EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

29 April 2024

NP02 2024 Annual Report to the CERN-SPSC

The ProtoDUNE NP02 Collaboration

Abstract
In this document we report general progress on the NP02 experimental activities at CERN since the last SPSC annual report.

Keywords
CERN-SPSC annual report; ProtoDUNE LAr-TPC; CERN Neutrino Platform.

CERN-SPSC-2024-019 / SPSC-SR-350
30/04/2024

Contents

1 Introduction

This document describes the continuation of the NP02 activities between April 2023 and April 2024, i.e., since the last SPSC annual report.

A significant progress was achieved within the DUNE collaboration in 2023 towards the implementation of the second DUNE Far Detector (FD2) module based on the Vertical Drift (VD) technology. This process included the Final Design Reviews for all the TPC components of FD2.

The VD tests at the Neutrino Platform and its successful achievements in 2021 and 2022 have been accurately described in the 2022 and 2023 reports. These reports include the performance assessment of the VD Charge Readout Planes (CRPs) both in the top-drift and bottom-drift configurations, as well as the first validations of VD Photon Detector (PD) cold electronics (CE) readout solution with Power-over-Fiber (PoF) and Signal-over-Fiber (SoF) proposed for the electrical isolation of the cathode-mount X-ARAPUCA modules.

Following the initial planning, the final design top-drift full Charge Readout Planes (CRP2 and CRP3) were tested successfully in the NP02 Cold Box. These two CRPs were then installed inside the NP02 cryostat at the end of 2022, after having disconnected and removed the existing dual-phase detector elements. The development of the FD2 Photon Detection System (PDS) also, according to initial plan, was entirely based on the cold-box test and validation campaign at the Neutrino Platform. A series of successive prototypes of double-sided cathode-modules and single-sided membrane-mount modules with dedicated CE readout boards, were produced and tested and strongly benefited of the opportunity of operating in actual experimental conditions in liquid argon (LAr) on the HV cathode and in combination with the top-drift CRPs. These activities allowed to finalise the PDS design for FD2, and to produce (fall 2022) and integrate in Module-0 (Jan 2023) 8 cathode-mount modules with on-board PoF/SoF electronics and 8 membrane-mount modules with CE electronics via standard copper cable transmission.

The cold-box tests campaign continued in 2023 in order to test the bottom-drift Charge Readout Planes (CRP4 and CRP5) and the successive, further optimized versions of the PoF/SoF based CE boards for the cathode modules of the PD system. The Module-0 programme implies equipping and rerunning the NP02 cryostat with the VD CRPs, VD PDS and other components such as the final High Voltage system (cathode, HV feedthrough and extender), in order to establish their integration and overall operation for the DUNE FD2.

The VD installation in the NP02, including two top-drift CRPs, two bottom-drift CRPs, 8-membrane and 8-cathode PD modules with state-of-the-art r/o cold electronics is presently under completion, with the goal of closing the cryostat in 2024 and filling it with LAr before the end of the year or at the beginning of 2025 at the latest. This report includes the description of the current status and planning for the continuation of the Module-0 activities.

In conclusion, since the last SPSC annual report of 2023, despite the very ambitious VD development schedule, there was excellent progress in achieving the foreseen experimental program and maturing the VD design to a final design level, preparing for the production readiness reviews in 2024 and/or early 2025.

2 CRP upgrades

The CRP activities since the previous SPSC report has mainly focused on the optimization and simplification of the anode panel construction. As reported previously, the anode planes for the FD2-VD provides three-view charge readout using two stacked, perforated PCBs with biased strip electrodes on one or both faces. The three sets of electrode strips are set at different angles relative to each other to provide charge readout from different projections.

In the first half of 2023, following the successful construction and testing campaign of the four Module-0 units, the CRP design details have been finalized. The strip orientations (+30°, -30°, 90°), strip pitch for the collection (5.1 mm) and induction (7.65 mm) channels, the total number of readout channels for each CRP (3072) and the composite frame designs were finalized and frozen.

Following the design finalization, a dedicated value engineering campaign for the anode panel construction has been conducted. As it was described in the previous reports, Module-0 anode panels were constructed by gluing six 3.2 mm thick, rectangle, double-sided perforated PCB segments together. Gluing process included preparation of each PCB segment, application of epoxy to the bounding surface, alignment between the neighbouring segments, treatment under vacuum for one day. Once the PCB segments were mechanically bonded to form an anode panel, electrodes on the induction-1, induction-2, and collection planes were bridged by screen-printing conductive ink patches onto them. Conductive ink is a silver filled epoxy, which need a special heat treatment around 120 °C for its polymerization. Once it is polymerized it becomes conductive. Both PCB gluing and application of conductive ink were labor intensive and time consuming processes during the Module-0 CRP construction. They required dedicated tooling and well controlled QA/QC procedures. Especially, conductive ink application on thousands of connections on each CRP was prone to mistakes and non-responsive readout channels.

In order to overcome the complications related to the gluing and conductive ink application, as well as reducing the construction time and cost, a new anode panel construction method has been developed. The new method replaced the six 3.2 mm thick double-sided rectangle perforated PCB segments for each anode panel with fourteen 1.6 mm thick one-sided segments. The new PCB geometry followed the strip orientation on each corresponding readout plane. This resulted into rectangle segments for shield and collection and trapezoid segments for the induction planes. With these new PCB segment geometries the conductive ink application is no longer required.

An anode plane is then constructed by bonding two corresponding planes to each other (shield and induction-1 or induction-2 and collection). Bonding is performed by the 3M-VHB double-sided tape. 3M is laminated on the shield and collection segments, and then perforated during the PCB production at the manufacturer site. Construction starts with laying down eight induction-1 (induction-2) segments on an optical table with their copper image facing down to the table. Then, the six shield (collection) segments are aligned and glued on the induction-1 (induction-2) segments by the 3M-VHB. The glued panel is kept under vacuum for an hour to remove any possible small bubbles that may be formed during the gluing. Figure 1 shows the details of the new PCB segments and an anode panel construction details.

In addition to the anode construction upgrades, improvements on the design of edge cards and of the

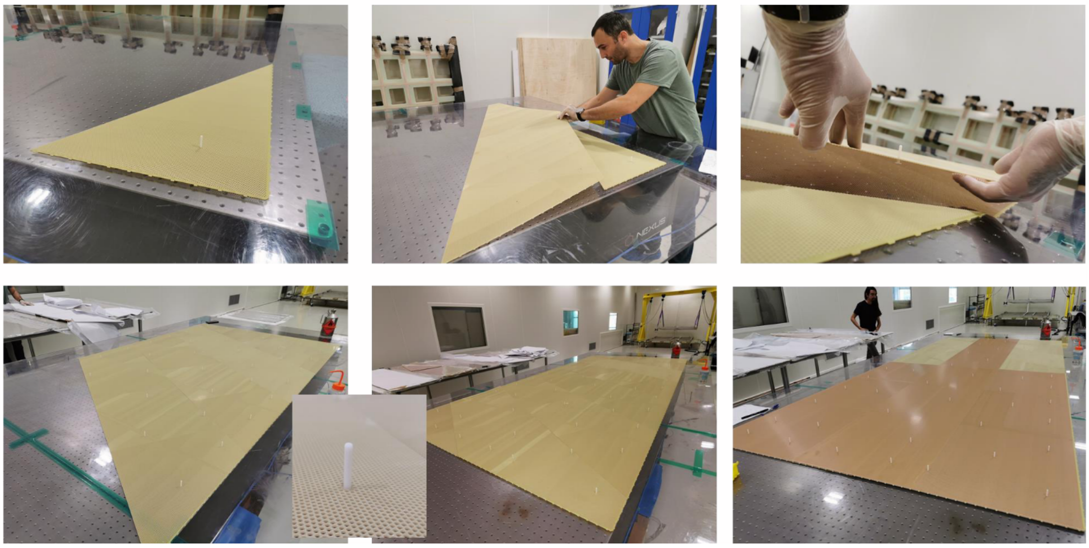

Figure 1: Various photos showing the details of new 1.6 mm thick one sided PCB segments and anode panel construction.

composite frames are also worth mentioning. Edge card design has been modified in order to minimize any possible mechanical pressure on their connectors. Regular openings on the cards were matched with the small teeth like structures on the anode panels. This provided uniform gap between the anode panels and minimized possible pressure on the edge cards. Based on the lessons learned from the CRP-4 and CRP-5 (bottom CRPs in NP02), the bottom composite frame design has been slightly modified to address Bottom Drift Electronics (BDE) cable routing request. Few openings on the structure allowed power and data cables to be routed within the frame. In addition, a thin bronze mesh was integrated into the composite frame to address the ground plane requirements of the BDE in a simplified way. Figure 2 shows mechanical rectification on the edge card structure (left) and openings in the composite frame structure for the cable routing (right).

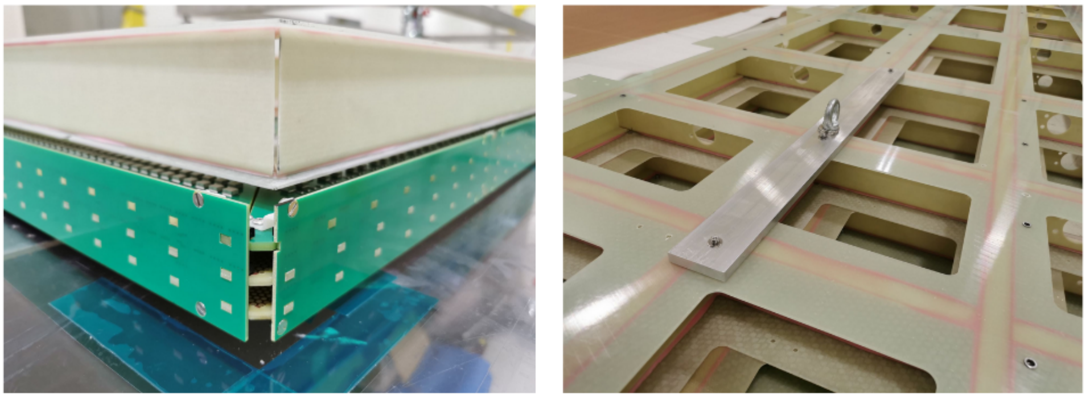

Figure 2: Left: new edge cards with regular openings to have better engagement with the anode panels and adapter boards. Right: Bottom CRP composite frame and openings for cable routing within the structure.

With the upgrades described above, two new CRPs were built, i.e. a Bottom (CRP-6) and a Top (CRP-7), at CERN from autumn 2023 to early 2024. Figure 3 shows the fully assembled CRPs in the clean room at Blg-185. CRP-7 assembly was performed using tooling developed by the Grenoble group for the CRP factories. This provided valuable feedback for the CRP assembly procedures and tooling for

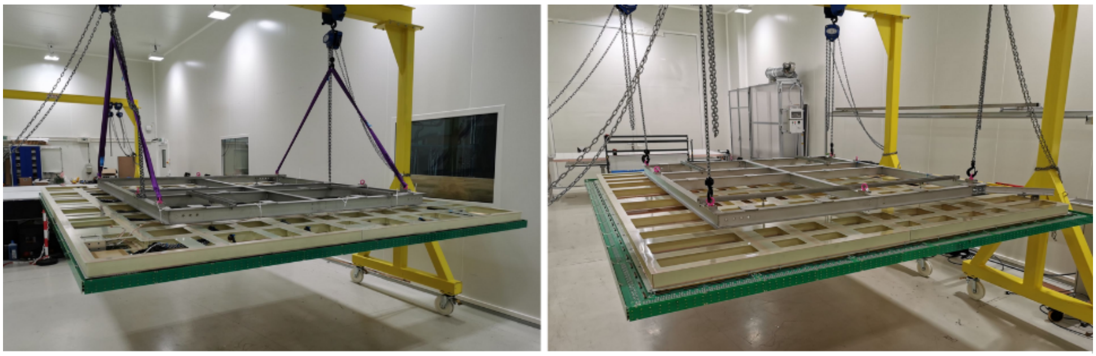

Figure 3: CRP-6 (left) and CRP-7 (right) that were assembled after various upgrades at the component level.

the DUNE FD2 production. Four companies were contacted for the production of the new perforated PCBs. Samples were purchased from Tecnomec S.r.l. and ALBA PCB. Then the full production for the prototypes were performed by ALBA PCB. Details of the cold-box test with CRP-6 are presented in Section 4.

3 Advancements on the Photon Detector System

According to the baseline design of the Vertical Drift FD2 Module, the PD modules (thin, large area X-ARAPUCA light trap photo-collectors with SiPM photo-sensors) will be installed behind the TPC filed-cage walls, along the corrugated SS membrane of the cryostat and embedded on the HV cathode thin structure, that separates the top and the bottom drift volumes of the TPC. Operating the PD modules on the cathode HV surface requires electrically floating photo-sensors and read-out (r/o) electronics. Power (IN) and Signal (OUT) must then be transmitted via non-conductive optical fiber cables. Power-over-Fiber (PoF) and Signal-over-Fiber (SoF) technologies can be employed for voltage isolation between source/receiver and embedded electronics in high voltage environments once developed for cold applications and low power dissipation in LAr. The main components of an electrically isolated PDS for the DUNE FD2 VD module are schematically represented in the block-diagram of figure 4.

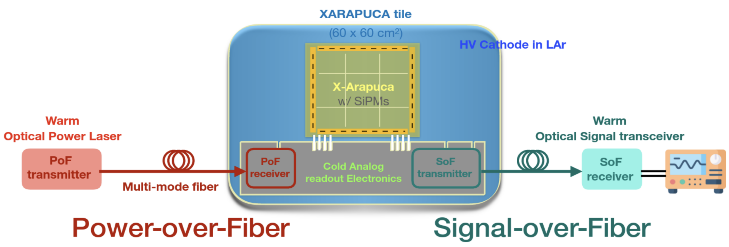

Figure 4: Cartoon of the PoF and SoF implementation for the FD2 PDS.

The development and the Cold Box test runs at CERN (in late 2021 and in 2022) demonstrated the innovative cold PoF-SoF technology for voltage isolation of the FD2 photon detector, immune from noise injection and signal distortion, and adequate for light signal transmission. The reviews of the FD2 PDS (Apr. 2023) came with a collection of recommendations looking toward the complete optimization of the cold r/o electronics, the finalization of the warm r/o stage (Signal-over-fiber output conversion and digitization), the integration with DAQ and other systems, and the preparation for mass production. These recommendations led to a large set of intense activities in the remainder of 2023 and in 2024 so far, such as the long-term testing of the cold electronics, the stability and tuning of the gain of the signals, channel to channel variation minimization, and - most prominent - the integration of the SoF conversion stage with the DAPHNE digitizer at the warm end of the FD2 PD electronics chain.

In parallel to the complete development of the electronics system, carried at FNAL, APC and INFN-MiBi and with validation tests at CERN Cold Box (see Sec.4.1), dedicated studies and lab test (INFN-Naples and CIEMAT) have been carried on the FD2 X-ARAPUCA detectors' efficiency. The results from these efforts, showing good efficiency within and beyond design expectations were first presented in July 2023 and confirmed in early 2024.

4 Cold Box tests

The Cold Box is an instrumental tool for the development, tests, and the characterisation of CRP and PD systems. Tests of full size components are possible in the Cold Box, which was used multiple times since the beginning of the test of the NP02 components. The Cold Box allows a quick turnaround cycle in TPC mode where electronics, PDS and CRP, and their integration are tested.

4.1 CRPs

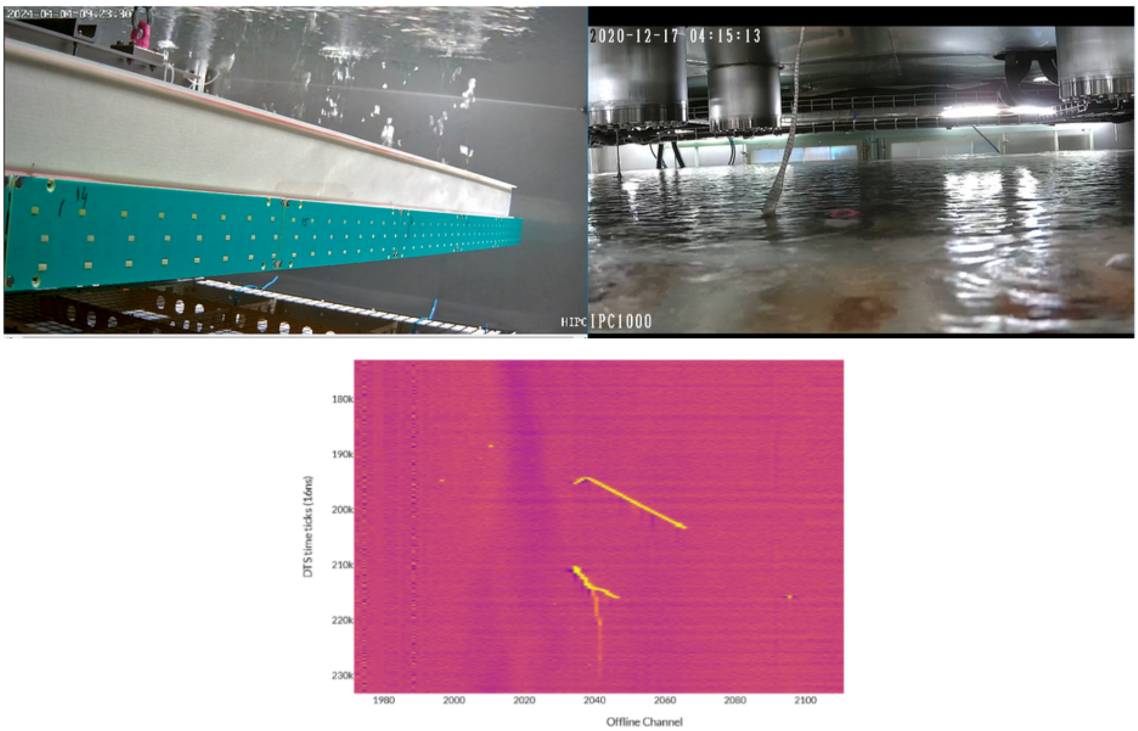

Figure 5: Top: CRP-6 submerged into the LAr and read to start data taking. Bottom: An example of a collection plane view of a cosmic ray track recorded with the CRP-6.

The first Cold Box test with CRP-6 was performed in November 2023. Figure 5 shows a nice image from CRP being submerged into the LAr and ready to start data taking, together with a cosmic ray track recorded right after nominal fields were set. The results showed that the new thin mesh based ground plane is not effective and noise levels were higher than the required levels. For the second cold-box run in January 2024, the ground plane of the CRP-6 was rectified and its positive effects on the noise levels were demonstrated. However, the second cold-box test revealed two new issues with the CRP-6: high and low noise channels on two corners of the CRP and non-uniform charge collection performance at the nominal fields, as already observed during the first run. Once the second cold-box run was finalized, the corners where the problematic channels are situated were inspected in details. Further tests on the corresponding edge cards and adapter boards did not show any unexpected features. Detailed investigations on the problematic channels are ongoing. On the other hand, the non-uniform charge

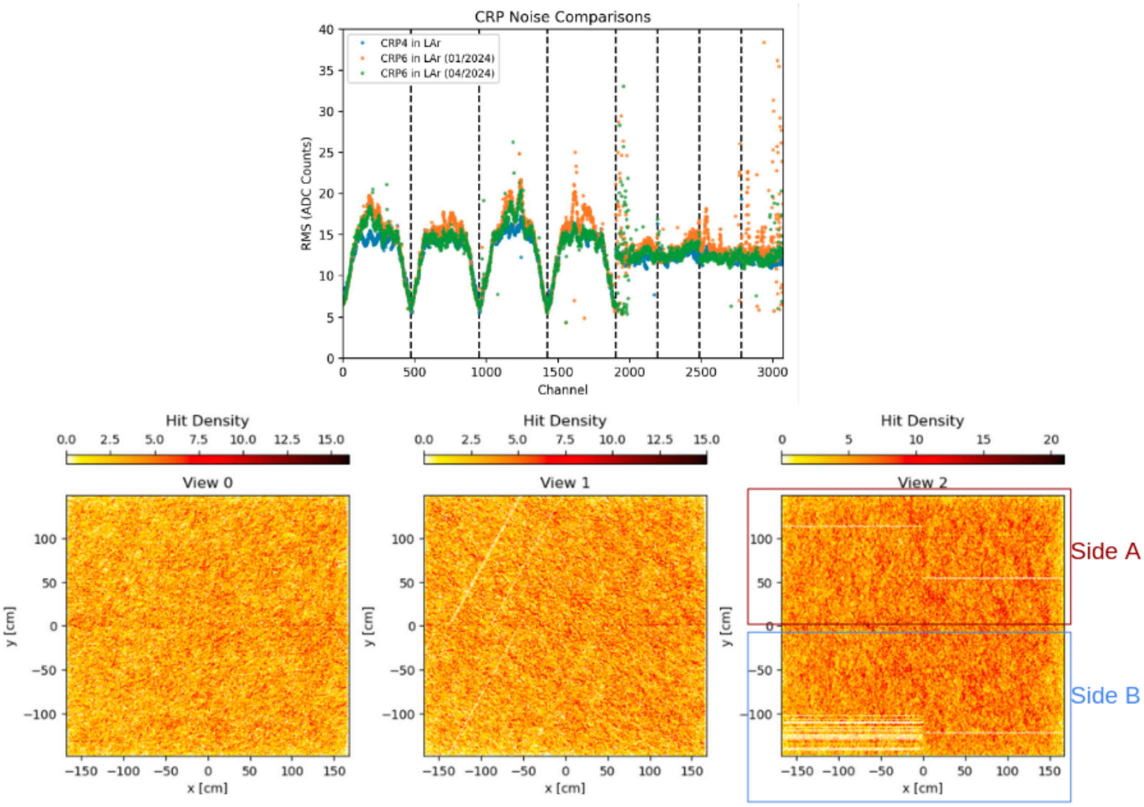

Figure 6: Top: CRP-6 noise levels at the second and third cold-box runs in comparison with the CRP-4 Bottom: Hit density distribution of the CRP-6 during the third cold-box runs where the reduction of problematic channels on side-A is clearly visible.

collection performance has been understood and associated with the not-fully transparent (for electrons) readout layers. The lack of full transparency at the nominal fields is a result of smaller effective hole size which is caused by partially overlapping holes between the stacked PCB segments. Visual inspections and image processing based analysis of the PCB segments has demonstrated non-conformal segments and ∼150 μm hole pattern shift in every 50 cm. Discussions with the vendor has concluded that the shift is coming from the PCB drilling process which was done in multiple steps where each step had 50 cm width. Further iterations with the vendor (also alternative ones) are ongoing to address the observed issues and produce new corrected PCB segments.

In order to extract more information about the observed issues and to see the effect of few small modifications, the third cold-box test with the CRP-6 was performed in April 2024. For this run, a new ground plane aiming at shielding also the power cable of the bottom drift electronics was installed on the CRP-6 A-side, edge cards on the problematic corners and the adapter board on side A problematic corner were replaced. As a result, noise levels on the A side were significantly improved and are brought down to the same levels as for CRP4 and CRP5 (see the top image in Figure 6). Presence of problematic channels on side B, which was not modified, remained similar while the number of open and high noise channels improved significantly on side A (see the hit density plots in Figure 6).

4.2 PDS

The sequence of NP02 Cold-box runs carried at Neutrino Platform (2023-24) provided functional and essential opportunity for the development and qualification for the Photon Detection System and its integration with the HV system and the CRPs and into DAQ.

Two production cycles of CE motherboards (DCEM) with optimized PoF receivers, SoF transmitters, DCDC converters and OpAmp components were tested, and a number of optimisations were introduced, on X-ARAPUCA mechanical and optical design, including a light-leakage protection kit to prevent disturbance from residual light from PoF receivers in the electronics box.

As an example of test results from recent CE optimization, the distribution of the signal amplitude from PD under LED calibration test pulse low illumination from DAPHNE read-out is shown in figure 7, on the left a persistence plot and on the right the single and multiple PEs signal amplitude distribution, showing high signal-to-noise ratio achievable with the latest electronics optimization.

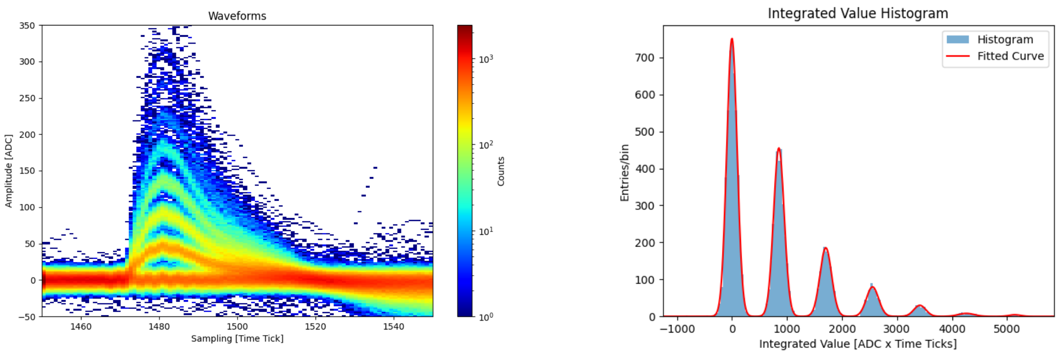

Figure 7: Photoelectron amplitude spectrum in low light levels. Left: Persistence Plot. Right: PEs signal amplitude distribution.

The analog chain integration using the newly developed ARGONRec board for SoF-to-DAPHNE interface has been demonstrated in the different Module 1 iterations (see Figure 8).

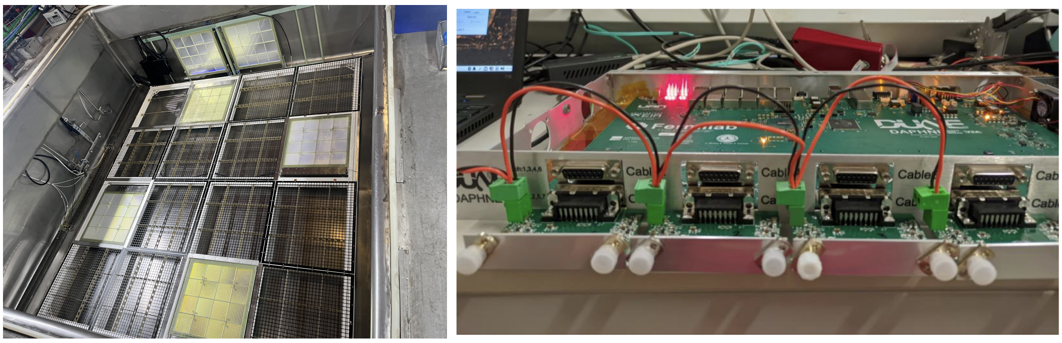

Figure 8: Left: PD Cathode Modules in the Cold Box. Right: (ARGONRec) Receiver for SoF signal and integration with DAPHNE.

In addition to hardware integration with DAPHNE, the PDS group is implementing firmware integration with the DAQ. Multiple booting, configuration, calibration, and operation tools are now in place for DAPHNE and the respective calibration system, and many of those have already been tested successfully at NP. We have proved we can automatize the calibration of the PDS detector using the calibration module, triggering both subsystems using commands from the timing interface (see Figure 9).

4.3 PNS run in the VD Cold Box

The Pulsed Neutron Source (PNS) run was conducted in the VD Cold Box in April 2024 to study the feasibility of using neutron capture as a standard candle for the absolute energy scale calibration of PDS

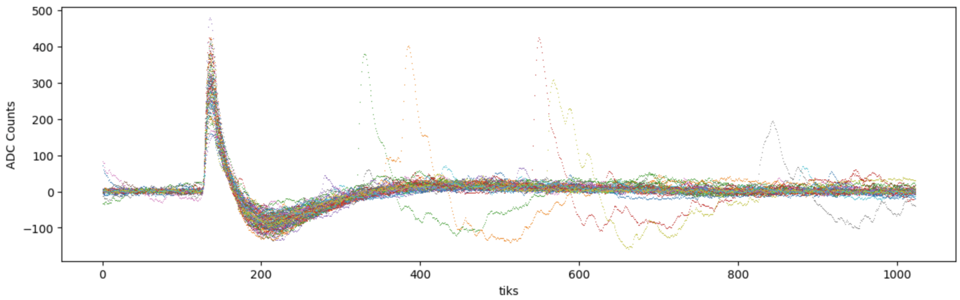

Figure 9: Pulses from the Calibration Module triggered by the timing command integrating the entire DAQ chain.

data. The primary objective of the run was to identify neutron capture signals using PDs. In addition, this run opened up an opportunity to look at the low energy neutron signals simultaneously from both PD and CRP readouts.

Installation: Neutrons were generated using a commercial Thermo Fisher $MP - 320$ Deuterium-Deuterium Generator (DDG), which produces mono-energetic 2.45 MeV neutrons with a flux of up to 10^6 neutrons per second. The PNS was installed on one of the side of the Cold Box as shown in Figure 10, with the neutron beam direction along the center of the active volume. The DDG was shielded on three sides by approximately 18 cm of polyethylene. The front face of the DDG was surrounded by lead blocks with thicknesses ranging from 5 to 10 cm, featuring an opening of approximately 12 cm $\times$ 12 cm. For safety, all doors allowing access to the Cold Box were interlocked such that the DDG turned off as soon as any door was opened.

Figure 10: PNS installation in VD Cold Box, Left: Yellow marker indicates the location of the PNS as seen from the top, Right: Polyethylene shielding covering the DDG.

Operation: The Radiation Protection team conducted an inspection on April 15, 2024, and upon inspecting the radiation levels at the maximum neutron production rate, the team approved the PNS run. Data collection for the PNS run commenced on April 16, 2024. A combined PDS and TPC data set was collected using the DAQ triggered by a TTL pulse synchronous with the neutron beam. During data collection, the PNS operated in burst mode with a pulse width of 400 microseconds, and the data acquisition window was approximately 1 ms. In addition to the PDS + CRP data collected over approximately 18 hours at a 4 Hz rate, we gathered around 2 hours of PDS-only data at a 40 Hz acquisition rate. The PNS operation spanned from April 15 to April 19, 2024.

Preliminary Studies: Shortly after obtaining the first data set, we began searching for indications of neutron captures in the PDS and CRP data. Figure 11 shows the number of peaks above 40 ADC counts for the PNS ON and OFF runs for the PDS channel closest to the PNS for the same number of readout windows (events). Figure 12 shows the number of single hits for PNS OFF and PNS ON run. With PNS ON we see a higher density of single hits closer to the PNS location. These preliminary plots indicates evidence of neutron capture in Argon. Further analysis of the PNS data is currently ongoing.

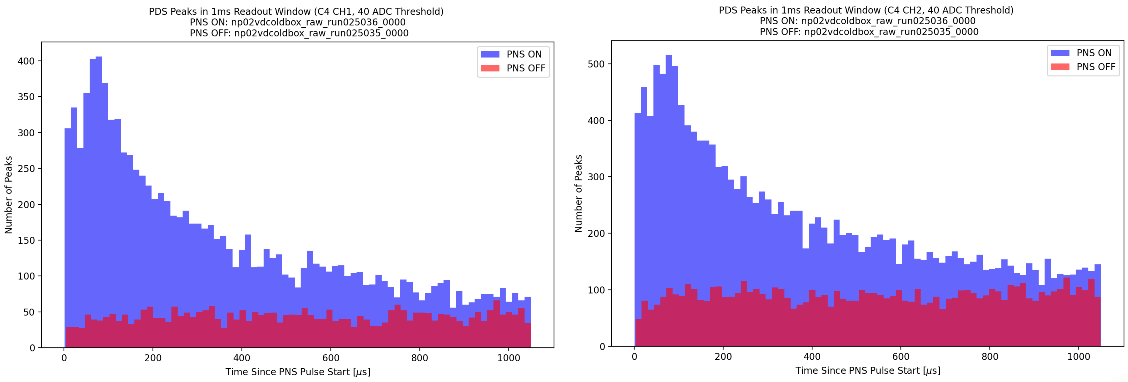

Figure 11: Number of peaks above a threshold of 40 ADC counts for PNS ON and PNS OFF runs for the X-ARAPUCA module closest to the PNS (C4). The number of events in all the distribution are equal, however there are fewer number of peaks above threshold of 40 ADC counts for PNS OFF distribution. Left C4 Ch1, Right C4 Ch2

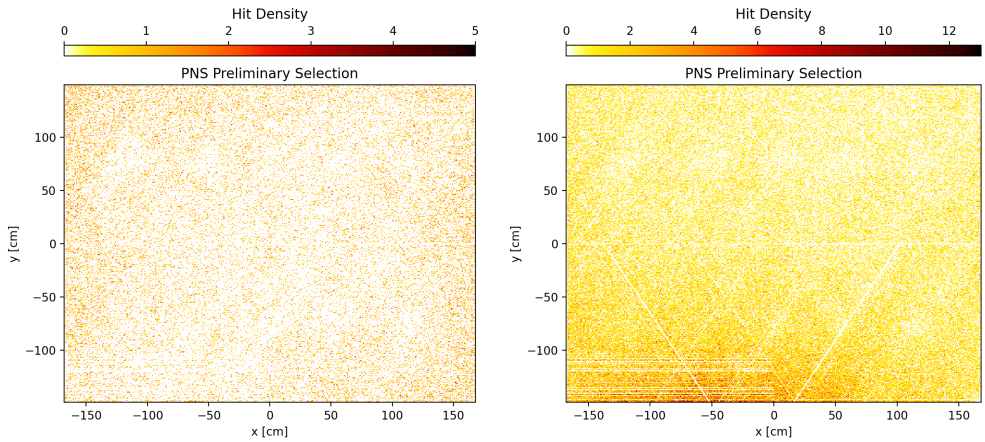

Figure 12: This is the (x,y) [i.e. looking from above] density plot of single hits selection for a CRP6 run without PNS (run 24772, left plot) and with PNS turned ON (run 25036 right plot). We can see a higher density of single hits closer to the PNS location for the right plot.)

5 Module-0

The Module-0 integration offers a large scale test with final detector elements. A 3D model view is shown in Figure 13. The design has been optimized to help validating most of the procedures foreseen for the DUNE Far Detector 2, from the transport of the detector components to their installation inside the cryostat.

Two CRPs are located at the top and two at the bottom. The cathode units are suspended from the top CRP supporting structures. The cathodes integrate the X-ARAPUCA photon detectors. Additional photon detectors are hanging along the cryostat membrane. The modular field cage surrounds the drift volume and is made 70% transparent at the level of the Photon detectors on the cryostat membrane. The

HV Feed-through and Extender are located right (Jura) side of the field cage. A beam plug, similar to that of NP04 is also planned (not shown in the picture).

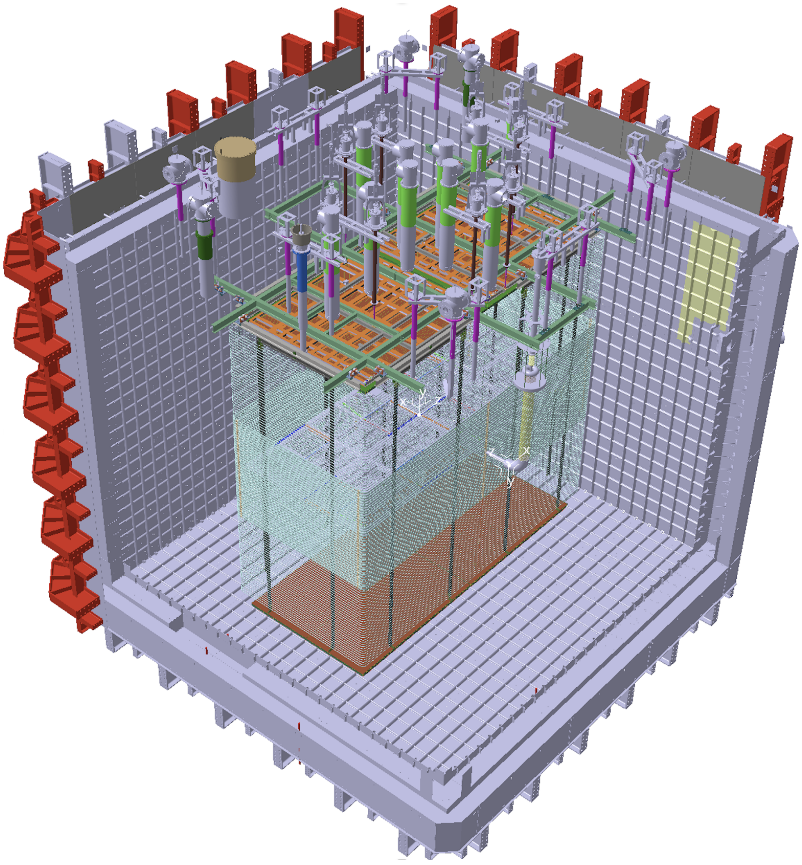

Figure 13: 3D view of the Vertical Drift Module-0 detector inside the NP02 cryostat. The TCO is located on the bottom left side.

5.1 PDS

The developments, the production, and the QA/QC test processes for the Photon Detector system in 2022 enabled the installation in early 2023 of 8 double-sided X-ARAPUCA modules, with readout CE by Power- and Signal-over-Fiber, on the cathode of the Vertical Drift Module-0 LArTPC inside the NP02 cryostat at EHN1. In addition, 8 single-sided X-ARAPUCA modules, with CE powered by traditional copper cables, were also installed on the membrane walls of the cryostat. Cables and fibers were also installed and routed toward the dedicated penetration on the NP02 cryostat roof. Figure 14 shows the modules installed in NP02.

Successively, in the course of 2023, 4 Cathode-mount X-ARAPUCA modules and 2 Membrane-mount modules with optimised PhotoCollector optical solutions and with state-of-the-art CE readout boards - from successive generations of development/iteration and production during all 2023 and first part of 2024 - were installed and tested in Cold Box (April 2023, January and April 2024). Optimal performance and reliability of the readout CE (both for Cathode and Membrane modules) were demonstrated from the most recent CB runs in 2024, definitely superior in all aspects of performance w.r.t. the previous generation CE production (fall 2022) currently implemented in NP02 Module-0 (PD installation in Jan. 2023) - and now baselined for production for FD2 PD.

After the January 2024 Cold Box run and in view of the NP02 demonstration run in fall, it was then proposed to the DUNE FD2 Technical Board and to Neutrino Platform to replace the CE electronics boards (DCEM 1.2) of the 8 NP02 Cathode-mount PD modules, shown in Figure 14, with the current new production (optimized DCEM 1.3.1 and corresponding sub-elements).

Access to the cathode in NP02 for this replacement was found technically possible, by removing the lower portion of the Field Cage panels (which is already performed) of the TPC and by installation of a lightweight Aluminum platform/bridge above the bottom CRP plane, across from side to side of the NP02 false-floor. The sequence of extraction of the PD modules from the cathode, replacement of the components and re-installation has been defined in detail, including time, resources and the team on the ground needed, and the swap approved for the period May-June '24, in time before TCO closing in July. Procurement of parts is well advanced and, at the time of writing, the first steps of the swap started at Neutrino Platform and inside NP02.

The CE exchange for the cathode-mount PD modules also allows to implement and experience mounting solutions and warm tests procedures re-designed for FD2, as for example the PoF fiber termination with the Optical Power Converters (OPC), directly mounted at the end of the PoF fibers, and the new electronics box for the DCEM board with its light leakage protection kit.

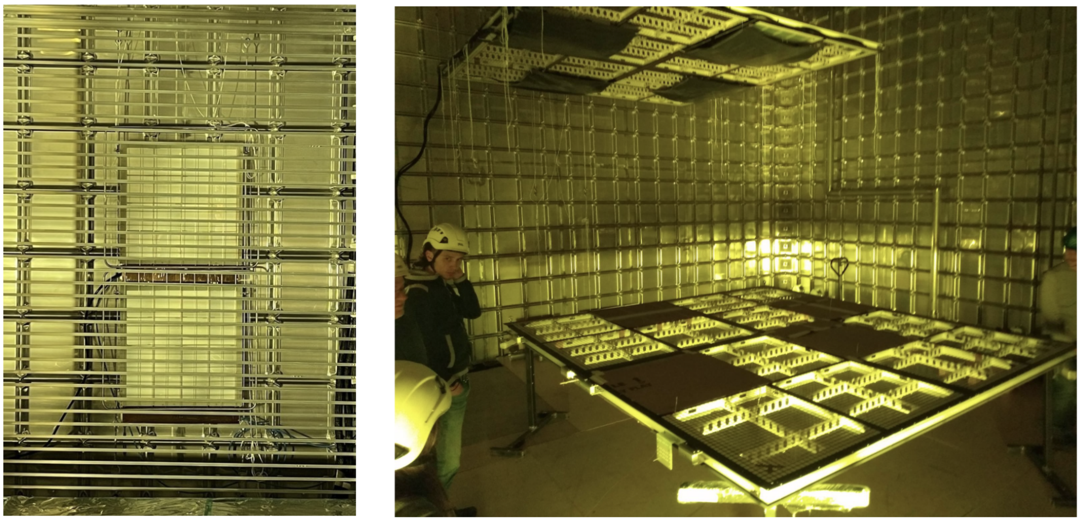

Figure 14: Photos of PDs installed in NP02 on the walls (left) seen through the field cage and on the cathode (right).

5.2 CRPs

The two top CRPs (CRP2 and CRP3) built, tested and validated in the Cold Box constitute the top plane of Module-0 while the two bottom CRPs (CRP4 and CRP5) constitute the bottom plane. The top CRPs have been installed in the cryostat in January and February 2023 while the two bottom CRPs have been installed in March and May 2023. The only worth mentioning activity related to the CRPs in Module-0 were regular noise runs with the top and bottom CRPs to monitor their status. In one of these regular noise runs in August 2023, $\sim$30 open channels were identified on CRP-5 in the region close to the TCO opening. Broken connectors were found once the corresponding edge cards were removed for inspection. Based on the full stability of the top CRPs measured since their installation, and the fact that the problematic region on CRP-5 was being located where the human activity (passage) was maximum, makes us to believe the problem is related to the installation activities inside the cryostat. All 12 edge cards in the problematic region have been replaced with new boards, and given the activities inside the cryostat have been minimal since then, no new open channels have been observed.

5.3 HV System: Cathode, Field cage and HV delivery

During 2023, the installation of the HV Field Cage (FC) was completed by hanging the lower panels to the already installed top and middle ranges of the FC. This operation was performed after the bottom CRP's were in their final position, fully cabled and validated in terms of electrical continuity and electronic noise. The FC electrical connection to the Cathode HV bus and to the ground (via the termination boards with voltage and current monitoring) was also executed and validated. The HV extender and the new HV feedthrough (HVFT) were also installed and electrically connected to the Cathode HV bus. The optical fiber bundles for the PoF and the SoF of the X-ARAPUCAs located in the cathode were routed from the cryostat floor to the cathode along the the bottom FC panels at the Jura side. The fibers are inserted inside C-shaped FRP beams, supported by the FC panels. The FC's stability and verticality was not affected by the addition of the fibre bundles. Figure 15 shows pictures w of the High Voltage system installed in NP02.

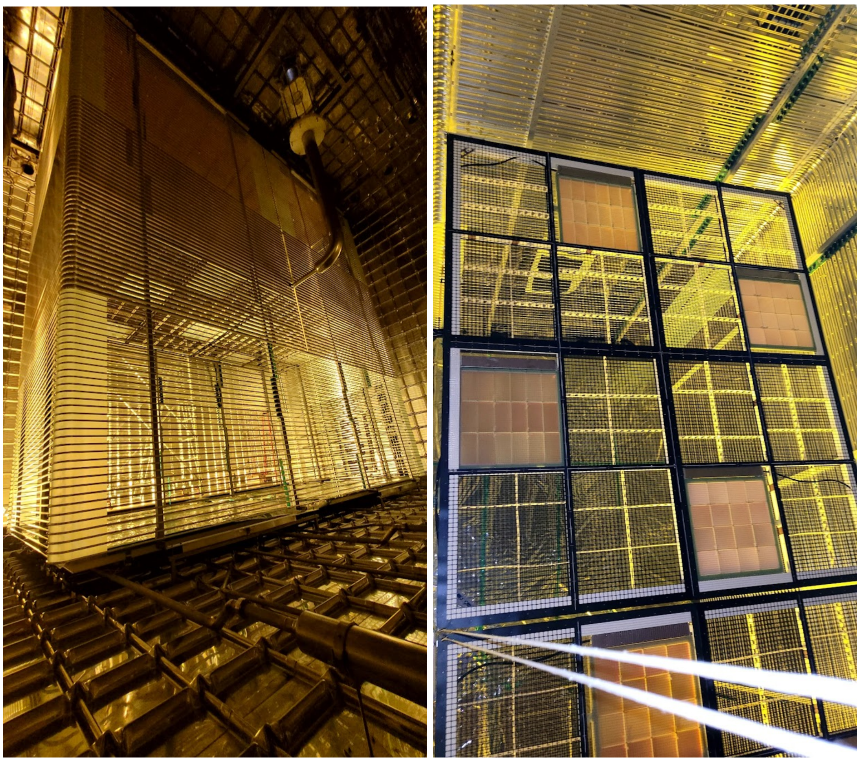

Figure 15: Pictures of the of the Vertical Drift Module-0 High Voltage system. inside the NP02 cryostat. Left: the Field Cage with thin and thick profiles and the HV Extender suspended from teh cryostat roof. Right: view of the Cathode suspended with Dyneema cables from the CRP supporting structure and surrounded by the field cage; the X-ARAPUCA PD modules integrated into the cathode modules are also visible.

The HVFT was temporarily removed in fall 2023 for long term validation tests in stand-alone mode at 300 kV. A first test run was successfully executed at the end of 2023 for about two week in a dedicated test stand, see Figure 16. A second test, to confirm the mechanical and electrical reliability of the HVFT after cryogenic thermal cycles, is planned in May 2024. The HVFT will be eventually installed in NP02 in view of the operation with the VD Module-0. At the same time the HV Power Supply (the same used for the NP02 run in 2022) and the HV cable will be installed.

In early 2024 a survey of the planarity of the cathode modules was carried out by the CERN Survey team. The results, shown in Figure 17, confirmed a maximum bowing of 2 cm at the center of the cathode modules. This matches the prediction obtained by Finite Element Analysis on the cathode 3D model.

Figure 16: Left: the new 300 kV HV feedthrough for NP02 being tested in standalone mode. Right: the test stand of the HV feedthrough for long term stability validation.

Together with a recent measurement of the Young module of the Cathode Frame beams at warm and at cryogenic temperature, this result consolidates the prediction of less than 1 cm for the maximum bowing of the cathode in LAr. This is contributing to the uncertainty on the drift distance and on the average electric field for less than 0.3 %. This parameter will directly be verified in LAr with the measurement of the track lengths of vertical cosmic muons.

The survey also indicates that, one year after installation, the Dyneema cables supporting the Cathode did not suffer of any elongation within the 1 mm measurement uncertainty.

As explained in the previous section, in March 2024, it was decided to replace the front end electronics of the X-ARAPUCA located inside the cathodes. For this purpose, all bottom panels of the FC were dismounted and stored along the walls of the NP02 cryostat. This operation was performed quickly and without any damage to the aluminum profiles, to the electrical components, to the optical fibers and to the bottom CRP. The reassembly of the Field Cage is planned in June 2024 after the X-ARAPUCAs have been upgraded.

The plans for the NP02 HVS commissioning and operation are the following.

Validation at "warm" before cryostat sealing: (1) ramp-up the FC termination PS channels up to nominal voltage (-1500 V) Keeping the CRP bias grounded; (2) ramp the HV up to 16 kV (10% of nominal Voltage on the Cathode) in few kV steps; (3) monitor the sum of all currents (HVPS and FC terminations) which should be constant at all HV PS voltage steps.

During purging, cool down and filling: (1) keep the HV PS and FC terminations activated; (2) monitor the current variations due the resistors values change with temperature; (3) activate cameras pointing at the Field Cage and the Beam Plug.

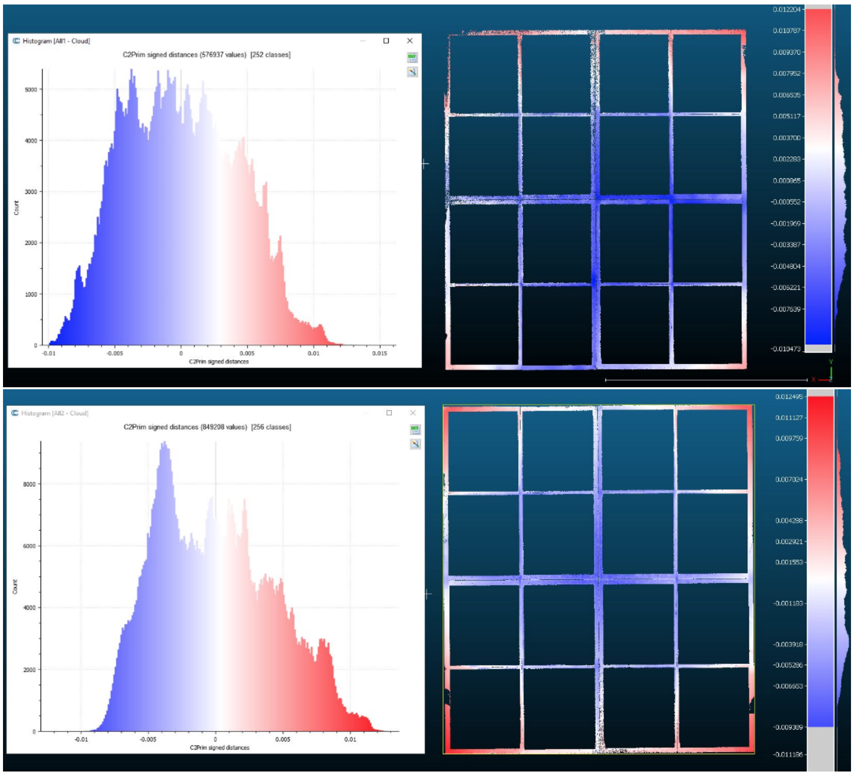

Figure 17: Result of the cathode planarity survey for the two cathode modules. The 2 cm central bowing matches the expectations.

After the filling with LAr is completed: (1) prepare to ramp up the Cathode and the FC terminations to the nominal voltages of -160 kV and -1.5 kV respectively; (2) the ramping up will be performed in steps of 10-15 kV at a rate of 200-500 V/s; (3) at each step, the HV's will be kept unchanged for several minutes to allow insulation surfaces exposed to electric field in LAr to properly charge up; (4) when nominal values are reached, monitor HV stability (currents, streamers) also with help of cameras (as in the past NP02 operations) while monitoring LAr purity; (5) the HV-PS and the FC terminations will be kept at the nominal values for most of the NP02 operation program unless different conditions are requested from BDE/TDE or PDS.

In case of Xe doping, the HV conditions should not be affected (as in the previous NP04 and NP02 operation).

Toward the end of the NP02 operation, a further HV test is envisaged: (1) ramping up (in steps) of the Cathode Voltage possibly up to -300 kV; (2) the biasing voltages (and the FC terminations) cannot be increased accordingly, resulting in a reduction of the transparency of the CRP shield layer for drifting electron.

If successful, this test will validate the FC distance from the membrane (70 cm) at the nominal HV conditions in FD2. Another possible test is the validation of the PDS-on-cathode robustness against HV instabilities, by inducing a controlled discharge of the Cathode HV.

5.4 Beam plug

The design of the beam plug and its supporting structure was finalized and structurally validated in 2023. The construction started in early 2024. The beam plug is split into two parts of the same length (about 2.m) and coupled together with CF flanges. The section facing the cryostat membrane is made out of stainless steel while the section facing the Field Cage is realized with a G10 tube with glued SS end caps. The construction of the two parts is completed; testing in vacuum and in cryogenic bath is ongoing, following procedures developed for the NP04 beam plug. A Stainless steel tower will support the beam plug at about 5 m from the cryostat floor, higher than the cathode level. To account for the high electric field in the surrounding of the cathode, a careful detailed study has been performed focusing especially on the shapes of the tower elements, potentially critical for electric field stability. With the beam plug split into two parts, it can be installed in its final location after the full VD detector is assembled. The two parts are inserted into the cryostat through the TCO or the manhole, moved to the "cryogenic side" of the cryostat along the short detector side, connected together on the false floor, lifted to the final location and placed to the supporting structure. This operation is planned at the time of the TCO closure (details are being finalized). Fig. 18 shows the 3D model of the beam plug and the supporting structure integrated into the NP02 cryostat as well as a picture of the G10 section of the beam plug being tested for vacuum tightness ready for the subsequent immersion in liquid nitrogen.

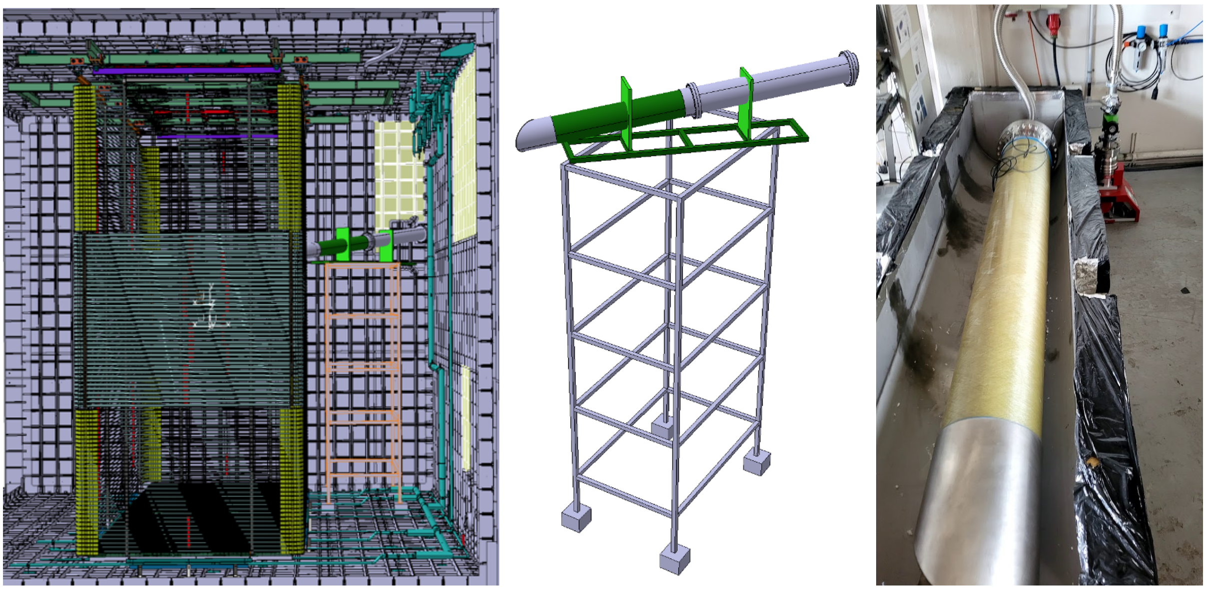

Figure 18: Left: 3D model of the Beam plug and the supporting structure integrated into the NP02 cryostat. Center: details of the two sections of the Beam Plug and the supporting tower. Right: picture of the G10 section of the Beam Plug being tested for vacuum tightness before immersion in LN2.

6 Integration tests

The installation of the Module-0 detector thoroughly developed the electrical tests needed for the installation of the DUNE far detector and it provided valuable insight into the mechanical installation process. However, due to the different interfaces to the far detector cryostat many of the mechanical installation steps have not been prototyped. After the Module-0 detector was installed the DUNE installation plan was reviewed and the steps in the installation that were not realistically tested in the Module-0 installation were identified and a set of goals for a dedicated mechanical installation prototyping campaign were established. The goals of the future tests are a follows:

- Test the cable tray installation and cabling of the top CRP,
- Prototype the construction of the CRP Support Structures and associated assembly tooling,
- Test the hoisting system for the CRP support structures,
- Test the installation of the CRP using the lift table,

- Investigate alternate fiber routing concepts for the cathode PDS modules,
- Prototype the cathode installation including the PDS fiber integration.
- Test the FC lifting and support system,
- Test the installation of the last FC end wall lower panels,
- Test the bottom CRP installation process,
- Test install the last Bottom CRP modules,
- Refine the BDE cable tray design and prototype the installation process,
- Test the access possibilities for the TCO closure.

As most the scientists and engineers designing the detector component and the installation tooling reside in Europe and will be traveling to CERN for the Module-0 and the various cold box tests, it is strongly preferred for the installation tests to take place at CERN. To execute the test effectively one will need to install mock-ups of the two types of CRP structures foreseen in DUNE FD2; install a corner of the Field Cage HV modules; install two cathode modules; and install two bottom CRP modules in critical locations. In order to do this a support structure (mimicking the cryostat) is needed to hold up the detector elements and associated installation tools. The dimensions of the support structure were defined by the detector elements to be installed and the plan to execute the test with full size final components at full height. When the size of the test setup we established the location of the test was determined. Given the size of the detector it was determined the best location for the test is in Building 185 which is already used for the Neutrino Platform efforts. The present design of the steel support structure is shown in Figure 19.

It is planned to construct the steel structure this summer and begin testing the detector installation in fall. Figure 20 shows the installation of the cathode modules as an example. Here a scaffold is used to allow workers to safely work around the cathode for cabling the PDS. A dedicated installation cart is designed to hold the cathode modules while the cabling is done. The last cathode modules need to be installed when the corner field cages are in place so carefully choreographing this step is critical.

Another functional integration test that cannot be performed in the NP02 is the one involving the chimneys that host the electronics cards for the top drift. The concept is amply demonstrated with the operation of NP02 between 2019 and 2021. The actual dimensions of the DUNE chimneys, though, cannot fit in the penetrations available in the NP02 cryostat. For this reason, a dedicated test stand was constructed and is being used to test the DUNE top electronics chimneys in cold. The aim of the test is to assess the temperature distribution inside of the chimneys, that will impact the overall noise performance of the electronics.

7 Summary and plans

CRP5 was installed in NP02 shortly after the SPSC meeting of 2023. The installation and alignment of the Field Cage was completed in June 2023. Since then, the effort went to upgrade and optimise the CRP and PD systems, as described in this document. Three Cold Box tests were performed between November 2023 and April 2024. They led to improvement of the CRP design and validation of PD onboard electronics, which is planned to replace the one actually installed on the NP02 cathode modules. The Beam Plug was constructed and it's being tested for leaks. Preliminary tests at warm are promising, and cold tests are ongoing.

The cryogenic instrumentation, e.g. the purity monitors, the calibration systems, e.g. the ionisation laser, and tools like cryogenics lights and cameras will be installed after the Temporary Construction Opening (TCO) is closed.

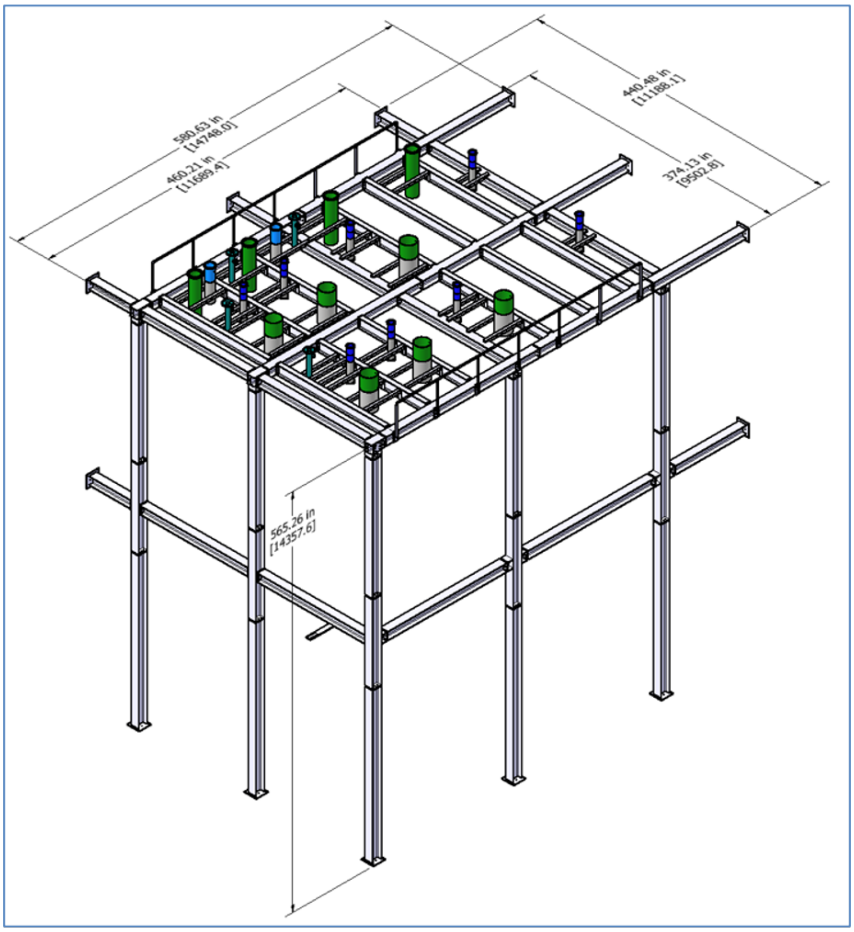

Figure 19: CAD model of the steel structure needed to support the installation test.

The material for the closure of the TCO is procured and it is available at CERN. The contract for the closure is also awarded, but the start date is still to be defined, and depends on the advancement of the NP02 preparation, as well as the NP04 data taking with beam.

A new major mechanical integration test stand is planned to be built in building 185. This will be a simplified 1:1 scale version of a portion of the DUNE FD-1 cryostat. It will allow to develop and validate the installation procedures for the DUNE-FD2 components in realistic conditions, and it is planned to start the installation in summer 2024.

The NP02 detector is mostly ready: the top and bottom CRPs with the respective electronics are installed and regularly checked (bias and noise levels) to ensure the functionality. Exchange of the electronics of the PD module on the cathode will be completed in June. The installation of the Field cage will follow, and the beam plug will be ready for installation at the beginning of the summer.

As the LAr cost significantly increased from the prices of 2021, it is prohibitive to have both the NP02 and NP04 cryostats full at the same time. After completion of the NP04 technical and scientific programme, the LAr will be transferred to NP02, possibly with the need of an additional purchase of 300 tons. The possibility of re-condensing the last 150 tons on argon from NP04 into NP02 is under study. As it happened for NP04, the TCO closure is delayed up to the last useful moment, because simple accessibility to the cryostat is fundamental. The actual TCO closure time will depend on the availability of the company that will perform the work, and more importantly by the completion of NP04 program, which is expected in fall of 2024. Beam time for NP02 will therefore be requested in 2025.

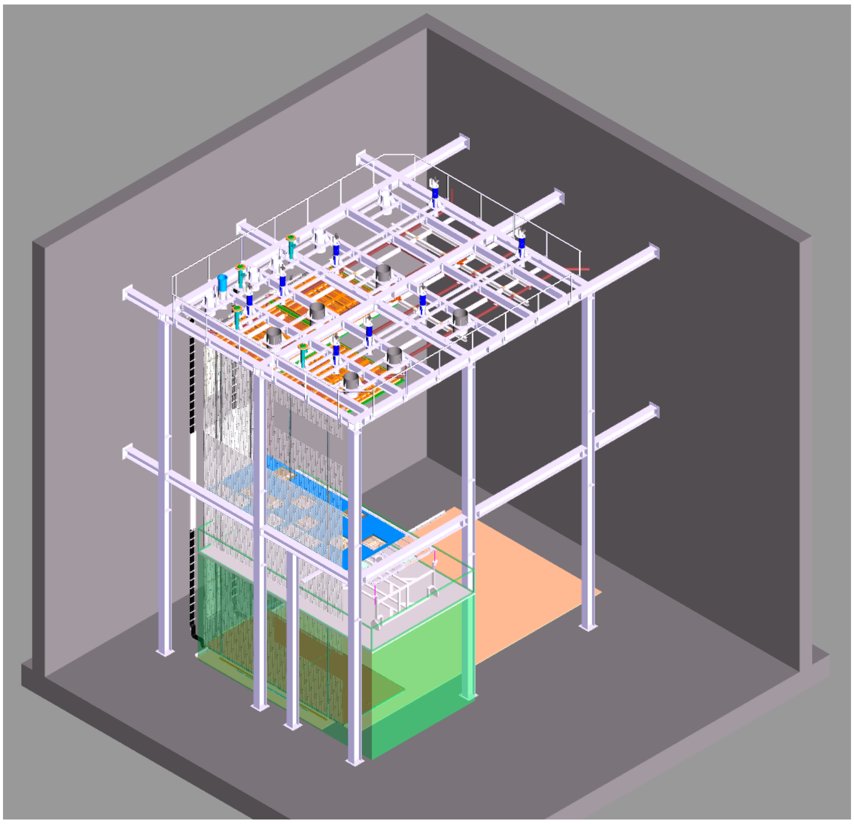

Figure 20: CAD model showing the installation test of the last cathode module. The cathode modules are on the installation carts and the field cage modules are in position.