



Measurement of the X-ARAPUCA's absolute photon detection efficiency for the deep underground neutrino experiment's vertical drift far detector

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Abstract The DUNE experiment will implement a photon detection system composed of X-ARAPUCA (XA) devices. These trap incoming VUV photons by internal reflection in a wavelength shifter light guide to be collected onto silicon photomultiplier arrays, sensitive to visible light. In the baseline design, dichroic filters are used to prevent photons from escaping. The configuration proposed for DUNE's Vertical Drift (VD) (VD) module has been characterised in liquid argon for the first time using dedicated cryogenic setups developed at CIEMAT and INFN Naples. Additionally, several alternative configurations, based on the design optimisation studies of an R&D campaign, have been evaluated. The results show an efficiency of up to $(4.5 \pm 0.4)\%$ at 4.5 V overvoltage, representing a significant improvement over previous XA implementations. Most notably, configurations without dichroic filters show an improvement of up to 18%, attributed to transmittance losses in the dichroic filters.

1 Introduction

The Deep Underground Neutrino Experiment (DUNE) is a next-generation dual-site experiment [1] that aims to measure the neutrino oscillation parameters with unprecedented precision [2], perform searches for physics beyond the Standard Model [3] as well as detect astrophysical neutrinos from the Sun and core-collapse supernovae within our galaxy [4] by instrumenting four 17 kt Liquid Argon Time Projection Chamber Far Detector (FD) modules. The first FD module will adopt the Vertical Drift (VD) technology, in which ionisation charges are drifted perpendicularly from a central cathode to two anode planes. This generates two fiducial volumes (top and bottom) of approximately 7 m in drift distance.

The Photon Detection System (PDS) of DUNE's FD-VD module consists of light collector devices ($60 \times 60 \text{ cm}^2$), called X-ARAPUCA (XA) [5], which are placed in the cathode structure (320 XAs) and at the inner sides of the cryostat walls (352 XAs). The XAs on the cathode must be sensitive to light produced in both drift regions, requiring that both surfaces be active, i.e., Double-Sided (DS). On the other hand,

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the XA modules mounted on the wall only have one sensitive side, or Single-Sided (SS).

Liquid Argon (LAr) is an ideal target for neutrino detection because interacting particles generate ionisation electrons and Vacuum Ultraviolet (VUV) scintillation light. The particle's energy deposits generate singlet and triplet states of Ar dimers (Ar_2^*) that de-excite emitting VUV photons (127 nm) with characteristic times $\tau_{\text{fast}} = 7.1 \text{ ns}$ and $\tau_{\text{slow}} = 1.66 \mu\text{s}$ [6]. The prompt-light signal provides the trigger and interaction time for non-beam events, such as supernovae and solar neutrinos, thereby reconstructing the drift coordinates of those interactions. To evaluate the performance of the PDS, the light yield, defined as the total Photo electron (PE) count detected onto the PDS per energy deposit, is the main figure of merit to be considered. To meet the scope of DUNE's physics program, an average light yield of 20 PE MeV^{-1} is required in the FD-VD module, which can be achieved with a Photon Detection Efficiency (PDE) of the XA device $>3\%$ [7].

This work presents the measurement of the absolute PDE and optimisation of the DUNE FD-VD XA device in a cryogenic LAr environment, performed by two research institutions: Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT) in Madrid and Istituto Nazionale di Fisica Nucleare (INFN) in Naples. Each institution has developed its own measurement to ensure the reliability of the results. Section 1 describes the implementation of the XA concept to DUNE's FD-VD module. The methodology is explained in Sect. 2. In Sect. 3, the cryogenic setup implemented at CIEMAT used to measure different XA configurations is presented. Section 4 shows the basic calibration and analysis steps. Section 5 provides a comprehensive description of the PDE measurements, and the XA optimisation is analysed by comparing all XA configurations measured at CIEMAT. In the same section, a cross-check of the CIEMAT results' PDE measurement performed in Naples is presented. Finally, Sect. 6 concludes with this work's main observations aiming to improve the XA design. The Appendices A, B, and C provide complementary information on Naples laboratory setup, as well as required Geant4 simulations and analysis corrections, respectively.

1.1 XA concept for DUNE

The XA is a compact, modular and scalable photon detector that can be adapted to different configurations and applications [8]. It is designed to operate at cryogenic temperatures and can detect VUV scintillation light with low noise. Its goal is to maximise the photon collection of the PDS while minimising the amount of expensive SiPMs required to achieve the desired PDE.

The XA entrance window is covered by a substrate coated on the external side with a p-Terphenyl (pTP) layer

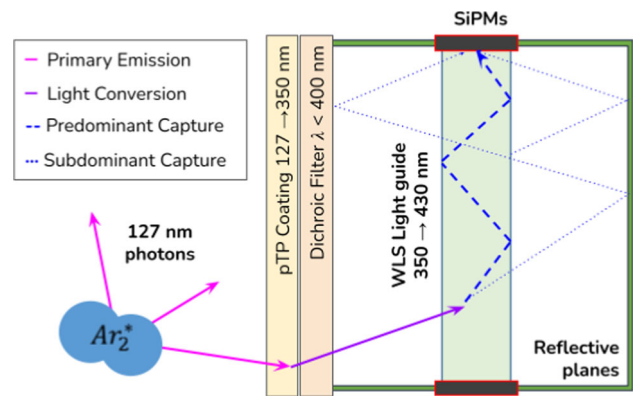


Fig. 1 Schematic of the XA working principle. Not to scale

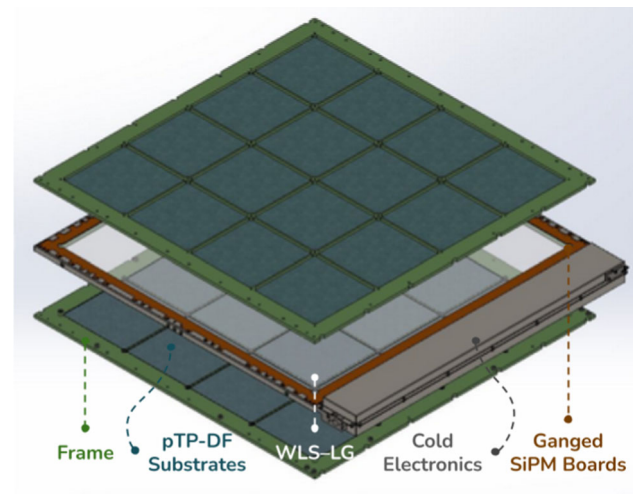


Fig. 2 Scheme of the XA-DS implementation for DUNE FD-VD module. Displayed are the substrates (top and bottom) and the WLS-LG layer in the middle. Substrates are surrounded by the XA mounting frame and the WLS-LG by the SiPM strips

($\sim 500 \mu\text{gcm}^{-2}$) to convert the incident 127 nm scintillation light into isotropically re-emitted 350 nm photons with a high efficiency [9]. The re-emitted light reaches the acrylic (polymethyl methacrylate) Wave-length Shifter Light Guide (WLS-LG) where it is further downshifted and isotropically re-emitted to the visible range (430 nm) thanks to the doping with a chromophore (see Fig. 1).

The WLS-LG re-emitted light can be trapped by total internal reflection (critical angle $\theta \sim 56^\circ$) and reach the surrounding SiPM arrays or escape and be reflected back into the WLS-LG by a thin-film Dichroic Filter (DF) coating, whose cutoff should be above 400 nm. The non-active surfaces of the XA are covered with a highly reflective **Specular Film** (VIKUITI^T) to reduce the absorption of the escaping photons and redirect them to the SiPM for enhanced collection probability. The XA technology has demonstrated its superior PDE compared to dip-coated shift light guides [10].

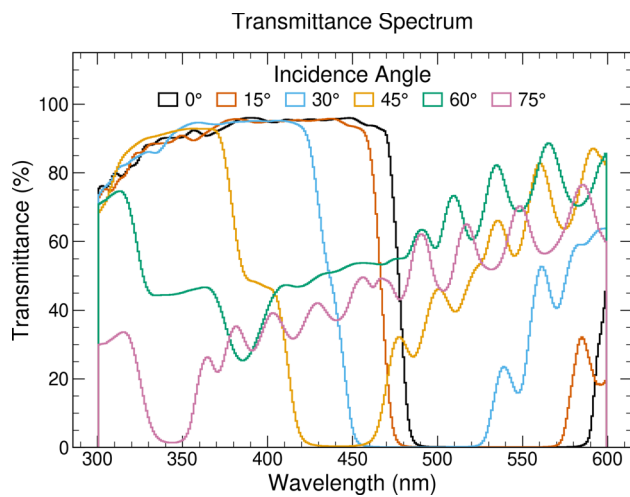


Fig. 3 DF transmission curves from [ZAOT](#) manufacturer measured in demineralised water for different angles of incidence [15]. The corresponding curves in LAr can be converted from these using Snell's law (e.g. 45° curve corresponds to 49° in LAr)

Figure 2 shows the XA implementation for the FD–VD module, whose surface ($60 \times 60 \text{ cm}^2$) is covered by 16 pTP-coated DFs ($14.6 \times 14.6 \text{ cm}^2$) arranged over a G10 grid frame. In each XA, 160 SiPMs are mounted on 8 flex-boards and positioned around the WLS–LG. These SiPMs ([FBK Triple-Trench](#) [11]) have an active area of $6 \times 6 \text{ mm}^2$. The XA mechanical frame consists of brackets holding the different components in place. The XA baseline design includes DFs from [ZAOT](#) manufacturer [12] and the 3.8 mm thick WLS–LG with a chromophore concentration of 80 mg kg^{-1} from [G2P](#) [13].

The mounted SiPMs are ganged in groups of five and deliver output data across two channels connected to the readout cold-amplifier. The signals are routed to the front-end electronics by custom-designed signal leading-boards [14]. This cold stage is composed of a main board with two cold transimpedance amplifiers, which are responsible for the active ganging of the SiPMs. Each input reads 80 SiPMs (half of the XA). The cold amplifier is held inside a metal casing mechanically attached to one side of the XA.

1.2 XA simulation

To estimate the device's response to the different optical components and inform about the specific XA configuration to be tested, a Monte Carlo (MC) simulation, described in detail in a forthcoming publication, of the whole XA has been developed to compute the device's PDE. This simulation implements the measured optical properties of all active components.

Figure 3 shows the transmittance of the implemented DF as a function of the incidence angle. These DFs must operate

in a medium (LAr) with a high refractive index ($n \sim 1.3$) and for light over a broad range of incidence angles. As a consequence, the measured transmittance curves exhibit a markedly non-ideal behaviour in two respects. First, the cut-off value shifts with the angle of incidence, compromising the target value of 400 nm, which is only maintained at 45°. Second, the non-zero transmittance above the cut-off wavelength allows photons to escape, thereby reducing the filter's confinement efficiency.

The simulation predicts that removing the dichroic coating increases the PDE by approximately 10–15%. This effect arises from the inherent angular dependence of the DF transmission curves combined with the broad angular distribution of the interacting photons. Specifically, the isotropic re-emission of photons by pTP results in a fraction being reflected by the DF, preventing their entry into the XA. Similarly, photons isotropically re-emitted by the WLS–LG exhibit a wide angular spread, causing a fraction to be transmitted through the DF and thus escape the XA. Even if the use of a DF enhanced the trapping of outgoing photons compared to a clear substrate, this improvement does not seem to compensate for the loss of incoming photons reflected by the DF in the first place. These studies have motivated the measurement of XA without DFs.

Another factor influencing the XA PDE is the WLS–LG chromophore concentration. The trapping efficiency of pTP emitted photons increases with the chromophore concentration, but at the same time, the attenuation length of the converted light is reduced, resulting in a counteractive behaviour that needs to be optimised. Three different concentrations of chromophore: 24, 40, and 80 mg kg^{-1} have been tested with the simulation for different WLS–LG thicknesses. The initial results suggest that a lower dye concentration with an increased optical path (thicker WLS–LG) can improve the XA performance.

Furthermore, the simulation predicts a compatible performance for double and single-sided configurations.

1.3 XA configurations

The predicted improvement in PDE for a configuration without DF has been assessed with the production of pTP-coated substrates without the addition of dichroic layers. These have been mounted and tested for both SS and DS configurations of the XA. Additionally, two WLS–LG designs have been produced by [G2P](#), one being the baseline choice, and the second has been produced with lower chromophore concentration and a thicker bar. Both are presented in Table 1.

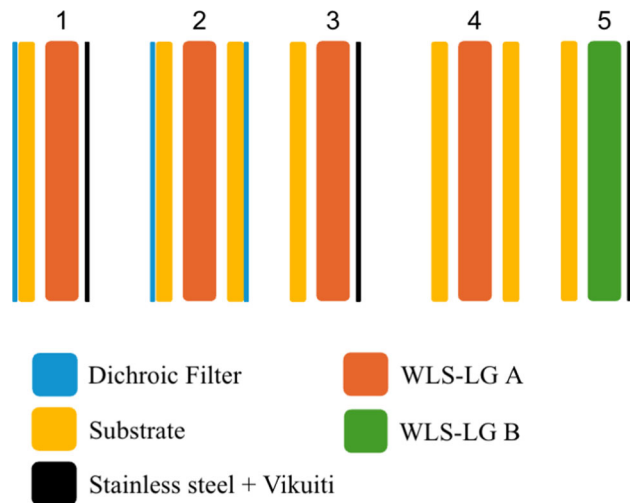
Table 2 shows the list of all tested XA configurations, and a diagram with the different elements is shown in Fig. 4. It is important to mention that the SS XA baseline design with DF has been measured in the first and last campaigns to verify the reproducibility of the results across two different assemblies.

Table 1 Tested WLS–LG configurations. Showing the baseline configuration (A) and the alternative model (B). The chromophore concentration is given in mg kg^{-1} of the acrylic substrate

Wavelength shifter light guide summary		
WLS–LG	Length $\times$ height $\times$ width	Chromophore
A	$(605 \times 605 \times 3.8 \text{ mm}^3)$	80 mg kg^{-1}
B	$(607 \times 605 \times 5.5 \text{ mm}^3)$	24 mg kg^{-1}

Table 2 Tested XA configurations at CIEMAT site

X-ARAPUCA configurations				
	Configuration	Filter	WLS–LG	Type
1	DF-XA-SS	Yes	A	Single-sided
2	DF-XA-DS	Yes	A	Double-sided
3	noDF-XA-SS	No	A	Single-sided
4	noDF-XA-DS	No	A	Double-sided
5	noDF-XA_24mg	No	B	Single-sided

**Fig. 4** Schematic representation of tested XA configurations at CIEMAT site

2 Methodology

The PDE is defined as the number of PEs measured by the photosensor device (the XA in our case) with respect to the true number of incident photons arriving at its surface ($\text{PDE}_{\text{XA}} = \text{PE}_{\text{XA}}/\gamma_{\text{true}}$).

We distinguish between two computation strategies: reference and simulation. These differ in the approach of measuring the true number of incident photons. Experimentally, the two methods have been realised by constructing two cryogenic setups that use ^{241}Am source to produce VUV scintillation photons in LAr. This ensures the PDE is assessed to reproduce the operating conditions of the DUNE experiment.

In both PDE computation methods the number of true collected PEs (PE_{XA}) is determined from the number of detected PEs in the XA (PE'_{XA}) and a factor (f^{XT}) to correct for the known probability of a secondary pulse, cross-talk (XT), in the XA SiPMs as follows:

$$\text{PE}_{\text{XA}} = \frac{Q}{Q^{\text{SPE}}} \cdot (1 - P^{\text{XT}}_{\text{XA}}) \equiv \text{PE}'_{\text{XA}} \cdot f^{\text{XT}}_{\text{XA}}, \quad (1)$$

where Q corresponds to the mean charge of the scintillation photons collected by the XA; Q^{SPE} is the corresponding SPE charge value and P^{XT} is the XT probability.

In the reference method, the number of incident photons in the XA is obtained from the PEs measured by a reference VUV-sensitive SiPM with known efficiency (PDE_{SiPM}). The true number of incident photons can be expressed in terms of the PEs detected by the reference SiPMs ($\gamma_{\text{true}} = \text{PE}_{\text{SiPM}}/\text{PDE}_{\text{SiPM}}$). A geometric factor (f^{geo}) accounts for the different active surfaces of the sensors and their relative positions. This method has the advantage of being less sensitive to global deficits in the predicted light level that could be introduced by impurities in LAr. The disadvantage is that the uncertainty in the reference SiPM's efficiency is directly propagated to the XA PDE measurement (as will be shown in Sect. 5). Crucially, these uncertainties are cancelled when comparing different XA configurations. Therefore, the corresponding PDE computation can be formulated as follows:

$$\text{PDE}_{\text{XA}}^{\text{reference}} = \frac{\text{PE}'_{\text{XA}} \cdot f^{\text{XT}}_{\text{XA}}}{\text{PE}'_{\text{SiPM}} \cdot f^{\text{XT}}_{\text{SiPM}}} \cdot \text{PDE}_{\text{SiPM}} \cdot f^{\text{geo}}, \quad (2)$$

for which f^{geo} , the ratio of the geometrical acceptances per unit area, has been evaluated with a simulation (see Appendix A.1).

In the case of the simulation method, the true number of incident photons is computed from the theoretical light-yield generated by an alpha particle and a MC simulation that takes into account the full geometry of the XA and is detailed in Appendix A.2. This method is highly sensitive to variations in the total scintillation light yield, which can be affected by LAr impurities that do not influence the slow light component and therefore cannot be monitored. A purification system and an analytical purity correction are needed to ensure that real setup measurements agree with the light production expected from the simulation. To evaluate the PDE, the following calculation is performed:

$$\text{PDE}_{\text{XA}}^{\text{simulation}} = \frac{\text{PE}'_{\text{XA}} \cdot f^{\text{XT}}_{\text{XA}}}{\text{MC}^{\text{photons}}} \cdot \frac{1}{f^{\text{bending}}} \cdot \frac{1}{f^{\text{purity}}}, \quad (3)$$

where f^{purity} is the purity correction of the liquid argon (see Sect. 5.2), and f^{bending} is an additional correction required to compensate for the bending of the XA light guide (see Appendix B).

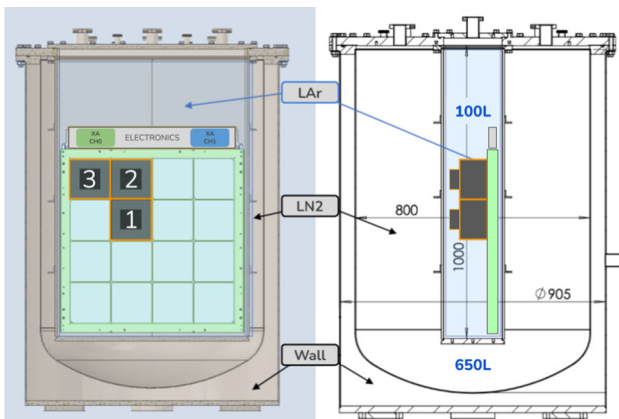


Fig. 5 Setup scheme of the cryogenic vessels available at CIEMAT for the XA's absolute efficiency measurement

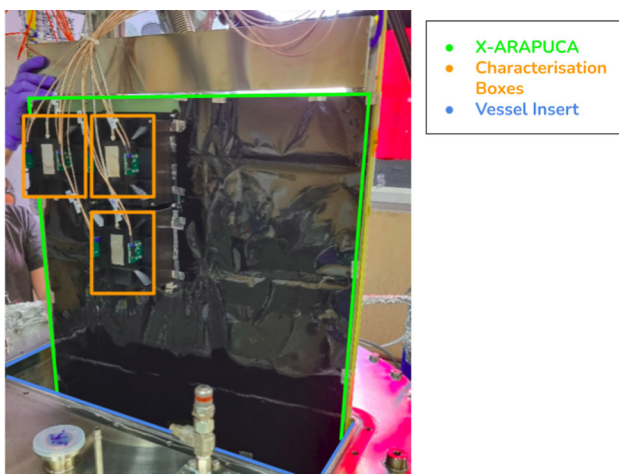


Fig. 6 Insertion of an XA inside the cryogenic vessel

3 Experimental setup

The experimental setup (see Fig. 5) consists of a ~ 650 L cylindrical vessel with an internal squared cassette (~ 100 L) that hosts the XA where grade 6.0 gaseous argon can be liquefied. The external vessel is filled with liquid nitrogen to serve as a cold reservoir for the inner volume. Before filling, successive vacuum cycles ($< 2 \times 10^{-5}$ mbar) are performed to avoid outgassing of the setup components, which might worsen the LAr purity. The gaseous argon liquefaction happens due to thermal contact with the liquid nitrogen reservoir. The setup is designed to maintain constant operating conditions (pressure and temperature) during the liquefaction process. The cold reservoir is filled with liquid nitrogen from an external tank and maintained at 2.7 bar to prevent the argon from freezing during liquefaction. The process is monitored by PT100 temperature sensors that provide live temperature readings of the LAr level inside the vessel.

The XA is introduced vertically (see Fig. 6) together with three characterisation boxes (one for each of the uniquely

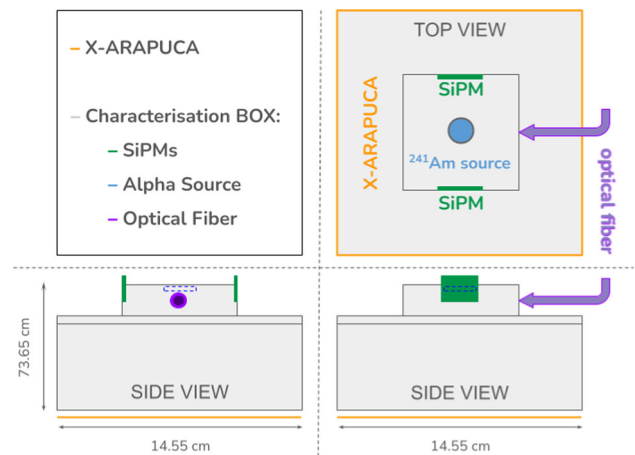


Fig. 7 Characterisation box hosting the reference sensors together with the ^{241}Am source and the inlet for the optical fibre used in calibration

distinct substrate-window positions of the XA). Each black box ($14.6 \times 14.6 \times 7.6 \text{ cm}^3$) hosts a ~ 55 Bq radioactive ^{241}Am source [16] that emits alpha-particles with energies 5.468 MeV, 5.443 MeV and 5.388 MeV and ratios of 85.2%, 12.8% and 1.7%, respectively. Together with the ^{241}Am source, two reference cryogenic VUV4 SiPMs (S13370–6075CN [17]) from Hamamatsu (HPK [18]) are placed inside each box (as represented in Fig. 7). These SiPMs are selected because of their high sensitivity to VUV light and stable performance at cryogenic temperature, making it possible to directly detect the scintillation light produced in LAr by the alpha particles emitted from the source. The scintillation photons produced by the source also reach the XA since one of the sides of the characterisation box is open to the XA window. To ensure that no other photons are detected, a black sheet covers the rest of the XA. For calibration purposes, an optical fibre guides light from an external laser source (405 nm) that can be operated by a waveform generator, providing a precise and sharp pulse of light and the appropriate trigger to the Data Acquisition (DAQ) (CAEN DT5725 [19]) simultaneously.

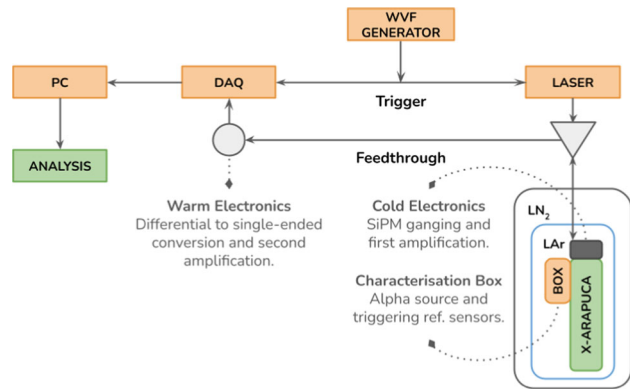
The sensors' dimensions and positions in the box with respect to the alpha source have been chosen to ensure appropriate illumination of the active surfaces with a Geant4 simulation (see Appendix A.1).

Regarding the reference SiPM, studies have shown that the efficiency of these VUV sensors at cryogenic temperature decreases with respect to the PDE measured by the manufacturer at room temperature [20]. In addition, the PDE depends on the incident angle of the photons [21]. The absolute PDE of these VUV reference SiPMs has been measured for 127 nm at 87 K and 4 V Overvoltage (OV) in a previous work [17], and corrected for the average incident angle of the photons in the current setup (16.1° , see Appendix A.1). The

Table 3 Reference SiPMs calibration results at 87 K and 127 nm light

HPK VUV4 (reference SiPMs)

OV (V)	Gain ($\times 10^6$)	S/N	$P_{\text{SiPM}}^{\text{XT}}$ (%)	PDE_{SiPM} (%)
4.0	8.0 ± 0.3	6.5 ± 2.1	25 ± 3	12.1 ± 1.1

**Fig. 8** Schematic representation of the data flow during data acquisition

main calibration results of these reference sensors are listed in Table 3. The gain and the signal-to-noise ratio (S/N) are computed from the charge of the Single Photoelectron (SPE) spectrum. The cross-talk probability (P^{XT}) is estimated from the same calibration data using the Vinogradov method [22]. The reference SiPMs have always been operated at the same OV, ensuring that the PDE is computed under the same conditions.

Each XA configuration is tested in data campaigns lasting three days to ensure data stability and repeatability. The data transmission chain and DAQ, involving the warm-amplification stage and the read-out system, are schematically represented in Fig. 8.

The setup implemented for the simulation method at INFN Naples also deploys the XA in LAr with an alpha source. The details of this setup are described in Appendix C.

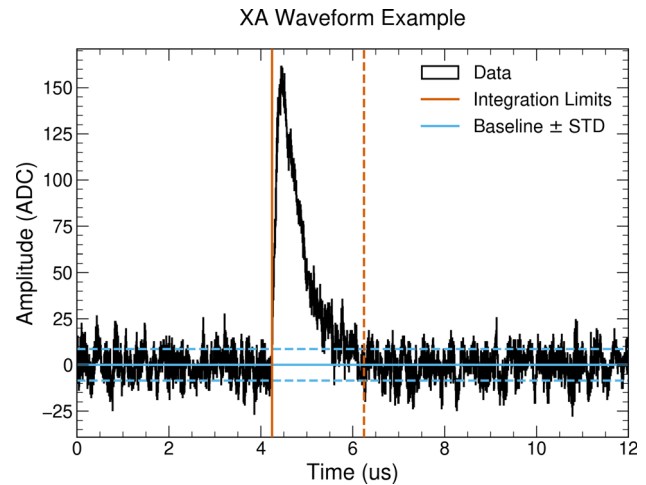
4 Data analysis

In the following, we present the common analysis steps of the data acquired at both CIEMAT and INFN setups. The XA has been operated with voltage values of 30.5 V, 31.5 V, 33 V and 34 V, corresponding to 3.5 V, 4.5 V, 6 V and 7 V overvoltage, respectively¹.

A standard set of data taken in a single campaign is shown in Table 4. The calibration and alpha source data are used in

Table 4 Main data types and their characteristics

Data type summary			
Type	Source	Trigger	Signal
Calibration	Laser	External	Pulsed
α -source	^{241}Am	DAQ	Scintillation
Muons	Cosmic	DAQ	Scintillation
Noise	None	Random	None

**Fig. 9** XA signal example from calibration data at 4.5 V overvoltage

the PDE computation, and the muon and noise data monitor the purity and stability of the setup.

4.1 XA calibration

The first step in the analysis is the XA gain calibration with data taken by illuminating the XA with a low-intensity pulsed laser source. The triggering scheme is provided by a pulsed generator that simultaneously feeds the laser and the DAQ. The result is a set of aligned waveforms with a defined time correlation. Figure 9 shows an example waveform for calibration data of the XA.

The charge integral is calculated on a fixed time window from the signal's rise time. To determine the gain, the mean charge of the SPE peak of the charge histogram is divided by the electron's charge and electronic amplification. The charge histograms are computed and fitted individually with Gaussian curves for each XA readout channel (see Fig. 10). The evaluated gain of the XA as a function of the overvoltage is shown in Fig. 11. The signal-to-noise ratio is determined as:

$$\text{SNR} = \frac{\mu_1}{\sqrt{\sigma_0^2 + \sigma_1^2}}, \quad (4)$$

¹ For reference, 3.5 V, 4.5 V and 7 V overvoltage correspond to 40%, 45% and 50% efficiency of the mounted SiPMs at room temperature.

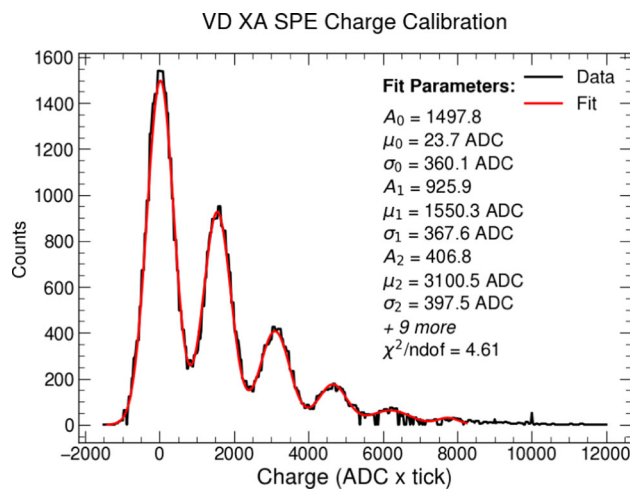


Fig. 10 Charge histogram for the XA at an overvoltage of 4.5V

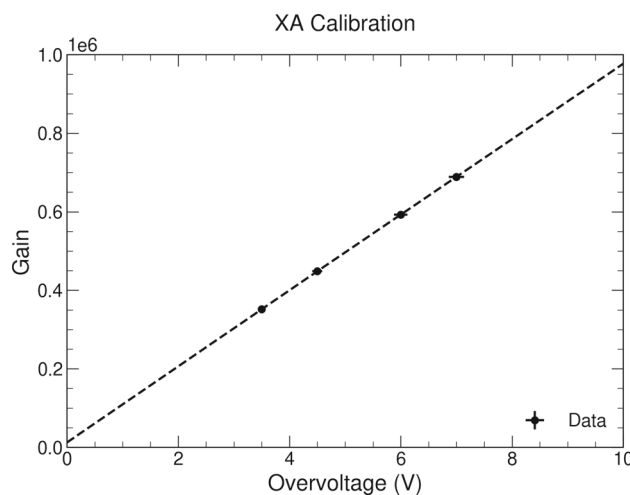


Fig. 11 Gain versus bias voltage, for the baseline XA configuration. The dashed line shows the function computed for the best-fit parameters

where μ_1 is the mean of the first Q^{SPE} distribution and σ_i are the corresponding Gaussian sigmas for the pedestals and first SPE peak.

Considering the same charge histogram, the cross-talk is calculated using the Vinogradov method from the signal density (normalised charge of the Gaussian fits) over the number of PEs. To obtain the real distribution of PEs (subtracting XT effects), it is necessary to consider the factor $f^{\text{XT}} = 1 - P^{\text{XT}}$. The final set of characterisation data extracted from calibration data is summarised in Table 5.

4.2 Scintillation charge analysis

The charge spectrum from the alpha particles' scintillation light is obtained to estimate the device's PDE. For this measurement, the light of the ^{241}Am source is triggered and evaluated.

Table 5 Average XA calibration results from combined analysis of both XA channels

XA Calibration (DF-XA)			
OV (V)	Gain ($\times 10^5$)	S/N	P^{XT} (%)
3.5	3.52 ± 0.03	3.1 ± 0.8	12.8 ± 0.3
4.5	4.48 ± 0.04	3.7 ± 0.9	18.4 ± 0.4
6.0	5.75 ± 0.04	4.1 ± 0.2	29.0 ± 0.2
7.0	6.89 ± 0.06	5.4 ± 1.3	32.6 ± 0.7

In the reference method, a characterisation box ensures the fixed position of the ^{241}Am source with respect to the photo-sensitive area of the XA and the two reference sensors. The reference SiPMs provide a coincidence trigger that excludes all noise from the analysis sample. Due to the reduced size of the box, any cosmic interaction is also quite constrained and, if present, easily removable with an amplitude condition. The charge of the scintillation light is obtained by integrating the waveforms of the two XA channels individually and combining their average values extracted from each Gaussian-fitted distribution.

Due to the finite size of the alpha source (non-point-like) and the SiPM positions within the characterisation box, the charge spectra of these present an asymmetric shape. Unlike the case of the XA response, their respective charges need to be first combined to recover a symmetric spectrum that can be fitted to a Gaussian.

The number of detected PEs (PE') is then computed from the mean charge of the scintillation photons over the SPE charge.

In Naples' setup, the position of the ^{241}Am source holder needs to be calibrated to ensure its stability (see Appendix C). The source height has been adjusted to different values above the XA (5 cm, 10 cm and 15 cm). At each height, measurements were taken at four different positions above the XA surface (see Appendix C). These different light measurements are compared against the simulation results of the setup (see Appendix A.2). The alpha signal is obtained by triggering on one channel, and the charge is reconstructed by independently integrating the waveforms from each XA channel over a $6.6 \mu\text{s}$ window and then combining the means.

By calculating the prompt ratio, defined as the ratio of the fast integral over the total integral, it is possible to select a region where argon nuclear recoils occur more frequently than electron recoils, allowing for the separation of alpha particles from cosmic muons. This is because alpha particles are more likely to interact via nuclear recoil than muons. The prompt ratio is calculated according to Eq. 5:

$$\text{Prompt} = \frac{\int_{t_0}^{t'} v(t) dt}{\int_{t_0}^T v(t) dt}, \quad (5)$$

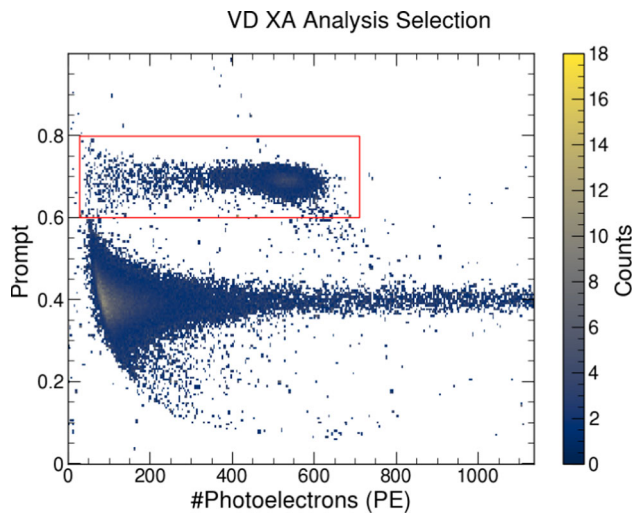


Fig. 12 Prompt distribution as a function of the total charge. In red is the selected region due to the scintillation of alpha particles

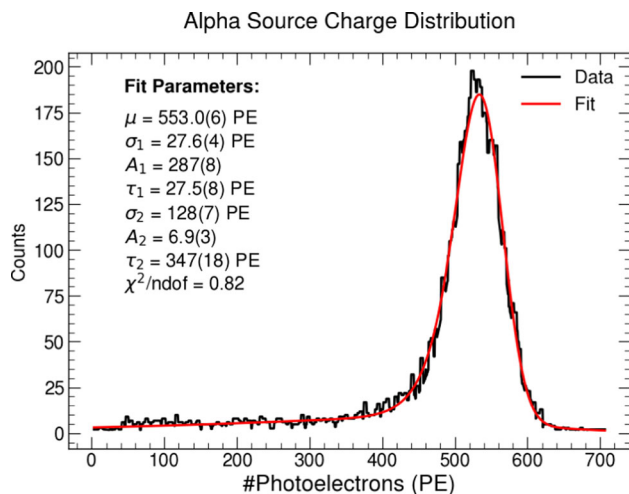


Fig. 13 Alpha's charge spectrum (XA overvoltage of 7 V and alpha source at position 2 (see Appendix C) and 15 cm above the XA), from channel 0

where $v(t)$ is the measured signal, t_0 is the start time of the waveform, and T is the waveform end time ($6.6\mu\text{s}$). The parameter t' represents the upper limit for the fast integral ($0.92\mu\text{s}$). An example of the excellent alpha/muon separation that this method provides is shown in Fig. 12.

The signal induced by alpha particles was selected on events with Prompt > 0.6 . After the selection, the charge spectrum results in a Gaussian with a long tail extending toward lower energies due to edge effects of the source holder, as shown in Fig. 13. To obtain the peak's central value, the distribution of the number of photoelectrons obtained was fitted with Eq. 6, which is the sum of two exponential functions multiplied by a complementary error function.

XA PDE BOX Variation

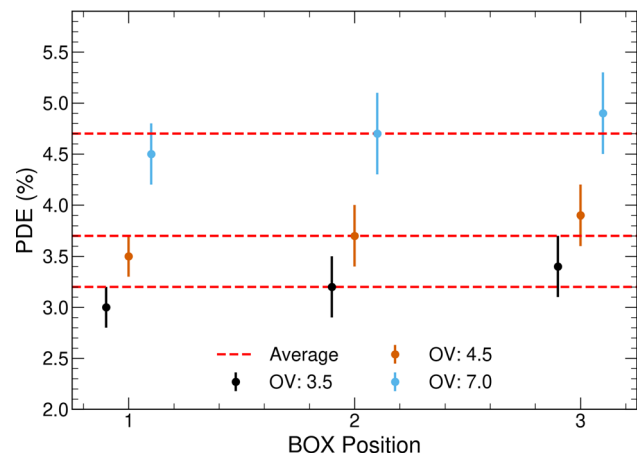


Fig. 14 Baseline XA PDE from the reference method. Showing the PDE as a function of characterisation box position. The dashed line represents the average position-weighted value of the PDE

$$y(Q) = \sum_{i=1}^2 A_i \cdot \exp\left(\frac{Q - \mu}{\tau_i} + \frac{\sigma_i^2}{2\tau_i^2}\right) \cdot \text{erfc}\left(\frac{1}{\sqrt{2}}\left(\frac{Q - \mu}{\sigma_i} + \frac{\sigma_i}{\tau_i}\right)\right) \quad (6)$$

The A_1 and A_2 values are the renormalisation factors of both functions; μ is the central position of the peak, σ_1 and σ_2 are the widths of both Gaussians, and τ_1 and τ_2 are the values responsible for the long tail.

5 Results

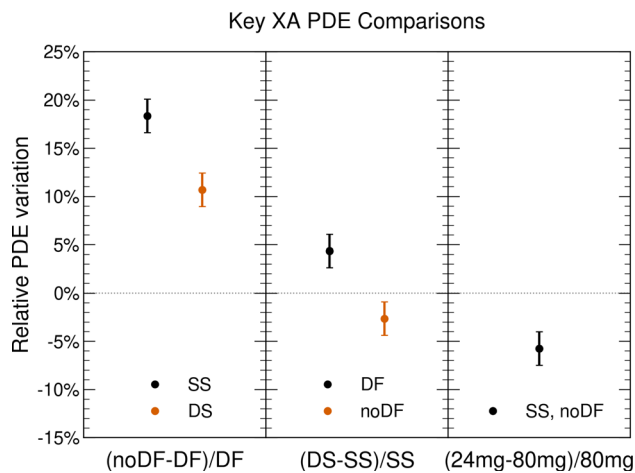
There are three main XA design choices that have been evaluated in this work: The performance of the cryostat wall (SS) and cathode (DS) XAs, the effect of the DF on the PDE, and the dependence of the WLS-LG dye concentration on the collection efficiency. In the following, we discuss the measurement results of the PDE for the baseline design, SS and DS, and its variation across the different configurations tested using the reference method. The stability and repeatability of the measurements have also been studied. The simulation method measurement is also shown as a cross-check of the reference method results.

5.1 Measurement of the PDE with the reference method

We evaluate the measured PDE values of the XA designs by averaging over the three characterisation box results, taking into account their respective XA surface contributions (see Fig. 14). Table 6 shows the PDE results for all the tested

Table 6 Results for the VD-XA absolute PDE for all tested configurations and OV values

VD-XA PDE results (%)				
	Config	OV 3.5 V	OV 4.5 V	OV 7 V
1	DF-XA-SS	3.2 ± 0.3	3.7 ± 0.3	4.7 ± 0.4
2	DF-XA-DS	3.5 ± 0.3	4.0 ± 0.4	5.0 ± 0.5
3	noDF-XA-SS	3.9 ± 0.4	4.5 ± 0.4	5.8 ± 0.6
4	noDF-XA-DS	3.8 ± 0.4	4.5 ± 0.4	5.6 ± 0.6
5	noDF-XA- _{24mg}	3.6 ± 0.4	4.3 ± 0.4	5.5 ± 0.6

**Fig. 15** Relative PDE variation, averaged over the three tested OVs, for the three configuration comparisons: DF vs no-DF (left), SS vs DS (centre), and chromophore concentration (right)

XA configurations, obtained with the reference method. The main source of error is the uncertainty on the reference SiPMs efficiency, PDE_{SiPM} (8.7%, obtained from previous measurements). It can be seen that the values of the PDE for the cryostat wall (SS) and cathode (DS) XA are well above the required value (3%).

To better illustrate the differences between the various configurations, Fig. 15 shows the relative PDE variation for the three configuration comparisons (DF vs no-DF, SS vs DS, and chromophore concentration), averaged over the three overvoltages. Notice that the overvoltage is not expected to have any impact on the relative variation of the PDE. Relative errors are smaller than the ones of the absolute results due to the cancellation of the PDE_{SiPM} term in the PDE_{XA} result.

The most important results of this comparison concern the difference between no-DF and DF devices (left panel of Fig. 15). One concludes that the XAs without DF presents a noticeable increase in PDE (18% and 11%) with respect to the SS and DS counterparts. As anticipated in Sect. 1, these results were expected because of the non-ideal behaviour of the implemented DFs. We have computed and confirmed this effect, strengthening the methodology and analytic tools developed for the optimisation and development procedures.

Next, the PDE for the 24 mg kg^{-1} chromophore concentration and 5.5 mm width WLS-LG configuration shows a modest decrease with respect to the baseline design (right panel of Fig. 15), pointing to the need for better implementation of the WLS-LG in the simulation. Further investigation of the result shows a different behaviour in the measured PDE depending on the position of the alpha source. The variation from box 1 to box 3 is up to 13% for the baseline WLS-LG (see Fig. 14), while a flatter response ($<5\%$) is measured for the lower chromophore concentration. This can be attributed to the expected larger attenuation length. This is a desirable feature for the DUNE PDS, as it allows for a more uniform light collection efficiency across the detector's volume.

The DS and SS configurations present compatible PDEs results (within errors), as expected from the simulation. The small differences observed between the DF and noDF variations (4% and -3% relative improvement in PDE, centre panel of Fig. 15) cannot be resolved with the current data. The fact that both configurations present similar results points to the preference for the detection of photons trapped through internal reflection in the WLS-LG. In other words, efforts to collect photons that have escaped the WLS-LG by exceeding the medium's critical angle are not efficient enough to result in measurable improvements.

The next step is to evaluate the stability and reproducibility of the measurements. This is crucial for ensuring that the PDE results are consistent over time. The gain monitoring of the sensors, as well as a stable and consistent PDE evaluation during all data runs, have been deemed necessary to consider a campaign successful.

In the case of CIEMAT's results, the readout can be tested along with the different campaigns. The gain/OV slope of the XA calibration is shown in Fig. 16. The results show a consistent gain/OV slope across all configurations ($\pm 2\%$), indicating that the experimental setup is operated at stable conditions and that the electronics of the XA are not drifting over the ~ 1 year period of data taking.

Three sets of runs for each XA configuration have been acquired. Figure 17 presents a set of results (for 4.5 V OV) that show the relative divergence of the PDE values for the second and third sets for all XA configurations with respect

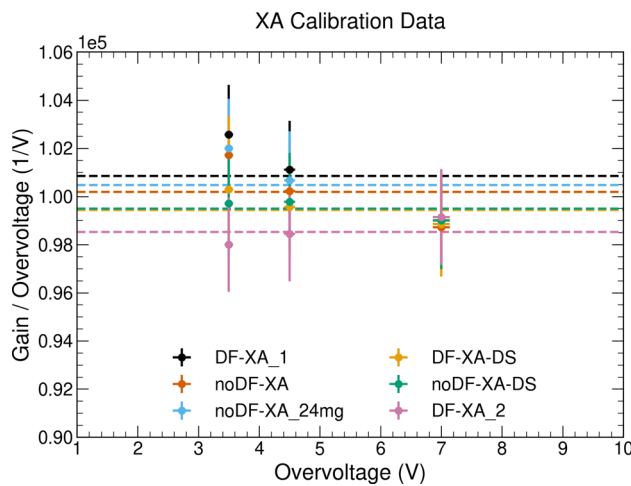


Fig. 16 CIEMAT's gain/OV slope for all tested XA configurations. Dashed lines represent the weighted average

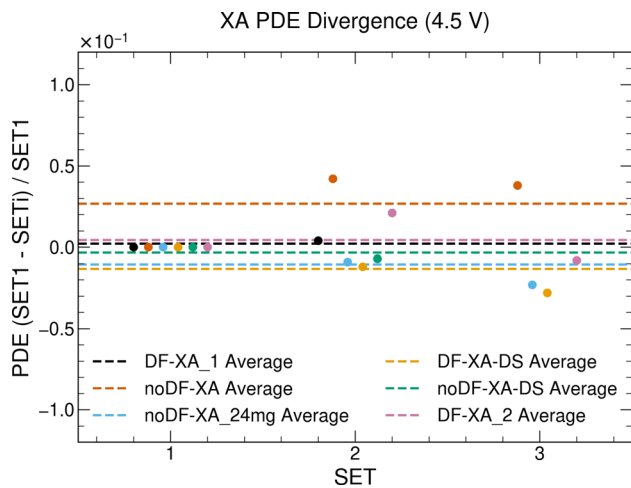


Fig. 17 Relative PDE deviation with respect to the first evaluated value for all XA configurations at 4.5 V overvoltage. The dashed lines represent the mean of the deviations

to the first computed value. As can be observed, the relative PDE variations fall within a 3% mean range that lies reasonably below the computed uncertainty of the XA PDE measurement ($\sim 9\%$).

5.2 Measurement of the PDE with the simulation method

In this section, we present the results obtained with the simulation method at the Naples setup. As explained in Sect. 2, the true number of incident photons is determined from a MC simulation considering the expected light-yield for the alpha source. Two correction factors should be taken into account, f^{purity} and f^{bending} . The LAr purity is a critical parameter, as the presence of contaminating impurities can affect the absolute light propagation [23]. This effect can be quantified by analysing the slow scintillation component of liquid argon

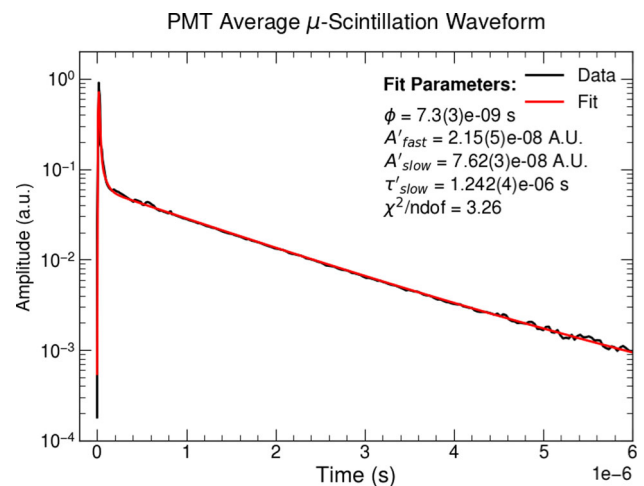


Fig. 18 Fitted LAr slow component of the scintillation light captured by the photomultiplier tube

(τ_{slow}), as impurities quench its intrinsic decay time of (1660 ± 100) ns [24]. An average waveform was calculated using signals from a Hamamatsu PMT R11065 inside the vessel, operated at 1500 V and triggered by cosmic muon interactions in LAr. The muons were selected based on the region with a prompt light ratio close to 0.4 (see Fig. 12).

The value of the slow component in the setup (τ'_{slow}) was obtained by fitting the tail of the result of the convolution of the slow component with a Gaussian filter (simulating the electronics response) and with the pTP response [25]. The fitted average waveform is shown in Fig. 18 and the value obtained is (1242 ± 4) ns. The liquid argon purity correction factor is therefore estimated with the equation:

$$f^{\text{purity}} = A_{\text{fast}} + A_{\text{slow}} \cdot \frac{\tau'_{\text{slow}}}{\tau_{\text{slow}}} = 0.94 \pm 0.06 \quad (7)$$

where the proportion between fast and slow components was calculated using the mean values obtained at [26–28].

A bending of the WLS-LG producing its misalignment with the SiPMs was observed in the Naples setup due to the use of an old version of the mechanical frames. As a consequence, a bending correction, described in Appendix B, needs to be applied.

Only the DF-XA-SS has been measured in Naples; the PDE results are shown in Table 7. These values are computed as the weighted mean from the results of the source heights and analysis positions.

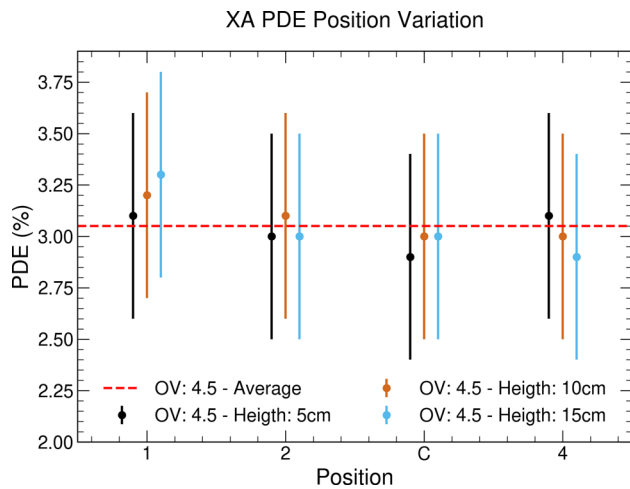
The large uncertainty attributed to the bending correction, $\sim 14\%$ (see Appendix B), has led to a larger uncertainty in the final PDE value of $\sim 15\%$.

5.3 XA PDE comparison

The PDE measurements of the baseline DF-XA-SS model are shown in Fig. 14 and Fig. 19 for the reference and simu-

Table 7 PDE as a function of OV for the baseline DF-XA-SS in the Naples setup

Photon detection efficiency	
OV (V)	INFN Naples
4.5	$(3.1 \pm 0.5)\%$
6.0	$(3.6 \pm 0.5)\%$
7.0	$(4.0 \pm 0.6)\%$

**Fig. 19** Baseline XA PDE from the simulation method. Showing example source height scan for 4.5 V overvoltage

lation methods, respectively, as a function of the alpha source position relative to the XA.

As can also be seen in Tables 6 and 7, these results show a minor but consistent difference ($\sim 16\%$) between the two methods, which can be attributed to the limitations of the bending correction for the simulation method presented in Appendix B. This correction was not required for CIEMAT's measurements thanks to the improved XA mechanical frame, which ensures the alignment between the WLS–LG and the SiPMs in all positions.

Both the reference and simulation methods show the expected increase in PDE for source positions that are closer to the device's edges, where the SiPMs are placed.

6 Conclusions

The work presented in this publication provides a comprehensive analysis of the performance of the XA proposed for the DUNE FD-VD PDS. It highlights the comparison of various XA configurations, allowing the DUNE collaboration to make an informed decision on the final choice of the XA device and continue the design development for future detectors.

We have proven the compatibility, reproducibility and reliability of the results by using two different methods and setups for the PDE measurement. The reference method has provided an absolute PDE of $(3.7 \pm 0.3)\%$ and the simulation method a value of $(3.1 \pm 0.5)\%$ at OV 4.5 V for the SS version of the baseline design. These results are compatible within 1σ and confirm that the device meets the minimal requirement set by DUNE's physics goals.

Having validated the results of the reference method, we present additional measurements carried out at CIEMAT. We demonstrate the improvement in PDE for XA configurations without DF, as expected from simulations. The measured increase is 18% and 11% for SS and DS configurations, respectively. The obtained PDE value is $(4.5 \pm 0.4)\%$ at 4.5 V OV. Therefore, we recommend removing the DF from the baseline XA in DUNE FD-VD design.

We observe a modest decrease in PDE for the WLS–LG of 24 mg kg^{-1} chromophore concentration and 5.5 mm width with respect to the baseline XA. Nevertheless, this configuration does have a flatter PDE across the XA surface. We conclude that the simultaneous modification of dye concentration and WLS–LG thickness requires further optimisation.

We also show that the XA-SS and DS models have similar efficiencies. This suggests that most of the photons that escape the WLS–LG are not collected.

The absolute PDE of the XA is a crucial parameter for the DUNE PDS, as it directly influences the detector's sensitivity to VUV light and, consequently, its ability to accurately reconstruct neutrino interactions. The results presented in this publication have been instrumental in optimising the proposed design for the XA and provide valuable insights for future DUNE PDS developments.

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Code Availability Statement This code/software will be made available on reasonable request. [Authors' comment: The codebase used for the current study is publicly available under <https://github.com/CIEMAT-Neutrino/SCINT>. Further information can be provided on reasonable request].

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Appendix A: Geant4 simulations

A.1 Reference method

The characterisation box at the reference setup has been designed using a Geant4 simulation with the goal of avoiding the shadowing of the inner surfaces, allowing light produced by the alpha particles to propagate directly to the different sensitive areas. The parameters of the characterisation box are presented in Table 8. The distance to the source is computed from centre-to-centre in 3D; the effective area of each sensor is defined as the inner surface with geometrical acceptance for light from the source; the number of collected photons is defined as the number of photons simulated to arrive at the effective surfaces; and finally, the average incidence angle is the average angle between the incoming photon vector and the sensor's surface normal, following the convention in which 0° corresponds to a perpendicularly impinging photon and 90° to a grazing one. This average angle is used to correct the absolute PDE of the reference SiPM measured in [17]. The correction is obtained from the angle-dependent PDE data reported in [21]. This yields a correction factor of 0.95 relative to the absolute PDE.

Figure 20 shows the simulated geometry. The walls of the characterisation box are 3D-printed from a black plastic material that fully absorbs the photons (shown here semi-transparently for illustration purposes). The source holder is displayed in blue. The two reference VUV4 SiPMs (red) and

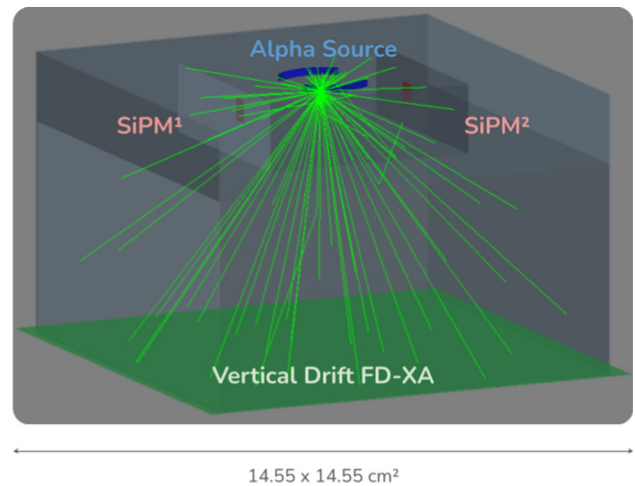


Fig. 20 MC simulation of the characterisation box tracking 100 photon trajectories

the XA (green) are also highlighted in colours and configured as sensitive areas to retrieve the number of arriving photons.

Instead of simulating alpha particles directly, the software generates exactly 195,636 γ (corresponding to a light yield of $51,000 \gamma/\text{MeV}^{-1}$ and a quenching factor of 0.7) and distributes them homogeneously over the source's radiative surface. These photons are propagated uniformly and isotropically across the LAr volume. The simulation provides the number of photons reaching the XA acceptance window as well as each of the reference SiPM sensors, which resulted in $25,900 \pm 240$ and $603 \pm 7 \gamma$, respectively. The uncertainties are derived from a box tolerance study in which we iterated over different geometrical sizes and sensor positions within the estimated manufacturing errors. The geometrical correction factor of Eq. 2 is also evaluated from this simulation:

$$f^{\text{geo}} = \frac{\text{MC}_{\text{SiPM}}^{\text{photons}}}{\text{MC}_{\text{XA}}^{\text{photons}}} = 0.0465 \pm 0.0007. \quad (8)$$

A.2 Simulation method

To estimate the PDE of the XA, it is necessary to compare the number of detected PEs with the number of photons pro-

Table 8 Simulation parameters from the characterisation box simulation. See text for details

Characterisation box simulation			
Parameters	Input/output	XA	Ref. SiPM
Distance to source (mm)	Input	74	29
Effective area (mm ²)	Input	145.5×145.5	6×6
Collected photons	Output	25 900	603
Incidence angle	Output	18.4°	16.1°

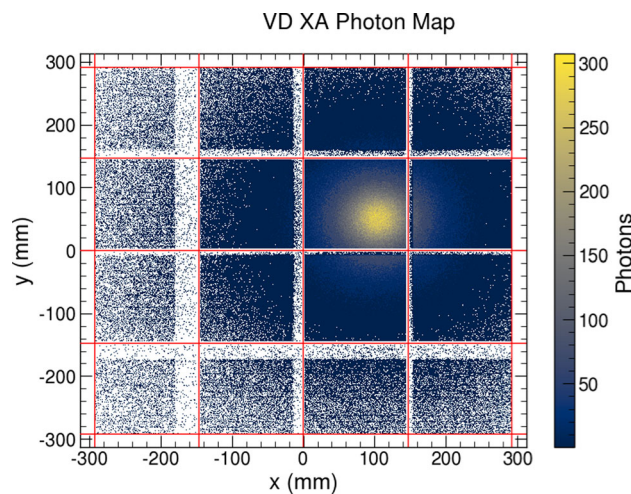


Fig. 21 Mapping of the photons arriving at the XA, where the red squares are the optical windows

duced by scintillation reaching the sensor's optical windows. The key difference between this method and the previously presented reference method is that this simulation is required to provide the absolute number of true photons rather than a relative value. This may be less robust due to the uncertainties in the optical properties of the components at cryogenic temperature and their implementation in a MC simulation. The photon count was estimated using a Geant4 simulation. Photons were generated isotropically from the source and propagated through the LAr medium until they reached the XA. The different positions of the alpha source used during the measurement (four positions in the plane and three different heights) were simulated. To estimate the error, the source position was varied by 0.5 cm in x , y and z directions. From the simulation, one can extract the expected response of the XA in terms of photon collection.

Figure 21 shows the mapping of the photons arriving at the XA optical windows, indicated by red squares. The source is located at position 2 (see Appendix C) at a height of 5 cm. The presence of the shadow region is due to the photons coming from the source hitting the grids of the device. For the source placed 5 cm away, the ratio between photons hitting the grid and photons reaching the optical window is approximately 15%.

Equation 6 is used to fit the charge spectrum of the photons reaching the XA optical windows [29], as illustrated in Fig. 22.

Appendix B: Bending correction

A spring-loaded mechanism ensures optimal contact between the SiPM active surfaces and the WLS-LG edges, counteracting the cryogenic contraction of the system. With respect to

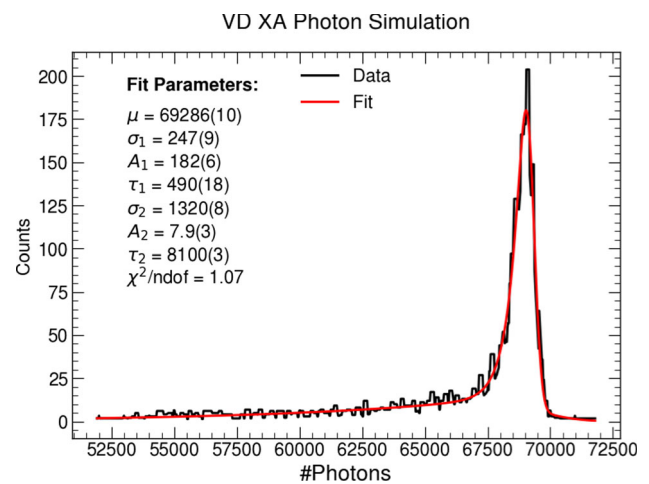


Fig. 22 Example of the number of photons reaching the optical windows

the design described in DUNE's Technical Design Report [7], the mechanical frame of the XA's baseline design underwent some modifications. Most noticeably, four clamping brackets were added to the frame to mitigate the WLS-LG misalignment under bending conditions, which can occur during horizontal assembly, storage, or transportation (see Fig. 23). This change was not implemented in the XA prototype measured by the INFN Naples team, requiring a bending correction in the calculation of the PDE (see Sect. 5.2). The resulting misalignment between the WLS-LG and the SiPMs was not present in CIEMAT's measurements, thanks to the aforementioned mechanical improvements and the vertical orientation during data taking.

During the inspection phase of the Naples setup, it was discovered that the light guide had bent and there was a significant misalignment between the light guide plane and the SiPM flex boards. This issue can be attributed to the fact that during the measurement phase, the XA was positioned horizontally, with the light guide supported on only two sides rather than all four. As this was one of the first XA prototypes, the problem observed in this test led to the inclusion of additional support points for the light guide in the design, which were improved in subsequent devices. The emptying of the vessel was performed in a slow and controlled manner, minimizing the likelihood of inducing any additional mechanical stress or deformation during this phase.

To account for this issue, the misalignment shifts of the SiPMs relative to the centre of the light guide along each side were carefully measured. A representation of the misalignment is shown in Fig. 24, where the central and the edge part (top and bottom) of the XA components are schematised. A vertical shift of approximately 5 mm was observed at the midpoint, and a vertical offset of about 2 mm was noted at the edges.

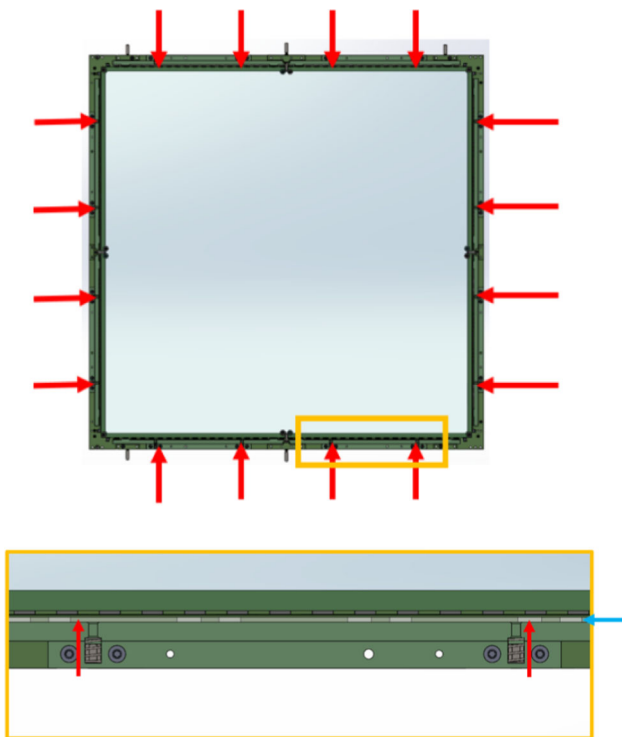


Fig. 23 Schematic representation of the VD XA spring-loaded mechanism. SiPMs are mounted between the WLS-LG and an acrylic interface strip (blue arrow). Springs (red arrow) apply constant pressure orthogonal to this interface. Thermal shrinkage at cryogenic temperatures of the WLS-LG is 6 mm, which causes the springs to partially decompress to 11.5 mm. These springs are mechanically constrained to exert force and translate solely orthogonal to the WLS-LG face. At each side of the frame, the centre position of the XA is reinforced by a clamping bracket

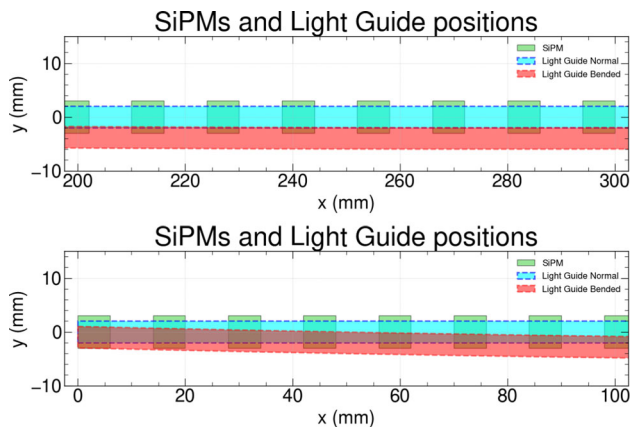


Fig. 24 Schematic of the bent XA light guide. The upper panel shows the central region of the light guide, while the lower panel shows the edge region. The green squares represent the internal SiPMs, each with a side length of 6 mm and a centre-to-centre spacing of 14 mm. The blue region represents the unbent light-guide configuration, while the red region represents the bent light-guide configuration

Due to the close placement of the SiPM surfaces relative to the edges of the light guide, a correction factor was implemented to compensate for bending effects and adjust the photon collection efficiency. The active area of the SiPM and the WLS-LG surface are comparable, so any mismatch between them can lead to significant inefficiencies.

The bending was modelled using the catenary equation, which is a hyperbolic cosine function:

$$y = a \cdot \cosh(x/b) + c. \quad (9)$$

The ratio of the areas aligned with the ratio of the areas aligned with the SiPMs in the bent versus unbent light guide configurations was calculated to be $f^{\text{bending}} = 0.58 \pm 0.08$. The spread of the value comes from the uncertainty of the measurement of the displacement using a calibre (order of 0.5 mm). It is important to note that this bending correction was characterised after the measurements, and might have been more dramatic during the data taking. Nevertheless, we provide an absolute PDE value for the simulation method on the assumption that this correction holds and as a cross-check against the PDE computed using the reference method.

Appendix C: INFN Naples setup

The XA PDE was also measured at the Physics Department of the University of Naples Federico II and INFN. The photodetector module was placed horizontally inside a cryostat capable of holding up to 1 t of LAr.

The inner walls of the cryostat were lined with black Delrin material and hung on a stainless steel thermal shield, improving optical insulation and preventing the reflection of photons from the stainless steel wall of the cryostat. With the same purpose, a Delrin disk was placed at the bottom side of the shield. The cryostat was filled with LAr with a level of contamination of the order of ~ 5 ppm (< 1.5 ppm N_2 , < 1 ppm H_2O , < 1 ppm O_2 and others). The LAr was filtered using an in-line Trigon (Engelhard Q5-Cu0226) purifier, reducing the amount of oxygen diluted in the LAr to the level of tenths of ppb or less. Before filling, the cryostat was pumped to achieve a vacuum of $\sim 1 \times 10^{-3}$ after some cycles of pumping and purging with gaseous argon to reduce the contribution of outgassing. The cryostat was filled up to a height of 20 cm above the XA.

To monitor the liquid argon purity, a TPB-coated photo-multiplier tube from Hamamatsu R11065 (HPK) was used to measure the slow component of the liquid argon scintillation time profile. An optical fibre was used to drive pulsed laser flashes inside the cryostat to calibrate the XA module. A 250 Bq activity ^{241}Am source was placed above the XA in an arm connected to a motion feedthrough, allowing the source

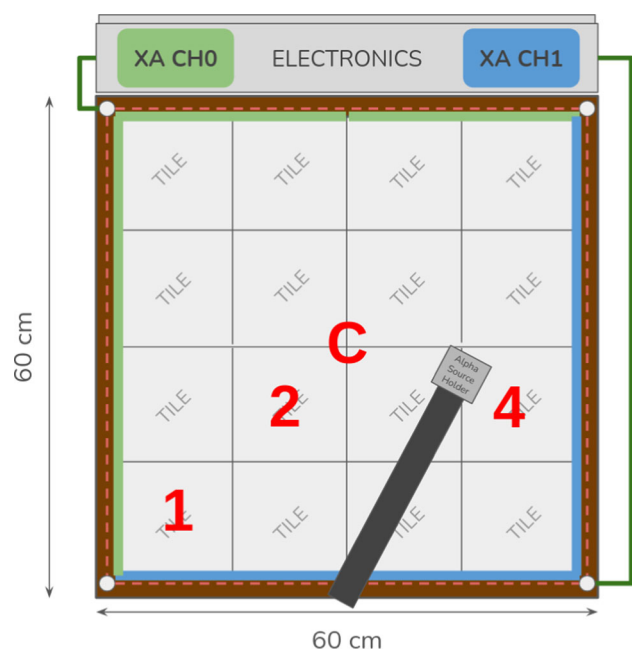


Fig. 25 XA channel arrangement in relation to the four reference positions of the alpha source

Table 9 Spatial coordinates of each position of the alpha source in relation to the XA centre as implemented for the simulation method in Naples' setup

Measurement source positions		
Position	x (cm)	y (cm)
1	22	21
2	10.5	5
C	0	0
4	-22.5	3

to be changed in position with respect to the XA. The motion system was able to vary linearly the distance from the XA and rotate the arm where the source was placed, providing to radiate a large portion of the photosensor (see Fig. 25 and Table 9). The test is done in different positions and heights to be sure that the efficiency is almost independent of the position. Alpha particles decaying from the ^{241}Am produced enough scintillation light for the final evaluation of the PDE. The data were digitised using a CAEN V1725, with a 14-bit ADC and a sampling frequency of 250 MHz. Each channel reads two sides of the XA and a schematic can be seen in Fig. 25.

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