X-ARAPUCA ABSOLUTE PHOTON DETECTION EFFICIENCY FOR DUNE FD-VD

measurements @CIEMAT

Sergio Manthey Corchado
on behalf of DUNE collaboration

GOBIERNO DE ESPAÑA MINISTERIO DE CIENCIA E INNOVACIÓN

Ciemat Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas

AIDA innova

Plan de Recuperación, Transformación y Resiliencia

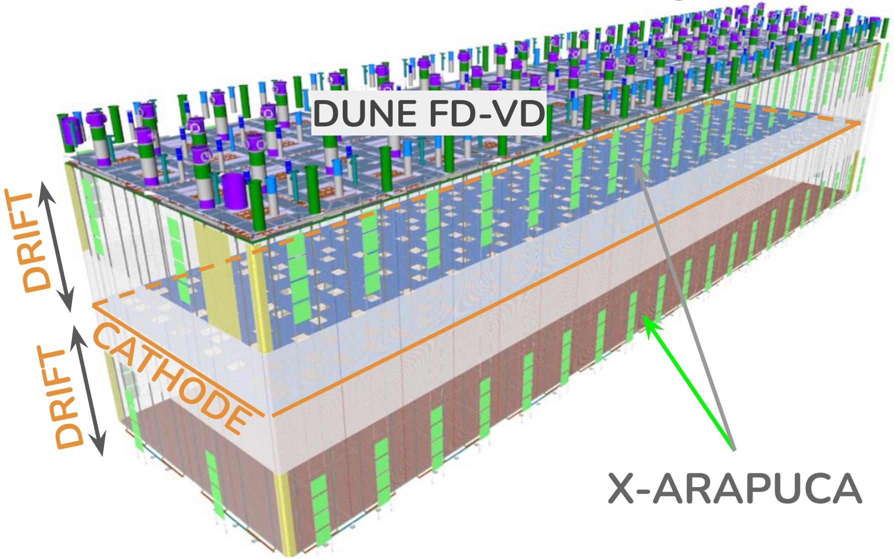
Introduction

- DUNE: Long-baseline (**1300 km**) neutrino oscillation experiment.
- **Neutrino ν_μ 1.2 MW** beam power → upgradeable to > 2 MW.
- Far Detectors: **4 LAr-TPC** (~ 70 kT).

- Measurement of ν_μ/ν_e dis-/appearance:
  - Neutrino **mass ordering**.
  - **CP violation**.
  - Precision on **mixing parameters**.
  - BSM searches.

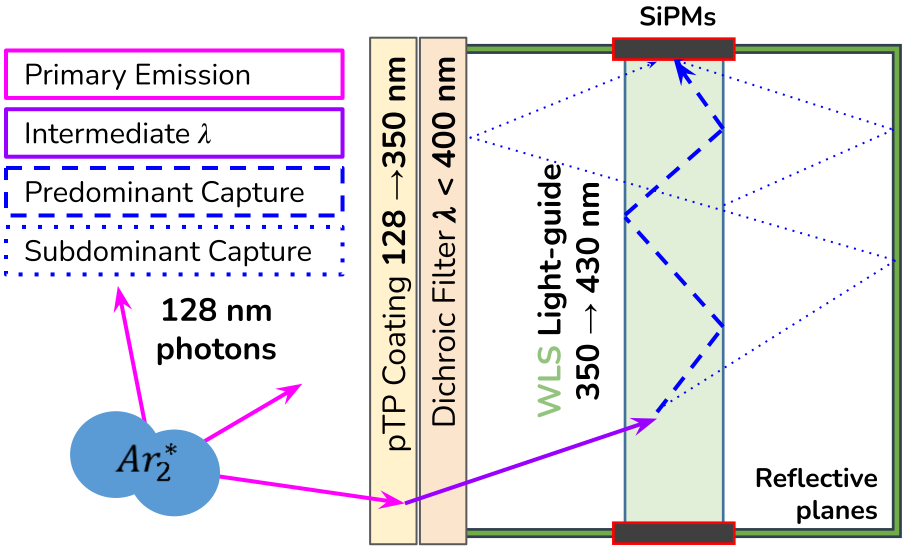
- Neutrinos from supernova bursts, sun and other low energy sources.

- **Photon Detection System (PDS)** measures LAr scintillation light.
- Composed of **672 X-ARAPUCA** tiles:
  - 320 **Cathode** mounted **double-sided.**
  - 352 **Membrane** mounted **single-sided.**



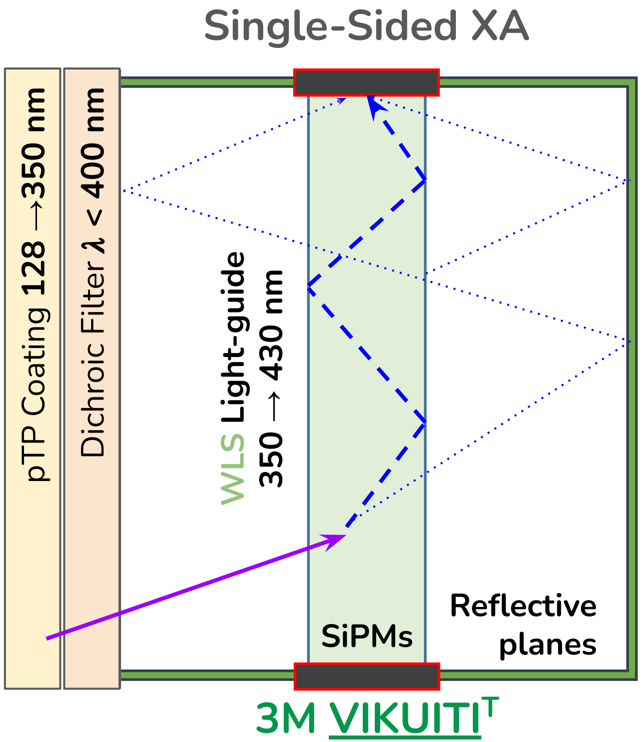
X-ARAPUCA: Concept

- **LAr** emits **scintillation** light in the VUV range **@128 nm**.
- VUV Photons are **shifted** to higher wavelengths with pTP & **trapped** by **dichroic filter** (400 nm cut-off) and **surface-reflection**.
- **WLS-bar further shifts & guides** light by internal reflection to surrounding **SiPMs** for **read-out**.
- **Large surface coverage** is achieved in a **cost-effective** manner.



[A.A. Machado et al 2018 JINST 13 C04026]

X-ARAPUCA: Single vs. Double-Sided



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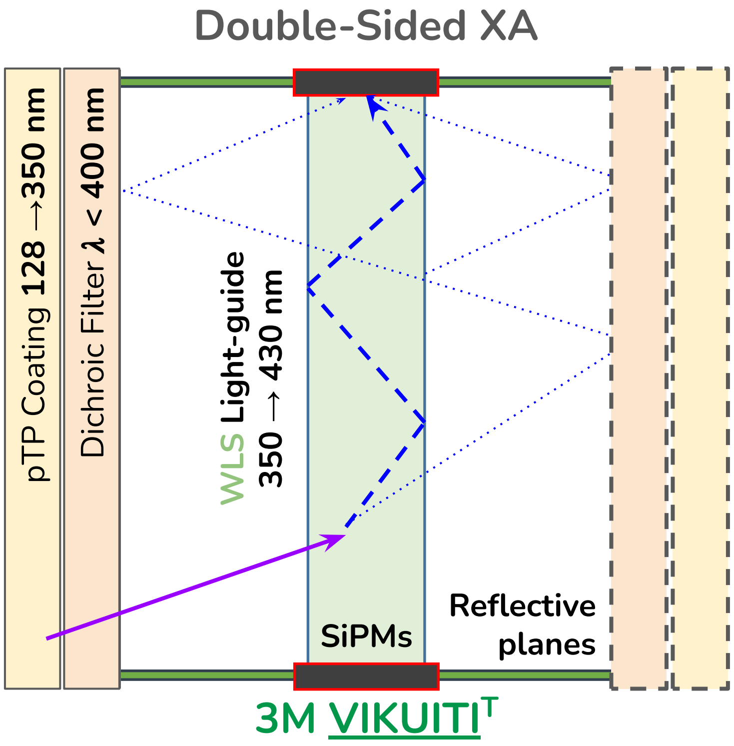
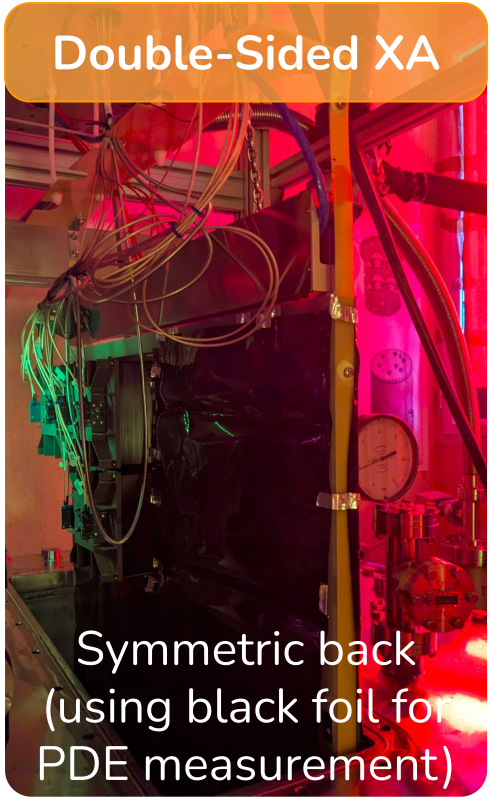
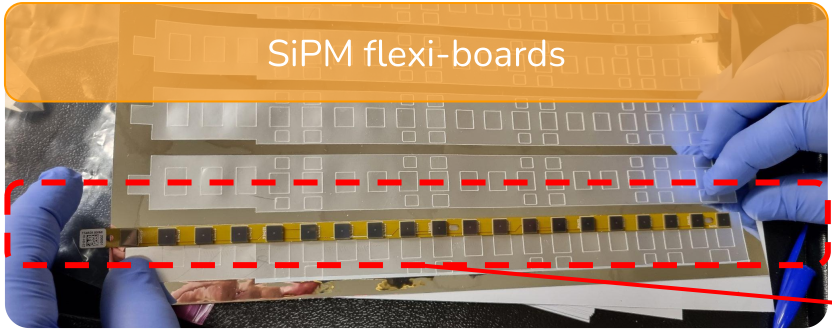
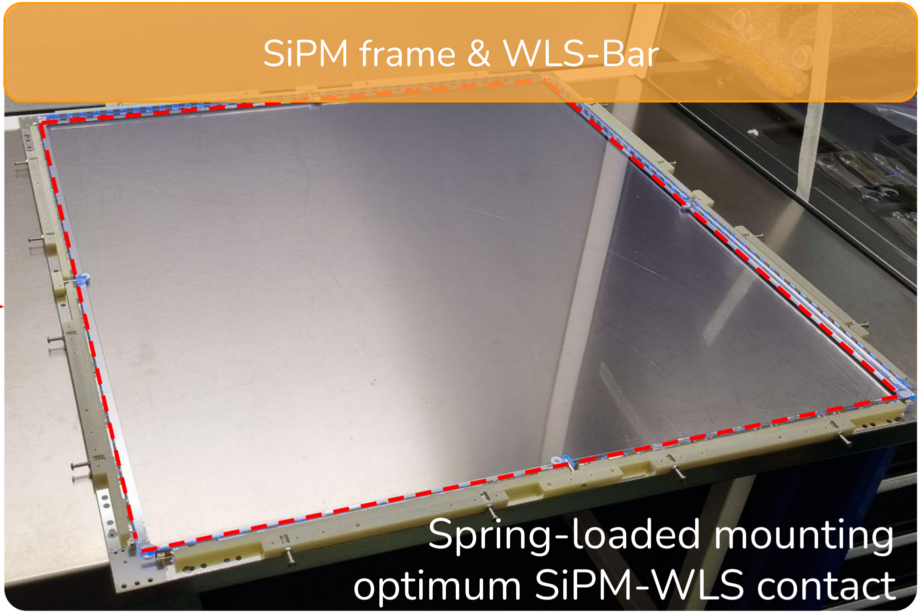




X-ARAPUCA: Vertical Drift Components

- **Design for VD**: XA tiles (~ 60 x 60 cm²) double-/single-sided for cathode/membrane.
- Mounted **160** sensors (flex circuits with 20 SiPMs passively ganged in groups of 5).





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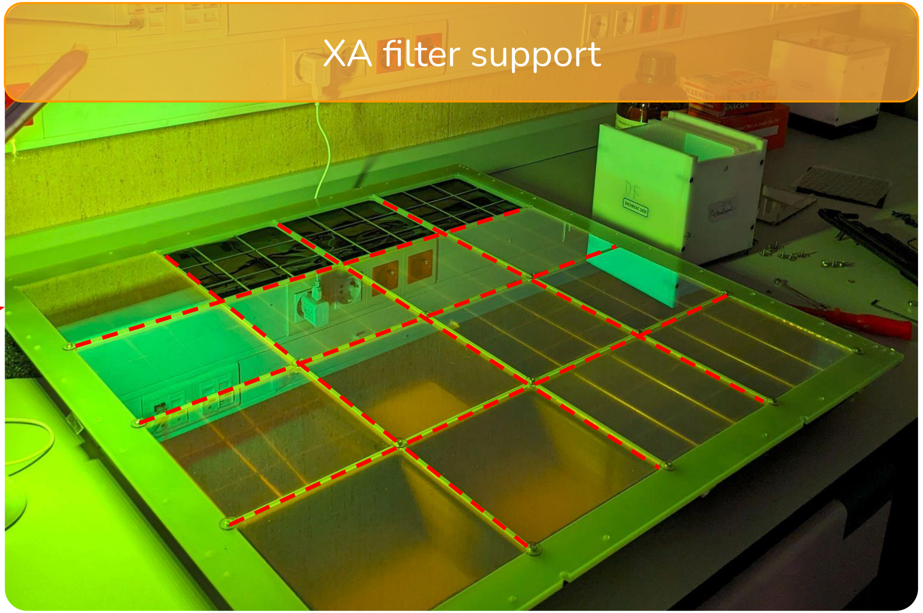


X-ARAPUCA: Vertical Drift Tested Configurations

All tested XAs mount FBK-TT SiPM.

With and without dichroic filter:

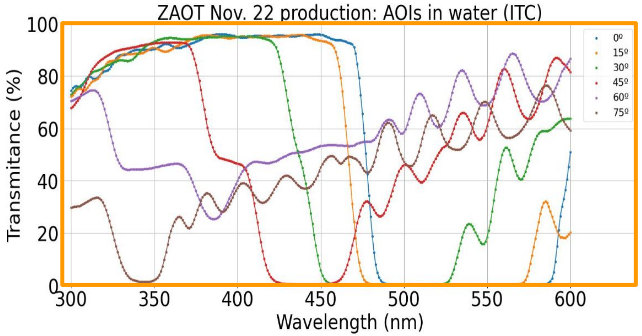
→ Test **non-ideal DF transmittance** **worsening PDE** **for VD-XA**.

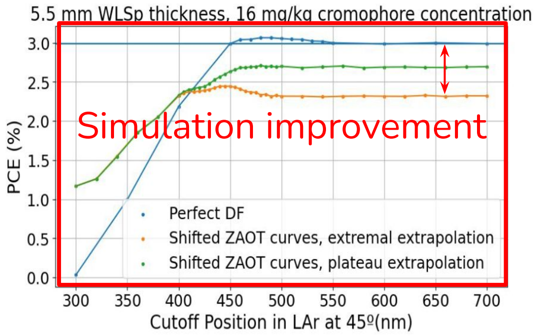
Optimize WLS-Bar **width** and **chromophore concentration** to reduce absorption.

→ Tested bars:

a. **3.8 mm & 80 mg/kg**
b. **5.5 mm & 24 mg/kg**

XA	WLS	Dichroic	pTP	Sided
1. Dichroic Single-Sided	a	ZAOT	ZAOT	Single
2. Dichroic Double-Sided	a	ZAOT	ZAOT	Double
3. Non-Dichroic Single-Sided	a	x	P.E.	Single
4. Non-Dichroic Double-Sided	a	x	ZAOT	Double
5. Non-Dichroic Single-Sided	b	x	P.E.	Single





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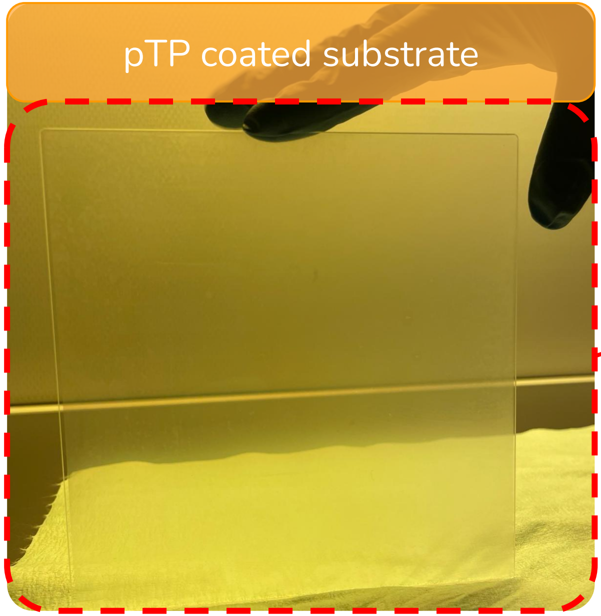
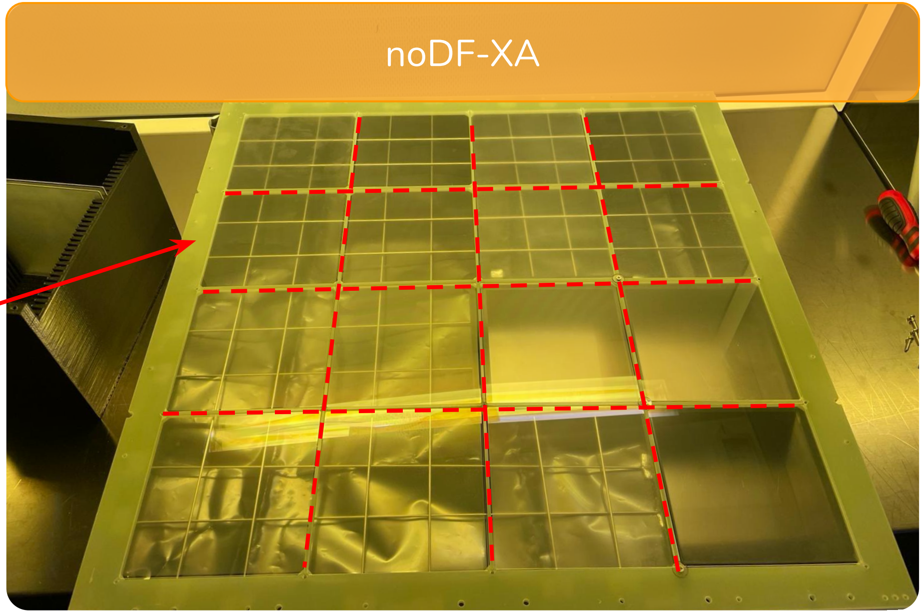


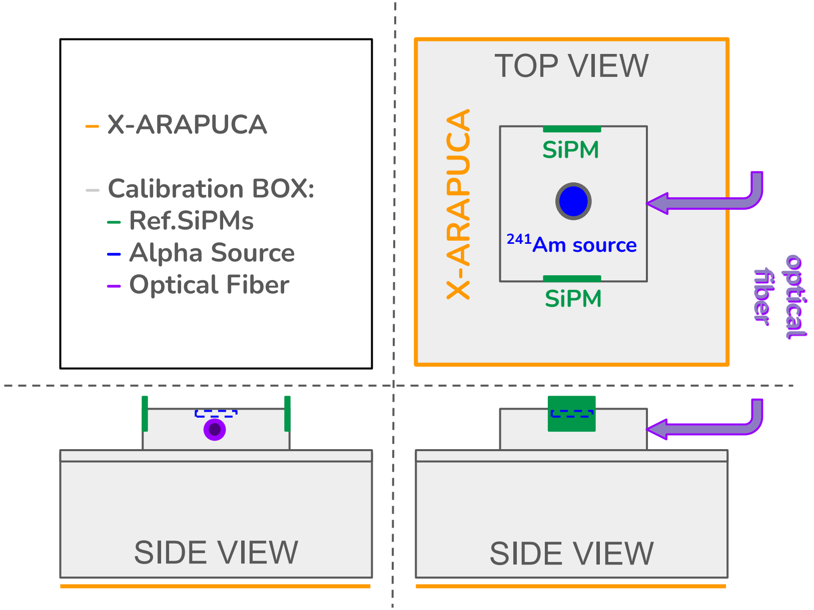


Photon Detection Efficiency Measurement

Direct PDE computation method.

$$\epsilon(\mathrm{XA}) = \frac{\#PE_{\mathrm{XA}}}{\#PE_{\mathrm{Ref.SiPM}}} \cdot \epsilon(\mathrm{Ref.SiPM}) \cdot f_{corr}$$

- $\#PE_{XA}$: PEs detected by the XA.
- $\#PE_{refSiPM}$: PEs detected by the reference SiPMs.
- **ε(ref SiPM)**: PDE for ref. SiPMs (from ref. [NIMA.2024.169347]).
- **Correction** factors ($f_{corr} = f_{geo} * f^{XA}_{XT} / f^{SiPM}_{XT}$):
  - f_{geo}: **Geometrical** → solid angle correction wrt. α source.
  - f_{XT}: **Cross-talk** → measurements on FBK/HPK SiPMs.



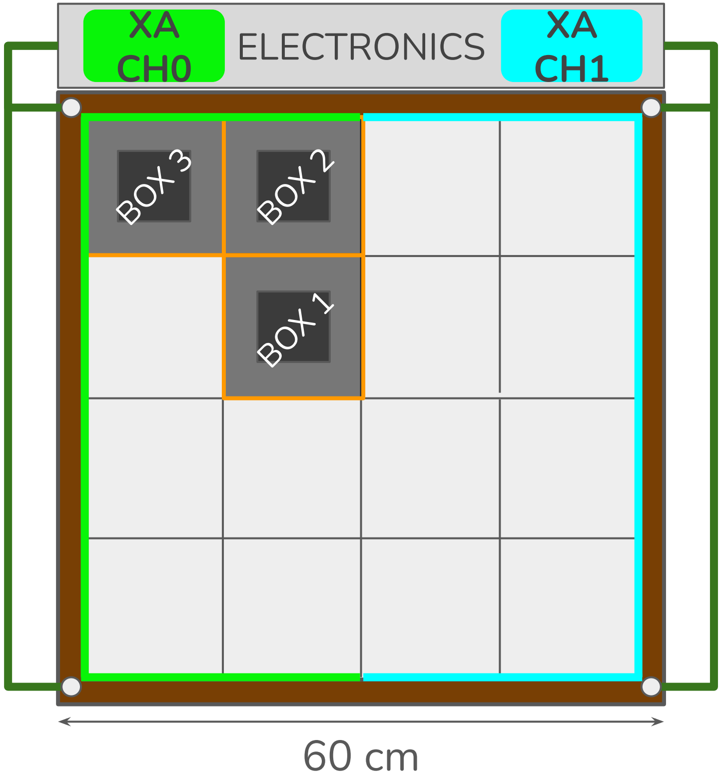
- **Mounted SiPMs: FBK-TT**.
- Characterised by **PDS Consortium.** [arXiv.2405.12014].
  - Cross-talk: (**16.1 ± 0.3**)%

- **Ref. SiPMs: HPK VUV4** S13370 – 6075CN.
- Characterised **@CIEMAT** for CT [NIMA.2024.169347].
  - Cross-talk: (**19.7 ± 0.3**)%
  - SiPM PDE @ VUV 128 nm: (**12.7 ± 1.1**)%

Calibration Layout

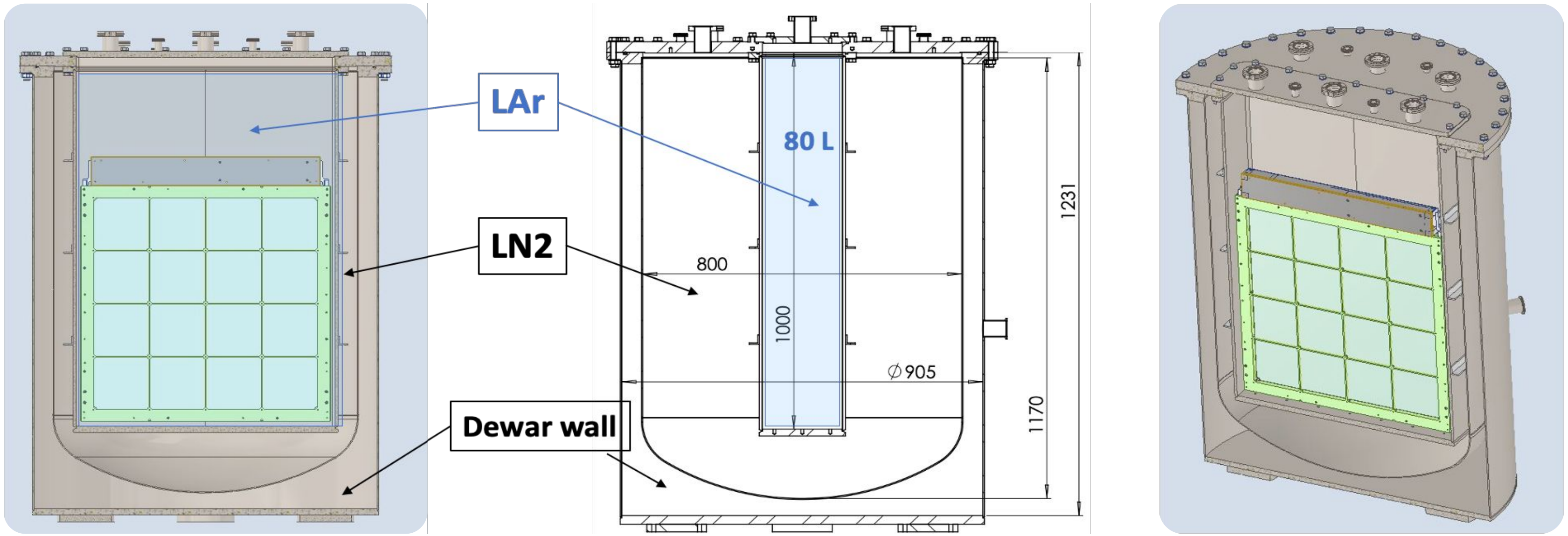
Absolute **PDE measurement**:

- XA read-out split into **2 channels** (combined during data analysis).
- **Calibration boxes** positioned in the **3 uniquely distinct** XA positions.
- Each box mounts **1 alpha source** & **2 ref. SiPM** with known PDE.
- **Average XA PDE** computed from weighted average of 3 calib. boxes.



Cryogenic Setup @CIEMAT

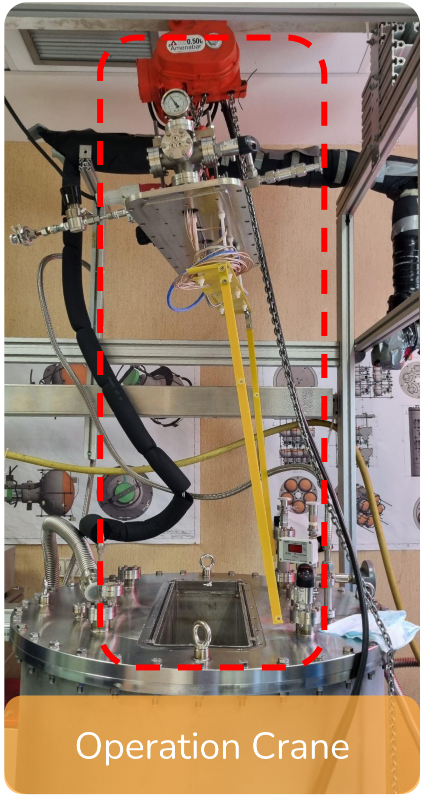
- Cryogenic vessel allows to liquify GAr and to **detect scintillation light** with the XA in the same conditions as in the DUNE FDs.



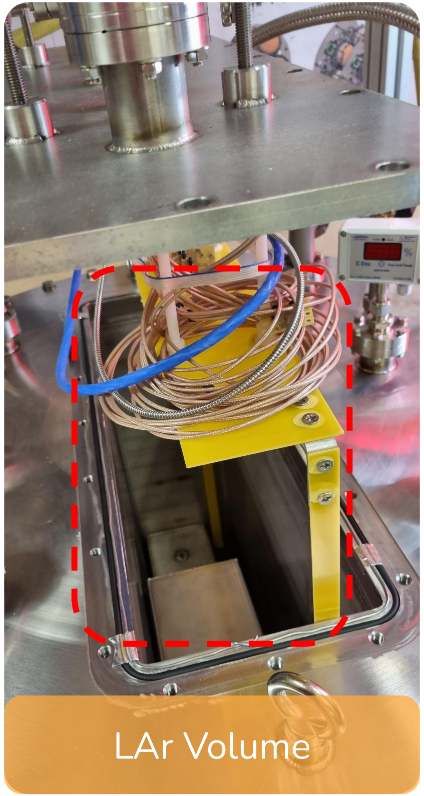
*GAr (99.9999% purity) is liquified with LN_2 at 2.7 bar

Cryogenic Setup @CIEMAT

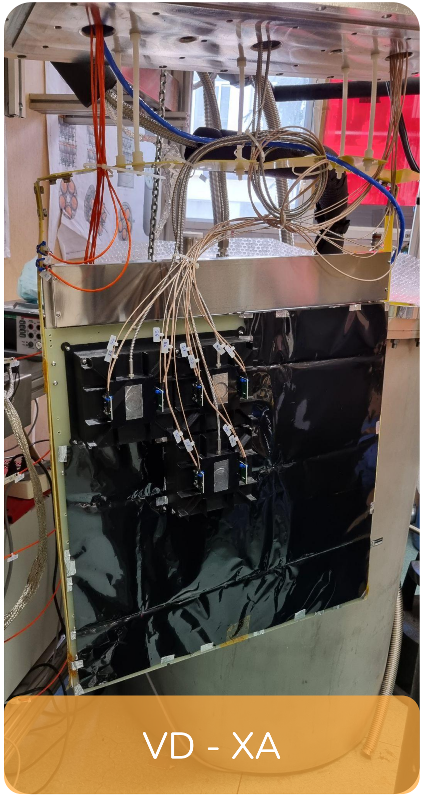
Cryogenic Vessel



Operation Crane



LAr Volume



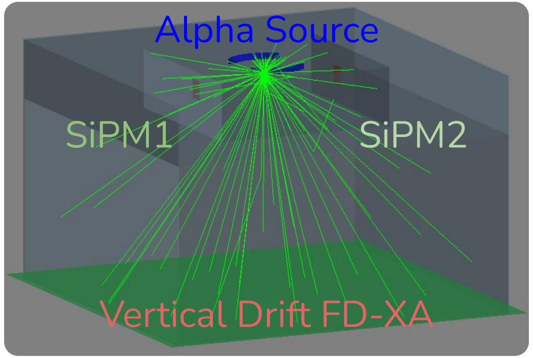
VD - XA

Calibration System Simulation

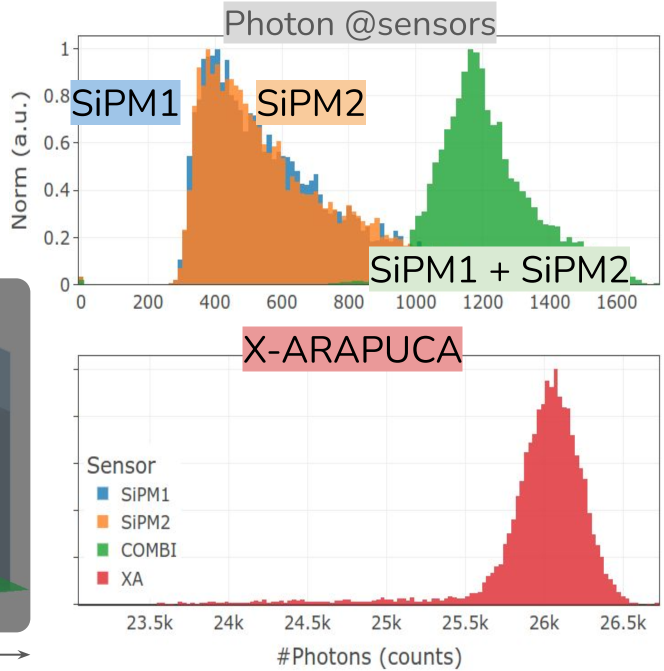
- Relative solid angle by **standalone GEANT4 simulation.**
- Accounts for the **differences in sizes/positioning** of ref. sensors.

$$f_{\text{geom}} = \frac{\Omega(\text{Ref.})}{\Omega(\text{XA})} = 0.047 \pm 0.001$$

Sensor	MEAN Ph.
XA-VD (21170 mm²)	25920
SiPM (12 mm²)	1206



14.55 x 14.55 cm²

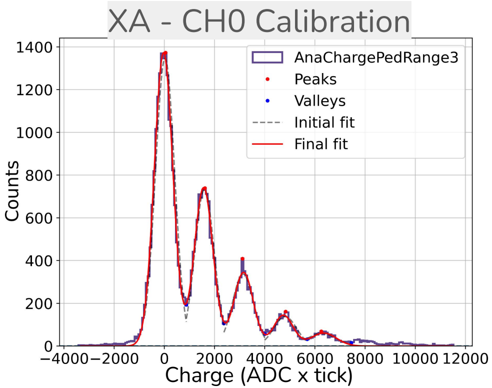


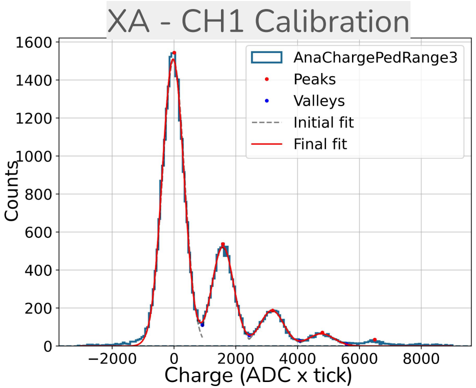
Data Taking: XA Characterization

- For each XA configuration & data-taking campaign.
- Calibration follows standard procedure: **compute baseline** from pretrigger, **subtract** to waveform, **integrate** pulse.

$$f(x) = \sum_{i=0}^{n} A_i \, e^{\frac{1}{2}\left(\frac{x-\mu_i}{\sigma}\right)^2}$$

$$S/N = \frac{\mu_1 - \mu_0}{\sigma}$$

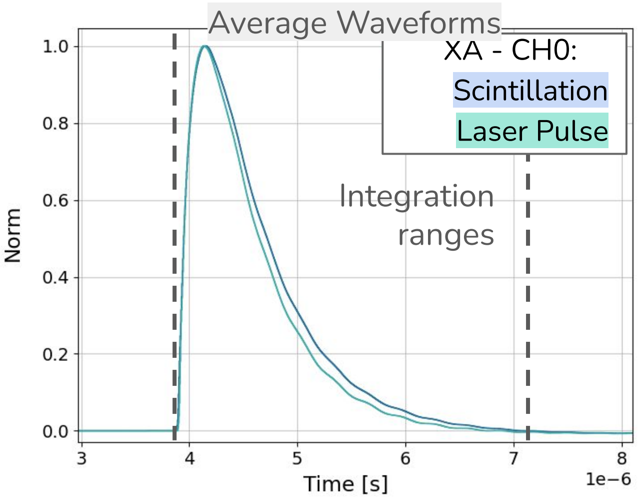


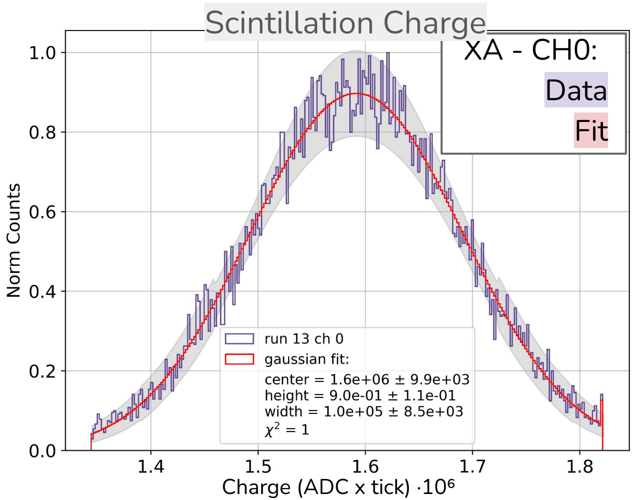


	XA - CH0		XA - CH1	
OV	Gain (e^-)	S/N	Gain (e^-)	S/N
4.5	**(4.51 ± 0.02) · 10^5**	**4.3 ± 0.1**	**(4.54 ± 0.03) · 10^5**	**4.6 ± 0.2**
5.5	(5.45 ± 0.02) · 10^5	5.21 ± 0.09	(5.50 ± 0.02) · 10^5	5.5 ± 0.2
7.0	(6.88 ± 0.05) · 10^5	6.5 ± 0.3	(6.93 ± 0.02) · 10^5	6.8 ± 0.7

Data Taking: Scintillation

- Scintillation signals are **triggered** using **coincidence** in both **SiPM** channels..
- Comparing wrt. laser pulse average waveform, scintillation clearly observed.
- Fitted distribution provides PE values (for ref. SiPM **fitted in addition).**





PDE Uncertainty

Error computation takes into account uncertainties associated to the following variables. Additional systematic uncertainties are being investigated.

- **Dominant**
  - **SiPM PDE (8.7%)**: From ref. constrained @CIEMAT [arXiv.2405.12014].
- Subdominant
  - XA #PE (~2%): From repeated gain measurement + gaussian fit of collected charge.
  - SiPM #PE (~2%): Gaussian fit of combined #PE collected per SiPM pair.
  - Geometric Factor (1.43%): From sim. + sensor deviation measurement.
  - XA XTALK (< 1%): From ref. [arXiv.2405.12014].
  - SiPM XTALK (< 1%): From ref. [NIMA.2024.169347].

PDE Results

- **PDE** values are computed from **weighted average** of 3 calibration boxes:
  - OV 4.5 V corresponding to 45 SiPM eff.

	Dichroic Filter	
	Single-Sided	**Double-Sided**
OV	1. DF-XA	2. DF-XA-DS
4.5	**(3.3 ± 0.4) %**	**(3.7 ± 0.4) %**

- Conclusions:
  - **Compatible performance** of **single vs. double-sided XA** configs.

PDE Results

- **PDE** values are computed from **weighted average** of 3 calibration boxes:
  - OV 4.5 V corresponding to 45 SiPM eff.

	Dichroic Filter		Non-Dichroic Filter	
	Single-Sided	Double-Sided	Single-Sided	Double-Sided
OV	1. DF-XA	2. DF-XA-DS	3. noDF-XA	4. noDF-XA-DS
4.5	**(3.3 ± 0.4) %**	**(3.7 ± 0.4) %**	**(4.2 ± 0.4) %**	**(4.1 ± 0.4) %**

- Conclusions:
  - **Compatible performance** of **single vs. double-sided XA** configs.
  - **Improvement 27% (single-sided)** & **11% (double-sided)** when **removing dichroic filters** due to non-ideal entrance transmittance and shifting cut-off for different angles.

PDE Results

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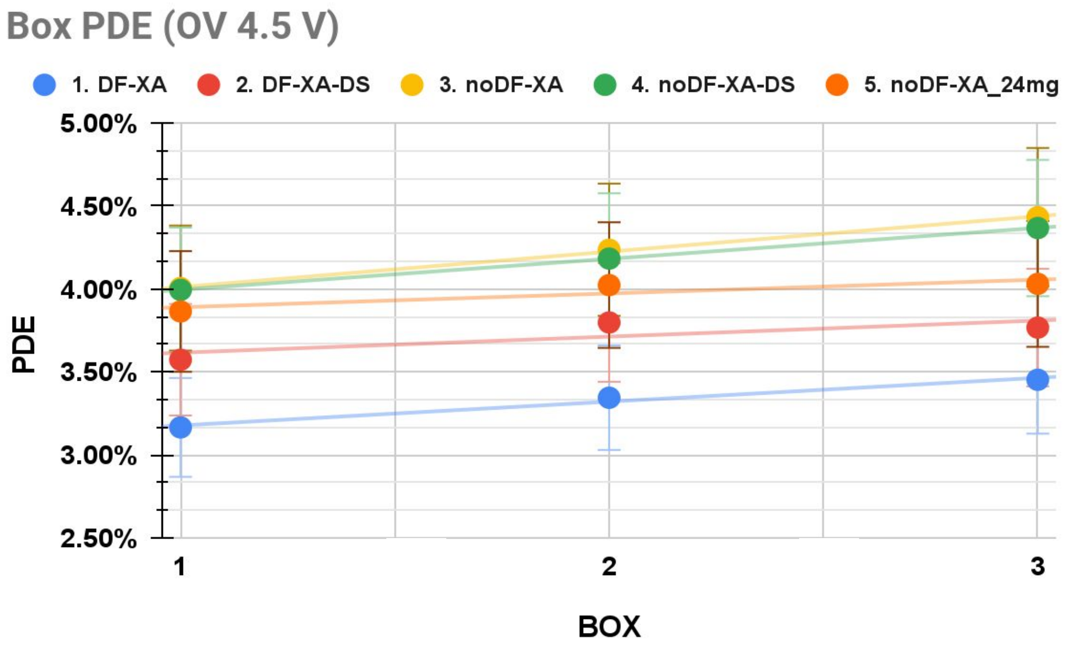
  - OV 4.5 V corresponding to 45 SiPM eff.

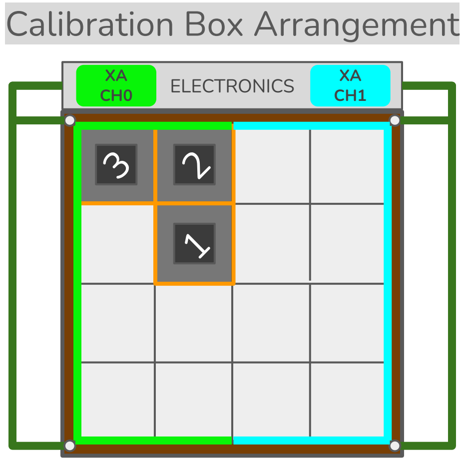
	Dichroic Filter		Non-Dichroic Filter		
	Single-Sided	Double-Sided	Single-Sided	Double-Sided	Single-Sided
OV	1. DF-XA	2. DF-XA-DS	3. noDF-XA	4. noDF-XA-DS	5. noDF-XA_24mg
4.5	**(3.3 ± 0.4) %**	**(3.7 ± 0.4) %**	**(4.2 ± 0.4) %**	**(4.1 ± 0.4) %**	**(4.0 ± 0.4) %**

- Conclusions:
  - **Compatible performance** of **single vs. double-sided XA** configs.
  - **Improvement 27% (single-sided)** & **11% (double-sided)** when **removing dichroic filters** due to non-ideal entrance transmittance and shifting cut-off for different angles.
  - Compatible performance of both tested **WLS-bar** configurations.

PDE Results

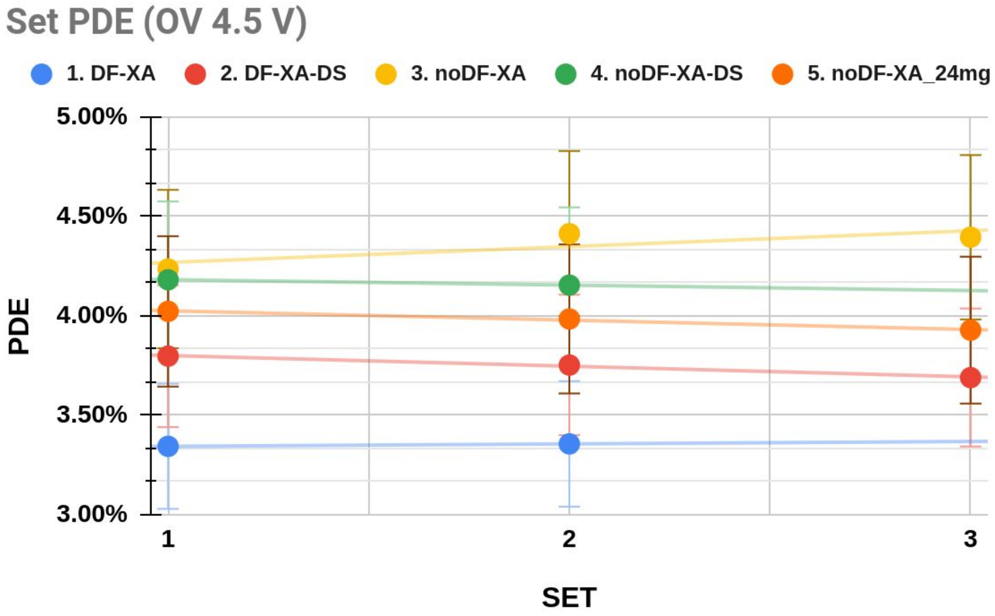
- PDE **homogeneity** across different positions always **within ~3%**. The **flattest distribution** corresponds to XA 5**.** mounting WLS-bar **model b** (chrom. 24 mg / kg & width 5 mm).





PDE Stability

- **PDE** measurement is **independent of the setup's LAr purity** (affects equally ref. SiPM and XA).
- To test this, taken up to **3 repeated sets** of data with **> 6 h spread** & up to **0.3 μs decrease in τ_{slow}** (as a measure of purity). **Standard deviation** across all measured values **2.23%**.



Conclusions

- Measured absolute **VD-XA PDE 4.2 ± 0.4 % @OV 4.5 V**. With compatible results between single- and double-sided measurements.
- Confirmed **improvement in PDE (27 % & 11 %) without dichroic filters** for tested samples and configurations.
- Additional optimization predicted by simulation (WLS-bar **24 mg/kg chromophore** concentration & **5.5 mm width**) shows **no measurable increase in PDE,** only slight improvement in homogeneity.
- Progress in **DUNE's XA design** HD-XA → VD-XA (LIDINE 2022 [C. Palomares et al.] & 2023 [C. Cattadori et al.])

Obrigado pela sua atenção!

Backup

X-ARAPUCA: Evolution

- XA optimization responds to a **collaboration-wide effort**.
- See LIDINE 2022 [C. Palomares et al.] & 2023 [C. Cattadori et al.].

Baseline **HD-XA** PDE **<= 2%** (initially).

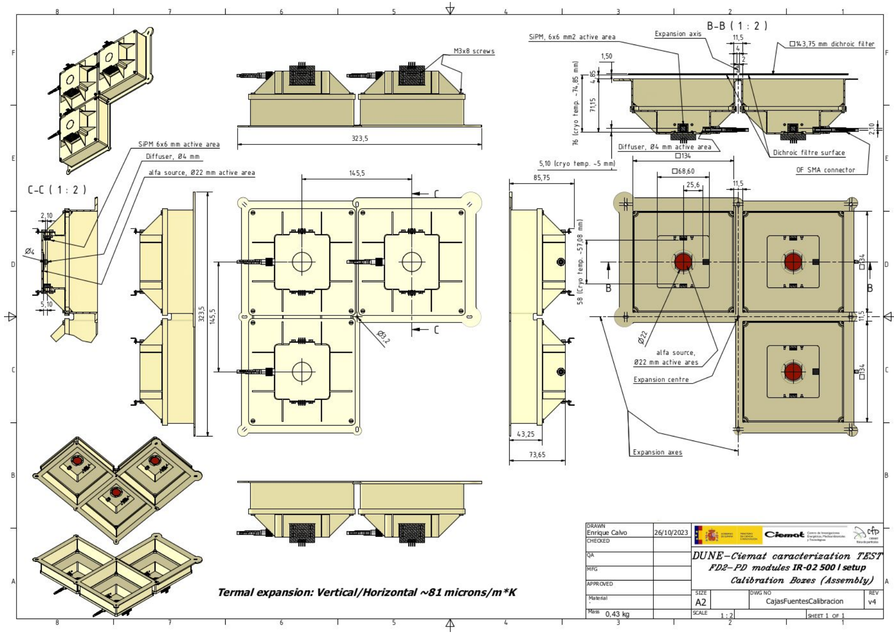
- **Change of WLS** → PDE ~2.5%.
  - G2P PMMA now BL for FD-HD & -VD.
- SiPM-WLS **contact/reflection** → PDE ~3.5%.
- **WLS cut** to recover photons → **PDE ~5%**

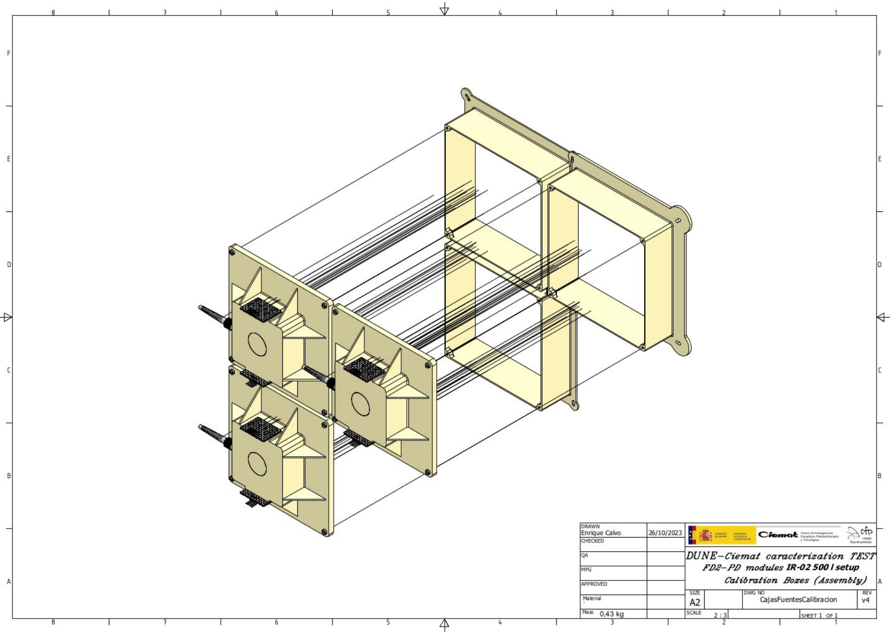
VD-XA PDE optimization presented today:

- **SiPM-WLS contact** (experience from HD).
- Understanding of the **filter application**.
- Simulation driven **WLS properties**.

Configuration	2022 HD-XA (G2P)	2023 HD-XA (Improvements)	2024 VD-XA (noDF)
Surface / SiPM	500 cm² / 48	500 cm² / 48	3600 cm² / 160
PDE	2.5 %	5 %	4.2 %
PDE · Surface / #SiPM	26	52	95

Calibration Box: Design





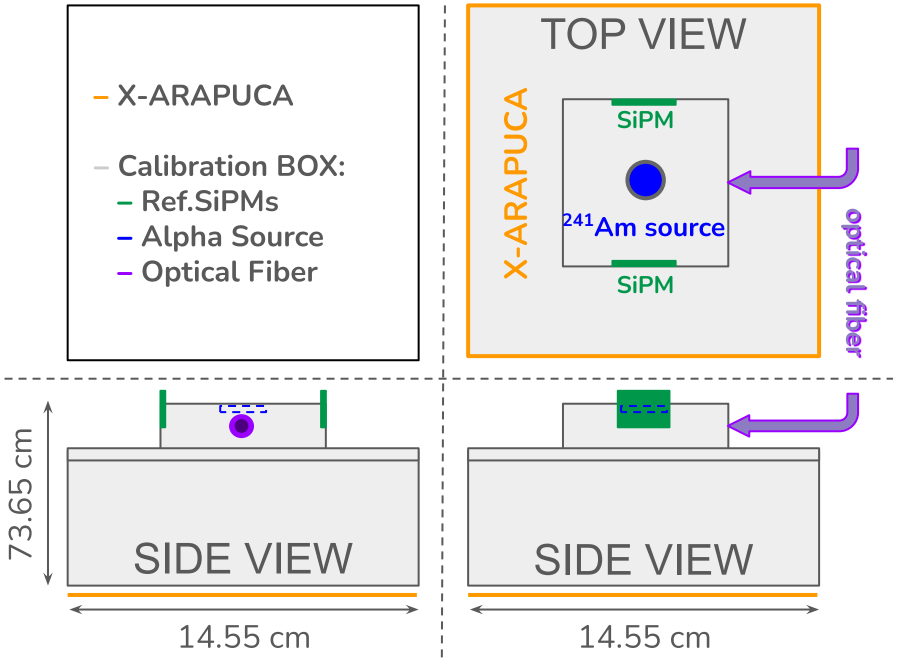
SiPM-WLS Coupling

Vertical Drift FD-XA designed without SiPM-WLS 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. Tested @Naples.

Calibration System



This **box designed** to allow scintillation photons to reach the XA (**no self-shadowing**) while ensuring ref. **SiPM detection** of **~60 PE** (limited by active area).

Each calibration box equips:

- Alpha source:
  - ^{241}Am $\rightarrow \alpha$ 5.48 MeV.
  - Activity (54.53 ± 0.82) Bq
  - Rate 27.6 Hz.
- **Characterised SiPM** (x2) HPK VUV4 with measured PDE (see next slide).
- **Optical fiber** for guides **405 nm laser** light for sensor calibration.

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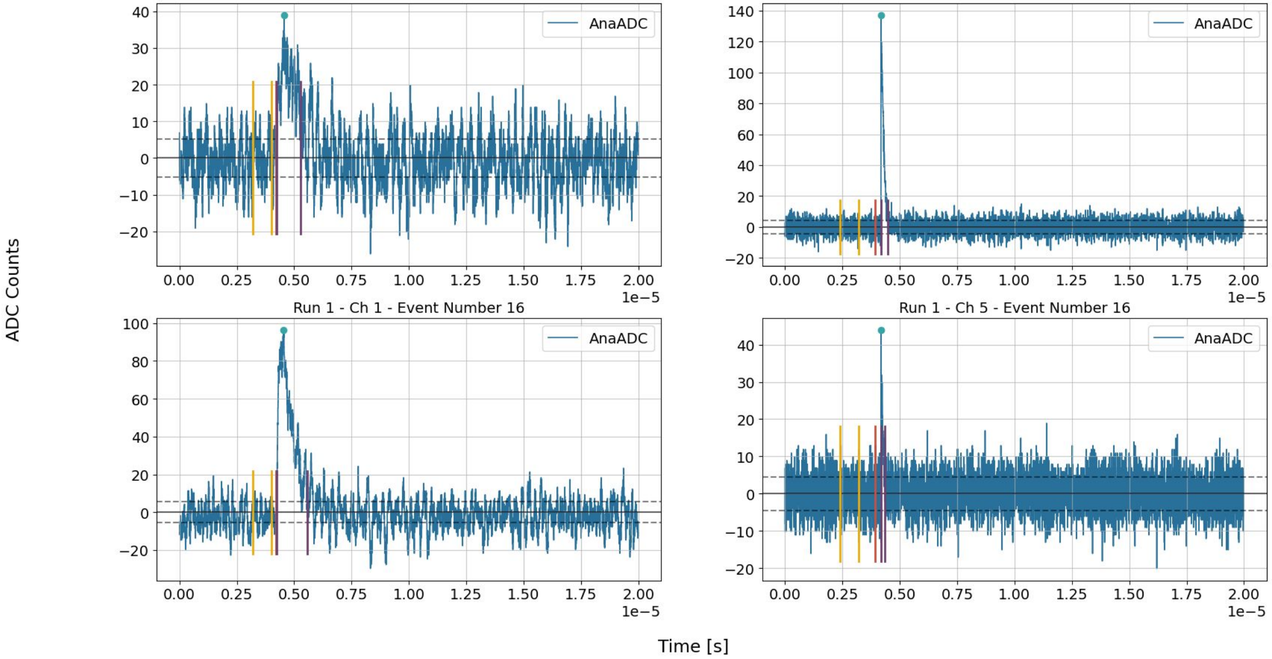
Data Taking: Raw Waveforms

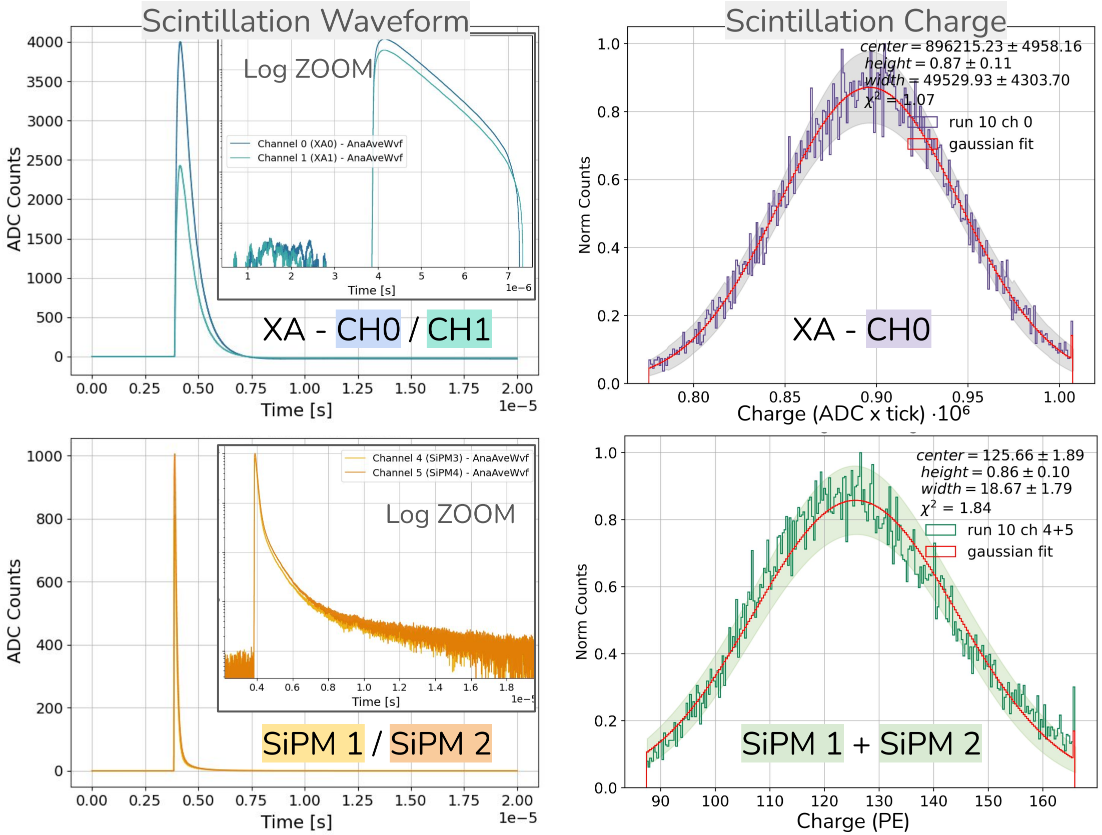
- Processing algorithm ensures correct **baseline subtraction** and **peak identification.**



- Waveform Peak.
- Min. Pre-Trigger STD.
- Pre-Trigger limit.
- Integration limits.

Data Taking: Scintillation

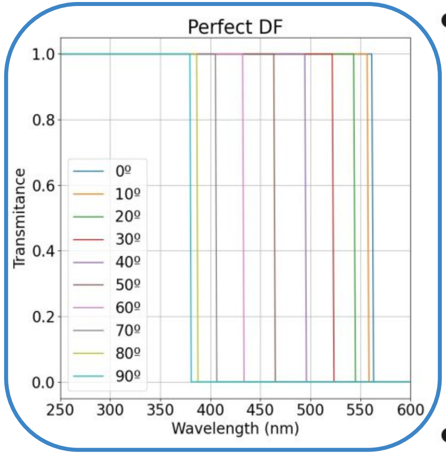
- Scintillation signals are **triggered** using **coincidence** in both **SiPM** channels.
- Waveform pulse **integrated** according to **average baseline cut**.
- Fitted distribution provides PE values (for ref. SiPM **fitted in addition)**.



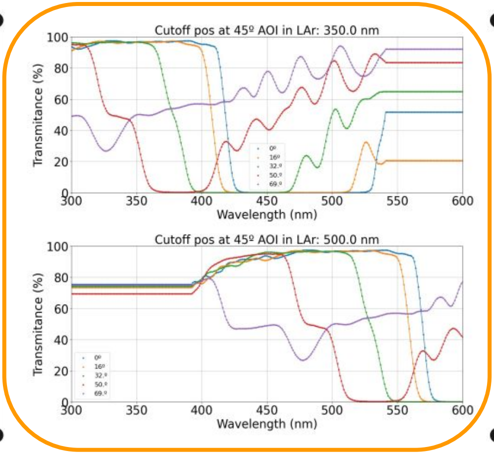
Simulation Results

- Improvements when removing dichroic filters due to non-ideal entrance absorption of the photons and shifting cut-off performance for different angles.

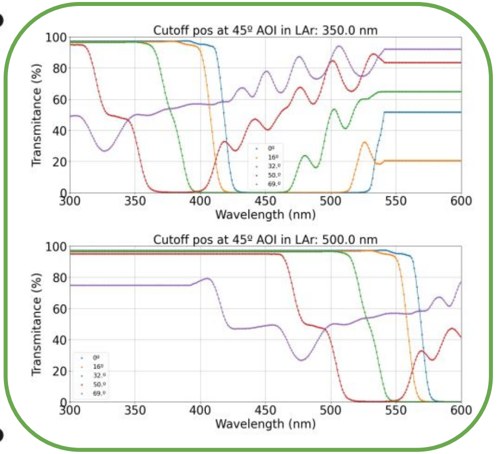
Ideal DF



Real DF (extremal extrapolation)

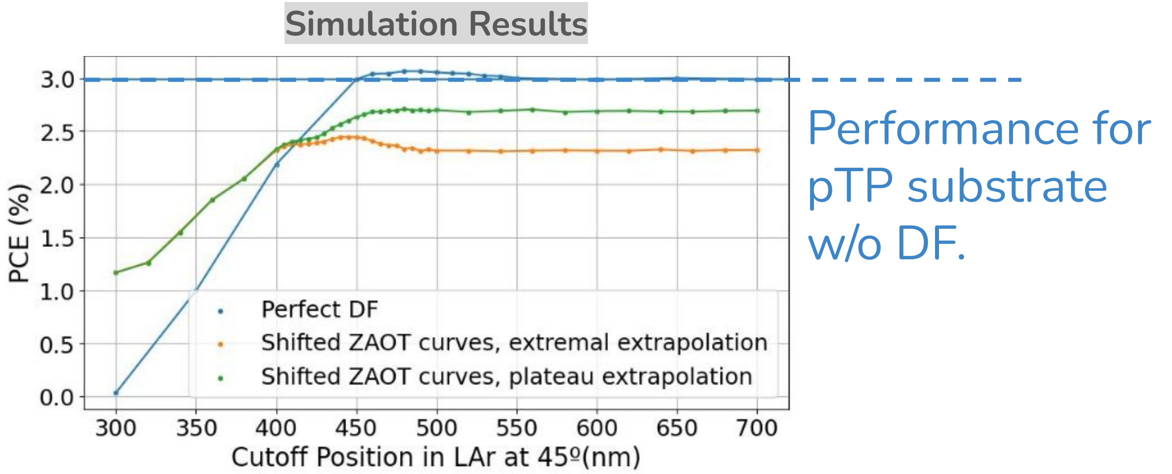


Real DF (plateau extrapolation)



Simulation Results

- Improvements when removing dichroic filters due to non-ideal entrance absorption of the photons and shifting cut-off performance for different angles.



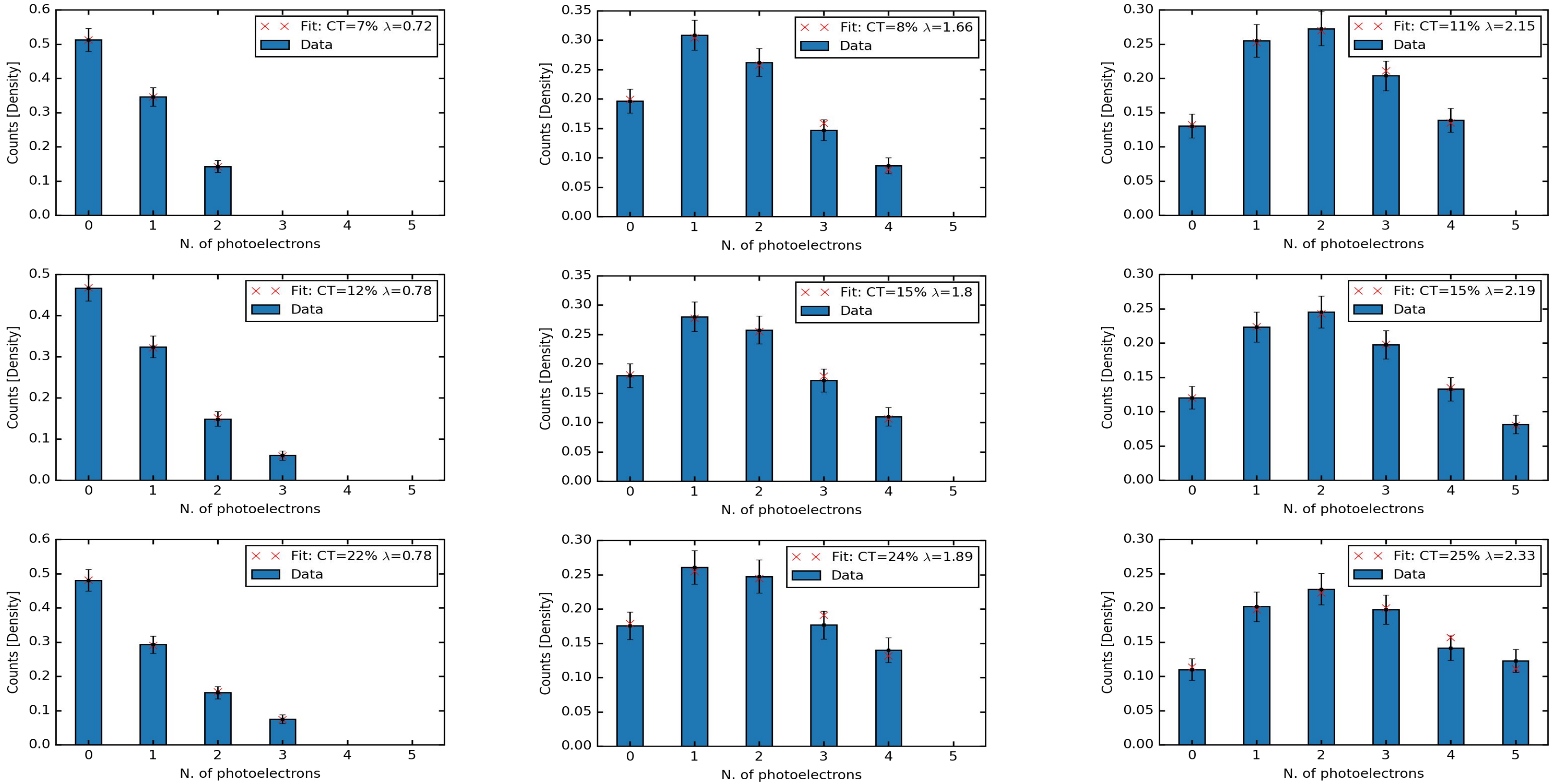
@J. Ureña

Cross-Talk Computation: SiPM

OV 2.5

OV 3.5

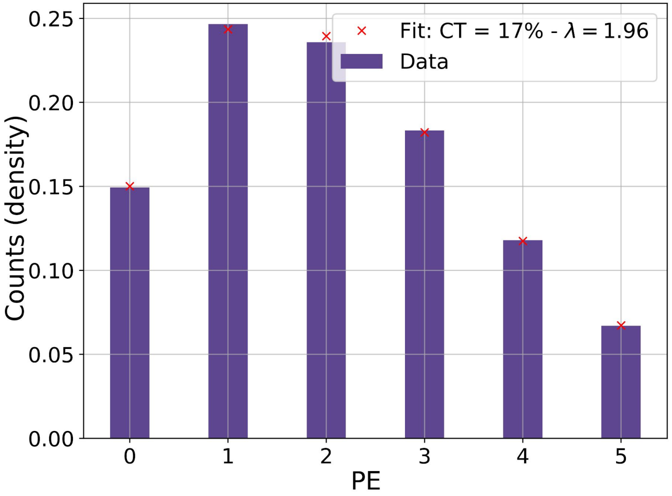
OV 4.5



Cross-Talk Computation: XA

- Selected method for computation **Vinogradov model:** Fit composite poissonian to describes the effect of cross-talk.

e.g. XA CH0 - OV 4.5 - XTalk Fit



XTalk from Data

XA	CH 0	CH 1
OV	XT %	XT %
7	33 ± 7	34 ± 2
4.5	19 ± 4	19 ± 1
3.5	14 ± 3	13 ± 1

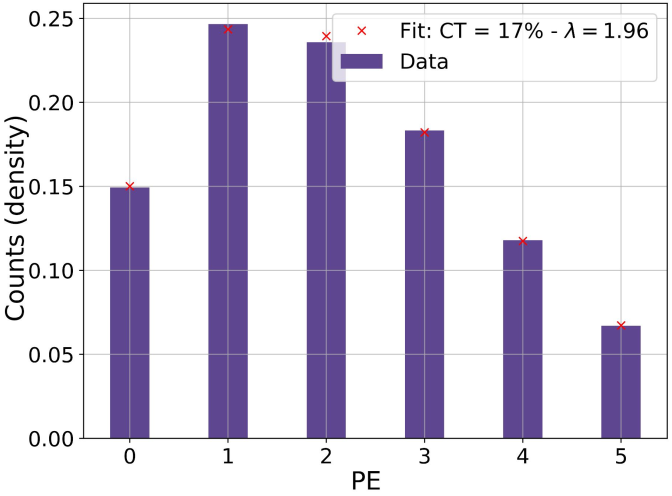
XTalk from Ref.

XA	FBK - TT
OV	XT %
7	32.5 ± 0.5
4.5	16.1 ± 0.3
3.5	12.7 ± 0.3

Cross-Talk Computation: XA

- Selected method for computation **Vinogradov model:** Fit composite poissonian to describes the effect of cross-talk.

e.g. XA CH0 - OV 4.5 - XTalk Fit



XTalk from Data

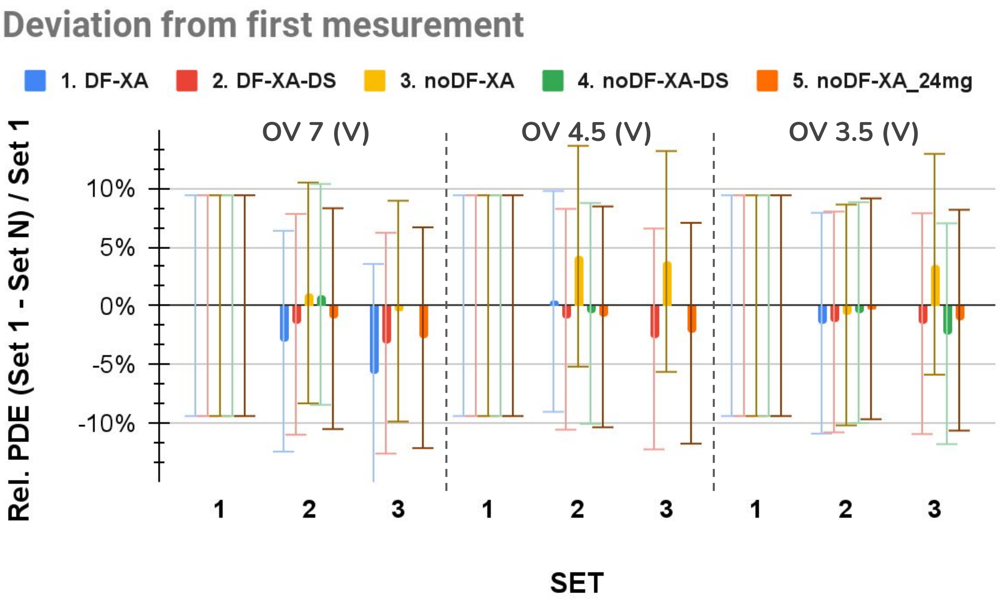
XA	CH 0	CH 1
OV	XT %	XT %
7	33 ± 7	34 ± 2
4.5	19 ± 4	19 ± 1
3.5	14 ± 3	13 ± 1

Duplication Factor

XA	CH 0	CH 1
OV	KDUP	KDUP
7	0.67±0.07	0.66±0.03
4.5	0.81±0.05	0.81±0.02
3.5	0.86±0.04	0.87±0.01

PDE: Stability

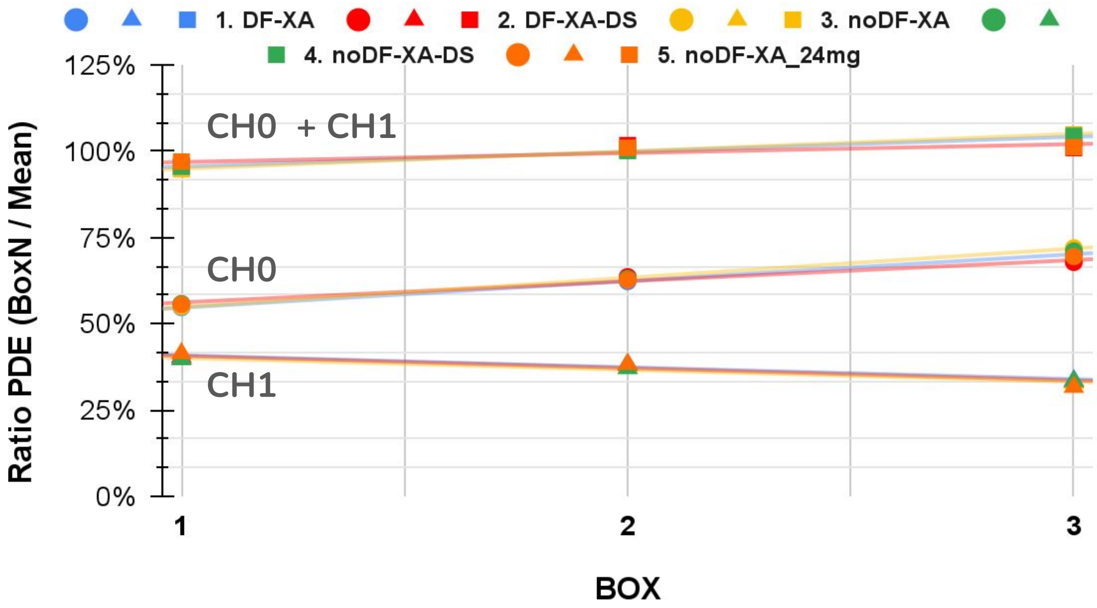
- **PDE** measurement is **independent of the setup's LAr purity** (affects equally ref. SiPM and XA).
- To test this, taken up to **3 repeated sets** of data with **> 6 h spread** & up to **0.3 μs decrease in τ_{slow}** (as a measure of purity). **Standard deviation** across all measured values **2.23%**.



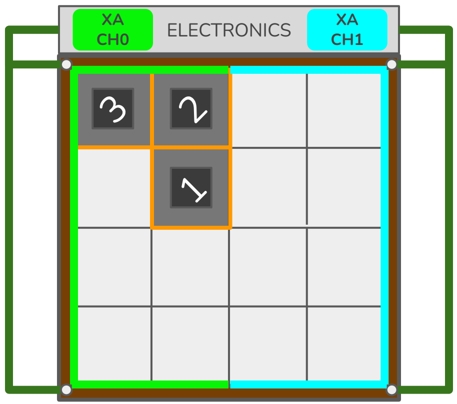
PDE: Results

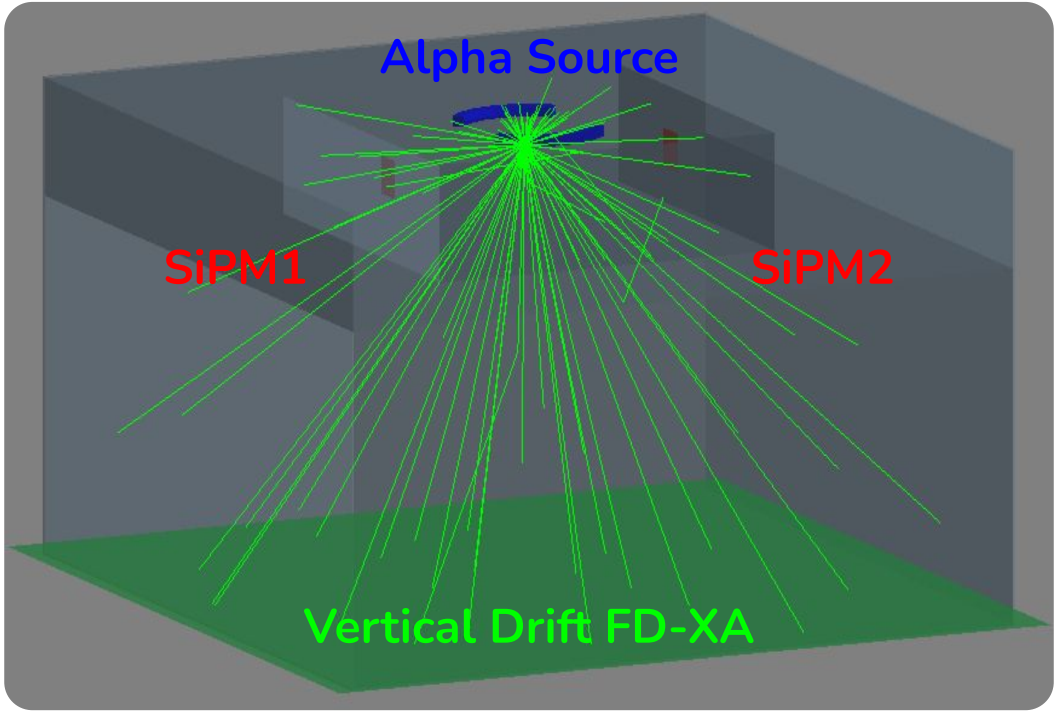
- PDE **homogeneity** across different positions **within 3%**. The channel PDE distribution (dependent on the CH & calibration boxes rel. arrangement) ranges from 55 - 70 % and is consistent across measurements.

Box ratio wrt. mean.



Calibration Box Arrangement





14.55 x 14.55 cm²

PDE Results: All OV

- PDE values are computed for 3 different OV settings of the XA:
  - OV 3.5, 4.5 & 7 V corresponding to 40, 45 & 50% SiPM eff.

OV	1. DF-XA	2. DF-XA-DS	3. noDF-XA	4. noDF-XA-DS	5. noDF-XA_24mg
3.5	(2.9 ± 0.3) %	(3.3 ± 0.3) %	(3.7 ± 0.3) %	(3.5 ± 0.3) %	(3.4 ± 0.3) %
4.5	**(3.3 ± 0.4) %**	**(3.7 ± 0.4) %**	**(4.2 ± 0.4) %**	**(4.1 ± 0.4) %**	**(4.0 ± 0.4) %**
7	(4.2 ± 0.4) %	(4.7 ± 0.5) %	(5.4 ± 0.5) %	(5.2 ± 0.5) %	(5.1 ± 0.5) %

- Conclusions:
  - **Compatible performance** of **single vs. double-sided XA** configs.
  - **Improvement 27% (single-sided)** & **11% (double-sided)** when **removing dichroic filters** due to non-ideal entrance transmittance and shifting cut-off for different angles.
  - Compatible performance of both tested **WLS-bar configurations**.