DUNE FD2-VD PDS:
Response to PDR Recommendations

Last Update: 29 March 2023
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Revision Change Log

Date of Revision	Revision PoC	Revision Notes
29 March 2023	D. Warner	Edits for clarity
25-Mar-2023	F. Cavanna	Advanced Draft for FD2 PDS Final Design Review
10-Mar-2023	F. Cavanna	Response to Recommendations from PDR - Initial draft for FD2 PDS Final Design Review

Introduction

This document provides the DUNE Far Detector 2 (FD2) Photon Detector System (PDS) responses to (N. 22) Recommendations from the FD2 PDS Preliminary Design Review (PDR) with links to pertinent documents with details of executions of recommendations (where applicable).

The FD2 PDS consists of cold photo-collectors known as X-ARAPUCA (XA) modules on the HV cathode and cryostat membrane, and the supporting infrastructure for operation, readout, and control.

There are four primary subsystems comprising the FD2 PDS:

1. Cathode-mounted photon detector (double-sided) including
    a. Cold Electronics board with Power-over-Fiber (PoF), Signal Conditioning stage and Signal-over-Fiber (SoF)
    b. PoF fibers (2 per board), SoF fibers (2 per board - one per channel)
2. Membrane-mounted photon detector (single sided) including
    a. Cold Electronics board with Signal Conditioning stage
    b. Copper cables (4 twisted pairs)
3. Warm Electronics including Signal digitization stage and SoF receiver for cathode-mount modules
4. Response Monitoring System (RMS) fibers and diffusers

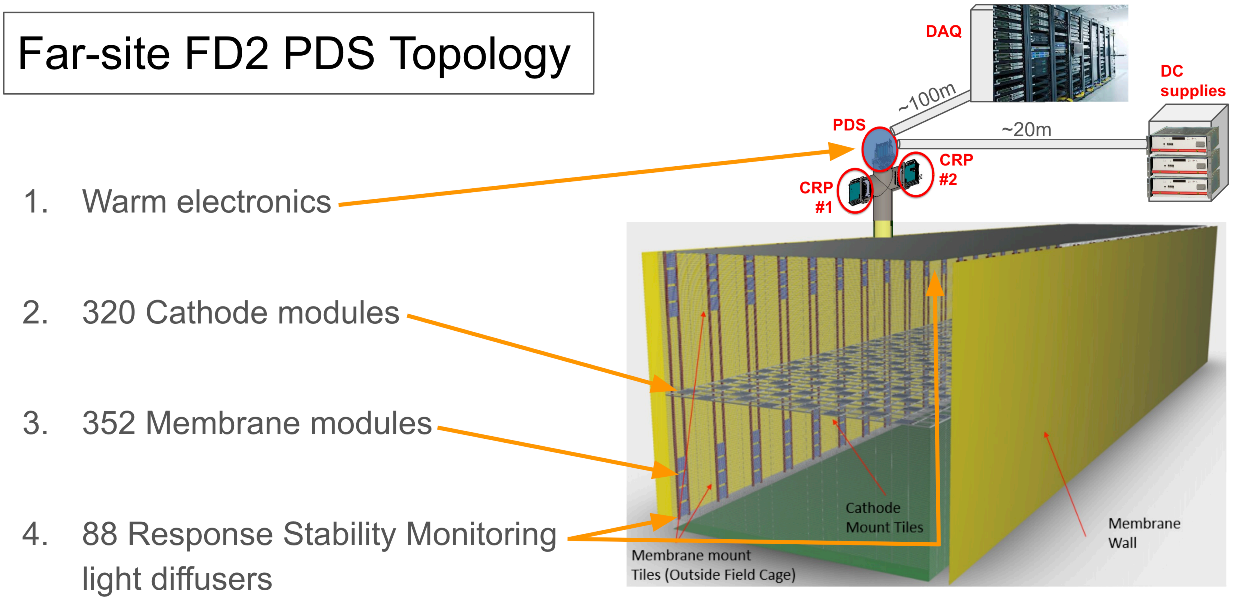


Figure 1. DUNE FD2 PDS topology at SURF.

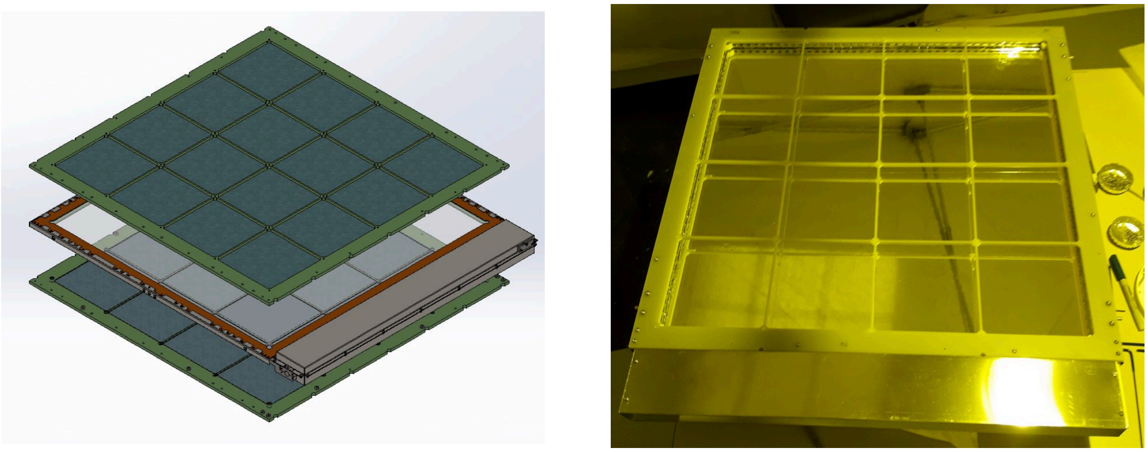


Figure 2. Exploded view and picture of a XARAPUCA module.

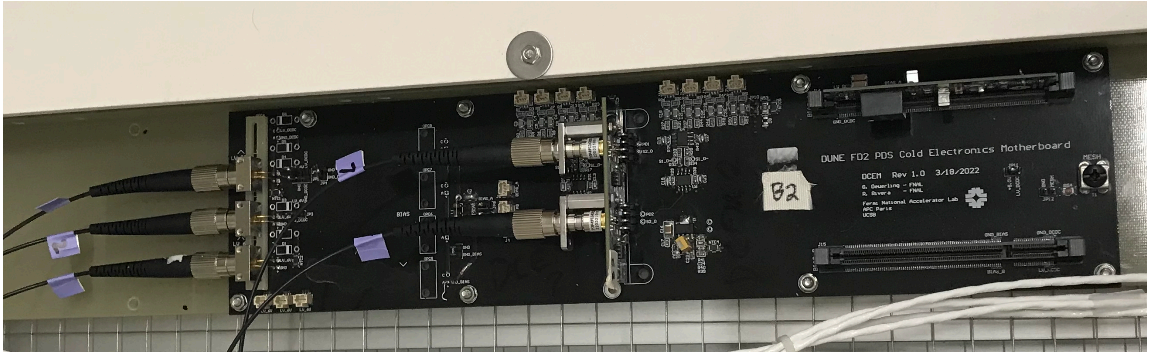


Figure 3. Cold Electronics board with Power-over-Fiber (PoF), Signal Conditioning stage and Signal-over-Fiber (SoF)

Recommendations #1 to #3 - Design concept, requirements, and physics performance.

R1. Formulate requirements to validate the design for approval by the TB and complete Consortium-held requirements and specifications.

- A set of TB specifications have been evaluated and recommended by the DUNE FD2 TB during the design development stage (2021-22). TB specifications/recommendations are now being approved as TB-held requirements (See Document linked below).

- A complete set of PD Consortium-held requirements and specifications for FD2 PDS design has been defined and approved by the PD Consortium (See Document linked below).

Ref.: TB-held Requirements

TB-held Requirement List for FD2 PDS - submitted for approval by TB.

Ref.: Consortium-held Requirements

Consortium-held Requirement List for FD2 PDS - approved by PD Consortium.

R2. Estimate the expected data rate, as a function of threshold in photo-electrons, from all known radiological background sources, including the rates from membrane-mount modules.

Identification of radiological background sources and their intensity in the underground far site are subjects of dedicated studies carried out by the DUNE Radiological Background Working Group. The best known source is ^{39}Ar (Beta emitter) with $1.01 \pm 0.08 Bq/kg$ in ^{nat}Ar specific activity. Work is in progress to define intensities of other known sources and in parallel dedicated MC simulations by the DUNE Low Energy working group are also in progress to evaluate impact on PD background rates.

- Expected ^{39}Ar event rate as a function of PE threshold for cathode-mount PD modules. A study has been performed based on analytic calculations and cross-checked with existing output of preliminary MC simulations (See Document *39Ar-Rates-vs-PE-Threshold* linked below).

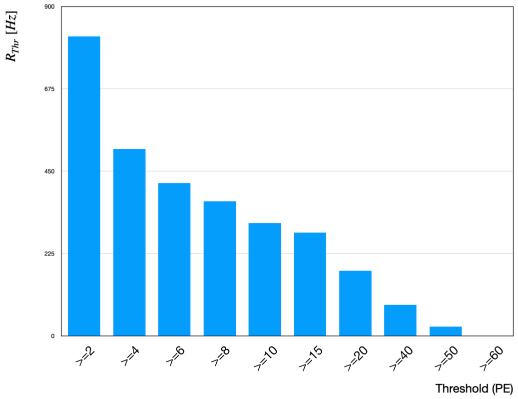


Figure 4. Expected event (data) rate in cathode-XA, as a function of threshold in photo-electrons

- For membrane-mount modules, a preliminary estimate of 39Ar event rate is in progress, taking into account the effect of the residual EF (low and non-uniform) in the volume behind the Field Cage enhancing LAr scintillation PhotonYield where the membrane-mount modules are located.

- An exhaustive full MC simulation is in progress, including all radioactive sources of background recently identified and quantitatively specified by the DUNE FD RadBackground WG and a complete detector/electronics response simulation to scintillation emission in Xe-doped LAr. First results on rad background for FD2 in underground at SURF are expected to be available by end of April

Ref.: ^{39}Ar event rate as a function of PE threshold for cathode-mount PD modules

39Ar-Rates-vs-PE-Threshold

R3. Justify the total number of modules in the system taking into account physics performance and overall cost. The justification should include a demonstration that the ratio of membrane- mount to cathode-mount modules and their geometric placement have been optimized.

Ratio [*N. membrane-mount modules* (352)] / [*N. cathode-mount modules* (320)] =**1.1.** In order to justify the number of cathode-mount modules vs. number of membrane-mount module it is convenient to start with the observation that the distance of any generic point in the bulk of the LAr volume to the cathode is shorter than the distance to the nearest membrane wall (on average by factor 2 shorter), therefore PD modules on the cathode have much larger acceptance for scintillation light isotropically emitted anywhere in most of the LAr volume. This suggests implementation of a larger optical coverage (OC = photo-sensitive Area/Total Area) of the cathode surface than for the membrane walls.

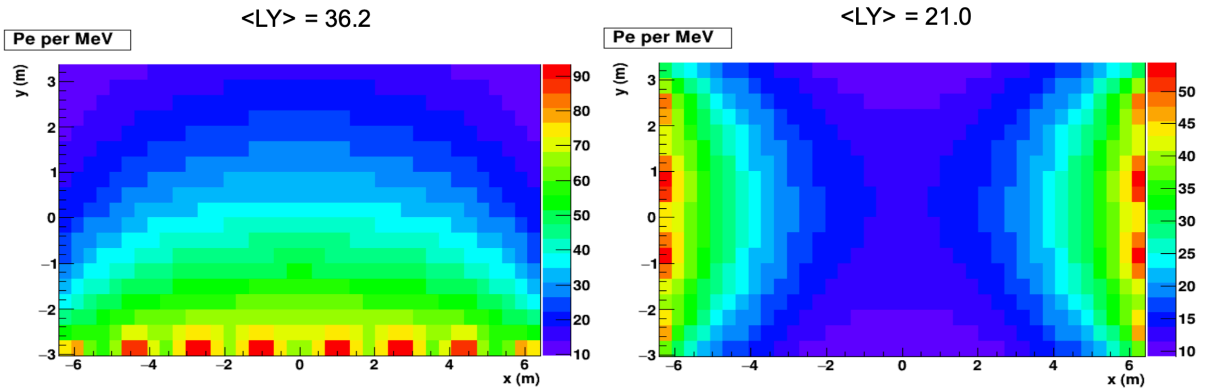


Figure 5. Light Yield maps [upper volume - transverse (x,y) plane at z=0, detector mid length] from MC simulation. [Left] Cathode only (OC 14%, 320 modules), [Right] Membrane only [OC 14%, 704 modules]

The optimal **ratio of membrane-mount to cathode-mount** was demonstrated by MC simulation with comparison of Light Yield maps corresponding to different coverages of cathode and cryostat walls. For example, the LY map of Fig.5 *[Left]* corresponds to *cathode coverage only (14%)* with 320 modules (and no modules on the membrane walls), compared to LY map *[Right]* with same coverage *(14%) only on the walls* with 704 modules (and none on the cathode). The (average) LY is much higher with cathode-only coverage than with wall-only coverage (even with double number of membrane modules). The PDS layout of the baseline design, taking into account physics performance, overall cost and space limitations behind the field cage, was found to be optimal with 320 modules on the cathode (OC=14%) and 352 modules on the four membrane walls (OC ~7%). The modules on the cryostat walls, placed behind the 70% transparent portion of the FieldCage closer to the anode planes, have the main purpose of providing a more uniform LY detection throughout the active LAr volume (shown in Fig.6 below, from TDR).

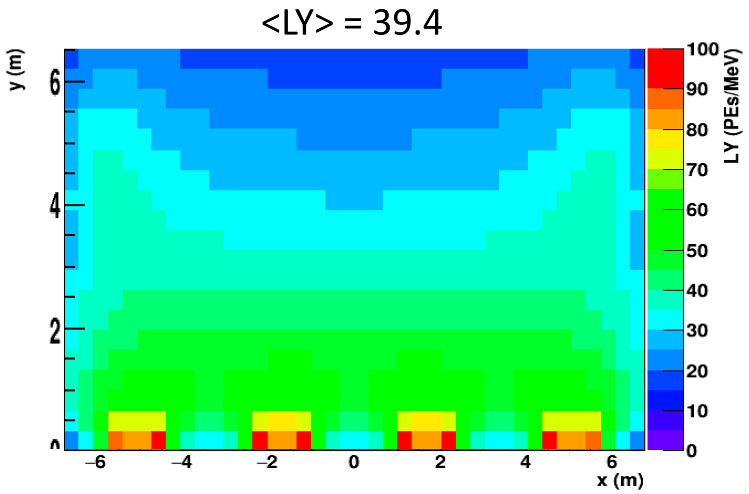


Figure 6-a. Light Yield map [upper volume - transverse (x,y) plane at z=0, detector mid length] for baseline design configuration - Ratio=1.1
[Cathode OC 14%, 320 modules / Membrane OC 7%, 352 modules]

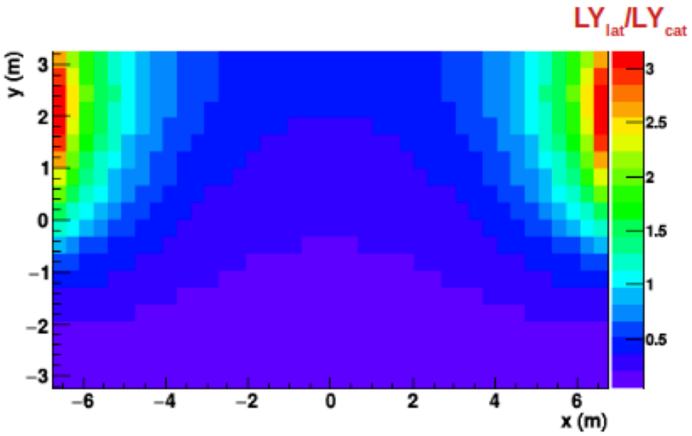


Figure 6-b. LY fraction detected by the lateral membrane-mount detectors over detected by the cathode-mount modules

Ref.: DUNE FD2 -VD Technical Design Report
FD2-VD TDR v.2 in EDMS

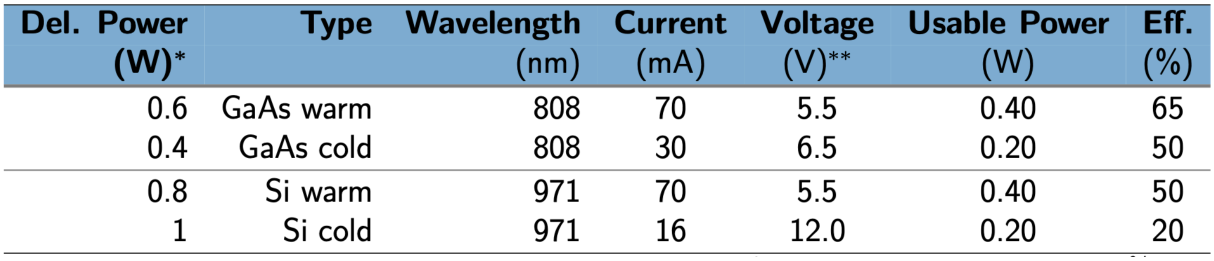
FD2 PDS Characterization by G4 Simulation

Recommendations #4 to #9 - Cathode-mount PDS

R4. State clearly which technology (Si/GaAs) will be pursued for which function as the baseline and demonstrate its feasibility at the required power levels.

GaAs technology will be pursued rather than Si technology for PoF of cathode-mount modules, as described in the FD2-VDTDR (See Document *FD2-VD TDR v.2 (Sec.6)* linked below).

Both technologies have been proven to meet the power needs of the cathode-mount modules/boards.



Del. Power (W)*	Type	Wavelength (nm)	Current (mA)	Voltage (V)**	Usable Power (W)	Eff. (%)
0.6	GaAs warm	808	70	5.5	0.40	65
0.4	GaAs cold	808	30	6.5	0.20	50
0.8	Si warm	971	70	5.5	0.40	50
1	Si cold	971	16	12.0	0.20	20

GaAs technology for the Optical Power Converter (OPC) of the PoF system was selected due to the higher efficiency shown in cold applications.

Table 1. Power estimates for PoF cathode SiPM systems. Numbers refer to individual OPC modules.

Ref.: DUNE FD2 -VD Technical Design Report
FD2-VD TDR v.2 in EDMS

R5. Consult with the fiber manufacturer on how to estimate the lifetime of fibers under PoF stress at cryogenic temperatures.

There are volumes of information on fibers in cryogenics (e.g. Properties of optical fibres at cryogenic temperatures, D. Lee, P R. Haynes and D. J. Skeen - Anglo-Australian Observatory, PO Box 296, Epping, NSW 1710, Australia Accepted 2001 April 30. Received 2001 April 18; in original form 2000 December 22) which describe long life operations. For our VD PoF system, we have tested half a dozen options to match our particular needs. Our baseline design has the following properties:

The fiber we are using consists of:

Fiber Core: 62.5um/0.27NA. The This core configuration has been used for decades and in many applications – including PoF. The loss at 808 nm is expected to be about 6 to 8 db per km. Since we are using 40 meter lengths, we expect around 0.3 dB. We have measured the loss to be approximately 0.2 dB or about 40 mW over the 40 meters. The fiber is rated to handle between 4 and 5 Watts. We operate our VD PoF system at approximately 1 W. That allows for plenty of headroom for power increase if needed. We tested at 3.5 Watts at room and cryo temps for a period of time to confirm viability.

Cladding: We have chosen a 200 um cladding. This is large for non-power PoF use but well suited for low light loss requirement applications, although 125 um would have been suitable and more in line with standard connector hardware. The 125um cladding thickness is retained as our backup plan if desired cost requires us to make a change. The 62.5/125 and 105/125 PoF fibers tested all meet our VD PoF light noise requirements. We tested several standard coating including polyimide and acrylate. These fiber coatings do not serve any optical function but are standard for fiber production. Both materials are capable of operating in cryogenics as a cladding protection mechanism. There is no lifetime issue associated with the thin layer applied to the fiber. PVDF 1.5 mm jacket (Polyvinylidene Fluoride) is a semi-crystalline structured highly inert, tough, and stable thermoplastic fluoropolymer. When exposed to flame, PVDF is non-flammable and does not drip. It is self-extinguishing and it is TL V0 compliant. The LOI is 44%. It also exhibits good resistance to UV light. The material will last decades in a cryogenic environment with no expected changes to properties. The PVDF has been used in several NASA fiber systems for reasons listed above.

R6. Begin a lifetime testing campaign for the DC-DC converters under established accelerated lifetime procedures to estimate the expected lifetime of the DC-DC converters when immersed in liquid Argon. (While less critical, a similar campaign estimating SiPM performance degradation over time while immersed in LAr would be beneficial to the project.)

A cold validation and lifetime testing program was launched at the time of the PDR and is now, as of the FDR, concluded successfully with a fully qualified and demonstrated solution available from LBL (See Document *LBL-StepUp* linked below).

The LBL Step-Up converter was designed with long term cold operation in mind. The selection of components was performed using two basic premises: the components have already been used in long term cryogenic applications, or the part type is easy to certify based on its construction and materials.

Ref.: LBL Step-Up DC-DC Converter
LBL-StepUp

R7. Complete the study of the effect of cathode high-voltage breakdown, and propose and demonstrate effective shielding and/or other mitigations.

Two joint studies from FNAL & BNL were conducted and have concluded. Mitigation strategies were defined and implemented in FD2 Module-0 and documented in the TDR (See Document *HV Impact Mitigation* linked below)

The two studies started from the same assumptions, and then diverged in the approach taken and analysis tools used (i.e. BNL used SPICE, and FNAL used ANSYS). It is acknowledged that the modeling problem is challenging due to the large scale (60m x 13m), the large quantity of elements of the system, and the complex topology of the X- ARAPUCA relevant details (i.e. distributed SiPMs, bias voltage, supply voltage, and signals). The conclusions from both simulations agreed to an order of magnitude.

In response to the understanding of the impact of the HV system breakdown, the following mitigation strategies were developed for the FD2 PDS Cathode-mounted XA and Membrane-mounted XA:

- Conductive shielding protecting the readout electronics and SiPM signal path was designed and implemented for both
- The cathode-mounted XA baseline topology was modified: XAs originally located in the cells of the cathode immediately adjacent to the field cage were moved inward by one cell, away from the field cage, and also a planned mounting topology requiring shared power and bias distribution among XA was changed to a topology of independently powered and biased XA.
- Membrane-mount XA shielding mesh was adopted to minimizing charge buildup on the non-conductive surfaces of the XA.

Ref.: DUNE FD2 PDS HV Impact Mitigation
PDS HV Impact Mitigation from EDMS

R8. Develop a realistic installation plan for the fibers, including successful demonstration using actual fiber

An installation plan for fibers was developed, documented, and executed for ProtoDUNE-VD Module-0 (See Document *DUNE FD2 PDS Installation Plan* linked below).

In cryostat at <2m height, cold-side team route and dress PoF/SoF fiber bundles through cathode module pair to their associated XA. Warm-side team, on cryostat roof, prepares Warm Electronics and PoF system for installation verification operation; verify fibers in associated feedthrough and connect to patch panel.

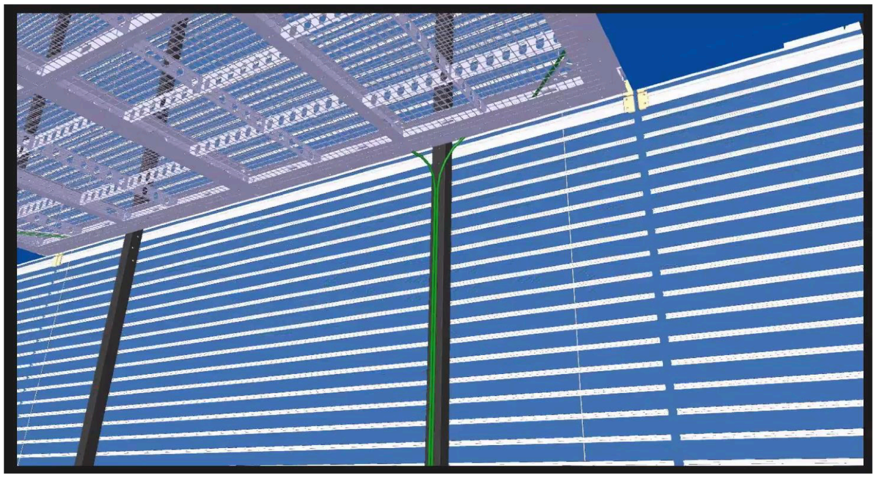


Figure 7. Fiber bundle exit point from cathode to field cage and down to cryostat floor.

Ref.: DUNE FD2 PDS Installation
Cathode-mounted Module Installation and Setup from EDMS

R9. Propose a design for a monitoring system of the cathode-mount PD modules, showing how many fibers/diffusers are needed and how and where they are mounted.

A response monitoring system (RMS) of the cathode- and membrane-mount PD modules was developed, documented, and executed for ProtoDUNE-VD Module-0 (See Document *DUNE FD2 PDS Installation Plan* linked below).

The FD2 PDS RMS components are replicated at 44 columns (2 RMS fiber diffusers kits per column) along the perimeter of the field. The RMS components to be installed at each column include (2) RMS fiber diffuser kits and (1) Flange and feedthrough kit.

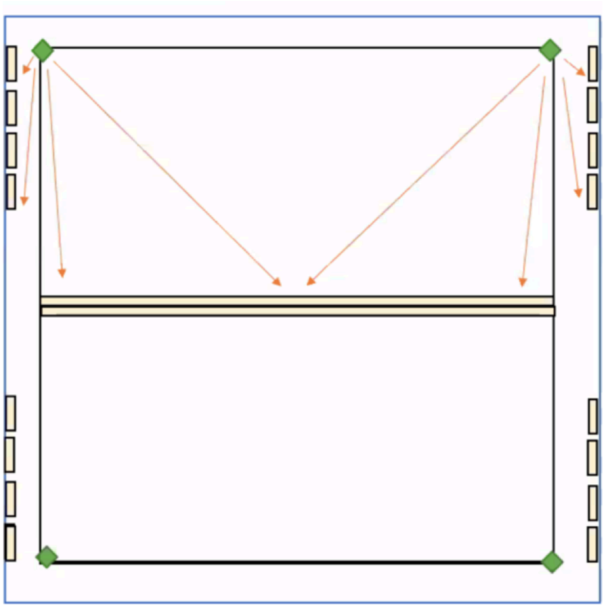


Figure 8. View from the short-side wall of the bottom and top RMS locations.

Ref.: DUNE FD2 PDS Installation

Response Monitoring System Installation and Setup from EDMS

Recommendations #10 to #12 - Membrane-mount PDS.

R10. Complete the design of the mechanical support system of the membrane-mount modules, in such a way as not to preclude supporting a significantly larger number of modules on the membrane (e.g., a factor of two).

The mechanical support system of the membrane-mount modules, was developed, documented, and executed for ProtoDUNE-VD Module-0 (See Document *DUNE FD2 PDS Installation Plan* linked below).

The mechanical support for the FD2 PDS Membrane-mounted XAs is made by a suspension support kit of 2 vertical parallel cables, 8 XA per column, replicated at 44 columns along the perimeter vertical membrane walls of the cryostat, and by (4) XA HV-shield mesh kits per column.

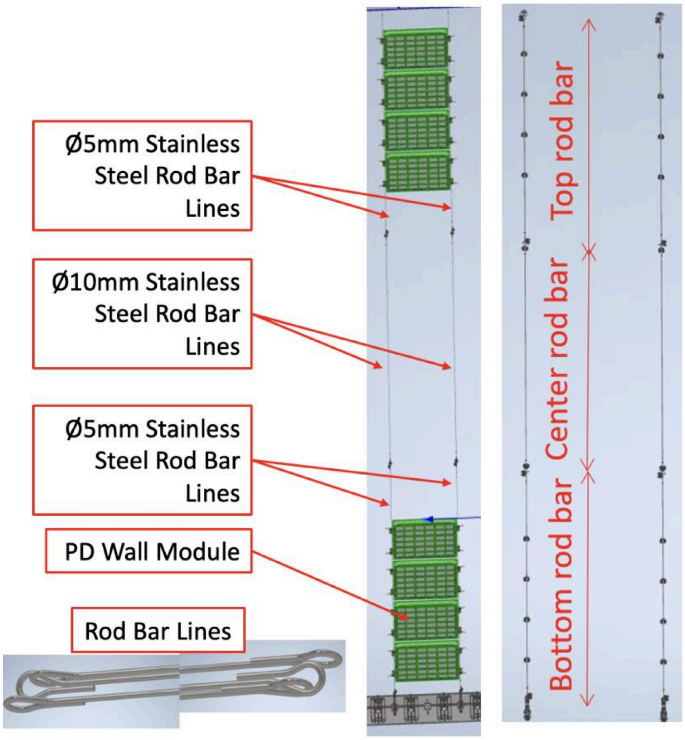


Figure 9. Components of the (2) suspension cable support kits (a left and a right).

While the mechanical support has the capability to hold a larger number of XAs per column if necessary, the baseline design of FD2 PDS, with its (44 x 8) 352 membrane-mount modules and 320 cathode-mount modules does not does not require additional of modules on the membrane walls.

Ref.: DUNE FD2 PDS Installation
Membrane-mounted X-ARAPUCA Installation and Setup from EDMS

R11. Evaluate the possibility of charge accumulation on the detector surfaces facing the field cage, discuss possible solutions with the HV group, and include the effect of any mitigating shield on the light detection efficiency.

Charge accumulation on membrane-mount detector surfaces facing the field cage was simulated, with mitigations documented and executed for ProtoDUNE2-VD Module-0 (See Document *DUNE FD2 PDS Installation Plan* linked below).

In response to the understanding of the impact of the HV system breakdown, mitigation strategies were developed for the FD2 PDS Membrane-mounted XA:

- Membrane-mount XA shielding mesh was adopted to minimize charge buildup on the non-conductive surfaces of the XA.

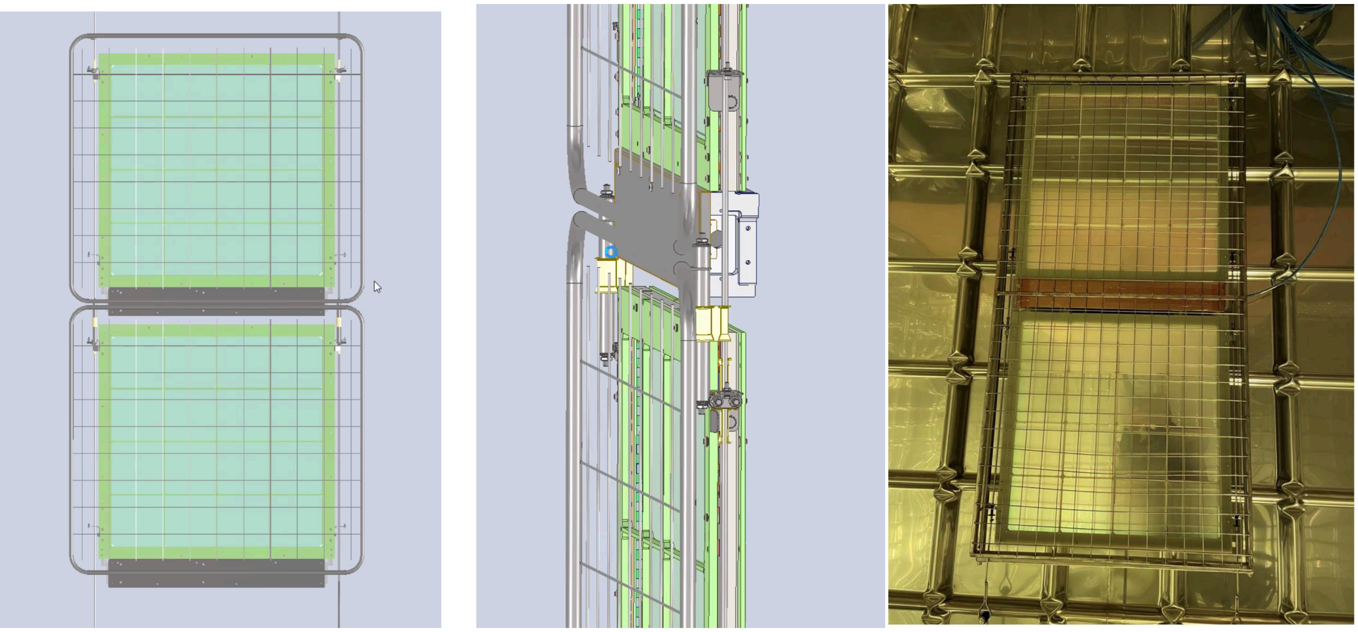


Figure 10. Membrane-mount XA shielding mesh and photo from Module-0 installation

Ref.: DUNE FD2 PDS HV Impact Mitigation
PDS HV Impact Mitigation from EDMS

R12. Propose a design for a monitoring system for the membrane-mount modules.

See R9: A response monitoring system (RMS) of the cathode- and membrane-mount PD modules was developed, documented, and executed for ProtoDUNE-VD Module-0 (See Document *DUNE FD2 PDS Installation Plan* linked below).

Ref.: DUNE FD2 PDS Installation
Response Monitoring System Installation and Setup from EDMS

Recommendations #13 to #14 - Lessons learned, prototyping, and Module 0

R13. Consider developing a dedicated infrastructure for testing and developing the PoF and other aspects of the system, rather than relying completely on test setups from other activities.

A cryogenic facility was constructed at the Neutrino Platform facility at the EHN1 building to test full size (60x60 cm^2 active area) XARAPUCA modules and read-out electronics, see Figure 11. This facility provides with final functionality check and validation in cold prior to deployment in protoDUNE-VD Module-0 cryostat and detector integration. A 70cm diameter 120cm tall open air Dewar contains the (non-purified) LAr bath and is sealed with a custom-made lid that ensures light tightness and free exit for GAr boil-off. A trolley with a winch allows insertion and extraction of a PD module in and out of the liquid. To minimize the usage of liquid argon and ensure safe warm-up and fast operation turnaround, a stainless steel box sized to fit the XARAPUCA module is inserted inside the Dewar and filled with LAr. At the end of the test, when extracting the module while still cold, nitrogen gas flowing under the box and contained by a polyethylene skirt, will prevent frost condensing on the modules. PoF optical fibers and SoF fibers are routed via dedicated black corrugated tube and feedthroughs to the lid of the dewar and allow for cold electronics power and readout during test. A calibration system with a LED pulsed flasher and diffuser is installed inside the Dewar. Temperature sensors and a slow control system will be used to monitor the LAr level and temperatures at different heights inside the inner vessel.

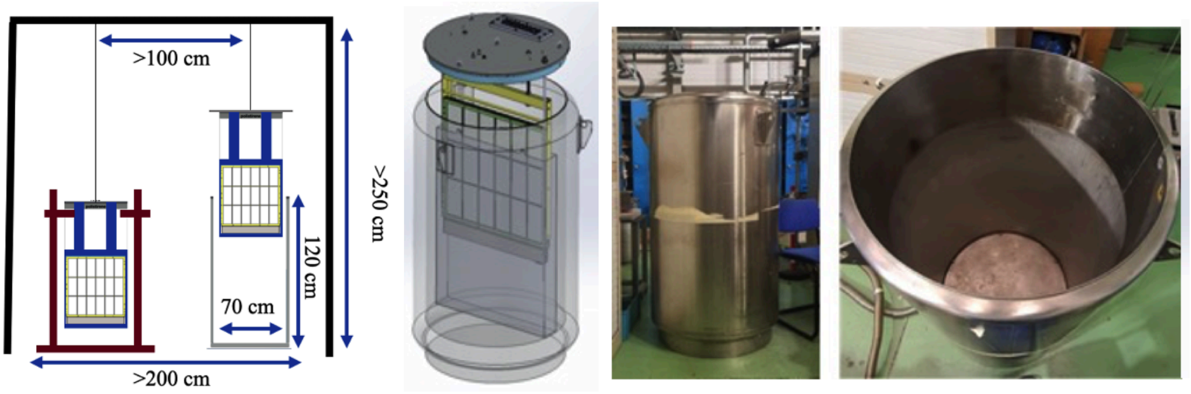


Figure 11. Cryo-test facility at CERN NP for full size XARAPUCA modules and read-out electronics tests.

Ref.: DUNE FD2 -VD Technical Design Report
FD2-VD TDR v.2 in EDMS

R14. Develop a schedule with milestones for technical decisions on each item still in development or optimization phase for concluding the optimization effort in time for the FDR.

A schedule with milestones for technical decisions was proposed and has been executed. Design validation has been completed (in time for FDR)

Options for critical items still in development at PDR time were resolved and baseline selected (or moved into risk mitigation opportunities, if applicable).

Recommendations #15 - Documentation and interfaces

R15. Complete the interface documents, with priority to the interfaces with the BDE electronics, HVS and cryostat systems and complete the approval process, to start a rigorous change control mechanism.

The interface documents with other subsystems have been evolving since the PDR and are anticipated to stabilize in advance of the FDR.

Ref.: DUNE FD2 PDS Interface

Consortium-consortium Documents in preparation

Recommendations #16 to #22 - Procurement, QA, risks, cost estimate and schedule

R16. Update the number of spares to be produced for the various components using a bottom-up process and an understanding of the yield and update the cost estimates accordingly.

Spare quantities were revisited by component and incorporated in the January 2023 FD2 PDS cost and schedule overhaul (See Documents *FDR FD2 PDS Cost and Schedule* linked below).

Ref.: FDR FD2 PDS Cost and Schedule
FD2 PDS Gantt Chart in EDMS

R17. Cross check the cost estimates provided in P6 to the latest estimates and update accordingly.

Cost estimates were revisited by component and incorporated in the January 2023 FD2 PDS cost and schedule overhaul (See Documents *FDR FD2 PDS Cost and Schedule* linked below).

Ref.: FDR FD2 PDS Cost and Schedule
FD2 PDS Gantt Chart in EDMS

R18. Rework the risk register and use it as a guide to prioritize work in order to refine the cost impact and reduce the probability of still open risks before the FDR.

The risk register was reworked in January and February 2023 in collaboration with Project management.

Ref.: FDR FD2 PDS Risk Register
FDR_FD2_PDS_Risk_Register (excel file) in EDMS

R19. As a risk mitigation, the option of all membrane-mount modules should be carried in case it is assessed that the design of the cathode-mount system will not converge within the required time.

The all membrane-mount topology has been retired.

R20. Pursue further testing options at CSU and Fermilab and secure the needed resources and priority to complement the plans for testing with the Cold Box at CERN.

Full module cold test facilities at INFN-Napoli, CSU, and FNAL were evaluated and incorporated in the January 2023 FD2 PDS cost and schedule overhaul (See Documents *FDR FD2 PDS Cost and Schedule* linked below).

Ref.: FDR FD2 PDS Cost and Schedule
FD2 PDS Gantt Chart in EDMS

R21. Update the procurement plan as soon as the baseline design for all the components has been finalized and the candidate vendors identified. This process must conclude before the FDR.

The procurement plan has been revisited by component and the module-0 experience has been incorporated in the January 2023 FD2 PDS cost and schedule overhaul (See Documents *FDR FD2 PDS Cost and Schedule* linked below).

Ref.: FDR FD2 PDS Cost and Schedule
FD2 PDS Gantt Chart in EDMS

R22. Develop a comprehensive QA/QC plan for production based on evolving experience including realistic time estimates for conducting the tests, the resources required, and the software tools required to store and access the results.

The QA/QC plan has been revisited by component, with time per unit estimates, and incorporated in the January 2023 FD2 PDS schedule overhaul.