IN2P3 perspectives for DUNE

Neutrino oscillations provide today the only experimental evidence of physics beyond the Standard Model. The smallness of neutrino masses, the study and interpretation of the neutrino mixing matrix and the pattern of neutrino masses represent a natural window on physics at the Grand Unification scale.

Given the magnitude of the θ_{13} mixing angle, fundamental measurements such as the determination of the neutrino mass hierarchy and the search for CP violation in the neutrino sector, can be addressed in the following years by long-baseline neutrino oscillation experiments with conventional muonic neutrino beams of very high intensity. Beams should reach at the MW scale in terms of power of the proton beams needed to generate neutrinos. The experiments make use of near detectors at short-baseline to determine the beam composition, flux and cross-sections, and very massive far detectors at long-baseline to measure the disappearance of ν_μ, appearance of ν_e and potentially ν_τ appearance. These measurements can be repeated in the neutrino and anti-neutrino mode of the beam. The measurement of the asymmetry of $\nu_\mu \rightarrow \nu_e$ oscillation probabilities for neutrinos and anti-neutrinos and its dependence on the neutrino energy is sensitive to the mass hierarchy and the CP violation phase δ.

The necessity to identify in the final state of neutrino interactions electrons (and possibly taus) and to reconstruct the oscillations patterns as a function of the neutrino energy requires very fine grained far detectors with good energy resolution. At the same time far detectors should ensure target mass for neutrinos at the level of multi-10kton scale in order to collect enough statistics. The Liquid Argon Time Projection Chamber (LAr TPC) detector technology fully satisfies these apparently conflicting requirements. The LAr TPC is a modern version of bubble chamber detectors, which were at the basis of main past discoveries in neutrino physics. The LAr TPC ensures similar reconstruction quality of the neutrino final states, as in old bubble chambers, but with fast electronic readout and modularity appropriate for scaling to very large size detectors.

At the time being, the only financed future long-baseline experiment is DUNE. DUNE is hosted by the Long Baseline Neutrino Facility (LBNF) in the USA. With a baseline of 1300 km DUNE is conceived to be highly sensitive to matter effects which are at the basis of the mass hierarchy determination. In this configuration, Mass Hierarchy and δ_{CP} effects can be easily disentangled. At the far site, four modules of LAr TPC, each one with a 10kton fiducial mass, will provide fine-grained tracking giving excellent identification of final state products and hence neutrino flavor and energy determination. The first two modules are planned to start operating with the LBNF neutrino beam since 2026. The program is then staged foreseeing progressively the inclusion of the other detector modules and the increase of the beam intensity which will start with *O*(MW) power.

The DUNE experiment is based on a worldwide effort, obtained by merging in 2014 the European design study LAGUNA-LBNO and the former USA long-baseline project LBNE. European physicists, with a strong French component, gave so far major contributions to the design and optimization of the physics reach of DUNE and of its Far Detector design. A French physicist was involved in 2014 in the Interim International Executive Board (IIEB), which designed the current configuration of the experiment. This includes four 10kton LAr far detector modules, a fine gained near detector to control beam systematics and the multi-MW high intensity neutrino beam. The IIEB produced at the end of 2014 the E-LBNF Letter of Intention, which gathered the DUNE collaboration. The collaboration was then formally created in 2015. The French components of DUNE includes at moment the following IN2P3 groups: APC, I2PI, LAPP, LAL, LPSC and the CEA/Irfu group. The DUNE collaboration produced in 2015 a Conceptual Design Report (CDR). In 2017 the LBNF facility had its groundbreaking and started construction. In 2018 DUNE issued an Intermediate Design Report (IDR) and in 2019 a Technical Design Report (TDR). The construction of the 10kton far detector modules is based on two declinations of the LAr Time Projection Chamber technology: single-phase (with collection of the electrons from LAr ionization in the liquid phase) and dual-phase (based on the collection of electrons in the gas phase and on the possibility of amplifying them with avalanches occurring in micro-pattern gas detectors). DUNE developed since its foundation both technologies, as progressively described in the CDR, IDR and TDR. Full-scale scale prototypes (300 ton fiducial mass) have been built at CERN for both technologies. The single-phase prototype (ProtoDUNE-SP) was constructed in advance and started seeing first tracks in September 2018, the dual-phase prototype (ProtoDUNE-DP) saw its first tracks 11 months later, in August 2019.

After the LBNF groundbreaking, in 2017 DUNE created international Consortia (on the model of the LHC collaboration for sub-detector elements) for the design and construction of the 10kton modules for both SP and DP technologies. Three Consortia are SP specific (Anode Plane Assemblies, SP Photon detection, SP Cold Electronics), other three are DP specific (Charge Readout Planes, DP Photon detection, DP TPC Electronics). Other Consortia are in common for SP-DP: DAQ, High Voltage, Computing, Cryogenic instrumentation and controls. Two French physicists currently ensure the leadership of the DP Consortia for the Charge Readout Planes and the DP TPC electronics. IN2P3 groups contribute as well to the DAQ and dual-phase Photon Detection Consortia. IN2P3 is also member of the Computing Consortium, where CCIN2P3 is one of the computing centers already integrated in the DUNE offline computing since 2018. The Consortia have been driving the development and editing of the IDR and TDR documents during the last two years.

The participation of the IN2P3 groups to DUNE was reviewed by the IN2P3 Scientific Council of June 2018 (report). DUNE was included in 2018 in the French Roadmap for the TGIR infrastructures. A joint CEA/IN2P3 TGIR project for DUNE was submitted in 2019 and it is currently being reviewed by the HC-TGIR. The project includes contributions to the dual-phase detector construction and to the PIP-II high intensity program aimed at increasing the power of the proton source at FERMILAB.

The primary physics program of DUNE experiment is based on:

1) Precision measurements of the parameters governing $\nu_\mu \rightarrow \nu_e$ and $\nu_\mu \rightarrow \nu_\tau$ oscillations with the goal of measuring the charge-parity (CP) violating phase δ_{CP}. A δ_{CP} 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.
2) Determining the neutrino mass ordering (the sign of Δm^2_{31}, often referred to as the neutrino mass hierarchy).
3) Precision tests of the three-flavor neutrino oscillation paradigm through studies of muon neutrino disappearance and electron neutrino appearance in both muonic neutrino and antineutrino beams, including the measurement of the mixing angle θ_{23} and the determination of the octant in which this angle lies

4) Search for proton decay in several important decay modes. The observation of proton decay would represent a groundbreaking discovery in physics, providing a portal to Grand Unification
5) Detection and measurement of the neutrino flux from possible core-collapse supernova (SNa) within our galaxy

The search for n-nbar oscillations is another interesting subject for DUNE. The study of nuclear effects in the neutrino energy measurement and in n-nbar oscillations is also a point of collaboration with the community of French nuclear theorists, who have been traditionally involved in these topics. The IN2P3 groups are strongly involved in the DUNE physics analysis with contributions to the CP violation analysis and the assessment of its systematics, the three flavors oscillations analysis and tau appearance, the search for SNa neutrinos and the development of the events reconstruction, electron identification and energy flow. Five Ph.D. thesis are ongoing and additional ones are starting.

DUNE has all the features to represent a kind of ultimate long-baseline neutrino oscillations experiment. In particular, it has the unique feature to be sensitive to direct detection of all three neutrino flavors, including ν_τ. The experimental program relies on these main aspects:

a) High beam power
b) Strong matter effects and low systematic uncertainties with the near detector measurements with the exclusive identification of neutrino flavors
c) High statistics and spectral information in the far detectors.

The IN2P3 groups currently involved in DUNE, together with the CEA/Irfu group, have a long-standing record of commitment and detector and analysis expertise. They have been supporting strong R&D activities in view of the preparation of the DUNE. In particular, French researchers are heavily involved with the instrumental development of the dual-phase technology. The dual-phase technology is an evolution of the classic LAr TPC including the possibility of amplifying the ionization deposited in LAr thanks to detectors positioned in the gas phase just a few millimeters above the liquid level. This technology offers several practical advantages in simplifying and making cheaper the construction of very large detectors while augmenting at the same time their performance.

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. The last plane of wires collects the electrons while the previous ones work by induction providing bipolar signals. In the dual-phase design, electrons drift vertically towards an extraction grid just below the liquid-vapor interface. After reaching the grid, a local electric field (2kV/cm), 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 (~30 kV/cm), 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. Amplified electrons are then collected on a finely segmented anode with two perpendicular collection views. Having two collection views offers also advantages with respect to the readout by induction by increasing the S/N ratio and avoiding that signals of nearby particles cancel out when overlapping due to the bipolar signals. The readout pitch (3mm) is almost a factor two finer than in SP while the number of readout channels is less than half of an equivalent SP module. The higher S/N ratio and the possibility of having lower energy thresholds in DP provide in particular opportunities in the study of SNa neutrinos and the detection of the de-excitation photons of the final states of the hit Ar nuclei.

Liquid argon R&D already started at IPNL in 2006 on the Charge Readout electronics and DAQ for very large TPC detectors. The Scientific Council of IN2P3 in June 2013 approved the proposal of the IN2P3 groups, at that time involved in LAGUNA-LBNO, for the construction of a dual-phase prototype at CERN (LBNO-DEMO). LBNO-DEMO, started before the creation of DUNE, eventually became in 2015 ProtoDUNE Dual-Phase.

ProtoDUNE-DP is a full-scale prototype, demonstrator of the dual-phase liquid argon technology foreseen for a DUNE 10kton module. ProtoDUNE-DP has an active volume of 6x6x6 m^3, representing 1/20 of the readout system of a final 10kton detector. The French groups have strong expertise and ensure driving roles in ProtoDUNE-DP and in the DUNE-DP Consortia. They have the responsibility of the LEM and anodes (CEA/Irfu); the light readout electronics (APC-LAPP); the mechanics of the Charge Readout Planes (LAPP); the analog and digital front-end electronics, the timing system and the DAQ system (IP2I); the mechanics of the signal feedthrough chimneys (LAL).

A sub-set of the charge readout and DAQ system (1280 channels over 7680 channels) had been already successfully operating since the Fall 2016 on the 3x1x1m^3 prototype at CERN. The final CRPs and LEMs design was tested in 2018 at CERN in a dedicated cold-box setup before being integrated in ProtoDUNE-DP since the end of 2018. The construction of ProtoDUNE-DP was completed by March 2019. The cryostat was closed at the beginning of June 2019 then the detector filling took until August 9th. After an initial period devoted to the CRPs commissioning first tracks were collected immediately after having powered the LEMs at 2.9 kV on August 29th. More than 1.2 M of events corresponding to 130 TB of data have been acquired so far with the LEMs progressively commissioned at higher voltages/gains. ProtoDUNE-DP is actually taking data with cosmic rays. The SPSC has approved in January 2019 a second running phase for both ProtoDUNE SP and DP after LS2 including detector improvements and further use of the beam to study physics systematics for DUNE.

Immediate perspectives for the IN2P3 in DUNE include the running exploitation and data analysis of ProtoDUNE-DP, the continuation of the physics analysis involvements in DUNE and refinements of the detector design elements for DUNE based on the experience and feedback acquired with ProtoDUNE-DP. Medium term perspectives will include the running of ProtoDUNE-DP after CERN LS2 and the analysis of beam data for the assessment of the far detector systematics. Then since 2022 the project is expected to enter in the construction and installation phase of the detector elements of the far detector which should be concluded by 2026. The running and exploitation of DUNE offers IN2P3 a very long-term perspective for at least a decade since 2026 with a very reach physics program in neutrino oscillations and astro-particle physics. The program offers opportunities for having new groups joining and large perspectives of growth of the involved French community, and capitalizing the preparation and R&D efforts occurred over the last 13 years.