DUNE status and perspectives

Report for the meeting of the Conseil Scientifique de l'IN2P3 :

Neutrinos réacteurs et accélérateurs 28-29 Juin 2018

Note: this document is a synthesis guiding to a much broader documentation set, accessible to the reader via the hyperlinks contained in the report.

Section 1: Involvement of the IN2P3 groups in DUNE and related R&D activities (ProtoDUNE dual-phase/WA105).

The IN2P3 groups currently involved in DUNE, together with the CEA/Irfu group, have a **long-standing record** of commitment, detector and analysis expertise, R&D activities in view of the preparation of the DUNE long-baseline experiment. The history of this involvement and the contributions provided so far by the IN2P3 groups will be recalled in this section.

The French groups:

APC (led by T.Patzak), CEA/Irfu (led by M. Zito), IPNL (led by D.Autiero), LAPP (led by D.Duchesneau), LPNHE (led by J.Dumarchez) and OMEGA (led by C. de La Taille,

have been contributing 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) (link).

The LAGUNA and LAGUNA-LBNO projects have thoroughly investigated the feasibility and the complex technical issues related to the construction, in the eligible European underground sites, of giant neutrino detectors, as well as the study of their physics performance with neutrino beams. The measurement in 2012 of a large value of the θ_{13} mixing angle (paper) opened the way to a relatively easy accessibility of the next fundamental measurements in neutrino mixing, such as the determination of the mass hierarchy and the search for CP violation in the neutrino sector. These goals became achievable by exploiting conventional long-baseline neutrino beams coupled to large underground detectors, with of the order of a few 10kton target masses.

As outcome of the **LAGUNA-LBNO design study**, it was identified the Pyhäsalmi underground site which could host large size liquid argon TPCs with dual-phase charge readout. The TPC considered for the first phase of the LBNO experimental program had a fiducial mass of 20 kton. This Far Detector was supposed to be exploited with a multi-GeV neutrino beam (CN2PY), to be produced by using protons extracted from the CERN SPS accelerator and travelling over a baseline of 2300 km.

The liquid argon TPC represents a modern version of the bubble chamber. It allows to completely reconstructing the final state of neutrino interactions reconstruction. It also provides particle identifications by combining range and specific ionization measurements and it represents a uniform electromagnetic calorimeter.

The key differentiating concept of the **dual-phase design** is the amplification of the ionization signal in an avalanche process 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 the LAr. In the dual-phase design, electrons drift vertically upward towards an extraction grid just below the liquid-vapor interface. After reaching the grid, an electric field stronger than the drift field extracts the electrons from the liquid up into 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 these high-field regions. The amplified electrons are then collected on a finely segmented anode with two perpendicular collection views. The anode and the LEM are 1 mm tick printed circuit board units of 50x50 cm^2 that are assembled in sandwiches separated by a 2 mm gap. 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 and the obtained gain is of the order of a few tens (typical gain ~20).

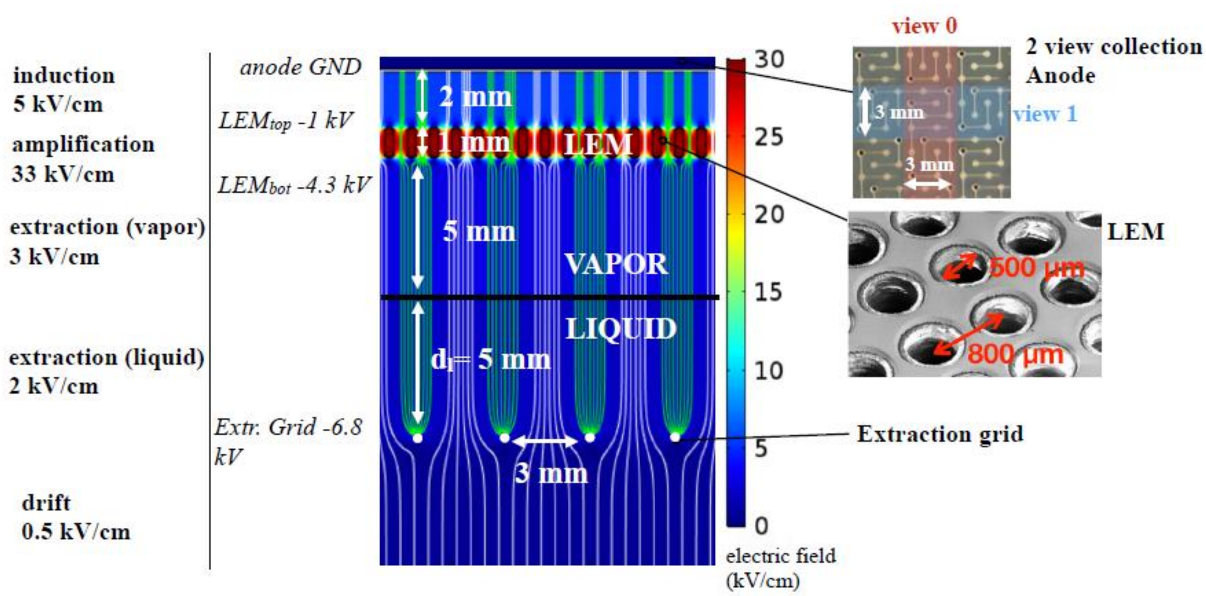

Figure 1.1 dual-phase Extraction/Amplification/Collection stack implemented in the Charge Readout Planes by integrating the extraction grid and the LEM-Anode sandwiches

The dual-phase design offers **several improvements and a complementary approach** with respect to the single-phase technology in view of constructing very large size underground detectors as summarized below:

- The gain on the ionization signal obtained in the gas phase allows for a robust and tunable and a lower detection thresholds and for compensating the potential charge attenuation due to long drift paths

- By enabling very long drift paths the detector has a larger fiducial volume and there is no dead material in the LAr drift volume
- The longer projective geometry allows for fewer readout channels, typically less than half of a corresponding single-phase detector despite a finer readout pitch (3 mm). The readout channels are implemented in two identical, orthogonal, collection views.
- The Far Detector has fewer construction modules simplifying the production and installation
- There is full accessibility and replaceability to all the electronics (even to the cryogenic front-end electronics) during detector operation.

The setup studied in LAGUNA-LBNO was allowing for effectively measuring the oscillation patterns as a function of the energy over the first and second maxima, resulting in a complete experimental assessment of the neutrino oscillations phenomenology with an optimal sensitivity to the mass hierarchy determination, as well as world-level competitive CP search reach. This exploitation of the spectral information is a common aspect also with the DUNE experiment.

Following these studies performed with the LAGUNA-LBNO project, the **LBNO Expression of Interest** was submitted in June 2012 to the CERN SPS Committee **(**CERN-SPSC-2012-021; SPSC-EOI-007, slides). The **SPSC supported** the LBNO physics case encouraging the successive steps in view of a proposal for LBNO. In particular, the SPSC recommended the construction of a **full scale prototype of the dual-phase liquid argon Far Detector** (later on approved by CERN as the WA105 experiment): "*the SPSC supports the double-phase LAr TPC option as a promising technique to instrument very large LAr neutrino detectors in the future. The SPSC therefore encourages the LBNO consortium to proceed with the R&D necessary to validate the technology on a large scale.*" See minutes of the 106th Meeting of the SPSC 26-27 June 2012 (link); Minutes of the 107th Meeting of the SPSC 23-24 October 2012 (link); Minutes of the 108th Meeting of the SPSC 15-16 January 2013 (link).

The physics case for LBNO, the liquid argon R&D and the project to build a large-scale prototype at CERN were also extensively discussed within the French **GDR neutrino community**. The GDR neutrino, together with the IN2P3-IRFU Working Group 4, in the redaction of the IN2P3-IRFU perspective documents, recommended LBNO in high priority among the future long-baseline projects: Groupe de travaille de prospective IN2P3-IRFU : « Neutrino : masses , oscillations. Désintégration du proton » 16/2/2013 (link). Synthése du Groupe de travaille 17/2/2013 (link). These recommendations on the French roadmap for neutrino physics were submitted in September 2012 to the Open Symposium of the European Strategy Preparatory Group in Krakov: Open Symposium - European Strategy Preparatory Group 10-12 September 2012, **"**Neutrinos: masses, oscillations; proton decay. A roadmap proposal by the French physicists" **(**link). The GDR neutrino then produced a document, where, in addition to recalling the interest for the LBNO experiment, it highly recommended the continuation of the LAr R&D. The participation to the construction of the LAr detector prototype at CERN were as well highly recommended: Update of the proposed French roadmap for Neutrino Physics, May 26th 2013 (link).

In parallel, the LBNO LOI was considered by the **European Strategy Group** (EGS), which acknowledged as well among its priorities the physics case proposed by the LBNO EoI. The ESG consequently encouraged CERN to develop an experimental program in order to support the role of the European groups in the long-baseline neutrino physics: European Strategy group "*Proposed Update of the European Strategy for Particle Physics*" Erice 25 January 2013 (link):

"*Rapid progress in neutrino oscillation physics, with significant European involvement, has established a strong scientific case for a long-baseline neutrino programme exploring CP violation and the mass hierarchy in the neutrino sector. CERN should develop a neutrino programme to pave the way for a substantial European role in future long-baseline experiments. Europe should explore the possibility of major participation in leading neutrino projects in the US and Japan.*"

The physics considerations developed by the ESG leading to this statement are discussed in details in the the European Strategy group "Physics Briefbook" CERN-ESG-005 13 January 2013 (link). These statements then were leading CERN to set up the Neutrino Platform in order to support the R&D related to the joint long-baseline program with the US.

The French groups had already, since a few years, **direct involvements in the R&D efforts on the liquid argon detector technology** within LAGUNA/LAGUNA-LBNO as well as thanks to specific R&D activities.

The **CEA/Irfu group in 2010** launched a R&D to test the feasibility of using bulk Micromegas to instrument dual-phase readout LAr TPCs. The CEA/Irfu group had been working in collaboration with the ETHZ, Liverpool and IPNL groups.

The large number of charge readout channels, needed for the few-10kton LAr detector sizes, naturally called for R&D efforts in view of the development of large-scale readout solutions. These efforts pointed to high-integration levels, costs reductions and aimed to performance improvement with respect to standard charge readout systems in LAr TPCs, such as the one of ICARUS.

An R&D on the charge readout electronics had been pursued with these goals at IPNL since 2006. This R&D was performed also in collaboration with the Swiss groups of LHEP Bern and ETHZ. It focused on two main axes:

a) The development of cryogenic front-end electronics based on 0.35 um CMOS ASIC amplifiers.
b) The development of a modern, easily scalable to large detector dimensions, low-cost DAQ system based on the uTCA technology standard used in the telecommunication industry. The design was relying on replacing the physics processors on the digitization units by virtual processors emulated in low cost FPGAs and on developing a dedicated time/trigger distribution system to align ADC sampling on all the digitization units.

The LABEX LIO program also supported since 2012 the installation at IPNL of a dedicated liquid argon laboratory with a TPC prototype (200 liters pure liquid argon mass and 600 liters total mass), designed on purpose as test bench for the R&D on the readout electronics and the dual-phase detectors. This was in the first liquid argon TPC installation in France and it is still a unique facility, which allowed for a full expertise consolidation on all the aspects of the LAr TPC detector technology.

The R&D related to ProtoDUNE dual-phase/DUNE is also supported since 2015 by the European project **AIDA2020** in the framework of *Working Package 8/ Networking activity 7* (WP8/NA7): Large scale cryogenic liquid detectors.

In 2013 the LBNO collaboration then submitted to the SPSC a proposal for the construction of a full scale prototype demonstrator of the dual-phase liquid argon technology (**LBNO-DEMO, 6x6x6 m^3** active volume) in the CERN North Area. The participation of the IN2P3 groups (APC, IPNL, LAPP, LPHNE, OMEGA) to LBNO-DEMO was reviewed by the IN2P3 Scientific Council of June 2013 (see: document submitted to the CS IN2P3, CS IN2P3 open presentation slides of 28/6/2013) and then supported by the IN2P3 management. The CEA/Irfu participation to LBNO-DEMO was approved in parallel by the CEA/Irfu Scientific Council.

The CERN Research Board approved the LBNO-DEMO experiment as **WA105** in August 2013, under the condition of requiring from the collaboration a Technical Design Report document, which was then submitted to the SPSC Committee in March 2014.

The IN2P3 groups were then approved by IN2P3 to contribute to WA105. They took the responsibility of the following items: the **charge readout electronics**; the **light readout electronics**, the **data acquisition system**, **the motorization and mechanical design of the Charge Readout Planes** (CRP, which support the dual-phase gas detectors and the segmented anode plates performing the charge collection); the **HV feedthrough** for the cathode.

In 2014 the situation evolved very quickly at the international level bringing to a **merging the European and USA efforts in the actual international long-baseline program DUNE/LBNF**. The HEPAP P5 committee reformulated the US roadmap bringing to a redefinition of a US hosted long-baseline program redesigned with the international contribution (P5 Executive Summary, P5 Report, P5 Slides by S. Ritz): the **Long Baseline Neutrino Facility (LBNF).** The US and European Neutrino communities then met and defined common goals at the APPEC International Meeting on Large Neutrino Infrastructures held in Paris in June 2014.

In August 2014 it was created an Interim International Executive Board (IIEB) for LBNF, chaired by the Fermilab Director N. Lockyer and with international membership, in order to gather an international collaboration and write a **Letter Of Intent** (LOI) for the new long-baseline experiment. The experiment was temporary named **ELBNF**. The **IN2P3/CEA groups** actively contributed to the definition of this new experimental program. D.Autiero was appointed as IIEB member from France. The ELBNF LOI was,submitted by the ELBNF proto-collaboration to the Fermilab Physics Advisory Committee in January 2015. **The ENLBF experiment, then renamed as DUNE**, was based on four liquid argon TPC far detector modules of 10 kton active mass, for a total target mass of 40 kton, to be hosted at 1500 m depth at the SURF laboratory in the Homestake mine (1300 km distance from FNAL). The experimental setup was also including a Near Detector and a neutrino beam of 1.2 MW proton beam power, upgradable to 2.4 MW.

The neutrino beam and detector underground infrastructure including the cryostats and cryogenics are in the scope of the **LBNF** project while the ELBNF/**DUNE** collaboration takes care of the Near Detector and of instrumenting the four cryostat with the Far Detectors. The **PIP-II** project takes care of the upgrades needed at Fermilab for the high intensity proton beam source, required to produce the neutrino beam.

The **DUNE collaboration** was then formally formed in March 2015 and passed a **CD1-refresh DOE review** in the summer 2015 with the submission of a Conceptual Design Report (main documents: CDR Vol. 2 Physics, CDR Vol. 3 LBNF, CDR Vol. 4 Far Detectors).

After the consolidation of the DUNE collaboration, the WA105 experiment at CERN, for which a Memorandum of Understanding had been finalized with CERN during 2015, was integrated in the DUNE collaboration since December 2015 as **ProtoDUNE dual-phase** (ProtoDUNE-DP, Coordinators: D. Autiero, T. Hasegawa). The activities of the IN2P3 groups in DUNE/dual-phase ProtoDUNE were then structured in the **IN2P3 Master-Project WA105-DUNE**.

Since its integration in DUNE, ProtoDUNE-DP underwent regular **reviewing and follow-up activities** with both the SPSC and LBNC committees:

SPSC Review 2014 slides SPSC-TDR-004 document, **SPSC Review 2015** slides SPSC-SR-158 document, **SPSC Review 2016** slides SPSC-SR-184 document, **SPSC Review 2017** slides SPSC-SR-206 document, **SPSC Review 2018** slides review document DUNE-doc-8267; **LBNC Review** January 2016, April 2016, June 2016, October 2016, March 2017, June 2017, October 2017, February 2018, May 2018.

Since 2015 the construction of another, **smaller scale dual-phase prototype, (3x1x1 m^3 active volume)** to be installed at CERN in Hall 182, had also been launched, on a shorter time scale than the 6x6x6 prototype, by the groups contributing to WA105/ProtoDUNE dual-phase. Both the 3x1x1 and the 6x6x6 (ProtoDUNE dual-phase) are prototypes supported by the **CERN Neutrino Platform**. The purpose of the 3x1x1 was to build a first prototype of the cryostat with the LNG membrane technology by GTT. This technology was foreseen for LBNO and for the DUNE Far Detector modules. The implication in the 3x1x1 prototype allowed CERN achieving the needed expertise and establishing a collaboration agreement with GTT. The 3x1x1 also represented a first prototyping/integration effort of various detector components to be developed and successively deployed on ProtoDUNE dual-phase. The construction of the 3x1x1 prototype was completed by the fall 2016. The 3x1x1, after the commissioning of its cryogenic system lasting until May 2017, started taking cosmic ray data in June 2017 and was running until November 2017.

On September 1st 2016, the DOE under the Secretary for Science and Energy approved the **CD-3a milestone for LBNF**, paving the way to start ~$300M in construction at far site in FY17

In April 2017 ProtoDUNE dual-phase successfully passed its Technical Design Review scrutinizing the design and production readiness of the various detector elements.

The LBNF project had its groundbreaking ceremony in July 2017. Immediately after the LBNF groundbreaking, the DUNE collaboration started the formation of the **Consortia for the construction of the Far Detector modules**. The Far Detector Consortia are based on the model of the sub-detector collaborations of the LHC experiments. The Consortia have to take care of the design, construction and installation of the Far Detector elements and of the related organization of the involved groups and funding. The current planning of the DUNE collaboration foresees that the first Far Detector module will be built with the single-phase technology while the second Far Detector module will be built with the dual-phase technology.

The DUNE collaboration then formed in August 2017 three specific single-phase Consortia (**APA, Cold Electronics, Photon Detection System**), three specific dual-phase consortia (**CRP, TPC electronics, Photon Detection System**) and three common consortia taking care of the construction of the items for both the single and dual phase detectors (**High Voltage System, Slow Control and Cryogenic Instrumentation, Data Acquisition**).

D. Autiero was appointed leader of the **dual-phase TPC electronics Consortium**, based on a collaboration of institutes from France, Japan and USA. The dual-phase TPC electronics Consortium covers several items going from the analog cryogenic electronics for the charge readout, the timing distribution system, the digital electronics for the charge readout, to the digital electronics for the light readout, which is derived from a similar uTCA design as the one for the charge readout. D. Duchesneau was then appointed as interim leader of the Consortium taking care of the **Charge Readout Planes (CRP)** construction, in which there is as well a strong involvement of IN2P3 (LAPP for the Charge Readout Planes mechanics and hanging system) and CEA/Irfu (LEM and anodes production and QA/QC). The IN2P3 groups involved in the dual-phase TPC electronics consortium are also naturally involved in the Data Acquisition Consortium since all the DAQ front-end is included in the TPC electronics consortium and they have to assure an optimal design and construction of the DAQ back-end which is in the scope of the DAQ Consortium. Similarly, there is an involvement of the IN2P3 groups also in the Photon Detection System. The LBNC meeting of February 2018 carefully scrutinized the first months of activity of the Far Detector Consortia (link).

September 2017 saw the approval of the UK funding (88 M$) for the participation to the LBNF/DUNE/PIP-II projects. In the fall 2017 the DUNE collaboration started the process, based on the Far Detector Consortia organization, to produce by May 2018 a Far Detector **Technical Proposal.** This proposal is including both the single and dual-phase detector module designs. It will be further evolved by April 2019 to a Technical Design Report, containing the full technical details needed to launch the Far Detector construction. Both documents (TP and TDR) contain a detailed description of the design, construction and installation procedures of the far detector modules. The Technical Proposal is mainly focusing on the design aspects. The TDR is expected to be much more detailed and about five times longer than the Technical Proposal. The Technical Proposal is already a document counting in total about 700 pages. It has has been completed on schedule by the Consortia and an ad hoc editorial team and submitted to the LBNC committee in May 2018.

The Technical Proposal was unfortunately not yet public at the time of the editing of this report but it is supposed to become soon public, before the meeting of the CS IN2P3 in June 2018. This issue concerns the some of the hyperlinks already embedded in this report. The Technical proposal is structured in the following way: Volume 1: Executive Summary, Physics Computing and Calibration (about 100 pages); Volume 2: The Single-Phase Far Detector Module Design (about 300 pages); Volume 3: The Dual-Phase Far Detector Module Design (about 300 pages).

An overview of the content of the Technical Proposal given to the LBNC in May 2018 is available here (slides). This presentation (slides), given at the same LBNC meeting, instead **describes the content of the Dual-Phase Far Detector Module Design volume**. The content of this volume has been based on major contributions of the IN2P3 and CEA/Irfu groups.

The DUNE Far Detector **TDR** will also include the experience derived from the operation of the two ProtoDUNE detectors (single and dual-phase ProtoDUNE) at CERN. These two prototypes are currently under construction. ProtoDUNE single-phase is expected to take data with the beam for one month just before Long Shutdown 2 (LS2) and then cosmic ray data during LS2. ProtoDUNE dual-phase is expected to close the detector construction in October 2018. It is then foreseen to base the ProtoDUNE dual-phase operation experience for the TDR only on cosmic rays data taking.

The scope of the two ProtoDUNEs and the kind of running experience in view of the TDR had been discussed by DUNE with CERN directorate and the LBNC in the **ProtoDUNE Goals for CD-2 and CD-3 document**, submitted to CERN in March 2017 (DUNE-doc-2765). The operation experience requested to validate the Far Detector technical design for the TDR was then defined to be based on cosmic rays data taking "*validating the design from the perspective of basic detector performance, this can be achieved with cosmic ray data alone. This is essential from the perspective of establishing the design for the LBNC and DOE reviews*".

The DUNE construction schedule implies that the Far Detector design should be already known now in great details and this if fully reflected in the schedule of the TP and TDR process. The far detector modules design is based on the design of the two ProtoDUNEs, which are expected to be full scale demonstrators of the detector elements foreseen for the Far Detector modules construction.

The IN2P3 groups, including about 30 FTE subdivided in about equal parts among researchers and engineers, since 2015 have been committed to ProtoDUNE dual-phase and more in general to DUNE, providing main hardware contributions and assuming also several coordination roles in the collaboration (going from **physics analysis, computing, detector developments to general coordination**). A list of *past*/currently active **coordination roles in DUNE** covered by IN2P3 researchers is shown below:

- D.Autiero: Member of the DUNE Executive Committee since 2015, Leader of the dual-phase TPC Electronics Consortium, ProtoDUNE dual-phase co-coordinator, Editor of the dual-phase Technical Proposal volume
- J. Dawson: Editor of the Technical Proposal for the dual-phase electronics chapter
- D. Duchesneau: *member of Speakers Committee*, ProtoDUNE dual-phase co-coordinator, technical lead in the dual-phase Photon Detection Consortium, interim leader of the CRP Consortium
- S. Galymov: *Deputy coordinator of the far detector optimization task-force.* Editor of the Technical Proposal for the dual-phase electronics chapter
- Y. Karyotakis: Co-coordinator of joint SP-DP beamline instrumentation WG

- J. Marteau Deputy coordinator of the DUNE DAQ working group
- T. Patzak: *Co-coordinator of long-baseline physics working group*, chair of the DUNE Speakers Committee,
- E. Pennacchio, ProtoDUNE-DP Computing Liaison
- A. Tonazzo *co-coordinator of atmospheric neutrinos working group*

The **IN2P3 hardware contributions to the construction of WA105/ProtoDUNE dual-phase** and consequently, extendable to the Far Detector consortia are listed below:

- APC+OMEGA+LAPP: Light readout electronics
- IPNL: Front-end analog charge readout cryogenic electronics, charge readout digital electronics, DAQ and timing system, DAQ back-end, online computing/storage
- LAPP: Charge Readout Planes hanging system, Charge Readout Planes mechanical frames design, beam instrumentation
- LPNHE Cathode HV feedthrough

The LPNHE group contributed in ProtoDUNE dual-phase to the cathode HV feedthrough, which was already deployed in 2016 on the 3x1x1 prototype, but did not join DUNE and since December 2017 they are no more participating to ProtoDUNE dual-phase.

The IN2P3 groups have been also providing **specific coordination roles** since the start of the WA105 experiment in 2014 until 2017:

- D.Autiero (Chairman of the Technical Board, DP-ProtoDUNE co-coordinator)
- D. Duchesneau: (6x6x6 EHN1 integration WG co-coordinator, DP-ProtoDUNE co-coordinator)
- S. Galymov: Analysis coordinator
- T. Patzak: Chairman of WA105 institutional board
- E. Pennacchio: Software Manager

Since November 2017 the construction of WA105/ProtoDUNE dual-phase is managed by a **Technical Committee** including: D.Autiero (IPNL), Ines Gil-Botella (CIEMAT), D. Duchesneau (LAPP) E. Mazzucato (CEA/Irfu), F. REsnati (CERN).

The French DUNE groups organized, in collaboration with IN2P3, CEA/Irfu and the DUNE management, in January 2018 a meeting (Journée DUNE France) addressing the current and future contributions to DUNE in view of structuring a **IR project** (Infrastructure de Recherche) to fund the DUNE Far Detector construction and possible beam contributions. The Journée DUNE France meeting included a **workshop** open to the French HEP community and an afternoon session more focused on discussions on the planning of future DUNE activities (**Physics, Computing, Electronics/DAQ, LEM detectors, Mechanics, Beam**). A detailed overview of the IN2P3 activities in DUNE, given at the Journée DUNE workshop, can be found in this presentation (slides). Discussions on the possible involvement of the LAL laboratory in DUNE took also place at the Atelier longbaseline neutrinos in January 2018.

In March 2018 DUNE was included in the **2018 French National Research Infrastructures Roadmap** (document).

The **DUNE/LBNF projects are continuing to receive excellent support in the US** from DOE and from the Trump administration, for which DUNE/LBNF is a high priority project (see Science and Technology Highlights in the first year of the Trump administration document). Final funding allocated for FY 2019 (95 M$) exceeded expectations and the budget recommended by the House of Representatives/Senate committees (which was around 80M$, see Ed Blucher slides on the DUNE status shown at the May 2018 DUNE collaboration meeting).

Section 2: DUNE Physics

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.

A detailed up-to-date description of the DUNE physics potential is contained in Volume 1 of the Far Detector Technical Proposal. A few points are summarized in this section.

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 Detector measurements for the fluxes determination and systematics. The Near Detector 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 $\nu_\mu \rightarrow \nu_e$ 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, providing a possible explanation for the matter-antimatter asymmetry in the universe

– determining the neutrino mass ordering (the sign of Δm^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 ve flux from possible core-collapse supernova within our galaxy

The DUNE sensitivity depends of course on the detector and beam **staging strategy,** which is described below, and on the systematic uncertainties assessed with the Near Detector at a level to be kept smaller than the Far Detector statistical uncertainties:

- Year 1: 20 kt far detector fiducial mass, 1.07 MW 80 GeV proton beam with 1.47×10^{21} protons-on-target per year and initial near detector constraints;
- Year 2: Addition of the third 10 kt far detector module, for a total far detector fiducial mass of 30 kt;
- Year 4: Addition of the fourth 10 kt far detector module, for a total far detector fiducial mass of 40 kt, and improved systematic constraints from near detector analysis;
- Year 7: Upgrade of beam power to 2.14 MW for a 80 GeV proton beam.

From these staging assumptions follow the sensitivity curves reported below extracted from the Far Detector Technical Proposal, and a table of physics milestones, computed by assuming normal hierarchy and oscillation parameters from the best fit NuFit 2016 values:

Physics milestone	Exposure (kt · MW · year)	Exposure (years)
1° θ_{23} resolution ($\theta_{23} = 42^\circ$)	29	1
CPV at 3σ ($\delta_{CP} = -\pi/2$)	77	2
MH at 5σ (worst point)	209	5
10° δ_{CP} resolution ($\delta_{CP} = 0$)	252	5
CPV at 5σ ($\delta_{CP} = -\pi/2$)	253	5
CPV at 5σ 50% of δ_{CP}	483	8
CPV at 3σ 75% of δ_{CP}	775	12
Reactor θ_{13} resolution ($\sin^2 2\theta_{13} = 0.084 \pm 0.003$)	857	13

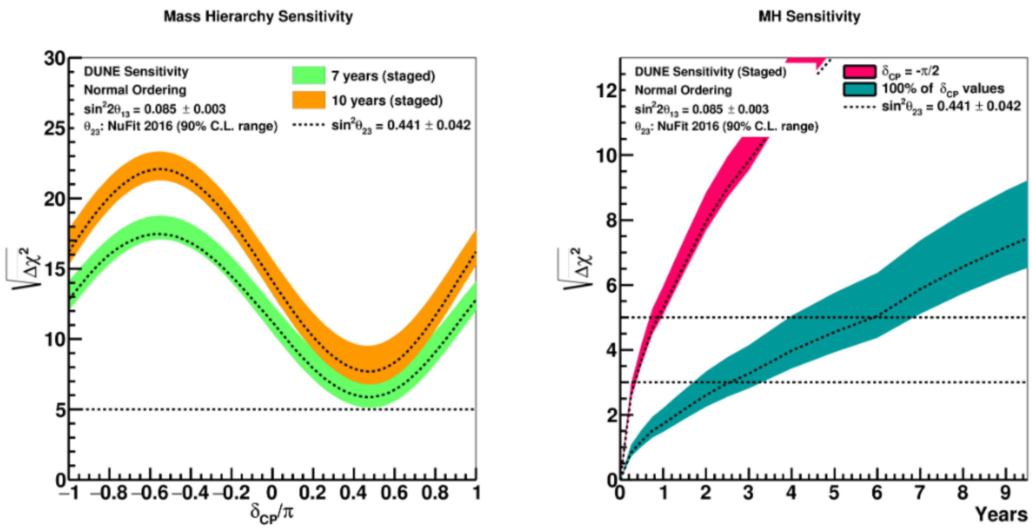

Figure 2.1: The square root of the mass hierarchy discrimination metric $\Delta\chi^2$ is plotted as a function of the unknown value of $\delta_{\rm CP}$ for exposures of seven and ten years (left). The minimum significance — the lowest point on the curve on the left — with which the mass hierarchy can be determined for all values of $\delta_{\rm CP}$ and the significance for a true value of $\delta_{\rm CP}$ =-$\pi/2$ as a function of years of running under the staging plan described in the text (right). The shaded regions represent the range in sensitivity corresponding to different true values of θ_{23}.

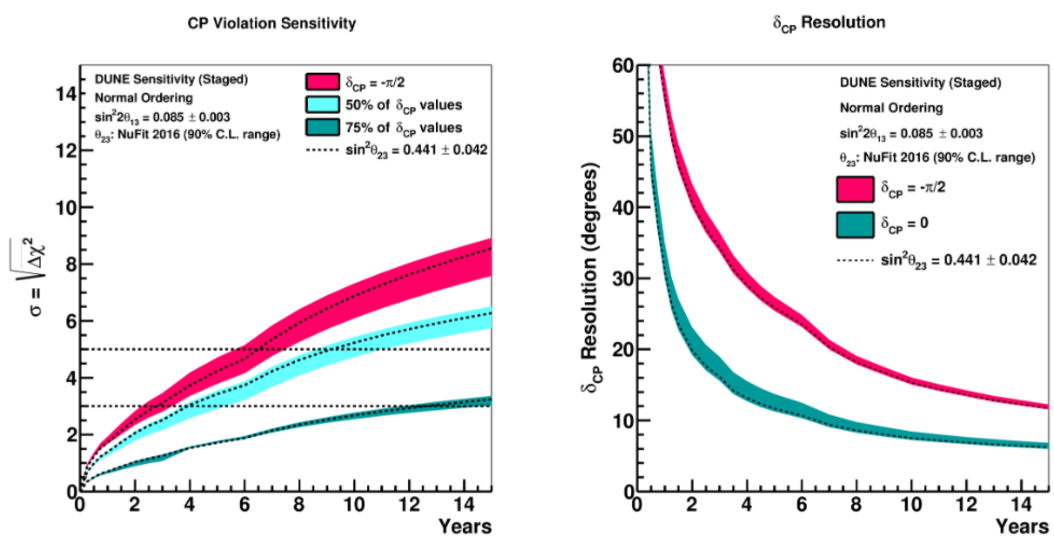

Figure 2.2: The significance with which CP violation can be determined for 75% and 50% of $\delta_{\rm CP}$ values and for $\delta_{\rm CP}$ =-$\pi/2$ (left) and the expected 1σ resolution (right) as a function of exposure in years using the proposed staging plan outlined in this chapter. The shaded regions represent the range in sensitivity corresponding to different true values of θ_{23}. The plots assume normal mass hierarchy.

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 (see Section 1). The IN2P3 groups are planning to contribute to several aspects of the DUNE Far Detector online (trigger definition in the DAQ for SNa burst neutrinos and other event flows) and offline analysis concerning:

- 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 n-nbar oscillations
- Selection of SNa 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. Currently two analysis thesis are in progress at APC and IPNL on aspects related to the dual-phase Far Detector reconstruction and physics sensitivity: one addressing electron identification and the reconstruction of electromagnetic showers and the other one addressing systematics for the CP violation measurement and the reconstruction of the neutrino energy. Other aspects which are in the process of being developed concern **nuclear effects** in the neutrino energy reconstruction and in the interaction of SNa neutrinos (for which there is a strong tradition in the French nuclear theory community, and tau identification and related systematics to the CP measurement. The strong implications in the Electronics, Photon Detection and DAQ Consortia imply a commitment on the development of the **online processing algorithms** for the definition of the events trigger and selection based on the charge and light readout information. A particularly challenging aspect for the DAQ system and the online analysis concerns the **selection of SNa burst neutrinos**, which typically span over a time window of 10 seconds and the rejection of fake triggers related to radiological activity. The dual-phase design allows also operating at low detection thresholds and detecting the nuclear de-excitation photons from the potassium and chlorine excited states following the SNa neutrino interactions on Ar nuclei. The detection of these photons opens the way to disentangling neutrino from anti-neutrino interactions and neutral current interactions. The search **for n-nbar oscillations** and the related nuclear effects is also an interesting subject for DUNE, recently a collaboration has started with the French nuclear theorists historically working on this subject and now connected to DUNE, as J.M. Richard at IPNL.

Section 3: Status of IN2P3 hardware contributions and R&D activities

A detailed summary of the involvement of the IN2P3 groups on the hardware contributions has been provided in **Section 1 and via the related links accessible in the text**. These contributions are based on the R&D activities, which have been culminating with the construction of ProtoDUNE dual-phase. They included as well a preparatory phase with dedicated tests and development activities as well as the construction and operation of the 3x1x1 prototype. The current involvement in the Far Detector Consortia activities is reflecting the activities of the groups in ProtoDUNE dual-phase and it is described in details in the dual-phase Far Detector Technical Proposal. **A presentation summarizing the status of**

ProtoDUNE dual-phase and the operation experience from the 3x1x1 prototype has been given at the May 2018 LBNC meeting (slides).

The 3x1x1 prototype has been operating during summer 2017. The detector demonstrated the dual-phase operation over a surface of 3 m^2, however its running conditions were limited to the maximum HV which could be applied to the extraction grid before sparking occurred. This was -5kV instead of -6.8 kV. The maximum voltage applicable to the grid affects also the voltages applicable to the two LEM sides (and consequently their gain), by taking into account the constraints that the anode should be at ground and the one on collection field which should be established in between the top face of the LEM and the anode. -6.8 kV is the potential to be applied to the extraction grid, which would be necessary in order to set the nominal values of the extraction, amplification and collection fields. This HV issue on the grid was traced back, after dedicated tests and detector inspection, to a faulty HV connector and to a short occurring in between the LEM and a block of grid wires not correctly tensioned and sagging in the direction of the LEMs plane. The Charge Readout Plane design for the 3x1x1, which also showed some non-planarity issues, was different, due to its earlier design, from the one specifically designed in 2016-2017 for ProtoDUNE dual-phase, where these HV, planarity and grid issues should be absent. In addition, a cold-box setup has been built by CERN in order to perform HV tests of the ProtoDUNE dual-phase CRPs, currently under construction, before they are installed in the detector cryostat. Also the design of the LEM for ProtoDUNE dual-phase has been improved with respect to the one of the LEM of the 3x1x1 by including larger guard rings at the borders in order to achieve in a stable way higher operating voltages (up to 3.5 kV). This new design has been systematically tested and compared to the old one by exploiting a high pressure (3.3) bar gas chamber built by CEA/Irfu. Other operation aspects of the 3x1x1 including the cryostat and cryogenics, liquid argon purity, very high voltage, charge readout electronics and DAQ and the photon detection system have been fully satisfactory. The detector has been acquiring more than 400K cosmic events. A detailed paper (60 pages) on the 3x1x1 construction and operation is in the process of being submitted.

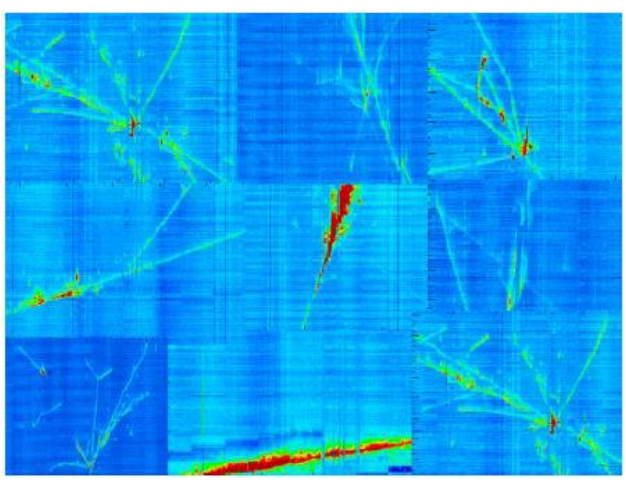

Figure 3.1 A compilation of raw data cosmic ray event diplays acquired with the 3x1x1 prototype

Aspects of ProtoDUNE dual-phase design are described in details in the Technical Proposal and in the presentation of the Technical proposal given at the LBNC May 2018 meeting (slides). ProtoDUNE dual-phase is in construction with the goal of closing the Temporary Construction Opening of the Cryostat in October 2018. The field cage has been already installed, see the picture below. The CRP planes are being assembled in the clean room installed Hall 185, where the ICRAUS detector had been refurbished. The readout electronics and DAQ system have been already produced as well as the 36 photomultipliers of the light readout.

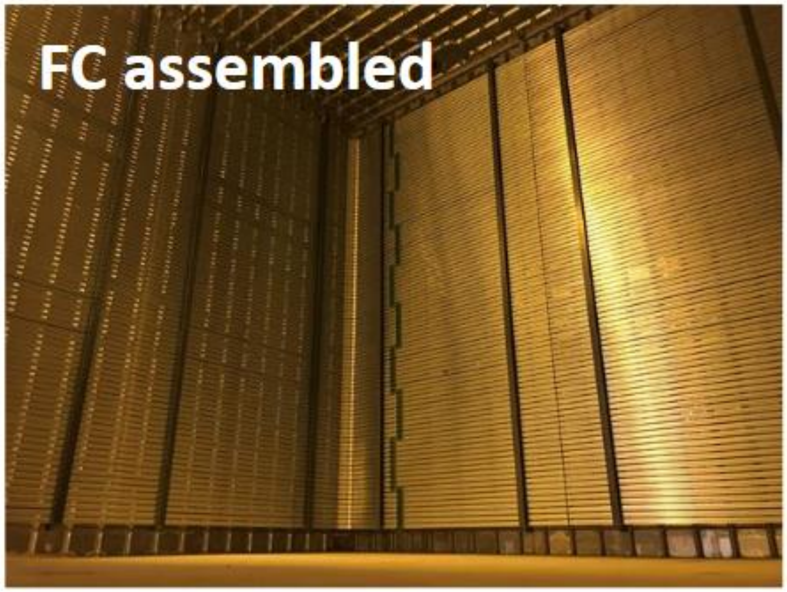

Figure 3.2 Field Cage of ProtoDUNE dual-phase after the completion of its installation inside the cryostat

The CRP design of ProtoDUNE dual-phase, worked out by LAPP, is the outcome of a long process aimed at guaranteeing planarity conditions of +- 0.5 mm over a surface of 3m^2, independently on gravity sagging effects and on possible deformations occurring at cold due to the temperature gradient present in the gas phase and differential effects in the thermal contraction. This design was accurately studied with simulations and characterized with cold bath tests coupled to photogrammetry measurements. In order to cope with the planarity requirements the CRP structure is made of a main frame built in INVAR (which has little thermal contraction effects and it is not affected by the temperature gradient in the gas), coupled to a G10 frame. The G10 frame has the same thermal contraction effects as the LEM-anode sandwiches which supports. The G10 frame is then free to shrink horizontally with respect to the INVAR frames which is supporting it from the top. A set of decoupling mechanisms allow for the horizontal relative movement of the G10 frame with respect to the INVAR frame while keeping the its vertical position precisely constrained. The CRP should be also precisely positioned at the interface in between the gas and the liquid with the requirement of having the extraction grid immersed and the LEM dry (the grid-LEM gap is 1 cm). Each CRP is suspended with 3 adjustable metallic wires from the roof of the cryostat. LAPP also designed the CRP hanging system, stepping motors and related feedthroughs and all the tooling for the CRP assembly facility, which is operated at CERN in the clean room of hall 185 (slides 9-16). A the 10 kton module is expected to include 80 CRP based on the ProtoDUNE dual-phase design, covering a detection surface of 60x12 m^2

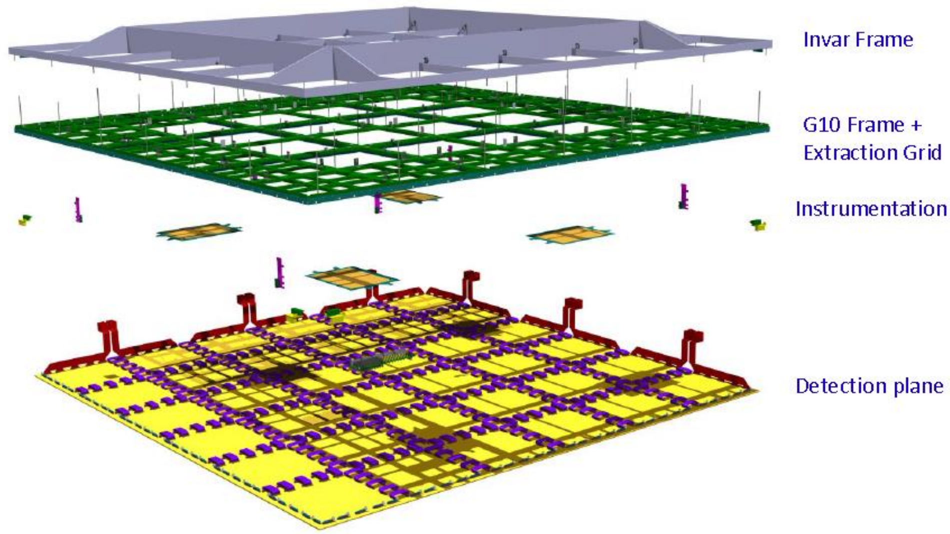

Figure 3.3 Design of the 3x3 m^2 Charge Readout Plane of ProtoDUNE dual-phase

The charge readout electronics for ProtoDUNE dual-phase (cryogenic analog electronics, digital electronics, timing system and DAQ system) is the outcome of an R&D activity started at IPNL in 2006. The main aspect of the development concerned:

a) the design of a cryogenic analog ASIC, optimized since 2012 for the dual-phase dynamic range, and of the related analog front-end cards; b) the design of the AMC digitization cards in uTCA standard with 10 Gbit/s connectivity; c) the design of the timing/trigger system based on the White Rabbit standard, d) the design of the DAQ back-end and online processing system.

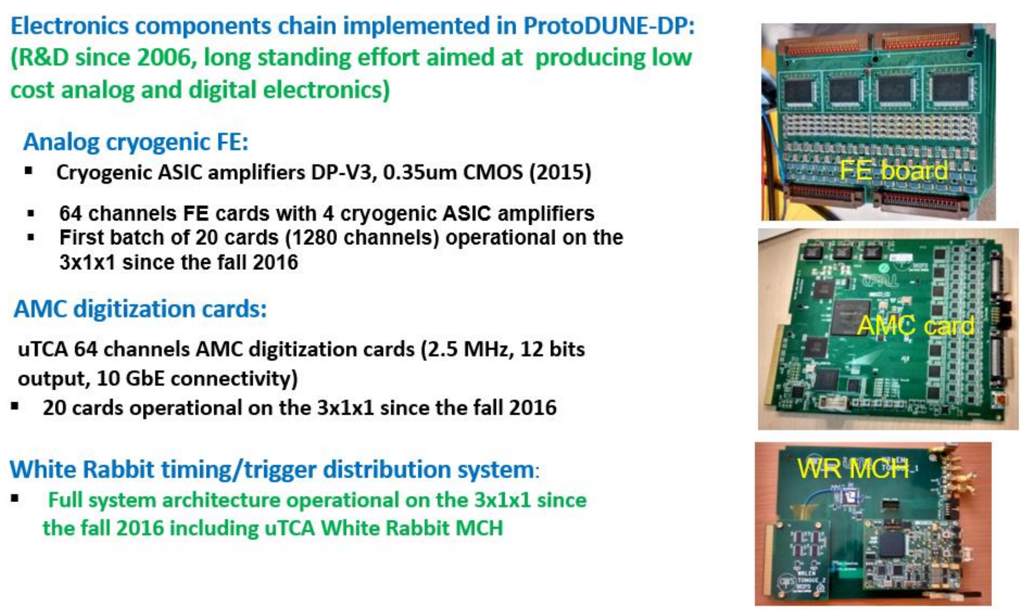

Figure 3.4 Components of the ProtoDUNE dual-phase charge readout and timing system

A feature of the dual-phase design is that all the electronics is completely accessible during detector operation. The cryogenic analog front-end cards are plugged at the bottom of specific penetrations (the Signal Feedthrough Chimneys), which are tight with respect to the cryostat inner volume containing pure LAr. The chimneys allow positioning the FE cards at cold (110 K) and at a short distance (~50 cm) with respect to the CRP. The analog FE cards can be then extracted from the chimneys and replaced, without contaminating the detector, by using long blades sliding inside the chimneys. The digital electronics is at warm, sitting on the cryostat roof. It is completely decoupled and shielded with respect to the analog electronics and it benefits of a high performance network architecture used in the telecommunication industry such as uTCA. This allows reducing costs and benefiting of the technological evolution of the market, for instance moving from the 10 Gb/s to the 40 Gb/s standard, as it is presently happening. Both the analog FE cards and the digital cards in the uTCA crates have 64 channels/card. This architecture results in a very compact and cheap readout system. Chimneys have in ProtoDUNE dual-phase/DUNE a signal granularity of 640 channels per chimney. Each chimney is coupled to a corresponding uTCA crate. A pre-production of 20 FE cards and 20 digital AMC cards for 1280 channels has been successfully operational on the 3x1x1 detector since the fall of 2016 together with the complete timing and trigger system based on White Rabbit.

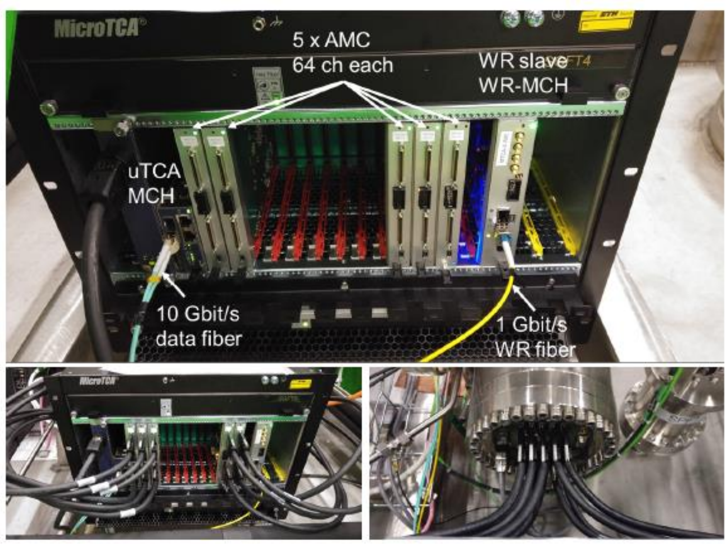

Figure 3.5 Charge readout uTCA digital electronics implemented on the 3x1x1 prototype

ProtoDUNE dual-phase counts 7680 charge readout channels, which have been already produced. It represents 1/20 of a Far Detector dual-phase module, which will imply the deployment of 240 uTCA crates hosting 2400 AMC digitization cards (for more details see slides 17-24). In addition to the charge readout electronics and timing system, IPNL also provided the design of the online processing and storage farm of the DAQ back-end for protoDUNE dual-phase. This system has been designed in order to cope with a data bandwidth of 20 GB/s. A reduced version of this system was also operating on the 3x1x1 detector and allowed optimizing the final design and the software. The DAQ aspects implemented for ProtoDUNE-DP, also in view of their implementation for the 10 kton dual-phase detector design are described in details in the following documents (document, slides).

The **ProtoDUNE dual-phase light readout digital electronics** (provided by APC in collaboration with LAPP and OMEGA) is also based on the uTCA form factor. This readout electronics is integrated in a similar design as the charge readout digital electronics, including the White Rabbit timing distribution system and a similar interface to the DAQ back-end and it is part of a common IN2P3 design effort. The light readout digitization cards are derived from the charge readout cards design with a mezzanine FE stage incorporating the CATIROC chip for fast triggering (see slides 25-26). This digitization system will be used to read an array of 36 cryogenic photomultipliers in ProtoDUNE dual-phase, which could become 720 in the DUNE 10 kton far detector module, by assuming the same photo-coverage density as in ProtoDUNE dual-phase (1 PMT/m^2). The DUNE light readout electronics implies the deployment of 5 uTCA crates hosting 45 light digitization AMC cards. The IN2P3 groups are also strongly involved in the light readout simulations for both ProtoDUNE dual-phase and DUNE.

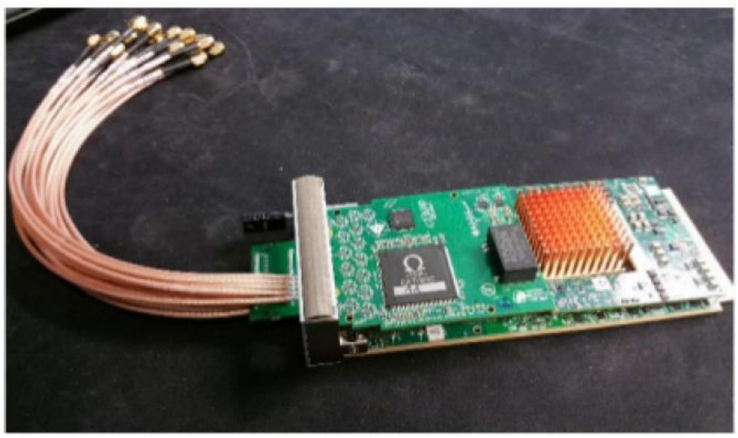

Figure 3.6 Light Readout uTCA digitizer AMC card

Section 4: Future IN2P3 construction activities foreseen for DUNE

The IN2P3 groups have provided main contributions to ProtoDUNE dual-phase on the electronics, DAQ and detector mechanics, as described in Sections 1 and 3. The design of the 10 kton dual-phase far detector is relaying on the same detector elements to be tested in ProtoDUNE dual-phase. Differently with respect to some aspects of the single-phase design, there are no internal competing design options to be assessed on the TDR time scale. It is natural to assume that the IN2P3 groups could provide main **contributions to the dual-phase Far Detector construction**, based on the expertise and the leading contributions that they have been providing so far. The funding model which is being developed is based on a IR project with funding availability around 2021/2, which is now possible given the inclusion of DUNE in the French Roadmap of research infrastructures. There are about 30 FTE actually working on the project about evenly shared among physicists and engineers. This IN2P3 community is foreseen to be strengthened by increasing the size of the actual groups and by having new groups joining the project (see Section 6). The IN2P3 groups have a strong involvement in the **Far Detector Consortia**, with also leadership positions. The IN2P3 groups are in a very good position, based on their involvement and expertise, to propose coherent and very visible contributions to DUNE. The Consortia have been producing by May 2018 a Far Detector Technical Proposal. This document is now expected to evolve to the **Technical Design Report** scale on the time scale of one year. The TDR will be incorporating as well full costing, installation procedures and, last but not least, the operation experience of the two ProtoDUNEs. This is meant to provide a final validation for both the single and dual-phase designs in view of the 10 kton detector modules construction. An overview of the Far Detector Technical Proposal content for the dual-phase design module can be seen in this presentation (slides).

The R&D on the **dual-phase LAr TPC readout electronics and DAQ** is a long-standing investment, which started in 2006. It already involved technical and scientific manpower for a total amount of man-years corresponding to a good fraction of the possible hardware investment which would be needed to fully equip a 10 kton module. The digital electronics is a common IN2P3 project covering both charge and light readout. The effort covers as well the analog electronics and an integrated timing and DAQ environment. The design, which was aiming since the beginning at the implementation on large detectors, has now reached full maturity. A sub-set of the system has been successfully operating since the Fall 2016 on the 3x1x1 detector. Costs and full system aspects are well known from the massive productions, which were performed in order to equip ProtoDUNE dual-phase, and from the corresponding QA/QC and integration work.

A presentation of the **dual-phase TPC Electronics consortium** activities to the LBNC meeting of February 2018 can be found here (slides). The LBNC committee acknowledged the validity of the approach followed so far, as written in the Committee report: "*The DUNE DP Electronics Consortium takes advantage of considerable R&D work and experience going back more than a decade. The protoDUNE DP Electronics system was constructed in 2016 and has been successfully utilized in the 3x1x1 detector. The baseline design for DUNE DP electronics is well defined. We commend the work done to date and the successful establishment of this consortium. This effort is well positioned to produce a detailed TDR. We look forward to results from protoDUNE DP* ". The implementation of the 10 kton Far Detector will be a complex enterprise implying an extrapolation by a factor 20 of the work which has been provided for the system produced for ProtoDUNE dual-phase. There is widely room for new collaborators on many aspects in order to bring to the successful construction and operation this large system based on an already sound design.

The dual-phase electronics consortium also implies a sophisticated **mechanics contribution** on the construction of the signal feedthrough chimneys, which are precise mechanics penetrations with UHV specifications. The readout electronics implies as well the DAQ related development of the **online processing system and algorithms**, for the definitions of triggers and events streams selections. This system, which will have to deal with a huge data flow, will also be a challenging and stimulating enterprise from the point of view of DAQ, computing and physics analysis. The IN2P3 groups have also a natural involvement in **the Photon Detection System and DAQ Consortia** where they are actively contributing.

The activity on the **CRP mechanics and hanging system** was started in 2014 with the TDR design of WA105/ProtoDUNE dual-phase. This contribution implies very peculiar R&D and design aspects and it has strategic interconnections with the CEA/Irfu activity on the LEM and anodes design and production chain for ProtoDUNE dual-phase and for DUNE. Both activities refer to the **CRP consortium**. The contributions provided so far brought to the development of the CRP mechanical structure design, of its hanging system and of all the tooling, assembly procedures, QA/QC chain, transportation and installation procedures for the CRP modules. The CRP 3x3 m^2 modules developed for DUNE are the same foreseen for the dual-phase 10 kton module, which would require the installation of 80 CRPs. A first model of the CRP production facility has been put in place at CERN in the large clean room of Hall 185 and it has also been benefiting of the recent addition of the cold-box in building 182 for the CRP tests. Full details on the CRP design and organization in view of the 10 kton module construction are provided in the Technical Proposal Volume 3 (link) and in the corresponding overview presentation (slides). The IN2P3 groups have as well a coherent planning in order to have a strong impact on the **Physics Analysis, software, simulation and reconstruction developments and computing** as described in **Sections 2 and 5** of this document.

Section 5: Planning and contributions to DUNE Computing

The following table summarizes the main parameters needed to evaluate the event size for a DUNE 10kton Single Phase and Dual Phase Far Detector module:

	Dual Phase 10 kton	Single Phase 10kton
Number of TPC channels	153600	384000
DAQ sample rate	2.5 MHz	2 MHz
Drift distance	12 m	3.6 m
Drift time	7.5 ms	2.25 ms
# Drift/readout	(continuous streaming)	2.4
Samples/readout	20000	10800
Pitch size	3.125 mm	5 mm
Event size	**4.2 GB (1 drift window)**	**6.2 GB**

For a 10kton SP module, 384000 channels (pitch=5mm) and 10800 samples/readout bring to an event size of ~6GB; for a 10kton DP module, 153600 channels (pitch=3.2 mm) and 20000 samples/readout bring to an event of 4.2GB.)

In the dual-phase design, due to a good S/N ratio (the RMS noise is at the level of 1-2 ADC counts) lossless compression is applied at the front-end allowing compressing the readout data flow by a factor 10 , bringing the event size to 0.42 GB. Recording the entire module drift window can be considered a pessimistic figure, since events are normally contained in smaller detector regions. A far detector module can be treated as 20 smaller detectors (with similar number of readout channels to the ProtoDUNE dual-phase prototype currently under construction at CERN), running in parallel, and each one defining a Region of Interest (ROI). For beam or cosmic events, it is possible to record only the interesting ROI(s) with the compressed size of a single ROI being 22 MB.

A 10Kton module will have to deal with events originated for beam interaction, cosmics and atmospheric and supernovae candidates (SNB). Before presenting the anticipated data volume, it is important to point out that it is assumed that the DAQ system back-end will be constituted by a cluster of PCs allowing for the search of charge triggers and event building. This cluster of PC should allow defining different output streams: beam, cosmic, SNB. Beam and cosmic events.

The anticipated annual, uncompressed data volume for a 10kton SP are:

Event type	Data Volume SP (PB/year)	Assumptions
Beam interaction	0.03	800 beam+ 800 rock muons, 10Mev threshold in coincidence with beam time;
Cosmics and atmospherics	10	10MeV threshold
Supernova candidates	0.5	30 seconds full readout, on average 1 fake SN trigger/month

Lossless compression will be applied which is expected to provide as much as 4x reduction in data volume

The anticipated annual, uncompressed data volume for a 10kton DP are:

Event type	Data Volume DP (PB/year)	Assumptions
Beam interaction	0.007	800 beam+ 800 rock muons, this becomes 700 GB/year if just 2 ROIs/event are dumped on disk
Cosmics and atmospherics	2.33	this becomes 233 TB/year if just 2 ROIs/event are dumped on disk
Supernova candidates	0.06	10 seconds full readout, all ROIs are dumped on disk

Lossless compression will be applied which is expected to provide as much as 10x reduction in data volume. The beam neutrino events produce in DUNE a tiny amount of data if compared to other sources, the largest amount coming from cosmics. The data volume to be stored on disk for each 10kton module is of the order of:

- 300 TB/year for one DP module, assuming a compression factor of 10 and to dump just 2ROIs on disk
- 2.5PB/year for one SP module, assuming a compression factor of 4. This number can be substantially reduced by applying zero suppression. This aspect is under study.

The DUNE computing model is a work in progress, since major advances will take place over the next year on several fronts. Anyway, it is clear that DUNE is planning to use the HEP infrastructure already developed. The DUNE collaborations is planning to have the primary raw data repository at Fermilab, with derived samples and processing distributed among collaborating data centers. The volume of SNB data candidate data and cosmics data are vastly larger than the beam neutrino events, so it is useful to handle the SNB and cosmic data stream separately from beam data. In particular, having a substantially more modest data stream containing beam neutrino will make processing and distribution of these data a lot quicker and more efficient

Data processing is being designed to run on HEP grid resources: the first pass reconstruction can be handled at FERMILAB; the reprocessing, it will be necessary to repeat processing to use more refined calibration data, to improve the reconstruction with new algorithms developed from first analysis on raw data. This reprocessing will take place at Fermilab and other participating institutions For the two ProtoDUNEs, raw data will be stored at Fermilab and at CERN; in particular during the “ProtoDUNE DP-SP Joint Data Challenge” that took place in April 2018, the integration of CERN and Fermilab storage and CPU resources has been successfully tested. The collaboration is now extending this integration for the ProtoDUNEs and DUNE to other institutions who have access to substantial storage and CPU resources.

Several Monte Carlo simulation campaigns will be needed as well in DUNE; the size of the simulation will be an order of magnitude larger that the number of foreseen beam events. Contributions to this effort can be distributed across the collaboration and grid resources worldwide. The software used for simulation and reconstruction is based on LArSoft, a toolkit that provides a software infrastructure and algorithms for the simulation, reconstruction and analysis of events in Liquid Argon Time Projection Chambers. The reconstruction time per event has been evaluated for ProtoDUNE Monte Carlo events. Hit finding and shaping is found to take around 2 minutes/event with a 2 GB memory footprint; Higher-level pattern recognition occupies 10-20 minutes/event with a 4-6 GB memory footprint. This time will be probably higher on real data; the possibility to run reconstruction on real data will be fundamental for the testing and improving the algorithms. On the other hand, ProtoDUNE represents only 4-5% of the final volume of the far detectors, and computing technologies are evolving fast: the optimization of reconstruction algorithms also taking into account the new architectures is needed and this will be a challenging task for the future years.

The IN2P3 groups rely on the CCIN2P3 is already constantly contributing to ProtoDUNE dual-phase since 2013: all collaborators in WA105/ProtoDUNE could have an account at CCIN2P3, where disk (and tape) space, and CPU resources are provided. Before LArSoft, the code used for simulation and reconstruction was based on Qscan, a general LArTPC software framework, and optimized for Dual Phase, in particular for ProtoDUNE. This code, much simpler and faster than LArSoft, has been used to characterize the

6x6x6 by running Monte Carlo simulation, and it is at the base of the ProtoDUNE dual-phase online processing, where fast data analysis is needed. WA105Soft code development is centralized at CCIN2P3, and an SVN server is also available (everyone in the Collaboration can have access): a complete working environment has been created, and CCIN2P3 is playing a major role in the ProtoDUNE dual-phase software activities. LArSoft was also installed in 2015. This local installation at CCINP23 has been used in particular to develop the code to integrate the dual phase geometry in LArSoft and for the activity of the detector optimization task force (TF1) of DUNE. Since June 2018 CCIN2P3 will provide extra resources for disk space and CPU for ProtoDUNE dual-phase and the DUNE developments.

Possible long term contributions from CCIN2P3 to DUNE can be identified as following:

- CCIN2P3 can become a Tier-1 to host the raw data, and assure their reprocessing. CCIN2P3 (and other institutions in France) can also be a Tier-2 center
- Contributions to massive Monte Carlo productions are expected as well
- In general, by allowing the creation of an account to all collaborators, CCIN2P3 can provide a working environment (as it is now) to allow code development and data analysis
- For sure one or more databases will be necessary for handling information about the hardware productions (related to the construction activities carried on by the IN2P3 groups and for the experimental conditions, calibration data. CCIN2P3 can host a replica of these databases

The IN2P3 groups are in the process of elaborating a DUNE computing project, in collaboration with CCIN2P3, which will ensure a sound contribution to the DUNE simulation and analysis and a full support for the developments of the French DUNE community including the IN2P3 groups and CEA/Irfu.

Section 6: Extension of the IN2P3 participation to DUNE

Following recent evolutions in the project such as: the LBNF groundbreaking in July 2017; the creation of the Consortia for the Far Detector construction in DUNE and the inscription of DUNE to the National Roadmap of Research Infrastructures in 2018, the IN2P3 participation to DUNE is expected to increase and to be further strengthened. New people and groups are expect to join in addition to those in the IN2P3 and CEA groups, already historically involved in WA105/ProtoDUNE dual-phase and DUNE.

First, the LAL laboratory has shown a strong interest for DUNE. LAL is the phase of joining the project. Contacts among the physicists already involved in DUNE, LAL physicists and the Direction of LAL have been systematically developing since the fall 2017. These discussions have been consolidating at the "Journée DUNE France" and at the "Atelier Long-Baseline Neutrinos", respectively held at LPNHE and at LAL in January 2018. LAL has definitively matured the willingness to join the IR project for DUNE. Several areas of contributions on the dual-phase Far Detector construction are in the process of being discussed with the LAL physicists and technical services. These areas are covering mechanics for the feedthrough chimneys, electronics and the DAQ system. LAL is also interested in providing a strong contribution to the proton source for the DUNE beam via the PIP-II project together with IPNO and CEA. This contribution being planned on the neutrino beam, which is a crucial aspect for the DUNE sensitivity, is shortly mentioned in Section 7. The LAL participation to DUNE/PIP-II is foreseen to be formally discussed at a joint IPNO-LAL Scientific Council in the fall 2018.

Section 7: Interests in contributing to the beam PIP-II program

IN2P3 and CEA are interested in contributing, in addition to the Far Detector construction, also to the **neutrino beam** via the **Fermilab PIP-II program** (link). The Accelerator divisions of IPNO and LAL are discussing possible contributions to the PIP-II accelerator project and more specifically on the second Spoke **section of the superconducting linac (SSR2). The expertise and experience of IPNO and LAL in the** conception of a fully equipped cryomodules (including superconducting cavity, power coupler and frequency tuning system) is known worldwide through several contributions in national, European and international projects like cryomodule series production (Spiral2, ESS), power coupler assembly and processing (XFEL) and cryomodule design and prototyping (SPL, MYRRHA). IPNO and LAL have all the expertise, the experience and the technological facilities required to contribute significantly to PIP-II SSR2 cryomodules. However, RF and mechanical engineers with SRF expertise are at this moment and till mid 2019 totally invested in the series production of ESS cryomodules. Additionally, IPNO have signed a 2-years R&D contract with SCK-CEN for the design and the production of a prototype cryomodule (2017-2019) for MYRRHA project and will be involved in the commissioning of Spiral2 superconducting linac in the coming months. At the sight of the current availability of the SRF technical staff of IPNO and LAL, a significant contribution as the mechanical design and prototyping of the SSR2 cavity, power coupler and frequency tuning system could not be initiated before at least 12 months. However, collaboration in the framework of a R&D program (to be defined) could be started immediately. This program, which might contain activities on cavity surface preparation and treatment to improve current performances (high gradients and high quality factors), design activities on power couplers or cold tuning system, would be very valuable to PIP-II

Section 8: Conclusions

Given their long-standing involvement and expertise in the LAr detector R&D, in neutrino physics and the participation "ab initio" to the experimental program that brought to the current definition of DUNE, the IN2P3 groups are in excellent conditions of providing main contributions to DUNE. The IN2P3 groups have already a strong visibility and level of commitment in the DUNE collaboration. This opportunity is coming from a systematic involvement in the R&D activities, physics and experiment planning, which is now dating up to 12 years ago. The construction contributions via the Far Detector Consortia can follow the current hardware commitments and expertise achieved with ProtoDUNE dual-phase. They can be funded via an IR project, given the fact that DUNE is now included in the French Roadmap for Research Infrastructures. The IN2P3 contribution is in the process of being strengthened by new groups which will join the program working on the detector and on the beam and by the reinforcement of the existing groups. The IN2P3 community is also planning to have an important impact on the physics analysis, software developments and computing (thanks to the collaboration with CCIN2P3).