2nd ANNUAL MEETING
Valencia, 24-27 April 2023

CIEMAT R&D on light readout for cryogenic neutrino detectors (WP9)

CIEMAT Neutrino Group

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GOBIERNO DE ESPAÑA
MINISTERIO DE CIENCIA E INNOVACIÓN
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Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas
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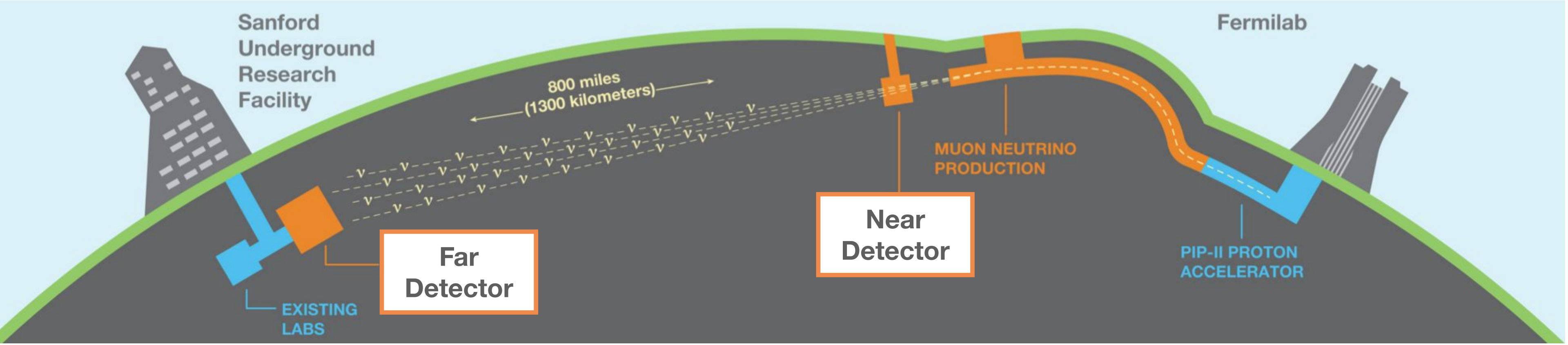
LAr TPCs for neutrino physics

DUNE: The flag-ship for the upcoming decades



DUNE SCIENCE GOALS:

- Precision neutrino oscillation measurements
- Low energy neutrinos (SN & solar)
- Beyond Standard Model Physics

DUNE Phase I: FD1-HD + FD2-VD
- Technologies decided (under development/ production)

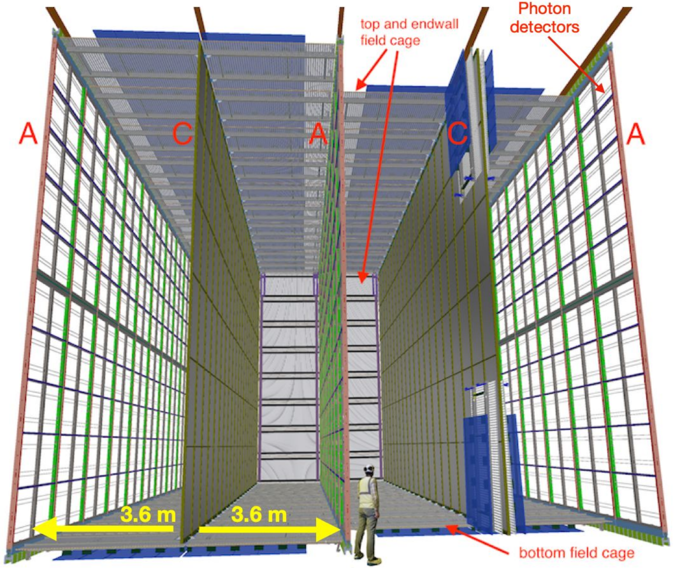
DUNE Phase II: opportunity for R&D on LAr TPCs

DUNE FD-Phase I: first two FD modules

DUNE FD1 (HD)

Single Phase + Horizontal Drift

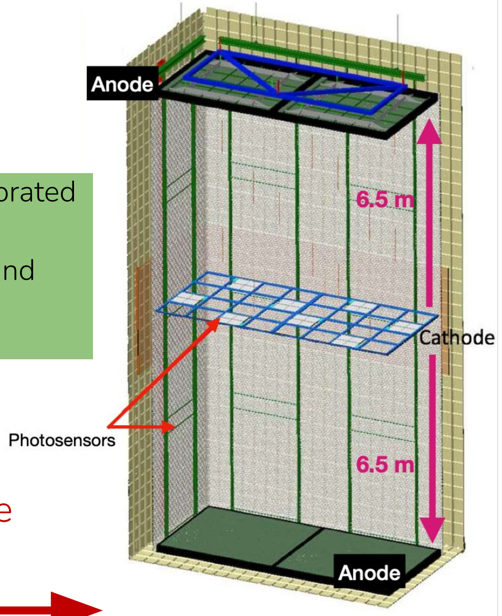
- Charge readout based on wires
- Light readout behind wires based on SiPM photon collectors



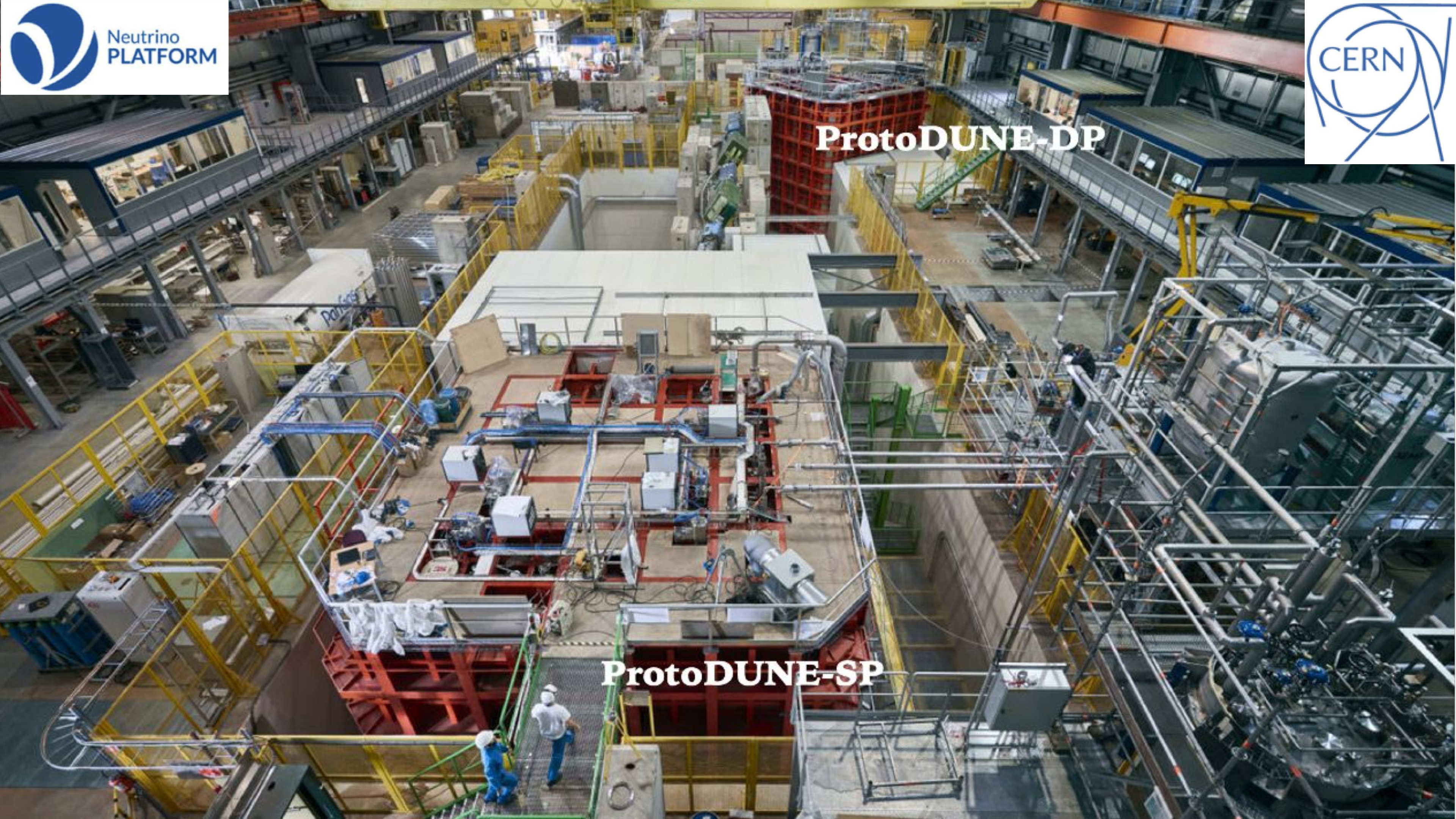
DUNE FD2 (VD)

Single Phase + Vertical Drift

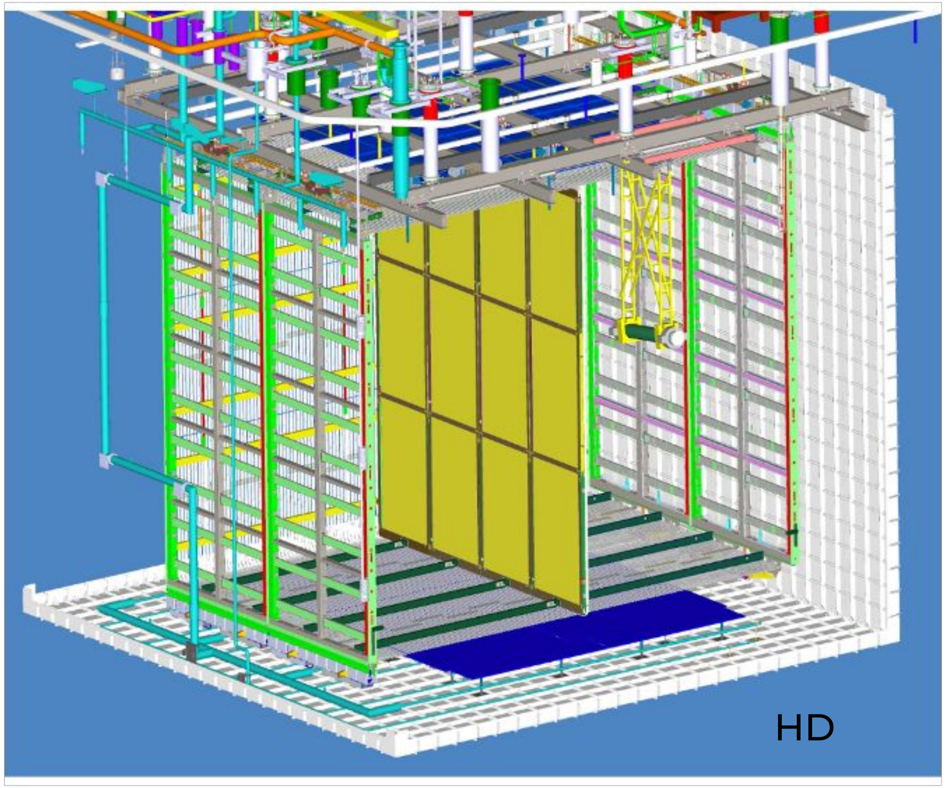
- Charge readout based on perforated PCBs
- Light readout on the cathode and walls based on SiPM photon collectors

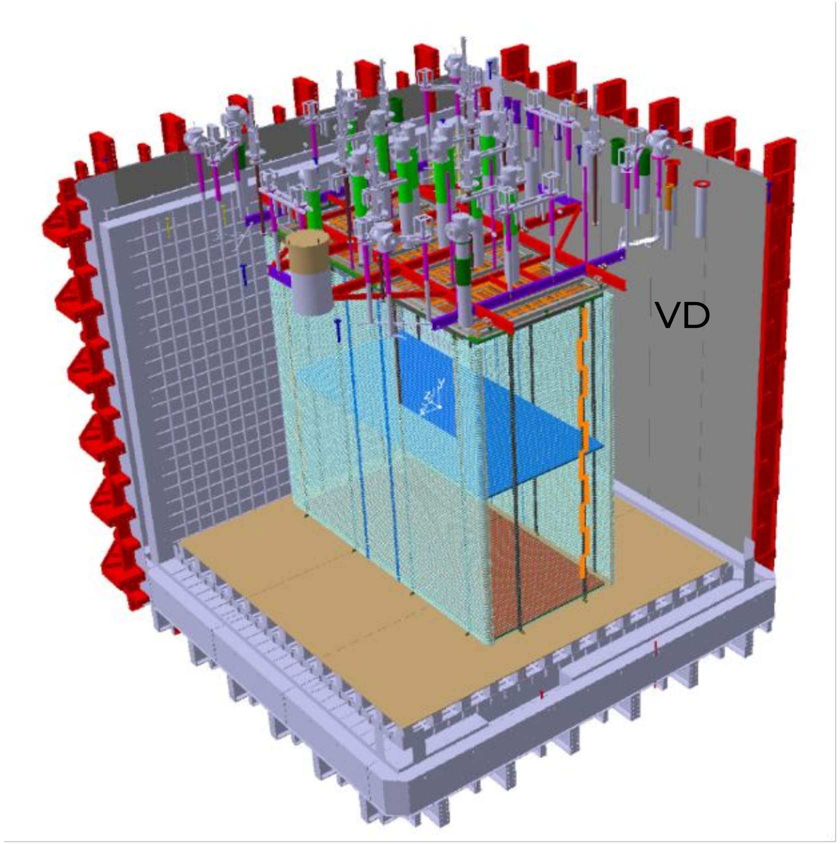


Move to a cheaper and more efficient configuration

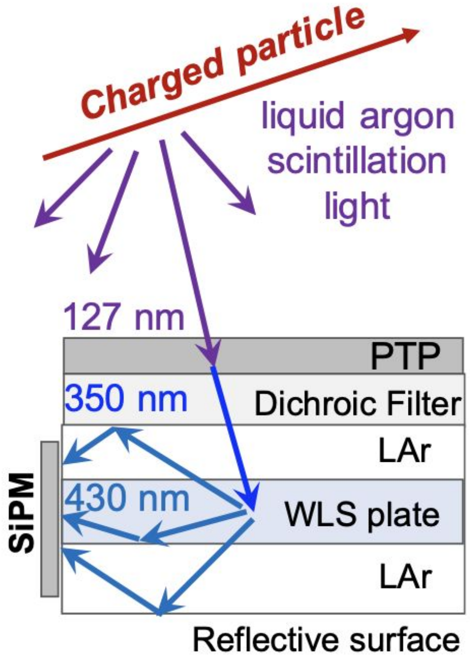

Neutrino
PLATFORM
CERN
ProtoDUNE-DP
ProtoDUNE-SP

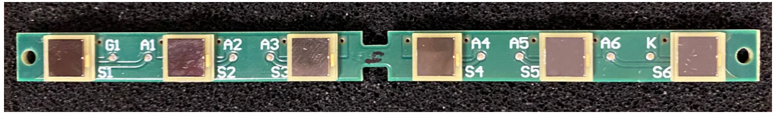
ProtoDUNE-HD & ProtoDUNE-VD at CERN

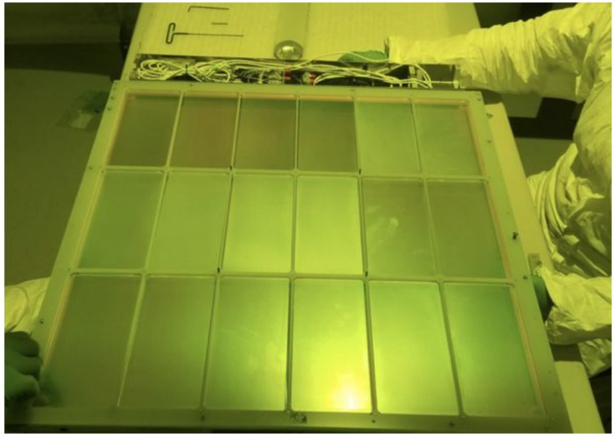


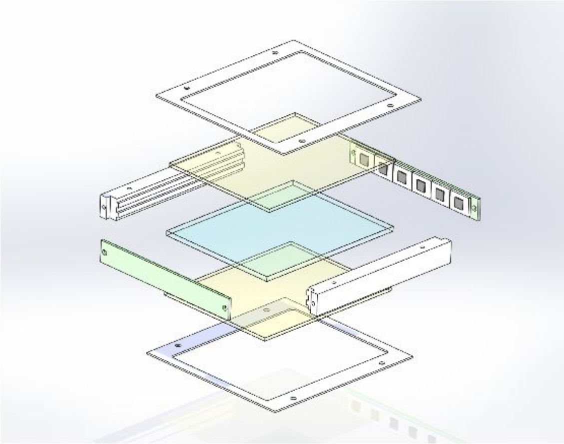


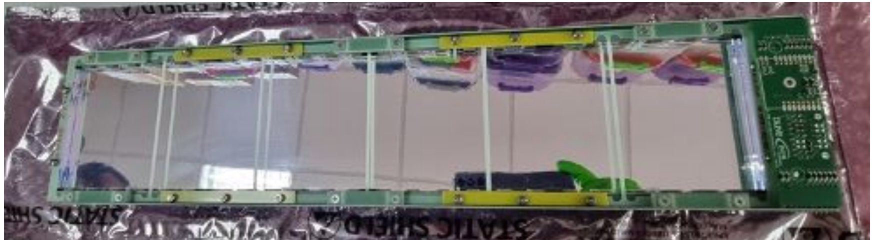
Photon Detectors for DUNE: X-ARAPUCAs





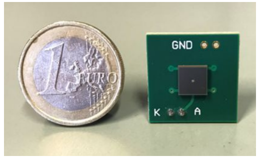






R&D related to PDS FD1-HD

Final results of HPK SiPM characterization

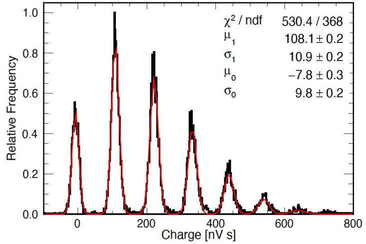


SiPM development in collaboration with Hamamatsu and FBK:

- New cryogenic sensors fulfilling the DUNE requirements
- Appropriate to be used in X-ARAPUCAs

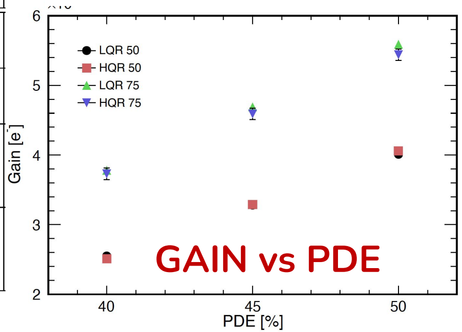
Characterization and cryo reliability tests of standalone SiPMs and groups of 6 sensors per PCB (ganging mode):

- At room T and after 20 thermal cycles in LN_2
- IV-curves, gain, S/N, DCR, cross-talk, afterpulses
- Individual and ganged tests



HPK MPPC models

Model	Characteristics
HPK S13360-9932 50μ-LQR	Cell pitch 50μm, low quenching resistance (280 kΩ) at 77 K
HPK S13360-9933 50μ-HQR	Cell pitch 50μm, high quenching resistance (660 kΩ) at 77 K
HPK S13360-9934 75μ-LQR	Cell pitch 75μm, low quenching resistance (280 kΩ) at 77 K
HPK S13360-9935 75μ-HQR	Cell pitch 75μm, high quenching resistance (660 kΩ) at 77 K

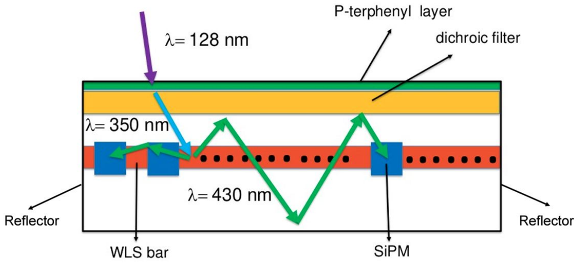


RESULTS for selected HPK 75-HQR

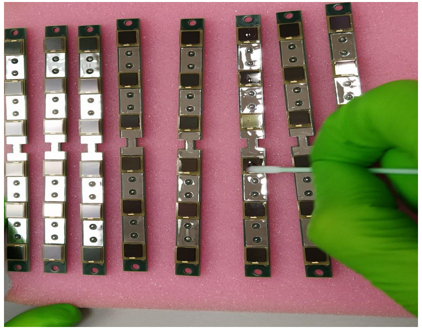
(paper ready to be submitted to journal)

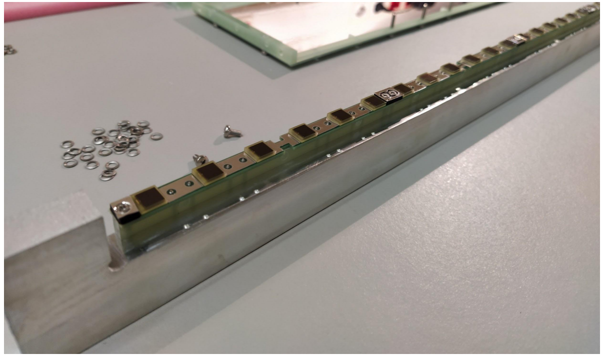
Parameter	Requirement	Test Result (Mean/Std Dev)
Gain	2 to $8 \cdot 10^6$	$5.7 \cdot 10^6$ / $9.08 \cdot 10^4$
Cross-talk probability	<35% at Vop	13.62% / 1.29%
After-pulsing probability	<5% at Vop	1.49% / 0.35%
Global DCR	< 100 mHz/mm^2	73.68 mHz/mm^2 / 26.6 mHz/mm^2
Thermal cycles	>20	Negligible variation on V_{bd} R_q after 20 cycles

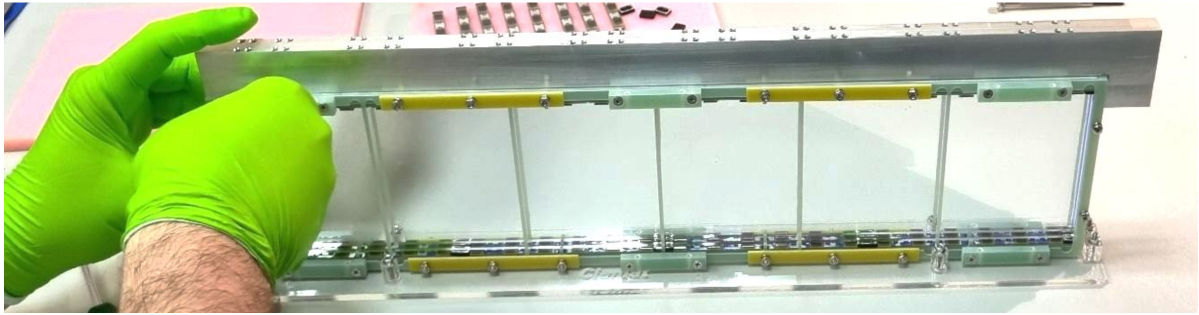
74 X-ARAPUCA supercells assembly



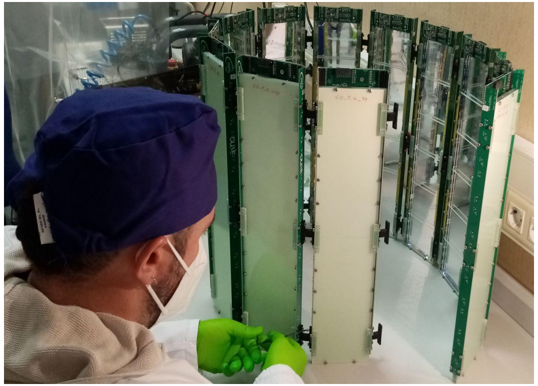
Assembly and testing 74 (out of 160) X-ARAPUCAs at CIEMAT prior to their installation in ProtoDUNE at CERN

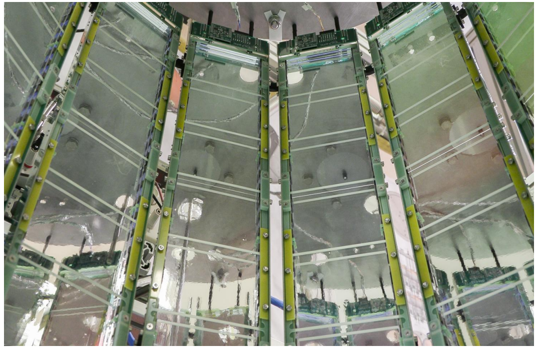






74 X-ARAPUCA supercells testing





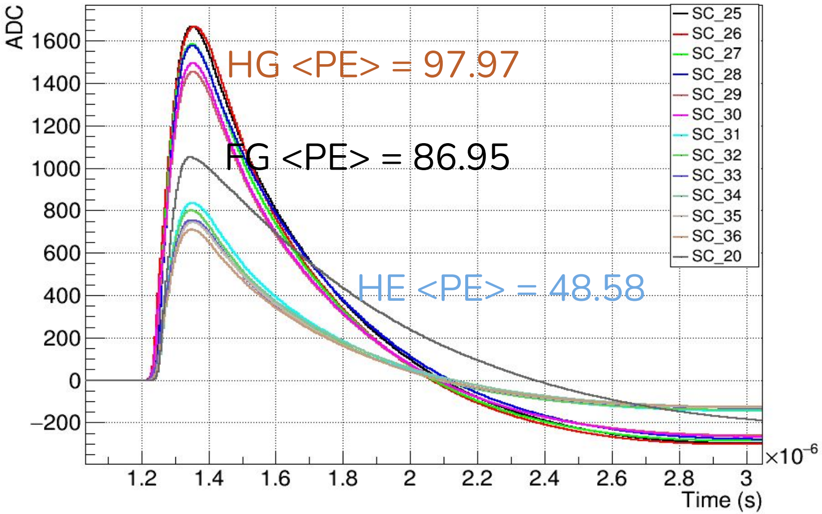
@ CIEMAT

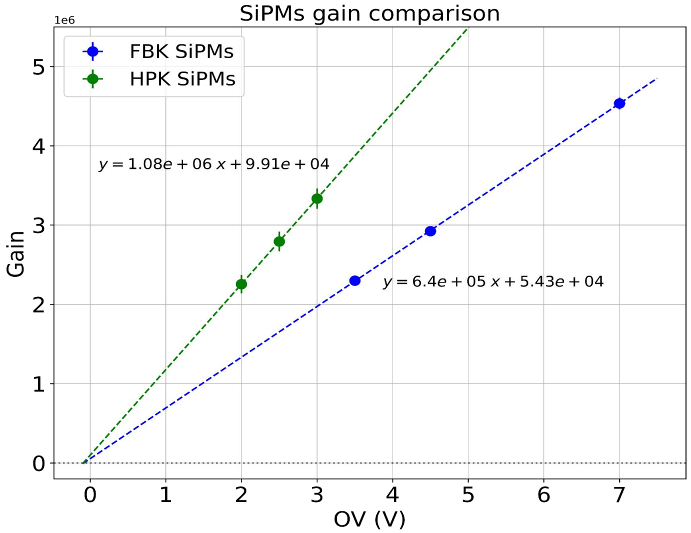
- A vessel with 300 l of Liquid N_2 accommodating **up to 14 XA's**
- Light from 405nm Laser
- CIEMAT tested 74 XA out of 160

SiPM type	WLS bar type	Number
HPK	Glass2Power	16
HPK	Eljen	34
FBK	Glass2Power	14
FBK	Eljen	10

74 X-ARAPUCA supercells test results

- 3 X-ARAPUCA configurations tested: **HPK+G2P (HG)**, **FBK+G2P (FG)** and **HPK+Eljen (HE)**
- Goals:
  - Test their correct operation at cryogenic temperature
  - Characterization in terms of: **gain**, **SNR** and **Dark Current Rate**



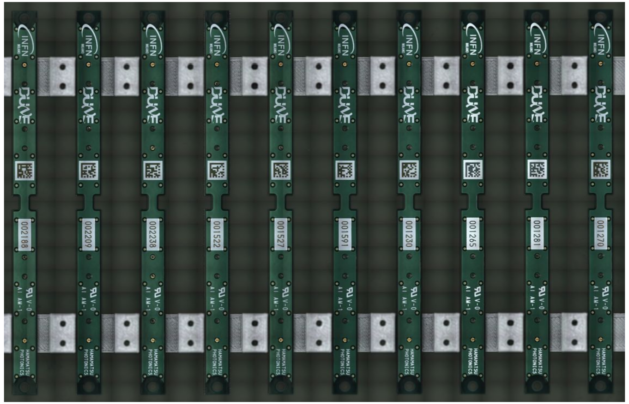


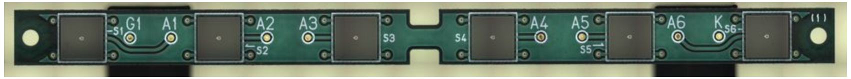
- **SNR ~6.5** for PDE 45% at CT (requirement SNR > 2)
- **Dark count** is below requirement (**<1.7 kHz**) at CT except for Eljen WLS plates

Production phase: Mechanical measurements of SiPM boards

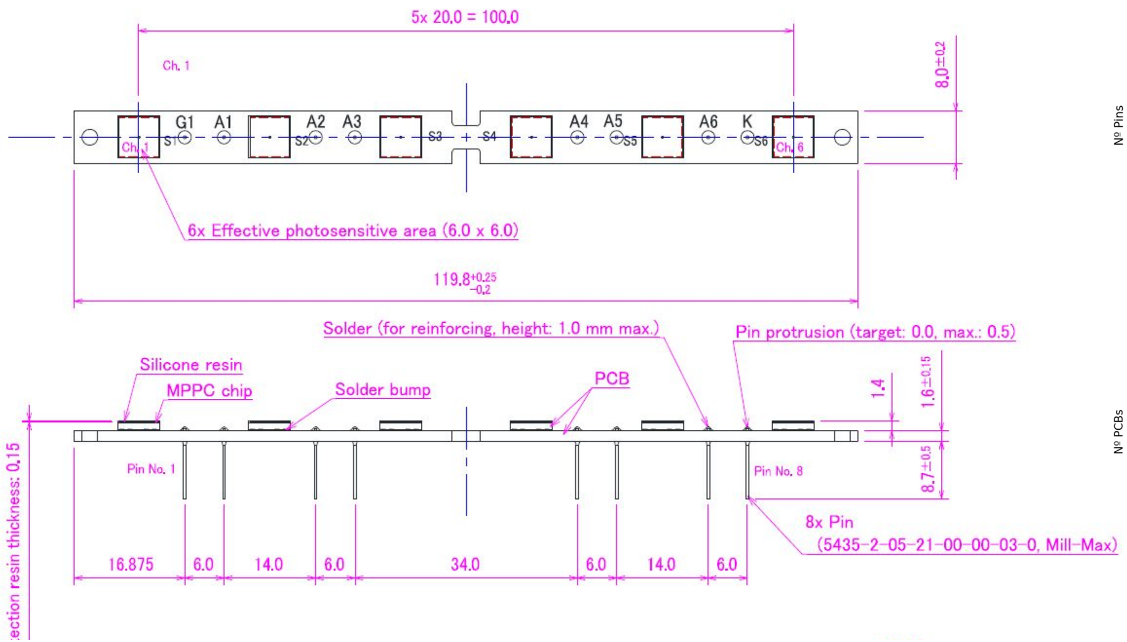
Measurements made with a 3D vision machine

Model: QUICK VISION Active 404
Precision: ±1.5 μm

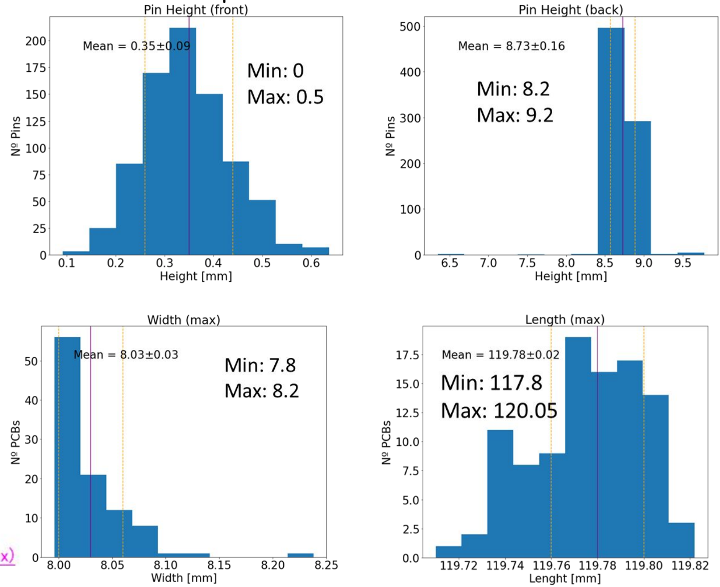


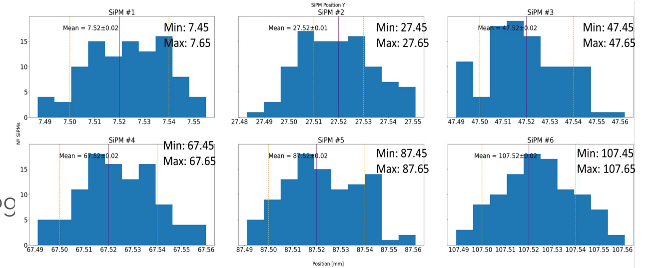


Production phase: Check real dimensions agains specs



Some examples :

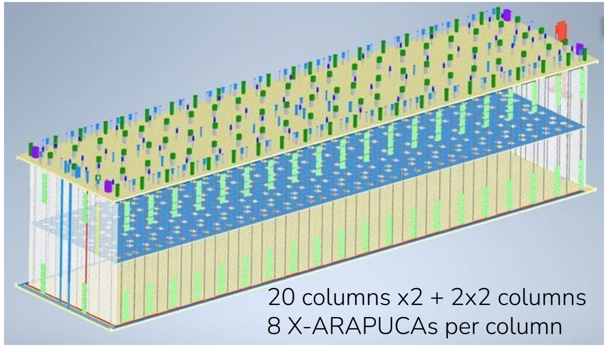


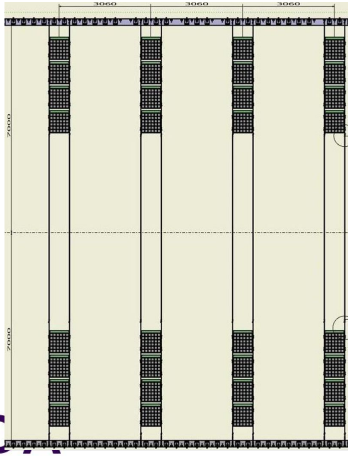


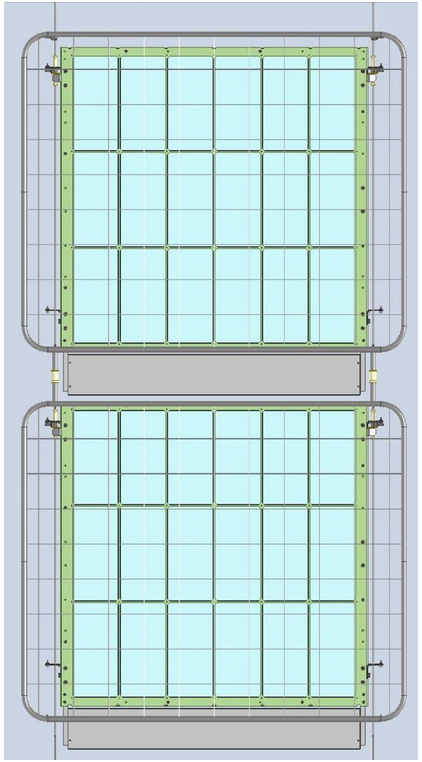
All specified dimensions checked :
SiPMs positions, dimensions, pins positions, …

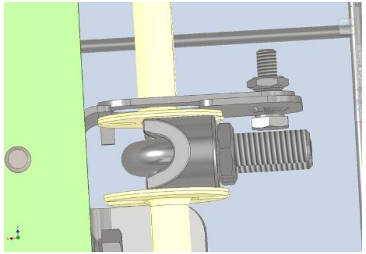
R&D related to PDS FD2-VD

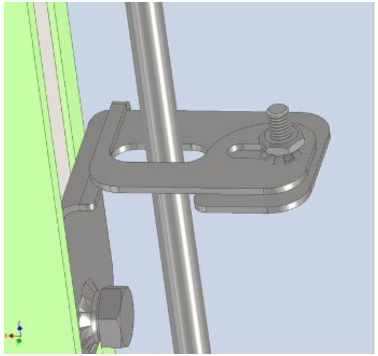
Membrane X-ARAPUCAs mechanical design and production for DUNE FD2

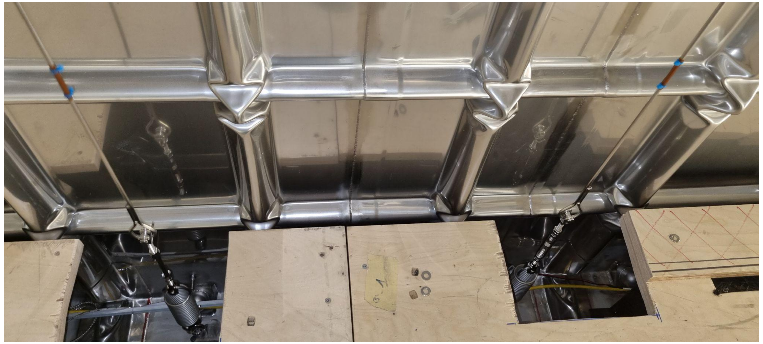


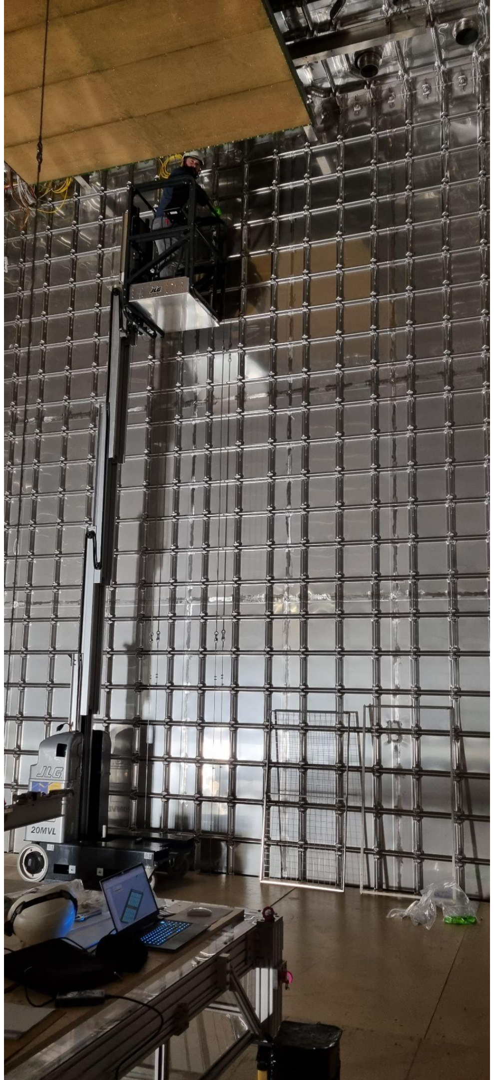








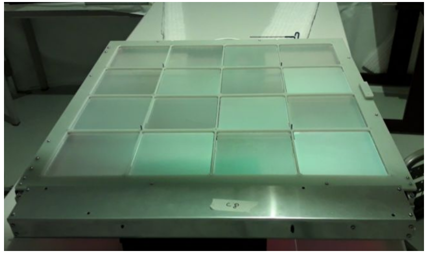


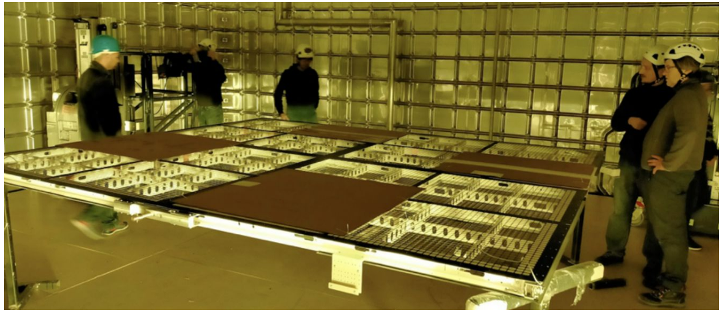

JLG
20MVL

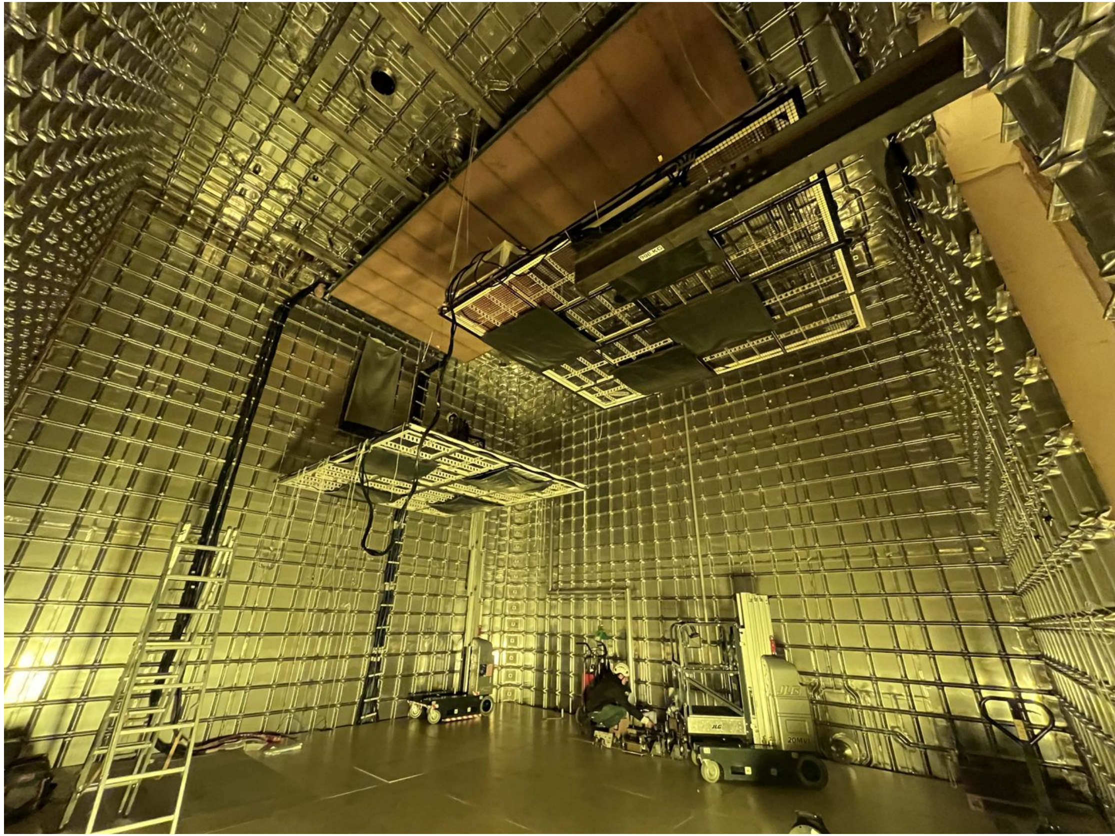
XAs installation in ProtoDUNE-VD

ProtoDUNE-VD

Installation of XAs on cathode

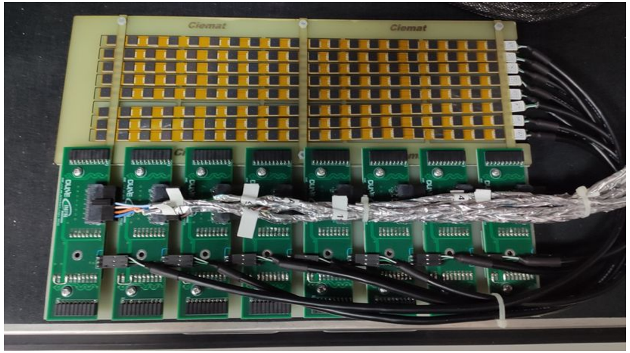






Tests of SiPMs in flexi boards

Test setup with 8 flex-boards connected to HD cold amplifiers (8 channels)



Aim:

- Check the **reliability of the soldering in LN_2**
- Check that there are **no SiPMs with high DCR**
- Check that all SiPMs are **well connected to the board**

Tests sequence:

IV reverse at room temperature to verify operation before thermal cycling

IV reverse in LN_2 (2^{nd} cycle thermal cycle)

Dark Counts Rate in LN_2 (3^{rd} thermal cycle)

Check SiPMs connection illuminating them one by one (room temperature)

Test results:

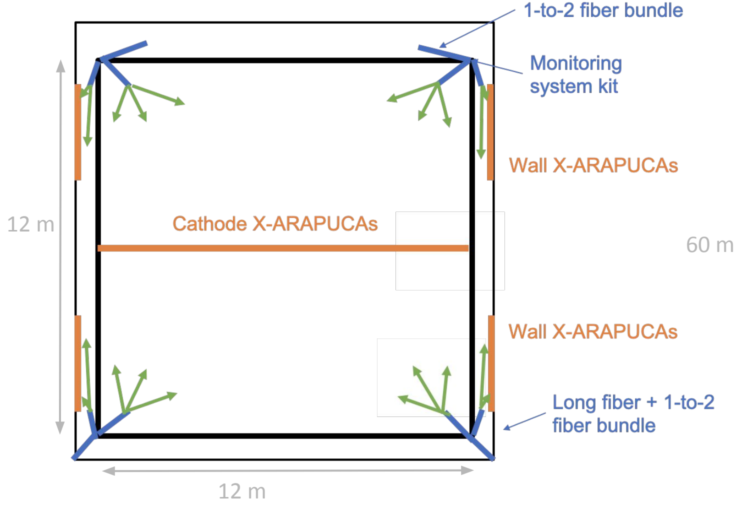
- ➔ All the boards passed the tests
- ➔ IV results in specifications
- ➔ No bad connections found on the SiPMs soldering to the flex boards

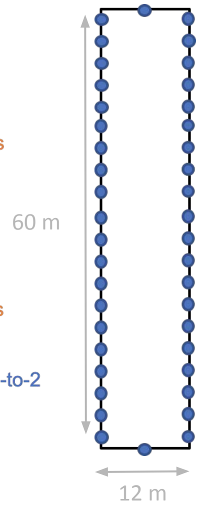
Flex-board	RT	LN2
	V_BR (V)	V_BR (V)
200011	51,80	41,90
200035	51,95	42,00
200034	51,90	42,05
200026	51,90	41,90
200033	51,90	42,00
200032	51,95	41,90
200031	51,90	41,90
200017	51,85	41,90
200006	51,90	41,90
200007	51,90	41,90
200030	51,95	42,00
200008	51,90	41,90
200009	51,85	41,90
200021	51,90	41,95
200010	51,85	41,90
Average	51,89	41,93
Vmax-Vmin	0,15	0,15

Flex-board	DCR (Hz)
200011	194,56
200035	127,57
200034	192,41
200026	168,89
200033	297,66
200032	137,43
200031	403,72
200017	334,11
200006	166,59
200007	380,97
200030	301,77
200008	637,97
200009	306,47
200021	422,84
200010	602,96
Average	311,73

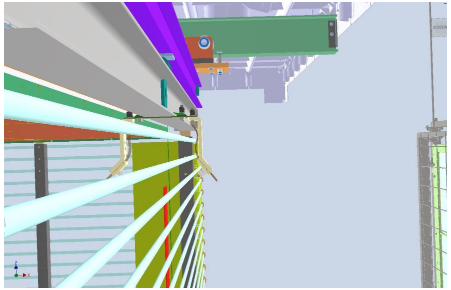
F2-VD Light Response Monitoring System

- Based on quartz fibers solarization resistant (two models tested in ProtoDUNE-VD).
- For every X-ARAPUCA membrane column (44 total columns) two monitoring-system kits are installed at the top/bottom beams that support the field cage





Monitoring system locations in FD2-VD (top view)

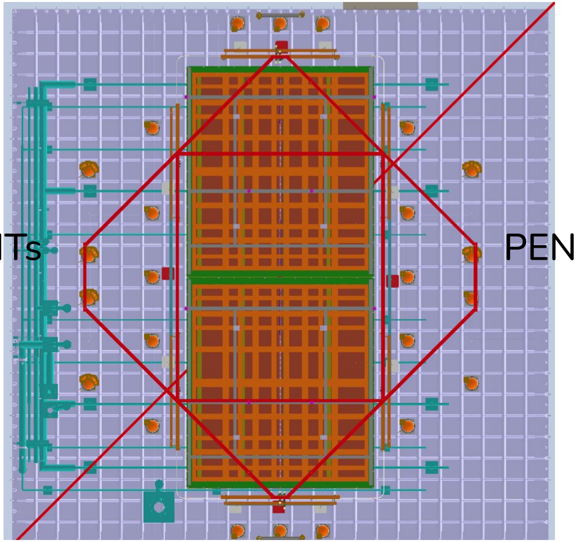


Top monitoring-system kit

Monitoring-system kit installation in ProtoDUNE-VD

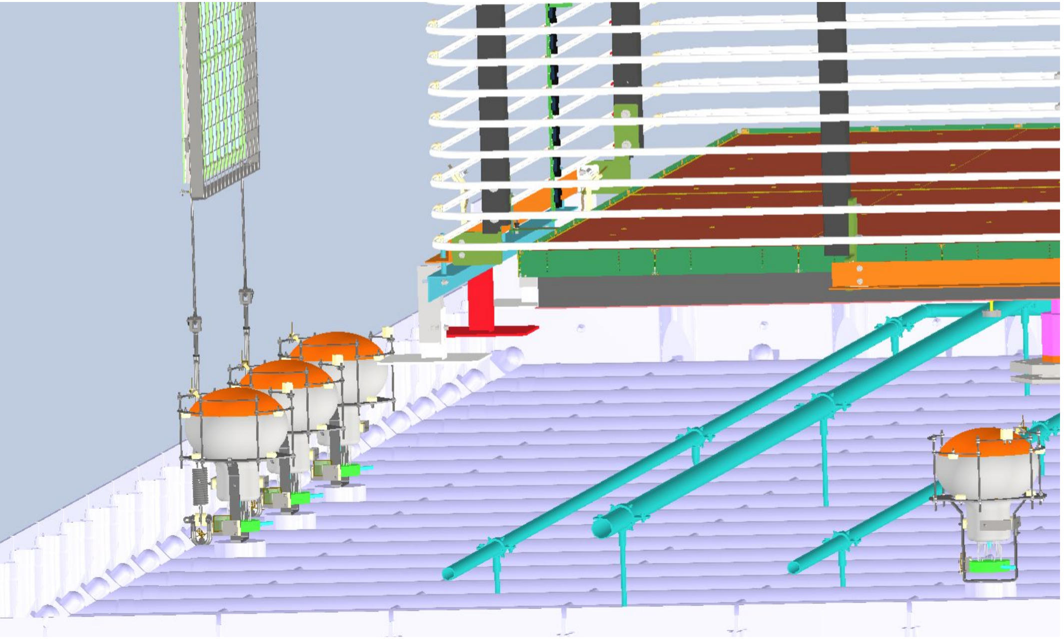
LED illuminated fiber pointing towards cathode X-ARAPUCAs in ProtoDUNE-VD

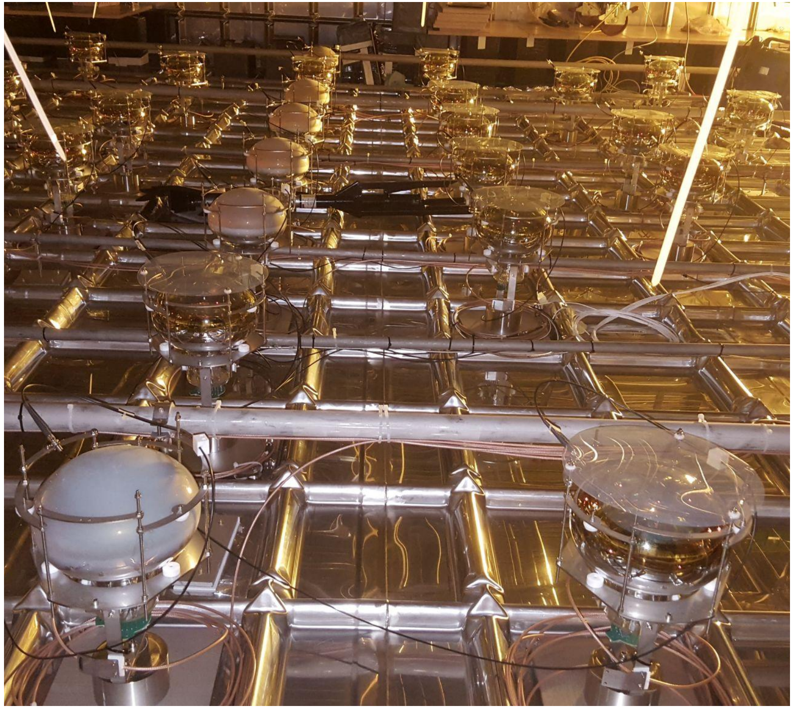
PMT installation in ProtoDUNE-VD



- Installation of 24 PMTs from ProtoDUNE-DP to ProtoDUNE-VD outside the field cage
- Goals:
  - Monitor the light yield
  - PDE X-ARAPUCA efficiency measurement by comparing with PMT QE
  - Study scintillation light production, propagation and absorption
- Successful and stable operation of PMTs in ProtoDUNE-DP with well known performance

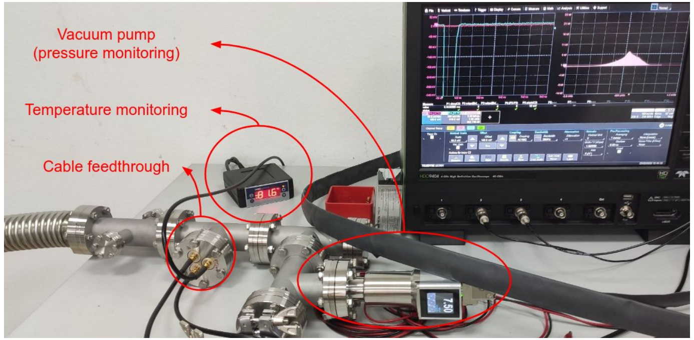
PMT installation in ProtoDUNE-VD





R&D on photon detectors and development of cryogenic setups

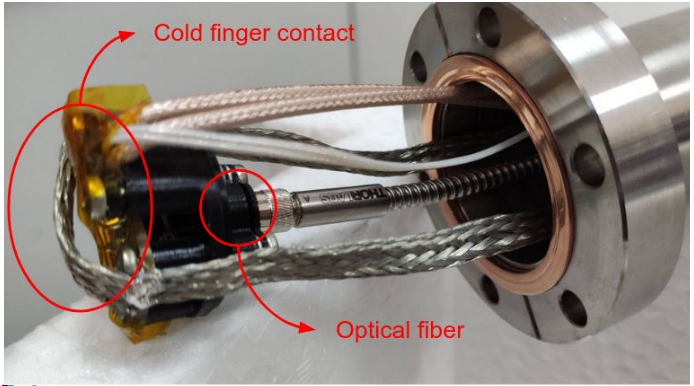
VUV SiPM characterization at LN_2 temperature



- VUV4 SiPM Hamamatsu, model S13370-6075CN
- PDE at cold can be computed by comparing the number of PEs detected sending the same amount of light at room and cryogenic T (obtained with a cold finger)

Measured by manufacturer

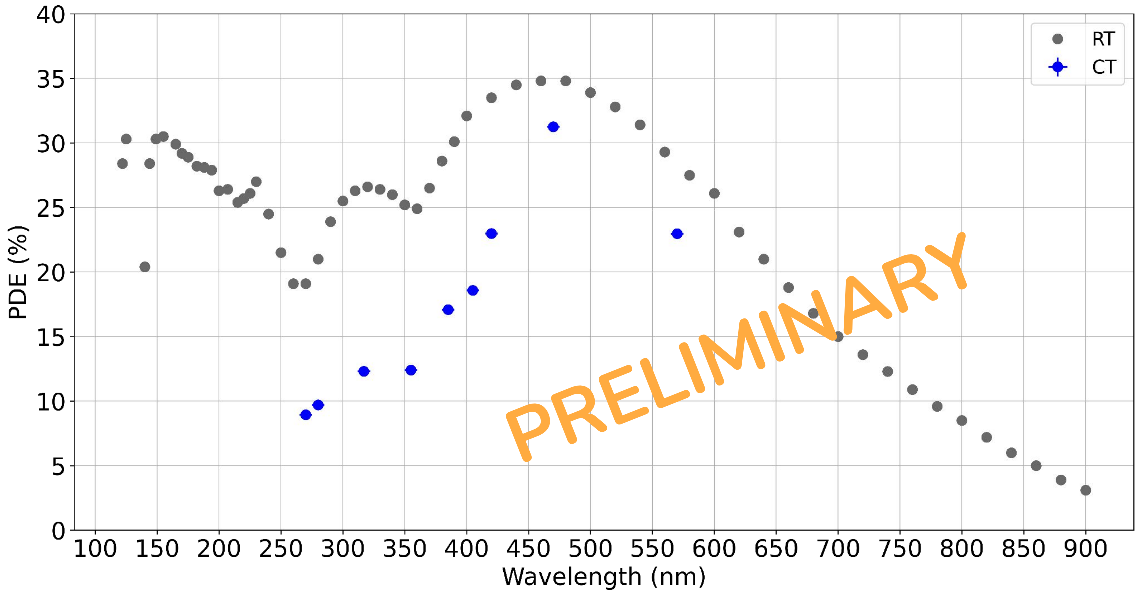
$$\frac{PDE_{CT}}{PDE_{RT}} = \frac{\#PE_{CT}}{\#PE_{RT}}$$



Procedure:

1. Calibration measurements at RT for three different OV values.
2. High-intensity light pulses at RT for different wavelengths.
3. Cooldown of the system to LN_2 temperature.
4. Calibration measurements at CT for three different OV values.
5. High-intensity light pulses at CT for different wavelengths.

VUV SiPM characterization at cryo T



- Decrease of the PDE at cryogenic temperature
- It also depends on the wavelength

RESULTS

Wavelength (nm)	PDE_CT (%)
270	8.94 ± 0.21
280	9.71 ± 0.22
317	12.31 ± 0.24
355	12.41 ± 0.22
385	17.09 ± 0.22
405	18.58 ± 0.25
420	22.98 ± 0.26
470	31.25 ± 0.25
570	22.97 ± 0.23

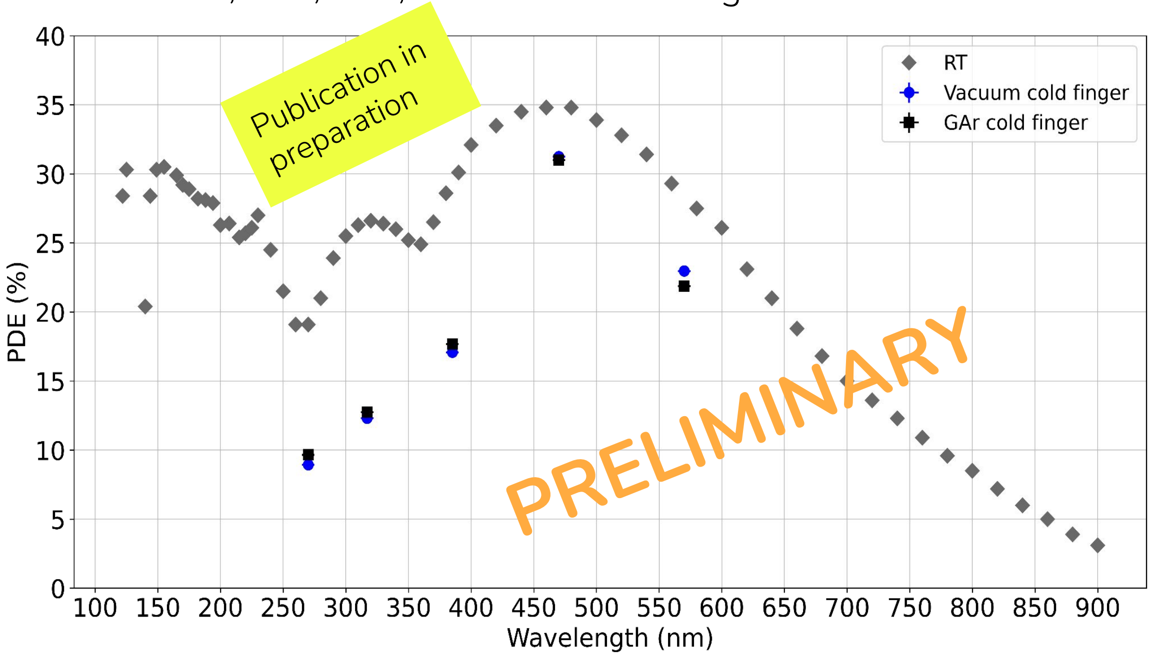
VUV SiPM characterization at cryo T (crosscheck)

- A second system with GAr is used for comparison
- Both methods provide similar results

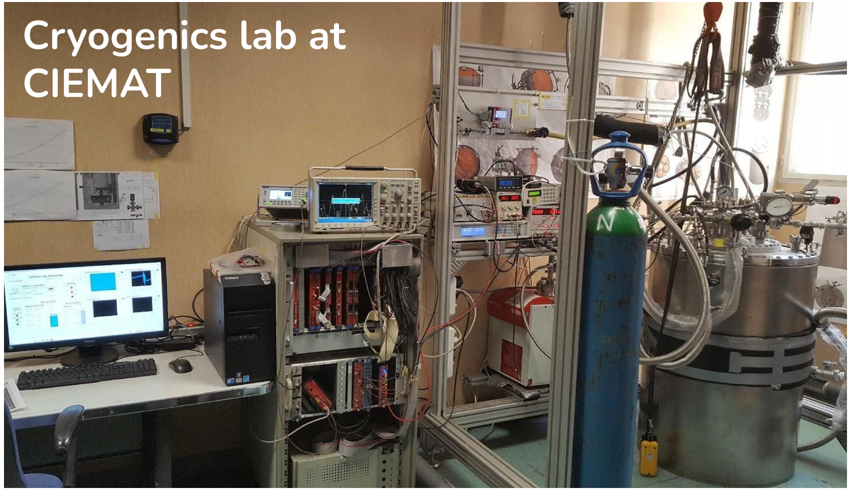
	PDE_CT (%)	
Wavelength (nm)	**Cold finger vacuum setup**	**GAr setup**
270	8.94 ± 0.21	9.66 ± 0.23
317	12.31 ± 0.24	12.75 ± 0.25
385	17.09 ± 0.22	17.67 ± 0.28
470	31.25 ± 0.25	31.01 ± 0.37
570	22.97 ± 0.23	21.87 ± 0.31

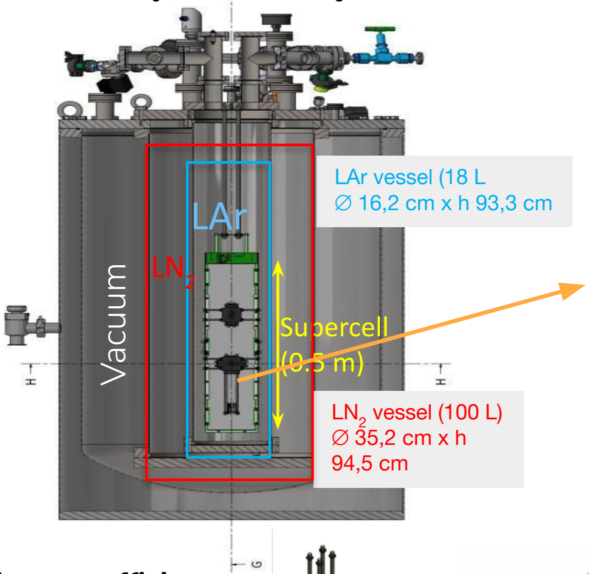
RESULTS

270, 317, 385, 470 and 570 nm light sources used

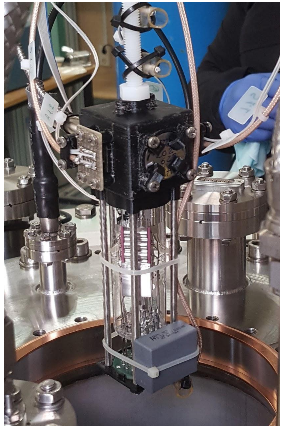


X-ARAPUCA detection efficiency setup

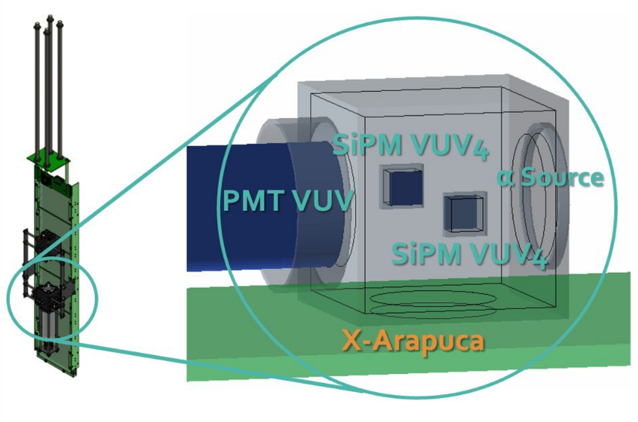




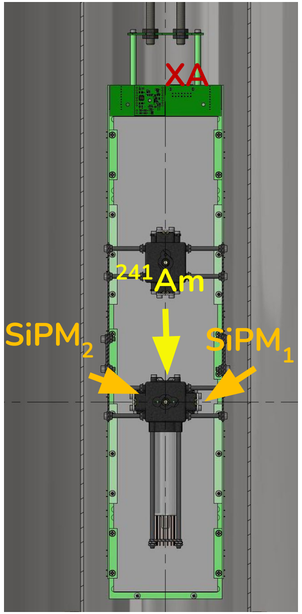
immersed in LAr



- **The efficiency is measured from the reference SiPMs with known efficiency**
- 2 **VUV sensitive SiPMs** are symmetrically placed with respect to the X-ARAPUCA and the **α source (^{241}Am)**
- 1” PMT (VUV sensitive) is used to get the τ_{slow} and scintillation light monitoring
- 3 configurations of XA tested: WLS plates from Eljen and Glass to Power and SiPMs from HPK and FBK

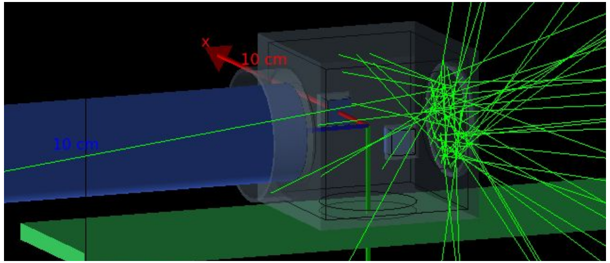


Final results of DUNE FD1-HD X-ARAPUCA detection efficiency



Method (A): reference SiPM comparison

$$\epsilon_A(XA) = \frac{PE_{mm^2}\,(XA)}{PE_{mm^2}(SiPM)} \cdot f_{corr} \cdot \epsilon(SiPM)$$



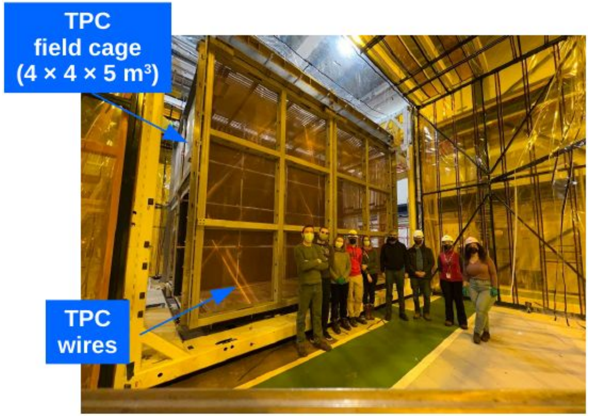
Method (B): simulation based $\epsilon_B(XA) = 100 \cdot \frac{PE(XA)}{\gamma_{expected}} \cdot f'_{corr}$

Publication in preparation

Method	PDE (FBK + EJ) %	PDE (HPK + EJ) %	PDE (HPK + G2P) %
(A)	**1.63 ± 0.12**	**1.78 ± 0.14**	**2.38 ± 0.18**
(B)	1.56 ± 0.12	1.72 ± 0.14	2.28 ± 0.19

- Results from both methods in agreement
- G2P plates present a higher efficiency

SBND Photon Detection System



120 8" Hamamatsu R5912 Cryogenic PMTs mounted behind the wire planes

→ 96 coated with TPB, 24 uncoated

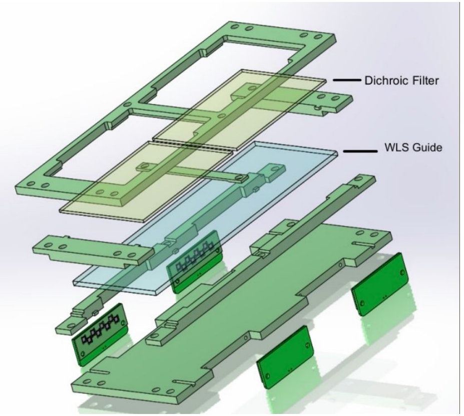
192 X-ARAPUCAs

→ Half coated with pTP, half uncoated

Wavelength-shifting (TPB) reflector foils on the Cathode Plane Assembly.

Start of operations by the end of 2023

SBND X-ARAPUCA



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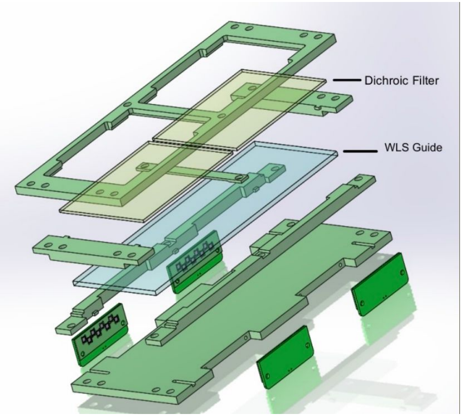
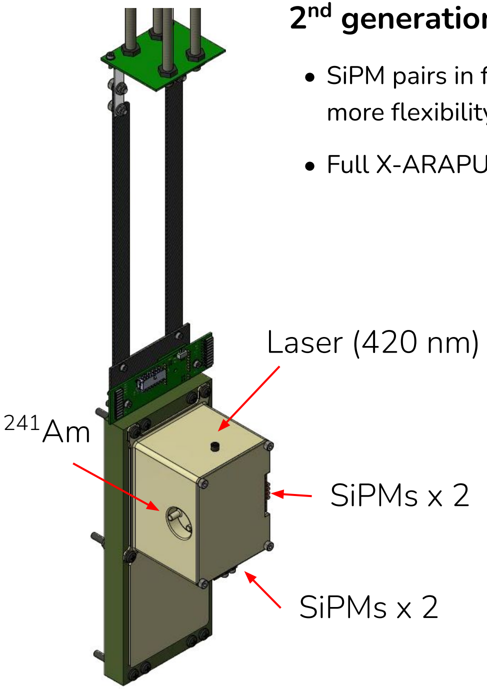


Measurements of SBND X-ARAPUCA PDE

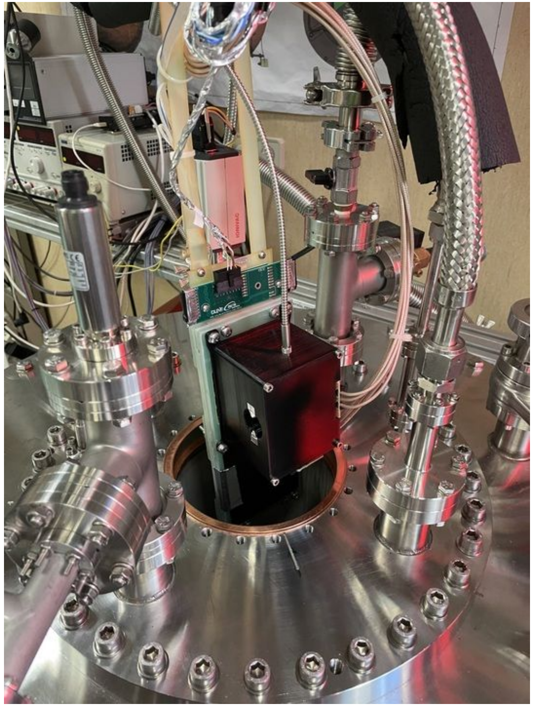


SBND X-ARAPUCA

2nd generation calibration box

- SiPM pairs in front of each light source to minimize angular uncertainties. Also more flexibility for triggers.
- Full X-ARAPUCA window coverage to eliminate shadowing effects.

4 X-ARAPUCA configurations tested		
SiPMs	**WLS Bar**	**Filter**
SensL	Eljen 286	pTP coated 400 nm cutoff
SensL	Eljen 280	450 nm cutoff (only visible light)
HPK	Glass to power (blue)	pTP coated 400 nm cutoff
HPK	Glass to power (green)	450 nm cutoff (only visible light)



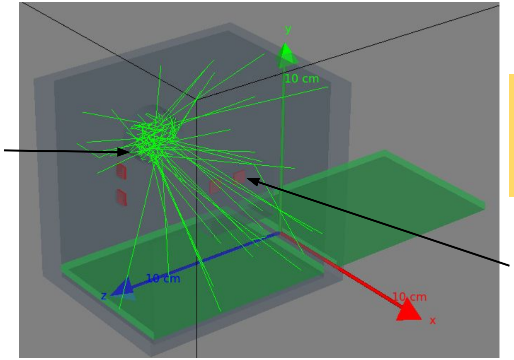
First measurements of PDE for both VUV and visible light

AIDA innova

Preliminary tests of SBND X-ARAPUCA PDE

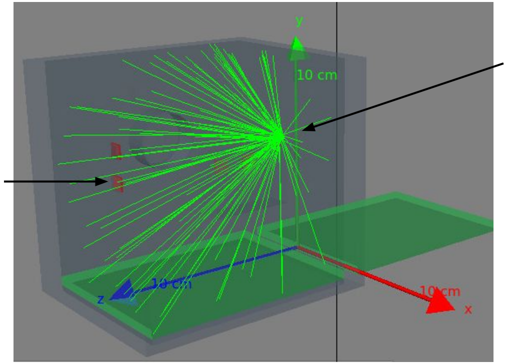
G4 simulations of the setup

^{241}Am



VUV light from α source

SiPMs x 2

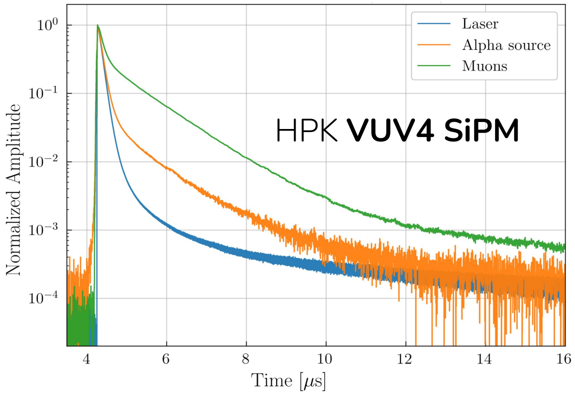


Laser (420 nm)

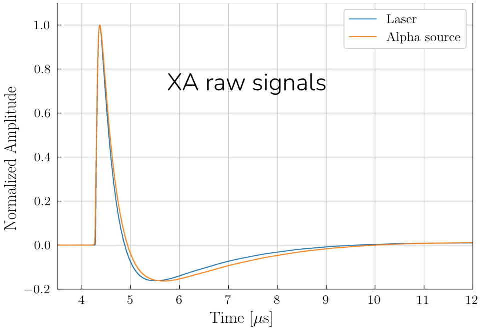
Visible light from laser

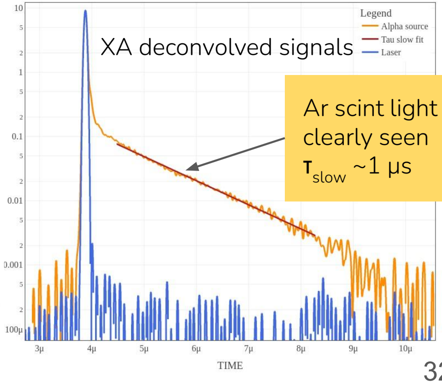
SiPMs x 2

Measured averaged waveforms



VUV XA (SensL SiPMs + Eljen 286 bar)





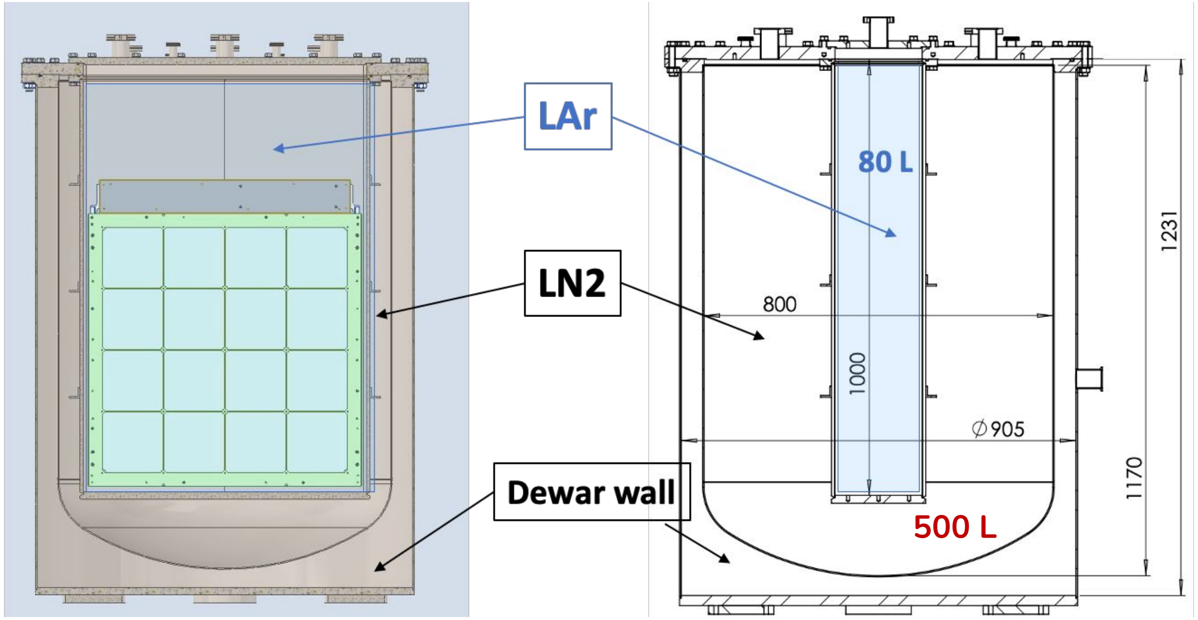
Ar scint light clearly seen τ_{slow} ~1 μs

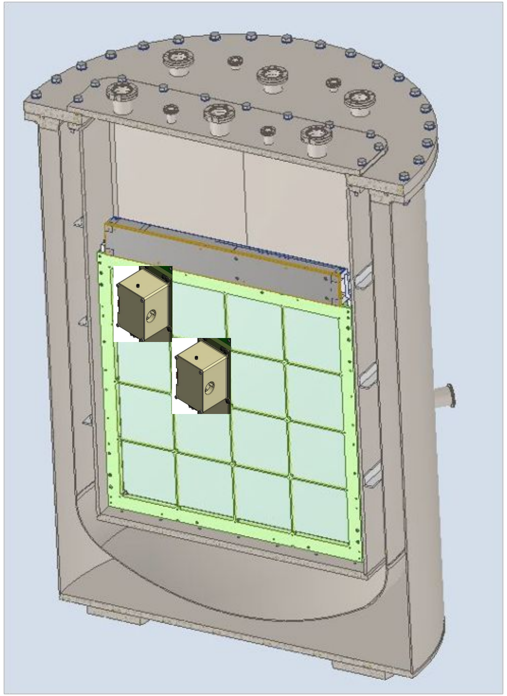
Data analysis in progress

AIDA innova

New setup for FD2-VD X-ARAPUCA modules PDE measurement

- PDE measurement in several positions by moving the calibration box (with α-source + 4 VUV SiPM reference sensors) to different windows
- Same methodology, same cryogenics system, bigger vessels to allocate larger X-ARAPUCAs

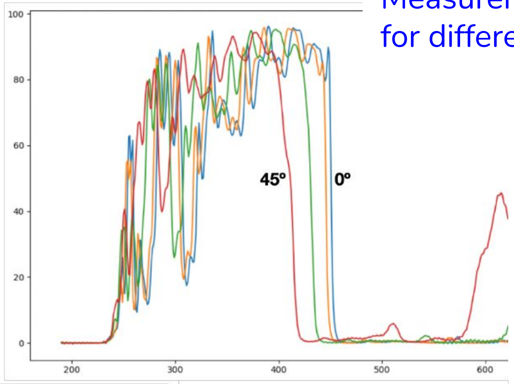




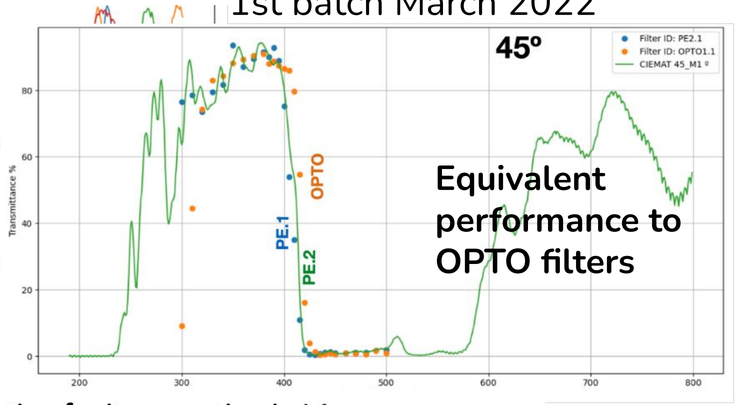
R&D on dichroic filters

Spanish company Photon-Export able to provide high quality filters

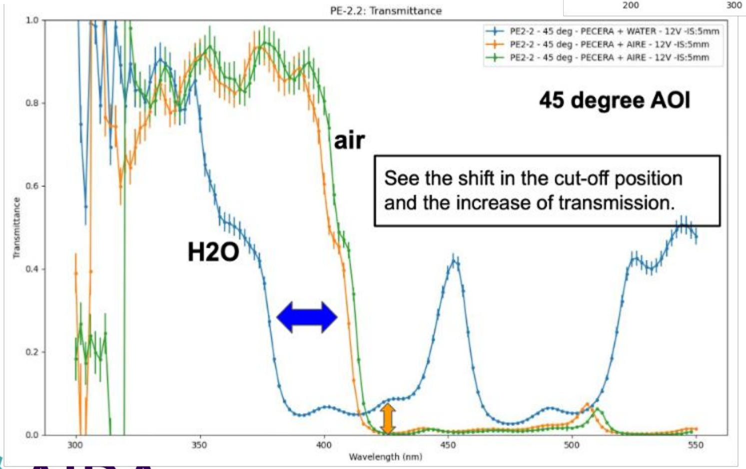
Measurements done at CIEMAT for different angles



1st batch March 2022



Equivalent performance to OPTO filters



Optimization for its operation in LAr

increasing the filter effective refractive index

Current filters optimized for 45 deg incident light and air medium
For a medium with higher refractive index (H_2O, LAr):

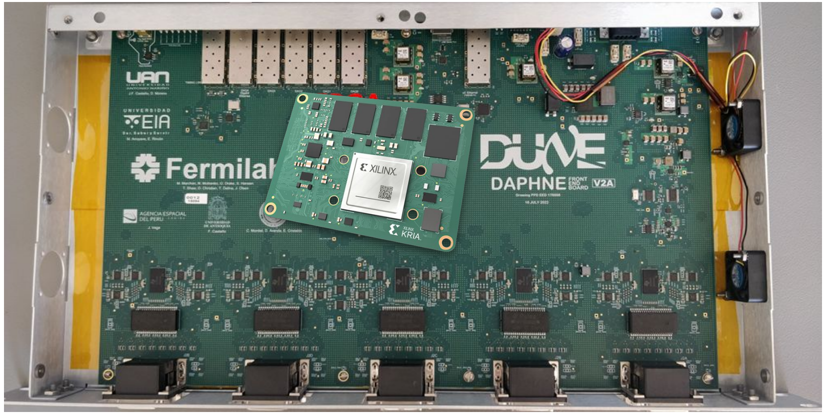
- Cut-off λ moves to lower values: $\frac{\lambda_2}{\lambda_1} = \sqrt{1-(\frac{n_1}{n_2}\sin\theta)^2}$
- Reflectivity above cut-off decreases: $R = \left|\frac{n_1-n_2}{n_1+n_2}\right|$

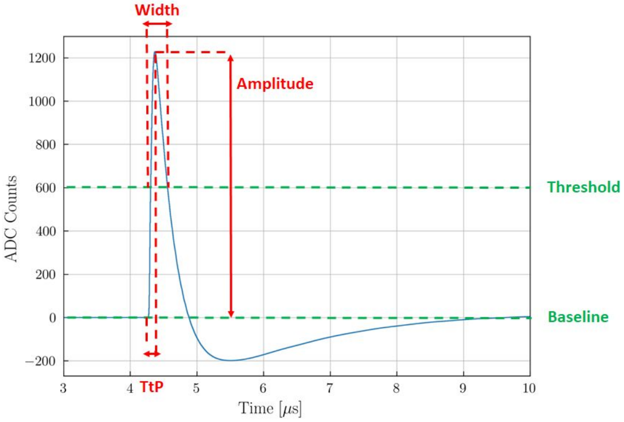
R&D on DAPHNE front-end readout electronics

New Firmware developments for DAPHNE V3 (under design) based on the new Xilinx KRIA SOM that will replace current FPGA and MCU. Now working on DAPHNE V2A:

- Design and implementation of a **self-trigger algorithm** for zero suppression, based on signal amplitude coincidence on two channels (same VD X-ARAPUCA).
- **Real-time calculation** of different parameters (trigger primitives) from the SiPM's waveform:
  - Peak Time
  - Width (signal width above threshold)
  - Amplitude (at peak-time)
  - Charge (area above baseline)
  - Number of PEs

The **online PDS trigger algorithm** in the DAQ will use those parameters for the global trigger decision (also working in the algorithm definition using signal and background simulation)





Summary

CIEMAT neutrino group is involved in R&D for light readout systems for LAr TPCs

1. R&D on **new cryogenic SiPM models** for DUNE → final characterization results
2. Development of **assembly and test facilities for cryogenic photon detector systems at large scale**
    a. Including a **dedicated setup for absolute VUV light detection efficiency at cryogenic temperature** (being used for DUNE FD1, SBND, DUNE FD2 photon detectors)
3. Design and production of dedicated **PDS mechanical and calibration systems** for the DUNE FD2 Photon Detection System → being tested in ProtoDUNE-VD at CERN
4. **Optimization of photon collectors** (X-ARAPUCAs)
    a. Dichroic filters
    b. Front-end electronics
5. Starting an effort on **alternative photon detectors** to increase the photocoverage and PDE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¡GRACIAS!
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