Photon Detection System – Horizontal Drift

Ettore Segreto
UNICAMP (Brazil)

Final Design Review
March 14, 2023

Conselho Nacional de Desenvolvimento Científico e Tecnológico

SÃO PAULO RESEARCH FOUNDATION

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Charge

The committee should consider:

1) How design choices satisfy the requirements.
2) The completeness of the documentation of mechanical specifications, including 3D model and the 2D drawings for standard and custom components as well as the Compliance Office evaluation focusing on both safety and the proper application of design codes and standards.
3) The completeness of the documentation of electrical specifications, including system schematics, drawings, connections, and grounding details.
4) Whether transportation and installation plans are mature enough to provide assurance that the PDS components, as currently designed, can be safely transported and installed within the detector.
5) Whether lessons learned from ProtoDUNE-SP and other prototypes have been appropriately incorporated within the current design and if the design has been validated through the integration, testing, and installation of Module 0 components for ProtoDUNE-II.
6) If draft documentation detailing plans for procurement, manufacturing, quality control, and part identifiers exists at a sufficient level of maturity for this stage of the design.
7) If project planning materials including interface documents, risk assessments, schedules, and cost estimates exist at a sufficient level of development for this stage of the design.
8) Whether recommendations from previous reviews have been appropriately addressed.

9) List of the documents can be faound here: https://edms.cern.ch/document/2812570/1

PD Consortium structure

More than 50 Participating Institutions *distributed among Latin America, North America, Europe and Asia*

Ettore Segreto
Lead

Flavio Cavanna
Deputy for FD2

David Warner
Francesco Terranova
Technical Coordinators

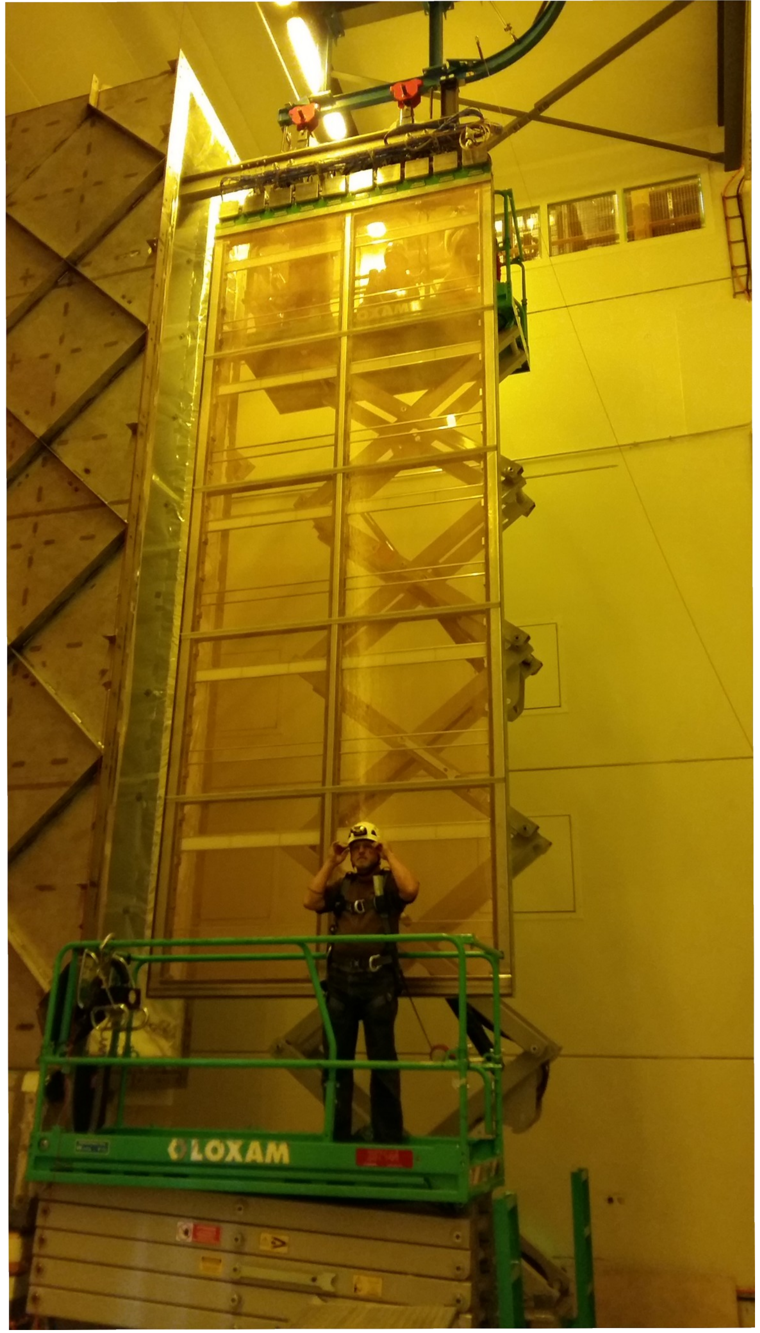
Physics/Simulations WG
Conveners
Laura Paulucci
Michel Sorel
Andrzej Szelc

Light Collector WG
Conveners
Ana Machado
Carla Cattadori
Carmen Palomares

Photosensor WG
Conveners
Vishnu Zutshi
Inés Gil-Botella
Alessandro Montanari

Electronics/Cabling WG
Conveners
Claudio Gotti
Deywis Moreno

protoDUNE WG
Conveners
Paola Sala
Zelimir Djurcic
Jaroslav Zalesak

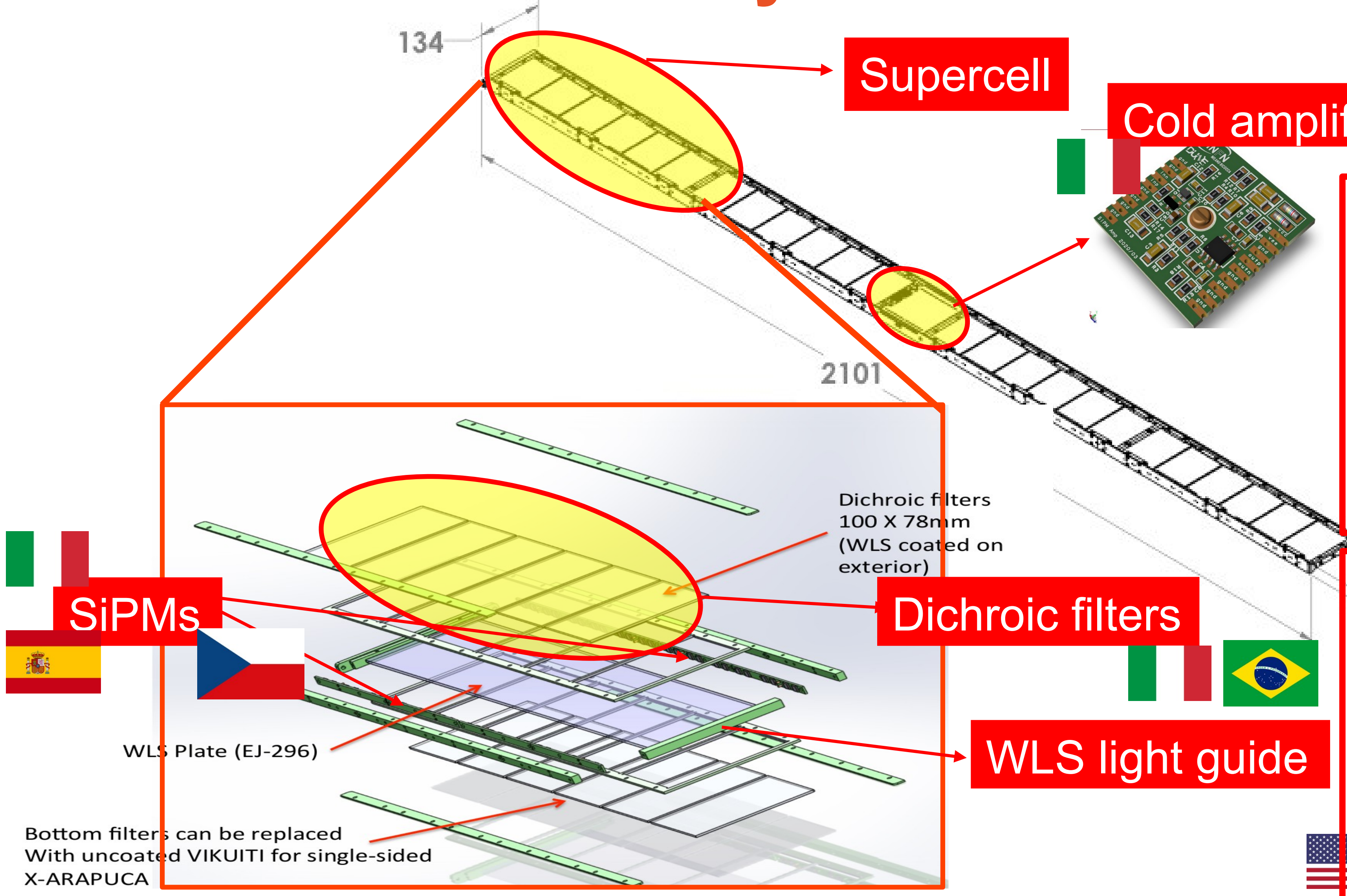


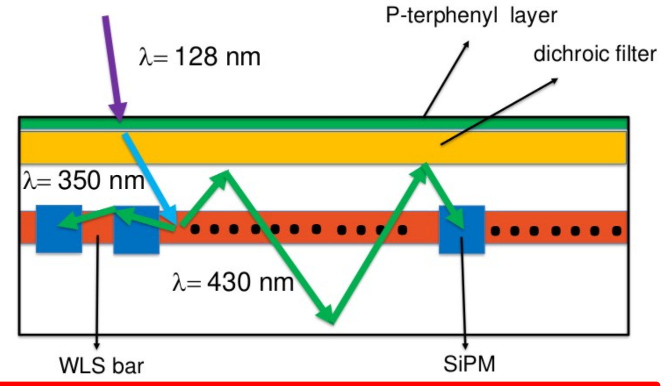
PDS – Horizontal Drift

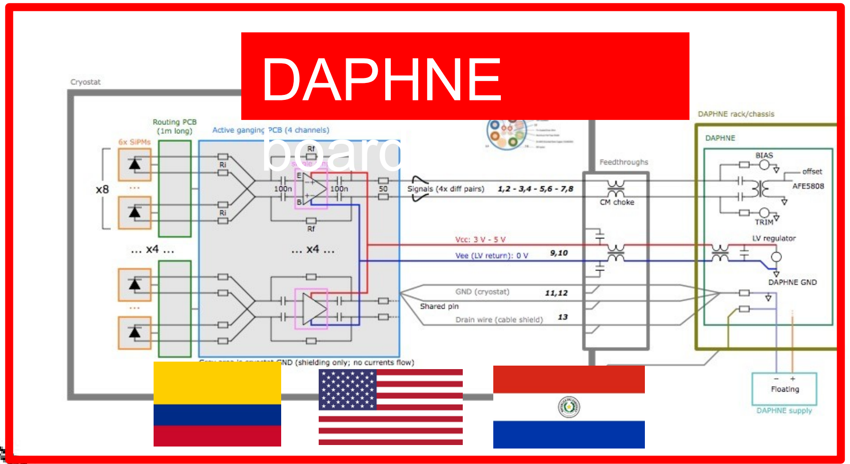
Bar shaped modules (210 cm x 12 cm) slided inside the APA frames between wire planes

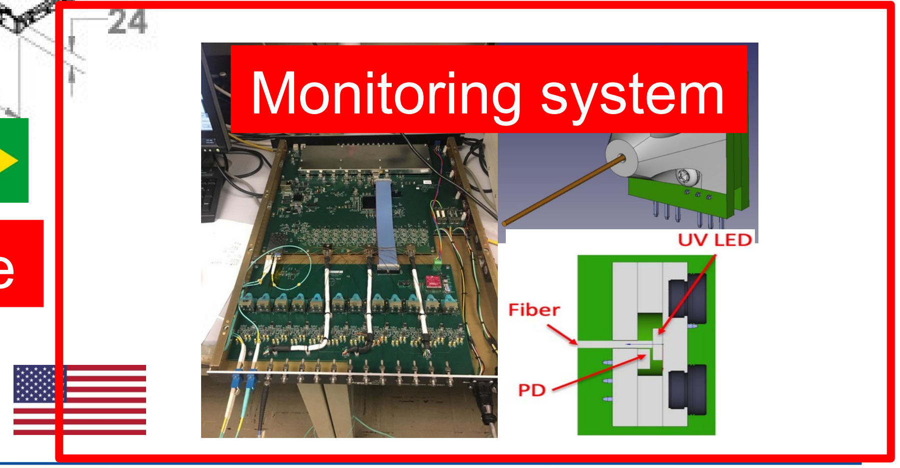
- 10 modules per APA , ***1,500 modules in total***
  - *500 double sided modlues (detect light from boths sides – Central APAs)*
  - *1000 single sided (detect light from one side – Lateral APAs)*
- Cold electronics, ganging SIPM signals, at the center of each bar
- Ganged signals read-out by DAPHNE board (warm electronics)
- Monitoring system with external LED pulsers, optical fibers and diffusers

Photon Detection System – FD1









PDS baseline configuration

Component	Description	Quantity
Light Collector	X-ARAPUCA	4 supercell/module - 10 modules/AP – 1500 modules (1000 single sided; 500 double sided) in total
Dichroic filters	100 mm x 77 mm (1 mm thickness)– cutoff @ 400 nm	6 (12) filters/supercell – 24 (48) filters/module – 48,000 filters in total
WLS plates	100 mm x 470 mm (3.5 mm thick): G2P	1 plate/supercell – 4 plates/module – 600 plates in total
Photosensor	6 mm×6 mm: Hamamatsu MPPC & FBK SiPM	192 SiPMs per module; 288,000 total
SiPM signal summing	1 active circuit per supercell	4 channels/module; 6000 total
Readout electronics	Based on commercial ultrasound chip	4 channels/module; 6000 total
Calibration and monitoring	Pulsed UV via cathode-mounted diffusers	51 diffusers/CPA side; 204 diffusers for 4 CPA sides

EB Held Requirements

Label	Description	Specification (Goal)	Rationale	Validation
FD-3	Light yield	$>$ 20 PE/MeV (avg), $>$ 0.5 PE/MeV (min)	Gives PDS energy resolution comparable to that of the TPC for 5-7 MeV SN νs, and allows tagging of $>$ 99 % of nucleon decay backgrounds with light at all points in detector.	Supernova and nucleon decay events in the FD with full simulation and reconstruction.
FD-4	Time resolution	$< 1\,\mu s$ (< 100 ns)	Enables 1 mm position resolution for 10 MeV SNB candidate events for instantaneous rate $< 1\,m^{-3}ms^{-1}$.	
FD-15	LAr nitrogen contamination	< 25 ppm	Maintain 0.5 PE/MeV PDS sensitivity required for triggering proton decay near cathode.	In situ measurement

LBNF/DUNE

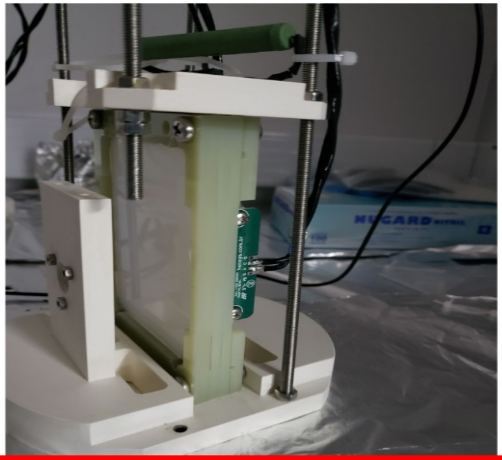
EB Held Requirements

See L. Paulucci talk

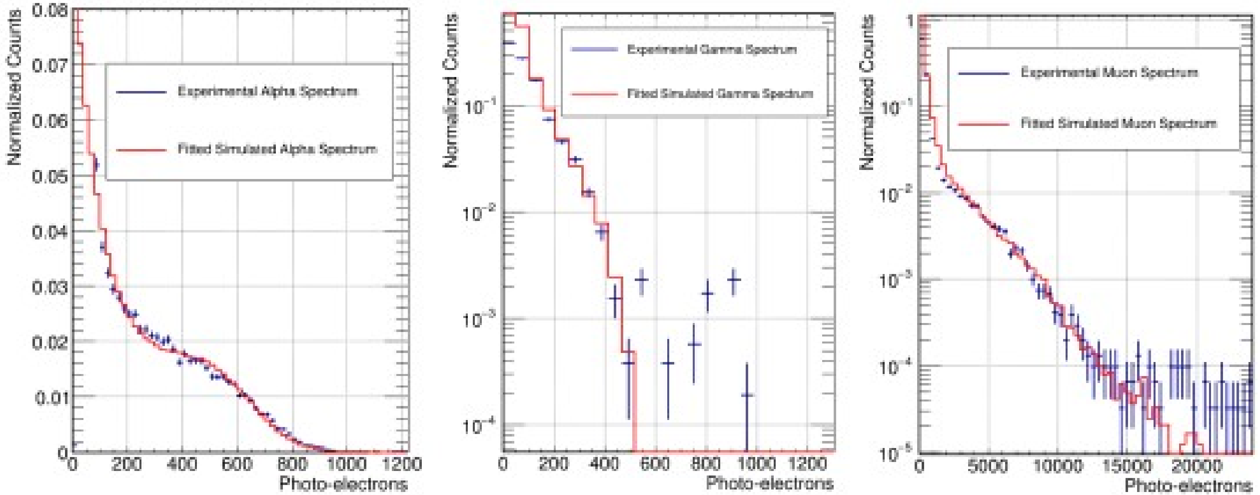
Description	Specification	Estimated performance	Rationale
Light Yield	>20 PE/MeV (avg), >0.5 PE/MeV (min)	~30 PE/MeV (avg), ~5 PE/MeV (min)	Supernova calorimetry and NDK fiducialization
Time resolution	< 1 μs Goal: < 100 ns	Fast sampling (62.5 MHz)	Enables 1 mm position resolution along drift direction
Signal to noise	> 4	~6 (from ProtoDUNE-SP)	Sufficiently high to keep data rate within electronics bandwidth limits and to ensure efficient trigger

- Performance estimated through ***a complete MC simulaiton*** assuming a detection efficiency of the *X-ARAPUCA of 3%*
- **A detection efficiency of 2% is enough to meet requirements**

X-ARAPUCA validation – small scale prototypes



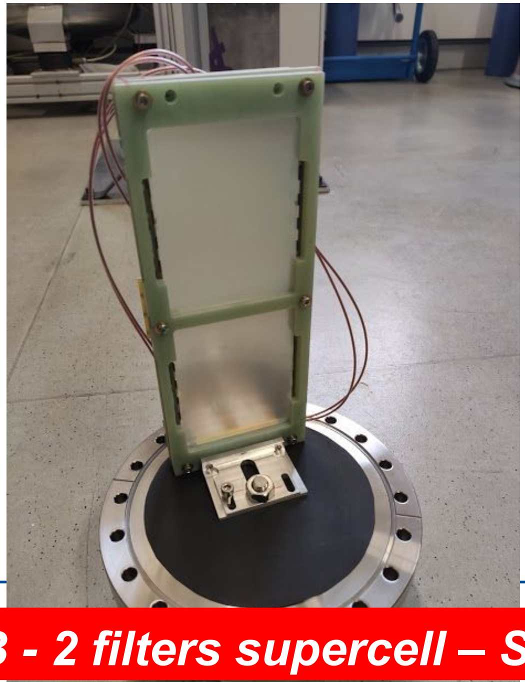
UNICAMP - 1 filter supercell



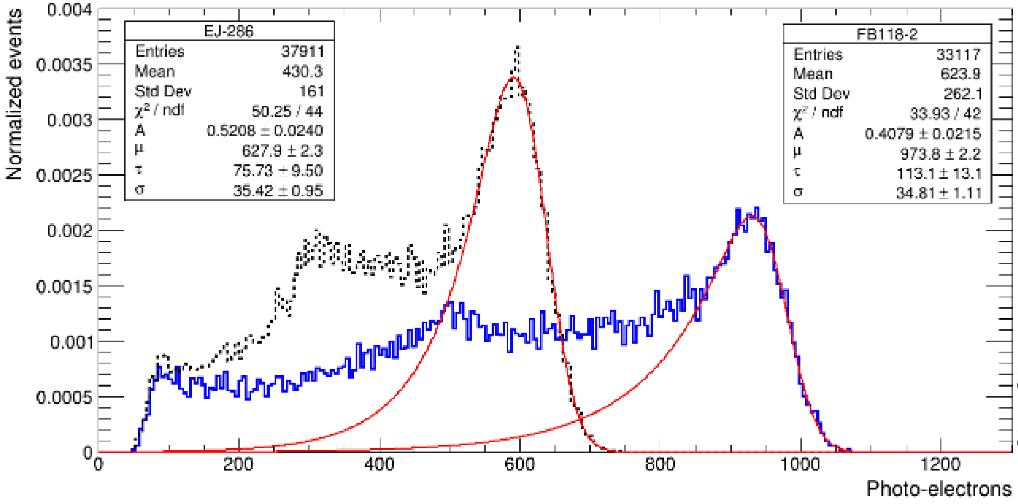
- 8 Hamamatu MPPC (non-downselcted)
- 1 ELJEN WLS plate
- 1 OPTO filter

Efficiency estimated with α, μ

ε = 2.3 ± 0.4 % @ 50% PDE



MiB - 2 filters supercell – SBND model



- *16 Hamamatsu MPPC (non-downselcted)*
- *1 G2P (ELJEN) WLS plate*
- *2 OPTO filters*

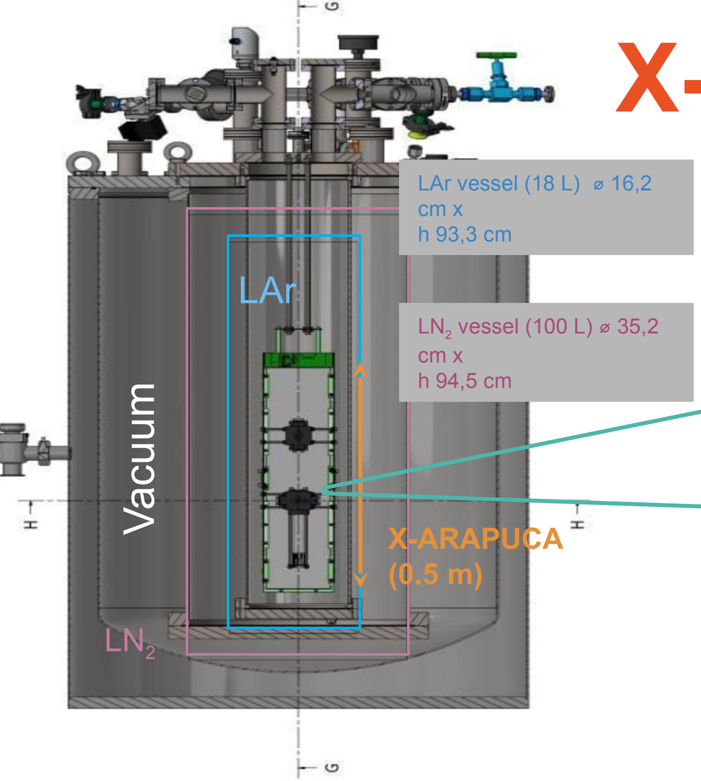
ε_{ELJ} = 1.9 ± 0.1 % (@ 50% PDE – ELJ)

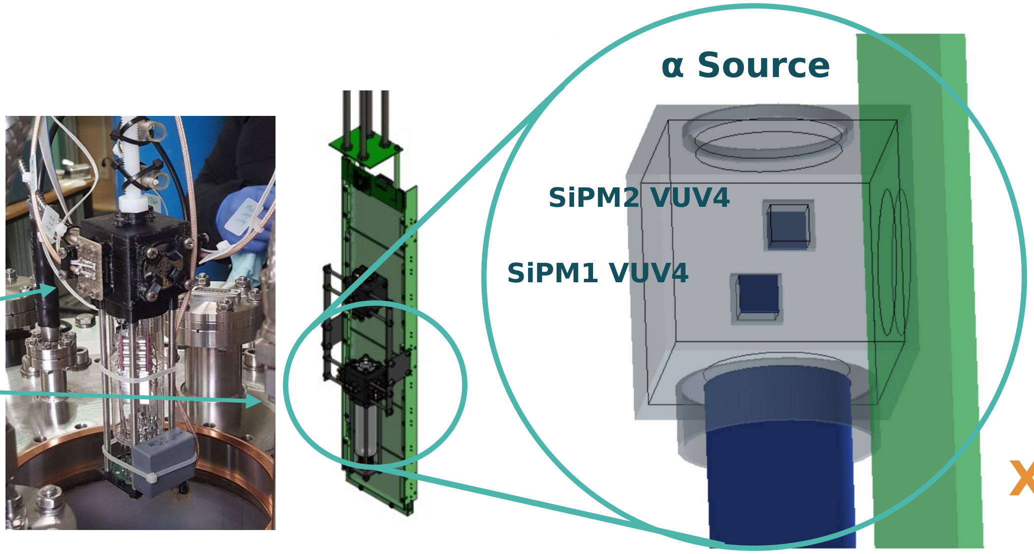
ε_{G2P}= 2.9 ± 0.1 % (@ 50% PDE - G2P)

Efficiency estimated with α particles

X-ARAPUCA validation – supercell

CIEMAT





2 VUV sensitive **SiPMs** are symmetrically placed with respect to the **X-ARAPUCA** and alpha source (^{241}Am)

$$\epsilon_{XA}\,(\%) = \frac{PE_{mm^2}\,(XA)}{PE_{mm^2}\,(Ref.\ SiPM)} \cdot f_{corr} \cdot \epsilon(Ref.\,SiPMs)$$

$$\epsilon_{XA}\,(\%) \;=\; 100 \cdot \frac{PE(XA)}{\gamma_{\text{expected}}} \cdot f'_{corr}$$

ϵ(Ref. SiPMs) = 11.3%

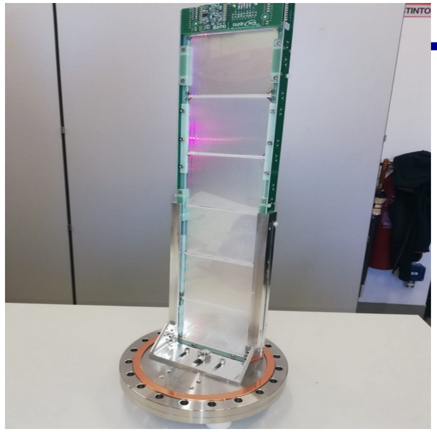
ε_{XA}(%) - DIRECT MEASUREMENT (VUV4 Comparison)

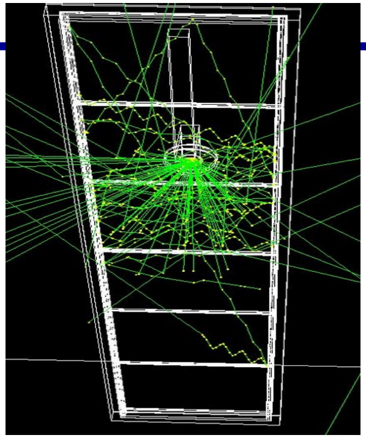
	FBK+EJ	HPK +EJ	HPK +G2P
PDE 40%	1.41 ± 0.11	1.56 ± 0.12	**2.12 ± 0.16**
PDE 45%	1.63 ± 0.12	1.78 ± 0.14	**2.38 ± 0.18**
PDE 50%	2.01 ± 0.15	1.93 ± 0.15	**2.58 ± 0.20**

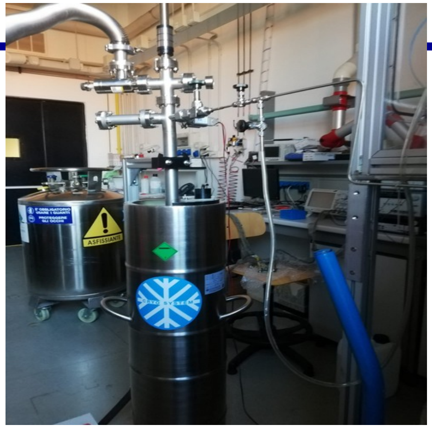
ε_{XA}(%) - CROSSCHECK (From known LY and MonteCarlo)

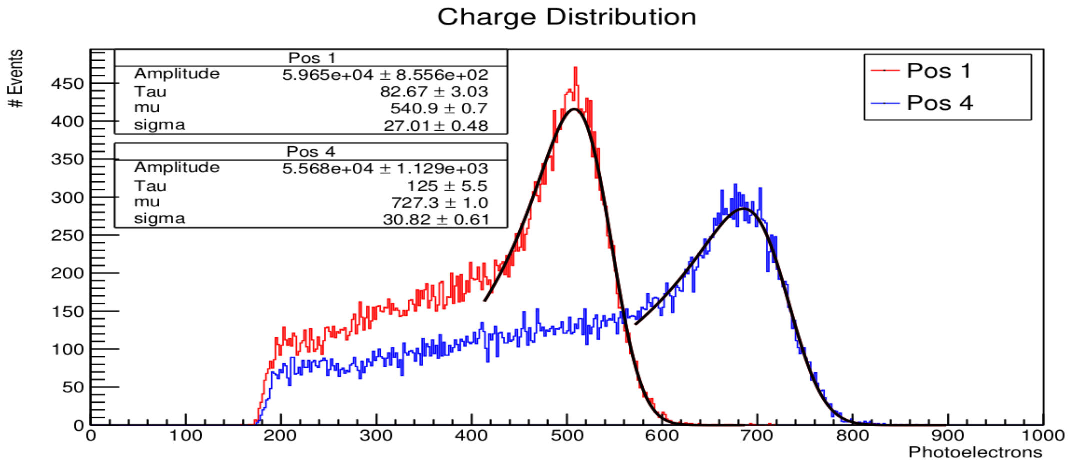
	FBK+EJ	HPK +EJ	HPK +G2P
PDE 40%	1.34 ± 0.10	1.51 ± 0.12	**2.02 ± 0.17**
PDE 45%	1.56 ± 0.12	1.72 ± 0.14	**2.28 ± 0.19**
PDE 50%	1.93 ± 0.15	1.87 ± 0.15	**2.51 ± 0.21**

X-ARAPUCA validation – supercell





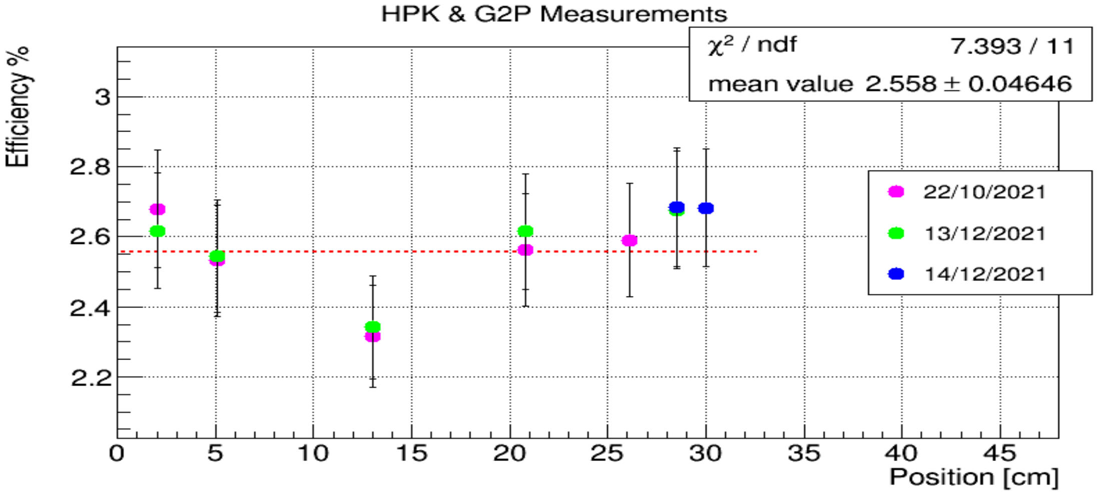




Method: z-scanning of the whole cell (~2 Sr) with an ^{241}Am exposed α source

(JINST 16 (2021)09027).

$$\epsilon = \frac{4\pi \cdot \alpha \text{ peak(ADC)}}{\text{s.ph.e.(ADC)} \cdot f_{int} \cdot \text{LY}_{\text{LAr}} \cdot \text{En}_{\alpha} \cdot \text{q}_{\alpha} \cdot \Omega}$$



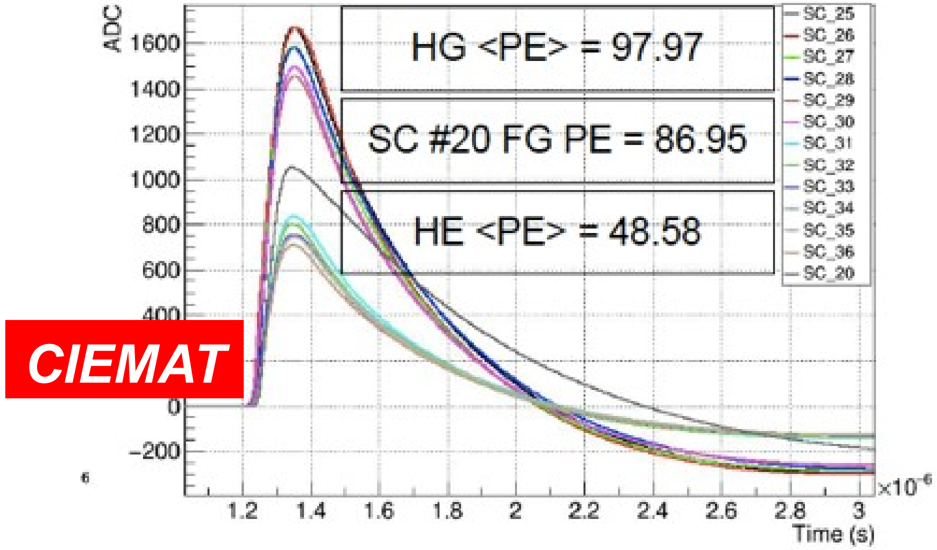
No correction for LAr purity applied. Expected: +2% to +5%

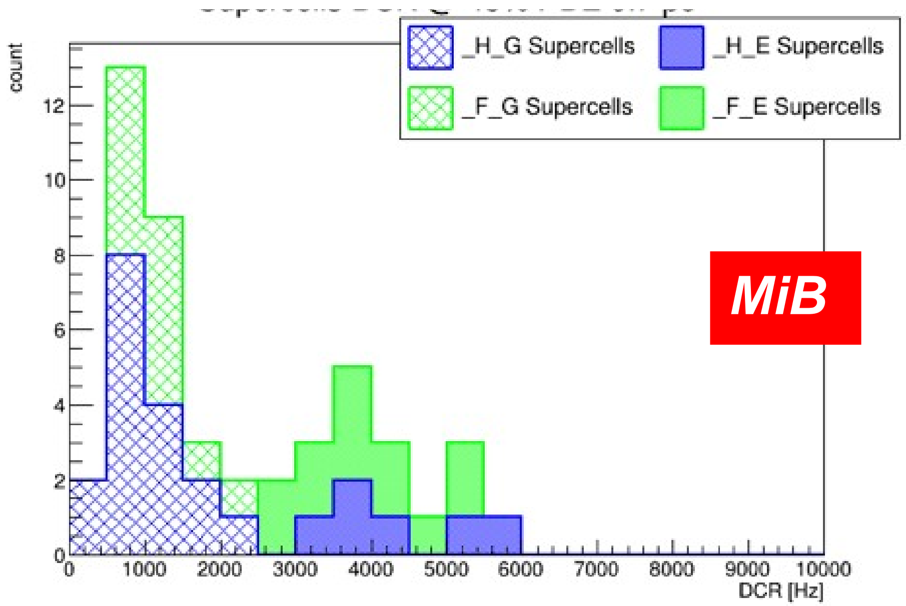
	SiPM PDE	XA PDE MiB Xtalk corr.	XA PDE CIEMAT Xtalk corr.
HPK & G2P	50%	**2.2** (0.15)	**2.51** (0.21)
FBK & G2P	50%	**2.0** (0.14)	
FBK & Eljen	50%	**1.7** (0.14)	**1.56** (0.12)

- The efficiency can be slightly improved ***with the optimization of AOI of the filters***

WLS plates

- The new WLS plate developed by ***INFN-MiB*** and the ***Material Science Department @ MiB*** and produced by the italian compnay **Glass2Power (G2P)** performs better than *EJ-286* (presented as baseline option at the Preliminary Design Review)
  - **Higher light yield (~25-30%):** *higher conversion efficiency* and *better optical properties of the lightguide*
  - **Reduced dark count rate:** *PMMA does not scintillate (unlike the EJ-286 polistyrene matrix)*
- G2P WLS-plates represent our baseline. Waiting for final validtion in protoDUNE

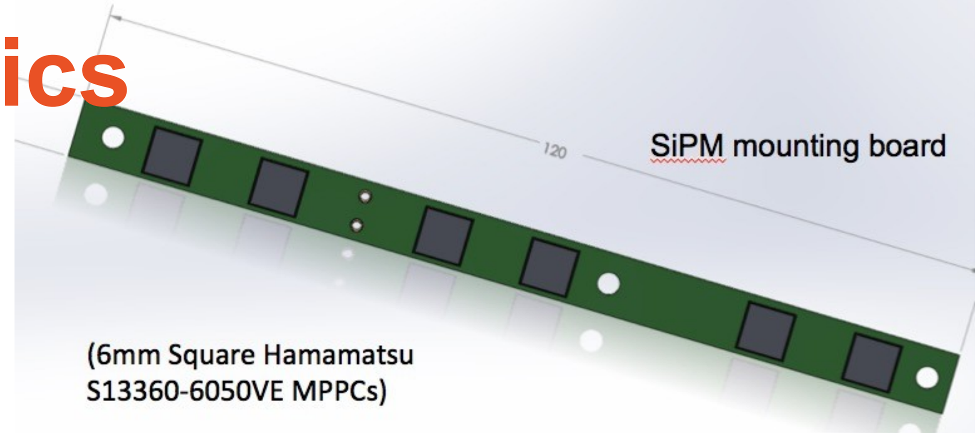




Stability of pTP films

- pTP film is coated on the glass side of the dichroic filter. **The film is robust and mechanically stable at LAr temperature**. *Cooling down needs to be relatively slow (few mm/min during our tests)*
- **No evidence of cracking or of detachment** in tens of tests performed at *UNIMCAP, MiB, CIEMAT, CSU and in the ARAPUCAs extracted from protoDUNE (Run 1)*
- The eventual solubility of pTP in LAr will be studied at the *PULArC* facility at UNICAMP;
- PULArC is a complete test stand for the purification of LAr. It consists of a 90 liters, vacuum tight cryostat, a Barber Nichols submerged pump, two purity monitors, scintillation light detectors. Possibility of using different filtering media;
- pTP coated filters will be immersed in liquid argon for few days and then the liquid will be filtered through a sintered disk to remove flakes and through a molecular sieve to capture dissolved pTP. Molecular sieve will be analyzed to check for the presence of captured pTP. Same procedure as https://arxiv.org/pdf/1804.00011.pdf (J. Asaadi et al.)

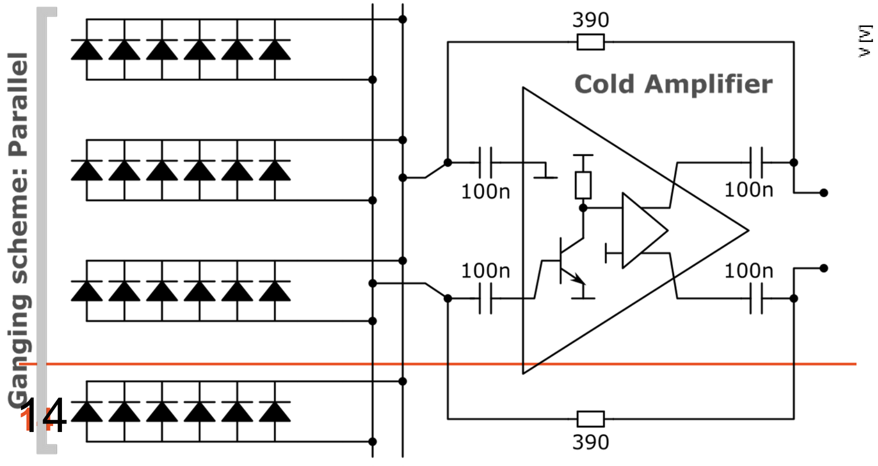
Photosensors and Cold Electronics

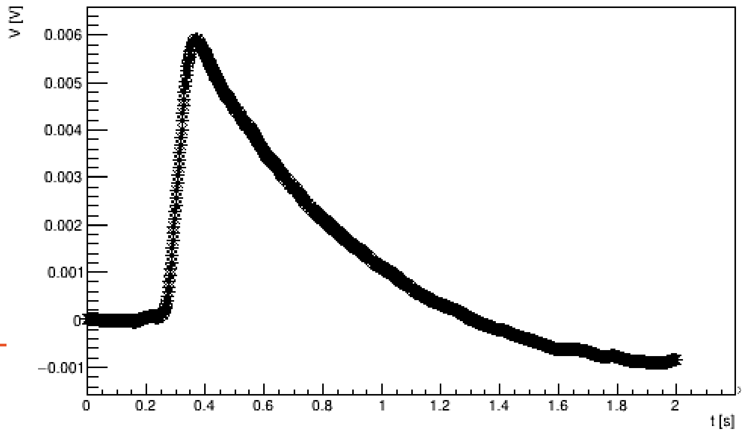


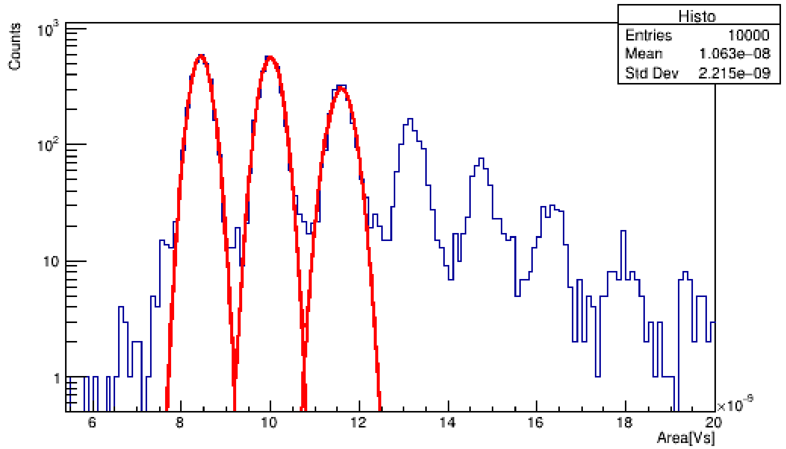
- Down-selection to two final completed in Sep. 2021: **50% sensors from Hamamatsu** (custom SiPM S16517) **and 50% from FBK** (custom SiPM NUV-HD-CRYO-TT)
- Production and test of SiPMs for ProtoDUNE-HD completed in March 2022. **Failure rate in QC testing <1% over 4000 SiPMs.**

See F. Terranova talk

- PRR passed on December 2022
- Cold Electronic Design based on commercial components (SiGe BJT, BiCMOS opamp)
- Design essentially unchanged since 2021, extensively tested in many labs
- S/N≈8 at SiPM overvoltage that gives 45% PDE (both SiPM vendors). Rise time ≈70 ns, dynamic range up to 2000 p.e. (C. Brizzolari *et al* 2022 *JINST* **17** P11017 https://doi.org/10.1088/1748-0221/17/11/P11017)



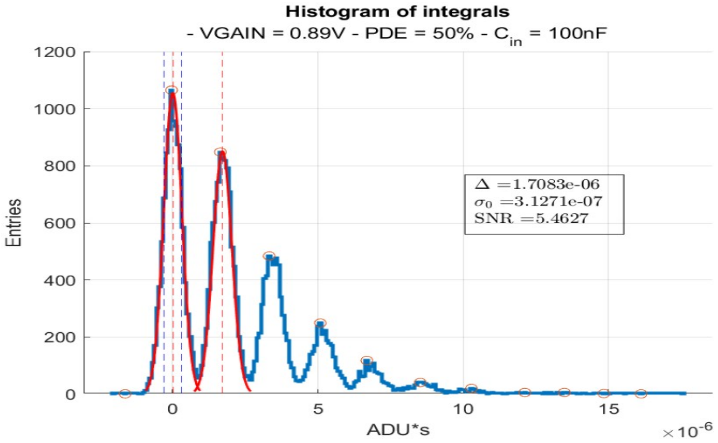




DAPHNE

See F. Terranova talk

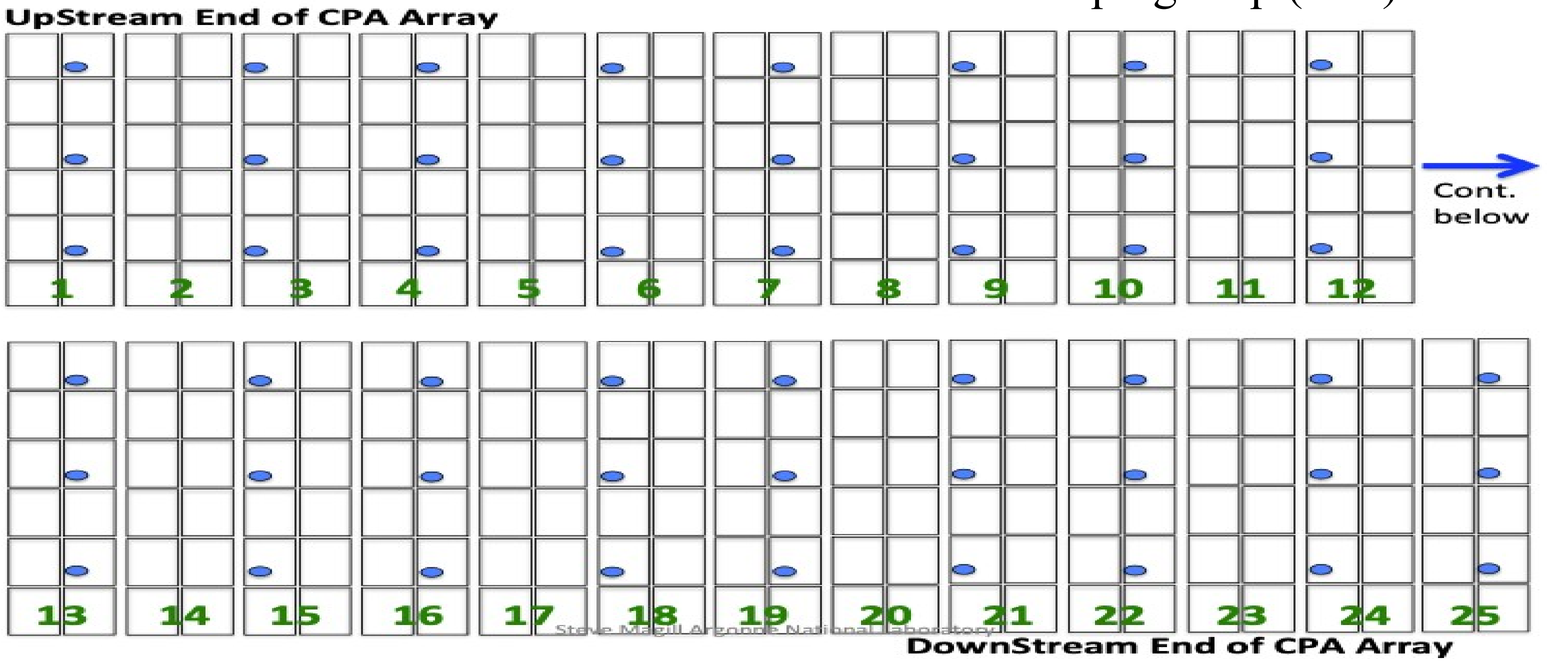
- ***40 channels/65 Msps/14 bits***;
- ***Analog front-end validated in multiple sites. S/N ratio > 5 and 2000 pe dynamic range;***

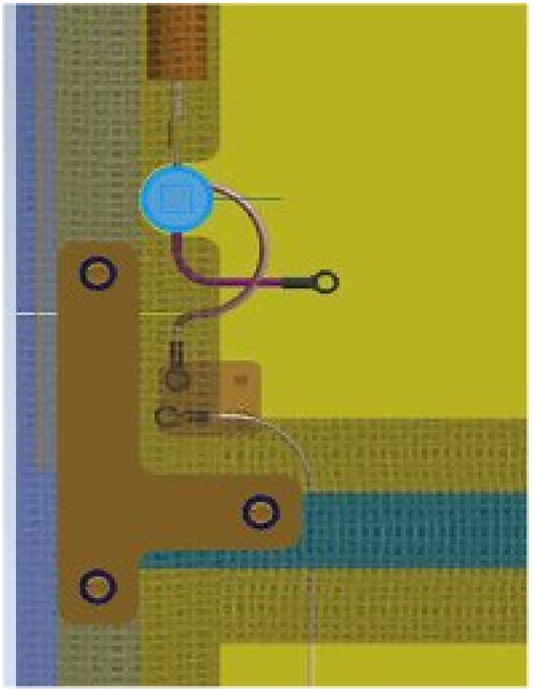


- *Self-triggering mode validated in multiple labs;*
- *DAPHNE V2 installed at CERN in April*
- *Integration of DAPHNE into the DAQ system is progressing*;
- DAPHNE V3 under development:
  - Upgraded digital system. Kria K26 System-on-Module (SoM) by Xilinx. 10 Gb links

Monitoring System

- **Schematic of FD1-HD cathode plane** (60 m × 12 m) showing the locations of the calibration and monitoring system diffusers
  - -Calibration and monitoring system with a total of ***204 diffusers: 51 on each side of the two CPA panels***
  - -Each diffuser illuminates a region of *4 m × 4 m on APAs 3.6 m away*
  - -The diffuser locations will be in the CPA field-shaping strip (FSS) notches.



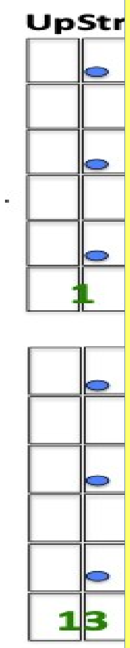


- *Quartz fibers are used to transport light from the optical feedthrough* (at the cryostat top) through the field cage ground plane, and through field cage strips to the CPA top frame.
- ***A total of 17 calibration modules*** (12 calibration channels per module) will be built for FD1-HD.

Monitoring System

- **Schematic of FD1-HD cathode plane** (60 m × 12 m) showing the locations of the calibration and monitoring system diffusers

  -Calibration and monitoring system with a total of 204 diffusers: 51 on each side of the two CPA panels



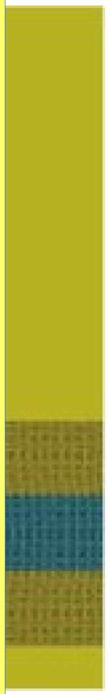
- Design largely based on the monitoring/calibration system developed for protoDUNE-HD 1

  -minimal conceptual changes since then (mostly focused on cost optimization)

Additional prototyping/testing: The system components have also been verified at dedicated test stands.

  -Single-channel pulser boards have been extracted from the 12-channel design.

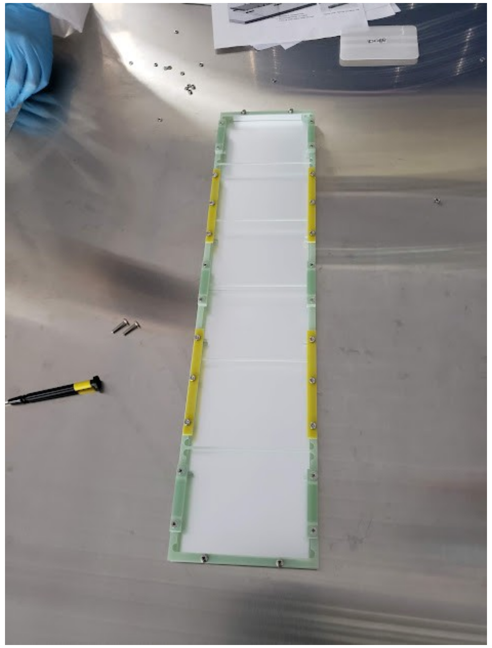
  -Several of single-channel boards are now used for QA/QC at ANL, also at CERNand Fermilab in cold box tests.

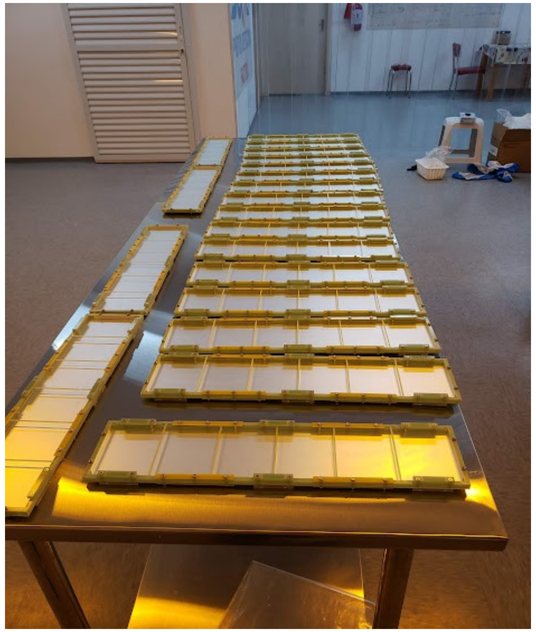


- Quart … ge ground plane, and through field cage strips to the CPA top frame.
- A total of 17 calibration modules (12 calibration channels per module) will be built for FD1-HD.

ProtroDUNE - Filter production and supercell pre-assembly

- ***1,200 Dichroic filters produced in Brazil (OPTO Eletronica)***
- Filters *coated with paraTerphenyl at the large coating facility at UNICAMP – 43 evaporations*
- Mechanical components ***Prodcued in Brazil by Equatorial Systems***
- *Supercells pre-assembled at UNICAMP and shipped to CIEMAT, CSU and MiB for final integration integration (SiPM, WLS plates) and cold test*





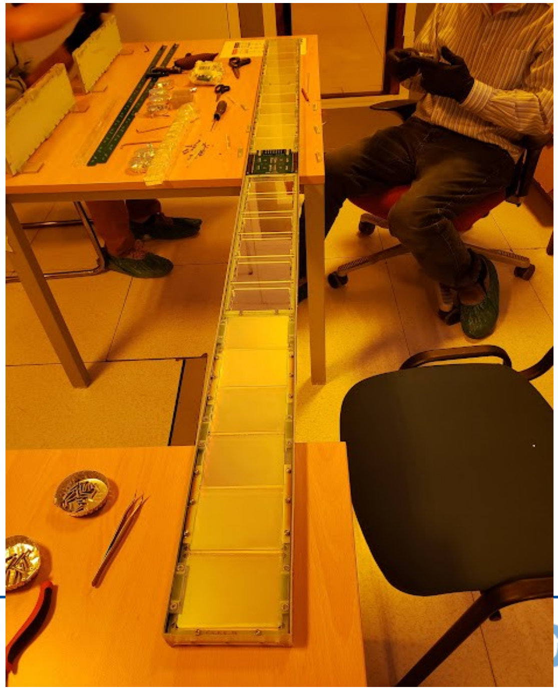

ProtoDUNE modules assembly/test

- ***30 single sided X-ARAPUCA modules assembled at CERN***, *starting from the supercells pre-assembled @ MiB and CIEMAT*
  - The process is very complicate and time consuming. Will not be adopted for DUNE FD1 ***(D. Warner talk)***

- **10 double sided X-ARAPUCA modules pre-assembled and tesed at CSU**

- *Each module was functionally tested in the scanner before installtion in APAs*

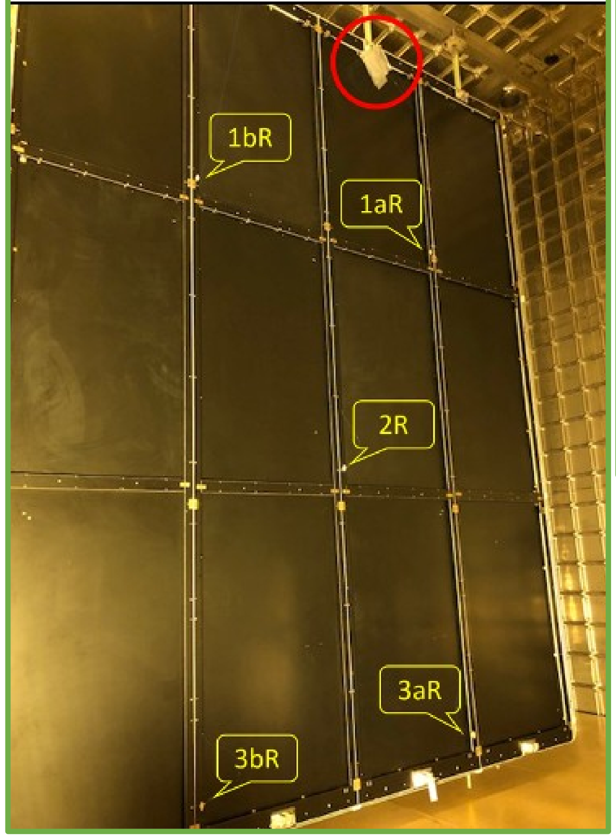
- **40 modules successfully installed**. APA1, AP2, APA4 tested in the cold box
  - *No failures of modules during cool down and warm up*
  - *1 failure in 1 supercell in APA2 already before the cool-down. Defective channel traced to bad connection and engineering control implemented (new connector)*



ProtoDUNE monotoring/calibration

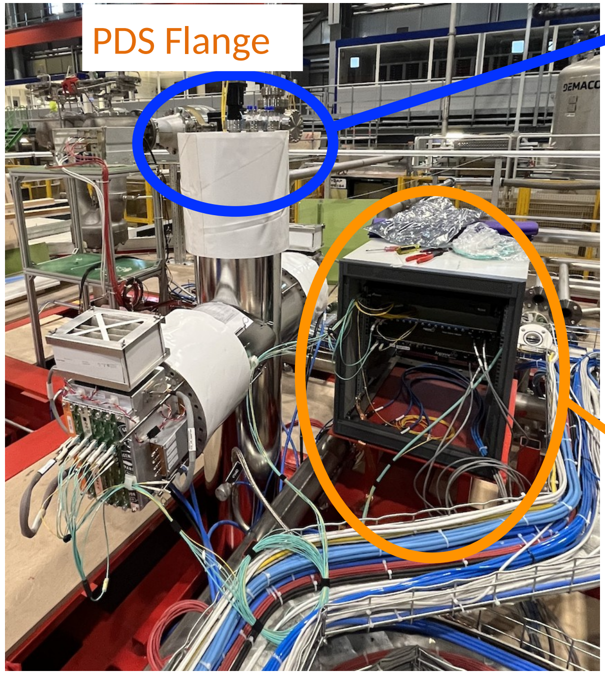
- **Calibration system components installed in ProtoDUNE-HD-II**

Beam right side installation at CPA

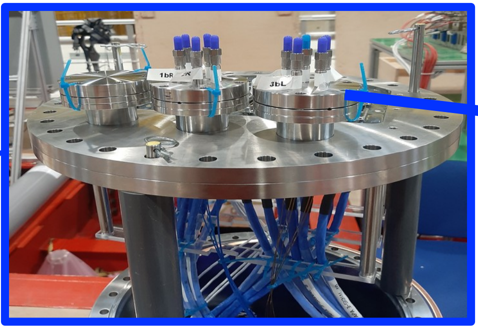


Optical Fibers

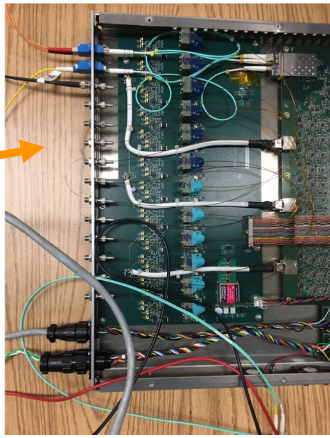
3D-printed PEEK diffusers



Optical Feedthroughs

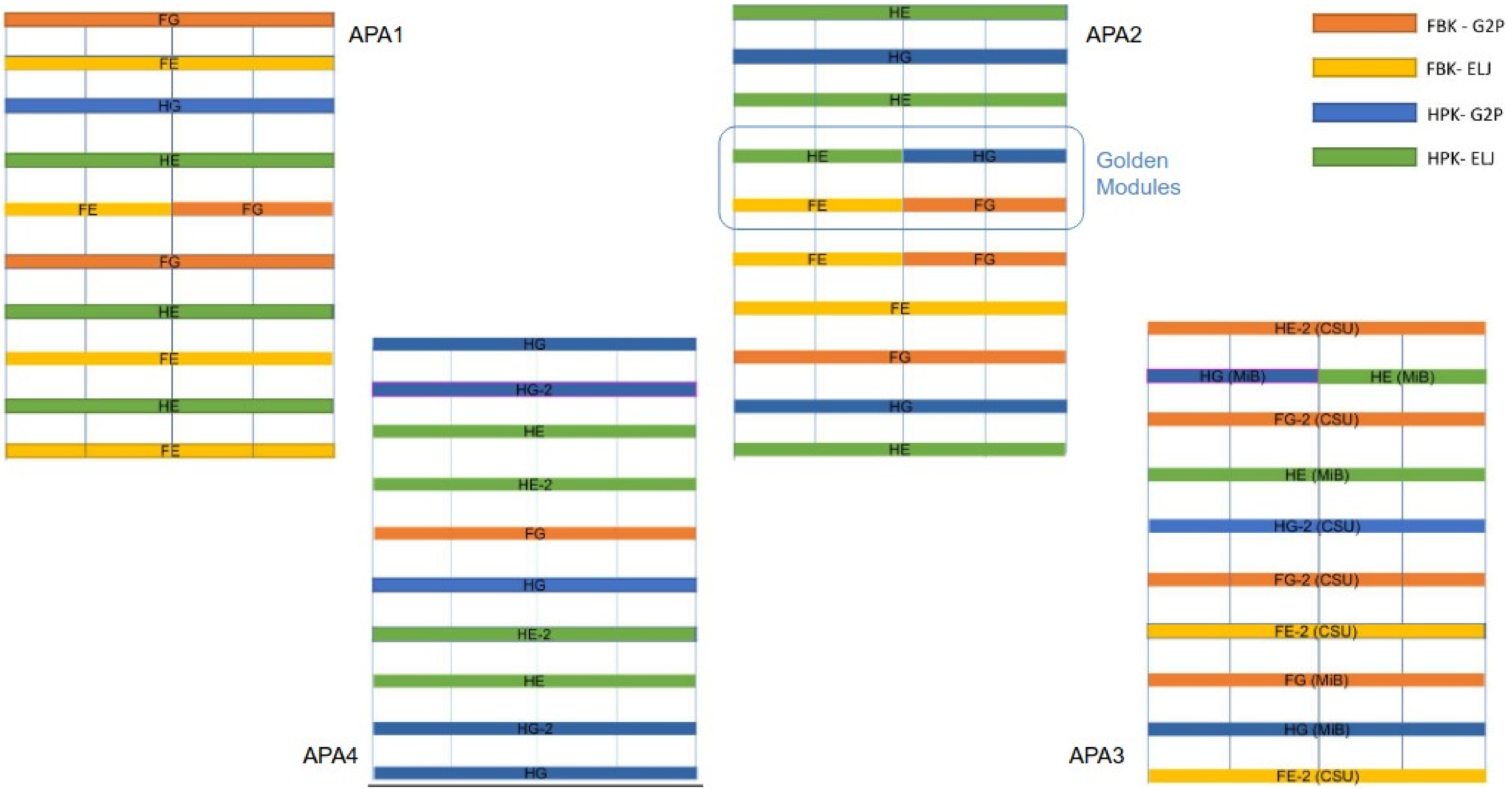


Calibration Electronics



- **Successful integration with the ProtoDUNE network and slow controls**

ProtoDUNE modules distribution



ProtoDUNE modules distribution

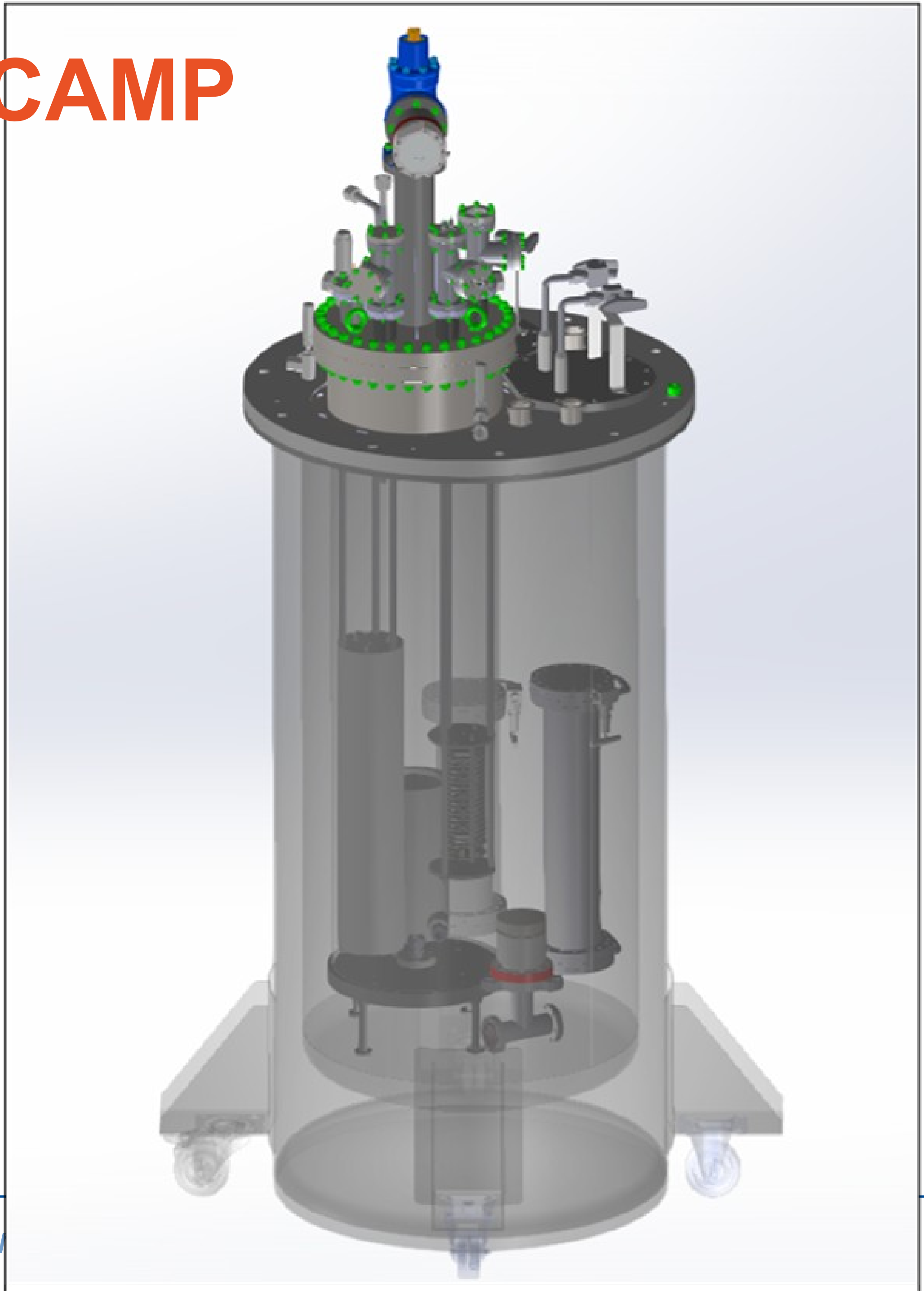
Conclusions

- PDS of FD1-HD ***meets the requirements of average and minimal Light Yield***
- Detection efficiency of X_ARAPUCA supercell can be *slightly improved with small optimization of the filters*
- **PTP film has been demonstrated to be robust**. No flaking or detachments in tens of tests performed
- *Photosensors passed PRR in December. Cold electronics developed at PRR level*
- **DAPHNE design is mature**. *DAPHNE V2 will be installed in protoDUNE in April*
- *Monitoring system largely based on the one developed for protoDUNE* Run 1. ***Additional validation performed in different labs and at CERN***

Supercell tests and validation

- ProtoDUNE 2 module QC consisted in ***LN2 immersion of supercells for 30 modules at CIEMAT (74 supercells) and Milano Bicoca (56 supercells)***
  - *120 supercells werer illuminated by LEDs. Dark count rate and relative DE were measured. Two SiPM PCBs (over 480) were replaced due to high DCR during testing.*
- **10 modules were assembled completely and immersed in LN2 at CSU** (as intended for DUNE installation)
  - *Operational and functional test, but backcground noise too high for DCR measurements. Will be improved for DUNE.*
  - .

PULArC @ UNICAMP



LBNF/DUNE