CS IN2P3 October 2021

Status of the DUNE project

Abstract

In this document we report general progress on the DUNE IN2P3 project and on the status of the prototyping activities at CERN since the last CS report in 2018 and the evolution of these activities towards the construction of the 2nd DUNE far detector based on the Vertical Drift design.

Contents

1. Overview 4
1.1. Introduction 4
1.2. Historical development 5
1.3. The dual-phase LAr TPC technology 7
1.4. Evolution of the dual-phase to Vertical Drift 8
1.5. Outlook on the experimental efforts on protoDUNE dual-phase 12
1.6. The Vertical Drift detector design 14
1.7. Recent progress on the Vertical Drift 16
1.8. The kick-off of the DUNE TGIR program 17
1.9. DUNE construction status 18
1.10. DUNE Physics update 19
1.11. Conclusions 21

2. Completion of ProtoDUNE dual-phase run in 2020 22
2.1. Introduction 22
2.2. High Voltage extender repair operation in June 2020 22
2.3. Completion of the NP02/protoDUNE dual-phase run in August 2020 23
2.4. NP02 Cryostat inspection in February 2021 25

3. Evolution of the dual-phase design to the Vertical Drift 29
3.1. Experience learned from dual-phase operation 29
3.2. Perforated anodes and simplifications possible thanks to the Vertical Drift design 30
3.3. Convergence on the Vertical Drift design for the construction of the second DUNE Far Detector module 33

4. Vertical Drift test activities at the CERN Neutrino Platform 2021-2023 and path to the second Far Detector module construction 37
4.1. Vertical Drift HV system test in the NP02 cryostat in 2021 37
4.2. Cold-box tests of Vertical Drift CRPs 41
4.3. 2021 CRP tests 43
4.4. Continuation of the CRPs and detector components tests campaign in 2022 in view of the *Vertical Drift Module-0* 45
4.5. Vertical Drift *Module-0* operation 47

4.6. Vertical Drift Far Detector module production and installation 49

1 Overview

1.1 Introduction

The DUNE long-baseline neutrino experiment benefits from the support from various entities such as the **LBNF project**, the **PIP-II project**, the **DUNE Collaboration** and the **CERN Neutrino Platform**. The main components of the DUNE experiment long-baseline configuration are shown in Figure 1. The **LBNF (Long Baseline Neutrino Facility) project** takes care of the construction of all infrastructures needed by DUNE. These include the neutrino beam and the Near Detectors infrastructures at Fermilab, the underground infrastructure at the Sanford Underground Research Facility (SURF) in South Dakota, including the cryostat and cryogenic system for the Far Detector modules. The **PIP-II project** includes the upgrades needed at Fermilab for the high intensity proton driver, required to produce the neutrino beam. The **DUNE Collaboration** provides the Near Detectors, the instrumentation of Far Detector modules inside the LBNF cryostats and the Computing and Analysis organization.

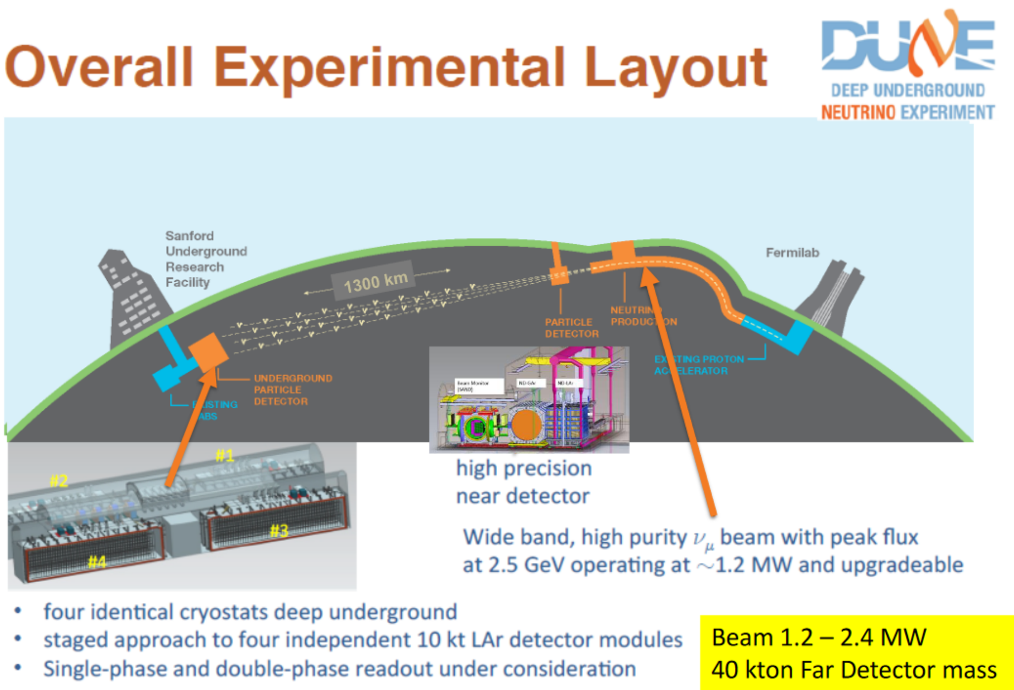

FIG. 1: Main components of the DUNE long-baseline neutrino experiment.

Strong detector prototyping activities carried out by the DUNE Collaboration have been supported at CERN by the **CERN Neutrino Platform** since 2014. In particular the CERN Neutrino Platform has set up an extension of the EHN1 hall, hosting the two protoDUNE detectors for the dual-phase and single-phase technologies (NP02 and NP04 CERN experiments). These are currently the largest Liquid

Argon TPC detectors in the world. The CERN Neutrino Platform also supports other test activities, such as: the $3 \times 1 \times 1m^3$ prototype in building 182, tests of the High Voltage system components still in building 182 and a clean room assembly facility in building 185. **CERN** is also involved in the design and production of the cryostats and cryogenic systems for DUNE.

This report describes recent progress on the DUNE IN2P3 project since the last review at the IN2P3 Scientific Council occurred in 2018.

The report contains a summary description of:

- the status of the DUNE experiment and of the DUNE IN2P3 project;
- the experimental activities carried out so far by the IN2P3 groups on the dual-phase with a return of experience from the operation of NP02/ProtoDUNE dual-phase
- the progress of the IN2P3 project towards the construction of the second DUNE Far Detector module, based on the Vertical Drift design which evolved from the dual-phase
- the Vertical Drift design activities and the related test activities currently at the CERN Neutrino Platform

The report is written with the goal of providing reference material in view of the CS IN2P3 meeting of October 2021. The text is intentionally limited in length and organized in order to guide the reader through a broader set of materials. In addition to this summary report, written with the intent of providing a first general view to the reader, a large amount of additional slides and documents may be helpful in order to get a more detailed picture of various aspects. These additional documents are accessible via hyperlinks contained in the report. The most up-to-date documents correspond to the slide sets of the DUNE TGIR kick-off meeting of May 2021 and the Vertical Drift Conceptual Design Document (CDR) draft of August 2021.

1.2 Historical development

The IN2P3 groups have a long standing record of commitment, detector and analysis expertise and R&D activities in view of the preparation of DUNE. Development activities on the Liquid Argon (LAr) detectors started in 2006 with R&D on the charge readout electronics at IPNL/IP2I, supported also by the LIO LABEX. The French groups have been participating since 2008 to the R&D and design study for liquid argon far detectors within the European programs LAGUNA (Large Apparatus studying Grand Unification and Neutrino Astrophysics, 2008-2011) and LAGUNA-LBNO (Long Baseline Neutrino Oscillations, 2011-2014). Then in 2014 they contributed with the International Interim Executive Board (IIEB) to the LBNF LOI and in 2015 to the foundation of the DUNE experiment. Since the beginning of DUNE the IN2P3 groups have been constantly contributing in a strong way to the experiment, up to the definition of an IN2P3 contribution to the construction of the 2nd Far Detector module, now supported by a TGIR program.

The IN2P3 experimental contributions have covered various prototyping phases at increasing complexity and maturity, supported by the CERN Neutrino Platform infrastructure: the $3 \times 1 \times 1 m^3$ dual-phase prototype, the NP02/protoDUNE dual-phase experiment and the ongoing cold-box and Vertical Drift Module-0 activities, carried out in view of finalizing the detector components for the 2nd DUNE far detector module.

A graphical timeline of these efforts is presented in Figure 2. Additional information concerning the historical development of the project can be found in the two previous reports to the IN2P3 Scientific Council: CS IN2P3 2013 Report, Slides; CS IN2P3 2018 Report, Slides.

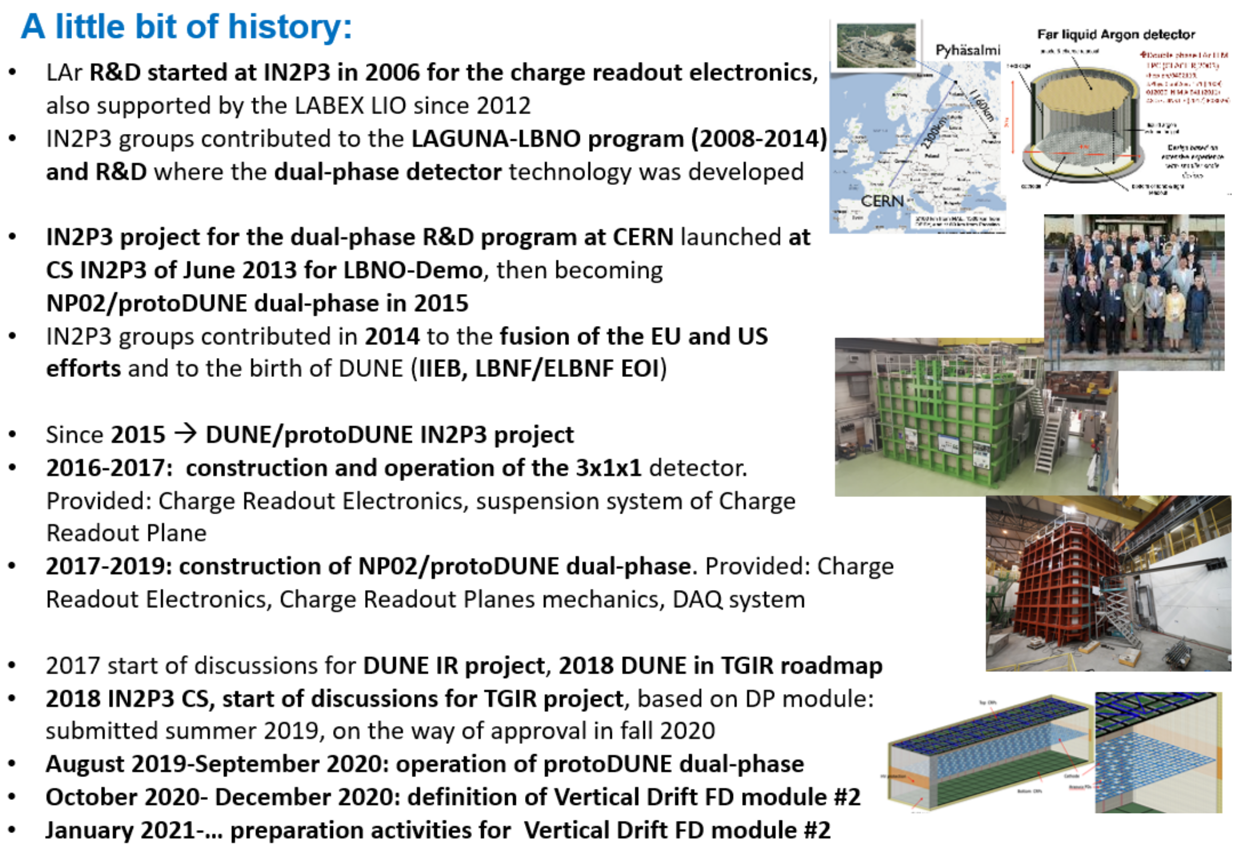

FIG. 2: History of the IN2P3 efforts on the DUNE project.

The period elapsing since the last IN2P3 Scientific Council review the DUNE project in June 2018 was characterized by a very intensive phase which is now continuing with a series of activities launched on the path for the construction of the second DUNE Far Detector Module:

- the completion in 2019 of the installation of NP02/ProtoDUNE dual-phase and the conclusion of its first phase of operation (2019-2020)

- the approval of the DUNE TGIR project (Fall 2020)
- the evolution of the dual-phase to the Vertical Drift design and its adoption by the DUNE collaboration for the construction of the second DUNE Far Detector module (end of 2020)
- the start of the test campaign at CERN for the validation of the detector elements for the Vertical Drift detector (2021-2023): High Voltage tests in NP02; cold-box tests of new Charge Readout planes for the Vertical Drift; tests of the cathode and photon detection elements for the Vertical Drift; Vertical Drift Module-0.
- the finalization of the design of the second Far Detector module (CDR in Fall 2021) and of its construction and installation activities (2021-2027)

1.3 The dual-phase LAr TPC technology

The IN2P3 groups have been intensively contributing to the development of the dual-phase Liquid Argon Time Projection Chamber technology (see for instance the report at the last CS IN2P3 in 2018: Report, Slides). This detector design was developed for a DUNE detector module cheaper and easier to build and install than the traditional single-phase/horizontal drift module design based on wire chambers.

The dual-phase technique exploits the amplification of the ionization signal in avalanche processes occurring in the gas phase. In the single-phase design, electrons drift horizontally to the anode, which consists of a set of induction and collection wire layers immersed in LAr. In the dual-phase design, electrons drift vertically upward towards an extraction grid placed just below the liquid-vapor interface. After reaching the grid, an electric field stronger than the drift field extracts the electrons from the liquid to the gas phase. Once in the gas, electrons encounter micro-pattern gas detectors with high-field regions, called Large Electron Multiplies (LEM), also called in other HEP applications "Thick GEM". The LEM amplify the electrons in avalanches that occur in the high-field regions present inside their holes pattern. The amplified electrons are then collected on a finely segmented anode with two perpendicular collection views. The anode and the LEM are printed circuit board units of $50 \times 50cm^2$ that are assembled in sandwiches. The LEMs are 1mm thick and separated by a 2 mm gap from the anodes. The avalanche process happens is pure argon, in absence of a gas quenching component, the containment of the UV photons produced in the avalanches is performed geometrically within the holes. The obtainable gain ranges from a few units to tens. The LEM/anode sandwiches are assembled in larger units: the Charge Readout Planes (CRP) of $3 \times 3m^2$ surface. The CRPs are precisely aligned parallel to the liquid gas-interface with the liquid level ideally positioned at the middle of a 10mm gap defined by the extraction grid, immersed in the liquid, and the LEM bottom surface in the gas phase. Details of the dual-phase anode stack implemented in the CRPs are shown in Figure 8. The dual-phase design also allows complete accessibility to the cryogenic analog electronics via the signal feedthrough chimneys and the exploitation of cost optimized conventional digital electronics installed on the cryostat roof.

The gain obtainable in the gas phase could also compensate for the signal losses due to electronegative impurities present in liquid argon absorbing the ionization electrons. The drift distance considered for a dual-phase DUNE detector module extends to 12m, equivalent to a drift time of about 8ms with a drift field of 500V/cm. A voltage of -600 kV has to be applied to the cathode in order to generate this field. The original assumptions on the LAr purity at the time of the DUNE CDR/TDR were based on the achievement of an electron lifetime in LAr of 3ms. The experience with the protoDUNE detectors at CERN showed that with the implemented membrane cryostat technology and associated purification system lifetime values could be achieved exceeding by one order of magnitude these original assumptions.

1.4 Evolution of the dual-phase to Vertical Drift

The purity record achievements strongly reduce the need for amplification at the level of the anodes. However the detector design and configuration developed for the dual-phase is still very appealing for the DUNE experiment from practical and economical points of view.

Recent developments since 2020, as well as the experience acquired with protoDUNE dual-phase, have shown how to evolve the dual-phase design into a new version (**Vertical Drift**) which no longer requires amplification in the gas phase. The Vertical Drift preserves all advantages of the dual-phase design based on strips implemented on printed circuit boards instead of wires for the readout of the electrons on the anodes. This new design is also more robust with respect to issues related to the long term stability of the micro-pattern detectors used in the gas phase (development of sparking activity) and to their dependence on environmental conditions inside the cryostat, such as: bubbles, perturbations of the LAr surface at the interface in between the liquid and the gas and possible presence of floating debris.

The construction and installation advantages related to the CRP design and the modular vertical geometry of the field cage are completely maintained. Another optimization process for the Vertical Drift design was performed by splitting the drift space in two vertical volumes (top-drift and bottom-drift, see Figure 3). This arrangement reduces the high voltage requirement at the cathode from -600

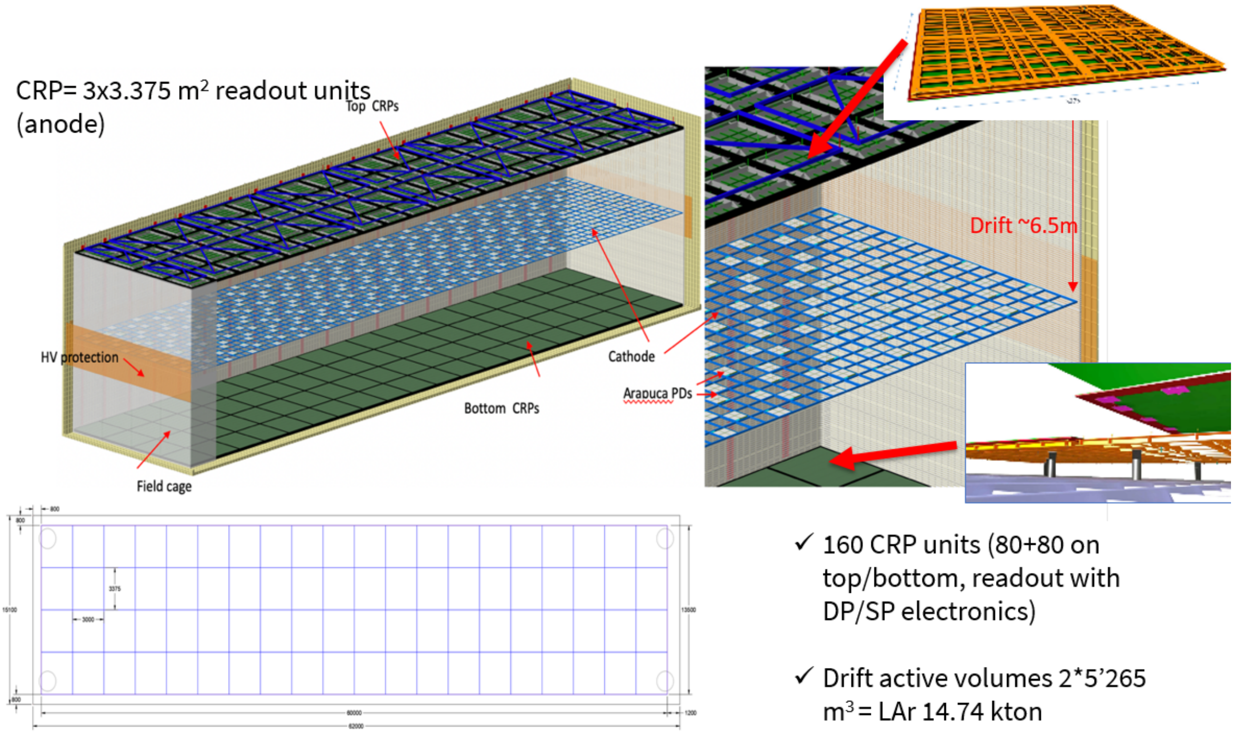

FIG. 3: 3D view of the Vertical Drift DUNE Far Detector module with the top and bottom drift volume separated by the cathode at middle height of the detector.

kV to about -300 kV, removing thus the necessity for additional R&D still needed to achieve 600 kV.

Skipping the need for additional R&D steps concerning the optimization of the LEM gas detectors and the High Voltage to reach 600 kV, together with the relaxation of environmental aspects on the liquid-gas interface inside the cryostat, contributed overall in speeding up the construction program for the second DUNE Far Detector module.

The top-drift volume preserves also full accessibility to the charge readout electronics associated to the top CRPs, which are suspended from the roof, as in the dual-phase design (see Figure 4). The electronics design developed for the dual-phase is also better suited to the layout of top-drift CRP structure (see Figure 5), with beneficial aspects on the CRP structures mechanics, heat dissipation and mitigation of risks which may affect the top of the cryostat, as the presence of bubbles.

From the point of view of the physics sensitivity a large design effort was made, thanks to the Vertical Drift configuration, to ensure a maximal exploitation of the cryostat LAr volume. The fiducial mass for the second DUNE Far Detector module based on the Vertical Drift design reaches almost 15 kton. The optimization of the target mass for neutrino interactions, together with cheaper and faster construction and installation schedules affecting the second Far Detector module, represent an important enhancement for the physics program. The charge readout reconstruction performance, per unit of target mass, for the second DUNE Far Detector module is similar to the one of the first DUNE

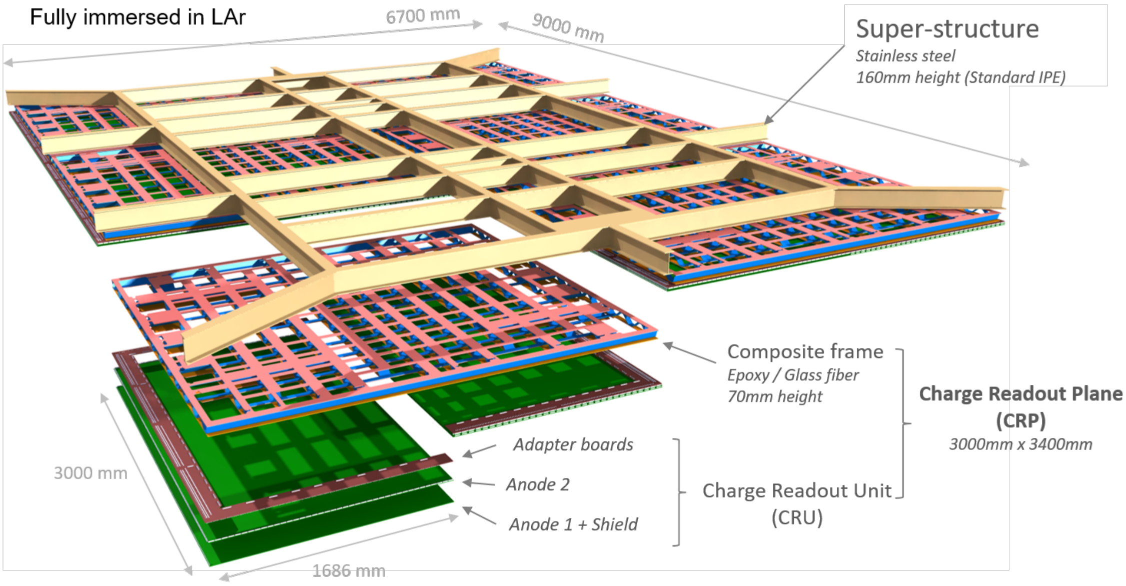

FIG. 4: Vertical Drift CRP superstructures for the top-drift volume.

module but the larger target mass allows collecting more neutrino interactions.

The Photon Detection System (PDS), including the installation of photo-detectors (X-ARAPUCA tiles, derived the ARAPUCA photo-detectors already used for the first Far Detector module) on the cryostat walls and on the cathode surface (see Figure 6), offers better performance and sensitivity than in the first DUNE module, in particular for low energy physics.

In order to allow the scintillation light reaching the photo-detector walls the field cage design has been optimized adopting thinner profiles ensuring 70% transparency. However the integration of the X-ARAPUCA in the cathode structure requires operating them at about -300 kV, which is a new challenge. A backup option is based on photo-detectors operation only on the cryostat walls, providing similar performance as in the first DUNE Far Detector module.

Since summer 2020 the developments for a system for the operation of the photo-detectors on the cathode focused on the Power over Fibre (PoF) technology to decouple the photo-detectors powering from the detector ground. Adequate voltage to power the Silicon PhotoMultipliers (SiPM) with PoF technology was demonstrated in cryogenic conditions. Study of interference with other detector components, long term stability and scaling-up are the next challenges. The readout must also be decoupled from the ground, and therefore the output signals must be transmitted optically to the outside of the cryostat. Two possibilities are under considerations: ADC operating at cold and transmission of the digitised signal or analog transmission of the photo-detectors signals over optical fibers with a linear voltage to optical converter operating in LAr.

Aspects related to the evolution from the dual-phase design and the definition of the Vertical Drift

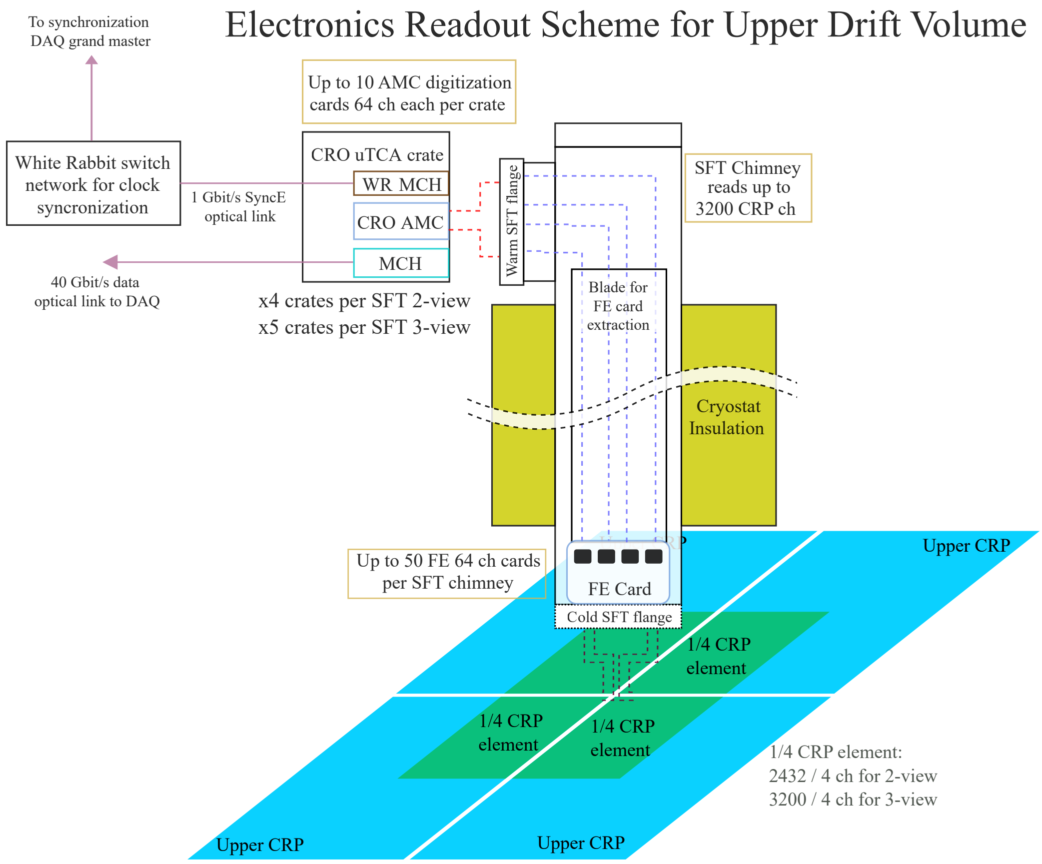

FIG. 5: System architecture of the top-drift charge readout electronics.

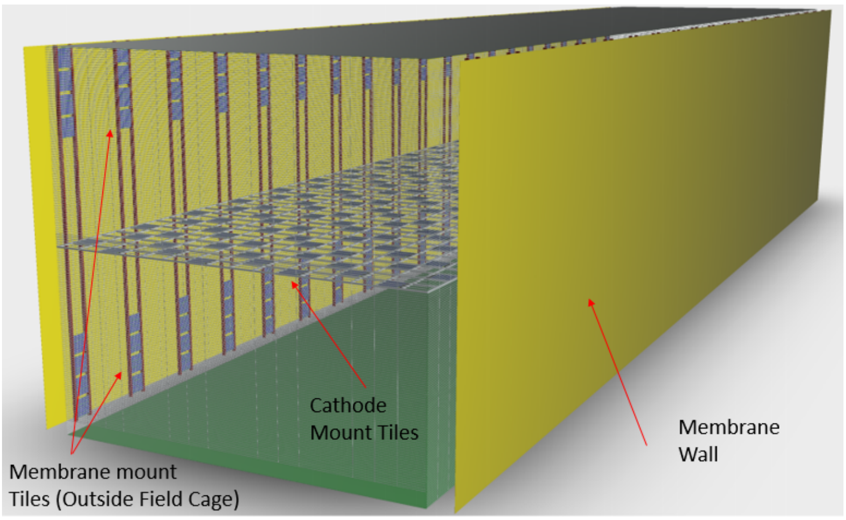

FIG. 6: Photo-detectors tiles coverage on the cryostat wall and on the cathode in the Vertical Drift Far detector module.

module are further developed in a dedicated Section of this report (Sec 3).

Some additional information on the running of protoDUNE dual-phase and the acquired experience on the understanding of the detector is summarized in the following paragraph.

1.5 Outlook on the experimental efforts on protoDUNE dual-phase

The prototyping efforts on the dual-phase supported by the IN2P3 groups are described in details in the report for the previous CS IN2P3 in 2018 Report, Slides.

The 2021 report instead covers the most recent news on protoDUNE dual-phase, since the period corresponding to its installation, started in 2018, up to the end of its first run period. For protoDUNE dual-phase the IN2P3 groups provided : the Charge Readout Electronics, the Charge Readout Planes mechanics and the DAQ system.

The installation of protoDUNE dual-phase was completed in the Spring 2019. After detector filling, operation was started in August 2019. The first year of operation of protoDUNE dual-phase was completed, as originally foreseen, in September 2020.

Full details about the experimental activity supported by the IN2P3 groups at the CERN Neutrino Platform are contained in the annual reports systematically submitted by NP02/protoDUNE dual-phase to the CERN SPSC committee. An exhaustive list of previous report documents is also contained in the 2018 CS IN2P3 DUNE report.

The most recent SPSC documents are listed below:

- SPSC, Running after LS2 meeting, January 2019: slides, document SPSC-P-358
- SPSC Review 2019: slides, document SPSC-SR-251
- SPSC Review 2020: slides, document SPSC-SR-269
- SPSC Review 2021: slides, document SPSC-SR-287

In August 2019 a component of the High Voltage system of protoDUNE dual-phase, the extender pipe connecting the high voltage feedthrough to the cathode, developed a short circuit with the field cage at about 1/4 of the field cage length, taking as starting point the position of the anodes. The high voltage feedthrough is located on the cryostat roof while the cathode is placed at the bottom of the cryostat, at more than 6m depth from the LAr surface level. The extender contains the conductor bringing the high voltage from the feedthrough to the cathode surrounded by a G10 cylinder. In order to contain the electric field inside the extender volume a set of equally spaced conductive rings are distributed outside the G10 cylinder, all along the length of the extender. Those rings are connected with equipotential links to the field cage rings located at the same height.

A parasitic connection developed in August 2019 between the HV conductor inside the extender and one of the field cage equipotential links. This short path introduced a distortion in the drift field of the detector, mostly present after the first quarter of the drift space, from the position of the

Charge Readout Planes anodes. This field distortion allowed nonetheless the detector to operate and the assessment of several important aspects of the dual-phase technology but it limited the exploitable drift space inside the detector and more importantly it prevented the full demonstration of the operation of the high voltage system at '300 kV. Some nice examples of cosmic ray events collected during the operation of NP02/protoDUNE dual-phase are shown in Figure 7.

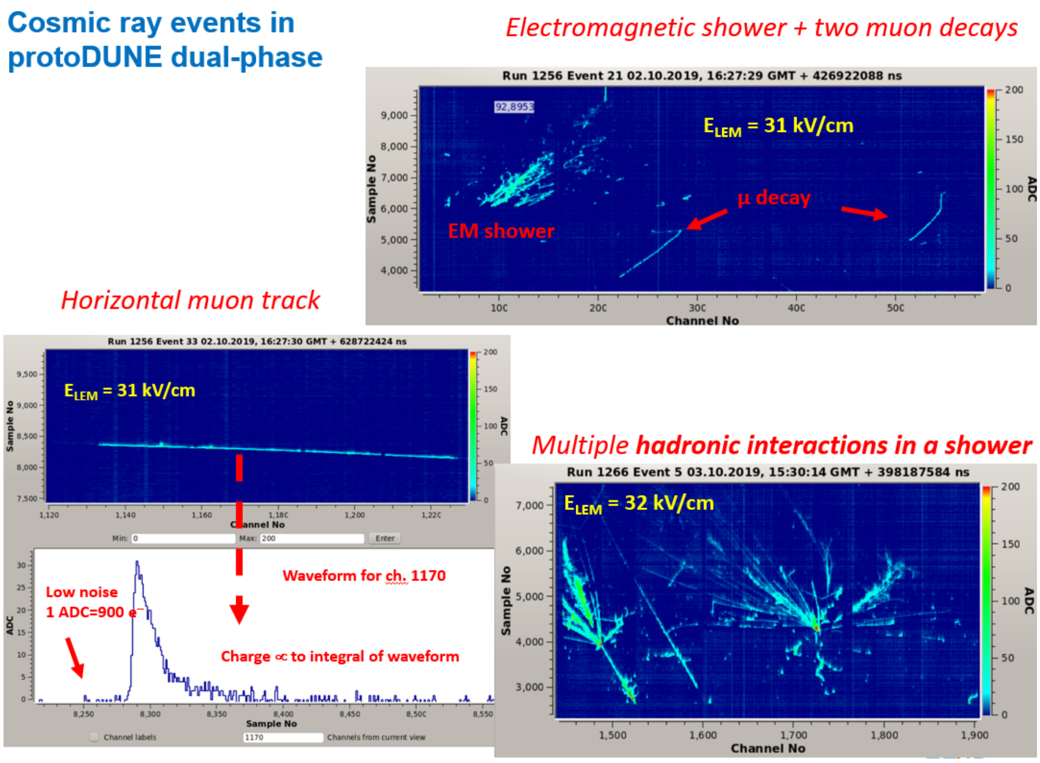

FIG. 7: Examples of cosmic ray events collected during the operation of NP02/protoDUNE dual-phase.

CERN developed a mitigation program for the extender High Voltage issue. The first step was attempting an "in situ" repair intervention on the extender in summer 2020. This intervention was executed in order to cut the path allowing the short circuit connection from the extender to the field cage. In parallel CERN developed a new, simplified, design of the extender which was tested in a standalone setup in Summer 2021 and eventually implemented in protoDUNE dual-phase. The demonstration of the validity of this new HV extender design and the operation of the high voltage system at -300 kV are an important aspect also for the operation of the Vertical Drift module, as described later.

A first operation period of protoDUNE dual-phase lasted since August 2019 to April 2020. The detector was then partially emptied in order to perform the intervention aimed at repairing the extender fault. After the intervention the amount of removed liquid argon was quickly refilled, using LAr from emptying the single-phase protoDUNE detector.

The operation of protoDUNE-dual phase was restarted in August 2020 and it was stopped in September 2020, as foreseen by the end of the first run period.

The repair attempt did not fix the parasitic connection between the extender and the field cage but it displaced this issue about 20cm below the position where the first short had been discontinued by the intervention.

At the end of the run, the NP02 cryostat was then completely emptied and warmed up in order to get access to the detector for upgrade operations and the replacement in 2021 of the HV extender with an extender featuring a completely new design.

A first inspection inside the NP02 cryostat after the end of the run was performed via the man-hole access in February 2021. The extender repair attempt, the following completion of the protoDUNE dual-phase run and the detector inspection inside the cryostat are described in **Section**: 2.

1.6 The Vertical Drift detector design

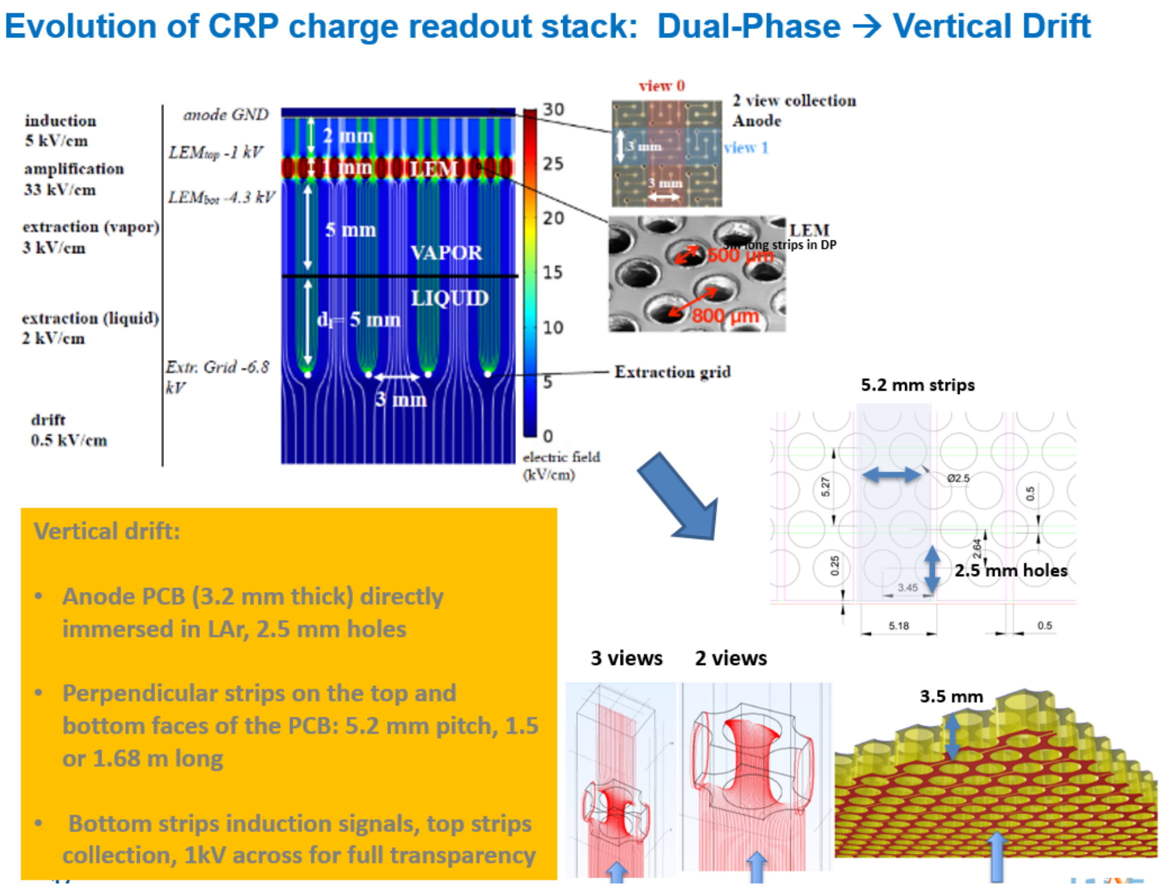

FIG. 8: Evolution of the dual-phase anode stack design to the simpler Vertical Drift perforated anodes.

During Summer 2020 parallel test activities performed at the CERN Neutrino Platform showed that perforated anodes immersed in liquid argon (see Figure 8) could effectively simplify the dual-phase Charge Readout Plane (CRP) design by replacing the anode-LEM sandwiches, operating in the gas phase.

The perforated anode tests offered the opportunity to evolve the dual-phase to the Vertical Drift design. The Vertical Drift design, as previously mentioned, is simpler than the dual-phase and less sensitive to environmental conditions, like the state of the LAr surface and the presence of dust or other debris contaminants. Furthermore, it does not need further R&D activities on the LEMs. Additional R&D activities had been already planned for expected phase-II of NP02 in order to improve the LEMs stability and active surface.

By not needing strong R&D activities, while keeping all the interesting aspects in terms of construction/installation simplicity and economy of the dual-phase, the Vertical Drift design opened the way for its quick implementation for the second DUNE Far Detector module.

A conceptual proposal document describing this new detector design, replacing the dual-phase, was promptly written during the Fall 2020. The foreseen phase-II running period of NP02 was then reconverted to the operation of the Vertical Drift **Module-0**, aimed in 2023 at testing the final version of all Vertical Drift detector elements before entering the production phase.

The Vertical Drift design underwent several DUNE reviews in the US and it was quickly adopted by the DUNE collaboration as preferred option for the second DUNE Far Detector module. The conversion from the dual-phase to the Vertical Drift design is described in more details in **Section** 3.

The Vertical Drift proposal document, written at the end of 2020, described the design of the Vertical Drift detector, as well as the tests program, associated to NP02, in order to fully validate the evolution of the new CRPs based on the perforated anodes and other aspects of the Vertical Drift design.

This new test campaign naturally replaced the one scheduled for the phase II of NP02. The new tests program, described in **Section** 4, foresee three main items:

- first tests of the new CRPs to be performed in the Fall of 2021 by using a refurbished version of the cold-box, originally developed to test the dual-phase CRPs;
- replacement of the NP02 High Voltage extender with a new one with simplified design, where the weaknesses seen with the protoDUNE dual-phase extender have been corrected
- tests of the new HV extender during the Fall of 2021 by re-running the protoDUNE dual-phase detector;
- continuation of the Vertical Drift CRPs tests campaign in 2022 in view of the preparation for the *Module-0* tests in 2023

- equipping and rerunning the NP02 cryostat with Vertical Drift CRPs and other components in 2023 in order to establish the *Module-0* operation for the DUNE second Far Detector module and start mass production for the second Far Detector module.

1.7 Recent progress on the Vertical Drift

The requirement of demonstrating 300 kV for the Vertical Drift module motivated a very aggressive schedule. This resulted in operating again already in 2021 protoDUNE dual-phase, in order to test quickly the new High Voltage extender design. ProtoDUNE dual-phase was refilled, after the installation of the new extender in July 2021, and has been put back in operation since August 2021. A first operation phase is focused on the stability tests of the high voltage system at 300 kV. The high voltage system including the new extender was ramped up for the first time on September 15th, reaching 300 kV.

With a similarly aggressive schedule, the cold-box campaign for the tests of the new vertical drift CRPs quickly advanced in 2021. The refurbishment of the cold-box for the Vertical Drift tests, including the implementation of a purification system and the displacement of the cold-box to the EHN1 hall, has been completed. The components for the test of the first Vertical Drift CRP (shared among the top and bottom drift layouts) including the perforated anodes; readout electronics and DAQ; signal feedthrough chimneys and a cathode module were produced and tested in 2021.

The CRP perforated anodes are being assembled together. It is then foreseen to assemble them together with the CRP structure in October and start the cold-box operation at the end of the month of October. In parallel efforts are being conducted to prepare for the cold-box tests of full top and bottom drift CRPs to be performed in 2022 and for the operation of the Vertical Drift Module-0 in 2023.

The second Far Detector design and organization made large progress in 2021.

After the proposal document the DUNE collaboration produce a Conceptual Design Report (CDR) for the Vertical Drift module.

A draft version of the CDR was submitted in August 2021 by the LBNC Committee with a positive feedback expressed in the September LBNC review (from the closeout report of the LBNC committee of September 2021 meeting: *A year ago the Vertical Drift concept was a glint in a few peoples eyes. We have observed an ambitious R&D program which is enjoying amazing success. We have reviewed the technical aspects in the Spring of the year and recently reviewed a complete Conceptual Design Report. DUNE has our comments, and we have discussed their path to what we anticipate will be a recommendation for approval of the CDR by the end of the year*).

It is then expected that the second DUNE Far Detector module CDR will be published in November.

The document reviewed by the LBNC Committee can be accessed at this address: CDR draft.

The CDR draft document should be considered as the main source of information associated to this report, concerning the Vertical Drift second Far Detector module design, organization, test campaigns and production and installation schedules.

1.8 The kick-off of the DUNE TGIR program

In addition to the definition of the Vertical Drift design, Fall 2020 saw also the approval of the TGIR program supporting IN2P3 and CEA for contributions to the DUNE Far detector and the PIP-II program to achieve the large proton intensity needed for the LBNF neutrino beam for DUNE.

CEA/Irfu leads the contribution to the PIP-II project. IN2P3 leads the contribution to the DUNE second Far Detector module based on the Vertical Drift technology, with an overall contribution on various detector items at the level of about one half of the cost of the module.

A TGIR kick-off meeting was held in May 2021 with the participation of the DUNE IN2P3 groups and institutions, the IN2P3 management. International contributions to the meeting were provided by the DUNE collaboration, the LBNF project and the CERN Neutrino Platform.

The material of the TGIR kick-off meeting (Kick-off meeting web site) may provide a detailed view of the status of the DUNE experiment and of the IN2P3 activities in DUNE. This material is naturally very pertinent to this report. In particular this list of presentations covers specific aspects:

- Accelerators Physics DAS presentation on the IN2P3 TGIR program for DUNE
- LBNF project leader and Fermilab deputy director status report on LBNF
- DUNE spokesperson report on DUNE physics goals, organization and status
- IN2P3 DUNE project leader report on the DUNE IN2P3 project and the evolution from the dual-phase to Vertical Drift
- DUNE Charge Readout Planes Consortium Leader overview on the Vertical Drift 2nd Far Detector module
- Report by the CERN Neutrino Platform leader on the CERN Neutrino Platform and support to Vertical Drift test
- Report by the Technical Coordinator of the second DUNE Far Detector module on The path to the Vertical Drift module: milestones and schedule

Another very important milestone for the realization of this program corresponded to the approval in June 2021 by the CERN Council of the CERN support for the construction of the cryostat for the second DUNE Far Detector module.

1.9 DUNE construction status

An overview of the DUNE project and of the IN2P3 implications can be also found in this DUNE status talk given at the IRN Neutrino meeting in June 2021.

DUNE is an experiment in construction phase. The LBNF project had its groundbreaking ceremony in July 2017 and it is in an advanced phase. Since 2017 the Reliability Project upgrades to the SURF laboratory and all pre-excavation works were completed. The main excavation works for the construction of the three DUNE caverns started in April 2021 and are expected to be completed by April 2024. Immediately after the LBNF groundbreaking, the DUNE collaboration started the formation of Consortia for the construction of the Far Detector modules. These Consortia are based on the model of the sub-detector collaborations for the LHC experiments. The Consortia organization currently covers the construction of the first and second Far Detector modules, the Near Detectors and Computing.

IN2P3 physicists ensure the leadership of two Consortia involved in the construction of the second Far Detector module: D. Autiero is the leader of the Top-Drift Electronics (TDE) Consortium (involving groups from France, Japan and US) and D. Duchesneau is the leader of the Charge Readout Planes (CRP) Consortium (involving groups from France, CERN and US).

A description of the IN2P3 groups activities (including the list of participants) is contained in the DUNE IN2P3 project talk given at the TGIR kick-off meeting in May 2021.

The DUNE IN2P3 project includes groups from APC Paris, IJCLAB Orsay, IP2I Lyon, LAPP Annecy, and LPSC Grenoble. The project benefits as well of the technical support from CC-IN2P3 Lyon and of the electronic service of CENBG Bordeaux. Current manpower involvement includes actually more than 50 people, about equally shared among physicists and engineers. This number is growing with new hiring processes and internal mobility.

The IN2P3 groups contribute to the construction of the top-drift electronics (IP2I and CENBG) and associated mechanics with the signal feedthrough chimneys (IJCLAB), of the Charge Readout Planes (LAPP and LPSC) and of the cathode (IJCLAB), which is provided via the High Voltage Consortium. An involvement is also under construction in the Photon Detection System (APC) for which the technology is being developed in order to operate the photon detectors on the cathode at 300 kV.

The IN2P3 groups are also also naturally involved in the Data Acquisition, since the DAQ front-end for the top-drift is included in the TDE consortium and they have thus to ensure an optimal design and construction of the DAQ back-end, in the scope of the DAQ Consortium. IN2P3 contributes as well to the DUNE Computing Consortium (IP2I and CC-IN2P3). All IN2P3 groups ensure as well, in parallel to the detector development and construction activities, strong and steady contributions to the DUNE analysis and software developments and reconstruction activities.

1.10 DUNE Physics update

The DUNE physics sensitivity and status and the LBNF status were presented at the TGIR kick-off meetings in May.

Neutrino oscillations are currently the only experimental evidence of physics beyond the Standard Model. The determination of the mass hierarchy and the search for CP violation are fundamental measurements, which could bring to important discoveries, for which the DUNE experiment is optimally placed having unique characteristics among which the possibility of exploiting the spectral information and accurate events reconstruction in the LAr TPC.

The primary science program of LBNF/DUNE focuses on fundamental open questions in neutrino and astro-particle physics, addressed with the Far Detector events detection, complemented with the Near Detectors measurements for the fluxes determination and systematics.

The Near Detector complex and the high intensity neutrino beam will offer as well the opportunity of a rich ancillary physics program, beyond the primary mission of the experiment, addressing: cross-section measurements; searches for sterile neutrinos and beyond the SM physics searches.

The primary physics program is based on:

- Precision measurements of the parameters that govern $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations, with the goal of measuring the charge-parity (CP) violating phase δ CP, where a value differing from zero or π would represent the discovery of CP violation in the leptonic sector, relating to the understanding of the matter-antimatter asymmetry in the universe,

- Determining the neutrino mass ordering (the sign of $\Delta m^2{}_{31}$), often referred to as the neutrino mass hierarchy

- Precision tests of the three-flavor neutrino oscillation paradigm through studies of muon neutrino disappearance and electron neutrino appearance in both ν_μ and anti-ν_μ beams, including the measurement of the mixing angle θ_{23} and the determination of the octant in which this angle lies

- Search for proton decay in several important decay modes. The observation of proton decay would represent a ground-breaking discovery in physics, providing a portal to Grand Unification of the forces

- Detection and measurement of the ν_e flux from possible core-collapse supernova within our galaxy

A detailed description of the DUNE physics potential is contained in the TDR physics volume published in 2020. The DUNE sensitivity depends of course on the detector and beam staging strategy, which is described in the TDR physics volume, and on the systematic uncertainties, assessed with the Near Detectors at a level to be kept smaller than the Far Detector statistical uncertainties

In addition to the TDR physics volume a set of papers have been published covering various details:

- Long-baseline neutrino oscillation physics potential of the DUNE experiment
- Neutrino interaction classification with a convolutional neural network in the DUNE far detector
- First results on ProtoDUNE-SP liquid argon time projection chamber performance from a beam test at the CERN Neutrino Platform
- Supernova Neutrino Burst Detection with the Deep Underground Neutrino Experiment
- Prospects for Beyond the Standard Model Physics Searches at the Deep Underground Neutrino Experiment
- Experiment Simulation Configurations Approximating DUNE TDR
- Deep Underground Neutrino Experiment (DUNE) Near Detector Conceptual Design Report
- Searching for Solar KDAR with DUNE
- Design, construction and operation of the ProtoDUNE-SP Liquid Argon TPC
- Low exposure long-baseline neutrino oscillation sensitivity of the DUNE experiment

Papers on the performance results of protoDUNE dual-phase are in preparation and the dual-phase TDR volume is also foreseen to be published.

The IN2P3 groups have been deeply involved in the Physics sensitivity analysis of LBNO and ensured the coordination of physics working groups in DUNE and of the dual-phase reconstruction and Computing.

The IN2P3 groups plan contributing to several aspects of the DUNE Far Detector online analysis (trigger definition in the DAQ for SN burst neutrinos and other event flows) and offline analysis, concerning:

- Events simulation, reconstruction, particles identification, energy and kinematical measurements
- Search for CP violation and determination of the hierarchy of neutrino masses.
- Studies on cosmic ray events, atmospheric neutrinos and search for proton-decay
- Search for ν_τ appearance
- Search for n-nbar oscillations
- Search for SN burst neutrinos

These contributions benefit also from the synergies deriving from the fact that the IN2P3 community is at the same time coherently involved in the detector developments and in the software, reconstruction and analysis developments. The Far Detector analysis and simulation is based on common single/dual phase tools such as LArSoft.

The involvement in the long-baseline oscillation studies is naturally the main goal for the IN2P3 groups. Three theses were defended respectively at APC, IP2I and LAPP,on aspects related to the dual-phase Far Detector reconstruction and electron identification and the reconstruction of electromagnetic showers; addressing the kinematical searches for ν_τ appearance in DUNE; on the study and simulation of the scintillation light in liquid argon. Another two theses will be defended soon: on events reconstruction in LAr and on the development of online processing algorithms for the definition of the events trigger needed for SNa neutrino bursts searches. Other thesis projects are in progress.

Other analysis aspects which are being developed concern nuclear effects in the neutrino energy reconstruction and in the interaction of SN neutrinos (for which the IN2P3 groups can benefit of a strong tradition in the French nuclear theory community). The search for n-nbar oscillations and the related nuclear effects is also an interesting subject for DUNE. Also in that case there is an opportunity of collaboration with the French nuclear theorists historically working on this subject and now connected to DUNE, as J.M. Richard at IP2I.

1.11 Conclusions

Since the last review by the IN2P3 CS in 2018, despite the sanitary situation due to the Covid-19 outbreak, there was excellent progress in completing the foreseen operation program of NP02/ProtoDUNE dual-phase and in evolving the NP02 experimental activities on the basis of the operation experience, the lessons learned and new developments to the Vertical Drift design. The Vertical Drift has set up a sound program, in rapid progress, which is now at the basis of the second DUNE Far Detector module. This effort benefits of the strong support from the DUNE collaboration, Fermilab and DOE, the CERN Neutrino Platform and a TGIR program in France.

2 Completion of ProtoDUNE dual-phase run in 2020

2.1 Introduction

The main phases of the NP02/protoDUNE dual-phase construction and operation are summarized below:

- NP02/protoDUNE dual-phase $6 \times 6 \times 6m^3$ construction (2018-2019)
- All four CRPs tested in cold-box tests program in Summer 2018
- Start of detector operation in August 2019, development of the HV extender issue
- LEM and CRPs stability studies (August 2019-April 2020)
- HV surgery intervention: preparation + execution+ refilling (May-July 2020)
- Continuation of the operation after HV surgery in August 2020
- Completion of dual-phase NP02 Phase-I operation period September 2020
- Cryostat inspection in February 2021

This Section mostly contains an update on operation and results of protoDUNE dual-phase in 2020.

Detailed information on the operation experience in 2019 is contained in the 2020 SPSC protoDUNE dual-phase annual report: slides, document SPSC-SR-269

2.2 High Voltage extender repair operation in June 2020

The repair attempt of the High Voltage extender was performed on June 17th 2020, accordingly to the expected schedule.

The access to the extender was possible from the cryostat penetration of the high voltage feedthrough, after having removed the feedthrough. This limited access needed the development of specific tooling and training. The operation was then performed following what learned during the training activities performed on a mock-up installed in building 182.

The operation was executed as expected, with no technical difficulties in handling the needed customized tools from outside the cryostat and in removing the first 3 cable connections present in between the extender and the field cage. The short circuit appeared in August 2019 had been localized since that time at the level of the first connection. Additional two connections were removed as well to have a safety margin.

An accelerated movie of a few minutes shows the highlights of the intervention: movie of the HV extender surgery.

The cryostat was then refilled in a couple of days with LAr from NP04, using a new piping implemented in order to allow for a direct transfer. The last week of July 2020 was used to perform HV commissioning tests after the repair. The plan was then to exploit a window of operation of four weeks in August 2020 before emptying the cryostat at the beginning of September.

During that last week of July 2020 it appeared that, despite the extender surgery operation had been technically very successful, a surface current was flowing on the extender from the ring (where the crack in the G10 insulation layer causing the short circuit had appeared in August 2019) down to the fourth ring. The fourth ring was the first ring still connected to the field cage after the operation. This current was creating a new short circuit path, deported by 3 rings (18 cm) below the position of the short which had appeared in August 2019.

The surface current on the extender dielectric was not continuous but composed by sparks (flashover). A picture of one of the largest sparks could be taken by using one of the cryogenic cameras in the dark. This picture allowed confirming the new situation and documenting the flashower current in between the first and fourth ring.

The intervention on the first 3 extender rings unfortunately could not fix the issue with the HV extender and could not re-establish a uniform and constant drift field over 6m. The field configuration was then similar as the one present before the intervention with some additional features affecting the stability of the cathode-extender HV connection, which were later on confirmed with a direct inspection in February 2021.

2.3 Completion of the NP02/protoDUNE dual-phase run in August 2020

Having emptied the top part of the cryostat for a few weeks, also heated up the insulation material around the membrane and made worse the problem of bubbling. It took a couple of weeks in order to define a new operational procedure to get rid of the bubbles since the procedure used during past months for that purpose had become ineffective.

At the end of the run, at the beginning of September, a dedicated investigation of bubbling and surface instabilities was performed by introducing new cameras in the cryostat via a feedthrough. A few points of bubbling on the walls and also deeper level in the field cage were spotted.

Once got rid of the bubbles, around half of August 2020, it was realized that also the CRPs had became more unstable by having a grid sparking rate more than a factor ten worse than the one recorded in the previous months and reported in the April 2020 SPSC report. The sparking rate of the LEMs was instead quite similar to past records.

There were dedicated investigations performed on this new issue affecting the CRP grids. After having rejected the possibility of alignment issues of the CRPs with respect to the liquid surface, it appeared that this new issue could be related to a thermal effect which affected the CRPs grid structure.

This effect could be probably due to the stronger thermal excursion happened during the quick cryostat refilling after the HV surgery. The effect could be caused by a release of the wires tensions during that thermal cycle and/or to the presence of floating filaments on the LAr surface. There was a clear hint of contamination of dust in the grid. This was observed by operating the CRPs in pure gas and seeing an improvement of the maximum voltage that the grids could stand, by burning with time the dust present thanks to its exposure to high voltage in the gas.

It is possible that dust contamination was reshuffled with the fast refilling in July 2020. The inspection performed in March 2021 had also as a main task to check the presence of contamination in the cryostat and in particular of materials and dust trapped in the CRP grids.

Despite the new issues which appeared after the HV extender surgery intervention, which had no equivalent in the past operation records, and despite the limited time window available before the foreseen emptying of the cryostat in September, the foreseen program of tests was completed in a very intensive working period.

Additional tests were performed as well and many new aspects were understood. The investigation of the new CRP grid HV issues provided also a hint of what could have caused such instabilities which in the past were observed at much smaller rate and mentioned in the annual SPSC report of April 2020. Hints pointed out to the presence of debris in the grids which seemed to have worsened with respect to the past and to possible effects on grid wires tension. Improvements on the CRP structure had already been foreseen in the program of improvements for the phase II of protoDUNE dual-phase.

Additional tests on the LEMs/CRP were completed as well. The effect of controlled injections on N2 was tested with respect to possible quenching of LEMs/grids sparking and on the light readout response. CRP microphonic effects were fully characterized in the normal CRP operation conditions and also with the CRPs immersed in liquid.

The LAr bubbling was investigated with the help of additional cameras, as already mentioned above. The CRPs were also operated while completely immersed in LAr in order to check this effect on LEMs and grid sparking. It was expected to have the LEMs and grid sparking completely disappearing when the CRPs were immersed in LAr. Instead some sparking activity was also observed in these conditions. A complete outlook on the issue of the HV extender was also completed, allowing to define a new design aimed at preventing the issues observed since 2019. Overall the amount of aspects learned was quite large and interesting.

Extended details may be accessed in a dedicated presentation, given to the LBNC Committee in September 2020 just after the end of the protoDUNE dual-phase run: ProtoDUNE dual-phase, LBNC September 2020.

In that presentation the next plans for the phase II of protoDUNE dual-phase were described as well. A list of checks/inspections was defined, to be performed as soon as the cryostat could become accessible in order to check for the presence of dust contamination, the status of LEMs and grids and the points of sparking/hot spots, the status of the HV system etc... This additional information eventually supported the model extracted from the running experience in August 2020.

Overall this last operation experience of protoDUNE dual-phase supported the improvements program that had been planned on the LEMs/CRPs plus some other measures in order to improve environmental aspects inside the cryostat. For what concerns the LEMs there had been also, in parallel to the end of the NP02 run, a standalone test activity on new LEMs with encouraging results on improved performance and stability.

2.4 NP02 Cryostat inspection in February 2021

On February 17th, 2021 a first access inside the NP02 cryostat was performed via the manhole. The goal of this first inspection after the emptying of the cryostat was to check the general cleanliness of the interior and to perform several observations on the main detector components.

A list of items to inspect and control was compiled already in September 2020. The items covered during this first inspection were the following:

- Collection of samples of contamination (dust/filaments) inside the cryostat, particular care had to be taken in accessing without introducing other contamination or removing/reshuffling the dust material around
- Status of TPB coating on coated PMTs
- Status of the resistors connecting the extender to the cathode

- Presence on material trapped in the CRP grids
- Presence of spark traces connected to grids sparking
- Presence of spark traces connected to LEMs sparking and other signs of LEMs deterioration (carbonization spots)

The walls, the top of the CRP structure and the surface of the anodes of the CRP4 were very clean. Only very few dust particles or deposits at certain locations were visible. Some very thin 'metallic' powder was accumulated below some ground grid tube holes.

Samples of dust and debris found on the floor were collected and brought back to outside. They were tiny plastic pieces of cable protection, some black tape and a few dust particles. Figure 9 shows different images of the observed and collected residues described above.

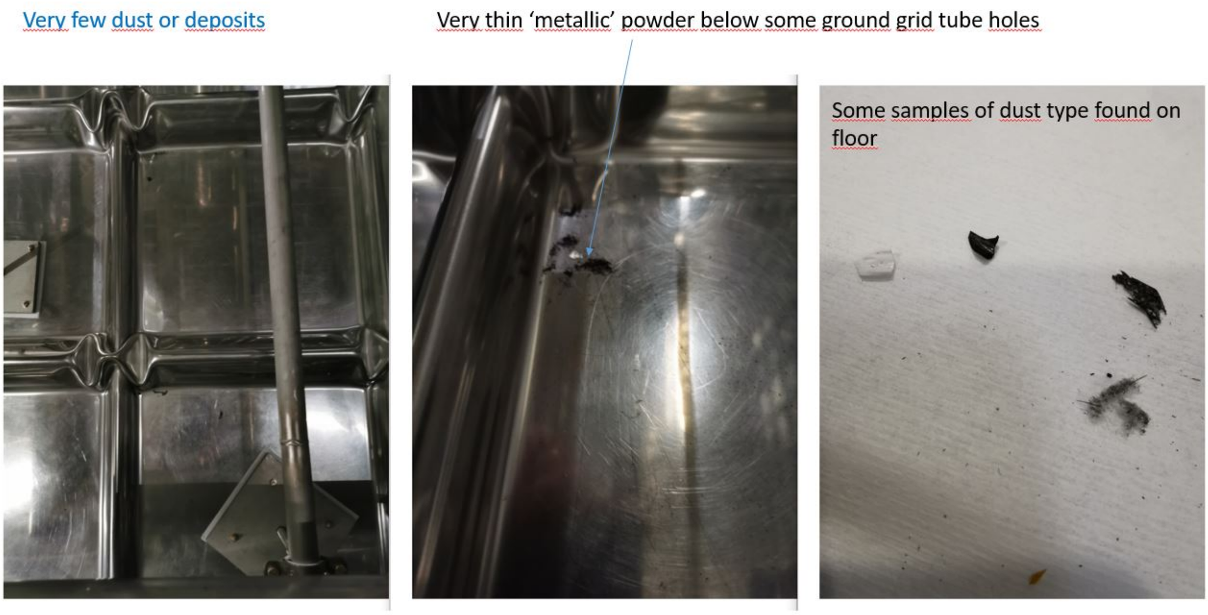

FIG. 9: Photos of different type of dust observed and collected on the NP02 cryostat floor.

The cathode connection to the last ring of the extender was made through a resistive chain (two 50 MOhm parallel resistors in series with other two 50 MOhm parallel resistors) protected into a shrinkable tube.

There was a hint from the HV operation after the extender "surgery" repair, that such a chain was damaged and fully or partially open by discharges from the cathode or the extender (the current from the HV-PS to the cathode was lower then nominal and highly unstable).

Visual inspection confirmed this hypothesis. The resistors were all "exploded" (see figure Figure 10) indicating that they experienced a (possibly instantaneous) very high voltage drop across them (and consequently a considerably high power was also dissipated through them). The failure is most likely due to a temporary too high voltage difference between the cathode and the extender; this could happen for instance in case of a sudden drop of the voltage on the extender with the cathode discharging all its stored energy through the resistors.

FIG. 10: Photos of the connection between the cathode and the HV extender made of a resistor chain. The blown resistors are visible inside the partially exploded shrinkable tube. The failure is most likely due to a temporary too high voltage difference between the cathode and the extender.

A portable UV LED light was used to illuminate the floor and the top of the photomultipliers in order to check if there were damages on the TPB coating. As a result no TPB debris were seen on the floor and the direct coating on the PMT tubes appeared very uniform as can be seen on the Figure 11.

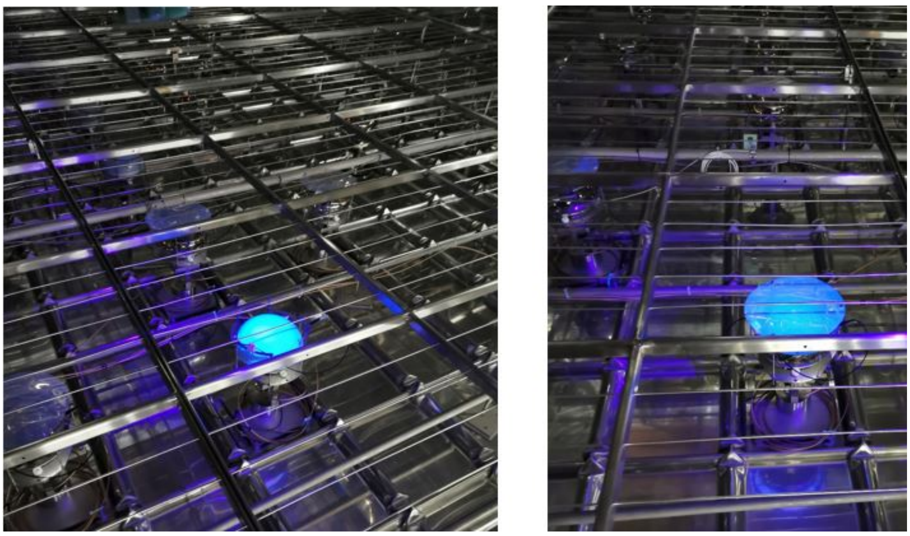

FIG. 11: Photos of different type of dust observed and collected on the NP02 cryostat floor.

The PEN sheets were all in good shape but one which was partially detached from its support and staying on the side of its PMT (PMT 23). It was found from the light data recorded during refilling that the signal showed a strange behaviour in this PMT starting on the 7th of July 2020 when the liquid level was at around 5 meters.

The other main operation during this first inspection was to image at high resolution the CRP from the floor using a camera with a 200 mm focal distance lens. This setup was able to image the LEMs in details showing even the 50 μm diameter holes.

From the pictures taken, a few issues were observed like the presence of filaments, dust residue in corners of the grid comb and carbonisation spots on several LEM corners. On one of the pictures two plastic washers (a few mm diameter), not belonging to the CRP, appeared to be stuck in between the extraction grid and the surface of the LEM (see Figure 12).

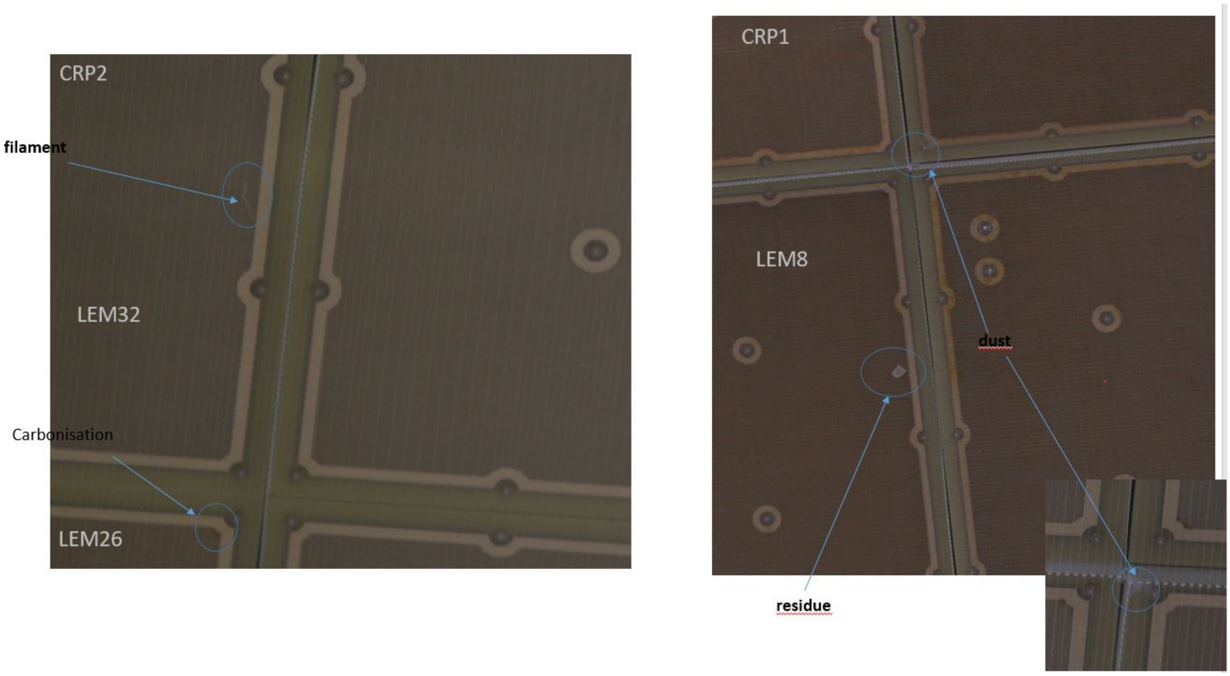

FIG. 12: Photos of LEMs and grids of both CRPs having elements between the extraction grid and the LEM surface as well as some evidence of carbonisation spots.

The removal of the extender performed in May 2021 in order to replace it with the new extender based on improved design, allowed for a direct check of the point where the G10 insulation had a failure in August 2019, generating a short circuit path to the field cage.

Indeed after having removed the equipotential rings, a carbonisation spot, corresponding to a crack in the FR4 insulation was clearly visible in correspondence to the second ring (see Figure 13).

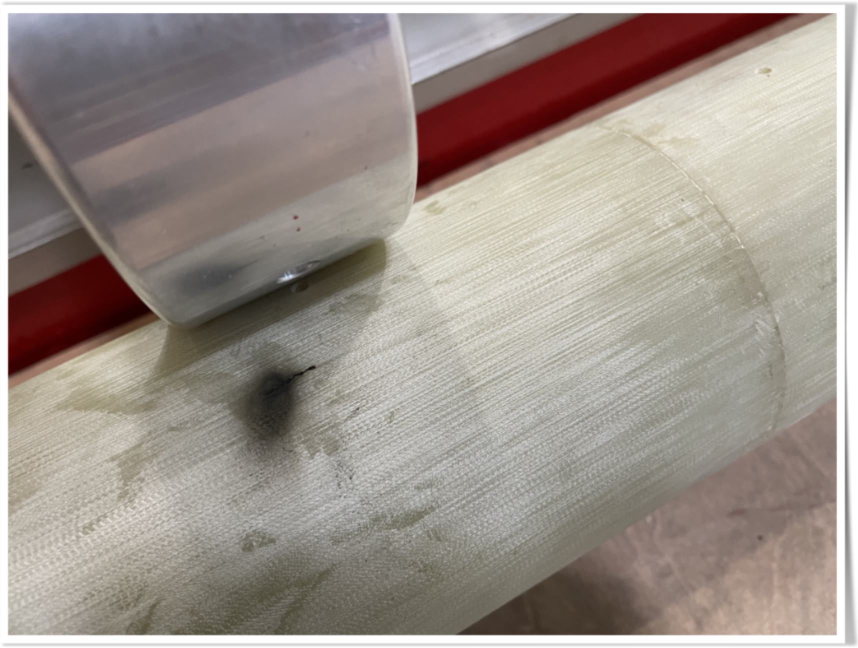

FIG. 13: Localization of the fault in the G10 insulation below the second equipotential ring, after having removed the old NP02/protoDUNE dual-phase High Voltage extender.

3 Evolution of the dual-phase design to the Vertical Drift

3.1 Experience learned from dual-phase operation

A description of the operation results of protoDUNE dual-phase is reported in Section 2.

The present section instead summarizes the main aspects learned from the dual-phase operation and describes the evolution of the dual-phase design to the Vertical Drift for the construction of the DUNE second Far Detector module.

The main aspects from the NP02/protoDUNE dual-phase running experience are listed below:

- A gain of ≈ 6 was shown to be obtainable but the LEMs performance was tending to degrade over long time periods, related to an increase in their sparking rates

- A LEM design improvement program was already in progress since spring 2020 at CEA in order to increase the LEM active surface and improve LEMs stability over long time periods;

- The operation experience of protoDUNE dual-phase also showed that the CRP grids had issues of sparking instabilities. Grid sparking should in principle not be possible, given the fact that the grid is immersed in LAr. Grid sparking, given the very high voltage applied ($\approx 8kV$) may cause damages to the readout electronics which are not mitigated by the electronics protection components designed in order to prevent damages from LEMs sparking, occurring at lower voltages and involving smaller energies. An upgrade program of the CRP design, aimed at improving its stiffness and planarity and introducing prevention and protection mechanisms against grid sparking, had been already launched;

- The operation experience of protoDUNE dual-phase showed that environmental aspects in the cryostat were affecting the CRP stability. These environmental aspects where including movements of LAr surface due to bubbling in various points for the cryostat/field cage, direct presence of bubbles, presence of dust/debris contaminating the CRP grids.

A dedicated workshop, involving the World community of micro-pattern gas detector experts, was organized at CERN in April 2020, in order to discuss the experience learned from protoDUNE dual-phase and to confirm the R&D program in order to achieve better stability: Workshop on the LEM/Thick GEM cryogenic utilization in pure Argon over large detection surfaces, Indico link.

The phase-II R&D program on the LEMs/CRPs and its schedule had been already discussed at the SPSC in 2020 (see the section on the 2020 SPSC NP02 annual report on ”Preparation for Phase II and schedule”) and they were further refined and described in the presentation given to the LBNC Committee in September 2020, just after the end of the protoDUNE dual-phase run (see **Section** 2.

In addition to the foreseen LEMs and CRPs improvement program, for the Phase II running of NP02/protoDUNE dual-phase (2020-22), more efforts appeared to be needed on other fronts:

- The improvement of environmental conditions (cleanness and status of the LAr surface), affecting the CRP stability from what learned from the protoDUNE operation, looked feasible with some additional efforts
- The High Voltage design improvements were quite clearly defined for operation at 300 kV, by improving the extender design. However, in order to reach 600 kV, a parallel High Voltage R&D program had been launched and required still time to be completed

3.2 Perforated anodes and simplifications possible thanks to the Vertical Drift design

The other return of experience from the operation of the protoDUNE detectors was that very good LAr purity levels achieved (target figure 3-5 ms electrons lifetime, achieved figure larger than 30 ms). This achievement was making the LEMs gain much less required in order to compensate for signal attenuation during long drift distances.

Since Summer 2020, considerable progress was achieved in DUNE with respect to the dual-phase efforts, by reconverting the dual-phase to a simplified design which does not need anymore the amplification stage of the LEMs.

The LEM-anode sandwiches could be replaced by simpler perforated anodes with readout strips operating immersed in LAr. This new readout PCB design is not affected by the CRP/LEM high voltage issues or risks of sparking. Neither it is sensitive to the status of the LAr surface, as observed during the protoDUNE dual-phase operation for the dual-phase CRPs. The adoption of the perforated anodes also did not imply spending additional time on the completion of the LEMs R&D program, which was aimed at achieving better LEMs stability with time.

Following successful tests performed on the perforated anodes at the CERN Neutrino Platform in Summer 2020 the dual-phase design was then reconverted to a simplified version based on the perforated anodes replacing LEM/anode sandwiches.

A detailed proposal document was produced during Fall 2020 for a DUNE Far Detector module based on this new detector design, which was eventually named "Vertical Drift". The list of signatories of this proposal document, committing as well to related tests campaign of the detector components, further extended and strengthened the NP02 collaboration.

The evolution from the dual-phase to the Vertical Drift included as well a major simplification in the High Voltage (HV) system. For the original dual-phase design the HV system was still needing the completion of R&D activities in order to generate and distribute 600 kV at the level of the cathode. 600 kV were needed in order to ensure optimal drift conditions over 12m, although the DUNE TDR was assuming 300kV as minimal requirement for 12m.

In the Vertical Drift design, by splitting the drift volume in two halves with the cathode at middle height of the cryostat (see Figure 14), the HV requirement is reduced to about 300 kV to be applied to the cathode. These conditions can be achieved with the present state of the art design, after having corrected the weak point in the extender design which was observed during the ProtoDUNE dual-phase operation. This is another aspect allowing for a faster approach towards the construction of the second DUNE Far Detector module.

The Vertical Drift design is very similar to the dual-phase for what concerns its geometrical layout. It is naturally preserving all the advantages developed with the dual-phase in terms of costs, simplicity and rapidity of construction/installation.

It therefore preserves and extends the investments and R& D efforts of several years in the development of the dual-phase design, performed with the support of the CERN Neutrino Platform. The Vertical Drift design maximizes as well the DUNE physics sensitivity by optimizing the amount of

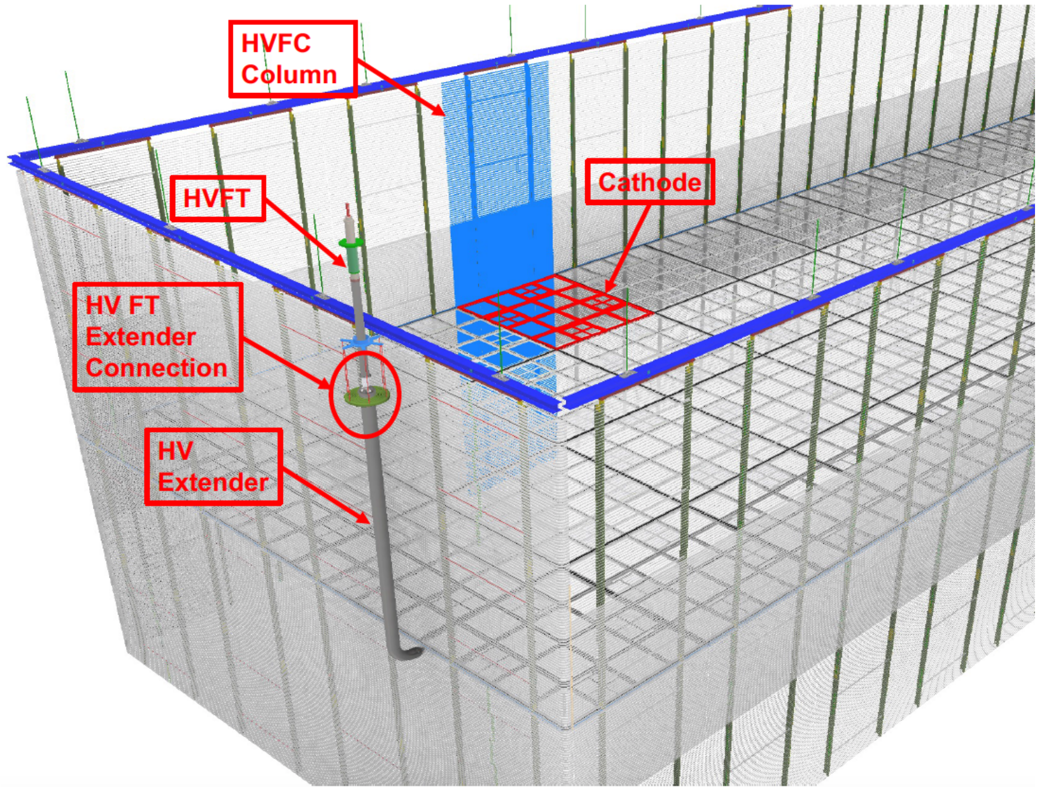

FIG. 14: 3D model of the High Voltage system of the Vertical Drift second DUNE far detector module.

active LAr within the cryostat, reaching almost 15 kton active mass. Apart the perforated anodes which are a new detector component, the Vertical Drift design is largely based on the reconfiguration of existing and already well tested detector elements.

A question may naturally arise about possible disadvantages of the Vertical Drift design compared to dual-phase, in particular for what concern the signal amplitude in absence of gain in the gas phase.

The signal reduction related to unitary gain in the Vertical Drift is however compensated by a few favorable differences with respect to the dual-phase configuration:

1. a factor 2 is gained by not having to share the charge among two perpendicular collection views present in the dual-phase anodes

2. a factor 1.7 is gained by the increase in the strips pitch (5.2mm instead of 3.1 mm used for the dual-phase). 5.2 mm pitch is similar to the pitch exploited in the single-phase detector design

3. a factor 1.6 is gained by the absence of the characteristic dual-phase electrons extraction and collection efficiencies (overall efficiency amounting to 0.63)

Taking into account the factors listed above, the Vertical Drift design features a global signal increase factor of 5.3 compared to a dual-phase detector at unitary gain. This factor compensates the loss of gain. The dual-phase gain requirement in the DUNE TDR requirement was indeed corresponding to a gain 6.

In addition, the TDR dual-phase goal gain requirement of 6 was defined in order to compensate for signal losses over more unfavorable drift conditions (electric field intensity 250V/cm with 300kV at the cathode, 12m drift length, 5ms electrons lifetime in liquid argon).

When these conditions are re-scaled to the more favorable drift geometry present in the Vertical Drift detector (electric field intensity of about 500V/cm with 300 kV at the cathode; 6.5m drift length, 6 ms lifetime in liquid argon) the requirement described in the dual-phase TDR is relaxed by a factor 5.2 (this is equivalent to requiring a dual-phase of ≈ 1 instead than 6).

By taking into account the anode geometry and drift factors (electric field intensity 500V/cm with 300 kV at the cathode; 6.5m drift length, 6 ms lifetime in liquid argon), the minimal signal strength in the Vertical Drift detector is then stronger than the one foreseen by the DP requirements (gain=6) by a factor 4.6. This factor can be further improved by considering electron lifetimes larger than 6ms, as already achieved in the protoDUNEs.

Another merit factor of the Vertical Drift, affecting the electronics noise, is in the lower strips capacitance (around 100 pF/m) to be accounted for about 1.5 m strips length. This figure has to be compared to 160pF/m for 3m strips length, in case of the dual phase CRPs configuration.

3.3 Convergence on the Vertical Drift design for the construction of the second DUNE Far Detector module

The Vertical Drift Design answers the question: "Can we think of a simplified dual-phase detector without LEMs (so not needing the additional efforts in order to complete LEMs/CRP and HV developments) which could be immediately built for DUNE, quickly and at affordable costs ?"

The Vertical Drift Design indeed provides the following advantages:

- LEMs are no more needed, neither the extraction grid. The CRPs evolve to a simplified version hosting the perforated anodes
- No further improvements are needed at the cryostat level to ensure better stability of LAr surface. Vertical Drift which uses components completely immersed can work with the currently known cryostat conditions
- There is no need to complete the R&D to achieve 600 kV. Operation at $approx 300kV$ is sufficient
- All detector components developed for dual-phase (CRPs, electronics, field cage, cathode, HV system) and associated investments are maintained

- The detector geometry is optimized to increase the sensitive volume, reaching almost 15 kton. This aspect is very much needed for the physics sensitivity
- There are large cost and time reductions even with respect to the dual-phase design. 20M$ are saved also from the point of view of installation costs in South Dakota
- Tests at CERN on Vertical-Drift perforated anodes, performed since beginning of summer 2020, were successfully pursued for more complicated configurations such as a 3 views layout and confirmed the idea of evolving from the LEM design
- Developments were pursued since September 2020 in order to optimize the geometry and engineering of the detector and to reach a convergence with the Collaboration and the funding agencies. This process was completed in December 2020.

During Fall/Winter 2020/21 there was consequently a fast international convergence among funding agencies on the proposal of building the second DUNE Far Detector module based on the Vertical Drift design. The Vertical Drift passed quickly several reviews, including: the LBNC Committee, a Fermilab Director's review and a DOE Independent Project Review (IPR). At the end of 2020, the Vertical Drift quickly became the preferred option by the DUNE collaboration and the funding agencies to build a second Far Detector module.

In the conceptual design proposal document, in addition to all technical details briefly mentioned above one, can find as well a description of the tests campaign foreseen at CERN to demonstrate the detector design, further developed in **Section** 4.

This test campaign, which replaced the dual-phase phase-II program, in particular foresaw for 2021:

- Replacing the NP02 HV extender with one of simplified design, by accessing the cryostat via the man-hole, and re-running the protoDUNE dual-phase detector in order to check the HV stability
- Performing full integration tests of the new Vertical-Drift CRPs with perforated anodes with a refurbished version of the cold-box. This cold-box was already used for the tests of the dual-phase CRPs. It is now including purification, drift volume and signals readout.

The second Far Detector Design and organization made large progress in 2021. After the Vertical Drift proposal document the DUNE collaboration produced a Conceptual Design Report (CDR) for the Vertical Drift module. A draft version of the CDR was submitted in August 2021 to the LBNC Committee which expressed a positive feedback during the September 2021 LBNC review. It is expected then that the second DUNE Far Detector module CDR will be published in November 2021.

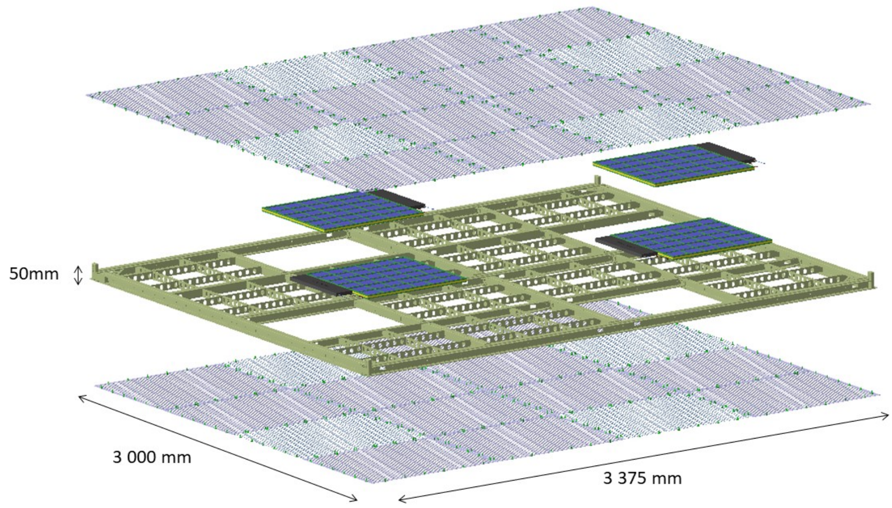

FIG. 15: Conceptual design of a unit cathode module with four integrated photo-detector units in blue.

The CDR draft document should be taken as the main source of information associated to this report concerning the Vertical Drift second Far Detector module design, organization, test campaigns and production and installation schedules.

The reader of this report can access in the CDR full engineering details on the Vertical Detector configuration on the various detector components. Some examples of the design developed in the CDR for the CRPs, top-drift electronics layout and Photon Detection System have been already shown in the Overview Section of this report (Sec 1.11).

The cathode plane, inhering the modularity of the protoDUNE dual-phase cathode, requires an all new design due to the unique requirements imposed by the Vertical Drift configuration foreseeing the cathode position at middle height of the detector. This layout requires minimizing the cathode thickness and ensuring good planarity. The cathode must be suspended from the top CRPs superstructure with a system of wires and should also integrate the photo-detectors modules. Figure 15 shows the conceptual design of a cathode module, matching the footprint of the CRP. Figure 16 shows the suspension system of six cathode units from a top-drift CRP superstructure.

In parallel to the design progress, the Vertical Drift tests campaign at the CERN Neutrino Platform had as well, in the last months, a very rapid progress as described in more details the next Section (Sec 4).

The construction of the second DUNE Far detector module based on the Vertical Drift design is supported by the TGIR program with an overall contribution on various detector items at the level of about one half of the cost of the module.

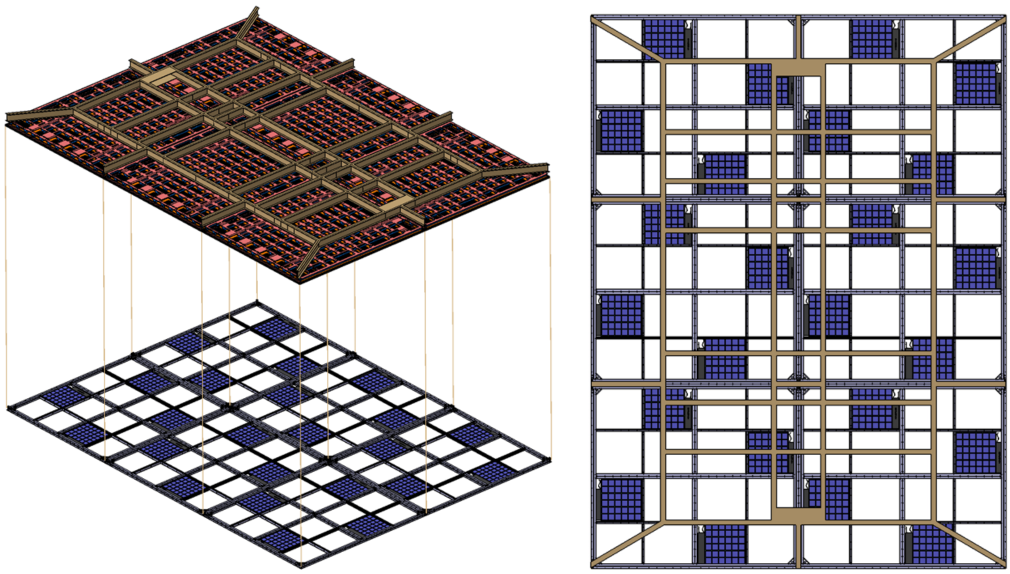

FIG. 16: Conceptual view of a six-unit cathode supermodule suspended from a top-drift CRP superstructure. Left: side view. Right: top view from the CRP superstructure (the mesh and the CRPs themselves are not shown).

Another important milestone for the realization of this program corresponded to the approval in June 2021 by the CERN Council of the CERN support for the construction of the cryostat for the second DUNE Far Detector module.

A DUNE TGIR kick-off meeting was held in May 2021. A few presentations at this meeting were in particular focused on the Vertical Drift design and may be interesting in order to get more details:

- IN2P3 DUNE project leader report on the DUNE IN2P3 project and the evolution from the dual-phase to Vertical Drift
- DUNE Charge Readout Planes Consortium Leader overview on the Vertical Drift 2nd Far Detector module
- Report by the CERN Neutrino Platform leader on the CERN Neutrino Platform and support to Vertical Drift test
- Report by the Technical Coordinator of the second DUNE Far Detector module on The path to the Vertical Drift module: milestones and schedule

IN2P3 physicists ensure the leadership of two Consortia involved in the construction of the second Far Detector module: D. Autiero is the leader of the Top-Drift Electronics (TDE) Consortium (involving groups from France, Japan and US) and D. Duchesneau is the leader of the Charge Readout Planes (CRP) Consortium (involving groups from France, CERN and US).

A description of the IN2P3 groups activities (including the list of participants) is contained in the DUNE IN2P3 project talk given at the TGIR kick-off meeting in May 2021 (see slides 20-21). The DUNE IN2P3 project includes groups from APC Paris, IJCLAB Orsay, IP2I Lyon, LAPP Annecy, and LPSC Grenoble. The project benefits as well of the technical support from CC-IN2P3 Lyon and CENBG Bordeaux. The current manpower involvement includes actually more than 50 people about equally shared in between physicists and engineers. This number is growing with new hiring and internal mobility.

The IN2P3 groups contribute to the construction of the top-drift electronics (IP2I and CENBG) and associated mechanics with the signal feedthrough chimneys (IJCLAB), of the Charge Readout Planes (LAPP and LPSC) and of the cathode (IJCLAB), which is provided via the High Voltage Consortium. An involvement is also under construction in the Photon Detection System (APC) for which the technology is being developed in order to operate the photon detectors on the cathode at 300 kV.

The IN2P3 groups also also naturally involved in the Data Acquisition since the DAQ front-end for the top-drift is included in the TDE consortium and they have thus to ensure an optimal design and construction of the DAQ back-end, in the scope of the DAQ Consortium.

4 Vertical Drift test activities at the CERN Neutrino Platform 2021-2023 and path to the second Far Detector module construction

This section describes the NP02 integration tests program in 2021, 2022, 2023 aiming at demonstrating the design of the Vertical Drift detector components and performing a final integration test before mass production.

4.1 Vertical Drift HV system test in the NP02 cryostat in 2021

A full scale test of the High voltage distribution system in the vertical drift layout is an essential milestone to demonstrate its design.

On the basis of the experience with protoDUNE dual-phase, the complexity of the extender design, as implemented in 2019, has been highly reduced by simplifying the extender to a bare metallic pipe with a diameter of $\approx 20cm$ and highly electro-polished outer surface, the HV discharge protection being provided by the dielectric rigidity of the LAr itself (see Figure 17.

A new High Voltage feedthrough from UCLA, with improved design resolving a few issues observed in both protoDUNE single-phase and dual-phase, was also developed in the past months.

The most critical components of the new extender design were tested in a dedicated setup at

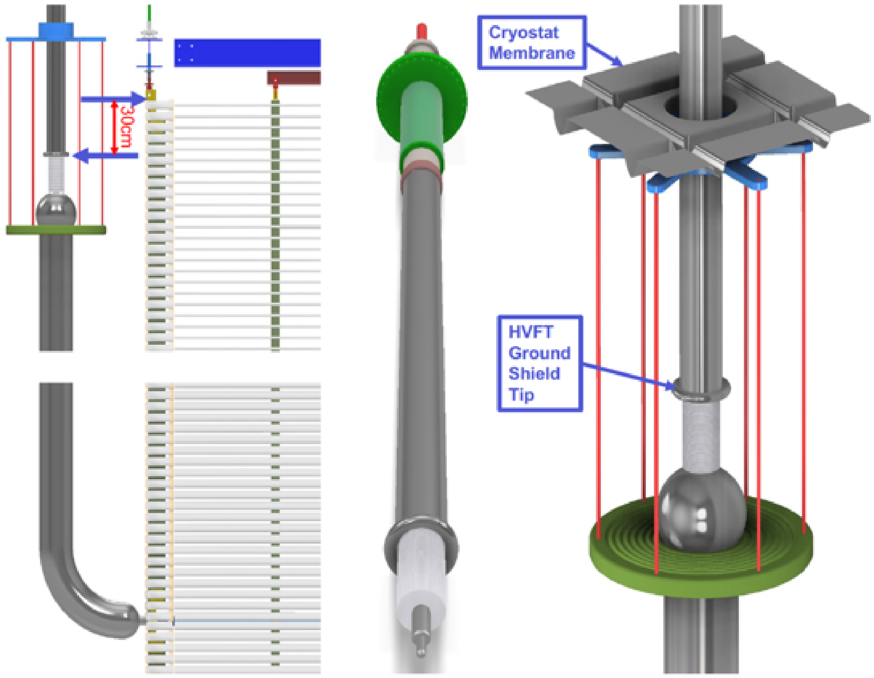

FIG. 17: New design of the High Voltage extender and of its coupling mechanism to the High Voltage feedthrough.

Fermilab in June 2021. Those components are: the High Voltage feedthrough, the coupling connection between the feedthrough and the extender, the G10 disk, supporting the extender coupling, and its suspension system.

The first tests performed at Fermilab spotted some design issues in the extended coupling system. Tests have been then continued at CERN. The design of the coupling element between the high voltage feedthrough and the new extender has been improved until when providing satisfactory results in the standalone CERN High Voltage tests (see Figure 18). The perfected design of the extender coupling mechanism developed in July 2021 includes several improvements among which: a donut shaped coupling head in order to reduce charging up effects of the insulator covering the high voltage feedthorugh termination; the replacement of the G10 supporting disk with a UHMW-PE disk; the implementation of a sleeve to channel bubbles formation.

It was planned since the Fall 2020 to perform the full scale test of the entire High Voltage distribution system at nominal voltage in the NP02 cryostat, allowing for a realistic evaluation of the new HV system performance.

The old extender operated since 2019 in protoDUNE dual-phase was foreseen to be removed and replaced with the new one coupled to the newly designed HV feedthrough. The extender exchange can be accomplished without re-opening the cryostat structure with access for personnel and materials

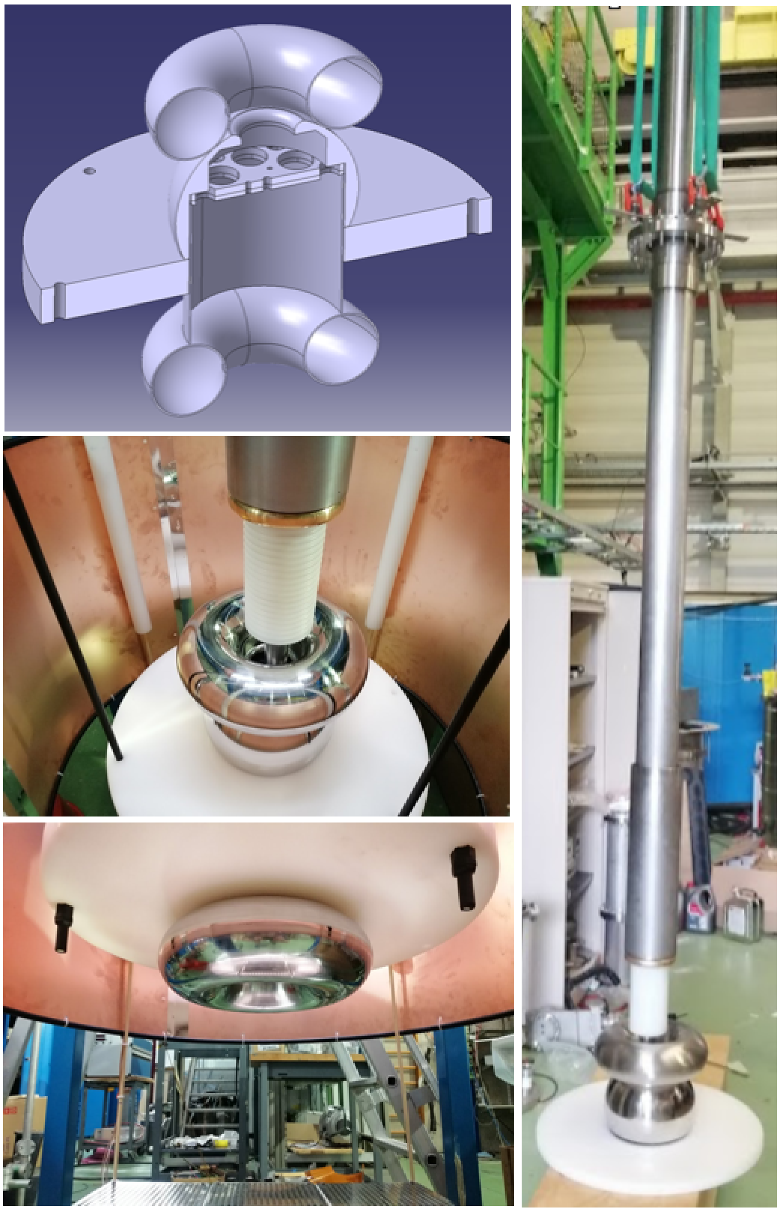

FIG. 18: Standalone test of the High Voltage feedtrough and extender coupling element set up at CERN in July 2021.

happening via the man-hole. This allows speeding up the test significantly.

The requirement of demonstrating 300 kV for the Vertical Drift module motivated a very aggressive schedule, operating again already in 2021 protoDUNE dual-phase, in order to test quickly the new HV extender design.

After the successful completion of the standalone tests of the new high voltage feedthrough and extender coupling mechanism in July 2021, these detector elements, together with the full extender pipe, have been implemented in ProtoDUNE dual-phase.

Figure 19 shows some details of the new extender and of its coupling mechanism to the High Voltage feedthrough immediately after its installation in NP02/protoDUNE dual-phase. Figure 20 provides a

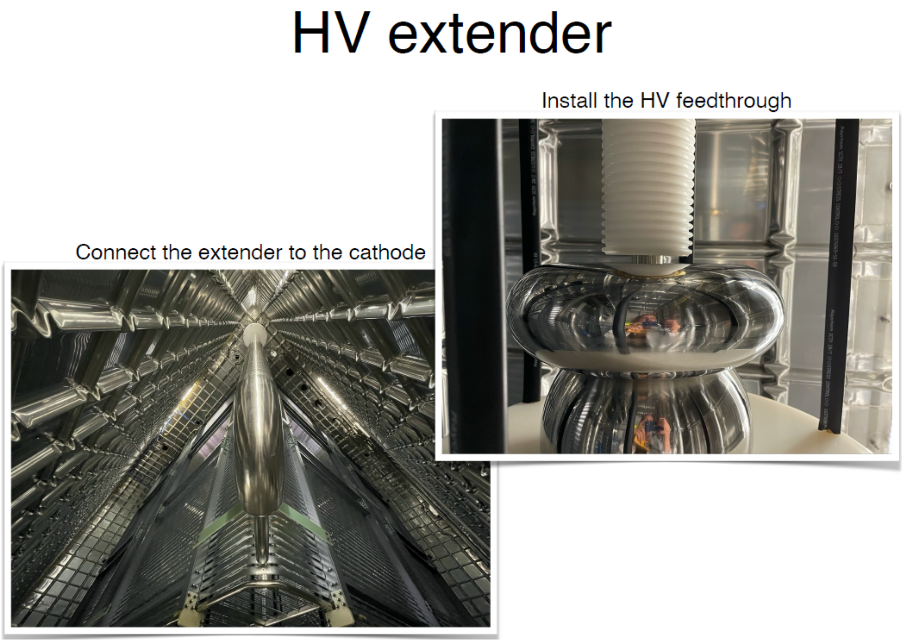

FIG. 19: Details of the new High Voltage extender in NP02/protoDUNE dual-phase immediately after its installation.

fish-eye view of the inside of the detector immediately after the new extender installation.

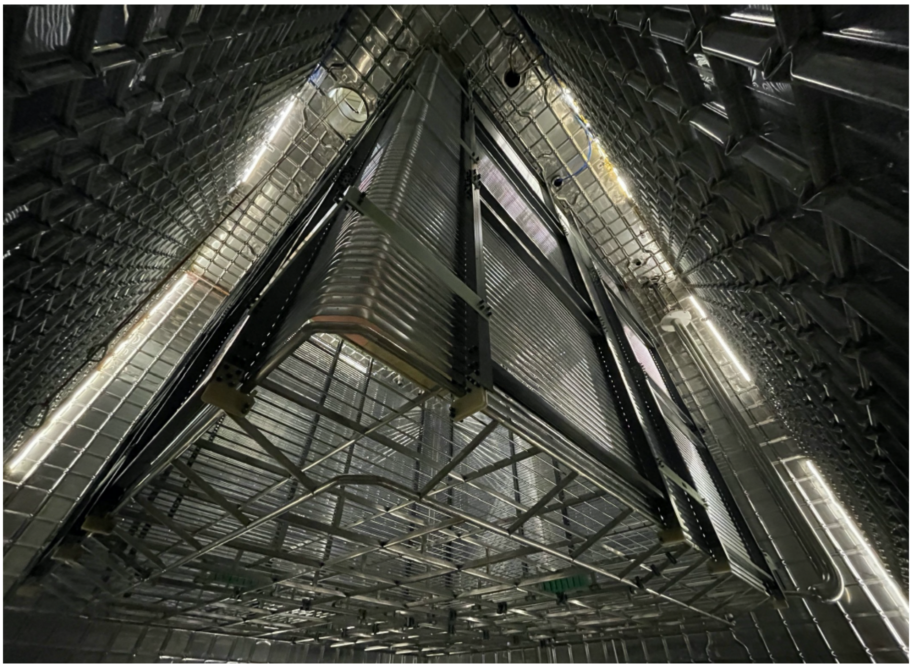

FIG. 20: Fish-eye view from the floor of protoDUNE dual-phase cryostat after the installation of the new high voltage extender

The NP02/protoDUNE dual-phase detector was then refilled with liquid argon in August 2021. A first operation phase is focused on the stability tests of the high voltage system at 300 kV. This dedicated test phase can be then followed by the possibility of operating the already functional dual-phase detector in order to measure tracks over the full 6m drift length.

The High Voltage tests in NP02 are supposed to be run in parallel to the cold-box tests described in the following paragraph. At the end of the tests, the LAr contained in NP02 will be then moved in 2022 to NP04.

On September 15th 2021, immediately after the completion of the NP02 cryostat filling, the high voltage system including the new extender was ramped up for the first time and could reach in a short time period 300 kV without any problems. The tests program at 300kV is currently in progress.

4.2 Cold-box tests of Vertical Drift CRPs

This tests campaign is based on the cold-box built in 2018 for the CRPs of NP02/protoDUNE dual-phase. Its aim is to characterise and validate the design and the construction procedures of full scale Vertical Drift CRPs (for the top and bottom drifts equipped with their own electronics chain). Both top and bottom CRPs will be tested by hanging them from the cold-box roof.

The main objectives of these integration tests are:

- mechanical tests of the perforated PCB anode assembly (CRP) in cryogenic conditions
- characterisation of the performance of the perforated anode and of the full electronics chain (top and bottom) in terms of signal to noise ratio and its stability
- mechanical test of the cathode module in cryogenic conditions
- test the light readout system concept
- test the integrated system as a whole and evaluate the interplay between the powering scheme, the charge readout electronics and the light readout system

The IN2P3 groups are providing for the cold-box test campaign of the Vertical Drift CRPs: the CRP mechanical structures; the complete electronics chain for a full top-drift CRP with 3200 channels (cryogenic FE cards, digitization cards, timing system, low voltage generation system and the newly developed uTCA crates with 40 Gbit/s connectivity); five mini-chimneys (including flanges) adapted for the cold-box roof configuration; a cathode module with the design foreseen for the Vertical Drift detector; the electronics and opto-electronics components to test the analog solution to read out the X-ARAPUCA photo-detectors on the cathode; the optical fibers data infrastructure and the DAQ system.

The NP02 cold-box was used in the past as an open-bath like cryostat, with the liquid argon level kept constant by compensating evaporation losses with a continuous supply of liquid argon. This configuration did not include LAr purification.

In order to provide a suitable environment for the new tests, the NP02 cold-box has been moved to EHN1 and is undergoing a major upgrade, meeting the following requirements:

- hosting CRPs of dimension 3×3.375 m^2, slightly larger than the DP CRP
- LAr level stability maintained within +/- 5 mm
- absolute vapor pressure stabilized to a few mbar around the nominal value
- drift distance of at least 20 cm with a drift field of 500 V/cm
- liquid argon purity compatible with electron drift over 20 cm

The new cold-box location is at the Neutrino Platform facility, next to the NP02 cryostat. It takes advantage of the cryogenic and safety infrastructures of NP02. The cryogenic system allows filling the cold-box, purifying the LAr to better than 1 ppb O_2 equivalent contamination and maintaining stable pressure and liquid argon level. This will be achieved by condensing the boil-off with the NP02 condenser and by re-injecting the argon filtered through a new set of O_2 and H_2O filters. The CRPs will be assembled in the already existing clean room infrastructure in Building 185.

The cold-box upgrade covers three aspects: (1) improving the leak tightness, (2) changing the number and the diameter of roof penetrations and (3) reinforcing the mechanical structure to cope with higher operating pressure. The sealing between the box and the roof must be upgraded to improve the overall tightness. The nominal over-pressure will be in the range of 40-80 mbarg.

The roof of the cold-box has been modified according to Figure 21.

The roof is now including new penetrations to accommodate the high voltage feedthrough, power and signal feedthroughs for the photo-detectors and the feedthroughs for the purity monitor.

Other penetrations are implemented with larger radius to host the cold electronics feedthroughs and the feedthrough for the HV bias of the anode.

The cold-box will be on detector ground as NP02 and NP04 cryostats in order to profit from all the controls already available in the detector rack zone. Figure 22 shows the schematic of the cold-box ground, decoupled from the building ground and how the grounding of equipment and cables will be implemented in the cold-box.

The upgrade of the cold-box setup has been completed, the test of the first CRP is expected to start at the end of October 2021.

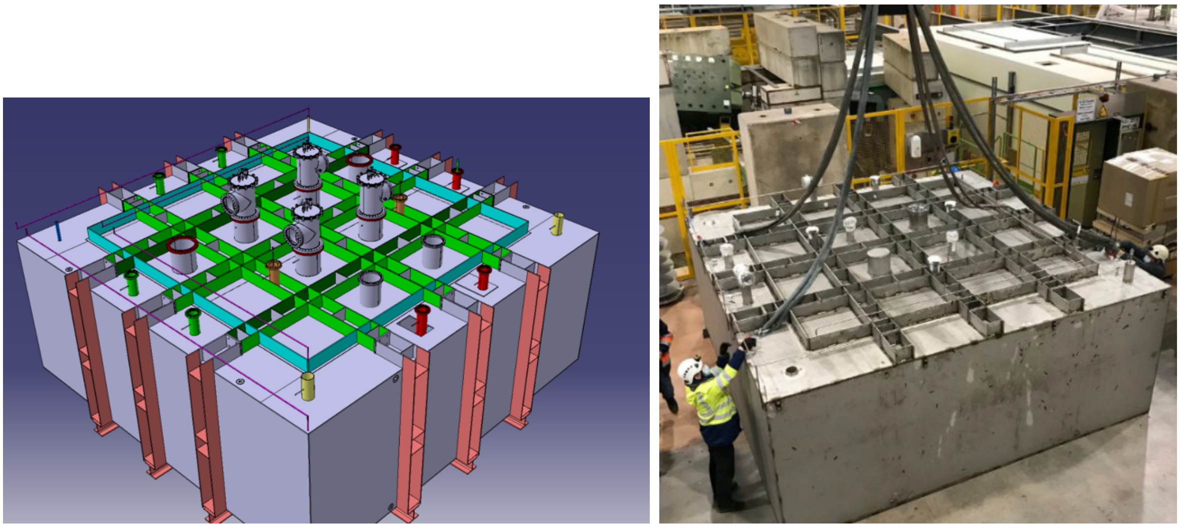

FIG. 21: 3D model of the upgraded cold-box and cold-box installation at EHN1

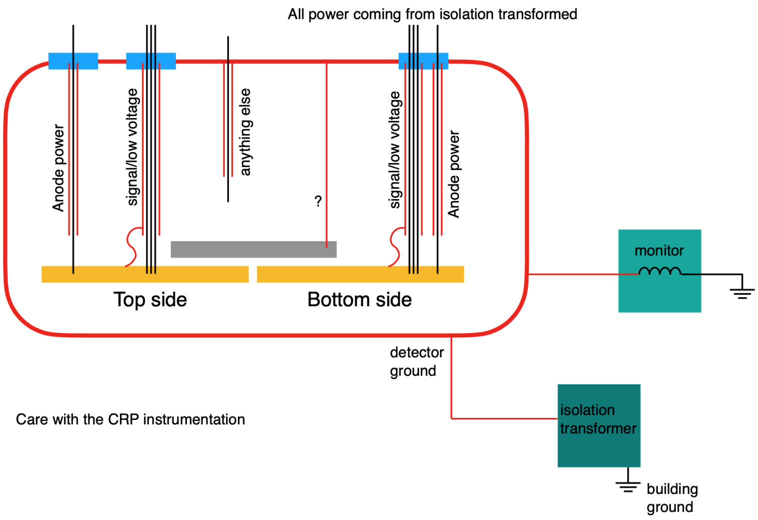

FIG. 22: Grounding schematics of the cold-box and the detector components.

4.3 2021 CRP tests

A first test of a vertical Drift CRP will be then performed in the Fall 2021 by integrating in a single CRP the 3 view and the 2 view layouts in order to test the two alternatives at the same time (see Fig. 23).

Given the availability of the anode PCBs to build the first CRP and the operation schedule of the cold-box, it is foreseen for these initial tests to exploit a single CRP divided in two halves with the top and bottom drifts readouts simultaneously present. For this purpose a special CRP structure supporting the anodes has been designed to be compatible with both types of electronics (see Figure 24).

The refurbishment of the cold-box for the Vertical Drift tests, including a purification system and its displacement to the EHN1 hall have been completed. The components for the test of the first Vertical

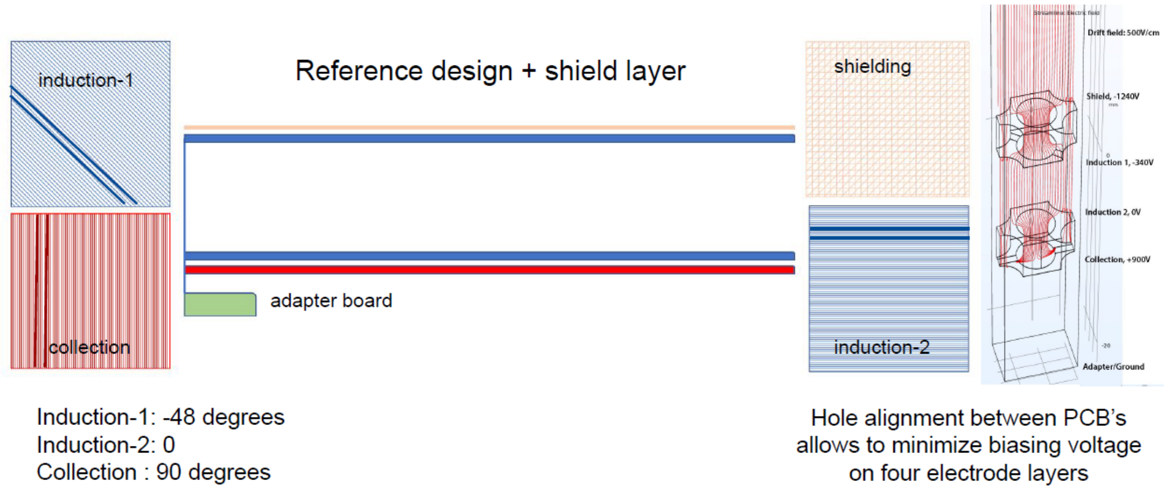

FIG. 23: Vertical Drift perforated anodes configuration for the tests in 2021.

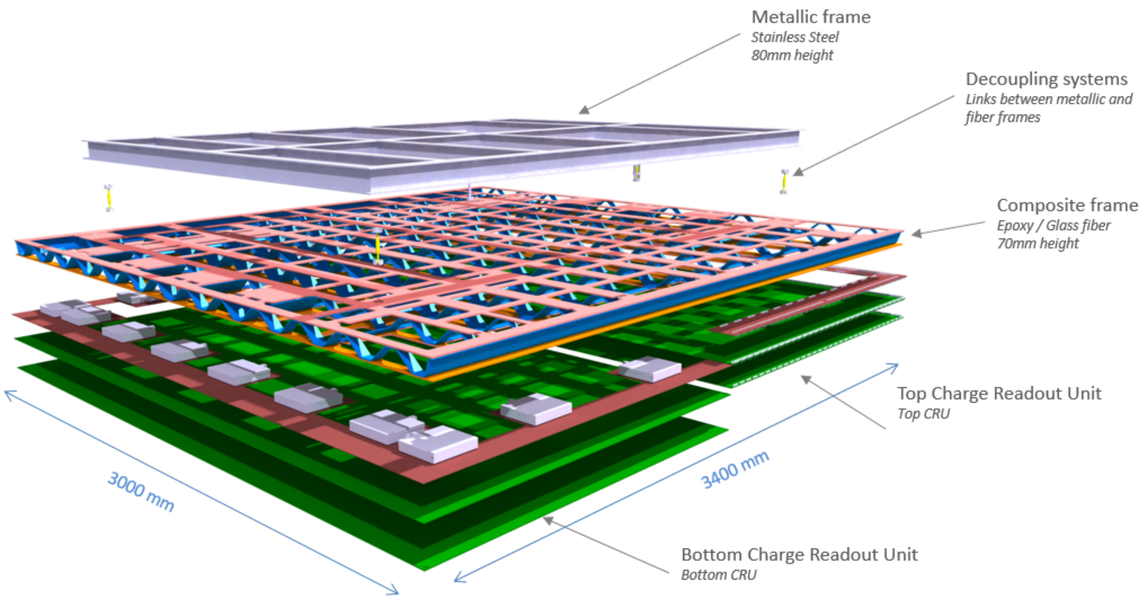

FIG. 24: 3D model of the shared CRP (including top/bottom drift electronics) for first cold-box test in 2021.

Drift CRP (shared among the top and bottom drift layouts) including the perforated anodes, readout electronics and DAQ, signal feedthrough chimneys were produced and tested in 2021. A cathode module with the same design foreseen for the Vertical Drift detector was produced as well in order to be used for the cold-box tests.

An integration test of the chimneys and all elements of the charge readout electronics chain and DAQ was already performed in July 2021 (see Figure 25).

The perforated anode PCB panels for the CRP construction are being assembled together in the clean room of building 185. The sequence of operations includes the gluing of PCBs to form panels

FIG. 25: Integration test of the elements of the top-drift electronics charge readout chain performed at at CERN Neutrino Platform in July 2021.

of $1.7m \times 3m$ for both anode layers, the soldering of the connectors, the connection of the electronic adapter boards and the mechanical connection of the full charge readout units to the support structure. Electrical and quality tests are performed at different steps of the construction.

It is then foreseen to assemble the anodes them with the CRP structure in October and start the cold-box operation at the end of October. The first cold-box operation cycle will be lasting at least a month. The schedule of the 2021 CRP cold-box tests is shown in Figure 26. The schedule cold-box has been essentially kept on time despite the interference with the heavy activities related to the High Voltage extender test in NP02/protoDUNE dual-phase.

4.4 Continuation of the CRPs and detector components tests campaign in 2022 in view of the *Vertical Drift Module-0*

A general schedule for the cold-box CRP tests in 2021-22 is shown in Figure 27.

After the successful completion of the first CRP tests in 2021, the cold-box tests campaign of the Vertical Drift CRPs is supposed to continue in 2022. Full top-drift and bottom-drift CRPs configurations will be tested with final anodes layout and mechanical structures closer to the final CRPs designed for the Vertical Drift Far detector. These components will be the final ones to be then inserted in the NP02 cryostat for the *Module-0* test.

The completion of this program by the end of 2022 is then essential in view of providing the final

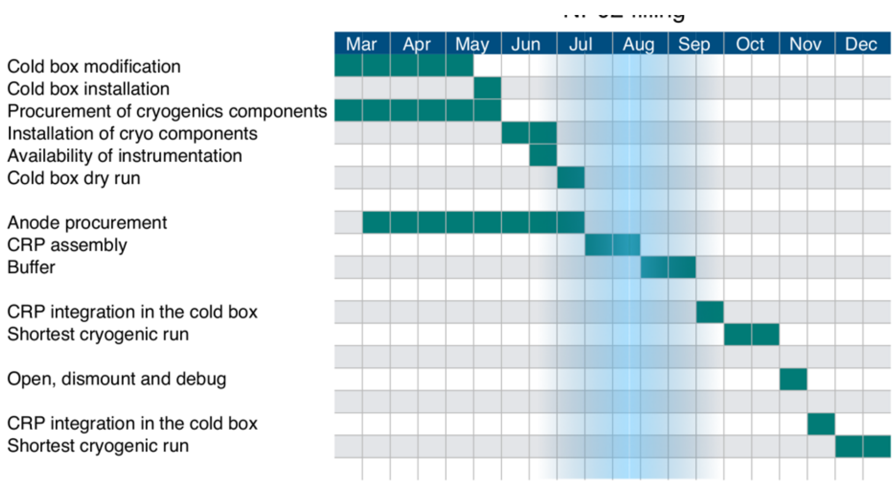

FIG. 26: Details of the NP02 schedule for the cold-box first tests of a Vertical Drift CRP, the blue shaded region represents the overlap with the NP02 LAr filling for the extender HV test.

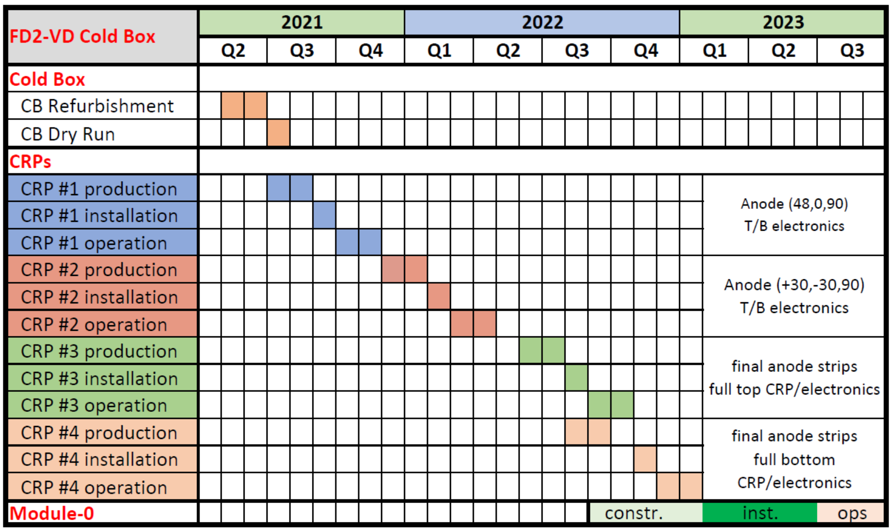

FIG. 27: Schedule of the foreseen cold-box test activities for the Vertical Drift CRPs foreseen in 2021 and 2022.

design for the *Module-0* integration test in 2023 and for the Far Detector production, as mentioned in the following paragraph. The developments of the photo-detector (PD) system operating at HV, integrated in the Vertical Drift cathode/field cage, will also continue in 2022, moving from proof of concept tests to PD system integrated in the entire detector.

Since summer 2020 the developments for a system for the operation of the photo-detectors on the cathode focused on the Power over Fibre (PoF) technology to decouple the photo-detectors powering from the detector ground. Adequate voltage to power the Silicon PhotoMultipliers (SiPM) with PoF technology was demonstrated in cryogenic conditions. Study of interference with other detector components, long term stability and scaling-up are the next challenges. The readout must also be decoupled from the ground, and therefore the output signals must be transmitted optically to the outside of the cryostat. Two possibilities are under considerations: ADC operating at cold and transmission of the digitised signal or analog transmission of the photo-detectors signals over optical fibers with a linear voltage to optical converter operating in LAr.

4.5 Vertical Drift *Module-0* operation

The Vertical Drift design has been adopted by the DUNE Collaboration for the implementation of the second Far Detector module. Before entering into the production phase for the second Far Detector module it is foreseen, as it is planned also for the first Far Detector module, to undergo a full integration test at CERN *Module-0* on the basis of the final detector design of the detector elements.

For this purpose it is foreseen to exploit the NP02 cryostat. The operation of NP02-II as Vertical Drift Module-0 is expected to occur in 2023. These results will enable final design adjustments for the second DUNE Far Detector production.

The Module-0 will include two full top-drift and two full bottom-drift CRPs with the final design for production for the DUNE Far Detector module.

The CRPs will be installed in their natural positions with the top-drift CRPs suspended from the cryostat roof and the bottom CRPs lying on the cryostat floor. This will allow testing the final configuration including mechanical supports and cable lengths.

Given the dimensions of the NP02 field cage and the fact that the Vertical Drift CRPs are, in one dimension, larger than the dual-phase CRPs, the top and bottom CRPs will be complemented with dummy CRPs (see Figure 28).

This allows closing the drift field lines on the complete $6 \times 6m^2$ top and bottom surfaces. The top-drift CRPs will be hanging from a CRP superstructure, similar as the one foreseen for the Vertical Drift detector and integrating a full-size hanging system for the cathode modules.

The cathode modules will be located at middle height in the cryostat (see Figure 29). The design of the cathode modules will be the final one integrating the ultimate choice for the resistive mesh, used in order to slow down the energy flow to mitigate possible cathode discharge processes.

One of its sides, the field cage will be fully equipped, from the cathode to the anode, with the thinner profiles foreseen in order to ensure 70% transparency. This configuration will allow testing the light collection on the photo-detectors tiles installed on the cryostat walls.

Similarly as in the Far Detector module, the cathode will be also installed with photo-detectors operating at high voltage. Given the position of the cathode a symmetric drift of 3m will be available for the top and bottom CRPs. It will be possible to operate the cathode at 300 kV. Lower operation voltages could be also exploited in order to slow down the drift velocity and simulate drift spaces longer

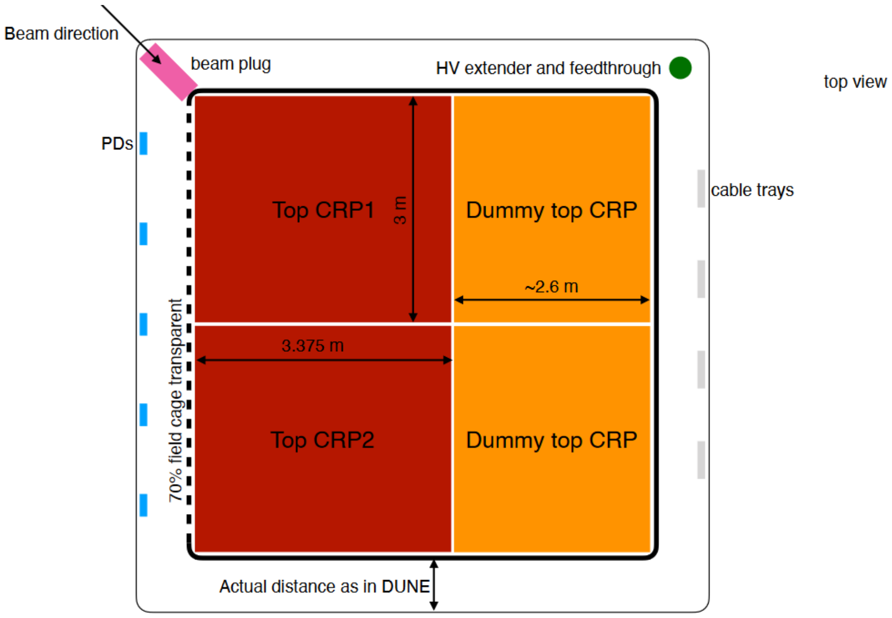

FIG. 28: Conceptual top view sketch of the Module-0 configuration.

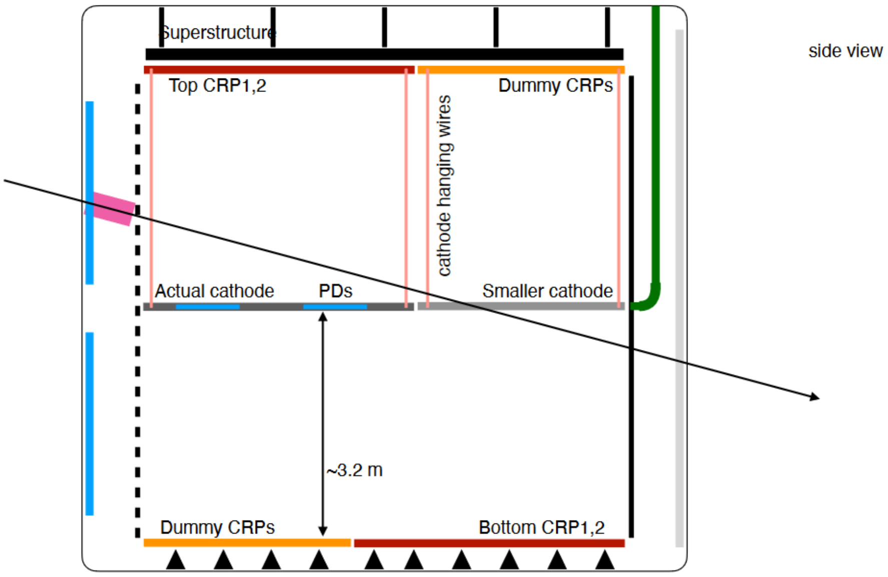

FIG. 29: Conceptual side view sketch of the Module-0 configuration.

than 3m.

A beam-plug will also be installed on the field cage in order to allow the beam particles to enter the fiducial volume without interacting with the liquid argon surrounding the field cage.

An overall test schedule including the Module-0 operation for both the first and second DUNE Far detector modules is presented in Figure 30.

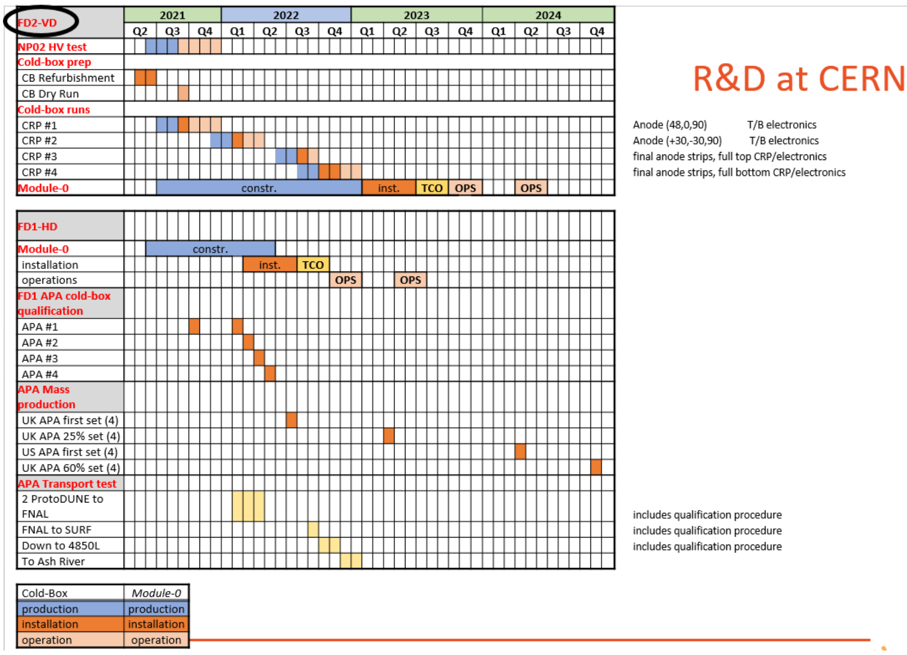

FIG. 30: Overall test schedule including the Module-0 operation for both the first and second DUNE Far detector modules.

4.6 Vertical Drift Far Detector module production and installation

A Production Readiness Review (PRR) is foreseen to take place at the end of 2023 in order to launch the mass production of the various elements for the construction of the second DUNE Far Detector module. The production process will span over about 3 years since the date of the PRR (see Figure 31).

The assembly of the second Far Detector module will happen in 2027 over period of 7 months (see Figure 32). This is a shorter period than what needed for the first detector, for which the installation will start earlier, in Spring 2026.

Detailed installation procedures and schedules have been prepared by taking into account all the particular aspects of the Vertical Drift configuration which has most of its detector elements suspended from the cryostat roof.

Similarly, detailed production and QC schedules have been defined (see Figure 31) for the different detector elements, including the logistic aspects for the shipment and handling in the underground facility.

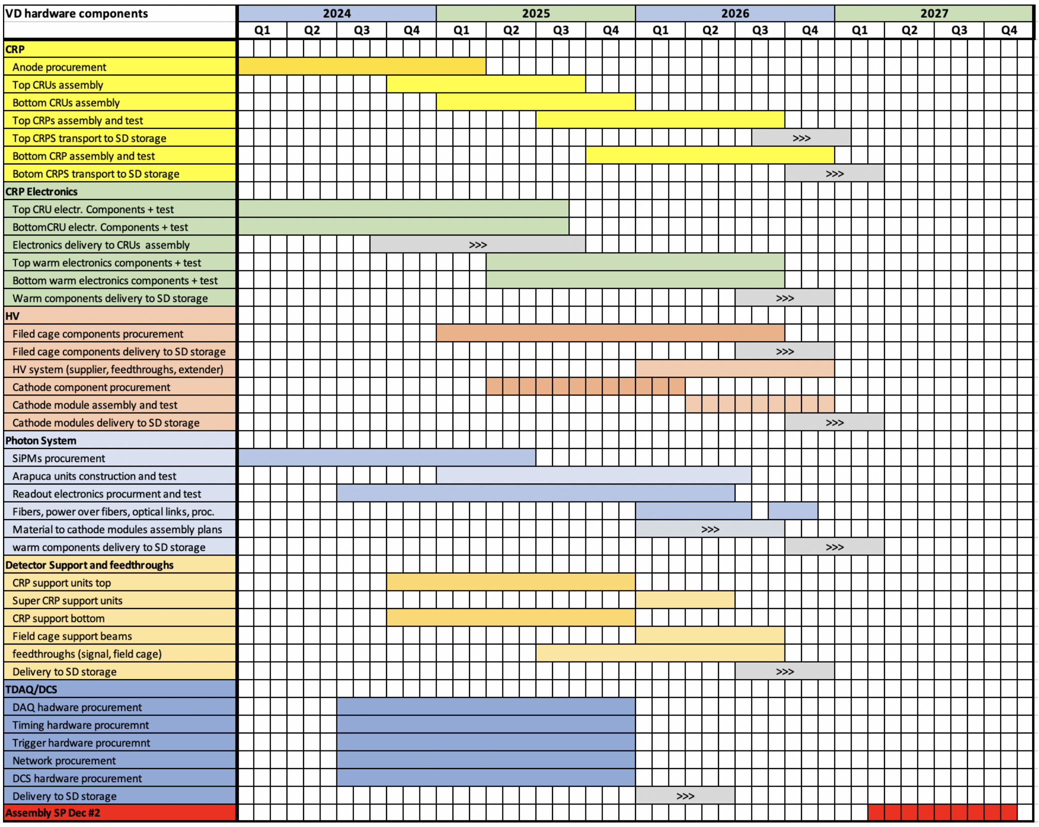

FIG. 31: Production schedule for the components of the Vertical Drift second DUNE Far Detector module

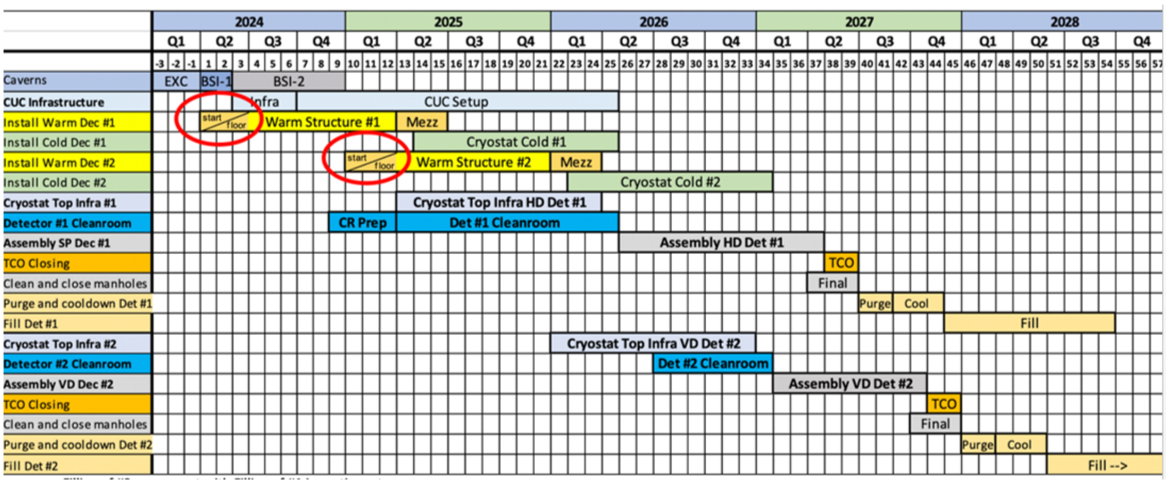

FIG. 32: Installation schedule of the first two DUNE Far detector modules.