Optimization of the X-Arapuca Photon Collector for the DUNE FD1 and FD2

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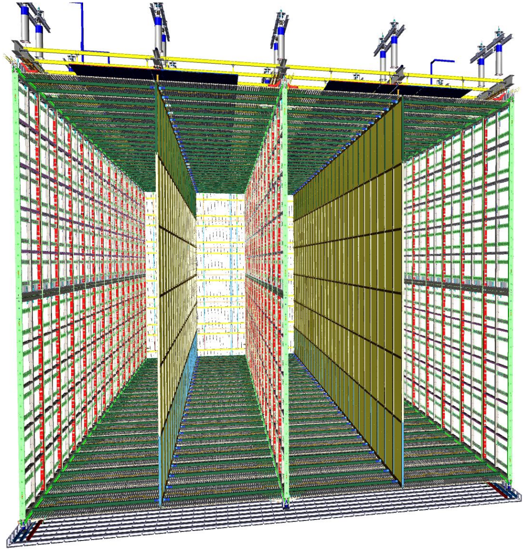
on Behalf of the DUNE Collaboration

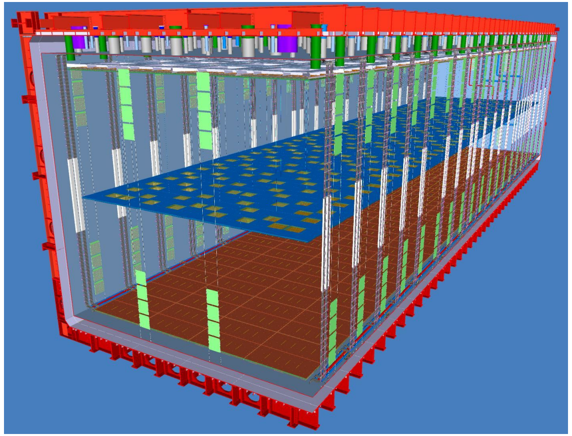
The DUNE PDS



FD1

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

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

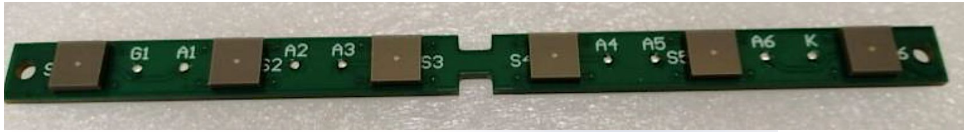


FD2

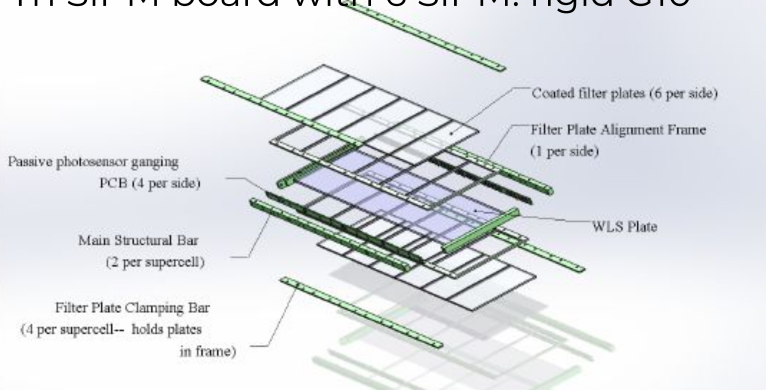
- 6000 XA devices (48 x 10 cm^2) embedded in the three Anodic Planes
- SIPM: 48 x 6x6 mm^2 (1.73 cm^2 or 3.9% Si coverage) ganged @ 48
- LArTPC: Horizontal Drift

- 320 XA devices (58 x 58 cm^2) on the cathode (320kV) → PoF bias/readout
- 320 XA devices on the membrane
- SiPM: 160 x 6 x 6 mm2 (5.8 cm^2 Si, 1.6% Si coverage) ganged @80
- LArTPC: Vertical Drift Technology

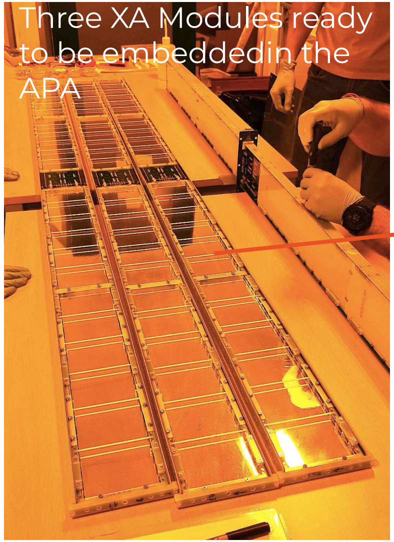
The FD1 PDS & X-Arapuca device

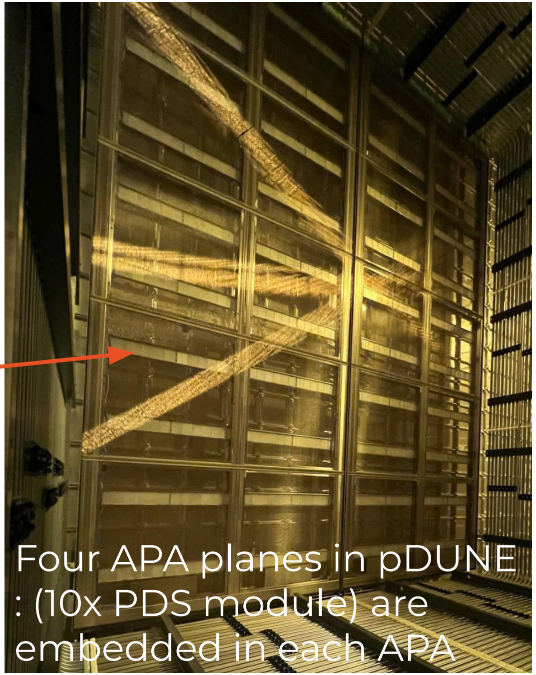


Th SiPM board with 6 SiPM: rigid G10



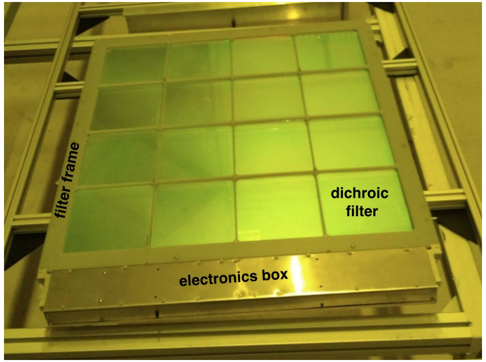
- FD1-XA: (50 x 10 cm^2)
- 4 SuperCells/module
- 10 module/APA
- 1500 Total Modules
- 1000 Double sided 500 single sided

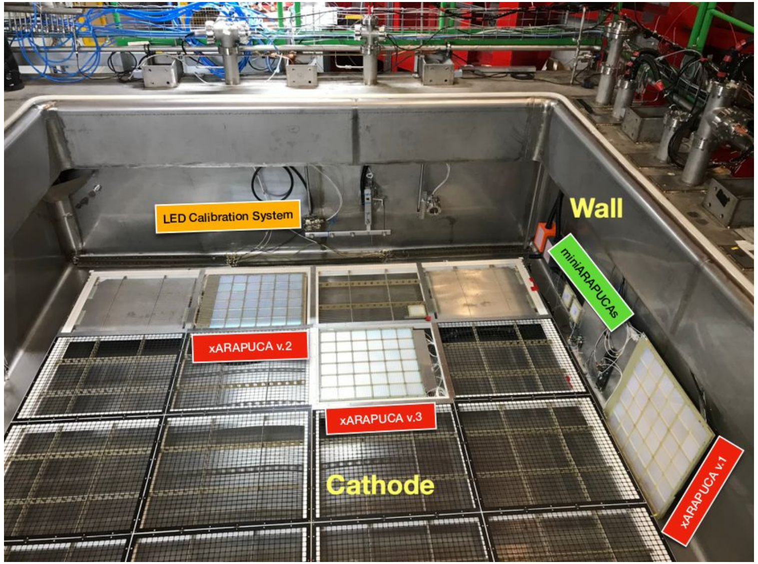




The FD2 PDS & X-Arapuca device

	WLS dimples	DF size (mm^2)	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	

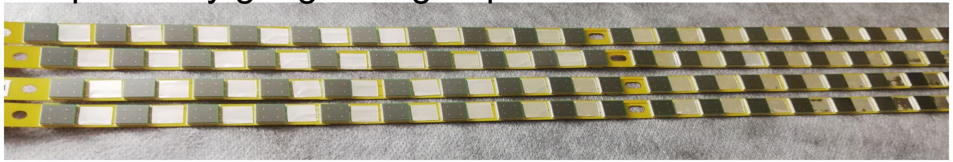




In pDUNE-FD2 8 Memb-XA +8 cath.-XA + (6 optimized) deployed in 2023

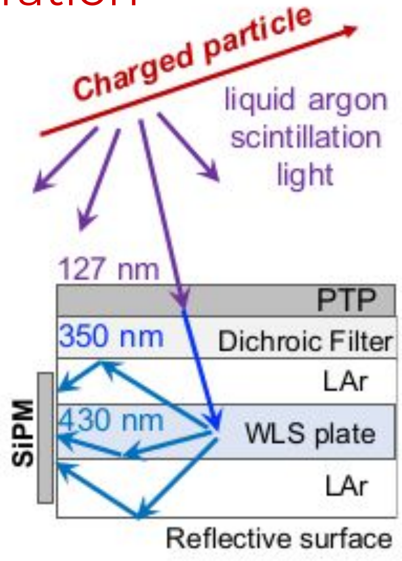
2 x Cath-XA & 1 x memb-XA in the CERN Coldbox

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



Optimization (and measurements) of the XA PDE

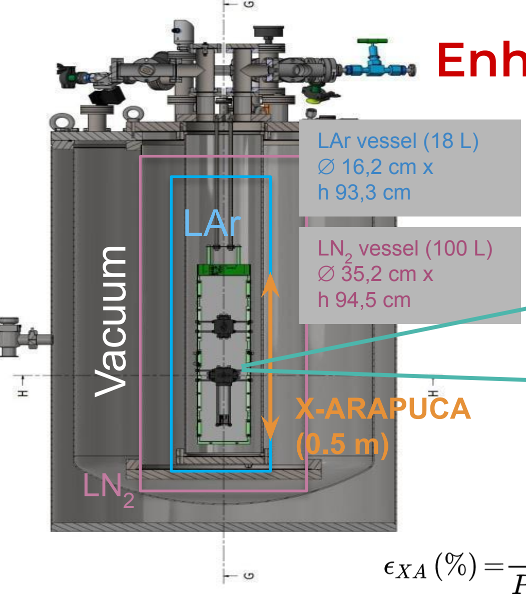
- Developed methods and setup to accurately measure the absolute PDE of the XA device and
- Developed accurate simulation of the photon transport in the device
- Improved the XA components quality and configuration
  - ✓ WLS-LG plate (FD1 & FD2)
    - High grade PMMA embedding WLS-dye* showed superior 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)

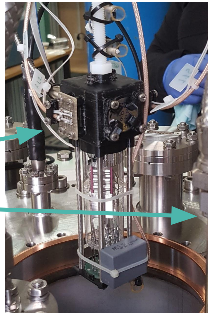


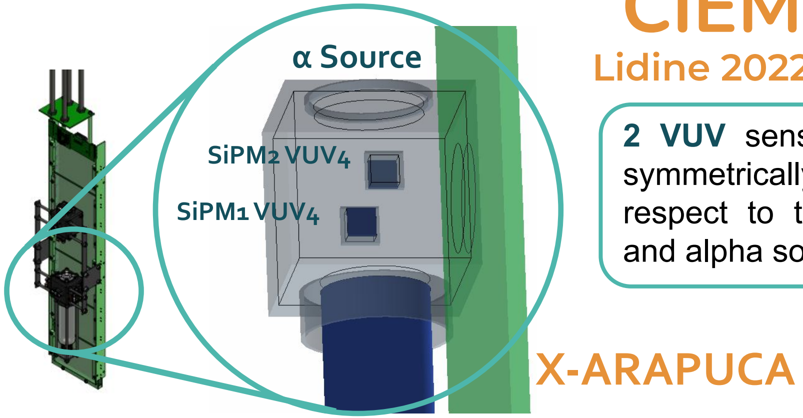
Enhancement of the BL FD1-XA PDE

CIEMAT results

Lidine 2022- update 2023







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

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

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

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)

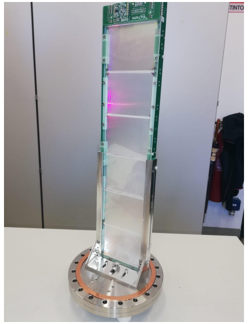
	FBK+EJ	HPK +EJ	HPK +G2P
PDE 40%	1.34 ± 0.10	1.51 ± 0.12	2.02 ± 0.17
PDE 45%	**1.56** ± 0.12	**1.72** ± 0.14	**2.28** ± 0.19
PDE 50%	1.93 ± 0.15	1.87 ± 0.15	2.51 ± 0.21

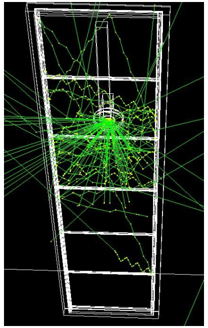
High grade PMMA embedding WLS-dye.

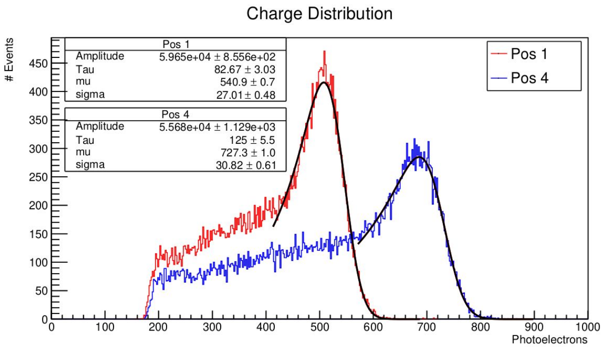
+30%

Enhancement of the BL FD1-XA PDE : INFN-MiB

update 2023

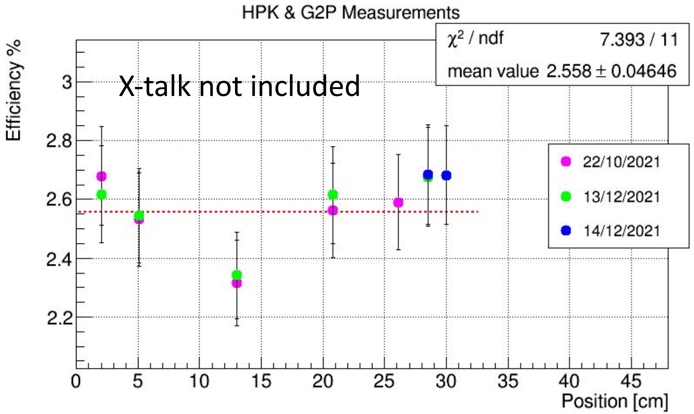






Method: z-scanning of the whole cell (~2 Sr) with an ^{241}Am exposed α source (JINST 16 (2021)09027)

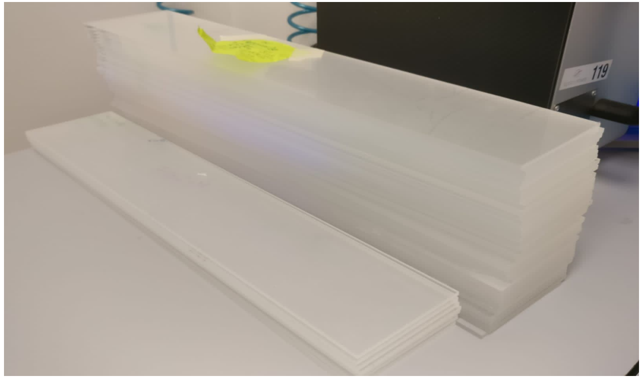
$$\epsilon = \frac{4\pi \cdot \alpha \text{ peak(ADC)}}{\text{s.ph.e.(ADC)} \cdot f_{int} \cdot \text{LY}_{\text{LAr}} \cdot \text{En}_{\alpha} \cdot \text{q}_{\alpha} \cdot \Omega}$$



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

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

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

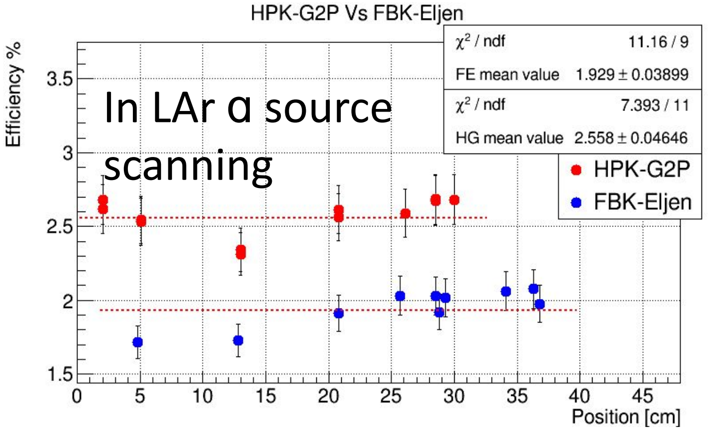
- **80 x WLS slabs for FD1-pDUNE:** 48.0 x 9.3 x 0.38 cm^3

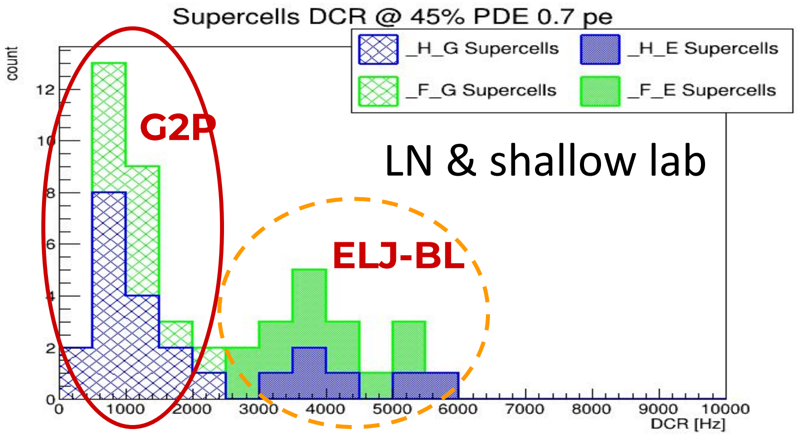
Validated Casting, Laser cut and edge polishing procedures of the WLS from the as-casted plates..

- **16 (M0)+ 6 (M1)** WLS slabs for pDUNE-FD2: 60.7 x 60.7 x (0.38 & 0.55) cm^3

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

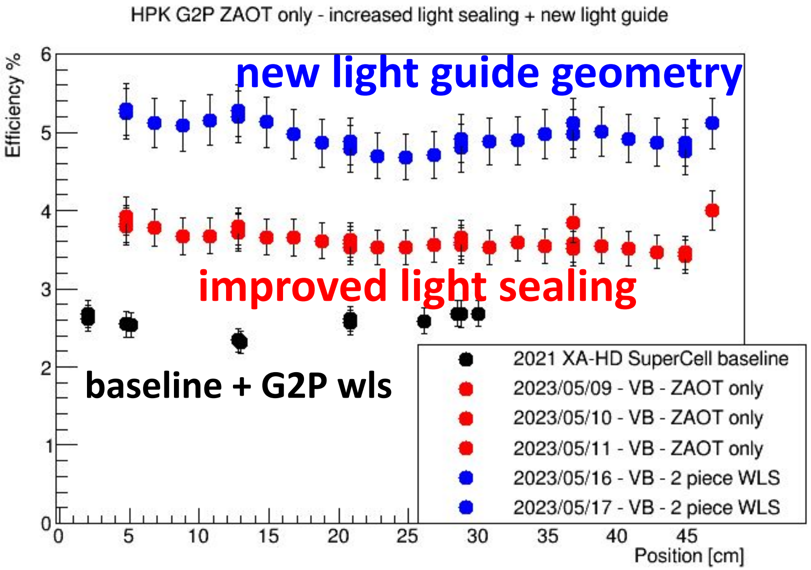


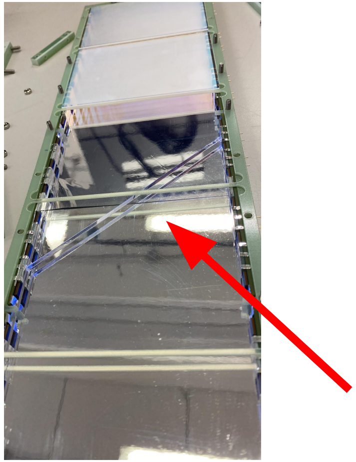


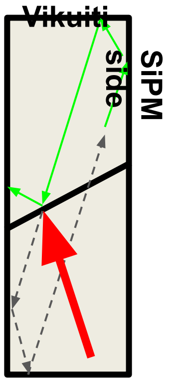
FD1: Modified WLS-LG geometry

Major improvement of the FD1 XA PDE cutting the WLS-LG in two parts by a 40° cut and improved LG light-sealing

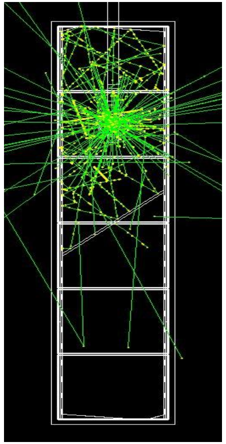
- optimization via optical sims
- measurements with MiB setup

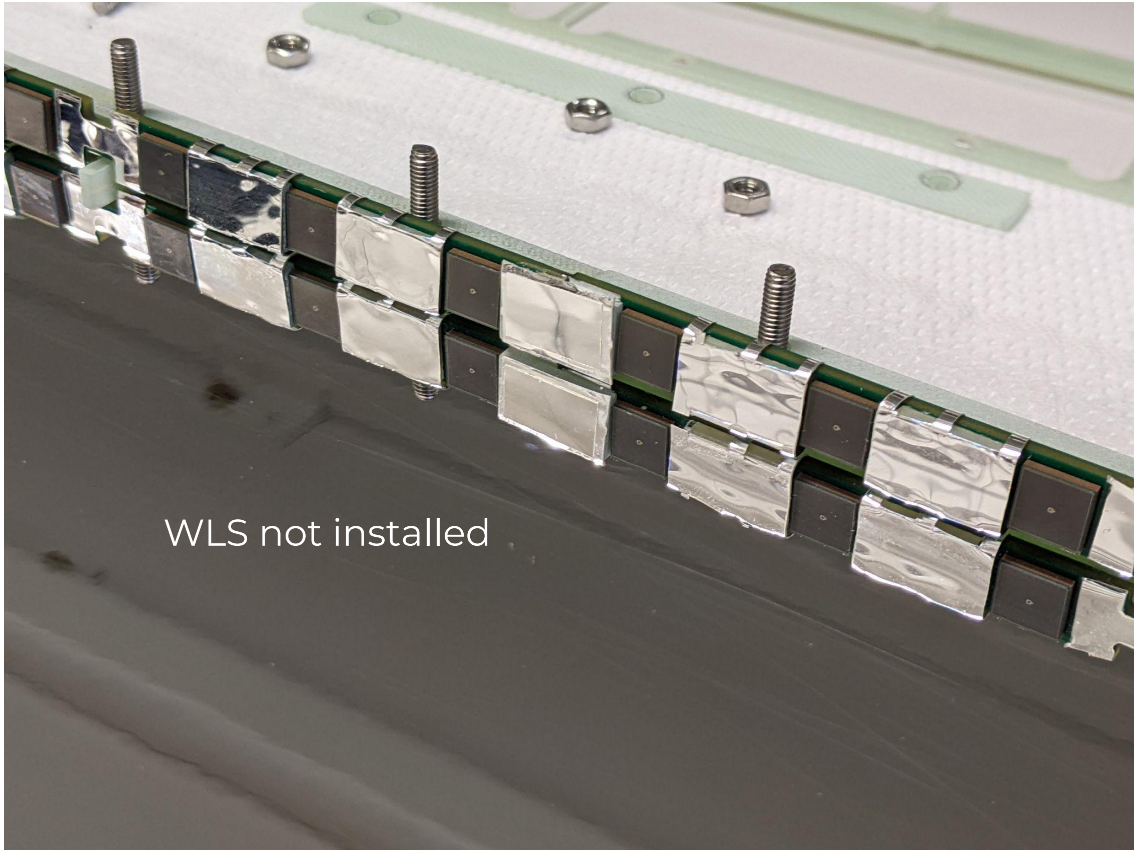






40° cut in the middle with Vikuiti applied




WLS not installed

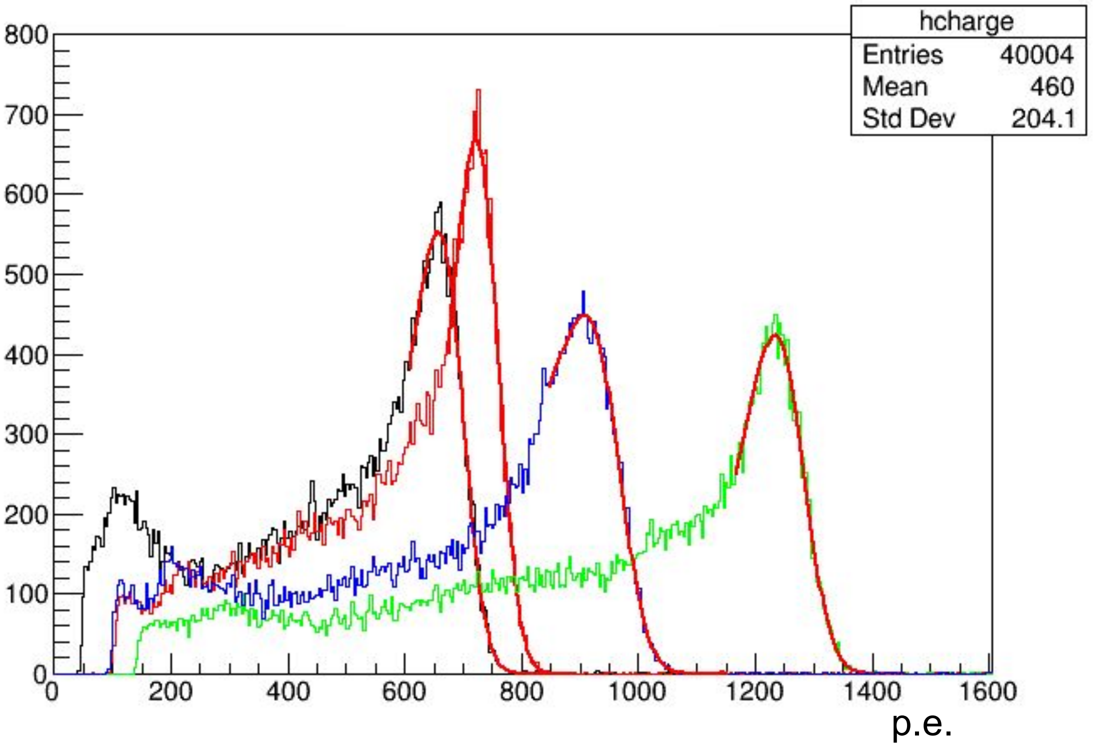

with WLS

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

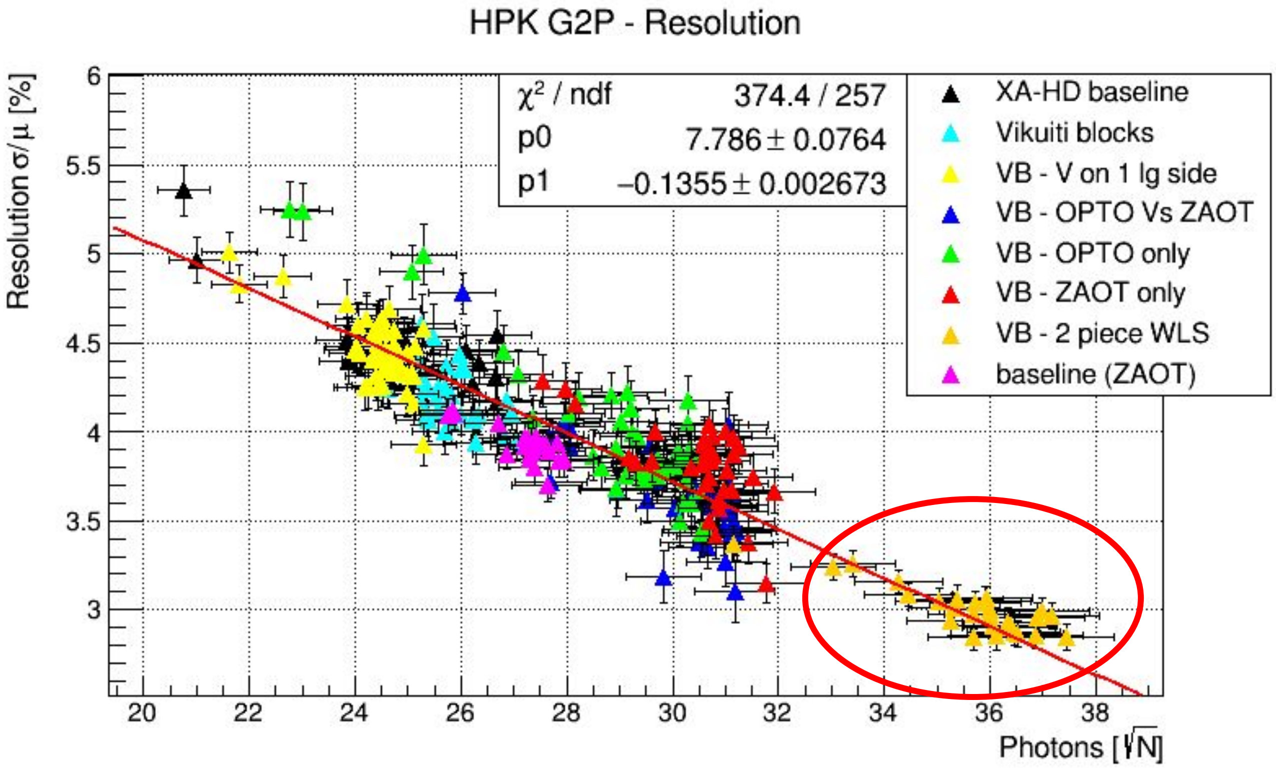
All taken in the middle of the 3rd dichroic filter

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 lg improves the energy resolution w.r.t. all the other configurations



WLS-LG: Attenuation length (λ_{att})

- **Both the Absorbance of the pTP photons & the λ_{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)
- λ_{att} (400-500 nm) is the leading parameter for high PCE.
  - **Required: λ_{att} > Optical Path**

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

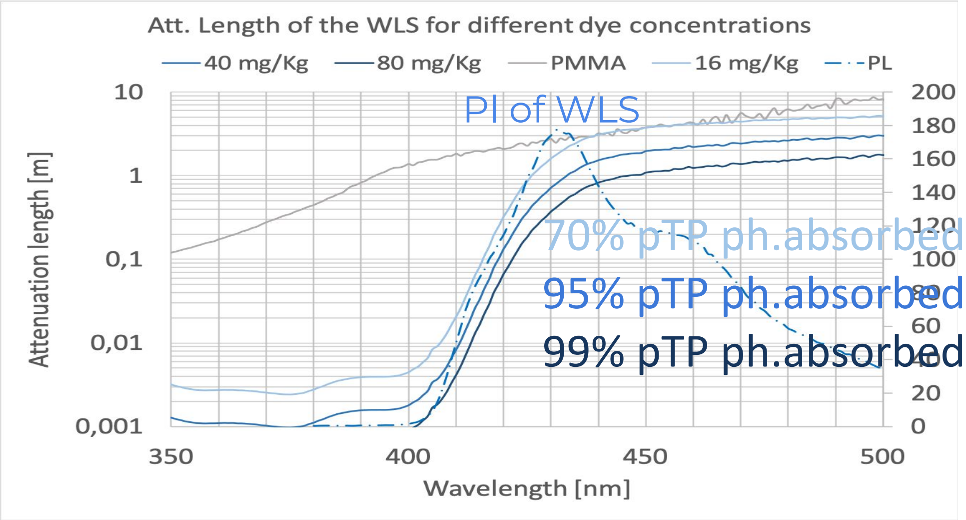
$T = I/I_o \exp(-d/\lambda_{att})$

$A = \varepsilon\, c\, d$

ε = molar extinction coeff.

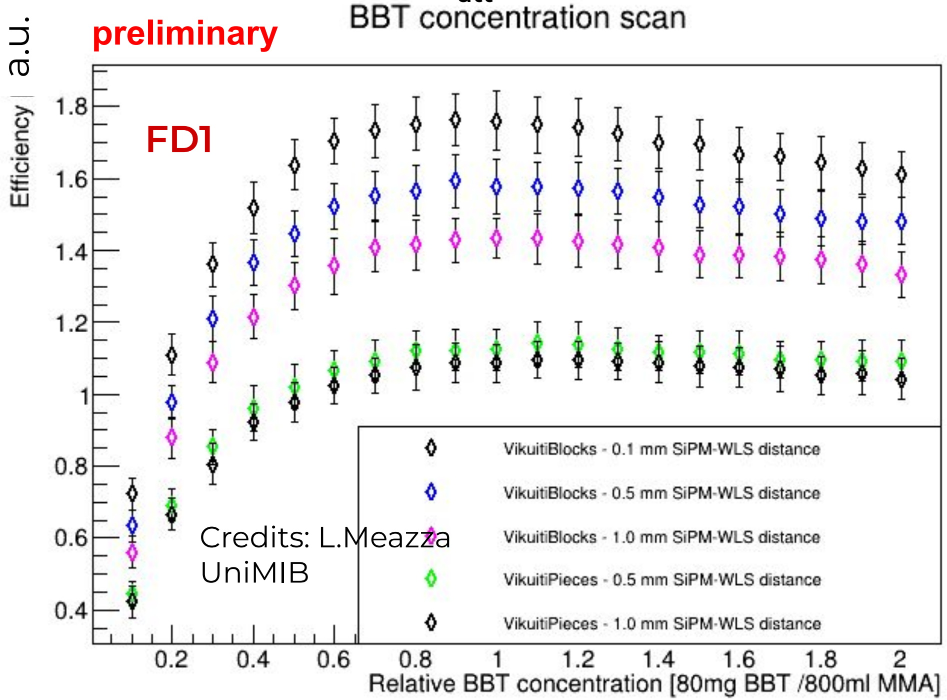
c = concentration

d = optical path

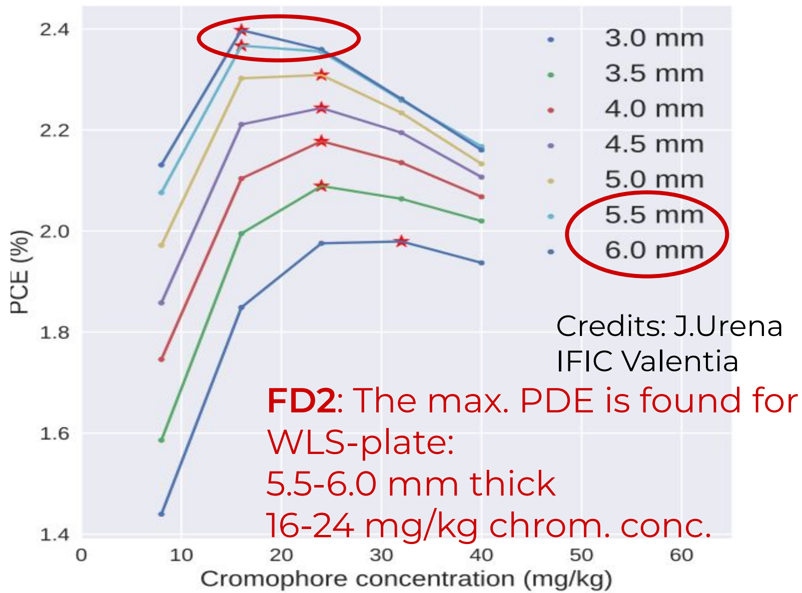


WLS- LG: chromophore concentration and thickness optimization for FD1 and FD2

OP ~ 10-100 cm; λ^{opt}_{att} =37 cm; thick=3.8mm



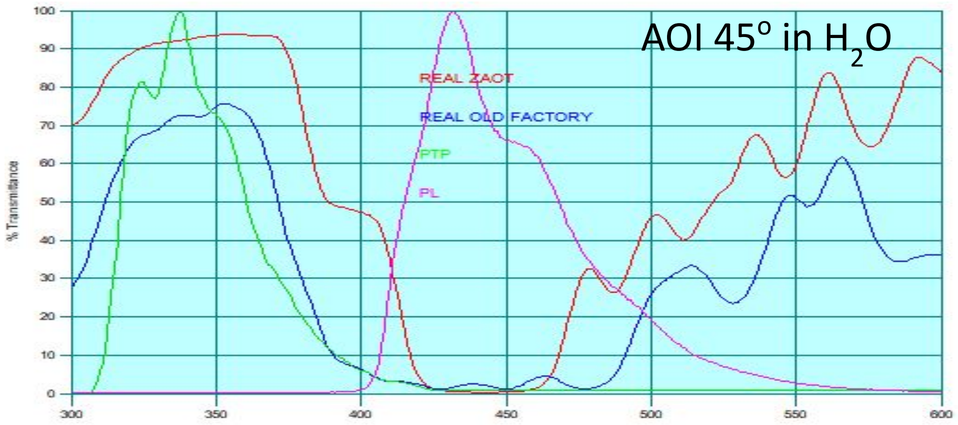
OP ~ 60-200 cm; λ^{opt}_{att}~ 200 cm; thick = 5.5 mm



FD2: The max. PDE is found for WLS-plate:
5.5-6.0 mm thick
16-24 mg/kg chrom. conc.

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^2 to 15 x 15 cm^2 to increase XA the active surface



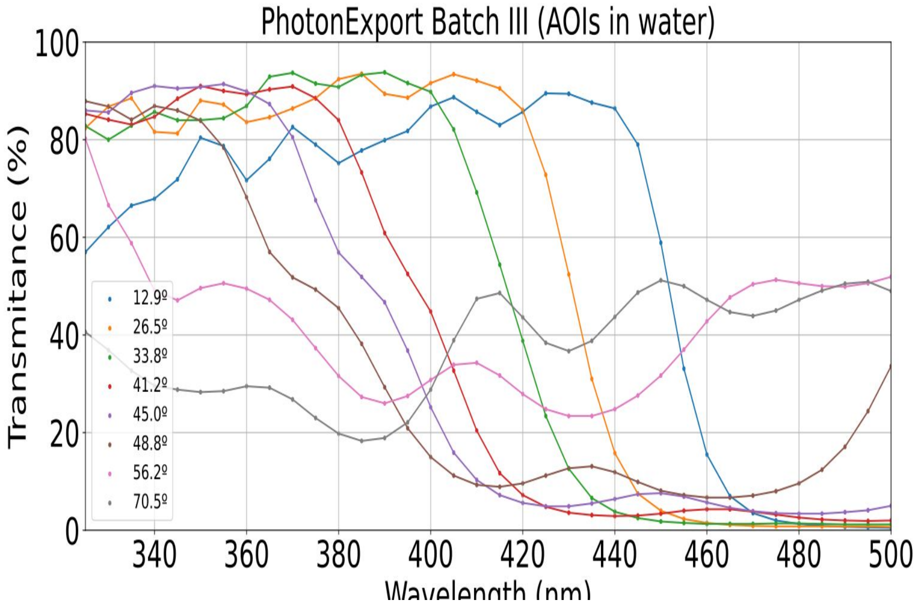
		Subs	Design
OPTO	FD1	B270	45° Air
ZAOT	FD2	BF33	45° LAr
Photon Export	FD2	F.silica	45° LAr

The DF T curves measured in H2O

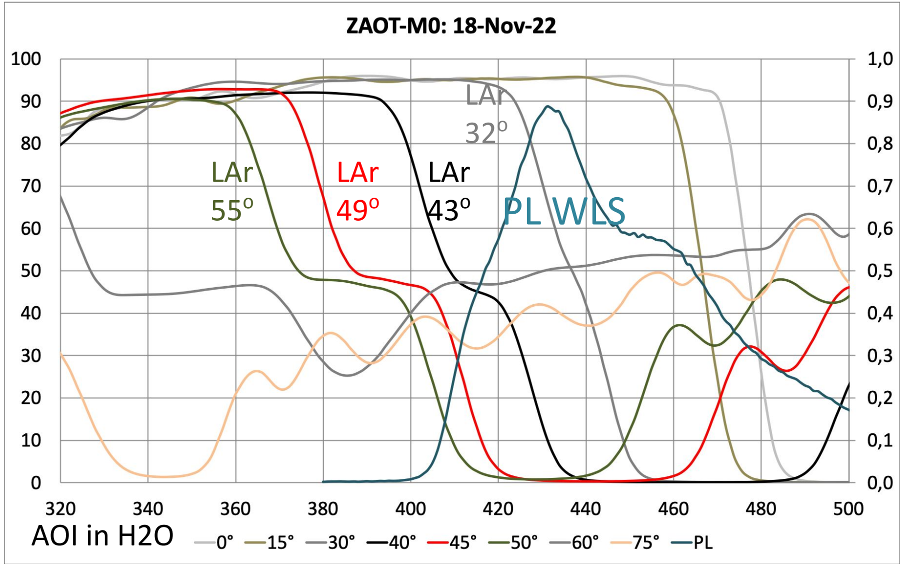
AOI H2O-to-LAr trasnformed by Snell law

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

PE- DF: T Curves: 14.5 x 14.5 cm^2 for Module-0

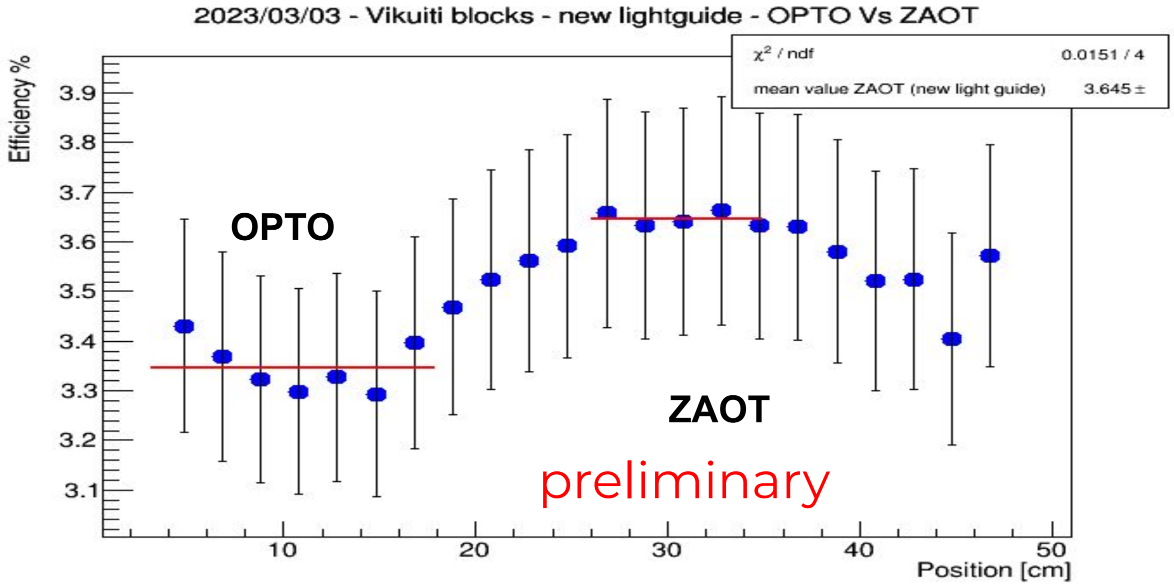


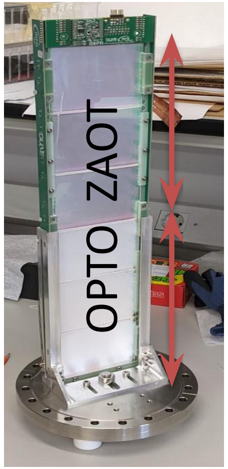
ZAOT-DF: T Curves: 14.5 x 14.5 cm^2 for Module-0



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





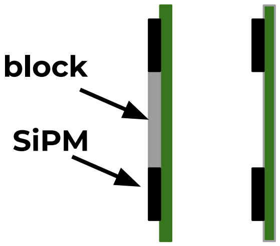
Summary

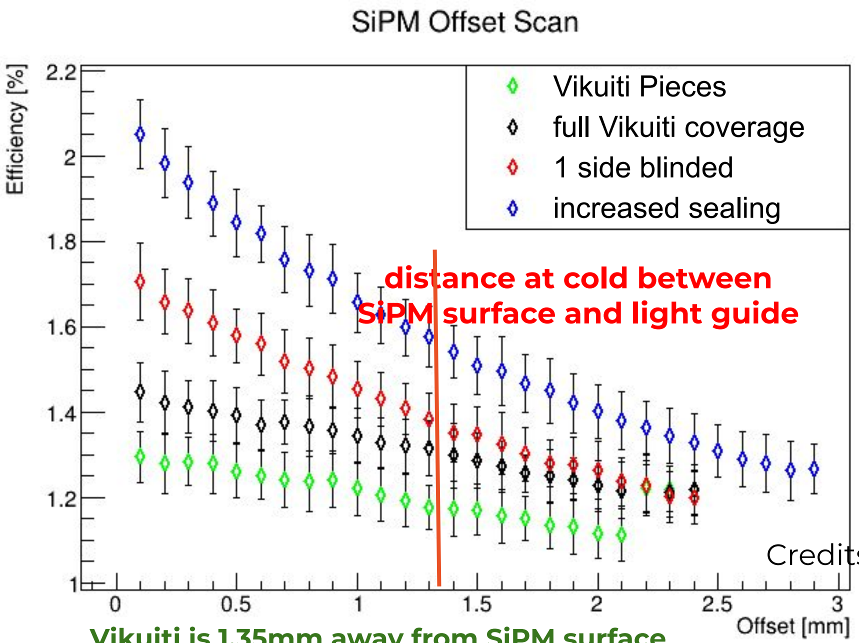
- ➢ The PDE of the DUNE PDS building block has been measured and improved
- ➢ For **The BL-FD1-XA (EJ WLS) a PDE <= 2% was measured**
- ➢ The optimization of the FD1-XA components & relative configuration
  - ✓ **Change of the BL WLS-LG → PDE~ 2.5%**
    - The G2P PMMA WLS-LG is now the BL for FD1 & FD2
  - ✓ **SiPM-to-WLS-LG contact & reflectors → PDE ~3.5%**
  - ✓ **WLS geometry** to recover photons ineffective paths→ **PDE ~5%**
- ➢ The **PDE of the FD2-BL XA** as deployed in the **FD2-Module0** has been measured (F.Di Capua's talk) **~ 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

FD1: 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

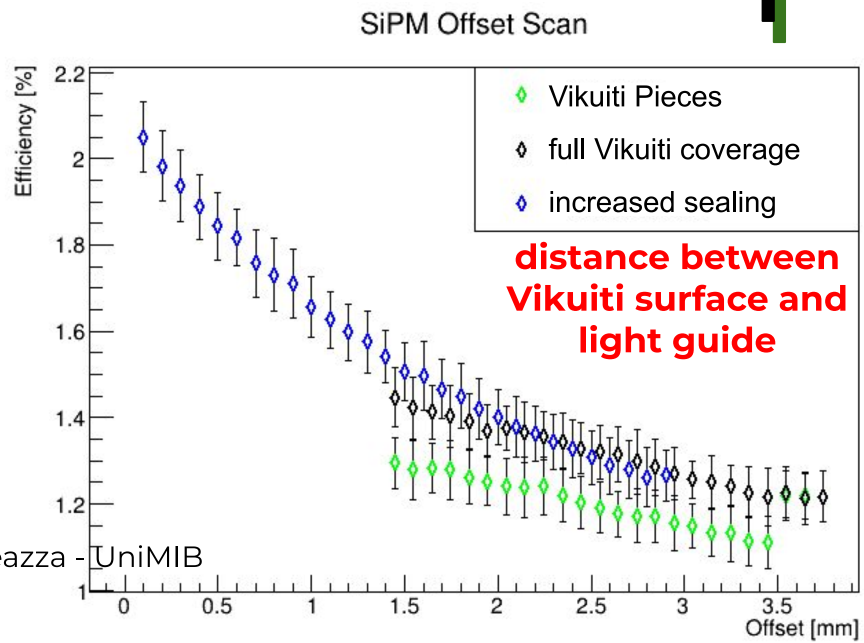
→ proposed a wider (+1 mm) WLS-LG & to flush reflector to SiPMs





Vikuiti is 1.35mm away from SiPM surface

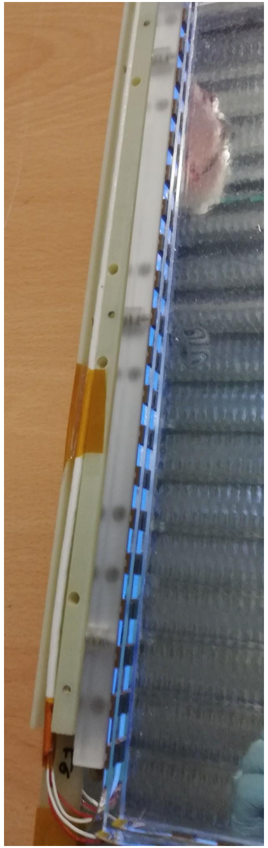
Credits: L.Meazza - UniMIB



FD2: SIPM - to Lightguide coupling

FD2-XA designed with no SiPM-to-WLS-LG gap .
To follow the 1% shrink of the PMMA → ~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 (λ_{att})

For PMMA WLS-LG in LAr, the critical angle (θ_c)= 56°

- For $\theta > \theta c$ photons get trapped and guided by LG-TIR to SiPMs.
  - **λ_{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.**