RAPPORT OF THE THESIS MANUSCRIPT OF
Mr. Philippe COTTE

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The work carried out by Philippe Cotte and summarized in his thesis "**Le projet WA105: un prototype de Chambre à Projection Temporelle à Argon Liquide Diphasique utilisant des détecteurs LEMs**" corresponds to one of the main topics on Experimental Particle Physics nowadays: the study of the neutrino physics and the development of the technology in preparation for the next generation of neutrino experiments. This work represents the pioneering efforts to demonstrate the feasibility of the liquid argon technology at large scale developing different TPC prototypes in view of the next generation of large size neutrino detectors.

Neutrino physics is one of the fundamental topics in Particle Physics, with a big impact on Astroparticle Physics and Cosmology, still to be explored. In the latest years, great improvements on the experimental field have contributed to understand the neutrino oscillation phenomenon. This is only possible if neutrinos are massive, which is the first indication of new physics beyond the Standard Model of Particle Physics. In 2015 Profs. T. Kajita and A.B. McDonald were awarded the Nobel prize in physics for the discovery of the neutrino mass through neutrino oscillations. It is an evidence that the studies of the neutrino oscillations are appreciated for having considerably deepened our understanding of the Nature. In spite of the excellent improvements in the last years, fundamental neutrino parameters are still unknown. The octant of θ_{23}, the neutrino mass ordering and the CP violation phase δ will be studied by the next generation of long-baseline neutrino oscillation experiments. One of the most advanced projects is DUNE.

The long-baseline Deep Underground Neutrino Experiment (DUNE) is a planned dual-site neutrino experiment projected to be in operation in 2026. This experiment will study high-energy neutrinos from a new, high-intensity neutrino beam (LBNF) generated by a megawatt-class proton accelerator at Fermilab, after propagating over a distance of 1300 km to a far detector located deep underground at the Sanford Underground Research Facility (SURF) in Lead, South Dakota. The far detector will be composed by four large LArTPC detectors of 10-kt fiducial mass each. DUNE considers both single- and dual-phase designs for the far detectors.

The largest LAr tracking calorimeter ever built is the 600 ton ICARUS detector and a 40 kton DUNE detector represents a substantial scale-up in detector size. A mandatory milestone in view of future long-baseline experiments is a concrete prototyping effort towards the envisioned large-scale detectors. The CERN Neutrino Platform was created with this goal. In particular, two dual-phase liquid argon prototypes have

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been developed and operated: a 3x1x1 m^3 demonstrator and a 6x6x6 m^3 prototype (protoDUNE-DP) within the WA105 project. P. Cotte has developed in his thesis several studies and measurements which are crucial for the successful operation of both LAr TPCs. This establishes the basis for continuing the development and improvement of this technology towards the future LAr TPC experiments.

The manuscript contains 180 pages divided in five chapters. The first part of the thesis contains an extensive and detailed description of the neutrino oscillation physics including the main experimental results, the DUNE project and its physics goals and the description of the dual-phase liquid argon TPCs (DLArTPC) of the WA105 project. The main experimental work is presented in the second part of the thesis, including the simulation and characterization of critical devices for protoDUNE-DP and the analysis of data taken with cosmic muons in the 3x1x1 m^3 demonstrator.

The **first chapter** of the thesis contains a short historical introduction about particle physics and an extensive explanation about the neutrino oscillation phenomenon, including the main experimental variables accessible by previous and future neutrino experiments. The cases of two and three-neutrino flavors are discussed and some equations with the impact of the matter effects in the oscillations are derived. The state-of-the-art of the neutrino oscillation measurements is summarized, emphasizing the main open questions. In addition, there are several short annexes with extra information on neutrino properties beyond oscillations like the number of families, the neutrino mass and its nature. Some parts are a bit repetitive with respect to the main text of the chapter. It is important to remark the impressive bibliography contained at the end of this chapter, including historical papers very relevant for the subject.

The **second chapter** presents the long-baseline DUNE experiment, motivating the technological choices of the project, the scientific goals and expected sensitivities to the neutrino mass ordering and CP violation. Previous long-baseline neutrino experiments are also summarized together with their main achievements. The DUNE neutrino beam and proposed near detector are also described in the context of the neutrino oscillation physics.

The **third chapter** contains the description of the experimental setups where the work of the thesis is developed. The WA105 project is composed by two dual-phase LAr TPC prototypes at the ton scale that have been installed and operated at CERN during 2016-2019. The main characteristics of these detectors are described in detail, including many quantitative information relevant to understand the next chapters. Pros and cons of the dual-phase LAr technology are discussed with special emphasis on the charge amplification and collection subsystems, led by the CEA Saclay group. The main physics processes involved in the charge extraction, amplification in the Large Electron Multiplier (LEM) devices and readout in argon are explained in detail. Several plots are provided to illustrate the behavior of the main physical variables in different conditions that will be measured in the next chapters.

The **forth chapter** presents an important part of the original work developed by P. Cotte in his thesis. The LEMs for the Charge Readout Planes (CRP) were manufactured by the ELTOS company. The LEMs and anodes for protoDUNE-DP have been tested at CEA Saclay and at CERN between 2015 and 2019 and P. Cotte has developed critical simulations of the electric fields in the charge readout planes to understand the impact in the charge collection. The thickness of the LEMs is a critical parameter with an important impact

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on the expected gain of the devices. In this work, a detailed set of measurements was carried out with the development of a dedicated experimental setup and specific methodology at CEA Saclay, where all LEMs of CRP1 and CRP2 were tested. These measurements were compared with the ones obtained by ELTOS. In addition, HV tests on the LEMs helped to identify problems in the LEM design that were solved for the next model to be used in protoDUNE-DP. The effective gain of the LEMs as a function of the LEM voltage was also measured in a high pressure chamber at Saclay and the results were compared with previous measurements in small prototypes. The continuity of the anode readout channels was also verified in the 72 anodes of protoDUNE-DP. After the assembly of the LEMs and anodes in the CRP frames, the CRPs were tested in a dedicated cryogenic box at CERN. This test was an important step to operate the CRPs in real conditions prior their installation in protoDUNE-DP.

Besides the experimental tests, dedicated simulations of the LEMs were developed with ANSYS to study the impact of the dead regions with no amplification holes in the transmission efficiency and in the reconstructed energy. The LEM and anode collection efficiencies were also studied as a function of the amplification, extraction and induction fields. These simulations are compared with real data taken with cosmic muons traversing the 3x1x1 m^3 demonstrator at CERN in chapter five.

The last chapter is devoted to the measurements taken between June and November 2017 with the 3x1x1 m^3 dual-phase LAr TPC demonstrator at CERN using cosmic rays. These data allowed to test the technological choices towards the optimization of the 6x6x6 m^3 detector and study the gain stability along the 3 m^2 of the CRPs. Critical problems in the extraction grid limited its operation up to 5 kV instead of 6.2 kV (nominal voltage). As a consequence, the operation of all different fields was limited. Nevertheless, the 3x1x1 m^3 showed a good performance to detect muon event tracks and showers even with lower fields than the expected nominal ones. The dQ/ds distributions were measured for selected runs of cosmic muons and stable field conditions. The charging up effect and the stability of the gain on the CRP surface were also tested. Finally the effective gain was obtained from the data and compared with previous small prototypes results. An important effort in improving the track reconstruction is developed for this analysis for the runs at low extraction field, with a different treatment of the noise suppression. A phyton code was developed by P. Cotte and the results were compared with LArSoft.

The work presented in the thesis contains a clear description of the methodology, the experimental setups, the physics processes involved in the simulations and the validation of them using a sample of real data acquired with a liquid argon TPC demonstrator operated with cosmic muons at CERN. The main results of the thesis are the characterization and understanding of the LEMs and anodes performance for protoDUNE-DP and future dual-phase LAr TPCs and the analysis of data taken with the 3x1x1 m^3 demonstrator at CERN and their comparison with dedicated simulations.

The thesis contains clear explanations about the conceptual contributions and innovative methods developed by P. Cotte. The results were very useful to detect some problems in the design of some elements and to verify and understand several processes never tested at this scales. Improvements on the LEMs design were possible thanks to this work. Nevertheless, the work is not finished yet since several aspects of the dual-phase LAr TPC technology need to be better understood and tested in the protoDUNE-

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DP. However, this thesis represents an important step towards the operation and data analysis of the future dual-phase LAr detectors and will serve as a reference for further studies.

In **summary**, I consider that manuscript is of high quality, the results presented are original and of great interest in the context of neutrino physics and in particular for the future long-baseline neutrino oscillation experiments. Therefore, **I strongly support the defense of this thesis.**

With my best regards,

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