Grant Agreement No: 101004761

AIDAinnova

Advancement and Innovation for Detectors at Accelerators

Horizon 2020 Research Infrastructures project AIDAINNOVA

MILESTONE REPORT

STATUS REPORT ON CRPS

MILESTONE: MS38

Document identifier:	AIDAinnova-MS38
Due date of milestone:	End of Month 23 (March 2023)
Report release date:	30/06/2023
Work package:	WP9: Cryogenic Detectors
Lead beneficiary:	CNRS/LAPP
Document status:	Final

Abstract:

Task 9.3 foresees the study of a novel charge readout scheme for very large time projection chambers, called Vertical Drift. This technology avoids using planes of wires to collect the signals of the electrons from charged particle ionization, at the end of their drift path. This kind of development program, included in task 9.3, is unprecedented and totally innovative in the domain of liquid argon (LAr) Time Projection Chambers (TPC). In Vertical Drift planes of wires are replaced by stacks of perforated printed circuit boards integrated in Charge Readout Planes (CRP) of 3x3.3 m^2 placed to cover the surface at the top of the detector. This active surface receives the electrons drifting thanks to a uniform electric field aligned along the vertical axis. The cryogenic ASIC amplifiers used to read the signals are integrated in this layout in front-end cards hosted in cryostat penetrations called “signal feedthrough chimneys” which make them accessible from outside during detector operation. The digitization electronics on the “warm” side is cabled to warm flanges closing the top part of the chimneys. This technology, which is foreseen to equip the second DUNE Far Detector module, underwent extensive large-scale tests at the CERN Neutrino Platform in 2021-2022. These tests successfully demonstrated its validity. This report describes the work and developments performed to achieve the milestone devoted to the CRPs.

For more information on AIDAinnova, its partners and contributors please see http://aidainnova.web.cern.ch/

The Advancement and Innovation for Detectors at Accelerators (AIDAinnova) project has received funding from the European Union's Horizon 2020 Research and Innovation programme under Grant Agreement no. 101004761. AIDAinnova began in April 2021 and will run for 4 years.

Delivery Slip

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Executive summary

Task 9.3 has been dealing with the developments associated to the demonstration of the Vertical Drift (VD) charge readout technology which is a novel design of LAr TPC detectors based on the use of perforated printed circuit boards instead of wire planes for the readout of the ionization signals in LAr Time Projection Chambers (TPC)

The Vertical Drift design is particularly suited to build and instrument very large LAr detectors in a simpler and cost effective way. VD is foreseen to be deployed for the second DUNE Far Detector module (FD-2). Task 9.3 focuses on the demonstration of the configuration for the readout of the top-drift volume of FD2 by developing an optimized configuration for the Charge Readout Planes (CRP) and their associated electronics. The Charge Readout Planes host the perforated Printed Circuit Boards anode planes and are used to collect the ionization signals from the TPC drift volume and provide three independent views imaging of the tracks left by charged particles in liquid argon.

This milestone status report includes the results from an intensive prototyping campaign on the Vertical Drift technology, which was conducted in 2021-2022 by using the infrastructure provided by the CERN Neutrino Platform including a dedicated Cold-Box cryostat of the exact size of a VD Charge Readout Plane unit. This campaign included the successful development and tests of the first two Charge Readout Planes corresponding to the final layout foreseen for the top drift volume of FD2 and of their associated electronics and signal feedthrough chimneys.

1. INTRODUCTION

Task 9.3 Vertical Drift (VD) Charge Readout encompasses detector development oriented towards the construction of the second DUNE LAr Far Detector module (FD-2). Vertical Drift is a very innovative technique that allows reading the ionization of charged tracks in LAr Time Projection Chambers without instrumenting the anode surface with wire planes, instead exploiting Charge Readout Plane (CRP) units (each one covering a 3x3.3 m^2 active surface) made of two layers of perforated anode Printed Circuit Boards (PCB). The anode perforated PCB copper layers are segmented in strips of about 5 mm pitch in order to define readout views. The two PCB layers provide two views (at +-30 degrees (with respect to the beam direction in FD-2) reading induction signal and a last view at 90 degrees collecting the electrons. The Vertical Drift layout and the use of perforated anodes instead of wire planes make the construction and installation of very-large detectors cheap and effective.

The anode planes are coupled to dedicated cryogenic Front-End (FE) and digitization warm electronics (altogether defined as: Top Drift Electronics, TDE) explicitly developed and optimized for this configuration present in the upper part of the drift volume of the DUNE VD Far Detector module. Special mechanical cryostat penetrations "Chimneys" host the FE boards with cryogenic amplifiers, preserving their accessibility at any time without interfering with the detector operation. Vertical Drift is an evolution and further simplification of the Dual-Phase technique already developed in AIDA2020. Both the Dual-Phase and the Vertical Drift developments have been strongly supported by the CERN Neutrino Platform infrastructure located in the EHN1 hall.

The demonstration at large scale of this unprecedented detector technology, corresponding to the Vertical Drift for the DUNE top drift volume of FD-2, is the goal of task 9.3 and represents an essential step before moving to the construction of the DUNE FD-2. In the years 2021 and 2022, CRP planes with perforated anodes were constructed and tested, together with the associated readout electronics and chimneys, at the CERN Neutrino Platform with a dedicated cold-box cryostat, capable of hosting and running in LAr TPC configuration a complete VD CRP.

The tests campaign at the CERN Neutrino Platform foresaw the test of the first Vertical Drift CRP (CRP1, shared CRP including both top-drift and bottom-drift) configurations in the fall of 2021, including two consecutive cold-box runs. CRP1 was tested again in a modified version, CRP1b, including some improvements of the grounding for the bottom-drift readout in May-June 2022 with a new cold-box test. In the year 2022 crucial tests in the cold-box of the first two complete versions (CRP2 and CRP3) of Vertical Drift CRPs in their final strip layout configuration foreseen for DUNE FD-2 were performed. These tests were successfully accomplished between July and November 2022 providing excellent results which validated the CRP design. This milestone reports about the CRP developments that occurred since 2021 and on its place in the overall goal of demonstrating the Vertical Drift technology, pursued by task 9.3.

2. ACTIVITIES AND RESULTS

2.1. VERTICAL DRIFT COLD-BOX TESTS AND CRP DEVELOPMENT

Vertical Drift Charge Readout Planes (CRPs) with perforated anodes were constructed and tested at the CERN Neutrino Platform with a dedicated Cold-Box (CB) cryostat. The year 2021 saw a very intensive test program at the CERN Neutrino Platform in the EHN1 hall, where a new Cold-Box (CB) cryostat was equipped nearby the NP02 cryostat, to share the same cryogenics system, for the tests of the Vertical Drift CRPs [1]. The Cold-Box has the precise footprint capable of containing a single CRP module. The CB can be operated in Time Projection Chamber configuration with 30 cm vertical drift space located in between the CRP lower surface and the cathode plane. This drift distance allows collecting very large samples (order of millions) of cosmic rays that can be exploited to fully characterize the CRP behavior and of its associated electronics, both covered by task 9.3. The CRP is suspended from the roof of the Cold-Box (Figure 1) that can be inserted and extracted from the top of the Cold-Box to seal the cold-box cryostat and define the detector configuration with the drift space in the TPC (Figure 2).

Fig. 1: A Vertical Drift top-drift Charge Readout Plane (CRP2) suspended from the cold-box roof while being transported to the cold-box location. The bottom surface in copper of the first layer of perforated anodes PCBs is visible from below. On the sides one can see the flat cables delivering signals from the anodes to the chimneys hosting the cryogenic readout amplifiers

In order to test the CRPs at warm, while allowing access to them during the tests, and optimize their electrical configuration and verify all connectors a complementary setup to the Cold-box (the Faraday Cage) was also developed and built in 2022.

Fig. 2: Cold-box cryostat built for the tests in TPC mode of the Vertical Drift Charge Readout Planes. This top view shows the top of the cold-box roof with the CRP suspended while being lowered in order to close the cold-box cryostat (at the bottom) with a cathode module laying on its floor

The Faraday cage (Figure 3) is closed at its top by the cold-box roof with the CRP suspended below. This configuration allows performing for each CRP first a test at warm in the Faraday Cage and then move the roof to the cold-Box in order to perform the test at cold with liquid argon in TPC mode. The Faraday cage completely shields the CRP strips from picking up, as antennas, EMI noise from the environment, while preserving complete access for people and working space around the CRP during tests. In 2022 all CRP tests (CRP1b, CRP2, CRP3) were systematically conducted in two steps: with a first operation at warm in the Faraday cage in order to cross-check the noise levels and the electrical connections, and then with an extensive run in the cold-box filled with LAr and operated in TPC mode.

Fig. 3: CRP2 while being tested at warm in the Faraday cage setup before undergoing a cold-box test. The CRP is suspended from the cold-box roof which closes the top side of the Faraday Cage. The cold-box roof is fully instrumented with the analogue readout electronics and the uTCA digitization system and in a cold-box test in TPC mode.

The analogue cryogenic amplifiers are hosted at the bottom of the chimneys (Figure 4). The chimneys are pipes going through the insulation of the roof of the cryostat until they reach a location, inside the cryostat gas ullage, very close to the CRP. The bottom of each chimney is sealed by a cold flange printed circuit board (Fig. 4) which prevents the contamination of the ultra-pure LAr environment of the cryostat during access to the FE electronics or chimney operation. The FE cards with the cryogenic amplifiers, mounted on blades, are plugged in to connectors located on the top surface of the cold flange PCB. The bottom side of the cold flange has connectors which are used to plug flat cables extracting the signals (from charge collection or induction views) from the CRP. The FE cards operate at a temperature of about 110 K present in the cryostat ullage space. The chimney is closed at the top with a vertical warm flange which includes the connector to cable the amplified signals to the digitization electronics contained in uTCA crates on the cryostat roof and is filled with N_2 to avoid humidity condensation on the FE cards. Five chimneys are integrated on the cold-box roof in order to allow for the tests of the top-drift charge readout planes.

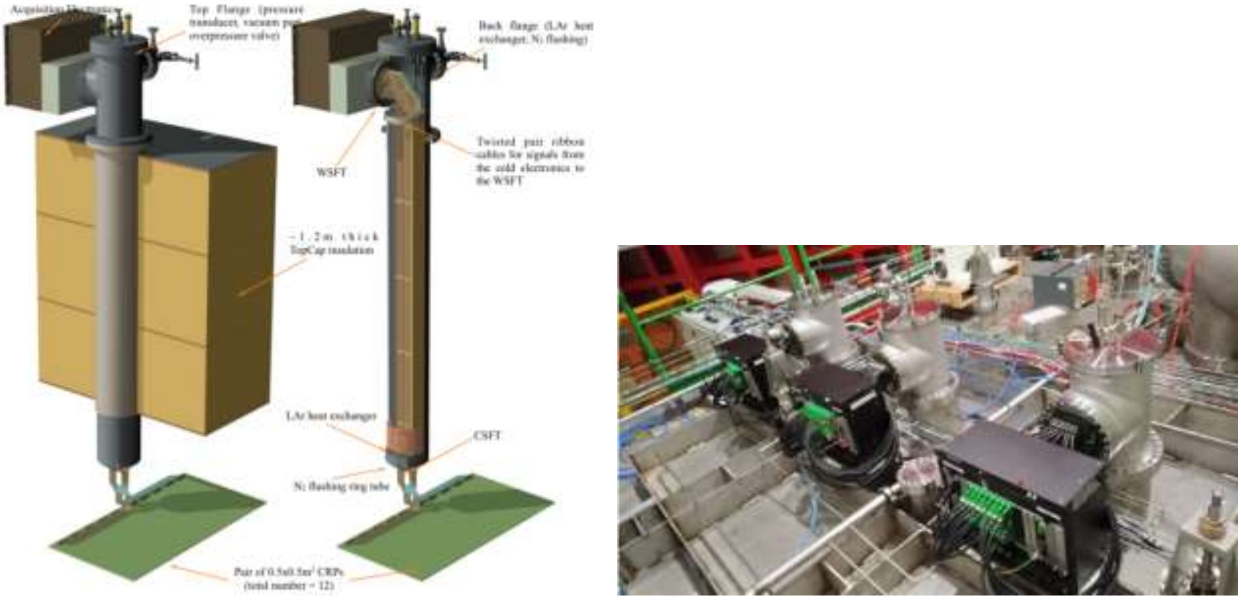
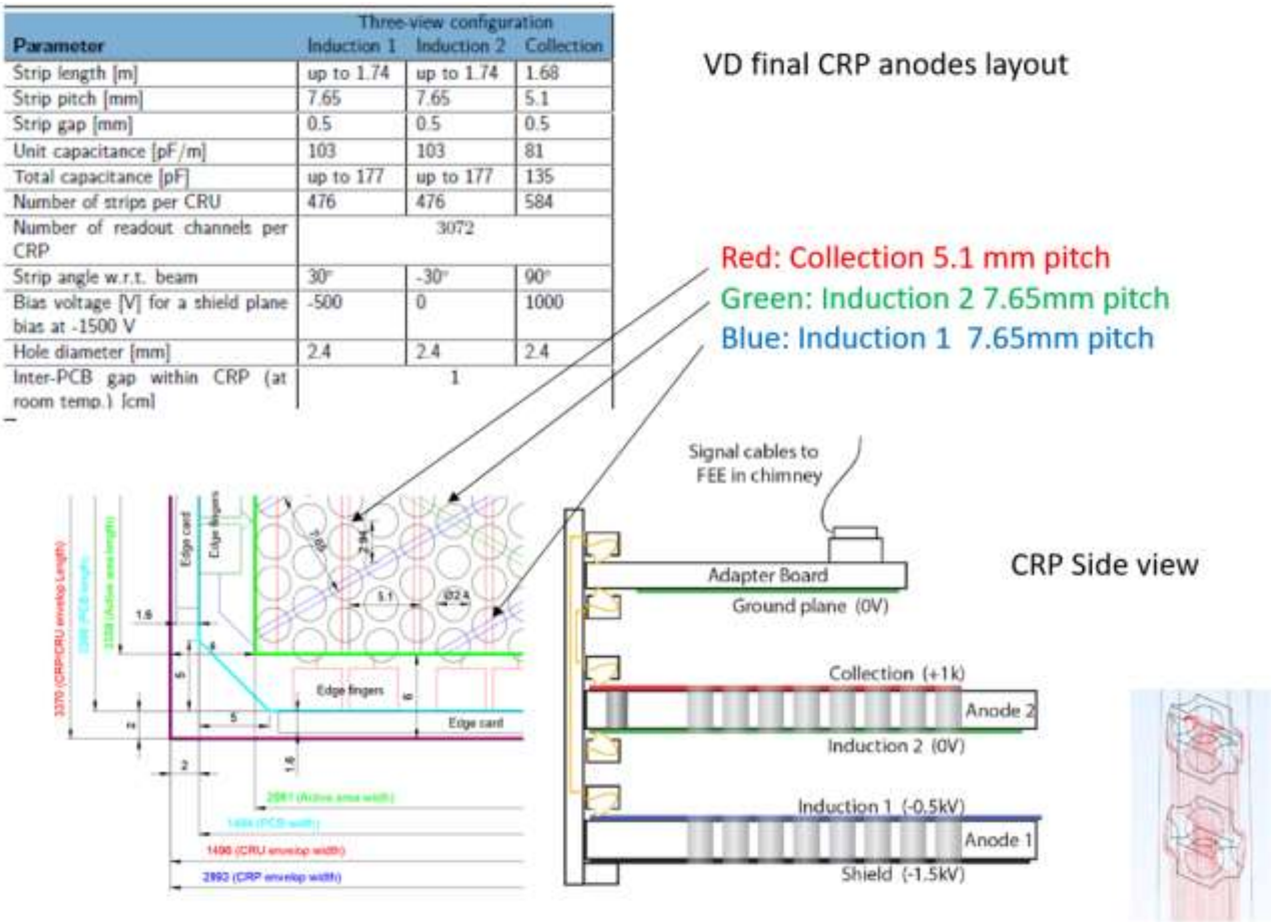


Fig. 4: (Left) Illustration of a signal feedthrough chimney hosting the cryogenic amplifiers and going through the cryostat insulation (closed view and section of the chimney pipe showing the blade with the FE card plugged on the cold flange) (Right) view of the top of the system for the current implementation in the Cold-Box tests for the Vertical Drift.

The first CRP prototype (CRP1) was successfully tested in November-December 2021. This CRP was shared among the top-drift, on which task 9.3 is focused, (TDE) and bottom-drift (BDE) readouts developed for the DUNE Vertical Drift Far Detector module. This CRP was re-tested both in the Faraday cage and in the cold-box in May-June 2022 (CRP1b) after having implemented some grounding improvements needed by the BDE readout. This test provided an occasion to also check the stability of the response after a long time and several manipulations occurred to the CRP.

Following the tests on CRP1, and physics optimization studies based on simulations of the reconstruction of neutrino events in FD-2, the Vertical Drift channels layout and strip orientation (3 views at 90°, +30° and -30° with respect to the beam) (Fig.5) were finalized in a common geometry for the top-drift and bottom-drift CRPs. This configuration was primarily implemented and tested in 2022 on CRP2 and CRP3, which represent the first Vertical Drift CRPs with the final layout and are both top-drift CRPs. The channel count corresponds to 48 FE cards (hosted in 5 chimneys) and 48 AMC digitization cards (hosted in 5 uTCA crates) per CRP, for a total of 3072 charge readout channels. The first full-size top-drift CRP (CRP2) was constructed and tested in July 2022 during the continuation of the cold box tests campaign foreseen in 2022 (Fig.6). A second full-size top-drift CRP (CRP3), with the same strip layout as CRP2, was also fully tested in October 2022.



Parameter	Three-view configuration Induction 1	Induction 2	Collection
Strip length [m]	up to 1.74	up to 1.74	1.68
Strip pitch [mm]	7.65	7.65	5.1
Strip gap [mm]	0.5	0.5	0.5
Unit capacitance [pF/m]	103	103	81
Total capacitance [pF]	up to 177	up to 177	135
Number of strips per CRU	476	476	584
Number of readout channels per CRP	3072		
Strip angle w.r.t. beam	30°	-30°	90°
Bias voltage [V] for a shield plane bias at -1500 V	-500	0	1000
Hole diameter [mm]	2.4	2.4	2.4
Inter-PCB gap within CRP (at room temp.) [cm]	1		

Fig. 5: Final layout of the strips segmentation implemented on the stack of anode perforated PCBs constituting CRP2

Fig. 6: Cold-Box roof top view during CRP2 operation with 5 chimneys each one cabled to a uTCA digitization crate (black boxes)

In the CRP stack two perforated anode PCBs (each one 3.2 mm thick), segmented in strip with a pitch going from 5.1 to 7.65 mm, ensure 3 independent views. The first perforated PCB facing the drift volume has only its top face readout with copper strips implementing an induction view (Induction 1). A bipolar signal is induced by the approach and departure of the electrons along their trajectories on Induction 1 by the flow of electrons coming from the drift volume and passing through the holes of the perforated PCB (2.4 mm diameter). The electrons then continue their path (se Fig. 5) passing through the holes of the second perforated PCB. There they leave an induction signal on the bottom layers segmented in the induction 2 strips and eventually are collected by the strips implemented on the top layer of this second PCB (Collection View). The PCB surfaces are set at progressively higher voltages (see Fig. 5) which are needed to define the flow of the electrons through the holes in such a way that the induction views are transparent and the electrons are collected only by the last view. The signals from the different readout layers implemented on the stack of the two perforated PCBs are collected at the sides of the CRP by "edge cards" routing the signals to adapter boards at the top of the CRP hosting the connectors to plug the flat cables which will then bring these signals to the chimneys. This readout solution guarantees the routing of the signals introducing little dead space on the CRP sides.

The stack of the two perforated PCBs is integrated and supported by a composite structure frame. A CRP, in order to ease its transportation and installation, is divided in two halves (CRU) which can be assembled together after transportation in the final CRP (see Fig.9). The perforated PCB panels have then the size of a CRU (3336x1444 mm) and are each one assembled by gluing together 6 sub-panels of smaller dimensions (see Fig. 7). After gluing, the electrical continuity of the strips across different sub-panels is ensured by implementing silver printed joints. Details of the CRP structures with pictures taken during the CRP assembly process are shown in Figure 8.

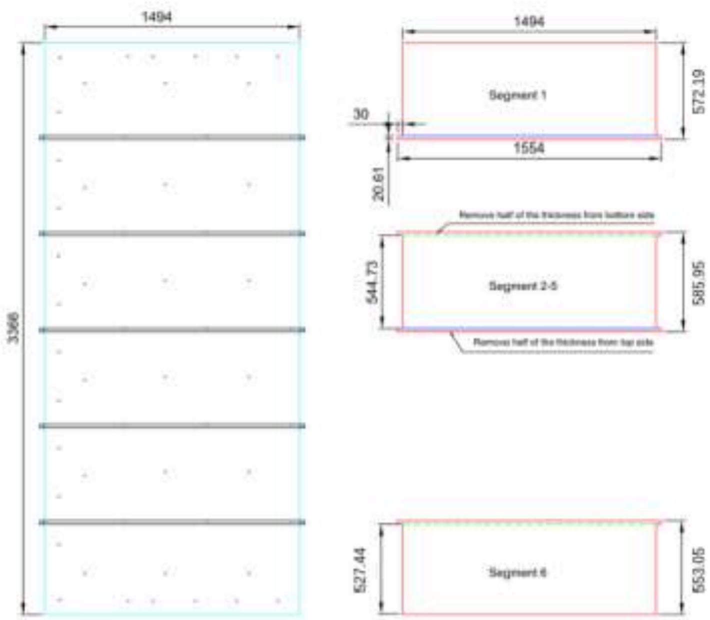


Fig. 7: Assembly from sub-panels of a perforated PCB panel corresponding to a CRP half

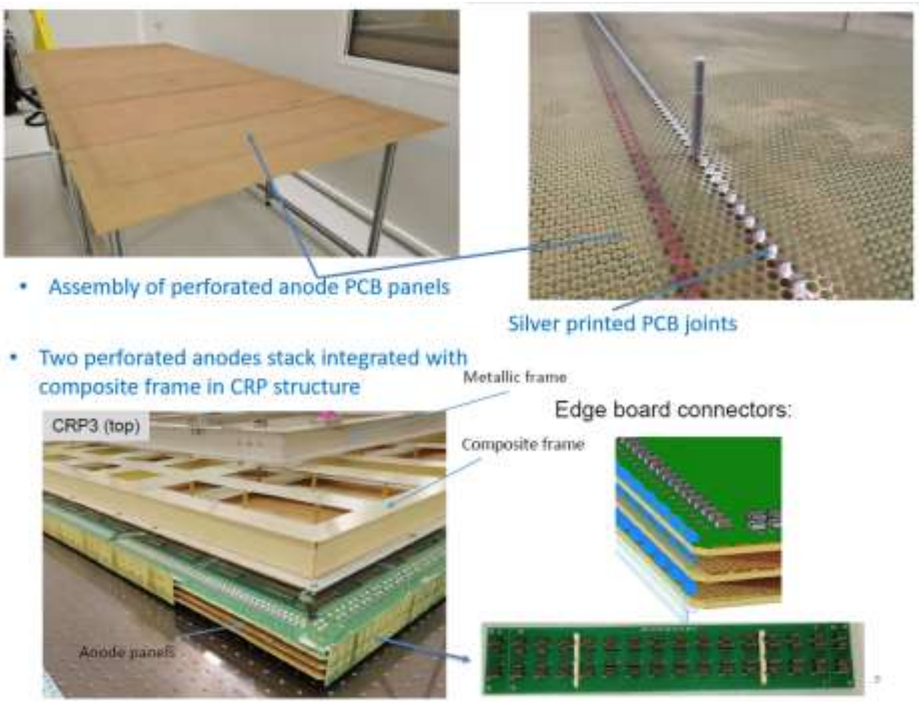


Fig. 8: Structural details of the perforated PCB panels and a CRP including the composite frame support structure and a stack of two layers of perforated PCBs from pictures taken during the CRP construction

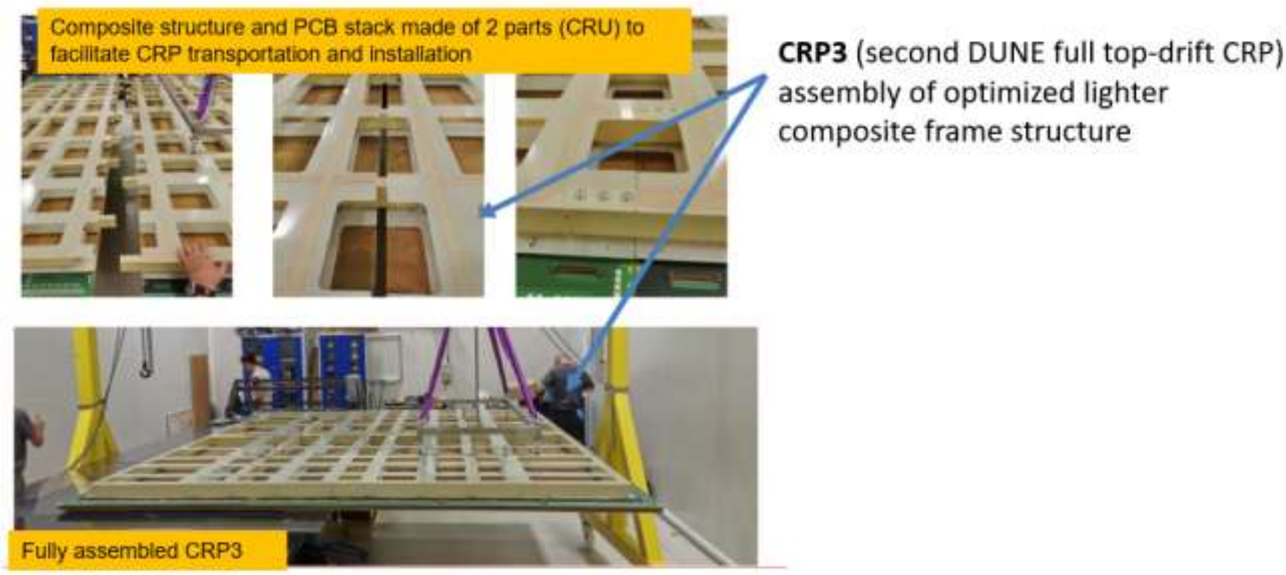


Fig. 9: Assembly of the two halves (CRUs) composing CRP3 and final view of CRP3 fully assembled. The composite structure of CRP3 corresponds to an optimized version, lighter than the first one implemented on CRP2

The CRP construction demonstrated fulfilling the planarity specifications. In 2022, the Cold-Box tests of the final CRP layout demonstrated the good performance of the CRP and of its associated electronics, including the operation of the chimneys. The results completely fulfilled expectations. A very large sample of cosmic ray tracks was collected to characterize the stable operation of the detector and the uniformity response of the CRP. A typical event containing cosmic ray tracks is shown in Fig. 10. This test program fully demonstrated the Vertical Drift readout. The two final top-drift CRPs (CRP2 and CRP3) have then been integrated at the end of 2023 inside the NP02 cryostat for the global Module-0 integration test (ProtoDUNE-VD).

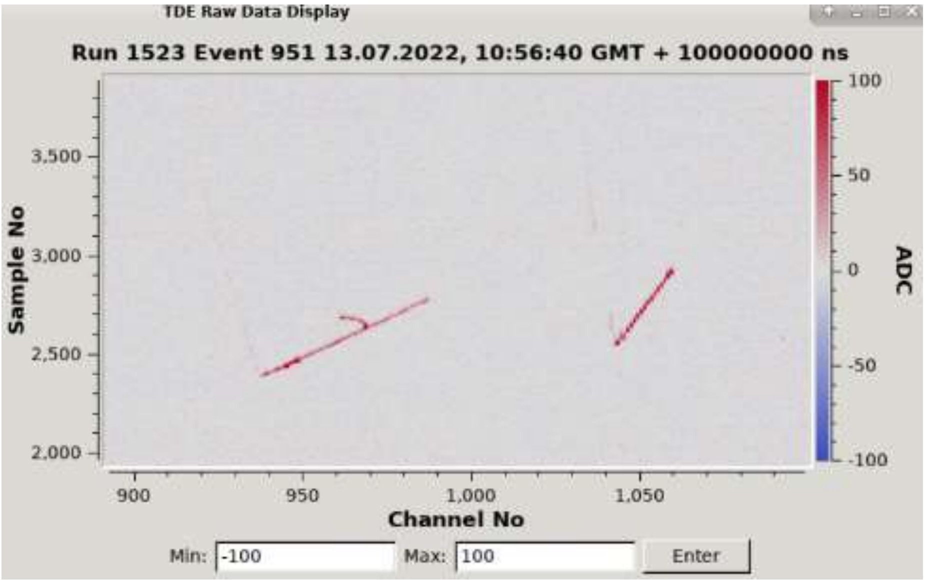


Fig. 10 Example of clean cosmic ray tracks collected during the operation of CRP2 in the Cold-Box

Cold box operation runs repeated at large time distance on the same CRP, after several thermal cycles and manipulation on the CRP structures, demonstrated the robustness of the CRPs and the reproducibility of the CRP operation and results. This is shown in Figure 11, where the dE/dx response measured on CRP1/CRP1b with large samples of cosmic ray tracks is compared between the November 2021 and June 2022 runs. The two Landau distributions in black and red measured at different epochs are perfectly overlaying.

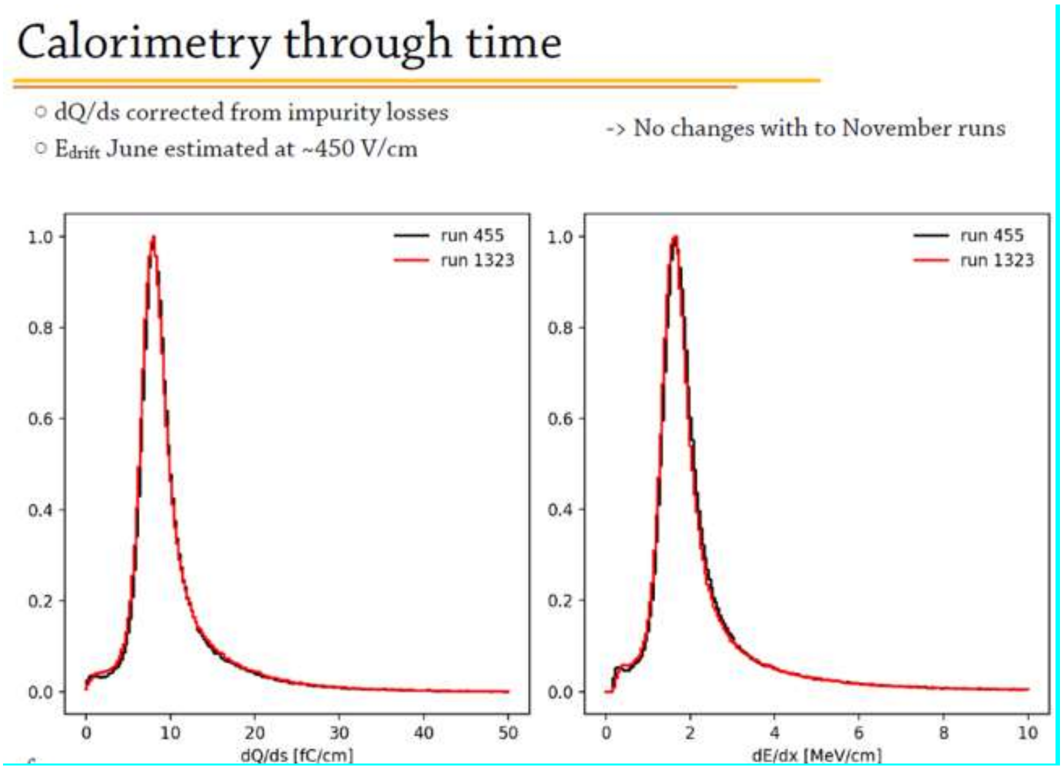


Fig. 11: Stability in the dE/dx response of CRP1 comparing two different cold-box runs CRP1/CRP1b

3. REFERENCES

[1] NP02 Collaboration (2022) *Yearly progress report on NP02* CERN-SPSC-2022-014; SPSC-SR-308 (2022) https://cds.cern.ch/record/2805710

ANNEX: GLOSSARY

Acronym	Definition
ASIC	Application Specific Integrated Circuit
CB	Cold-Box cryostat/Time Projection Chamber
CRP	Charge Readout Plane (3x3.3m^2 readout unit of Vertical Drift)
DUNE	Deep Underground Neutrino Experiment
FD-2	Second DUNE Far Detector module (15 kton active LAr mass)
FE	Front-End
FR4	Flame Retardant 4 (PCB material)
LAr	Liquid Argon
PCB	Printed Circuit Board
TDE	Top Drift Electronics
TPC	Time Projection Chamber
VD	Vertical Drift