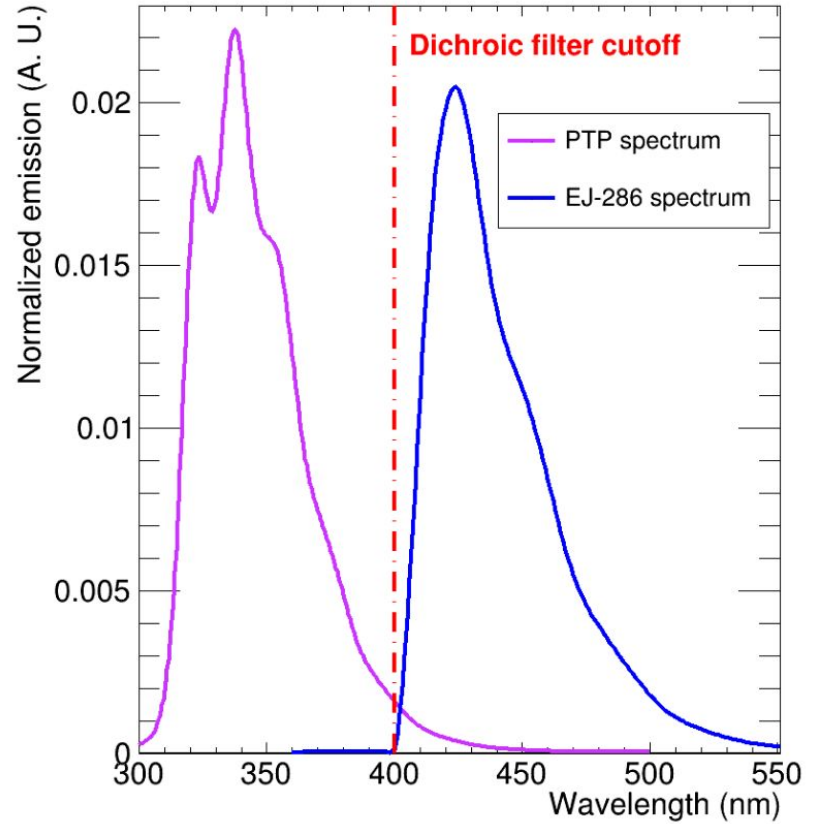
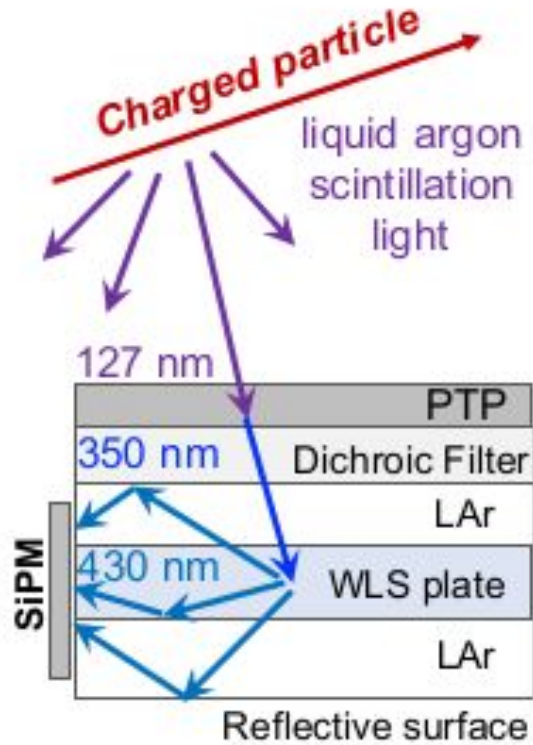


# Attivita' 2023: PhCollector

C.M. Cattadori - INFN Milano Bicocca

Lecce - 7 Novembre 2023

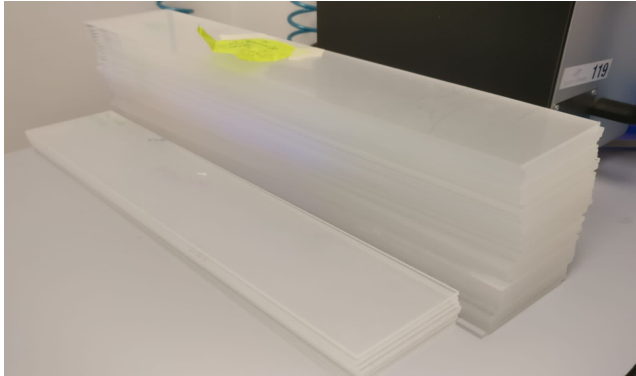




# Attività' 2023: Produzione

- Produzione WLS-Lightguides (WLS-LG) per
  - Module 0 di FD2
  - Module 1 di FD2 (+R&D)
  - Setup di misura della PDE (CIEMAT e Napoli)
  - Individuazione di un partner industriale per la produzione di massa per FD1 & FD2:
  - Produzione e QC dei prototipi del Partner Industriale
- R&D e produzione dei  $\frac{2}{3}$  dei Filtri Dicroici in dimensione x 2.3 rispetto a FD1
  - Module 0 di FD2
  - Module 1 di FD2
  - Setup di misura della PDE (CIEMAT e Napoli)

# G2P WLS: Production for pDUNE FD1 & FD2



Glass-to-Power Co. <https://www.glasstopower.com/> is now the BL manufacturer and DUNE industrial partner.

Showed R&D and mass production capabilities



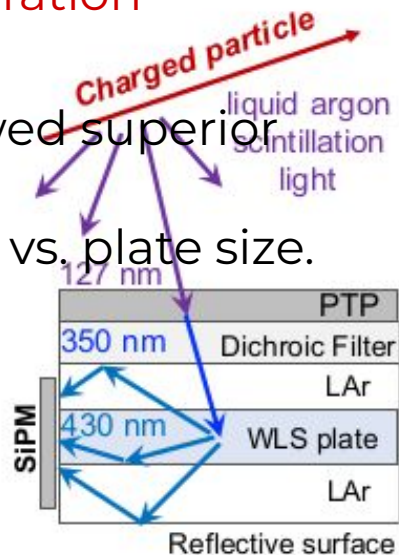
- **80 x WLS slabs for FD1-pDUNE:**  
 $48.0 \times 9.3 \times 0.38 \text{ cm}^3$

**Validated Casting, Laser cut and edge polishing procedures of the WLS from the as-casted plates..**

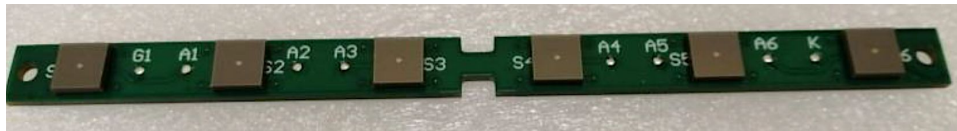
- **20 (M0)+ 10 (M1) WLS slabs for pDUNE-FD2:**  
 $60.7 \times 60.7 \times (0.38 \text{ \& } 0.55) \text{ cm}^3$

# Optimization (and measurements) of the XA PDE

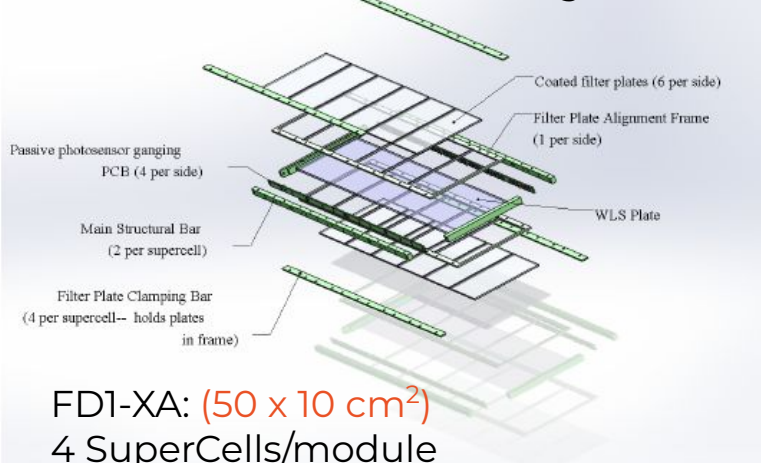
- Optimized both setup & methods to accurately measure the absolute PDE of the XA device and
- Developed accurate simulation of the photon transport in the device
- Improved the XA components quality and configuration
  - ✓ WLS-LG plate (FD1 & FD2)
    - High grade PMMA embedding WLS-dye\* showed superior performances of the BL PVT product\*\*.
    - Tailored WLS-dye concentration and thickness vs. plate size.
  - ✓ WLS-LG Optical sealing (both FD1 & FD2)
    - Enhanced light trapping in the WLS
  - ✓ SiPM to WLS-LG coupling (both FD1 & FD2)
  - ✓ Dichroic Filters (only FD2)



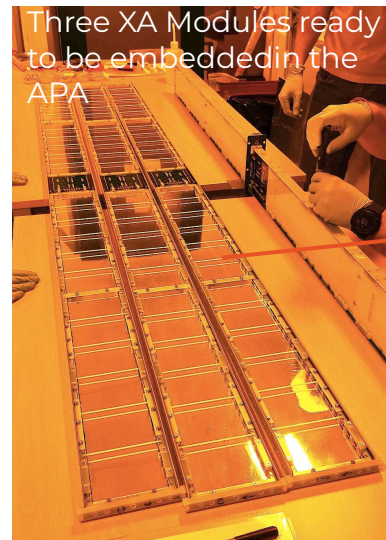
# The FD1 PDS & X-Arapuca device



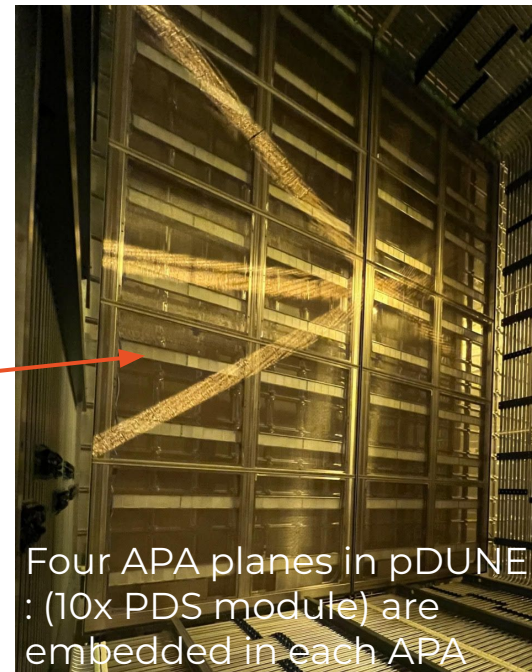
Th SiPM board with 6 SiPM: rigid G10



- FD1-XA: (50 x 10 cm<sup>2</sup>)
- 4 SuperCells/module
- 10 module/APA
- 1500 Total Modules
- 1000 Double sided 500 single sided



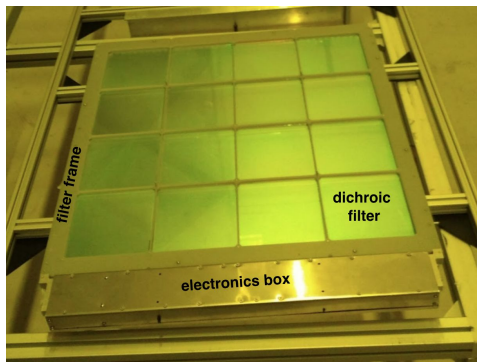
Three XA Modules ready to be embedded in the APA



Four APA planes in pDUNE : (10x PDS module) are embedded in each APA

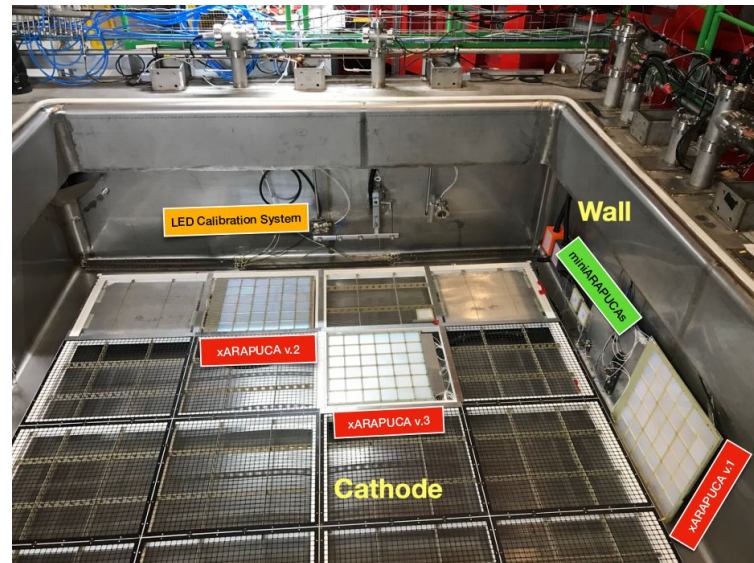
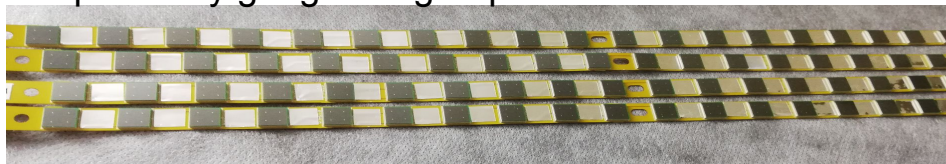
# The FD2 PDS & X-Arapuca device

	WLS dimples	DF size (mm <sup>2</sup> )	DF	SiPM	PoF	SoF	shared elec. box
M1		100x200	ZAOT	HPK			x
M2		100x200	ZAOT	HPK			x
M3	x	100x200	ZAOT	HPK			x
M4	x	100x200	ZAOT	HPK			x
M5	x	150x150	PE	FBK		x	
M6	x	150x150	PE	HPK			
M7	x	150x150	PE	HPK			
M8	x	150x150	PE	FBK			
C1		100x200	ZAOT	HPK	x	x	
C2		100x200	ZAOT	HPK	x	x	
C3		150x150	PE	FBK	x	x	
C4	x	150x150	PE	HPK	x	x	
C5	x	150x150	ZAOT	HPK	x	x	
C6	x	150x150	ZAOT	HPK	x	x	
C7	x	150x150	ZAOT	FBK	x	x	
C8	x	150x150	ZAOT	HPK	x	x	



In pDUNE-FD2 8 Memb-XA +8 cath.-XA + (6 optimized) deployed in 2023

4 (of 8) flex circuits with 20 SiPMs passively ganged at groups of 5



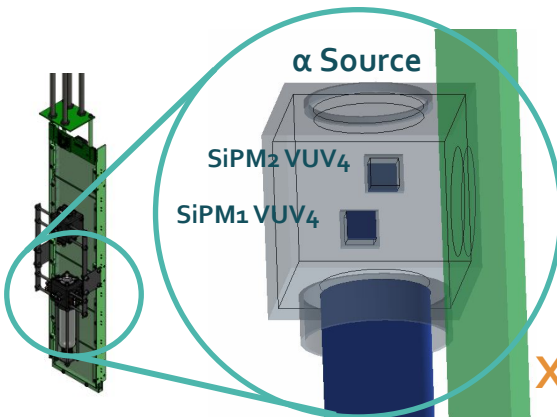
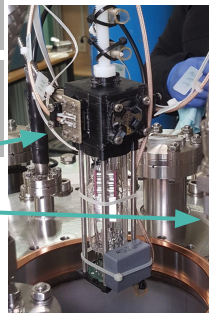
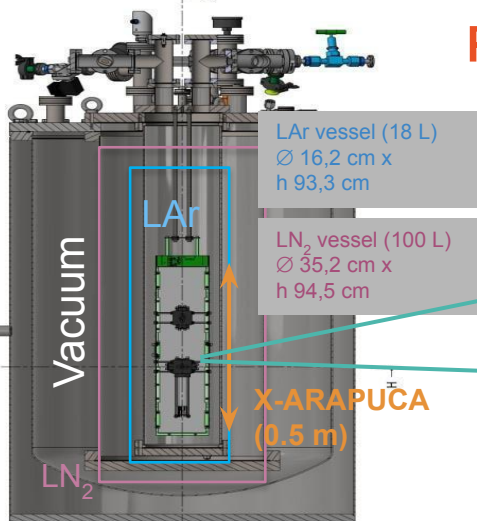
2 x Cath-XA & 1 x memb-XA in the CERN Coldbox

# FD1-XA: Assessment of the PDE

# CIEMAT results

Lidine 2022- update 2023

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



X-ARAPUCA

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

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

$\epsilon_{XA} (\%)$  - DIRECT MEASUREMENT  
(VUV<sub>4</sub> Comparison)

$\epsilon_{XA} (\%)$  - CROSSCHECK  
(From known LY and MonteCarlo)

$\epsilon(Ref. SiPMs) = 11.3\%$

PDE 40%

PDE 45%

PDE 50%

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

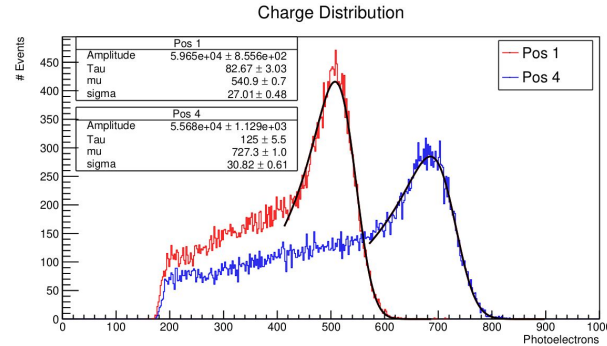
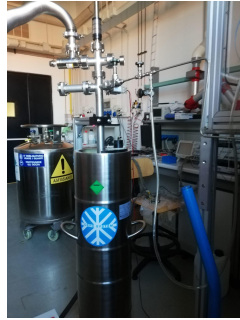
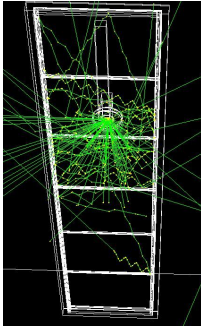
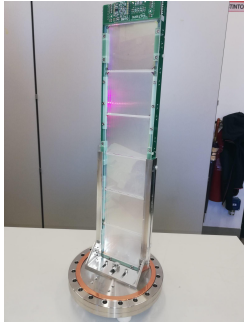
	FBK+EJ	HPK +EJ	HPK +G2P
PDE 40%	1.34 ± 0.10	1.51 ± 0.12	2.02 ± 0.17
PDE 45%	<b>1.56 ± 0.12</b>	<b>1.72 ± 0.14</b>	<b>2.28 ± 0.19</b>
PDE 50%	1.93 ± 0.15	1.87 ± 0.15	2.51 ± 0.21

High grade PMMA embedding WLS-dye.

**+30%**

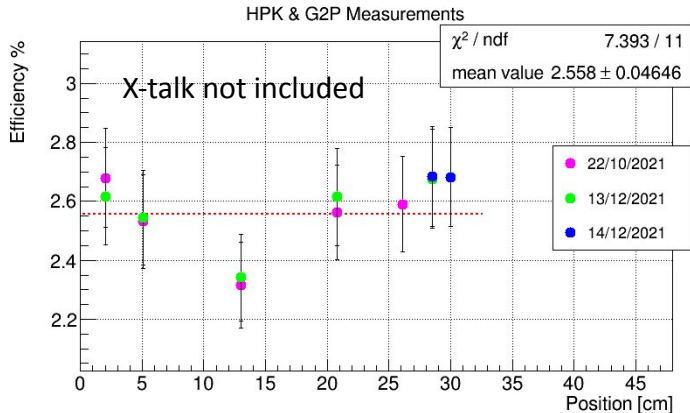






Method: z-scanning of the whole cell ( $\sim 2$  Sr) with an  $^{241}\text{Am}$  exposed  $\alpha$  source [\(JINST 16 \(2021\)09027\)](#)

$$\epsilon = \frac{4\pi \cdot \alpha \text{ peak(ADC)}}{\text{s.p.h.e.(ADC)} \cdot f_{int} \cdot LY_{LAr} \cdot En_{\alpha} \cdot q_{\alpha} \cdot \Omega}$$



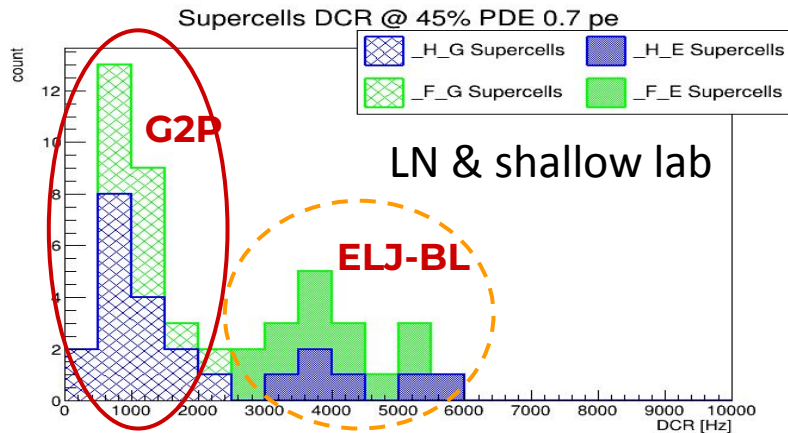
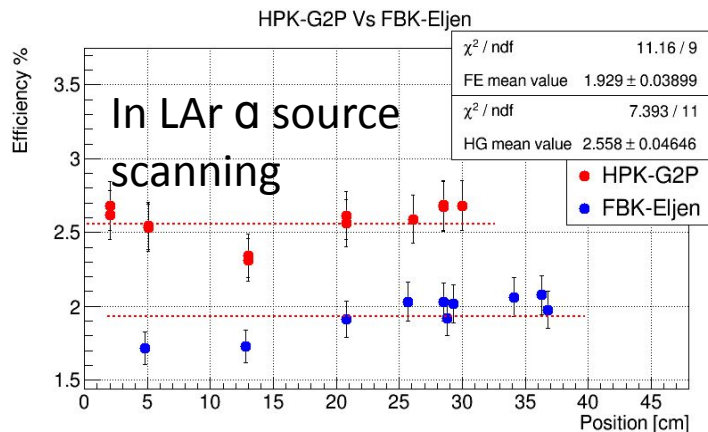
No correction for LAr purity applied.  
Expected: < 8%

Joint paper in preparation

	SiPM PDE	XA PDE MiB Xtalk corr.	XA PDE CIEMAT Xtalk corr.
HPK & G2P	50%	<b>2.49 (0.15)</b>	<b>2.51 (0.21)</b>
FBK & G2P	45%	<b>2.1 (0.23)</b>	1.87 (0.15)
FBK & Eljen	45%	<b>1.8 (0.18)</b>	<b>1.56 (0.12)</b>

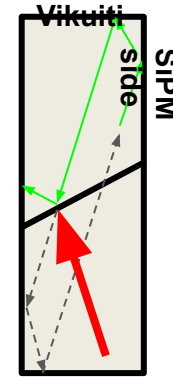
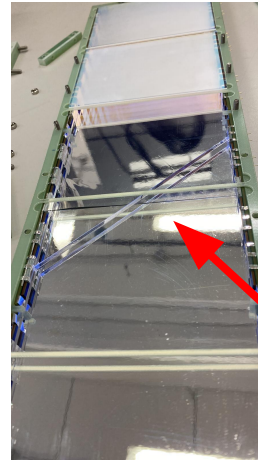
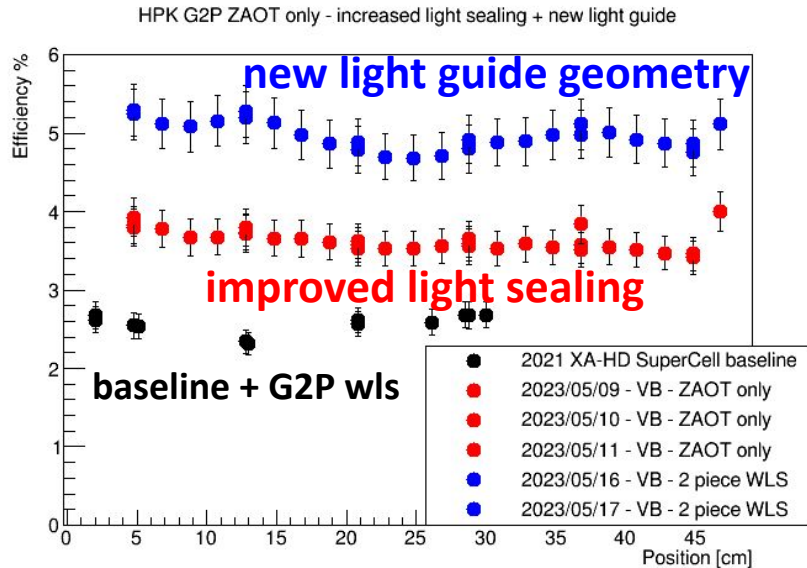
# G2P-WLS features & Performances

- **Superior Cryoresilience:** No cracks or failures in cooling/warming cycle at rate of 3-4 mm/sec of the 80 x FD1 pDUNE & 16 x FD2 Module-0 plates
- Superior light guiding surfaces as casted
- Superior LY and DCR of XA cells with PMMA vs PVT (BL) WLS

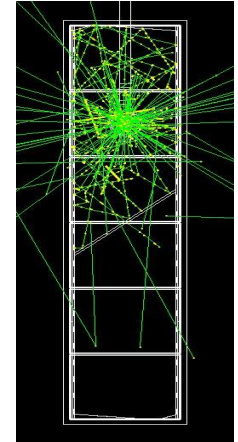


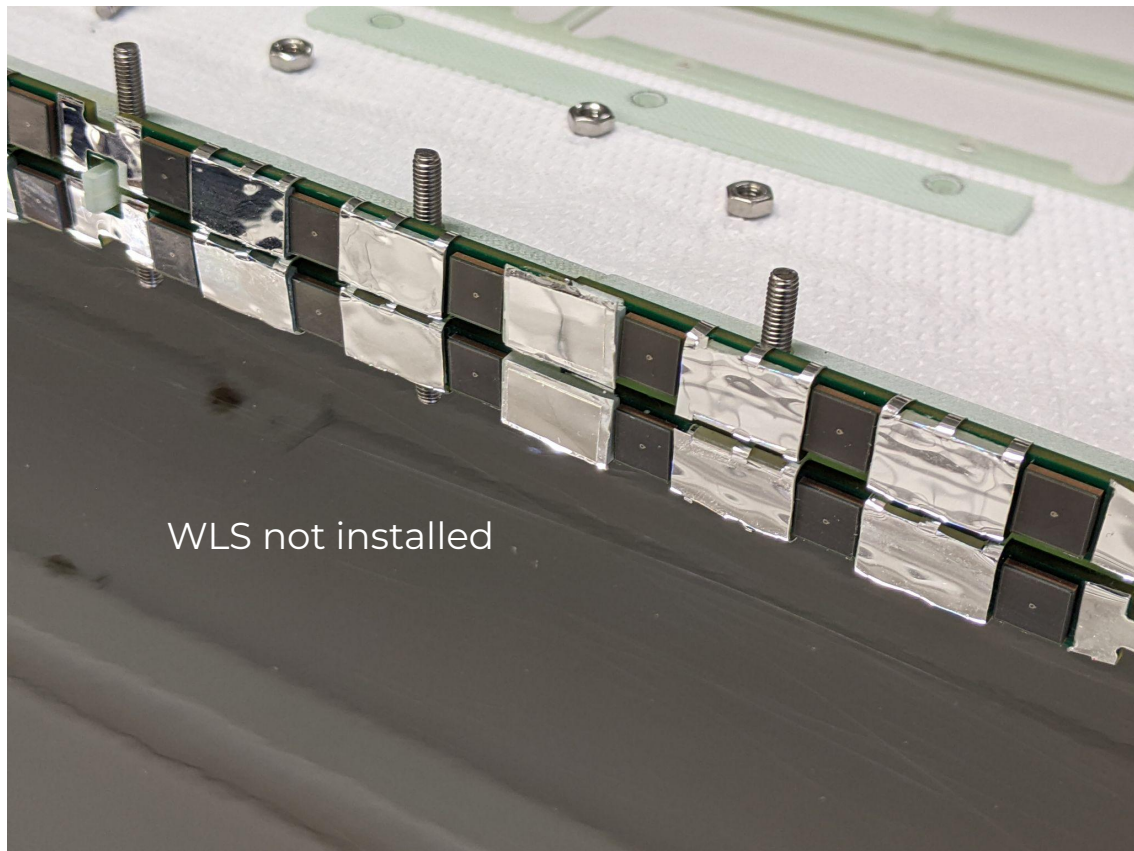
# FD1: Modified WLS-LG geometry

Major improvement of the FD1 XA PDE cutting the WLS-LG in two parts by a 40° cut and improved LG light-sealing optimization via optical sims measurements with MiB setup

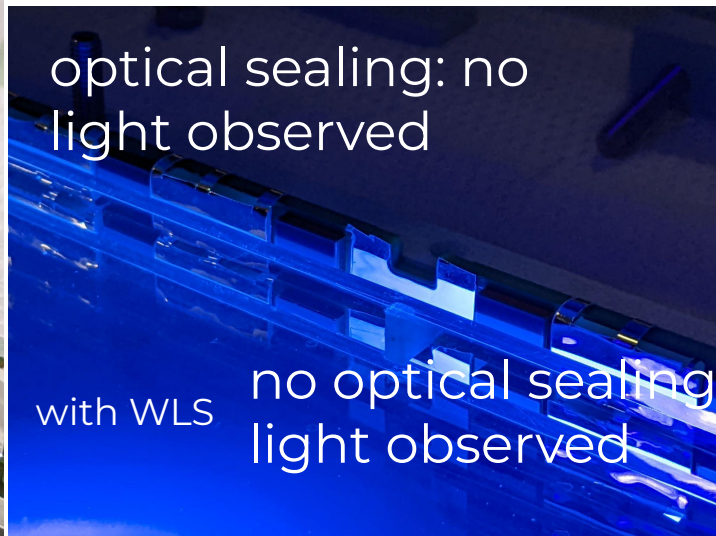


40° cut in the middle with Vikuiti applied





WLS not installed



optical sealing: no light observed

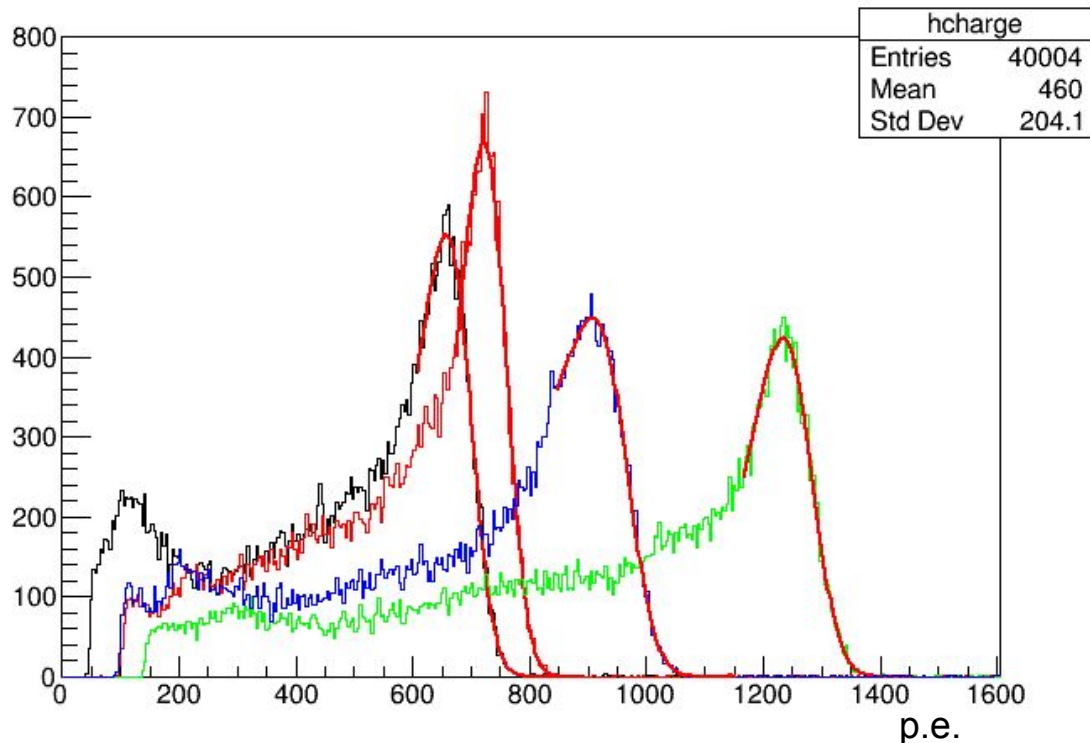
with WLS no optical sealing light observed

# Alpha Spectra resolution, p.e. calibrated

- baseline
- p-DUNE WLS, NO G10 blocks, ZAOT
- p-DUNE WLS, G10 blocks, ZAOT
- WLS with cut, G10 blocks, ZAOT

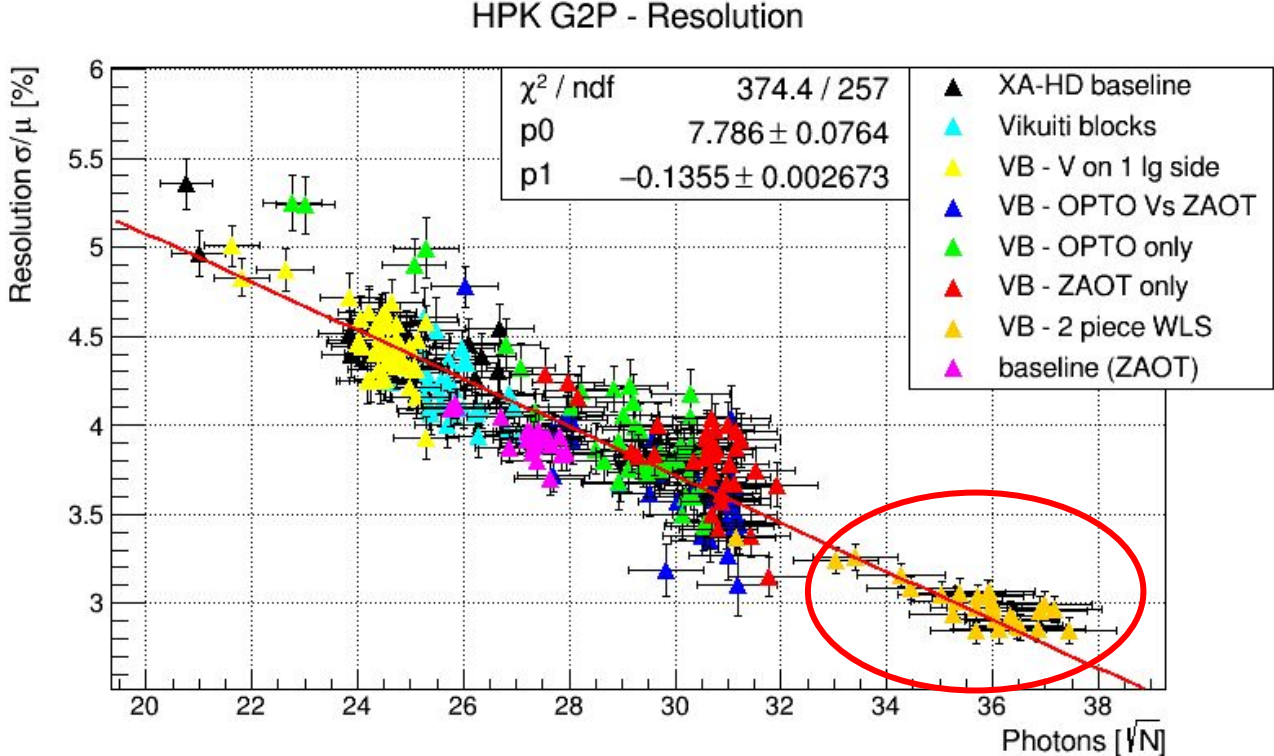
All taken in the middle of the 3rd dichroic filter

**mu = 692.704**    **sigma = 31.4929**  
**mu = 749.976**    **sigma = 30.3693**  
**mu = 962.185**    **sigma = 38.2959**  
**mu = 1272.26**    **sigma = 38.0256**



# Alpha Spectra resolution

- The 2 pieces WLS Ig improves the energy resolution w.r.t. all the other configurations



# WLS-LG: Attenuation length ( $\lambda_{att}$ )

- Both the Absorbance of the pTP photons & the  $\lambda_{att}$  of the photons emitted by the secondary WLS depends on the WLS chromophore concentration
  - The chromophore concentration & WLS-LG thickness are tuned to maximize the Photon Collection Efficiency (PCE)
- $\lambda_{att}$  (400-500 nm) is the leading parameter for high PCE.
  - **Required:  $\lambda_{att} > \text{Optical Path}$**

$$A = \log_{10}(1/T)$$

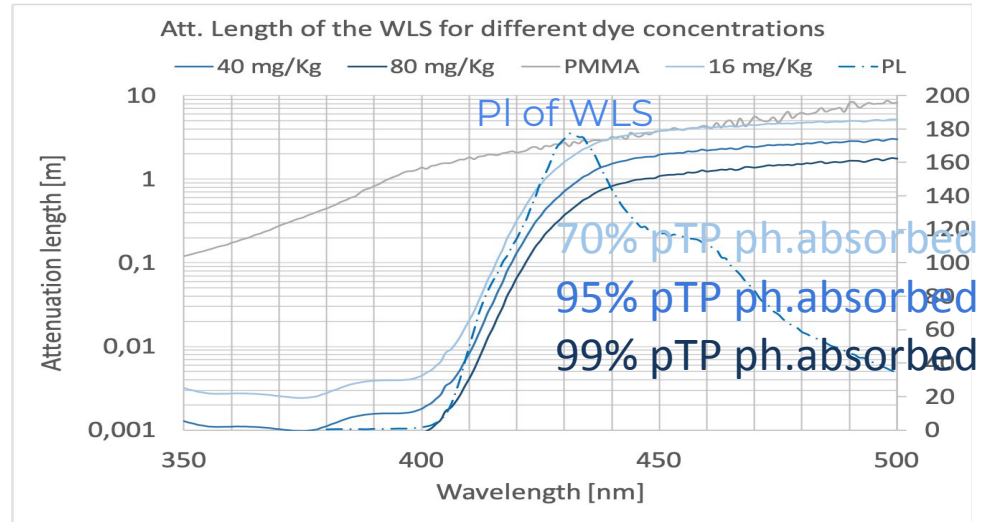
$$T = I/I_0 \exp(-d/\lambda_{att})$$

$$A = \epsilon c d$$

$\epsilon$  = molar extinction coeff.

$c$  = concentration

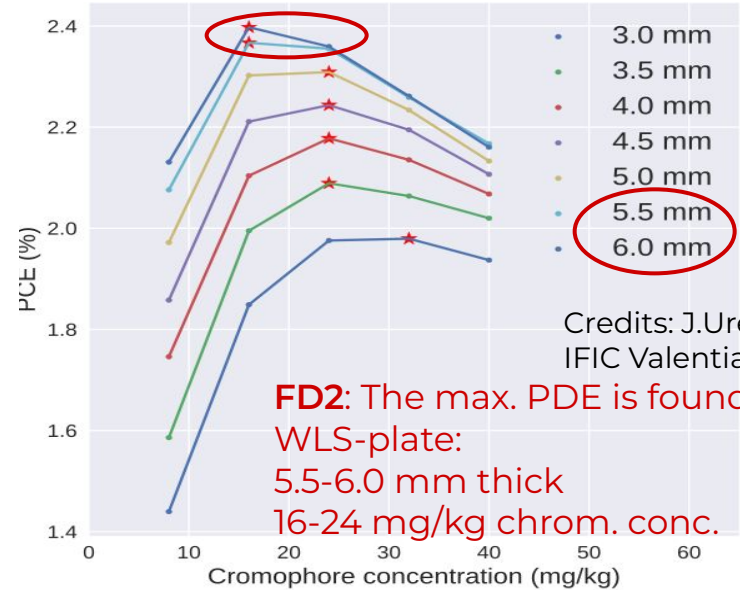
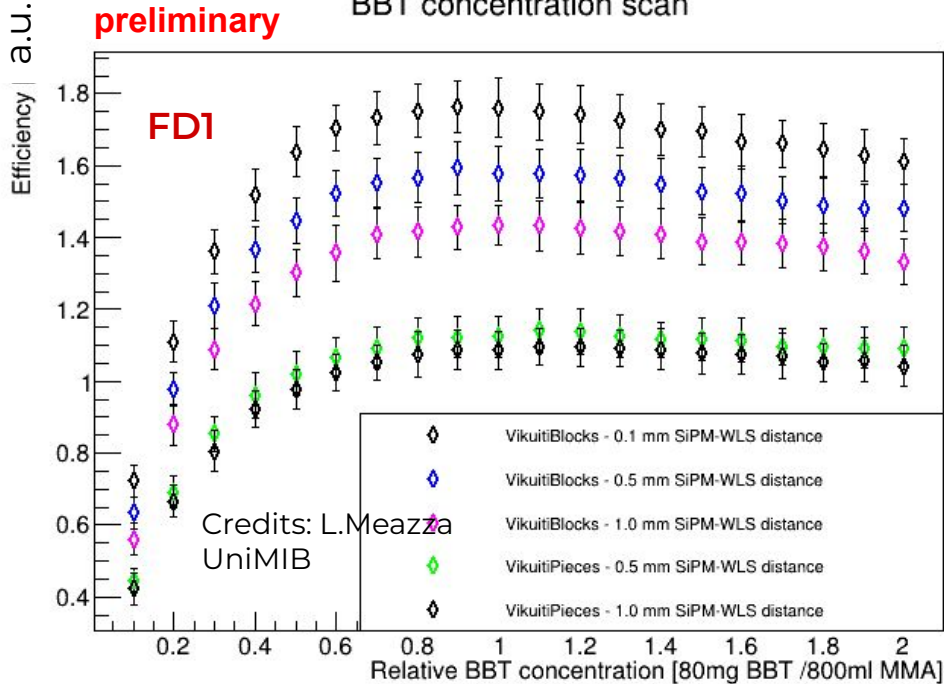
$d$  = optical path



# WLS- LG: chromophore concentration and thickness optimization for FD1 and FD2

OP ~ 10-100 cm;  $\lambda_{att}^{opt} = 37$  cm; thick=3.8mm  
 BBT concentration scan

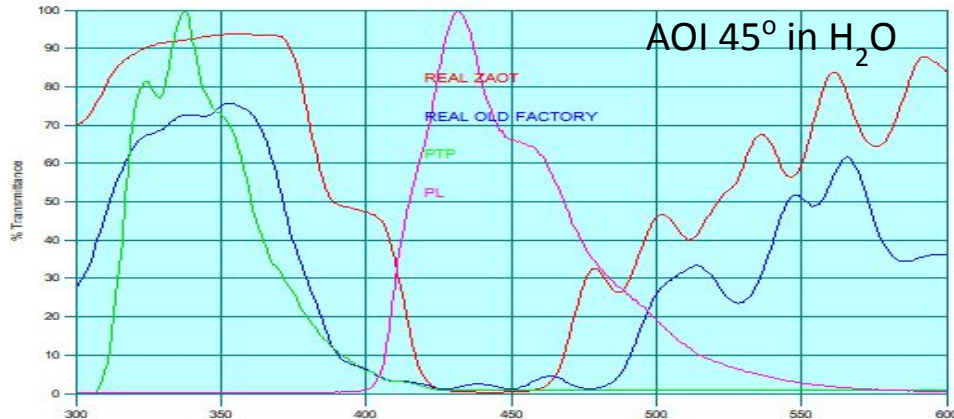
OP ~ 60-200 cm;  $\lambda_{att}^{opt} \sim 200$  cm; thick = 5.5 mm





# Dichroic Filter Optimization for the FD2 Module-0

- Found two new vendors for FD2 production
- DF Designed to operate in LAr (@45°), pass 300-400 nm & reflect 400-500 nm
- **Pro:** Improved transmittance in the pTP emission range
- **Pro:** Improved reflectivity in the WLS-LG emission range
- **Cons:** Narrower reflectivity window
- Size increased from 10 x 10 cm<sup>2</sup> to 15 x 15 cm<sup>2</sup> to increase XA the active surface



		Subs	Design
OPTO	FD1	B270	45° Air
ZAOT	FD2	BF33	45° LAr
Photon Export	FD2	F.silica	45° LAr

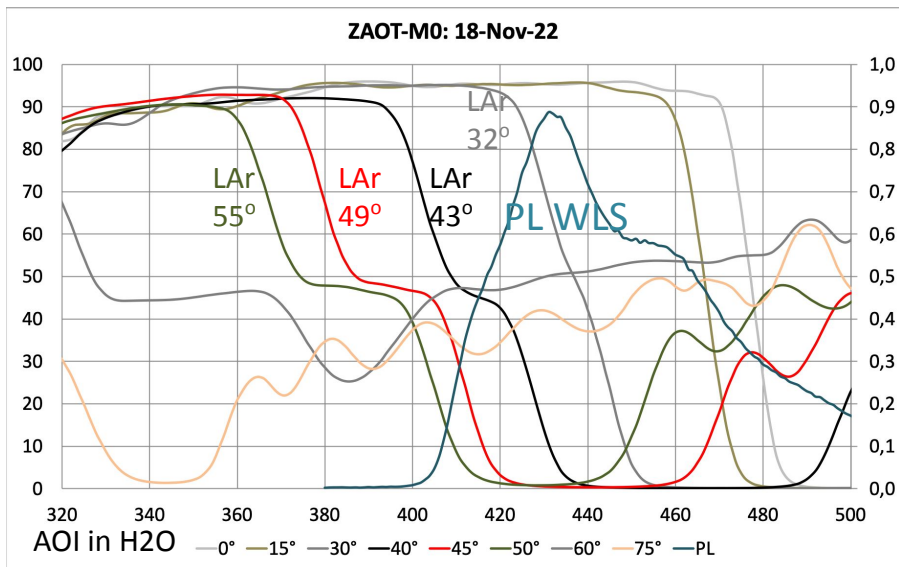
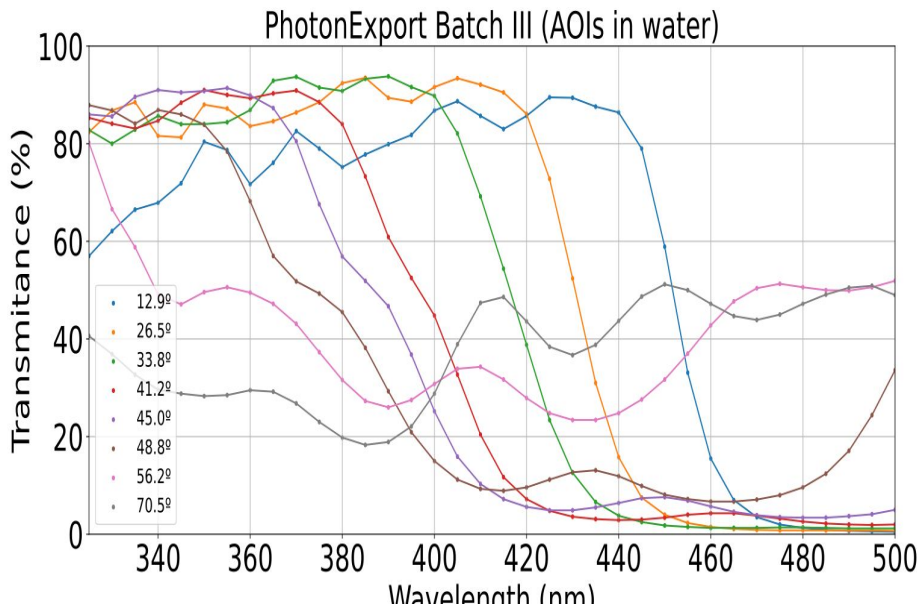
# The DF T curves measured in H2O for the 20 x FD2 MO

AOI H2O-to-LAr transformed by Snell law

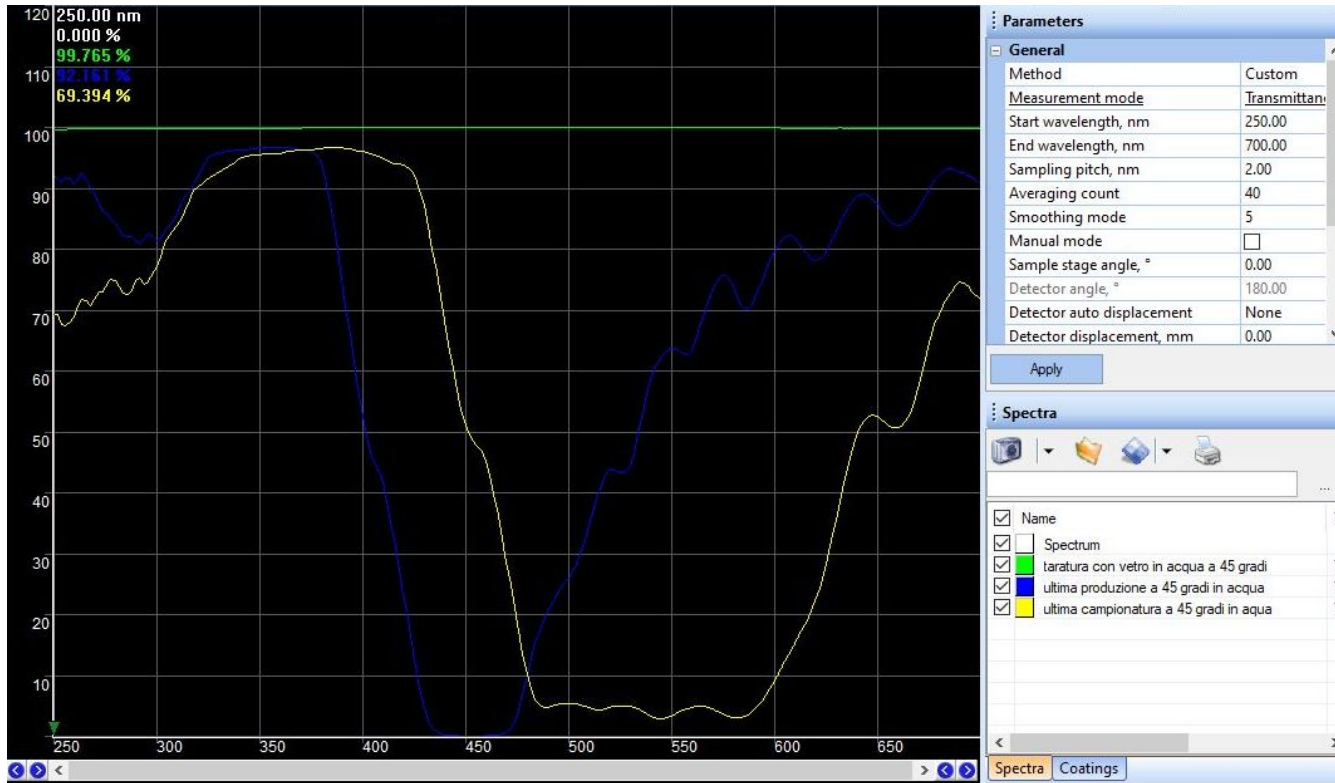
$$\text{Cutoff } (n) \Rightarrow \lambda = \lambda_0 \sqrt{1 - \frac{n_1^2}{n_2^2} \sin^2 \theta}$$

PE- DF: T Curves: 14.5 x 14.5 cm<sup>2</sup> for Module-0

ZAOT-DF: T Curves: 14.5 x 14.5 cm<sup>2</sup> for Module-0



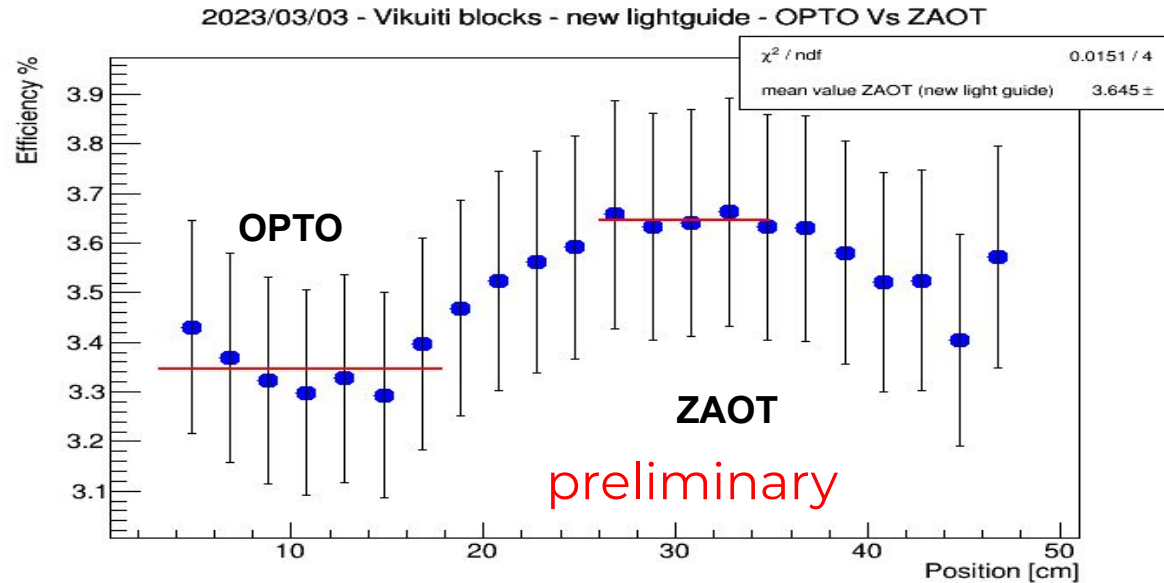
# DF design for the 6 x FD2-M1 modules



Spostato il cutoff a 480 nm

# Assessment of Module-0 DF performances in a XA in LAr

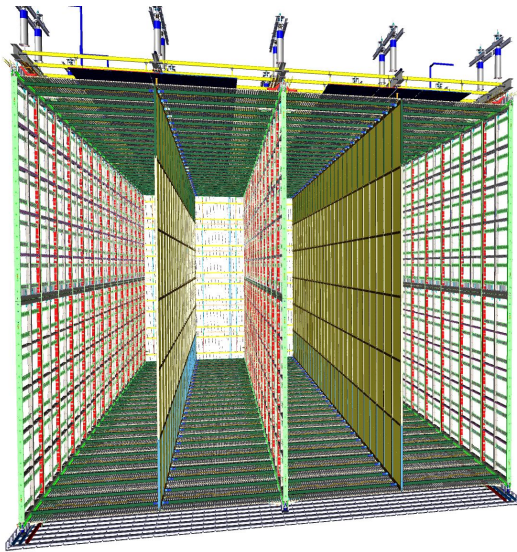
- the PDE of one FD1-XA equipped with three BL DF (OPTO), three FD2 (ZAOT) has been measured with the MiB setup in LAr
- +10% PDE well reproduced by G4 simulations



# Summary

- The PDE of the DUNE PDS building block has been measured and improved
- For **The BL-FD1-XA (EJ WLS) a PDE  $\leq$  2% was measured**
- The optimization of the FD1-XA components & relative configuration
  - ✓ **Change of the BL WLS-LG  $\rightarrow$  PDE  $\sim$  2.5%**
    - The G2P PMMA WLS-LG is now the BL for FD1 & FD2
  - ✓ **SiPM-to-WLS-LG contact & reflectors  $\rightarrow$  PDE  $\sim$  3.5%**
  - ✓ **WLS geometry to recover photons ineffective paths  $\rightarrow$  PDE  $\sim$  5%**
- The **PDE of the FD2-BL XA** as deployed in the **FD2-Module0** has been measured (F.Di Capua's talk)  **$\sim$  2% (preliminar)**
- **FD2-XA PDE optimization** is being pursued
  - ✓ Optimization of the **WLS chromophore concentration** & thickness (M1)
  - ✓ Optimization of the **Dichroic Filters (Module0 & Module1)**
  - ✓ Optimization of the **SiPM-to-WLS-LG contact**

# EXTRA

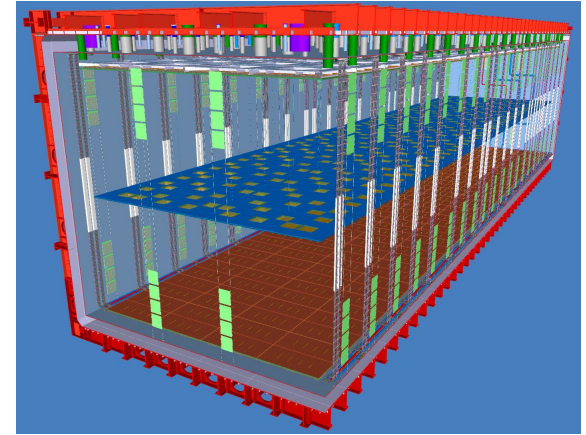


**FD1**

- 6000 XA devices ( $48 \times 10 \text{ cm}^2$ ) embedded in the three Anodic Planes
- SIPM:  $48 \times 6 \times 6 \text{ mm}^2$  ( $1.73 \text{ cm}^2$  or 3.9% Si coverage) ganged @ 48
- LArTPC: Horizontal Drift

LY requirement to boost the trigger (p-decay) and energy resolution (SN  $\nu$ ) capabilities of the DUNE PDS::

- $LY_{\min} > 0.5 \text{ PE/MeV}$
- $LY_{\text{ave}} > 20 \text{ PE/MeV}$
- **PDE of XA: 2%-3%**
- $S/N > 4$
- $\text{DCR}/\text{ch} < 1 \text{ kHz}$

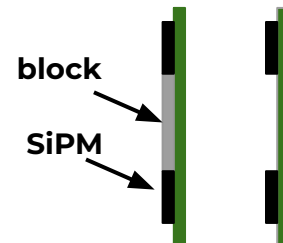


**FD2**

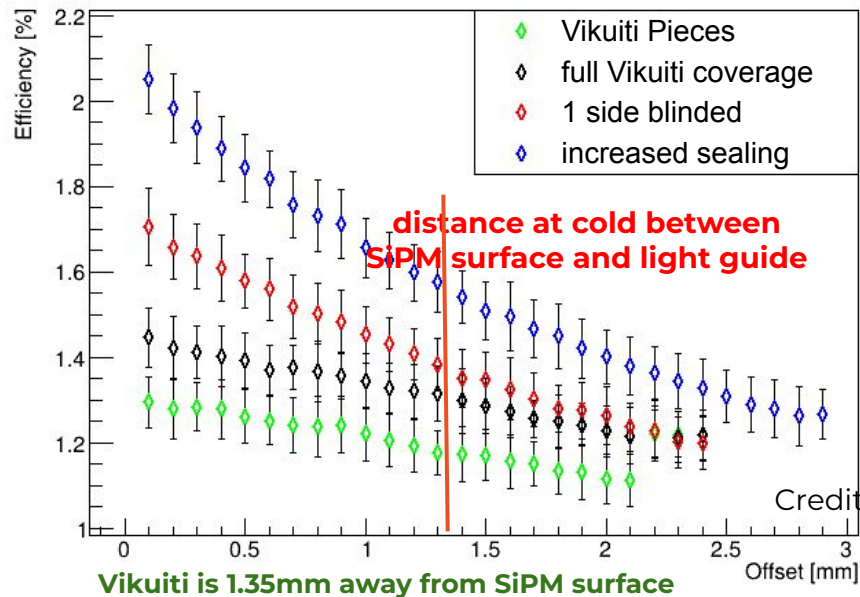
- 320 XA devices ( $58 \times 58 \text{ cm}^2$ ) on the cathode (320kV)  $\rightarrow$  PoF bias/readout
- 320 XA devices on the membrane
- SIPM:  $160 \times 6 \times 6 \text{ mm}^2$  ( $5.8 \text{ cm}^2$  Si, 1.6% Si coverage) ganged @80
- LArTPC: Vertical Drift Technology

# FDI: Study of the LG-to-(SiPM & reflectors) position

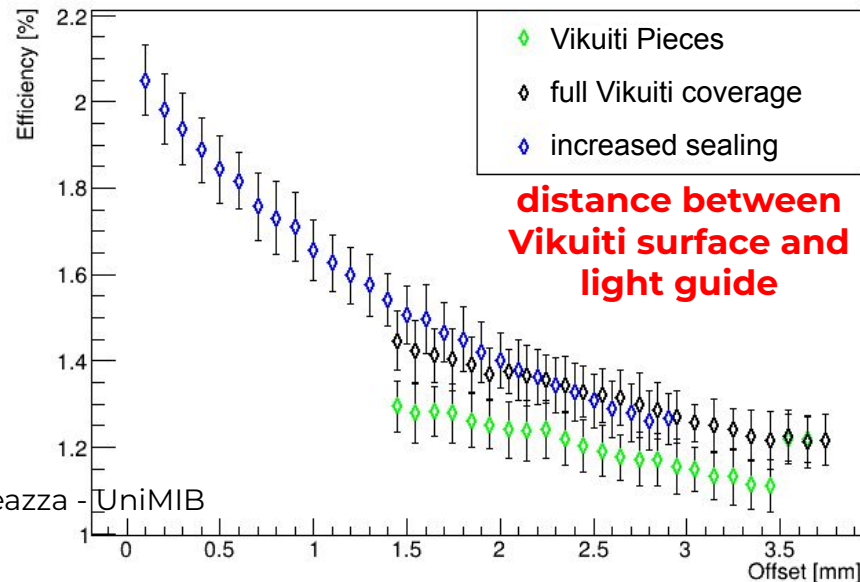
- **PDE is strongly dependent on the SiPM-LG distance and**
    - **distance of the Vikuiti reflector** seems to be the main factor
- proposed a wider (+1 mm) WLS-LG & to flush reflector to SiPMs



SiPM Offset Scan



SiPM Offset Scan



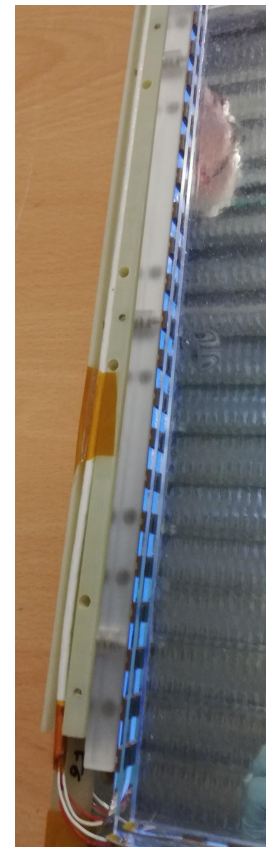
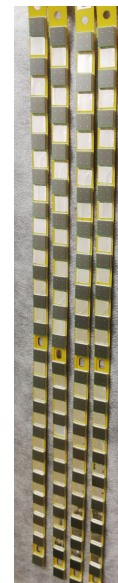


## FD2: SiPM - to Lightguide coupling

FD2-XA designed with no SiPM-to-WLS-LG gap .

To follow the 1% shrink of the PMMA  $\rightarrow$  ~6 mm

- SiPMs located on flex circuits + spring loaded mount
- SiPM in dimple cuts (flat or cylindrical) machined at the edges of WLS



# WLS-LG: Attenuation length ( $\lambda_{att}$ )

For PMMA WLS-LG in LAr, the **critical angle** ( $\theta_c$ ) =  $56^\circ$

- For  $\theta > \theta_c$  photons get trapped and guided by LG-TIR to SiPMs.
  - $\lambda_{att} >$  **Optical Path (OP)**

- For  $\theta < \theta_c$  photons leaves the LG and are guided by DF to SiPMs.

- Tens of reflections may happen before reaching the SiPMs: required **superior Optical Density of the DF in the range 440-500 nm**

