ProtoDUNE-VD Photon Detection System

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Introduction

The ProtoDUNE-VD detector at CERN constitutes the large-scale demonstrator for the second DUNE far detector module (FD2). It follows the so-called “vertical drift” approach, with readout anode planes at the top and bottom of the cryostat and the cathode in the middle. The field cage covers all four lateral sides. The photon detection system (PDS) consists of sixteen 60x60 cm^2 photon collectors, called X-ARAPUCAs (XA), which have been integrated into the transparent cathode inside the active volume, and along the cryostat walls outside the active volume.

Detector installation began in December 2022 and will be completed in May 2023. PDS activities have been carefully integrated within the global ProtoDUNE-VD installation schedule. Being this extremely tight, XA assembly and tests have been carried out at CERN in parallel with their installation. A team of more than twenty physicists, engineers, and technicians, with an average simultaneous presence at CERN of six people, have participated in those activities. This has been a very useful exercise, where production, assembly, test, and installation procedures have been tested and improved. Those procedures and the lessons learned are exposed in this document. They constitute a crucial input towards the FD2 Production Readiness Review (PRR).

Description of ProtoDUNE-VD PDS

A detailed description of the PDS is given elsewhere as part of the documentation for the FD2 PDS FDR. In this section a short summary is presented.

The basic detector unit of the FD2 PDS is the X-ARAPUCA, which aims at collecting liquid argon scintillation light (128 nm) and Xe doping converted light (178 nm) both with high efficiency. The basic elements of XAs are i) wavelength shifters (WLS), to shift the light from the VUV to the visible range, ii) dichroic filters, to act as light acceptance window and to trap the converted visible light, iii) Silicon Photomultipliers (SiPM), used to transform the visible light into electrical signals, and iv) cold electronics, necessary to amplify SiPM signals and send them to the warm outer readout system.

ProtoDUNE-VD has been equipped with sixteen XAs, half of them in the cathode and the other half near the cryostat membrane, as shown in figure 1. The membrane XA modules are represented in yellow on the left-hand side panel. Four membrane modules were installed above the cathode and the other four below the cathode height in a symmetrical disposition. All membrane modules are single-sided detectors located parallel to the shorter sides of the cathode (see figure 2). The positions of the double-sided modules installed in the cathode are shown in the right-hand panel of figure 1. While membrane modules use standard electronics powered and readout with copper cables[2], given the high voltage in the cathode, no electrical connections are possible there between the cold and the warm electronics.

[2] One of the modules in the membrane will use an optical fiber to transfer the signal (SoF).

Instead, optical fibers are used to power the cold electronics board and the SiPMs (*power over fiber*, PoF), and to take out their signals (*signal over fiber*, SoF).

Other elements of the PDS are the “cold” cables/fibers connecting the XAs with the outside of the cryostat, the flange at the cryostat port, the “warm” cables/fibers from the flange to the readout electronics (DAPHNE), the class-4 lasers used for PoF and the warm readout electronics, which digitizes the analog signals provided by the “cold” electronics.

In addition, a response monitoring system (RMS) based on a pulsed UV-light will be used to calibrate and monitor the photon detector's response over time.

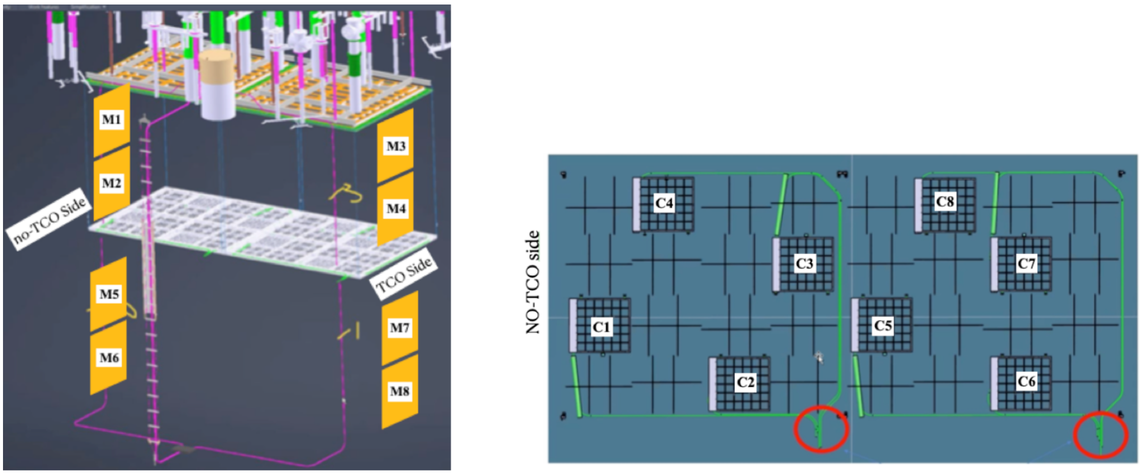


Figure 1. Distribution of X-ARAPUCAs in ProtoDUNE-VD. Left: membrane modules (M1-M8) outside the field cage. Right: top view of the two cathodes, with indication of the eight XAs (C1-C8).

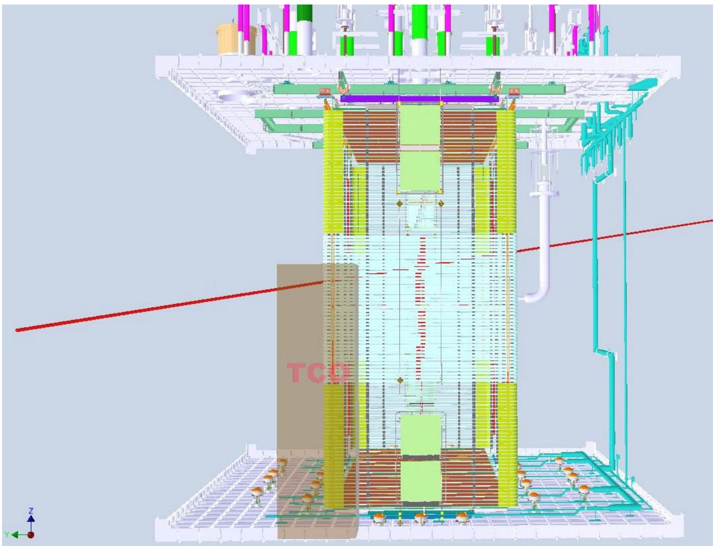


Figure 2. ProtoDUNE-VD 3D model. View from the TCO side with the four membrane-mounted XAs. Also visible are the different widths of the FC profiles, which are thinner (70% transparency) at the top and bottom in order to increase light collection in the membrane XAs and overall light collection uniformity of the PDS.

Description of X-ARAPUCA components

As mentioned above, the X-ARAPUCA constitutes the basic unit of the PDS. Figure 3 shows an assembled WLS frame with shielding and enclosure at the top panel, a module with its externally visible components indicated in the left-hand side panel while some of its internal components are shown in the right-hand side panel. All the different components of the XA, are listed below:

- WLS Frame
- SiPM flex PCB
- flex to motherboard cables
- WLS plate
- copper clad
- electrical shielding
- filter frame
- vikuiti covers
- dichroic filters
- electronics box
- motherboard

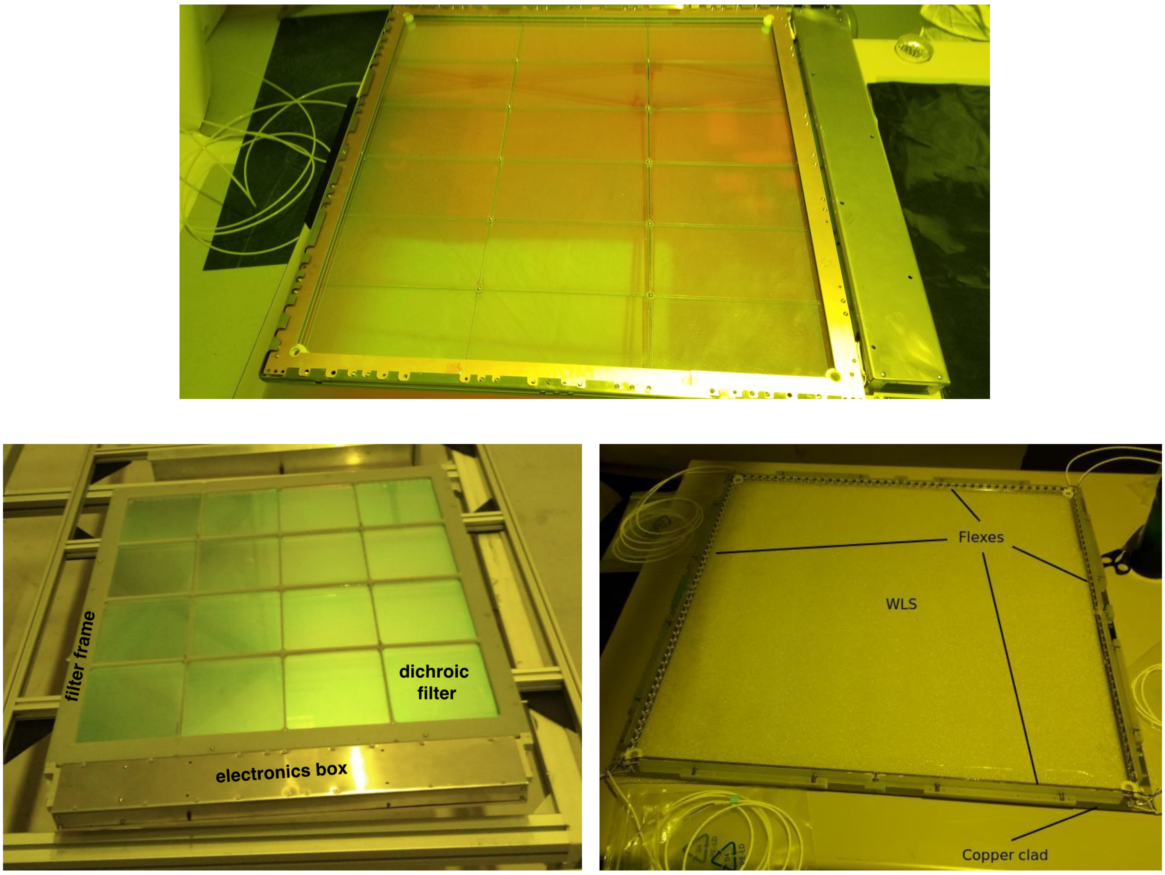


Figure 3. Top: Assembled WLS frame with shielding & enclosure Left: Fully assembled cathode module. Right: Internal XA components.

As shown in figure 4-top-left the mechanical frame consists of a set of eight mechanical parts located in the center of the module that provides, via a spring-based mechanism, support to hold the SiPM flex PCB’s and appropriate contact of these sensors to the WLS plate laterals. It also contains four blocks with pins to hold the WLS plate. It has threaded lateral holes for attaching the supporting clamps for the membrane modules necessary for its installation in the cryostat. It also provides blocks for the installation of the pins set necessary for the installation of the modules in the cathode. The mechanical frame is sandwiched between two pairs of C-shaped copper clads (see figure 4-bottom-left) attached to both sides of the frame (front and back). Stainless steel u-channels are connected along the laterals of the module creating a continuous electrical shield to protect the SIPM’s, flex PCB’s and cables from possible cathode discharge (see figure 4-bottom-left).

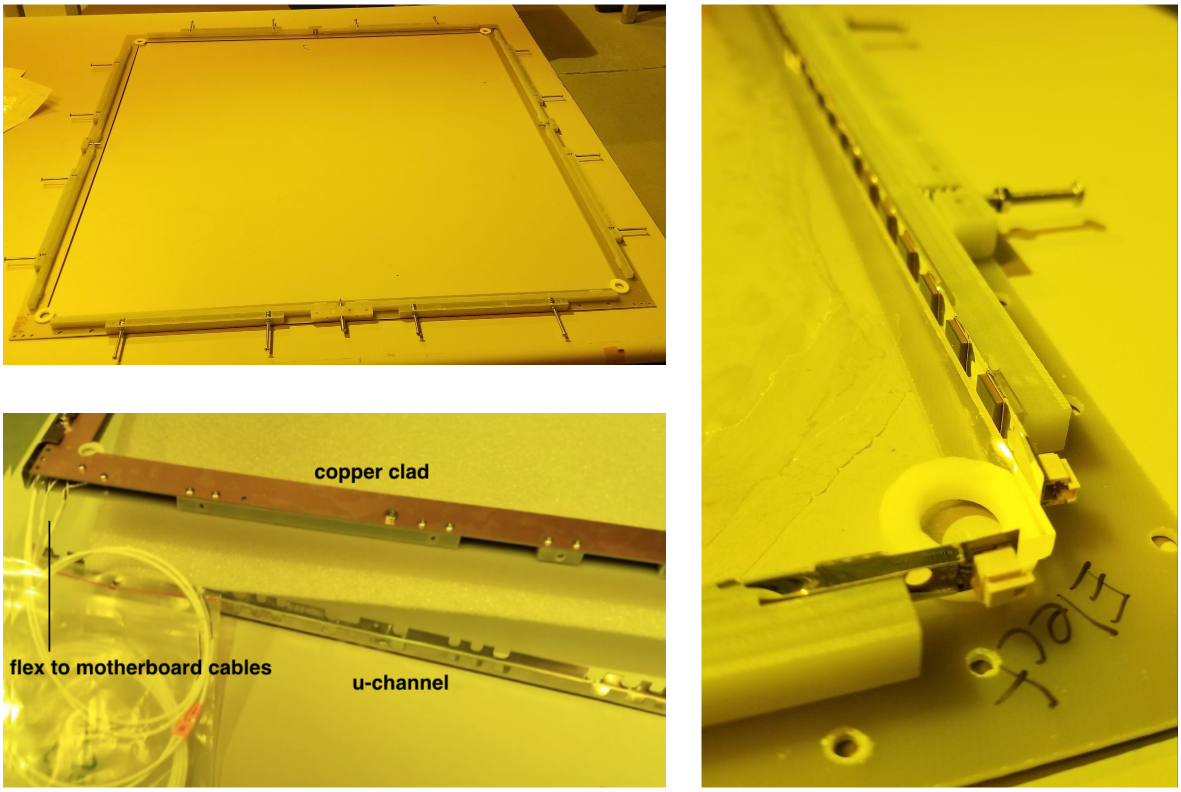


Figure 4. Top-left: Mechanical frame with springs retracted. Right: SiPM Flex PCB’s installed with backing springs extended. Bottom-left: U-channel Shielding prior to install on copper clads. In this photograph the flex-to-motherboard cables are also visible .

The SiPM Kapton flex PCB’s are populated with 20 SiPMs equally displaced along its length and provide electrical connection for power and data readout of the sensors (see figure 4-right). Each module has eight SiPM flex PCB’s, two installed per module side. One cable per PCB (see figure 4-bottom-left) is routed from the corresponding flex connector along the laterals of the module and under the electrical shielding pieces toward the electronic box located at the bottom of the module. The eight grounding connections of the copper clads through the routing flex to motherboard cables are made at the four corners of the frame close to where the SiPM flex connectors are located. A pair of forklift arms are installed at the bottom corners of the modules to hold the electronic box where the cold electronics are located (see figure 5-top_left). This box also contains apertures for the insertion of the routing cables which are connected to the board.

The dichroic filters are installed in the modules through a G10 frame cutoff as a grid with positioning places that are designed for perfect vertical (membrane) and horizontal (cathode) operation of the modules (see figure 5-right). The single-sided membrane modules are equipped with a front filter frame and a flat backplane G10 while the double-sided modules have a front frame and a back frame for positioning their dichroic filters.

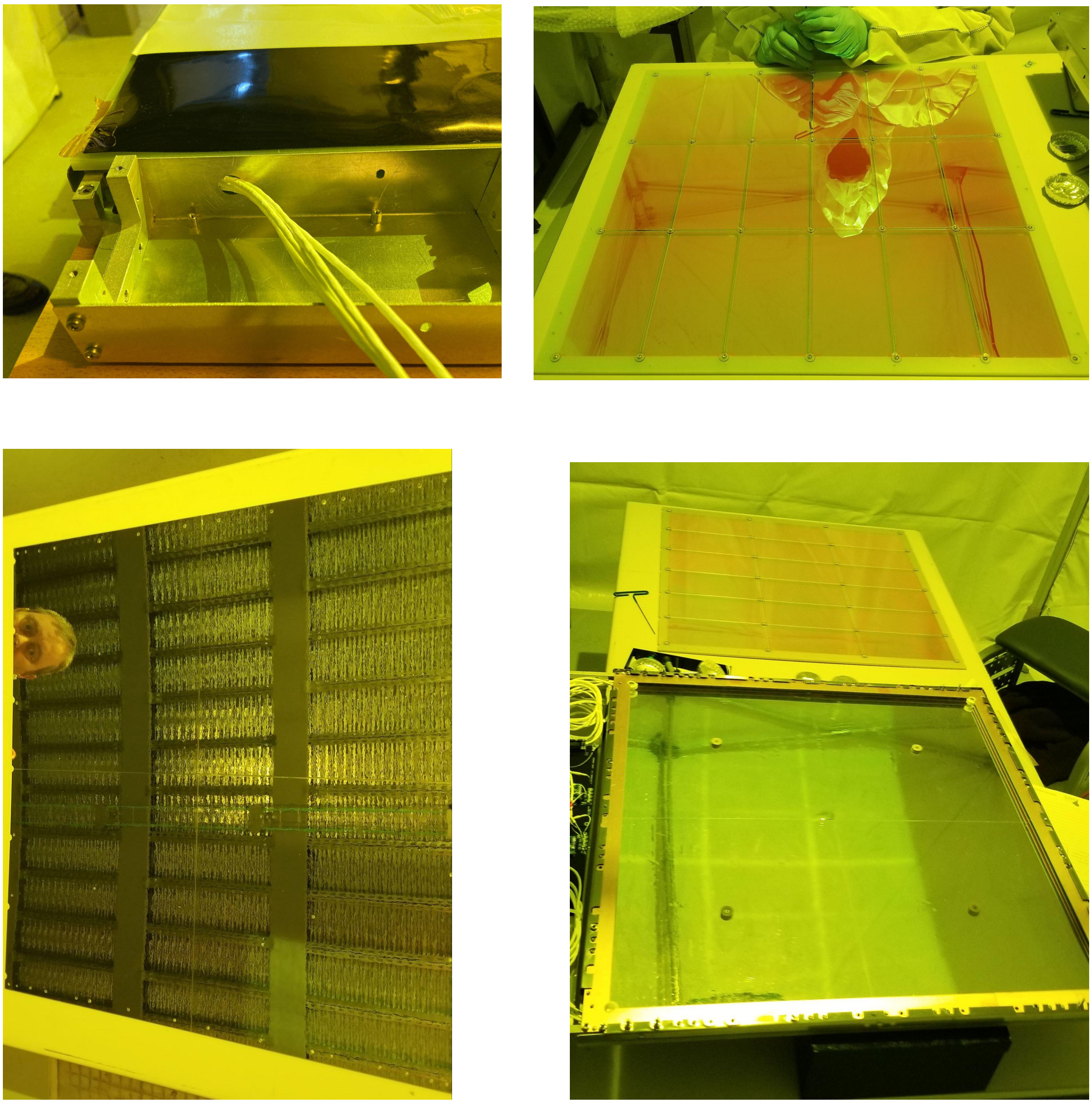


Figure 5. Top-left: Forklift arms & enclosure installed. Top-right: 100 x 200 Dichroic filter frame. Bottom-left: Vikuiti installed on membrane backplate. Bottom-right: Filter plate frame ready to be mounted to WLS frame.

Another important detail of the modules is that most of their internal surfaces have to have high reflectivity to the WLS-converted light in order to maximize photon collection efficiency. For that, Vikuiti sheets are applied to the non-active surface of the SiPM flex PCB's, copper clads, G10 backplane (membrane only, see figure 5-bottom-left), and internal sides of the filter frame ribs.

Configuration for each module

Different types of components were used to configure the 16 modules installed in ProtoDUNE-VD (see Table 1). Two different vendors were used for SiPMs (Hamamatsu – HPK – and Fondazione Bruno Kessler- FBK) and another two for dichroic filters (ZAOT and PhotonExport – PE). The first six modules (M1-M4, C1-C2) were equipped with rectangular filters (100x200), while the consortium moved to a square configuration (150x150) for subsequent modules once demonstrated that the coating uniformity was satisfactory. All WLS plates were produced by the same vendor, Glass to power, but a design with lateral optical dimples (see figure 6) was adopted for 11 of the modules while the first 5 modules had no dimples. Simulations have shown that dimples in front of SiPMs act as a lens, focusing light into the sensor and hence increasing the light collection.

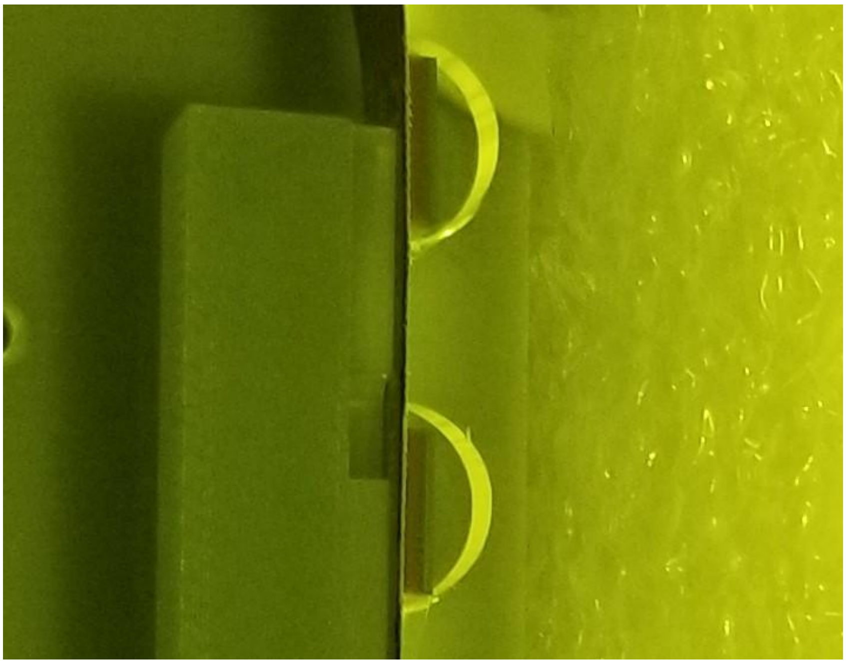


Figure 6. WLS Plate with dimples

As mentioned above, membrane modules use copper cables for powering and readout, while cathode modules are forced to use optical fibers given the high voltage environment. One of the membrane modules will be read out with SoF, in order to attempt to compare the difference between combining different types of readout and using only SoF.

	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	

Table 1. Configuration of all XA modules installed in ProtoDUNE-VD.

Pre-assembly at production sites

This will be covered in a separate document. Parts for the X-ARAPUCA frames were procured & manufactured at Iowa and CSU. The components were test fit and frames assembled at NIU before final shipment to CERN. After delivery the pre-assembled frames were fully dismounted and its components visually inspected at CERN.

Delivery of components to CERN

Components have been produced in multiple sites around the world, mostly in Europe and the US. Given the tight schedule, detailed tracking of all shipments (more than 60) has been carried out (see Figure 7) in order to guarantee the timely reception of all components. Adequate shipment addressing and reception actions according to the origin and delivery site (Meyrin or Prevessin) were taken by the involved teams to minimize transport time.

Product	Size	Weight (kg)	From	To	Responsible	Date sent	Date expected	Date delivered	Collected by	Company	Tracking number
Electronics box	31x7x6 in.	1.36	Iowa City	CERN-Meyrin	Paul Debbins	13/12/2022	19/12/2022	19/12/2022, 11:38	Anselmo	FedEx	7707 6696 5099
ZAOT dichroic filters (37 units, 97x97 mm)	15x19x29 cm	1.55	Unicamp	CERN-Meyrin	Ana/MCecilia	12/12/2022	20/12/2022	20/12/2022, 11:36	Anselmo	UPS	1ZE286536791072173
ZAOT dichroic filters (78 units, 200x100 mm)	26x37x44 cm	8.75	Unicamp	CERN-Meyrin	Ana/MCecilia	12/12/2022	20/12/2022	20/12/2022, 11:36	Anselmo	UPS	1ZE286536790230388
ZAOT dichroic filters (42 units, 200x100 mm) (6 units, 77x100)	17x37x47 cm	5.60	Unicamp	CERN-Meyrin	Ana/MCecilia	12/12/2022	20/12/2022	20/12/2022, 11:36	Anselmo	UPS	1ZE286536791509791
Membrane Suspension Lines, PD modules fixation & the light calibration system elements	300 x 16 cm	20.0	CIEMAT	CERN-Prevessin	Iván Martín	14/12/2022	20/12/2022	20/12/2022	Anselmo	Cedex	
HPK SiPMs (700 units bought by Fermilab through CERN)	22x26x31 cm	1.0	HPK	CERN-Meyrin	Wei Shi			12/12/2022	Anselmo		
Fibers, diffusers, SMA FT	14x14x9 in.	2.27	ANL	CERN-Prevessin	Zelimir	21/12/2022		6/01/2023, 10:15	F. Resnati	FedEx	540651804252
PoF Fibers	1 box		MH GoPower Taiwan	CERN-Prevessin	Bill P.	19/12/2022			F. Resnati	DHL	8377656350.
HPK SiPMs (700 units bought by Fermilab through CERN)	22x26x31 cm	1.0	IFIC-Valencia	SCEN-Italy	Anselmo	29/12/2022	30/12/2022	??	SCEN	UPS	1Z208A4A8692947378
6 Flex Circuits with Hamamatsu SIPMs	30x40x8cm	1.0	NIU	CIEMAT	K.Francis	5/1/2023	9/1/2023		A. Verdugo	UPS	1ZK8604T0400003018
2 DMEM boards	34x32x8 cm	1	Milano-Bicocca	CERN-Prevessin	C.Gotti	12/1/2023		16/1/2023	Franciole	UPS	1Z66A73Y0496195320
Cables from flex to motherboard (100 units)			Fermilab	CERN-Prevessin		17/01/2023	19/01/2023	19/01/2023	Franciole (20/01)	FedEx	606030526619
DCEM v1.2-copper and Capacitors 4.7uF	18x12x3 in.	0.59	Fermilab	CERN-Prevessin		12/1/2023		17/1/2023, 10:02	Manuel	FedEx	606030526560
Frame for 2nd membrane module		12.7	Fermilab	CERN-Prevessin		12/1/2023		17/1/2023, 10:02	Dante	FedEx	606030526550
LBL bias cards	14x12x3 in	0.45	BERKELEY	CERN-Prevessin		9/1/2023	23/1/2023	23/1/2023 at 9:55	Franciole	FedEx	393223029126
Two Counterweigh structures for the top membrane PD moudules	Cilindre of diam 100 mm x 1800 mm length	30	Ciemat	CERN-Prevessin	Iván Martín/Enrique Calvo	18/01/2023	23/01/2023	24/01/2023, 9:41	Ivan	TNT	304746365
Vikuiti for the SiPM boards.	15x15x4 in.	01.04	Fort collins	CERN-Meyrin		13/01/2023	16/01/2022	16/01/2022	Franciole	FedEx	393401192740
1st Top mesh frame	32x60x3 in.	16.78		CERN-Prevessin	James Eksi	20/01/2023	23/1/2023	24/1/2023, 10:11	Anselmo	FedEx	771075836301
35 PE filters	40x40x40 cm	4	IFIC-Valencia	Campinas	Anselmo	19/01/2023	24/1/2023	24/1/2023, 14:34	A. Machado	UPS	1Z208A4A0494611200
Assembly frame for membrane modules	54x5x5 in	7.48	Fort collins	CERN-Meyrin	Dave Warner	19/01/2023	23/01/2023	23/1/2023, 11:03	Anselmo	FedEx	393639548397
WLS (no dimples), 3 units	607 x 607 mm		INFN Milano Bicocca	CERN_Prevessin	C. Cattadori		22/01/2023	22/01/2023	C. Cattadori	C. Cattadori	

Figure 7. Shipment tracking for PDS components.

Assembly of X-ARAPUCAs at CERN

The final X-Arapuca modules assembly occurred at CERN by a reduced team of trained people. Two people were necessary at all times. The production rate for trained people is about one and a half modules per day.

A clean area (see figure 8) was set up inside the PDS room to avoid dust deposition and maintain a well-delimited assembly area with only two people inside. This area consisted of a clean tent equipped with an air filter, a sticky tac at the entrance, and all the necessary equipment for body protection (suit, face masks, hair nets, nitrile gloves, and shoe protection).

Modules were initially disassembled to include the WLS plate, flexes, and flex-to-board cables and reassembled for electronics testing. Just before installation in the cryostat, the dichroic filters were assembled. About an hour was necessary for this procedure including 30 minutes for the assembly of the filters to the frames and 30 minutes for the mounting of the frames to a cathode module. Along the procedures, the module was cleaned with argon gas to help remove small residues that could remain on the components even with all the care taken inside the clean tent (figure 8).

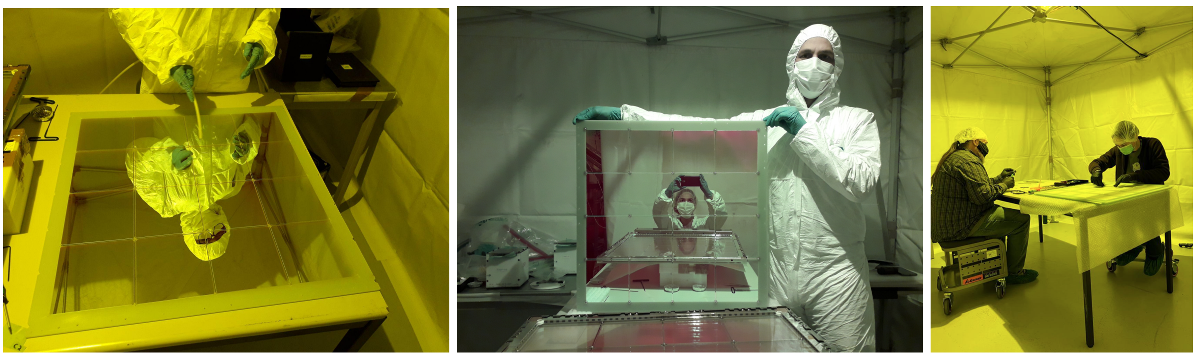


Figure 8. Clean tent and cleaning process (left) of the modules using compressed gas.

Assembly procedure

Modules arrived in different stages of assembly in order to test the best scenario for the shipment procedure at the far detector site. Some modules were shipped with or without a (fake, except in one case) WLS plate, with or without the shielding C-shape channels in place, with or without Vikuiti attached to different parts, with or without fake filters already installed in the filter frame. In any case, the first step was to disassemble the module for the installation of the different components. This step was done either completely or partially, depending on the evaluated needs.

Modules that arrived without a fake WLS had their springs already compressed. Nevertheless, it was verified that the standoffs that hold them sometimes became loose, which resulted in: the arrival of loose springs and/or the need to completely disassemble the whole module to adjust the standoffs. This problem was solved for the last shipments with the gluing of the standoffs to their G10 parts. Even with this, all modules that received a Vikuiti cover of their copper clads had to be fully disassembled for the covering of those components *in situ*.

The full detailed assembly procedure is described in another document. The basic steps on site were:

1. Disassemble the module
2. Cover different parts with Vikuiti if not already covered
3. Inclusion of WLS plate and SiPM flexes
4. Cabling and grounding
5. Assembly of top copper clad
6. Assembly of conductive shielding
7. Assembly of top and bottom frames and electronic box
8. Cold test
9. Disassembly of filter frame(s)
10. Inclusion of filters on frame(s)
11. Assembly of filter frame(s)

Lessons learned

Protection of WLS

The WLS protective layer was removed only from the borders when placed inside the modules and kept in place until the assembly of the top and bottom frames for testing. Although the cold test did not remove this protective layer and could be kept in place until the final filter assembly, for a few times it would fragment given the cooling/warming conditions or gather residues during the LAr immersion, therefore the decision to fully remove it before testing. During assembly, a piece of foam was placed on top of the WLS to prevent potential damages from shocks or occasional contact. Also, a thick black plastic was used to transport the module between the assembly room and the testing area, being removed at the last possible instant to avoid exposure to unfiltered light.

Problems with spacers

The white plastic washer used to isolate the WLS bar from the Vikuiti-covered copper clad (see figure 9) could get loose, especially after the module was subjected to the LAr environment. When a washer of this kind did not have a perfect fit (usually due to imperfections in the round cuts to copper), a piece of Kapton tape was used to keep this element in place. This issue has been traced back to a tolerance issue in how the copper clad boards are manufactured and is currently being addressed.

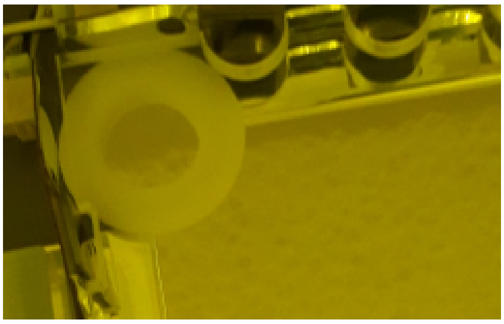


Figure 9. Detail of the plastic washer used to isolate the WLS bar from the Vikuiti-covered copper clad.

Problems with Vikuiti on the backplane

As mentioned above, membrane mount XAs have filters only on the side facing the field cage, while they have an FR4 plate (the *backplane*) covered with Vikuiti on the back side facing the membrane. Vikuiti was installed on the backplane at the XA components production site for most modules, but it was installed at CERN for some of them. A recurrent problem has been observed in a significant fraction of XAs: Vikuiti has partially detached from the backplane during cold testing. Several hypotheses were suggested:

- Too large Vikuiti pieces
- Overlap of Vikuiti pieces
- Presence of air bubbles on the Vikuiti
- Presence of frost when extracting the module due to inadequate warm-up
- Too fast cooling down

A number of tests were conducted to understand the source of the problem, testing all hypotheses above. Given the time constraints, no extensive systematics studies could be done, but it was proven that avoiding the risks listed below significantly reduced the problem. However, it has been understood that further R&D is needed.

Problems with Vikuiti on the copper clad

Initially, covering the copper clad was done by cutting enough material to cover both sides of the clad (the copper and the G10 side), applying it on one side and bending the material to cover the other side, making holes along the process with a puncher and clearing them with cutting tools. This was done to avoid the risk of covering the SiPMs with the Vikuiti if it was applied only to the G10 surface and became detached. This design guarantees that the screws put on the copper side hold the Vikuiti even if it detaches, and it has been shown to work as expected after a cold test of the modules. Nevertheless, the process of uniformly applying the Vikuiti to a ~60cm long side and bending it has proven to be challenging. The solution was to use a laser cut printer to provide the holes already (instead of using the puncher) and make smaller pieces to be applied individually. Care was taken to avoid (or isolate, if needed) overlaps of Vikuiti. This new design was easier to apply and gave good results after the modules were tested in the cold.

One problem that is common to cover the copper clad and covering the backplanes is to make sure the holes are clear since Vikuiti partially covering a hole can apply a force contrary to the path of the screw and rests of Vikuiti inside the hole can also make passing a screw through it harder.

Problems with Vikuiti on flexes

Vikuiti has proven to be a material that resists bending. To attach it to the flexes, the initial idea of bending and gluing it to the back of the flex along the whole length of the flex had to be abandoned. It required too much handling of the SiPMs, and the result was unsatisfactory. For the HPK flexes, it was possible (not to mention easy) to apply Vikuiti as a single piece only to the front face of the whole flex. For the FBK, however, given the large size of the SiPM base on the flex, this was not a possibility. Moreover, the epoxy deposited on the flex made the adherence of the Vikuiti challenging. In the end, squares of Vikuiti were individually placed on the FBK flexes (Figure 10). There were no signs of Vikuiti detachment on any flexes after the cold tests.

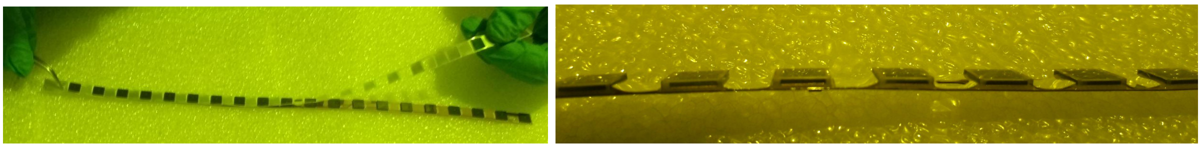


Figure 10. Left: application of a single strip of Vikuiti to an HPK flex. Right: Vikuiti on FBK flex. Note the irregularity of the application with Vikuiti bending closer to the SiPM borders.

In the end, the application of Vikuiti to different surfaces has been shown by simulations to be an essential factor in increasing the XA detection efficiency. However, after the assembly of the 16 ProtoDUNE-VD modules, it becomes clear that a more automated way of covering the components must be pursued.

Electronics installation

The electronics boards are installed when the module is fully assembled with the electronics box in place (see figure 11). Spacers should avoid contact between the back of the board and the electronics box. Cables from the flexes should be labeled regarding the geometry distribution chosen for the SiPMs and the channels on the board. As the length of those cables should be the same in the electronics box, the distribution of the cables will be uneven. The recommendation is to connect the cables first, avoiding any entanglement.

Then begins to coil at the end closer to the final position of the cables in radiuses that fit inside the electronic box:

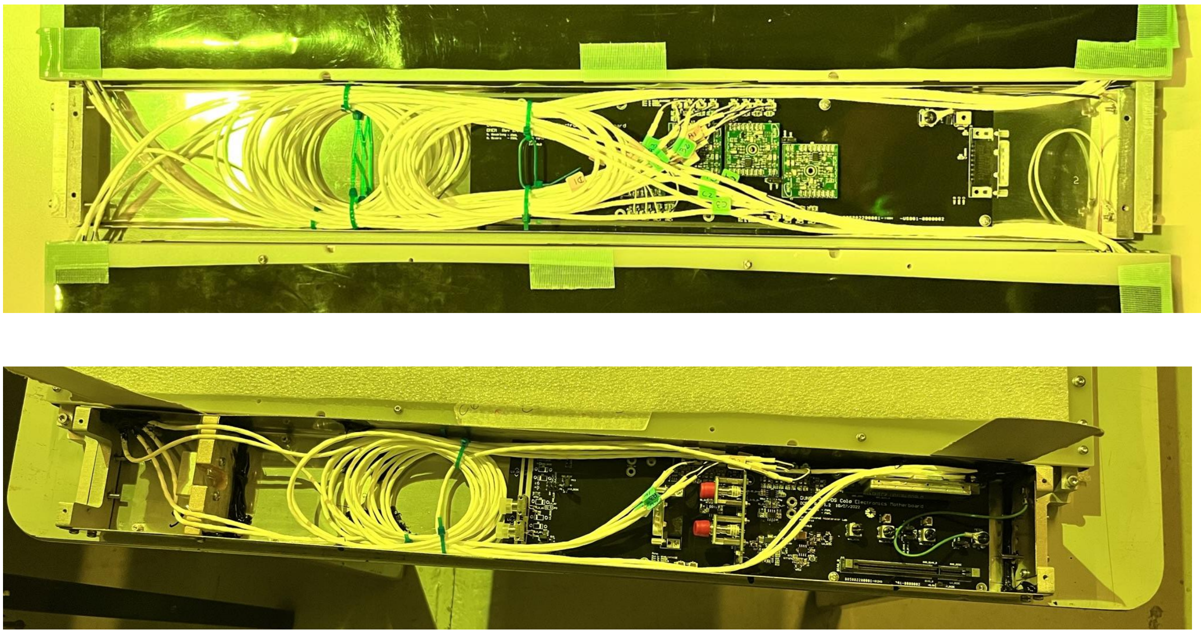


Figure 11. Distribution of cables inside the electronic box. Top: between two membrane modules. Bottom: for a cathode module. The ground connection between the board and the electronics box must be checked for a cathode module.
For cathode modules, the clamp for the fibers must be in place, and sufficient space for later connection of the fibers must be available.

Before closing the electronics box a final check should be performed to ensure proper mapping between SiPMs, module, motherboard, LED driver and DCDC board. If possible, measure the resistance between the test point ground in the board and the frame with a multimeter, which should be below 1 Ohm.

Assembly at production sites

The lessons learned confirm the need of sending fully assembled modules to the far detector site, except for the filter frames that should be shipped with the filters in place for final assembly on site. We have received at the Neutrino Platform assembled modules that arrived in perfect conditions nearly 100% of the times (the exception was a single module slightly damaged during transportation). This will speed up the process on site, buying us the necessary time in case of any contingency but also allowing more free time for the cranes and reducing the amount of material inside the cavern that needs to be sent back to the surface.

Other lessons learned

Additional information can be found in a separate document in EDMS 2875448.

Cold electronics assembly and testing

As described above, cathode and membrane mount XAs have different cold electronics. In this section, the description of the main electronics components (a full description is given elsewhere as part of the FDR documentation), the assembly of the boards, and the tests carried out prior to installation are described separately for both types of modules. It is worth noting that a different sequence is expected for FD2, where more time will be available for planning, reception of components, and assembly. Nevertheless, this process constituted a very useful exercise, with many lessons learned towards the PRR.

Cold Electronics with Signal-over-Fiber

The electronic boards consist of four independent stages of which three are independent printed circuit boards (PCB):

1. the motherboard PCB,
2. the DCDC daughter PCB,
3. the laser driver daughter PCB,
4. the Optical Power Converter (OPC) stage.

The motherboard PCB (DCEM 1.2, shown in Figure 12) contains the Power-over-Fiber (PoF) receivers (OPCs, Optical Power Converters) and related circuits, the voltage regulation components (LDO), and the signal input circuit (first and second stage amplification). It is populated with a connector where the DCDC daughter PCB can be inserted, whereas the laser driver daughter card is soldered at the middle of the board onto dedicated pins. The board contains multiple jumpers that allow choosing the desired electronics configuration (i.e. switch between PoF and power supply as a source for the low voltage).

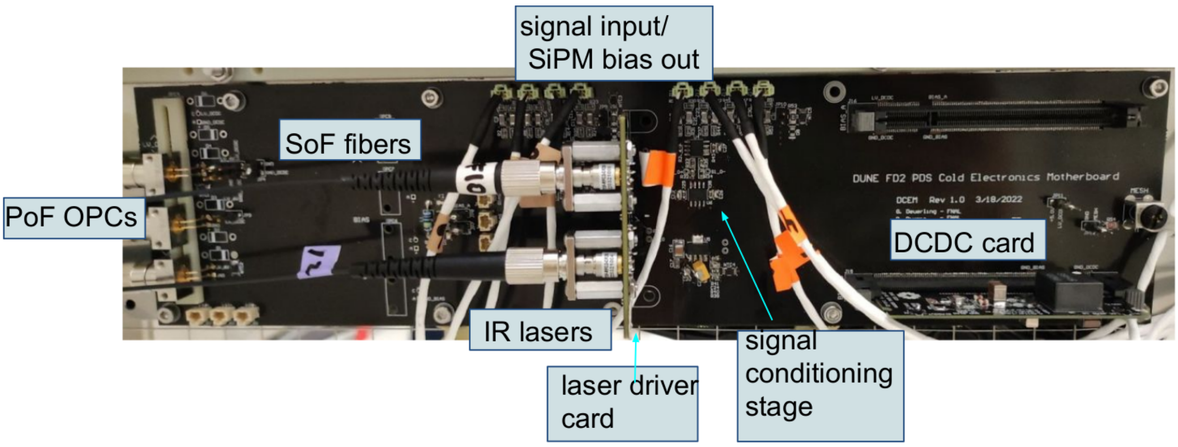


Figure 12. A DCEM 1.2 motherboard populated with a DCDC card, laser adapter card, lasers, and PoF receivers (OPCs). It is connected to an X-ARAPUCA (signal input cables) and to the corresponding SoF and PoF fibers.

The main population of surface-mounted (SM) components was made by the PCB producer company (Cirex). This is the correct procedure but given time constraints at the moment of fabrication, a fraction of the DCEM motherboards had to be hand-populated at Fermilab.

Additionally, a large number of capacitors were replaced by hand after the first population. The OPCs were hand-populated at Fermilab. Two types of OPCs were used: silicon (Si) and gallium-arsenide (GaAs). All motherboards were hand-carried to CERN (figure 13-left shows a part of the boards upon arrival) and had to undergo a modification procedure at CERN. A document that explained in detail the modifications needed in each board was prepared; the modification procedure has been summarized in Appendix 2.

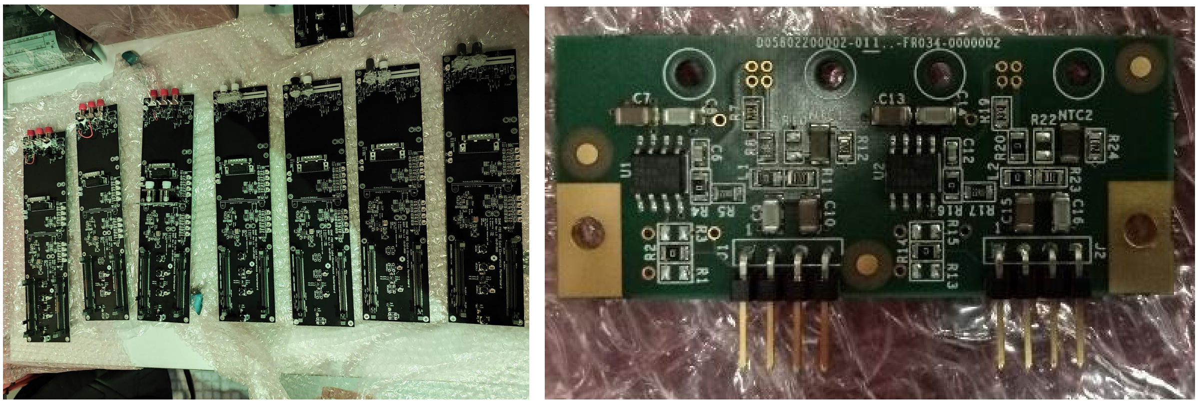


Figure 13. Left: a group of DCEM 1.2 boards with either 3 Si OPCs (red, left) or 2 GaAs OPCs (gray, right). Right: Laser adapter card as received from PCB company.

Each board has a unique identification number that allows for tracking its origin and population type. Table 2 describes the population of the DCEM boards.

Board Number	Fabrication	PoF type	DCDC	Module
01240	Cirex	GaAs	LBL891	C2
01224	Cirex	GaAs	LBL886	C3
01212	Cirex	GaAs	LBL893	C1
01242	Cirex	GaAs	PICO8	C4
01223	Cirex	GaAs	PICO14	C5
01220	Cirex	Si	LBL887	C8
01222	hand	Si	PICO9	C7
01243	hand	GaAs	LBL892	C6
01232	Cirex	copper	-	M5

Table 2. Configuration of DCEM boards used in ProtoDUNE-VD.

The laser adapter cards (see figure 13-right) were produced and populated in industry. They were hand carried from APC (Paris) to CERN. The lasers and the resistor that determines the laser bias were hand-soldered at CERN.

The lasers used were fabricated by Lasermate with two different focal lengths ("defocusing") that allow for improving the efficiency of the light transmission in LAr. In addition, lasers had two types of connectivity: FC connectors and pigtails. The pigtail lasers must be connected to the cathode fibers using an FC-FC connector; an additional aluminum piece was fabricated to hold the FC-FC connector in place.

Two types of DCDC bias cards were used (see figure 14). They were produced by Iowa and LBL, shipped to Fermilab, and then hand-carried to CERN. The LBL DCDC cards are the baseline option for the PDS cathode bias. The PICO cards make use of an off-the-shelf component, the "PICO", and were the first produced and tested. They were all tested before shipment to CERN and configured to bias the two types of SiPMs used in the modules (HPK and FBK). They were re-configured at CERN to provide between 47 and 47.5V for HBK modules and between 32 and 33V for the FBK modules. They were re-tested at room temperature and in the cold to verify the voltage output.

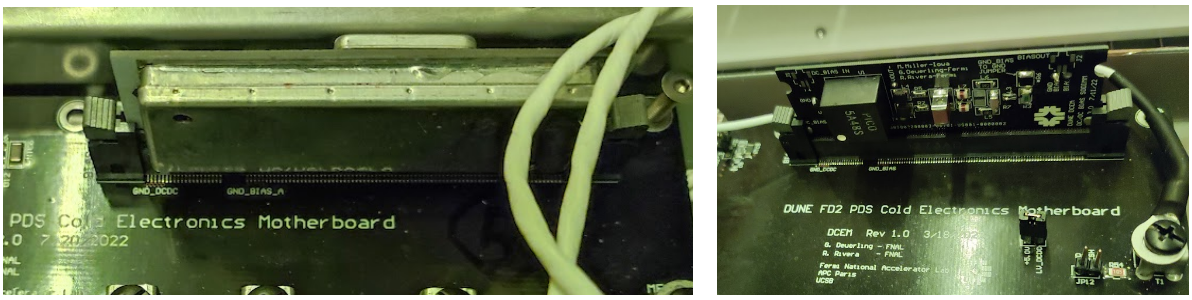


Figure 14. Left: LBL-DCDC card with shielding. Right: PICO DCDC card.

A testing protocol was defined to ensure the correct functioning of the electronics boards before assembly within the XA:

1) powered with copper at room temperature.
2) powered with copper in LAr.
3) powered with PoF at room temperature.
4) powered with PoF in LAr.

A list of parameters to be measured in each test was defined. Tests 1) and 2) reference the expected board behavior when fully powered. In test 3) the board is underpowered since the power consumption at room temperature is higher than PoF can provide. It will serve as a reference to the expected behavior after ProtoDUNE-VD installation before filling. Check 4) is the most important since the board is in its final configuration, and at this point, it was thoroughly checked to detect any anomalies. Once the board has passed check 4), it is ready to be installed in the module. The parameters measured during these tests were recorded in a shared document (see figure 15). Once the board is prepared and connected, the time to test it is around 30 min, including both Sof and PoF.

Module	Board	PoF type	DCDC	Lasers	Vin (cold and warm)	Voffset 1	Voffset 2
Units							
Expected values							
C1	1212	GaAs	LBL 893	200uW FC	6.25	288.8 mV	278.6 mV
C2	1240	GaAs	LBL 891	500uW pig	6.25	280.4 mV	289.9 mV
C4 v1	1242	GaAs	PICO 8	200uW pig	6.25	289.3 mV	280.4 mV
C4 v2	1242	GaAs	PICO 8	200uW pig	6.25		
C3 v1	1224	GaAs	LBL 886	500uW FC	6.25	285.8 mV	290.5 mV
C3 v2	1224	GaAs	LBL 886	500uW FC	6.25		
C6	1243	GaAs	LBL 889	200uW FC	6.25		
C6	1243	GaAs	LBL 892	200uW FC	6.25		
C8	1220	Si	LBL 887	500uW pig	6.25		
C7	1222	Si	PICO 8	200uW FC	6.25	291	285
C7	1222	Si	PICO 9	200uW FC	6.25		
C7	1222	Si	PICO9	200uW FC	6.25		
C3	1224	GaAs	LBL 886	500uW FC	6.25		
C5	1223	GaAs	PICO12	200uW FC	6.25		
C5	1223	GaAs	PICO14	200uW FC	6.25		
C6	1243	GaAs	LBL 892	200uW FC	6.25		

Module	Board	Copper Warm: Current in no DCDC	Current in w DCDC	LDO OpAmp	LDO-DCDC	DCDC Vout	CH 1 - Kout1	CH 2 - Kout2	CH 1 - Kout2	CH 2 - Kout1	CH 1 - Kout3	CH 2 - Kout3	FFT ok?	signal test ok?
Units		mA	mA	V	V	V	mV	mv	mv	mv	mv	mv		
Expected values		oard, 135? tot		4.08	5.09	max 55/??								
C1	1212	73	125	4.966	5.106	4.26 and u	80	30	35	65				all 8 ok
C2	1240	76	103	4.991	5.105	56.53	120	44						all 8 ok
C4 v1	1242	76	129	5.003	5.112	56.5	42	7						all 8 ok
C4 v2	1242						58	21	28	43				
C3 v1	1224	77	124	4.977	5.1	36.4	229	120						all 8 ok
C3 v2	1224					33.1								
C6	1243	75	109	4.998	5.117	53.3	57	54	43	64				all 8 ok
C6	1243	74	110	4.998	5.107	56.37	53			49				all 8 ok
C8	1220	78	104	4.992	5.1	53.3					157	189	ok	all 8 ok
C7	1222	72	128	4.992	5.097	55.33	16	33	20	31		20MHz? nothing w		done at APC
C7	1222	72	111	4.991	5.096	34.1							ok	all 8 ok
C7	1222	77	113	4.991	5.096	34.26					60	70	ok	all 8 ok
C3	1224		124				175	205						
C5	1223	76	128	4.995	5.097	55.78								
C5	1223	76	129	4.995	5.096	56.13					85	65		all 8 ok
C6	1243													

Module	Board	Copper COLD: LAr depth	Current in	DCDC out	LDO OpAmp	LDO DCDC	Ch1-Kout1	Ch2-Kout2	Ch1-Kout3	Ch2-Kout3	FFT
Units		cm	mA	V	V	V	mV	mV	mV	mV	MHz
Expected values		50cm min	d/60? with	47 or 31			100-200	100-200			
C1	1212	60cm	81	46.57	5.024	5.171	164	56			ok
C2	1240	55cm	69	47.08	5.062	5.14	112	40			ok
C4 v1	1242	50cm	58	47.43	5.003	5.113	105	13			ok
C4 v2	1242										
C3 v1	1224	60cm	86	33.88	4.972	5.122	170	90		small peak at ~3	
C3 v2	1224	35cm	83	32.2	4.97	5.117					
C6	1243	37cm	70	47.5	5.136	5.136	2 (with k2	8 (with k1)			
C6	1243	45cm	86	47.07	4.985	5.155	58				ok
C8	1220	45cm	68	46.5	5.085	5.12			124	120	ok
C7	1222										
C7	1222										
C7	1222	45cm	50	30.6	5	5.13			18	191	ok
C3	1224										
C5	1223										
C5	1223	45cm	58	46.6	5.028	5.049			104	155	ok
C6	1243										

Module	Board	PoF Warm: PoF out	DCDC out	LDO OpAmp	LDO DCDC	PoF Cold: PoF out	LDO OpAmp	LDO DCDC	DCDC out	Ch1-Kout1	Ch2-Kout2	Ch1-Kout3	Ch2-Kout3	FFT ok?
Units		V	V	V	V	V	V	V	V	mV	mV			
Expected values						6.4			47 or 31	100-200	100-200			
C1	1212	4.403	42.3	4.415	4.398	6.206	5.023	5.168	46.55	159	70			ok
C2	1240	4.78	50.6	4.76	4.64	6.99	5.063	5.144	47.06	114	42			ok
C4 v1	1242	4.12	48	4.1	3.9	7.01	5.004	5.115	47.44	108	12			ok
C4 v2	1242													
C3 v1	1224	4.49	32	4.465	4.36	6.175	4.968	5.12	34.5	164	95			ok
C3 v2	1224													
C6	1243													
C6	1243	4.51	45	4.385	4.494	6.156	4.985	5.156	47.06			142	oscilaltion	
C8	1220	6.76	53.3	4.992	5.101	6.17	5.085	5.119	46.5			126	117	ok
C7	1222													
C7	1222													
C7	1222	6.82	34.65	4.99	5.097	6.33	5	5.13	30.7			155	126	ok
C3	1224													
C5	1223													
C5	1223	4.442	47.69	2.936	4.421	7.02	5.03	5.046	47.08			195	100	aks around
C6	1243	4.5	45	4.5	4.5					96 (red fit	170			

Figure 15. Table of parameters measured for each of the cathode boards. It also contains information on the DCDC and laser configuration.

An additional SoF board was installed on the membrane. This board and the corresponding XA module will be powered using copper; therefore, the board has no OPCs and no DCDC adapter card.

Lessons learned

Failure of electronics components

Hand population of electronics boards should be avoided. A high rate of failure of components was detected, in particular, of certain capacitors. These components are very sensitive and were replaced by hand. It is suspected that this is the most probable cause of failure. Further tests will be conducted to confirm this hypothesis.

Electronic board handling

The assembly room was not equipped with adequate ESD (electrostatic discharge) protection at the beginning of the assembly. The weather and dry environment in the area caused electrostatic discharges on the components. It is known that the effect of such discharges may not be immediately evident but could manifest itself after some use of the component. Capacitors are especially sensitive to this. Short circuits were also found to be caused by excessive flux on the board and metal scraps. The procedure in electronics handling was improved after some time and should be adequately implemented in the FD2 production sites.

Lasers

Lasers are also ESD-sensitive components. Those should be handled and soldered with care and ESD protective measures. In addition, connecting them to fiber through the FC connector exerts considerable torque on them, which can cause the solder to become disconnected or break the pin inside the laser. Mechanically, lasers must be well secured to the laser adapter before soldering. A combination of metallic spacers and washers was used to this end. Once the laser dimensions are defined in production, adequate dimension spacers should be fabricated.

Voltage distribution

There have been unknowns concerning the required PoF laser output to achieve the correct powering of the electronics board. A pre-calibration of the OPCs should be considered to estimate the expected power output of the OPCs. This, combined with the known power consumption and load impedance of the board (measured in the tests with a power supply), would provide the necessary information to determine the laser power needed.

The DCDC bias card voltage output is susceptible to its voltage input and temperature. The adapter cards should be prepared using exactly the same voltage as provided by the motherboard and verified in LAr.

The capability to test the board with a power supply is important since it provides a reference to the expected behavior of the board when correctly powered. The capability should be kept. It should be determined whether the use of jumpers is an option.

DCEM 1.2 motherboards testing

Several test points were identified as key to determining the correct functioning of the boards. A connector or set of pins should be added to the motherboard design to facilitate this testing during production.

The use of high-precision resistors at certain points of the transmitter circuit is important to reduce differences in the laser output between boards

We used different types of lasers to evaluate the difference in the performance.

The final configuration of the electronics board was implemented at CERN, where the following was changed: gain, laser offset, capacitors, and LDO configuration. A shared document with instructions has been written. A summary is presented in Appendix 2.

Mechanical layout of the board

Fibers and cables must be connected by hand to the board. No tooling can assist with this task. Therefore, adequate spacing must be foreseen between components to allow these manipulations (assuming an adult man hand) in the expected uncomfortable circumstances (once the module is placed on the cathode) without risking an incorrect connection or the breaking of the surrounding components

Tests in LAr

It's important to note that the cold tests must be in at least 50-60cm of LAr. Otherwise, the response of lasers will not be stable. A connector should be added to perform the cold tests without any soldering.

Cold Electronics with Signal-over-Copper

Membrane X-ARAPUCAs M1, M2, M3, M4 are read out by the “HD-style” cold amplifier developed for FD1 (EDMS 2805804). The DMEM v1.0 motherboard (EDMS 2795424) was designed to host up to 4 HD-style amplifier daughter cards. Figure 16 shows a photograph of the board in the cold box, mounting three amplifiers out of four. A single “blue” cable, developed for FD1, with DB15 connectors at both ends, connects each DMEM to the warm electronics through the flange. Each cable includes four differential signal pairs (4 channels, signals in AC, and SiPM bias in DC) and four smaller wires (power supplies of the amplifiers and ground reference).

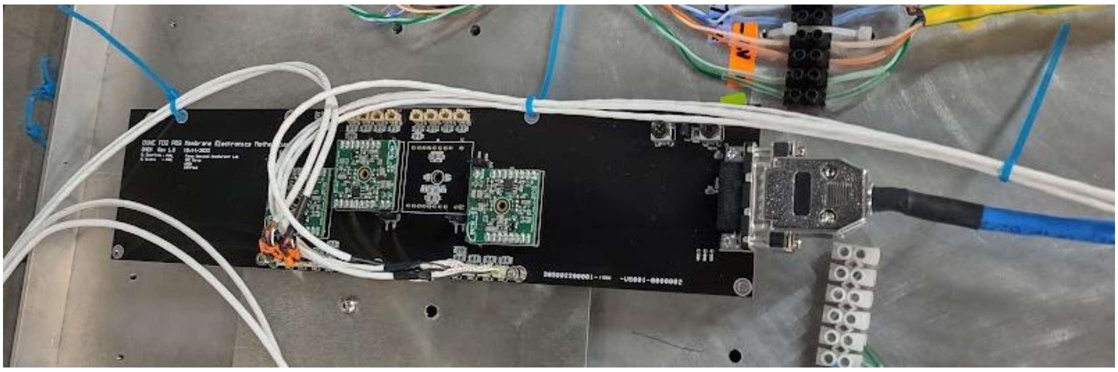


Figure 16. Photograph of the DMEM mounted in the cold box. The white coaxial cables connect the SiPMs to the DMEM (one cable per flex, four cables per channel). The blue cable connects the DMEM to the outside.

Eight DMEM v1.0 boards in total were produced and populated by Cirexx. All boards were shipped to Milano Bicocca, and a subset of them was then brought to CERN. The amplifiers come from a small production of 30 devices originally meant as spares for FD1, built by Aemme Elettronica. One DMEM (2 amplifiers) was used for M1-M2, and another DMEM (2 amplifiers) was used for M3-M4. Due to stringent time constraints, most of the testing was done at CERN during installation, while more detailed tests on a smaller setup were done in parallel in Milano Bicocca.

Although already well tested for FD1, the HD-style amplifier needed additional work to be ready for FD2 due to the different SiPM ganging configuration and other boundary conditions. The optimization phase coincided with the installation of ProtoDUNE-VD. For this reason, there is a difference between the configuration installed for M1-M2, mounted first, and the configuration installed for M3-M4 mounted a few weeks later. Although we expect all membrane ARAPUCAs to satisfy the requirements, we believe that the configuration installed in M3-M4 will perform better than the one of M1-M2. In both cases, the original 47 uF power supply bypass capacitors on the DMEM, as per BOM populated by the vendor, were replaced with devices of the same value but higher voltage rating, which have been proven to degrade less with thermal cycling (C3216X5R1E476M160AC). For M1-M2, the amplifier daughter cards are unmodified, i.e. identical to the original HD design. On the DMEM, the amplifier feedback resistors were changed from 2k (original BOM) to 390 (same value as used in the HD). Figure 17 shows the signal shape and the single photoelectron peaks measured in Milano-Bicocca with this configuration, with Hamamatsu SiPMs in LN2 at 45 V (+3 V overvoltage).

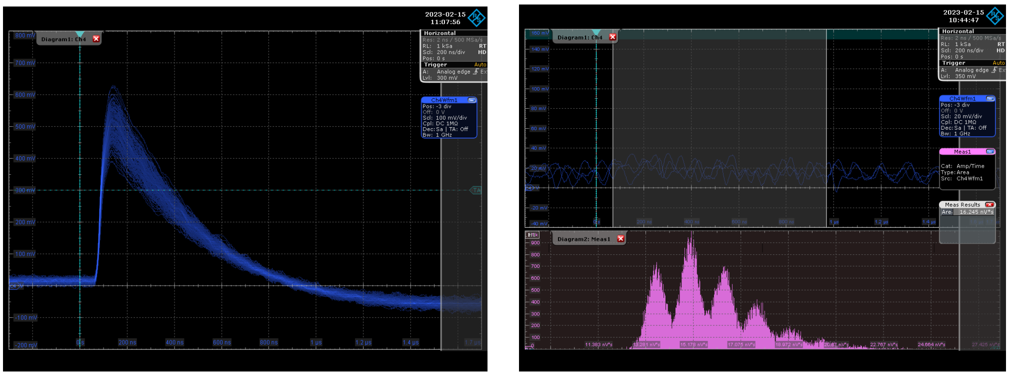


Figure 17. Signal shape and S/N of the DMEM as mounted in M1-M2 (Hamamatsu SiPMs in LN2 at +3 V overvoltage). The undershoot that follows the signal is due to the warm second stage used for these measurements.

For M3-M4, the amplifier daughter cards were modified, adding two 50 ohm resistors in series with the two output pins of the THS4531 opamp (see figure 18). This improves stability at high frequencies and allows the amplifier to operate with higher values of feedback resistance. On the DMEM, the amplifier feedback resistors were changed from 2k (original BOM) to 1.2k, which seemed to give the best performance with the VD hybrid ganging scheme. Figure 19 shows the signal shape and the single photoelectron peaks measured in Milano-Bicocca with this configuration, with Hamamatsu SiPMs in LN2 at 45 V (+3 V overvoltage).

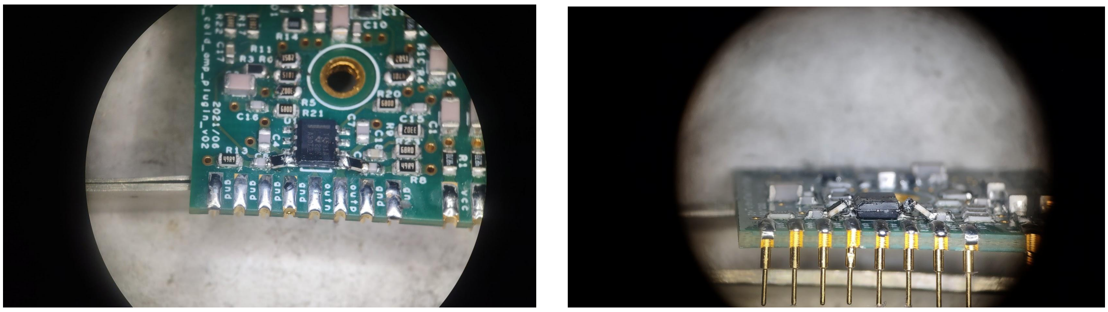


Figure 18. Photograph of the HD amplifier modified with the addition of two 50 ohm resistors at the outputs of the THS4531.

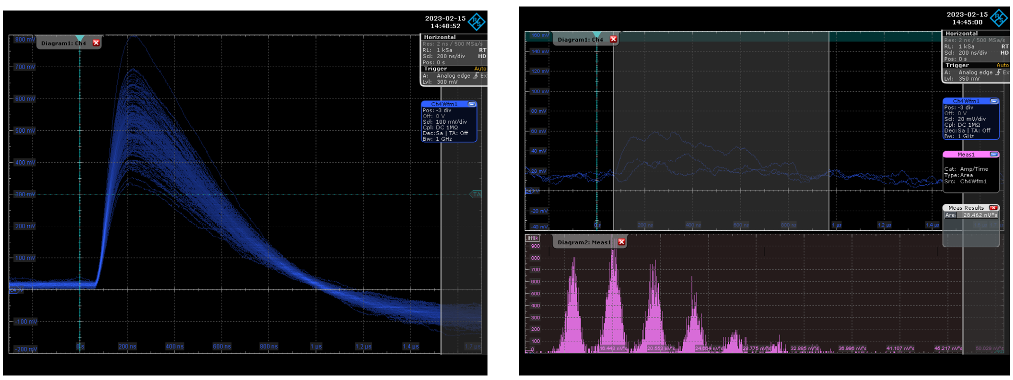


Figure 19. Signal shape and S/N of the DMEM as mounted in M3 and M4 (Hamamatsu SiPMs in LN2 at +3 V overvoltage). The undershoot that follows the signal is due to the warm second stage used for these measurements.

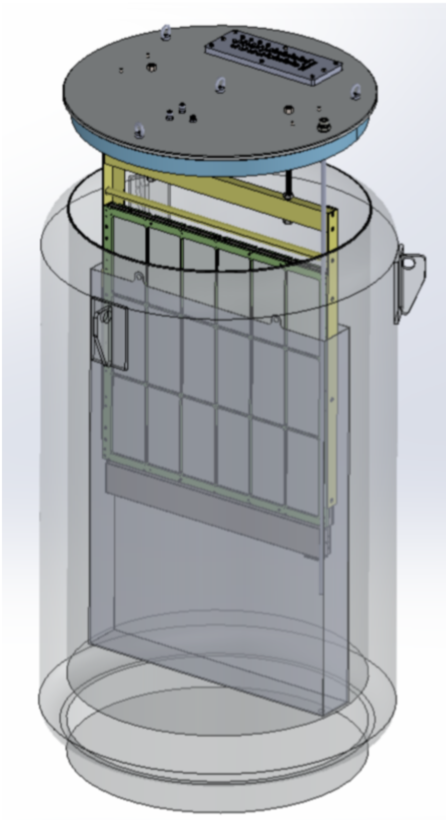
X-ARAPUCA tests before installation

As mentioned above, the extremely tight installation schedule prevented full X-ARAPUCA assembly at production sites. As a consequence, testing and validation of XAs had to be done at CERN prior to installation. Full validation, e.g. XA efficiency measurements, could not be performed since this requires a complex cryogenics system with purified liquid argon. Nevertheless, a LAr testing setup was assembled at EHN1, enabling minimal testing to ensure all modules were operational and producing the expected signals.

Figure 20. Aerial view of the testing area during its installation in December 2022

Description and operation of testing setup

A testing setup has been assembled at EHN1 in front of the PDS room (see figure 20). As shown in figure 21-left, it comprises a 70 cm diameter, 120 cm tall open dewar equipped with a dedicated lid to ensure light tightness. An inner stainless steel box with dimensions 70x10x100 cm^3, sufficient to hold a XA, has been used to reduce the LAr consumption and to simplify LAr extraction before XA cooldown (see figure 21-right). The photon collector is held by a dedicated support structure attached to the lid, suspended from a winch allowing for both vertical and lateral movements. The lid has the optical and electrical feed-throughs to inject controlled light with an LED, power the XA (SiPMs and cold electronics), and read out its signal. An additional SUBD-25 feedthrough reads six temperature sensors placed at different heights within the XA support structure (visible on the left hand side of the XA frame in figure 22). This allows for temperature and liquid level measurements during the cool-down and warm-up phases. A KF16 flange with a stainless steel tube running to the bottom of the inner box allows for controlled LAr filling with the lid closed. Several other ports for pressure release are also available. A table next to the dewar has several power supplies, a pulse generator, and an oscilloscope. A closed rack beside the table holds the class-4 lasers used for PoF.



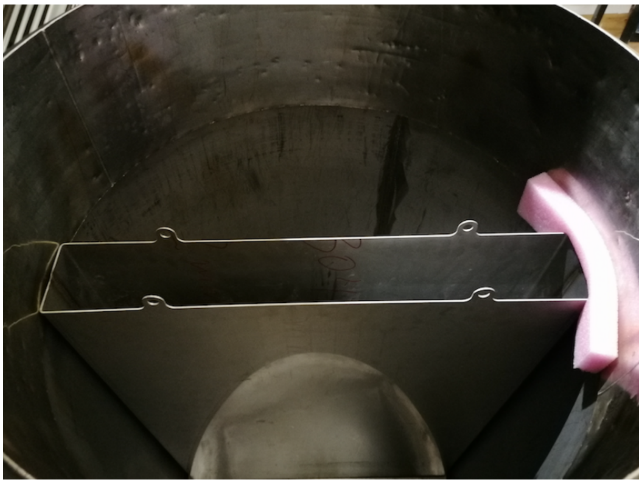


Figure 21. Left: 3D model of some of the elements of the testing setup, the open dewar, the inner box, the lid, the XA and its support. Right: the inner box.

A dark box was available next to the dewar to perform warm tests before insertion in LAr, mainly to check the module integrity and all electrical and optical connections.
After warm tests, the XA is transferred to the dewar with an almost empty inner box such that only the electronic box is immersed in LAr. With the module inside and the lid closed LAr is injected through the KF16 port. The cooldown phase takes about 90 minutes. This ensures gradients no larger than 100 K affect large surface XA components, such as the WLS plate, minimizing the risk of breaking due to differential contraction.

A transparent plastic cylinder is set up to avoid water condensation during warm-up (see Figure 23). The plastic tent is sealed to both the lid and the top of the dewar so that the amount of incoming air when opening the lid is minimized. The plastic tent is flushed with gas nitrogen (GN2) at all times to evacuate the air inside and to create a slight overpressure avoiding air inside the tent once the lid is opened. Once the temperature of the entire XA is above the dew point, the plastic tent is opened and lifted. XA is visually inspected, mainly to check for Vikuiti detachment, and a few pictures are taken.

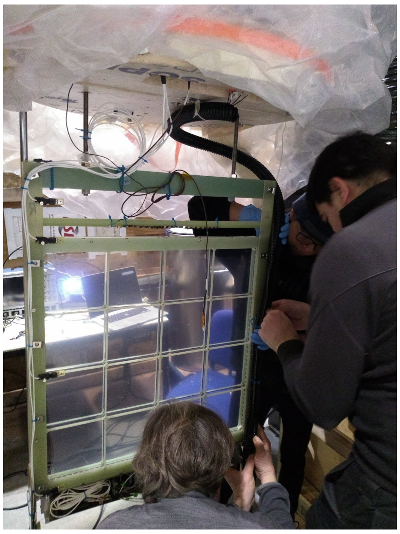


Figure 22. Cathode XA hanging from the dewar lid.

Figure 23. Left: plastic tent surrounding the XA with GN2 flashing. Right: plastic tent with XA displaced from dewar vertical to avoid cold gasses that would slow down the warmup process.

Membrane module tests

Membrane modules M1, M2, M3 and M4 share the electronics box between two modules. For this reason, the electronics box must be installed in the first module and tested in the cryogenics environment. After the warm-up, the electronics box must be removed to repeat the procedure with the second module. Both procedures must be completed using all four amplifiers connected to the board since removing one of the amplifiers drastically changes the behavior of the electronics.

After the cooldown, a power supply on the warm stage provides the indicated bias voltage. The first noise estimation of the signal is evaluated by making an FFT analysis (see figure 24-left). A second and more detailed study uses different bias voltages and estimations of the single PE shape.

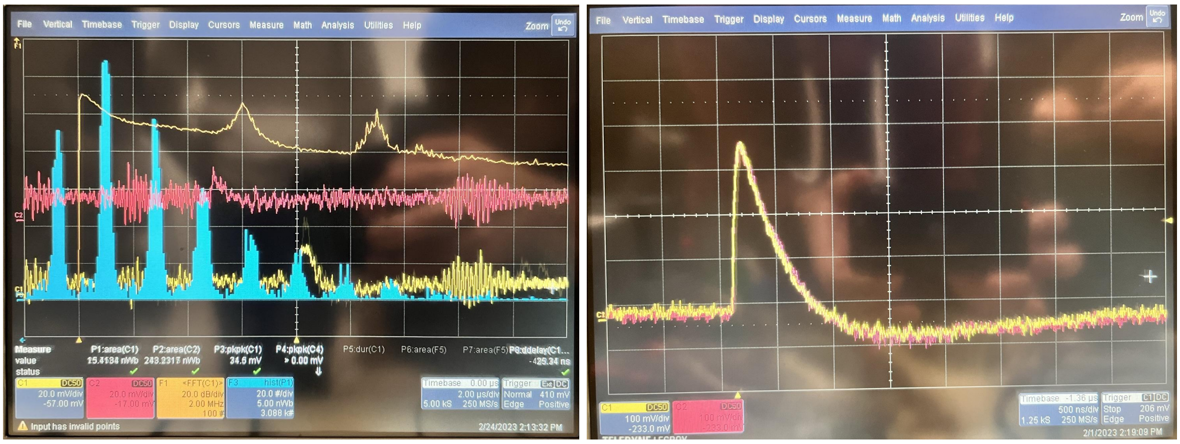


Figure 24. Left: FFT analysis and charge histogram of membrane modules. Right: Comparison between signals produced by cosmics in the two XA channels.

A final test is made without the LED light. The amplitude of the signals in both channels is compared. If the response to scintillation is similar, the test guarantees the value of the gain is the same (see figure 24-right).

A detailed analysis of the data collected for some of the modules is presented in Appendix 3.

Cathode module tests

The most challenging part of testing this technology is to guarantee the safety of the personnel involved in the tests. Cathode modules use PoF and Sof. Power over fiber can be especially dangerous considering that solving any issues require intervention on the fibers. The setup (see figure 25) consists of a mini rack hosting high-power (up to 1.5W) IR (808nm) lasers to bias the OPC and the Koheron receivers. The rack is fully light-shielded. Five fibers connect the mini-rack to the dewar. Three of them (PoF fibers) are dedicated to bring the power to bias the XA electronics in the dewar, and two fibers (SoF fibers) are dedicated to bring the signal from the XA readout channels to the Koheron receivers. Fibers are inserted into a robust plastic corrugated tube such that there is no exposed portion of fibers in the full path from the mini-rack to the dewar lid. This prevents fiber from being damaged during lid opening/closing operations and, at the same time, provides a second protection for personnel operating the setup. The fiber shielding implemented in the setup and the operation procedure defined, which establish to turn on the laser only when all the fibers are connected, makes the full setup a class 1 system for laser safety, despite the class 4 laser involved. The full setup fulfills the requirements of CERN for laser safety, and it passed a laser safety review.

Figure 25. Top-left: the high-power laser case, located inside the mini-rack. Top-right: general view of the dewar, the mini-rack and the corrugated black tube used to protect the fibers in its path from the mini-rack to the dewar lid. Bottom-left: Detail of the corrugated black tube entering in the mini-rack. Bottom-right: 3D printed box used as strain relief for fibers connected to the dewar lid FC-FC feedthrough, also serving a protection against laser light leakage.

Fibers have to be carefully installed. An accurate inspection of the tip of each fiber must be done using the microscope before any connection. New fibers and new FC-FC connectors should be used. Once the system is assembled, it should not be dismounted until the end of the tests. Fibers must be clearly distinguishable from each other, mainly to prevent any mismatching between SoF and PoF.

It was proven during the R&D phase that SoF lasers and PoF OPC are not stable in shallow LAr. The hydrostatic pressure plays a key role in the test results, being necessary at least 30 cm of LAr above the electronics box. While for membrane XAs, the electronics box could be at the top, for cathode XAs it is mandatory to have the box at the bottom.

Some of the setup components inside the dewar are shown in figure 26. Fibers are routed from the lid to the electronic box at the XA bottom. This path inserts fibers in the same black tube used in ProtoDUNE-VD (see sec). The electronic box is open, and fibers are connected to SoF lasers and PoF OPC. An inspection of the tip of each fiber must be done using the microscope and cleaned with the proper tools. The electronic board ground is checked (1MOhm from the electronic board to the electronic box), and the electronic box is grounded to the dewar lid. A LED on the X-Arapuca center provides a tunable light signal. A SiPM flex board (20SiPM) is installed close to the XA to monitor the PoF/SoF light leakage.

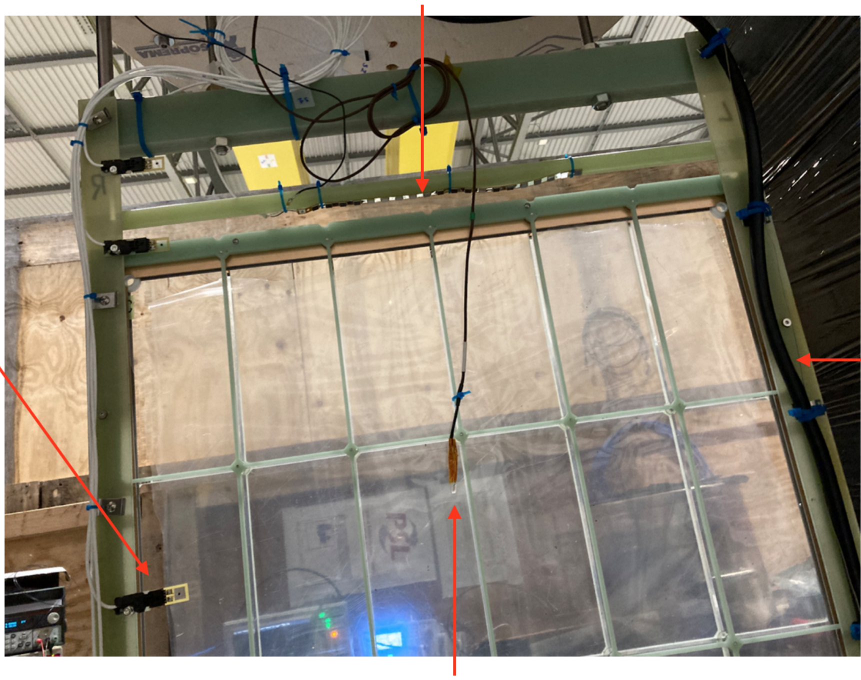


Figure 26. Fibers are routed to the XA bottom, where the electronic box is located. The dewar fiber is shielded inside with the same black tube used in ProtoDUNE-VD. A LED is placed in the center of the XA to provide a tunable light source. A SiPM flex board is placed close to the XA to monitor the PoF/SoF light leakage.

Holes were made in the electronic boxes to allow the LAr to circulate inside the box. On the other hand, this is inconvenient from the point of view of the light leakage from the PoF. For this reason, small covers were installed on top of those holes to allow the circulation of the LAr while avoiding leakage.

The electronics box was inspected before the modules were installed on the frame below the lid. We checked that the ground connection between DCEM and the electronics box is present and tight. To cool down and warm up might take half a day; ensuring the connections at this point is very important.

Testing the connection between the flexes and the main board is more difficult compared with HD technology. One way to test the continuity in a flex, for example, is to measure the voltage across the terminals of the flex. One should identify a voltage proportional to the incident light even without any bias voltage applied. Nevertheless, the response of the entire channel cannot be tested this way. Given the arrangement of SiPMs on the flexes and the connection of those in parallel to the board, only with one flex connected to the board, the tester will measure the same voltage as in the case of all SiPMs connected.

For this reason, a study comparing the charge per unit of time between channels is needed. This charge will be proportional to the number of flexes connected to a channel. For this test, only cosmics scintillation is used because, with the LED, it is very difficult to control the homogeneity of light between channels.

On the other hand, we saw many issues with the soldering of different components like capacitors or resistors. All boards were tuned, assembled, or refurbished at CERN. Particularly the resistors to control the feedback on the opamps can change the board's behavior dramatically, for example, if those are disconnected or present a wrong resistance value. A comparison between channels is necessary again. In this case, the baseline of the signal will give us information about the gain. To make a fair comparison, it´s necessary to read both channels with the same fiber and Koheron. In any case, the operator will have a slight difference, around 10 percent, between channels because the mere act of disconnecting and connecting the FC-FC connector will change the efficiency of the path. In any case, this methodology is very helpful in detecting hardware issues on the board.

In our case, it was very difficult to distinguish the noise from the setup from the one produced by issues on the assembly of the boards. The best approach to this issue was to decrease the setup's contribution to the signal's noise. We did this through techniques such as EM isolation of the setup and enhancing the grounding e scheme, among others. A useful tool for this purpose is calculating the FFT of both channels. The FFT has a very characteristic shape when environmental noises are below the desired threshold. Looking for these differences in all the modules was of great help in finding either the issue with the setup or the assembly of the electronics.

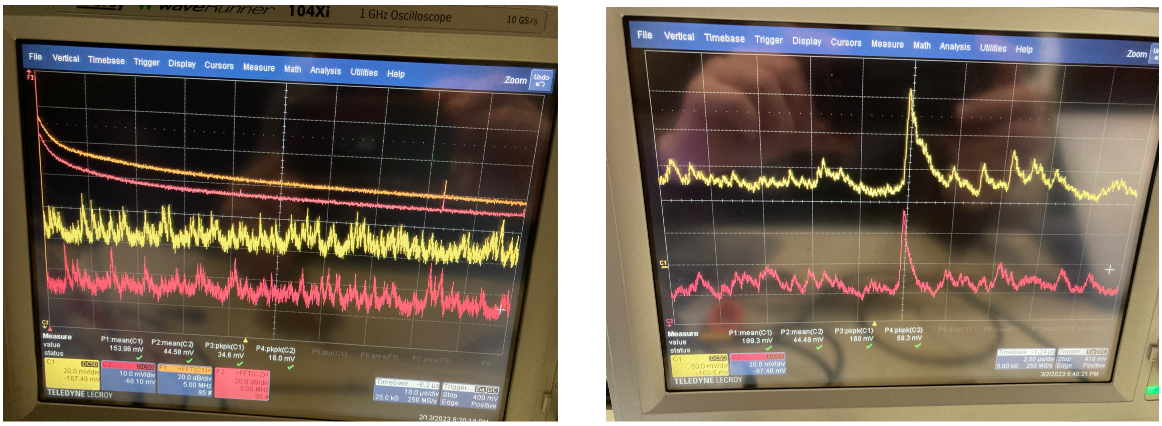


Figure 27. Typical FFT (left) and LED response (right) from a cathode XA with the biased SiPMs.

Studies about single photoelectrons could not be performed because of the light leakage on the dewar. The offset and power consumption are measured, registered, and compared to the previous tests with the electronic boards.

Lessons learned

The noise is highly dependent on the setup. The dewar and the warm side equipment must be electrically isolated from the floor and appropriately connected to an excellent common ground. The dewar must act as a Faraday cage preventing electromagnetic radiation; all holes on the LID must be shielded, grounded and light-tightened.

The connection of the ranger must be removed before the data taking, as well as any connections to sensors that aren't needed for the test, such as temperature sensors, cryogenic control, etc., to prevent any EM radiation from interfering with the test.

New fibers and new FC-FC connectors should be used instead of refurbished fibers. Once the system is assembled, it should not be dismounted until the end of the tests.

Light leakage is still present. Fiber shielding and electronic box tightness need to be improved.

Installation of membrane modules

In total, eight X-ARAPUCAs are installed in the membrane walls. 4 are placed at the top part of the membrane, at ~6 m height, and four at the bottom (at ~2 m height). The X-ARAPUCA modules are held by a pair of stainless steel suspension lines placed at ~10 cm from the membrane (see figure 28). Additionally, a stainless-steel mesh is placed in front of the module as protection against discharges. Given the time constraints the need for this shielding mesh was only realized a few months before its installation. A different design was used for upper and lower modules. Upper XAs used a heavy shielding mesh which needed a counterweight to keep the force balance avoiding bending of the vertical suspension lines. A better design, which will be used as baseline for FD2, was adopted for lower modules, which will be installed later.

The installation of the X-ARAPUCAs at the top required using a scissor lift and the participation of qualified personnel to work at heights. A dedicated procedure has been developed to install the X-ARAPUCAs safely, including the module preparation, the transport to the clean room, and the final placement in the suspension lines. The installation procedure is described in a dedicated document.

Installation of suspension lines

The suspension lines (see figure 28) were installed well before XA installation when the non-TCO CRP was the only detector element in the cryostat. The two lines in each pair are 68 cm apart and attached to two M10 bolts at the cryostat membrane's upper and lower horizontal corners (see figure 29-right). Each line is composed of three different sections, i) upper 5 mm diameter rod, ii) central 12/10 mm diameter tube, and iii) lower 5 mm diameter rod, all connected with shackles (nylon spacers are used to center the rod bars in the shackle), as shown in figure 29-left. Each rod has several wire rope grips (see figure 30-left) prepositioned to support the XAs. Each XA is supported by two wire rope grips on two parallel rods. Two nylon printed pieces isolate the XA support from the support lines (see figure 30-right).

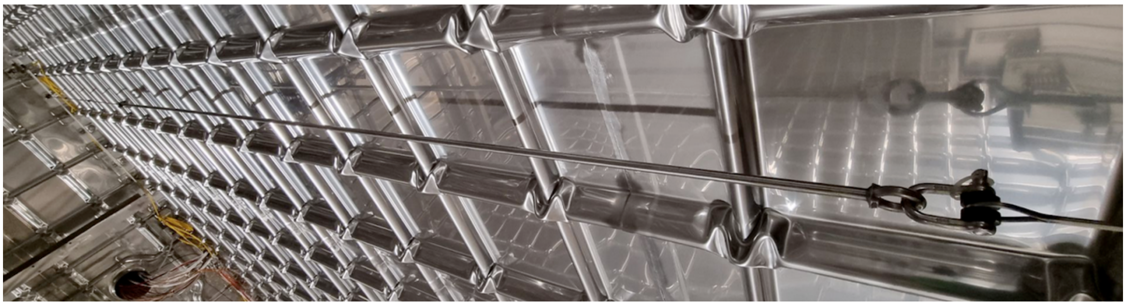


Figure 28. One of the two stainless steel suspension lines installed in each of the two short field cage walls.

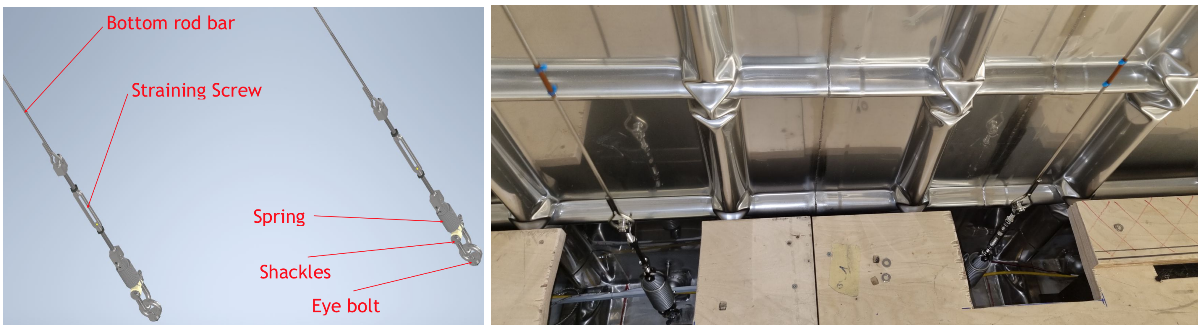


Figure 29. Left: 3D model of the lower section of the suspension lines, with an indication of the different components. Right: photograph of the non-TCO side suspension lines installed in ProtoDUNE-VD.

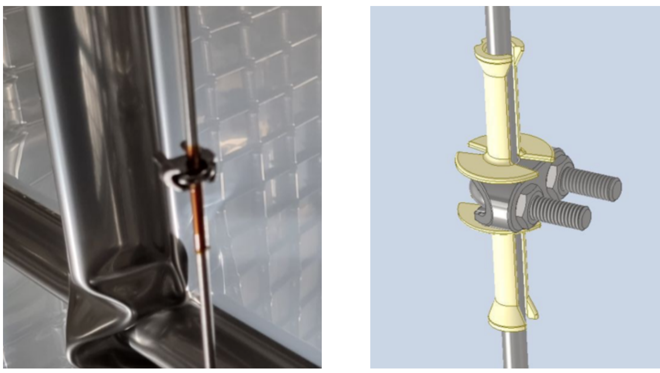


Figure 30. Left: wire rope grip used to support the XA. Right: 3D model with the detail of the nylon 3D printed piece used to isolate the module from the suspension line electrically.

Figure 31. Pre-assembled suspension lines folded in three different sections.

The suspension lines were pre-assembled, like a chain, at CIEMAT, packed, cleaned, and sent to CERN, ready to be mounted inside the ProtoDUNE-VD cryostat (see figure 31). Installation starts from the upper corner towards the bottom, anchoring the upper rod to the M10 bolt welded on the top cryostat membrane, as shown in figure 32-left. Once connected to the top, the line is unfolded. The length of the suspension line can be adjusted by a straining screw with a range of 75 mm. This facilitates anchoring to the M10 bolt at the bottom of the cryostat. The straining screw is also used to preload a force of 10-12 kg, corresponding to 30-40 mm spring traction.

Figure 32. Left: anchoring one of the suspension lines to the top of the cryostat. Right: the connection between the top and middle sections of the suspension line. The middle section has a larger diameter to reduce the electric field at the surface since this section is closer to the cathode.

Preparation in clean room

The membrane X-ARAPUCA modules are prepared in the clean room before installation. This process is different for upper and lower modules. The former has a single electronics box for a pair of modules, while the latter has individual electronics boxes. All connections inside the electronic box are established in the PDS room before installation (see figure 33).

To reduce the risk of damage during the installation, a dedicated frame was manufactured to transport those two modules from the PDS room to NP02 and position them in their final location at the suspension lines. Finally, during transportation, the modules must be covered so UV light does not deteriorate PTP. In summary, four steps are followed in the module preparation:

1. Cover the filters with black plastic to protect them from VUV light.
2. Install the hard protective cover as mechanical protection.
3. Install the metal holders (four per module, two on each side) that fix the module to the stainless steel lines; see figure 34-left. They include a scissor-like security closing tightened with a screw to attach it to the stainless-steel line.
4. Fixation of the modules on the installation support, shown in figure 34-right.

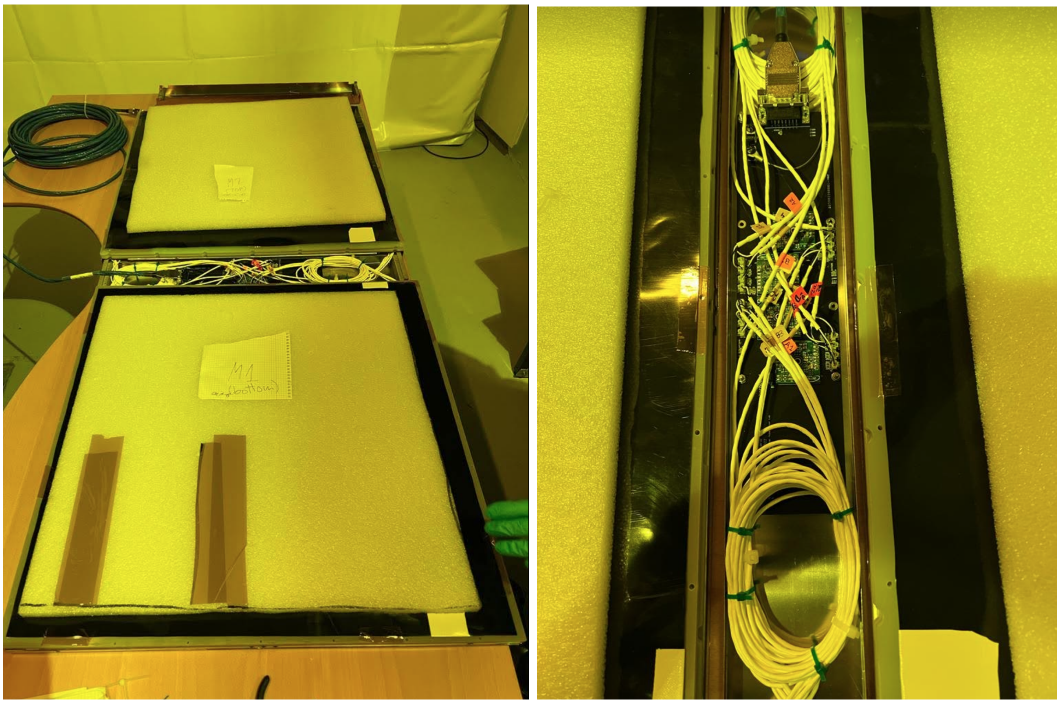


Figure 33. Left: two upper membrane XA with a common electronic box in the center before installation in the transport frame. Right: detail of electronic box connections.

Figure 34. Left: metal holder installed on the membrane X-ARAPUCA. It has a scissor-like security closing tightened with a screw to attach to the stainless-steel line. Right: transport and installation support frame for two membrane modules.

Finally, two people transported the X-ARAPUCA modules from the assembly room to the cryostat, while a third person assisted them in opening the doors, etc. The light lamp inside the cryostat was covered with the Kapton plane to protect the filters from the VUV light.

To be installed in April, lower membrane modules will follow a slightly different procedure. The transport frame will be slightly modified to transport one module at a time from the PDS room to the NP02 cryostat.

Installation of X-ARAPUCAS

Three elements were installed at each operation: the X-ARAPUCA modules, the shielding mesh and the counterweight (only for upper modules). All three elements rest on wire rope clamps on the stainless steel lines.

The lower XAs will be directly placed on the suspension lines by two operators since this position is suitable for direct installation (see figure 35-left). In comparison, the installation of upper XAs required two scissor lifts and at least three operators, one per scissor lift and another in the ground. In both cases, the XA module is placed first, then the counterweight, and the mesh at the end. The modules are placed on the vertical rods such that their weight is supported simultaneously by four metallic holders resting on wire rope clamps (see figure 35-right). The safety locks on each metallic holder are closed, and their corresponding screws are tightened.

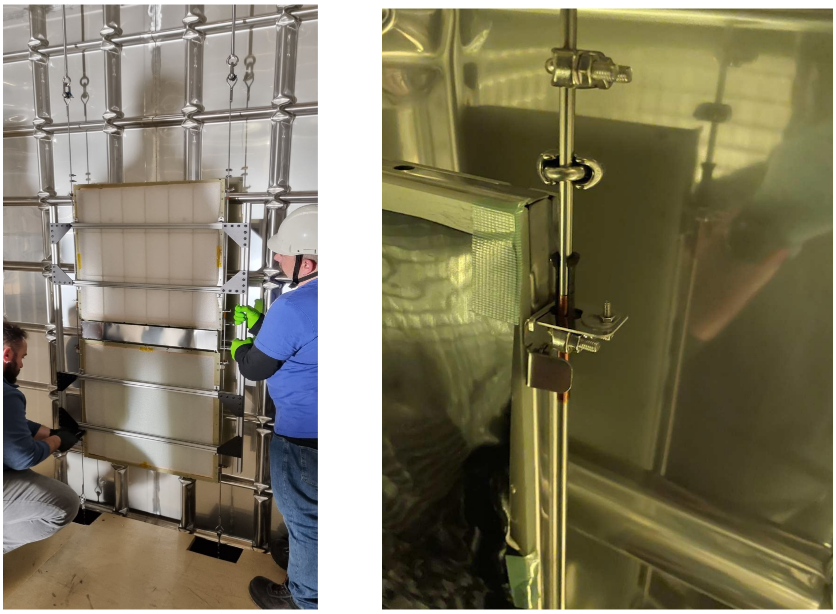


Figure 35. Left: Picture of the installation of the X-ARAPUCA modules in the bottom part of the membrane. Right: Detail of the metallic holders resting on the wire rope clamps.

In the case of the top X-ARAPUCA modules, this operation was performed at heights. Two scissors lifts were placed at the two sides of the vertical rods at a distance of around 0.75 meters from each other (see figure 36). When expanded, the cage of one of the scissor lifts was centered between the vertical rods. The other scissor lift did support the installation.

Figure 36. Picture of the two operators at the two scissor lifts during the installation.

The support frame was customized for this operation, adding a steel ledge to let the support frame lay directly on the scissor-lift cage (see figure 37-center). Also, an eyebolt was attached, and a safety rope was designed to secure the modules during the elevation. The purpose of the safety rope was to secure the element to be installed during the procedure. It always held redundancy, as the elements were permanently fixed by the ledge secured with cable ties or by the operators. A ratchet strap can tighten the safety rope (see figure 37-left). A picture of the safety rope is shown in figure 37-left). One end of the safety rope is directly attached to the support frame to be installed using a carabiner. The other end is either attached to the scissor lift when going up/down or to an anchoring point during the installation at the top. An eyebolt on the roof M10 bolt between the two vertical suspension lines. This was the anchor point used to secure the elements during the installation. Figure 37-right shows the support frame held by the safety rope in a dedicated test before installation.

Figure 37**.** Left: View of the safety rope. Center: Detail of the steel ledge added to the support frame. Right: The safety rope holding the support frame.

A picture of the top membrane module already in place during the installation is shown in figure 38. The left (right) panel shows the module before (after) removing the protections.

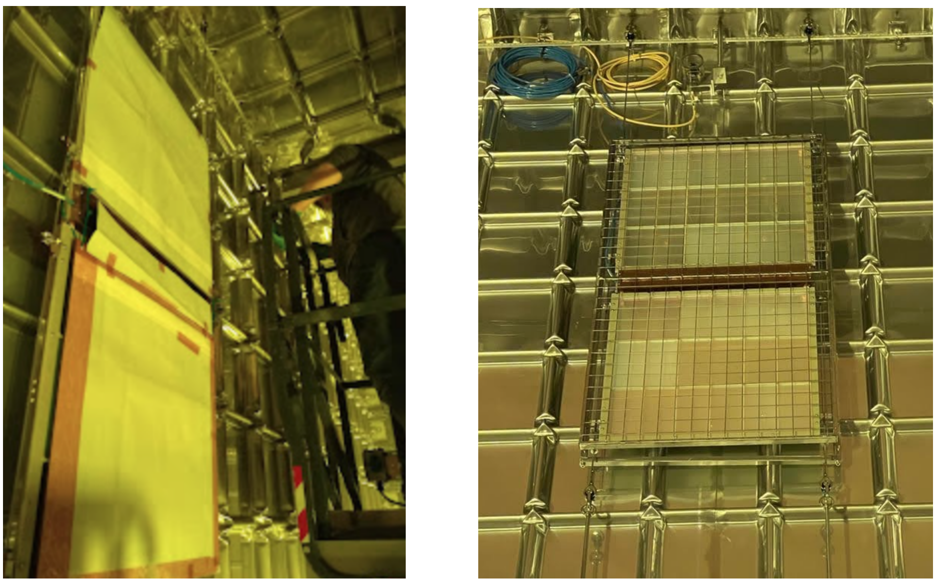


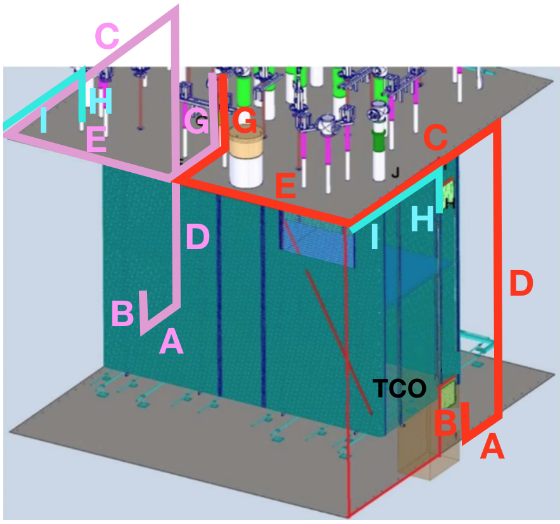
Figure 38. Pictures of the final layout of the top membrane X-ARAPUCA after the installation. Left (Right) shows the module with (without) the temporary protections.

Cable routing

Figure 39 shows the cable path for membrane XAs as well as the length of cables. The final cable lengths include 3 m of slack (length’).

Each of the two upper module pairs have a single cold cable exiting the electronics box between the two modules. The cable runs vertically behind the shielding mesh until it reaches the upper horizontal cryostat corner (see figure 38). From there it will be routed in cable trays towards the PDS cryostat port.

Lower modules have individual electronic boxes and cold cables. Although those XAs have not been yet installed, cables for non-TCO modules (27 m long) have been already deployed since the vertical cable tray (shared with the BDE) is behind the field cage wall and not easily accesible (pink section D in figureFigure 39-left). Cables for the TCO side (28.5 m long) can be deployed at a later stage since the corresponding cable tray is outside the field cage area and can be easily accessed (red section D in figureFigure 39-left).



	TCO-side		non-TCO side	
	bottom	top	bottom	top
A	1330		650	
B	1500		1500	
C	5680		5000	
D	7900		7900	
E	4200	4200	4200	4200
F	1600	1600	1600	1600
G	3300	3300	3300	3300
H		1400		1400
I		3800		3800
Length	**25510**	**14300**	**24150**	**14300**
Length’	**28500**	**16500**	**27000**	**16500**

Figure 39 Left: Cable path for membrane XAs. Right: Cable lengths with indication of each of the sections. The final cable length includes 2-3 m of slack (length’).

Lessons learned

The mesh and the XAs were electrically shorted after the installation due to the misalignment between the modules and the shielding mesh frame. As the supports of the XAs were conductive and the metallic frame was so close, this was a bridge bypassing the 1MOhm between GND and GND Mesh.

Insulating bits were required to guarantee electrical insulation for the non-TCO upper membrane modules. To address this G10 washers 2mm thick were installed between the module mechanical supports to avoid electrical connection. Insulating bits were designed and 3D printed for the TCO upper membrane module.

A larger distance between the metallic supports and the mesh frame is required.

Installation of cathode modules

Three elements were installed at each operation: the X-ARAPUCA modules, the mesh support brackets and the conductive mesh. Before the XA placement on the cathode, a set of supporting blocks must be installed on the cathode frame to support the modules.

Cathode preparation

XA modules are installed in the cathode using a 3-pin system as support. For this, G10 blocks are attached to the cathode supporting structure, as shown in figure 40.

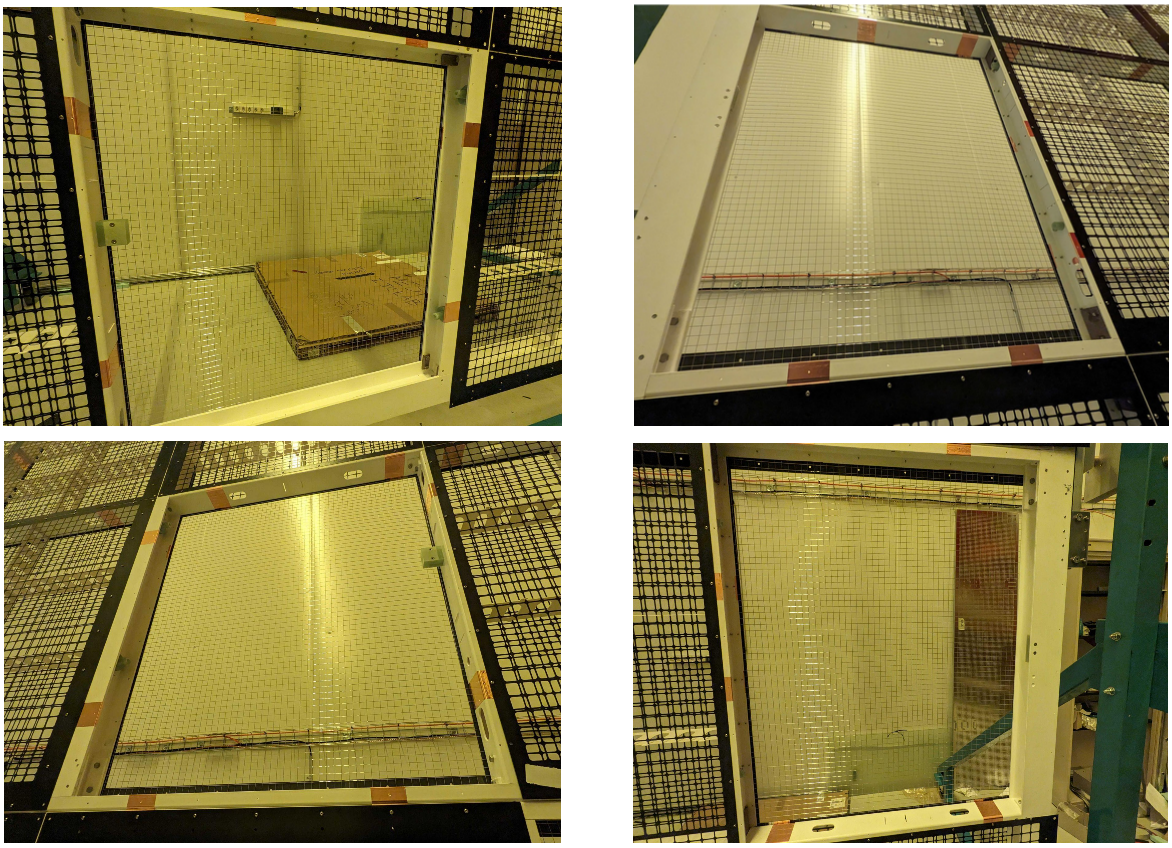


Figure 40. Cathode 2 supporting structure for all positions. The side with two pins (on the right for the top figures and the left for the bottom figures) has the same mechanism on all positions. The side with one support has a G10 block to be screwed to the cathode frame if it is attached to it (the pictures on the right), or a pin is used if the position is central (two pictures on the left).

Preparation in clean room

Cathode modules undergo a preparation in the clean tent similar to the one of membrane modules (see sec) regarding module protection and transportation. The main difference resides on the support pieces. A G10 block is mounted on the cathode modules that are attached directly to the cathode frame (see figure 41). For this, the single supporting pin is removed, and the 30 mm screws on the frame are replaced by 35 mm ones during the final module assembly procedure. The other modules are installed, each with 3 pins. The positions of the pins (1 on one side and two on the other) depend on the module position on the cathode, and this should be noted and adjusted prior to the shielding installation during module assembly.

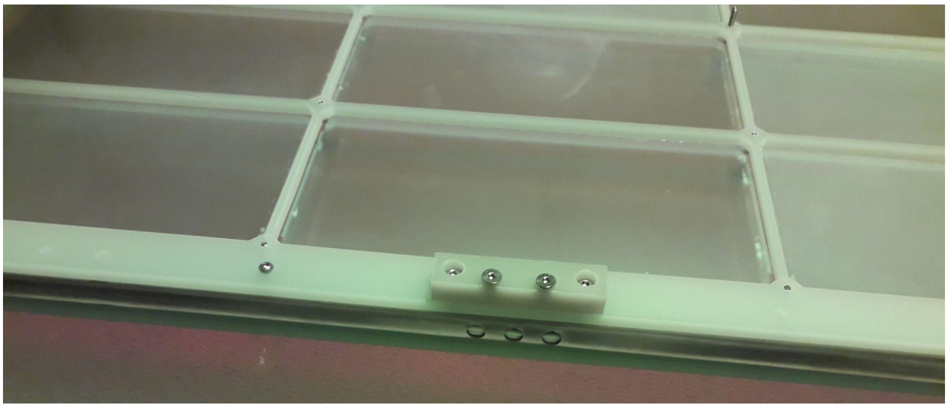


Figure 41. Detail of G10 block attached to cathode module C2. The two center holes are for cathode frame attachment.

Installation of X-ARAPUCAS

The membrane transport frame was slightly modified (see figure 42) to transport one module at a time from the PDS room to the NP04 cleanroom, where the cathode was standing in a vertical position on the so-called cart wall (see figure 43-left). Modules were covered with thick black plastic to avoid exposition to unfiltered light during transportation (see figure 43).

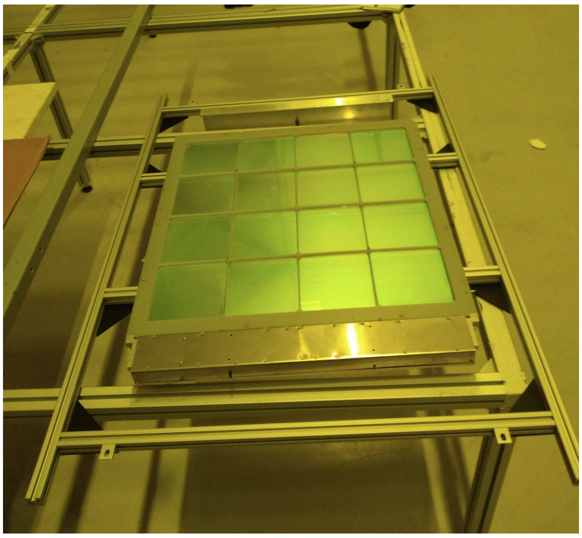


Figure 42: Cathode XA on transport frame

Once the XA is released from the transport frame, the installation on the cathode frame is quite straightforward. The two pins on one side need to be introduced into the supporting holes, and the other support needs to be screwed in place. If the module is to be attached to the cathode frame, a piece of G10 is already put into its frame. Otherwise, there is a two-piece G10 block: the front one has to be removed for the pin to be inserted and then screwed back in.

Figure 43: Installation of cathode modules with first cathode on cart wall

To finish the installation of the cathode modules, the mesh support brackets are mounted on each side using the four longer screws in the filter frames (see figure 44-left). After that, the conductive mesh is positioned and screwed on the cathode frame, with the mesh support brackets holding the mesh (see figure 44-right). The mesh on the front of the modules (where the electronic box opens) has to be removed and later put back in for the fiber installation.

With all modules installed in the cathode and protected with cardboard panels, the cathode was transferred to the cryostat (see figure 45).

Figure 44. Left: Placement of the mesh support brackets (4 per side per module). Right: the cathode module and conductive mesh are in position.

Figure 45. Left. All four cathode modules installed and protected with cardboard panels. Right: Inserting the first cathode on NP02 cryostat

Protection of modules

After the installation in the clean room, modules were protected on both sides with cardboard pieces that were attached to the cathode frame with zip ties (see figure 45-left). Those served a double purpose: they protected the filters from unfiltered light but also from eventual shocks of the modules with tools and transportation chains.

Another type of protective covers (thin black plastic) were used once finalized all operations in the cathode, and with the cathode inside the cryostat. Those were used to protect against dust and residual unfiltered light.

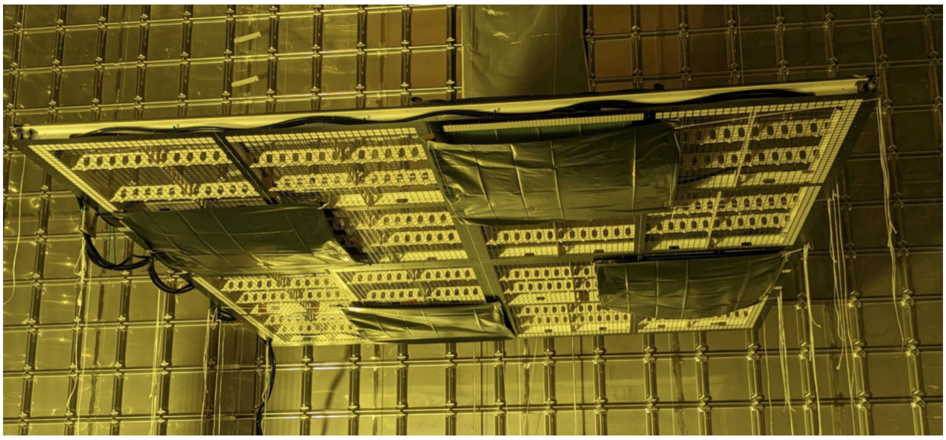


Figure 46. Final cathode XA protective covers

Routing and distribution of optical fibers in cathode frame

A total of 64 optical fibers (62.5µm core and 40 meters length) were installed along the cathode frame. The optical fibers were equally distributed in eight black PTFE tubes of 30 meters in length (8 PTFE tubes X 8 fibers per tube = 64 optical fibers). Figure 47 shows the diagram of the optical fiber assembly bundle of approach transition from 8 PTFE tubes to 4 PTFE tubes to help the fibers installation along the cathode frame.

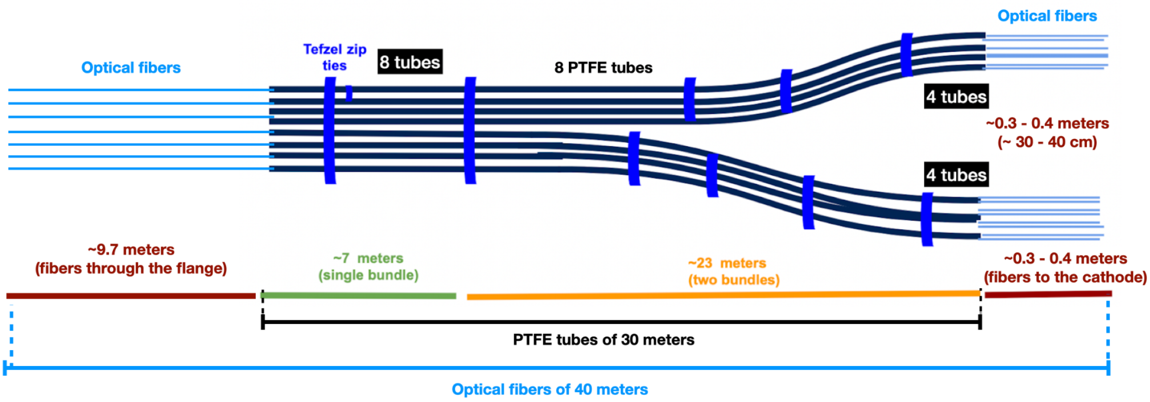


Figure 47. Optical fiber assembly bundle for PoF and SoF optical fibers.

The optical fibers were installed in two sections, the first four tubes were rotated along the non-TCO side cathode, and the second four tubes were rotated along the TCO side cathode. Figure 48 shows the tube's rotation path along the cathode (green lines). One PTFE tube per module was installed (each tube contains 8 optical fibers for Signal-over-Fiber (SoF), Power-over-Fiber (PoF), and spares).

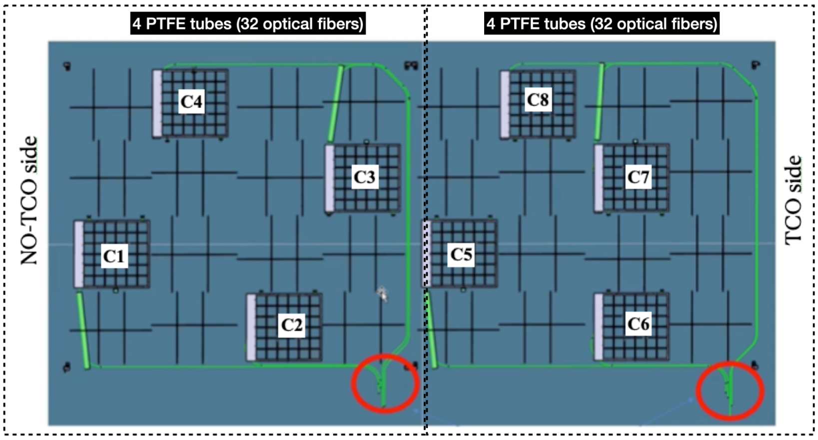


Figure 48. Distribution of XAs in the cathodes, with indication in green of the fiber tube path.

The cathode was placed at a height of 1 m from the floor to help with tube rotation (see Figure 49). Then, the optical fiber bundle was moved under the cathode (the floor was covered by plastic to protect the tubes from the dirt). Gloves were used at all times during the installation.

Figure 49. Fiber bundle moved under the cathode. The cathode was placed at ~1m working high for tube routing.

A black PET mesh covered the optical fibers connected to modules (~30-40cm) to keep them together and protected during tube routing (see figure 50). After the tube is rotated along the cathode and reaches the module's electronic box. The PTFE tube was secured by the holder located inside the electronic box (see figure 50).

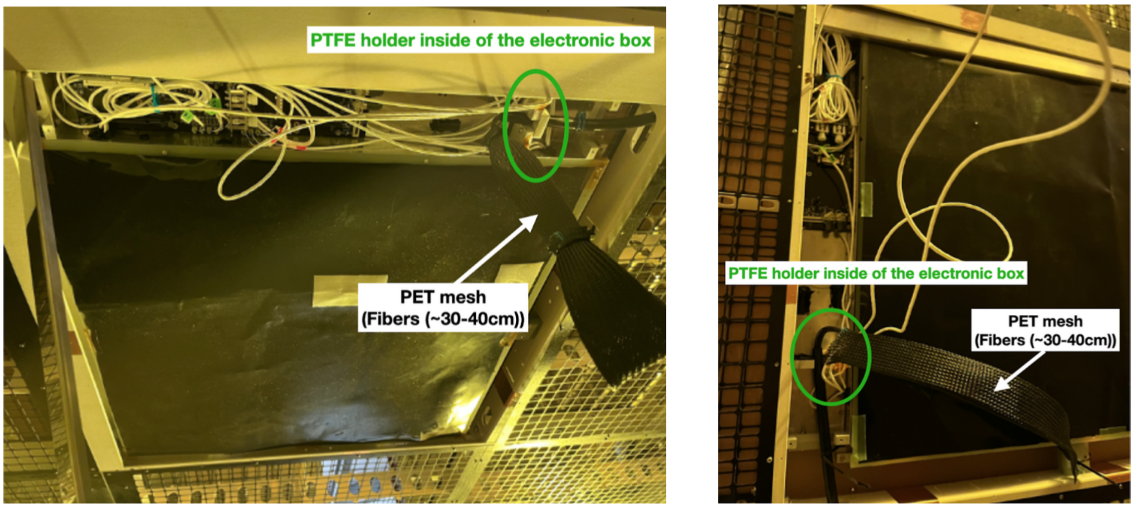


Figure 50. Example of one PTFE tube secured in the module's electronic box.

As shown in figure 51, the tubes were dressed and secured with tefzel zip ties along the cathode frame using the available holes in the cathode frame. Some parts of the fiber bundle were secured to a G10 clapping plate (see figure 51-bottom-right)

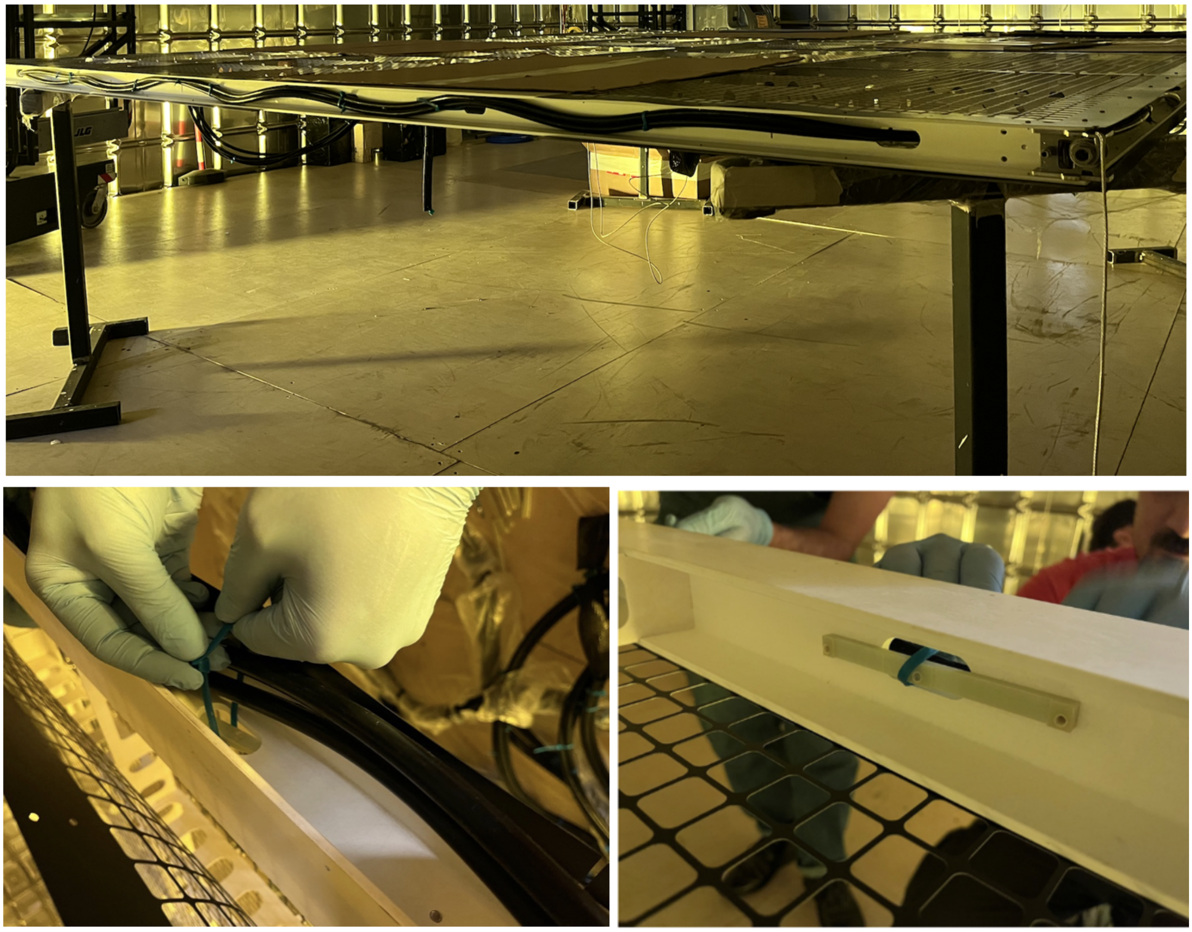


Figure 51. Optical fiber bundle dressing to the edge of the cathode using tefzel zip ties and an example of secured points where G10 clamping plates were used (bottom-right).

The two sets of 4 tubes were rotated directly under the fiber support hanging off the cathode, these are the fiber bundle exit points from the cathode and were secured by tefzel zip ties (see figure 52).

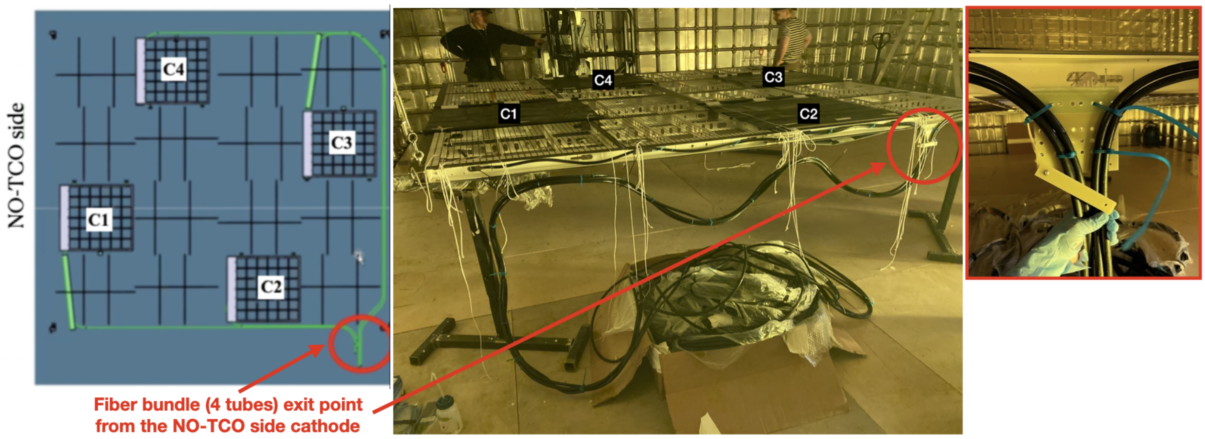


Figure 52. Optical fiber bundle (4 tubes) rotating mapping for four module locations including fiber route exit point from the NO-TCO side cathode.

Table 3 shows the optical fiber taggings specifying the tube ID and the fibers ID (SoF, PoF or spares). Green tags correspond to the SoF fibers, white tags correspond to PoF fibers and red tags correspond to spare fibers.

	Cathode (NO-TCO side)				Cathode (TCO side)			
Tubes Number	T1	T2	T3	T4	T5	T6	T7	T8
Tagging	SoF(T1-F1)	SoF(T2-F1)	SoF(T3-F1)	SoF(T4-F1)	SoF(T5-F1)	SoF(T6-F1)	SoF(T7-F1)	SoF(T8-F1)
	SoF(T1-F2)	SoF(T2-F2)	SoF(T3-F2)	SoF(T4-F2)	SoF(T5-F2)	SoF(T6-F2)	SoF(T7-F2)	SoF(T8-F2)
	PoF(T1-F3)	PoF(T2-F3)	PoF(T3-F3)	PoF(T4-F3)	PoF(T5-F3)	PoF(T6-F3)	PoF(T7-F3)	PoF(T8-F3)
	PoF(T1-F4)	PoF(T2-F4)	PoF(T3-F3)	PoF(T4-F4)	PoF(T5-F4)	PoF(T6-F4)	PoF(T7-F4)	PoF(T8-F4)
	S(SoF-T1-F5)	S(SoF-T2-F5)	S(SoF-T3-F5)	S(SoF-T4-F5)	PoF(T5-F5)	PoF(T6-F5)	PoF(T7-F5)	PoF(T8-F5)
	S(SoF-T1-F6)	S(SoF-T2-F6)	S(SoF-T3-F6)	S(SoF-T4-F6)	S(SoF-T5-F6)	S(SoF-T6-F6)	S(SoF-T7-F6)	S(SoF-T8-F6)
	S(PoF-T1-F7)	S(PoF-T2-F7)	S(PoF-T3-F7)	S(PoF-T4-F7)	S(PoF-T5-F7)	S(PoF-T6-F7)	S(PoF-T7-F7)	S(PoF-T8-F7)
	S(PoF-T1-F8)	S(PoF-T2-F8)	S(PoF-T3-F8)	S(PoF-T4-F8)	S(PoF-T5-F8)	S(PoF-T6-F8)	S(PoF-T7-F8)	S(PoF-T8-F8)
Module to be inslated	C1	C2	C3	C4	C5	C6	C7	C8

Table 3. Tagging used by tubes and fibers in the cathode.

Once the tubes were dressed along the cathode and secured in the PTFE holders located inside of the module's electronic box, the fiber's ends (PoF and SoF) were connected to the OPCs (Figure 53 shows the fibers connections for module C1, T1->C1). Once the PoF fibers were connected to the OPCs in the DCEM board, the connection between fiber end and OPCs were epoxied with black silicone. Table 3 summarizes the mapping of the optical fibers used in SoF and PoF for each DCEM motherboard. Modules C1, C2, C3, C4, C5 and C6 used two 2 SoF and 2 PoF. Modules C7 and C8 used 2 SoF and 3 PoF.

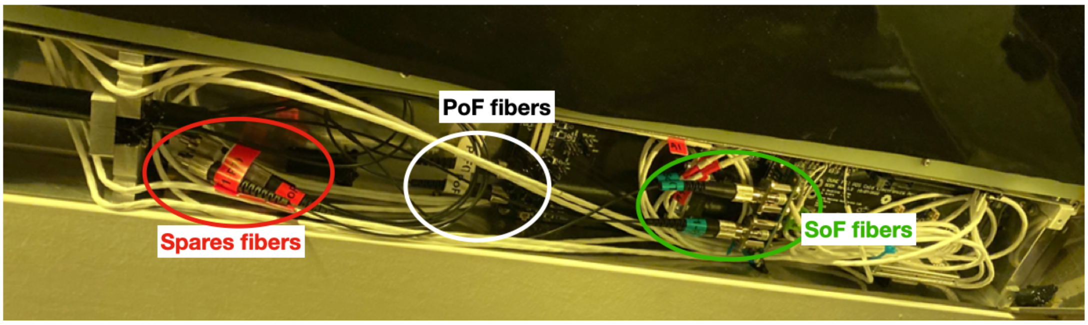


Figure 53. Fiber’s end connection to the DCEM motherboard.

Lessons learned

Problem with installation in some of the cathode positions

Because of the electronic box, modules need first to be taken high up inside the cathode void to then be positioned in place. Removing the electronics box lid and temporarily removing the screws that join the 2pc support arms, fixation of the module, and further closing the box and reintroduction of the screws are needed for some positions to allow installation (see figure 54).

One thing to be noted is that the single pin on one of the module’s sides is located at the same height as the center of mass of the module without the electronic box. It may be desirable to include extra support attached to the frame for the electronic box to prevent bending of the module or consider to move to a 4-point support as in the membrane detectors.

Figure 54. Removal of electronic box lid for installation of C2.

Fiber's length connected to the DCEM motherboards within the electronic box.

When we connected the optical fibers to the DCEM motherboards, we noticed that ~30-40cm fiber length (see Figure 44) was a bit long to fix connections inside the DCEM electronic box. For the optical fiber bundle assembly for DUNE FD2, we will leave ~15cm instead of ~30-40 cm.

Anchor points along the cathode frame.

The tube's routing was secured with tefzel zip ties along the cathode. Available holes were used to pass through the zip ties, however the holes were not designed to satisfy this task. There were some sections along the cathode frame where it was necessary to use G10 clamping plates to secure the tubes. It would be convenient to design dedicated holes along the cathode frame to secure the tubes using zip ties.

Helix shape of the PTFE tubes (tube's shape).

During the assembly and shipment of the optical fiber bundle to CERN (tubes were packaged in a box), the PTFE tubes acquired a helix shape. The helix shape makes the tube manipulation difficult during the installation processes (routing, moving, and sections where the tubes need to be straight). SDSMT lab has shown that an option to put the tubes straight is using the heating gun without damaging the fibers (a transparency test was done before and after straightening the tube). In addition, to reduce the helix shape it could be done by transporting the optical fiber bundle in boxes with larger areas.

Installation of response monitoring system

ProtoDUNE-VD incorporates a pulsed UV-light system to calibrate and monitor the photon detector's response over time. The calibration system produces UV light flashes with variable pulse amplitude, width, repetition rate, and duration. The calibration data recorded by the PDS will be used to characterize and calibrate the photon detector's gain, crosstalk, time resolution, channel-to-channel timing, and PDS stability over time. Examples of potential time instabilities to be monitored include the dissolution of PTP coatings over time or drift in the power of the readout electronics lasers.

The system design, which has both warm and cold components, is the same as the one foreseen for FD2. Fibers with bare fiber-end points or with a small diffuse element at the fiber end are mounted on the beams that support the field cage at the top and the bottom of the cryostat. These fibers transport light from the optical feedthrough (at the cryostat top) to the bare fiber-end points. Warm components of the system include electronics boards with controlled pulsed-UV sources (275 nm and 367 nm) and warm optics.

Installation of cold components

Inside the cryostat, four monitoring-system kits are installed (see figure 56 and figure 55):

1. one at the center of the field cage top beam in the side opposite of the TCO.
2. one at the center of the field cage top beam on the TCO side.
3. one at the center of the field cage bottom beam in the side opposite of the TCO.
4. one at the center of the field cage bottom beam on the TCO side.

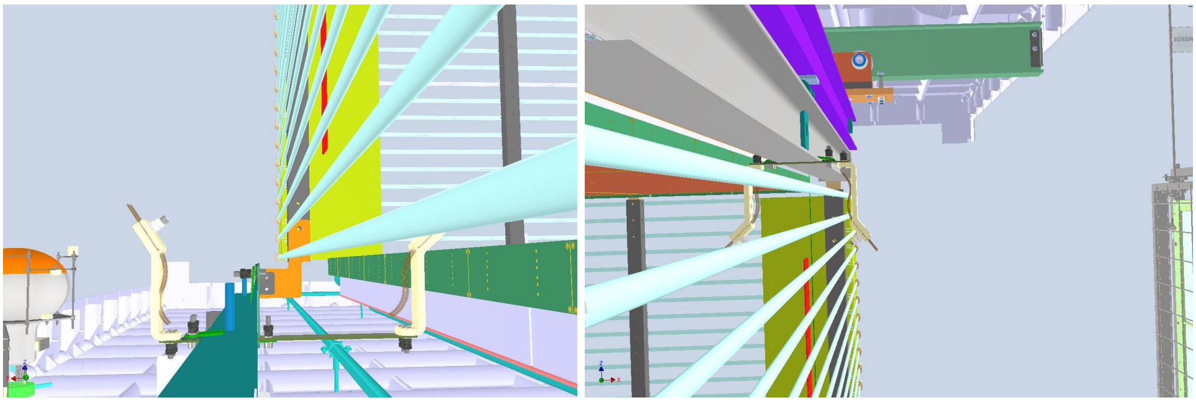


Figure 55. Monitoring system kits at the field cage's bottom (left) and top (right).

The following fibers are installed on each of the monitoring-system kits:

1. 1-to-2 fiber bundle (16-m Thorlabs FG200AEA) with bare ends where one fiber endpoints at the cathode X-ARAPUCAs and the other end points towards the top membrane X-ARAPUCAs placed on the side opposite to the TCO; and one alternative fiber (17-m Polimicro FVP600660710 600um core) with a diffuser pointing towards the cathode X-ARAPUCAs.
2. 1-to-2 fiber bundle (16-m Thorlabs FG200AEA) with bare ends where one fiber endpoints at the cathode X-ARAPUCAs and the other end points towards the top membrane X-ARAPUCAs placed on the TCO side; and one alternative fiber (17-m Polimicro FVP600660710 600um core) with bare-end pointing towards the cathode X-ARAPUCAs.
3. A 22-m long fiber (Thorlabs FG400AEA 400um core) attached with a vacuum-compatible SMA connector to a 1-to-2 fiber bundle (Thorlabs FG200AEA) of 2 m with bare ends where one endpoint at the cathode X-ARAPUCAs and the other end points towards the bottom membrane X-ARAPUCAs placed on the side opposite to the TCO.
4. A 22-m long alternative fiber (Polimicro FVP600660710 600um core) attached with a vacuum compatible SMA connector to a 1-to-2 fiber bundle (Thorlabs FG200AEA) of 2 m with bare ends where one endpoint at the cathode X-ARAPUCAs and the other end points towards the bottom membrane X-ARAPUCAs placed on the side opposite to the TCO.

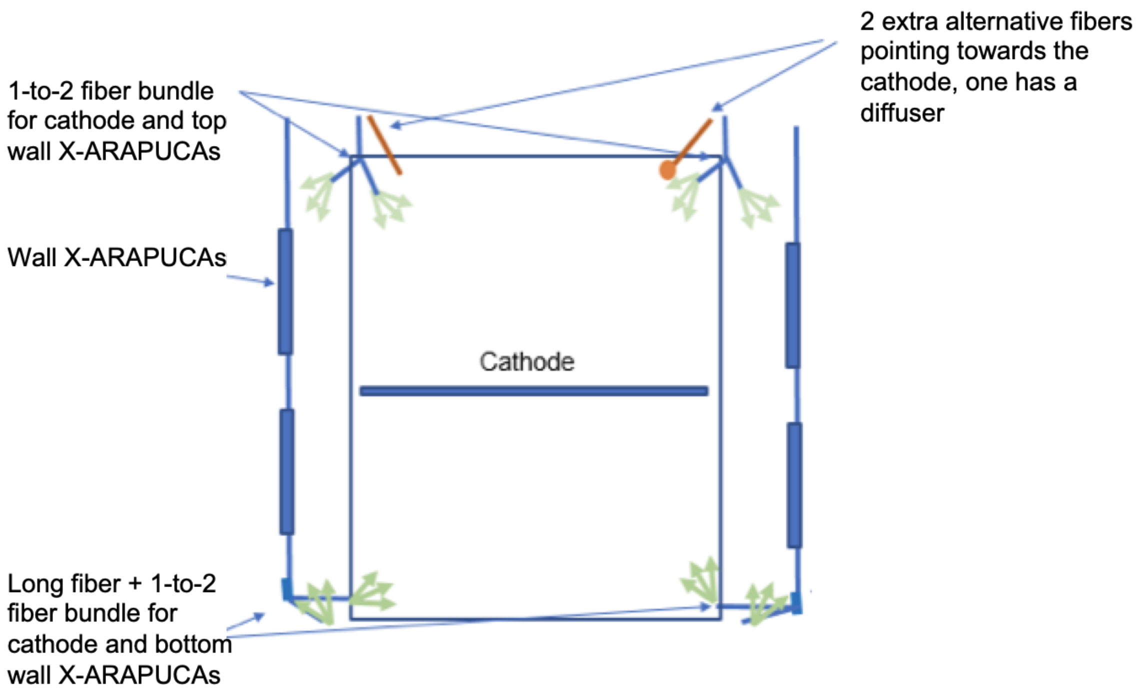


Figure 56. Diagram of the monitoring fibers installed in ProtoDUNE-VD.

The procedure for the installation of the top fibers is as follows:

- Installation of the monitoring system kit on the beam that supports the field cage: fiber bundle with one fiber pointing towards the cathode and another towards the wall; and alternative fiber pointing towards the cathode (see figure 57-left).
- The beam is raised to the top, and the fibers are placed in the final configuration.
- Checked that light from all three fibers can be seen turning on the LED (see figure 57-right)
- Left cables routed at the beam edge to be routed.
- Routing cables towards the flange.

Similarly, for installation of the bottom fibers:

- Installation of the monitoring system kit on the beam: fiber bundle with one fiber pointing toward the cathode and another toward the wall.
- Routing cables towards the flange.
- Checked that light from the two fibers can be seen turning on the LED at the flange connector.

Figure 57. Left: picture of the monitoring system kit being installed at the top beam. Right: picture of the fiber pointing towards the cathode X-ARAPUCAs being tested (blue point below the CRP).

Plans for installation of warm components

The warm components of the PDS calibration and monitoring system include optical feedthroughs, optical fibers that connect optical feedthrough with the calibration light source, and the calibration electronics board that serves as the light source and provides interfaces to trigger/DAQ components of the ProtoDUNE-VD.

Electronics Calibration Module

At this point we have concluded additional R&D, following the successful operation in ProtoDUNE-SP-I, with a value engineering and fabricated the full system for operation and data collection in ProtoDUNE-SP, phase II (or ProtoDUNE-HD). The electronics calibration board (Calibration Module) is built with 12 optical output channels (see figure 58) and integrated with the ProtoDUNE DAQ and timing systems at CERN (see figure 59) to enable the operation and triggering in ProtoDUNE-SP-2 run.

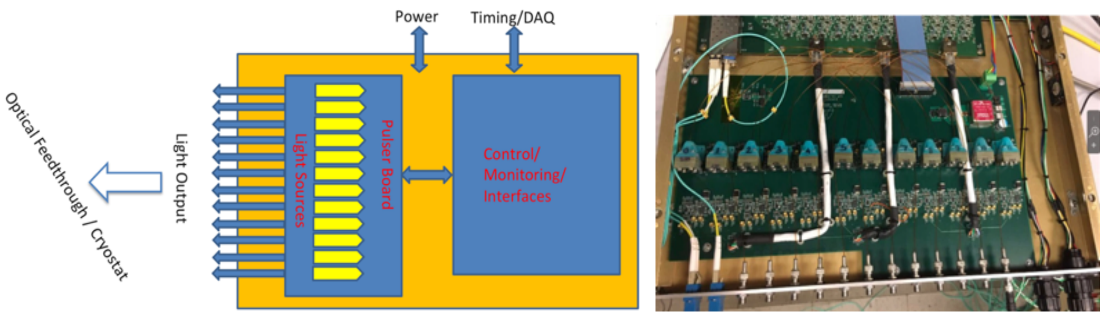


Figure 58. Left: Calibration Electronic Module schematics (control board with power and timing/DAQ interfaces; pulser board with light sources and light output interface). Right: physical realization of the module for ProtoDUNE-SP-II at Argonne test stand.

FigureFigure 59. Left: ProtoDUNE-SP-II Cryostat at CERN with electronic racks at the top. Middle and right: PDS electronics calibration modules (5-channel prototype module and 12-channel module for ProtoDUNE-SP-II) tested and integrated with timing and DAQ system at CERN.

Based on the above expertise we proceed to build the electronics module for ProtoDUNE-VD operation, with 12 UV-light calibration channels (six channels with 275 nm LEDS, and six channels with 367 nm LEDs). At this point we procured components for the electronics calibration module and will build, test, integrate the module locally at Argonne National lab, and then ship to CERN for installation, integration, and operations with ProtoDUNE-VD.

Warm Fibers

We will ship six sets of polymicro quartz fiber cables, each with SMA connectors on both ends, and with fiber protected in a teflon jacket. Figure 58 (left) shows the warm fiber piece.

Optical feedthroughs

Optical feedthrough fits the PDS flange (shown in the next section). We shipped the five-channel optical feedthrough from the US (shown in figure 60, right). This optical feedthrough fits to one of three available PDS flange CF40 ports for the monitoring fibers. Another optical feedthrough was shipped from CIEMAT, also fitting to the CF40 port.

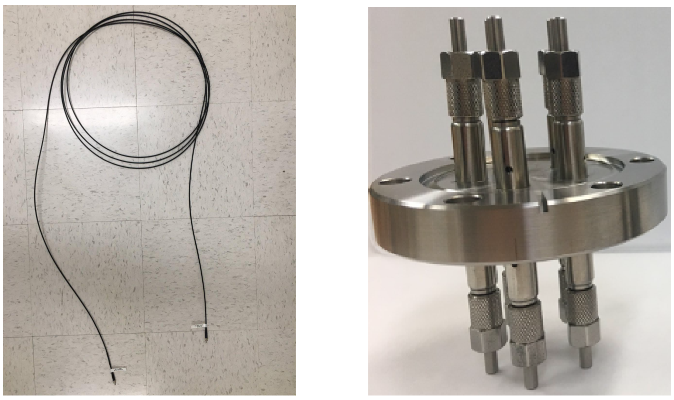


Figure 60. Left: Warm Optical Fiber. Right: Optical feedthrough units for ProtoDUNE. The feedthrough is attached to the optical flange to transport UV light from the Calibration Module to the diffuse fiber ends, via the optical fiber system.

Installation Procedure

Once the PDS flange is installed, the cold fibers will be pulled up and attached to the bottom SMA connectors of the optical feedthrough by use of SMA-to-SMA connectors. Warm fibers will be routed from the optical feedthrough to the calibration module back-end. The feedthrough side of the warm fibers is attached, via SMS-to-SMA connectors, to the upper end of the optical feedthrough. The other end of the warm fibers is easily screwed into the calibration module back-end.

The calibration module will be installed at the top of ProtoDUNE-VD cryostat in the fall of 2023. The calibration module is a self-contained 1U size electronic module that fits an existing rack at the ProtoDUNE-VD. Cables for module power and light source bias will be attached at the module backend and routed to Wiener power supplies.

Lessons learned

The person installing the fibers in the monitoring system kit must be careful to place them in the right position as they can move when the bolts are tight and the pointing direction of the fibers could change.

It was also noticed that the optical feedthrough installation needs SMS-to-SMA connectors additionally rounded up to fit within the feedthrough space provided in the PDS flange.

Plans for flange Installation

All PDS cables/fibers will be extracted from the cryostat using the same port, which is shared with the bottom drift electronics (BDE), see figure 61-left. A T-shaped tube will be used to allow the installation of PDS and BDE cables and fibers, being assigned the top opening to the PDS. In order to facilitate the process of inserting the PTFE tubes (see Sec. Routing and distribution of optical fibers in cathode frame), and their coexistence with BDE cables, a 7'' stainless steel tube (the "septum") runs down the chimney and connects the PDS flange with the cryostat interior.

The PDS flange has three main sets of elements (see figure 61-right):

- A conical 3'' to 7'' adaptor for a flange with 8 ports to extract SoF and PoF fibers
- 3 CF40 ports, two for the monitoring fibers and one for SoF on a membrane module
- 8 DSUB-15 connectors for membrane XAs

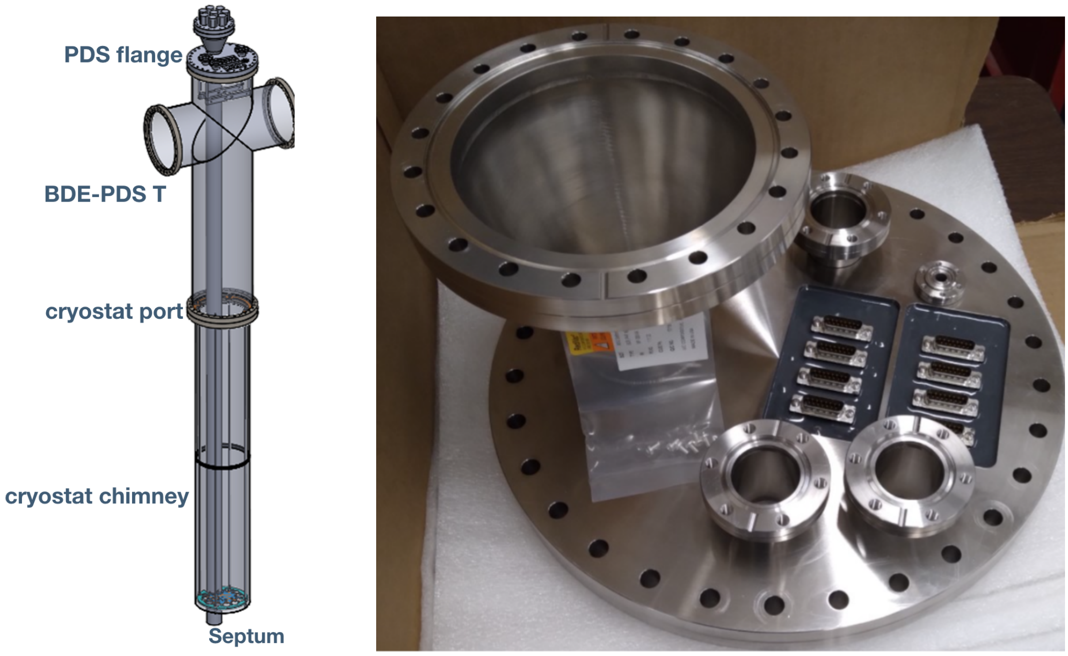


Figure 61. Left: elements on the cryostat port assigned to the PDS. Right: PDS flange for ProtoDUNE-VD.

Installation of the flange and all associated hardware is foreseen for mid-May, after installation of the last bottom CRP. This operation comprises three different phases, described below.

The first phase begins with the septum preparation and includes routing the 8 PTFE tubes inside the septum. This operation will be performed on the cryostat floor (or temporary floor). The BDE strain relief, visible at the bottom of figure 61-left, should be available at that moment, what requires coordination with BDE consortium. With the 8-tube bundle inside, the septum will be lifted on the scissor lift towards the cryostat port. A cord, attached to the flange side of the septum, will be used to pull-up the septum through the chimeney. The septum will be temporarily holded on top of the cryostat port by a special piece, as the one shown in figure 62-left.

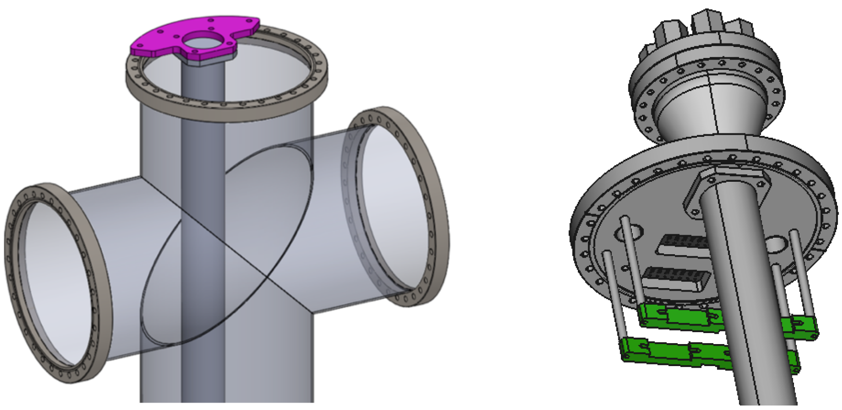


Figure 62. Left: In pink, temporary support for septum. Right: Septum connected to the flange. Green elements are the cables/fibers strain reliefs.

In the second phase, all BDE cables, PDS RMS fibers, membrane SoF fibers (for M5) and PDS HD-style cold cables will be pulled up simultaneously and routed towards the appropriate port on the T.

In the third phase, the flange is positioned on top of the cryostat port at a distance of about 50 cm, holded by a tripod which. The copper gasket is installed at that point. Once all connections are carefully established, the septum can be released from its temporary support, lifted towards the flange and connected by four M8 bolts. Finally the flange is lowered using the winch and closed with M8 bolts.

Plans for warm electronics (DAPHNE)

For both cathode-mounted and membrane-mounted XA modules, the output of the cold PDS electronics will be digitized using “DAPHNE” modules developed to read out the FD1 XA modules.

DAPHNE was designed to digitize and read out signals from the 40 “supercell” channels of the 10 XA modules associated with each FD1 Anode Plane Assembly. DAPHNE also provides the SiPM bias voltages and power for the FD1 PDS cold electronics. The differential inputs to DAPHNE are AC coupled. This allows the SiPM bias voltages to be carried on the same pair of wires as is used for the supercell signals. A coarse adjustment to the SiPM bias voltage can be made for groups of 8 signals. A fine adjustment (0-4V) can be made for each channel. DAPHNE provides the means to measure the bias current drawn by any of the 40 supercells.

DAPHNE is organized into five groups of eight channels. Eight-channel Texas Instruments AFE5808A ultrasound “analog front end” ICs are used to digitize the signals. On DAPHNE, the AFE5808A provides 14-bit digitization at 62.5 MSPS. The combination of two amplifiers and a voltage-controlled attenuator in the AFE5808A allows a wide range of input voltages to be matched to the dynamic range of the analog-to-digital converter (ADC).

Prototype DAPHNE modules used a microcontroller to program the AFE5808As and to control the various DACs and multiplexers used for functions such as setting SiPM bias voltages and monitoring currents. A Xilinx Artix field programmable gate array (FPGA) processed the ADC data and output data to the DUNE DAQ Front-End Link eXchange (FELIX) modules using 4.8 Gbps optical links.

In response to the decision to use 10/100 Gigabit Ethernet switches and network interface cards rather than FELIX modules in the DUNE DAQ readout modules, a revised version of DAPHNE that will be capable of 10 Gigabit Ethernet output is being developed. The analog portion of the new version will be almost identical to the current DAPHNE, but the microcontroller and the Artix FPGA will be replaced by a Zynq ultrascale+ SoC (implemented using a Kria K26 module produced by Xilinx). The development of the revised DAPHNE is expected to be complete by the end of 2023. A version of DAPHNE that provides for the conversion of optical signals from cathode-mounted XA modules will be developed for use in DUNE FD2.

For ProtoDUNE-VD, signals from cathode-mounted XA modules will be converted from optical to electrical signals using commercial “Koheron” boards consisting of a photodiode coupled to a transimpedance amplifier. If ProtoDUNE-VD runs in 2023, the existing version of DAPHNE will be used (with FELIX readout). If ProtoDUNE-VD runs in 2024, the final version of DAPHNE will be used (with GbE readout) and, if available, also with integrated optical to electrical signal conversion.

Installation of warm components

The power over fiber laser modules will be located in a dedicated powered mini-rack placed close to the PDS flange. This rack will have safety interlocks and access control. The DAPHNE modules and the modules that convert optical signals to electrical signals will be located in an unpowered mini-rack also placed close to the PDS flange. Power for the DAPHNEs and the optical receivers will be provided by MPOD low voltage modules located in a nearby rack. For membrane-mounted XAs, the same 5m long cables as are used for ProtoDUNE-II HD will be used between the PDS flange and DAPHNE.

Plans for full chain validation

Before the TCO of the NP02 cryostat is welded closed, each of the XA modules will be read out to ensure that all cable connections have been made correctly. This is not completely trivial for the cathode-mounted modules because both the SiPMs and the laser diodes used in the signal path require different bias at room temperature than at liquid argon temperature. Negative temperature coefficient (NTC) resistors which function as open switches in liquid argon are used in the cold electronics modules to provide the required higher SiPM bias voltage and larger laser driver baseline current at room temperature.

In DUNE, DAPHNE is intended to operate in “self-triggered mode” in which trigger logic in DAPHNE determines when to read out waveform data. This mode of operation has not yet been fully validated. The number of PDS channels in ProtoDUNE-VD is small enough that DAPHNE can and at least initially will operate in “streaming” mode. In this mode all waveform data will be read out. This will allow trigger algorithms to be validated using real data as well as simulated data before DAPHNE is operated in self-triggered mode.

Schedule

Figure 63 shows the ProtoDUNE-VD assembly, testing and installation schedule, with its bulk in February and March. The testing setup was assembled in December and commissioned in January. A test assembly for the first X-ARAPUCA was done the third week of December, but that XA was disassembled and assembled again in January, to resolve some minor problems. The second module was assembled the last week of January. Although some initial testing was done for both modules, they were tested again with better understanding of the testing setup right before installation of the dichroic filters and final installation on the cryostat. Those two non-TCO upper membrane modules, being the first in being assembled, tested and installed, constitute an important challenge and milestone.

Massive XA production began on January 27th with the first cathode module assembly. The testing setup had to undergo some modifications in order to enable cathode module testing, and a safety inspection for class-4 lasers had to be passed. Testing began on February 9th.

With the system and all procedures better understood, assembly, testing and installation for 10 modules (4 non-TCO cathode, 2 TCO upper membrane and 4 TCO cathode) was carried out in about a month. Since the second week of March, and with the overall ProtoDUNE-VD schedule being delayed, assembly and testing of the last four membrane modules is more relaxed. Installation of those modules have been scheduled for April 25th and 26th.

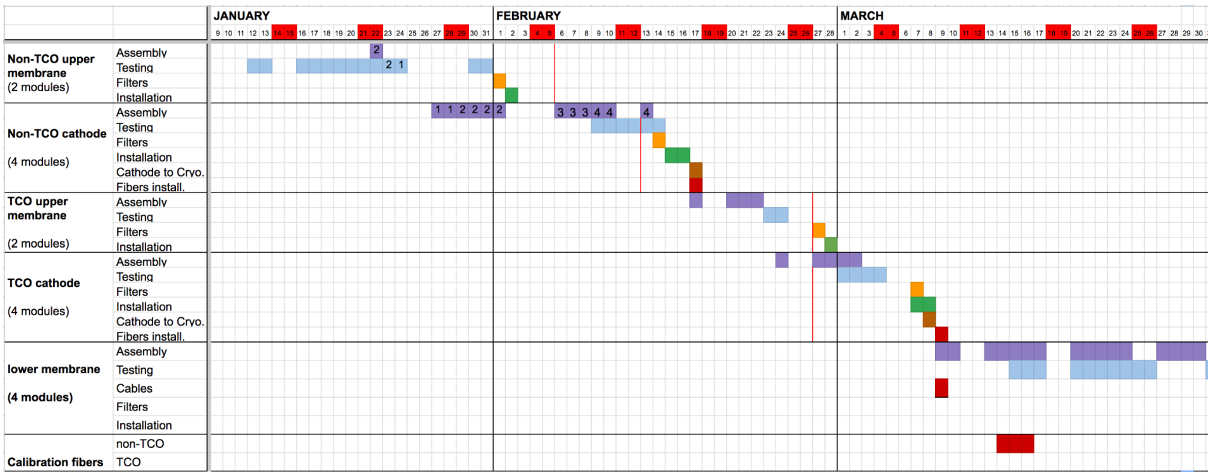


Figure 63. ProtoDUNE-VD PDS assembly, testing and installation schedule.

Bookkeeping

This was an essential part of the assembly, testing and installation processes. Four different type of documents were maintained as google docs:

1. Availability of components
2. Mapping
3. X-ARAPUCA one by one walkthrough
4. Testing results

In order to guarantee timely availability of all the XAs components, of equipment and of parts related to the modules assembly, electrical tests (cold and warm) and installation in the cryostat, a weekly round contacting the individual material providers started approximately two months prior to the modules assembly activities start at CERN and has been executed following their status up until the final deliveries. Given the extensive number of components a module contains, a thorough list of available items for each module was designed such that they could be completely assembled in the shortest time possible avoiding interruptions at this particular stage. Such level of organization was also required as it allowed for on time preparations of the module testing facility as it depends on arrangements for the use of adequate amounts of LAr and for installation of the different power and readout setups necessary for the configurations of the membrane and cathode modules tested (Cu, PoF and SoF). In parallel, the development, production and shipment of the different parts necessary for the installation of each module was also monitored such that the PDS activities in the cryostat have been performed attending the overall integration schedule. An example of the google doc used to monitor the status and availability of components for each arapuca is shown in figure 64.

	Membrane (non-TCO) Installation Feb 2nd		CATHODE (non-TCO) Installation Feb 8th				Membrane (TCO) Installation Feb 28th		CATHODE (TCO) Installation in Cathode Feb 28th			
Component	M1	M2	C1	C2	C3	C4	M3	M4	C5	C6	C7	C8
DATE assembled needed			Feb 6th	Feb 6th	Feb 9th	Feb 10th	Feb 20th	Feb 21st	Feb 24nd	Feb 27rd	Feb 28th	March 1st
Frame	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN
Flex and SiPMs	OK at CERN (Hamamatsu)	OK at CERN (Hamamatsu)	OK at CERN	OK at CERN	Ok at CERN (FBK)	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN (FBK
Vikuiti for Flex	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN (insttallation to be done on flexes)	OK at CERN (insttallation to be done on flexes)	OK at CERN	OK at CERN	OK at CERN	OK at CERN
Vikuit for ribs	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	Ok at CERN
Vikuiti for backplane	OK at CERN (4 pieces for one backplane)	OK at CERN (Installed on backplane)	N/A	N/A	N/A	N/A	Come installed on backplane.	Come installed on backplane.	N/A	N/A	N/A	N/A
Cables from flex to MB	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	OK at CERN	Ok at CERN	Ok at CERN	Ok at CERN	Ok at CERN	Ok at CERN	Ok at CERN
Motherboard	Two vendor-populated (2) DMEM v1.0 and two hand populated at CERN. Worried about 47uF X5R caps (Peter is bringing them). WE DON'T KNOW YET WICH BOARD WILL BE INSTALLED. NO WORRY ABOUT SHIPMENTS		Ok at CERN (laser adaptors w/lasers, motherboards, LBL bias)	Ok at CERN (laser adaptors w/lasers, motherboards, LBL bias)	Ok at CERN (laser adaptors w/lasers, motherboards, LBL bias)	Ok at CERN (laser adaptors w/lasers, motherboards, LBL bias)	Ok at CERN (modifications being done)	Ok at CERN (modifications being done)	Ready	Need different laser to test it	Need different laser to test it	Need different lase test it
Electronics box	Peter (1 box) & Bias cards		OK at CERN	OK at CERN	OK at CERN	OK at CERN	Ok at CERN		Ok at CERN.	Ok at CERN	Ok at CERN	Ok at CERN
HD-style Cold cables	OK at CERN		N/A	N/A	N/A	N/A	Ok at CERN	Ok at CERN	N/A	N/A	N/A	N/A
WLS	OK at CERN (not dimpled)	OK at CERN (not dimpled)	OK at CERN (not dimpled)	OK at CERN (not dimpled)	OK at CERN (not dimpled)	OK at CERN (dimples)	OK at CERN (dimples)	OK at CERN (dimples)	OK at CERN (dimples)	OK at CERN (dimples)	OK at CERN (dimples)	OK at CERN (dim
Filters	OK at CERN (ZAOT 100x200)	OK at CERN (ZAOT 100x200)	OK at CERN (ZAOT 100x200)	OK at CERN (ZAOT 100x200)	OK at CERN (PE 143x143)	OK at CERN (PE 143x143)	Ok at CERN	Ok at CERN	Ok at CERN.	Ok at CERN.	Ok at CERN.	Ok at CERN.
Shielding Mesh	Arrived on the 24th to be pick up on 25th		N/A	N/A	N/A	N/A	Ok at CERN (finishing and cleaning)	Ok at CERN (finishing and cleaning)	N/A	N/A	N/A	N/A
Counterweight	OK at CERN	OK at CERN	N/A	N/A	N/A	N/A	Ok at CERN	Ok at CERN	N/A	N/A	N/A	N/A
Mounting vertical lines	OK at CERN/Installed	OK at CERN/Installed	N/A	N/A	N/A	N/A	OK at CERN/Installed	OK at CERN/Installed	Ok at CERN	Ok at CERN	Ok at CERN	Ok at CERN
Response Monitoring System	OK will be brought from CIEMAT on Jan 23rd						N/A	N/A	N/A	N/A	N/A	N/A
Penetration	Not til February - first module cables will not be pulled up until BDE cables are ready to be pulled up. Flange at CERN. Septum sent to production. Expected at CERN end Feb. Hardware at CERN.											
Frame to hold two mem. modules	OK at CERN		N/A	N/A	N/A	N/A	OK at CERN		N/A	N/A	N/A	N/A
Cathode fibers	N/A	N/A	Ok at CERN	Ok at CERN	Ok at CERN	Ok at CERN	N/A	N/A	Ok at CERN	Ok at CERN	Ok at CERN	Ok at CERN
Cathode Frame-to-Mesh supports	N/A	N/A	Ok at CERN	Ok at CERN	Ok at CERN	Ok at CERN	N/A	N/A	Ok at CERN	Ok at CERN	Ok at CERN	Ok at CERN

Figure 64. Status and availability of components for each X-ARAPUCA. .

The second document is devoted to the mapping between the different components in each X-ARAPUCA, with special emphasis on the electronics components (including SiPM flex boards, motherboards and their respective connections), which have been characterized individually before assembly. Figure 65 shows an example.

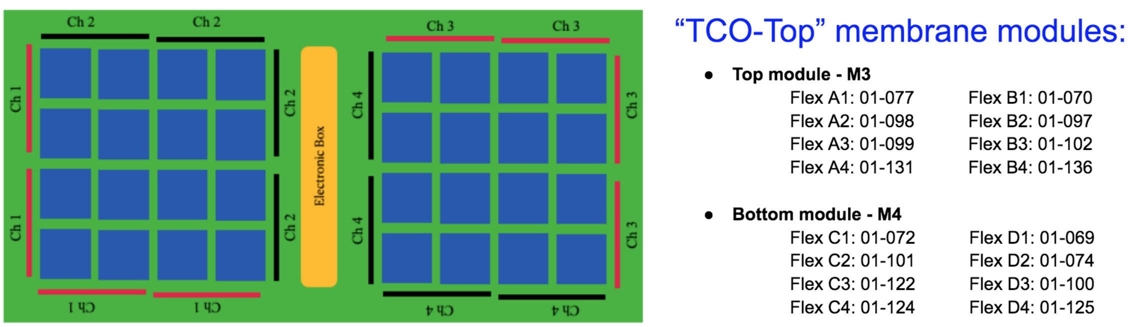


Figure 65. Mapping of SiPM flex boards showing the serial number of each board and its location in the X-ARAPUCA

The third document summarizes in a table (see figure 66) all relevant information for each module, including its configuration (type of SiPM, filters, WLS, electronics, etc), the manufacturing process and observations, and the tests it underwent, including the most relevant findings.

			Picture link	Detailed description	Detailed manufacturing process
Assembly date	10/02/2023		https://cernbox.cern.ch/s/DUVKGMPdYJBrAYj		
Assembled in clean room	YES			Full assembly was performed in the tent	
Assembly team	Laura, Franciole, Jay, and Diana				
HPK / FBK	HPK			Flex A1: 01-082 Flex B1: 109 Flex A2: 111 Flex B2: 110 Flex A3: 124 Flex B3: 115 Flex A4: 129 Flex B4: 122	
ZAOT / PE	PE			Evaporation on Jan 2023. From XX PE production	Detailes about PTP coating ....
Filter size	150 x 150			Bottom filters from box PHOTON EXPORT 02 from Run 03 #-3 to box PHOTON EXPORT 03 Run 02 #1. Top filters from box PHOTON EXPORT 03 from Run 02 #2 to Run 03 #5	
WLS dimples	YES			Channel A with squared dimples and B with round dimples. WLS Dimension: 607 x 607 mm Production date: 11/2022 Serial number: 2022P001S001T01I007	
WLS spacers	NO				
Frame version					
Vikuiti on flexes	Yes			Vikuiti masks pre-cut at CSU	Laser cut vikuiti masks were installed on all flexes. The tabs were removed from the mask before its installation on the flexes. The thin protective layer is removed just before placement on the module.
Vikuiti on ribs	Yes			Vikuiti stickers pre-cut at CSU	Laser cut vikuiti stickers for the ribs were installed with its thin protective layer. The layer is removed just before the filter frame assembly on the module.
Position in cathode					
Readout type				DCEM: 1242 DCDC: PICO 8 SOF 1: 221107004 - 200uW - pigtail SOF 2: 221107005 - 200uW - pigtail POF: Comments: bad SoF connection in the first test	
Electronics box					
Grounding					
Cable disposition in box					
Module protection					
Installation					
TESTS	**Cold/warm**	**Date**		**Detailed description**	**Important findings**
Test 1		15/02/2023	11:00	C4 assembled in the frame at 11:20. The black tube routing the cables have been inserted in the thicker black tube to avoid light leakeages (see pics). Module is inserted in the dewar at 11:43, and a dry test is performed (no LAr). With the PoF OFF, we can see a clear light signal in the independent SiPM flex at a threshold of 20mV (at a rate of hundreds of Hz). With the PoF ON, we see a lot of signal: Light leakeage is still there.	The baseline configuration + the black tube to rout the fibers do not remove the light leakeage. Therefore the black tube routing the cable is not the (only) responsible of the light leakeage. It seems that the connectors are the responsibles.
Test 2	Warm	15/02/2023	13:00	Now the assembly includes the thicker black tube + the connectors are outside the dewar. The flange has been drilled in order to pass the connectors through it (see pics). The module is inserted in the dewar at 13h03, and a dry test is performed (no LAr). With the PoF ON we see much less activity on the independent SiPM flex!	The configuration with the black tube + the connectors outside the dewar remove the light leakeage. A last test is needed in order to understand the role of the connectors.
Test 3	Warm	15/02/2023	15:00	Now cable routing is back to the baseline design, using the thin black tube, but the connectors in lid are mantained outside (pics).	
Test 4	Cold	15/02/2023	16:00	C4 immersed in LAr, with the same configuration as Test 3.	

Figure 66. One-by-one X-ARAPUCA walkthrough example.

The forth document includes details about the tests, some of them summarized in this document.

APPENDIX 1: Testing sequence

The testing sequence is as follows:

1. With the lid next to the dewar, the XA is mounted on the support structure and all connections to the flange are established.
2. The module is introduced on the dark box, and tests at warm are conducted to verify all connections
3. The module is then extracted from the dark box and transferred to the dewar, the inner box almost empty (15 cm LAr at the bottom), sufficient to cover the electronics box at the bottom of the XA. In the case the inner box has more than the required LAr level (from a previous test), a cryogenic pump is used to transfer LAr from the inner box to the dewar before inserting the module.
4. The XA is inserted into the inner box slowly, especially while the electronic box is immersed. With the lid closed, LAr filling can start at about 1 cm/minute.
5. Filling stops once the liquid is about 10 cm above the top XA border, triggered by one of the temperature sensor stops.
6. Testing ….
7. To avoid water condensation during the warm-up process, a transparent plastic cylinder is set up. The plastic tent is sealed to both the lid and the top of the dewar so that the amount of air incoming when opening the lid is minimized.
8. Before opening the lid, the plastic tent is flushed with gas nitrogen (GN2) to evacuate the air inside and to create a slight overpressure avoiding air inside the tent once the lid is opened.
9. The lid is lifted until the full XA and its support frame are above the dewar upper edge. The lifting speed is such that GN2 fills the volume inside.
10. The lid is displaced horizontally until the XA is outside the dewar vertical. In this way, cold gas argon from the dewar is avoided on the XA, and the warm-up process can be accelerated. Further, warm-up speed is achieved by heating the incoming GN2 with a heat gun applied to a stainless steel coil connected to the GN2 line.
11. Once the temperature of the entire XA is above the dew point, the plastic tent is opened and lifted
12. XA is visually inspected, mainly to check for Vikuiti detachment, and a few pictures were taken.

APPENDIX 2: Electronics configuration for each module

TableTable 4 shows the electronics configuration for each cathode module. The columns "SoF 1" and "SoF 2" indicate the serial number of the laser used in each DCEM 1.2 board.

Module	PoF type	DCDC	laser adapter	Lasers	SoF 1	SoF 2
C1	GaAs	LBL	07	200uW FC	221104008	221104007
C2	GaAs	LBL	05	500uW pig	221106004	221106005
C3	GaAs	LBL	08	500uW FC	221105003	221105004
C4	GaAs	PICO	06	200uW pig	221107004	221107005
C5	GaAs	PICO	10	200uW FC	221104003	221104009
C6	GaAs	LBL	02	200uW FC	221104002	221104001
C7	Si	PICO	09	200uW FC	221104004	221104005
C8	Si	LBL	11	500uW pig	221106003	221106006

Table 4. Electronics configuration for each cathode module.

A number of component modifications were necessary on all DCEM 1.2 boards (SoF) in order to implement the desired configuration. Such changes were listed and explained in a shared document. The modifications carried out are summarized below.

Replacement of capacitors:

After fabrications of the boards it was found that some of the ferro-ceramic capacitors used would not be adequate for use in cryogenic conditions. Table 5 lists the type of components that had to be changed, and the part name that was used to replace them after being validated through independent testing.

Capacitance	Size	Quantity per board	New Part Number
110 uF	1210	2	AVX 1210ZD107MAT2A
47 uF	1206	3	TDK GRT31CR61A476KE13L
4.7 uF	1206	16	Murata GRJ31CZ72A475KE01L
4.7 uF	0805	8	TDK C2012X7R1H475K125AE

Table 5. List of capacitors in DCEM 1.2 fabricated in December 2022 that were replaced.

Configuration of voltage regulators:

The DCEM 1.2 boards were produced with two low drop-out voltage regulators, each of which could be used either for the DCDC card or for the SoF circuit, or for both. Their part numbers are LP3964 and ADM7151. The first was on the first prototype boards, while the second was found later and added in this board version. They have different characteristics, with the ADM7151 expected to be better in terms of noise performance. It was decided to have a separated LDO for the DCDC card and for the transmitter circuit. Since there is a delicate interplay between the LDO and the DCDC card input, it was decided to continue using the LP3964 to provide 5.09V to it. The ADM7151 is then used to provide the LV to the SoF (4.99V). In order to implement this configuration, the following resistor values had to be implemented. The identification of the resistors correspond to the schematic of the DCEM 1.2 from 10/27/2022.

- R73=R75=R86=R76= 0
- R74 and R87 open

Increase in amplification stage gain:

The DCEM 1.2 boards were produced with a total voltage gain of x10, while its predecessor design had x20. After a first test it was concluded that this modification decreased the SNR more than was desired. The resistors that define the voltage offset and the gain on the second amplifier therefore needed to be replaced, using Susumu high precision SMD resistors. The following values were modified with respect to the BOM:

- R90=R91=13k
- R12=R29=820
- R21=R38=755 (1.5k in parallel to 1.6k)

Additional modifications:

The DCEM 1.2 design implemented a series of options for possible tests, in addition to some experimental features. The board therefore needed additional interventions in order to be configured as required for ProtoDUNE. This is the list of required interventions:

- Remove NTC5 and NTC3
- Connection of jumpers:
    - Use PoF bias: JP6, JP8
    - Connection of grounding to mech (through 1 MΩ):JP12
    - Join bias A and B (use a single DCDC bias card to bias all xArapuca SiPMs): JP5,JP14
    - Join the circuit ground to the DCDC input ground: JP4

Output voltage of DCDC cards:

The output voltage of the DCDC converter cards is very sensitive to both the temperature and the input voltage. It is believed that this is the reason for which the cards in their original configuration did not provide the desired bias voltage. By changing the resistor that acts on the input voltage, it is possible to modify the output. However, this value had to be found experimentally, through several iterations. A similar procedure was needed for each type of bias card; the needed resistor value was found to be consistent between different cards of the same type. For example, for the bias card used for FBK SiPMs (which need 32 V bias), the original value of R25 was 1kOhm, with an output of 36.4 V and 34.5 V at room temperature and in LAr respectively. The value of the resistor was gradually increased until it was found that 43kOhm provided the desired 33.1 V at room temperature and 32.2 V in LAr.

Configuration of the Laser Adapter cards:

Ideally the laser adapter cards were to be prepared and tested at APC prior to final assembly at CERN. This was not possible since after arrival to Fermilab, the new type of lasers had to be characterized. They were later shipped directly to CERN due to lack of time. For this reason the configuration of some of the laser adapters had to be finalized at CERN.

Four new types of lasers were used in the assembly, made up of two options for the "defocusing" (which determines the laser output power at room temperature: 200 or 500 uW) and two connectivity options: FC receptacles and pigtailed lasers. Once the type of laser to be used on a laser card is determined, one resistor on each channel (R10 and R22) need to be added to the laser adapter card to set the value of the laser current. The DC current on the laser in LAr is equal to the offset voltage divided by this resistor.

After the motherboards were configured, it was verified that there was some dispersion in the value of the voltage offset. The lowest and highest values were evaluated, found to be 278 and 290 mV respectively. The less defocused (500 uW) laser needs a higher offset current, therefore the following configuration was decided.
Defocused lasers 500uW:

- R24=R12= 27 (production value, no change needed):
  → Room temperature current between 11.6 and 12.1 mA.
- R22=R10= 68
  → **Current in LAr between 4.1 and 4.26 mA**

Defocused lasers 200uW:

- R24=R12= 27 (production value, no change needed)
  → Room temperature current between 10.9 and 11.37 mA.
- R22=R10= 82
  → **Current in LAr between 3.4 and 3.5 mA**

Also to be noted, this version of laser adapter cards contains an error in the silkscreen concerning the connection of the lasers. This was clarified in the document containing the instructions and will be corrected in the next version.

APPENDIX 3: Detailed analysis of membrane XA tests

Data taking was different for each module, mostly due to time constraints. For some of them a scan in overvoltages was performed, for others a scan in LED intensity or cosmic rays data, or a combination of these. The data analysis performed right after the module's warm up consisted basically in:

- the computation of the Signal to Noise ratio (SNR) for LED data,
- the estimate of the gain ratio between the two channels of the modules based on cosmic rays data,
- FFT studies for the noise evaluation, namely a try to guess which is its source.

As an example of the entire procedure module M3 will be considered. In this case data was taken with two different bias voltages, V_{bias}, (44V and 45V) and three values of LED intensity (1.75V, 1.76V, 1.78V). Finally, a sample of cosmic rays data with trigger on Ch 0 (setting a threshold value) was recorded. Figure 67 shows a typical waveform and the average over 10000 samples. For some modules, an oscillation which is always superimposed to the signal. The average plot (figure 67-right) allows one to choose the integration window (kept fixed), needed to build the charge histogram and compute the SNR (see figure 68). For this module, a SNR of 5.58 was obtained at 45% of PDE, a value above the requirements.

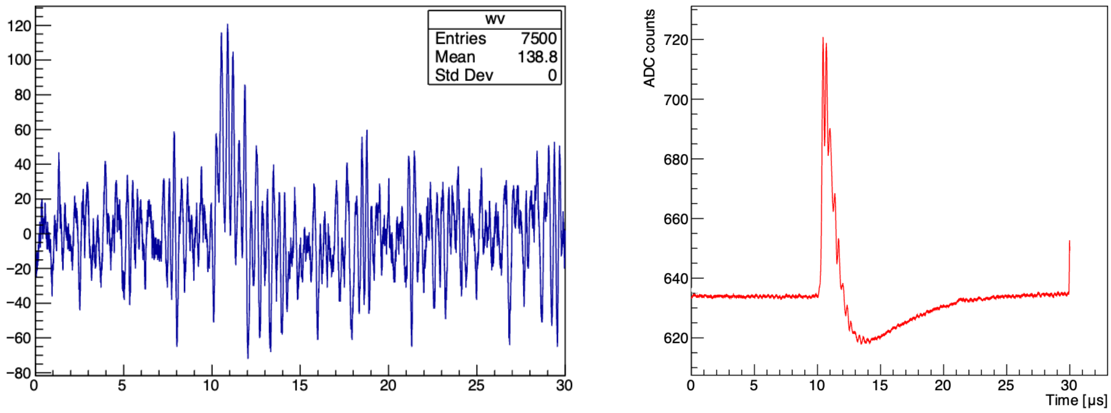


Figure 67: Typical waveform and average of 10'000 waveforms sampled at Vbias=45V (45% PDE).

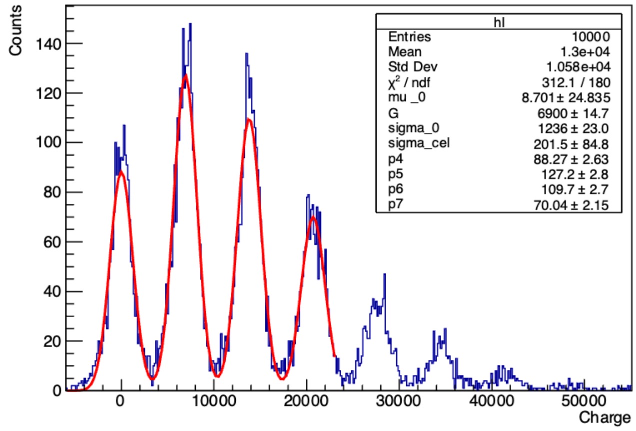


Figure 68: Charge histogram obtained integrating the waveforms. The SNR is the ratio between G (Gain, the distance between peaks) and "sigma_0".

A detailed analysis of the zero photoelectron (p.e) peak in figure 68 can help in understanding the source of the noise (or some of its components, such as the superimposed oscillation). Figure 69, showing the average over 0 p.e. waveforms, proves that the oscillation does not occur only in the presence of a signal. so the hypothesis was that it was due to the trigger.

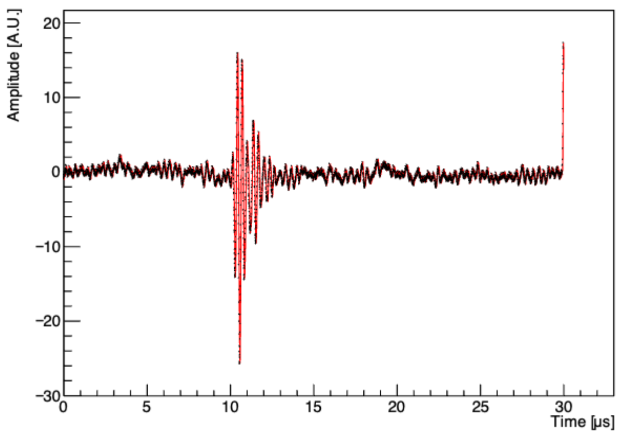


Figure 69: Average of the 0p.e.'s waveforms.

Further confirmations come from the FFT analysis (see figure 70). A very effective test is the comparison between the average of the power spectral densities of the waveforms (gray) and the spectral density of the averaged waveforms (red). This is performed both for noise-like waveforms (the one extracted from the 0p.e. peak) and the signal-like ones. Typically, all the random-noise components cancel out when taking the average of the waveforms in the time domain, so the power spectral density results lower along the entire spectrum. The evidence that some components "survive" to this operation is the proof that some components are trigger related.

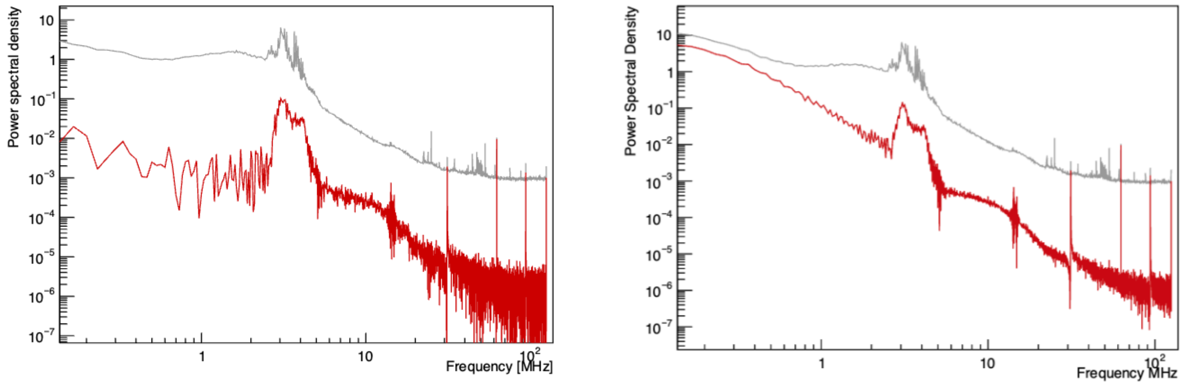


Figure 70: Average Power Spectral Density (gray) and spectral density of the averaged waveforms (red) for the 0p.e. (left) and signal-like ones (right).

The cosmics ray data analysis was focused on comparing the gain of the two readout channels of the X-ARAPUCA (see figure 71). The same value is expected for both channels since on average cosmic rays should induce the same amount of light in them. Even if this can be estimated just looking at the average waveform (assuming that both channels see the same amount of light), the procedure involves a waveform par waveform inspection. It is worth noting the similar behavior of the two channels: they show the same oscillations (probably related to a grounding issue) and in most of the cases the amplitude of the signal is almost the same, as in figure 71-middle (figure 71-left shall be considered an exception). The gain ratio is then computed as the ratio of the amplitude of the average (figure 71-right), which in this case it is about 1.1.

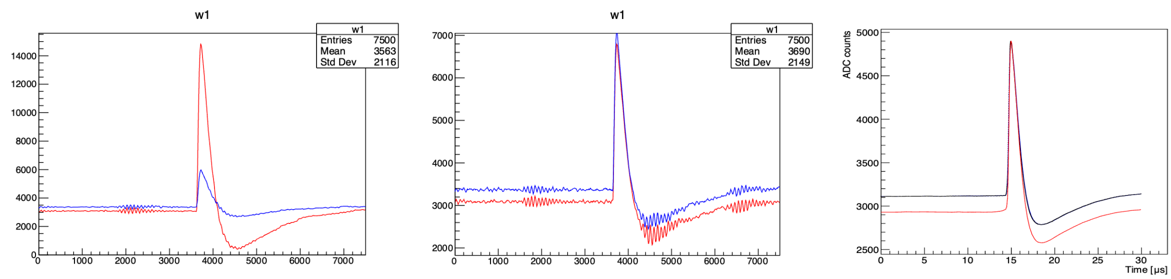


Figure 71: Channel 0 and 1 comparison for single waveforms (left and middle panels) and average (right panel)

Table 6 shows the results of SNR for different overvoltages and the gain ratio of the two readout channels for the modules that were extensively tested (M3 and M4). For M4 the trigger signal was delayed in order to move the weird oscillations on the tail of the signal.

	SNR for 44 V (40% PDE)	SNR for 45 V (45% PDE)	SNR for 46 V (50% PDE)	Gain ratio between channels (cosmics)
M3	4.3	5.6	//	1.1
M4	//	6.1	7.6	0.97

Table 6. Results for M3 and M4. Signal-to-Noise ratio (SNR) for different overvoltages evaluated with LED pulsed light, and gain ratio between the two XA channels using cosmics.