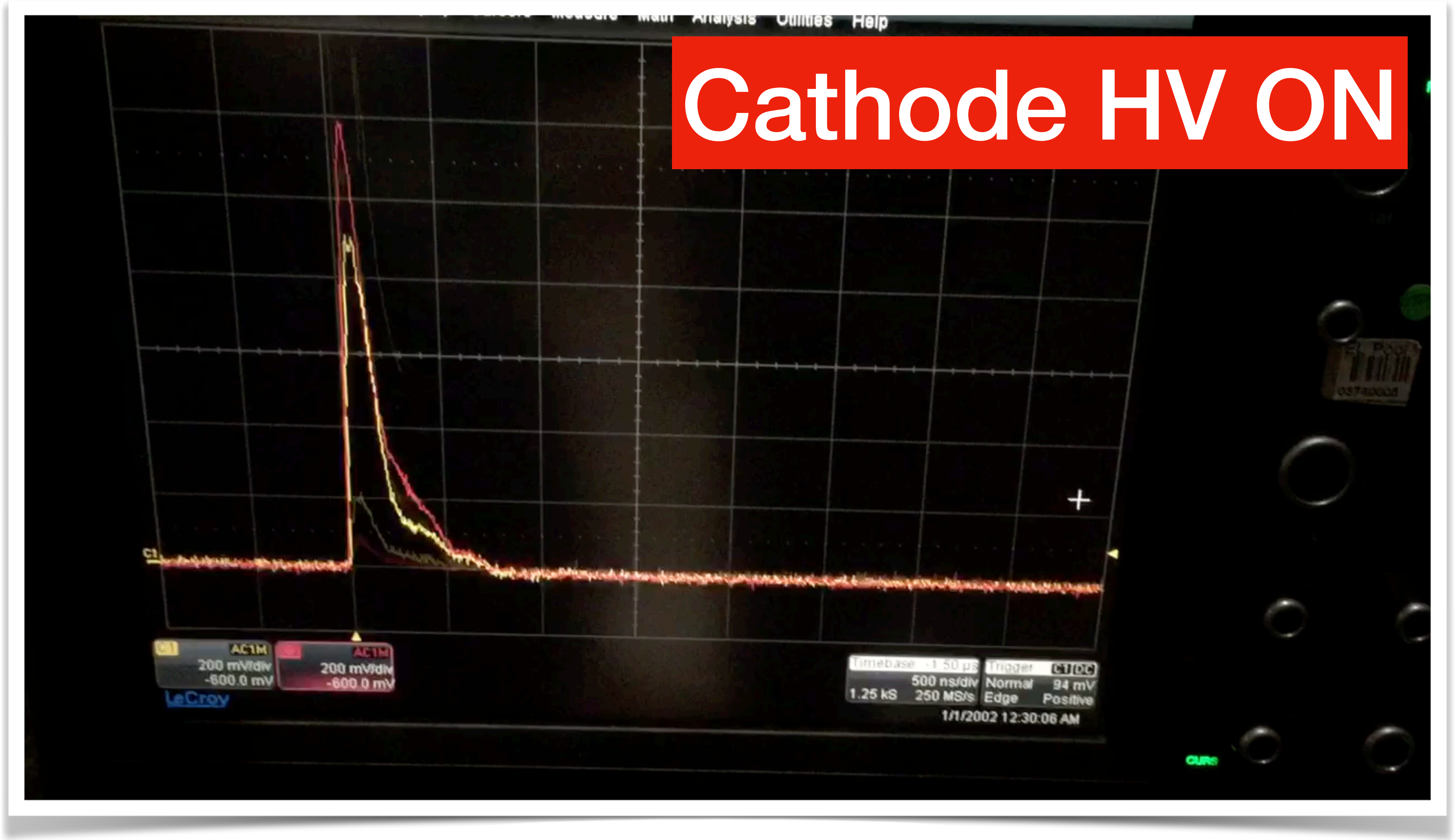
Cosmic Muons



Demonstration of FD2 PDS w/ PoF and SoF

Cosmics Run

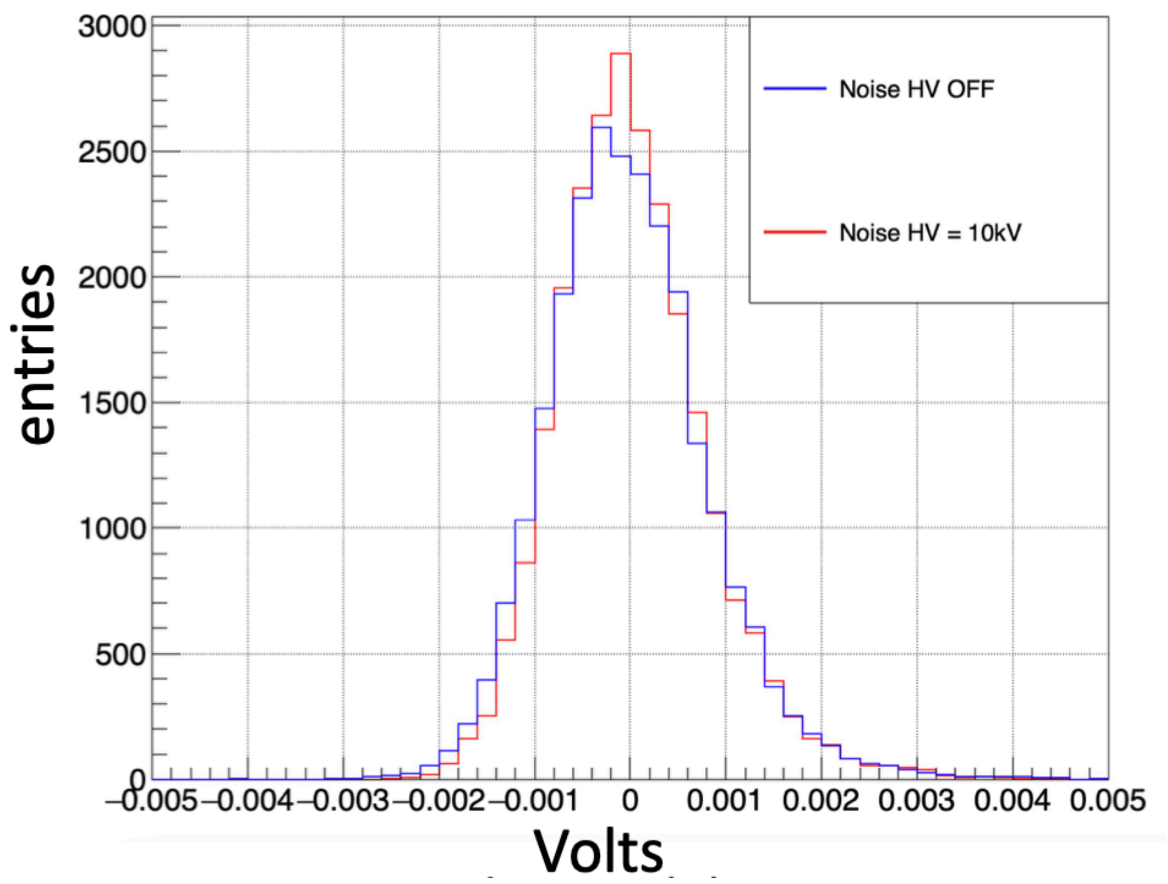




Milestones by End’21

PoF is turned ON on Dec. 15, 2021 at CERN - ColdBox Experiment.

Clean signals immediately seen on scope

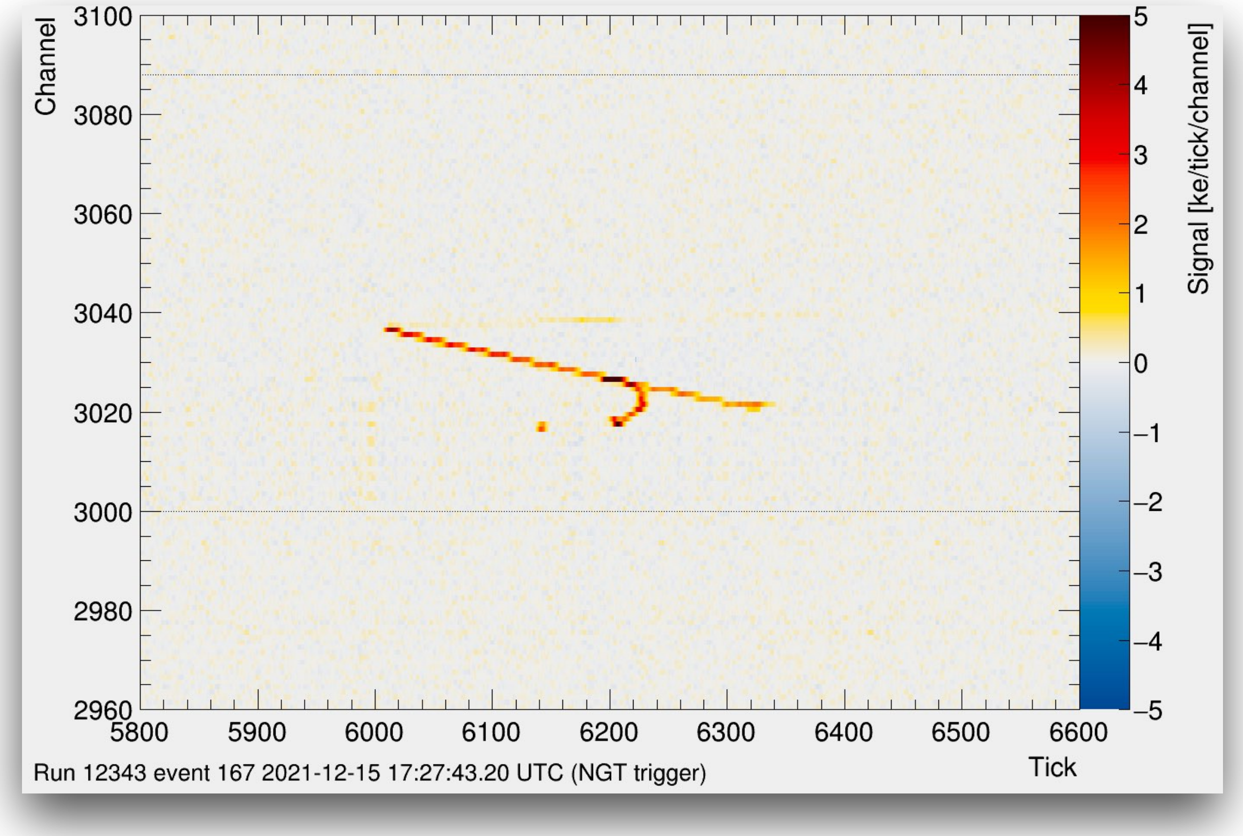


HV OFF:
Mean = -0.05 mV
Sigma =0.77 mV

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

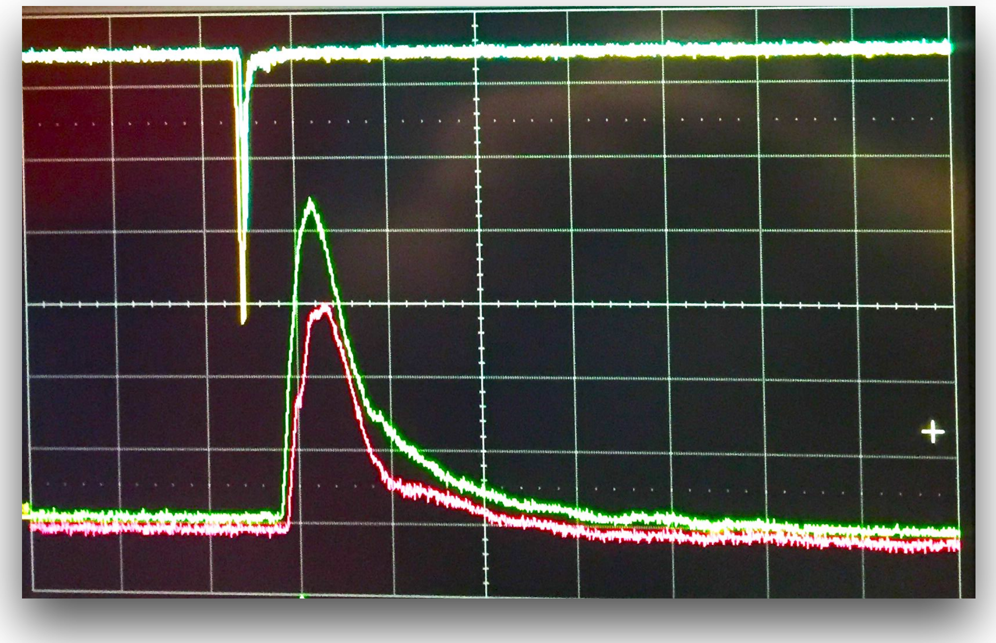
VD PDS signals with Cathode HV ON in LAr

No noise increase or signal distortion when HV ON



Ext. Muon Trigger signals

LArTPC (CRP): crossing muon track images



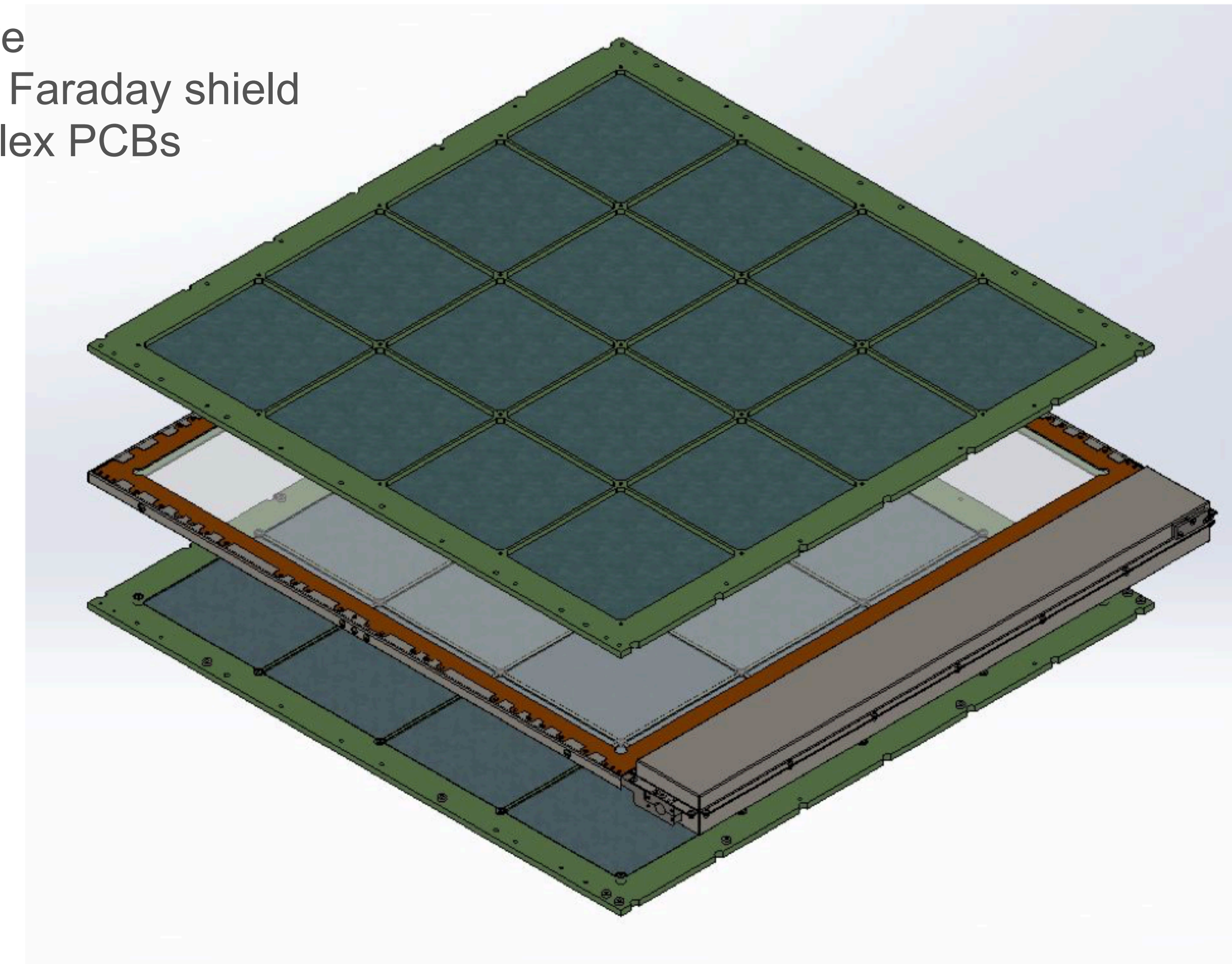
LArPDS (xARAPUCA): in sync signals *(Ch.1 and Ch.2)*

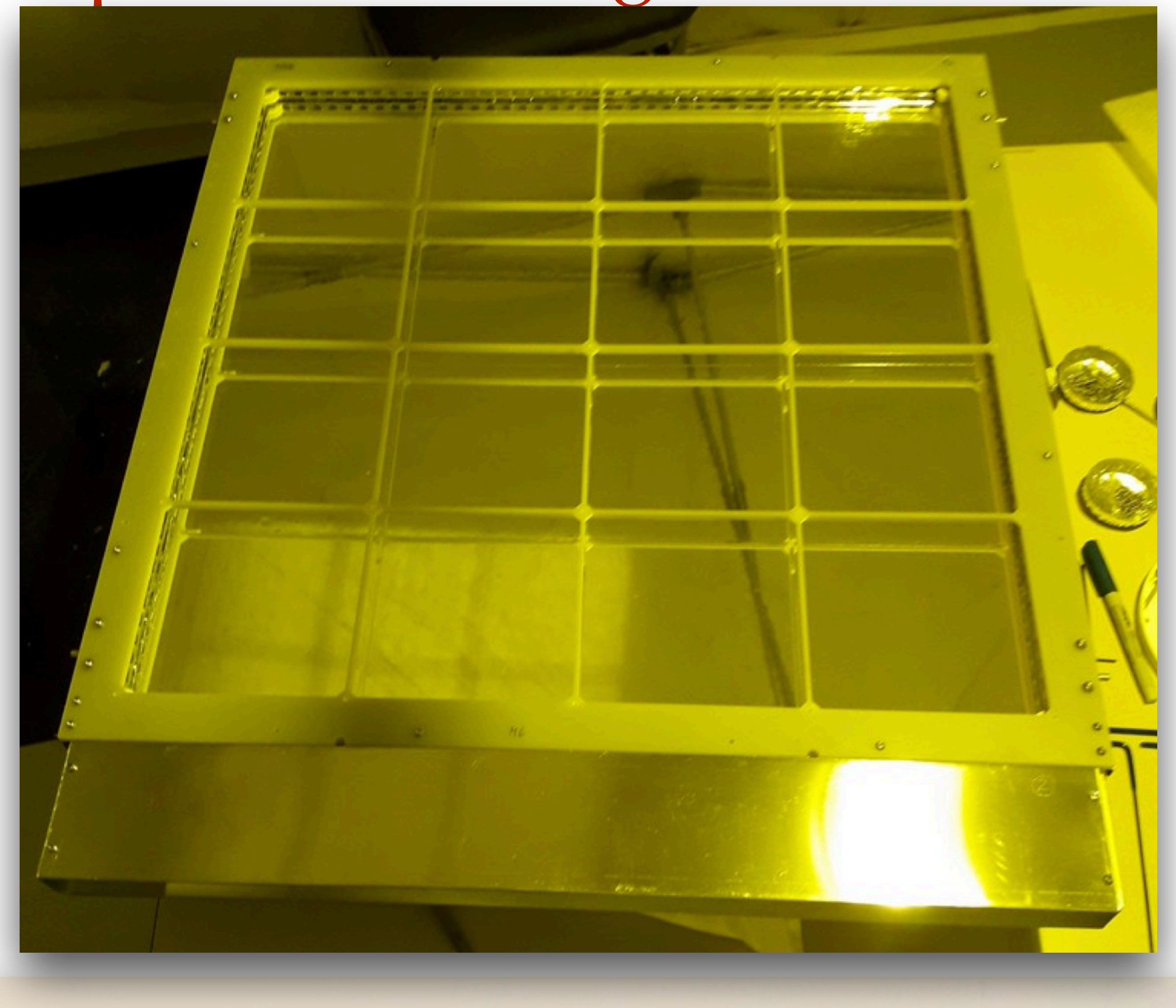
$$\mathrm{SNR}=\langle Q_{1PE}\rangle/\sigma_N \simeq 3$$

Design Optimization 2022 & Milestones

xARAPUCA optimized design

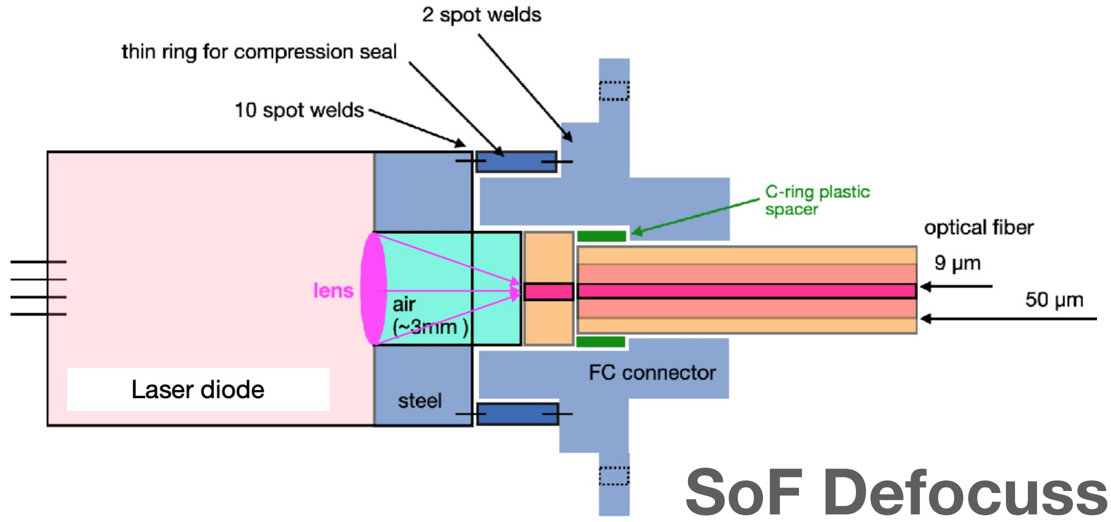
Conductive
C-shaped Faraday shield
for SiPM flex PCBs



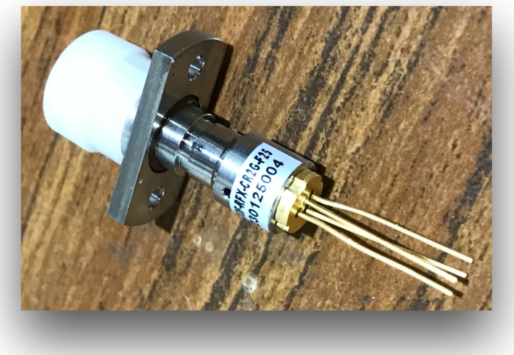


LAr optimized
dichroic filters

Light tight Faraday box
for electronics

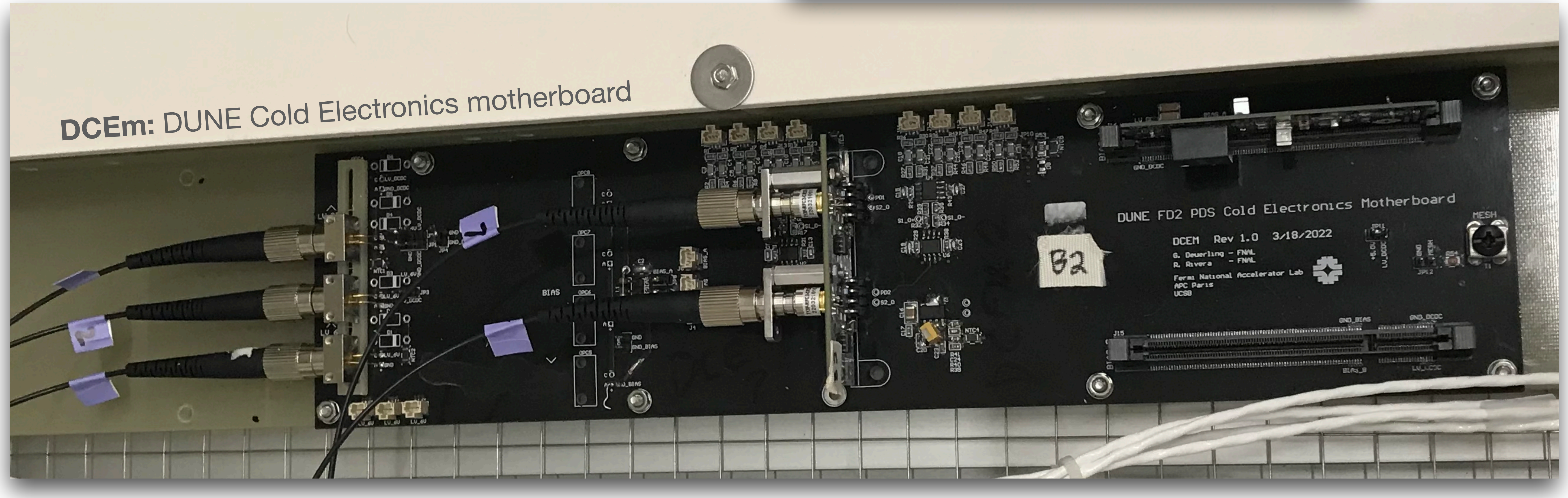


SoF Defocussed
FP Laser Diode



PoF High Efficiency
GaAs OPC

PoF Fiber



DCEm: DUNE Cold Electronics motherboard

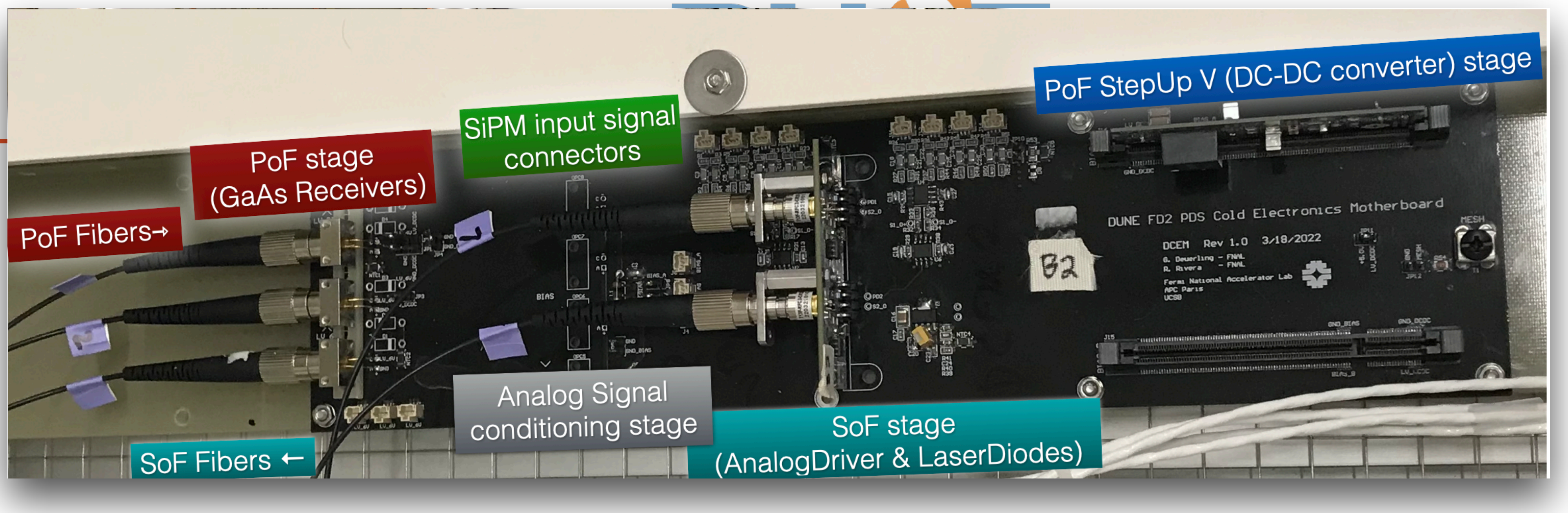
SoF Fiber

V StepUp
Cryo DC-DC Converter

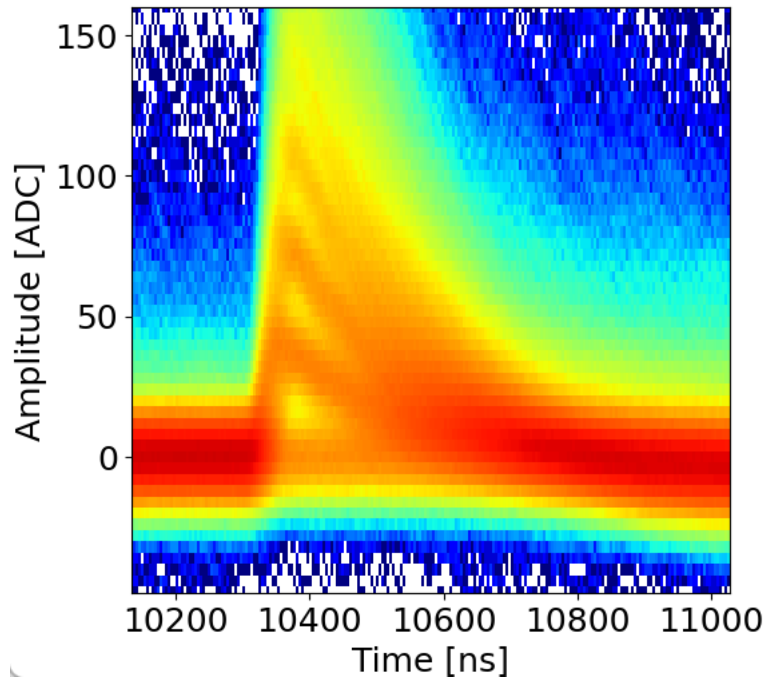
Cold Box tests progression - 2022 design optimization

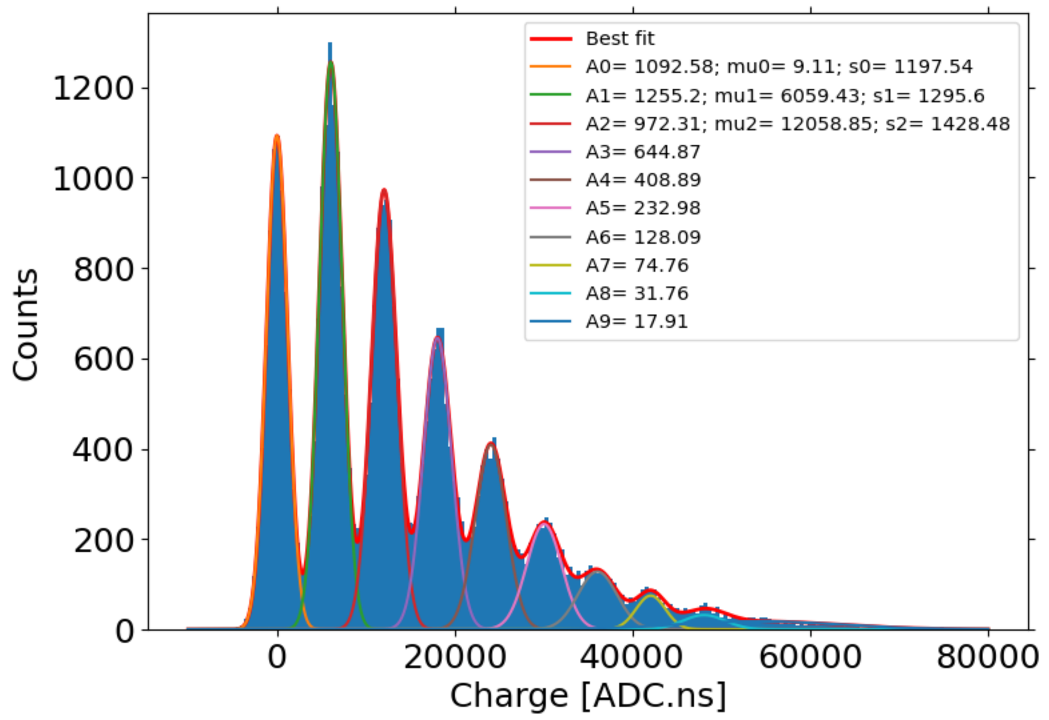
- ☑ ~~HighEfficiency GaAs PoF~~
- ☑ Integrated PoF/Analog CE/SoF DCEm board
- ☑ xARAPUCA design improvement

  (SiPM-WLS optical contacts, frame mechanics, LAr optimized dichroic filters)
- ☑ Single PE Sensitivity (ColdBox Run - Sept.2022)
- ☑ Noise/Light Leakage
- ☑ Gain and dynamic range
- ☑ Time resolution



Milestone by End'22

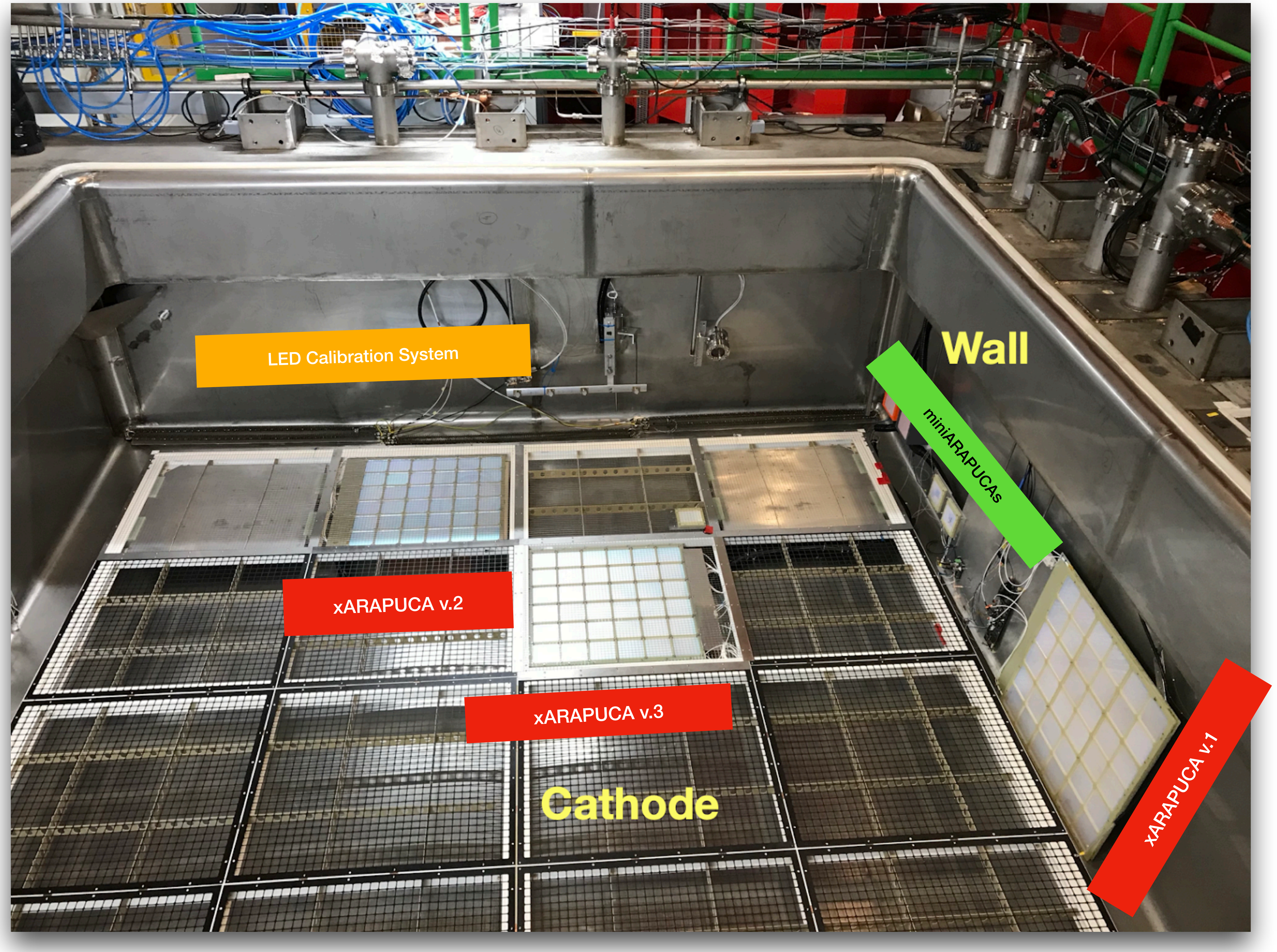




S/N >4

Dynamic Range: $1 \rightarrow > 1000$ PE

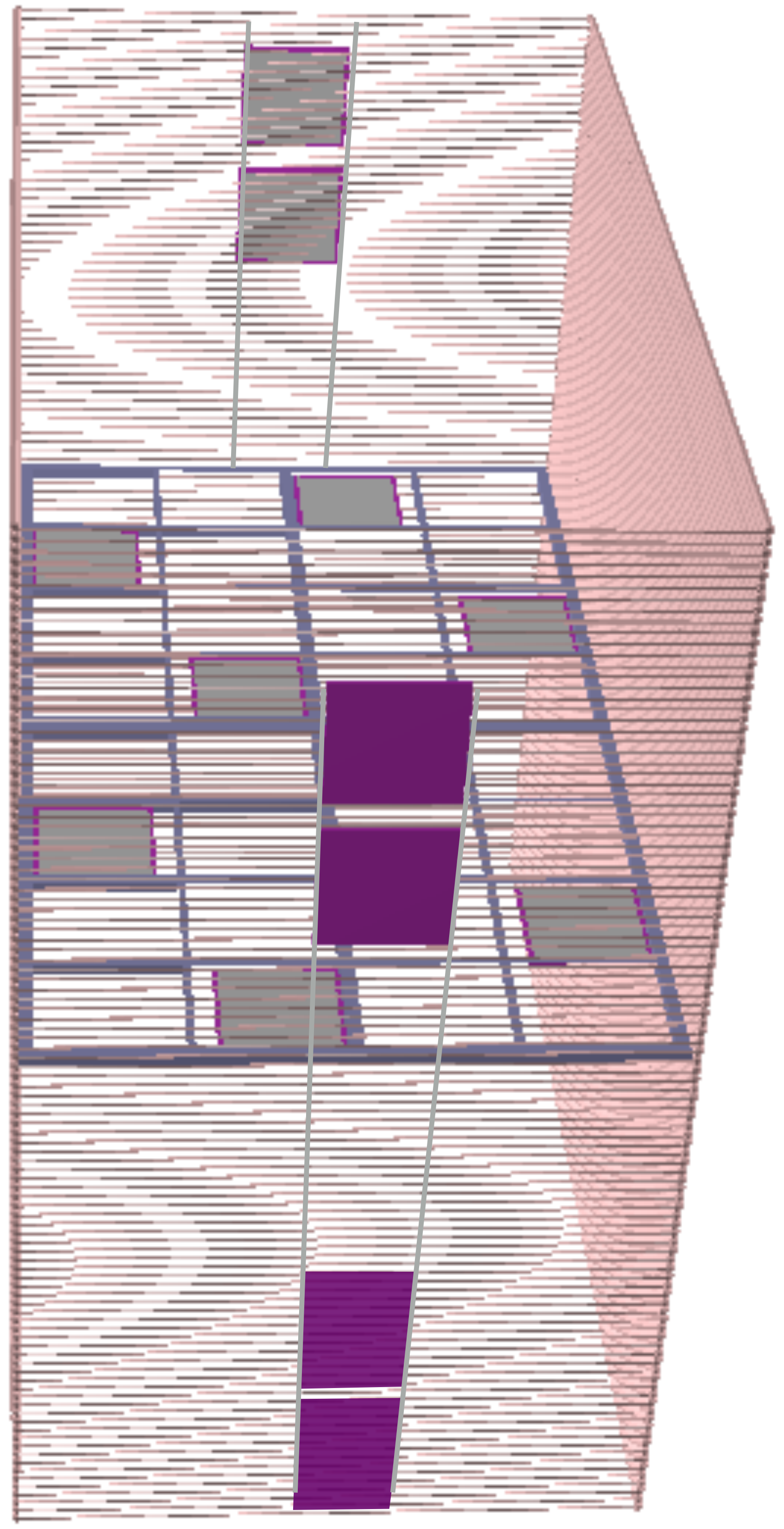
$\sigma_t < 10$ ns

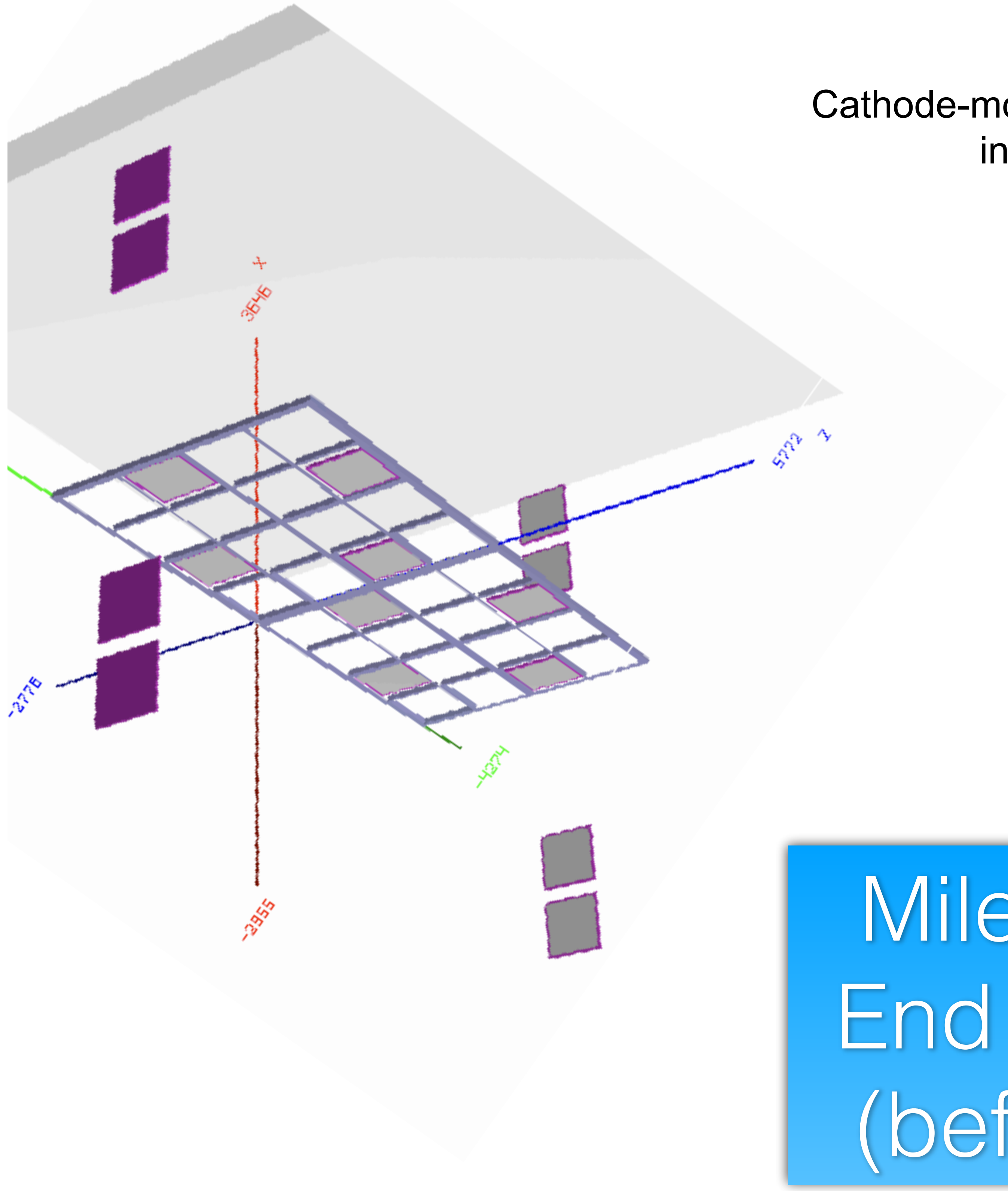


- protoDUNE-VD (Module-0)

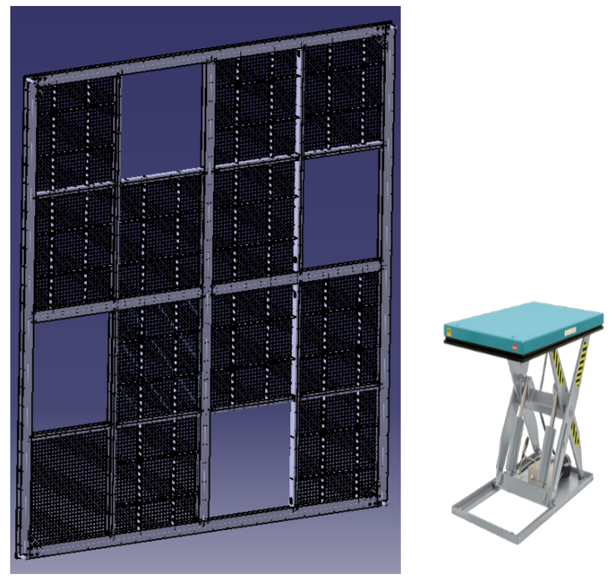
FD2 PDS Module-0 Installation Steps
(start December'22 - completed by March'23)

- 8 Cathode-mount XA
- 8 Membrane-mount XA in 2 columns
  4 XA on each column; 2 XA at top and 2 XA at bottom

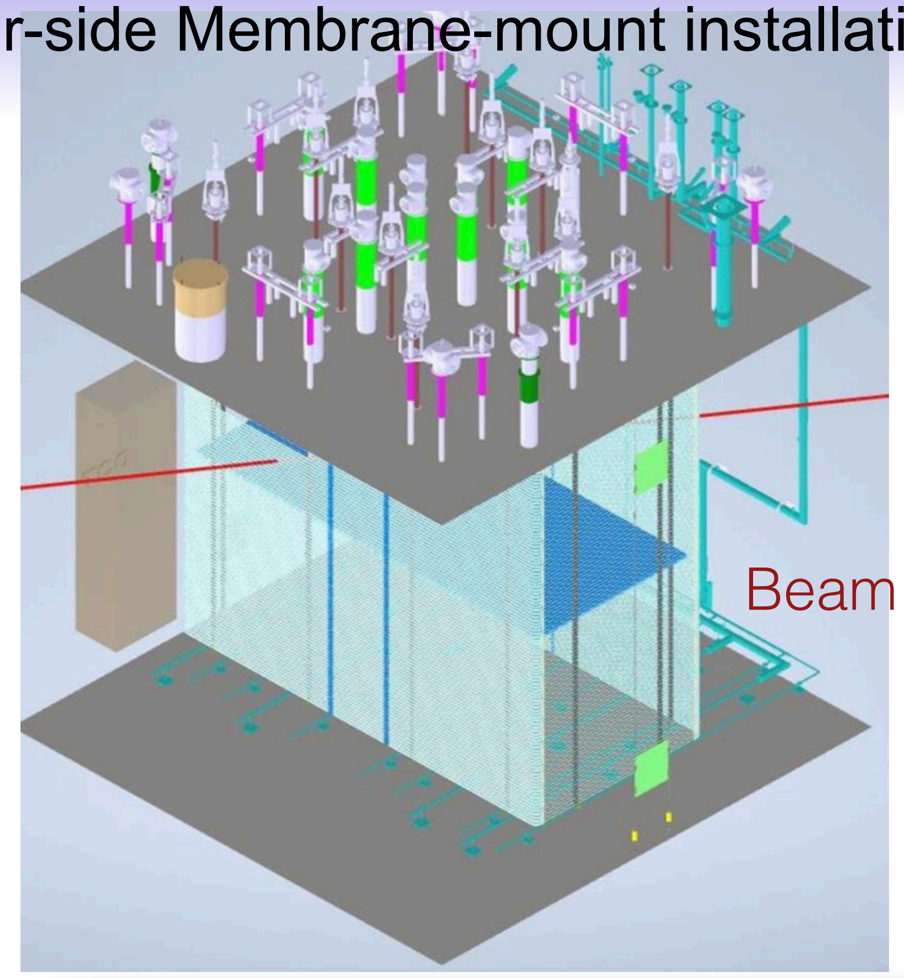




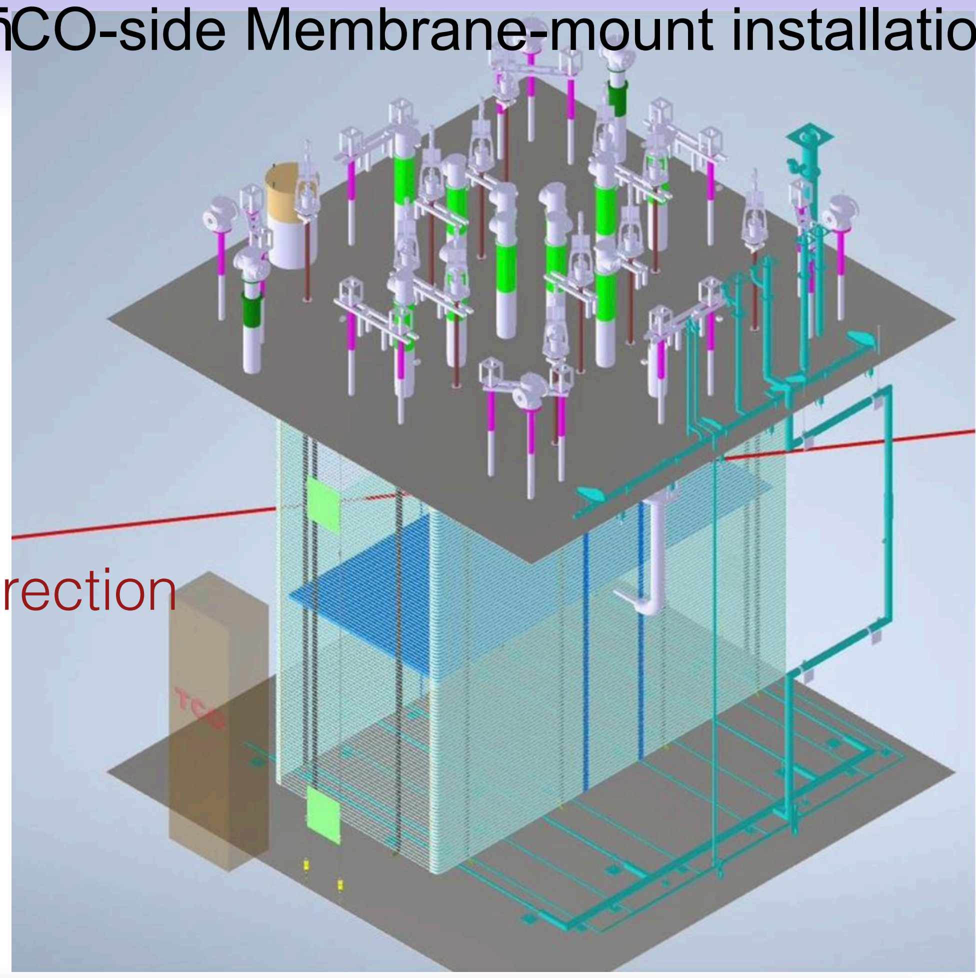
Cathode-mount X-ARAPUCA installation into cathode modules



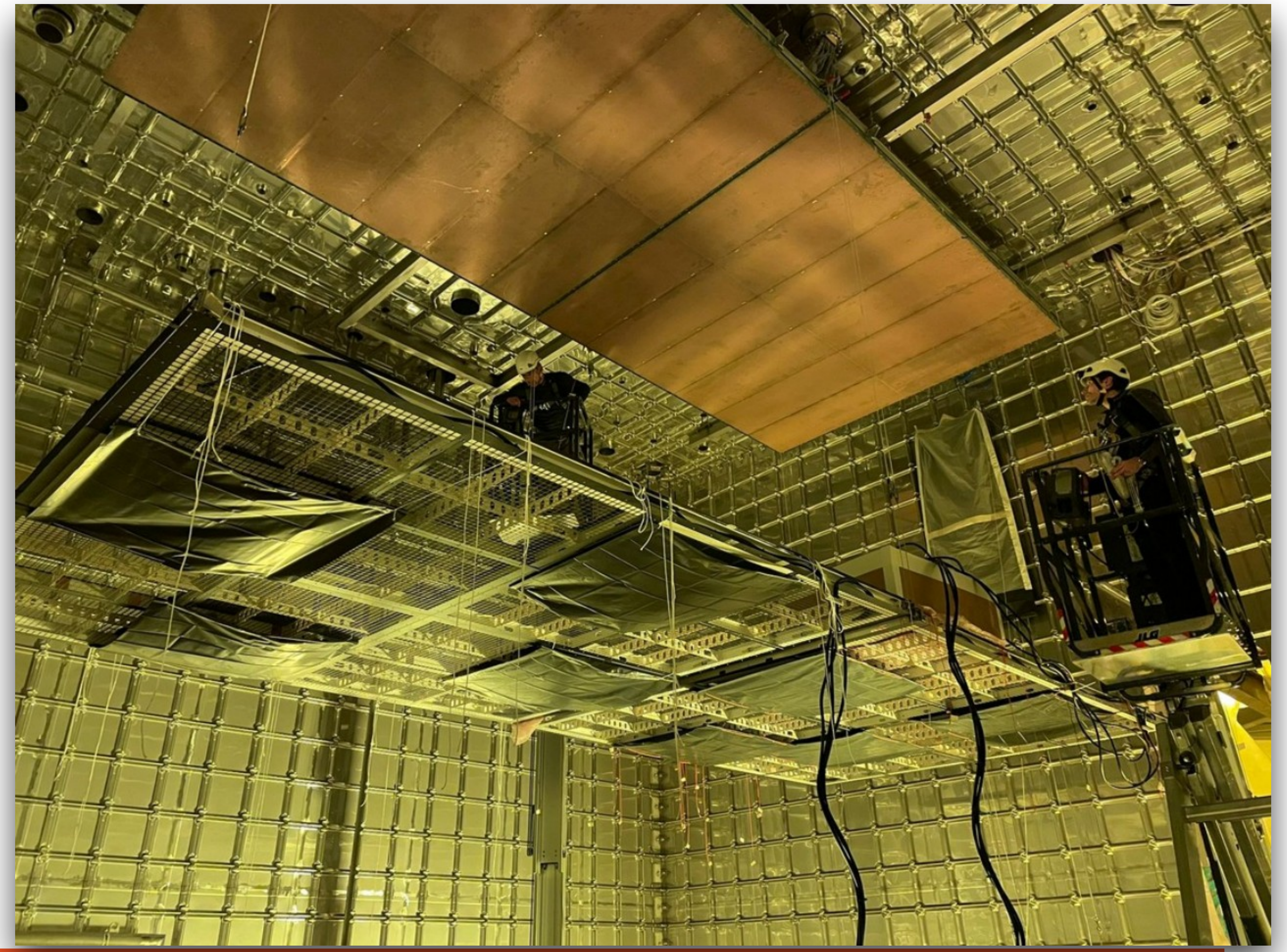
Far-side Membrane-mount installatio



TCO-side Membrane-mount installatio

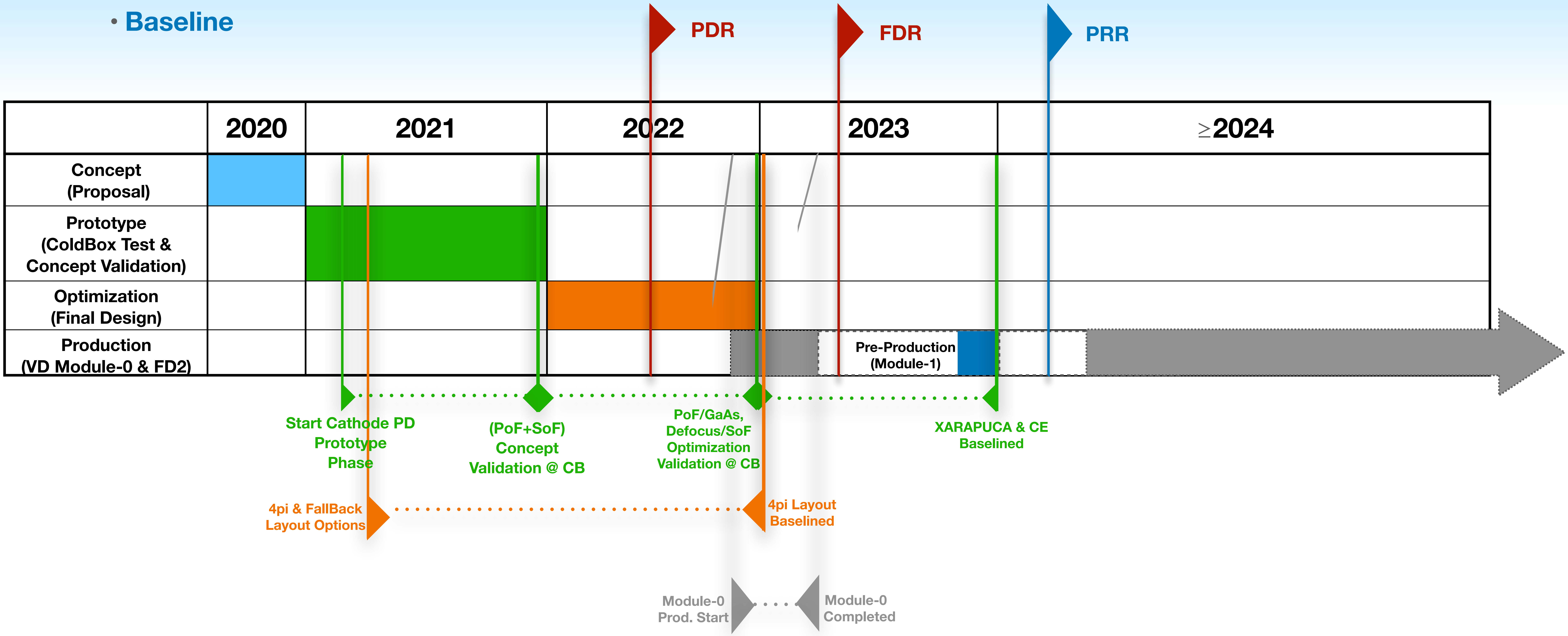


Milestone by End March'23 (before FDR)



FD2 VD Photon Detector Path

- Timeline & Milestones
- **Validations**
- **Baseline**



PDR

FDR

PRR

2020

2021

2022

2023

≥2024

Concept (Proposal)

Prototype (ColdBox Test & Concept Validation)

Optimization (Final Design)

Production (VD Module-0 & FD2)

Pre-Production (Module-1)

Start Cathode PD Prototype Phase

(PoF+SoF) Concept Validation @ CB

PoF/GaAs, Defocus/SoF Optimization Validation @ CB

XARAPUCA & CE Baselined

4pi & FallBack Layout Options

4pi Layout Baselined

Module-0 Prod. Start

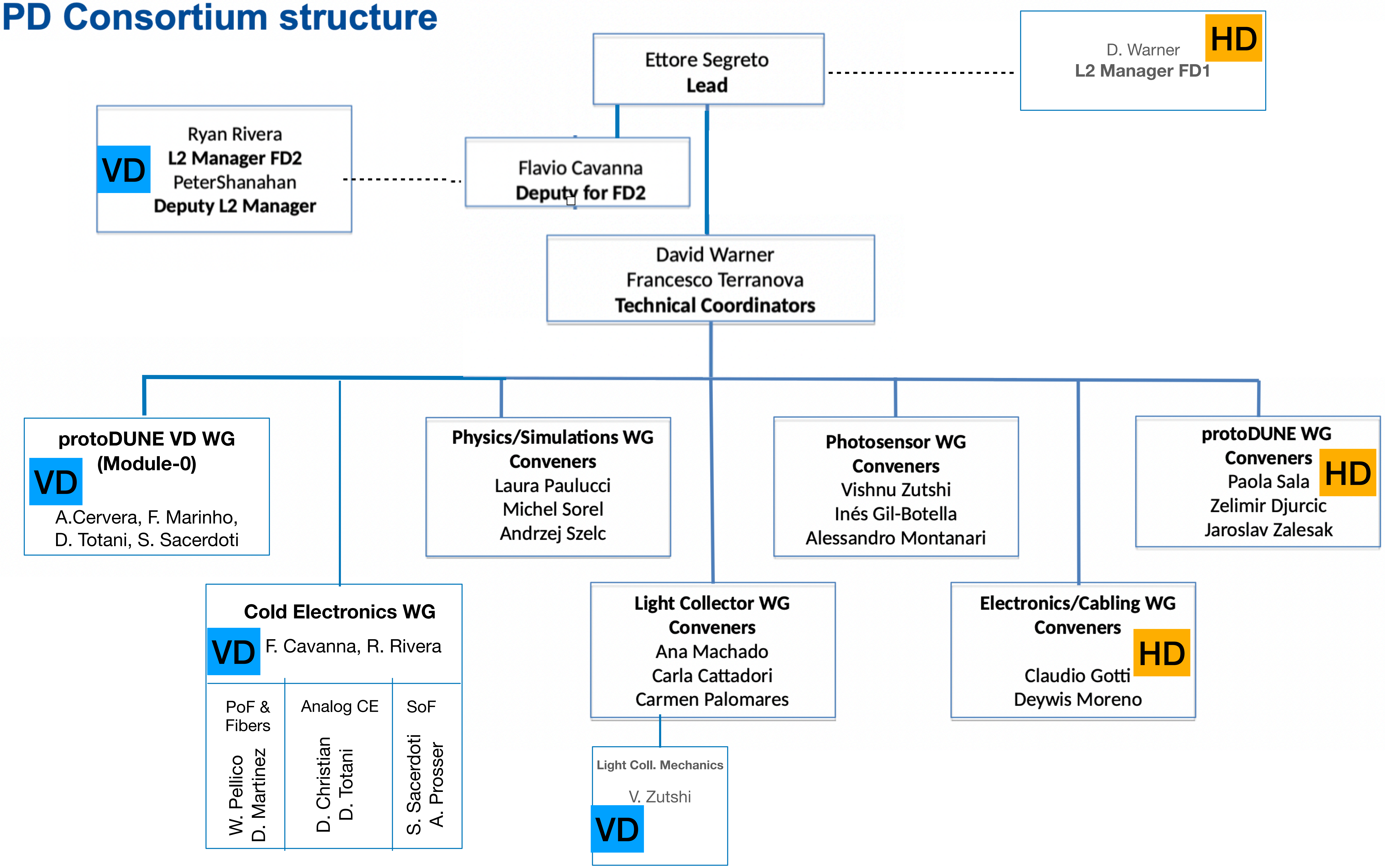
Module-0 Completed

Back Up

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

Module-0 ⇒ Module-1

PD Consortium structure



Ettore Segreto
Lead

D. Warner
L2 Manager FD1
HD

Ryan Rivera
L2 Manager FD2
PeterShanahan
Deputy L2 Manager
VD

Flavio Cavanna
Deputy for FD2

David Warner
Francesco Terranova
Technical Coordinators

protoDUNE VD WG
(Module-0)
VD
A.Cervera, F. Marinho,
D. Totani, S. Sacerdoti

Physics/Simulations WG
Conveners
Laura Paulucci
Michel Sorel
Andrzej Szelc

Photosensor WG
Conveners
Vishnu Zutshi
Inés Gil-Botella
Alessandro Montanari

protoDUNE WG
Conveners
Paola Sala
Zelimir Djurcic
Jaroslav Zalesak
HD

Cold Electronics WG
VD
F. Cavanna, R. Rivera

PoF & Fibers	Analog CE	SoF
W. Pellico D. Martinez	D. Christian D. Totani	S. Sacerdoti A. Prosser

Light Collector WG
Conveners
Ana Machado
Carla Cattadori
Carmen Palomares

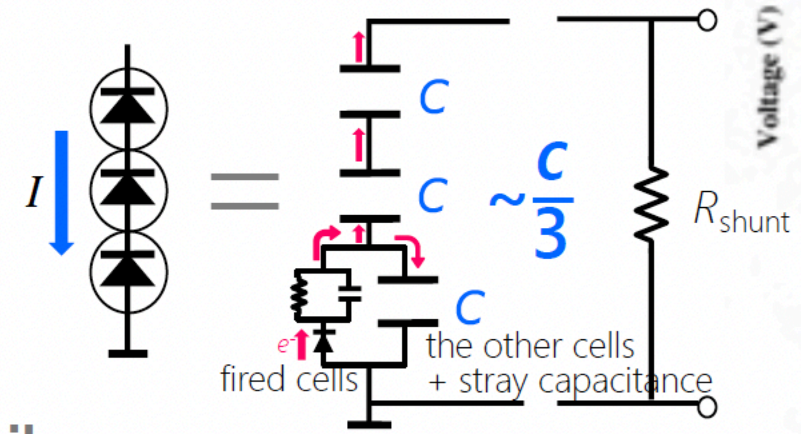
Light Coll. Mechanics
V. Zutshi
VD

Electronics/Cabling WG
Conveners
HD
Claudio Gotti
Deywis Moreno

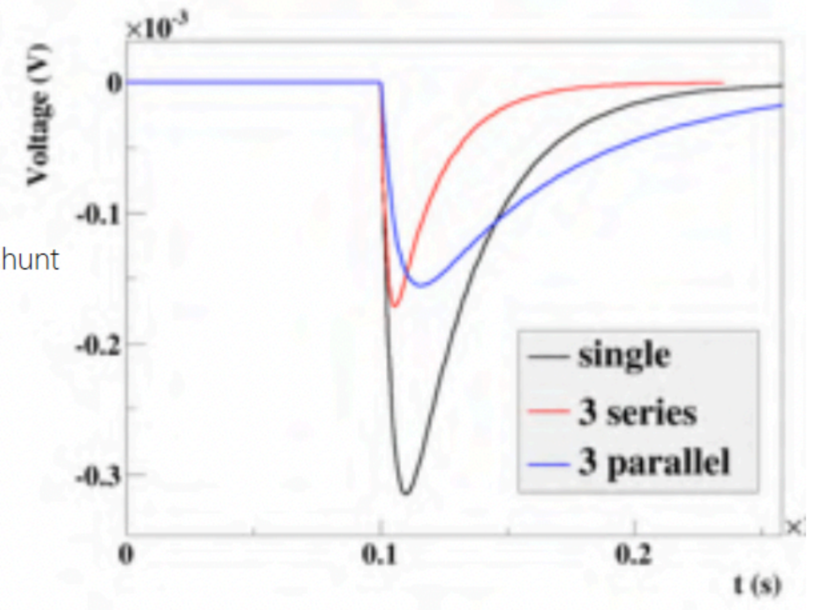
Parallel or Series?

- **Parallel**
  - Charge preserved, but amplitude reduced
  - Better S/N
  - Increasing capacitance→slow rise and long tail
    - Not optimal for timing and high rate
  - Need to group SiPMs with same breakdown voltage
- **Series**
  - Both charge and amplitude reduced (signal gain reduced)
  - Reduced capacitance→fast signal
    - Better for timing
  - Automatic over-voltage adjustment even with different breakdown voltages
  - Need higher bias voltage (× *N*)
- **Hybrid**
  - Connected in series, but with decoupling capacitor in between
  - Series connection for signal and parallel connection for bias
  - Common bias voltage
- **Combination**

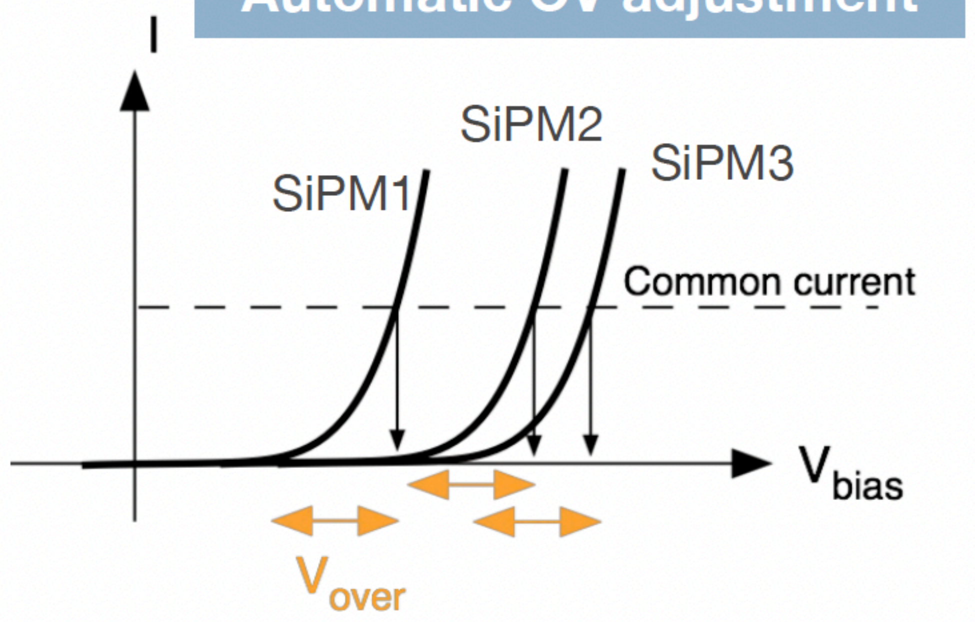
Series connection



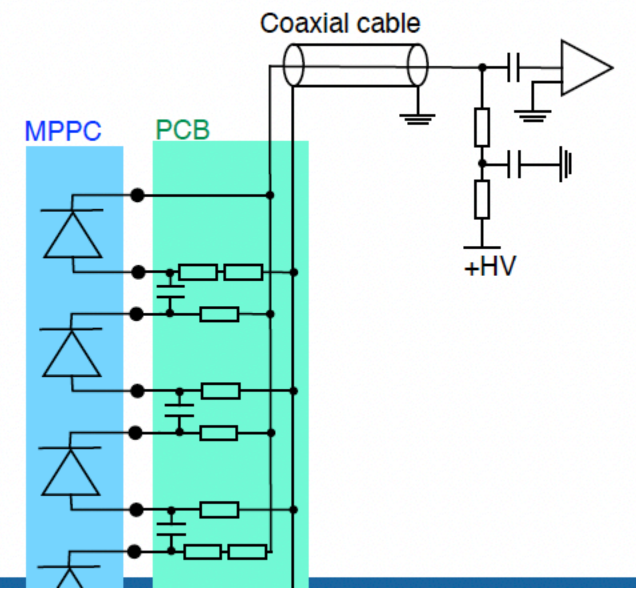
Comparison of signal shape



Automatic OV adjustment



Hybrid connection



- Study for detector LY calibration

Pulsed neutron source for PDS 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

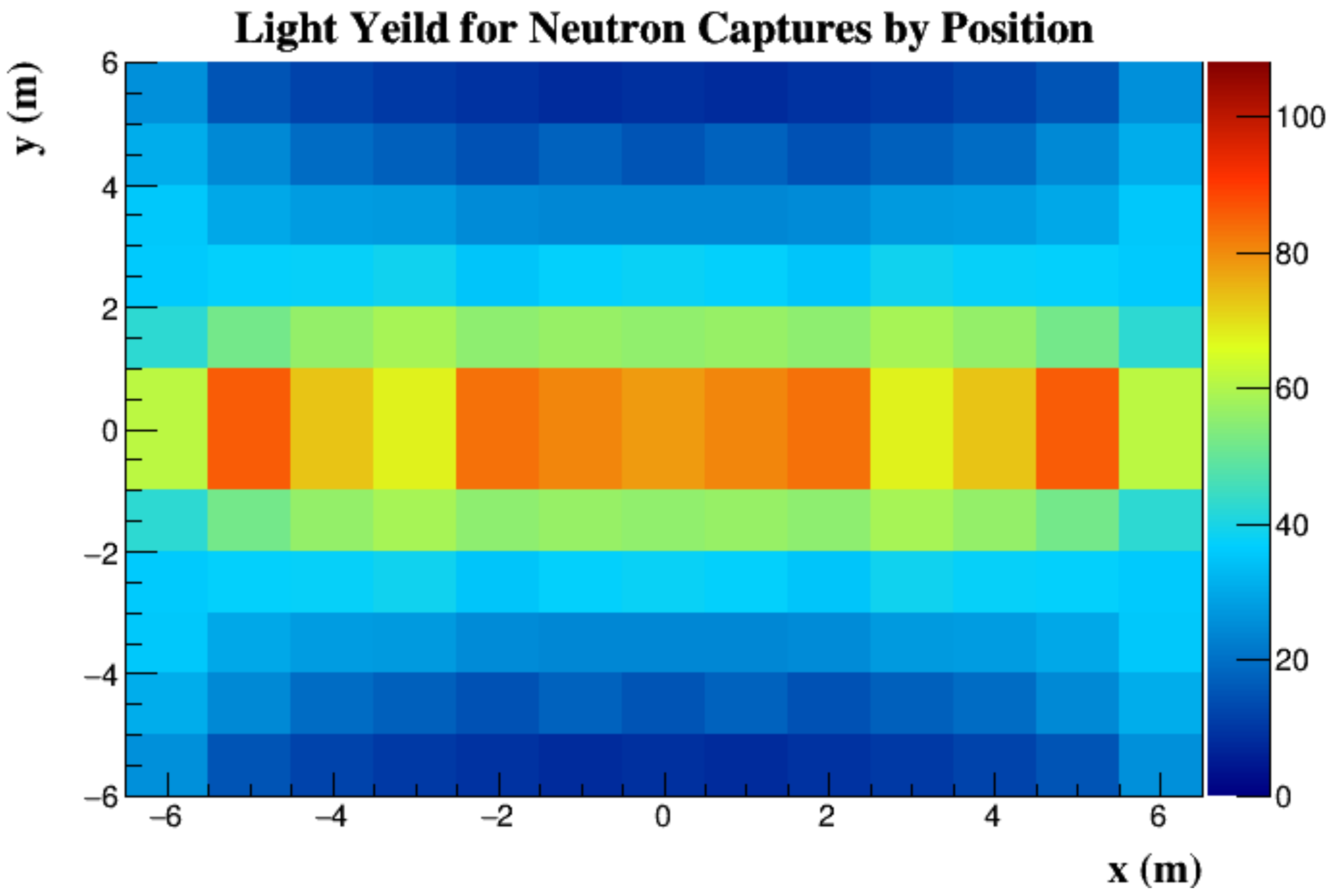


Fig: LY from neutron capture in LAr using Geant4 standalone simulation for DUNE VD

- 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.

-Rates:

-Calculate $r_i = f_i \cdot r_{Vox}$ $(= 50,\ 105,\ 93,\ 60,\ 25)$: N. of dcy's per sec per voxel with En. in 0.1 MeV-bins with avg En. $\langle E \rangle_i$

“data”= evt w/ N_{PE} signal detected by typical XA on the cathod

- ^{39}Ar evt. Rate as a function of threshold in PE:

for every $i,\ k$

IF $\langle N_{PE} \rangle_{i,k} \geq N_{PE}^{Thr}$ $\quad \{ \ R_{Thr} = R_{Thr} + r_i \ \}$

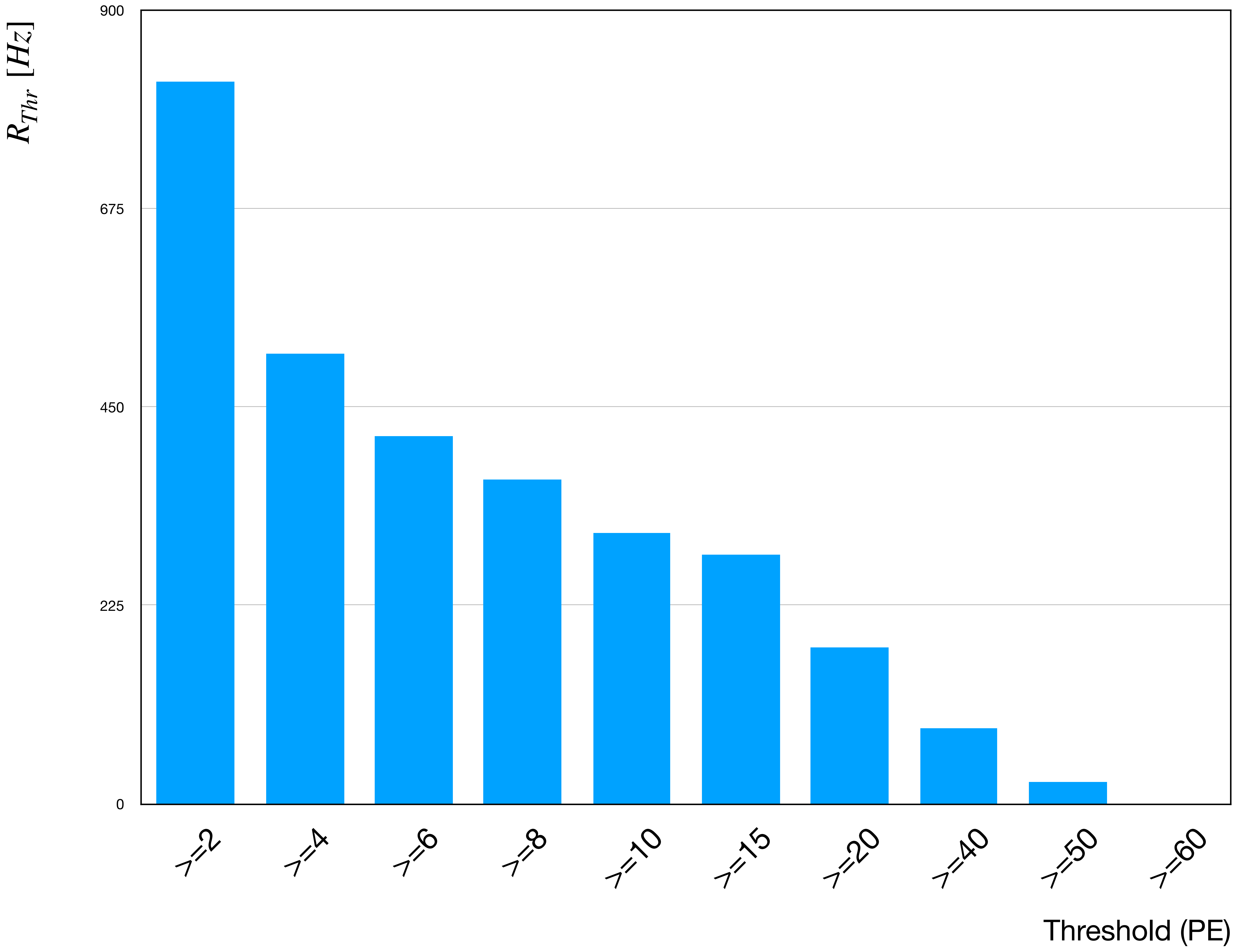
	Rate Thr >=2	Rate Thr >=4	Rate Thr >=20
Vox 1	333	333	178
Vox 2	283	178	0
Vox 3	178	0	0
Vox 4	25	0	0
Vox 5	0	0	0
Rate (all Vox)	**818**	**511**	**178**

Notes:

1. NO ^{39}Ar decays at >~2m distance from XA generate detectable signals (ie $\geq 2\ PEs$) in XA

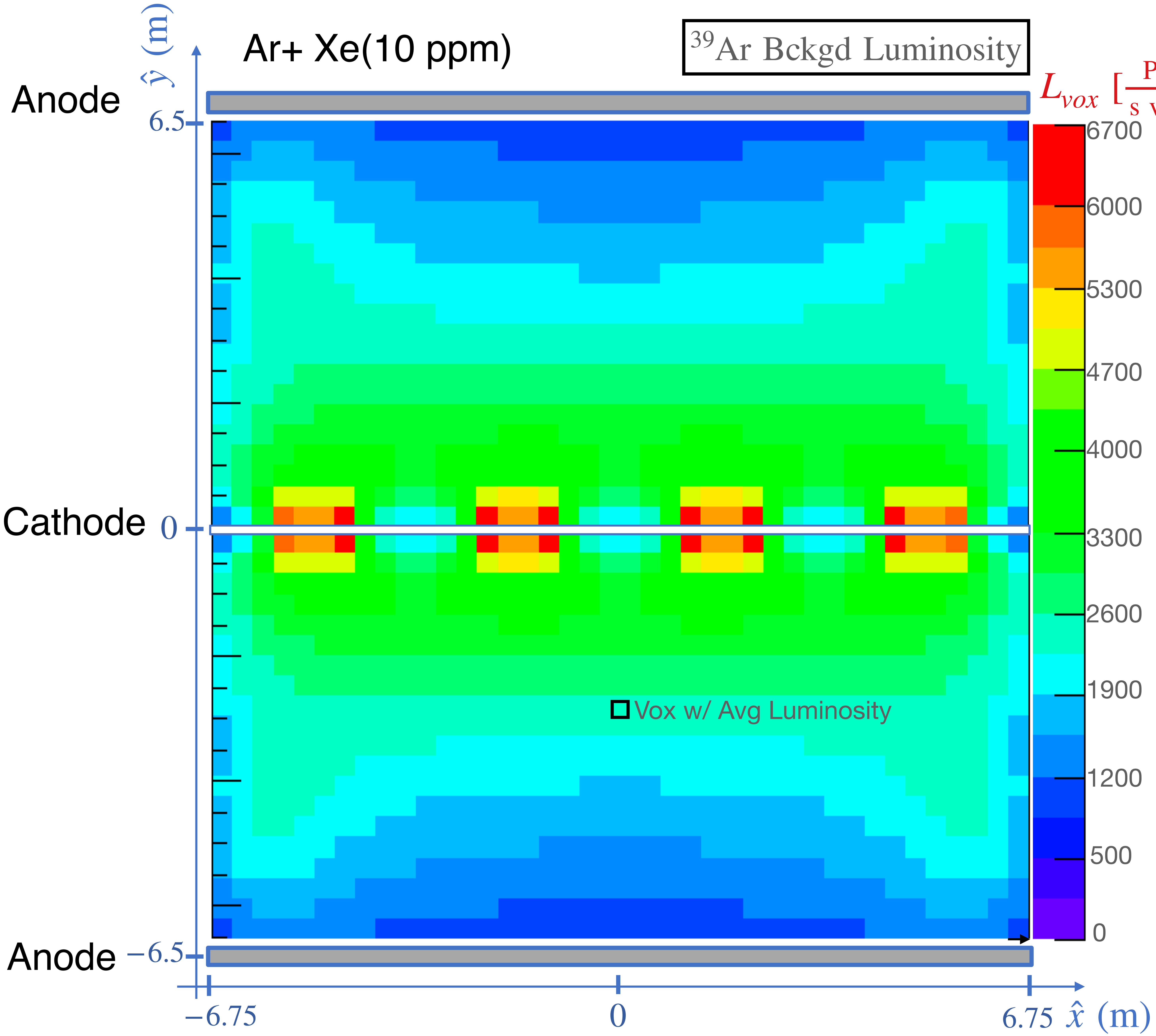
2. ^{39}Ar decays with $> 4\ PEs$ detectable signals in one XA are ALL from **<~1m distance** from the XA

expected data rate in XA, as a function of threshold in photo-electrons



Rates in the plot account for contributions from a ^{39}Ar decays in a column of LAr ~2m high (4 voxels) above a (generic) XA on the cathode.
Contributions from off-axis columns of voxels around the XA should be added.
Solid angle subtended by the XA to the centre of these off-axis voxels will be much smaller (and correspondingly contributions to event rates small, but the number of voxels large). In total, rates in XA will be - guess - a factor 2 or 3 larger than in the plot when contributions from all off-axis voxels will be added.

^{39}Ar Background



- ^{39}Ar decay rate is 1.1 Bq/kg = 1.1 dcy/s/kg $\rightarrow r_{vox} = 333$ dcy/s/vox
- ^{39}Ar dcy avg deposited energy per sec per Voxel (beta spectrum end point 0.5 MeV): $\langle E \rangle_{dcy} \simeq 0.22$ MeV/dcy

  → In voxel: $\langle E \rangle_{vox} = r_{vox} \cdot \langle E \rangle_{dcy} \simeq 66$ MeV/s/vox
- $\langle \text{LY} \rangle \simeq 39$ PE/MeV averaged value in the $0 < z < 3\ m$ detector portion around the central transverse plane at $z = 0$ (from TDR, G4 standalone simulation)
- "Luminosity L" - N. of PE per sec from ^{39}Ar dcys in LAr Voxel detectable by the PDS (all modules):
  - $\langle L \rangle_{vox} = \langle \text{LY} \rangle \times \langle E \rangle_{vox} \simeq 2600$ PE/s/vox - in avg. Voxel
  - Most luminous Voxels (red) are those immediately above XA modules on the Cathode w/ $L_{vox-1} \simeq 7000$ PE/s (mostly detected by XA underneath).
- "Sensitivity S_{XA}" - N. of PE per sec "sensed" by XA from ^{39}Ar dcys in Voxel (from analytical calculation):
  - XA on Cathode detects $S_{XA}(\text{vox}-1) \simeq 8000$ PE/s from ^{39}Ar in Voxel-1 above it (Table in backUP, ~300 dcy/s w/ avg 25 PE/evt)

The two numbers (L_{vox} and S_{XA}) seem in reasonable agreement (somehow confirming the approximate analytical calculations vs full G4 simulation)

the VD Reference design

- The VD PDS reference design has different and more performant objectives than those of the design implemented in HD PDS, by exploiting the greater flexibility of the new VD TPC mechanics, while keeping costs and power dissipation in LAr within the same limits as the HD PDS.

- The main objective in the VD PDS Reference design is to make the LY uniform throughout the volume and higher on average, so as to be able to perform calorimetry and space reconstruction (and therefore also Trigger with max efficiency) down to a very low threshold ⇒ enabling extension of DUNE Physics reach in the UG Low Energy range.

- The added risk is from operating PDS on HV planes (i.e. requiring transmission of Power and Signal over fiber)

- The HD requirements are comfortably met in the VD Reference design. The HD requirements thus represent the *minimum requirements* for VD, while the VD goals are more stringent and ambitious - and motivate the 4pi design.

- *Risk Opportunity: the Reference Photon Detector is completely independent and redundant to the Charge TPC. This represents a big risk mitigation for physics if the TPC needs some maintenance period or will show some problems with time*

Results can be seen in figures 3 and 4 for a DUNE module (box internal dimensions of 480 mm x 93 mm x 6 mm).

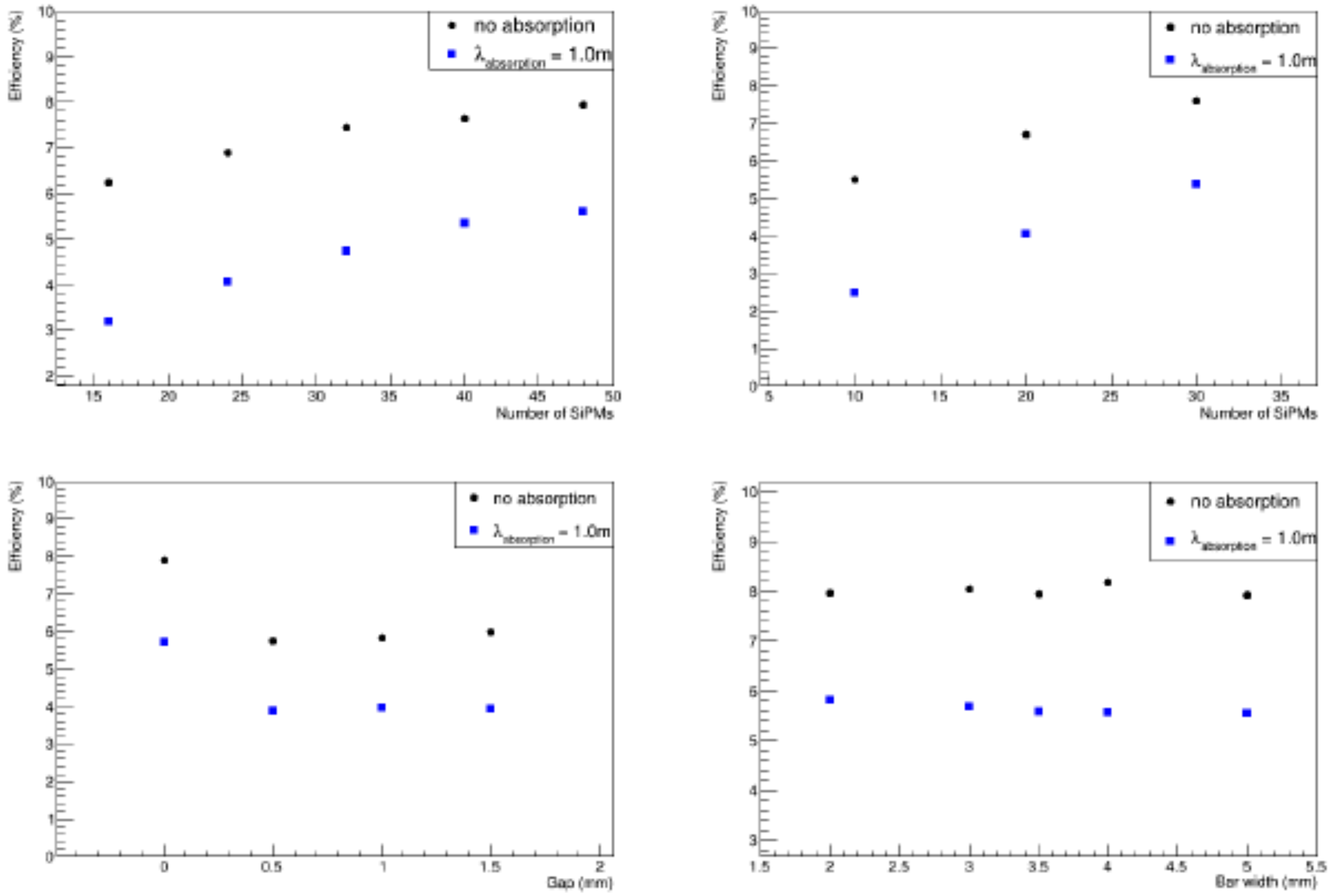
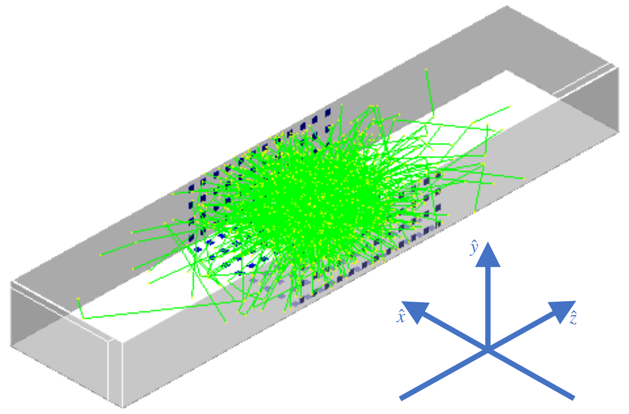
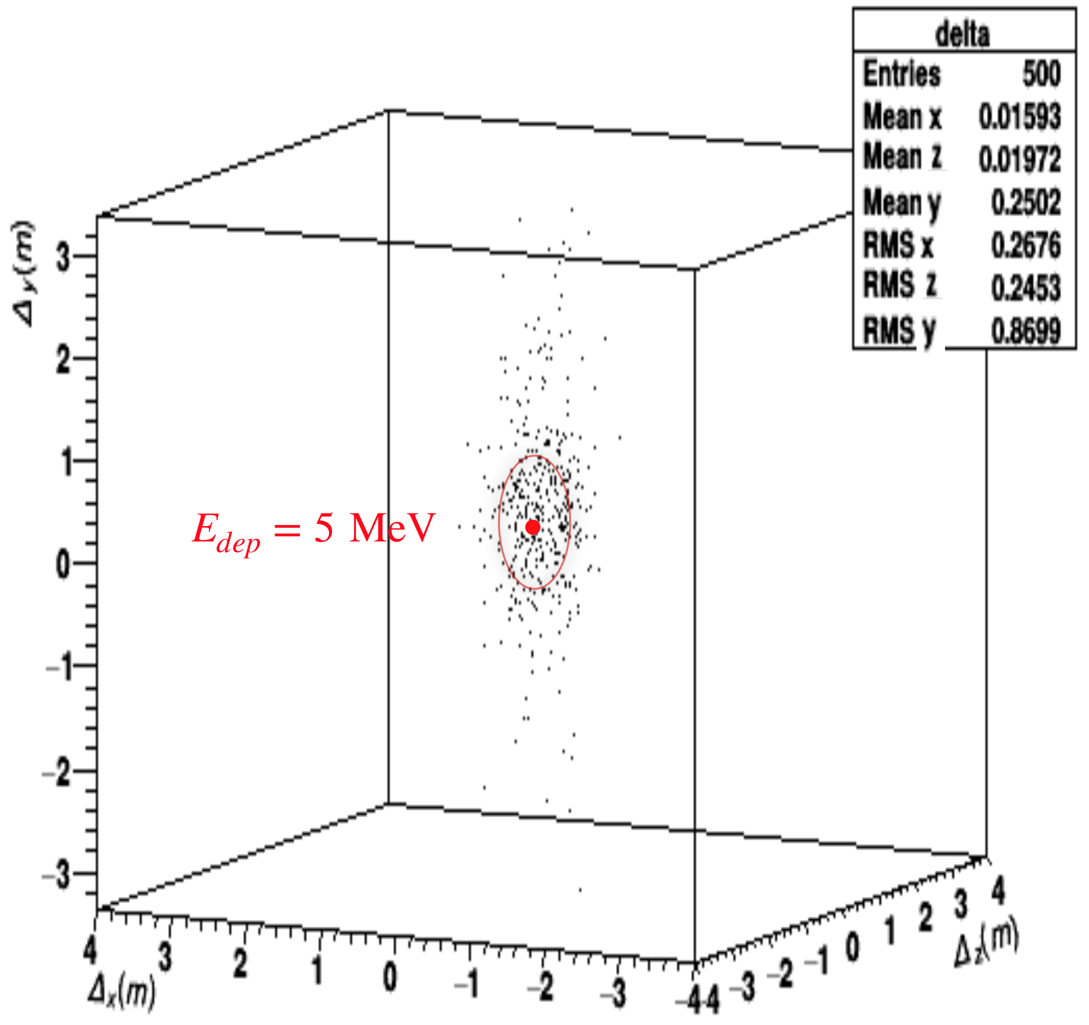


Figure 3. Efficiency studies for X-ARAPUCA as a function of (from top to bottom, left to right): (a) number of SiPMs equally spaced along the longer sides of the box; (b) number of SiPMs equally spaced on the shorter sides of the box; (c) spacing between the WLS bar and the SiPMs; (d) bar width. Results obtained for a device of internal size 480 mm x 93 mm x 6 mm, with 6x6 mm^2 SiPMs, and bar width of 3.5 mm, except when varied in case (d).

Position reconstruction and Spatial Resolution

position reconstruction from the barycenter of the detected light pattern of the event

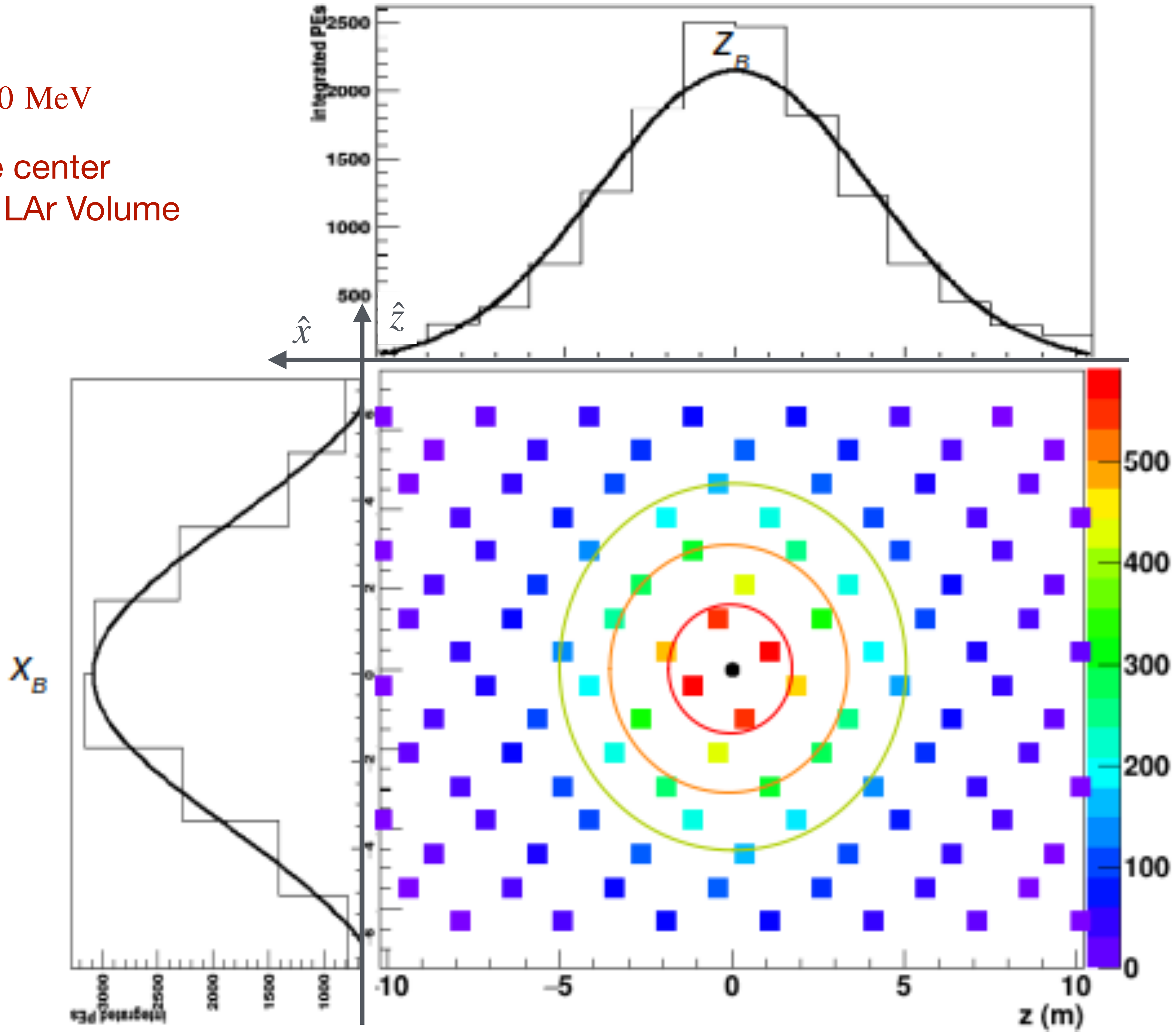


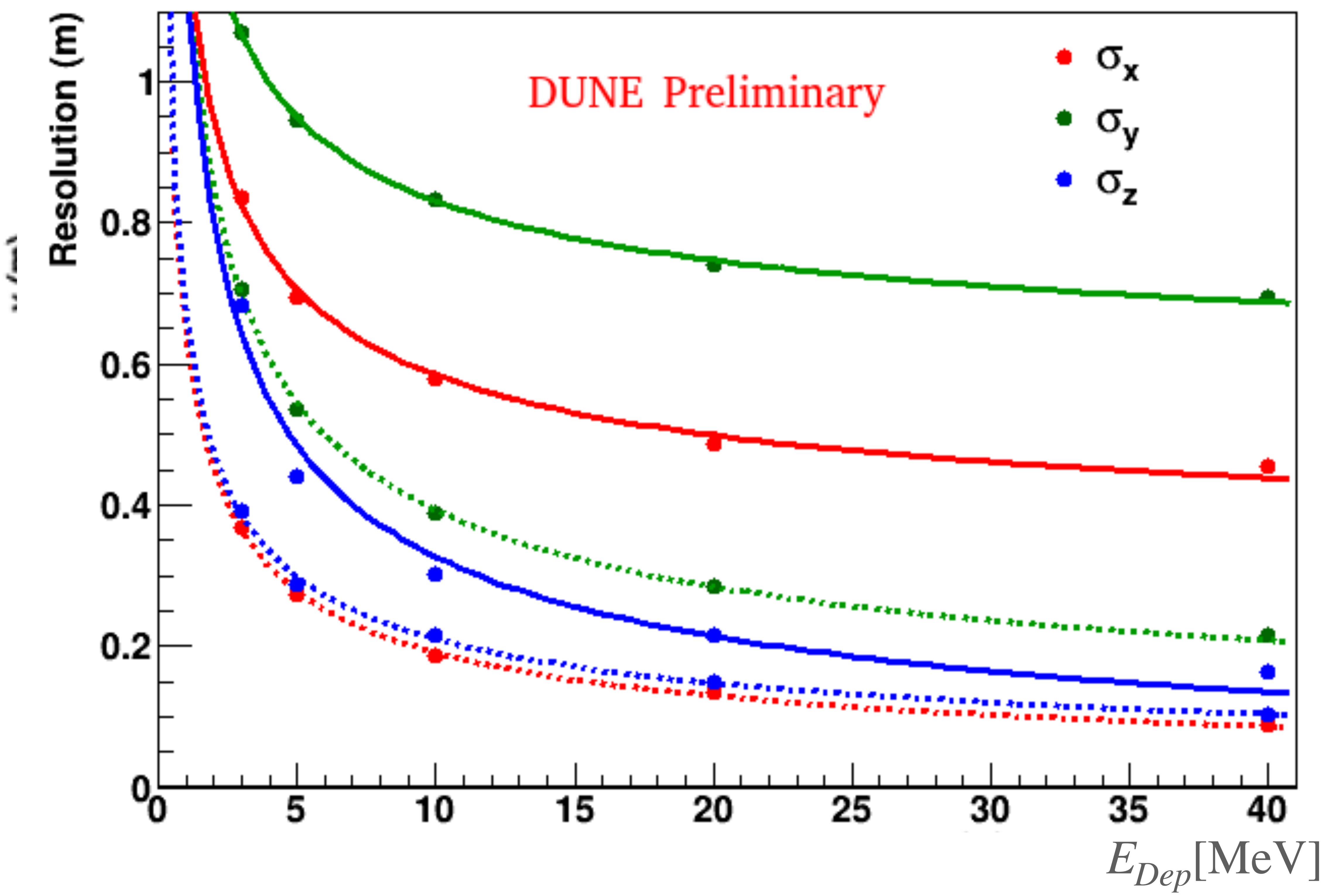


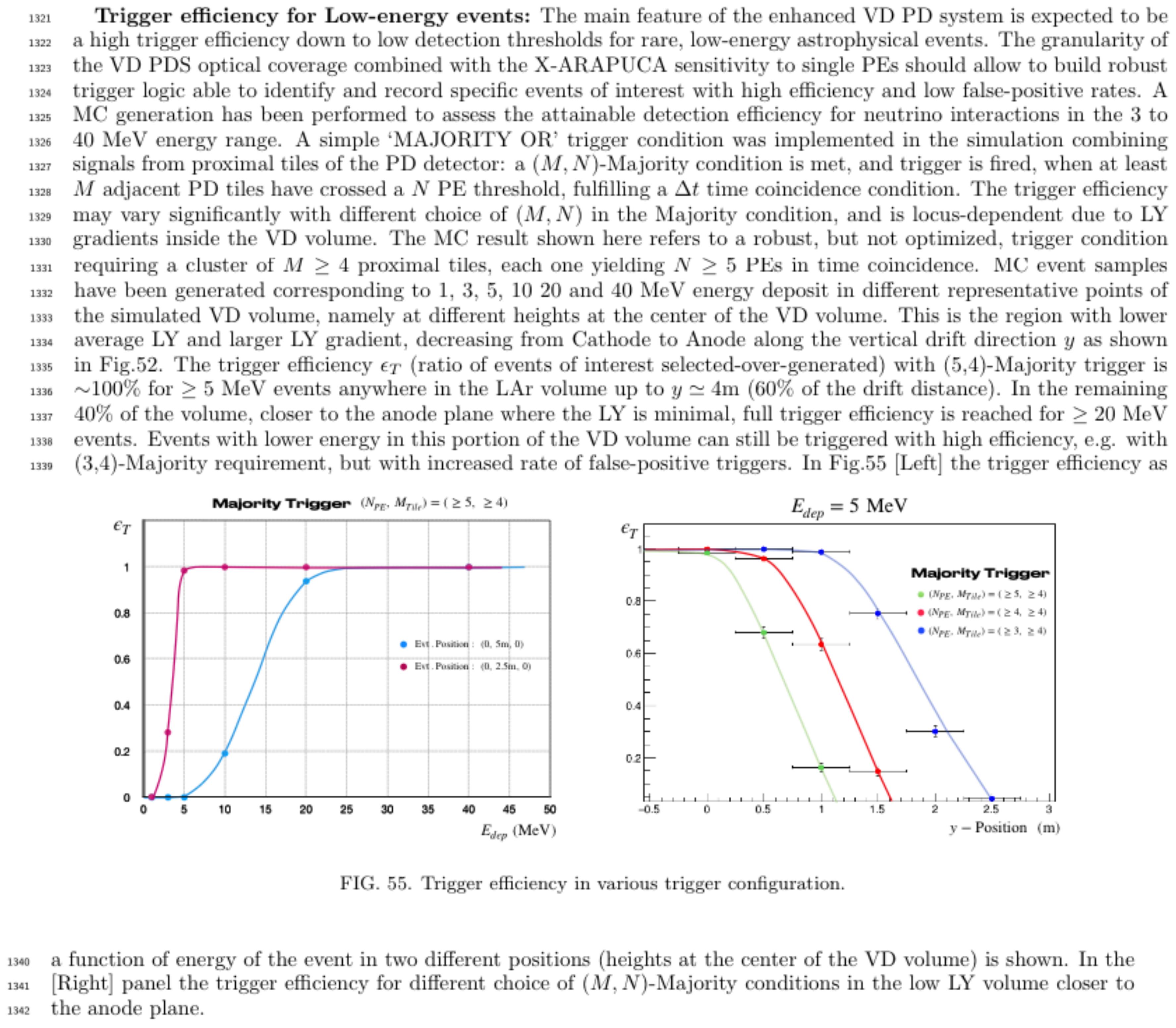
Space resolution = rms of the distributions of the difference between reconstructed and true position coordinates.

$E_{dep} = 40$ MeV

at the center
of (upper) LAr Volume



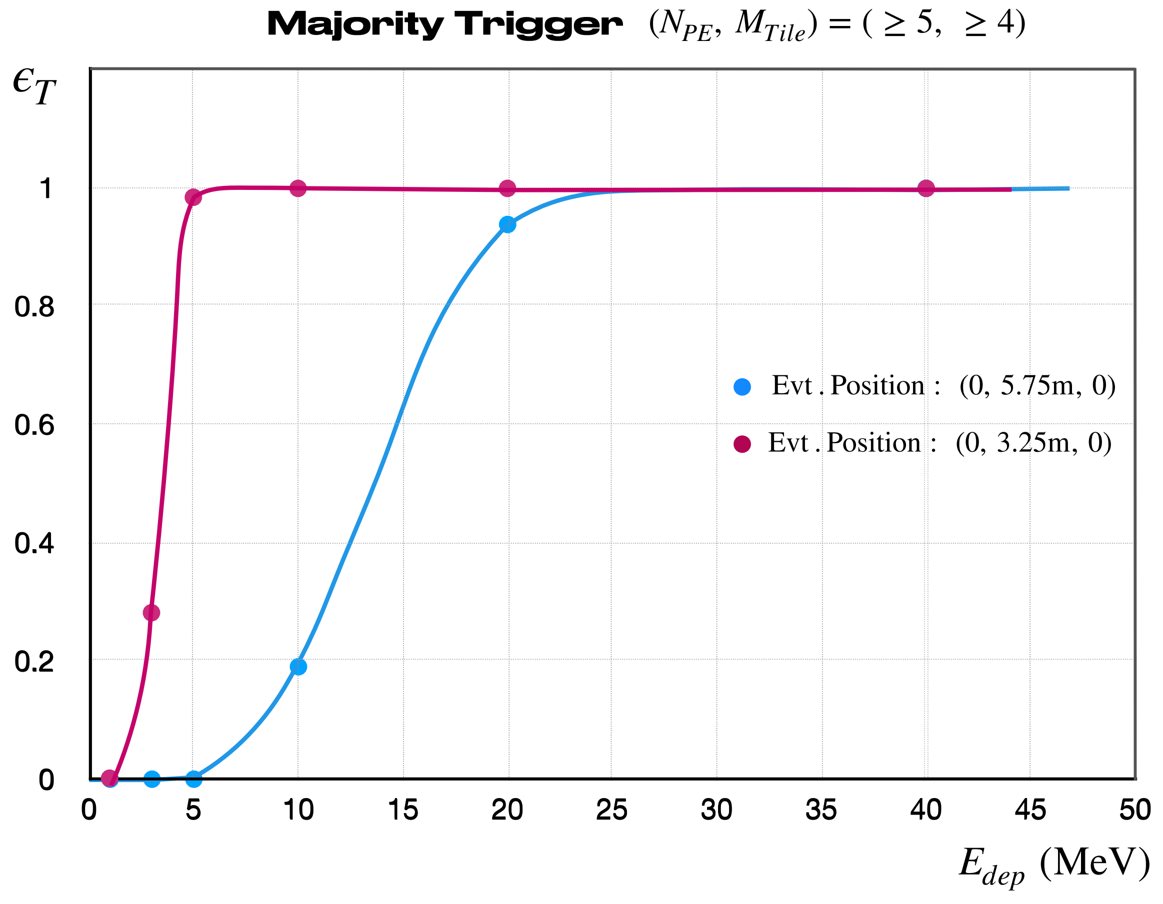


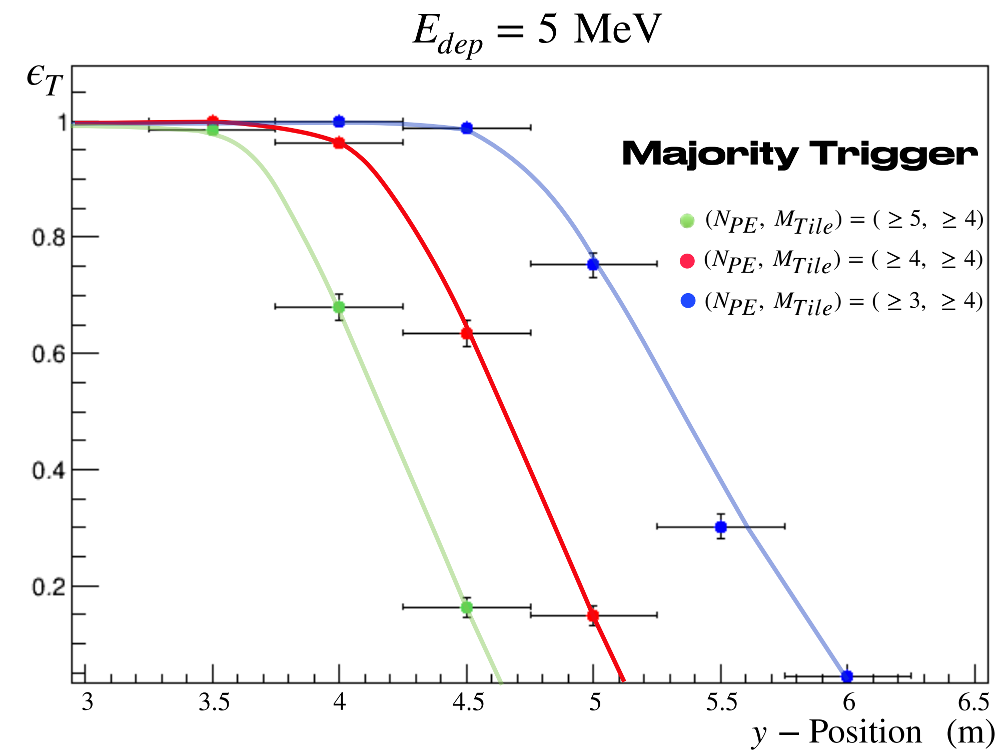


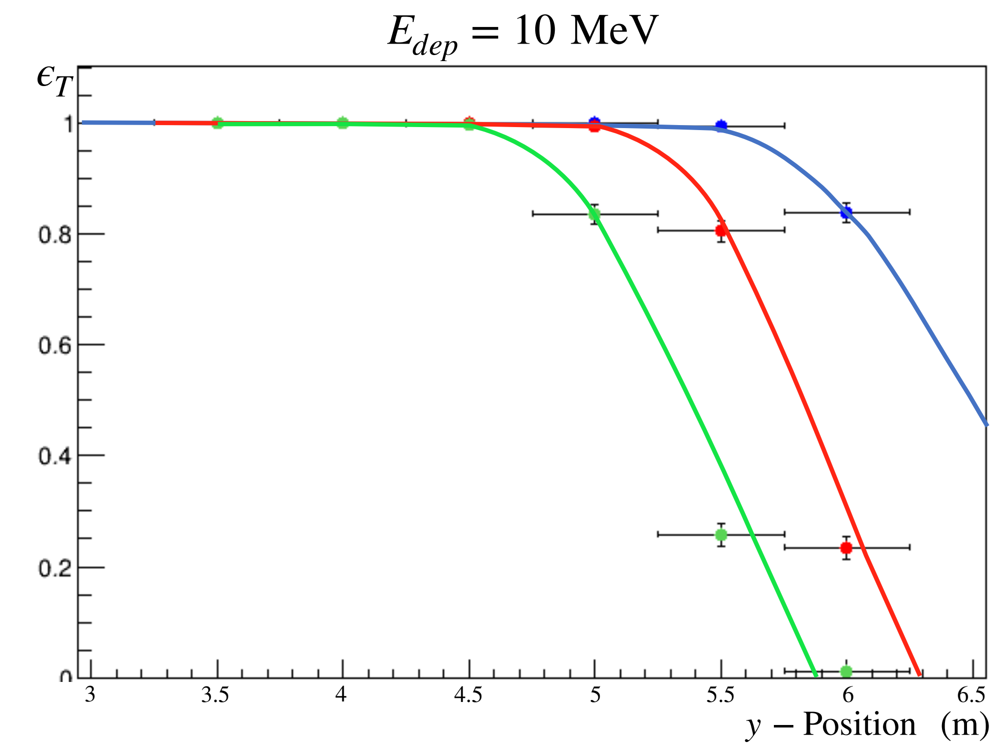
Trigger efficiency for Low-energy events: The main feature of the enhanced VD PD system is expected to be a high trigger efficiency down to low detection thresholds for rare, low-energy astrophysical events. The granularity of the VD PDS optical coverage combined with the X-ARAPUCA sensitivity to single PEs should allow to build robust trigger logic able to identify and record specific events of interest with high efficiency and low false-positive rates. A MC generation has been performed to assess the attainable detection efficiency for neutrino interactions in the 3 to 40 MeV energy range. A simple 'MAJORITY OR' trigger condition was implemented in the simulation combining signals from proximal tiles of the PD detector: a (M, N)-Majority condition is met, and trigger is fired, when at least M adjacent PD tiles have crossed a N PE threshold, fulfilling a Δt time coincidence condition. The trigger efficiency may vary significantly with different choice of (M, N) in the Majority condition, and is locus-dependent due to LY gradients inside the VD volume. The MC result shown here refers to a robust, but not optimized, trigger condition requiring a cluster of $M \geq 4$ proximal tiles, each one yielding $N \geq 5$ PEs in time coincidence. MC event samples have been generated corresponding to 1, 3, 5, 10 20 and 40 MeV energy deposit in different representative points of the simulated VD volume, namely at different heights at the center of the VD volume. This is the region with lower average LY and larger LY gradient, decreasing from Cathode to Anode along the vertical drift direction y as shown in Fig.52. The trigger efficiency ϵ_T (ratio of events of interest selected-over-generated) with (5,4)-Majority trigger is ~100% for ≥ 5 MeV events anywhere in the LAr volume up to $y \simeq 4$m (60% of the drift distance). In the remaining 40% of the volume, closer to the anode plane where the LY is minimal, full trigger efficiency is reached for ≥ 20 MeV events. Events with lower energy in this portion of the VD volume can still be triggered with high efficiency, e.g. with (3,4)-Majority requirement, but with increased rate of false-positive triggers. In Fig.55 [Left] the trigger efficiency as

FIG. 55. Trigger efficiency in various trigger configuration.

a function of energy of the event in two different positions (heights at the center of the VD volume) is shown. In the [Right] panel the trigger efficiency for different choice of (M, N)-Majority conditions in the low LY volume closer to the anode plane.







operations at -300 kV

- *PoF technology was developed and is commonly utilized for voltage isolation. No conductive connections are employed and no electrical power is transmitted - (optical power transmitted via glass fiber, with highest dielectric strength).*
- ○ *PDS is at 0 differential voltage*
- ○ *ProtoDUNE-SP did run with optical fibers to diffusers on cathode at 180kV over 18 months operation and for a short period HV was raised at 250 kV -*
- ○ *ColdBox1 test in Dec.21 demonstrated and validated the PoF / SoF solution to operate PD lying on the TPC HV cathode in LAr at cold Temperature, supplying with the required power for SiPM and Electronics and transmitting undistorted, noise immune analog signals over the range of interest (from 1 PE to thousand PEs), without the least interference with TPC electronics.*
- ○ *A 300 kV proof of operation is foreseen within the ProtoDUNE/NP02-Module0 plan, starting in 2023. No 300 kV tests are envisaged for PDS (nor for any other FD2 detector component) in 2022.*

PoF	**808nm Laser Optical Pwr per unit (tunable)**	**GaAs LPC Electrical Pwr per unit**	**Efficiency (Opt-to-Elec)**	**N. of PoF units (Laser, Fiber, LPC) per DCEm**	**GaAs LPC Elec.Pwr delivered (% of max setting) per DCEm**	**Pwr headroom (redundancy) per DCEm**	**Current (delivered)**	**Voltage (delivered)**	**DCEm Power request (including DC-DC)**	**DCEm Voltage**	**DCEm Current**
in Cold	1.2 W (max)	0.6 W (max) 0.32 W (set point)	50%	3	0.95 W (set point) [3 X 0.32 W] (53% of max)	0.85 W [3 X 0.28 W]	145 mA [3 X 48 mA]	6.5 V	450-650 mW	5 V	90-120 mA

Cosmic Run - CB B++ - Sept.16

◉ X-Arapuca (v.2) (2chs.) on the Cathode + DCEm Board **w/ PoF and SoF**

The two channels are set at different gain
(and are normalized to same area (n. of PEs) in the plots)

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:

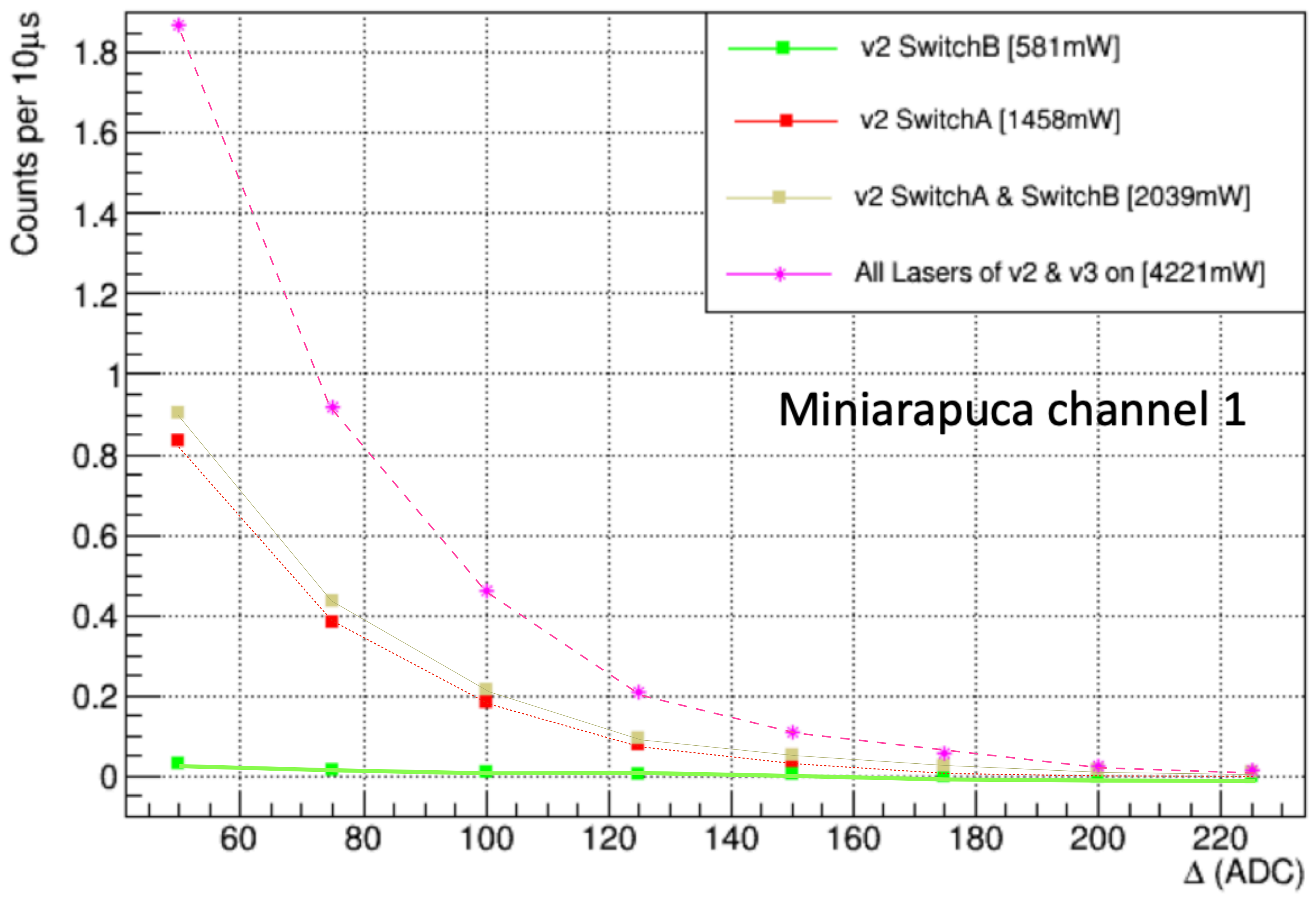
Low-frequency O(100kHz) observed in December-March ColdBox runs mitigated/solved by improving the grounding and shielding connections.

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)*

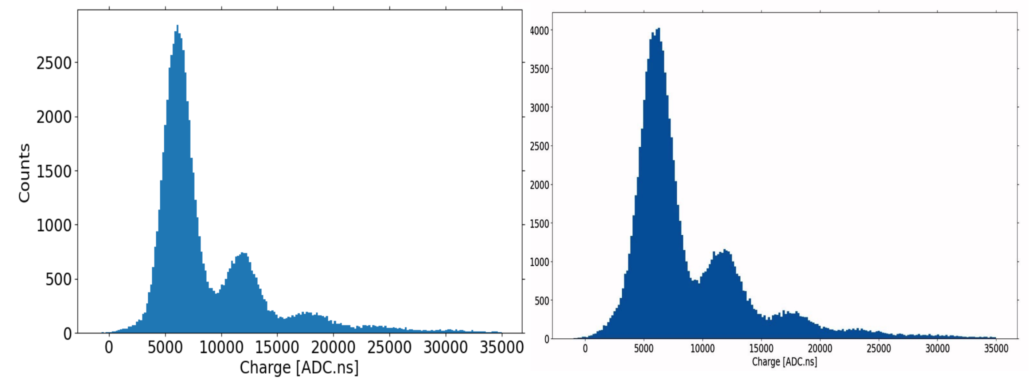
Pulse height (ADC) counts above threshold in 10μs window at increasing PoF units ON (up to max deliverable power)



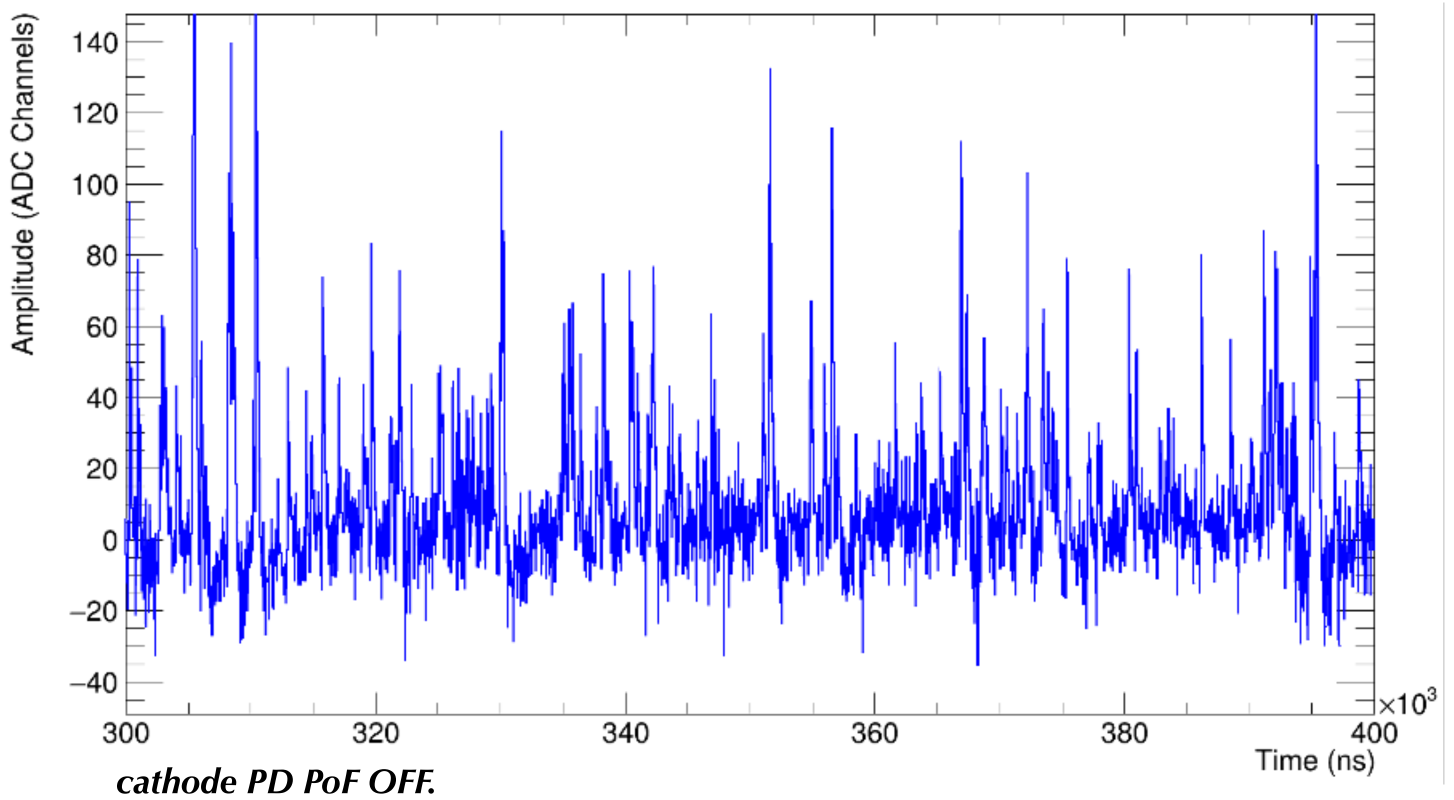
Pulse Rate (above-threshold):

	Ambient Light PoF OFF (Fig.1)	*Reduced Ambient Light PoF OFF (Fig.2)*	*Reduced Ambient Light PoF ON (Fig.3)*
Pulse Rate ($10 \times 10\ cm^2$ 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*	$0.9\ kHz/mm^2$	$0.1\ kHz/mm^2$	$0.3\ kHz/mm^2$

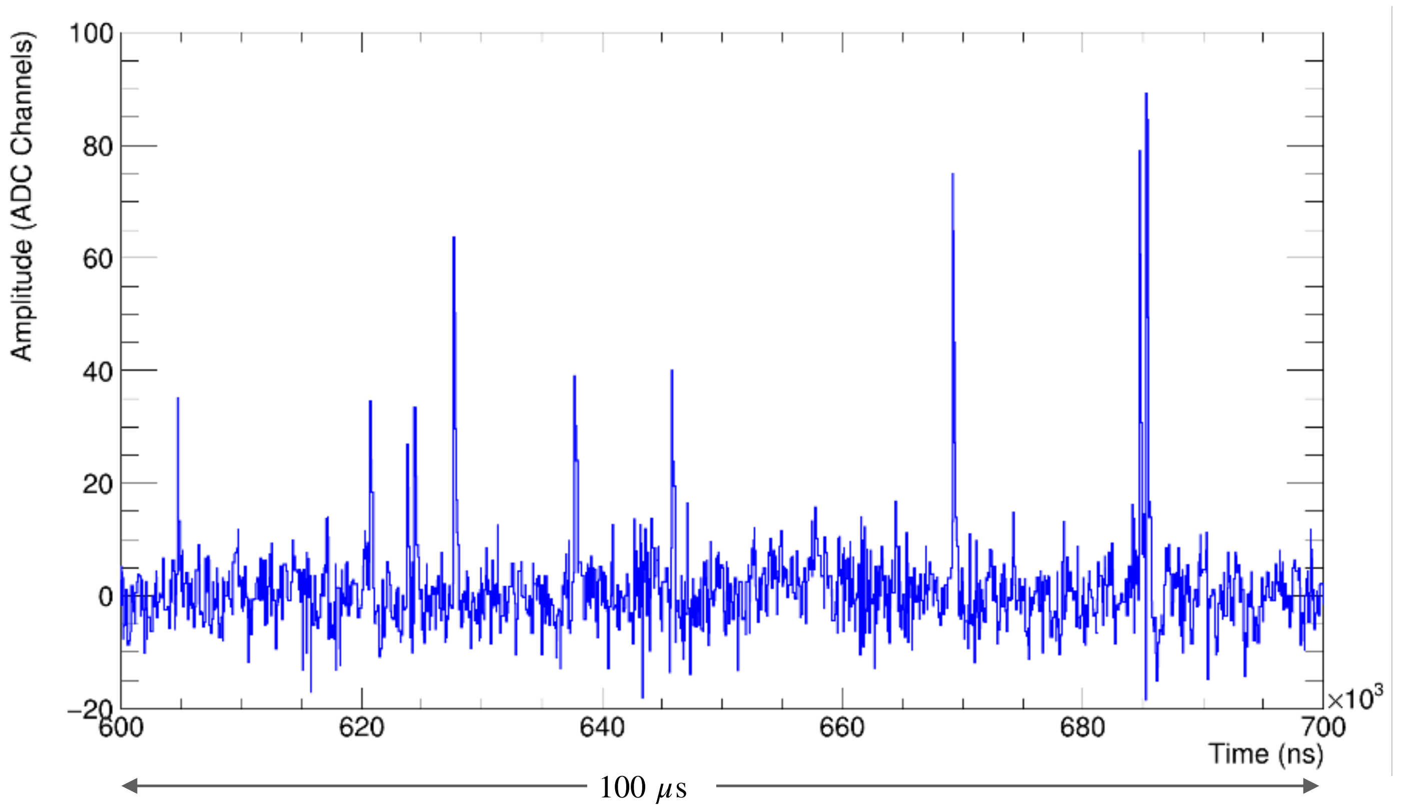
Pulse Charge Distribution:
(first peak)
1PE $\simeq 6000\,\mathrm{ADC} \times \mathrm{ns}$



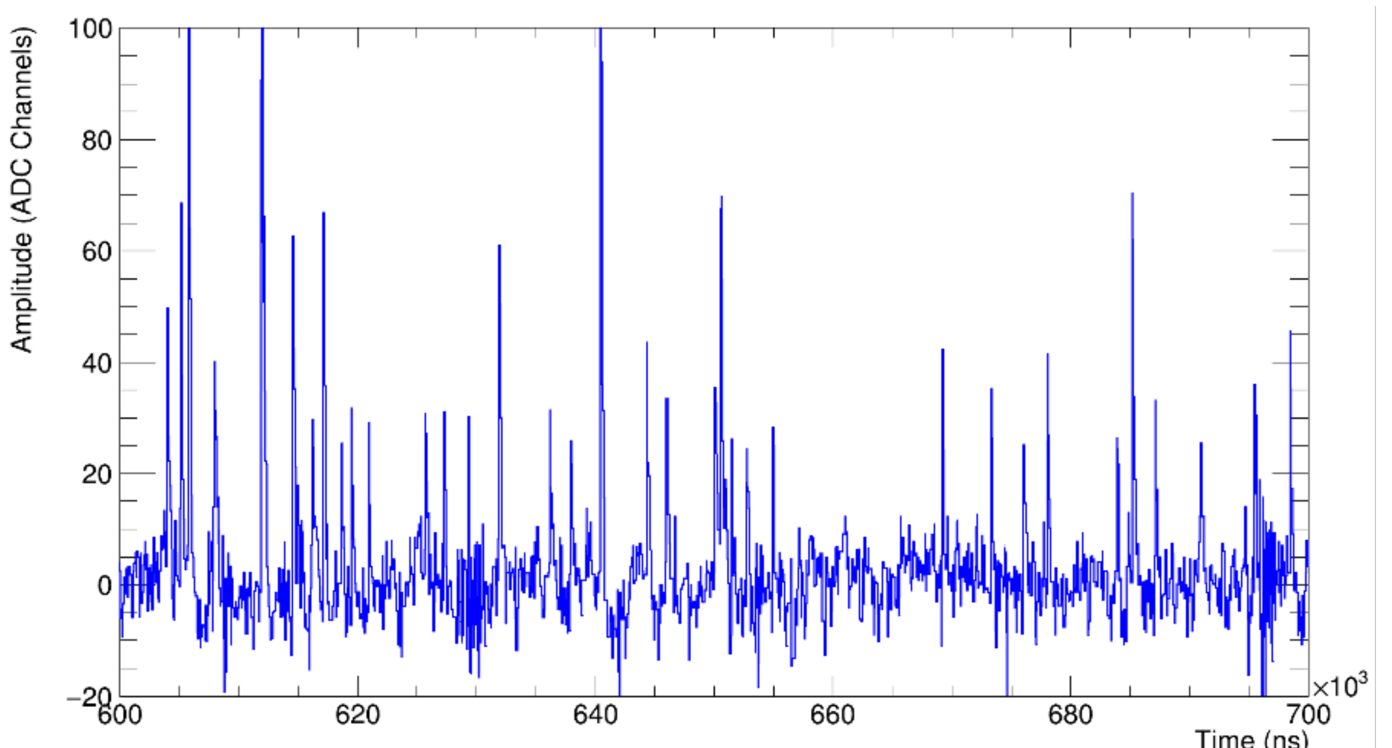
◉ mini-Arapuca on the Wall



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]