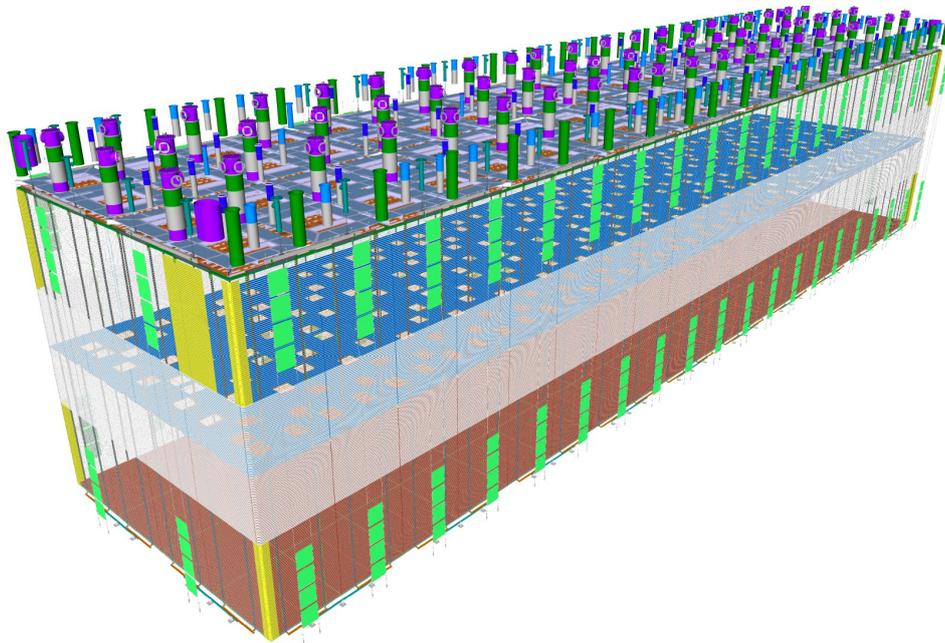


Status of the DUNE project CSI IN2P3 March 2026

February 5, 2026

Abstract

In this document we summarize the general progress since the last CSI report in 2021 on the DUNE IN2P3 project, on the experimental activities at the CERN Neutrino Platform and on the construction of the 1st DUNE far detector module, based on the Vertical-Drift design.



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1 Introduction

The IN2P3 groups have been involved for almost 20 years, first in the R&D activities in view of the preparation of DUNE and then in the birth and development of the DUNE experiment itself.

Development activities on the Liquid Argon (LAr) detectors started in 2006 with the R&D on the charge readout electronics at 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 start of [DUNE](#) the IN2P3 groups have been contributing in a strong way to the design and definition of a Far Detector module based on the Liquid Argon Time Projection Chamber (LArTPC), but with a design easier to implement than the traditional one based on wire chambers and [pioneered](#) by the ICARUS Collaboration. This contribution, first focusing on the development of the Dual-Phase (DP) design and then evolving on a simplified and optimized version of the DP, called Vertical-Drift (VD), is supported since 2021 by a specific TGIR/IR* program (see [DUNE TGIR kick-off meeting](#) of May 2021). All these activities have been strictly interconnected to an intensive large-scale prototyping program carried out at the CERN Neutrino Platform since 2014. The full information about the historical development of the project can be retrieved from the previous reports to the IN2P3 Scientific Council: CS IN2P3 2013 [Report](#), [Slides](#); CS IN2P3 2018 [Report](#), [Slides](#); CS IN2P3 2021 [Report](#), [Slides](#).

The transition from the Dual-Phase to the Vertical-Drift, aimed at simplifying the detector construction, having more stable operation, reducing production and installation costs and increasing the sensitive volume to 15 kton, was already presented in details at the CSI of October 2021. In that occasion the intended IN2P3 contributions to the Vertical-Drift module (Charge Readout Planes, Top-Drift Charge Readout electronics, Cathode plane and Signal-Over-Fiber (SOF) in the photon detection system) were also discussed at length.

This document summarizes the latest developments, focusing on the period elapsed since the CSI of 2021. This last period has seen the concrete implementation of what was presented in 2021 as IN2P3 contributions to the Vertical-Drift Far Detector module, which is now in construction. In the same period, intensive experimental activities at CERN were as well continued to be carried on with success.

2 Status of the DUNE/LBNF construction at SURF

The DUNE long-baseline neutrino [experiment](#) relies on the support from various organizational 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 represented in [Figure 1](#): the **LBNF (Long Baseline Neutrino Facility) project** takes care of the construction of all infrastructures needed for 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 high intensity neutrino beam; the **DUNE Collaboration** provides the Near Detectors, the instrumentation of Far Detector modules, contained inside the LBNF cryostats, and the Computing/Analysis organization.

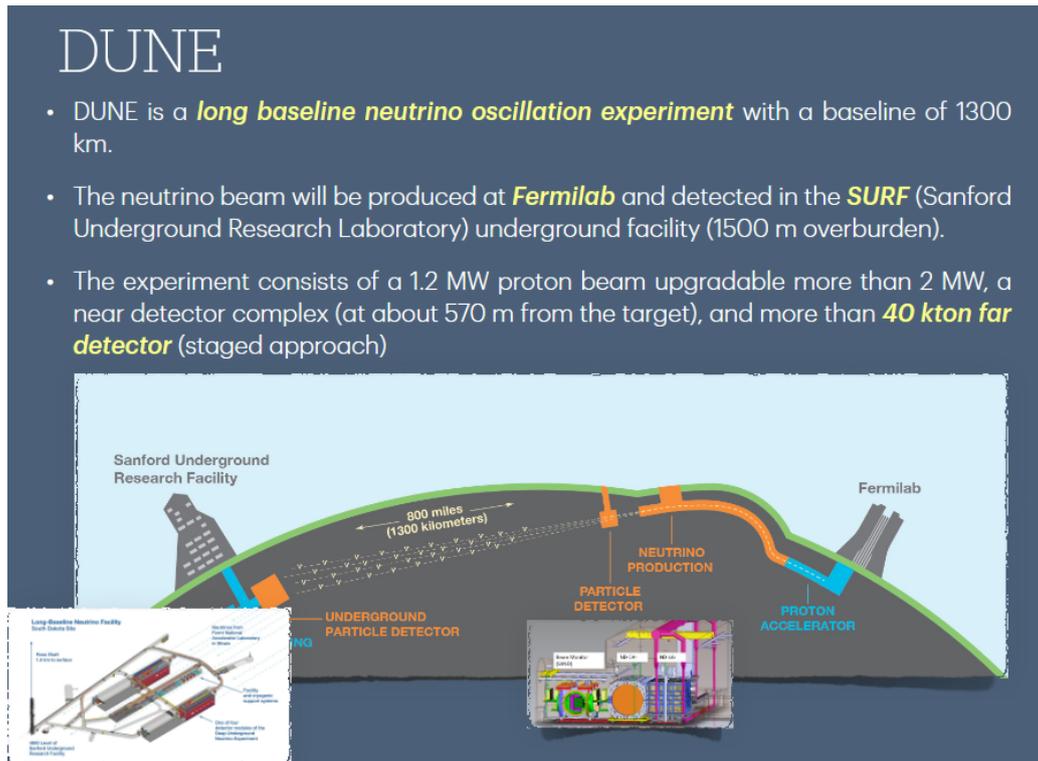


Figure 1: Main components of the DUNE long-baseline neutrino experiment.

In parallel to the construction of the experimental setup in the USA, intensive detector prototyping activities carried out by the DUNE Collaboration have been supported at CERN since 2014 by the **CERN Neutrino Platform**

In particular the CERN Neutrino Platform set up an extension of the EHN1 hall, hosting the two protoDUNE detectors for the Dual-Phase/Vertical-Drift and Horizontal-Drift designs (the NP02 and NP04 CERN experiments). These are currently the largest Liquid Argon TPC detectors in the world. The CERN Neutrino Platform also supported other test activities, such as: the $3 \times 1 \times 1 \text{ m}^3$ prototype in building 182, the Cold-Box TPC tests of the Vertical-Drift CRP at EHN1, tests of the High Voltage system components still in building 182 and a clean room assembly facility and Vertical-Drift installation test mock-up in building 185. **CERN** is also responsible within LBNF of the design and production of the first two far detector modules cryostats and of the cryogenic systems for DUNE.

The DUNE Collaboration was launched in 2015, strongly supported by the 2013 update of the [European Strategy for Particle Physics](#) and the 2014 [Report](#) of the US Particle Physics Project Prioritization Panel (P5). This support has been renewed by the [P5 update](#) released in December 2023 and the [ESPP process](#) in 2025.

The P5 updated of 2023 reaffirmed DUNE as highest priority HEP project in the USA and defined a staged approach in two phases. The **Phase I** beamline will produce a wide-band neutrino beam with up to 1.2 MW beam power, designed to be upgradable to more than 2 MW. The Phase I Near Detector includes a movable LArTPC with pixel readout (ND-LAr), integrated with a downstream muon spectrometer (TMS), and an on-axis magnetized neutrino detector (SAND). The ND-LAr+TMS detector system can be moved sideways over a range of off-axis angles and neutrino energies (the DUNE-PRISM concept), for an optimal characterization of the neutrino-argon interactions. The Phase I FD includes the first two LArTPC modules based on the Vertical-Drift and Horizontal-Drift. The **Phase II** of

DUNE includes an enhanced multi-megawatt beam, the third and fourth far detector modules, and an upgraded ND complex with the addition of a gas Argon TPC detector.

The major project related to the excavation of the underground caverns infrastructure at SURF was timely [completed](#) in 2024, see Figure 2.



Figure 2: Picture of a far detector cavern at SURF.

The DUNE Collaboration in 2024 decided, in order to guarantee an aggressive schedule for physics, that the Vertical-Drift module should be the first far detector module to be installed (more details in next section).

CERN, is on schedule with the production of the elements of the cryostats for the first two far detector modules, including both their warm (iron structure) and cold (insulation and stainless steel corrugated cryogenic membrane) structures. The cryostats warm structures material has been already shipped in 2025 from Europe to SURF and it is ready for installation (Figure 3).

The year 2025 was then focused on the instrumentation of the caverns in order that CERN could start installing the first cryostat module in summer 2026.

The installation of the Vertical-Drift detector is foreseen in 2027-2028 after the completion of the construction of the first cryostat. This will be followed by one year needed to purge and fill the cryostat with liquid argon. It is then expected to start physics data taking in 2029. The general LBNF/DUNE construction timeline and main milestones are reported in Figure 4.

3 Progress of the IN2P3 DUNE Project

The contributions of the IN2P3 groups to the Vertical-Drift Far Detector module were already presented at the CSI meeting of 2021. The IN2P3 groups are contributing to about half of the first DUNE far detector module (Figure 5) by taking care of: the Charge Readout Planes (CRP) for the top-drift and the production of the composite mechanical structures for the CRPs of the bottom-drift; the Top-Drift Charge Readout Electronics (TDE) and the feed-through penetrations (Chimneys) hosting the



Figure 3: Iron elements of the warm structure of a DUNE cryostat stored at the DUNE warehouse center in Rapid City.

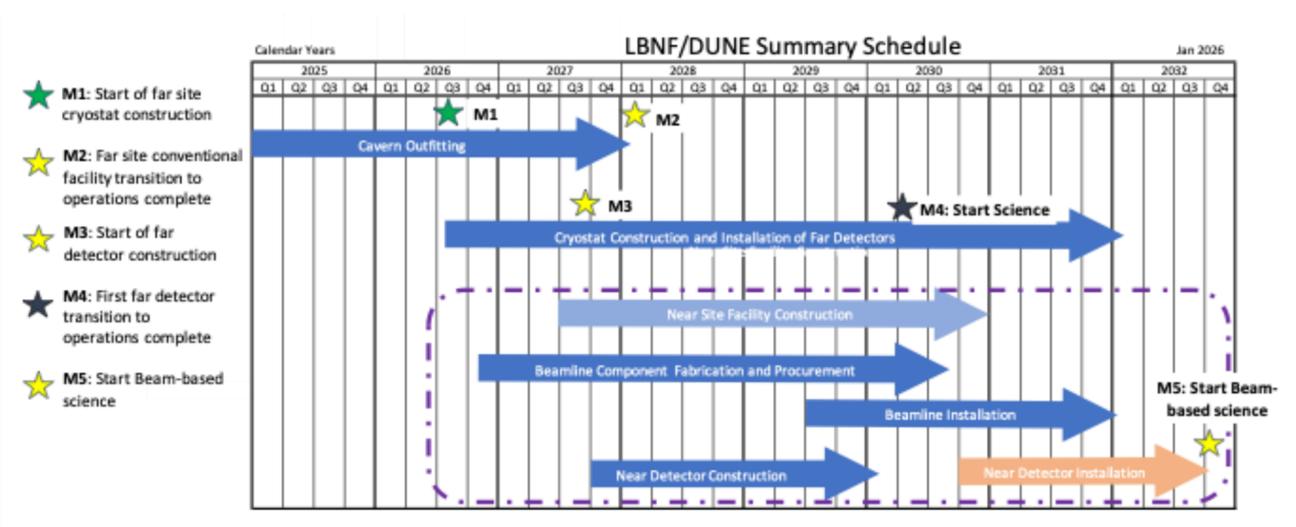


Figure 4: LBNF/DUNE construction timeline and milestones

analog cryogenic TDE front-end boards; the Cathode Plane and the Signal-Over-Fiber components in the Photon Detection System (PDS).

The DUNE Collaboration is organized in Consortia for the construction and operation of the experiment. The IN2P3 groups ensure the leadership of two main detector Consortia (D. Duchesneau leader of the CRP Consortium and D. Autiero leader of TDE Consortium). IN2P3 contributes as well to the High Voltage Consortium with the Cathode, to the Photon Detection System Consortium with the SOF components). IN2P3 is also playing an important role in the Computing Consortium with the direct involvement of CCIN2P3 in the computing activities at the level of about 10% of the needs of the Collaboration and by having management roles in the Computing Consortium.

The IN2P3 contributions to DUNE were completely defined by the end of 2022. They underwent a KDP2 project review at the beginning of 2023 in view of the signature of the DUNE Memorandum Of Understanding (MOU). The KDP2 review thoroughly addressed and precisely engaged all the contributions of the IN2P3 groups, including the final deliverables and the corresponding budgets, as

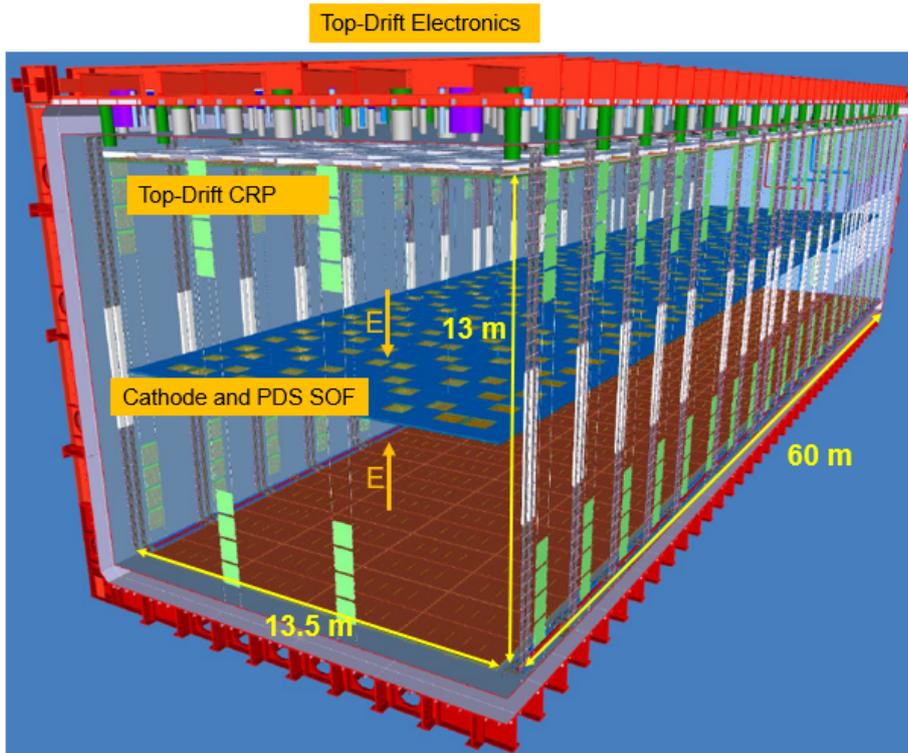


Figure 5: 3D view of the Vertical-Drift DUNE far detector module

well as the needed manpower in terms of researchers, technical personnel provided by the laboratories and CDD to be provided on the IR* funding. The KDP2 process also confirmed the global DUNE funding from the IR* program for a total of about 20Meur (including: detector core costs, CDD, missions, CERN activities, transportation, installation, and contingency. The hardware core costs for the detector construction correspond to 15.4Meur of which 83% have been already engaged in the period 2023-2025, with very little use of the contingency.

The signature of the DUNE MOU by IN2P3 was finalized in the fall of 2023. Production activities, foreseen to extend through 2024/2025/2026, started immediately at the end of 2023, with the production of the cryogenic ASIC chips for the TDE.

The DUNE Collaboration published in 2024 the DUNE Far Detector Vertical Drift Technology Technical Design Report, where the complete detector design information is accessible ((A. Abed Abud et al 2024 JINST 19 T08004)).

In 2024 the Collaboration also re-optimized the installation schedule in order to maintain an aggressive physics schedule and to better profit of the different installation procedures for the two far detector modules. It was then decided that the Vertical-Drift should be the first module to be installed. This new installation schedule was anyway compatible with schedule of the IN2P3 contributions deliverables, as it had been defined at the KDP2 review. This decision put a big responsibility on the IN2P3 team for a timely start of the DUNE physics program. It was also a recognition of the interest and validity of the Vertical-Drift design, in terms of performance and practical advantages for the production and simplicity of installation and operation of the detector. The Vertical-Drift design is currently also taken into account for the third DUNE module. The production of the wire chambers Anode Plane Assemblies (APA), constituting the basic elements of the Horizontal-Drift module, is

currently on schedule for the installation of the second Far Detector module in 2029.

The production process of the different elements of the detector is organized in DUNE with a series of reviews validating the final design of all elements. For the production of each detector element a dedicated Production Readiness Review (PRR) is organized in order to give green-light to the production activities. An important series of PRR reviews already happened in 2024 for most of the elements of the TDE readout chain, Chimney vessels, Cathode frames and meshes, CRP frames, and SOF components. The organization of the productions with very large tenders required strong administrative efforts in 2024 and 2025 involving the administrations of the laboratories and of the CNRS Regional Delegations. Intensive technical and scientific activities were then needed in order to ensure the follow-up of the productions and the associated Quality Controls.

The outcome of the activities carried on in 2024 and 2025 is that these large production activities were kept on schedule and on budget. The IR* funding profile, which presented large engagement peaks in 2024/2025 was also kept within expectations thanks to the help and support of IN2P3 and of the MESRI. Some additional details on the status of different deliverables are given in the next specific paragraphs.

3.1 TDE electronic elements (IP2I,LP2I)

The production of the various parts of the TDE charge readout system is in very advanced state and it will be completed by the summer 2026. The production activities for the components started at the end of 2023. In 2024 the Consortium passed most of the PRR Reviews and launched the main tenders for the procurements and assembly. Several TDE infrastructure components, as the microTCA units, are commercial (COTS). The TDE system is based on two main boards of 64 channels: the Front-End Board (FEB) and the microTCA Advanced Mezzanine Card (AMC). The FEB is hosting the cryogenic ASICs and providing the amplification of the detector charge signals. The AMC ensures the digitization of the amplified signals and the data transmission in UDP jumbo packets on the DAQ Ethernet network. The FEBs and the AMCs are assembled by industrial partners mounting main components provided by CNRS. They are both produced in about 4000 units, The assembly companies have been required to ensure the highest possible level of quality tests in situ including optical and X-ray inspections and flying probe tests systematically executed on all boards produced. In addition, all boards undergo full functional tests at IP2I and LP2I using dedicated test benches which were developed over a few years in order to mimic the detector operation of the given board and validate its response at high accuracy (1% for the FEB) performing the data analysis on real time. These QC tests are executed with the same automated equipment (see for instance the FEB bench in Figure 6) in the two sites and on real time with respect to the monthly production batches. The production yield is very high and close to 100%. A few boards (at the per mill level) with minor issues, although having passed the industry quality tests, were detected by the functional tests. They are then foreseen to be repaired by the assembly companies with the goal of achieving 100% production yield.

The status of the TDE productions is detailed below. For simplicity for each item in brackets it is indicated the nominal number of units needed to be installed on the detector. A suitable fraction of spares is also included in all productions.

- (15360) Cryogenics ASICS LARZIC: completed at the beginning of 2024
- Main AMC components (FPGA, ADCs, Buffers), completed in 2024
- KEL connectors, completed in 2024

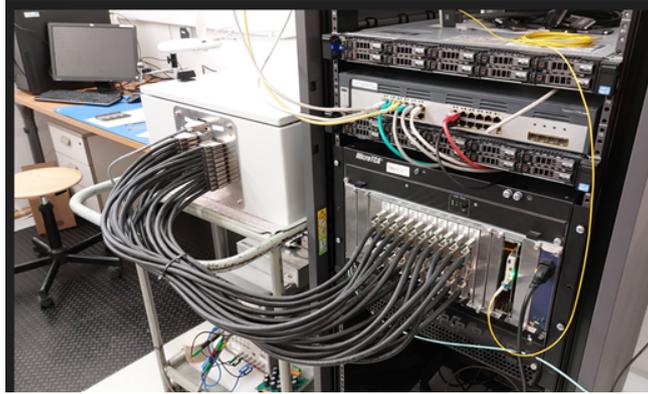


Figure 6: TDE FEB test-bench system

- (320) microTCA crates, completed in 2025
- (320) microTCA end-nodes, tendering in 2025, completion of deliveries by June 2026
- (320) Timing end-nodes, tendering in 2025, production completed
- (3840) FEB, 43% produced including spares, completion by June 2026
- (3840) AMC, 69% produced including spares, completion by June 2026

It is then foreseen during the second part of 2026 to focus on the preparation of the shipment of the TDE chain elements to SURF and on the preparation of their installation process.

3.2 TDE Chimneys (IJCLAB)

The production contracts for the chimney mechanical vessels were assigned at the end of 2024. They foresaw the production of 105 chimneys: 63 chimneys containing 48 FEB (V48) and 42 chimneys containing 24 FEB (V24). The production and QC activities are in progress with 38 units V24 produced (see Figure 7) and 41 V48 units produced. Specific integration tests of the large size chimneys with the electronics were carried out at CERN in 2024 and thermal tests were carried out at IJCLAB in 2025. Production activities are proceeding in 2026 concerning the inner parts of the chimneys (FEB guiding systems, blades, cabling and PCB flanges) for which the productions have to be launched soon.

3.3 Cathode modules (IJCLAB)

The cathode module composite frames production (80 units) was launched in 2025. The production and the associated QC process performed at IJCLAB (see Figure 8) are well in progress, half of the cathode frames have been produced. The production of the suspension system (TAD and LADD) of the cathode modules (PRR in September 2025) is going to be launched. The cathode resistive meshes are being produced, 80% was produced by the end of 2025 and the remaining 20% is under delivery at the beginning of 2026.

3.4 Charge Readout Planes (LAPP)

The CRP composite mechanical structures are organized by Charge Readout Units (CRU) covering half of the CRP. The large tendering activities for the procurement of the CRU composite structures for both the top CRPs (160 CRU frame units, see Figure 9) and bottom CRPs (160 CRU frame units) were launched in 2025. The company in charge of the production of the frames will start



Figure 7: Chimney vessel acceptance test at IJCLAB

deliveries in the spring of 2026. LAPP strongly contributed to the improvements in the perforated PCB anodes design and production scheme in collaboration with CERN. The implementation of these refinements in the production scheme has slightly delayed the production of the anode PCBs which is under the responsibility of CERN. Other activities concern the design, development, prototyping of main mechanical components for the top detection plane consisting of 64 suspension systems holding the Super-Structures with the CRPs to the cryostat roof, the top CRP cable tray network and cabling. The PRR of those systems will occur by summer 2026 in order to be able to launch the production of those components just afterwards. LAPP is also centralizing the production of the flat cables for the top CRPs and the Chimneys by performing a global purchase of the connectors from KEL, of the cables from Hitachi and the production of the cables will be carried out in 2026.

3.5 Top CRP assembly factory (LPSC)

The top CRP assembly factory was set-up at LPSC in 2024/2025 (see Figure 10) and it passed its specific DUNE Production Readiness Review to start the production of the CRPs in June 2025. However the massive CRP production (72 units at LPSC) did not start yet related to an external factor, the availability of the anode perforated PCBs which is under responsibility of CERN. The production of the anode PCBs underwent an additional series of improvements and tests in order to simplify the PCB productions assembly and the associated quality. The tendering process for the anode PCBs has been then launched by CERN. This set of refinements slightly postponed the the start of anode PCBs production, however the Top CRP productions by IN2P3 is still on time with respect to the far detector Vertical-Drift installation schedule. The facility has been nevertheless been used for specific assembly tests of CRPs for the anode tests and in particular in the period of the CERN safety pause



Figure 8: Cathode module cryogenic testing at IJCLAB

in 2025. The current CRP production schedules foresees the completion of the top CRP production by February 2028.

LPSC also takes care of the production of the transportation boxes for the CRUs shipment to SURF and of the level meters measuring the liquid argon level in the cryostat with respect to the top-drift CRP, for both of them the productions are in progress.

3.6 Signal-Over-Fiber Elements (APC)

Signals from the PDS X-ARAPUCA modules installed on the HV cathode are transmitted via optical fiber out of the cryostat to the warm electronics. In total 320 optical transmitter cards (of 2 channels each) will be produced. The 640 optical signals are received by 80 8-channel optical receivers which are interfaced to the PDS digitizer (DAPHNE). Both SOF transmitter and receiver devices have been tested in the Cold-Box runs and are currently operating in ProtoDUNE Vertical-Drift. The production process has advanced through a Stage 1 PRR for the procurement of the long lead-time SOF components (lasers and photodiodes) which is underway. Stage 2 PRRs for the PDS cold electronics and warm electronics are expected in the first semester 2026. Upon PRR approval, production of the PCBs for the transmitters and receivers will commence, with delivery to the PDS Consortium anticipated in the first quarter of 2027.



Figure 9: Prototype of a top CRP composite frame from the manufacturing company in June 2025

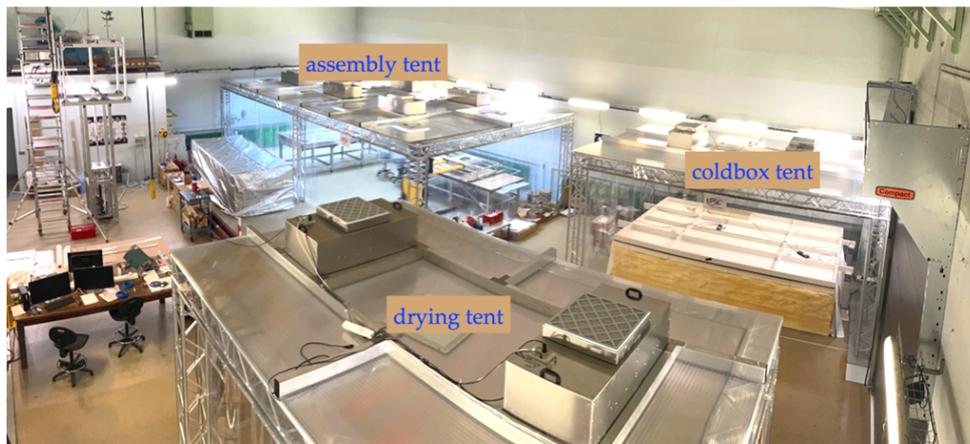


Figure 10: Top CRP assembly factory at LPSC

3.7 Human resources

The human resources in DUNE were scrutinized and engaged at the time of the KDP2 review on a year-by-year basis in each laboratory, including the detector installation. An annual monitoring of the resources has shown that the resources have been inline with the expectations and the engagements subscribed by the laboratories for the technical personnel. The project has been running with stable human resources during the last two years with some small variations which are due to the expected level of engagement of the technical personnel in different phases of the project for the various activities. Currently the number of persons involved is 81, corresponding to 45.8 ETP. The breakdown at the end of 2025 was including 37 persons (27.6 ETP) among the research personnel of which 9 are PhD students, and 44 people (18.3 ETP) among the technical staff. Among the technical personnel 2 CDD paid on the IR* funds are operating at IP2I and LP2I since the end of 2024 for the TDE activities. Additional CDDs are being recruited for other contributions.

The details of the human resources in each laboratory are given in the table in Figure 11.

In addition to the IN2P3 laboratories contributing to DUNE (APC, IP2I, IJCLAB, LAPP, LPSC, LP2I) in summer 2024 it was also created the IRL PPC at the Chicago University. The IRL PPC hosts the IN2P3 DUNE Technical Responsible and it acts as facilitator for the DUNE IN2P3 activities in the USA, in view of the preparation for the Vertical-Drift Far Detector Installation. The IRL PPC also contributes to joint programs with the Chicago University for the exchange of personnel and for

	Research personnel		Technical Personnel		Total	
	Number	ETP	Number	ETP	Number	ETP
APC	11	7,85	5	0,85	16	8,7
IJCLAB	5	3,2	17	6,35	22	9,55
IP2I	5	5	8	3,6	13	8,6
LAPP	6	5,13	5	2,37	11	7,5
LP2I/IRL	5	3,4	3	2	8	5,4
LPSC	5	2,98	6	3,1	11	6,08
Total	37	27,56	44	18,27	81	45,83

Figure 11: Distribution of personnel among the IN2P3 laboratories contributing to the DUNE project

PhD students.

A list of main roles in the DUNE Collaboration ensured by IN2P3 members is mentioned below:

- D.Autiero: Top-Drift Electronics Consortium leader
- D.Duchesneau: Charge Readout Planes Consortium leader, ProtoDUNE Vertical-Drift Run Coordinator
- E.Pennacchio: Co-coordinator of the Production Group in the Computing Consortium and liaison person for ProtoDUNE Vertical-Drift computing
- A.Tonazzo: Member of the Co-spokesperson Search Committee for the ongoing election of the Co-spokesperson in 2026.
- L.Zambelli: ProtoDUNE Data Reconstruction and Analysis working group Co-coordinator

IN2P3 pays since 2023 annual DUNE Common Fund (CF) contributions amounting to 3000 USD per PhD. The list of PhD who were counted for the 2025 CF contribution is the following: APC: S.Sacerdoti, T.Patzak. A.Tonazzo, C. Mironov, J.Coelo, J.Dawson; IJCLAB: F.Cavalier, L.Simard, T.Houdy, Y.Kermaidic; IRL PPC C. Cerna; LAPP: D.Duchesneau, P. del Amo Sanchez, L.Manzanillas, L.Zambelli, A.Lopez Moreno; LPSC: J.S.Real, J.S.Ricol, A. Robert, J.Collot, S. Calvez; IP2I: D. Autiero, K.Dhanmeher, S.Galymov, E. Pennacchio; LP2I: C.Jollet, A.Meregaglia.

3.8 Summary on the IN2P3 project status

The detector contributions of the IN2P3 groups to the Vertical-Drift module successfully developed corresponding to what was presented at the CSI meeting of October 2021. The productions are well on track, with high quality and yield and carried on within the foreseen budgets, as defined at KDP2 review.

The IN2P3 activities, as defined in 2023, remain fully aligned with the DUNE overall installation schedule. This includes the Vertical Drift module as the first installed module, expected for 2027-2028, supporting the goal of starting data collection in 2029.

- Most of PRR have been passed and all IN2P3 contributions are in production
- TDE is expected to complete the productions of all the electronics components and chimneys in summer 2026, with a comfortable advance.
- The CRP frames are in production and the CRP factory is ready for the CRP integration
- Cathode frames and resistive meshes are in production
- Chimneys vessels productions are expected to be completed by 2026 while other parts are about to start being in production
- The PDS SOF transmitter and receivers components are in procurement
- All consortia installation procedures and tooling are in phase of validation at CERN installation mock-up facility

In parallel to the large production efforts, the IN2P3 groups also continued carrying on the experimental activities at the CERN Neutrino Platform, successfully run NP02/ProtoDUNE Vertical-Drift and prepared and performed the Vertical-Drift installation mock-up test at CERN (more details in next paragraph). These activities needed a continuous presence of IN2P3 members at CERN for several months.

4 Experimental activities at the CERN Neutrino Platform

An aerial view of the CERN Neutrino Platform installation at EHN1 is visible in Figure 12 showing the NP02 and NP04 experiments with similar cryostats containing 770 tons of LAr. The Neutrino Platform provides a unique cryogenic infrastructure for the large-scale tests of the DUNE LArTPCs.



Figure 12: View of the EHN1 hall showing at the top-left the cryostat of NP02/ProtoDUNE Vertical-Drift and at the bottom-right the cryostat of NP04/ProtoDUNE Horizontal-Drift

More details on the experimental activities at the CERN Neutrino Platform can be found in the yearly reporting to the CERN SPSC Committee:

- SPSC Review 2021: [slides](#), [document SPSC-SR-287](#)
- SPSC Review 2022: [slides](#), [document SPSC-SR-308](#)
- SPSC Review 2023: [slides](#), [document SPSC-SR-331](#)
- SPSC Review 2024: [slides](#), [document SPSC-SR-350](#)
- SPSC Review 2025: [slides](#), [document SPSC-SR-366](#)

In summary, the Vertical-Drift design had already been successfully demonstrated by campaigns of Cold-Box tests of the CRPs in 2021-2022. The Cold-Box is a dedicated Liquid Argon TPC which allows testing individual CRPs and PDS modules by collecting large samples of cosmic ray tracks. The operation and stability tests of the new 300 kV high voltage system needed to drift over about 6m were also implemented in 2022 in the NP02 experiment which had a dedicated run with the Dual-Phase CRPs collecting 6m long tracks, representing the current world record in terms of drift length.

In 2023 the Charge Readout Planes, which had been already tested and characterized in the Cold-Box tests of 2021 and 2023, were integrated, with the other Vertical-Drift detector elements, as the cathode modules and the PDS, within the NP02 cryostat. The detector configuration was corresponding to a full slice of the Vertical-Drift detector with 3.4m of top and bottom drift lengths (see Figure 13), two top CRPs, two bottom CRPs and two cathode modules at middle height with PDS (Figure 14). This integration exercise was successful and it allowed validating the Vertical-Drift construction procedures and the interfaces between the different detector elements.

Other specific tests were carried on in parallel such as the tests of the larger size chimneys and on some integration aspects of the DAQ system.

NP02 could not be immediately filled with liquid argon due to the increase on the European markets of the energy and liquid argon costs related to the war in Ukraina. Nevertheless, specific Cold-Box tests to improve the anode design for the Vertical-Drift Far detector CRPs were continued to be carried-on systematically.

The filling and commissioning of NP02/ProtoDUNE Vertical-Drift eventually took place at the end of 2024. However, the commissioning and operation of the detector was interrupted between January and May 2025 due to access limitations to the EHN1 hall. This pause was imposed by CERN after a safety incident that occurred in one of the buildings hosting Neutrino Platform activities. Although unrelated to the operation of ProtoDUNE Vertical-Drift, all Neutrino Platform activities were halted during this safety review. The pause largely impacted the integration of most systems, which had to delay their on-site commissioning. Despite the safety pause ProtoDUNE Vertical-Drift had a very smooth and successful operation in 2025. The detector systematically operated (run Co-coordinator D. Duchesneau) collecting cosmic rays and in addition it recorded about 5 million of beam triggers thanks to a dedicated test-beam line capable of bringing charged particles of selected momenta inside the active volume of the detector. An event display of a drift window acquired on a beam trigger is shown in Figure 15.

The detector performance was excellent and meeting all expectations. The stability and reliability of the detector operation and of the DAQ system did not require the presence of shifters from the collaboration. This operation campaign associated also to dedicated test configurations allowed for several refinements of the Vertical-Drift far detector set-up, for instance the mitigation of the noise induced by the power supply system of the cathode. The liquid argon purity was also demonstrated reaching an electrons lifetime above 20ms. The cathode was also operated at 300kV, which corresponds to a factor two higher voltage than what required for the nominal drift field of 500V/cm over 3.4m

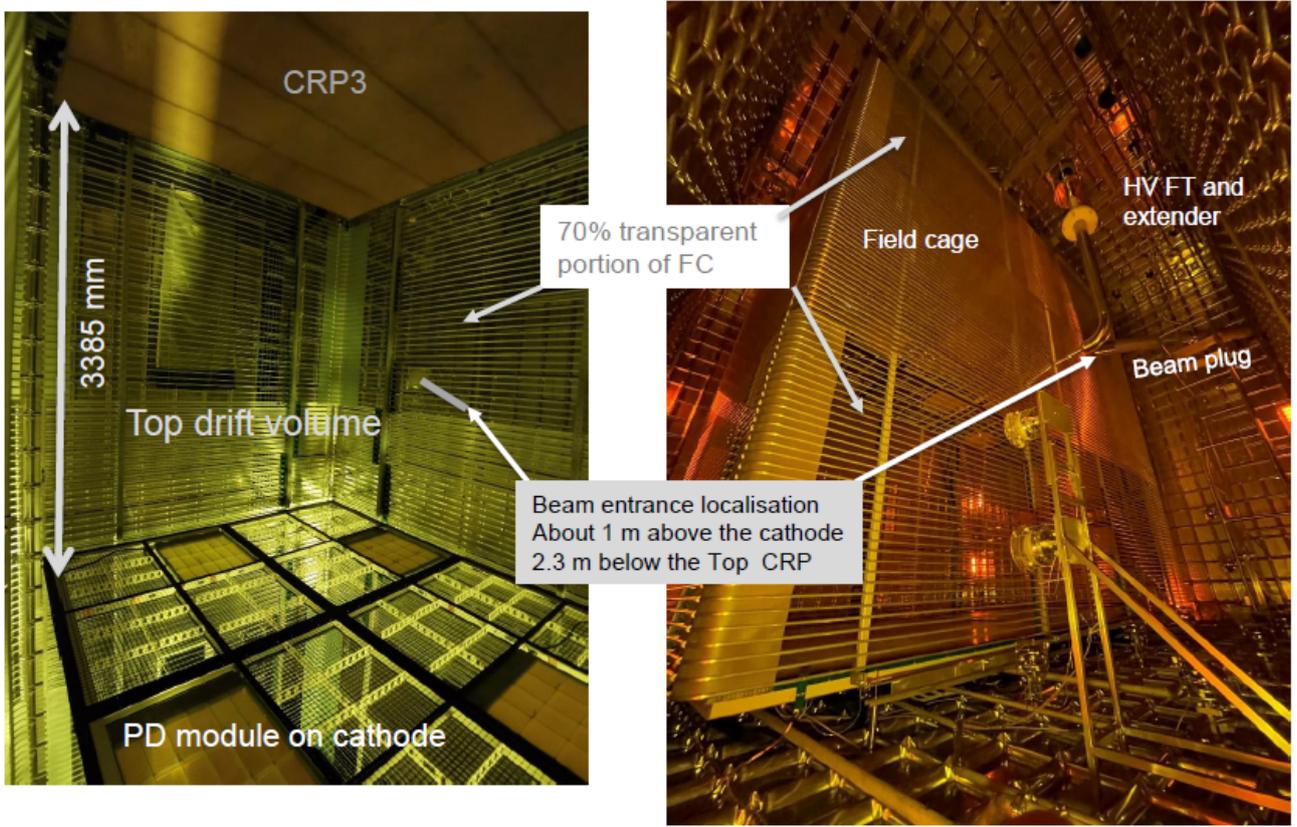


Figure 13: Internal views of ProtoDUNE Vertical-Drift. Left: view of the top-drift volume including one of the top CRP (CRP3) and the cathode with the PDS system; Right: external view of the field cage with the HV system delivering the high voltage to the cathode

distance. The detector will be kept operating at long-term during 2026 in order to accumulate statistics and establish stability records over long time periods and continue performing some specific tests and DAQ developments which may help in acquiring additional experience and perfecting some aspects of the operation of the Vertical-Drift far detector module.

Important analysis efforts are also ongoing in view of exploiting the large sample collected by NP02/ProtoDUNE-Vertical of beam particles interactions and cosmic rays in view of improving the DUNE reconstruction, and assessing some finer details, as the charge reconstruction in the small gap in between two CRP planes. In particular, these analyses are essential to test and improve the reconstruction algorithms for a better particles identification and energy reconstruction efficiency of the charge and light collection systems in DUNE. The collected samples of hadronic beam data, in the momentum range of 1 to 8 GeV/c, are invaluable inputs to better understand, and model, the neutrino final-state interaction in argon, which is one of the largest sources of systematic uncertainty in DUNE. The forthcoming ProtoDUNE Vertical-Drift Xenon doping campaign will increase the light collection efficiency of the PDS X-ARAPUCA modules, as planned for the Vertical-Drift Far Detector module. Understanding the scintillation light propagation and detection properties are important for the far detector simulation and trigger design for rare events such as supernova burst. Finally, ProtoDUNE data also serve as a test-bench for the far detector calibration strategies (laser, pulsed neutron source) and as first inputs for the estimation of the detector systematics to the sensitivities of DUNE. The data sample provided by NP02/Protodune Vertical-Drift constitutes the last chance to perform analysis on

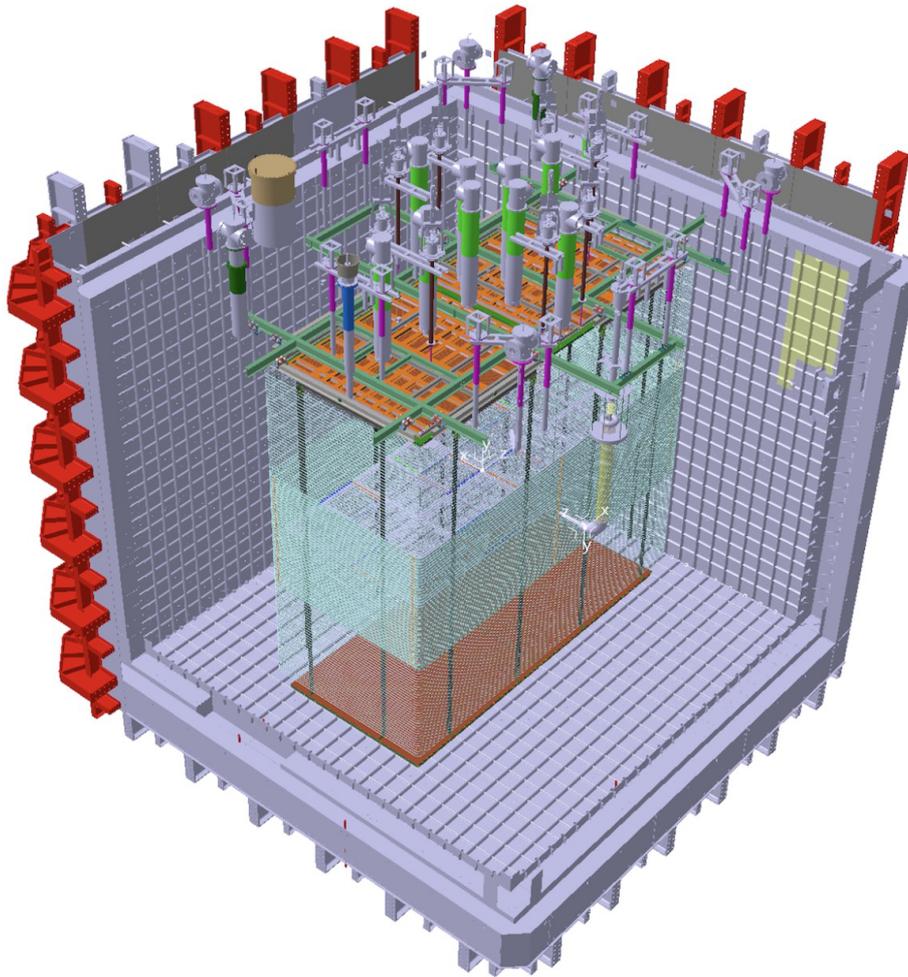


Figure 14: 3D view of NP02/protoDUNE Vertical-Drift

real detector data before the operation of the Vertical-Drift module.

The Vertical-Drift integration mock-up facility built in Building 185 (Figure 16) in order to mimic the installation procedures inside the cryostat at SURF, up to 13m height, was also delayed by the safety pause and started operating at the end of 2025. This facility has already been used to carry on a set of dedicated installation tests of various detector elements such as the CRP planes and their cabling, cathode modules, PDS modules cabling integration, field cage modules installation. The outcome of these activities allows for refinements and improvements of the installation procedures foreseen for the Vertical-Drift module, precise evaluations of the time taken by the installation activities and the associated required manpower.

5 DUNE Physics program

A DUNE Physics update will be presented in details in a dedicated talk at the March 2026 CSI. The section in this document limits reminding a few points characterizing the uniqueness of DUNE and of its physics program. An older but complete picture of the DUNE physics sensitivity is also contained in the [DUNE physics TDR](#) published in 2020. This picture has been updated in 2025 with the [DUNE Science Program](#), DUNE input to the European Strategy for particle physics.

Neutrinos of 3 families have been detected and oscillations between the families were observed. The three mixing angles and the two mass splittings have been measured with precisions at the few

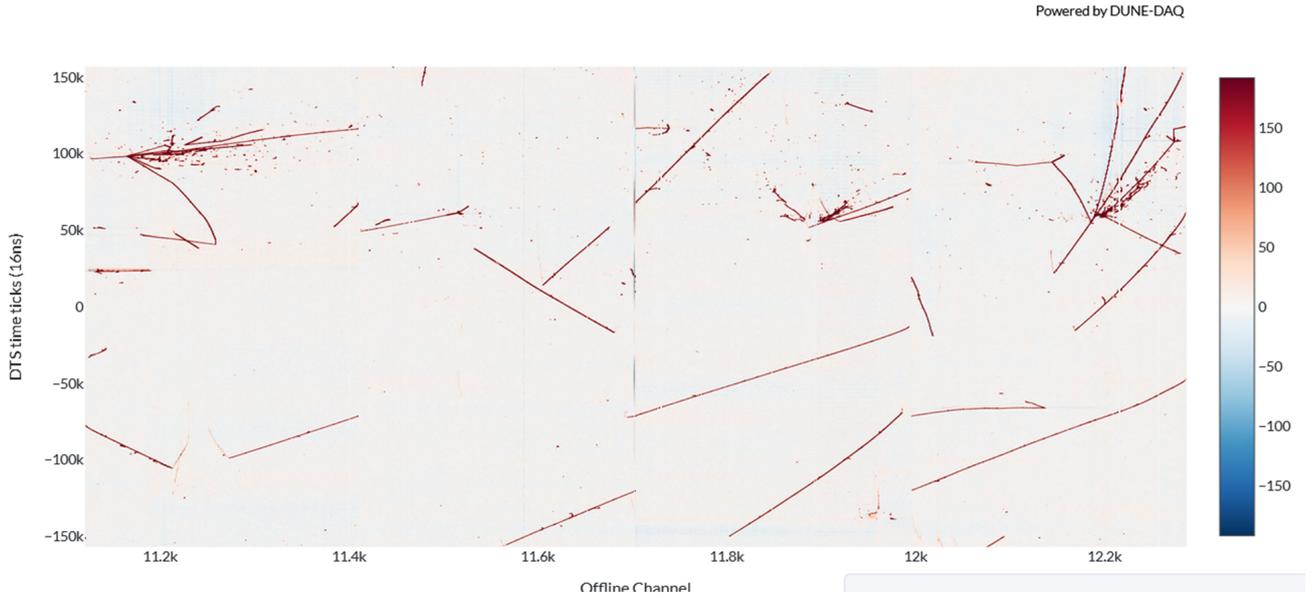


Figure 15: Drift window acquired with the TDE system from the top-drift CRP3 collection view in ProtoDUNE Vertical-Drift. At the top-left it is visible the interaction of a charged pion from the beam (short horizontal track before the hadronic shower). The image contains several cosmic ray tracks. At the top-right one can also notice the shower of a cosmic ray hadron.

percent level. Neutrino masses thus remain the first and so far only manifestation of physics beyond the Standard Model in particle physics experiments. Although neutrino oscillations are a well established experimental fact there are still several unknown aspects of neutrinos:

- The absolute value of neutrino masses
- Whether neutrinos are Dirac or Majorana fermions
- The neutrino masses hierarchy (normal or inverted)
- Whether the charge-parity (CP) symmetry is violated in the leptonic sector
- Is the PMNS matrix unitary and is the 3-neutrino flavour paradigm complete

The precise study of oscillations with Long-Baselines (LBL) is a privileged tool to investigate standard and non-standard neutrino properties. The last three points in the above list are likely to be measured in the next 10 years with critical contributions from Long-Baseline experiments. The next generation experiments as Hyper-Kamiokande (HK) in Japan and the Deep Underground Neutrino Experiment (DUNE) in the US, represent the forefront of this endeavor.

DUNE is a long-baseline neutrino oscillation experiment with a baseline of 1300 km. The experimental setup consists of a 1.2 MW proton beam upgradable to more than 2 MW, a near detector complex (at about 570 m from the target to measure the still unoscillated neutrino beam), and a more than 40 kton mass far detector complex with 1500m overburden. The near detector complex includes a movable LAr pixellated detector system exploiting the PRISM technique in order to measure the neutrino flux at different angles (i.e. different energies). This allows for a better fluxes extrapolation at the far detector site, reducing the dependency on the accuracy of interaction models.



Figure 16: Vertical-drift installation mock-up facility at CERN building 185.

The far detector technology is based on the Liquid Argon Time Projection Chamber (LArTPC), which was proposed by C.Rubbia in 1977. The LArTPC provides at the same time a homogeneous massive target for neutrino interactions and a ionization detector, similar to an electronic version of the bubble chambers. The detector combines imaging capability with excellent energy resolution allowing measuring the track-showers tree of the single particles produced in the final state of neutrino interactions and the detection of the scintillation light. The detector is capable of low thresholds down to solar neutrino physics and the detection of exclusive final states. The tracking and calorimetry are performed with $0.035 X_0$ sampling and 5mm pitch. The detector provides excellent electron identification, π_0 rejection and charged particles identification with dE/dx measurements.

The LArTPC represents then an ideal detector for neutrino oscillations, for the detection of core collapse supernovae neutrinos and for proton decay searches. The DUNE far detector measures the neutrino spectra in a wide band beam exploiting the spectral information in the oscillation pattern, including the 2nd oscillation maximum. The determination of the mass hierarchy and the search for CP violation are both performed in the same experiment by studying the $\nu_\mu \rightarrow \nu_e$ oscillations both with neutrinos and antineutrinos.

Matter effects and CP are degenerate since they both impact neutrino and antineutrino in opposite ways, however matter effects depend on the hierarchy whereas CP effects do not. Narrow band experiments basically just “count” the appeared neutrinos. There are therefore solutions with CP conserving phases in one hierarchy which overlap to CP violating phases in the opposite hierarchy.

The specific advantages of DUNE in the search of CP violation are:

- Higher energy (and therefore longer baseline) with larger matter effects
- The use of a Wide Band Beam (WBB) which allows for spectral information exploitation

DUNE is the only experiment capable of determining the mass ordering by separately measuring the $\nu_\mu \rightarrow \nu_e$ oscillation with neutrinos and antineutrinos. In DUNE the wide band neutrino beam, combined with the long-baseline, breaks the degeneracy between CP violation and matter effects. The allowed regions, as resulting from the measurement, for the normal and inverted hierarchy are well separated with no degeneracies. This allows the determination of both the CP violation and mass hierarchy in the same experiment.

DUNE will measure oscillations spanning over more than a full oscillation period. DUNE can measure the oscillation parameters at each bin of L/E and a broad L/E range is essential to resolving all parameters at once. It is likely that new physics would distort the result as a function of L/E, so DUNE has as well a unique sensitivity to new physics.

An example of the unique potential of DUNE is shown in Figure 17. Existing Super-K atmospheric data weakly favor normal hierarchy and lower octant. In this scenario, atmospheric experiments will not reach 5σ for the mass ordering discovery. DUNE is the only experiment capable of reaching more than 5σ even in the most pessimistic case.

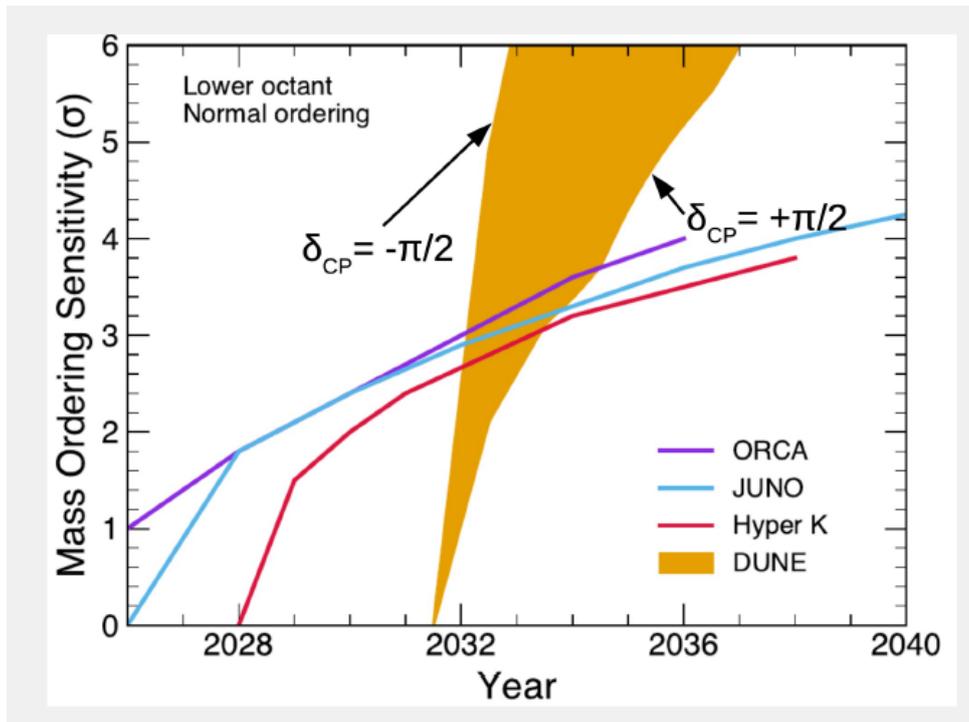


Figure 17: Mass hierarchy sensitivity of the DUNE experiment

In summary, DUNE is then uniquely capable of performing CP violation search, mass hierarchy determination and 3 neutrinos phenomenology and verification of the PMNS unitarity, including τ appearance, within the same set-up and with high significance for discovery.

DUNE can also reach the best ultimate precision of $6-16^\circ$ in the δ_{CP} measurement (Figure 17). DUNE will also produce world-leading precision results (in the sector of long-baseline experiments) on θ_{13} which have comparable accuracy with reactor experiments and thus sensitive to new physics via this comparison.

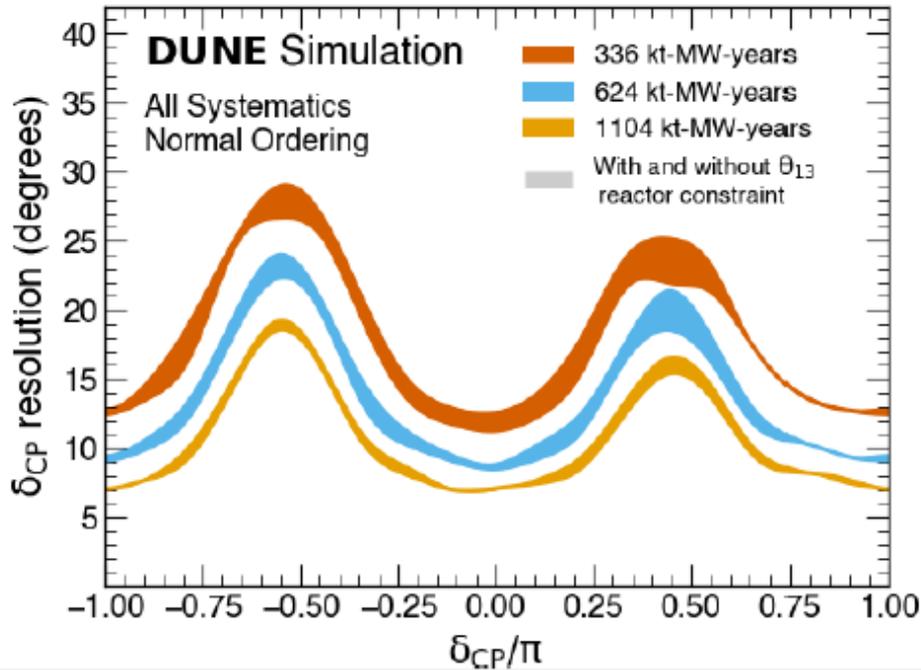


Figure 18: DUNE accuracy in the measurement of the CP phase δ

The P5 process and the European strategy were at the basis in 2014 of the creation of DUNE. Since the IN2P3 CSI of 2021 there was a new P5 update in 2023 and the update of the European Strategy for Particle Physics in 2025. Both processes have been strongly re-stating the relevance of the DUNE physics program. As for instance mentioned in the [CERN-ESU-2025-002](#) of December 2025:

“The global neutrino programme has made significant advances towards the determination of neutrino masses and leptonic mixing, and the construction of the next generation of accelerator-based neutrino experiments is progressing rapidly. The CERN Neutrino Platform is a focal point of European participation in the global long-baseline neutrino programme. In particular, the current commitments to the LBNF/DUNE project have been decisive and remain a priority for CERN.”

The IN2P3 groups have been systematically contributing to the DUNE analysis and software development activities as well as to the analysis of the data from the large-scale prototype detectors at the CERN Neutrino Platform. L. Zambelli is co-convener of the Data Reconstruction and Analysis (DRA) Working Group on the analysis of the ProtoDUNE data.

A short summary of the involvement of the IN2P3 groups on different analysis topics, in addition to the activities related to the analysis and exploitation of the ProtoDUNE data, is listed below:

- **APC: Atmospheric neutrinos, sterile and supernova neutrinos, and systematics studies.** The APC group is highly focused on the study of atmospheric neutrinos, which will provide complementary measurements to the beam and will be the only source of neutrinos during the first years of operation of the far detector. Associated studies and developments have been concerning: energy and angular resolution, development of alternative angular reconstruction algorithms, events containment, identification and reconstruction of Michel electrons for $\nu/\bar{\nu}$ separation and the development of machine-learning tools for vertex reconstruction. After initiating this activity within DUNE, the group led the first paper on this topic and are contributing to numerous studies, including reconstruction and systematic uncertainties. The group is also active in the analysis of the PDS data.
- **LAPP: Anode response, solar neutrinos.** The LAPP group is heavily involved in the perfor-

mance studies of the Vertical Drift anode technology with the simulation of the signals formation and the dual-phase LEMs, with the development of dedicated analysis tools ([LARDON](#)) systematically exploited during the prototyping activities. It also has an active role in the DUNE low energy physics program, working on a dedicated analysis framework to leverage DUNE's potential for detecting low-energy neutrinos, with a particular focus on solar neutrinos, for which they developed dedicated discrimination techniques and proposed a shielding strategy to make solar neutrino physics with DUNE feasible.

- **IJCLAB: Low energy events and calibrations.** The IJClab group is mainly involved in the characterization of the DUNE Far Detector prototype detector response in various energy regimes spanning from sub-MeV radiologicals up to few GeV charged particles coming from the CERN SPS beam. In a LArTPC, the most prominently distributed radiological backgrounds are ^{39}Ar decays (500 keV). Other contaminants, coming from ^{232}Th and ^{238}U chains, can be found in the detector structures (field cage, cathode, etc). The detector response can be studied with these events: from the drift electric field uniformity to the ionization electron recombination. The reconstruction efficiency of radiological clusters is directly connected to future analyses of low energy neutrino events coming for solar or supernova neutrinos.
- **IP2I: LBL neutrino oscillations and energy reconstructions** The IP2I group contributed in setting up the far detector simulations for both the dual-phase and Vertical-Drift. The group studied neutrino oscillations with the appearance of τ neutrinos by exploiting kinematical techniques for the signal selection. An important aspect for exploitation of the spectral sensitivity for the CP search corresponds to the resolution in the reconstruction of the neutrino energy from final state particles. The intrinsic limitations due the neutrino interaction physics as well as the ultimate resolution achievable were assessed. The group also assessed the electromagnetic calorimetry performance of the far detector in measuring the energy of the electrons in ν_e CC interactions, particularly relevant at the 2nd oscillation maximum.
- **LP2iB: LBL neutrino oscillations and energy reconstructions** The LP2iB group is also working intensively on the measurement of the energy of final state particles in neutrino interactions and of electromagnetic showers with new reconstruction tools. Particular efforts were taken in assessing with simulations and ProtoDUNE data the impact on the energy reconstruction performance of gaps existing in between adjacent CRPs which may introduce losses in the charge readout. The group is also studying the use of graph neural networks for particle identification and energy reconstruction, with the goal of mitigating known limitations of the convolutional neural network-based hit classification used within the official Pandora reconstruction chain.
- **LPSC: LBL neutrino oscillations, atmospheric neutrino and ML.** The LPSC group participates to the development of a new fitting framework recently introduced in DUNE, GUNDAM, to perform oscillation analysis with both Frequentist and Bayesian methods. Their focus is mostly on the LBL analysis. GUNDAM was deployed at scale in an HPC environment (allocation awarded on Kraken in Grenoble) and validated by the group, which is now using it to prepare a new sensitivity study. LPSC is involved in a joint ND+LBL effort to achieve the first joint ND+FD DUNE fit, including the impact of a more detailed model of the systematic uncertainties. The group is working also on sub-GeV EM shower reconstruction, investigating the use of a new machine-learning-based framework, SPINE.

Since 2021 35 DUNE papers were published and 11 PhD theses were defended in the IN2P3 groups. Members of the IN2P3 DUNE groups had leading roles for the following papers: Reconstruction of atmospheric neutrinos in DUNE's horizontal-drift far-detector module [arXiv:2601.05697](#), ProtoDUNE dual-phase performance paper (under Collaboration review).

10 additional PhD thesis projects are currently in progress. The list of theses already defended is shown below:

- E.Chardonnet (APC, 2021) Study of the response of the dual-phase liquid argon TPC, ProtoDUNE Dual-Phase at CERN, and the development of tools improving the detector performances for the DUNE experiment at Fermilab
- A.Cohen (APC, 2024) Études du signal de neutrinos de Supernova dans le DUNE Far Detector en utilisant la technologie LAr TPC Vertical-Drift
- I.Cheong Hong (APC, 2026) Neutrino reconstruction in the DUNE experiment using Machine Learning
- C.Sironneau (APC, 2025) Sensibilité à l'existence des neutrinos stériles par le biais des neutrinos atmosphériques dans le détecteur lointain de DUNE
- J.Dai (LPSC, 2024) Physique des neutrinos et contribution à l'expérience DUNE
- J.Pinchart (LPSC-LAPP, 2025) Formation des signaux de la TPC à dérive verticale de DUNE et étude de la transparence des anodes à travers la dynamique des porteurs de charge dans l'argon liquide
- T.Kosc (IP2I, 2021) Kinematic Search for tau appearance in the DUNE experiment
- Q.David (IP2I, 2022) Development of the DAQ system for the acquisition of core collapse supernova neutrinos in a DUNE far detector module
- G.deLauretis (IP2I, 2026) Reconstruction of the neutrino energy in the LAr TPC of the DUNE experiment far detector
- E.Lavaut (IJCLAB, 2025) DUNE's far detector prototype : calibrating at the MeV-scale
- P.Kunzé (LAPP, 2022) Études des données du prototype TPC à argon liquide double phase pour l'optimisation de l'expérience d'oscillation de neutrinos DUNE

6 Computing activities

The IN2P3 DUNE project is a main contributor to the DUNE Computing Consortium activities, involving the resources made available by CCIN2P3. This contribution to the project was also discussed and prepared in the KDP2 review in 2023 and it has been regularly achieved in these last years following expectations. IN2P3 is currently the third contributor to DUNE for disk space after Fermilab and CERN and it also provides considerable resources in terms of CPU for data and simulations and tape space. The CCIN2P3 provides to the IN2P3 groups a working environment identical to Fermilab which is exploited by the DUNE IN2P3 groups for the development of analysis and algorithms. The computing coordinator within the DUNE IN2P3 project (E.Pennacchio) is also ensuring a management role in the DUNE Computing Consortium by being co-responsible of the production group for data processing and MC simulations and the liaison person for the computing activities concerning ProtoDUNE Vertical-Drift at CERN.

7 Conclusions

Since the CSI presentation in October 2021 the IN2P3 DUNE project consolidated its expected contributions to the Vertical-Drift DUNE Far detector module. The project passed the IN2P3 KDP2 review in 2023 organized for the signature of the MOU. The funding support of the IR* allowed entering since the end of 2023 in the construction phase which is progressing on schedule, within the expected

costs and within high quality standards. Most of the IR* core detector funding was engaged in 2024-2025. In 2024 the DUNE Collaboration decided to install the Vertical-Drift as first far detector module, recognizing the validity and the practical aspects of this design. The IN2P3 groups have been carrying on the DUNE construction activities in parallel with the successful continuation of the experimental tests activities at the CERN Neutrino Platform as well as a steady engagement to the analysis and computing activities. We are then looking forward to the start of the detector installation at SURF in 2027 and a timely physics exploitation of the first DUNE far detector module.